Snowmass2021 - Letter of Interest

Searches for Boosted Dark Matter at Surface Experiments

NF Topical Groups:

■ (NF3) Beyond the Standard Model

CF Topical Groups:

■ (CF1) Dark matter: particle-like

TF Topical Groups:

■ (TF08) BSM model building
■ (TF09) Astro-particle physics & cosmology

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Abstract: This Letter of Interest discusses a new search strategy of boosted dark matter at surface neutrino experiments. We show how the enormous cosmic-ray induced background events can be rejected and briefly mention future prospects of relevant boosted dark matter searches in a few benchmark experiments such as those at Fermilab Short-Baseline Neutrino program and ProtoDUNE detectors at CERN. Possible future plans along the ideas presented here are also briefly discussed.

Introduction: As a well-motivated dark matter (DM) candidate, most of the focus in the DM phenomenology has been driven to the weakly interacting massive particle (WIMP). DM direct/indirect experiments and collider experiments, unfortunately, have made null observations so far, excluding a wide range of parameter space in relevant DM models. This situation is stimulating speculations on new DM theories beyond WIMP. Boosted dark matter [1] (BDM) is one of the most actively investigated and probed such theories [2–18]. A prominent feature of BDM is that a relativistic (light) DM component (literally *boosted* DM) can be produced at a location with a gravitational potential, e.g., the Galactic Center (GC), in the present universe and reach the earth with an energy greater than the energy thresholds of neutrino experiments.

Large-volume neutrino experiments installed deep underground such as DUNE and Super-/Hyper-K have been considered in order to probe BDM signals [8, 19, 20]. Since the flux of cosmic rays is quite small in deep underground, the main background is the neutral current scattering of atmospheric neutrinos, which can be reduced by using the directional information of the BDM [1–3, 5, 6, 8, 15] or (almost completely) rejected in scenarios allowing a signal with secondary signatures in addition to the primary target recoil, e.g., inelastic BDM (iBDM) [7, 9, 12, 16, 17] and dark-strahlung [13]. By contrast, surface-based neutrino experiments such as the Short-Baseline Neutrino program (SBN) and the NuMI Off-axis ν_e Appearance (NOνA) face an enormous amount of cosmic-ray induced background. For example, the flux of cosmic muons is about $10^{10}\ \mathrm{m}^{-2}\,\mathrm{yr}^{-1}$ on the earth surface. In this Letter of Interest, we propose strategies for searching for BDM in surface neutrino experiments over those background events.

Background rejection strategies: It is possible to utilize features resulting from unique event topologies of the BDM signal to reject the cosmic-ray induced background, for example, in the cases of iBDM [7] and dark-strahlung, a dark gauge boson bremsstrahlung from BDM [13] (see the l.h.s. of Figure 1). The number of cosmic-ray induced events being inseparable from the iBDM signals at ProtoDUNE are conservatively estimated to be smaller than $100\ \mathrm{yr}^{-1}$ [10]. In addition, the atmospheric neutrino-induced background events cannot mimic the iBDM events due to their signal features. We therefore expect that it is possible to perform iBDM searches under a tractable level of backgrounds. Inspired by the results in Ref. [10] and other opportunities, the second phase of ProtoDUNE plans to implement triggers to take comic data and to enable searches for iBDM or dark-strahlung signals.

On the other hand, it is non-trivial to search for elastically scattering BDM (eBDM) signals that are featureless hence easily mimicked by typical backgrounds mentioned above. In order to resolve this problem, we proposed the idea of *Earth Shielding* [11] which makes use of the directional information of BDM coming from a specific area with a gravitational potential such as GC, Sun, and dwarf spheroidal galaxies.

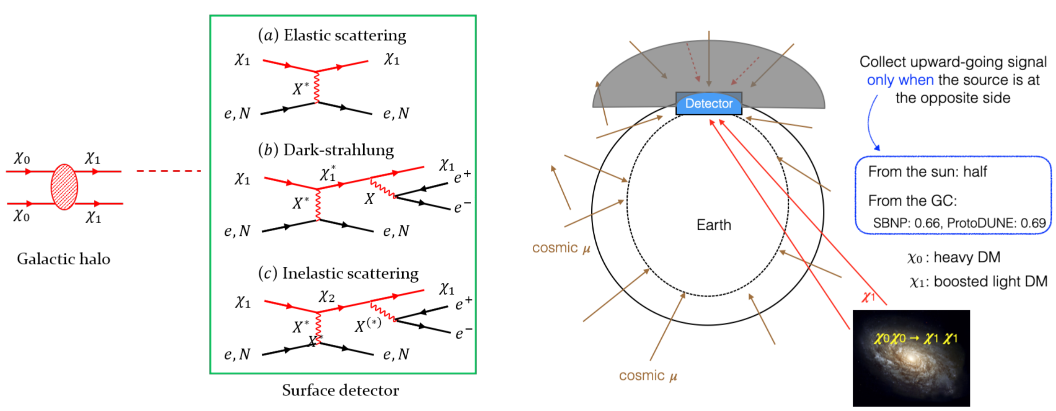

Figure 1: l.h.s.: Example BDM signal processes at a surface detector. r.h.s.: A schematic depiction of the idea of *Earth Shielding*.

The key observation is that the cosmic ray cannot penetrate the earth unlike the BDM, and hence we can take only *upward*-going signals when a detector becomes located in the opposite side of the BDM source. In the case that BDM comes from the GC, a simple geometric consideration suggests that the SBN detectors at Fermilab and the ProtoDUNE detectors at CERN, which are surface detectors located on the northern hemisphere, can use $\sim 65\%$ and $\sim 70\%$ of the signal flux incident for a year, respectively, without suffering from the cosmic-ray-induced backgrounds. A schematic depiction of this idea is shown in the r.h.s. of Figure 1.

Earth Shielding essentially enables us to suppress cosmic-ray-induced backgrounds, leaving atmospheric neutrinos to be the major source of backgrounds, as they can easily pass through the earth. We found that the expected number of atmospheric-neutrino-induced events with recoil electron energy $E_e \geq 30$ MeV is about $40.2\ \mathrm{yr}^{-1}\,\mathrm{kt}^{-1}$. In order to reject these neutrino-induced events as well, one can add the angular cut around the GC. In the case of the SBN detectors and the ProtoDUNE detectors, we found that an angular cut of $\sim 30^\circ$ with respect to the GC direction would improve the experimental sensitivity by a factor of ~ 2.

Example experiments: There exist surface experiments that can be sensitive to the eBDM, iBDM, and dark-strahlung signals, based on the aforementioned search strategies. Key characteristics of several example detectors are summarized in Table 1. The signal-to-background ratio of future data collected according to the Earth Shielding idea is expected to *modulate daily* due to the rotation of the earth and become maximized when the signal origin is facing the earth surface opposite to the detector location. In the reference model of two component BDM where the lighter DM interacts with the Standard Model particles via a dark photon, we found that experimental reaches of our benchmark detectors can be better than the current limits by an order of magnitude [11].

Detector	Target material	Active volume $w \times h \times l$ [m^3]	Active volume mass [kt]	Fiducial volume mass [kt]	Depth	Electron E_{th} [MeV]	Electron θ_{res}
MicroBooNE	LArTPC	$2.56 \times 2.33 \times 10.37$	0.089	0.055	~ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
ICARUS	LArTPC	$2.96 \times 3.2 \times 18\ (\times 2)$	0.476	~ 0.3	~ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
SBND	LArTPC	$4 \times 4 \times 5$	0.112	~ 0.07	~ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
ProtoDUNE SP	LArTPC	$3.6 \times 6 \times 7\ (\times 2)$	~ 0.42	~ 0.3	on ground	~ 30	$\sim 1^\circ$
ProtoDUNE DP	LArTPC	$6 \times 6 \times 6$	~ 0.3	~ 0.21	on ground	~ 30	$\sim 1^\circ$

Table 1: Summary of key characteristics of several surface detectors. The numbers with the "$\sim$" symbol are our estimations based on those of similar detectors due to the lack of official announcement. "$\times 2$" in parentheses indicates that the relevant detector is composed of two consecutive equal-sized sections.

Future plans: Motivated by the encouraging results in Refs. [10, 11], we are now planning to perform a dedicated study to investigate the eBDM, iBDM, and dark-strahlung signal sensitivities at ICARUS of SBN with detector responses carefully included, as its detector is featured by detector technology and volume similar to those of ProtoDUNE. To improve the signal acceptance under a large number of cosmic-ray events, we will develop dedicated triggering algorithms in collaboration with experimentalists. In addition, we are planning to investigate the sensitivity of various surface detectors to different models of non-standard dark sectors, including semi-realistic detector effects and relevant backgrounds.

Summary and outlook: The next-generation neutrino experiments will provide excellent opportunities in searching for BDM [16, 21]. While most of the analyses are focused on the experiments installed deep underground, we suggest that the considerations of the unique event topology of iBDM/dark-strahlung and the Earth Shielding idea for elastically scattering BDM should make the surface neutrino experiments promising in the search for the BDM signals. Our proposal is very generic and thus can be straightforwardly applied to any existing and future surface-based experiments, and therefore, it can be an important aspect of both the neutrino-frontier physics program and the cosmic-frontier physics program in the next decade and beyond.

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