Light Dark Matter Searches at Accelerators and the LDMX Experiment

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Abstract Accelerator-based experiments are playing an increasingly essential role in exploring the nature of dark matter. Several approaches have been proposed to search for light dark matter at collider and beam-dump experiments, providing unique sensitivity to several well-motivated scenarios. In this contribution, we review the current experimental situation and future efforts in that domain, emphasizing the advantages and challenges of each technique. A new proposal offering unprecedented sensitivity to directly annihilating thermal dark matter, the LDMX experiment, is also presented.

Keywords Light dark matter · Accelerators · Missing momentum · LDMX

1 Introduction

Collider and beam-dump experiments are increasingly recognized as indispensable tools in exploring dark matter (DM) in the vicinity of the known matter scales. Recent theoretical developments have motivated a large number of new ideas, a significant fraction of which could be explored in the near future. Among those models, thermal DM consisting of a relic whose density is set from nongravitational interactions with the standard model (SM) stands as particularly well-motivated. This scenario only requires that the DM-SM interaction rate exceeds the Hubble expansion in the early Universe for DM to thermalize, a rather generic condition. Cosmological constraints also restrict the mass of viable thermal DM to the keV–TeV range, a scale suggested by familiar matter.

Weakly interacting massive particles (WIMPs), an elegant realization of this paradigm, cover roughly the GeV–TeV range and have driven the experimental searches for the last decades. While WIMPs remain a well-motivated possibility, the simplest scenarios are becoming increasingly constrained. Less extensively studied, light DM spans the MeV–GeV region, and can be viewed as a paradigm where

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DM need not be tied strongly to Electroweak Symmetry breaking. Such a possibility arises naturally if the DM resides in a dark sector (DS) that interacts only feebly with the SM through a new set of interactions [1–3]. Such sectors are common in extensions of the SM, and a new force would extend the characteristics of thermal DM over the MeV–GeV range. Moreover, minimal DS models tend to exhibit a large degree of predictiveness, another attractive feature.

Dark matter annihilation leading to thermal equilibrium can only proceed through a few generic scenarios, depending on the DM and mediator (MED) mass. In the regime $m_{\text{MED}} < m_{\text{DM}}$, dark matter annihilates into DS particles, without any contact with the SM. The secluded annihilation rate, governed by the DM-mediator coupling in the DS, can be compatible with thermalization over a wide range of values [4, 5]. On the other hand, direct annihilation into SM particles occurs when $m_{\text{MED}} > m_{\text{DM}}$, and provides a clear, well-defined target. In that regime, the rate scales as

$$\langle \sigma v \rangle_{\text{direct}} \sim \frac{g_D^2 g_{\text{SM}}^2 m_{\text{DM}}^2}{m_{\text{MED}}^4}. \tag{1}$$

Since the dark sector coupling constant g_D (assuming perturbativity) and mass ratio $m_{\text{DM}}/m_{\text{MED}}$ are at most $\mathcal{O}(1)$, the SM-mediator coupling g_{SM} must be above a certain threshold to be compatible with a thermal history. In other words, the dimensionless combination y must satisfy:

$$y \equiv \frac{g_D^2 g_{\text{SM}}^2}{16\pi^2} \left(\frac{m_{\text{DM}}}{m_{\text{MED}}} \right)^4 > \langle \sigma v \rangle_{\text{relic}} \; m_{\text{DM}}^2 \tag{2}$$

which is qualitatively valid regardless of the DM nature. The lower bound defines a predictive target

$$y_{\text{target}} \equiv g_D^2 \, g_{\text{SM}}^2 \left(\frac{m_{\text{DM}}}{m_{\text{MED}}} \right)^4 \tag{3}$$

as a function of the DM mass to achieve thermalization with the SM. Larger values correspond to models where direct annihilation is only a subdominant process determining the DM abundance.

While the argument, so far, is applicable to any type of interactions between the SM and the DS, the vector/kinetic mixing portal is by far the most viable among renormalizable operators [3, 6]. In the most popular scenario, the interaction between the DS and the SM is mediated by a dark photon (A') with a dark photon–photon mixing strength ϵ. Variations on this theme include models in which the mediator couples preferentially to baryonic (leptophobic DM), leptonic (leptophilic DM), or $(B - L)$ currents. Dark matter annihilation on the CMB power spectrum provides important constraints on the vector portal (see for example Ref. [7]), ruling out direct annihilation of Dirac fermions. The remaining possibilities experience reduced annihilation due to velocity suppression (scalar and Majorana DM) or population suppression if the leading annihilation involves an excited state (pseudo-Dirac DM).

Besides directly annihilating thermal DM, the experimental approaches discussed below are also sensitive to a broad array of models. Those include secluded thermal DM, asymmetric DM in which the DM abundance arises from a primordial asymmetry [8]; SIMP DM containing new resonances in the DS [9]; models with different cosmological histories, such as ELDER DM [10]; freeze-in models with heavy mediators [11, 12]; new force carriers decaying to SM particles [2] or searches for millicharged particles [13, 14].

In the following, we'll briefly review the different techniques to search for DM at accelerators, with a focus on directly annihilating thermal DM. Colliders and fixed-target experiments have already explored a large portion of the parameter space, and they are poised to make significant progress in the coming decade. The description of a new proposal to search for DM, the LDMX experiment, will close the discussion.

2 Dark Matter Searches at Accelerators

Compared to other approaches, fixed target and collider experiments offer several key advantages. Relativistic DM production is largely independent of the details of the DS, as illustrated in Fig. 1. In some models, e.g., Majorana fermion DM interacting through a vector, the direct detection cross section σ_{DD} is drastically reduced through its dependence on the DM velocity. On the other hand, DM particles are produced relativistically at accelerators, and the scattering cross section is only

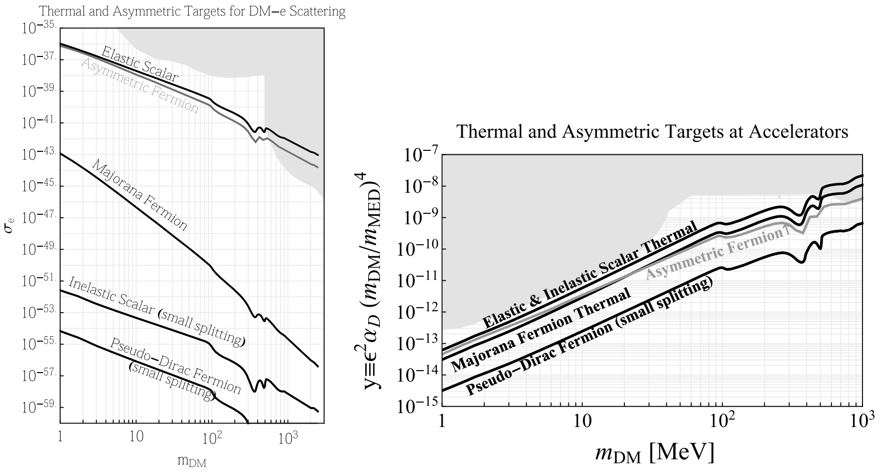

Fig. 1 Targets for directly annihilating thermal DM and asymmetric DM for (left) nonrelativistic electron-DM scattering probed by direct detection experiments and (right) relativistic accelerator-based experiments. The various lines depict the scalar, Majorana, inelastic, and pseudo-Dirac DM annihilating through the vector portal. Current constraints are shown in gray-shaded areas. Figures taken from Ref. [3]

weakly dependent on the velocity. In the pseudo-Dirac case, DM (now labeled χ_1) is accompanied by a heavier state (χ_2), and annihilation or scattering can proceed dominantly via off-diagonal couplings between the light mediator and the χ_1 and χ_2 particles. Direct detection scattering can be heavily suppressed when the DM kinetic energy is insufficient to produce the heavier state [15]. In contrast, the lighter state can readily up-scatter to the excited state when scattering off a nucleus.

Besides detection capabilities, accelerator-based experiments also offer a way to study the DS structure and determine the parameters of a Lagrangian. The mass of the mediator could be measured with visible SM decays, as well as specific type of reactions for invisible decays. The nature of the mediator-SM coupling, another fundamental property, could be investigated using proton (quark coupling) or electron (leptonic coupling) beams. Experiments detecting DM by its scattering in a target would also provide insights about the DS coupling constant.

While accelerator-based approaches have many advantages, some possibilities remain only accessible to direct detection experiments, such as freeze-in models with an ultralight mediator or ultralight bosonic DM. Direct detection would also be desirable to establish the cosmological nature of any observation. A multipronged approach would therefore be advocated to explore as much parameter space as possible and untangle the physics of the dark sector.

On the experimental side, several techniques have been proposed to search for DM signatures. As a broad organizing principle, they can be classified as follows:

- **Missing mass**: the DM signature is identified as a resonance in the recoil mass distribution against a fully reconstructed final state, for example, $e^+e^- \to \gamma(A' \to \chi\bar{\chi})$ annihilations. As all particles (including initial ones) but the DM must be well measured, this type of search is usually performed at e^+e^- colliders or positron beam dumps.
- **Missing momentum/energy**: the DM is radiated off the incoming electron/proton in $eZ \to eZ(A' \to \chi\bar{\chi})$ or $pp \to X(A' \to \chi\bar{\chi}\ X = \gamma, \text{jet})$ and identified through the missing energy/momentum carried away by the DM particles. This approach requires a detector with excellent hermicity, and the possibility to measure each incoming particle separately in some instances.
- **Electron and proton beam dump**: the production mechanism relies on meson decays, such as $\pi^0/\eta^{(\prime)} \to \gamma(A' \to \chi\bar{\chi})$, or radiation off electrons ($eZ \to eZ$ $(A' \to \chi\bar{\chi})$) or protons ($pe(p) \to pe(p)A'$, $A' \to \chi\bar{\chi}$). The DM is usually detected in a downstream detector via $e\chi \to e\chi$ or $N\chi \to N\chi$ scattering. This technique has the advantage or probing the DM interaction twice, providing sensitivity to the DS-mediator coupling, but requires a large incoming flux to compensate for the reduced yields.
- **Direct dark photon searches**: search for the mediator through its decays into SM particles. This approach is essential for $m_{A'} < 2m_\chi$, when the mediator decays visibly. Many production mechanisms are possible, e.g., $e^+e^- \to \gamma A'$, $eZ \to eZA'$ or neutral meson decays. The mediator is usually reconstructed though its leptonic decays.

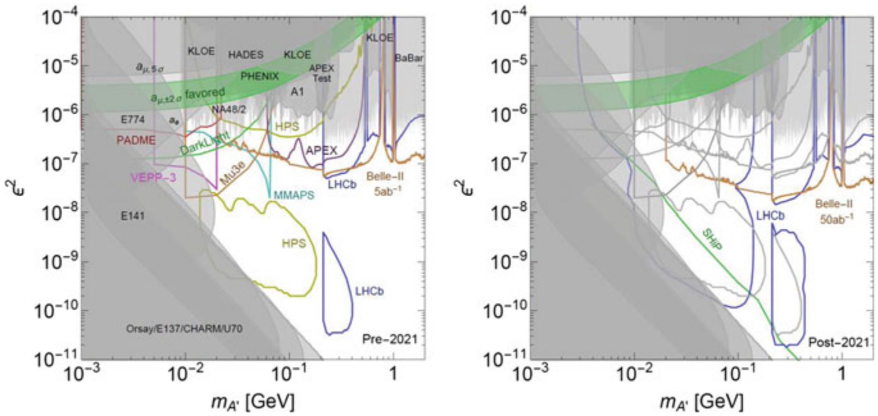

Fig. 2 Existing constraints on visibly decaying dark photons (shaded regions) and projected sensitivities of future and proposed experiments (solid lines). Visible decays of the mediator dominate in the secluded annihilation regime. Courtesy R. Essig

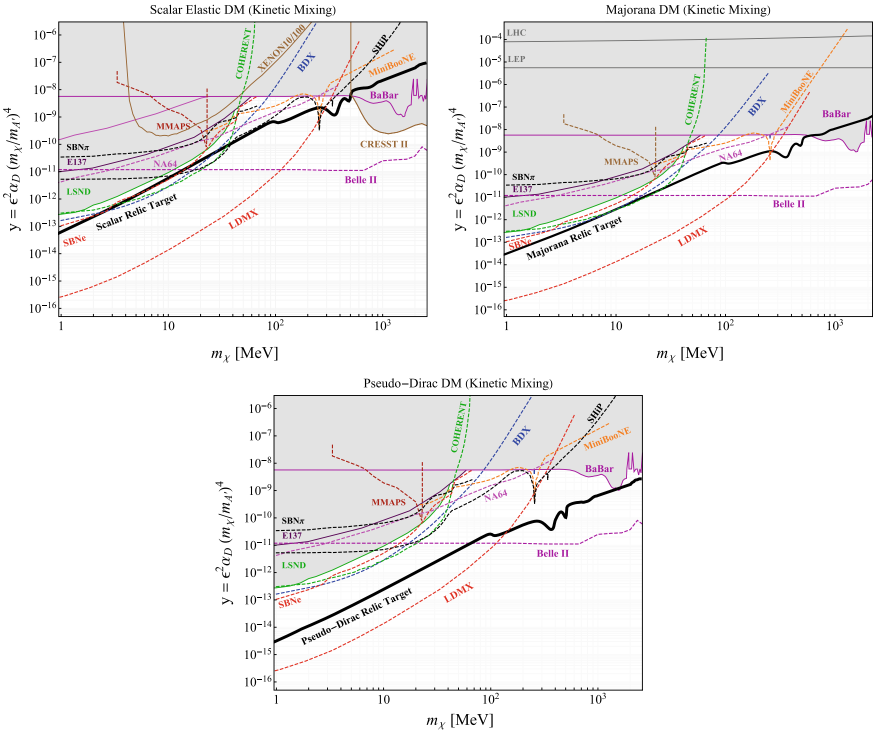

Fig. 3 Current constraints (shaded regions) and sensitivity estimates (dashed/solid lines) on the parameter y for (top left) elastic DM, (top right) Majorana DM, and (bottom) pseudo-Dirac DM. The calculations are performed using $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$, *conservative values* of the parameters. For larger ratios or smaller values of α_D, the accelerator-based experimental curves shift downward, but the thermal relic target remains invariant. Courtesy G. Krnjaic

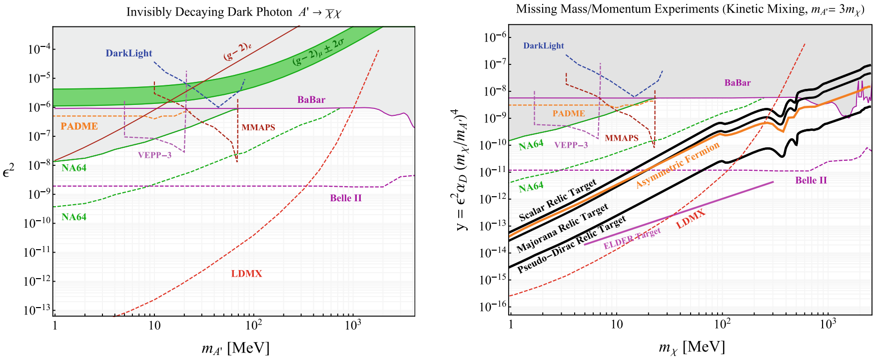

Fig. 4 Left: current constraints (shaded regions) and sensitivity estimates (dashed lines) on the kinetic mixing ϵ. The green band shows the values required to explain the (g-2)$_\mu$ anomaly [19]. Right: corresponding curves on the parameter y, together with the asymmetric DM and ELDER targets (orange and magenta lines). The calculations are performed sing $m_{A'} = 3m_\chi$ and $\alpha_D = 0.5$, *conservative values* of the parameters. For larger ratios or smaller values of α_D, the accelerator-based experimental curves shift downward, but the thermal relic target remains invariant. Courtesy G. Krnjaic

Current constraints and sensitivity estimates for visibly decaying dark photon searches are displayed in Fig. 2. Past measurements have already excluded a sizeable fraction of the parameter space [16–18], including values suggested by the discrepancy between the measured and predicted value of the muon anomalous magnetic moment [19]. In the short term, searches from the APEX, HPS, PADME, and LHCb experiments will further explore the low-mass region [2, 20, 21]. On a longer timescale, collider (e.g., LHCb, Belle-II) and future beam-dump experiments (e.g., SHiP) are projected to almost entirely probe dark photon masses below ∼400–500 MeV. New approaches and/or facilities would be needed to improve the coverage above that mass range.

The present status and prospects for directly annihilating DM with a kinematically mixed dark photon are shown in Fig. 3 for various type of DM. While important progress has been achieved from searches at existing facilities or reinterpretation of previous results (see, e.g., [22, 23]), a next generation of experiment is clearly needed to explore the most interesting region of parameter space. The missing momentum approach seems to offer the best sensitivity at low masses, while collider experiments (e.g., Belle-II) would be better suited to explore the high mass region via the missing mass technique. A potential realization of the missing mass approach, the LDMX experiment, is discussed below. Constraints on a few other scenarios, including invisible dark photon decays, asymmetric DM, and ELDER DM, are shown in Fig. 4.

3 The LDMX Experiment

The "Light DarkMatter eXperiment" (LDMX) [24] aims to precisely measure missing momentum and energy in electro-nuclear collisions in a thin target with unprecedented sensitivity. To achieve high statistics, LDMX plans to use a low current, high-repetition electron beam with a 4–10 GeV energy. In the first phase, LDMX would collect a sample of 4×10^{14} electrons on target (EOT) at a rate of 10^8 electrons per second ($\sim 1\ e^-$ per bunch), before increasing the sample size by two orders of magnitude in Phase-II. The proposed DASEL beam-line at SLAC [25], CEBAF at Jefferson Lab, or a new beam-line at CERN [26] are potential candidate to host this experiment. Beside dark matter, electro-nuclear and photo-nuclear reactions of broader interest to the neutrino community could be also studied with LDMX.

The kinematics of every incident electron is reconstructed both up- and downstream of the target by a tracking system placed into a weak magnetic field, while additional neutral activity is detected by electromagnetic (ECAL) and hadronic (HCAL) calorimeters downstream of the target, with a sensitive area extending onto the beam axis itself. The upstream tracker will reject with very high efficiency stray low-energy particles from the beam halo that could mimic the DM signal. These four detector systems: the upstream tagging tracker, the downstream recoil tracker, the forward ECAL, and HCAL hadronic calorimeter form the majority of the LDMX experimental concept. To keep the detector compact and the field in the ECAL minimal, the tagging tracker is placed inside the bore of a dipole magnet and the recoil tracker in its fringe field. This layout is illustrated in Fig. 5.

The tracker and calorimeters must be able to contend with a high rate of events producing one of the several dominant topologies. Electrons might not interact significantly in the target, resulting in a hard track through both trackers and an energetic shower in the ECAL. Electrons could also emit an energetic photon while interacting in the target. These "hard bremsstrahlung" topologies feature a low-energy recoil electron similar to signal electrons and two showers in the ECAL, with large combined shower energy, separated by a few cm. Finally, trident events contain two or three tracks reconstructed by the tracker (depending on kinematics) and several ECAL showers. In addition, the calorimeters must veto with extreme efficiency a wide variety of sub-dominant backgrounds, such as a hard bremsstrahlung photon undergoing a photo-nuclear reaction producing only a few energetic ($\mathcal{O}(1\ \mathrm{GeV})$) neutrons escaping from the nucleus.

These considerations call for a fast, high-precision tracking system and a high-speed, high-granularity Silicon calorimeter, used in conjunction with a hadron calorimeter to achieve the desired level of rejection. The LDMX concept plans to meet these challenges by leveraging technology under development for the silicon sampling calorimeter for the CMS high luminosity forward calorimeter upgrade [27], and the tracking technology developed for the HPS experiment [28].

The sensitivity of the LDMX experiment is shown in Fig. 3 for the thermal relic DM scenarios described previously. LDMX will have unprecedented sensitivity surpassing all existing and projected constraints by orders of magnitude for DM masses

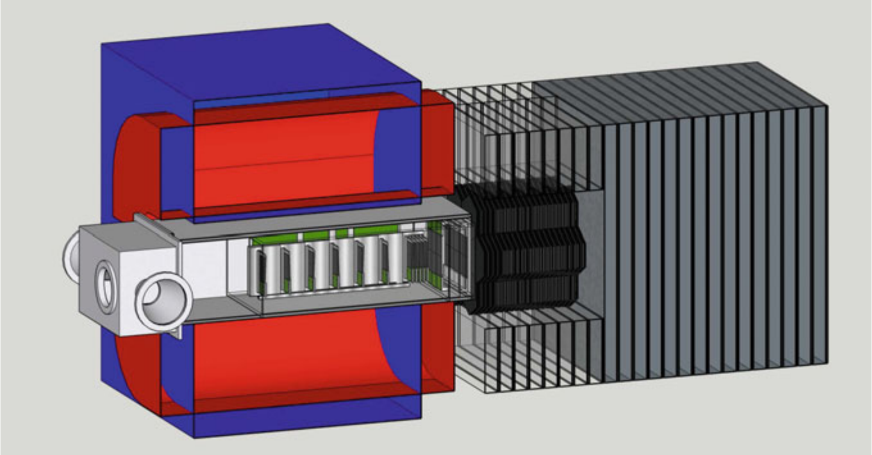

Fig. 5 A cutaway overview of a potential LDMX detector design showing, from left to right, the trackers and target in the spectrometer dipole, the forward electromagnetic, and hadronic calorimeters. The final design is still under study. Courtesy T. Nelson

below a few hundred MeV. LDMX aims in its first phase to fully explore the scalar and Majorana fermion thermal DM parameter space in that mass range, and the remaining possibilities in its second phase. The experiment will also greatly improve the sensitivity to invisible dark photon decays, asymmetric DM, ELDER/SIMP scenarios and light long-lived neutral particles.

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