Draft version January 30, 2019
Typeset using LaTeX twocolumn style in AASTeX61

SUB-THRESHOLD BINARY NEUTRON STAR SEARCH IN ADVANCED LIGO'S FIRST OBSERVING RUN

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ABSTRACT

We present a search for gravitational waves from double neutron star binaries inspirals in Advanced LIGO's first observing run. The search considers a narrow range of binary chirp masses motivated by the population of known double neutron star binaries in the nearby universe. This search differs from previously published results by providing the most sensitive published survey of neutron stars in Advanced LIGO's first observing run within this narrow mass range and including times when only one of the two LIGO detectors was in operation in the analysis. The search was sensitive to binary neutron star inspirals to an average distance of $\sim 85\,\mathrm{Mpc}$ over 93.2 days. We do not identify any unambiguous gravitational wave signals in our sample of 103 sub-threshold candidates with false-alarm-rates of less than one per day. However, given the expected binary neutron star merger rate of $\mathcal{R} \approx 100 - 4000\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, we expect $\mathcal{O}(1)$ gravitational wave events within our candidate list. This suggests the possibility that one or more of these candidates is in fact a binary neutron star merger. Although the contamination fraction in our candidate list is $\sim 99\%$, it might be possible to correlate these events with other messengers to identify a potential multi-messenger signal. We provide an online candidate list with the times and sky locations for all events in order to enable multi-messenger searches.

Keywords: gravitational waves, binary neutron stars, double neutron stars, multimessenger astronomy

1. INTRODUCTION

Advanced LIGO (Aasi et al. 2015) conducted its first observing run (O1) from September 12, 2015 to January 19, 2016. Previous analyses of the 51.5 days of coincident LIGO Hanford and LIGO Livingston data led to three detections of binary black hole mergers (Abbott et al. 2016a,b,c, 2018a; Nitz et al. 2018). No binary neutron star (BNS) or neutron-star, black-hole (NSBH) systems were observed (Abbott et al. 2016d) in O1. We revisit this data with a gravitational wave search targeted at binary neutron star masses and provide a list of candidate events. Searches that catalog low signal-to-noise ratio (SNR) events probe significantly deeper into the cosmos. At low SNR it can be difficult to claim an unambiguous detection, but the multi-messenger nature of BNS systems (Abbott et al. 2017a) can be leveraged to identify authentic gravitational wave events. Comparisons of catalogs provide a discovery space for a host of multi-messenger signals (Smith et al. 2013; Burns et al. 2018). Temporal and/or spatial coincidences between candidates in distinct astrophysical channels could strongly support a multi-messenger discovery.

Most LIGO analyses have required two detectors to identify candidate gravitational wave events (Babak et al. 2013). In Advanced LIGO's first observing run, this requirement excluded nearly half of the available data[1] from analysis (Abbott et al. 2016c). Previous compact binary coalescence (CBC) searches using prototype LIGO (Allen et al. 1999) and TAMA300 (Tagoshi et al. 2001) data analyzed single detector time. In O1, the PyCBC pipeline cataloged single detector triggers primarily for detector characterization purposes, and the search for gravitational waves associated with gamma-ray bursts (Abbott et al. 2017b) also analyzed times with one operating interferometer. In Advanced LIGO's second observing run, GW170817 was first identified as a LIGO Hanford trigger by the GstLAL online pipeline with an estimated false-alarm-rate of ~ 1 / 9000 years (Essick et al. 2017). We include single interferometer data in our search, and we assign significances to O1 single detector candidates for the first time, although we note that others have previously suggested methods to rank these candidates (Cannon et al. 2015; Messick et al. 2017; Callister et al. 2017).

1-OGC (Nitz et al. 2018) recently provided a catalog of gravitational wave candidates in O1 data obtained via the Gravitational Wave Open Science Center (GWOSC)[2] (Vallisneri et al. 2015). The search presented here differs in several major ways. First, we target binary neutron star systems exclusively by applying a mass model to increase sensitivity to those systems (Cannon et al. 2013; Fong 2018). Second, we use a denser grid of template waveforms to minimize signal loss caused by the discrete nature of the template bank (Owen 1996). Third, we include an additional 44.5 days of single detector time in our analysis to increase the analyzed time and improve the sensitivity of the search. Fourth, we include additional coincident data that was not analyzed in 1-OGC. Finally, we include all candidates with false-alarm-rates less than one per day in our list and we provide BAYESTAR (Singer & Price 2016) sky localization estimates for each candidate to encourage multi-messenger followup surveys.

2. SEARCH DESCRIPTION

We used the GstLAL-based inspiral pipeline to conduct a matched-filter analysis (Allen et al. 2012; Cannon et al. 2012; Messick et al. 2017; Sachdev et al. 2019; GstLAL 2018; LIGO Scientific Collaboration 2018; Gstreamer 2018) of data provided by GWOSC and spanning September 12, 2015 to January 19, 2016. GWOSC data is only available for times that pass Category 1 data quality checks (Abbott et al. 2018b), leaving 48.6 days of coincident data and 44.5 days of single detector data. We exclude times known to have hardware injections from our analysis and apply no additional data quality cuts. Additional information on the data quality and hardware injections is available via GWOSC.

2.1. *Template bank*

Matched-filter based analyses correlate the data with a discrete bank of template waveforms (Owen & Sathyaprakash 1999; Harry et al. 2009; Ajith et al. 2014) that model the gravitational wave emission of compact binaries (Blanchet et al. 1995; Buonanno et al. 2009; Ajith et al. 2007). The template bank used for this search was designed to maximize sensitivity to BNS mergers with component masses and spins motivated by double neutron star binary observations (Ozel et al. 2012; Thorsett & Chakrabarty 1999; Abbott et al. 2017c). For astrophysical reasons, we consider component spins that are purely aligned or anti-aligned with the orbital angular momentum, and we limit the dimensionless spin magnitude to be ≤ 0.05 (Abbott et al. 2016e). We model the component masses of our target population with a Gaussian distribution where $\bar{m} = 1.33 M_{\odot}$, $\sigma = 0.05 M_{\odot}$ (Ozel et al. 2012). We

[1] Data that passes Category 1 data quality checks. These DQ cuts eliminate $\sim 6\%$ of coincident time.

[2] https://www.gw-openscience.org/

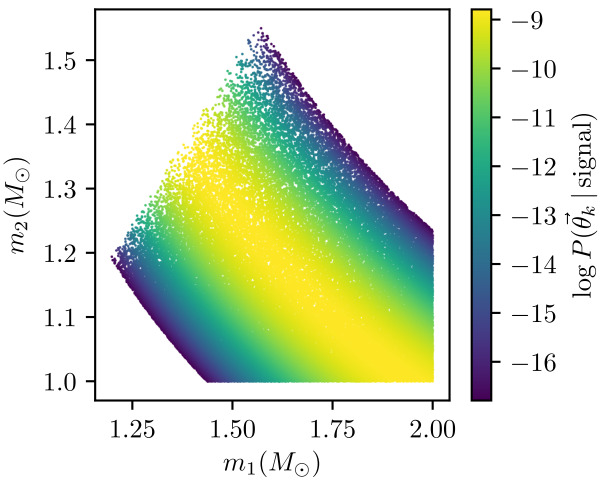

Figure 1. The template bank used for this search as depicted in component masses, m_1, m_2, where $m_1 > m_2$. The colors represent the logarithm of probability that a signal is recovered by a template t_k (with parameters $\vec{\theta}$); for this search, we have chosen a BNS population model with a mean mass of $\bar{m} = 1.33M_\odot$ and a standard deviation of $\sigma = 0.05M_\odot$. The population model considers three standard deviations in chirp mass. Although this population model neglects effects due to redshift, redshift effects are considered when we estimate the sensitivity of the search.

consider three standard deviations in mass and transform coordinates from component mass to chirp mass, $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$, as the chirp mass is the primary parameter that affects the gravitational wave signal (Finn & Chernoff 1993). We broaden the resulting chirp mass distribution to allow for statistical errors in our measurements and we increase the mean of the distribution to account for redshift. This results in a bank that covers detector frame chirp masses of $\mathcal{M} \in (1.04M_\odot, 1.36M_\odot)$.

The final bank of 65 634 template waveforms was constructed with the `TaylorF2` approximant and a minimum match of .99, which ensures that signals with arbitrary parameters have a 99% match with at least one template in the bank. This high precision limits the loss of signals due to using a discrete template bank to $\sim 3\%$; previous searches in O1 data have used template banks that allowed signal loss up to $\lesssim 10\%$ (Dal Canton & Harry 2017; Mukherjee et al. 2018; Nitz et al. 2018).

2.2. *Estimating significance of events*

We use a likelihood-ratio statistic, $\mathcal{L}$, to rank candidate events by their SNR, an autocorrelation based signal consistency check, the sensitivity of each detector at the time of the candidate, and the time and phase delays between different gravitational wave observatories (Cannon 2008; Cannon et al. 2013; Dent & Veitch 2014; Cannon et al. 2015; Messick et al. 2017; Hanna et al. 2019; Sachdev et al. 2019). In addition we include an astrophysical prior, which provides the probability that a signal from a BNS source population is recovered by a particular template in the bank (Fong 2018). The template bank and the prior probabilities associated with each template are shown in Fig. 1.

Candidate events are assigned a false-alarm-rate that describes how often a candidate with a likelihood-ratio statistic at least as high as its own is expected to occur; the false-alarm-rate thus acts as a measure of how often the noise can be expected to produce a candidate with similar properties. The first gravitational wave detections had an extremely low false-alarm-rate (less than 1 / 100,000 years). Here we are interested in digging considerably deeper into the noise probing events with false-alarm-rates as high as 1 / day.

To estimate the false-alarm-rate for candidate events, we use triggers not found in temporal coincidence between the interferometers when both LIGO detectors were operating to estimate the background of noise-like events (Cannon et al. 2013; Cannon et al. 2015; Messick et al. 2017). Single detector events also have their background estimated from the set of non-coincident triggers found when both LIGO detectors were operating, which amounts to 48.6 days of data. We estimate our background from the 48.6 days of coincident data. When a single detector candidate has a higher likelihood ratio than any candidate in the background, we bound its false-alarm-rate to 1 / 48.6 days.

2.3. *Estimating the sensitivity of the search*

The search sensitivity was estimated via Monte Carlo methods. We first generated a set of BNS signals arising from systems with parameters consistent with local populations — we chose a Gaussian distribution for component masses with $m_{\text{mean}} = 1.33M_\odot, \sigma_m = 0.05M_\odot$ and an isotropic distribution for spin. The injected population was modeled to a redshift of $z = 0.2$, and probed a space-time volume of 0.77 Gpc^3 yr. We rejected 17 738 506 simulated signals which had SNRs below 3 to reduce the number of compute cycles. The remaining 112 073 fake signals were injected into the data and subsequently searched for by the detection pipeline. At a given false-alarm-rate threshold, we estimate the overall sensitivity of the search via:

$$\langle VT \rangle = \langle VT_{\text{injected}} \rangle \frac{N_{\text{recovered}}}{N_{\text{total sims}}} \tag{1}$$

where $N_{\text{recovered}}$ varies with the false-alarm-rate threshold. This search is approximately 30% more sensitive at the 1 / 100 year threshold than the previous BNS search presented at the end of Advanced LIGO's first observing run (Abbott et al. 2016d). The inclusion of single detector time in our analysis leads to a $\sim 33\%$ improvement in our estimated $\langle VT \rangle$ at the 1 / day level.

3. RESULTS

We find no unambiguous gravitational wave events, but we identify 103 candidates with false-alarm-rates less than one per day. We provide the time, SNR, and false-alarm-rate of each candidate in Table 1, as well as the probability that the candidate is astrophysical in origin (p_a). We compute p_a using FGMC methods (Farr et al. 2015; Cannon et al. 2015). When the p_a assigned to single detector candidates via FGMC exceeds the estimated single detector p_a bound in (Callister et al. 2017), we substitute the lower bound. The associated source parameters and sky localization estimates obtained via BAYESTAR (Singer & Price 2016) are provided on the LIGO Document Control Center at https://dcc.ligo.org/public/0158/P1900030/001/index.html.

Although we cannot identify any one candidate from our list as astrophysical, we can estimate the number of true signals buried in the list from our search sensitivity and the expected binary neutron star merger rate. At a false-alarm-rate threshold of 1 / day, we estimate $\langle VT \rangle = 6.7 \times 10^5\,\mathrm{Mpc}^3\,\mathrm{yr}$. The LIGO Scientific Collaboration recently estimated the local merger rate of binary neutron star systems to be $\mathcal{R} \approx 100 - 4000\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ at 90% confidence (Abbott et al. 2018a); we adopt a nominal value of $1000\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. We therefore expect that $\langle VT \rangle \times \mathcal{R} = 0.67^{+2.0}_{-.60}$ of the candidates presented here are gravitational wave signals from binary neutron star coalescences. We stress that although the number of expected events depends on uncertainties in both $\langle VT \rangle$ and $\mathcal{R}$, the expected number remains at most $\mathcal{O}(1)$.

A single signal in our candidate list would imply a contamination fraction of 99%. We provide the coalescence times in Table 1 and approximate sky localizations online to encourage multi-messenger searches that have the ability to illuminate true signals buried in the candidate list.

4. DISCUSSION

We have presented a search for gravitational waves from BNS mergers. Although no gravitational wave signal was clearly identified in either single or double interferometer time, we have provided a list of candidate events with false-alarm-rates less than one per day. The parameters for this search overlap with those of gravitational wave catalogs GWTC-1 (Abbott et al. 2018a) and 1-OGC (Nitz et al. 2018). No shared events are found between this candidate list and GWTC-1. While the GstLAL pipeline identified a low-mass marginal candidate, 151012A, in GWTC-1, the detector frame chirp mass is not covered by the bank used here. We note that five single detector candidates meet the selection criteria for inclusion in GWTC-1 (Abbott et al. 2018a).

For 1-OGC, we define overlapping candidates as those that share coalescence times to a precision of two decimal places as differences between the pipelines and the template banks can account for small differences in the measured time of arrival. We find 15 BNS candidates in common with 1-OGC. This is not unexpected; 1-OGC has a trigger rate of ~ 3000 per day. They do not assign any of the overlapping candidates a false-alarm-rate of less than one per day. The variation in estimated false-alarm-rates can arise from differences in the pipelines, template banks, and mass models used in the searches.

In the hopes of enabling multi-messenger, subthreshold follow-up, we have also provided the coalescence times and sky localizations of the 103 candidates with false-alarm-rates less than 1 / day. The analysis of single detector time yielded 15 of the 103 candidates presented in our list, and nearly half of the analyzed data was obtained during times at which only one detector was operating; this highlights the importance of continuing to analyze single interferometer time in future gravitational wave searches.

5. ACKNOWLEDGMENTS

We thank Peter Shawhan, Thomas Dent, and Jonah Kanner for useful feedback and discussion. This work was supported by the National Science Foundation through PHY-1454389, OAC-1841480, PHY-1700765, and PHY-1607585. Computations for this research were performed on the Pennsylvania State University's Institute for CyberScience Advanced CyberInfrastructure (ICS-ACI). This research has made use of data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gw-openscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U.S. National Science Foundation. Virgo is funded by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by Polish and Hungarian institutes. SRM thanks the LSSTC Data Science Fellowship Program, which is funded by LSSTC, NSF Cybertraining Grant-1829740, the Brinson Foundation, and the Moore Foundation. Funding for this project was provided by the Charles E. Kaufman Foundation of The Pittsburgh Foundation. SC is supported by the re-

Date	FAR (yr^{-1})	SNR	p_a
2015-09-14T18:35:13.66^H	145.45	8.59	3.75×10^{-3}
2015-09-18T06:38:39.21	261.92	8.04	2.18×10^{-3}
2015-09-18T22:47:27.39†	193.46	8.52	2.92×10^{-3}
2015-09-19T00:05:01.08	326.71	7.63	1.78×10^{-3}
2015-09-21T10:10:02.92^H	7.52	8.10	6.95×10^{-2}
2015-09-22T11:26:08.35	312.67	8.61	1.86×10^{-3}
2015-09-23T13:47:35.79	165.39	8.56	3.38×10^{-3}
2015-09-24T00:53:02.68	19.68	8.45	2.29×10^{-2}
2015-09-24T05:57:35.24	107.32	8.71	4.88×10^{-3}
2015-09-25T01:24:33.74	56.59	9.15	8.73×10^{-3}
2015-09-25T21:15:15.92	38.39	8.58	1.25×10^{-2}
2015-09-26T23:51:25.50	56.05	8.39	8.81×10^{-3}
2015-09-27T14:28:55.77	243.80	8.60	2.32×10^{-3}
2015-09-29T01:46:01.42†	251.32	8.50	2.26×10^{-3}
2015-09-29T12:25:33.33	358.03	8.64	1.62×10^{-3}
2015-10-01T00:21:02.89	293.57	8.70	1.97×10^{-3}
2015-10-01T05:32:40.37	15.49	8.94	2.83×10^{-2}
2015-10-02T01:49:03.99	118.27	9.21	4.49×10^{-3}
2015-10-02T04:01:03.45	190.83	8.99	2.96×10^{-3}
2015-10-04T22:32:11.75^H	30.52	8.17	1.53×10^{-2}
2015-10-05T07:12:04.91	104.11	8.46	5.02×10^{-3}
2015-10-05T22:29:34.31	139.59	8.24	3.88×10^{-3}
2015-10-09T23:08:05.70	292.60	8.19	1.98×10^{-3}
2015-10-12T02:40:22.39	142.27	8.42	3.82×10^{-3}
2015-10-12T14:26:43.18	322.93	8.35	1.80×10^{-3}
2015-10-13T14:29:57.73^H	37.36	9.02	1.28×10^{-2}
2015-10-14T05:29:42.91†	149.36	8.75	3.68×10^{-3}
2015-10-18T19:03:46.85^H	7.52	8.05	0.181
2015-10-19T17:37:05.25	124.01	8.78	4.30×10^{-3}
2015-10-24T09:01:50.34^L	94.09	10.56	5.53×10^{-3}
2015-10-24T09:03:52.00^L	7.52	9.69	7.96×10^{-2}
2015-10-24T19:53:05.66	360.26	8.57	1.61×10^{-3}
2015-10-28T12:24:31.67^H	7.52	9.06	0.181
2015-10-28T17:03:45.19†	16.08	8.82	2.74×10^{-2}
2015-10-28T17:05:21.17†	0.78	10.63	0.289
2015-10-29T08:27:29.92	345.02	9.04	1.68×10^{-3}
2015-10-29T11:48:01.64	58.64	8.78	8.45×10^{-3}
2015-10-29T12:05:48.00	363.99	8.24	1.59×10^{-3}
2015-10-29T19:18:33.06	193.47	8.26	2.92×10^{-3}
2015-10-30T00:08:56.47	358.38	8.55	1.62×10^{-3}
2015-10-30T04:08:58.11	240.56	8.44	2.35×10^{-3}
2015-10-31T10:27:43.77	320.37	8.05	1.81×10^{-3}
2015-10-31T11:30:36.72	329.59	8.35	1.76×10^{-3}
2015-10-31T22:01:00.91^L	331.06	7.97	1.76×10^{-3}
2015-11-01T11:13:23.94^L	12.17	8.65	3.50×10^{-2}
2015-11-04T13:37:23.67†	103.50	8.43	5.05×10^{-3}
2015-11-04T15:16:09.12†	69.89	9.12	7.23×10^{-3}
2015-11-05T06:20:44.61	312.42	8.56	1.86×10^{-3}
2015-11-06T07:44:18.43	95.56	8.42	5.45×10^{-3}
2015-11-06T10:07:13.79†	172.79	8.55	3.25×10^{-3}
2015-11-06T11:05:19.24	211.28	9.18	2.67×10^{-3}
2015-11-06T22:32:34.11	190.79	8.33	2.96×10^{-3}
2015-11-10T00:32:55.28†	313.96	8.86	1.85×10^{-3}
2015-11-12T20:56:57.33	287.61	8.63	2.01×10^{-3}
2015-11-15T20:03:17.46	26.66	8.35	1.73×10^{-2}
2015-11-15T23:04:35.21	359.97	8.42	1.61×10^{-3}
2015-11-16T10:59:11.86	189.42	8.24	2.98×10^{-3}
2015-11-17T06:34:02.07^H	7.52	8.84	0.181
2015-11-20T21:07:08.38†	15.60	8.95	2.81×10^{-2}
2015-11-21T22:26:44.55	104.06	8.65	5.02×10^{-3}
2015-11-26T13:34:13.65	6.09	8.68	6.23×10^{-2}
2015-11-28T08:29:19.80	229.16	8.16	2.46×10^{-3}
2015-11-28T14:05:27.32	128.85	8.55	4.16×10^{-3}
2015-11-29T03:39:34.71	250.42	9.27	2.27×10^{-3}
2015-12-02T10:45:49.81	201.50	9.24	2.80×10^{-3}
2015-12-02T15:17:48.11	308.63	9.28	1.88×10^{-3}
2015-12-02T17:38:00.95†	363.08	8.14	1.60×10^{-3}
2015-12-03T20:18:18.94	110.58	8.37	4.76×10^{-3}
2015-12-04T01:53:39.14	225.02	9.09	2.50×10^{-3}
2015-12-04T21:14:59.74†	8.89	9.04	4.57×10^{-2}
2015-12-05T10:16:47.45	284.26	8.59	2.03×10^{-3}
2015-12-06T06:50:38.17^L	77.45	7.72	6.64×10^{-3}
2015-12-08T09:27:47.71	344.81	8.27	1.68×10^{-3}
2015-12-08T13:22:36.24	47.36	8.76	1.03×10^{-2}
2015-12-09T07:25:24.68	141.65	7.85	3.84×10^{-3}
2015-12-14T18:15:44.85	145.53	8.43	3.75×10^{-3}
2015-12-14T19:32:20.42	145.58	8.72	3.75×10^{-3}
2015-12-15T06:04:29.41	20.34	8.49	2.23×10^{-2}
2015-12-15T10:53:01.22	154.61	8.78	3.58×10^{-3}
2015-12-18T00:56:19.12	83.80	8.19	6.19×10^{-3}
2015-12-18T09:59:11.16	147.23	8.71	3.72×10^{-3}
2015-12-20T05:33:58.81	300.99	7.86	1.92×10^{-3}
2015-12-22T10:08:48.42	234.05	9.22	2.41×10^{-3}
2015-12-23T00:07:10.93	18.95	8.99	2.36×10^{-2}
2015-12-23T12:23:35.72	60.11	10.25	8.26×10^{-3}
2015-12-23T13:50:49.48	178.46	8.00	3.16×10^{-3}
2015-12-23T16:13:55.82	290.02	8.98	1.99×10^{-3}
2015-12-24T23:05:56.58	47.49	10.08	1.03×10^{-2}
2015-12-24T23:06:28.51	146.99	9.55	3.72×10^{-3}
2015-12-24T23:06:57.04	70.65	9.42	7.16×10^{-3}
2015-12-25T02:16:31.87	320.05	8.49	1.82×10^{-3}
2015-12-28T21:04:05.90^H	160.93	8.57	3.46×10^{-3}
2015-12-29T11:50:15.09^H	234.41	8.23	2.41×10^{-3}
2015-12-31T11:20:54.32^H	180.00	8.82	3.13×10^{-3}
2016-01-02T02:47:29.35	356.13	7.51	1.63×10^{-3}
2016-01-02T02:54:39.60	239.65	8.11	2.36×10^{-3}
2016-01-03T02:29:54.78†	237.44	8.56	2.38×10^{-3}
2016-01-03T17:23:13.26	208.47	8.91	2.70×10^{-3}
2016-01-08T09:21:19.61	136.59	8.89	3.95×10^{-3}
2016-01-08T10:09:33.90†	218.62	8.52	2.58×10^{-3}
2016-01-12T05:19:01.34	107.14	8.34	4.89×10^{-3}
2016-01-15T08:37:05.94	328.35	8.19	1.77×10^{-3}
2016-01-19T05:40:13.04†	228.18	8.85	2.47×10^{-3}

Table 1. Binary neutron star triggers from Advanced LIGO's first observing run with a false-alarm-rate (FAR) less than one per day. We provide the time of coalescence, false-alarm-rate, SNR, and astrophysical probability (p_a) for each candidate. Events marked by H, L were found as single-detector triggers in LIGO-Hanford or LIGO-Livingston, respectively. Events marked by a † occurred within 0.01 seconds of a trigger in 1-OGC (Nitz et al. 2018). We expect $\mathcal{O}(1)$ of these candidates to be gravitational waves.

search programme of the Netherlands Organisation for Scientific Research (NWO). HF acknowledges support from the Natural Sciences and Engineering Research of Council of Canada (NSERC) and the Japan Society for the Promotion of Science (JSPS). This paper has been assigned the document number LIGO-P1800401.

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