The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.  
http://hdl.handle.net/2066/199324

Please be advised that this information was generated on 2019-01-29 and may be subject to change.
Search for sub-solar mass ultracompact binaries in Advanced LIGO’s first observing run

The LIGO Scientific Collaboration and The Virgo Collaboration  
(Dated: August 19, 2018)

We present the first Advanced LIGO and Advanced Virgo search for ultracompact binary systems with component masses between 0.2 $M_\odot$ – 1.0 $M_\odot$ using data taken between September 12, 2015 and January 19, 2016. We find no viable gravitational wave candidates. Our null result constrains the coalescence rate of monochromatic (delta function) distributions of non-spinning (0.2 $M_\odot$, 0.2 $M_\odot$) ultracompact binaries to be less than $1.0 \times 10^6$ Gpc$^{-3}$yr$^{-1}$ and the coalescence rate of a similar distribution of (1.0 $M_\odot$, 1.0 $M_\odot$) ultracompact binaries to be less than $1.9 \times 10^4$ Gpc$^{-3}$yr$^{-1}$ (at 90% confidence). Neither black holes nor neutron stars are expected to form below $\sim 1M_\odot$ through conventional stellar evolution, though it has been proposed that similarly low mass black holes could be formed primordially through density fluctuations in the early universe. Under a particular primordial black hole binary formation scenario, we constrain monochromatic primordial black hole populations of 0.2 $M_\odot$ to be less than 33% of the total dark matter density and monochromatic populations of 1.0 $M_\odot$ to be less than 5% of the dark matter density. The latter strengthens the presently placed bounds from micro-lensing surveys of MAssive Compact Halo Objects (MACHOs) provided by the MACHO and EROS collaborations.

INTRODUCTION

The era of gravitational wave astronomy began with the observation of the binary black hole merger GW150914 [4]. Since then, four additional binary black hole mergers [2–5] and one binary neutron star merger [0] have been announced as of November 2017. Thus far, Advanced LIGO and Advanced Virgo searches have targeted binary systems with total masses from 2–600 $M_\odot$ [7, 8], but the LIGO and Virgo detectors are also sensitive to ultracompact binaries with components below 1 $M_\odot$ if the compactness (mass to radius ratio) is close to that of a black hole. White dwarf binaries, while often formed with components below one solar mass, are not sufficiently compact to be a LIGO/Virgo gravitational wave source. Neutron stars or black holes are sufficiently compact as would be other exotic compact objects. Previous gravitational wave searches for sub-solar mass ultracompact binaries used data from initial LIGO observations from Feb 14, 2003 – March 24, 2005 [9, 10]. Advanced LIGO [11] presently surveys a volume of space approximately 1000 times larger than the previous search for sub-solar mass ultracompact objects therefore improving the chances of detecting such a binary 1000-fold.

In conventional stellar evolution models, the lightest ultracompact objects are formed when stellar remnants exceed $\sim 1.4M_\odot$, the Chandrasekhar mass limit [12, 13]. Beyond the Chandrasekhar mass limit, electron degeneracy pressure can no longer prevent the gravitational collapse of a white dwarf. The lightest remnants that exceed the Chandrasekhar mass limit form neutron stars [13]. When even the neutron degeneracy pressure cannot prevent collapse, heavier stellar remnants will collapse to black holes. Some equations of state predict that neutron stars remain stable down to $\sim 0.1M_\odot$ [15]: there is no widely accepted model for forming neutron stars below $\sim 1M_\odot$, though a recent measurement does not exclude the possibility of 0.92$M_\odot$ neutron star [16]. Observationally, black holes appear to have a minimum mass of $\sim 5M_\odot$ with a gap between the observed neutron star masses and black hole masses [17, 18]. Detecting ultracompact objects below one solar mass could challenge our ideas about stellar evolution or possibly hint at new, unconventional formation scenarios.

Beyond conventional stellar evolution, one of the most prolific black hole formation models posits that primordial black holes (PBHs) could have formed in the early universe through the collapse of highly over-dense regions [20–24]. It has been suggested that PBHs could constitute a fraction of the missing dark matter [24], though this scenario has been constrained [25]. LIGO’s detections have revived interest in black hole formation mechanisms and, in particular, the formation of primordial black holes (PBHs) [26, 27]. Though there are proposals on how to distinguish a primordial black hole distribution from an astrophysical one [28], disentangling them is challenging when the populations overlap in mass. Hence, detection of sub-solar mass ultracompact objects would provide the cleanest signature for determining primordial formation. Still, recent proposals for non-baryonic dark matter models can produce sub-solar mass black holes either by allowing a lower Chandrasekhar mass in the dark sector [29], or by triggering neutron stars to collapse into $\sim 1M_\odot$ black holes [30].

This letter describes a gravitational wave search for ultracompact binary systems with component masses between 0.2 $M_\odot$ and 1.0 $M_\odot$ using data from Advanced LIGO’s first observing run. No viable gravitational wave candidates were identified. We briefly describe the data analyzed and the anticipated sensitivity to sub-solar mass ultracompact objects, as well as the search that was conducted, which led to the null result. We then describe
FIG. 1. Distance to which an optimally oriented and aligned equal-mass ultracompact binary merger would produce at least SNR 8 in each of the LIGO Livingston and LIGO Hanford detectors as a function of component mass, based on the median sensitivity obtained from our analyzed data.

how the null result constrains the merger rate of sub-solar mass binaries in the nearby universe. We consider the merger rate constraints in the context of binary merger rate estimates most recently given by Sasaki et al. [27] thereby constraining the fraction of dark matter density made up of PBHs between 0.2 $M_\odot$ and 1.0 $M_\odot$. Finally, we conclude with a discussion of future work.

SEARCH

We report on data analyzed from Advanced LIGO’s first observing run, taken from September 12, 2015 – January 19, 2016 at the LIGO Hanford and LIGO Livingston detectors. After taking into account data quality cuts [31] and detector downtime, we analyzed a total of 48.16 days of Hanford-Livingston coincident data. The data selection process was identical to that used in previous searches [32].

During Advanced LIGO’s first observing run, each LIGO instrument was sensitive to sub-solar mass ultracompact binaries at extra-galactic distances. Figure 1 shows the maximum distance to which an equal-mass compact binary merger with given component masses would be visible at a signal-to-noise ratio of 8 in either LIGO Hanford or LIGO Livingston.

The search was conducted using standard gravitational wave analysis software [33,38]. Our search consisted of a matched-filter stage that filtered a discrete bank of templates against the LIGO data. The peak SNR for each template for each second was identified and recorded as a trigger. Subsequently, a chi-squared test was performed that checked the consistency of the trigger with a signal [34]. The triggers from each LIGO detector and gravitational wave template were combined and searched for coincidences within 20 ms. Candidates that pass coincidence were assigned a likelihood ratio, $\mathcal{L}$, that accounts for the relative probability that the candidates are signal versus noise as a function of SNR, chi-squared, and time delay and phase offset between detectors. Larger values of $\mathcal{L}$ were deemed to be more signal-like. The rate at which noise produced candidates with a given value of $\mathcal{L}$ was computed via a Monte Carlo integral of the noise derived from non-coincident triggers, which we define as the false alarm rate of candidate signals.

Our discrete bank of 500,332 template waveforms [39] conformed to the gravitational wave emission expected from general relativity [40,41]. The bank covered component masses in the detector frame between 0.19 – 2.0 $M_\odot$ with 97% fidelity. While we restrict our analysis of the search results to the sub-solar region, we have allowed for the possibility of high mass ratio systems. Our template bank assumed that each binary component has negligible spin. Relaxing that assumption is a direction for future work, but is a computationally challenging problem requiring resources well beyond those used for this and previous LIGO analyses. We integrated the template waveforms between 45–1024 Hz, with the longest waveform lasting about 470 seconds. Advanced LIGO is sensitive down to $\sim 15$ Hz, but integrating from that frequency would have been too computationally burdensome. Our choice to integrate from 45 Hz to 1024 Hz recovered 93.0% of the total possible SNR that integration over the full band would have provided. Additional details are described in [39].

No viable gravitational wave candidates were found. Our loudest gravitational wave candidate was consistent with noise and had a false alarm rate of 6.19 per year.

CONSTRAINT ON BINARY MERGER RATE

We constrained the binary merger rate in this mass region by considering nine monochromatic mass distributions with equal component masses and negligible spin. We constructed sets of simulated signals with component masses $m_i \in \{0.2, 0.3, \ldots, 1.0\} M_\odot$ distributed uniformly in distance and uniformly on the sky. We injected 374,480 simulated signals into the LIGO data and conducted a gravitational wave search with the same parameters as described in section . We then calculated our detection efficiency as a function of distance, $e_i(r)$. This allowed us to compute the volume-time, $\langle VT \rangle$, that was accessible
We follow a method originally proposed by [43, 44] and recently used to constrain $\sim 30 M_\odot$ PBH mergers by [27].

We assume an initial, early-universe, monochromatic distribution of PBHs. As the universe expands, the energy density of a pair of black holes not too widely separated becomes larger than the background energy density. The pair decouples from the cosmic expansion and can be prevented from prompt merger by the local tidal field, determined primarily by a third black hole nearest the pair. The initial separation of the pair and the relative location of the primary perturber determine the parameters of the initial binary. From those, the coalescence time can be determined. Assuming a spatially uniform initial distribution of black holes, the distribution of coalescence times for those black holes that form binaries is

$$dP = \begin{cases} 
\frac{3}{8} \int \frac{f}{t_c} \left( \frac{t}{t_c} \right)^{3/8} dt, & t < t_c \\
\frac{3}{8} \int \frac{f}{t_c} \left( \frac{t}{t_c} \right)^{-1} dt, & t \geq t_c
\end{cases} \quad (3)$$

where $t_c$ is a function of the mass of the PBHs and the fraction of the dark matter they comprise:

$$t_c = \frac{3 c^5}{170 (G m_i)^{5/3} (1 + z_{eq})^{1/3} \left( \frac{8 \pi}{3 H_0^2 \Omega_{DM}} \right)^{4/3}} f^7 \quad (4)$$

This expression is evaluated at the time today, $t_0$, then multiplied by $n_{BH}$, the current average number density of PBHs, to get the model event rate [27]:

$$\mathcal{R}_{mode} = n_{BH} \frac{dP}{dt} \bigg|_{t=t_0} \quad (5)$$

Given the measured event rate, $\mathcal{R}_{90,i}$, and a particular mass, the above expression can be inverted to find a constraint on the fraction of dark matter in PBHs at that mass. The results of this calculation using the measured upper limits on the merger rate are shown in Fig. 3. A discussion on how some assumptions of this model may affect the constraints on $f$ shown in Fig. 3 are discussed in [29]. The non-detection of a stochastic background in the first observing run of Advanced LIGO [35] also implies an upper limit on the merger rate and therefore the PBH abundance. In particular, it is shown that the non-detection of a stochastic background yields constraints that are about a factor of two weaker than the targeted search [46, 49].

CONCLUSION

We presented the first Advanced LIGO and Advanced Virgo search for ultracompact binary mergers with com-
FIG. 3. Constraints on the fraction of dark matter composed of primordial black holes for monochromatic distributions \(f = \Omega_{\text{PBH}} / \Omega_{\text{DM}}\). Shown in black are the results for the nine mass bins considered in this search. For this model of primordial black hole formation, LIGO finds constraints tighter than those of the MACHO collaboration \([50]\) for all mass bins considered and tighter than the EROS collaboration \([51]\) for \(m_i \in (0.7, 1.0)M_\odot\). The curves shown in this figure are digitizations of the original results from \([50–53]\). We use the Planck “TT,TE,EE+lowP+lensing+ext” cosmology \([54]\).

components below \(1 M_\odot\). No viable gravitational wave candidates were found. Therefore, we were able to constrain the binary merger rate for monochromatic mass functions spanning from \(0.2 – 1.0 M_\odot\). Using a well-studied model from the literature \([27, 43, 44]\), we constrained the abundance of primordial black holes as a fraction of the total dark matter for each of our nine monochromatic mass functions considered.

This work was only the first step in constraints by LIGO on new physics involving sub-solar mass ultracompact objects. The constraints presented in Fig. 2 (and consequently those that arise from the model of binary formation we consider shown in Fig. 3) may not apply if the ultracompact binary components have non-negligible spin since the waveforms used for signal recovery were generated only for non-spinning binaries. Future work may either quantify the extent to which the present search could detect spinning components, or expand the template bank to include systems with spin. Third, we should consider more general distributions of primordial black hole masses; extended mass functions allow for the possibility of unequal mass binaries, and the effect of this imbalance on the predicted merger rate has not been quantified. We also stress that our present results do not rule out an extended mass function that peaks below \(0.2 M_\odot\) and extends all the way to LIGO’s currently detected systems at or above \(30 M_\odot\). Each model would have to be explicitly checked by producing an expected binary merger rate density that could be integrated against Advanced LIGO and Advanced Virgo search results.

The first two areas of future work are computational challenges. Lowering the minimum mass and including spin effects in the waveform models could easily increase the computational cost of searching for sub-solar mass ultracompact objects by an order of magnitude each, which would be beyond the capabilities of present LIGO data grid resources.

Advanced LIGO and Advanced Virgo have not reached their final design sensitivities. The distance to which Advanced LIGO will be sensitive to the mergers of ultracompact binaries in this mass range should increase by a factor of three over the next several years \([55]\). Furthermore, at least a factor of ten more data will be available than what was analyzed in this work. These two facts combined imply that the merger rate constraint should improve by \(\gtrsim 2\) orders of magnitude in the coming years.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidencia i Conselleria d’Innovació, Recerca i Turisme and the Conselleria d’Educació i Universitat del Govern de les Illes Balears, the Conselleria d’Educació, Investigació, Cultura i Esport de la Generalitat Valenciana, the National...
Science Centre of Poland, the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the Paris Île-de-France Region, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFI), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the Natural Science and Engineering Research Council Canada, the Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS and the State of Niedersachsen/Germany for provision of computational resources. Funding for this project was provided by the Charles E. Kaufman Foundation of The Pittsburgh Foundation. Computing resources and personnel for this project were provided by the Pennsylvania State University. This article has been assigned the document number LIGO-P1800158-v12.

(The LIGO Scientific Collaboration and the Virgo Collaboration)

S. Shandera 88

1 LIGO, California Institute of Technology, Pasadena, CA 91125, USA
2 Louisiana State University, Baton Rouge, LA 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 OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia
6 LIGO Livingston Observatory, Livingston, LA 70754, USA
7 Laboratoire d'Annecy de Physique des Particules (LAPP), Univ. Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France
8 University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
9 Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany
10 Leibniz Universität Hannover, D-30167 Hannover, Germany
11 NCSA, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
12 University of Cambridge, Cambridge CB2 1TN, United Kingdom
13 Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
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 Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
19 International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India
20 University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
21 Università di Pisa, I-56127 Pisa, Italy
22 INFN, Sezione di Pisa, I-56127 Pisa, Italy
23 Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
24 OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia
25 Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France
26 SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
27 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, F-91898 Orsay, France
28 California State University Fullerton, Fullerton, CA 92831, USA
29 APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
30 European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
31 Chennai Mathematical Institute, Chennai 600113, India
32 Università di Roma Tor Vergata, I-00133 Roma, Italy
33 INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
34 Universität Hamburg, D-22761 Hamburg, Germany
35 INFN, Sezione di Roma, I-00185 Roma, Italy
36 Cardiff University, Cardiff CF24 3AA, United Kingdom
37 Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
38 Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam-Golm, Germany
39 Korea Institute of Science and Technology Information, Daejeon 34141, Korea
40 West Virginia University, Morgantown, WV 26506, USA
41 Università di Perugia, I-06123 Perugia, Italy
42 INFN, Sezione di Perugia, I-06123 Perugia, Italy
43 Syracuse University, Syracuse, NY 13244, USA
44 University of Minnesota, Minneapolis, MN 55455, USA
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 Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary