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Light Dark Matter at Neutrino Experiments

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Sub-GeV Dark Matter particles upscattered by cosmic rays gain enough kinetic energy to pass the thresholds of large volume detectors on Earth. We then use public Super-Kamiokande and MiniBooNE data to derive a novel limit on the scattering cross section of Dark Matter with electrons that extends down to sub-keV masses, closing a previously allowed wide region of parameter space. We finally discuss search strategies and prospects at existing and planned neutrino facilities.

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Introduction. Evidences for Dark Matter (DM) are all based on its gravitational effects, other possible interactions of this unexplained component of the Universe are currently unknown. Some information about these interactions is obtained by *direct detection* (DD) experiments, which aim at observing the scattering of DM particles off Standard Model (SM) targets [1]. This has resulted in a huge experimental effort that, in the absence of any clear DM detection, has set strong limits on the DM-SM interactions for DM masses above few GeV, see e.g. [2–4].

This situation is accompanied by the severe bounds that the LHC is putting on TeV-scale new physics, that cast some doubts on natural solutions to the hierarchy problem, see e.g. [5]. This undermines part of the motivation (i.e. the connection between naturalness and thermal relic DM) that lead to expect Dark Matter particles in the mass range where the above DD experiments are most sensitive. It is therefore no surprise that, especially in recent years, the community has vigurously pursued the exploration of lighter DM candidates, in terms of both model building and phenomenological tests (see [6] for a recent report).

The quest to determine the interactions of sub-GeV DM candidates is challenged by the low energy thresholds required by DD experiments. Indeed, the average DM velocity $v \approx 10^{-3}$ in the Milky Way halo implies that sub-GeV DM induces recoils in typical SM targets below $O(\text{keV})$, a value for which "standard" experiments like Xenon1T lose sensitivity.

A possibility to overcome this issue consists in devising new target materials and detector concepts that can be sensitive to very low-energy recoils. This direction has been widely explored in recent years, and it has resulted in the proposal and realisation of several experiments (see again [6] for a review).

Another strategy to directly detect sub-GeV DM consists in relying on subdominant DM populations with much larger velocities, so that their scattering off detectors can induce energetic recoils. A concrete example consists in ordinary DM particles upscattered in high-temperature areas of the Sun, a possibility which has been explored for DM-electron interactions in [7] and for DM-nucleon ones in [8]. The internal dynamics of non-minimal dark sectors can also result in relativistic dark species, that could give signals in large detectors on Earth [9].

In this letter we propose a new detection strategy of sub-GeV Dark Matter, based on the subdominant component with larger kinetic energy that is unavoidably generated by cosmic rays (CRs) that scatter off DM. Such upscattered light DM can induce visible recoils in large volume detectors, by means of the very same interactions that accelerated it. Focusing on DM contact scatterings with electrons with cross section σ_e, we use public data of Super-Kamiokande (Super-K) and MiniBooNE to derive a new model-independent limit $\sigma_e \lesssim 10^{-(33-34)}$ cm^2. This limit constitutes the strongest existing constraint on Dark Matter lighter than a few MeV, and extends to DM masses much smaller than a keV. The possibility to probe CR interactions with light DM was first pointed out in the recent [10], that derived constraints on DM from modifications of CR spectra. Our proposal tests directly the accelerated DM component by looking at its effects in detectors on Earth, rather than in CRs.

We finally discuss how searches for such a DM component could be optimised at Super-K, and the gain that one would achieve at large volume detectors with lower electron thresholds, like DUNE. Our proposal is robust against effects that typically hamper other detection strategies of light DM, like the possible existence of other SM-DM interactions or of small mass gaps in the dark sector.

From cosmic rays to DM scatterings on Earth. A diffuse flux ϕ_i of particles with a scattering cross section σ_i with DM, of mass $M_{\rm DM}$, induces a DM flux per solid angle

$$\frac{d\phi_{\rm DM}}{d\Omega}(E_{\rm DM}, b, l) = \frac{J(b,l)}{M_{\rm DM}} \int dE_i \, \frac{d\phi_i}{d\Omega}(E_i) D_i^{\rm DM}(E_i, E_{\rm DM})\, \sigma_i, \tag{1}$$

where $J(b,l) = \int_{los} d\ell \rho_{\rm DM}$ is the integral of the DM energy density $\rho_{\rm DM}$ over the line of sight in the direction

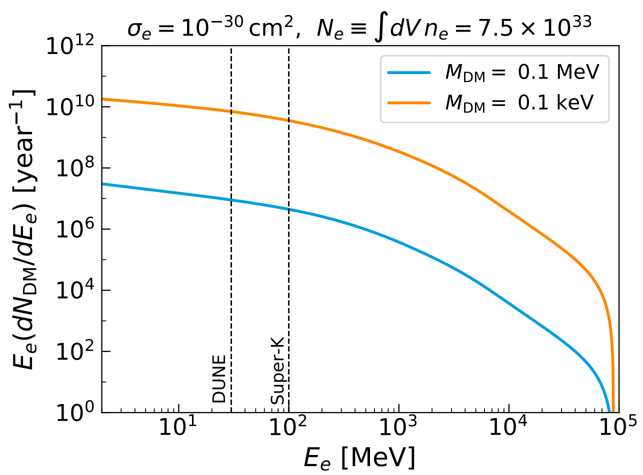

FIG. 1: Energy spectrum of electrons scattered by Dark Matter. The vertical dashed lines indicate the low-energy thresholds considered at Super-K (100 MeV) and DUNE (30 MeV).

of galactic coordinates (b, l), and where we assume for simplicity that the CR flux ϕ_i is homogeneous inside the region of integration, which we take as customary as a cylinder centered on the galactic center (GC), with radius R and height $2h$. D_i^f is a transfer function that encodes the energy spectrum of the particle f induced by a scattering with particle i. Assuming f to be initially at rest in the lab frame, its final energy reads

$$E_f = m_f + K_f^{\max}\frac{1-\cos\theta}{2},\ K_f^{\max} = \frac{2m_f(E_i^2 - m_i^2)}{m_i^2 + m_f^2 + 2m_f E_i}, \tag{2}$$

where θ is the scattering angle in the center-of-mass (CM) frame. If the scattering is isotropic in the CM frame then the distribution of $E_f - m_f$ is flat, so that

$$D_i^f = \frac{1}{K_f^{\max}(E_i)}\,\Theta\left(K_f^{\max}(E_i) + m_f - E_f\right)\Theta\left(E_f - m_f\right), \tag{3}$$

where Θ denotes the Heaviside step function. The number of DM scatterings with the target particles T in a volume (e.g. of a detector), per time per solid angle per final energy E_T of the target particle, is then given by

$$\frac{dN_{\rm DM}}{dt\, d\Omega\, dE_T} = \int dV\, dE_{\rm DM}\, n_T \sigma_T\, D_{\rm DM}^T(E_{\rm DM}, E_T)\,\frac{d\phi_{\rm DM}}{d\Omega}, \tag{4}$$

where σ_T is the scattering cross-section of DM with the target particle and n_T their number density.

As anticipated in the Introduction we focus on cosmic-ray electrons. We use their flux as provided in [11] for electron energies between 2 MeV and 90 GeV. To compute $J(b, l)$ we use an NFW DM density profile [12] with $\rho_{\rm DM}(r = 8.5\ \mathrm{kpc}) = 0.42\ \mathrm{GeV/cm^3}$ and $r_s = 20$ kpc. The precise choice of the profile has a mild impact on our treatment, because we integrate over wide areas and because the DM flux is linear in $\rho_{\rm DM}$ (analogously in a broad sense to the case of DM decay). Assuming a target material containing electrons ($T = e$) and a DM-electron cross-section constant in energy results in the energy spectrum of the target electrons shown in Figure 1, obtained by integrating eq. (4) over the whole cylinder with $R = 10$ kpc and $h = 1$ kpc

An experiment that appears now in a privileged position to be sensitive to these events is Super-K, because of its unmatched large volume and because a sizeable fraction of events survive the energy threshold $E_e > 100$ MeV used in current analyses (see e.g. [13]). As evident from Figure 1, lower E_e thresholds would allow to collect more signal, but we are not aware of any existing experiment where the gain from the smaller thresholds is enough to compensate the much smaller size. Thinking ahead, DUNE [14] will be ideally placed to test light DM via its unavoidable relativistic component, given its expected thresholds of $E_e > 30$ MeV (see e.g. [15]).

New constraints on light DM. Super-K has recently performed a search for boosted Dark Matter in its "electron elastic scatter-like" events with $E_e >$ 100 MeV [13], in data corresponding to 161.9 kiloton-years exposure. We use the total measured number of events reported in that paper in the first energy bin $0.1 < E_e/\mathrm{GeV} < 1.33$, $N_{\rm SK} = 4042$, to place a conservative limit on light DM as

$$N_{\rm DM} < N_{\rm SK}\,. \tag{5}$$

We determine $N_{\rm DM}$ by integrating eq. (4) over the total solid angle, 2628.1 days of data-taking [13], and $E_e > 100$ MeV. We include Earth attenuation in the computation of $N_{\rm DM}$ by writing the average kinetic energy loss of a DM particle as

$$\frac{dK_{\rm DM}}{dz} = -n_e\sigma_e \int dK\, K D_{\rm DM}^e(K_{\rm DM}, K), \tag{6}$$

where z is the depth from the Earth surface. We then assume for simplicity a constant $n_e \simeq 8\times 10^{23}\ \mathrm{cm}^{-3}$ and integrate between $z = 0$ and the direction-dependent distance between Super-K and the Earth surface ($\simeq 1$ km at the zenith), ignoring DM deflections. We use the DM kinetic energy obtained this way in eq. (4) to determine the events in the detector[1].

The resulting limit on an energy-independent σ_e is shown as a shaded area in Figure 2. The even more

[1] An analogous simplified treatment has been shown to be a good and conservative approximation of numerical results in [16] ('method b'). This is good enough for our purpose, in particular in light of the constraints we will derive from MiniBooNE.

conservative limit obtained by working with $h = 100$ pc, instead of 1 kpc, is also shown as a thin line for comparison. The limits coming from the two higher energy bins given in [13] result in weaker constraints than the one we show. Our procedure sets limits in the ballpark of $\sigma_e < 10^{-33}$ cm^2 for $M_{\rm DM} \lesssim 0.1$ keV, that slowly degrade at larger masses.

The behaviors of our exclusions can be analytically understood as follows. For 10 MeV $\gtrsim M_{\rm DM} \gtrsim 0.1$ keV all cosmic rays with energy > 100 MeV make the Super-K electrons pass the threshold, so that the number of signal events $N_{\rm DM}$ at Super-K scales as $N_{\rm DM} \propto 1/M_{\rm DM}$, following the DM number density. Then, since $N_{\rm DM} \propto \sigma_e^2$, the excluded cross section scales $\propto M_{\rm DM}^{1/2}$. For $M_{\rm DM} \lesssim$ 0.1 keV the energy transferred from the CR electrons to the DM enters a regime where it is suppressed as $M_{\rm DM}^{-1/2}$, because it scales as $M_{\rm DM}E^2/m_e^2$. Therefore the minimal CR energy $E_{\rm min}$ required to transfer at least ≈ 100 MeV to the DM increases at lower masses as $M_{\rm DM}^{-1/2}$. Since the CR flux scales roughly as $\phi_i \propto E^{-3}$, its integral is proportional to $E_{\rm min}^{-2} \propto M_{\rm DM}$. This compensates the $1/M_{\rm DM}$ in $N_{\rm DM}$ from the DM number density, resulting in roughly flat limits on σ_e. For $M_{\rm DM} \gtrsim 10$ MeV, the energy trasnferred to the electrons in Super-K scales as $m_e E_{\rm DM}^2/M_{\rm DM}^2$, therefore the limit of integration in the CR energy is linear in $M_{\rm DM}$. Proceeding as before we get $N_{\rm DM} \propto \sigma_e^2 M_{\rm DM}^{-1} M_{\rm DM}^{-2}$, where the first $M_{\rm DM}$ factor is the usual consequence of the DM number density. This leads to the observed scaling of the limits as $\sigma_e \propto M_{\rm DM}^{3/2}$. As explained above, in the smallest and largest $M_{\rm DM}$ regions shown in Figure 2, the shape of our limits is driven by the CR electron of larger energies. Following [11], we have included their spectra only up to 90 GeV. For more than a decade above those energies the spectral index of electrons does not become softer [17], and this would e.g. allow to linearly extend our constraints to $M_{\rm DM}$ smaller and larger than what shown in Figure 2.

The region $\sigma_e \gtrsim 10^{-29}$ cm^2 that is not excluded by Super-K is accessible at surface neutrino detectors[2]. To demonstrate this point, we use the MiniBooNE measurement [20] of 2 events of $\nu - e$ scattering, in a region defined by $\cos\theta_e > 0.9$ along the line between the detector and the neutrino beam, and by $75 < E_e/\mathrm{MeV} < 850$. DM accelerated by CR electrons induce a number of electron scatterings at MiniBooNE that we determine using eq. (4) with the same energy and angular cuts, a volume of 818 kton ($N_e \simeq 3 \times 10^{32}$) and an exposure time of 100 seconds. This time is an extremely conservative estimate that we extract from [20], assuming that the 'off-beam' measurements correspond to only 20 ns for each of the 5.1×10^9 beams. We include the Earth attenuation using eq. (6), where the amount of crust that DM goes across depends on θ_e, the azimuthal angle ϕ_e and the depth of the booster $\simeq 6$ meters [21]. For simplicity we conservatively take the same value for the depth of MiniBooNE, corresponding to that of its center [22]. We finally impose the number of signal events to be smaller than 2. The resulting constraint is displayed in Figure 2. It extends to $\sigma_e \gtrsim 10^{-27}$ cm^2, that we do not show as that would require a treatment of DM scattering through the atmosphere, which goes beyond the purpose of this paper. The analysis of more MiniBooNE data should allow to close the small gap between the Super-K and MiniBooNE exclusions at $M_{\rm DM} \gtrsim 10$ MeV.

[2] See [18] for a recent list of such experiments with references, and [19] for a study of boosted DM at proto-DUNE.

Sensitivities at Super-K and DUNE. We determine them using the signal spatial information, i.e. the larger number of signal events expected from the direction of the galactic center. We integrate the signal over a cone with axis centered on the direction of the GC and opening angle of 10°, corresponding to the opening angle from Earth of the height of the cylinder assumed to contain the CR electrons, $h = 1$ kpc. In an actual search at neutrino experiments, the background could be estimated at Super-K using part of the space complementary to the cone as a control-region, similarly to what has been done in [13]. The uncertainty on the background would then be dominated by statistics, so that we determine the reach on light DM by imposing

$$\left.\frac{N_{\rm DM}}{\sqrt{N_{\rm DM} + N_{\rm bkg}}}\right|_{\rm a.h.}^{10^\circ} = 2\,. \tag{7}$$

The subscript refers to the fact that we only use the fraction of the events above horison, to be conservative with respect to the attenuation of the DM flux from Earth crossing.

In practice, we determine $N_{\rm bkg}^{\rm SK}$ at Super-K by multiplying the total events measured in the first energy bin [13] by the fraction of the sky over which we integrate $\simeq 0.01$, i.e. using the observed isotropy of the background. We determine $N_{\rm bkg}^{D}$ at DUNE assuming 200 kton-year of data (to have the same number of electron-year of Super-K), and using $\left. dN_{\rm bkg}^{D}/dt\right|_{10^\circ} =$ 0.1 event/kton-year [15]. We finally multiply the Super-K (DUNE) background events by 0.37 (0.32), i.e. by the time the GC is above the horizon, that we determine with [23, 24]. For the signal, we integrate eq. (4) over the above cone (the signal fraction surviving is $\simeq 0.15$) and then also multiply by 0.37 (0.32) at Super-K (DUNE). Other large-volume detectors, like Hyper-K, have also promising sensitivities that can be determined as above.

The resulting sensitivities are displayed in Figure 2. The smallest values of the cross sections to which both Super-K and DUNE are sensitive to are such that the Earth would be actually transparent to DM. This would

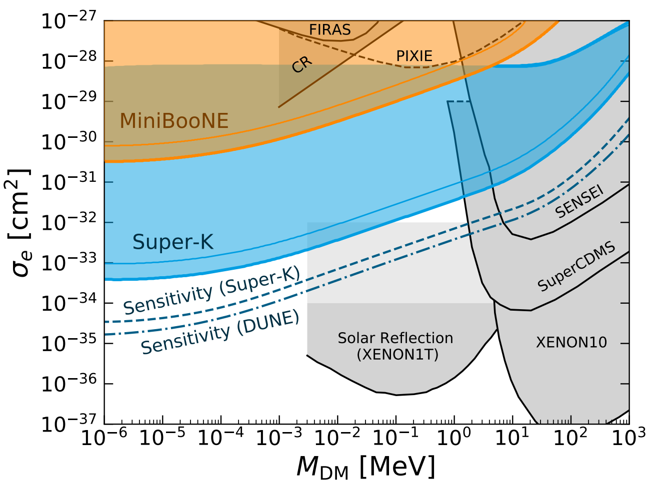

FIG. 2: Limits from Super-K (shaded blue) and MiniBooNE (shaded orange) and sensitivities at Super-K (blue dashed line) and DUNE (blue dot-dashed line) on the DM-electron scattering cross section derived in this work. They correspond to a height of the cosmic-ray electron cylinder $h = 1$ kpc, the limits for a more conservative choice $h = 100$ pc are shown as thin lines. We also show CMB anisotropies limits from FIRAS and sensitivities from PIXIE [25], direct detection limits from Xenon-10 [26], Super-CDMS [27] and SENSEI [28], cosmic-ray limits from [10] and limits from DD of solar-reflected DM [7]. See text for more details.

allow, when performing an actual search, to gain sensitivity both from using events under the horison, and by performing a full optimization of the region of integration (which we expect would have a wider opening angle in the direction of the galactic plane).

Other light DM searches. In Figure 2 we also display constraints from a variety of searches:

- ◇ direct detection constraints from Xenon-10 [26] and Super-CDMS [27], that we stop at $\sigma_e = 10^{-29}$ cm^2 to conservatively account for Earth attenuation, and because larger cross sections are anyway probed by the SENSEI surface run [28];
- ◇ constraints from CMB anisotropies from the FIRAS experiment, and related projections at PIXIE [25];
- ◇ constraints from the observed cosmic-ray electron spectra [10], that to be conservative we do not extend below the $M_{\rm DM}$ range given in [10], because there the kinematical regime driving the shape of the line changes;
- ◇ The Xenon1T constraints induced by the population of DM reflected by the core of the Sun [7], whose large temperature can provide the DM with enough kinetic energy to pass the thresholds of DD experiments on Earth.

The Sun constraints are given in [7] up to $\sigma_e = 10^{-34}$ cm^2, and down to $M_{\rm DM} = 3$ keV. We do not show them for $M_{\rm DM} < 3$ keV because, in that and lower mass ranges, the simple one-scattering regime with the core of the Sun is not enough to give the target electrons in the detectors enough energy to pass the cut of 0.19 keV used in [7]. Therefore the study of those masses requires a treatment that goes beyond the purpose of this letter. We also do not extend these limits above $\sigma_e = 10^{-32}$ cm^2, because they make the radial extension of the radiative area of the Sun become much larger than the related DM-electron interaction lengths, $R_{\rm rad} \simeq 0.5 R_{\rm sun} \gg (\sigma_e n_e)^{-1}$, where e.g. $n_e \approx 10^{23}$ cm^{-3} at the edge between the radiative and convective areas [29]. Therefore DM particles are expected to scatter several times in the radiative and convective regions, whose temperatures are much smaller than in the core of the Sun, leading to the expectation that the limits of [7] will be strongly affected[3]. A more precise determination of this effect goes beyond the purposes of this paper. This obstruction might be less severe for the SENSEI [28] and Super-CDMS [27] sensitivities to DM reflected from the Sun, shown in [7]. However, in the absence of a detailed simulation of propagation of DM in the Sun and of its effects on such detectors, we refrain from showing those sensitivities in our plots.

We finally remark that, in presence of additional interactions with the SM (e.g. with nucleons), the physics of DM escaping the Sun will become even more dependent on the outer Sun layers. Our limits from Super-K are instead more robust against assuming such an extra interaction (they would actually improve thanks to the extra upscattered component from cosmic-ray protons), until it prevents DM from reaching the detector.

We do not show limits on σ_e coming from the combination of CMB and BBN data [30–32], as they may be attenuated or evaded depending on other model assumptions, like the existence of additional dark radiation or annihilation channels for Dark Matter. Analogously, we do not show CMB constraints on annihilating DM, as they strongly depend on the specific model under consideration, and for example they are weak if DM coannihilates with a non-degenerate component, or if its annihilation is p-wave (see e.g. [33]).

On concrete light DM models. A plethora of models of sub-GeV DM and dark sectors have recently been proposed: just to name a few SIMPs [34, 35], ELDERs [36], light dark sectors and/or DM from supersymmetry [37], from leptogenesis [38], from the hierarchy problem [39, 40], or demanded by observed anomalies, e.g. in B decays [41, 42]. Inspired by this rich model-building activity, we now briefly comment about the ap-

[3] Fig. 3 of [7] indeed shows that for $\sigma_e = 10^{-33}$ cm^2 the maximal DM energy is smaller than for smaller cross sections.

plication of our results to some concrete models of light DM. A more detailed exploration of the following and other applications, while certainly interesting, goes beyond the purpose of this letter.

An explicit example for which our strategy looks particularly promising is that of dark sectors with small mass splittings, see e.g. the fermion pseudo-Dirac DM models of [43, 44]. These models can have sizeable DM-electron interactions while evading limits from cosmology, SENSEI, Super-CDMS etc. because in these energy domains the DM-electron scattering is inelastic. Our proposal avoids that limitation thanks to its larger energy regimes, and therefore stands out as a prominent possibility to directly test such DM candidates.

We also studied for simplicity energy-independent contact interactions. The impact of these searches to other regimes can be grasped by observing that the energy exchanges that drive our sensitivities are of the order of the threshold of the neutrino detectors, $E_e > 30 - 100$ MeV. Therefore the performance of our proposal, with respect to other DD probes that rely on smaller energy exchanges (e.g. Sun reflection, CMB, Super-CDMS and SENSEI-like experiments), would be better than what displayed in Figure 2 if σ_e grows with increasing energy (e.g. as in the case of SM neutrinos), and would be worse in the opposite case (e.g. for mediators much lighter than $O(100)$ MeV, see e.g. [45]).

We would finally like to stress that, if the relic particle χ interacting with electrons constitutes a subdominant component of Dark Matter, $f = \Omega_\chi/\Omega_{DM} < 1$, then our constraints and sensitivities on σ_e are relaxed by $\sqrt{f}$, unlike the more severe rescaling by f of other DD probes.

Conclusions and Outlook. The results presented in this letter demonstrate that large-volume neutrino experiments have a promising potential to probe unexplored regimes of light-DM interactions with the SM. This physics case relies on our novel proposal to test the energetic DM component that is unavoidably generated by scatterings with CR electrons in the galaxy. The conservative limit we set using public Super-K data excludes previously allowed wide regions of parameter space, and that could be improved if a dedicated search would be performed in existing data at Super-K, see Figure 2. The prospects of other large neutrino experiments, like Hyper-K and DUNE, also look bright.

Thinking about possible future directions, going to lower electron energy thresholds would increase the signal by allowing to be sensitive to a larger fraction of the upscattered DM (see Figure 1). That would pose the challenge of dealing with much larger backgrounds, e.g. from solar neutrinos [46]. While we do not explore this regime further here, we encourage the experimental collaborations to pursue that direction, for example by employing the peculiar modulation of the signal.

Note added. When this work was in preparation, ref. [47] appeared proposing the same idea that DM upscattered by cosmic rays can give observable effects in Earth detectors. That work is complementary to ours in that it focuses on DM-nucleon interactions and on signals at detectors like Xenon-1T, while we focus on DM-electron interactions and on signals at large neutrino experiments.

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