Direct Deflection of Dark Matter

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Thematic Areas: (CF1) Dark Matter: Particle-like, (CF2) Dark Matter: Wave-like, (IF1) Quantum Sensors, (TF9) Astro-particle physics and cosmology, (TF10) Quantum Information Science

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Introduction: Recently, we have proposed a new approach ("direct deflection") to search for sub-MeV particle-like dark matter (DM) that exploits long-range interactions [1]. The approach is based on inducing collective effects in the DM fluid on detector length-scales that can leave a measurable trace in resonant detectors.

DM that is produced directly through its couplings to the thermal bath of the early universe provides a viable and compelling cosmological origin for its observed abundance. "Freeze-in" is one such example, in which out-of-equilibrium processes involving extremely feeble couplings between Standard Model (SM) and DM particles slowly populate the DM sector over cosmological timescales. For sub-MeV DM, independent bounds on new light forces that mediate such interactions motivate the consideration of long-ranged interactions with the electromagnetic sector of the SM. In these models, DM interacts with the SM through a kinetically mixed dark photon A' of mass $m_{A'} \lesssim 10^{-9}$ eV $\sim (100 \text{ m})^{-1}$ [2]. Hence, DM appears "millicharged" on $\lesssim 100$ m length-scales, allowing it to weakly couple to standard electromagnetic fields with effective charge $q_{\text{eff}} = \epsilon e'/e$, where ϵ and e' are the A' kinetic mixing parameter and gauge coupling, respectively, and e is the SM electric charge.

Overview: A charge-symmetric, spatially uniform DM population passes through a shielded region, with an electric field oscillating at angular frequency $\omega \sim 100$ kHz. We refer to this region as the "deflector." As millicharged DM passes through the deflector, it is subject to an electric force that separates positively and negatively charged particles. This creates a propagating wave train of alternating millicharge and millicurrent densities, which diffuse outwards due to dispersion in the DM velocity distribution. DM particles easily penetrate electromagnetic shielding, inducing small oscillating electromagnetic fields within a quiet shielded detection region. These fields have known oscillation frequency and phase, and can be measured using an electric field pickup antenna coupled to a resonant LC circuit and SQUID amplifier tuned to frequency ω. Relative to the DM wind, the apparatus rotates once per sidereal day, inducing a strong directionality as well as a large (> 1) fractional daily modulation to the signal. This provides an additional handle to discriminate a DM signal from unforeseen systematics or noise at the deflector frequency.

This technique is based on tested technology, complements and competes with other direct detection proposals in the keV-MeV mass-range, and is sensitive to much smaller masses, going beyond current astrophysical constraints for DM lighter than a keV. The anticipated reach of various experimental configurations is shown in Fig. 1.

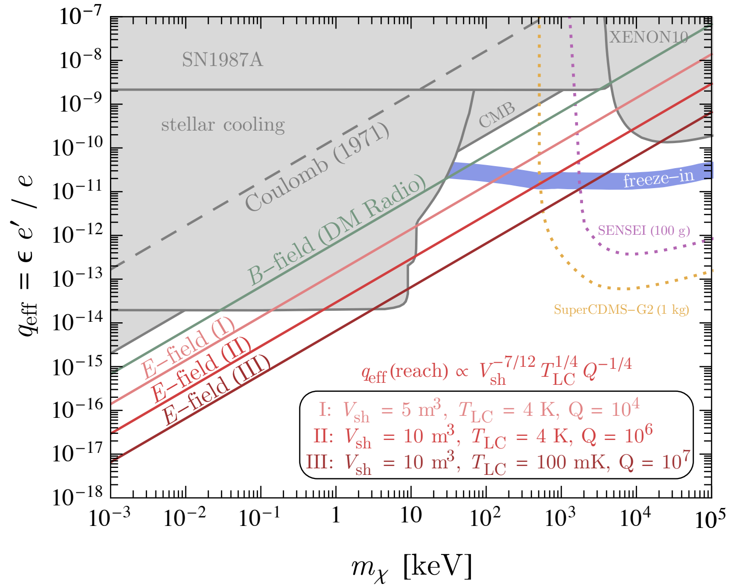

FIG. 1. From Ref. [1], the anticipated reach to millicharged dark matter in the $q_{\rm eff} - m_\chi$ plane for various experimental configurations of our setup, compared to existing constraints (shaded gray). In all cases, we assume a year of integration time, a spatially-averaged deflector field-strength of $\langle E_{\rm def} \rangle = 10$ kV/cm, and $\omega = 100$ kHz. The green line corresponds to the projected reach of a detector optimized for detection of magnetic fields, such as the DM Radio experiment [3]. The reach of dedicated LC resonators optimized for detecting electric fields is also shown. The lines labelled "E-field (I-III)" correspond to various deflector/shield volumes, LC circuit temperatures, and quality factors as indicated in the legend.

Experimental Prospects and Future Directions: A direct deflection apparatus has two components: the deflector and the detector. The deflector is a capacitor driven at high voltage and synced to a precise clock. This appears to be achievable without major technology R&D. The detector is a large, high-Q-factor resonant antenna, with dimensions and Q-factor both comparable to the DM Radio program [3]. However, an important distinction is that for DM Radio, the "large" element of the resonant LC circuit is the inductor (magnetic pickup), while direct deflection is most powerful with a large capacitative element for electric-field pickup. This is because the DM-induced electric fields downstream of a deflector are $\sim 1000\times$ larger than the corresponding magnetic fields, which are suppressed by the DM wind velocity $\sim 10^{-3}c$. For this reason, while the required R&D is similar in some respects to DM Radio, a separate effort with a focus on electric-field pickup is required. We welcome new collaborators interested in developing realistic detector and deflector concepts.

Similar techniques can be more generally applied beyond what is considered here. Such ideas include, e.g., the application of specifically engineered field configurations to accelerate, focus, or trap DM near standard direct detection scattering targets or resonant detectors. Furthermore, generalizations of the proposed experimental setup could be used to search for alternative types of DM-SM interactions. For example, oscillating spin-polarized samples could be used to deflect and detect particle DM that interacts through macroscopic spin-coupled forces. We leave such considerations to future work.

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