B. P. Abbott ... S. E. Hollitt ... D. J. Hosken ... E. J. King ... J. Munch ... D. J. Ottaway ... P. J. Veitch ... et al. (LIGO Scientific Collaboration and Virgo Collaboration)

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Search for transient gravitational waves in coincidence with short-duration radio transients during 2007–2013

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
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We present an archival search for transient gravitational-wave bursts in coincidence with 27 single-pulse triggers from Green Bank Telescope pulsar surveys, using the LIGO, Virgo, and GEO interferometer network. We also discuss a check for gravitational-wave signals in coincidence with Parkes fast radio bursts using similar methods. Data analyzed in these searches were collected between 2007 and 2013. Possible sources of emission of both short-duration radio signals and transient gravitational-wave emission include starquakes on neutron stars, binary coalescence of neutron stars, and cosmic string cusps. While no evidence for gravitational-wave emission in coincidence with these radio transients was found, the current analysis serves as a prototype for similar future searches using more sensitive second-generation interferometers.

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I. INTRODUCTION

Plausible models for coincident or near-coincident emission of both radio and gravitational-wave (GW) transients exist for a number of astrophysical phenomena, including single neutron stars, merging neutron star binaries, and cosmic string cusps. Identification of a GW in close temporal and spatial coincidence with a fast radio burst or other radio transient could place significant constraints on the source of emission, with further constraints possible based on the morphology of the gravitational-wave signal. In this paper, we present a search for GWs in coincidence with millisecond-scale duration radio transient pulses. We have conducted externally triggered searches for gravitational waves with the LIGO/Virgo/GEO network in coincidence with both Galactic single-pulse pulsar candidates from the Green Bank Telescope and a sample of cosmological fast radio burst (FRB) candidates from the Parkes Telescope. Individual radio pulses range from 1 to tens of ms in duration and were observed in frequency bands from hundreds of MHz to 1 GHz. The LIGO Scientific Collaboration (LSC) and Virgo Collaboration regularly search for continuous gravitational waves arriving from the direction of known radio pulsars (see, e.g., Refs. [1,2] for recent examples), and a search for gravitational waves in coincidence with a Vela pulsar glitch was conducted previously [3].

The present work marks the first LIGO/Virgo search in coincidence with radio transients and serves as a prototype for searches with advanced interferometers. Given that the origin of these radio transients is currently unclear, our analysis is designed to search broadly for a gravitational-wave transient burst, without requiring a specific type of waveform.

The paper is organized as follows. After briefly describing the network of gravitational-wave interferometers used in this analysis in Sec. II, we discuss possible mechanisms leading to joint emission of ∼few hundred Hz gravitational waves and radio transient signals. We describe the radio data used in the analysis in Sec. IV, followed by the gravitational-wave search methods and results in Secs. V and VI, respectively. We conclude with a discussion of future prospects for joint analysis of radio and gravitational-wave data in Sec. VII.

II. GRAVITATIONAL-WAVE INTERFEROMETER NETWORK

The LIGO Scientific Collaboration and Virgo Collaboration operate a network of power-recycled Fabry-Perot Michelson interferometers designed to be sensitive to very small relative changes in length (on the order of one part in 10^{21}) of the two orthogonal detector arms. LIGO operates two sites in the United States, one in Livingston Parish, Louisiana, and another at the Hanford site in Washington. Both LIGO facilities operate an interferometer with an arm length of 4 km (called L1 and H1, respectively), and Hanford operated an additional smaller, collocated interferometer (H2) until September 2007 [4]. The LIGO Scientific Collaboration also operates a 600 m interferometer, GEO 600, near Hannover, Germany (G1) [5]. The Virgo Collaboration operates a single 3 km interferometer near Cascina, Italy (V1) [6].

Since this paper involves the analysis of radio transients across a period of several years of initial detector data, multiple science runs of these interferometers are used. Data analyzed in this paper are drawn from summer 2007, coincident with LIGO's fifth and Virgo's first science run, as well as late 2009, coincident with LIGO's sixth and Virgo's third science run. FRB candidates discussed in this paper are coincident with GEO 600 Astrowatch data ranging from 2011 to 2013 and in some cases Virgo's fourth science run, which took place in summer 2011. See

[*]Full author list given at end of the article.

Ref. [7] for a comparison of sensitivities for these instruments from 2007 to 2014.

The LIGO/Virgo network has undergone extensive upgrades to second-generation instruments and during the first Advanced LIGO observation run made the first direct detection of a gravitational-wave transient [8]. After reaching design sensitivity, the Advanced LIGO [9] and Advanced Virgo [10] detectors will have an order of magnitude improvement in range relative to their first-generation counterparts. Additional advanced interferometers are scheduled to join the global network in the future, including Kagra in Japan [11] and a third LIGO site in India [12].

III. POTENTIAL SOURCES OF JOINT RADIO AND GRAVITATIONAL-WAVE EMISSION

There are a number of astrophysical phenomena that may plausibly produce gravitational waves in close coincidence with radio frequency emission. We focus this discussion on a few types of sources which may produce both GWs and radio pulses with frequency and duration suitable to the instruments being used in this analysis. More detailed discussion can be found in Ref. [13].

A. Single neutron stars

Transient gravitational-wave emission can occur when a temporary deformation of a rapidly rotating neutron star creates a quadrupolar moment. Typically, this is believed to happen as a result of crust cracking from magnetic, gravitational or superfluid forces, dubbed a starquake [14,15]; or from other asteroseismic phenomena resulting in the shifting of the neutron star's crust [16]. Asteroseismology may result in several types of quasi-normal oscillatory modes of the neutron star which could produce GW emission. These include torsional modes at low frequencies [17] and the f-mode, with GW emission believed to typically peak around 2 kHz [18]. The amplitude of the GW emission even in optimistic cases, however, is small enough that sensitivity to this type of source will be limited to our own Galaxy even in the advanced detector era.

Radio pulsars result from beamed emission from the poles of a rapidly rotating, highly magnetized neutron star sweeping past the Earth, producing reliably periodic radio signals. The asteroseismic events described above may result in a distinct increase in the rotation rates of these neutron stars, typically followed by a gradual return to their original period. This phenomenon, called a pulsar glitch, has been observed across a large number of pulsars, especially younger ones (see, e.g., Ref. [19] and references therein). A search for gravitational-wave emission from quasinormal modes in coincidence with the observed glitching of pulsars was the subject of a previous LSC publication [3]. Models for neutron star asteroseismic phenomena similar to those under discussion have also motivated previous gravitational-wave searches in coincidence with soft gamma repeater flares [20].

A related phenomenon to radio pulsars is the rotating radio transient (RRAT). RRATs emit short-duration radio pulses similar in character to pulsars but are distinguished by their lack of predictable periodic behavior. RRATs may be "dying" pulsars near the end of their life cycles, neutron stars with especially high magnetization, or conventional pulsars of which the observation is often obscured by intervening matter between the pulsar and Earth, although it is also possible that other phenomena may manifest observationally as RRATs [21].

The standard indication of an asteroseismic event in an isolated neutron star is a pulsar glitch, but there are plausible mechanisms that could result in the observation of a transient radio pulse. This could simply be through the pulsar radio emission coming into view from the Earth as the pulsar's orbit shifts slightly, but there is also some evidence that pulsarlike radio emission can be "switched on" in coincidence with a glitching mechanism [22–24]. For some models, gravitational waves emitted by neutron stars are predicted to be detectable at a distance scale on the order of kiloparsecs with first generation of interferometers. We therefore consider single neutron stars as possible sources of coincident GW and radio transient events.

B. Binary neutron star coalescence

The most easily observable transient gravitational-wave signature in the frequency range of LIGO and Virgo is the merger of a binary system of compact objects, specifically neutron stars or black holes. In the final moments before the compact objects merge, the upward sweep in frequency of the gravitational wave emission is predicted to produce a characteristic chirplike signal. Recent evidence suggests that neutron star binary mergers may create at least some fraction of FRBs [25].

Compact binary coalescence is currently the only confirmed source of directly detectable gravitational waves [8]. Once design sensitivity is reached in the advanced detector era, the ground-based network of interferometers is predicted to detect several to a few hundred binary coalescence GW signals per year of operation [26].

There are several models for radio emission in coincidence with a compact binary coalescence GW signal. This may be pulsarlike radio emission, either from the reactivation of the dormant pulsar emission in one of the neutron stars through interactions prior to merger [27] or by a hypermassive neutron star, which may sometimes be produced as an intermediate state before collapse to a black hole [28]. Another possible mechanism is the radiation at radio frequencies as a result of magnetospheric interactions [29].

Given an appropriate density in the surrounding environment, the gravitational waves emitted by a compact binary coalescence may induce electromagnetic radiation through magnetohydrodynamic interactions. While this interaction would directly produce radiation at the same relatively low frequencies as the GWs themselves, up-conversion through inverse Compton radiation may result in emission at radio frequencies [30]. This particular magnetohydrodynamic mechanism does not necessarily require neutron star coalescence as the mechanism for production of the GWs, but this class of source is likely to be able to produce GWs of suitable amplitude and may be surrounded by an environment suitable to this mechanism [31].

While the sensitivity of the LIGO/Virgo network to gravitational waves from compact binary coalescence scenarios is dependent on the mass, spin, and other properties of the merging objects, interferometers in the initial detector era were typically sensitive to mergers of two neutron stars out to a distance on the order of 10 Mpcs [26].

C. Cosmic strings

Cosmic strings, formed during symmetry breaking in the early Universe, are topological defects thought to be capable of emitting large amounts of energy from their cusps or kinks [32]. A cosmic string cusp may emit gravitational waves with a $f^{-4/3}$ frequency dependence up to a cutoff frequency [33], potentially at frequencies and amplitudes detectable by ground-based interferometers [34,35]. The same cusps may produce short-duration linearly polarized radio bursts [36], a mechanism that has previously been proposed as the origin of the original Lorimer burst [37]. Unlike GWs from other sources discussed, cosmic string cusps could theoretically produce detectable GWs at cosmological distances, which makes them particularly interesting in the context of Parkes FRBs with dispersion measures (DMs) indicative of cosmological distances.

D. Other potential sources

The three classes of sources resulting in simultaneous GW and radio emission described above are not an exhaustive list of theoretical joint sources, but most other types of sources are outside the scope of the analyses described in this paper due to the frequency or duration of the predicted GW and/or radio emission not being well suited to the instruments described in this analysis. For example, some scenarios in which gamma-ray bursts (GRBs) may also result in radio emission are not explicitly considered in developing this analysis; prompt radio emission models [38,39] predict signals at much lower frequencies than the Green Bank and Parkes telescopes can detect, and GRB radio afterglows [40] occur on longer time scales inconsistent with the short radio pulses that are the subject of the searches described in this paper. Core-collapse supernovae have also been proposed as plausible sources of short-duration radio pulses [22] and GW emission. However, we do not explicitly include supernovae among the classes of emission for which we are searching when designing the analysis as there are no observed nearby core-collapse supernovae in close coincidence with the radio transients under consideration.

IV. RADIO PULSE DATA

A. Green Bank single-pulse analysis data

The Robert C. Byrd Green Bank Telescope is the world's largest fully steerable single-dish radio telescope. In the summer of 2007 a drift-scan pulsar survey was conducted in a band of 350 ± 25 MHz [41]. This time frame was during Initial LIGO's fifth science run and Initial Virgo's first science run. In addition to the identification of continuously observable pulsars, a "single-pulse" archival search was performed to look for transient emission of millisecond-scale duration radio pulses. The drift-scan team provided LIGO/Virgo with 33 of these observed single-pulse triggers, ten of which were confirmed to originate from sources with repeated emission through followup observations, thus most likely originating from a pulsar or RRAT. Some of the triggers exhibited only a single radio pulse, while others show several pulses within a 2 min window, but in order to be considered a viable astrophysical signal, all pulses were required to exhibit the $1/f^2$ dispersion behavior expected as a result of dispersion in the interstellar medium.

For each of the 33 candidates, right ascension, declination, dispersion measure, and arrival time at solar system barycenter were provided. The dispersion measures provided (between 15 and 170 $\mathrm{pc\,cm^{-3}}$) are in general consistent with a population of sources from within our own Galaxy. For purposes of the gravitational-wave search, barycentric arrival times were adjusted to UTC arrival times at the detector using code previously applied to LIGO pulsar analyses [2] and cross-checked against conversions to the detector frame provided by Green Bank for a subset of triggers.

A survey of the Galaxy's Northern Celestial Cap was conducted with the Green Bank Telescope in 2009 and 2010 [42]. The single-pulse analysis searching for RRATs or related phenomena was more automated than in the drift-scan analysis and resulted in seven published candidates being reported. These radio triggers corresponded to Initial LIGO's sixth and Initial Virgo's third science runs and were treated identically to drift-scan triggers for GW analysis purposes.

B. Parkes fast radio bursts

The report of FRBs originating from apparently cosmological distances [43–45] has led to an increased interest in short-duration radio transients. These radio transients resemble the original Lorimer burst [46] reported by Parkes in 2007. Since then, Arecibo and Green Bank have each reported an FRB [47,48]. The origin of these FRBs is unclear, with several possible astrophysical sources and terrestrial backgrounds posited as the origin of these radio bursts. Recent followup observations of the Arecibo burst in particular indicate it is a repeating phenomenon [49], which substantially narrows the range of plausible sources. An observed correlation with another astrophysical signal would do much to clarify the nature of these bursts and help confirm their nature as a previously unknown astrophysical phenomenon.

The FRBs of interest for a gravitational-wave search (i.e., omitting bursts from 2001, prior to the construction of sensitive GW interferometers) have observed fluences ranging from 0.55 to 7.3 Jy ms, observed width from 0.64 to 15.6 ms, and dispersion measures suggesting cosmological origin, ranging from 563 to 1629 $\mathrm{pc\,cm^{-3}}$ [50]. While most of these FRBs did not occur during LIGO/Virgo science runs, we performed a check in the Virgo science run data and GEO 600 Astrowatch data when available.

Given the difference in the dispersion measure and other properties, the FRBs are most likely primarily a distinct class of sources compared to the RRAT-like observations in the previous section. Current evidence points to an astrophysical origin, especially as known perytons exhibit properties distinct from FRBs [51]. Several of the emission mechanisms discussed in Sec. III are considered viable candidate progenitors, including neutron star and compact binary coalescing systems [52–54].

C. Short duration radio transients not analyzed

Potential FRBs from sources other than the above were considered but were not coincident with an active network of GW interferometers. In some cases, this was because they occurred during times before sensitive GW data were available [55,56]. This includes the original Lorimer burst [46]. Neither radio transient reported to be observed in coincidence with a GRB in Ref. [57] was coincident with LIGO/Virgo data [58]. The first observation of Arecibo's reported FRB [48,49] occurred during the LIGO and Virgo network upgrade to advanced interferometers and fell during a time in which GEO 600 was not collecting science data as part of its Astrowatch program, with published followup observations also occurring prior to the first Advanced LIGO observation run. Although FRB110523, identified by Green Bank Telescope [47], occurred during Initial Virgo's fourth science run, Virgo was not taking data at the time of the event.

V. ANALYSIS METHOD

A. Procedure

The search for gravitational waves in coincidence with short radio transients was conducted using the X-PIPELINE analysis package [59]. This software has been used for a number of GW searches in coincidence with astrophysical triggers. The analysis procedure for this search was modeled directly after conceptually similar searches for GWs in coincidence with gamma-ray bursts [58,60], but the parameters were modified to account for the particular types of GW sources under consideration. Similar adjustments between GRB and radio transient searches can be used to design radio transient searches in advanced interferometers.

For each radio trigger analyzed, we use X-PIPELINE to conduct a coherent search for a GW signal consistent with the location and time of the radio signal. The physical locations of the individual GW interferometers in the network and the antenna patterns based on their orientations are used to reject potential GW signals that are not consistent with the radio signal's sky location, and only signals within ± 2 minutes of the radio trigger are considered. Coherent and incoherent energy combinations are calculated for each potential trigger, and a series of two-dimensional cuts is applied to reject triggers physically inconsistent with a GW. The false alarm probability of any surviving triggers after all cuts is estimated based on the "time-lag" method. This utilizes interferometric data outside but near the on-source window but introduces hundreds of artificial time offsets between the interferometers that are much larger than the time of flight of a real GW signal in order to obtain statistics on the significance of background in which no coherent signal is present. These procedures are discussed in more detail in Ref. [58], with adjustments for our specific analysis as described below.

B. Analysis-specific search parameters

Our frequency range, temporal and spatial coincidence windows, veto methods, and other parameters were selected to handle a range of possible astrophysical emission mechanisms consistent with short radio pulses as discussed in Sec. III. Where allowed by calibration [61], the frequency range was between 64 Hz and approximately 3 kHz. The majority of GW searches cut off at 2 kHz due to rising shot noise and increased computational costs at higher frequency. However, increasing the upper frequency range for this analysis allows us to include a large subset of possible GW emission from single neutron stars. This increase in frequency also requires us to perform the search over a much denser grid of points on the sky, but the excellent spatial resolution of radio telescopes relative to many other astrophysical observations makes this adjustment feasible.

The on-source time window when searching for GW signals around the radio pulse was taken to be ± 120 s around the observed radio pulse. While it is difficult to exhaustively cover all possible scenarios for time separation between radio and GW emission, the time window selected covers the offsets between emission for the range of scenarios informing the design of the analysis. Since the radio pulse arrival times are corrected for dispersion, there is very little additional uncertainty in the time-of-flight difference between the two types of emission. For analyses in coincidence with Green Bank triggers, the angular uncertainty on the sky is taken to be 0.55 deg. This accounts for two effects, including 95% of Green Bank's total beam width for a 350 MHz signal and including a small adjustment for the drift of the source across the sky during the time span over which X-PIPELINE conducts a test for a self-consistent GW signal.

Unlike recent GW searches in coincidence with GRBs that used similar procedures [60], our background vetoing procedures do not rely on the assumption that the GW signal will be circularly polarized. While this is a reasonable assumption for signals in coincidence with gamma-ray bursts, the greater variety of possible astrophysical sources we consider in this analysis does not justify this assumption.

C. Simulated waveforms

While we do not require a particular signal morphology for our gravitational wave signal, we tune the analysis and characterize its performance based on an ensemble of simulated waveforms. These ten waveforms include:

(i) damped sinusoids at peak frequencies of 1750 and 2300 Hz and decay time constants of 0.26 and 0.13 s, respectively, representing typical emission expected from neutron star asteroseismic events under different assumptions for the neutron star equation of state [18];

(ii) cosmic string cusp waveforms with upper frequency limits of 300 and 1000 Hz;

(iii) linearly polarized Gaussian-envelope sine waves at central frequencies of 235 and 945 Hz with a quality factor of 9;

(iv) circularly polarized Gaussian-envelope sine waves at central frequencies of 150 and 300 Hz, also with a quality factor of 9;

TABLE I. Analyzed Green Bank Telescope single-pulse candidates.

						90% C.L. upper limit ($h_{rss}\times10^{-22}$ Hz$^{-\frac{1}{2}}$)		
Trigger name	Modified Julian day (geocentric)	Right ascension	Declination	Dispersion measure (pc cm^{-3})	Interferometer network	150 Hz sinusoid	Neutron star-neutron star	1750 Hz sinusoid
RRAT 1704-0440	54240.38329	$17^h04^m54.4^s$	−4°40′37.9″	43 ± 1	H1H2L1V1	3.51	4.08	18.6
RRAT 1537+2350	54243.25237	$15^h37^m47.4^s$	23°50′51.1″	15 ± 1	H1H2L1V1	2.33	2.91	10.5
RRAT 1636+0131	54317.05160	$16^h36^m19.4^s$	01°31′07.1″	30 ± 2	H1H2L1V1	3.03	3.60	31.7
RRAT 1651+0130	54317.06177	$16^h51^m42.0^s$	01°30′57.4″	29 ± 1	H1H2L1V1	3.21	3.91	27.8
RRAT 0206-0443	54239.76133	$02^h06^m11.0^s$	−04°43′33.4″	15 ± 1	H1H2L1V1	4.17	5.29	23.2
RRAT 0801-0746	54289.78625	$08^h01^m37.5^s$	−07°47′03.2″	38 ± 1	H1H2L1V1	3.85	4.24	193.
RRAT 0808-0746	54289.79101	$08^h08^m43.3^s$	−07°46′58.9″	36 ± 1	H1H2L1V1	3.55	4.32	72.5
RRAT 0858-0746	54289.82543	$08^h58^m23.9^s$	−07°46′31.4″	40 ± 3	H1H2L1V1	4.35	4.32	14.4
RRAT 0719-1907	54296.74455	$07^h19^m38.3^s$	−19°07′30.2″	27 ± 1	H1H2L1V1	3.96	4.66	21.8
RRAT 2324-0507	54240.64681	$23^h24^m22.2^s$	−05°07′36.0″	15 ± 1	H1H2V1	6.09	5.95	28.6
RRAT 2006+2021	54272.36809	$20^h06^m54.8^s$	20°21′05.8″	66 ± 1	H1H2V1	6.01	6.77	17.4
RRAT 1610-0128	54268.26252	$16^h10^m58.4^s$	−01°28′04.0″	27 ± 1	H1H2V1	5.90	6.71	21.7
RRAT 0706-1058	54315.66206	$07^h06^m43.2^s$	−10°58′20.3″	19 ± 1	H1H2V1	5.21	5.79	25.6
RRAT 0606-0129	54267.84394	$06^h06^m37.5^s$	−01°29′23.9″	17 ± 3	H1H2V1	5.86	5.89	25.2
RRAT 0645-0128	54267.87160	$06^h45^m39.5^s$	−01°28′58.1″	15 ± 2	H1H2V1	5.14	5.65	24.2
RRAT 1336-2034	54294.01362	$13^h36^m28.2^s$	−20°34′21.8″	19 ± 1	H1H2V1	5.63	5.98	25.1
RRAT 0526-1908	54296.66537	$05^h26^m04.9^s$	−19°08′48.8″	26 ± 2	H1H2V1	5.64	5.90	25.0
RRAT 1926+2021	54272.33975	$19^h26^m41.9^s$	20°21′29.1″	21 ± 1	H2L1V1	7.39	115.	17.5
RRAT 1914-1129	54315.16846	$19^h14^m46.3^s$	−11°29′33.5″	91 ± 1	H1H2L1	3.01	3.32	15.4
RRAT 1132+2455	54228.11976	$11^h32^m09.2^s$	24°55′58.7″	24 ± 1	H1H2L1	2.65	2.90	12.8
RRAT 1059-0102	54274.03007	$10^h59^m31.9^s$	−01°02′01.6″	18 ± 1	H1L1V1	4.35	5.67	70.5
RRAT 1944-1017	54281.29872	$19^h44^m08.6^s$	−10°17′07.2″	31 ± 1	H1H2L1	2.84	3.33	15.6
RRAT 0807-1057	54315.70287	$08^h07^m02.7^s$	−10°57′41.4″	18 ± 1	H1H2	5.66	5.39	22.8
RRAT 0614-0328	54224.97146	$6^h14^m37.8^s$	−3°28′44.9″	18 ± 1	H1L1	2.50	3.06	1062
RRAT 0544-0309	54226.94475	$5^h44^m46.3^s$	−3°9′44.8″	67 ± 1	H1L1	2.51	3.05	165.0
GBNCC 04413	55163.27053	$2^h3^m27.6^s$	70°22′43.7″	21 ± 1	H1V1	5.78	5.55	328.0
GBNCC 04743	55169.16190	$0^h53^m24.0^s$	69°38′45.2″	90 ± 1	H1V1	8.43	9.03	138.0

(v) a compact binary coalescence signal from merging 1.4 solar mass neutron stars;

(vi) a compact binary coalescence signal from a 1.4 solar mass neutron star and a 50 solar mass black hole.

These waveforms were selected to broadly represent the types of gravitational wave signals that may occur in coincidence with radio pulses without focusing too heavily on a specific morphology. In addition, the last three waveform types describe specific signals used in previous LIGO searches in order to facilitate sensitivity comparisons with previous work.

VI. ANALYSIS RESULTS

A. Green Bank pulsar surveys

Of the 33 single-pulse radio candidates from the Green Bank drift-scan survey, 25 were analyzable with at least three interferometers in the LIGO/Virgo network. Of the seven RRAT candidates identified in the Northern Celestial Cap survey, only two were analyzable with two or more interferometers in the gravitational wave network.

None of these 27 radio pulses resulted in viable GW candidates. The most significant result for a single candidate was a 2.7% single trial false alarm probability for RRAT 1944-1017, which is completely consistent with background for an ensemble of 27 trials. Table I shows information about each radio candidate, including information about the radio source, as well as GW network and upper limits on h_{rss} (root sum squared strain) for three of the simulated GW waveforms. The last two entries in the table are the Northern Celestial Cap survey triggers.

In addition to individual analysis of the radio candidates, we also perform a weighted binomial test of the p-value distribution of the most significant surviving trigger from the GW analysis, using the same methodology as employed previously in searches for GWs in coincidence with GRBs [7,58]. This distribution is plotted against expectation in Fig. 1. The test yields a background probability of 30%, which is consistent with the null hypothesis.

Possible association between GRBs and FRBs has been widely discussed (see, e.g., Refs. [25,57,62,63]), with indications that at least a subset of radio bursts may be coupled with gamma-ray bursts. We therefore follow previous LIGO analyses [60] and calculate 90% confidence level exclusion distances, for two of our simulated circularly polarized waveforms, assuming an optimistic standard siren in which ∼1% of a solar mass is converted to gravitational-wave energy. A histogram of these distance constraints is shown in Fig. 2. In general, limits in the few to tens of Mpc range indicate that we would be sensitive to a GW signal under these assumptions well outside of our own Galaxy, but at substantially less than the cosmological distances measured for FRBs. For the 150 Hz sine-Gaussian waveform, using standard calculations [64] about $\sim 4 \times 10^{52}$ ergs of energy would have to be emitted for a detectable source emitting isotropically at a distance of 20 Mpc.

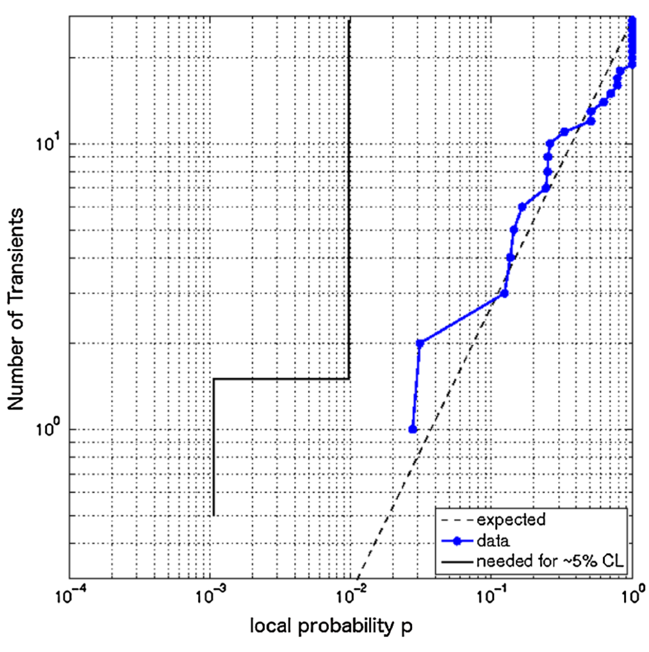

FIG. 1. Cumulative distribution of p-values from the analysis of 27 radio triggers from Green Bank for evidence of a GW transient associated with the event. The expected distribution in the absence of a signal is indicated by the dashed line. Points at p-value of unity are triggers with no event in the on-source region after selection cuts.

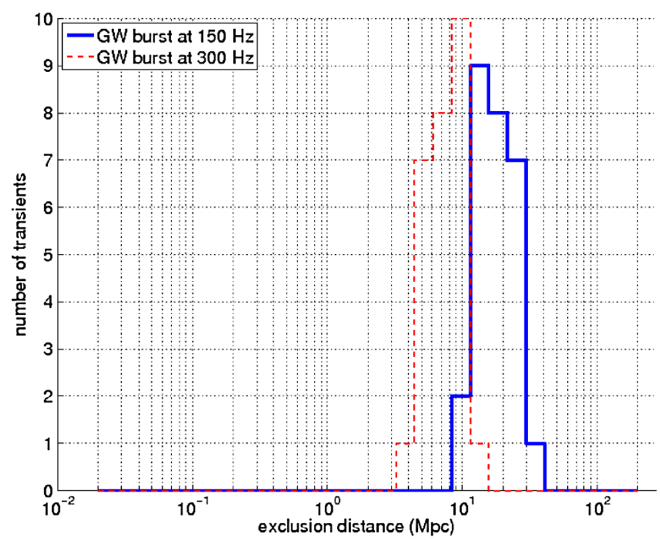

FIG. 2. Histograms for the sample of Green Bank radio transients of distance exclusions at 90% confidence level for possible GRBs associated with radio transients. Waveforms are circularly polarized sine-Gaussian GW burst models with central frequency of 150 and 300 Hz.

TABLE II. Analyzed FRB candidates from the Parkes telescope. No evidence of gravitational-wave emission was observed in coincidence with these FRBs.

Trigger name	Modified Julian day (geocentric)	Right ascension	Declination	Dispersion measure (pc cm^{-3})	Interferometer network
FRB 110626	55738.89810	$21^h03^m43^s$	$-44°44'19''$	723.0	G1V1
FRB 110703	55745.79142	$23^h30^m51^s$	$-02°52'24''$	1103.6	G1V1
FRB 110220	55612.08041	$22^h34^m38.2^s$	$-12°33'44''$	944.8	G1
FRB 120127	55953.34122	$23^h15^m6.3^s$	$-18°25'37''$	555.2	G1
FRB 130628	56471.16527	$9^h03^m2.5^s$	$3°26'16''$	469.7	G1
FRB 131104	56600.75279	$6^h44^m10.4^s$	$-51°16'40''$	779.3	G1

B. Parkes telescope FRBs

We examined a list of 14 FRBs [50] from Parkes, occurring as early as 2001 but primarily concentrated within the last five years. While none of the event times corresponded to science runs for Hanford or Livingston, eight of the FRBs corresponded to times when GEO 600 Astrowatch data were available, and two of these also corresponded to data from Initial Virgo's fourth science run. After omitting two of these FRBs for which GEO data were too nonstationary to yield a quality GW analysis, we searched for GWs in coincidence with a total of six Parkes FRBs. Analysis parameters were kept as similar as feasible to the Green Bank drift-scan analysis described previously. However, the upper end of the frequency range was lowered to 1764 Hz due to the range over which GEO data are calibrated [7], and the higher frequency damped sinusoids were left out of the set of GW morphologies simulated. Since the triggers are nominally at cosmological distances and we are unlikely to be sensitive to damped sinusoid-type signals from neutron stars outside our own Galaxy, this limitation is not a major concern.

There was no evidence of a gravitational-wave signal for any of these FRBs (the most significant single trial p-value was 0.07), although it should be noted that the smaller GEO interferometer is less sensitive than the larger interferometers. As such we treat this analysis primarily as a check for loud candidates and do not quote sensitivity upper limits for this search. Instead a list of currently published FRBs without evidence for corresponding GW emission is given in Table II. Since these are not consistent in terms of DM or other characteristics with the RRAT-like candidates identified by Green Bank, we do not include these in the binomial test or other distributional studies presented in Figs. 1 and 2.

VII. CONCLUSIONS AND FUTURE PROSPECTS

The searches described in this current paper should be viewed largely as prototypes for future searches with instruments that will eventually be an order of magnitude more sensitive than the best sensitivities presented here. Since much is currently unknown about FRBs and related phenomena, identification of a GW in close coincidence with a radio burst could provide insight into both the distance and, depending on the GW morphology, astrophysical origin of the radio transient.

In addition to more sensitive searches in coincidence with fast radio bursts, efforts are also underway within the LIGO and Virgo collaborations to analyze radio transients of longer durations resulting from instruments operating at lower frequency than the Green Bank or Parkes telescopes. Since these transients have properties very different than the ones described here and are not generally expected to come from the same sources, substantially different analysis methods are required to address searches for GWs in coincidence with these signals [65].

In the case of fast radio bursts, it is worth noting that arguments based on the Parkes field of view and observation time suggest that if FRBs are in fact of astrophysical origin, the vast majority of FRBs are currently missed by radio telescopes [45,66]. Accounting for possible anisotropies in the distribution of FRBs and including both mid-galactic and high-latitude survey data, the all-sky rate for FRBs is estimated to be between 1100 to 9600 FRBs per day above a threshold fluence of 4.0 Jy ms [67]. While externally triggered searches can look for signals with amplitudes of as much as ~3 lower than all-sky searches [68], if such a population of FRBs generated detectable gravitational-wave signals, statistical arguments suggest they would be likely to show up in all-sky transient searches (e.g., Ref. [69]) as well. However, these detections would not be clearly associated with a FRB and thus lack the ability of a multimessenger search in constraining the possible source of FRBs. In the coming years, statistical information on FRBs is likely to be dramatically improved, especially as wider field radio instruments come online [70–72].

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Khazanov,[108] N. Kijbunchoo,[38] Chunglee Kim,[77] J. Kim,[109] K. Kim,[110] Nam-Gyu Kim,[77] Namjun Kim,[41] Y.-M. Kim,[109] E. J. King,[102] P. J. King,[38] D. L. Kinzel,[6] J. S. Kissel,[38] L. Kleybolte,[28] S. Klimenko,[5] S. M. Koehlenbeck,[9] K. Kokeyama,[2] S. Koley,[10] V. Kondrashov,[1] A. Kontos,[11] M. Korobko,[28] W. Z. Korth,[1] I. Kowalska,[61] D. B. Kozak,[1] V. Kringel,[9] A. Królak,[111,112] C. Krueger,[18] G. Kuehn,[9] P. Kumar,[70] L. Kuo,[73] A. Kutynia,[111] B. D. Lackey,[36] M. Landry,[38] J. Lange,[113] B. Lantz,[41] P. D. Lasky,[114] A. Lazzarini,[1] C. Lazzaro,[64,43] P. Leaci,[79,29] S. Leavey,[37] E. O. Lebigot,[31,71] C. H. Lee,[109] H. K. Lee,[110] H. M. Lee,[115] K. Lee,[37] A. Lenon,[36] M. Leonardi,[88,89] J. R. Leong,[9] N. Leroy,[24] N. Letendre,[7] Y. Levin,[114] B. M. Levine,[38] T. G. F. Li,[1] A. Libson,[11] T. B. Littenberg,[116] N. A. Lockerbie,[105] J. Logue,[37] A. L. Lombardi,[101] J. E. Lord,[36] M. Lorenzini,[13,14] V. Loriette,[117] M. Lormand,[6] G. Losurdo,[58] J. D. Lough,[9,18] H. Lück,[18,9] A. P. Lundgren,[9] J. Luo,[78] R. Lynch,[11] Y. Ma,[51] T. MacDonald,[41] B. Machenschalk,[9] M. MacInnis,[11] D. M. Macleod,[2] F. Magaña-Sandoval,[36] R. M. Magee,[56] M. Mageswaran,[1] E. Majorana,[29] I. Maksimovic,[117] V. Malvezzi,[26,14] N. Man,[53] V. Mandic,[84] V. Mangano,[37] G. L. Mansell,[21] M. Manske,[17] M. Mantovani,[35] F. Marchesoni,[118,34] F. Marion,[7] S. Márka,[40] Z. Márka,[40] A. S. Markosyan,[41] E. Maros,[1] F. Martelli,[57,58] L. Martellini,[53] I. W. Martin,[37] R. M. Martin,[5] D. V. Martynov,[1] J. N. Marx,[1] K. Mason,[11] A. Masserot,[7] T. J. Massinger,[36] M. Masso-Reid,[37] S. Mastrogiovanni,[79,29] F. Matichard,[11] L. Matone,[40] N. Mavalvala,[11] N. Mazumder,[56] G. Mazzolo,[9] R. McCarthy,[38] D. E. McClelland,[21] S. McCormick,[6] S. C. McGuire,[119] G. McIntyre,[1] J. McIver,[101] D. J. McManus,[21] S. T. McWilliams,[103] D. Meacher,[53] G. D. Meadors,[30,9] J. Meidam,[10] A. Melatos,[85] G. Mendell,[38] D. Mendoza-Gandara,[9] R. A. Mercer,[17] E. L. Merilh,[38] M. Merzougui,[53] S. Meshkov,[1] C. Messenger,[37] C. Messick,[91] R. Metzdorff,[60] P. M. Meyers,[84] F. Mezzani,[29,79] H. Miao,[45] C. Michel,[65] H. Middleton,[45] E. E. Mikhailov,[120] L. Milano,[68,4] A. L. Miller,[5,79,29] J. Miller,[11] M. Millhouse,[32] Y. Minenkov,[14] J. Ming,[30,9] S. Mirshekari,[121] C. Mishra,[16] S. Mitra,[15] V. P. Mitrofanov,[49] G. Mitselmakher,[5] R. Mittleman,[11] A. Moggi,[20] M. Mohan,[35] S. R. P. Mohapatra,[11] M. Montani,[57,58] B. C. Moore,[90] C. J. Moore,[122] D. Moraru,[38] G. Moreno,[38] S. R. Morriss,[86] K. Mossavi,[9] B. Mours,[7]

C. M. Mow-Lowry,[45] C. L. Mueller,[5] G. Mueller,[5] A. W. Muir,[83] Arunava Mukherjee,[16] D. Mukherjee,[17] S. Mukherjee,[86] K. N. Mukund,[15] A. Mullavey,[6] J. Munch,[102] D. J. Murphy,[40] P. G. Murray,[37] A. Mytidis,[5] I. Nardecchia,[26,14] L. Naticchioni,[79,29] R. K. Nayak,[123] V. Necula,[5] K. Nedkova,[101] G. Nelemans,[52,10] M. Neri,[46,47] A. Neunzert,[72] G. Newton,[37] T. T. Nguyen,[21] A. B. Nielsen,[9] S. Nissanke,[52,10] A. Nitz,[9] F. Nocera,[35] D. Nolting,[6] M. E. N. Normandin,[86] L. K. Nuttall,[36] J. Oberling,[38] E. Ochsner,[17] J. O'Dell,[124] E. Oelker,[11] G. H. Ogin,[125] J. J. Oh,[126] S. H. Oh,[126] F. Ohme,[83] M. Oliver,[67] P. Oppermann,[9] Richard J. Oram,[6] B. O'Reilly,[6] R. O'Shaughnessy,[113] C. D. Ott,[76] D. J. Ottaway,[102] R. S. Ottens,[5] H. Overmier,[6] B. J. Owen,[82] A. Pai,[106] S. A. Pai,[48] J. R. Palamos,[59] O. Palashov,[108] C. Palomba,[29] A. Pal-Singh,[28] H. Pan,[73] C. Pankow,[17,107] F. Pannarale,[83] B. C. Pant,[48] F. Paoletti,[35,20] A. Paoli,[35] M. A. Papa,[30,17,9] H. R. Paris,[41] W. Parker,[6] D. Pascucci,[37] A. Pasqualetti,[35] R. Passaquieti,[19,20] D. Passuello,[20] B. Patricelli,[19,20] Z. Patrick,[41] B. L. Pearlstone,[37] M. Pedraza,[1] R. Pedurand,[65,127] L. Pekowsky,[36] A. Pele,[6] S. Penn,[128] R. Pereira,[40] A. Perreca,[1] M. Phelps,[37] O. J. Piccinni,[79,29] M. Pichot,[53] F. Piergiovanni,[57,58] V. Pierro,[8] G. Pillant,[35] L. Pinard,[65] I. M. Pinto,[8] M. Pitkin,[37] H. J. Pletsch,[9] R. Poggiani,[19,20] P. Popolizio,[35] A. Post,[9] J. Powell,[37] J. Prasad,[15] V. Predoi,[83] S. S. Premachandra,[114] T. Prestegard,[84] L. R. Price,[1] M. Prijatelj,[35] M. Principe,[8] S. Privitera,[30] G. A. Prodi,[88,89] L. Prokhorov,[49] O. Puncken,[9] M. Punturo,[34] P. Puppo,[29] M. Pürrer,[83] H. Qi,[17] J. Qin,[51] V. Quetschke,[86] E. A. Quintero,[1] R. Quitzow-James,[59] F. J. Raab,[38] D. S. Rabeling,[21] H. Radkins,[38] P. Raffai,[54] S. Raja,[48] M. Rakhmanov,[86] P. Rapagnani,[79,29] V. Raymond,[30] M. Razzano,[19,20] V. Re,[26] J. Read,[23] C. M. Reed,[38] T. Regimbau,[53] L. Rei,[47] S. Reid,[50] D. H. Reitze,[1,5] H. Rew,[120] F. Ricci,[79,29] K. Riles,[72] N. A. Robertson,[1,37] R. Robie,[37] F. Robinet,[24] A. Rocchi,[14] L. Rolland,[7] J. G. Rollins,[1] V. J. Roma,[59] J. D. Romano,[86] R. Romano,[3,4] G. Romanov,[120] J. H. Romie,[6] D. Rosińska,[129,44] S. Rowan,[37] A. Rüdiger,[9] P. Ruggi,[35] K. Ryan,[38] S. Sachdev,[1] T. Sadecki,[38] L. Sadeghian,[17] L. Salconi,[35] M. Saleem,[106] F. Salemi,[9] A. Samajdar,[123] L. Sammut,[85,114] E. J. Sanchez,[1] V. Sandberg,[38] B. Sandeen,[107] J. R. Sanders,[72] B. Sassolas,[65] B. S. Sathyaprakash,[83] P. R. Saulson,[36] O. E. S. Sauter,[72] R. L. Savage,[38] A. Sawadsky,[18] P. Schale,[59] R. Schilling,[9,†] J. Schmidt,[9] P. Schmidt,[1,76] R. Schnabel,[28] R. M. S. Schofield,[59] A. Schönbeck,[28] E. Schreiber,[9] D. Schuette,[9,18] B. F. Schutz,[83] J. Scott,[37] S. M. Scott,[21] D. Sellers,[6] D. Sentenac,[35] V. Sequino,[26,14] A. Sergeev,[108] G. Serna,[23] Y. Setyawati,[52,10] A. Sevigny,[38] D. A. Shaddock,[21] M. S. Shahriar,[107] M. Shaltev,[9] Z. Shao,[1] B. Shapiro,[41] P. Shawhan,[63] A. Sheperd,[17] D. H. Shoemaker,[11] D. M. Shoemaker,[64] K. Siellez,[53] X. Siemens,[17] M. Sieniawska,[44] D. Sigg,[38] A. D. Silva,[12] D. Simakov,[9] A. Singer,[1] L. P. Singer,[69] A. Singh,[30,9] R. Singh,[2] A. Singhal,[13] A. M. Sintes,[67] B. J. J. Slagmolen,[21] J. R. Smith,[23] N. D. Smith,[1] R. J. E. Smith,[1] E. J. Son,[126] B. Sorazu,[37] F. Sorrentino,[47] T. Souradeep,[15] A. K. Srivastava,[95] A. Staley,[40] M. Steinke,[9] J. Steinlechner,[37] S. Steinlechner,[37] D. Steinmeyer,[9,18] B. C. Stephens,[17] D. Stiles,[97] R. Stone,[86] K. A. Strain,[37] N. Straniero,[65] G. Stratta,[57,58] N. A. Strauss,[78] S. Strigin,[49] R. Sturani,[121] A. L. Stuver,[6] T. Z. Summerscales,[130] L. Sun,[85] P. J. Sutton,[83] B. L. Swinkels,[35] M. J. Szczepańczyk,[97] M. Tacca,[31] D. Talukder,[59] D. B. Tanner,[5] M. Tápai,[96] S. P. Tarabrin,[9] A. Taracchini,[30] R. Taylor,[1] T. Theeg,[9] M. P. Thirugnanasambandam,[1] E. G. Thomas,[45] M. Thomas,[6] P. Thomas,[38] K. A. Thorne,[6] E. Thrane,[114] S. Tiwari,[13,89] V. Tiwari,[83] K. V. Tokmakov,[105] C. Tomlinson,[87] M. Tonelli,[19,20] C. V. Torres,[86,†] C. I. Torrie,[1] D. Töyrä,[45] F. Travasso,[33,34] G. Traylor,[6] D. Trifirò,[22] M. C. Tringali,[88,89] L. Trozzo,[131,20] M. Tse,[11] M. Turconi,[53] D. Tuyenbayev,[86] D. Ugolini,[132] C. S. Unnikrishnan,[98] A. L. Urban,[17] S. A. Usman,[36] H. Vahlbruch,[18] G. Vajente,[1] G. Valdes,[86] N. van Bakel,[10] M. van Beuzekom,[10] J. F. J. van den Brand,[62,10] C. Van Den Broeck,[10] D. C. Vander-Hyde,[36,23] L. van der Schaaf,[10] J. V. van Heijningen,[10] A. A. van Veggel,[37] M. Vardaro,[42,43] S. Vass,[1] M. Vasúth,[39] R. Vaulin,[11] A. Vecchio,[45] G. Vedovato,[43] J. Veitch,[45] P. J. Veitch,[102] K. Venkateswara,[133] D. Verkindt,[7] F. 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(LIGO Scientific Collaboration and Virgo Collaboration)

A. M. Archibald,[136] S. Banaszak,[17] A. Berndsen,[137] J. Boyles,[138] R. F. Cardoso,[139] P. Chawla,[140] A. Cherry,[137] L. P. Dartez,[86] D. Day,[17] C. R. Epstein,[141] A. J. Ford,[86] J. Flanigan,[17] A. Garcia,[86] J. W. T. Hessels,[136,142] J. Hinojosa,[86] F. A. Jenet,[86] C. Karako-Argaman,[140] V. M. Kaspi,[140] E. F. Keane,[143] V. I. Kondratiev,[136,144] M. Kramer,[145,146] S. Leake,[86] D. Lorimer,[139] G. Lunsford,[86] R. S. Lynch,[147] J. G. Martinez,[86] A. Mata,[86] M. A. McLaughlin,[139] C. A. McPhee,[137] T. Penucci,[148] S. Ransom,[149] M. S. E. Roberts,[150] M. D. W. Rohr,[17] I. H. Stairs,[137] K. Stovall,[151] J. van Leeuwen,[136,142] A. N. Walker,[17] and B. L. Wells[17,152]

[1]*LIGO, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[3]*Università di Salerno, Fisciano, I-84084 Salerno, Italy*
[4]*INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*
[5]*University of Florida, Gainesville, Florida 32611, USA*
[6]*LIGO Livingston Observatory, Livingston, Louisiana 70754, USA*
[7]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France*
[8]*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
[9]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[10]*Nikhef, Science Park, 1098 XG Amsterdam, Netherlands*
[11]*LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[12]*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos,São Paulo, Brazil*
[13]*INFN, Gran Sasso Science Institute, I-67100L'Aquila, Italy*
[14]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[15]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[16]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560012, India*
[17]*University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA*
[18]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[19]*Università di Pisa, I-56127 Pisa, Italy*
[20]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[21]*Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[22]*The University of Mississippi, University, Mississippi 38677, USA*
[23]*California State University Fullerton, Fullerton, California 92831, USA*
[24]*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
[25]*Chennai Mathematical Institute, Chennai 603103, India*
[26]*Università di Roma Tor Vergata, I-00133 Roma, Italy*
[27]*University of Southampton, Southampton SO17 1BJ, United Kingdom*
[28]*Universität Hamburg, D-22761 Hamburg, Germany*
[29]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[30]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Potsdam-Golm, Germany*
[31]*APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France*
[32]*Montana State University, Bozeman, Montana 59717, USA*
[33]*Università di Perugia, I-06123 Perugia, Italy*
[34]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[35]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[36]*Syracuse University, Syracuse, New York 13244, USA*
[37]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[38]*LIGO Hanford Observatory, Richland, Washington 99352, USA*
[39]*Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary*
[40]*Columbia University, New York, New York 10027, USA*
[41]*Stanford University, Stanford, California 94305, USA*
[42]*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
[43]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[44]*CAMK-PAN, 00-716 Warsaw, Poland*
[45]*University of Birmingham, Birmingham B15 2TT, United Kingdom*

[46]Università degli Studi di Genova, I-16146 Genova, Italy
[47]INFN, Sezione di Genova, I-16146 Genova, Italy
[48]RRCAT, Indore MP 452013, India
[49]Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
[50]SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom
[51]University of Western Australia, Crawley, Western Australia 6009, Australia
[52]Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, Netherlands
[53]Artemis, Université Côte d'Azur, CNRS, Observatoire Côte d'Azur, CS 34229, Nice cedex 4, France
[54]MTA Eötvös University, "Lendulet" Astrophysics Research Group, Budapest 1117, Hungary
[55]Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France
[56]Washington State University, Pullman, Washington 99164, USA
[57]Università degli Studi di Urbino 'Carlo Bo', I-61029 Urbino, Italy
[58]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
[59]University of Oregon, Eugene, OR 97403, USA
[60]Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France
[61]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
[62]VU University Amsterdam, 1081 HV Amsterdam, Netherlands
[63]University of Maryland, College Park, Maryland 20742, USA
[64]Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA
[65]Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France
[66]Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
[67]Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
[68]Università di Napoli 'Federico II', Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
[69]NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
[70]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada
[71]Tsinghua University, Beijing 100084, China
[72]University of Michigan, Ann Arbor, Michigan 48109, USA
[73]National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
[74]Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
[75]University of Chicago, Chicago, Illinois 60637, USA
[76]Caltech CaRT, Pasadena, California 91125, USA
[77]Korea Institute of Science and Technology Information, Daejeon 305-806, Korea
[78]Carleton College, Northfield, Minnesota 55057, USA
[79]Università di Roma 'La Sapienza', I-00185 Roma, Italy
[80]University of Brussels, Brussels 1050, Belgium
[81]Sonoma State University, Rohnert Park, California 94928, USA
[82]Texas Tech University, Lubbock, Texas 79409, USA
[83]Cardiff University, Cardiff CF24 3AA, United Kingdom
[84]University of Minnesota, Minneapolis, Minnesota 55455, USA
[85]The University of Melbourne, Parkville, Victoria 3010, Australia
[86]The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA
[87]The University of Sheffield, Sheffield S10 2TN, United Kingdom
[88]Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
[89]INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
[90]Montclair State University, Montclair, New Jersey 07043, USA
[91]The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[92]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[93]School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
[94]Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India
[95]Institute for Plasma Research, Bhat, Gandhinagar 382428, India
[96]University of Szeged, Dóm tér 9, Szeged 6720, Hungary
[97]Embry-Riddle Aeronautical University, Prescott, Arizona 86301, USA
[98]Tata Institute of Fundamental Research, Mumbai 400005, India
[99]INAF, Osservatorio Astronomico di Capodimonte, I-80131, Napoli, Italy
[100]American University, Washington, D.C., 20016, USA
[101]University of Massachusetts-Amherst, Amherst, Massachusetts 01003, USA

[102]University of Adelaide, Adelaide, South Australia 5005, Australia
[103]West Virginia University, Morgantown, West Virginia 26506, USA
[104]University of Biał ystok, 15-424 Biał ystok, Poland
[105]SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
[106]IISER-TVM, CET Campus, Trivandrum Kerala 695016, India
[107]Northwestern University, Evanston, Illinois 60208, USA
[108]Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
[109]Pusan National University, Busan 609-735, Korea
[110]Hanyang University, Seoul 133-791, Korea
[111]NCBJ, 05-400 Świerk-Otwock, Poland
[112]IM-PAN, 00-956 Warsaw, Poland
[113]Rochester Institute of Technology, Rochester, New York 14623, USA
[114]Monash University, Victoria 3800, Australia
[115]Seoul National University, Seoul 151-742, Korea
[116]University of Alabama in Huntsville, Huntsville, Alabama 35899, USA
[117]ESPCI, CNRS, F-75005 Paris, France
[118]Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
[119]Southern University and A&M College, Baton Rouge, Louisiana 70813, USA
[120]College of William and Mary, Williamsburg, Virginia 23187, USA
[121]Instituto de Física Teórica, University Estadual Paulista/ICTP South American Institute for Fundamental Research, São Paulo, São Paulo 01140-070, Brazil
[122]University of Cambridge, Cambridge CB2 1TN, United Kingdom
[123]IISER-Kolkata, Mohanpur, West Bengal 741252, India
[124]Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
[125]Whitman College, 345 Boyer Avenue, Walla Walla, Washington 99362 USA
[126]National Institute for Mathematical Sciences, Daejeon 305-390, Korea
[127]Université de Lyon, F-69361 Lyon, France
[128]Hobart and William Smith Colleges, Geneva, New York 14456, USA
[129]Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland
[130]Andrews University, Berrien Springs, Michigan 49104, USA
[131]Università di Siena, I-53100 Siena, Italy
[132]Trinity University, San Antonio, Texas 78212, USA
[133]University of Washington, Seattle, Washington 98195, USA
[134]Kenyon College, Gambier, Ohio 43022, USA
[135]Abilene Christian University, Abilene, Texas 79699, USA
[136]ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, Netherlands
[137]Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia V6T 1Z1, Canada
[138]Department of Physics and Astronomy, Western Kentucky University, Bowling Green, Kentucky 42101, USA
[139]Dept. of Physics and Astronomy, West Virginia University, Morgantown, West Virginia 26506, USA
[140]Department of Physics & McGill Space Institute, McGill University, 3600 Univesity Street, Montreal, QC H3A 2T8, Canada
[141]Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, Ohio 43210, USA
[142]Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
[143]SKA Organization, Jodrell Bank Observatory, SK11 9DL, United Kingdom
[144]Astro Space Center of the Lebedev Physical Institute, Profsoyuznaya str. 84/32, Moscow 117997, Russia
[145]Max Planck Institute for Radio Astronomy, Auf dem Hugel 69, 53121 Bonn, Germany
[146]The University of Manchester, Oxford Rd, Manchester M13 9PL, United Kingdom
[147]National Radio Astronomy Observatory, Green Bank, West Virginia 24944, USA
[148]Department of Astronomy, University of Virginia, Charlottesville, Virginia 22904-4325, USA
[149]National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA
[150]Eureka Scientific, Inc., 2452 Delmer Street, Suite 100, Oakland, California 94602-3017, USA
[151]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[152]Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, USA

[†]Deceased.