

Constraints on dark matter boosted by supernova shock within the effective field theory framework from the CDEX-10 experiment

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Supernova shocks can boost dark matter (DM) particles to high, yet nonrelativistic, velocities, providing a suitable mechanism for analysis within the framework of the nonrelativistic effective field theory (NREFT). These accelerated DM sources extend the experimental ability to scan the parameter space of light DM into the sub-GeV region. In this study, we specifically analyze DM accelerated by the Monogem Ring supernova remnant, whose age (~ 68000 yr) and distance to Earth (~ 300 parsec) are strategically matched to enable detection with current terrestrial detectors. Utilizing the 205.4 kg · day data obtained from the CDEX-10 experiment at the China Jinping Underground Laboratory, we derive new constraints on boosted DM within the NREFT framework. The NREFT coupling constant exclusion regions now penetrate the sub-GeV mass range, with optimal sensitivity achieved for operators $\mathcal{O}_3$, $\mathcal{O}_6$, $\mathcal{O}_{15}$ in the 0.4–0.6 GeV mass range.

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I. INTRODUCTION

Convincing evidence from both astrophysical observations and cosmological studies supports the existence of dark matter (DM, χ) [1], which accounts for approximately 26.8% of the universe's energy budget [2]. Among the various DM candidates, weakly interacting massive particles (WIMPs) remain one of the most compelling. Extensive experimental efforts have been devoted to the direct detection (DD) of WIMPs through nuclear recoil signals, including XENON [3], LUX [4], PandaX [5],

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DarkSide [6], CRESST [7], SuperCDMS [8], CoGeNT [9], and CDEX [10–20]. However, to date, no experiment has observed a conclusive DM signal. This persistent null result continues to make dark matter one of the most profound mysteries in modern physics.

Traditional DD experiments conduct searches for DM through spin-independent (SI) and spin-dependent (SD) elastic scattering with ordinary nucleons (χ -N). These experiments often rely on the standard halo model (SHM), which assumes that DM velocities follow a Maxwell-Boltzmann distribution with a local standard of rest velocity of 238 km/s and an escape velocity cutoff of 544 km/s [21]. However, light DM particles in the sub-GeV mass range remain undetectable within this conventional framework due to insufficient momentum transfer to overcome detector energy thresholds of current technologies. To address this limitation, various novel methodologies have been emerged to enhance DD sensitivity to lower DM mass regimes. For instance, inelastic scattering mechanisms, such as the Migdal effect, can extend the parameter space into the $m_\chi \sim \mathcal{O}(100 \text{ MeV})$ region [18,22]. Another promising strategy involves investigating boosted DM with higher momentum. In this context, potential sources of acceleration include high-energy cosmic rays [20,23–28], blazars [29,30], neutrinos [31–34], the Sun [35–39], and black halos [40,41], etc. These (semi) relativistic DM particles enable current DD experiments to explore parameter space as low as $m_\chi \sim \mathcal{O}(10 \text{ keV})$, remarkably extending the discovery potential beyond traditional approaches.

Recently, supernova shocks have been proposed as a novel source of boosted DM. In this scenario, DM particles are accelerated through collisions with high-velocity nuclei within supernova remnants [42], achieving speeds exceeding $0.01c$, an order of magnitude greater than typical DM velocities predicted by the SHM. In the case of ultralight DM particles, they can attain maximum velocities up to double the supernova shock speed through elastic scattering. This enhanced, yet nonrelativistic, velocity regime ($v \lesssim 0.1c$) establishes supernova shock acceleration as a particularly well-suited mechanism for probing dark matter-nucleon interactions within the nonrelativistic effective field theory (NREFT) framework [43,44], which systematically parametrizes χ -N interactions through fourteen distinct operators. Besides conventional velocity-independent SI and SD scattering models, the NREFT architecture also encompasses numerous velocity-dependent operators. Under the supernova shock boost mechanism, the sensitivity of velocity-dependent interactions may increase by several magnitudes over that under SHM predictions, thereby substantially expanding the investigable parameter space for the corresponding operators.

The detectability of supernova shock accelerated DM critically depends on the progenitor supernova remnant's spatiotemporal characteristics. Only supernova remnant

with appropriate age matching its distance to Earth could be an ideal candidate, providing currently observable DM fluxes. In this work, the Monogem Ring remnant [45] emerges as an optimal candidate, fulfilling this temporal-spatial coincidence criterion. Based on the $205.4 \text{ kg} \cdot \text{day}$ exposure data from the CDEX-10 experiment [46], which employs p -type point contact high-purity germanium (PPCGe) detectors at the China Jinping Underground Laboratory (CJPL) [47,48], we derive a set of constraints on NREFT operators. Our analysis incorporates simulation of Earth shielding effects [49–53] from CJPL's 2400 m rock overburden through a modified version of the CJPL_ESS simulation package [54] developed by CDEX Collaboration.

II. EFFECTIVE FIELD THEORY

The NREFT provides a model-independent framework for describing χ -N scattering processes. This approach systematically expands the effective Lagrangian in powers of momentum transfer(q), where operators are truncated at leading order and next-to-leading-order to ensure computational tractability [43]. Within this formalism, all possible χ -N interactions can be parametrized through linear combinations of four fundamental Galilean-invariant quantities:

$$i\vec{q}, \quad \vec{v}^\perp, \quad \vec{S}_\chi, \quad \vec{S}_N. \quad (1)$$

Here, $\vec{S}_\chi$ and $\vec{S}_N$ denote the spins operators of the DM particle and nucleon, respectively; $\vec{q}$ represents the momentum transfer vector during scattering; and $\vec{v}^\perp$ represents the transverse relative velocity between DM and nucleon. The NREFT framework initially derives 11 fundamental operators from these four Galilean invariants [43], with Ref. [44] extending this to 15 operators by incorporating interactions mediated by higher-spin (beyond spin-0 or spin-1) fields. Each operator $\mathcal{O}_i$ is weighted by the coupling constants c_i^0 (isoscalar) and c_i^1 (isovector), reflecting the distinct nuclear response to DM interactions. One can calculate the differential cross section of χ -N scattering with formula Eq. (2):

$$\begin{aligned} \frac{d\sigma_N(v, E_R)}{dE_R} &= \frac{2m_T}{4\pi v^2} \left(\frac{1}{2j_\chi + 1} \frac{1}{2j_N + 1} \sum |\mathcal{M}|^2 \right) \\ &= \sum_k \sum_{\tau=0,1} \sum_{\tau'=0,1} R_k \left(\vec{v}^\perp, \frac{\vec{q}^2}{m_N^2}, \{c_i^\tau c_j^{\tau'}\} \right) \\ &\quad \times W_k^{\tau\tau'}(\vec{q}^2 b^2). \end{aligned} \quad (2)$$

The differential cross section depends on the relative velocity v between DM and target nucleon, as well as the energy transfer E_R during the collision. Here, m_T denotes the mass of the target nucleus, while j_χ and j_N represent the spins of the DM particle and nucleus, respectively. The EFT Galilean-invariant amplitude $|\mathcal{M}|$

is the product of WIMP and nuclear matrix elements. It is averaged over initial-state WIMP as well as nuclear magnetic quantum numbers (M_χ , M_N) and summed over final magnetic quantum numbers. The index k designates eight distinct WIMP-nucleon interaction types: M , Δ , Σ' , Σ'' , Φ' , and Φ'' , which transform as vector charge, vector transverse magnetic, axial transverse electric, axial longitudinal, vector transverse electric, and vector longitudinal operators, respectively, appending two interference terms $\Phi''M$ and $\Delta\Sigma'$. The WIMP response functions R_k and nuclear response functions W_k encapsulate the dynamics of these interactions. The coupling constants c_i^r are embedded in R_k , directly modulating the differential cross section. Conversely, W_k characterizes nuclear-specific properties (where b indicates the nuclear size [43]) and varies across target nuclei. This work will only focus on isoscalar interactions and the superscript 0 of coupling constant c_i^0 will be omitted in later paragraphs, ignoring the isovector c_i^1 .

Crucially, NREFT operators exhibit a pronounced momentum dependence ($\sim q^n$), contrasting with conventional SI ($\mathcal{O}_1$) and SD ($\mathcal{O}_4$) cross sections that lack such scaling. The velocity scaling of the cross section σ_N follows $\sigma_N \propto v^{2\alpha}$, where α corresponds to the combined power of momentum q and velocity v in the operator's analytic form (Table I). Under the SHM with typical DM velocities ($\mathcal{O}(100 \text{ km/s})$), SI/SD interactions dominate due to their

velocity-independent nature. However, in scenarios with boosted DM velocities [e.g., $\mathcal{O}(10^3\text{--}10^4 \text{ km/s})$], which remaining nonrelativistic, higher-order velocity-dependent operators may experience cross section enhancements of orders of magnitudes, potentially surpassing SI/SD contributions.

III. DM BOOSTED BY SUPERNOVA EJECTA

During the expansion of a supernova shock wave, the initial stellar ejecta propagates outward and sweeps up the surrounding interstellar medium (ISM). The early evolution (first 100–200 yr) constitutes the free expansion phase (or ejecta-dominated phase), characterized by the swept-up ISM mass being negligible compared to the stellar ejecta mass. The transition to the Sedov-Taylor phase [55] occurs once the mass of the ambient matter swept up by the remnant exceeds the mass of the stellar ejecta. During this transition the shock begins to decelerate significantly. This phase is governed by the Sedov-Taylor solution, which expresses the shock expansion radius and velocity as functions of time since explosion, on the basis of the explosion energy E_{SN} , ejecta mass M_{ej} , and the ambient ISM density n_0 . According to Refs. [56,57], the shock radius is obtained as

$$R_s(t) = R_0 \left(\left(\frac{t}{t_0} \right)^{-5\lambda_{\text{FE}}} + \left(\frac{t}{t_0} \right)^{-5\lambda_{\text{ST}}} \right)^{-1/5} \quad (3)$$

Meanwhile, the shock velocity is derived as

$$V_s(t) = \frac{R_0}{t_0} \left(\frac{R_s(t)}{R_0} \right)^6 \times \left(\lambda_{\text{FE}} \left(\frac{t}{t_0} \right)^{-5\lambda_{\text{FE}}-1} + \lambda_{\text{ST}} \left(\frac{t}{t_0} \right)^{-5\lambda_{\text{ST}}-1} \right), \quad (4)$$

where the scaling parameters λ_{FE} (free expansion phase), λ_{ST} (Sedov-Taylor phase), characteristic radius R_0 , and characteristic time t_0 exhibit distinct values depending on supernova types and circumstellar environments. For a type Ia supernova expanding across a uniform ISM, $\lambda_{\text{ST}} = 2/5$, $\lambda_{\text{FE}} = 4/7$, $R_0 = \left(\frac{3M_{\text{ej}}}{4\pi m n_0} \right)^{1/3}$, and $t_0 = \left(R_0 \left(\frac{M_{\text{ej}} m n_0}{0.38 E_{\text{SN}}^2} \right)^{1/7} \right)^{7/4}$, where m denotes the mean mass of the ISM. Meanwhile, for a type II supernova, the shock expands through a dense wind structured by its progenitor star before reaching the ISM. In this case, $\lambda_{\text{ST}} = 2/3$, $\lambda_{\text{FE}} = 6/7$, $R_0 = \frac{M_{\text{ej}} V_w}{M}$, and $t_0 = \left(R_0 \left(\frac{\dot{M}}{36\pi} \left(\frac{18M_{\text{ej}}}{40E_{\text{SN}}} \right)^{-5/2} \left(\frac{40E_{\text{SN}}}{18M_{\text{ej}}} \right)^{-9/2} \right)^{1/7} \right)^{7/3}$, where V_w represents the presupernova wind velocity and $\dot{M}$ denotes the mass loss rate. The density of the presupernova wind is expressed as [57]

TABLE I. Complete set of NREFT operators governing DM-nucleus interactions, with their corresponding cross section velocity scaling in the form of $\sigma_N \propto v^{2\alpha}$. Here α denotes the total power of momentum transfer q and relative velocity v in each operator's structure. Notably, $\mathcal{O}_2$ is typically excluded, as it cannot be derived from the leading-order nonrelativistic reduction of relativistic operators in effective field theory frameworks [44].

Operator	Formula	v -scale of σ_N
$\mathcal{O}_1$	$1_\chi 1_N$	0
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$	...
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_N^\perp)$	4
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$	0
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}_N^\perp)$	4
$\mathcal{O}_6$	$(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	4
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}_N^\perp$	2
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}_N^\perp$	2
$\mathcal{O}_9$	$i\vec{S}_N \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$	2
$\mathcal{O}_{10}$	$i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$	2
$\mathcal{O}_{11}$	$i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$	2
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}_N^\perp)$	2
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}_N^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	4
$\mathcal{O}_{14}$	$i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}_N^\perp)$	4
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \times \vec{v}_N^\perp) \cdot \frac{\vec{q}}{m_N}$	6

TABLE II. Parameters used for Monogem Ring modeling.

Parameter	Value
Supernova type	II
λ_{ST}	2/3
λ_{FE}	6/7
m (Mean mass of ISM)	$1.27m_p$
D (Distance to Earth)	300 parsec
Age	68000 yr
E_{SN} (Explosion energy)	8.38×10^{50} erg
n_0 (Surrounding ISM density)	$3.73 \times 10^{-3} \text{ cm}^{-3}$
M_{ej} (Mass of supernova ejecta)	$5M_{\odot}$
V_w (Presupernova wind velocity)	10 km/s
$\dot{M}$ (Mass loss rate)	$10^{-5}M_{\odot}/\text{yr}$

$$\rho(r) = \frac{\dot{M}}{4\pi V_w r^2}, \quad (5)$$

with $V_w = 10 \text{ km/s}$, and $\dot{M} = 10^{-5}M_{\odot}/\text{yr}$ following Ref. [56].

The Monogem Ring, the investigated target in this work, exhibits an angular diameter of 25° on the celestial sphere as one of the closest known supernova remnants to Earth. Comprehensive analyses combining Sedov-Taylor hydrodynamical modeling, x-ray observations, and Galactic cosmic-ray propagation simulations [58–60] constrain its key parameters: distance to Earth $D = 300$ parsec, age Age = 68000 yr, explosion energy $E_{\text{SN}} = 8.38 \times 10^{50}$ erg, and surrounding ISM density $n_0 = 3.73 \times 10^{-3} \text{ cm}^{-3}$ [45]. In the analysis below, the Monogem ring is treated as type II supernova, with the mean mass of ISM $m = 1.27m_p$ (mass of proton), and the mass of supernova eject $M_{\text{ej}} = 5M_{\odot}$ (mass of the Sun) according to the typical values in Ref. [57]. All parameters used for Monogem Ring modeling are summarized in Table II.

Accurate modeling of boosted DM flux distributions requires precise characterization of the nuclear composition of supernova ejecta, as the χ -N scattering cross sections exhibits strong dependence on the species of nuclei. Table III summarizes the mass fractions of dominant nuclei in supernova ejecta, derived from the ensemble-averaged results of five simulations in Ref. [61]. The dominant nuclei are hydrogen and helium, occupying approximately 90% of the total ejecta.

In this analysis, the supernova ejecta is modeled as a thin spherical shell with time-dependent radius $R_s(t)$ and expansion velocity $V_s(t)$, governed by the dynamical equations Eqs. (3) and (4), respectively. This approximation is supported by both the Sedov-Taylor solution [62], wherein the ejecta mass becomes concentrated near the shock front, and the more recent Chevalier model [63] demonstrating that supernova remnants exhibit sharply defined density gradients at the ejecta-environment

TABLE III. Mass fractions of the most abundant nuclei in supernova ejecta, derived from the averaged results in Ref. [61].

Nucleus	f_i
^1H	0.493
^4He	0.35
^{16}O	0.1
^{28}Si	0.02
^{12}C	0.015
^{56}Fe	0.007
^{20}Ne	0.005
^{24}Mg	0.005
^{32}S	0.005
^{14}N	0.004
^{23}Na	0.0004

interface. Under this thin-shell approximation, the DM particles encounter rate with the ejecta shell is given by

$$4\pi R_s(t)^2 \frac{\rho_\chi}{m_\chi} V_s(t), \quad (6)$$

where $\rho_\chi = 0.3 \text{ GeV/cm}^3$ represents the local DM density near the Monogem Ring. Considering the suppressed χ -N scattering cross section, the probability of multiscattering can be neglected. Under this assumption together with thin-shell approximation, the probability of a DM particle being boosted by a high-velocity nucleus is formally expressed:

$$\sum_i \left(\frac{M_{\text{ej}} f_i}{m_i} + 4\pi \int_0^{R_s(t)} n(r) r^2 dr \delta_{i,1} \right) \frac{1}{4\pi R_s(t)^2} \sigma_{\chi i}. \quad (7)$$

Here, $\frac{M_{\text{ej}} f_i}{m_i}$ represents the number of nuclei of species i , and $n(r)$ denotes the density of the presupernova wind, derived from Eq. (5). The integral quantifies nuclei swept up by the wind, and $\delta_{i,1}$ exclusively considers the hydrogen contribution. $\frac{1}{4\pi R_s(t)^2}$ arises from flux dilution across the expanding shell surface. To derive the velocity-dependent DM velocity, generalize the cross section to its differential form $\frac{d\sigma_{\chi i}}{dv}$, related to energy differentials through

$$\frac{d\sigma_{\chi i}}{dv} = m_\chi v \frac{d\sigma_{\chi i}}{dE}, \quad (8)$$

where $E = \frac{1}{2} m_\chi v^2$. The resultant flux of upscattered DM particles with velocity v at scattering instant t becomes

$$\begin{aligned} \Phi(v, t) = & \int dE \delta\left(E - \frac{1}{2} m_\chi v^2\right) \rho_\chi V_s(t) \\ & \times \sum_i \left(\frac{M_{\text{ej}} f_i}{m_i} + 4\pi \int_0^{R_s(t)} n(r) r^2 dr \delta_{i,1} \right) v \frac{d\sigma_{\chi i}}{dE}, \end{aligned} \quad (9)$$

where $V_s(t)$ represents the velocity of nuclei in the ejecta before the collision, and v denotes the velocity of upscattered DM particles. The parameter m_χ in Eq. (8) is implicitly included in the formula for the differential cross section. For terrestrial detection, the DM velocity v and upscattering time t must satisfy $v = D/(\text{Age} - t)$. Applying temporal delta function constraints to Eq. (9), we obtain Earth-arriving DM particles flux:

$$\Phi_{\text{Earth}}(v) = \frac{1}{4\pi D^2} \int \Phi(v, t) \delta(t - (\text{Age} - D/v)) dt. \quad (10)$$

The differential cross section formalism in the NREFT framework, as established in Ref. [43], enables numerical computation of the boosted DM flux on Earth. To facilitate this analysis, we adapted the Capt'n General [64,65], originally designed to analyze the solar DM capture within the NREFT framework, by refactoring its Fortran core into a Python implementation. Key parameters as well as equations governing the Monogem Ring's shock dynamics were implemented. The Earth-directed DM flux Φ_{Earth} in Eq. (10), can be numerically evaluated through parametric inputs of DM mass m_χ , selected operator $\mathcal{O}_i$ in Table I, and its corresponding coupling constant c_i . Figure 1 illustrates the computed terrestrial DM flux Φ_{Earth} for $(m_\chi, c_{15}^2 m_v^4) = (0.5 \text{ GeV}, 1.6 \times 10^{25})$ as well as $(m_\chi, c_{15}^2 m_v^4) = (1.0 \text{ GeV}, 1.9 \times 10^{23})$, revealing velocity distribution features in 4300–4550 km/s range. The top three contributing nuclides, ^1H , ^{28}Si , and ^{56}Fe are displayed separately. The sharp peak in the low velocity region arises from hydrogen's dominant abundance in the ejecta. Under the assumption of uniform ejecta expansion velocity, each nuclide generates a characteristic highest velocity edge, a consequence of elastic scattering kinematics where heavier nuclei impart greater momentum transfers to DM particles. The substantial contributions from ^{28}Si and ^{56}Fe , despite their modest mass fractions, originate from the nuclide correlation in NREFT cross sections. Furthermore, the observed increase in flux with rising velocity further demonstrates the intrinsic correlation between interaction cross sections and momentum transfer dynamics within the NREFT framework.

IV. DATA ANALYSIS

The recoil spectra for dark matter-nucleus elastic scattering in direct detection experiments are represented as

$$\begin{aligned} \frac{dR}{dE_R} &= \frac{\rho_\chi}{m_\chi m_N} \int_{v_{\min}(E_R)}^{\infty} v f(v) \frac{d\sigma_{\chi N}}{dE_R} d^3v \\ &= \frac{1}{m_N} \int_{v_{\min}(E_R)}^{\infty} \Phi_{\text{Earth}}(v) \frac{d\sigma_{\chi N}}{dE_R} d^3v, \end{aligned} \quad (11)$$

where Φ_{Earth} [Eq. (10)] corresponds to $\frac{\rho_\chi}{m_\chi} v f(v)$ in conventional analysis. In this work, the recoil spectra is computed

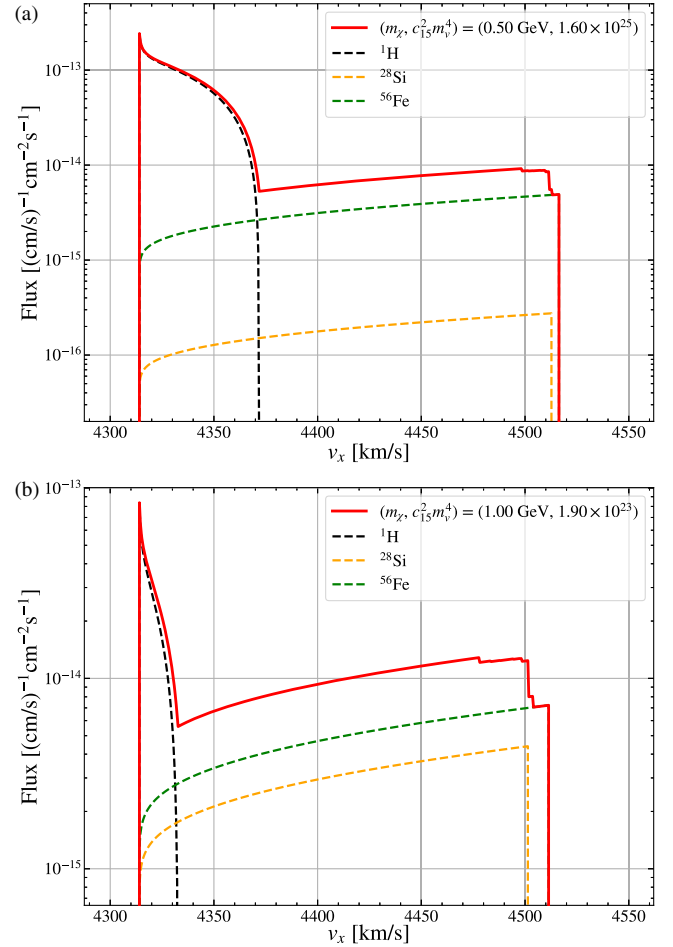


FIG. 1. Flux of boosted DM particles that can be detected on Earth, calculated using operator $\mathcal{O}_{15}$ with $(m_\chi, c_{15}^2 m_v^4) = (0.5 \text{ GeV}, 1.6 \times 10^{25})$ (a) as well as $(m_\chi, c_{15}^2 m_v^4) = (1.0 \text{ GeV}, 1.9 \times 10^{23})$ (b). Here, $m_v = 246 \text{ GeV}$ denotes the weak mass scale.

utilizing the WIMpy_NREFT [66] package, replacing its default Maxwell-Boltzmann velocity distribution $f(v)$ with our numerically derived $\Phi_{\text{Earth}}(v)$ profile from Eq. (10).

In germanium semiconductor detectors, the detected energy, E_{det} , relates to the actual nuclear recoil energy, E_R , owing to the quenching factor Q_{nr} , implying that $E_{\text{det}} = Q_{nr} E_R$ [67–69]. In our analysis, the value of Q_{nr} calculated using the TRIM package [70] with a 10% systematic error is utilized.

This study uses the 205.4 kg · day exposure data obtained from the CDEX-10 experiment [46]. Previous studies have detailed the corresponding data processing procedures, including energy calibration, physics event selection, bulk-surface event discrimination, and a series of efficiency corrections [14–17]. The analysis threshold of CDEX-10 is 160 eVee, with a combined efficiency of 4.5% [16]. Figure 2 illustrates the final spectrum in the energy range of 0.16–12 keVee, along with fits for characteristic K -shell x-ray peaks from internal cosmogenic radionuclides such as

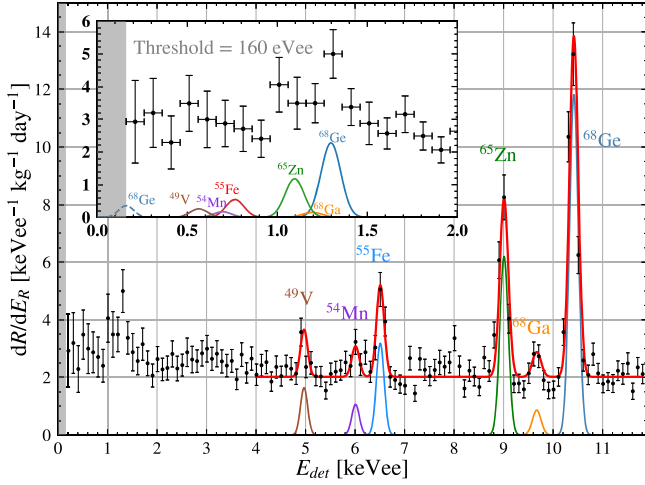


FIG. 2. Measured spectrum with error bars from the 205.4 kg · day exposure data obtained from CDEX-10 in the energy range of 0.16–12 keVee. The red line represents the background model fit via χ^2 minimization in the range of 4–11.8 keVee, including identified K -shell x-rays of cosmogenic radionuclides, displayed separately with other colors. The inset displays the contributions of L - and M -shell x-ray peaks, whose intensities are derived from corresponding K -shell lines.

^{49}V , ^{54}Mn , ^{55}Fe , ^{65}Zn , ^{68}Ga , and ^{68}Ge . The inset displays the L -shell and M -shell x-ray peaks of these radionuclides, with the corresponding intensities derived from the K -shell peaks via fluorescence ratios [71]. The energy resolution of CDEX-10 is described by $\sigma(E_{\text{det}}) = 35.8 + 16.6 \times \sqrt{E_{\text{det}}}$ (eV), where E_{det} is expressed in keV.

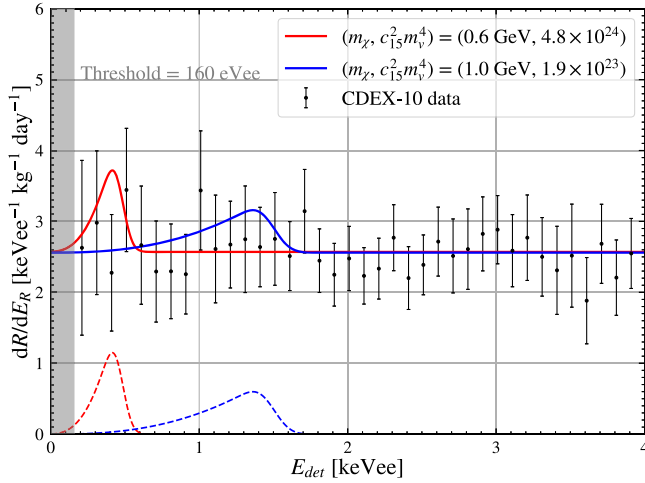


FIG. 3. Residual spectrum of CDEX-10 after subtracting the characteristic x-ray contributions in the energy region 0.16–4.00 keVee. The red and blue lines represent the predicted spectrum of supernova boosted DM for $(m_\chi, c_{15}^2 m_v^4) = (0.6 \text{ GeV}, 4.8 \times 10^{24})$ and $(m_\chi, c_{15}^2 m_v^4) = (1.0 \text{ GeV}, 1.9 \times 10^{23})$, where the coupling constants correspond to the upper limits at 90% C.L. The dashed lines represent the expected signals deposited by boosted DM without background.

After spectrum fitting and subtracting the contributions of characteristic x-rays, we employ the residual spectrum to determine the constraints on coupling constants via χ^2 minimization [12]. The χ^2 function is defined as

$$\chi^2(m_\chi, c_i^2 m_v^4) = \sum_{j=1}^N \frac{[n_j - B_j - S_j(m_\chi, c_i^2 m_v^4)]^2}{\sigma_j^2}, \quad (12)$$

where n_j represents the measured event rate in the j^{th} energy bin, σ_j the total uncertainty incorporates both statistical and systematic uncertainties. The term $S_j(m_\chi, c_i^2 m_v^4)$ represents the predicted event rate for operator $\mathcal{O}_j$. The background component B_j denotes the assumed background originates from the Compton scattering of high-energy γ rays, modeled as a linear continuum $a \cdot E + b$. For each operator $\mathcal{O}_i$ and given m_χ , the optimal $c_i^2 m_v^4$ values are determined via χ^2 minimization in the energy range of 0.16–12.00 keVee. Given that no significant DM signals are observed, the results are presented as upper limits on the coupling constants at the

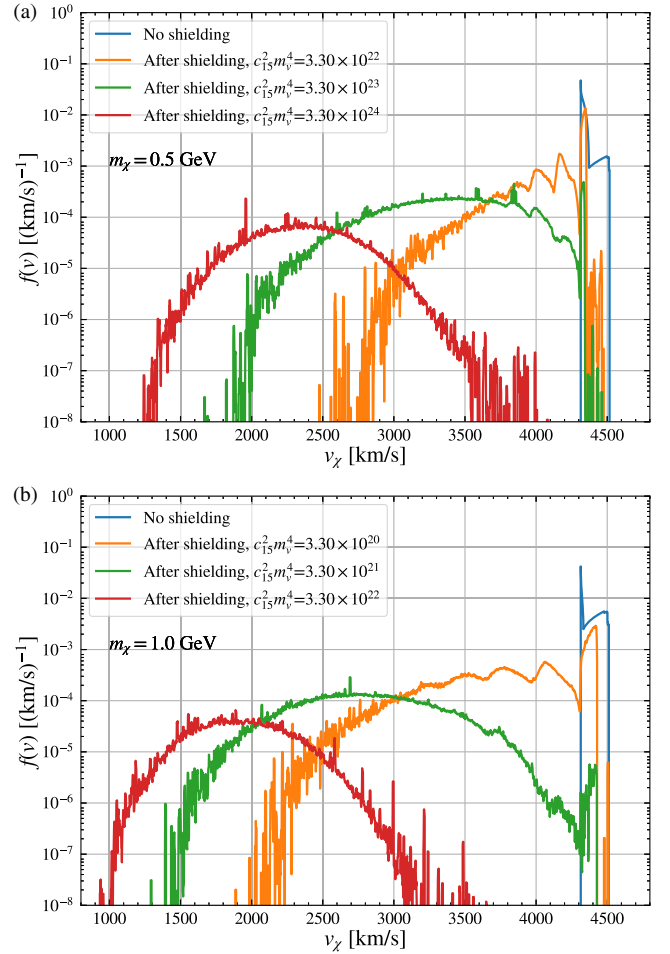


FIG. 4. Velocity distribution of 0.5 (a) and 1.0 GeV (b) DM under $\mathcal{O}_{15}$ interactions. The blue line represents the $f(v)$ of boosted DM reaching the Earth without shielding.

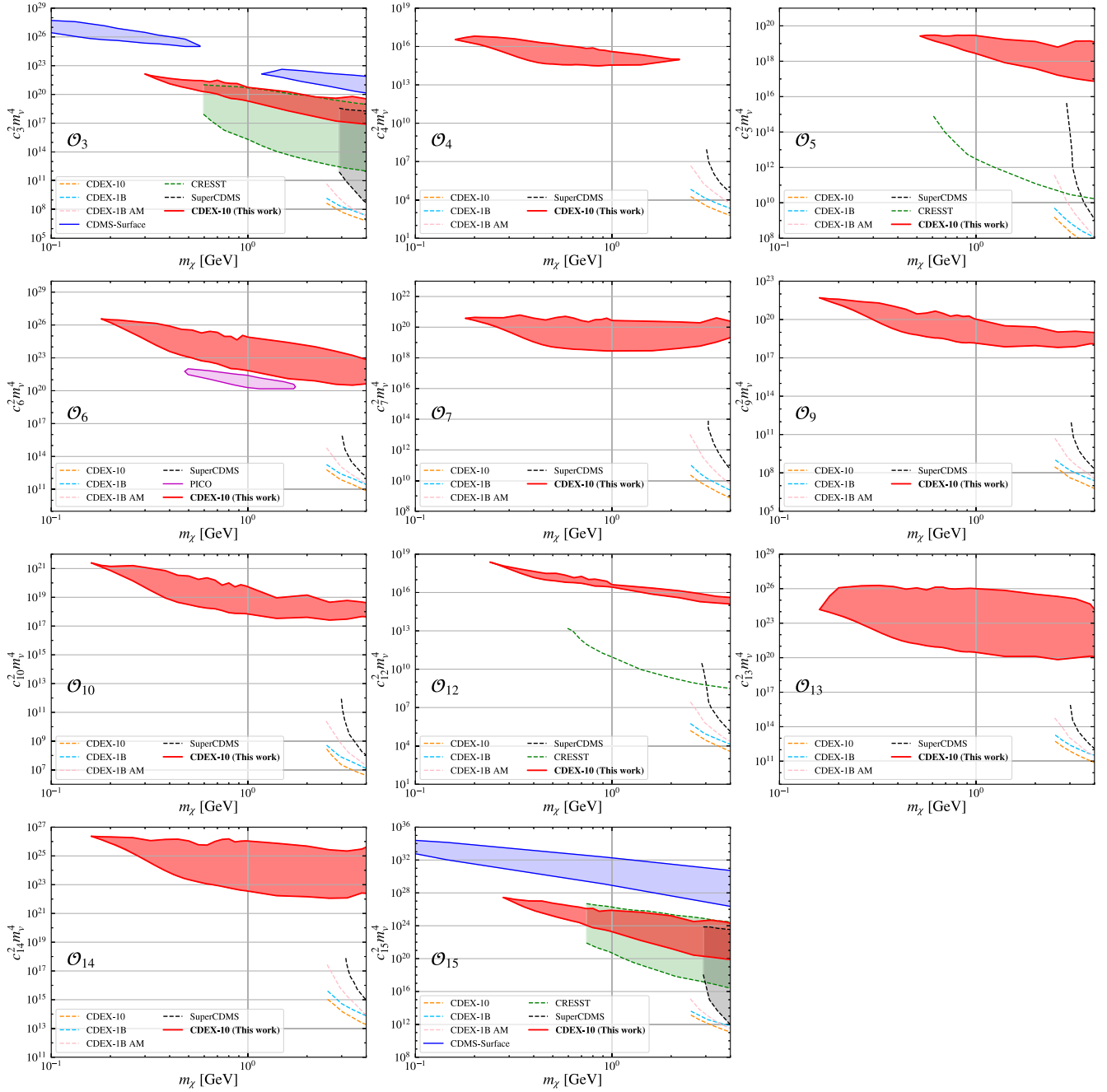


FIG. 5. Exclusion limits on NREFT coupling constants in the mass range of 0.1–4.0 GeV. Dashed lines correspond to constraints derived under the SHM scenario, including results from CRESST [75], SuperCDMS [74], CDEX-10, and CDEX-1B [19], where “CDEX-1B AM” indicates the annual modulation (AM) analysis from the CDEX-1B experiment. Solid lines correspond to exclusion regions obtained from supernova shock boosted DM analyses. The constraints from CDMS-Surface [76] and PICO [77] experiments are detailed in Ref. [42]. The red lines indicate the 90% confidence level exclusion limits for CDEX-10 derived in this work.

90% confidence level (C.L.), derived using the Feldman–Cousins method [72]. Figure 3 illustrates the boosted DM spectrum corresponding to the upper limit at the 90% C.L. for $(m_\chi, c_{15}^2 m_v^4) = (0.6 \text{ GeV}, 4.80 \times 10^{24})$ and $(m_\chi, c_{15}^2 m_v^4) = (1.0 \text{ GeV}, 1.90 \times 10^{23})$.

The 2400-meter rock overburden at CJPL induces significant Earth attenuation of DM fluxes through χ -N scattering, effectively decelerating particles, dispersing fluxes, and finally reducing detectable recoil energies. This is the so-called Earth shielding effect or Earth attenuation [49–53].

To quantify this effect, a Monte Carlo simulation package CJPL_ESS [54] was developed by the CDEX Collaboration, in which a detailed geometric model and the rock compositions of Jinping Mountain are implemented. In this research, the package was upgraded by implanting the cross section formalism in the NREFT framework as well as incorporating the boosted DM source according to Φ_{Earth} as defined in Eq. (10). Furthermore, to enhance simulation credibility, Earth's atmosphere is also incorporated into the CJPL_ESS, whose effect can be significant within the exclusion region. The atmosphere is modeled with a thickness of 80 km, and the density profile across different altitudes complies with the U.S. Standard Atmosphere [73]. Figure 4 displays simulation examples for the cases of $m_\chi = 0.5$ and 1.0 GeV for operator $\mathcal{O}_{15}$. For larger coupling constants, the DM velocity distribution exhibits enhanced retardation after Earth shielding.

The exclusion regions at 90% C.L. for supernova boosted DM are illustrated in Fig. 5 as red lines. Here, the lower boundaries are derived using the minimal- χ^2 method, while the upper boundaries are determined using the modified CJPL_ESS simulations, incorporating Earth attenuations. Operators $\mathcal{O}_1$, $\mathcal{O}_8$, and $\mathcal{O}_{11}$ are excluded due to excessively large coupling constant values at lower boundaries, which preclude detectable energy deposition in CJPL_ESS simulations and consequently prevent meaningful exclusion region determination. The dashed lines in Fig. 5 represent published exclusion limits on NREFT coupling constants under the SHM scenario, as obtained from SuperCDMS [74], CRESST [75], CDEX-1B, and CDEX-10 [19]. Other solid lines correspond to exclusion results for supernova boosted DM scenarios published by Ref. [42], incorporating data from CDMS-Surface [76] and PICO [77] data for operators $\mathcal{O}_3$, $\mathcal{O}_6$, and $\mathcal{O}_{15}$. This investigation establishes the most stringent constraints to date for operators $\mathcal{O}_3$ and $\mathcal{O}_{15}$, in the mass range of 0.2–0.6 GeV. For other operators, the derived exclusion regions extend into previously unexplored sub-GeV parameter space, demonstrating novel coverage beyond existing experimental results.

V. DISCUSSION

High-velocity nuclei in supernova shock fronts constitute a potent acceleration mechanism for DM particles. This investigation focuses on the ejecta of the Monogem Ring supernova remnant, characterized by substantial yet non-relativistic expansion velocities ($v \lesssim 0.1c$), rendering it particularly suitable for NREFT analysis. Since the exclusion results are highly depended on the parameters, we have also performed the analysis on type Ia supernova to examine its robustness. The discrepancy can be controlled under 4%, demonstrating the reliability of this approach.

The sensitivity of NREFT operators to specific detector materials imposes certain limitations on research. For

instance, systems with spin-0 targets exhibit no sensitivity to purely spin-dependent operators such as $\mathcal{O}_6$ [42]. Furthermore, analyses become infeasible when the corresponding nuclear response functions remain unknown (e.g., tungsten [75]). Detectors composed by nature germanium are not subject to these restrictions and maintain responsiveness across all operator scenarios, enabling comprehensive investigation of χ -N scattering interactions and subsequent derivation of exclusion limits. Capitalizing on the pronounced cross-section dependence on momentum transfer inherent to the NREFT frameworks, our analysis achieves sub-GeV mass region with supernova boosted DM source. Operators exhibiting significant velocity scaling such as $\mathcal{O}_3$, $\mathcal{O}_6$, and $\mathcal{O}_{15}$ demonstrate particular sensitivity improvements. At higher mass ranges (>1 GeV), boosted DM exerts reduced efficacy compared to that under SHM in exclusion. This weakness originates from spherical diffusion effects during DM propagation from the supernova core to Earth, resulting in ρ_χ depletion spanning multiple orders of magnitude.

Operators $\mathcal{O}_1$, $\mathcal{O}_8$, and $\mathcal{O}_{11}$ are excluded from effective constraint determination because the Earth shielding retardation is too strong at lower exclusion boundaries to collect detectable energy deposition in CJPL_ESS simulation. This limitation is mainly due to dual mechanisms. Primarily, these operators exhibit limited velocity scaling characteristics (for example, $\mathcal{O}_1 \sim v^0$ while $\mathcal{O}_{15} \sim v^6$), negating the velocity enhancement benefits inherent in the boosted DM system. Concurrently, the nuclear recoil cross sections in the NREFT framework exhibit significant dependence on target nuclide properties. The more enhanced χ -N coupling under these particular operators in comparison with others induces substantial signal attenuation through the Earth shielding effect. For instance, the spin-0 nuclides in the mountain rock have no contribution to spin-dependent operator $\mathcal{O}_4$, yet they all make contributions to spin-independent operator $\mathcal{O}_1$. This dual mechanism, when combined with density depletion from diffusion attenuation of ρ_χ , prevents detectable energy deposition in CJPL_ESS simulations at coupling constants approaching lower exclusion boundaries. Consequently, no statistically significant exclusion boundaries could be established for these operators.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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- [1] R. L. Workman *et al.* (Particle Data Group), *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
 - [2] A. Cho, *Science* **339**, 1513 (2013).
 - [3] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **131**, 041003 (2023).
 - [4] J. Aalbers *et al.* (LUX-ZEPLIN Collaboration), *Phys. Rev. Lett.* **131**, 041002 (2023).
 - [5] S. Li *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **130**, 261001 (2023).
 - [6] P. Agnes *et al.* (DarkSide Collaboration), *Phys. Rev. Lett.* **121**, 081307 (2018).
 - [7] A. H. Abdelhameed *et al.* (CRESST Collaboration), *Phys. Rev. D* **100**, 102002 (2019).
 - [8] R. Agnese *et al.* (SuperCDMS Collaboration), *Phys. Rev. D* **97**, 022002 (2018).
 - [9] C. E. Aalseth *et al.* (CoGeNT Collaboration), *Phys. Rev. D* **88**, 012002 (2013).
 - [10] S. K. Liu *et al.* (CDEX Collaboration), *Phys. Rev. D* **90**, 032003 (2014).
 - [11] W. Zhao *et al.* (CDEX Collaboration), *Phys. Rev. D* **88**, 052004 (2013).
 - [12] Q. Yue *et al.* (CDEX Collaboration), *Phys. Rev. D* **90**, 091701 (2014).
 - [13] W. Zhao *et al.* (CDEX Collaboration), *Phys. Rev. D* **93**, 092003 (2016).
 - [14] L. T. Yang *et al.* (CDEX Collaboration), *Chin. Phys. C* **42**, 023002 (2018).
 - [15] H. Jiang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **120**, 241301 (2018).
 - [16] H. Jiang *et al.* (CDEX Collaboration), *Sci. China Phys. Mech. Astron.* **62**, 31012 (2019).
 - [17] L. T. Yang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **123**, 221301 (2019).
 - [18] Z. Z. Liu *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **123**, 161301 (2019).
 - [19] Y. Wang *et al.* (CDEX Collaboration), *Sci. China Phys. Mech. Astron.* **64**, 281011 (2021).
 - [20] R. Xu *et al.* (CDEX Collaboration), *Phys. Rev. D* **106**, 052008 (2022).
 - [21] D. Baxter *et al.*, *Eur. Phys. J. C* **81**, 907 (2021).
 - [22] M. J. Dolan, F. Kahlhoefer, and C. McCabe, *Phys. Rev. Lett.* **121**, 101801 (2018).
 - [23] T. Bringmann and M. Pospelov, *Phys. Rev. Lett.* **122**, 171801 (2019).
 - [24] J. B. Dent, B. Dutta, J. L. Newstead, and I. M. Shoemaker, *Phys. Rev. D* **101**, 116007 (2020).
 - [25] C. V. Cappiello and J. F. Beacom, *Phys. Rev. D* **100**, 103011 (2019).
 - [26] K. Bondarenko, A. Boyarsky, T. Bringmann *et al.*, *J. High Energy Phys.* **03** (2020) 118.
 - [27] G. Guo, Y. L. S. Tsai, M. R. Wu, and Q. Yuan, *Phys. Rev. D* **102**, 103004 (2020).
 - [28] G. Elor, R. McGehee, and A. Pierce, *Phys. Rev. Lett.* **130**, 031803 (2023).
 - [29] J. W. Wang, A. Granelli, and P. Ullio, *Phys. Rev. Lett.* **128**, 221104 (2022).
 - [30] A. Granelli, P. Ullio, and J. W. Wang, *J. Cosmol. Astropart. Phys.* **07** (2022) 013.
 - [31] Y. Jho, J. C. Park, S. C. Park, and P. Y. Tseng, *arXiv:2101.11262*.
 - [32] A. Das and M. Sen, *Phys. Rev. D* **104**, 075029 (2021).
 - [33] Y. Zhang, *Prog. Theor. Exp. Phys.* **2022**, 013B05 (2021).
 - [34] W. Chao, T. Li, and J. J. Liao, *arXiv:2108.05608*.
 - [35] H. An, M. Pospelov, J. Pradler, and A. Ritz, *Phys. Rev. Lett.* **120**, 141801 (2018).
 - [36] T. Emken, C. Kouvaris, and N. G. Nielsen, *Phys. Rev. D* **97**, 063007 (2018).
 - [37] H. An, H. Nie, M. Pospelov, J. Pradler, and A. Ritz, *Phys. Rev. D* **104**, 103026 (2021).
 - [38] T. Emken, *Phys. Rev. D* **105**, 063020 (2022).
 - [39] Z. Y. Zhang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **132**, 171001 (2024).
 - [40] R. Calabrese, M. Chianese, D. F. G. Fiorillo, and N. Saviano, *Phys. Rev. D* **105**, 103024 (2022).
 - [41] Z. H. Zhang *et al.* (CDEX Collaboration), *Phys. Rev. D* **108**, 052006 (2023).
 - [42] C. V. Cappiello, N. P. A. Kozar, and A. C. Vincent, *Phys. Rev. D* **107**, 035003 (2023).
 - [43] A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu, *J. Cosmol. Astropart. Phys.* **02** (2013) 004.
 - [44] N. Anand, A. L. Fitzpatrick, and W. C. Haxton, *Phys. Rev. C* **89**, 065501 (2014).
 - [45] J. R. Knies, M. Sasaki, and P. P. Plucinsky, *Mon. Not. R. Astron. Soc.* **477**, 4414 (2018).
 - [46] Z. She *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **124**, 111301 (2020).
 - [47] K. J. Kang *et al.*, *Front. Phys.* **8**, 412 (2013).
 - [48] J. P. Cheng *et al.*, *Annu. Rev. Nucl. Part. Sci.* **67**, 231 (2017).
 - [49] T. Emken and C. Kouvaris, *J. Cosmol. Astropart. Phys.* **10** (2017) 031.
 - [50] D. Hooper and S. D. McDermott, *Phys. Rev. D* **97**, 115006 (2018).

- [51] T. Emken and C. Kouvaris, *Phys. Rev. D* **97**, 115047 (2018).
- [52] B. J. Kavanagh, *Phys. Rev. D* **97**, 123013 (2018).
- [53] T. Emken, R. Essig, C. Kouvaris, and M. Sholapurkar, *J. Cosmol. Astropart. Phys.* **09** (2019) 070.
- [54] Z. Z. Liu *et al.* (CDEX Collaboration), *Phys. Rev. D* **105**, 052005 (2022).
- [55] A. Bamba and B. J. Williams, Supernova remnants: Types and evolution, in *Handbook of X-ray and Gamma-ray Astrophysics* (Springer Nature, Singapore, 2022), p. 77.
- [56] M. Cardillo, E. Amato, and P. Blasi, *Astropart. Phys.* **69**, 1 (2015).
- [57] P. Cristofari, P. Blasi, and D. Caprioli, *Astron. Astrophys.* **650**, 11 (2021).
- [58] P. P. Plucinsky, S. L. Snowden, B. Aschenbach, R. Egger, R. J. Edgar, and D. McCammon, *Astrophys. J.* **463**, 224 (1996).
- [59] S. E. Thorsett, R. A. Benjamin, W. F. Briskin, A. Golden, and W. M. Goss, *Astrophys. J.* **592**, L71 (2003).
- [60] B. Müller, A. Heger, D. Liptai, and J. B. Cameron, *Mon. Not. R. Astron. Soc.* **460**, 742 (2016).
- [61] T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, *Astrophys. J.* **576**, 323 (2002).
- [62] L. I. Sedov, *Similarity and Dimensional Methods in Mechanics* (Academic Press, New York, 1959).
- [63] R. A. Chevalier, *Astrophys. J.* **258**, 790 (1982).
- [64] P. Athron *et al.*, *Eur. Phys. J. C* **81**, 992 (2021).
- [65] N. A. Kozar *et al.*, [arXiv:2105.06810](https://arxiv.org/abs/2105.06810).
- [66] B. J. Kavanagh and T. Edwards, [10.5281/zenodo.1230502](https://zenodo.org/record/1230502).
- [67] A. K. Soma *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **836**, 67 (2016).
- [68] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, *Nucl. Instrum. Methods Phys. Res., Sect. B* **268**, 1818 (2010).
- [69] B. J. Scholz, A. E. Chavarria, J. I. Collar, P. Privitera, and A. E. Robinson, *Phys. Rev. D* **94**, 122003 (2016).
- [70] J. F. Ziegler, Transport of ions in matter, <http://www.srim.org/>.
- [71] J. N. Bahcall, *Phys. Rev.* **132**, 362 (1963).
- [72] G. J. Feldman and R. D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).
- [73] U. S. Government Printing Office, U.S. Standard Atmosphere, Reports No. NOAA-S/T-76-1562; No. NASA-TM-X-74335, 1976, <https://ntrs.nasa.gov/citations/19770009539>.
- [74] K. Schneck *et al.* (SuperCDMS Collaboration), *Phys. Rev. D* **91**, 092004 (2015).
- [75] G. Angloher *et al.* (CRESST Collaboration), *Eur. Phys. J. C* **79**, 43 (2019).
- [76] I. Alkhatib *et al.* (SuperCDMS Collaboration), *Phys. Rev. Lett.* **127**, 061801 (2021).
- [77] C. Amole *et al.* (PICO Collaboration), *Phys. Rev. D* **100**, 022001 (2019).