Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO's Second Observing Run

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We present a search for subsolar mass ultracompact objects in data obtained during Advanced LIGO's second observing run. In contrast to a previous search of Advanced LIGO data from the first observing run, this search includes the effects of component spin on the gravitational waveform. We identify no viable gravitational-wave candidates consistent with subsolar mass ultracompact binaries with at least one component between 0.2 $M_{\odot}$–1.0 $M_{\odot}$. We use the null result to constrain the binary merger rate of (0.2 $M_{\odot}$, 0.2 $M_{\odot}$) binaries to be less than 3.7×10^5 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ and the binary merger rate of (1.0 $M_{\odot}$, 1.0 $M_{\odot}$) binaries to be less than 5.2×10^3 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Subsolar mass ultracompact objects are not expected to form via known stellar evolution channels, though it has been suggested that primordial density fluctuations or particle dark matter with cooling mechanisms and/or nuclear interactions could form black holes with subsolar masses. Assuming a particular primordial black hole (PBH) formation model, we constrain a population of merging 0.2 $M_{\odot}$ black holes to account for less than 16% of the dark matter density and a population of merging 1.0 $M_{\odot}$ black holes to account for less than 2% of the dark matter density. We discuss how constraints on the merger rate and dark matter fraction may be extended to arbitrary black hole population models that predict subsolar mass binaries.

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Introduction.—Gravitational-wave and multimessenger astronomy progressed remarkably in Advanced LIGO [1] and Advanced Virgo's [2] second observing run, which included the first observation of gravitational waves from a binary neutron star merger [3] and seven of the ten observed binary black hole mergers [4–7]. These detections, as well as the candidates presented in the gravitational-wave transient catalog [7], have led to a better understanding of the populations of compact binaries detectable by ground based interferometers [8]. These observations, however, represent just a portion of the parameter space that Advanced LIGO and Advanced Virgo currently search [9,10] and are sensitive to [11]. We report on an extension of the searched parameter space in data obtained during O2 to compact binaries with component masses < 1 $M_{\odot}$. To distinguish between other astrophysical compact objects (e.g., white dwarfs) that are not compact enough to form binaries that merge within LIGO's sensitive frequency band, we label our target population as *ultracompact*. This is the second search for subsolar mass ultracompact objects in Advanced LIGO data and the fourth since initial LIGO [12–14], as well as the first search to incorporate spin effects into the modeling of the gravitational-wave emission.

There is no widely accepted mechanism for the formation of ultracompact objects with masses well below a solar mass within the standard model of particle physics and the standard Λ cold dark matter (ΛCDM) model of cosmology. Neutron stars are expected to have masses greater than the minimum Chandrasekhar mass [15] minus the gravitational binding energy. Calculations in Ref. [16] and more recently in Ref. [17] found the minimum mass of a neutron star to be 1.15 $M_{\odot}$ and 1.17 $M_{\odot}$, respectively. These predictions closely agree with the lowest currently measured neutron star mass of 1.17 $M_{\odot}$ [18]. Similarly, black holes formed via established astrophysical collapse mechanisms are not expected to have masses below the maximum mass of a nonrotating neutron star, which recent pulsar timing observations [19] suggest is $\sim$2 $M_{\odot}$. We note that there is one model that predicts that rapidly rotating collapsing cores could fission and produce a neutron star binary [20,21], though this is not a favored astrophysical mechanism for the production of binary systems.

A detection of a subsolar mass object in a merger would therefore be a clear signal of new physics. Indeed, there are several proposals that link subsolar mass compact objects to proposals for the nature of dark matter, which makes up nearly 85% of the matter in the Universe. One possibility is that black holes with masses accessible to ground based interferometers could have formed deep in the radiation era from the prompt collapse of large primordial overdensities on the scale of the early time Hubble volume [22,23]. The size and abundance of any such PBHs depends on the spectrum of primordial perturbations and on the equation of

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state of the early Universe [24–27]. An alternative inflationary mechanism proposes that vacuum bubbles nucleated during inflation may result in black holes (with masses that can be around a solar mass) after inflation ends [28].

A different class of possibilities, explored more recently, is motivated by ideas for the particle nature of dark matter. For example, dark matter may have a sufficiently complex particle spectrum to support cooling mechanisms that allow dense regions to collapse into black holes at late times, in processes analogous to known astrophysical processes [29]. Alternatively, dark matter may have interactions with nuclear matter that allow it to collect inside of neutron stars and trigger their collapse to black holes [30–36]. The details of when dark matter can collapse a neutron star to form a black hole or another exotic compact object are still under investigation [37], but the postulated black holes will have masses comparable to the progenitor neutron star mass, or perhaps smaller if some matter can be expelled by rapid rotation of the star during collapse.

A detection of a subsolar mass black hole would have far-reaching implications. In the PBH scenario, the mass and abundance of the black holes would constrain a combination of the spectrum of initial density perturbations on very small scales and the equation of state of the Universe at a time when the typical mass inside a Hubble volume was of the order of the black hole mass. For particle dark matter scenarios, the abundance of subsolar mass black holes would provide a direct estimate of the cooling rate for dark matter. The black hole mass would constrain the masses of cosmologically abundant dark matter particles through, for example, the Chandrasekhar relation for fermions [29] or analogous relations for noninteracting bosons [38,39]. In the case in which all black holes are observed to be near but not below the mass of neutron stars, the abundance of such objects would constrain the dark matter-nucleon interaction strength, as well as the dark matter self-interaction strength and mass(es) [36].

This Letter reports on the results of a search for gravitational waves from subsolar mass ultracompact binaries using data from Advanced LIGO's second observing run. No significant candidates consistent with a subsolar mass binary were identified. The null result places the tightest constraints to date on the merger rate and the abundance of subsolar mass ultracompact binaries. We describe an extension of our merger rate constraints to arbitrary populations and models under the assumption that the horizon distance controls the sensitivity of the search. We once more consider the merger rate constraints in the context of merging PBH populations contributing to the dark matter [14]. We describe how to extend the dark matter fraction parametrization to other models by separating LIGO observables from model dependent quantities. Finally, we conclude with a discussion of the implications of this search.

Search.—We analyze data obtained from November 30, 2016, to August 25, 2017, during Advanced LIGO's second observing run (O2) [40]. Noise artifacts are linearly subtracted from the data; this includes strong sinusoidal features in both detectors due to injected calibration frequencies and the ac power grid, as well as laser beam jitter in the LIGO-Hanford detector data [41]. We find that 117.53 days of coincident data remain after the application of data quality cuts [42–46]. The Advanced Virgo interferometer completed commissioning and joined Advanced LIGO in August 2017 for 15 days of triple coincident observations [7]; however, we report only on the analysis of data obtained by the LIGO Hanford and LIGO Livingston interferometers.

The search was conducted using publicly available gravitational-wave analysis software [47–53]. The initial stage of the search performed a matched-filter analysis using a discrete bank of template waveforms generated using the TaylorF2 frequency-domain, post-Newtonian inspiral approximant. This waveform was chosen since negligible power is deposited in the merger and ringdown portion of the waveform for low-mass systems [54]. The template bank used for this search was designed to recover binaries with component masses of 0.19 $M_{\odot}$–2.0 $M_{\odot}$ and total masses of 0.4 $M_{\odot}$–4.0 $M_{\odot}$ in the detector frame with 97% fidelity, as in Ref. [14]. The search presented here, however, additionally includes spin effects in the modeling of the gravitational waveform. The bank is constructed to recover gravitational waves originating from binaries with component spins purely aligned or antialigned with the orbital angular momentum, and with dimensionless spin magnitudes of 0.1 or less. The inclusion of spin effects required denser placement of the waveforms in the template bank; the resulting bank had 992 461 templates, which is nearly twice as large as the nonspinning bank used in Ref. [14].

In order to reduce the computational burden, matched filtering was performed only for a subset of Advanced LIGO's full sensitive band [11]. The choice to only analyze the 45–1024 Hz band led to a detector averaged signal-to-noise ratio (SNR) loss of 8% when compared to the full ~10–2048 Hz frequency band. This estimated SNR loss is a property of Advanced LIGO's noise curves and is independent of the templates used in the search; the discrete nature of the template bank causes an additional $\lesssim 3\%$ loss in SNR.

Gravitational-wave candidates that were found coincident in both the Hanford and Livingston detectors were ranked using the logarithm of the likelihood ratio, $\mathcal{L}$ [47–49]. For a candidate with a likelihood ratio of $\mathcal{L}^*$, we assign a false-alarm rate (FAR) of

$$\mathrm{FAR}(\log \mathcal{L}^*) = \frac{N}{T} P(\log \mathcal{L} \geq \log \mathcal{L}^* | \mathrm{noise}), \qquad (1)$$

where N is the number of observed candidates, T is the total live time of the experiment, and $P(\log \mathcal{L} \geq \log \mathcal{L}^* | \mathrm{noise})$

describes the probability that noise produces a candidate with a ranking statistic at least as high as the candidate's.

The search recovered the previously detected signal GW170817 [3], which was observed along with an electromagnetic counterpart [55]. This signal is consistent with a binary neutron star. No other viable gravitational-wave candidates were identified. The next loudest candidate was identified by a template waveform with a chirp mass of 0.23 $M_\odot$ and a SNR of 9.5. The candidate was consistent with noise and assigned a FAR of 3.25 per year.

Constraint on binary merger rate.—As in Ref. [14], we consider nine populations of equal mass, nonspinning binaries that are δ-function distributed in mass, i.e., $m_i \in \{0.2, 0.3, \ldots, 1.0\}$. We injected 913931 fake signals into our data; the injections were randomly oriented and spaced uniformly in distance and isotropically across the sky. The recovered signals provide an estimate of the pipeline's detection efficiency as a function of source distance for each equal mass population. This in turn allows us to estimate the sensitive volume-time accumulated for each mass bin. We once more use the loudest event statistic formalism [56] to estimate the upper limit on the binary merger rate to 90% confidence,

$$\mathcal{R}_i = \frac{2.3}{\langle VT \rangle_i}. \tag{2}$$

These upper limits are shown for equal mass binaries and as a function of chirp mass in Fig. 1. Although our template bank includes systems with a total mass of up to 4 $M_\odot$, we place bounds on the merger rate of systems only where both components are $\leq 1\ M_\odot$. We estimate that detector calibration uncertainties [7,57,58] and Monte Carlo errors lead to an uncertainty in our rate constraint of no more than 20%.

Advanced LIGO and Virgo's horizon distance scales as

$$D_{\text{horizon}} \propto \mathcal{M}^{5/6} \sqrt{\int_{f_{\min}}^{f_{\max}} \frac{f^{-7/3}}{S_n(f)} df}, \tag{3}$$

where $S_n(f)$ is the noise spectra of the detector and $f_{\min}$ and $f_{\max}$ are 45 and 1024 Hz, respectively [59]. For a null result, we therefore expect $\mathcal{R}(\mathcal{M}) \propto \mathcal{M}^{-15/6}$ provided that the horizon distance controls the sensitivity of the search. The observed power law dependence of the rate constraint on the chirp mass is within ~4% of the expected $\mathcal{M}^{-15/6}$ dependence; this is well within the error bound on the rate upper limit and is strong evidence that the chirp mass is the primary parameter that dictates the sensitivity of the search. Therefore our upper limits from equal mass systems also apply to unequal mass systems within the range of mass ratios we have searched over. For verification, we performed a small injection campaign over five days of coincident data with injected component masses distributed between 0.19 $M_\odot$ and 2.0 $M_\odot$ with at least one component

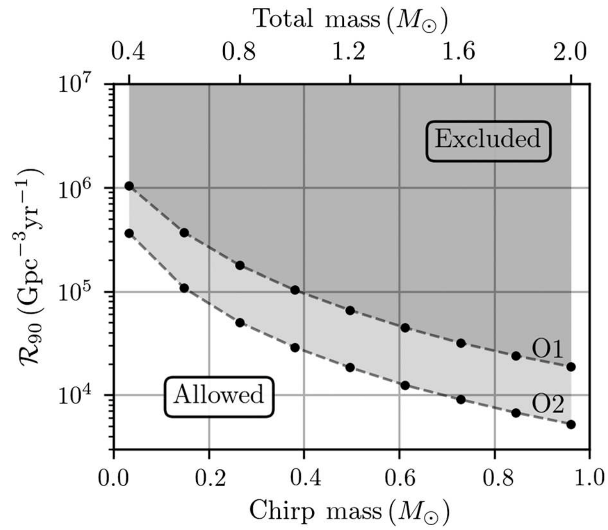

FIG. 1. The constraint on the merger rate density for equal mass binaries as a function of total mass (top) and chirp mass (bottom). The two sets of lines show the constraints for the O1 search [14] and the O2 search presented here. The null result from O2 places bounds that are ~3 times tighter than the O1 results. The majority of this improvement is due to the increased coincident observing time in Advanced LIGO's second observing run (~118 days vs ~48 days), though the improved sensitivity of the detectors led to an observed physical volume up to ~50% larger than in O1 for subsolar mass ultracompact binaries.

$<1.0\ M_\odot$. The search sensitivity remained a function of the chirp mass; this implies that the rate constraints found from the equal mass injection sets can therefore be applied to systems with arbitrary mass ratios provided that both component masses lie within 0.20 $M_\odot$ and 1.0 $M_\odot$, where our injection sets were performed.

The Advanced LIGO and Virgo rate upper limit can be expanded as

$$\mathcal{R}(\mathcal{M}_1, \mathcal{M}_2) = \int_{\mathcal{M}_1}^{\mathcal{M}_2} \mathcal{R}(\mathcal{M}) \times \psi(\mathcal{M}) \mathrm{d}\mathcal{M}, \tag{4}$$

where $\mathcal{R}$ is the rate density as a function of chirp mass and $\psi(\mathcal{M})$ denotes the black hole population distribution in chirp mass. We ignore the effects of redshift due to the small detector range for subsolar mass binaries. Setting $\psi(\mathcal{M}) = \delta(\mathcal{M})$ then reveals the form of the LIGO constraining rate density, $\mathcal{R}(\mathcal{M})$, which is shown in Fig. 1. For a given model, $\psi(\mathcal{M})$, $\mathcal{R}(\mathcal{M}_1, \mathcal{M}_2)$ provides the LIGO rate constraint on that model for chirp masses between $\mathcal{M}_1$ and $\mathcal{M}_2$. The resulting rate constraints allow direct comparison of subsolar mass ultracompact object models with LIGO observations.

General constraints on subsolar mass black hole dark matter.—We convert our limits on the merger rate of subsolar mass ultracompact objects into a constraint on the abundance of PBHs using our fiducial formation model [60] first developed in Refs. [23,61] and used previously in

LIGO analyses [12,14]. We consider a population of equal mass PBHs that is created deep in the radiation era. We model the binary formation via three-body interactions, though others have considered the full field of tidal interactions [62]. By equating the model's predicted merger rate with the merger rate upper limit provided by Advanced LIGO and Virgo, we can numerically solve for the upper limit on the PBH abundance. These constraints are shown in Fig. 2 [63].

This interpretation is highly model dependent; the mass distribution, binary fraction, and binary formation mechanisms all have a large effect on the expected present day merger rate and consequently the bounds on the PBH composition of the dark matter. The Advanced LIGO and Virgo observables can be separated from the model dependent terms:

$$f_{\mathrm{CO}} = \frac{\rho_{\mathrm{lim}}}{\rho_{\mathrm{CDM}}} \times \frac{1}{f_{\mathrm{obs}}} = \frac{\mathcal{R}(M_{\mathrm{tot}}) T_{\mathrm{obs}} M_{\mathrm{tot}}}{\rho_{\mathrm{CDM}}} \times \frac{1}{f_{\mathrm{obs}}}, \quad (5)$$

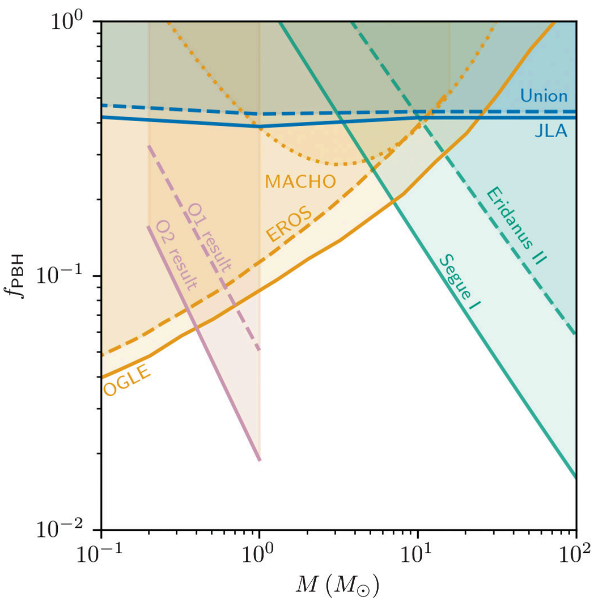

FIG. 2. Constraints on the fraction of dark matter comprising δ-function distributions of PBHs ($f_{\mathrm{PBH}} = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$). Shown here are (pink lines) Advanced LIGO constraints from the O1 (dashed lines) and O2 ultracompact binary search presented here (solid lines), (orange lines) microlensing constraints provided by the OGLE (solid line), EROS (dashed line) [64], and MACHO (dotted line) collaborations [65], (cyan lines) dynamical constraints from observations of Segue I (solid line) [66] and Eridanus II (dashed line) [67] dwarf galaxies, and (blue) supernova lensing constraints from the Joint Light-curve Analysis (solid) and Union 2.1 (dashed) datasets [68]. There is an inherent population model dependency in each of these constraints. Advanced LIGO and Advanced Virgo results carry an additional dependence on the binary fraction of the black hole population. Advanced LIGO and Advanced Virgo results use the Planck "TT,TE,EE+lowP+lensing+ext" cosmology [69].

where T_{obs} is the duration of the observation (in the analysis presented here, 117.53 days). Here we use f_{CO} to refer to the dark matter fraction in ultracompact objects instead of f_{PBH} to emphasize that this is generally applicable to other compact object models that could contribute to the dark matter [29], and not just PBHs. The first term, $\rho_{\mathrm{lim}}/\rho_{\mathrm{CDM}}$, represents the upper limit on the fraction of the dark matter contained in presently merging subsolar mass ultracompact binaries. In the second term, f_{obs} describes the fraction of subsolar mass ultracompact objects that are observable by Advanced LIGO and Virgo for a particular model. This is set by the binary fraction and the probability density of binaries merging at present day. Note that the merger rate density must be converted from a function of chirp mass to total mass; this can be done by mapping to total mass for each mass ratio on an equal chirp mass curve.

Equation (5) applies to any dark matter model that predicts the formation of dark compact objects. The abundance of those dark compact objects can then be expressed as a fraction of the dark matter density.

Conclusion.—We presented the second Advanced LIGO and Advanced Virgo search for subsolar mass ultracompact objects. No unambiguous subsolar mass gravitational-wave candidates were identified. The null result allowed us to place tight constraints on the abundance of subsolar mass ultracompact binaries.

This work represents an expansion of previous initial and Advanced LIGO and Advanced Virgo subsolar mass searches. First, we broadened the searched parameter space to increase sensitivity to systems with non-negligible component spins. Second, we presented a method to extend our constraints on the binary merger rate to arbitrarily distributed populations that contain subsolar mass ultracompact objects. Combined with the existing rate limits, this may already be enough to begin constraining collapsed particulate dark matter models [29] or the cross section of nuclear interactions [30–34,36]. Finally, we provided a method to separate Advanced LIGO and Advanced Virgo observables from model dependent terms in our interpretation of the limits on PBH dark matter.

Ground based interferometer searches for subsolar mass ultracompact objects will continue to inform cosmological and particle physics scenarios. Advanced LIGO and Advanced Virgo began a yearlong observing run in early 2019, with improved sensitivities [70]. Advanced Virgo will have more coincident time with the Advanced LIGO detectors over its next observing run, which will improve network sensitivity and aid in further constraining the above scenarios.

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