Dark Matter Annihilation inside Large-Volume Neutrino Detectors

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New particles in theories beyond the standard model can manifest as stable relics that interact strongly with visible matter and make up a small fraction of the total dark matter abundance. Such particles represent an interesting physics target since they can evade existing bounds from direct detection due to their rapid thermalization in high-density environments. In this work we point out that their annihilation to visible matter inside large-volume neutrino telescopes can provide a new way to constrain or discover such particles. The signal is the most pronounced for relic masses in the GeV range, and can be efficiently constrained by existing Super-Kamiokande searches for dinucleon annihilation. We also provide an explicit realization of this scenario in the form of secluded dark matter coupled to a dark photon, and we show that the present method implies novel and stringent bounds on the model that are complementary to direct constraints from beam dumps, colliders, and direct detection experiments.

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Introduction.—Cosmological observations provide nearly unambiguous evidence for a nonbaryonic form of matter, commonly known as dark matter (DM), as a dominant component of the Universe [1]. Despite extensive searches, the microscopic identity of DM is yet to be revealed. In the absence of a convincing signal thus far, terrestrial and astrophysical searches have placed stringent constraints on the nongravitational interactions of DM over a wide mass range [2–4].

While DM might consist of just a single new particle, it could also be composed of several. Indeed, many theories of new physics beyond the standard model (SM) predict one or more stable particles, each of which could contribute to the total density of DM. An intriguing example is a new species χ that interacts strongly with ordinary matter (in the sense of large interaction cross sections and not necessarily the *strong force*) but that makes up only a tiny fraction $f_\chi = \rho_\chi/\rho_{\rm DM} \ll 1$ of the total DM mass density. Such relics might seem easy to detect in existing laboratory searches for DM through their scattering with nuclear targets, but they turn out to be much more elusive, see, e.g., Refs. [5,6]. This is simply because a strongly interacting DM component would be slowed significantly by scattering with matter in the atmosphere or the Earth before reaching the target, leading to energy depositions in the detector that are too small to be observed with standard methods [7].

Owing to their interactions with ordinary matter, a strongly interacting dark matter component (DMC) would be trapped readily in the Earth and thermalize with the surrounding matter. Furthermore, for lighter DM, strong matter interactions allow Earth-bound DM particles to distribute more uniformly over the entire volume of the Earth rather than concentrating near the center. Together, this can make the DM density near the surface of the Earth tantalizingly large, up to $\sim f_\chi \times 10^{15}$ cm^{-3} for DM mass of 1 GeV [8–11]. Despite their large surface abundance, such thermalized DMCs are almost impossible to detect in traditional direct detection experiments as they carry a minuscule amount of kinetic energy $\sim kT = 0.03$ eV. A few recent studies have proposed searches for such a trapped DMC fraction via up scattering through nuclear isomers [12,13], electric field acceleration [9], and collisions [14], via bound state formation [15], and by utilizing low threshold quantum sensors [16–18].

In this work, we propose a novel detection scheme for a GeV-scale DMC χ with matter fraction $f_\chi \ll 1$ and a large effective scattering cross section with nucleons $\sigma_{\chi n} \gtrsim 10^{-34}$ cm^2. The scheme is based on the direct annihilation of the Earth-bound population of DMCs within the active volumes of large neutrino telescopes. As annihilation releases up to $2m_\chi$ of visible energy, it naturally provides a dramatic signal for detection of the relic. Currently, the Super-Kamiokande (SK) experiment, owing to its enormous fiducial volume and relatively low detection energy threshold, provides the most stringent probe of Earth-bound DMCs via annihilation. We demonstrate that Earth-bound DMC particles in the mass range of $\sim(1\text{–}5)$ GeV can be efficiently constrained via their local annihilation at SK. The lower end of the mass range is determined by the finite temperature of the Earth, whereas, the upper end is set primarily by the gravitational suppression of the surface density of the χ particles. A similar scheme for direct annihilation inside large-volume detectors has previously been discussed for the case of millicharged DM particles [9]. To illustrate the power of the method within a specific model, we apply it to secluded dark matter that connects to the SM through a dark photon [19], and derive new constraints on the parameter space.

Accumulation and distribution of DMC.—Consider a DMC χ with mass m_χ, DM fraction f_χ, effective nucleon cross section $\sigma_{\chi n}$, and self-annihilation cross section $\langle\sigma v\rangle_{\rm ann}$. If the relic density of χ arises from thermal freeze-out, the fraction f_χ can be determined from the annihilation rate in the early Universe with an approximate relation $f_\chi \propto 1/\langle\sigma v\rangle_{\rm ann}(T \simeq m_\chi/25)$. Extrapolating this high-temperature cross section to the present-day terrestrial environment depends in a crucial way on the underlying microphysics. In what follows we will concentrate for the most part on s-wave annihilation, which implies a nearly constant $\langle\sigma v\rangle_{\rm ann}$.

The total number of χ particles N_χ inside the Earth evolves as

$$\frac{dN_\chi}{dt} = \Gamma_{\rm cap} - N_\chi \tau_{\rm evap}^{-1} - N_\chi^2 \tau_{\rm ann}^{-1}. \qquad (1)$$

The right-hand side of this equation contains the capture, evaporation, and annihilation rates; we will discuss each of them in detail below. If dynamical equilibrium is reached, $dN_\chi/dt = 0$.

Starting with the capture rate $\Gamma_{\rm cap}$, we can write it as

$$\Gamma_{\rm cap} = f_{\rm cap} \times \Gamma_{\rm geom} = f_{\rm cap} \times \sqrt{\frac{8}{3\pi}} \frac{f_\chi \rho_{\rm DM} v_{\rm gal}}{m_\chi} \times \pi R_\oplus^2, \quad (2)$$

where $\rho_{\rm DM} = 0.4\ {\rm GeV\,cm^{-3}}$ denotes the local Galactic DM density, $v_{\rm gal} = 220$ km/s is the typical velocity of the DM particles in the Galactic halo, and $R_\oplus$ is the radius of the Earth. We have also defined here the *geometric capture rate* ($\Gamma_{\rm geom}$), which occurs when all the χ particles that impact the Earth get trapped. The quantity $f_{\rm cap}$ denotes the capture fraction that accounts for deviations from the geometric rate; for strongly interacting DMCs, for which the Earth is optically thick, $f_{\rm cap}$ depends on the relic mass. It approaches unity for $m_\chi \gg m_A$, where m_A is a typical nuclear mass in the Earth, while lighter DMCs have a reduced $f_{\rm cap}$ due to reflection. We use the recent numerical simulations of Ref. [20] to estimate the value of $f_{\rm cap}$, which are found to agree reasonably well with previous analytical estimates [8]; for $m_\chi = 1$ GeV we find $f_{\rm cap} \simeq 0.1$.

In order to determine $\tau_{\rm evap}^{-1}$ and $\tau_{\rm ann}^{-1}$, we need to address the spatial distribution of the Earth-bound DM particles inside the Earth. To this end, we introduce the number density of captured χ particles $n_\chi(r)$, along with the dimensionless radial profile function, $G_\chi(r)$,

$$\int_{r=0}^{R_\oplus} dr\, 4\pi r^2 n_\chi(r) = N_\chi, \qquad G_\chi(r) \equiv \frac{V_\oplus n_\chi}{N_\chi}. \quad (3)$$

For the uniform, radius independent, distribution of χ, the profile function is trivial, $G_\chi(r) = 1$. To determine $n_\chi(r)$, one turns to the Boltzmann equation that combines the effects of gravity, concentration diffusion, and thermal diffusion [10,21]. Moreover, noting that the diffusional timescales for χ particles are short compared with all other scales in the problem, one can use the hydrostatic equilibrium equation

$$\frac{\nabla n_\chi(r)}{n_\chi(r)} + (\kappa + 1)\frac{\nabla T(r)}{T(r)} + \frac{m_\chi g(r)}{k_B T(r)} = 0, \qquad (4)$$

where $T(r)$ denotes the temperature profile of the Earth and $g(r)$ is its density profile, which we obtain from Refs. [22,23]. The coefficient responsible for thermal diffusion, $\kappa \sim -1/[2(1 + m_\chi/m_A)^{3/2}]$, is independent of $\sigma_{\chi n}$ as long it remains approximately constant within the range of thermal energies. Rescaling to write this expression in terms of $G_\chi(r)$, it is, importantly, independent of the total number of trapped particles N_χ. Upon solving Eq. (4), we find that for $m_\chi \lesssim 5$ GeV the density profile is relatively constant and increases only mildly toward the Earth's center. For larger m_χ, the χ particles tend to settle toward the core and have much smaller density near the surface.

Evaporation is particularly important for light DMCs because thermal processes within the Earth can give sufficient amount of energy to the particles for escape. In the optically thick regime, evaporation of strongly interacting DMCs is impeded by their scattering with material in the Earth and the atmosphere on the way out [8]. We adopt the Jeans expression for the evaporation rate in this regime [8],

$$\tau_{\rm evap}^{-1} = G_\chi(R_{\rm LSS}) \times \frac{3R_{\rm LSS}^2}{R_\oplus^3} \times \frac{v_{\rm LSS}^2 + v_{\rm esc}^2}{2\pi^{1/2} v_{\rm LSS}} \exp\left(-\frac{v_{\rm esc}^2}{v_{\rm LSS}^2}\right), \quad (5)$$

where $R_{\rm LSS}$ and $v_{\rm LSS}$ are the radius and DM thermal velocity at the last scattering surface of the χ particle. The radius $R_{\rm LSS}$ is the value for which a typical thermal χ particle can escape without undergoing any further scattering. For the large elastic cross sections of primary interest here, $R_{\rm LSS}$ lies near the surface of the Earth or in the atmosphere, i.e., $R_{\rm LSS} \simeq R_\oplus$.

Qualitatively, we find that evaporation is always negligible for DM heavier than 10 GeV, and is always important for $m_\chi \lesssim 1$ GeV irrespective of the DM-nucleon scattering cross section [20,24–26]. Together with the radial distribution $G_\chi(r)$ discussed above, this dictates a mass range over which the direct annihilation of DMCs within the volumes of neutrino telescopes can be observed:

$$1\ \mathrm{GeV} \lesssim m_\chi \lesssim 5\ \mathrm{GeV}. \qquad (6)$$

Outside of this mass domain, either $G_\chi(R_\oplus)$ or $\tau_{\rm evap}$ is very small, and the corresponding annihilation signal is extremely weak.

Finally, the annihilation rate is given by

$$\begin{aligned}\tau_{\rm ann}^{-1} &= \frac{4\pi}{N_\chi^2}\int_0^{R_\oplus} dr\, r^2 n_\chi^2(r)\langle\sigma v\rangle_{\rm ann} \\ &\simeq \frac{4\pi\langle\sigma v\rangle_{\rm ann}}{V_\oplus^2}\int_0^{R_\oplus} dr\, r^2 G_\chi^2(r),\end{aligned} \qquad (7)$$

where in the second line we have assumed an approximately constant annihilation cross section $\langle\sigma v\rangle_{\rm ann}$, i.e., energy-independent s-wave annihilation.

Combining these terms, it is straightforward to integrate Eq. (1) and solve for N_χ. For most of the parameter space relevant for our problem, either the annihilation or evaporation counter balances the accumulation on timescales $t_{\rm eq}$ shorter than the lifetime of the earth so that $dN_\chi/dt \to 0$. In this case the solution is easily found, $2N_\chi = [(\tau_{\rm ann}/\tau_{\rm evap})^2 + 4\Gamma_{\rm cap}\tau_{\rm ann}]^{1/2} - \tau_{\rm ann}/\tau_{\rm evap}$. Depending on the strength of evaporation, two important regimes can be found: $N_\chi \simeq \sqrt{\Gamma_{\rm cap}\tau_{\rm ann}}$ when the evaporation is negligible and $N_\chi \simeq \Gamma_{\rm cap}\tau_{\rm evap}$ when it is important.

Direct annihilation inside neutrino telescopes.—We now compute the annihilation event rate of a DMC within the detector volume of SK:

$$\Gamma_{\rm ann}^{\rm SK} = \langle\sigma v\rangle_{\rm ann} n_\chi^2(R_\oplus) V_{\rm SK} = \langle\sigma v\rangle_{\rm ann}\frac{N_\chi^2 G_\chi^2(R_\oplus) V_{\rm SK}}{V_\oplus^2}. \qquad (8)$$

For this analysis we use the fiducial volume of SK, $V_{\rm SK} = 2\times 10^{10}\ \mathrm{cm}^3$. If evaporation can be neglected, this reduces to a simple intuitive result,

$$\Gamma_{\rm ann}^{\rm SK} = \Gamma_{\rm cap}\times\frac{V_{\rm SK}G_\chi^2(R_\oplus)}{4\pi\int_0^{R_\oplus} r^2 dr G_\chi^2(r)} \xrightarrow{G_\chi\to 1} \Gamma_{\rm cap}\times\frac{V_{\rm SK}}{V_\oplus}, \qquad (9)$$

where the second relation applies in the limit of a uniform distribution. For sufficiently large scattering cross sections $\sigma_{\chi n}$ and $m_\chi = 2$ GeV, we find annihilation rates in SK of $\Gamma_{\rm ann}^{\rm SK} \simeq 10^6\ \mathrm{yr}^{-1}(f_\chi/10^{-5})$ with a DM density of $\simeq 10^5(f_\chi/10^{-5})\ \mathrm{GeV\,cm^{-3}}$ at SK's depth [in the limit of zero annihilation, maximal DM density is $\simeq 10^9(f_\chi/10^{-5})\ \mathrm{GeV\,cm^{-3}}$]. If the annihilations result in *visible energy*, such rates are very significant, and may even exceed any counting rates in SK by orders of magnitude. We note that this is a drastic departure from the tiny event rate expected for a weakly interacting DM candidate that does not build a large overconcentration near the surface of the Earth [27].

Given the relevant energy range of annihilations equal to $m_\chi = 1$–5 GeV, the closest SK experimental analysis for our purposes is the search for dinucleon decay of Ref. [28,29], where the main background is from atmospheric neutrinos. The SK Collaboration has shown that in certain decay channels, such as $nn \to 2\pi^0 \to 4\gamma$, cuts on fiducial volume, energy, invariant mass, and multiplicity remove essentially all background, achieving single-event sensitivity [28]. Based on these considerations, we derive an anticipated SK exclusion on annihilating DMCs under the assumptions that the final state allows for a similar background-free identification and can be detected with an efficiency of 10% as in Ref. [28]. To do so, we compare our predicted detection rates with the limit rate of three events for a 282.1 kiloton-yr exposure: $\Gamma_{\rm ann}^{\rm SK} < \Gamma_{\rm lim}^{\rm SK} = 0.24\ \mathrm{yr}^{-1}$. While a full experimental analysis is needed, our calculation indicates that new exclusions on the DM-nucleon scattering cross section could be obtained from existing SK data over the mass range of $m_\chi \simeq 1$–5 GeV, even when the annihilating species χ makes up only a tiny fraction of the DM density.

We illustrate the anticipated SK sensitivity to DMC annihilation as a function of χ mass m_χ and per-nucleon cross section $\sigma_{\chi n}$ in Fig. 1 for $f_\chi = 10^{-4}, 10^{-6}, 10^{-8}$, and 10^{-10}. Note that, to make a connection with direct detection constraints, we define an effective per nucleon scattering cross section via $\sigma_{\chi A} = \sigma_{\chi n}A^2(\mu_{\chi A}/\mu_{\chi n})^2$ where A is the mass number of the nuclei, and $\mu_{\chi A(n)}$ is the reduced mass of the DM-nucleus (nucleon) system. At the lower end of the DMC mass range, the shapes of the exclusion regions are solely determined by thermal evaporation, whereas at the upper end they are set by both thermal evaporation and rapid depletion of the surface density of Earth-bound DM due to gravity. Note that the anticipated sensitivity of this method extends down to very tiny DMC fractions. Quantitatively, for $f_\chi = 10^{-10}$, $m_\chi = 2.5$ GeV, and $\sigma_{\chi n} = 10^{-28}\ \mathrm{cm}^2$, the expected event rate at SK can be as high as 15 events per year, which constitutes a detectable signal. Note as well that the assumption of a background-free search is not entirely crucial for obtaining bounds. Indeed, as Fig. 1 shows, the change from $f_\chi = 10^{-4} \to 10^{-6}$ leads to a modest reduction of the excluded parameter space at large m_χ. Since the signal is proportional to f_χ, a

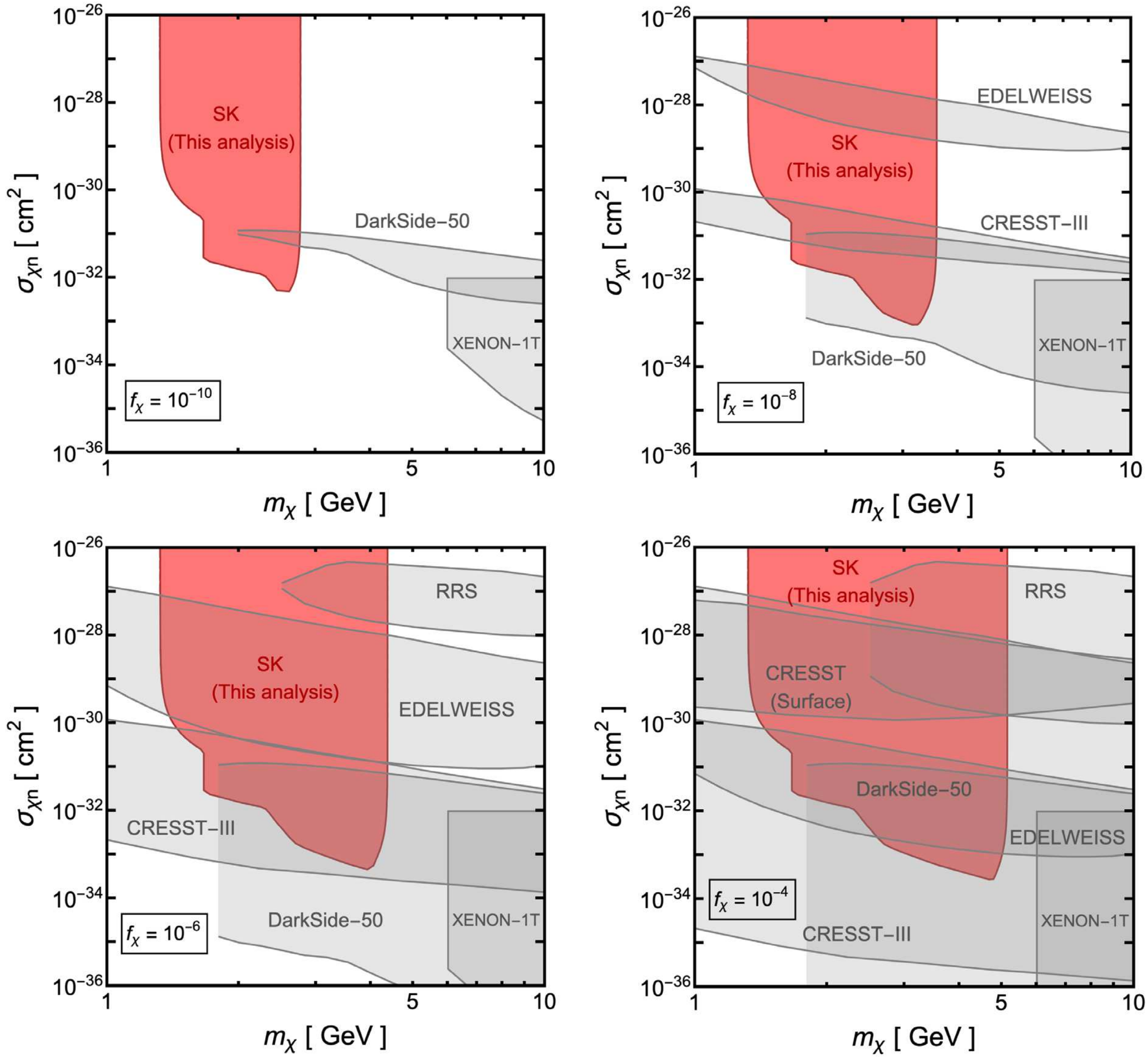

FIG. 1. Expected constraints on the DM-nucleon scattering cross-section $\sigma_{\chi n}$ from nonobservation of DMC annihilation inside the fiducial volume of Super-Kamiokande (red shaded). Each panel shows a specific mass fraction f_χ: $f_\chi = 10^{-10}$ (top left), $f_\chi = 10^{-8}$ (top right), $f_\chi = 10^{-6}$ (bottom left), $f_\chi = 10^{-4}$ (bottom right). For comparison we also show the estimated constraints from direct detection experiments including CRESST III [30], CRESST surface [31], XENON [32], EDELWEISS surface [33], RRS [34], and Darkside-50 [35] (gray shaded).

similar reduction would occur if the experimental limit rate were weakened by a similar factor, $\Gamma^{\rm SK}_{\rm lim} \to 100 \times \Gamma^{\rm SK}_{\rm lim}$. We conclude that the limits from SK are robust, and should be applicable to a wide class of models.

Also shown in Fig. 1 for comparison are exclusions from several surface and underground direct detection experiment searches [30–35]. To adjust the experimental bounds given for $f_\chi = 1$ to the smaller fractions of interest here, we have applied the simplified method described in Ref. [14]. As shown in Ref. [36], this approach gives a reasonable approximation to more computationally intensive calculations such as Refs. [37–40]. We note, however, that the simplified method we use tends to overestimate slightly the exclusions at small $f_\chi \ll 1$ [36]. Thus, the unexcluded regions where our SK annihilation proposal shows new sensitivity are expected to be robust.

Secluded relic model.—To illustrate our results in a concrete model, we consider a dark sector with a Dirac fermion DMC χ coupled to a dark photon A' with the low-energy effective Lagrangian

$$\mathcal{L} = -\frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2 + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi, \tag{10}$$

where ϵ describes kinetic mixing with the photon, $m_{A'}$ is the mass of dark photon, $D_\mu = \partial_\mu - i g_d A'_\mu$, and $g_d \equiv \sqrt{4\pi\alpha_d}$ is the dark coupling constant.

Annihilation of χ to dark photons which subsequently decay to SM particles, $\chi\bar{\chi} \to A'A'$ with $A' \to \mathrm{SM}$, is possible for $m_{A'} < m_\chi$ [19] and efficiently depletes the abundance of χ to produce $f_\chi \ll 1$ for moderate α_d. The annihilation rate during freeze-out can receive a significant nonperturbative enhancement for larger $\alpha_d \gtrsim 0.05$ and $m_\chi \gg m_{A'}$ [41,42]. We compute f_χ in terms of the model parameters assuming thermal freeze-out by approximating the potential between annihilating χ and $\bar{\chi}$ with a Hulthèn potential, which has been shown to give a very good estimate of the full result [43,44]. The perturbative cross section for χ to scatter on a nucleus (Z, A) is related to the model parameters by [19]

$$\sigma_{\chi A} = \frac{16\pi Z^2 \alpha \alpha_d \epsilon^2 \mu_{\chi A}^2}{m_{A'}^4}, \tag{11}$$

where Z is the atomic number of the nuclei, m_A is its mass, and α is the fine-structure constant.

In Fig. 2 we show the sensitivity of our approach to this representative model for $m_\chi = 2.5$ GeV and $\alpha_d = 0.3$ as a function of $m_{A'}$ and ϵ. For these values, the DM fraction of χ is approximately $f_\chi \simeq 3 \times 10^{-9}$, with a mild dependence on $m_{A'}$. The red shaded region in the figure shows the anticipated exclusion from SK, where we apply the same assumptions regarding the experimental sensitivity as before. Note that, for the A' mass range considered the primary dark photon decay modes are to leptons and pions,

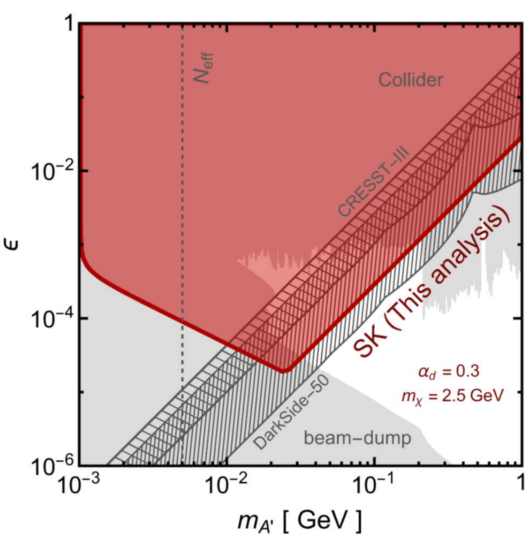

FIG. 2. Anticipated sensitivity to a dark photon-mediated DMC χ for mass $m_\chi = 2.5$ GeV, gauge coupling $\alpha_d = 0.3$ in terms of the dark photon mass $m_{A'}$, and kinetic mixing ϵ from annihilation of Earth-bound χ inside Super Kamiokande (red shaded). The DM fraction f_χ of χ is determined from the model parameters assuming thermal freezeout in the early Universe. Also shown are bounds from direct DM searches at CRESST III [30] and DarkSide-50 [35] (gray hatched), as well as searches for a visibly decaying dark photon [45–48] (gray shaded).

and are therefore visible and distinctive. In particular, the annihilation process $\chi\bar{\chi} \to 2A' \to 2(e^+e^-)$ is very similar in terms of SK signature to $nn \to 2\pi^0 \to 4\gamma$ decay [28]. To ensure that the dark photons produced by $\chi\bar{\chi}$ annihilation decay within the SK fiducial volume, we require further that the SK-frame decay length of the A' is less than 1 m, i.e., $\gamma c \tau_{A'} < 1$ m; this is important for $m_{A'} \lesssim 20$ MeV. We also show existing bounds on the scenario from direct DM searches [30,35], and from direct searches for a visibly decaying dark photon [45–48]. The dashed vertical line indicates the lower bound on $m_{A'}$ for a thermalized dark photon from the number of relativistic degrees of freedom during primordial nucleosynthesis in the early Universe [49].

A final comment is warranted on the possibility of observing the χ annihilation *outside* the Earth's volume using cosmic- and γ-ray detectors in the GeV range, such as AMS-02 [50] and Fermi-LAT [51]. By continuity, it is clear that some distribution of χ (a "Boltzmanian tail") is present in the atmosphere and above. Annihilation of $\chi\bar{\chi}$, with subsequent decay of A' generates electrons, muons, and pions, and therefore contributes to the observed electron and positron flux. While the counting rates of these experiments are much larger than in SK, there is a gain associated with the fact that the signal is collected from a large-volume, for which we take a characteristic orbit height, $h \sim 400$ km. The expected additional flux from DM annihilation in the atmosphere, given the SK bound, is

$$\Phi_{\rm ann} \sim \Gamma_{\rm SK} V_{\rm SK}^{-1} \times h < 10^{-10}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1} \tag{12}$$

which is far below the typical electron and positron fluxes measured by the AMS-02 [52] that are on the order of $\mathcal{O}(10^{-3}$–$10^{-2})\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in this energy range.

Summary and conclusion.—Earth-bound DM particles can be very abundant near the surface of the Earth if they are sufficiently light and strongly interacting. In this work, we point out that annihilation of an Earth-bound DM component at large underground detectors such as Super-Kamiokande provides a novel technique for their detection. The main strength of this proposal stems from the fact that the energy deposition due to annihilation of Earth-bound DM is not limited by their minuscule amount of kinetic energy, but can instead be as large as their invariant mass, $2m_\chi$. We have demonstrated that this approach can test strongly interacting DMC over the mass range $m_\chi =$ 1–5 GeV down to very small mass fractions, well beyond what is possible with other approaches. The upcoming gigantic underground detectors such as Hyper-Kamiokande [53], JUNO [54], DUNE [55], and THEIA [56] will significantly enhance the detection prospects of such Earth-bound DM.

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