Search for gravitational waves from high-mass-ratio compact-binary mergers of stellar mass and sub-solar mass black holes.

Alexander H. Nitz* and Yi-Fan Wang
Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), D-30167 Hannover, Germany and Leibniz Universität Hannover, D-30167 Hannover, Germany

(Dated: July 8, 2020)

We present the first search for gravitational waves from the coalescence of stellar mass and sub-solar mass black holes with masses between 20 - 100 M$_\odot$ and 0.01 - 1 M$_\odot$ (10$^{-3}$ M$_J$), respectively. The observation of a single sub-solar mass black hole would establish the existence of primordial black holes and a possible component of dark matter. We search the ~ 164 days of public LIGO data from 2015-2017 when LIGO-Hanford and LIGO-Livingston were simultaneously observing. We find no significant candidate gravitational-wave signals. Using this non-detection, we place a 90% upper limit on the rate of 30 − 0.01 M$_\odot$ and 30 − 0.1 M$_\odot$ mergers at < 1.2 × 10$^6$ and < 1.6 × 10$^5$ Gpc$^{-3}$yr$^{-1}$, respectively. If we consider binary formation through direct gravitational-wave braking, this kind of merger would be exceedingly rare if only the lighter black hole were primordial in origin (< 10$^{-4}$ Gpc$^{-3}$yr$^{-1}$). If both black holes are primordial in origin, we constrain the contribution of 1(0.1) M$_\odot$ black holes to dark matter to < 3(0.3)%.

I. INTRODUCTION

The first gravitational wave observation originating from the merger of two black holes was detected on September 14th, 2015 [1]. Since then, over a dozen binary black hole (BBH) mergers [2–8] have been reported along with two binary neutron star mergers [9, 10] by Advanced LIGO [11] and Virgo [12]. There are also dozens of additional candidates from the concluded third observing run of Advanced LIGO and Virgo [13]. Most recently, two new compact binary coalescences with high unequal mass [14, 15] have been reported; the mass ratios are ~ 3 and ~ 9, respectively.

The nature of dark matter remains a mystery given null results from particle experiments for direct dark matter search (see e.g., [16, 17] and recent notable exception [18]). The observation of BBH mergers has sparked renewed interest in primordial black holes as a possible contributor to dark matter [19–27]. However, the merger of stellar-mass primordial black holes may be difficult to separate from standard stellar formation channels. Black holes, such as those observed by LIGO and Virgo, may form through standard stellar evolution between 2 − 50M$_\odot$ [28–33]. Furthermore, gravitational-wave observation alone has not yet been able to determine if a component of a binary is either a neutron star or black hole [34, 35]; the observation of 1−2 M$_\odot$ component of a merger cannot be ruled out as a black hole. Although the observation of a coincident gamma-ray burst or kilonova, such as in the case of GW170817 [9, 36–39], can confirm the presence of nuclear matter, there is no clear way to determine if a merger involved a primordial black hole at the present time. In contrast, there is no known model which can produce sub-solar mass black holes by conventional formation mechanisms; the observation of a single sub-solar mass black hole would provide strong evidence for primordial black holes, which may form a component of dark matter.

There are a variety of constraints for the contributing fraction of primordial black holes to dark matter (see Refs. [40, 41] and references therein). Gravitational-wave astronomy provides a unique window; notably, the direct search for sub-solar black holes has constrained the mass range 0.2 − 2 M$_\odot$ for near equal-mass sources [42, 43] and the non-detection of a gravitational-wave astrophysical background by LIGO and Virgo has constrained primordial black holes with 0.01 − 100 M$_\odot$ [44]. Future space-based gravitational-wave detectors are expected to probe primordial black holes with mass 10$^{-8}$ − 1 M$_\odot$ [45]. Recently, very tight constraints from the NANOGrav pulsar timing array [46] are given by Ref. [47] for 0.001 − 1 M$_\odot$ black holes based on the non-detection of gravitational waves induced by scalar perturbations during the expected primordial black hole formation epoch. In this work, we focus on constraints obtained from direct observation of gravitational waves from primordial black holes.

So far, all observations of gravitational waves from BBH mergers were identified by searches targeting stellar-mass BBHs or neutron stars. Targeted searches for sub-solar mass binaries with component masses between 0.2−2 M$_\odot$ have so far yielded no detections [42, 43]. We report a search for sub-solar mass black holes in an unexplored region of parameter space: the merger of 0.01−1 M$_\odot$ sub-solar mass black holes with a 20−100 M$_\odot$ stellar-mass black holes. We summarize the region we search in comparison to past analyses in Fig. 1. We find no statistically significant gravitational-wave candidates and place the first constraints from gravitational-wave observation on the merger rate of these sources.



* alex.nitz@aei.mpg.de
**II. SEARCH**

We analyze the publicly available LIGO data, which covers the 2015-2017 observing period [48, 49]. This data contains \( \sim 164 \) days of LIGO-Hanford and LIGO-Livingston joint observation time. Virgo was also observing for the final month of this period, but had limited range in comparison to the LIGO instruments. We use the open-source PyCBC-based search pipeline [50, 51] configured similarly to the analysis of Ref. [3] to analyze the LIGO data, identify potential candidates, apply tests of each candidate’s signal consistency [52, 53], rank each candidate, and finally assess each candidate’s statistical significance [54–56]. The statistical significance of any candidate is assessed by comparing it to the empirically estimated rate of false alarms. This rate is estimated by creating numerous fictitious analyses that are analyzed in an identical manner to the search, but where time shifts between the data of the two LIGO observatories are applied. The time shift of each of these background analyses is greater than the light-travel-time between the two LIGO observatories, which ensures that astrophysical signals are not found in coincidence. The average sensitive distance of our analysis at a false alarm rate of 1 per 100 years is shown in Fig. 2.

The most sensitive searches for gravitational-waves from compact-binary mergers use matched filtering to extract the signal-to-noise from data for a given template waveform [50, 57]. Each template corresponds to the gravitational-wave signal for a single type of source. To search for sources with varied component masses, a discrete bank of template waveforms is required. For our search, we use a brute-force stochastic method to find the nearly 9 million templates required by our analysis (\( \sim 9 \) the size of the bank used in [42]). To save on computational cost, we search for up to the last 60s of each gravitational waveform. For the lowest mass sources, this implies that we analyze the data starting at a higher gravitational-wave frequency than for the heaviest sources, where we analyze the strain data starting from 20 Hz.

To model the gravitational-wave signal, we use EOB-NRv2, a model based on an effective one-body Hamiltonian approximation of general relativity in combination with a fitted merger and ringdown [58]. We assume our sources’ orbits have negligible eccentricity by the time of observation and that the component black holes are non-spinning. This choice is consistent with models of primordial black holes which predict negligible component spin [59–63]. We crosscheck the EOBNRv2 model against the recent numerical relativity surrogate EMRISur1dq1e4 [64]. We find both models to be consi...
FIG. 3. Comparison of the gravitational waveform for a 30 M⊙ - 0.01 M⊙ merger. The EOBNRv2 interpolant model used by our search is consistent with the EMRISur1d4lq4 numerical relativity surrogate model when the inclination of the source’s orbital plane is close to face-on/off. For sources with highly inclined orbital planes, higher order modes becomes increasingly important.

III. OBSERVATIONAL RESULTS

We find that the most significant candidate from our search was observed at a false alarm rate of 3 per year, and if it were astrophysical, would be consistent with the merger of a 23 M⊙ primary black hole with a 0.012 M⊙ secondary. Considering the time searched, our results are consistent with a null observation.

We place an upper limit at 90% confidence on the rate of mergers throughout the searched space using the loudest event method [69]. The upper limit $R_{90}$ is given as,

$$R_{90} = \frac{2.3}{VT}$$

where V is the sensitive volume of our analysis at the false alarm rate of the most significant candidate, and T is the total time searched. We simulate a population of sources distributed isotropically in the sky and binary orientation, and uniform in volume, to measure the sensitive volume of our analysis as a function of the primary and secondary masses. Fig. 4 shows the upper limit on the merger rate as a function of the secondary mass. Assuming a distribution of primary masses consistent with the black holes observed by LIGO and Virgo, we find that the rate of 0.01 M⊙ solar mass mergers is $< 1.7 \times 10^6$ Gpc$^{-3}$yr$^{-1}$ at 90% confidence.

IV. IMPLICATIONS FOR PRIMORDIAL BLACK HOLES

Whereas stellar-mass black holes can be either the product of stellar evolution or primordial in origin, given conventional stellar evolution, sub-solar mass black holes can only form in the primordial Universe. We consider two scenarios, the first that only the secondary, lighter black hole is primordial in origin and has only recently formed a binary, and a second scenario where both black holes are primordial in origin and formed a binary in the early Universe.

For the first scenario, binaries can form when a primordial black hole is dynamically captured by another
black hole due to gravitational-wave bremsstrahlung in the galactic field. To estimate the rate of mergers, we need the abundance of each type of black hole and their interaction cross-section. For two black holes with mass $m_1$ and $m_2$ and relative velocity $v$, the cross section for coalescence is given by Ref. [70] as

$$\sigma = 2\pi \left( \frac{8\pi}{6\sqrt{2}} \right)^{2/7} G^2 (m_1 + m_2)^{10/7} (m_1 m_2)^{2/7} c^{10/7} v^{18/7} (2)$$

where $G$ and $c$ are gravitational constant and speed of light, respectively. As shown by Ref. [23], the binaries are expected to quickly merge after formation and disruption by other primordial black holes can be neglected.

To constrain the primordial black hole distribution, we use the dark matter halo samples from the cosmological simulation project IllustrisTNG for galaxy formation [71]. In the redshift $= 0$ snapshot of the TNG-100 high resolution simulation, there are $\sim 10^5$ dark matter main subhalos with non-zero star formation within a $\sim 100$ Mpc size cube. For each main subhalo, we assume the dark matter number density follows the Navarro-Frenk-White (NFW) profile $\rho_{\text{NFW}}$ [72], and that primordial black holes constitute a fraction of dark matter with mass fraction $f_{\text{PBH}}$.

Estimating the abundance of black holes produced by standard stellar evolution is a challenge due to the lack of observational constraints. Nevertheless, the synthesis population study of Ref. [73] shows that $\sim 0.006\%$ of the total galactic halo mass including dark matter is in the form of stellar-origin black holes. As an approximation, we take this value as the universal fraction over dark matter main subhalos to infer the mass density $\rho_{\text{BH}}$ of stellar-origin black holes.

The rate density of dynamical captures between primordial and stellar-origin black holes is finally

$$R(m_1, m_2) = \sum_{\text{Halos}} \int_0^{\sqrt{2}R_{\text{halo mass}}} \frac{\rho_{\text{BH}} f_{\text{PBH}} \rho_{\text{NFW}}(r)}{m_1 m_2} \sigma v dr$$

where $m_1$, $m_2$ are the mass of stellar-origin and primordial-origin black holes, respectively. Assuming a uniform spatial distribution of stellar-origin black holes, the radius $r$ is integrated from the main subhalo center to $\sqrt{2}$ times of the radius which contains half of the stellar mass, $R_{\text{halo mass}}$. The relative velocity $v$ is approximated by the stellar dispersion velocity, provided by IllustrisTNG. We find that in this scenario, even for $f_{\text{PBH}} = 100\%$, this formation channel implies a merger rate $< 10^{-4}$ Gpc$^{-3}$ yr$^{-1}$, which is orders of magnitude below our observational constraints.

On the other hand, if both primary and secondary black holes are of primordial origin, Refs. [26, 74] give the merger rate for a binary with mass $m_1$ and $m_2$ as

$$R(m_1, m_2) = 3.3 \cdot 10^6 \cdot f_{\text{PBH}}^2 (0.7 f_{\text{PBH}}^2 + \sigma_{\text{eq}}^2) \frac{2\pi}{7} (m_1 m_2)^{3/7} \times (m_1 + m_2)^{48/7} \min \left( \frac{P(m_1)}{m_1}, \frac{P(m_2)}{m_2} \right) \left( \frac{P(m_1)}{m_1} + \frac{P(m_2)}{m_2} \right)$$

where $m$ and merger rate $R$ are in units of $M_\odot$ and Gpc$^{-3}$ yr$^{-1}$, respectively. $P(m)$ is the normalized primordial black hole mass distribution. $\sigma_{\text{eq}}$ accounts for the density perturbation from other dark matter at the matter radiation equality epoch and is suggested to be $0.005$ by Ref. [74].

The possibility that the currently observed stellar-mass BBH mergers were caused by primordial black holes is a topic of investigation [23–27, 75]. In the most optimistic case, where the majority of observed black holes by LIGO and Virgo are primordial in origin, $f_{\text{PBH}}^\text{primary} = 3 \times 10^{-3}$ by Ref. [75]. With this fixed fraction for the primary mass, we use our results to constrain the contribution of the secondary, sub-solar mass black hole to dark matter. We assume a two-valued mass distribution, i.e., $P(m_1) + P(m_2) = 100\%$. Thus the fraction in dark matter for the primary and secondary black hole is

$$f_{\text{PBH}}^\text{primary} = P(m_1) f_{\text{PBH}}^\text{primary}$$

The upper limit for $f_{\text{PBH}}^\text{primary}$ for a fixed fiducial primary mass $m_1 = 20(50) M_\odot$ and the average mass from the 2-OGC catalog ($\sim 37 M_\odot$) [3] are shown in Fig. 5. For the 2-OGC average case, we find that $0(0.1) M_\odot$ primordial black hole cannot exceed $3(0.3)\%$ of the total dark matter. In contrast, if we assume none of the LIGO/Virgo BBH detections are composed of primordial black holes, our results cannot constrain $f_{\text{PBH}}$.

Our constraints can be directly compared with the targeted search for near equal-mass sub-solar black holes [42, 43] based on the same formation scenario as described by Eq. 4. We also note that stringent constraints for sub-solar mass primordial black holes from pulsar timing arrays [47] have almost excluded the $0.001 – 1 M_\odot$ mass region. Nevertheless, any positive results from a direct search for sub-solar mass black holes will revolutionize

FIG. 4. The 90% confidence upper limit on the rate of mergers as a function of the mass of the secondary black hole, for a range of primary masses (various colors), and the average assuming a primary mass population consistent with observed BBH mergers from the 2-OGC catalog (black) [3].
current theories and may require novel mechanisms to suppress observable gravitational waves induced by primordial scalar density perturbations.

V. CONCLUSIONS

In this work we conduct a novel search for gravitational waves from the binary coalescence of high-mass-ratio sources, where the primary mass is 20-100 $M_\odot$ and the secondary mass is 0.01-1 $M_\odot$. We find no promising candidates, and thus place an upper limits on the merger rate and the abundance of primordial black holes.

The merging of a primordial black hole with a black hole formed through stellar evolution is extremely unlikely under the scenario of direct capture through gravitational-wave braking. A significantly more efficient binary formation mechanism would be required for this scenario to make a significant contribution. On the other hand, assuming both black holes are primordial in origin places constraints on the abundance of primordial black holes.

Currently, advanced LIGO and Virgo are continuously being upgraded [76], and the third generation of gravitational-wave detectors can further improve the horizon distance by an order of magnitude [77, 78]. At that point, it will be possible to probe the redshift evolution of stellar-mass binaries to distinguish primordial and stellar-origin black hole distributions [75]. From our results, we expect the constraint on sub-solar mass primordial black hole abundance to be $10^{3-4}$ times tighter than the current search, assuming a null result.

We make available the top candidates from our analysis along with the configuration files necessary to reproduce the search at https://github.com/gwastro/stellar-pbh-search.

ACKNOWLEDGMENTS

We acknowledge the Max Planck Gesellschaft and the Atlas cluster computing team at AEI Hannover for support. This research has made use of data, software and/or web tools obtained from the Gravitational Wave Open Science Center (https://www.gwopenscience.org), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO is funded by the U.S. National Science Foundation. Virgo is funded by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale della Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by Polish and Hungarian institutes.

[1] B. P. Abbott et al. (Virgo, LIGO Scientific), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016), arXiv:1602.03837 [gr-qc].
[2] A. H. Nitz, C. Capano, A. B. Nielsen, S. Reyes, R. White, D. A. Brown, and B. Krishnan, 1-OGC: The first open gravitational-wave catalog of binary mergers from analysis of public Advanced LIGO data, Astrophys. J. 872, 195 (2019), arXiv:1811.01921 [gr-qc].
[3] A. H. Nitz, T. Dent, G. S. Davies, S. Kumar, C. D. Capano, I. Harry, S. Mozzon, L. Nuttall, A. Lundgren, and M. Tápai, 2-OGC: Open Gravitational-wave Catalog of binary mergers from analysis of public Advanced LIGO and Virgo data, Astrophys. J. 891, 123 (2019), arXiv:1910.05531 [astro-ph.HE].
[4] A. H. Nitz, T. Dent, G. S. Davies, and I. Harry, A Search for Gravitational Waves from Binary Mergers with a Single Observatory, (2020), arXiv:2004.10015 [astro-ph.HE].
[5] T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, New search pipeline for compact binary mergers: Results for binary black holes in the first observing run of Advanced LIGO, Phys. Rev. D 100, 023011 (2019), arXiv:1902.10341 [astro-ph.IM].
[6] T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, New Binary Black Hole Mergers in the Second Observing Run of Advanced LIGO and Advanced Virgo, (2019), arXiv:1904.07214 [astro-ph.HE].
[7] B. Zackay, L. Dai, T. Venumadhav, J. Roulet, and M. Zaldarriaga, Detecting Gravitational Waves With Disparate Detector Responses: Two New Binary Black Hole Mergers, (2019), arXiv:1910.09528 [astro-ph.HE].
[8] B. P. Abbott et al. (LIGO Scientific, Virgo), GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, Phys. Rev. X 9, 031040 (2019), arXiv:1811.12907 [astro-ph.HE].
[9] B. Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration), GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119, 161101 (2017), arXiv:1710.05832 [gr-qc].

[10] B. Abbott et al. (LIGO Scientific, Virgo), GW190425: Observation of a Compact Binary Coalescence with Total Mass \( \sim 3.4M_\odot \), Astrophys. J. Lett. 892, L3 (2020), arXiv:2001.01767 [astro-ph.HE].

[11] J. Aasi et al. (LIGO Scientific Collaboration), Advanced LIGO, Class. Quantum Grav. 32, 074001 (2015), arXiv:1411.4547 [gr-qc].

[12] F. Acernese et al. (VIRGO), Advanced Virgo: a second-generation interferometric gravitational wave detector, Class. Quantum Grav. 32, 024001 (2015), arXiv:1408.3978 [gr-qc].

[13] LVC, Gracedb — gravitational-wave candidate event database.

[14] R. Abbott et al. (LIGO Scientific, Virgo), GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses, (2020), arXiv:2004.08342 [astro-ph.HE].

[15] R. Abbott et al. (LIGO Scientific, Virgo), GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object, Astrophys. J. 896, L44 (2020), arXiv:2006.12611 [astro-ph.HE].

[16] X. Cui, A. Abduslemi, W. Chen, X. Chen, Y. Chen, B. Dong, D. Fang, C. Fu, K. Giboni, F. Giuliani, L. Gu, Y. Gu, X. Guo, Z. Guo, K. Han, C. He, D. Huang, S. He, X. Huang, Z. Huang, X. Ji, Y. Ju, S. Li, Y. Li, H. Lin, H. Liu, J. Liu, Y. Ma, Y. Mao, K. Ni, J. Ning, X. Ren, F. Shi, A. Tan, C. Wang, H. Wang, M. Wang, Q. Wang, S. Wang, X. Wang, X. Wang, Q. Wu, S. Wu, M. Xiao, P. Xie, B. Yan, Y. Yang, J. Yue, D. Zhang, H. Zhang, T. Zhang, T. Zhang, L. Zhao, J. Zhou, N. Zhou, and X. Zhou (PandaX-II Collaboration), Dark matter results from 54-ton-day exposure of pandax-ii experiment, Phys. Rev. Lett. 119, 181302 (2017).

[17] R. Agnese, T. Aramaki, I. J. Arnquist, W. Baker, D. Balasis, S. Banik, D. Barker, R. Basu Thakur, D. A. Bauer, T. Binder, M. A. Bowles, P. L. Brink, R. Bunker, B. Cabrera, D. O. Caldwell, R. Calkins, C. Cartaro, D. G. Cerdeño, Y. Chang, Y. Chen, J. Cooley, B. Cornell, P. Cushman, M. Daal, P. C. F. Di Stefano, T. Doughty, C. Jena, M. H. Kelsey, A. Kennedy, A. Kubik, N. A. Kurinsky, B. Loer, E. Lopez Asamar, P. Lukens, D. Macdonell, R. Mahapatra, V. Mandic, N. Mast, E. H. Miller, N. Mirabolfathi, B. Mohanty, J. D. Morales Mendoza, J. Nelson, J. L. Orrell, S. M. Oser, K. Page, W. A. Page, R. Partridge, M. Penalver Martinez, M. Pepin, A. Phipps, S. Poudel, M. Pyle, H. Qiu, W. Rau, P. Redl, A. Reissetter, T. Reynolds, A. Roberts, A. E. Robinson, H. E. Rogers, T. Saab, B. Sadoulet, J. Sander, K. Schnee, R. W. Schnee, S. Scorza, K. Senapati, B. Sefarra, D. Speller, M. Stein, J. Street, H. A. Tanaka, D. Torback, R. Underwood, A. N. Villano, B. von Koszig, B. Welliver, J. S. Wilson, M. J. Wilson, D. H. Wright, S. Yellin, J. J. Yen, B. A. Young, X. Zhang, and X. Zhao (SuperCDMS Collaboration), Results from the super cryogenic dark matter search experiment at soudan, Phys. Rev. Lett. 120, 061802 (2018).

[18] E. Aprile et al. (XENON), Observation of Excess Electronic Recoil Events in XENON1T, (2020), arXiv:2006.09721 [hep-ex].

[19] S. Hawking, Gravitationally collapsed objects of very low mass, Mon. Not. Roy. Astron. Soc. 152, 75 (1971).

[20] B. J. Carr and S. W. Hawking, Black holes in the early Universe, Mon. Not. Roy. Astron. Soc. 168, 399 (1974).

[21] A. Dolgov and J. Silk, Baryon isocurvature fluctuations at small scales and baryonic dark matter, Phys. Rev. D 47, 4244 (1993).

[22] K. Jedamzik, Primordial black hole formation during the QCD epoch, Phys. Rev. D 55, 5871 (1997), arXiv:astro-ph/9605152 [astro-ph].

[23] S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haimoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess, Did ligo detect dark matter?, Phys. Rev. Lett. 116, 201301 (2016).

[24] S. Cluses and J. García-Bellido, The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO, Phys. Dark Univ. 10, 002 (2016), arXiv:1603.05234 [astro-ph.CO].

[25] M. Sasaki, T. Suyama, T. Tanaka, and S. Yokoyama, Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914, Phys. Rev. Lett. 117, 061101 (2016), arXiv:1603.08338 [astro-ph.CO].

[26] Z.-C. Chen and Q.-G. Huang, Merger Rate Distribution of Primordial-Black-Hole Binaries, Astrophys. J. 864, 61 (2018), arXiv:1801.10327 [astro-ph.CO].

[27] V. De Luca, G. Franciolini, P. Pan, and A. Riotto, Primordial Black Holes Confront LIGO/Virgo data: Current situation, (2020), arXiv:2005.05641 [astro-ph.CO].

[28] C. L. Fryer, K. Belczynski, G. Wiktorowicz, M. Dominik, V. Kalogera, and D. E. Holz, Compact Remnant Mass Function: Dependence on the Explosion Mechanism and Metallicity, Astrophys. J. 749, 91 (2012), arXiv:1110.1726 [astro-ph.SR].

[29] C. S. Kochanek, Failed Supernovae Explain the Compact Remnant Mass Function, Astrophys. J. 785, 28 (2014), arXiv:1308.0013 [astro-ph.HE].

[30] T. Ertl, H.-T. Janka, S. E. Woosley, T. Sukhbold, and M. Ugliano, A TWO-PARAMETER CRITERION FOR CLASSIFYING THE EXPLODABILITY OF MASSIVE STARS BY THE NEUTRINO-DRIVEN MECHANISM, The Astrophysical Journal 818, 124 (2016).

[31] S. E. Woosley, Pulsational Pair-Instability Supernovae, Astrophys. J. 836, 244 (2017), arXiv:1608.08930 [astro-ph.HE].

[32] P. Marchant, M. Renzo, R. Farmer, K. M. W. Pappas, R. E. Taam, S. E. de Mink, and V. Kalogera, Pulsational pair-instability supernovae in very close binaries, Astrophys. J. 882, 36 (2019).

[33] R. Farmer, M. Renzo, S. de Mink, P. Marchant, and S. Justham, Mind the gap: The location of the lower pair-instability supernovae black hole mass gap 10.3847/1538-4357/ab518b (2019), arXiv:1910.12874 [astro-ph.SR].

[34] H. Yang, W. E. East, and L. Lehner, Can we distinguish low mass black holes in neutron star binaries?, Astrophys. J. 856, 110 (2018), Erratum: Astrophys.J. 870, 139 (2019)], arXiv:1710.05891 [gr-qc].

[35] B. P. Abbott et al. (LIGO Scientific, Virgo), Model comparison from LIGO–Virgo data on GW170817's binary components and consequences for the merger remnant.
B. Abbott et al. (LIGO Scientific, Virgo, Fermi-GBM, INTEGRAL), Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, Astrophys. J. Lett. 848, L13 (2017), arXiv:1710.05834 [astro-ph.HE].

B. P. Abbott et al. (GROND, SALT Group, OzGrav, DFN, INTEGRAL, Virgo, Insight-Hxmt, MAXI Team, Fermi-LAT, J-GRAM, RATIR, IceCube, CAESTRO, LWA, ePESTO, GRAWITA, RIMAS, SKA South Africa/MeerKAT, H.E.S.S., 1M2H Team, IKI-GW Follow-up, Fermi GBM, Pi of Sky, DWF (Deeper Wider Faster Program), Dark Energy Survey, MASTER, AstroSat Cadmium Zinc Telluride Imager Team, Swift, Pierre Auger, ASKAP, VINROUGE, JAGWAR, Chandra Team at McGill University, TTU-NRAO, GROWTH, AGILE Team, MWA, ATCA, AST3, TOROS, Pan-STARRS, NuSTAR, ATLAS Telescopes, BOOTES, CaltechNRAO, LIGO Scientific, High Time Resolution Universe Survey, Nordic Optical Telescope, Las Cumbres Observatory Group, TZAC Consortium, LOFAR, IPN, DLT40, Texas Tech University, HAWC, ANTARES, KU, Dark Energy Camera GW-EM, CALET, Euro VLBI Team, ALMA), Multi-messenger Observations of a Binary Neutron Star Merger, Astrophys. J. 848, L12 (2017), arXiv:1710.05833 [astro-ph.HE].

M. Soares-Santos et al. (DES, Dark Energy Camera GW-EM), The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera, Astrophys. J. 848, L16 (2017), arXiv:1710.05450 [astro-ph.HE].

D. A. Coulter et al., Swope Supernova Survey 2017a (SSS17a), the Optical Counterpart to a Gravitational Wave Source, Science 10.1126/science.aap9811 (2017), [Science358,1556(2017)], arXiv:1710.05452 [astro-ph.HE].

B. Carr and F. Kuhnel, Primordial Black Holes as Dark Matter, (2020), arXiv:2006.02838 [astro-ph.CO].

B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, Constraints on Primordial Black Holes, (2020), arXiv:2002.12778 [astro-ph.CO].

B. Abbott et al. (LIGO Scientific, Virgo), Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO’s Second Observing Run, Phys. Rev. Lett. 123, 161102 (2019), arXiv:1904.08976 [astro-ph.CO].

B. Abbott et al. (LIGO Scientific, Virgo), Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO’s First Observing Run, Phys. Rev. Lett. 121, 231103 (2018), arXiv:1808.04771 [astro-ph.CO].

S. Wang, Y.-F. Wang, Q.-G. Huang, and T. G. F. Li, Constraints on the Primordial Black Hole Abundance from the First Advanced LIGO Observation Run Using the Stochastic Gravitational-Wave Background, Phys. Rev. Lett. 120, 191102 (2018), arXiv:1610.08725 [astro-ph.CO].

Y.-F. Wang, Q.-G. Huang, T. G. Li, and S. Liao, Searching for primordial black holes with stochastic gravitational-wave background in the space-based detector frequency band, Phys. Rev. D 101, 063019 (2020), arXiv:1910.07397 [astro-ph.CO].

Z. Arzoumanian et al. (NANOGrav), The NANOGrav 11-year Data Set: High-precision timing of 45 Millisecond Pulsars, Astrophys. J. Suppl. 235, 37 (2018), arXiv:1801.01837 [astro-ph.HE].

Z.-C. Chen, C. Yuan, and Q.-G. Huang, Pulsar Timing Array Constraints on Primordial Black Holes with NANOGrav 11-Year Data Set, Phys. Rev. Lett. 124, 251101 (2020), arXiv:1910.12239 [astro-ph.CO].

M. Vallisneri, J. Kanner, R. Williams, A. Weinstein, and B. Stephens, The LIGO Open Science Center, Proceedings, 10th International LISA Symposium: Gainesville, Florida, USA, May 18-23, 2014, J. Phys. Conf. Ser. 610, 012021 (2015), arXiv:1410.4839 [gr-qc].

R. Abbott et al. (LIGO Scientific, Virgo), Open data from the first and second observing runs of Advanced LIGO and Advanced Virgo, (2019), arXiv:1912.11716 [gr-qc].

S. A. Usman et al., The PyCBC search for gravitational waves from compact binary coalescence, Class. Quant. Grav. 33, 215004 (2016), arXiv:1508.02357 [gr-qc].

A. H. Nitz, I. W. Harry, J. L. Willis, C. M. Biwer, D. A. Brown, L. P. Pekowsky, T. Dal Canton, A. R. Williamson, T. Dent, C. D. Capano, T. J. Massinger, A. K. Lenon, A. B. Nielsen, and M. Cabero, PyCBC Software, https://github.com/gwastro/pycbc (2018).

B. Allen, A chi**2 time-frequency discriminator for gravitational wave detection, Phys. Rev. D 71, 062001 (2005), arXiv:gr-qc/0409045 [gr-qc].

A. H. Nitz, Distinguishing short duration noise transients in LIGO data to improve the PyCBC search for gravitational waves from high mass binary black hole mergers, Class. Quant. Grav. 35, 035016 (2018), arXiv:1709.08974 [gr-qc].

A. H. Nitz, T. Dent, T. Dal Canton, S. Fairhurst, and D. A. Brown, Detecting binary object-mergers with gravitational waves: Understanding and Improving the sensitivity of the PyCBC search, Astrophys. J. 849, 118 (2017), arXiv:1705.01513 [gr-qc].

G. S. Davies, T. Dent, M. Tápai, I. Harry, C. McIsaac, and A. H. Nitz, Extending the pycbc search for gravitational waves from compact binary mergers to a global network, Phys. Rev. D 102, 022004 (2020), arXiv:2002.08291 [astro-ph.HE].

S. Mozzon, L. K. Nuttall, A. Lundgren, S. Kumar, A. H. Nitz, and T. Dent, Dynamic Normalization for Compact Binary Coalescence Searches in Non-Stationary Noise, (2020), arXiv:2002.09407 [astro-ph.IM].

C. Messick, K. Blackburn, P. Brady, P. Brockill, K. Cannon, S. Caudill, S. J. Chamberlin, J. D. E. Creighton, R. Everett, C. Hanna, R. N. Lang, T. G. F. Li, D. Meacher, C. Pankow, S. Privitera, H. Qi, S. Sachdev, L. Sadeghian, B. Sathyaprakash, L. Singer, E. G. Thomas, L. Wade, M. Wade, and A. Weinstein, Analysis Framework for the Prompt Discovery of Compact Binary Mergers in Gravitational-wave Data, (2016), arXiv:1604.04324 [astro-ph.IM].

Y. Pan, A. Buonanno, L. T. Buchman, T. Chu, L. E. Kidder, et al., Effective-one-body waveforms calibrated to numerical relativity simulations: coalescence of non-precessing, spinning, equal-mass black holes, Phys. Rev. D 81, 084041 (2010), arXiv:0912.3466 [gr-qc].

T. Chiba and S. Yokoyama, Spin Distribution of Primordial Black Holes, PTEP 2017, 083E01 (2017), arXiv:1704.06573 [gr-qc].

V. De Luca, V. Desjacques, G. Franciolini, A. Malhotra, and A. Riotto, The initial spin probability distribution of...
primordial black holes, JCAP 05, 018, arXiv:1903.01179 [astro-ph.CO].

[61] V. De Luca, G. Franciolini, P. Pani, and A. Riotto, The Evolution of Primordial Black Holes and their Final Observable Spins, JCAP 04, 052, arXiv:2003.02778 [astro-ph.CO].

[62] M. Mirbabayi, A. Gruzinov, and J. Noreña, Spin of Primordial Black Holes, JCAP 03, 017, arXiv:1901.05963 [astro-ph.CO].

[63] K. Postnov, A. Kuranov, and N. Mitichkin, Spins of black holes in coalescing compact binaries, Phys. Usp. 62, 1153 (2019), arXiv:1907.04218 [astro-ph.HE].

[64] N. E. Rifat, S. E. Field, G. Khanna, and V. Varma, Surrogate model for gravitational wave signals from comparable and large-mass-ratio black hole binaries, Phys. Rev. D 101, 081502 (2020), arXiv:1910.10473 [gr-qc].

[65] I. Harry, J. Calderón Bustillo, and A. Nitz, Searching for the full Symphony of black hole binary mergers, Phys. Rev. D 97, 023004 (2018), arXiv:1709.09181 [gr-qc].

[66] Y. Pan, A. Buonanno, M. Boyle, L. T. Buchman, L. E. Kidder, H. P. Pfeiffer, and M. A. Scheel, Inspiral-merging-ringdown multipolar waveforms of nonspinning black holes using the effective-one-body formulation, Phys. Rev. D 84, 124052 (2011), arXiv:1106.1021 [gr-qc].

[67] L. London, S. Khan, E. Fauchon-Jones, C. García, M. Hannam, S. Husa, X. Jiménez-Forteza, C. Kalaghatgi, F. Ohme, and F. Pannarale, First higher-multipole model of gravitational waves from spinning and coalescing black-hole binaries, Phys. Rev. Lett. 120, 161102 (2018), arXiv:1708.00404 [gr-qc].

[68] R. Cotesta, S. Marsat, and M. Pürrer, Frequency domain reduced order model of aligned-spin effective-one-body waveforms with higher-order modes, Phys. Rev. D 101, 124040 (2020), arXiv:2003.12079 [gr-qc].

[69] R. Biswas, P. R. Brady, J. D. E. Creighton, and S. Fairhurst, The Loudest Event Statistic: General Formalization, Properties and Applications, Class. Quantum Grav. 26, 175009 (2009), arXiv:0710.0465 [gr-qc].

[70] H. Mour and Y. Taniguchi, Runaway merging of black holes: analytical constraint on the timescale, Astrophys. J. Lett. 566, L17 (2002), arXiv:astro-ph/0201102.

[71] The illustrious simulation.

[72] J. F. Navarro, C. S. Frenk, and S. D. M. White, The Structure of cold dark matter halos, Astrophys. J. 462, 563 (1996), arXiv:astro-ph/9508025 [astro-ph].

[73] A. Olejak, K. Belczynski, T. Bulik, and M. Sobolewska, Synthetic catalog of black holes in the Milky Way, Astron. Astrophys. 638, A94 (2020), arXiv:1908.08775 [astro-ph.SR].

[74] Y. Ali-Haïmoud, E. D. Kovetz, and M. Kamionkowski, The merger rate of primordial-black-hole binaries, (2017), arXiv:1709.06576 [astro-ph.CO].

[75] Z.-C. Chen and Q.-G. Huang, Distinguishing Primordial Black Holes from Astrophysical Black Holes by Einstein Telescope and Cosmic Explorer, (2019), arXiv:1904.02396 [astro-ph.CO].

[76] B. P. Abbott et al. (VIRGO, KAGRA, LIGO Scientific), Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Rev. Rel. 21, 3 (2018), arXiv:1304.0670 [gr-qc].

[77] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker, N. Beveridge, S. Birindelli, S. Bose, L. Bosi, S. Braccini, C. Bradaschia, T. Bulik, E. Calloni, G. Cella, E. Coccia, C. Colacino, J. Colas, A. Cumming, L. Cunningham, E. Cuoco, S. Danilishin, K. Danzmann, G. D. Luca, R. D. Salvo, T. Dent, R. D. Rosa, L. D. Fiore, A. D. Virgilio, M. Doets, V. Fafone, P. Falleri, R. Flaminio, J. Franc, F. Frasconi, A. Freise, P. Fulda, J. Gair, G. Gemme, A. Gennai, A. Giazotto, K. Glampedakis, M. Granata, H. Grote, G. Guidi, G. Hammond, M. Hannam, J. Harms, D. Heinert, M. Hendry, I. Heng, E. Hennes, S. Hild, J. Hough, S. Husa, S. Huttner, G. Jones, F. Khalili, K. Koyekyan, K. Kokkotas, B. Krishnan, M. Lorenzini, H. Lück, E. Majorana, I. Mandel, V. Mandic, I. Martin, C. Michel, Y. Minenkov, N. Morgado, S. Mosca, B. Mours, H. Müller–Eh operands, R. Nawrodt, J. Nelson, R. Oshaughnessy, C. D. Ott, C. Palomba, A. Paoli, G. Parguez, A. Pasqualetti, R. Passaquieti, D. Passuello, L. Pinard, R. Poggiani, P. Popolizio, M. Prato, P. Pupp, D. Rabeling, P. Ragnani, J. Read, T. Regimbau, H. Rehbein, S. Reid, L. Rezzolla, F. Ricci, F. Richard, A. Rocchi, S. Rowan, A. Rüdiger, B. Sassolas, B. Sathyaprakash, R. Schnabl, C. Schwarz, P. Seidel, A. Šintes, K. Somiya, F. Speirits, K. Strain, S. Strigin, P. Sutton, S. Tarabrin, A. Thüring, J. van den Brand, C. van Leeuwen, M. van Vegel, C. van den Broeck, A. Vecchio, J. Veitch, F. Vetrano, A. Vicere, S. Vyatchanin, B. Willke, G. Woan, P. Wolfgang, and K. Yamamoto, The einstein telescope: a third-generation gravitational wave observatory, Classical and Quantum Gravity 27, 194002 (2010).

[78] D. Reitze et al., Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO, Bull. Am. Astron. Soc. 51, 035 (2019), arXiv:1907.04833 [astro-ph.IM].