

Constraints on Symmetric Dark Matter from Neutron Star Capture and Collapse

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Dark matter (DM) models with a conserved particle-antiparticle number, $n_\chi - n_{\bar{\chi}}$, and the asymmetry in the cosmological abundance $n_\chi \neq n_{\bar{\chi}}$, are known to be challenged by the existence of old neutron stars (NSs), as the sufficient accumulation of DM will lead to the collapse of NSs into black holes. We demonstrate that the applicability of these constraints is much wider and covers models with symmetric populations of DM, $n_\chi = n_{\bar{\chi}}$, as the process of DM capture regulated by a nucleon-DM scattering can be inherently asymmetric, $\sigma_{\chi n} \neq \sigma_{\bar{\chi} n}$. The asymmetry is induced by the interference of different types of χ - n interactions, provided that their combination is odd under charge conjugation in the DM sector, C_χ , and even under combined parity $P_{\chi+n}$. We provide a complete analysis of DM-nucleon bilinear χ - n interactions and find that this asymmetry is very generic. Using canonical NS parameters and local DM halo inputs, we exclude spin-averaged scattering cross sections down to $\sigma_{n\chi} \gtrsim 10^{-46} \text{ cm}^2$ at DM mass $m_\chi \lesssim 10^{10} \text{ GeV}$ for the maximally asymmetric capture rate and show that the constraints persist down to very small values of the cross-section asymmetry, $\mathcal{A} = (\sigma_{\chi n} - \sigma_{\bar{\chi} n})/(\sigma_{\chi n} + \sigma_{\bar{\chi} n}) \gtrsim 10^{-5}$.

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Introduction—The existence of dark matter (DM) is well established across a wide range of scales, from galactic dynamics to the cosmic microwave background [1–3]. A global experimental effort is underway to probe the feeble interactions between DM and ordinary matter. Underground detectors employing metric-ton-scale liquid noble gas targets now constrain spin-independent DM-nucleon cross sections down to $\sigma_{n\chi} \sim 10^{-47} \text{ cm}^2$ for DM masses $m_\chi \sim 100 \text{ GeV}$ [4–8]. However, event rates are suppressed for heavier DM masses as m_χ^{-1} with fixed local DM energy density. This presents a significant challenge for detecting very heavy DM candidates ($m_\chi \gtrsim 10^5 \text{ GeV}$). Such particles may arise from gravitational production in the early universe [9,10] or from interactions within hidden sectors [11] that help to evade unitarity bounds [12]. Nonetheless, this high-mass regime remains largely

unexplored by direct detection experiments, motivating the need for complementary approaches.

Compact astrophysical objects such as neutron stars (NSs) can serve as such a complementary laboratory. Due to their extreme gravitational potentials and nucleon densities $n_n \gtrsim 10^{38} \text{ cm}^{-3}$ [13,14], NSs can capture dark matter with cross sections orders of magnitude smaller than those accessible to terrestrial experiments [15–22]. Once captured, DM particles thermalize through repeated scattering and accumulate at the stellar core [19], and if DM cannot efficiently annihilate, its self-gravity can eventually overcome quantum and thermal pressure, triggering collapse into a black hole (BH) whose subsequent growth destroys the host NS.

This mechanism has been used to exclude large portions of parameter space in various nonannihilating DM models based on the observations of old pulsars. The existing literature (see, e.g., Refs. [23–26]) identified two necessary conditions that must be fulfilled for the effective accumulation of DM inside a NS. (A) The DM sector must distinguish between DM (χ) and anti-DM ($\bar{\chi}$) states and conserve the number of particles minus antiparticles, $n_\chi - n_{\bar{\chi}}$. (B) An unspecified mechanism in the early universe must arrange for the *asymmetric* population of DM, $n_\chi - n_{\bar{\chi}} \neq 0$.

The first condition removes from further considerations “self-conjugate” dark matter such as real scalars or

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Majorana fermions. Condition B is far less trivial and requires the dynamical generation of the particle-antiparticle asymmetry in the DM sector, perhaps with some analogy with baryogenesis [27–29]. The simplest freeze-in or freeze-out scenarios will not lead to asymmetric DM, as χ and $\tilde{\chi}$ are created and annihilated in pairs.

The main observation of this Letter is that the class of DM models that are probed by NS $\rightarrow$ BH transition is, in fact, much wider and includes particle-antiparticle *symmetric* DM provided that, in addition to condition (A), (B) the capture of χ and $\tilde{\chi}$ in NS is asymmetric. For the capture based on $\chi - n$ scattering, an asymmetry in the cross section is essential, such that $\sigma_{\chi n} \neq \sigma_{\tilde{\chi} n}$.

In this Letter, we demonstrate that this condition can be fulfilled quite generically and without very exotic interactions, owing much to the fact that a NS is, by itself, built with n , p , e , etc, and not with their antiparticles. At a technical level, the cross section asymmetry, $\sigma_{\chi n} \neq \sigma_{\tilde{\chi} n}$, arises due to interference between χ - n scattering amplitudes with different charge-conjugation and parity properties. Specifically, we find that such interference must be odd under both C_χ (which interchanges χ and $\tilde{\chi}$) and $C_\chi P_{\chi+n}$, where P is the common spatial parity transformation on both DM and nucleons. Many examples of similar type asymmetries are known, starting from, e.g., $\sigma_{e^- p} \neq \sigma_{e^+ p}$ due to interference of single and double photon exchange [30–32], (anti)neutrino-nucleon scattering [33,34], and other CP -violating phenomena [35,36].

This asymmetry in scattering leads to a differential capture rate between χ and $\tilde{\chi}$, favoring the accumulation of one species—assumed here to be DM—inside the NS. Over time, this asymmetric capture mechanism builds up a net DM population that may exceed the collapse threshold and induce BH formation, as shown in Fig. 1. While we limit our considerations to relatively short-range interactions, one could also note that the existence of a long-range χ - n force acting differentially on χ and $\tilde{\chi}$ may also result in the differential DM accumulation.

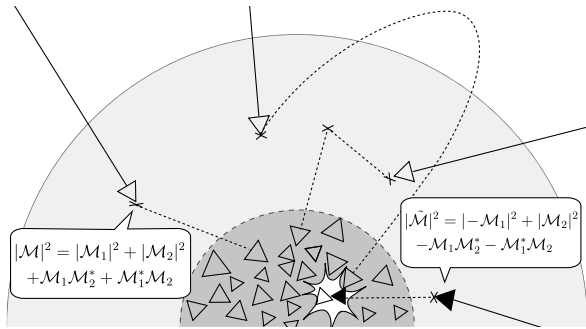


FIG. 1. A schematic diagram illustrating the asymmetric capture of DM and anti-DM by neutron stars. The interference between the two effective operators in the Lagrangian leads to different scattering cross sections for DM and anti-DM. Asymmetric accumulation of DM in sufficient quantity leads to the eventual collapse of the NS to a BH.

In the remainder of this Letter, we present stringent new NS constraints on symmetric fermionic dark matter. Describing χ - n interactions as operators in effective field theory, we identify the necessary operator pairs (odd under C_χ and $C_\chi P_{\chi+n}$) leading to asymmetric DM capture. Parametrizing the cross section asymmetry, $\mathcal{A}$, we derive constraints on $\{m_\chi, \sigma_{\chi n}, \mathcal{A}\}$ parameter space from the existence of old NSs with $t_{\text{age}} \approx 10^{10}$ yr. The resulting limits apply to $m_\chi \gtrsim 10^7$ GeV and extend far beyond current and planned DM detection experiments.

Interference-induced asymmetry—We characterize the interaction between fermionic DM and nucleons through the following effective interactions:

$$\mathcal{L}_{\text{int}} = \sum_j g_j \mathcal{O}^j \mathcal{O}^n = \sum_j g_j (\bar{\chi} \Gamma \chi) (\bar{n} \Gamma' n), \quad (1)$$

where $\mathcal{O}^j$ represents the DM (nucleon) bilinear operators constructed from the fermionic field $\psi = \chi(n)$ and its Dirac conjugate $\bar{\psi}$ [37]. Second equality is a particular realization of $\mathcal{L}_{\text{int}}$ at dimension six level with Γ and Γ' representing Lorentz structures with appropriately contracted indices. Real parameters g_j are the Wilson coefficients. We chose the basis for Γ, Γ' in such a way that $\mathcal{O}^j$ are the eigenstates of charge conjugation that can be defined to act separately on the DM and nucleon fields. This way, Lorentz components of Γ 's are also eigenstates of spatial parity. In practice, it means that our choice of Γ, Γ' is achiral: $1, i\gamma_5, \gamma_\mu$, etc. Finally, index j labels all distinct $\Gamma \otimes \Gamma'$ combinations.

NSs consist of a dense population of unpolarized nucleons, which serves as a target for an incoming, also unpolarized, stream of χ and $\tilde{\chi}$. Gravitational acceleration brings the relative χ -nucleon energy to several 100 MeV, so that not only χn elastic scattering is possible, but also inelastic processes with π, γ production. We will concentrate on $2 \rightarrow 2$ elastic scattering as most important, but our treatment can be generalized to inelastic scattering as well. The asymmetric capture will occur provided that for the spin averaged momentum-transfer scattering cross sections, the asymmetry, defined as

$$\mathcal{A} = \frac{\sigma_{\chi n} - \sigma_{\tilde{\chi} n}}{\sigma_{\chi n} + \sigma_{\tilde{\chi} n}}, \quad (2)$$

is nonzero. Since the cross sections are some linear combinations of $g_i g_j$, our task is to identify which pairings would lead to $\mathcal{A} \neq 0$. It is easy to see that this requires the following:

C_χ -odd combination: two χ operators that belong to interfering terms must have opposite eigenvalues under the DM charge conjugation, $C_\chi(\mathcal{O}_1^\chi \mathcal{O}_2^\chi) = -\mathcal{O}_1^\chi \mathcal{O}_2^\chi$.

$C_\chi P_{\chi+n}$ -odd combination: due to the absence of defined directions and spin polarizations, the interference term must obey parity conservation or equivalently being $C_\chi P_{\chi+n}$ -odd.

The two conditions bear some resemblance to Sakharov's criteria for baryogenesis [38], but with key differences: the charge conjugation is applied to the DM part only, as the

TABLE I. C_χ and $C_\chi P$ eigenvalues for $\mathcal{L}_{\text{int}}$ with operator dimension ≤ 6 . [$\bullet + \circ$] or [$\square + \blacksquare$] operator pairs can lead to asymmetric capture. Note that antisymmetric tensor operators can also be contracted using a 4D Levi-Civita tensor, and the corresponding eigenvalues for that case are $\square - / +$.

$C_\chi/C_\chi P_{\chi+n}$	$\bar{\chi}\chi$	$i\bar{\chi}\gamma^5\chi$	$\chi_s^\dagger\chi_s$	$i\chi_s^\dagger\overleftrightarrow{\partial}_\mu\chi_s$	$\bar{\chi}\gamma_\mu\chi$	$\bar{\chi}\gamma_\mu\gamma^5\chi$	$\bar{\chi}\sigma_{\mu\nu}\chi$
$\bar{n}n$	$\bullet + / +$	$\blacksquare + / -$	$\bullet + / +$				
$i\bar{n}\gamma^5 n$	$\blacksquare + / -$	$\bullet + / +$	$\blacksquare + / -$				
$\bar{n}\gamma^\mu n$				$\circ - / -$	$\circ - / -$	$\blacksquare + / -$	
$\bar{n}\gamma^\mu\gamma^5 n$				$\square - / +$	$\square - / +$	$\bullet + / +$	
$\bar{n}\sigma^{\mu\nu} n$							$\circ - / -$

nucleon target is intrinsically baryon asymmetric. One can immediately see that these conditions cannot be satisfied in the lowest Born order by $\mathcal{L}_{\text{int}}$ that contains a single effective operator with definite C_χ property ($\pm$), as the square of the amplitude ($\propto g_i^2$) will be even under C_χ .

We list the $C_\chi/C_\chi P_{\chi+n}$ eigenvalues for DM-nucleon bilinear operator combinations $\mathcal{O}^X \mathcal{O}^n$ in Table I, where Lorentz indices are assumed to be contracted with the metric tensor. Although our discussion focuses on fermionic DM, the analysis can also apply to bilinears constructed from bosonic DM states, and we include them for completeness under χ_s notation. As evident from the table, there are 14 operator pairings that produce a nonzero $\mathcal{A}$. When considering only fermionic dark matter, this number decreases to 12. Moreover, some of the interference terms identically vanish upon χ and n spin averages, cutting the number of possible combinations to eight for fermionic DM. All these eight nonvanishing pairs have an overall $CP = +1$.

Since only very heavy fermionic DM can seed BH formation, there is another condition that helps to discriminate further between cases with nonzero $\mathcal{A}$ for fermionic DM. In the scattering process, the momentum transfer, however, is mostly limited by $|\vec{q}| \sim m_n c \ll m_\chi$. In addition, the energy transfer is also suppressed compared to $|\vec{q}|$, $q^0 \sim O(|\vec{q}|^2 m_\chi^{-1})$. Upon the spin average, most χ - $\bar{\chi}$ asymmetric combinations require an extra power of DM recoil momenta leading to an additional $\mathcal{A} \propto m_n/m_\chi$, $|\vec{q}|/m_\chi < 10^{-7}$ suppression when all g_i are assumed to be of similar size. This leaves only two nonsuppressed interfering pairs,

$$\mathcal{O}_S^X \mathcal{O}_S^n \text{ and } \mathcal{O}_V^X \mathcal{O}_V^n; \mathcal{O}_A^X \mathcal{O}_A^n \text{ and } \mathcal{O}_T^X \mathcal{O}_T^n, \quad (3)$$

where $\Gamma, \Gamma' = 1, \gamma_\mu, \gamma_\mu\gamma^5, \sigma_{\mu\nu}$ are referred to as S, V, A, T .

It is easy to calculate the χ - $\bar{\chi}$ cross section asymmetry for both of these cases. The Lagrangian

$$\mathcal{L}_{\text{int}}^{\text{SV}} = g_{SS}\bar{\chi}\chi\bar{n}n + g_{VV}\bar{\chi}\gamma_\mu\chi\bar{n}\gamma^\mu n \quad (4)$$

can be easily realized in models with spontaneously broken U(1) gauge symmetry and the dark Higgs. Such a theory would contain scalar and vector mediator particles, both giving rise to *spin-independent* interactions. In the limit of $|\vec{q}| \lesssim m_n \ll m_\chi$ with both particles initially mildly

relativistic, the asymmetry is given by

$$\mathcal{A}_{\text{SV}} \approx \frac{2g_{SS}g_{VV}}{g_{SS}^2 + g_{VV}^2}. \quad (5)$$

For a general case without a big hierarchy between the mass scales and couplings between these mediators, it is highly plausible to induce a sizable asymmetry for the capture process. The *spin-dependent* case in Eq. (3) involves interference of the axial-vector tensor interactions, both reducing to $\vec{s}_\chi \cdot \vec{s}_n$ structures in the nonrelativistic limit. With the Lagrangian,

$$\mathcal{L}_{\text{int}}^{\text{AT}} = g_{AA}\bar{\chi}\gamma_\mu\gamma^5\chi\bar{n}\gamma^\mu\gamma^5 n + \frac{1}{2}g_{TT}(\bar{\chi}\sigma_{\mu\nu}\chi)(\bar{n}\sigma^{\mu\nu}n), \quad (6)$$

the resulting asymmetry for nonrelativistic scattering is given by

$$\mathcal{A}_{\text{AT}} \approx \frac{2g_{AA}g_{TT}}{g_{AA}^2 + g_{TT}^2}. \quad (7)$$

The tensor interaction bears a strong resemblance to the interaction of two magnetic dipoles, while axial interaction is similar to a massless pseudoscalar exchange.

Finally, in exact analogy with the electrodynamics example, $\sigma_{e^-p} \neq \sigma_{e^+p}$, if one goes beyond the leading Born approximation, even a single operator $\mathcal{O}$ can induce an asymmetry, provided that it satisfies already established criteria. In particular, $\bar{\chi}\gamma_\mu\chi\bar{n}\gamma^\mu n$ and $\bar{\chi}\sigma_{\mu\nu}\chi\bar{n}\sigma^{\mu\nu}n$ are both C_χ -odd, P -even. Each of these operators *by itself* will induce a nonzero $\mathcal{A}$ due to the interference of the first and second order scattering amplitudes. This means that asymmetric capture can originate even from a single mediator. The resulting asymmetry relies on the details of the realization, but generically, it is loop and momentum ratio suppressed.

Asymmetries are generic in models without an exact C_χ symmetry, since UV completions then naturally generate multiple operators at the same heavy scale, whose unsuppressed interference yields $\mathcal{A} = O(1)$ when their Wilson coefficients are comparable. In Supplemental Material [39], we show (i) extension of $\mathcal{L}_{\text{int}}$ to higher-dimensional operators; (ii) explicit expressions for asymmetries $\mathcal{A}$ generated by Eqs. (4) and (6); and (iii) details of three different renormalizable models that can generate sizable asymmetries.

Dark matter capture and black hole formation—The process by which astrophysical bodies capture dark matter has been extensively studied in the literature [15–19,21,22,45–49]. We concentrate on the fermionic DM, as the phenomenology of bosonic-DM-induced NS $\rightarrow$ BH transmutation is far more intricate [21,50,51] and is left for future work. We follow standard treatment of DM capture and adapt it to symmetric DM with nonzero $\mathcal{A}$, assumed to be positive.

For a single isotropic in the χn center of mass frame scattering event, the average energy loss experienced by a DM particle is given by $m_n(1+z)^2 v_{\text{esc}}^2$ [52], where the DM velocity inside the neutron star is approximated by the escape velocity at the surface of the NS, $v_{\text{esc}} = \sqrt{2GM_*/R_*} \approx \mathcal{O}(0.6)$, and $1+z = (1 - 2GM_*/R_*)^{-1/2}$ is the corresponding gravitational redshift factor. Here, M_* and R_* denote the mass and radius of the NS, respectively. Noticeable deviation from the above approximation can occur [21,52] for mostly forward scattering due to, e.g., a light force mediator.

To be gravitationally captured by a NS, even a small loss of kinetic energy by a χ -particle can prevent its escape to asymptotic infinity, provided that

$$\Delta E_\chi > E_{\text{kin}}^\infty = m_\chi v_{\text{rel}}^2/2 \sim 10^{-6} m_\chi, \quad (8)$$

where $v_{\text{rel}} \sim 10^{-3} c$ is the χ -NS relative velocity at large separation. For DM masses $m_\chi \lesssim 10^6 m_n$, this energy can be easily dissipated through a single scattering event. For heavier DM, an average of $E_{\text{kin}}^\infty/\Delta E_\chi \sim 10^6 m_n/m_\chi$ scattering events is required for trapping. The capture probability, which naturally includes the effect of multiple scatterings [21,46], can then be modeled via a Poisson distribution,

$$P_{\text{cap}}^\chi \approx \frac{\sigma_{\chi n}}{\sigma_0} \times \min \left\{ 1, \frac{E_{\text{kin}}^\infty}{\Delta E_\chi} \right\}, \quad (9)$$

for an effectively thin target, where $\sigma_{\chi n}$ is the DM-nucleon scattering cross section, and $\sigma_0 \approx \pi R_*^2 m_n/M_* \approx 2.5 \times 10^{-45} \text{ cm}^2$ is an estimate of the NS's geometric capture cross section. Further refinement of these estimates can come from accounting for DM self-interaction [51,53], consideration of velocity distribution [46,54], and other effects [15,19,55].

The same treatment applies for the anti-DM capture probability, $P_{\text{cap}}^{\bar{\chi}}$. The total capture rate per unit time for DM and anti-DM in the NS is then

$$C_{\chi/\bar{\chi}} = n_{\chi/\bar{\chi}} v_{\text{rel}} \times \pi b^2 \times P_{\text{cap}}^{\chi/\bar{\chi}}, \quad (10)$$

and for numerical results, we use $v_{\text{rel}} \approx 350 \text{ km/s}$ and $n_{\chi/\bar{\chi}} = n_{\text{DM}}/2 \approx m_\chi^{-1} \times 0.2 \text{ GeV/cm}^3$ [3,54,56] as a typical input DM number density. The gravitational focusing results in an impact parameter much larger than the NS radius, $b = (6/\pi)^{1/4} R_* (1+z)(v_{\text{esc}}/v_{\text{rel}}) \sim 10^3 R_*$. This analysis applies equally to spin-independent and spin-dependent $\chi - n$ scattering. For heavy dark matter with

$m_\chi \gg m_n$, the momentum transfer is $q \sim m_n v_{\text{esc}}$, which exceeds the Fermi momentum, and the energy transfer is $\sim m_n v_{\text{esc}}^2$, also exceeding the Fermi energy. As a result, Pauli blocking, collective effects from density and spin correlations, and pairing effects can be neglected. In this regime, the large momentum transfer allows dark matter to resolve individual nucleons, so the independent single-nucleon scattering approximation is valid.

Once a net population of captured DM particles builds up, we can safely assume that any subsequently captured anti-DM particles will quickly annihilate with resident DM. Therefore, the growth rate of the net number of DM particles is given by the difference between the DM and anti-DM capture rates as described in Eq. (10),

$$\frac{dN_\chi}{dt} = C_\chi - C_{\bar{\chi}} \xrightarrow{P_{\text{cap}}^\chi \ll 1} n_{\text{DM}} v_{\text{rel}} \times \pi b^2 \times P_{\text{cap}}^\chi \frac{\mathcal{A}}{1 + \mathcal{A}}, \quad (11)$$

where the second limit is valid in the optically thin regime. In the large cross-section regime, where the approximated expression of $P_{\text{cap}}^\chi \gtrsim 1$, the capture probability saturates to unity for both DM and anti-DM, and the asymmetry of cross sections does not result in the preferential DM built up inside the NS.

The captured dark matter particles thermalize within the NS core quickly within t_{th} [19], forming a gravitationally bound halo. Once the total mass of captured DM exceeds a critical threshold, M_{crit} , this halo undergoes catastrophic collapse to form a BH. If the accretion rate of this black hole exceeds its Hawking evaporation rate, the black hole will inevitably grow and quickly consume the entire NS within a time interval t_{grow} .

For the collapse to occur, several conditions must be satisfied: the dark matter must trigger a self-gravitating instability, overcome its own thermal pressure, and reach the Chandrasekhar limit. The Chandrasekhar limit sets the critical mass M_{crit} for the dark matter parameter space of interest:

$$M_{\text{crit}} \approx \frac{M_{\text{pl}}^3}{m_\chi^2} \approx 1.6 \times 10^{-16} M_\odot \left(\frac{10^8 \text{ GeV}}{m_\chi} \right)^2, \quad (12)$$

where $M_{\text{pl}} = G^{-1/2}$ is the Planck mass, and $M_\odot$ is the solar mass. Further review and explicit expressions for the rates of capture, thermalization, and collapse can be found in Supplemental Material [39].

Constraints on symmetric dark matter—Thousands of pulsars have been observed in the Solar System neighborhood [57]. Meanwhile, old NSs with ages $t_{\text{age}} \approx 10^{10} \text{ yr}$ are abundant in our Galaxy; for instance, J1719-1438 is located 336 pc away with an estimated age of 11.4 Gyr, and J1737-0811 is located 206 pc away and is believed to be 8.34 Gyr old [57].

Based on these observations, we adopt a typical NS mass $M_* = 1.5 M_\odot$, radius $R_* = 12 \text{ km}$, and age $t_{\text{age}} = 10^{10} \text{ yr}$

for our analysis. The survival of such NSs imposes the condition

$$\frac{M_{\text{crit}}}{m_\chi dN_\chi/dt} + t_{\text{th}} + t_{\text{grow}} \geq t_{\text{age}}, \quad (13)$$

where the first term represents the accretion time and dominates over the other two timescales in the solar vicinity for the DM parameter space considered. We evaluate this constraint on the $\{m_\chi, \sigma_{\chi n}, \mathcal{A}\}$ parameter space for the fermionic DM.

The excluded parameter regions are shown as colored regions in Fig. 2 for various asymmetry factors $\mathcal{A}$. As expected, the exclusion region shrinks as $\mathcal{A}$ decreases, since a larger fraction of captured DM is annihilated by anti-DM. Moreover, one can recover existing constraints on asymmetric DM scenarios [55] by setting $\mathcal{A} = 1$ in our framework and taking twice the (anti-)DM density used in our calculation.

The sensitivity covers enclosed regions on DM mass vs cross-section plane. To the left and below the shaded region (i.e., for light m_χ and/or smaller $\sigma_{\chi n}$), the amount of captured DM in the NS lifetime is insufficient to induce gravitational collapse. As the asymmetry factor $\mathcal{A}$ decreases, less net DM can be accumulated, moving the lower-left boundary to the upper right. In contrast, the vertical boundary on the heavier mass side, largely insensitive to $\mathcal{A}$, is due to Hawking evaporation dominating the accretion rate. Such a boundary depends on the BH radiation, and we show the uncertainty

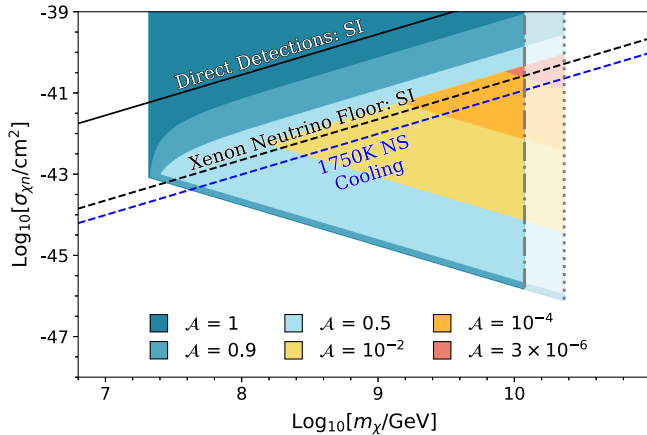


FIG. 2. The excluded $\{m_\chi, \sigma_{\chi n}\}$ parameter space for the symmetric fermionic DM model with different input values of the cross section asymmetry $\mathcal{A}$. The vertical gray dotted line and dot-dashed line correspond to two different treatments of the BH evaporation Page factor [58,59]. The black solid line represents the current existing constraints from direct detection experiments for spin-independent interactions [4–8], and the black dashed line indicates irreducible neutrino background (so-called “neutrino floor” or “fog”) for xenon detectors [60,61]. The blue dashed line is a hypothetical NS cooling constraint, assuming a (currently impossible) observation of a NS with surface temperature of 1750 K and full DM energy-to-heat conversion [62].

due to baseline assumptions with a gray-shaded region. The left boundary (vertical gray dot-dashed line) of the shaded region indicates the consideration of the Hawking radiation rate assuming full standard model particle spectrum emission, while the right boundary (vertical gray dotted line) corresponds to only photons and neutrinos being emitted [58,59]. Finally, when the DM-nucleon cross section is big enough, the capture probabilities of both DMs and anti-DMs are nearly 100%, making net DM number accumulation impossible.

For a sizable asymmetry $\mathcal{A}$, the NS limits on $\sigma_{\chi n}$ are generally stronger than constraints from direct detection experiments assuming spin-independent interactions [4–8], reaching beyond the solar-neutrino-induced direct detection fog reference value [60,61]. Therefore, the NS constraints complement the reach of terrestrial direct detection experiments, particularly at higher DM masses. Improved observations of NSs near or at the Galactic Center, where elevated values of n_χ are expected, will bring new sensitivity to $\sigma_{\chi n}$ and $\mathcal{A}$.

We also show a futuristic benchmark sensitivity from the heating of a NS by capture and annihilation of DM. This mechanism would require an efficient capture of both DM and anti-DM species, corresponding to scenarios with smaller $\mathcal{A}$. Suffice it to say that such a constraint would require the discovery of a NS with $\lesssim 10^{-5}$ smaller thermal luminosity compared to the coolest NS ever observed [63].

Summary and outlook—We have demonstrated that the mere existence of old NSs imposes powerful constraints even on symmetric DM. This new insight stems from the observation that operator interference leads to an asymmetric capture rate between DM and anti-DM. Our effective field theory framework identifies the minimal C_χ - and $C_\chi P_{\chi+n}$ -odd interference amplitudes required to generate such an asymmetry, and we specify ultraviolet completions that realize these features. By applying established results for capture rates, thermalization, and collapse dynamics, we show that the continued existence of NSs in the solar neighborhood already excludes significant regions of parameter space for symmetric DM, complementing terrestrial direct detection experiments.

Our Letter highlights a gap in the current literature: existing NS constraints have primarily focused on intrinsically asymmetric DM via NS collapse, which requires an additional process in the early universe that would ensure the dominance of DM or anti-DM. By showing that interference-driven capture asymmetries open a viable collapse channel even for symmetric DM, we extend the ability of NS probes into a new regime of DM models. Our Letter reinforces neutron stars as unique astrophysical laboratories whose extreme densities and gravitational fields enable novel detection pathways for DM, with promising prospects for future observational accomplishments. Future radio pulsar surveys, gravitational wave channels, and infrared searches for ultracold NSs will strengthen our understanding of NS structures and properties [64–67].

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Data availability—The data that support the findings of this article are openly available [68].

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