Can LIGO Detect Nonannihilating Dark Matter?

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Dark matter (DM) from the galactic halo can accumulate in neutron stars and transmute them into sub-$2.5M_\odot$ black holes if the dark matter particles are heavy, stable, and have interactions with nucleons. We show that nondetection of gravitational waves from mergers of such low-mass black holes can constrain the interactions of nonannihilating dark matter particles with nucleons. We find benchmark constraints with LIGO O3 data, viz., $\sigma_{\chi n} \geq \mathcal{O}(10^{-47})$ cm^2 for bosonic DM with $m_\chi \sim$ PeV (or $m_\chi \sim$ GeV, if they can Bose-condense) and $\geq \mathcal{O}(10^{-46})$ cm^2 for fermionic DM with $m_\chi \sim 10^3$ PeV. These bounds depend on the priors on DM parameters and on the currently uncertain binary neutron star merger rate density. However, with increased exposure by the end of this decade, LIGO will probe cross sections that are many orders of magnitude below the neutrino floor and completely test the dark matter solution to missing pulsars in the Galactic center, demonstrating a windfall science case for gravitational wave detectors as probes of particle dark matter.

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Introduction.—Dark matter (DM) is arguably the most compelling evidence for new physics. Extant searches have placed stringent constraints on nongravitational interactions of DM in a wide variety of particle physics scenarios [1–6]. However, a simple scenario—a heavy nonannihilating DM with feeble interactions with the ordinary matter—remains inadequately tested because of tiny fluxes in terrestrial detectors.

The leading constraint in this regime arises from the existence of old neutron stars (NSs) that would have imploded to black holes (BHs) due to gradual DM accretion if DM were to be a heavy nonannihilating particle that interacted with nucleons [7–30]. More specifically, the strongest constraint in this regime comes from the existence of a Gyr old pulsar close to Earth [11,20,22] even though NSs in denser parts of the Galaxy are predicted to be more susceptible to DM-induced implosion. This is in part because no old NSs have been detected in the denser inner parts of the Galaxy. In particular, the central parsec of the Galaxy shows a significant deficit of NSs [31]. While there are plausible astrophysical and observational explanations for the observed deficit, it has also led to speculations that the missing pulsars are a hint that NSs near the Galactic center have converted to BHs by accreting heavy nonannihilating DM [19]. This curious situation, coupled with the need to adequately probe heavy nonannihilating DM, demands new ideas.

In this Letter, we argue that gravitational wave (GW) detectors are a novel and complementary probe of heavy nonannihilating DM interactions with the baryonic matter. The key idea is that continued accumulation of DM particles in the NSs leads to anomalously low-mass BHs in the mass range $\sim(1\text{–}2.5)M_\odot$, and GWs from such low-mass BH mergers can be searched for by the LIGO-Virgo-KAGRA detector network. Given null detection so far, one already finds an interesting constraint on nonannihilating DM interactions. This constraint is contingent on the value of the "binary NS" (BNS) merger rate density, which has large uncertainties at present. If it takes the larger values currently allowed, the GW-inferred constraint can be the strongest constraint on DM interactions. With continued data taking, the existing detectors promise unprecedented sensitivity to nonannihilating DM interactions, revealing a new windfall science case for these remarkable detectors.

Mergers of low-mass BHs.—We consider the following sequence of events. A pair of NSs can be born and almost contemporaneously get locked into a binary at time t_f. The NSs then accrete DM for a period $\tau_{\rm collapse}$ from the galactic halo, at which point the DM accumulated in their cores collapses to tiny BHs. Then, the tiny BHs take a time $\tau_{\rm swallow}$ to transmute each host NS to a low-mass BH, that we call a "transmuted BH" (TBH) [32]. The net transmutation time is $\tau_{\rm trans} = \tau_{\rm collapse} + \tau_{\rm swallow}$. Mergers of these TBH-TBH pairs are detectable at the present time t_0 if $t_0 - t_f > \tau_{\rm trans}$. These timescales are computed in the following.

DM particles that transit through an optically thin NS can get captured due to their collisions with the stellar material. Considering contact interactions of DM with nucleons, one finds a capture rate [11,20]

$$C = 1.4 \times 10^{20}\ \mathrm{s}^{-1}\left(\frac{\rho_\chi}{0.4\ \mathrm{GeV\,cm^{-3}}}\right)\left(\frac{10^5\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\sigma_{\chi n}}{10^{-45}\ \mathrm{cm}^2}\right)\left(1-\frac{1-e^{-A^2}}{A^2}\right)\left(\frac{v_{\mathrm{esc}}}{1.9\times 10^5\ \mathrm{km\,s^{-1}}}\right)^2\left(\frac{220\ \mathrm{km\,s^{-1}}}{\bar{v}_{\mathrm{gal}}}\right)^2, \tag{1}$$

which depends on the ambient DM density ρ_χ, the DM mass m_χ, as well as its total interaction cross section with nucleons $\sigma_{\chi n}$. The factor involving $A^2 = 6 m_\chi m_n v_{\mathrm{esc}}^2/\bar{v}_{\mathrm{gal}}^2(m_\chi - m_n)^2$ accounts for inefficient momentum transfers at larger m_χ, given NS escape speed v_{esc} and typical DM speeds $\bar{v}_{\mathrm{gal}}$ in the galaxy. For a typical NS with mass $M_{\mathrm{NS}} = 1.35 M_\odot$ and radius of $R_{\mathrm{NS}} = 10$ km, the optical thinness requires $\sigma_{\chi n} \le 1.3\times 10^{-45}\ \mathrm{cm}^2$. For larger cross sections, the effects of multiple collisions are relevant and it mildly increases the capture rate at larger m_χ [33,34]. We neglect possible self-interactions among the DM particles and nuclear effects in the capture rate [35,36].

The captured DM, because of the strong gravitational potential of the neutron stars, sinks toward the core, thermalizes, and can collapse to a tiny black hole over a timescale $\tau_{\mathrm{collapse}} = C^{-1} N_\chi^{\mathrm{BH}}$, where $N_\chi^{\mathrm{BH}} = \max[N_\chi^{\mathrm{self}}, N_\chi^{\mathrm{Cha}}]$ denotes the number of DM particles that need to be captured and thermalized to create a nascent BH, cf. Refs. [11,13,20,22]. $N^{\mathrm{self}} \sim 1/m_\chi^{5/2}$ encodes the Jeans instability criterion, and is determined by the condition that DM density has to exceed the baryonic density within the stellar core. $N^{\mathrm{Cha}} \sim 1/m_\chi^2$ (or $1/m_\chi^3$) denotes the Chandrasekhar limit for bosonic (fermionic) DM, and is set by the effective pressure imbued by quantum mechanics, to prevent this collapse. Detailed numerical estimates, accounting for possible Bose-Einstein condensate (BEC) formation, are reviewed in the Supplemental Material (SM) [37].

The nascent BH, with a very small mass $M_{\mathrm{BH}} = m_\chi N_\chi^{\mathrm{BH}}$, consumes the NS host over a timescale of $\tau_{\mathrm{swallow}} = 10^{12} s (10^{-16} M_\odot / M_{\mathrm{BH}})$ [38–41], significantly smaller than stellar lifetimes. Hawking radiation and quantum aspects of accretion can slow down this effect for seed BHs of mass $M_{\mathrm{BH}} \gtrsim 10^{-19} M_\odot$ [42], providing a maximum DM mass of $\mathcal{O}(10^7)$ GeV (for bosons) and $\mathcal{O}(10^{10})$ GeV (for fermions) [11,13,20,22,42] for transmutation. The particle DM parameter space that leads to a successful transmutation of NSs is reported in [24].

The TBH merger rate density [24]

$$R_{\mathrm{TBH}} = \int dr \frac{df}{dr}\int_{t_*}^{t_0} dt_f \frac{dR_{\mathrm{BNS}}}{dt_f} \times \Theta\{t_0 - t_f - \tau_{\mathrm{trans}}[m_\chi, \sigma_{\chi n}, \rho_{\mathrm{ext}}(r, t_0)]\}, \tag{2}$$

is a fraction of the BNS merger rate density (R_{BNS}) that one would have *if there were no transmutations*, depending on the DM properties through τ_{trans}, and on astrophysical conditions. We assume a uniform 1D distribution df/dr of progenitor BNSs in Milky-Way-like galaxies, where $r \in (0.01, 0.1)$ kpc denotes the galactocentric distance. This affects the background DM density ρ_{ext} experienced by the progenitors, which we take to have a Navarro-Frenk-White profile $\rho_{\mathrm{ext}}[r, t_0] = \rho_{\mathrm{ext}}[r] = \rho_s/[(r/r_s)(1 + r/r_s)^2]$ [43,44], where $\rho_s = 0.47\ \mathrm{GeV\,cm^{-3}}$ and $r_s = 14.5$ kpc for a Milky-Way-like galaxy. Note that we do not consider the time evolution of the ambient DM density, and use its current value, i.e., $\rho_{\mathrm{ext}}(z = 0)$, in order to be conservative. The lower limit of the t_f integral, t_*, corresponds to $z_* = 10$, taken as the earliest formation time and dR_{BNS}/dt_f is the rate density of progenitor mergers for a given formation time [45]. The latter is proportional to the star formation rate $d\rho_*/dt$ (for which we take the Madau-Dickinson model [46]), the fraction of stellar mass in binaries $\lambda \approx 10^{-5}$ [45,47,48], and their merger time distribution at present time proportional to $(t_0 - t_f)^{-1}$ [45]. Only the shape of dR_{BNS}/dt_f is an independent assumption because the overall normalization R_{BNS} is taken to be a free parameter in the range (10–1700) $\mathrm{Gpc^{-3}\,yr^{-1}}$ favored by recent LIGO observations [49]. In addition to the above, we take $R_{\mathrm{NS}} = 10$ km, $T_{\mathrm{core}} = 2.1\times 10^6$ K, and a monochromatic mass distribution of the progenitors centered at $1.35 M_\odot$ for computing τ_{trans}. The dependence of R_{TBH} on various model assumptions is studied in the SM which additionally includes Refs. [50–65].

Data and statistics.—We estimate the TBH merger rate density for a chirp mass bin

$$R_{\mathrm{TBH},i} = p_i \times R_{\mathrm{TBH}}, \tag{3}$$

where p_i is the probability that the progenitor BNS has chirp mass $m_c = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ in the ith bin, given the probability distributions of $m_{1,2}$. The component NS masses are $m_2 < m_1$ by convention, with asymmetry parameter $q = m_2/m_1 < 1$. The masses $m_{1,2}$ are approximately Gaussian distributed between 1.08 and $1.57 M_\odot$, with mean $\approx 1.35 M_\odot$ and standard deviation $\approx 0.09 M_\odot$, as inferred from a large astrophysical sample [66]. The TBH-TBH mergers are thus predicted around the chirp mass $m_c \approx 1.15 M_\odot$. The NS mass distribution predicts $q_{\mathrm{min}} = 0.69$, consistent with the LIGO search criterion of $q > 0.1$ [67].

Given the non-detection of low-mass binary black holes (BBHs) in the LIGO O3 data [67], it is reasonable to assume a Poisson distribution for the event counts in each chirp mass bin. The binned rate density $R_{\mathrm{TBH},i}$ depends on the model parameters $\bar{\theta} = \{m_\chi, \sigma_{\chi n}, R_{\rm BNS}\}$. With a surveyed volume time $\langle VT \rangle_i$, called exposure hereafter, the likelihood for parameters $\bar{\theta}$ is

$$L_i = \exp[-R_{{\rm TBH},i} \times \langle VT \rangle_i], \quad (4)$$

where we use the $\langle VT \rangle_i$ provided by LIGO (MBTA pipeline) for its third observing run [67].

We will derive both Bayesian as well as frequentist constraints on the DM parameters. With current data, owing to the uncertainty on $R_{\rm BNS}$, the frequentist limits are not constraining and we show only the Bayesian limits. With more exposure, we find interesting sensitivities without any priors on DM and show frequentist forecasts.

For the Bayesian limits, the posterior for the parameters $\bar{\theta}$ is given by $P[\bar{\theta}] \propto \prod_i L_i[\bar{\theta}] \times \pi[\bar{\theta}]$. We assume log-uniform priors on $m_\chi \in (10^4, 10^8)$ GeV for bosonic DM without BEC formation, $m_\chi \in (10^{-3}, 10^3)$ GeV with BEC, and $m_\chi \in (10^8, 10^{11})$ GeV for fermionic DM, and log-uniform priors on $\sigma_{\chi n} \in (10^{-50}, 10^{-44})$ cm^2 for bosonic DM without BEC formation, $\sigma_{\chi n} \in (10^{-49}, 10^{-44})$ cm^2 with BEC, and $\sigma_{\chi n} \in (10^{-48}, 10^{-44})$ cm^2 for fermionic DM. The ranges for m_χ and $\sigma_{\chi n}$ are chosen to be somewhat larger than the parameter space where transmutation is possible ($\tau_{\rm trans} < 10$ Gyr). For smaller cross sections or masses outside the above ranges, the parameters will not be excluded by the LIGO data. For larger cross sections the likelihood becomes small, so that the exclusion contour is somewhat sensitive to the choice of the upper boundary of the prior on $\sigma_{\chi n}$ whenever we obtain a nontrivial constraint. We take a uniform prior on $R_{\rm BNS} \in (10, 1700)$ Gpc^{-3} yr^{-1} [49]. We sample the 3D posterior distribution of the parameters by using the EMCEE Markov Chain Monte Carlo sampler [68], and marginalize the posterior over the additional parameter $R_{\rm BNS}$ to find the marginal 2D posterior of $\{m_\chi, \sigma_{\chi n}\}$. We then identify the minimal region of the $m_\chi - \sigma_{\chi n}$ plane that contains 90% of the sampled points to present a 90% credible constraint in the $m_\chi - \sigma_{\chi n}$ plane.

We obtain frequentist limits using the likelihood $L = \exp[-\mu]$, with $\mu = R_{\rm TBH}\langle VT \rangle$ obtained by assuming a fixed value of $R_{\rm BNS}$. For simplicity, here we approximate that all likelihood is in a chirp mass bin around $m_c = 1.15 M_\odot$. Alternatively, to get hybrid-frequentist limits we use the marginal likelihood

$$L_m = \frac{e^{-\kappa_{\rm min}\mu} - e^{-\kappa_{\rm max}\mu}}{\mu \log[\kappa_{\rm max}/\kappa_{\rm min}]} \quad (5)$$

obtained by writing $R_{\rm BNS} = \kappa \times 1000$ Gpc^{-3} yr^{-1} in the likelihood L, and averaging over the nuisance parameter κ with a uniform prior in $(\kappa_{\rm min}, \kappa_{\rm max})$. Upper limits on μ (at 90% confidence) are then obtained by setting $\int_{\mu_{90}}^{\infty} d\mu L_{(m)} = 0.1$. If $R_{\rm BNS}$ were not uncertain, i.e., κ were fixed, there would be no nuisance parameter. In this case, for a null detection described by a Poisson process without background, the Bayesian and frequentist 90% upper limits on the expected number of signal events coincide at 2.303. We will use this to compare our Bayesian constraints with related frequentist limits.

GW limits on DM parameters.—In Fig. 1, the pink shaded regions labeled "LIGO O3" show the 90% credibility disfavored regions of the marginal 2D posteriors of $\{m_\chi, \sigma_{\chi n}\}$ for bosonic, fermionic, and BEC-forming DM. We find an upper limit of $\sigma_{\chi n} < 2.5 \times 10^{-47}$ cm^2 for $m_\chi = 5$ PeV (or 0.2 GeV) bosonic dark matter without (with) BEC formation, respectively, weakening as $\sim 1/m_\chi^{3/2}$ (or $\sim 1/m_\chi^2$) at smaller masses up to 0.06 PeV (or 4 MeV). For fermionic dark matter, $\sigma_{\chi n} < 2.4 \times 10^{-46}$ cm^2 for $m_\chi = 3.6 \times 10^3$ PeV, weakening as $\sim 1/m_\chi$ up to 240 PeV. These limits are roughly comparable to a lower limit on $\tau_{\rm trans} \leq 0.4$ Gyr (or 0.3 Gyr) for bosonic DM without (with) BEC formation and $\tau_{\rm trans} \leq 3$ Gyr for fermionic DM for $\rho_\chi = 0.4$ GeV cm^{-3}.

The dark green curves labeled by "$R_{\rm BNS} = 1050$ (or 1240, or 1200) Gpc^{-3} yr^{-1}" are frequentist 90% upper limits obtained by assuming a fixed value of $R_{\rm BNS}$ as noted. Our 90% credible Bayesian limits are numerically similar to these, allowing us to interpret these constraints in relation to each other. If $R_{\rm BNS} = 10$ Gpc^{-3} yr^{-1}, with current data we find no 90% frequentist constraint on the DM parameter space. The minimum values of $R_{\rm BNS}$ for which current data can start ruling out some of the DM parameter space in a frequentist analysis are approximately 900 (or 980, or 1110) Gpc^{-3} yr^{-1}, for bosonic DM without BEC formation, with BEC, and fermionic DM, respectively. We also ask, what is the hybrid-frequentist constraint that exactly mimics our Bayesian analysis, but without having to assume any priors on m_χ and $\sigma_{\chi n}$? For bosonic DM without BEC formation, using the range $\kappa \in (0.01, 1.7)$, the 90% hybrid upper limit gives $\mu_{90} \approx 54$. We recall that our Bayesian constraint is comparable to a 90% frequentist upper limit assuming $R_{\rm BNS} = 1050$ Gpc^{-3} yr^{-1}, which in turn is equivalent to taking the limits $\kappa_{\rm max,min} \to 1.05$, for which the 90% hybrid upper limit gives $\mu_{90} \approx 2.2$. The numerical value of μ_{90} for our hybrid analysis is therefore approximately $54/2.2 \approx 25$ times larger than for our benchmark Bayesian upper limit. For the case of bosonic DM with BEC formation and fermionic DM we find that our Bayesian limits are nominally stronger by factors of 28 and 29, respectively, compared to the hybrid limits. This is ascribable to the priors on DM parameters.

In Fig. 1, we also show the leading constraint from underground direct detection experiments [69], in the left panel as a shaded region labeled "LZ (2022)," as well as an exclusion limit from the existence of the pulsar PSR-J0437-4715 [11,20] as a shaded region. This

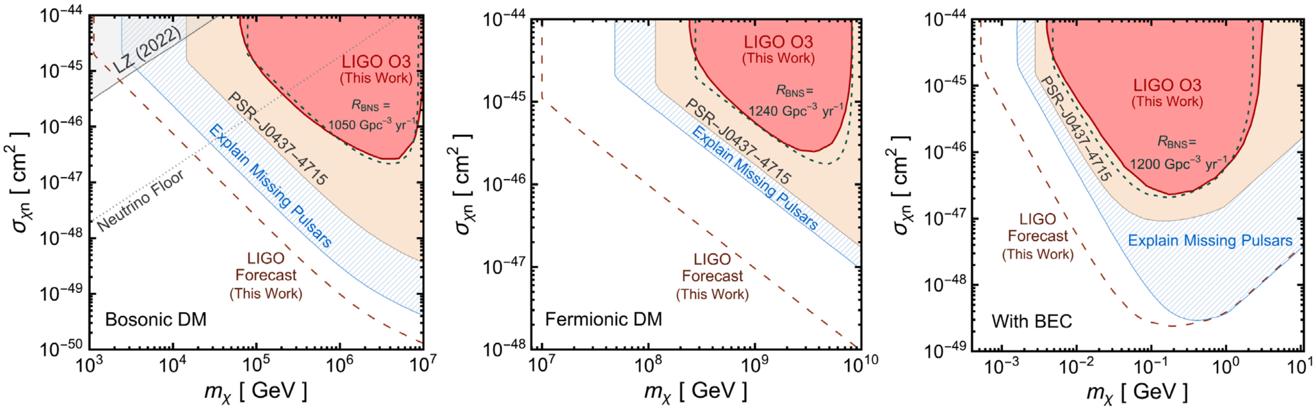

FIG. 1. Gravitational wave constraints on bosonic (left panel, without BEC; right panel, with BEC) and fermionic (middle panel) nonannihilating dark matter interactions with nucleons. These constraints apply to both spin-(in)dependent interactions as DM-neutron scattering is considered. Nondetection of BBH mergers by the LIGO O3 low-mass BH search (MBTA pipeline) [67] disfavors the pink shaded regions, as per our nominally 90% credible Bayesian limit obtained by marginalizing over $R_{\rm BNS} \in (10\text{–}1700)\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. A frequentist 90% confidence upper limit, obtained by assuming $R_{\rm BNS} = 1050$ (or 1240, or 1200) $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, shown with the green dashed line, roughly matches the corresponding Bayesian limits. The brown dashed line is a forecasted 90% confidence frequentist upper limit obtainable with 50 times the current exposure $\langle VT \rangle$ and marginalizing over currently allowed range of $R_{\rm BNS}$. The leading constraint from terrestrial experiments is shown as "LZ (2022)" (spin-independent) in the left panel [69]. The hatched blue region, labeled by "Explain Missing Pulsars," shows parameter space that would address the missing pulsar problem by invoking NS transmutation to BHs via DM accretion, without being in conflict with the existence of known pulsars, specifically PSR-J0437-4715, that disfavors the beige shaded region toward top right. We also show the neutrino floor for the direct detection experiments, below which potential discovery of a DM signal is hindered by neutrino backgrounds [70]; for fermionic DM the neutrino floor is above the range of cross sections shown. Note that the ranges of mass and cross section shown in the three panels are different.

particular pulsar, because of its relatively low core temperature and long lifetime provides the most stringent constraint on weakly interacting heavy nonannihilating DM. Apart from that, because of its close proximity, the ambient DM density and the surface temperature have been measured with small uncertainties, indicating the robustness of this constraint. Our current constraint, inferred from the existing LIGO data, is weaker than the PSR-J0437-4715 constraint. However, because of the entirely different systematics of GW detection as opposed to radio searches for pulsars, it is complementary and it has the potential to set the leading constraint with the upcoming GW observations. In Fig. 1, the blue-hatched region shows the DM parameter space that can putatively explain the scarcity of old pulsars in the central parsec of our Galaxy; it corresponds to DM parameters that can transmute all the 30 Myr old pulsars that are within 10 arc-minutes of the Galactic Center.

The curves labeled "LIGO Forecast" are forecasted hybrid-frequentist upper limits [90% confidence; marginalized over $R_{\rm BNS} \in (10, 1700)\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ [49]] that can be obtained in the future if the exposure $\langle VT \rangle$ grows to 50 times the current exposure, as may be possible by the end of this decade [71]. Conditionally, if $R_{\rm BNS} \gtrsim 28\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, our proposed method can supersede the EM-inferred constraints on nonannihilating DM interactions assuming 50 times more exposure than the current LIGO O3. With future detectors [72,73], the sensitivity can improve by several orders of magnitude (see SM for estimates). It is evident that the forecasted LIGO sensitivity can completely test the DM solution to the missing pulsar problem, and provides perhaps a unique way to probe DM-nucleon cross sections well below the neutrino floor.

Summary and outlook.—We have argued that nondetection of GWs from mergers of low-mass BBHs can be used to probe the particle nature of DM. Specifically, we use null detection of such events until the O3 run of the LIGO-Virgo-KAGRA collaboration to infer constraints on interactions of heavy nonannihilating DM with nucleons. Our benchmark constraints disfavor $\sigma_{\chi n} \geq \mathcal{O}(10^{-47})\ \mathrm{cm}^2$ for bosonic DM with PeV-scale mass if no BEC forms, and with GeV-scale if a BEC can form. We find $\sigma_{\chi n} \geq \mathcal{O}(10^{-46})\ \mathrm{cm}^2$ for 10^3-PeV-scale fermionic DM. We note that, the same low-mass BBH searches have recently been used to probe primordial BHs as DM [67,74–82] and an atomic DM model [67,78,83], and this is the *first* attempt to demonstrate that it also sheds light on $\sigma_{\chi n}$ quite generically for weakly interacting nonannihilating DM.

The presented constraint is sensitive to the uncertainty in the BNS merger rate density and priors on DM parameters. Current LIGO data suggests a broad range for $R_{\rm BNS} \in (10\text{–}1700)\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ [49]. With current data, the frequentist limits are not constraining unless $R_{\rm BNS} \geq 900\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. On the other hand, if $R_{\rm BNS} \approx 1700\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, at the upper end of the currently allowed range, GW detectors already provide leading sensitivity to interactions of DM with nucleons. The constraints are modestly sensitive to other astrophysical inputs, mainly the

DM density profiles in galactic halos that affect R_{TBH} with a nontrivial m_χ dependence. Uncertainties in BNS merger time delay distributions, star formation rate, etc., mainly lead to 50% level normalization uncertainties that are subsumed in the larger uncertainty on R_{BNS}. Uncertainties on the NS properties can cause a small ~20% level change. New particle physics such as self-interactions of DM or due to phases of NS matter could be important, but are outside of our scope here.

In the future, if there are detections of anomalously low-mass BBHs, it will be important to check if other source classes could fake a TBH-like signal. Besides novel objects such as primordial BHs, it is plausible that a fraction of BNSs may get incorrectly classified as low-mass BBHs. This can be mitigated if tidal deformation in the events is measured reliably and precisely [84]. In such a case, one would search for TBH events as a signal over the estimated background due to BNS events that were incorrectly classified as BBH events. For null detection, assuming a zero background gives conservative constraints on DM parameters. We anticipate that the sensitivity to TBH mergers can be improved with a more detailed analysis of LIGO data. It is also expected to have a distinctive redshift dependence [24].

Encouragingly, because of the planned upgrades of the LIGO-Virgo-KAGRA detectors and continued data taking, one expects spectacular sensitivity to DM parameter space by the end of this decade. We find this to be possible without assuming any priors on DM parameters. GW detectors may be able to look for nonannihilating DM that is much heavier and much more weakly interacting than will be possible using any other probe, covering the entire parameter space that explains the missing pulsars, and going well below the neutrino floor.

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[1] K. M. Zurek, Asymmetric dark matter: Theories, signatures, and constraints, Phys. Rep. **537**, 91 (2014).
[2] K. Petraki and R. R. Volkas, Review of asymmetric dark matter, Int. J. Mod. Phys. A **28**, 1330028 (2013).
[3] J. Cooley *et al.*, Report of the topical group on particle dark matter for Snowmass 2021, arXiv:2209.07426.
[4] K. K. Boddy *et al.*, Snowmass2021 theory frontier white paper: Astrophysical and cosmological probes of dark matter, J. High Energy Astrophys. **35**, 112 (2022).
[5] M. Baryakhtar *et al.*, Dark matter in extreme astrophysical environments, in *2022 Snowmass Summer Study* (2022), 3, arXiv:2203.07984.
[6] D. Carney *et al.*, Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter, arXiv:2203.06508.
[7] I. Goldman and S. Nussinov, Weakly interacting massive particles and neutron stars, Phys. Rev. D **40**, 3221 (1989).
[8] A. Gould, B. T. Draine, R. W. Romani, and S. Nussinov, Neutron stars: Graveyard of charged dark matter, Phys. Lett. B **238**, 337 (1990).
[9] G. Bertone and M. Fairbairn, Compact stars as dark matter probes, Phys. Rev. D **77**, 043515 (2008).
[10] A. de Lavallaz and M. Fairbairn, Neutron stars as dark matter probes, Phys. Rev. D **81**, 123521 (2010).
[11] S. D. McDermott, H.-B. Yu, and K. M. Zurek, Constraints on scalar asymmetric dark matter from black hole formation in neutron stars, Phys. Rev. D **85**, 023519 (2012).
[12] C. Kouvaris and P. Tinyakov, Constraining asymmetric dark matter through observations of compact stars, Phys. Rev. D **83**, 083512 (2011).
[13] C. Kouvaris and P. Tinyakov, Excluding Light Asymmetric Bosonic Dark Matter, Phys. Rev. Lett. **107**, 091301 (2011).
[14] N. F. Bell, A. Melatos, and K. Petraki, Realistic neutron star constraints on bosonic asymmetric dark matter, Phys. Rev. D **87**, 123507 (2013).
[15] T. Güver, A. E. Erkoca, M. Hall Reno, and I. Sarcevic, On the capture of dark matter by neutron stars, J. Cosmol. Astropart. Phys. 05 (2014) 013.
[16] J. Bramante, K. Fukushima, and J. Kumar, Constraints on bosonic dark matter from observation of old neutron stars, Phys. Rev. D **87**, 055012 (2013).
[17] J. Bramante, K. Fukushima, J. Kumar, and E. Stopnitzky, Bounds on self-interacting fermion dark matter from observations of old neutron stars, Phys. Rev. D **89**, 015010 (2014).
[18] C. Kouvaris and P. Tinyakov, Growth of black holes in the interior of rotating neutron stars, Phys. Rev. D **90**, 043512 (2014).
[19] J. Bramante and T. Linden, Detecting Dark Matter with Imploding Pulsars in the Galactic Center, Phys. Rev. Lett. **113**, 191301 (2014).
[20] R. Garani, Y. Genolini, and T. Hambye, New analysis of neutron star constraints on asymmetric dark matter, J. Cosmol. Astropart. Phys. 05 (2019) 035.
[21] C. Kouvaris, P. Tinyakov, and M. H. G. Tytgat, NonPrimordial Solar Mass Black Holes, Phys. Rev. Lett. **121**, 221102 (2018).
[22] B. Dasgupta, A. Gupta, and A. Ray, Dark matter capture in celestial objects: Light mediators, self-interactions, and complementarity with direct detection, J. Cosmol. Astropart. Phys. 10 (2020) 023.

[23] G.-L. Lin and Y.-H. Lin, Analysis on the black hole formations inside old neutron stars by isospin-violating dark matter with self-interaction, J. Cosmol. Astropart. Phys. 08 (2020) 022.

[24] B. Dasgupta, R. Laha, and A. Ray, Low Mass Black Holes from Dark Core Collapse, Phys. Rev. Lett. **126**, 141105 (2021).

[25] J. Fuller and C. Ott, Dark matter-induced collapse of neutron stars: A possible link between fast radio bursts and the missing pulsar problem, Mon. Not. R. Astron. Soc. **450**, L71 (2015).

[26] J. Bramante, T. Linden, and Y.-D. Tsai, Searching for dark matter with neutron star mergers and quiet kilonovae, Phys. Rev. D **97**, 055016 (2018).

[27] V. Takhistov, G. M. Fuller, and A. Kusenko, Test for the Origin of Solar Mass Black Holes, Phys. Rev. Lett. **126**, 071101 (2021).

[28] R. Garani, D. Levkov, and P. Tinyakov, Solar mass black holes from neutron stars and bosonic dark matter, Phys. Rev. D **105**, 063019 (2022).

[29] R. Garani, M. H. G. Tytgat, and J. Vandecasteele, Condensed dark matter with a Yukawa interaction, Phys. Rev. D **106**, 116003 (2022).

[30] H. Steigerwald, V. Marra, and S. Profumo, Revisiting constraints on asymmetric dark matter from collapse in white dwarf stars, Phys. Rev. D **105**, 083507 (2022).

[31] J. Dexter and R. M. O'Leary, The peculiar pulsar population of the central parsec, Astrophys. J. Lett. **783**, L7 (2014).

[32] V. Takhistov, Transmuted gravity wave signals from primordial black holes, Phys. Lett. B **782**, 77 (2018).

[33] J. Bramante, A. Delgado, and A. Martin, Multiscatter stellar capture of dark matter, Phys. Rev. D **96**, 063002 (2017).

[34] B. Dasgupta, A. Gupta, and A. Ray, Dark matter capture in celestial objects: Improved treatment of multiple scattering and updated constraints from white dwarfs, J. Cosmol. Astropart. Phys. 08 (2019) 018.

[35] F. Anzuini, N. F. Bell, G. Busoni, T. F. Motta, S. Robles, A. W. Thomas, and M. Virgato, Improved treatment of dark matter capture in neutron stars III: Nucleon and exotic targets, J. Cosmol. Astropart. Phys. 11 (2021) 056.

[36] N. F. Bell, G. Busoni, T. F. Motta, S. Robles, A. W. Thomas, and M. Virgato, Nucleon Structure and Strong Interactions in Dark Matter Capture in Neutron Stars, Phys. Rev. Lett. **127**, 111803 (2021).

[37] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.091401 for the dependence of transmuted black hole merger rate on various model assumptions.

[38] W. E. East and L. Lehner, Fate of a neutron star with an endoparasitic black hole and implications for dark matter, Phys. Rev. D **100**, 124026 (2019).

[39] T. W. Baumgarte and S. L. Shapiro, Neutron stars harboring a primordial black hole: Maximum survival time, Phys. Rev. D **103**, L081303 (2021).

[40] C. B. Richards, T. W. Baumgarte, and S. L. Shapiro, Accretion onto a small black hole at the center of a neutron star, Phys. Rev. D **103**, 104009 (2021).

[41] S. C. Schnauck, T. W. Baumgarte, and S. L. Shapiro, Accretion onto black holes inside neutron stars with piecewise-polytropic equations of state: Analytic and numerical treatments, Phys. Rev. D **104**, 123021 (2021).

[42] P. Giffin, J. Lloyd, S. D. McDermott, and S. Profumo, Neutron star quantum death by small black holes, Phys. Rev. D **105**, 123030 (2022).

[43] J. F. Navarro, C. S. Frenk, and S. D. M. White, The Structure of cold dark matter halos, Astrophys. J. **462**, 563 (1996).

[44] J. F. Navarro, C. S. Frenk, and S. D. M. White, A Universal density profile from hierarchical clustering, Astrophys. J. **490**, 493 (1997).

[45] S. R. Taylor and J. R. Gair, Cosmology with the lights off: Standard sirens in the Einstein Telescope era, Phys. Rev. D **86**, 023502 (2012).

[46] P. Madau and M. Dickinson, Cosmic star formation history, Annu. Rev. Astron. Astrophys. **52**, 415 (2014).

[47] R. W. O'Shaughnessy, V. Kalogera, and K. Belczynski, Short gamma-ray bursts and binary mergers in spiral and elliptical galaxies: Redshift distribution and hosts, Astrophys. J. **675**, 566 (2008).

[48] R. O'Shaughnessy, V. Kalogera, and K. Belczynski, Binary compact object coalescence rates: The role of elliptical galaxies, Astrophys. J. **716**, 615 (2010).

[49] R. Abbott *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), The Population of Merging Compact Binaries Inferred Using Gravitational Waves through GWTC-3, Phys. Rev. X **13**, 011048 (2023).

[50] J. F. Acevedo, J. Bramante, A. Goodman, J. Kopp, and T. Opferkuch, Dark matter, destroyer of worlds: Neutrino, thermal, and existential signatures from black holes in the sun and earth, J. Cosmol. Astropart. Phys. 04 (2021) 026.

[51] A. Ray, Celestial objects as strongly-interacting asymmetric dark matter detectors, Phys. Rev. D **107**, 083012 (2023).

[52] M. Boudaud, M. Cirelli, G. Giesen, and P. Salati, A fussy revisitation of antiprotons as a tool for dark matter searches, J. Cosmol. Astropart. Phys. 05 (2015) 013.

[53] J. N. Bahcall and R. M. Soneira, The universe at faint magnitudes. I. Models for the Galaxy and the predicted star counts., Astrophys. J. Suppl. Ser. **44**, 73 (1980).

[54] C. C. Steidel, K. L. Adelberger, M. Giavalisco, M. Dickinson, and M. Pettini, Lyman break galaxies at $z > 4$ and the evolution of the UV luminosity density at high redshift, Astrophys. J. **519**, 1 (1999).

[55] C. Porciani and P. Madau, On the association of gamma-ray bursts with massive stars: Implications for number counts and lensing statistics, Astrophys. J. **548**, 522 (2001).

[56] S. Banerjee, H. Baumgardt, and P. Kroupa, Stellar-mass black holes in star clusters: Implications for gravitational wave radiation, Mon. Not. R. Astron. Soc. **402**, 371 (2010).

[57] M. Dominik, K. Belczynski, C. Fryer, D. Holz, E. Berti, T. Bulik, I. Mandel, and R. O'Shaughnessy, Double compact objects I: The significance of the common envelope on merger rates, Astrophys. J. **759**, 52 (2012).

[58] S. Vitale, W. M. Farr, K. Ng, and C. L. Rodriguez, Measuring the star formation rate with gravitational waves from binary black holes, Astrophys. J. Lett. **886**, L1 (2019).

[59] F. Santoliquido, M. Mapelli, N. Giacobbo, Y. Bouffanais, and M. C. Artale, The cosmic merger rate density of compact objects: Impact of star formation, metallicity, initial mass function and binary evolution, Mon. Not. R. Astron. Soc. **502**, 4877 (2021).

[60] S. Mukherjee, T. Broadhurst, J. M. Diego, J. Silk, and G. F. Smoot, Impact of astrophysical binary coalescence time-scales on the rate of lensed gravitational wave events, Mon. Not. R. Astron. Soc. **506**, 3751 (2021).

[61] G. Steigman, B. Dasgupta, and J. F. Beacom, Precise relic WIMP abundance and its impact on searches for dark matter annihilation, Phys. Rev. D **86**, 023506 (2012).

[62] S. Barsanti, V. De Luca, A. Maselli, and P. Pani, Detecting Subsolar-Mass Primordial Black Holes in Extreme Mass-Ratio Inspirals with LISA and Einstein Telescope, Phys. Rev. Lett. **128**, 111104 (2022).

[63] A. Joglekar, N. Raj, P. Tanedo, and H.-B. Yu, Relativistic capture of dark matter by electrons in neutron stars, Phys. Lett. B **809**, 135767 (2020).

[64] N. F. Bell, G. Busoni, S. Robles, and M. Virgato, Improved treatment of dark matter capture in neutron stars II: Leptonic targets, J. Cosmol. Astropart. Phys. 03 (2021) 086.

[65] R. C. Nunes, Search for sub-solar mass binaries with Einstein telescope and cosmic explorer, Entropy **24**, 262 (2022).

[66] F. Özel and P. Freire, Masses, radii, and the equation of state of neutron stars, Annu. Rev. Astron. Astrophys. **54**, 401 (2016).

[67] R. Abbott *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), Search for subsolar-mass black hole binaries in the second part of Advanced LIGO's and Advanced Virgo's third observing run, arXiv:2212.01477.

[68] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman, emcee: The MCMC hammer, Publ. Astron. Soc. Pac. **125**, 306 (2013).

[69] J. Aalbers *et al.* (LZ Collaboration), First dark matter search results from the LUX-ZEPLIN (LZ) experiment, Phys. Rev. Lett. **131**, 041002 (2023).

[70] C. A. J. O'Hare, New Definition of the Neutrino Floor for Direct Dark Matter Searches, Phys. Rev. Lett. **127**, 251802 (2021).

[71] https://observing.docs.ligo.org/plan/.

[72] M. Maggiore *et al.*, Science case for the Einstein telescope, J. Cosmol. Astropart. Phys. 03 (2020) 050.

[73] M. Evans *et al.*, A horizon study for cosmic explorer: Science, observatories, and community, arXiv:2109.09882.

[74] B. Abbott *et al.* (LIGO Scientific Collaboration), Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D **72**, 082002 (2005).

[75] B. Abbott *et al.* (LIGO Scientific Collaboration), Search for gravitational waves from binary inspirals in S3 and S4 LIGO data, Phys. Rev. D **77**, 062002 (2008).

[76] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run, Phys. Rev. Lett. **121**, 231103 (2018).

[77] B. P. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO's Second Observing Run, Phys. Rev. Lett. **123**, 161102 (2019).

[78] R. Abbott *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run, Phys. Rev. Lett. **129**, 061104 (2022).

[79] A. H. Nitz and Y.-F. Wang, Search for gravitational waves from the coalescence of sub-solar mass and eccentric compact binaries, Astrophys. J. **915**, 54 (2021).

[80] A. H. Nitz and Y.-F. Wang, Search for Gravitational Waves from the Coalescence of Subsolar-Mass Binaries in the First Half of Advanced LIGO and Virgo's Third Observing Run, Phys. Rev. Lett. **127**, 151101 (2021).

[81] A. H. Nitz and Y.-F. Wang, Broad search for gravitational waves from subsolar-mass binaries through LIGO and Virgo's third observing run, Phys. Rev. D **106**, 023024 (2022).

[82] K. S. Phukon, G. Baltus, S. Caudill, S. Clesse, A. Depasse, M. Fays *et al.*, The hunt for sub-solar primordial black holes in low mass ratio binaries is open, arXiv:2105.11449.

[83] D. Singh, M. Ryan, R. Magee, T. Akhter, S. Shandera, D. Jeong, and C. Hanna, Gravitational-wave limit on the Chandrasekhar mass of dark matter, Phys. Rev. D **104**, 044015 (2021).

[84] D. Singh, A. Gupta, E. Berti, S. Reddy, and B. S. Sathyaprakash, Constraining properties of asymmetric dark matter candidates from gravitational-wave observations, Phys. Rev. D **107**, 083037 (2023).