Letter of Interest for the Light Dark Matter eXperiment

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The constituents of dark matter are still unknown, and the viable possibilities span a vast range of masses. Specific scenarios for the origin of dark matter sharpen the focus on a narrower range of masses: the natural scenario where dark matter originates from thermal contact with familiar matter in the early Universe requires the dark matter mass to lie between about an MeV to 100 TeV. Considerable experimental attention has been given to exploring Weakly Interacting Massive Particles in the intermediate mass range (a few GeV – a few TeV). The region between roughly 1 MeV and 1 GeV, however, is largely unexplored. Most of the stable constituents of known matter have masses in this lower range, tantalizing hints for physics beyond the Standard Model have been found which motivate new light states, and a thermal origin for dark matter works in a simple and predictive manner in this mass range as well. For all of these reasons, exploration of sub-GeV dark matter should be a priority. If there is an interaction between light DM and ordinary matter, as there must be in the case of a thermal origin, then there necessarily is a production mechanism in accelerator-based experiments. The most sensitive way to search for the production of light dark matter is to use a primary electron beam to produce DM in fixed-target collisions. The Light Dark Matter eXperiment (LDMX) is an electron-beam fixed-target missing-momentum experiment that has unique sensitivity to light dark matter in the sub-GeV range. This contribution will give an overview of the theoretical motivation, the main experimental challenges, how LDMX addresses these challenges, and projected sensitivities.

A predictive explanation for the origin of dark matter (DM), which is also compelling from an experimental perspective, is that of a thermal-relic from the early Universe. Thermal-relic DM can explain present-day observations if the mass of the DM is between roughly 1 MeV and 100 TeV. The interactions necessary for DM to thermalize with SM particles also imply that DM production at current accelerator facilities is possible up to roughly 1 TeV masses. The sub-GeV region of this parameter space is well-motivated and a critical piece for a comprehensive test of the thermal-relic hypothesis. Details of relevant dark matter models and recent reviews can be found in [1–6].

Fixed-target experiments offer a powerful tool for testing the sub-GeV parameter space. At fixed-target experiments, it is natural to express the relevant strengths of SM-DM interactions in terms of the dimensionless variable $y = \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$ related to the thermally averaged annihilation cross section. Figure 1 shows several thermal-relic targets represented as black parametric curves of y versus m_χ. These relic targets represent the upper bound for which a corresponding model would over-predict the relic abundance of DM and thus a lower bound for experiments to explore.

The Light Dark Matter eXperiment (LDMX) [7] is a fixed-target missing momentum experiment. LDMX will leverage ongoing LCLS-II upgrades [8] to attain high enough integrated luminosities to test the thermal targets shown in Figure 1. The Linac to End-Station A (LESA) will deliver beam to LDMX. With a dedicated injector laser, LESA will be capable of delivering as many as 10^{16} electrons on target (EoT). Electrons will impinge upon a thin ($0.1X_0$) tungsten target in an attempt to produce DM via processes like those shown in Figure 2. Tracking systems upstream and downstream of the target will provide measurements of the initial state of electrons and the momentum of recoiling electrons. Electromagnetic and hadronic calorimeters are placed downstream of the tracking system to characterize both electrons and particles produced in the target, the downstream tracker, or in the calorimeters themselves. In particular, the electromagnetic calorimeter will be a highly granular silicon-tungsten sampling calorimeter that can withstand the high radiation environment and provide detailed 3D measurements that makes it possible to isolate and veto rare background processes. Key backgrounds involve electronuclear and photonuclear interactions that transform visible energy into more difficult to detect secondary particles like neutrons and other hadrons.

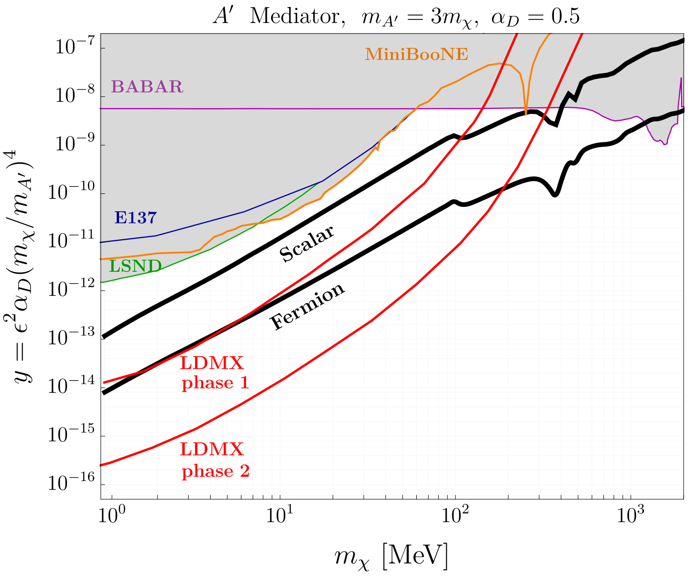

FIG. 1: Projected sensitivity in the y vs. m_χ plane for an LDMX run with 4×10^{14} electrons on target (EoT) with a 4 GeV beam energy (phase 1) and 1×10^{16} EoT (phase 2) with an 8 GeV beam energy. Benchmark thermal relic targets are shown as black lines. Experimental constraints are shown for the assumption of a mediator particle mass ($m_{A'}$) three times as large as the dark matter mass and coupling constant $\alpha_D = 0.5$ between the mediator and the dark matter. Grey regions are (model-dependent) constraints from beam dump experiments and *BABAR*.

Recent studies [9] of the detector design and performance of LDMX suggest that energy de-

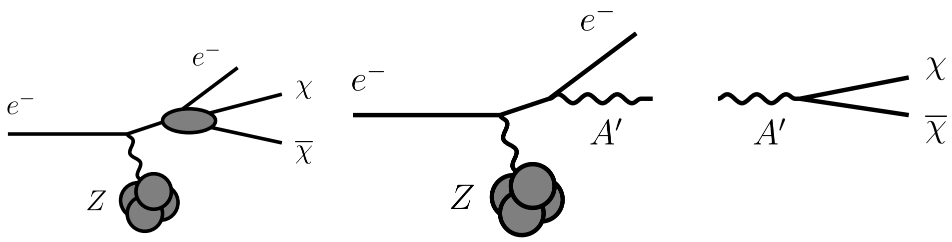

FIG. 2: Left: Diagram for direct dark matter particle-antiparticle production. Right: Diagram for radiation of a mediator particle, followed by its decay into dark matter particles.

positions in the calorimeters, pattern recognition algorithms, and recoil track multiplicities can be used to reject the vast majority of SM backgrounds expected while retaining at least 30% of signal events. Based on these studies, we show the sensitivity to dark photon models in Figure 1 assuming 4×10^{14} EoT ($\mathrm{E_e} = 4$ MeV) and 1×10^{16} EoT. All of these sensitivity projections suggest that LDMX can robustly test sub-GeV thermal-relic DM for mediator masses up to 900 MeV. These constraints complement direct detection experiments utilizing signatures of electron-recoil measurements and e^+e^- collider experiments.

LDMX will be operated in several stages, beginning with a 4 GeV electron beam and 4×10^{14} EoT. A second phase of LDMX will seek to acquire 1×10^{16} EoT with an 8 GeV beam. An increase in beam energy from 4 GeV to 8 GeV will increase sensitivity to high mass dark matter by providing a factor of 4 high signal yield for $m_{A'} = 500$ GeV. To obtain higher integrated luminosity, multiple electrons per time sample will be needed. Work is ongoing to optimize our trigger strategy and background vetoes, and to estimate dark matter signal efficiencies for multielectron events. Beyond phase II, LDMX may be able to exploit future facilities at CERN [10], which could provide an electron beam of 16 GeV. This increased beam energy would boost the signal yield for 500 MeV dark photons by a factor of 10 compared to a 4 GeV beam. Further optimization for high-mass dark matter can also be realized with targets of different materials and thicknesses. A 10% X_0 aluminum target, for example, could provide a yield enhancement of a factor of five over a 10% X_0 tungsten target [7].

While LDMX will focus on the missing momentum signature of dark matter produced in a thin target, it is also possible to search for dark matter production in the tungsten of the electromagnetic calorimeter (ECal), effectively using the ECal as an active target. This mode of operation will take advantage of increased signal rate from the increased target thickness (roughly the first X_0 of the ECal as compared to just the $0.1\ X_0$ target). Work is ongoing to understand backgrounds in this operating mode, to integrate a dark bremsstrahlung signal process into Geant4 in order to enable signal simulation within the ECal, and to estimate the sensitivity of such an analysis. Advanced algorithms are also being developed, including pattern recognition tools to exploit the highly granular nature of the ECal fully. Algorithms like graph neural networks are well suited to exploiting 3D hits reconstructed in the ECal. LDMX will also be capable of searching for signatures of new physics more generally, and measuring photonuclear and electronuclear cross sections [11]. Potential new physics scenarios LDMX can test include axion-like particles, millicharged particles, dark photons, and B-L gauge bosons [12].

LDMX is an electron fixed-target missing momentum experiment with broad sensitivity to dark matter models and other new physics scenarios. With the capabilities of the SLAC accelerator facilities, LDMX can robustly search for thermal relic dark matter produced via mediator with masses up to 900 MeV.

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