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All-sky search for long-duration gravitational-wave transients in the second Advanced LIGO observing run

The LIGO Scientific Collaboration and The Virgo Collaboration

ABSTRACT

We present the results of a search for long-duration gravitational-wave transients in the data from the Advanced LIGO second observation run; we search for gravitational-wave transients of 2 − 500 s duration in the 24 − 2048 Hz frequency band with minimal assumptions about signal properties such as waveform morphologies, polarization, sky location or time of occurrence. Targeted signal models include fallback accretion onto neutron stars, broadband chirps from innermost stable circular orbit waves around rotating black holes, eccentric inspiral-merger-ringdown compact binary coalescence waveforms, and other models. The second observation run totals about 118.3 days of coincident data between November 2016 and August 2017. We find no significant events within the parameter space that we searched, apart from the already-reported binary neutron star merger GW170817. We thus report sensitivity limits on the root-sum-square strain amplitude $h_{\rm rss}$ at 50% efficiency. These sensitivity estimates are an improvement relative to the first observing run and also done with an enlarged set of gravitational-wave transient waveforms. Overall, the best search sensitivity is $h_{\rm rss}^{50\%}$=2.7×10^{-22} Hz$^{-1/2}$ for a millisecond magnetar model. For eccentric compact binary coalescence signals, the search sensitivity reaches $h_{\rm rss}^{50\%}$=9.6×10^{-22} Hz$^{-1/2}$.

1. INTRODUCTION

The second observation run of the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) detectors ushered in the era of multi-messenger astronomy. In addition to the detection of further binary black hole systems (Abbott et al. 2017a,b,c), the first binary neutron star system GW170817 (Abbott et al. 2017d), associated with GRB 170817A (Abbott et al. 2017e) and corresponding electromagnetic radiation AT 2017gfo (Abbott et al. 2017f), were jointly detected. This led to searches for a post-merger signal from the binary neutron star event, including on the timescales presented in this paper (Abbott et al. 2017; Abbott et al. 2018a). In this paper, we update the results of the unmodeled long-duration transient search from the first Advanced LIGO observing run (Abbott et al. 2018b) with the data from the second observing run.

We use four pipelines, described below, with different responses across the parameter space, providing complementary coverage of the signal models we are interested in. The search was motivated by a wide range of poorly understood astrophysical phenomena for which predictive models are not readily available; these include fallback accretion, accretion disk instabilities and non-axisymmetric deformations in magnetars. Fallback accretion of ejected mass in newborn neutron stars can lead to deformation, causing the emission of gravitational waves until the star collapses into a black hole (Lai & Shapiro 1995; Piro & Ott 2011; Piro & Thrane 2012). Accretion disk instabilities and fragmentation can cause stellar material to spiral in a black hole, emitting relatively long-lived gravitational waves (Piro & Pfahl 2007; van Putten 2001, 2008). Non-axisymmetric deformations in magnetars, proposed as progenitors of long and short gamma-ray bursts (Metzger et al. 2011; Rowlinson et al. 2013), can also emit gravitational waves (Corsi & Mészáros 2009). Moreover, we introduce new waveforms families based on astrophysical phenoma such as fallback accretion down to the innermost stable circular orbit of a rapidly rotating black hole (van Putten 2016), highly eccentric binary black hole coalescences (Huerta et al. 2018), and gamma-ray burst & X-ray events (Corsi & Mészáros 2009).

Although this analysis targets sources for which the gravitational waveform is not well-described, it is possible for the long-duration searches to detect low-mass compact binary coalescences, typically searched for with matched filtering techniques. As discussed in other publications (Abbott et al. 2017d), the data containing the gravitational-wave signal resulting from GW170817 is corrupted by the presence of a short-duration (less than 5 ms), powerful transient noise event in one of the detectors (Abbott et al. 2017d). Using a data set where this short transient has been subtracted from the LIGO-Livingston data stream, the GW170817 signal is the most significant event of the search. As the searches reported in this paper does not add significantly to the many other studies carried out for this event (Abbott et al. 2017d; Abbott et al. 2018a,b, 2017), it has been decided to keep the original data set, veto the large transient noise and focus on any other long duration gravitational-wave signals.

The paper is organized as follows. We describe the data used in the analysis in Section 2. The algorithms used to analyze the data are outlined in Section 3. The results of the analysis and their implications are discussed in Section 4. Section 5 provides our conclusions and avenues for future research.

2. DATA

The second observation run lasted from November 25, 2016 to August 25, 2017. Between the first and second observing runs, a series of fixes and upgrades of the two LIGO detectors in Hanford, WA and Livingston, LA, allowed the run to begin with LIGO detectors' sensitivity reaching a binary neutron star range of $\sim$ 80 Mpc – please see Abbott et al. (2018c) for a discussion of the range metric. Thanks to commissioning break periods, Livingston's sensitivity increased steadily during the second observation run, finally reaching 100 Mpc. LIGO Hanford suffered from a 5.8 magnitude earthquake in Montana on July 6$^{\rm th}$ 2017, which induced a 10 Mpc drop in sensitivity, and this was not recovered during the science run. On August 1$^{\rm st}$, the Virgo detector joined the run with a binary neutron star range of 26 Mpc. It has been shown that adding the one-month Virgo data set does not improve the search sensitivity mainly because of the sensitivity difference between the detectors. We thus report the results of a two LIGO detector coincident search. The overlap in time when both detectors are taking data in suitable for analysis was approximately 118.3 days. The effective coincident time analyzed by each pipeline depends on the data segmentation choice and lies in the range 114.7 to 118.3 days.

Coincident data contains a large number of non-Gaussian transient noise events (glitches) of instrumental or environmental origin that mimic the characteristic of the targeted signals. For the first time, well identified sources of noise have been subtracted from the LIGO data (Davis et al. 2018). Yet, some glitches, typically lasting from a few milliseconds up to few seconds and varying widely in frequency, remain. Their presence, even the very short ones, may negatively impact the sensitivity of the searches (Abbott et al. 2018c). Time varying spectral lines are also a source of noise events for the long-duration transient searches. To veto these transient noise events, each pipeline implements specific glitch rejection criteria; because the search targets long-duration signals, short-duration glitches, which are usually the most problematic sources of noise, are easily suppressed. The next section provides more details about the noise rejection procedures that also may include data quality vetoes based on correlations with auxiliary channels (Aasi et al. 2012; Abbott et al. 2016).

3. SEARCHES

As in the previous analysis, we use four pipelines to search for transients that last between 2 – 500 s and span a frequency band of 24 – 2048 Hz. The use of multiple pipelines provides redundancy, and due to the differences in the clustering algorithms, lead to different sensitivities to different waveform morphologies or parts of the parameter space. Unmodeled searches for gravitational waves typically cast the analysis as pattern recognition problems. Gravitational-wave time-series are Fourier transformed in chunks of time, and spectrograms are created based on statistics derived from these Fourier transforms. Then pattern recognition algorithms are used to search for patterns, corresponding to gravitational waves, within spectrograms. In general, these consist of two classes. The first is seed-based (Khan & Chatterji 2009; Prestegard 2016), where thresholds are placed on pixel values in the spectrograms and pixels above this threshold are clustered together. The second is seedless (Thrane & Coughlin 2013, 2014), where tracks are constructed from a generic model and integrated across the spectrograms; in this analysis, we use Bézier curves (Farin 1996; Thrane & Coughlin 2013, 2014; Coughlin et al. 2015; Thrane & Coughlin 2015).

The pipelines used are the long-duration configuration of Coherent WaveBurst (cWB) (Klimenko et al. 2016), two different versions of the Stochastic Transient Analysis Multi-detector Pipeline - all sky (STAMP-AS) pipeline (Prestegard 2016; Thrane & Coughlin 2015), and the X-pipeline Spherical Radiometer (X-SphRad) (Fays 2017). These pipelines are the same, or slightly updated versions, of those used in the search for long-duration transients in the first observation run and fully described in (Abbott et al. 2017g). cWB is based on a maximum-likelihood-ratio statistic, built as a sum of excess power coherent between multiple detectors in the time-frequency representation of the interferometer responses (Klimenko et al. 2016). The search is performed in the frequency range 24 – 2048 Hz, on data where all poor quality periods have been discarded. The trigger events surviving the selection criteria to reject glitches are ranked according to their detection statistic η_c, which is related to the coherent signal-to-noise ratio (SNR). The selection criteria require the coherence coefficient c_c to be larger than 0.6, and the weighted duration of the candidate to be larger than 1.5 s. The first measures the degree of correlation between the detectors, while the latter measures the duration weighted by the excess power amplitude of the pixel on the time-frequency likelihood map. The trigger events are then divided in two samples according to their estimated mean frequency: 24-200 Hz and 200-2048 Hz. This allows for the isolation of the unexpected higher rate of glitches at low frequency during the first half of the O2 observation run. STAMP-AS uses the cross-correlation of data from two detectors to create coherent time-frequency maps of cross-power SNR with a pixel size of 1 s × 1 Hz covering 24 − 2000 Hz in combination with a seed-based (Zebragard) and seedless (Lonetrack) clustering algorithm. Significant spectral features, including wandering lines, are masked in the creation of the spectrograms. As in the search during the first observing run, Zebragard eliminates the short duration glitches by requesting that the fraction of SNR in each time bin be smaller than 0.5 and that the SNR ratio between the two detectors be smaller than 3. The X-pipeline Spherical Radiometer (X-SphRad) uses an X-pipeline (Sutton et al. 2010) back end in combination with a fast cross-correlator in the spherical harmonic domain (Cannon 2007) to search for gravitational-wave transients in the 24 − 1000 Hz frequency range. The method allows for the data to be processed independently of sky position and avoids redundant computations. A next-nearest-neighbor clustering algorithm is applied on a time-frequency representation of the data with a resolution of 1 s × 1 Hz to form trigger events, which are then ranked by the ratio of the sum of power in all the l>0 spherical harmonic modes to that in the l=0 mode. Significant spectral features such as standing power lines are removed using a zero-phase linear predictor filter that estimates the power spectrum and whitens the data (Chatterji 2005). Finally, X-SphRad eliminates triggers that coincide with poor quality data periods that have been identified using auxiliary channels. These periods are excluded from the analysis time by cWB, and STAMP-AS Zebragard analysis selects a subset of them according to a procedure described in (Frey 2018).

The false alarm rate of each search is estimated as a function of the pipeline's ranking statistic. Each use the data to perform this estimate, as opposed to a Gaussian approximation, because of the significant non-Gaussianity of the data, transient noise, and the non-stationarity of some of the spectral features. These glitches have a variety of causes, both environmentally driven such as from seismic events (Macleod et al. 2012; Coughlin et al. 2017) or magnetic fields (Kowalska-Leszczynska et al. 2017; Coughlin et al. 2016), and instrumental effects, such as test mass suspension glitches (Walker et al. 2017) and other sources of spectral features (Coughlin 2010). For all of the pipelines in this analysis, the correlation of data in different detectors is used to exclude data transients which are unlikely to be of astrophysical origin. To estimate the background for all pipelines used in this analysis, the time-slides methodology is applied (Was et al. 2010a,b), each one implementing its own version. The fundamental idea is to shift the detector data with non-physical relative time delays to eliminate any correlation from gravitational waves and re-analyze the data. The procedure is repeated until a total of 50 years coincident detector time has been analyzed, allowing us to estimate false alarm rates at the level of 1 event in 50 years.

4. RESULTS

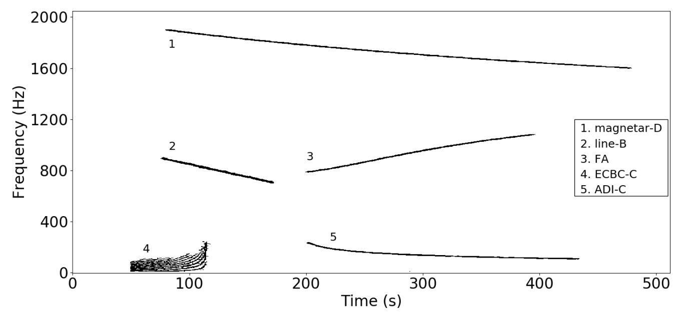

Figure 1. Time-frequency representations of a few model signals used in the search, showing a mix of chirp-up (FA, ECBC) & chirp-down (Magnetar, ADI) astrophysical waveforms as well as a linearly decreasing ad-hoc waveform (LINE). The harmonics of ECBC are also visible. The full set of waveforms (∼ 70) chosen for this analysis fully covers the search frequency band of 24-2000 Hz. The waveforms are shifted in time to show how they cover the parameter space in this axis as well.

Pipeline	FAR [Hz]	p-value	Frequency [Hz]	Duration [s]
cWB	1.4×10^{-7}	0.75	53–69	11
Zebragard	2.5×10^{-7}	0.92	1649–1753	29
Lonetrack	7.9×10^{-8}	0.80	608–1344	463
X-SphRad	9.7×10^{-8}	0.60	435-443	3

Table 1. Properties of the most significant coincident triggers found by each of the long-duration transient search pipelines during the second observation run. FAR stands for false alarm rate, while the p-value is the probability of observing at least 1 noise trigger at higher significance than the most significant coincident trigger.

None of the pipelines find a significant excess of coincident events. The most significant events found by each pipeline are reported in Table 1. Their false alarm rate is in agreement with the expected background estimation. Given the absence of a detection, we can derive upper limits on long-duration gravitational-wave transients' strain amplitude. We use 13 families of simulated gravitational-wave signals to estimate the sensitivity of each pipeline. The waveform families include a variety of astrophysically motivated waveforms and ad-hoc waveform models. For the astrophysical models, we include fallback accretion onto neutron stars (FA) (Piro & Thrane 2012), broadband chirps from innermost stable circular orbit waves around rotating black holes (ISCOchirp) (van Putten 2016), inspiral-only compact binary coalescence waveforms up to 2nd post-Newtonian order (Blanchet et al. 1996) (CBC), eccentric inspiral-merger-ringdown compact binary coalescence waveforms (ECBC) (Huerta et al. 2018), secular bar-mode instabilities in post-merger remnants (Lai & Shapiro 1995; Corsi & Mészáros 2009), newly formed magnetar powering a gamma-ray burst plateau (GRB-plateau) (Corsi & Mészáros 2009), black hole accretion disk instabilities (ADI) (van Putten 2001), post-merger magnetars (magnetar) (Dall'Osso et al. 2015), and neutron star spin down waveforms (MSmagnetar) (Lasky et al. 2017; Sarin et al. 2018). For the ad-hoc waveforms, we include monochromatic waveforms (MONO), waveforms with a linear (LINE), quadratic (QUAD) frequency evolution, white noise band-limited (WNB) and sine-Gaussian bursts (SG). The waveforms are designed to span a range of astrophysical models, as well as a wide duration and frequency parameter space to test the response of the algorithms across the parameter space. Figure 1 shows the coverage of a representative sample of the simulation set in the time-frequency space. The frequency band 10-300 Hz are well covered with the GRBplateau and ADI families. Astrophysical waveform families such as ISCOchirp and magnetar are characterised by a wide frequency coverage and populate the higher frequency band 700-2000 Hz. Ad-hoc waveforms families such as MONO, LINE, QUAD, WNB and SG span a wide frequency range and covers the band 50-800 Hz, filling in any potential gap in coverage from the other models.

A usual measure of gravitational-wave amplitude is the root-sum-square strain amplitude at the Earth, $h_{\rm rss}$,

$$h_{\rm rss} = \sqrt{\int_{-\infty}^{\infty} \left(h_+^2(t) + h_\times^2(t)\right) {\rm d}t}, \tag{1}$$

where h_+ and $h_\times$ are signal polarizations at Earth's center expressed in the source frame. We can relate this quantity to the gravitational-wave energy radiated by a source emitting isotropically at a given central frequency f_0 (Sutton 2013)

$$\begin{aligned} E_{\rm gw}^{\rm iso} &= \frac{\pi c^3}{G}\mathcal{D}^2 \int {\rm d}f\; f^2 \left(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right) \\ &\approx \frac{\pi^2 c^3}{G}\mathcal{D}^2 f_0^2 h_{\rm rss}^2, \end{aligned} \tag{2}$$

where $\mathcal{D}$ is the distance to the source and $\tilde{h}$ indicates a Fourier transform.

To estimate the $h_{\rm rss}$ at 50% detection efficiency, we add simulated waveforms coherently to detector data, uniformly distributed in time and over sky locations. The waveform polarization angle and the cosine of the inclination are also varied uniformly. Waveforms are generated at a variety of distances (or equivalently $h_{\rm rss}$) such that the 50% detection efficiency is well-measured. The events reconstructed are then "detected" if their false alarm rate is lower than the chosen value of 1/50 years. In Figure 2, we show the best results among all pipelines for almost all waveforms. A few differences in the pipeline recoveries stand out. Similar to the analysis from the first observing run (Abbott et al. 2017g), the response of cWB, Zebragard and X-SphRad are similar, while Lonetrack achieves about a factor of 2 improvement for the LINE and QUAD waveforms. Neither cWB nor Lonetrack were sensitive to the monochromatic signals.

We also compute the 90% confidence level limit on the rate of long-duration gravitational-wave transients assuming a Poissonian distribution of sources. To do so, we use the loudest event statistic method (Brady et al. 2004). We fold in the systematic uncertainty that arises from the strain amplitude calibration, which is 7% in amplitude and 3 degrees in phase, a conservative number used for both instruments in the frequency band analyzed here (Cahillane et al. 2017).

Figure 3 shows the rate as a function of distance for the eccentric compact binary coalescence signals considered in this analysis. For a $1.4 - 1.4$ solar mass binary with an eccentricity of 0.4, the 50% efficiency distance is 30 Mpc. For comparison, this is more than a factor 2 lower than what matched filter searches could reach for $1.4 - 1.4$ solar mass binaries with no eccentricity during the second observation run (Abbott et al. 2017d). Due to the improved sensitivity and greater duration of the second observation run above and beyond the first observation run, the rate limits for models used in previous analyses improved by a factor of $\sim$ 30%. The detection distances vary significantly from one signal to another. For example, the ADI waveforms have distance limits of tens of megaparsecs, while the magnetar waveforms have limits of tens of kiloparsecs. The difference in ranges is due mainly to the energy budget of the system,

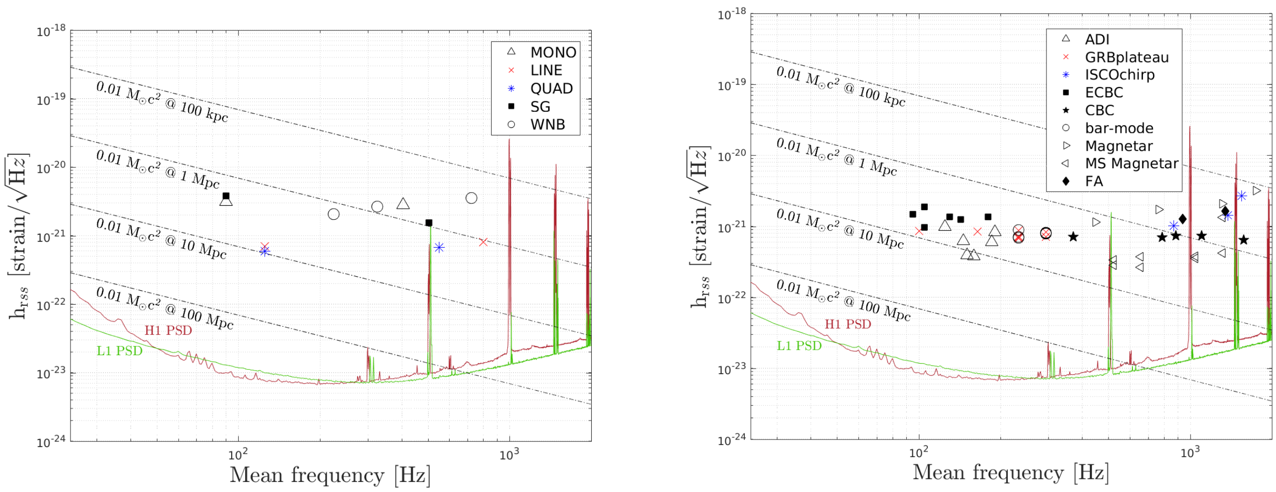

Figure 2. Upper limits on gravitational-wave strain versus frequency for sources detected with 50% efficiency and a false alarm rate of 1 event in 50 years. The lowest value among all 4 pipelines is represented on the plots. The left figure shows the "ad-hoc" waveforms' results while the "physical" waveforms are represented on the right. The average amplitude spectral density curves for both Hanford and Livingston are also shown.

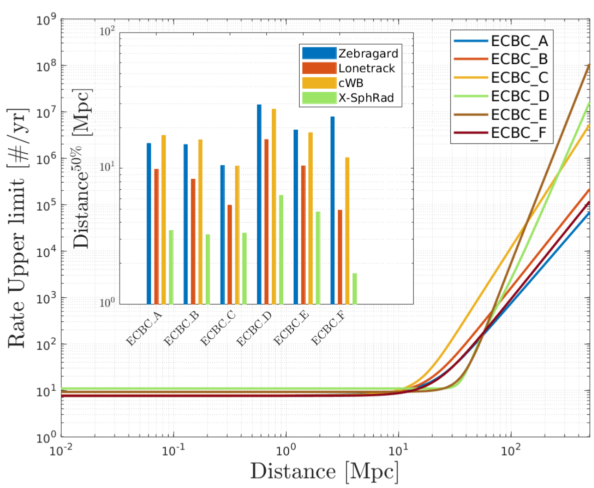

Figure 3. Upper limits (marginalizing over the second observation run amplitude calibration errors) on eccentric compact binary coalescences as a function of the distance at a 90% confidence level considering the best results for each waveform. The inset shows the distance at 50% detection efficiency for the pipelines in this analysis for comparison. ECBC_A, ECBC_B, and ECBC_C are $1.4 - 1.4$ solar mass binaries with eccentricities of 0.2, 0.4, and 0.6 respectively, while ECBC_D, ECBC_E, and ECBC_F are $3.0 - 3.0$ solar mass binaries with eccentricities of 0.2, 0.4, and 0.6 respectively, where the masses are quoted in the detector frame.

but also due to the overall signal morphologies, which can be more or less difficult for the pipeline clustering techniques to recover entirely.

5. CONCLUSIONS

We have performed an all-sky search for unmodeled long-duration gravitational-wave transients in the second observing run. This search did not lead to the detection of any new gravitational waves. In addition to the intrinsic gain due to detectors' sensitivity improvement and the length of the observing run, we have increased significantly the number of waveforms used to estimate the pipelines' sensitivity. The theoretical uncertainties of the models used are rather large, including the mechanisms, their amplitudes, and their potential rates, although it is likely we are sensitive to relatively small amplitude emissions within the Local Group.

With the recent arrival of Advanced Virgo to the advanced gravitational-wave detector network, its future improvements will merit its inclusion in analyses in the next observing runs. Overall, the expectation is that the design sensitivities for the gravitational-wave networks will yield gains of up to a factor of 10, depending on the frequency range considered (Abbott et al. 2018c).

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REFERENCES

Aasi, J., et al. 2012, CQGra, 29, 155002
—. 2015, CQGra, 32, 074001
Abbott, B. P., et al. 2016, CQGra, 33, 134001
—. 2017a, PhRvL, 118, 221101
—. 2017b, PhRvL, 119, 141101
—. 2017c, ArXiv e-prints, arXiv:1711.05578
—. 2017d, PhRvL, 119, 161101
—. 2017e, ApJL, 848, L13
—. 2017f, ApJL, 848, L12
—. 2017g, PhRvD, 95, 042003
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2018a, ArXiv e-prints, arXiv:1810.02581
Abbott, B. P., et al. 2018b, CQGra, 35, 065009
—. 2018c, CQGra, 35, 065010
Abbott et al. 2017, The Astrophysical Journal Letters, 851, L16
—. 2018a, ArXiv e-prints, arXiv:1805.11579
—. 2018b, Phys. Rev. Lett., 121, 161101. https://link.aps.org/doi/10.1103/PhysRevLett.121.161101
—. 2018c, Living Reviews in Relativity, 21, 3
Acernese, F., et al. 2015, CQGra, 32, 024001
Blanchet, L., Iyer, B. R., Will, C. M., & Wiseman, A. G. 1996, CQGra, 13, 575
Brady, P. R., Creighton, J. D. E., & Wiseman, A. G. 2004, CQGra, 21, S1775
Cahillane, C., Betzwieser, J., Brown, D. A., et al. 2017, PhRvD, 96, 102001
Cannon, K. C. 2007, PhRvD, 75, 123003
Chatterji, S. K. 2005, Thesis, MIT Physics department. http://dspace.mit.edu/handle/1721.1/34388
Corsi, A., & Mészáros, P. 2009, ApJ, 702, 1171
Coughlin, M. 2010, Journal of Physics: Conference Series, 243, 012010
Coughlin, M., Meyers, P., Kandhasamy, S., Thrane, E., & Christensen, N. 2015, PhRvD, 92, 043007
Coughlin, M., Christensen, N., De Rosa, R., et al. 2016, CQGra, 33, 224003
Coughlin, M., Earle, P., Harms, J., et al. 2017, CQGra, 34, 044004
Dall'Osso, S., Giacomazzo, B., Perna, R., & Stella, L. 2015, ApJ, 798, 25
Davis, D., Massinger, T. J., Lundgren, A. P., et al. 2018, arXiv:1809.05348
Farin, G. 1996, Curves and Surfaces for CAGD, Fourth Edition: A Practical Guide (Academic Press)
Fays, M. 2017, Cardiff University Thesis
Frey, V. 2018, Paris Saclay University Thesis
Huerta, E., et al. 2018, PhRvD, 97, 024031
Khan, R., & Chatterji, S. 2009, CQGra, 26, 155009
Klimenko, S., Vedovato, G., Drago, M., et al. 2016, PhRvD, 93, 042004
Kowalska-Leszczynska, I., Bizouard, M.-A., Bulik, T., et al. 2017, CQGra, 34, 074002
Lai, D., & Shapiro, S. L. 1995, ApJ, 442, 259

Lasky, P., Leris, C., Rowlinson, A., & Glampedakis, K. 2017, ApJL, 843, L1

Macleod, D., Fairhurst, S., Hughey, B., et al. 2012, CQGra, 29, 055006

Metzger, B., Giannios, D., Thompson, T. A., Bucciantini, N., & Quataert, E. 2011, MNRAS, 413, 2031

Piro, A., & Ott, C. D. 2011, 736, 108

Piro, A., & Pfahl, E. 2007, 658, 1173

Piro, A., & Thrane, E. 2012, 761, 63

Prestegard, T. 2016, University of Minnesota Thesis

Rowlinson, A., O'Brien, P., Metzger, B., Tanvir, N., & Levan, A. 2013, MNRAS, 430, 1061

Sarin, N., Lasky, P. D., Sammut, L., & Ashton, G. 2018, Phys. Rev. D, 98, 043011

Sutton, P. 2013, arXiv:1304.0210

Sutton, P., Jones, G., Chatterji, S., et al. 2010, NJPh, 12, 053034

Thrane, E., & Coughlin, M. 2013, PhRvD, 88, 083010

—. 2014, PhRvD, 89, 063012

Thrane, E., & Coughlin, M. 2015, PhRvL, 115, 181102

van Putten, M. H. P. M. 2001, 87, 091101

—. 2008, 684, L91

—. 2016, The Astrophysical Journal, 819, 169

Walker et al. 2017, Review of Scientific Instruments, 88, 124501

Was, M., Bizouard, M.-A., Brisson, V., et al. 2010a, CQGra, 27, 015005

—. 2010b, CQGra, 27, 194014

The LIGO Scientific Collaboration, The Virgo Collaboration, B. P. Abbott,[1] R. Abbott,[1] T. D. Abbott,[2]
S. Abraham,[3] F. Acernese,[4,5] K. Ackley,[6] C. Adams,[7] R. X. Adhikari,[1] V. B. Adya,[8] C. Affeldt,[9,10]
M. Agathos,[11,12] K. Agatsuma,[13] N. Aggarwal,[14] O. D. Aguiar,[15] L. Aiello,[16,17] A. Ain,[3] P. Ajith,[18] G. Allen,[19]
A. Allocca,[20,21] M. A. Aloy,[22] P. A. Altin,[8] A. Amato,[23] S. Anand,[1] A. Ananyeva,[1] S. B. Anderson,[1]
W. G. Anderson,[24] S. V. Angelova,[25] S. Antier,[26] S. Appert,[1] K. Arai,[1] M. C. Araya,[1] J. S. Areeda,[27]
M. Arène,[26] N. Arnaud,[28,29] S. M. Aronson,[30] S. Ascenzi,[16,31] G. Ashton,[6] S. M. Aston,[7] P. Astone,[32] F. Aubin,[33]
P. Aufmuth,[10] K. AultONeal,[34] C. Austin,[2] V. Avendano,[35] A. Avila-Alvarez,[27] S. Babak,[26] P. Bacon,[26]
F. Badaracco,[16,17] M. K. M. Bader,[36] S. Bae,[37] J. Baird,[26] P. T. Baker,[38] F. Baldaccini,[39,40] G. Ballardin,[29]
S. W. Ballmer,[41] A. Bals,[34] S. Banagiri,[42] J. C. Barayoga,[1] C. Barbieri,[43,44] S. E. Barclay,[45] B. C. Barish,[1]
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ShyamSundar,[59] K. Siellez,[77] M. Sieniawska,[55] D. Sigg,[46] L. P. Singer,[80] D. Singh,[88] N. Singh,[73] A. Singhal,[16,32] A. M. Sintes,[100] S. Sitmukhambetov,[107] V. Skliris,[105] B. J. J. Slagmolen,[8] T. J. Slaven-Blair,[65] J. R. Smith,[27] R. J. E. Smith,[6] S. Somala,[184] E. J. Son,[151] S. Soni,[2] B. Sorazu,[45] F. Sorrentino,[58] T. Souradeep,[3] E. Sowell,[83] A. P. Spencer,[45] M. Spera,[52,53] A. K. Srivastava,[110] V. Srivastava,[41] K. Staats,[57] C. Stachie,[64] M. Standke,[9,10] D. A. Steer,[26] M. Steinke,[9,10] J. Steinlechner,[133,45] S. Steinlechner,[133] D. Steinmeyer,[9,10] S. P. Stevenson,[167] D. Stocks,[50] R. Stone,[107] D. J. Stops,[13] K. A. Strain,[45] G. Stratta,[185,63] S. E. Strigin,[60] A. Strunk,[46] R. Sturani,[186] A. L. Stuver,[187] V. Sudhir,[14] T. Z. Summerscales,[188] L. Sun,[1] S. Sunil,[110] A. Sur,[55] J. Suresh,[81] P. J. Sutton,[105] B. L. Swinkels,[36] M. J. Szczepańczyk,[34] M. Tacca,[36] S. C. Tait,[45] C. Talbot,[6] D. B. Tanner,[30] D. Tao,[1] M. Tápai,[130] A. Tapia,[27] J. D. Tasson,[96] R. Taylor,[1] R. Tenorio,[100] L. Terkowski,[133] M. Thomas,[7] P. Thomas,[46] S. R. Thondapu,[59] K. A. Thorne,[7] E. Thrane,[6] Shubhanshu Tiwari,[116,117] Srishti Tiwari,[134] V. Tiwari,[105] K. Toland,[45] M. Tonelli,[20,21] Z. Tornasi,[45] A. Torres-Forné,[189] C. I. Torrie,[1] D. Töyrä,[13] F. Travasso,[29,40] G. Traylor,[7] M. C. Tringali,[73] A. Tripathee,[136] A. Trovato,[26] L. Trozzo,[190,21] K. W. Tsang,[36] M. Tse,[14] R. Tso,[47] L. Tsukada,[81] D. Tsuna,[81] T. Tsutsui,[81] D. Tuyenbayev,[107] K. Ueno,[81] D. Ugolini,[191] C. S. Unnikrishnan,[134] A. L. Urban,[2] S. A. Usman,[91] H. Vahlbruch,[10] G. Vajente,[1] G. Valdes,[2] M. Valentini,[116,117] N. van Bakel,[36] M. van Beuzekom,[36] J. F. J. van den Brand,[74,36] C. Van Den Broeck,[36,192] D. C. Vander-Hyde,[41] L. van der Schaaf,[36] J. V. VanHeijningen,[65] A. A. van Veggel,[45] M. Vardaro,[52,53] V. Varma,[47] S. Vass,[1] M. Vasúth,[49] A. Vecchio,[13] G. Vedovato,[53] J. Veitch,[45] P. J. Veitch,[56] K. Venkateswara,[178] G. Venugopalan,[1] D. Verkindt,[33] F. Vetrano,[62,63] A. Viceré,[62,63] A. D. Viets,[24] S. Vinciguerra,[13] D. J. Vine,[131] J.-Y. Vinet,[64] S. Vitale,[14] T. Vo,[41] H. Vocca,[39,40] C. Vorvick,[46] S. P. Vyatchanin,[60] A. R. Wade,[1] L. E. Wade,[120] M. Wade,[120] R. Walet,[36] M. Walker,[27] L. Wallace,[1] S. Walsh,[24] H. Wang,[13] J. Z. Wang,[136] S. Wang,[19] W. H. Wang,[107] Y. F. Wang,[92] R. L. Ward,[8] Z. A. Warden,[34] J. Warner,[46] M. Was,[33] J. Watchi,[101] B. Weaver,[46] L.-W. Wei,[9,10] M. Weinert,[9,10] A. J. Weinstein,[1] R. Weiss,[14] F. Wellmann,[9,10] L. Wen,[65] E. K. Wessel,[19] P. Wessels,[9,10] J. W. Westhouse,[34] K. Wette,[8] J. T. Whelan,[61] B. F. Whiting,[30] C. Whittle,[14] D. M. Wilken,[9,10] D. Williams,[45] A. R. Williamson,[141,36] J. L. Willis,[1] B. Willke,[10,9] W. Winkler,[9,10] C. C. Wipf,[1] H. Wittel,[9,10] G. Woan,[45] J. Woehler,[9,10] J. K. Wofford,[61] J. L. Wright,[45] D. S. Wu,[9,10] D. M. Wysocki,[61] S. Xiao,[1] R. Xu,[108] H. Yamamoto,[1] C. C. Yancey,[76] L. Yang,[119] Y. Yang,[30] Z. Yang,[42] M. J. Yap,[8] M. Yazback,[30] D. W. Yeeles,[105] Hang Yu,[14] Haocun Yu,[14] S. H. R. Yuen,[92] A. K. Zadrożny,[107] A. Zadrożny,[156] M. Zanolin,[34] T. Zelenova,[29] J.-P. Zendri,[53] M. Zevin,[57] J. Zhang,[65] L. Zhang,[1] T. Zhang,[45] C. Zhao,[65] G. Zhao,[101] M. Zhou,[57] Z. Zhou,[57] X. J. Zhu,[6] A. B. Zimmerman,[193] M. E. Zucker,[1,14] and J. Zweizig[1]

[1] *LIGO, California Institute of Technology, Pasadena, CA 91125, USA*
[2] *Louisiana State University, Baton Rouge, LA 70803, USA*
[3] *Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[4] *Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[5] *INFN, Sezione di Napoli, Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy*
[6] *OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[7] *LIGO Livingston Observatory, Livingston, LA 70754, USA*
[8] *OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[9] *Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
[10] *Leibniz Universität Hannover, D-30167 Hannover, Germany*
[11] *Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*
[12] *University of Cambridge, Cambridge CB2 1TN, United Kingdom*
[13] *University of Birmingham, Birmingham B15 2TT, United Kingdom*
[14] *LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[15] *Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
[16] *Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[17] *INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[18] *International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[19] *NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[20] *Università di Pisa, I-56127 Pisa, Italy*
[21] *INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[22] *Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
[23] *Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France*
[24] *University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA*
[25] *SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[26] *APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France*
[27] *California State University Fullerton, Fullerton, CA 92831, USA*
[28] *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France*
[29] *European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[30] *University of Florida, Gainesville, FL 32611, USA*
[31] *INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[32] *INFN, Sezione di Roma, I-00185 Roma, Italy*
[33] *Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France*
[34] *Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA*
[35] *Montclair State University, Montclair, NJ 07043, USA*
[36] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[37] *Korea Institute of Science and Technology Information, Daejeon 34141, South Korea*
[38] *West Virginia University, Morgantown, WV 26506, USA*
[39] *Università di Perugia, I-06123 Perugia, Italy*
[40] *INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[41] *Syracuse University, Syracuse, NY 13244, USA*
[42] *University of Minnesota, Minneapolis, MN 55455, USA*
[43] *Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy*
[44] *INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*
[45] *SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[46] *LIGO Hanford Observatory, Richland, WA 99352, USA*
[47] *Caltech CaRT, Pasadena, CA 91125, USA*
[48] *Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana," Università di Salerno, I-84081 Baronissi, Salerno, Italy*
[49] *Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary*
[50] *Stanford University, Stanford, CA 94305, USA*
[51] *Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
[52] *Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
[53] *INFN, Sezione di Padova, I-35131 Padova, Italy*
[54] *Montana State University, Bozeman, MT 59717, USA*
[55] *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
[56] *OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
[57] *Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA), Northwestern University, Evanston, IL 60208, USA*
[58] *INFN, Sezione di Genova, I-16146 Genova, Italy*
[59] *RRCAT, Indore, Madhya Pradesh 452013, India*
[60] *Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[61] *Rochester Institute of Technology, Rochester, NY 14623, USA*
[62] *Università degli Studi di Urbino "Carlo Bo," I-61029 Urbino, Italy*
[63] *INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
[64] *Artemis, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, CS 34229, F-06304 Nice Cedex 4, France*
[65] *OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
[66] *Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
[67] *Dipartimento di Fisica "E.R. Caianiello," Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[68] *INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy*

[69]Physik-Institut, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
[70]Univ Rennes, CNRS, Institut FOTON - UMR6082, F-3500 Rennes, France
[71]University of Oregon, Eugene, OR 97403, USA
[72]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
[73]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
[74]VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
[75]Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
[76]University of Maryland, College Park, MD 20742, USA
[77]School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
[78]Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
[79]Università di Napoli "Federico II," Complesso Universitario di Monte S.Angelo, I-80126 Napoli, Italy
[80]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[81]RESCEU, University of Tokyo, Tokyo, 113-0033, Japan.
[82]Tsinghua University, Beijing 100084, China
[83]Texas Tech University, Lubbock, TX 79409, USA
[84]Università di Roma Tor Vergata, I-00133 Roma, Italy
[85]The University of Mississippi, University, MS 38677, USA
[86]Missouri University of Science and Technology, Rolla, MO 65409, USA
[87]Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi," I-00184 Roma, Italy
[88]The Pennsylvania State University, University Park, PA 16802, USA
[89]National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
[90]Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
[91]University of Chicago, Chicago, IL 60637, USA
[92]The Chinese University of Hong Kong, Shatin, NT, Hong Kong
[93]Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
[94]Seoul National University, Seoul 08826, South Korea
[95]Pusan National University, Busan 46241, South Korea
[96]Carleton College, Northfield, MN 55057, USA
[97]INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
[98]Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
[99]OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
[100]Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
[101]Université Libre de Bruxelles, Brussels 1050, Belgium
[102]Sonoma State University, Rohnert Park, CA 94928, USA
[103]Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
[104]Columbia University, New York, NY 10027, USA
[105]Cardiff University, Cardiff CF24 3AA, United Kingdom
[106]University of Rhode Island, Kingston, RI 02881, USA
[107]The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
[108]Bellevue College, Bellevue, WA 98007, USA
[109]MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary
[110]Institute for Plasma Research, Bhat, Gandhinagar 382428, India
[111]The University of Sheffield, Sheffield S10 2TN, United Kingdom
[112]IGFAE, Campus Sur, Universidade de Santiago de Compostela, 15782 Spain
[113]Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
[114]INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
[115]Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
[116]Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
[117]INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
[118]Università di Roma "La Sapienza," I-00185 Roma, Italy
[119]Colorado State University, Fort Collins, CO 80523, USA
[120]Kenyon College, Gambier, OH 43022, USA
[121]Christopher Newport University, Newport News, VA 23606, USA
[122]CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
[123]Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
[124]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
[125]Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain

[126] *INFN Sezione di Torino, I-10125 Torino, Italy*
[127] *School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
[128] *Institute Of Advanced Research, Gandhinagar 382426, India*
[129] *Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
[130] *University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
[131] *SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[132] *California State University, Los Angeles, 5151 State University Dr, Los Angeles, CA 90032, USA*
[133] *Universität Hamburg, D-22761 Hamburg, Germany*
[134] *Tata Institute of Fundamental Research, Mumbai 400005, India*
[135] *INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy*
[136] *University of Michigan, Ann Arbor, MI 48109, USA*
[137] *Washington State University, Pullman, WA 99164, USA*
[138] *American University, Washington, D.C. 20016, USA*
[139] *University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
[140] *University of California, Berkeley, CA 94720, USA*
[141] *GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
[142] *Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, The Netherlands*
[143] *Directorate of Construction, Services & Estate Management, Mumbai 400094 India*
[144] *University of Białystok, 15-424 Białystok, Poland*
[145] *King's College London, University of London, London WC2R 2LS, United Kingdom*
[146] *University of Southampton, Southampton SO17 1BJ, United Kingdom*
[147] *University of Washington Bothell, Bothell, WA 98011, USA*
[148] *Institute of Applied Physics, Nizhny Novgorod, 603950, Russia*
[149] *Ewha Womans University, Seoul 03760, South Korea*
[150] *Inje University Gimhae, South Gyeongsang 50834, South Korea*
[151] *National Institute for Mathematical Sciences, Daejeon 34047, South Korea*
[152] *Ulsan National Institute of Science and Technology, Ulsan 44919, South Korea*
[153] *Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands*
[154] *Bard College, 30 Campus Rd, Annandale-On-Hudson, NY 12504, USA*
[155] *Chennai Mathematical Institute, Chennai 603103, India*
[156] *NCBJ, 05-400 Świerk-Otwock, Poland*
[157] *Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[158] *Cornell University, Ithaca, NY 14850, USA*
[159] *Hillsdale College, Hillsdale, MI 49242, USA*
[160] *Hanyang University, Seoul 04763, South Korea*
[161] *Korea Astronomy and Space Science Institute, Daejeon 34055, South Korea*
[162] *Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
[163] *NASA Marshall Space Flight Center, Huntsville, AL 35811, USA*
[164] *Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
[165] *INFN, Sezione di Roma Tre, I-00146 Roma, Italy*
[166] *ESPCI, CNRS, F-75005 Paris, France*
[167] *OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
[168] *Southern University and A&M College, Baton Rouge, LA 70813, USA*
[169] *Centre Scientifique de Monaco, 8 quai Antoine Ier, MC-98000, Monaco*
[170] *Indian Institute of Technology Madras, Chennai 600036, India*
[171] *Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
[172] *IISER-Kolkata, Mohanpur, West Bengal 741252, India*
[173] *Institut für Kernphysik, Theoriezentrum, 64289 Darmstadt, Germany*
[174] *Whitman College, 345 Boyer Avenue, Walla Walla, WA 99362 USA*
[175] *Université de Lyon, F-69361 Lyon, France*
[176] *Hobart and William Smith Colleges, Geneva, NY 14456, USA*
[177] *Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy*
[178] *University of Washington, Seattle, WA 98195, USA*
[179] *INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
[180] *Centro de Astrofísica e Gravitação (CENTRA), Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*

[181] *Marquette University, 11420 W. Clybourn St., Milwaukee, WI 53233, USA*
[182] *Indian Institute of Technology, Gandhinagar Ahmedabad Gujarat 382424, India*
[183] *Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
[184] *Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India*
[185] *INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
[186] *International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil*
[187] *Villanova University, 800 Lancaster Ave, Villanova, PA 19085, USA*
[188] *Andrews University, Berrien Springs, MI 49104, USA*
[189] *Max Planck Institute for Gravitationalphysik (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany*
[190] *Università di Siena, I-53100 Siena, Italy*
[191] *Trinity University, San Antonio, TX 78212, USA*
[192] *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*
[193] *Department of Physics, University of Texas, Austin, TX 78712, USA*

* Deceased, July 2018.