

Probing light particles with optically trapped sensors through nucleon scattering

Bhaskar Dutta^{1,*}, Dilip Kumar Ghosh^{2,†} and Sk Jeesun^{2,‡}

¹*Texas A&M University, College Station, Texas 77843, USA*

²*School of Physical Sciences, Indian Association for the Cultivation of Science, 2A & 2B Raja S.C. Mullick Road, Kolkata 700032, India*



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Optically levitated nanospheres are highly sensitive to the motion of their center of mass even under small momentum transfer. We propose detecting exotic particles via nucleon scattering in such spheres in the context of an ongoing experiment. We suggest that the 200 nm-diameter spheres, featuring a 4×4 array configuration and its upgrade, can achieve sensitivity to nuclear couplings of solar axionlike particles (ALPs), exclusively targeting previously unconstrained regions of parameter space. This setup can offer the first probe of a 14.4 keV solar ALP, which is difficult to find in axion experiments and conventional direct searches. Additionally, we also demonstrate the reach of the same experiment for other light beyond the standard model (BSM) scenarios. The same setup will be sensitive to pseudoscalar dark matter in the ~ 10 keV mass range. In contrast, a smaller sphere with a diameter of 15 nm benefits from overall coherence enhancement, enabling the detection of pseudoscalar and vector dark matter down to $\mathcal{O}(100)$ eV even with a single sphere. This smaller setup also offers the potential for the direct detection of Earth-bound dark matter strongly coupled with visible matter, even with its minimal velocity and tiny fractional abundance.

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I. INTRODUCTION

Many puzzles in the Standard Model (SM) of particle physics have yet to be solved. The first among these puzzles is its inability to explain the observed phenomena of the presence of dark matter in our Universe [1–4]. Despite extensive experimental and theoretical efforts to resolve these issues through exploration of various scenarios beyond the SM, our understanding remains elusive. The elucidation of dark matter (DM) evidence constitutes a significant theoretical and experimental challenge within the field of high-energy physics [5]. The null results for larger than GeV scale weakly interacting dark matter (DM) from direct search experiments have also motivated us to look for it in sub-GeV mass range [6–9]. For such low mass particles ($M \lesssim \mathcal{O}(1)$ GeV), the resulting nuclear recoil energy may fall significantly below the experimental threshold energy ($\mathcal{O}(\text{keV})$), thus eluding detection in

ongoing experiments, presenting an experimental challenge in identifying the distinctive signature of these light exotic particles.

Apart from DM, there also exist several other well-motivated beyond the Standard Model (BSM) scenarios which include *Axion* and *axionlike particles* (ALP). *Axion* is the pseudo-Nambu Goldstone boson (pNGB) associated with the spontaneously broken global symmetry $U(1)_{PQ}$ (also known as the *Peccei-Quinn* symmetry) and was proposed to solve the strong CP problem of QCD [10–12]. However, pNGBs may also appear in several BSM paradigms unrelated to the strong CP problem, which are generally known as ALP (e.g., [13]). The detection of such ALPs in direct detection (DD) experiments has been extensively studied [14–18].

Theories also predict strongly interacting DM particles that might evade detection in underground DD experiments [19–22]. These particles lose energy rapidly through multiple scatterings in the Earth's atmosphere and crust, preventing them from reaching detectors. Over time, such interactions can lead to a significant accumulation of DM density near Earth's surface [19–22]. Despite their large mass ($\sim \text{GeV}$), very low velocity ($v_{\text{DM}} \sim 10^{-5}c$) fails to produce sufficient recoil in DD experiments [19]. Attempts have been made to investigate this scenario through liquid heating [20], annihilation to a neutrino [22], or by accelerating such DM with reactors [23] or nuclear deexcitations

* Contact author: dutta@tamu.edu

† Contact author: tpdkg@iacs.res.in

‡ Contact author: skjeesun48@gmail.com

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[24]. However, a direct and robust probe of such a scenario is still absent due to the aforementioned threshold problem. This phenomenon, known as “Earth-bound DM,” presents unique challenges for conventional detection methods.

Recently, significant efforts have been directed toward developing new experimental facilities with a lower threshold energy to detect light exotic particles by looking at electron ionization [25] or excitation [26], placing new limits on interactions with photons and electrons, e.g., DAMIC [27], SENSEI [28], QROCODILE [29], EDELWEISS [30], using Graphene [31,32], superconductors [33–35], semiconductor devices [36,37], using molecular cloud ionization [38], dirac materials [26] etc. See Refs. [39–42] for recent progress in low threshold DD experiments.

However, nucleon couplings of these light particles, discussed so far, remain difficult to investigate [7,43–45] and several small scale experiments are currently being designed or proposed to constrain such couplings [46–50]. Optical monitoring of the recoil of levitated nanospheres in new tabletop experiments is increasingly being used to detect light BSM particles via nucleon couplings [51–55]. As proposed in [55], the ongoing experiment uses a single nanosphere with a diameter of (100–200) nm. However, current advances have already achieved a 3×3 array of such nanospheres [56] and its enhancement to a $\mathcal{O}(10) \times \mathcal{O}(10)$ array size for microspheres [57]. These optically trapped sensors are highly sensitive to the center-of-mass motion of the nanospheres, even at noise levels that approach the standard quantum limit (SQL) [58]. It has been proposed in Ref. [55] that with SiO_2 material, the setup with a single nanosphere is most sensitive to (three) momentum recoil of $q \sim \mathcal{O}(10)$ keV–few 100 keV for a sphere of 200 nm diameter (femtogram) and $q \sim 85$ eV – $\mathcal{O}(100)$ eV for a sphere of 15 nm diameter (attogram). The lower sensitivity limit is determined by the threshold, specifically the SQL, while the Form factors of the nanospheres control the upper limit, as discussed in the following. In comparison, the existing DD experiments are sensitive to momentum transfer $q \sim \sqrt{2m_N E_R} \gtrsim \text{few MeV}$ for nuclear recoil [59]. Recent experimental advances in other systems have demonstrated the ability to surpass SQL [60–63] and similar techniques have been proposed for levitated nanosphere setups [64,65]. These innovations could improve sensitivity, enabling the detection of even smaller recoil signals [55,66]. Making large arrays ($\sim 1000 \times 1000$ 2D arrays) in the future of such optically trapped sensors may enable further improvements in the search for light DM as well as other BSM particles [55], and some of the larger arrays have already been achieved [53,67,68] (e.g., arrays with 6100 neutral atoms [69]).

In this *paper*, we propose using the levitated nanosphere setup to detect nuclear interactions of light neutral BSM particles. We aim to probe the nuclear coupling of ALPs utilizing the 14.4 keV line flux of solar ALPs from ^{57}Fe

deexcitation [70]. We will demonstrate that the levitated nanosphere setup offers a powerful tool to explore a substantial portion of previously inaccessible parameter space. In particular, the realistic 4×4 array of large nanospheres has already achieved the ability to investigate unrevealed regions of the parameter space for ALP. The nuclear coupling of ALP at $\mathcal{O}(10)$ keV energy is also inaccessible by dedicated axion experiments. Additionally, we present a few examples of detecting pseudoscalar and vector DM through absorption processes using the dark matter flux from the galactic halo. Furthermore, we investigate the detection prospects for GeV-scale Earth-bound DM with extremely low kinetic energy (~ 0.03 eV) [22] which may offer a direct and robust detection complementary to alternative probes of this kind of DM.

The paper is organized as follows. In Sec. II, we discuss the scattering rate in the nanosphere setup. In Sec. III, we discuss relevant physics scenarios that can be detected utilizing large nanospheres with recoil momentum $\gtrsim \mathcal{O}(10)$ keV. In Sec. IV, we discuss the small nanosphere physics scenarios corresponding to the recoil momentum $\lesssim \mathcal{O}(10)$ keV. In Sec. V, we discuss the possible background and conclude in Sec. VI.

II. SCATTERING RATE

The differential recoil rate of a particle ϕ in the aforementioned single-nanosphere setup is given by

$$\frac{dR}{dq} = \int dE_\phi \frac{d\Phi_\phi}{dE_\phi} \frac{d\sigma}{dq} S(q), \quad (1)$$

where R , E_ϕ , and Φ_ϕ are the rate of recoil, energy, and incoming flux of ϕ , respectively. The lower limit of the integration would be the minimum E_ϕ required to generate a recoil of momentum q and will depend on the specific physics case considered. $S(q)$ is the structure factor that contains the details of the target material and is given as [55], $S(q) = [\sum_i N_i Z_i^2 F_H^2(qr_{A_i}) + N_p^2 F_c^2(q)]$. N_i denotes the number of different nuclei in the target, and the number of protons and neutrons (depending on the coupling of ϕ) in each nucleus is denoted by Z_i . $r_{A_i} = 1.22 \times A_i^{1/3}$ fm is the nuclear radius with mass number A . F_H is the Helm form factor [71]. The first term in $S(q)$ dominates in larger q (~ 10 – 100 keV), contributing to coherent scattering from the nuclei in larger spheres (e.g., 200-nm diameter). In contrast, the second term becomes significant at lower q ($\ll 2\pi/r_{sp} \lesssim 0.1$ keV), where coherent scattering involves the entire sphere. This behavior is a characteristic of smaller spheres (e.g., 15 nm diameter) and is governed by the form factor $F_c(q) = 3j_1(r_{sp}q)/(qr_{sp})$. Here, r_{sp} and N_p signify the radius of the sphere and the total number of protons and neutrons (depending on the coupling of ϕ) in the sphere, respectively.

TABLE I. Properties and experimental details of different types of SiO₂ nanosphere sensors [55].

Sensor type	r_{sp}	Mass of sphere (gm)	No. of nucleons	ω (kHz)	σ_{SQL}	Optimum range
<i>Large</i>	100 nm	7.6×10^{-15}	4.48×10^9	$2\pi \times 20$	1.87×10^4 eV	$\mathcal{O}(1) \lesssim q \lesssim \mathcal{O}(100)$ keV
<i>Small</i>	7.5 nm	3.2×10^{-18}	1.9×10^6	$2\pi \times 1$	85.7 eV	$85.7 \lesssim q \lesssim \mathcal{O}(100)$ eV

The smaller nanospheres can be sensitive to momentum up to $q \sim$ a few keV. However, for $0.1 \text{ keV} \lesssim q \lesssim 100 \text{ keV}$, coherence is lost, and the sensitivity scales with the number of nuclei $\sim \sum_i N_i Z_i^2$. Once the threshold, a few keV, is surpassed, larger nanospheres (e.g., 200 nm diameter) are more advantageous because of their $\sim 10^3$ -fold greater number of target nuclei compared to smaller ones (e.g., 15 nm diameter). The details of the nanosphere setup are shown in Table I.

In the following, we organize the discussion of light particle detections based on the recoil momentum of nanospheres and emphasize the parameter spaces relevant to various physics scenarios that benefit from sensitivity to different recoil momentum ranges.

III. LARGE NANOSPHERE ($q \sim \mathcal{O}(10)$ keV)

By the *large* sphere, we refer to optically trapped spheres of diameter 200 nm ($r_{sp} = 100$ nm). From the discussion in the introduction, it is clear that if the incoming particle has roughly $q \sim \mathcal{O}(10)$ keV momentum and satisfies $> 2\pi/r_{sp}$, it can scatter with individual nucleons in the sphere. Thus, for such particles, we need a large number of nucleons with momentum sensitivity as low as $\sim$ few tens of keV, and hence we use the *large* sphere for such particles. We consider a SiO₂ nanosphere with 200 nm diameter optically trapped in a harmonic potential with frequency $\omega = 2\pi \times 20$ KHz [55]. Si (O) has a mass number 28 (16) and the density of SiO₂ is 1.8 g/cm³. The SQL for momentum impulses for this sphere is $\sigma_{SQL} = \sqrt{m_{sp}\omega} = 1.8 \times 10^4$ eV. We now explore different scenarios in the following subsections.

A. Solar ALP (non-DM)

Axions and ALP are being investigated in numerous experiments with the assumption of some effective coupling of ALP with electron (g_{ae}), photon ($g_{a\gamma}$), or nucleon (g_{aN}) [72]. Among these couplings, the constraint on g_{aN} is obtained primarily in combination with g_{ae} and $g_{a\gamma}$ [73–76] since it is difficult to produce and detect ALP via a coupling g_{aN} . The Sun can emit ALPs with energy around both the $\sim$ keV and the MeV scale through nuclear deexcitations [70,77], Compton [78–81] or Primakoff processes [78,82–84]. DM detection experiments act as very sensitive probes of g_{ae} or $g_{a\gamma}$ as the electronic excitation is sensitive to $\sim$ keV recoil energy [16,85,86]. However, for the ALP-nucleon interaction, current DD experiments face the challenge of detecting very low-energy nuclear recoils [85,86]. The

coupling $g_{aN} \gtrsim 4 \times 10^{-5}$ has instead been constrained using a limited solar ALP flux with energy ~ 5.5 MeV, as observed in the Sudbury Neutrino Observatory (SNO) experiment [77]. Future experiments like JUNO and Hyper-Kamiokande will also be able to probe the 5.5 MeV flux [87].

Complementary to the experimental searches, there also exist stringent constraints on ALP couplings from astrophysical observations such as supernova cooling. Due to the high density of matter in supernovae, ALPs with nucleon or electron coupling can be produced through bremsstrahlung or Compton-like processes [88–95]. With the cooling argument, ALP with mass $\lesssim \mathcal{O}(100)$ MeV and nucleon coupling $\lesssim 10^{-6}$ is constrained [96]. ALP produced copiously in supernova explosions may also lead to a detectable signal in neutrino experiments like Super-Kamiokande [97], a null observation of which places the SN1987A “counts” constraint on ALP couplings [96].

In this work, our objective is to independently investigate nuclear coupling, relying solely on the 14.4 keV line. To probe the nucleon coupling of the ALP, we consider the following Lagrangian, $\mathcal{L}_{aN} \supset -ig_{ap}a\bar{N}\gamma^5 N$, where g_{ap} and N are the proton coupling and proton, respectively. The Sun can emit ALP with energy 14.4 KeV from deexcitation of the ⁵⁷Fe nucleus and flux $d\Phi_a/dE_a$ is discussed in detail in [70,98]. Upon reaching Earth, these ALPs scatter with the protons in the optically trapped nanospheres. One such process that causes nuclear recoil is $a(k_1) + N(k_2) \rightarrow \gamma(k_3) + N(k_4)$, and the amplitude will be similar to that of pion photoproduction [99]. Since we are dealing with solar ALPs with $\sim$ keV energy [so ($q \lesssim$ MeV)], the differential cross section $\frac{d\sigma}{dq}$ becomes identical to the one for $a + e \rightarrow e + \gamma$ with obvious replacements ($g_{ae} \rightarrow g_{ap}$, $m_e \rightarrow m_p$) [100,101] (see Appendix A). The differential event rate per trapped sphere is given by

$$\frac{dR}{dq} = \frac{d\Phi_a}{dE_a} \bigg|_{E_a=E_0} \frac{d\sigma}{dq} \bigg|_{E_a=E_0} \Theta(E_0 - E_a^{\min}) S(q) \quad (2)$$

where $E_a^{\min}$ is the minimum incoming kinetic energy required to generate a recoil momentum q and is given by

$$E_a^{\min} + \sqrt{(E_a^{\min})^2 - m_a^2} \approx q \quad (3)$$

in the limit $q^2 \ll 2m_p$. $E_0 = 14.4$ keV is the incoming ALP energy.

Nuclear coherence scattering occurs here, because the solar ALP has energy $E_a \sim 14.4$ keV. Since the flux energy

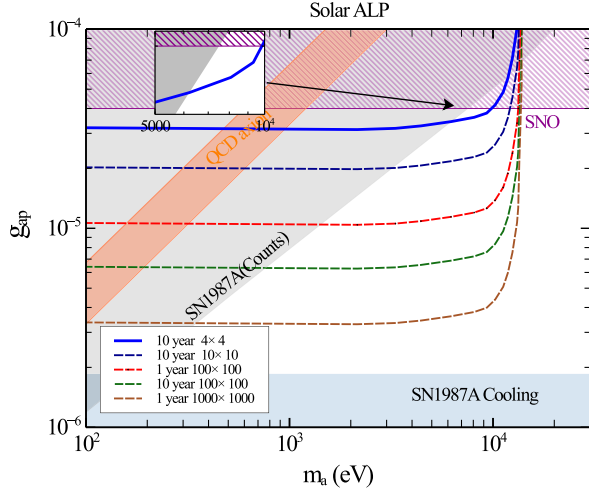


FIG. 1. Projected sensitivity at 90% CL on the $m_a - g_{ap}$ plane for solar ALP using different combination of levitated SiO_2 nanosphere array with 200 nm diameter and momentum threshold $0.75\sigma_{\text{SQL}}$. The different colored lines are projections for 4×4 array with 10-year integration time (blue solid), 10×10 array with 10-year integration time (dark blue dashed), and 100×100 array with 1-year integration time (red dashed), and 10-year integration time (green dashed); and finally 1000×1000 array with 1-year integration time (brown). Other existing constraints like SNO [77], SN1987A counts [96], SN1987A cooling [88] are also displayed.

is slightly less than $\sigma_{\text{SQL}} (\sim 18 \text{ keV})$, with a threshold momentum $> 1\sigma_{\text{SQL}}$, this set-up will not be able to record any event corresponding to this solar ALP line flux and will fail to place any constraint on g_{ap} . Hence, we use the optimistic $0.75\sigma_{\text{SQL}}$ as the threshold [55]. We assume a negligible background ($\ll 1$) for the chosen threshold [55] to obtain future projections.

Thus, for $m_a \leq 10 \text{ keV}$, using a 200 nm diameter sphere with total number of protons $N_T \sim 2.2 \times 10^9$, $\Phi_a \sim 4 \times 10^{23} (g_{ap})^2 \text{ cm}^{-2} \text{ s}^{-1}$ [70,98] and cross section $\sigma_{aN} \sim g_{ap}^2/m_N^2$ [96] the expected rate per sphere will be

$$R \approx N_T \Phi_a(E_a) \sigma_{ap}(E_a) \sim g_{ap}^4 10^{13} \text{ yr}^{-1}, \quad (4)$$

at $E_a \sim \text{keV}$. The future sensitivity at 90% CL obtained for the detection threshold $q_{th} = 0.75\sigma_{\text{SQL}}$ in the $m_a - g_{ap}$ plane is shown in Fig. 1. We use different colored lines to indicate the potential sensitivities obtained for varied configurations of array size and integration time (10 years 4×4 (solid blue), 10 years 10×10 (blue dashed), 1 year 100×100 (red dashed), 10 years 100×100 (green dotted), 1 year 1000×1000 (brown dashed dot).

We find that even the 4×4 array setup of the levitated sphere can be sensitive to $g_{ap} \sim 3 \times 10^{-5}$ while the 100×100 array for 1 year (10 year) experiments can be sensitive to $g_{ap} \sim 10^{-5} (7 \times 10^{-6})$ for $m_a \lesssim 10 \text{ keV}$. With the 1000×1000 array, it can be sensitive even up to $g_{ap} \sim 3 \times 10^{-5}$.

Constraints such as solar ALP flux at SNO [77], SN1987A counts [96] and SN1987A cooling [88] are also relevant in the parameter space shown by the pink, gray, and light blue shaded regions, respectively. The potential sensitivity obtained using nanospheres is complementary to the bound from the SN1987A counts [96] and thus would shed light on these previously unexplored regions. In the very low-mass region ($m_a < \mathcal{O}(10^3) \text{ eV}$), our projected sensitivities become independent of m_a and some of them can surpass those from other searches for ALP-nucleon couplings, including DM ALP experiments such as CASPER [102] and the SERF comagnetometer [103], e.g., as shown in Fig. 7 in Appendix A. Our projections in Fig. 1 constraining individual nucleon coupling of solar ALP are more robust than the constraints on the product of $g_{ae} \times g_{aN}$ [74,76,104] or $g_{a\gamma} \times g_{aN}$ [74,76,98,105]. These projections also go through the parameter space of the QCD axion shown by the orange band in Fig. 1 taken from [72,96]. As noted previously, solar ALPs can also be probed using a 15 nm diameter sphere. However, the $\sim 10^3$ -fold reduction in the number of target protons compared to larger spheres weakens potential sensitivities by approximately a factor of ~ 6 .

B. Sub-GeV pseudoscalar DM

Sub-GeV scale particles such as scalar, pseudoscalar, or vector are well-motivated DM candidates and are widely being studied [59,106]. Here we discuss the detection prospects of sub-GeV pseudoscalar galactic DM (χ_s) in large nanospheres. χ_s can be produced through different mechanisms and can saturate the observed density of DM [107,108]. Since cold DM at present is nonrelativistic ($v \sim 10^{-3}c$), it can be absorbed into target materials through the axioelectric effect ($\chi_s + e \rightarrow e + \gamma$) with a mono-energetic signal at $q \sim m_{\chi_s}$. This process allows constraints to be placed on the electron-DM coupling $g_{e\chi_s}$ from Xenon nT [17], PandaX [85], LZ [16], SuperCDMS [14], EDELWEISS [15], semiconductor devices [36]. However, as mentioned earlier, current direct detection experiments lose sensitivity to low-mass ($\lesssim \text{GeV}$) dark matter, since their relatively high detection thresholds weaken the constraint on the proton-DM coupling $g_{p\chi_s}$. Readers are referred to Refs. [46,48–50,109–112] for the recent efforts to probe sub-GeV DM-nucleon interactions. The levitated sphere can also probe $g_{p\chi_s}$ through the nuclear scattering process: $p + \chi_s \rightarrow p + \gamma$ calculated using the following effective Lagrangian: $\mathcal{L}_{\chi_s p} \supset -ig_{p\chi_s} \bar{p} \gamma^5 p \chi_s$. This analysis assumes stable dark matter without specifying its production mechanism. The recoil rate for the absorption of pseudoscalar DM with mass m_{χ_s} will be [113,114],

$$R = \frac{\rho_{\text{DM}}}{m_{\chi_s}} \sigma_{\chi_s p} S(q = m_{\chi_s}) \Theta(m_{\chi_s} - q_{th}) \quad (5)$$

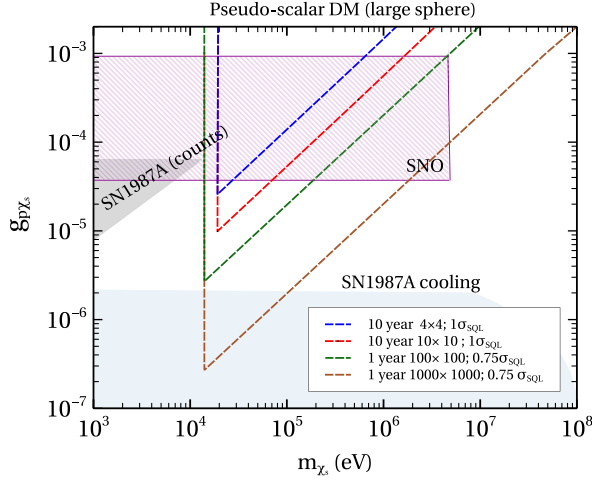


FIG. 2. Projected sensitivity at 90% C.L. on the $m_{\chi_s} - g_{p\chi_s}$ plane using different combinations of large (diameter 200 nm) nanosphere array. The different dashed colored lines are projections for 4×4 array (blue) and 10×10 array (red) with a 10-year integration time and a momentum threshold $1\sigma_{\text{SQL}}$. Projection with momentum threshold of $0.75\sigma_{\text{SQL}}$ for 100×100 array (green) and 1000×1000 array (brown) with 1 year integration time are also shown. Other existing constraints like SNO [77], SN1987A counts [96], SN1987A cooling [88] are also displayed.

with $\sigma_{\chi_s p}$ being the absorption cross section per proton [114] which is obtained from the amplitude quoted in Appendix A with $q \equiv m_{\chi_s}$ and $S(q)$ being the structure factor mentioned above. We consider the halo density of DM $\rho_{\text{DM}} = 0.3 \text{ GeV}/\text{cm}^3$.

We present the sensitivity at 90% CL for the 200-nm diameter levitated sphere setup in Fig. 2. The expected sensitivities with a 4×4 array and a 10×10 array with an integration time of 10 years and a detection threshold $q_{th} = 1\sigma_{\text{SQL}}$ are shown by blue and red dashed lines, respectively. The future sensitivities with the 100×100 and 1000×1000 arrays with the detection threshold $q_{th} = 0.75\sigma_{\text{SQL}}$ are shown by green dotted lines and brown dotted lines, respectively. For these two projected sensitivities, we consider a year-long integration time. Since the framework is analogous to the ALP-nucleon interaction, the constraints applicable to ALPs (on g_{ap}) are also relevant here. The other relevant constraints, such as SNO [77], SN1987A counts [96] and SN1987A cooling [88], are also displayed for comparison. The 4×4 array with an integration time of 10 years and detection threshold $q_{th} = 1\sigma_{\text{SQL}}$ can be sensitive to $g_{p\chi_s} \sim 3 \times 10^{-5}$ for $m_{\chi_s} \sim 10 \text{ keV}$ and can potentially constrain the parameter space that has not yet been excluded, as shown in Fig. 2. A 100×100 array has the potential to probe even up to $g_{p\chi_s} \sim 10^{-6}$, which is beyond the sensitivity of the SNO [77]. Finally, an optimistic 1000×1000 array search can even probe the region complementary to the bound from SN1987A cooling [88]. The sharp decrease in future sensitivities at low

masses occurs when q falls below the detection threshold. As previously shown, for pseudoscalar DM absorption, $q \sim m_a$, and therefore the detection threshold sets a lower mass cutoff for this setup. Similar projections can also be obtained for the sub-GeV scalar and vector DM. However, most of the parameter space in this range is ruled out by the existing experiment for these types of DM [115].

IV. SMALL NANOSPHERE ($q \lesssim \mathcal{O}(10) \text{ keV}$)

Now we turn our attention to the *small* sphere scenario with diameter 15 nm ($r_{sp} = 7.5 \text{ nm}$). The differential recoil rate and the structure factor $S(q)$ can be obtained from our earlier discussion. Such a small sphere with frequency $\omega = 2\pi \times 1 \text{ kHz}$ has SQL $\sigma_{\text{SQL}} \sim 85 \text{ eV}$. If the transferred momenta of the incoming particle $q \lesssim 2\pi/r_{sp}$, coherence scattering takes place throughout the sphere, leading to a sensitivity enhanced by the factor $\sim N_p^2$. This can be seen in the second part of $S(q)$. We present a few scenarios in the following subsections.

A. Sub-keV pseudoscalar DM

We continue our earlier discussion about pseudoscalar DM with nucleon coupling and consider the sub-keV mass regime. In Fig. 3 we show the upcoming sensitivities with a 15-nm diameter setup. To denote future sensitivities from various combinations of nanosphere arrays with 1 year integration time [single sphere (blue dashed), 10×10 (red dashed), 100×100 (green dotted), 1000×1000 (brown dotted)]. With a single 15-nm diameter levitated sphere

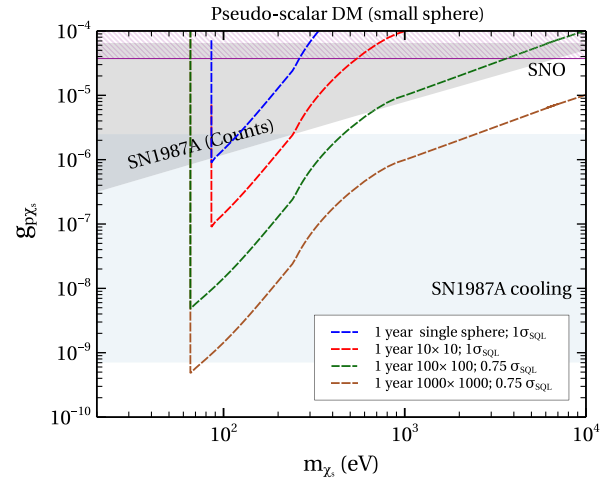


FIG. 3. Projected sensitivity at 90% C.L. on the $m_{\chi_s} - g_{p\chi_s}$ plane using different combinations of small (diameter 15 nm) nanosphere array. The different dashed colored lines are projections for 1 single sphere (blue) and 10×10 array (red) with 1 year integration time and momentum threshold $1\sigma_{\text{SQL}}$. Projection with momentum threshold $0.75\sigma_{\text{SQL}}$ for 100×100 array (green) and 1000×1000 array (brown) with 1 year integration time are also shown. Other existing constraints like SNO [77], SN1987A counts [96], SN1987A cooling [88] are also displayed.

setup, ALP DM can be probed up to $m_{\chi_s} \sim 85$ eV and $g_{p\chi_s} \sim 10^{-6}$, which is beyond the sensitivity of current DD experiments. The setup has the potential to go beyond the exclusion regions of the SNO [77] and the SN1987A counts [96] using only a 10×10 matrix with $q_{th} = 1\sigma_{SQL}$. With even larger array sizes such as 100×100 and 1000×1000 , achieving $q_{th} = 0.75\sigma_{SQL}$ can lead to a substantial improvement in the projected sensitivity and can probe even down to $m_{\chi_s} \sim 50$ eV. Again, the threshold momentum for the small nanosphere is reflected in the low-mass cutoff in the projections. Also note that smaller spheres can probe even larger masses, though the future sensitivities for $m_a \gtrsim 10^4$ eV will be weaker than those obtained with large spheres for the reason already explained.

Some of the potential sensitivities in Fig. 3 intersect with the parameter space previously excluded by supernova constraints [96]. However, these regions could serve as a complementary probe in terrestrial dark matter searches. Thus, DM searches with a levitated sphere can explore the previously unexplored region ($10^{-6} \lesssim g_{p\chi_s} \lesssim 10^{-4}$), opening new avenues for the phenomenology of BSM.

B. Sub-keV vector DM

Dark matter can also be a vector particle [115,116] and several works have been performed to constrain electrophilic light vector DM [14,16,17,26,36,85,117]. Here we consider the following effective interaction with the nucleon only with mass m_{χ_V} and coupling strength $g_{p\chi_V}$: $\mathcal{L}_{VP} \supset -ig_{p\chi_V}[\bar{p}\gamma_\mu p]\chi_V^\mu$. Following the previous discussion, we also show the future sensitivities in nanosphere setup for this DM through nucleon scattering in Fig. 4. The potential sensitivities of various combinations of nanosphere arrays follow the same convention as used in Fig. 3. With a single 15 nm diameter levitated sphere setup with $q_{th} = 1\sigma_{SQL}$ one can probe the vector DM up to $m_{\chi_V} \sim 85$ eV and $g_{p\chi_V} \sim 10^{-10}$. With larger array sizes such as 100×100 and 1000×1000 , achieving $q_{th} = 0.75\sigma_{SQL}$, it can potentially explore previously unconstrained regions. We also show the existing bounds of loop-induced electron recoil from Xenon-1T [59] as well as astrophysical bounds from Sun [118], the HB star [118], and SN1987A [119–121]. Following the recent analysis in [121], the SN1987A cooling bound weakens and constrains $g_{p\chi_V} \gtrsim 10^{-8}$. Apart from the astrophysical constraints, in the future, a nanosphere setup can provide the first direct constraint on the vector dark-matter-nucleon coupling in the sub-keV mass regime.

C. Earth-bound fermion DM

The ongoing DD experiments have a blind spot when it comes to strongly interacting DM, which remains undetectable by conventional search methods [19]. As mentioned earlier, DM particles with a very high cross section

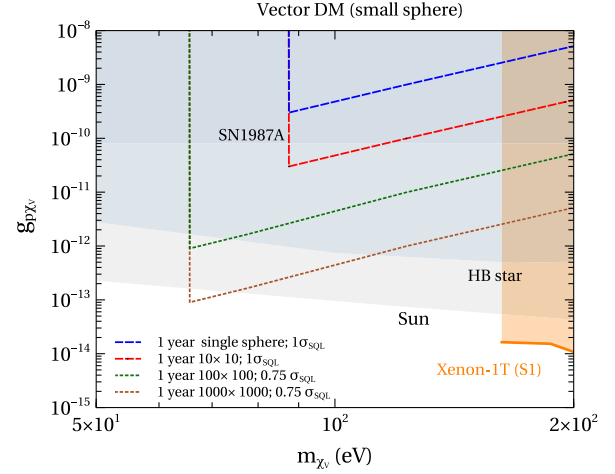


FIG. 4. Projected sensitivity at 90% C.L. on the $m_{\chi_V} - g_{p\chi_V}$ plane using different combinations of small (diameter 15 nm) nanosphere array. The different dashed colored lines are projections for 1 single sphere (blue) and 10×10 array (red) with 1 year integration time and momentum threshold $1\sigma_{SQL}$. Projection with momentum threshold $0.75\sigma_{SQL}$ for 100×100 array (green) and 1000×1000 array (brown) with 1 year integration time are also shown. Other existing constraints like from the Sun [118], HB star [118], and SN1987A [119,120] are also displayed.

($\sigma_{\chi N} \gtrsim 10^{-28}$ cm², χ is the fermion DM) with nucleons are expected to scatter with the Earth's crust and atmosphere and eventually thermalize with the surrounding matter [21,22]. Although only a tiny fraction $f_\chi (\ll 1)$ of the total density of DM can have such large cross sections, their accumulation within the Earth over a huge timescale can significantly enhance density [21,22]. Despite their high number density, these DM particles (χ) are associated with very small velocity ($\sim 10^{-6}/\sqrt{m_\chi/\text{GeV}}c$) and thus can escape conventional DM searches in large detectors [19]. Earth-bound DM has the highest density on the surface around $m_\chi \sim \text{GeV}$ [21] and has momentum $q \lesssim \mathcal{O}(10)$ keV. Hence, optically trapped *small* spheres become an ideal probe for such a scenario, which we explore here.

To calculate the recoil rate of such DM particles, the number density of captured DM n_χ is obtained using a simplified approach. For $m_\chi \gtrsim 1.5$ GeV, the evaporation rate is negligible [20]. Thus, the total DM number bound on Earth is given as [20]

$$N_\chi \approx \Gamma_{\text{cap}} t_\oplus \quad \text{with} \quad \Gamma_{\text{cap}} \sim f_c \Gamma_{\text{geo}}, \quad (6)$$

where Γ_{cap} and $t_\oplus$ signify respectively the DM capture rate and age of Earth [20]. Γ_{geo} is the maximum geometric capture rate of the earth and f_c is the capture fraction. For $M_\chi \gtrsim \mathcal{O}(\text{GeV})$ and $\sigma_{\chi n} \gtrsim 10^{-32}$ cm², f_c can be taken as constant ($f_c = 0.1$) to obtain a conservative projection [21]. See Appendix B for the details of computing the number density and the recoil rate.

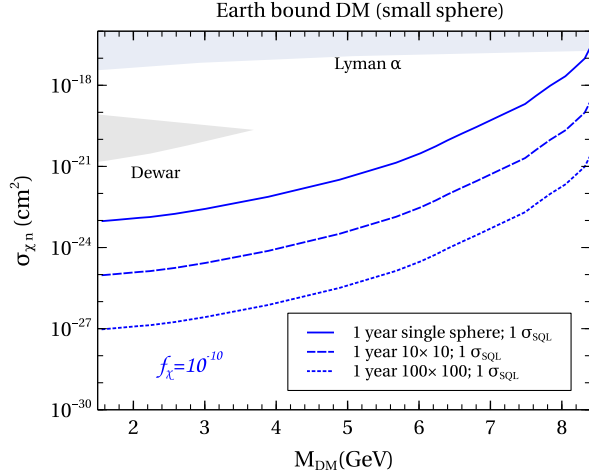


FIG. 5. Projected sensitivity at 90% CL on the $m_{\text{DM}} - \sigma_{\chi n}$ plane using different combinations of small (diameter 15 nm) nanosphere array. The different blue lines are projections for 1 single sphere (solid) and 10×10 array (dashed), and 100×100 array (dotted) with 1 year integration time and momentum threshold $1\sigma_{\text{SQL}}$. Other existing constraints like Lyman α [123], Dewar heating [20,124] are also displayed for comparison.

In Fig. 5 we show the projections shown by the blue lines obtained only for $f_\chi = 10^{-10}$ with the threshold $1\sigma_{\text{SQL}}$. The upcoming sensitivities for (a) 1 single sphere with 1 year (solid), (b) 10×10 array with 1 year (dashed), (c) 100×100 array with 1 year (dotted) are shown by blue lines. We have also portrayed the existing constraints from Lyman α [123], Dewar heating [20,124]. The expected reach for a single 1-year sphere is stronger than the existing constraints. For higher values of f_χ , the projected sensitivities obtained will scale accordingly [$\sigma_{\chi n} \times (f_\chi/10^{-10})$] and will be more stringent. Thus, an optically trapped sphere can provide direct detection of Earth-bound DM and can act as a complement to the bounds obtained through annihilation [22] or nuclear accelerators [125].

V. BACKGROUND

In our analysis, we assumed that the background was negligible. Compared to the large $\sim$ ton-size detectors, the recoil rates due to neutrinos are highly suppressed due to their smaller cross section. For example, with a single large nanosphere, the expected rate for neutrinos would be

$$R \approx N_T \Phi_\nu(E_\nu) \sigma_{\nu N}(E_\nu) \sim 10^{-19}/\text{year} \quad (7)$$

at $E_a \sim \text{KeV}$. Here we assume the number of incoming neutrinos (Φ_ν) $\sim 10^{11} \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ and the cross section ($\sigma_{\nu N}(E_\nu)$) $\sim 10^{-48} \text{ cm}^2$ for solar neutrinos [126]. Since neutrinos have energies $\gg 100 \text{ eV}$, the coherence effect does not occur for smaller spheres, leading to a suppressed rate $\sim 10^{-22}/\text{year}$. Low-energy secondary particles from high

energy radiation can be distinguished by placing conventional particle detectors around the setup [55].

The remaining background from the gas collision can be controlled for a large (small) nanosphere with a smaller temperature $\simeq 4 \text{ K}$ (300 K) and vacuum pressure $\simeq 10^{-12} \text{ mbar}$ (10^{-15} mbar) at SQL (evaluated in [55]). In this work, we find that the expected recoil rates corresponding to the points on the future sensitivity lines for a single-sphere setup always remain higher than the background for physics cases exhibiting a monochromatic recoil signature (ALP DM and vector DM). For the physics cases (solar ALP and earth-bound DM) featuring a spread in the differential recoil rate, the expected recoil rates corresponding to the points on the projected sensitivity lines for a single sphere setup remain an order of magnitude higher than the predicted background at SQL. To derive the projections using larger arrays, we also assume that the expected backgrounds remain small, which might be an optimistic assumption. This assumption holds for large spheres since at temperature $\simeq 4 \text{ K}$ and vacuum pressure $\simeq 10^{-12} \text{ mbar}$ the background drops drastically for $q \lesssim 0.75\sigma_{\text{SQL}}$ ($\sim 10 \text{ keV}$) [55]. On the other hand, for smaller spheres that form larger arrays, it is possible to reduce the background to the level of $0.75\sigma_{\text{SQL}}$, if one can achieve pressure even lower than the value mentioned before [55]. However, the necessary estimation of the background is beyond the scope of our analysis. This will be available only once the experiment starts operating and provides the required data for the background.

Finally, other noise-induced recoils can be easily isolated from DM or ALP signals using directional sensitivity and correlations within large arrays [52]. Thus, the recoil induced by those BSM particles can be identified, and future sensitivities obtained in this work can be achieved in the next run with a single small sphere or a 10×10 array of large spheres. It is also crucial to note that reaching or surpassing SQL [64,65] and trapping nanospheres in larger arrays [$\sim \mathcal{O}(100) \times \mathcal{O}(100)$] are difficult within current facilities and beyond the state-of-the-art for tweezer arrays, which would require substantial further technical development to achieve.

VI. CONCLUSION

In this work, we explore the potential of an ongoing tabletop experiment [55] using optically trapped SiO_2 nanospheres in the context of the search for exotic light particles. Conventional detection methods face challenges in observing small nuclear recoils, resulting in reduced sensitivity to nuclear interactions. In contrast, the optically trapped nanosphere setup offers the potential to probe previously unconstrained parameter space of the nuclear couplings of light particles due to its very low momentum sensitivity. A large (200 nm diameter) sphere and a small (15 nm diameter) sphere are sensitive to momentum recoil to $\mathcal{O}(10) \text{ keV}$ and $\mathcal{O}(100) \text{ eV}$, respectively.

Here, we propose using optically trapped nanospheres to investigate ALP-nucleon coupling with 14.4 keV solar ALPs, sub-GeV DM, and Earth-bound DM as an alternative to the multiton DD experiment searches. A 4×4 array of 200 nm nanospheres can explore previously uncharted parameter space of solar ALP using the 14.4 keV line flux, with sensitivity improving through larger arrays. In the near future, a 100×100 array of such spheres can probe $g_{ap} \gtrsim 10^{-5}$ for $m_a \lesssim \mathcal{O}(10)$ keV. The experimental probe of the nuclear coupling of solar ALP at $\mathcal{O}(10)$ keV energy has been proposed for the first time in this work.

Apart from solar ALP, this setup can also probe previously unexplored parameter space of sub-GeV pseudoscalar DM. Using smaller spheres (~ 15 nm) significantly improves sensitivity, where enhanced coherence compensates for the reduced target size. Larger arrays of such spheres allow for the probing of even smaller couplings. Along with the galactic DM, a smaller sphere offers the first direct probe of Earth-bound DM, where strongly interacting DM scatters within Earth's atmosphere and loses its kinetic energy significantly before reaching the detector. Despite the enhanced density accumulated on Earth, they escape conventional DD searches because of their extremely low kinetic energy. We show that even with a single small sphere, a significantly new parameter space of such strongly interacting "Earth bound" DM can potentially be probed with such setup.

Throughout this work, we find that arrays with different sphere sizes have the potential to probe complementary regimes: large (200 nm) spheres will be sensitive to $q \gtrsim \mathcal{O}(10)$ keV and small (15 nm) spheres to $q \lesssim \mathcal{O}(100)$ eV. In the future, an array of intermediate-sized (100 nm) spheres could optimize the sensitivity at $q \sim \mathcal{O}(1)$ keV, further improving the detection prospects for solar ALPs and Earth-bound DM. Levitated nanosphere sensors thus provide a promising avenue for BSM searches.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: ALP NUCLEON SCATTERING

ALP can interact with protons (neutrons) through the process described in Fig. 6, and we work in the rest frame of the initial state proton $N(k_2)$. The amplitude of the process $a(k_1) + N(k_2) \rightarrow N(k_3) + \gamma(k_4)$ is given by [99],

$$\mathcal{M} = ig_{ap} \left[-\bar{u}(k_3) \gamma_5 \frac{1}{k_2 - k_4 - m_p} \Gamma_N u(k_2) - u(\bar{k}_3) \Gamma_N \frac{1}{k_1 + k_2 - m_p} \gamma_5 u(k_2) \right] \quad (\text{A1})$$

where $\Gamma_N = [e\gamma^\mu + \frac{\kappa}{4m_p} \sigma^{\mu\nu} k_{4\nu}] \epsilon_\mu(k_4)$, m_p and q are the mass of the proton and the recoil momentum of the target. The averaged amplitude square is given by

$$|\mathcal{M}|^2 = [M_1^2 + M_2^2 + M_3^2], \quad \text{where} \quad , \quad (\text{A2})$$

$$M_1^2 = \frac{4m_p^2(3m_a^2 + E_a m_p) - 4(m_a^2 + 2E_a m_p)q^2 + \frac{\kappa^2}{m_p^2}(m_p^2 - q^2)^2(2E_a m_p - m_p^2 + q^2)}{(t - m_p^2)^2} \quad (\text{A3})$$

$$M_2^2 = \frac{m_p^2(3m_a^2 + 2E_a m_p) - (m_a^2 + 2E_a m_p)q^2}{E_a^2 m_p^2} - \frac{\frac{\kappa^2}{m_p^2}(m_a^2 + 2E_a m_p)(-4E_a^2 m_p^2 + m_a^2(m_p^2 - q^2) + 2E_a m_p(m_a^2 + m_p^2 - q^2))}{E_a^2 m_p^2} \quad (\text{A4})$$

$$M_3^2 = -8 \frac{m_a^2 + m_p^2 - q^2}{m_p^2 - t} + \frac{\frac{\kappa^2}{m_p^2} (m_a^2 - 2E_a m_p)(m_a^2 + 2E_a m_p - m_p^2 + q^2)}{(m_p^2 - t)} \quad (\text{A5})$$

In the limit $q \ll m_p$, this can be further simplified as

$$|\mathcal{M}|^2 \approx \frac{e^2 g_{ap}^2}{2} \left[\frac{4m_p^2(3m_a^2 + E_a m_p) - 4(m_a^2 + 2E_a m_p)q^2}{(m_p^2)^2} + \frac{m_p^2(3m_a^2 + 2E_a m_p) - (m_a^2 + 2E_a m_p)q^2}{E_a^2 m_p^2} - 8 \frac{m_a^2 + m_p^2 - q^2}{m_p^2} \right]$$

The differential cross section can be obtained by

$$\frac{d\sigma}{dq} = \frac{2q}{64\pi s} \frac{1}{(p_{cm}^i)^2} |\mathcal{M}|^2 \quad (\text{A6})$$

where, $s = (k_1 + k_2)^2$ is the Mandelstam variable and p_{cm}^i is given by

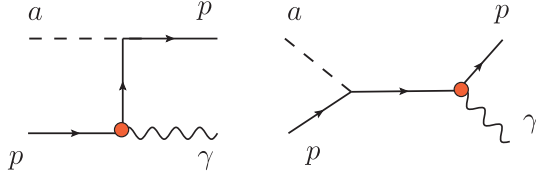


FIG. 6. Feynman diagram of ALP proton scattering.

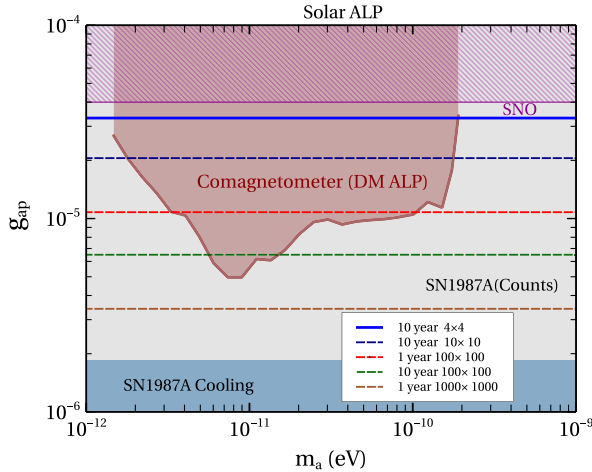


FIG. 7. Projected 90% CL sensitivity on the m_a vs g_{ap} plane for solar ALP using levitated SiO_2 nanosphere array with 200 nm diameter and momentum threshold $0.75\sigma_{\text{SQL}}$. The different colored lines are projections for 4×4 array with 10 year integration time (blue solid), 10×10 array with 10 year integration time (dark blue dashed), 100×100 array with 1 year integration time (red dashed), and 10 year integration time (green dashed); and finally 1000×1000 array with 1 year integration time (brown). Other existing constraints like SNO [77], SERF comagnetometer [103], SN1987A counts [96], SN1987A cooling [88] are also displayed.

$$(p_{cm}^i)^2 = \frac{1}{4s} (s - (m_a + m_p)^2)(s - (m_a - m_p)^2)$$

This can be further simplified in the limit $m_a \ll q$ as,

$$\frac{d\sigma}{dq} = \frac{2q}{16\pi(2m_p E_a)^2} \frac{e^2 g_{ap}^2}{2} \left[-\frac{8m_p E_a}{m_p^2} + \frac{m_p^2}{E_a m_p} - 8 \right]. \quad (\text{A7})$$

In Fig. 7 we depict the projected reach in the low mass region. Following the discussion in Sec. A, for the $m_a \lesssim \mathcal{O}(1)$ keV mass $\ll E_a = 14.4$ keV, solar ALP essentially behaves like a massless particle. So, the projected limits become independent of m_a , i.e., flat lines in all the low mass range. We show only the 10^{-12} – 10^{-9} eV region in Fig. 7 to compare with the results of the SERF comagnetometer experiment [103]. Other existing constraints shown in Fig. 1 are also relevant here.

APPENDIX B: EARTH BOUND DM RECOIL

The total captured DM number N_χ on Earth evolves as [20],

$$\frac{dN_\chi}{dt} = \Gamma_{\text{cap}} - N_\chi \Gamma_{\text{evap}}, \quad (\text{B1})$$

where, Γ_{cap} , Γ_{evap} signify the capture and evaporation rates, respectively. For this analysis, we ignore the DM annihilation. Thus, the total captured DM number throughout the Earth's age is given by

$$N_\chi = \frac{\Gamma_{\text{cap}}}{\Gamma_{\text{evap}}} (1 - e^{-\Gamma_{\text{evap}} t_\oplus}), \quad (\text{B2})$$

where $t_\oplus = 10^{17}$ s is the age of the Earth. Γ_{evap} is negligible for $M_\chi \gtrsim 1.5$ GeV and $\sigma_{\chi N} \gtrsim 10^{-27}$ cm² [20], and thus the equation mentioned above reduces to Eq. (6). The capture rate is given by $\Gamma_{\text{cap}} = f_c \Gamma_{\text{geo}}$, where Γ_{geo} is the DM particle rate encountered by the Earth, approximated as the geometric cross section of the earth multiplied by the local DM flux [125],

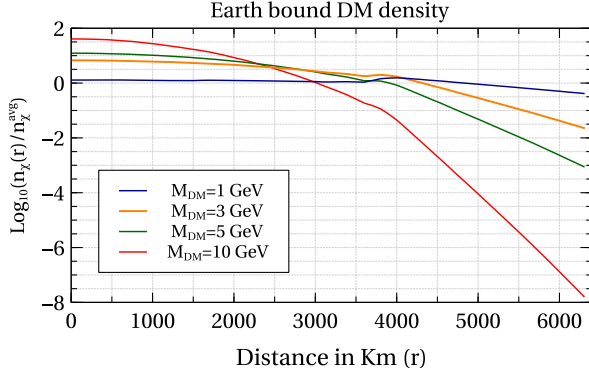


FIG. 8. Variation of number density of captured DM particles relative to the average number density with the distance from center for different DM masses $M_\chi = 1$ GeV (blue), 3 GeV (orange), 5 GeV (green), and 10 GeV (red) depicted by different colors.

$$\Gamma_{\text{geo}} = \pi R_\oplus^2 \frac{\rho_\chi}{m_\chi} v_{\text{eff}}, \quad (\text{B3})$$

$R_\oplus, v_{\text{eff}}$ are the radius of Earth and the local effective DM velocity (≈ 250 km/s), respectively [125].

Then the average DM number density in the Earth is given by $n_\chi^{\text{avg}} = 3N_\chi/(4\pi R_\oplus^3)$. However, because of the Earth's gravitational potential, the DM number density is not uniform; rather for heavier mass DM particles tend to accumulate toward the Earth's core. This can be evaluated as analogous to dilute gas particles in a spherically symmetric potential $V(r)$. The DM pressure density $p(r) = n_\chi(r)T$ (in natural units) is given by $p(r) \propto \exp(-V(r)/T)$ where $V(r)$ is the gravitational potential of each DM particle at radius r . Assuming a thermal equilibrium, we numerically evaluate $p(r)/p(0)$, $p(0)$ being the density at radius $r = 0$, using the density profile in Ref. [20] and the temperature profile in Ref. [127]. From the pressure density, one can easily evaluate the DM density $n_\chi(r)$ in terms of $n(0)$, using which the ratio $n_\chi(r)/n_\chi^{\text{avg}}$ can be obtained.

In Fig. 8 we show the variation of the captured DM density in terms of $\log_{10}(n_\chi(r)/n_\chi^{\text{avg}})$ with the distance

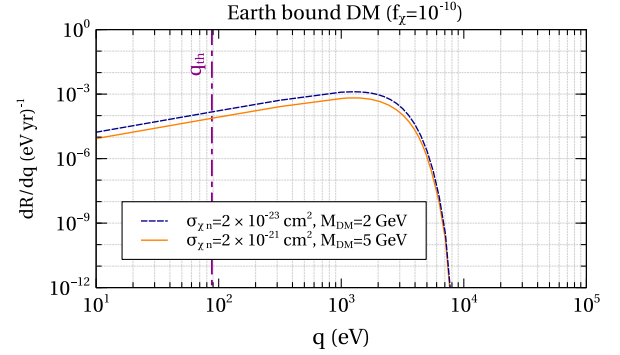


FIG. 9. Expected recoil rate in a single 15 nm diameter nanosphere with $f_\chi = 10^{-10}$, $f_c = 0.1$ for two benchmark points $M_\chi = 2$ GeV $\sigma_{\chi n} = 2 \times 10^{-23}$ cm²; and $M_\chi = 5$ GeV $\sigma_{\chi n} = 2 \times 10^{-21}$ cm².

r (in Km) from the center of the Earth. The results are shown for four different masses of DM $M_\chi = 1$ GeV (blue), 3 GeV (orange), 5 GeV (green), and 10 GeV (red) represented by different colors. Note that lighter DM particles $M_\chi \lesssim 1$ GeV are distributed almost uniformly at all distances from the center, whereas heavier DM particles tend to accumulate toward the center of the Earth. As a result, one can observe a significant decrease in the exact number density $n_\chi(R_\oplus)$ on the surface of the Earth compared to the average number density.

The earth-bound DM velocity distribution is given by

$$f_\chi^{\text{bound}} = \frac{1}{\mathcal{N}} \exp\left(-\frac{v^2}{v_{th}^2}\right) \Theta(v_{\text{esc}} - v_{th}), \quad (\text{B4})$$

where $v_{th} = \sqrt{8T_\chi/m_\chi}$ is the local thermal velocity, $T_\chi \sim 0.01$ eV (300 K) is the temperature of the Earth at the surface. v_{esc} is the Earth's escape velocity ~ 11 km/s in SI units. $\mathcal{N}$ is the general normalization constant. The expected recoil rate in a single 15 nm diameter nanosphere is shown in Fig. 9 with $f_\chi = 10^{-10}$, $f_c = 0.1$ for two benchmark points $M_\chi = 2$ GeV $\sigma_{\chi n} = 2 \times 10^{-23}$ cm²; and $M_\chi = 5$ GeV $\sigma_{\chi n} = 2 \times 10^{-21}$ cm².

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