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Direct detection of dark matter in the eV-to-GeV mass range

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Abstract

Identifying the nature of dark matter (DM) is one of the most important questions in particle physics and cosmology today and direct-detection experiments play an essential role in this endeavor. The search for DM particles with masses a few orders of magnitude below the proton mass ("sub-GeV DM") represents an important new experimental frontier that has been receiving increased attention, e.g. [1, 2, 3, 4].

Recent advances in silicon Charge Coupled Devices with an ultralow readout noise, so-called "skipper-CCDs", have demonstrated this technology as a powerful probe for sub-GeV dark matter [5]. We propose a skipper-CCD experiment with an active mass of 10 kg to reach unprecedented sensitivity to dark matter-electron scattering, for masses as low as 500 keV, as well as to bosonic dark matter that is absorbed by electrons, for masses as low as 1 eV. This experiment will also have enhanced sensitivity to low-mass dark matter interacting with nuclei.

Scientific Rationale

Traditional direct-detection searches, which look for DM particles scattering elastically off of nuclei, typically have very little sensitivity to sub-GeV mass DM. Indeed, the best current bounds are limited to very large cross sections below 1 GeV and are absent below ~ 120 MeV [6, 7, 8, 9]. While improved sensitivity at low DM masses to nuclear recoils from elastic scattering is possible with the next generation of experiments, it was first suggested in Ref. [1] that improved sensitivity to DM masses well below the GeV scale is possible by searching for signals induced by inelastic processes, for which a DM particle is able to deposit much more energy compared to the elastic scattering off of nuclei. In particular, one of the most promising avenues is to search for one or a few ionized electrons that are released due to DM particles interacting with electrons in the detector [1].

The scientific objectives presented here can be achieved using the skipper-CCD sensor technology, which we aim to push to its full potential with a detector of active mass of 10 kg. Description of the detector R&D associated to this proposal has been submitted to the working group GT08 under the name: *Toward a 10-kg skipper-CCD sensor*.

The proposed experiment will have sensitivity to single electrons, and will have zero background events in the 2–10 electron ionization-signal region ("dark current", i.e. thermal fluctuations of electrons from the valence to the conduction band, presents an irreducible source of single-electron events). Such an experiment will have unprecedented sensitivity to sub-GeV DM that interacts with electrons. In particular, this experiment can probe DM masses in the range of 500 keV to 1 GeV when the DM scatters off electrons through, for example, a "heavy" or "ultra-light" mediator [1, 10, 11, 12, 13], see Fig. 1. This would probe many well-motivated sub-GeV DM which have been combined into the orange region labeled "Key Milestone" in Fig. 1 (see [1, 2, 3, 4, 11] and references therein for additional discussions of these benchmark models). The same detector is also sensitive to bosonic DM that is absorbed by electrons, for DM masses in the range of ~1.1 eV (the silicon band gap) to ~1 keV, see Fig. 2 [14, 15, 16].

The ability to measure precisely the number of electrons will also, in fact, allow unprecedented sensitivity to DM interacting with nuclei, since such interactions can generate one or more ionized electrons in several ways: (i) from the interactions of the recoiling nucleus with the surrounding target material, (ii) from a low-energy photon that is radiated from the nucleus during the DM scattering event, where the photon subsequently converts in the material to electrons [17], or (iii) from the Migdal ffect, where the recoiling atom is ionized [18, 19]. The latter effect dominates for low-mass DM-nuclear scattering (see e.g. [20]), and would generate multiple electrons, which are easy to measure with the proposed experiment.

A setup with a single skipper-CCD already produced world leading limits in a direct-detection search for sub-GeV DM [21, 22] and detectors of 100 g (SENSEI [21, 22]) and 1 kg (DAMIC-M [23]) mass are under construction. A 10 kg experiment will extensively probe sub-GeV DM, with discovery sensitivity even if this kind of DM is only a small fraction of the amount required to explain the existing astrophysical and cosmological observations.

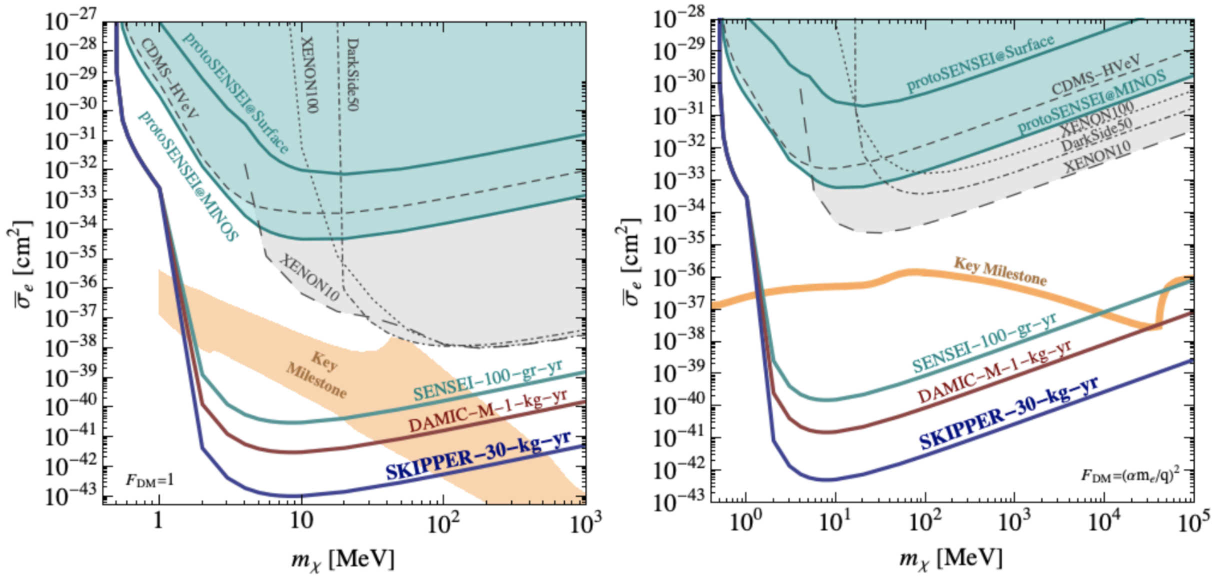

Figure 1: Projected sensitivity to dark-matter-electron scattering of a low-background silicon skipper-CCD array, assuming a 30 kg-year exposure (SKIPPER-30-kg-yr, blue line). Zero background for events with two or more electrons, and a fixed single-electron dark-count event rate are assumed. Projected sensitivities for SENSEI and DAMIC-M, two experiments under construction based on the skipper CCD technology, are shown with cyan and red solid lines, respectively. Existing experimental constraints are shown as shaded areas. The orange region labelled Key Milestone indicates expectations for well motivated theoretical models.. The left (right) plot assumes the dark-matter-electron interaction is mediated by a heavy (light) mediator**.** Forecasts and compilation of theoretical predictions by R. Essig [1, 2, 11, 12].

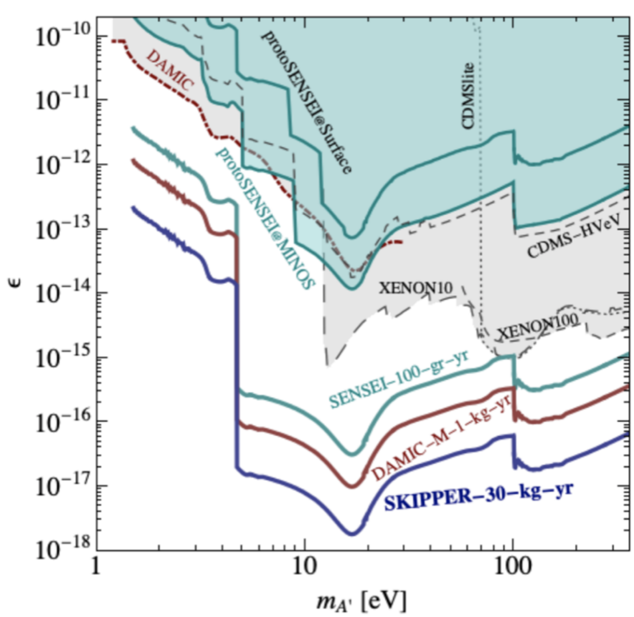

Figure 2: Projected sensitivity to dark photon kinetic mixing parameter, ε, for adsorbing dark-photon on electrons for a low-background silicon skipper-CCD array, assuming a 30 kg-year exposure (SKIPPER-30-kg-yr, blue line). Zero background for events with two or more electrons, and a fixed single-electron dark-count event rate are assumed. Projected sensitivities for SENSEI and DAMIC-M are shown with cyan and red solid lines, respectively. Existing experimental constraints are shown as shaded areas. Forecasts and compilation of theoretical predictions by R. Essig [1, 2, 11, 12].

Skipper CCDs for Dark Matter searches

Charge-coupled devices (CCDs) are pixelated sensors commonly used in scientific applications. Charge produced by ionizing radiation in the CCD is read out through an output amplifier hosted in the device. Arrays of large-area thick fully-depleted CCDs have been successfully deployed by the DAMIC experiment in a low-background environment deep underground to search for the ionization signals from particle DM [24]. However, the scientific reach of CCDs for probing electron recoils from DM interactions was limited by the root-mean-square (RMS) noise of $2e^-$ per pixel. Recently, single-electron charge resolution has been demonstrated [5, 23] with a skipper-CCD - a concept that was first developed in the 1990s [25, 26].

In conventional CCD readout, a reset pulse is first applied to remove the previous pixel's charge; a reference voltage is then measured, which corresponds to the charge left over by the reset; lastly, the pixel charge is transferred to the output node and added to the reset charge, and the corresponding signal voltage is measured (Figure 3a).

The difference between the signal and the reference voltage (V integrated over time T), usually performed in an analog circuit, provides a low-noise measurement of the pixel charge. This Correlated Double Sampling (CDS) technique [27] cancels the reset noise - the reset charge fluctuates after each reset - and also works as a filter for frequencies above ~1/T. An optimal integration time T is then found to minimize the noise. While larger integration times T decrease the white noise contribution, if T gets too large, the 1/f noise of the amplifier becomes dominant. For example in the DAMIC experiment at SNOLAB, which uses conventional CCDs to search for DM, an optimal RMS noise of ~$2e^-$ is obtained for T = 40 µs.

To reach noise levels well below $1e^-$, skipper-CCDs measure the pixel charge by averaging over a large number of repetitive, uncorrelated CDS measurements. The readout principle is illustrated in Fig. 3b. After a CDS sequence is completed, the pixel charge is moved out of the readout node and stored, and another CDS sequence is initiated. The charge is measured N times, and by taking the average of these

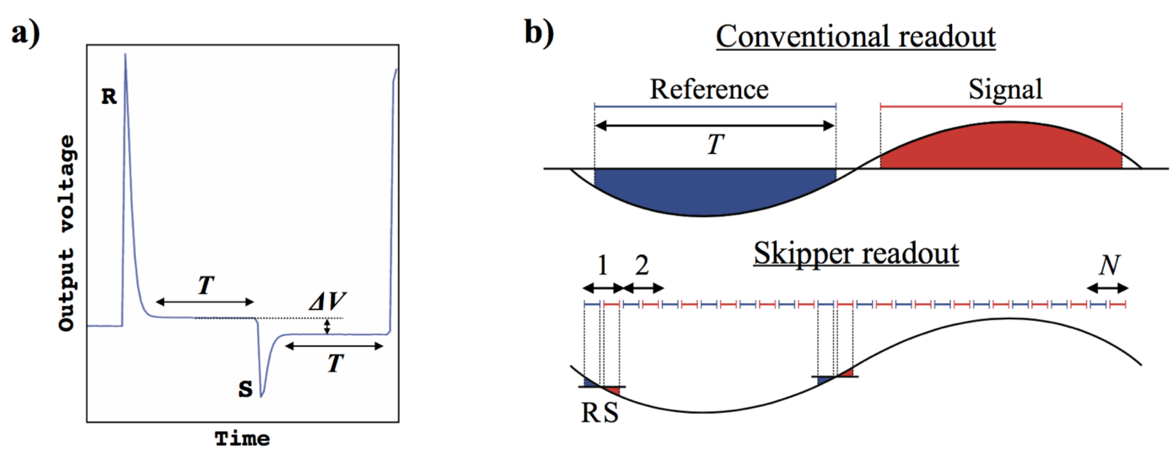

Figure 3 : a) CCD output signal for one pixel illustrating the principle of CDS (R: reset, S: charge transfer). b) Skipper vs. conventional readout: during the same time of a conventional readout, the pixel charge is measured N times in skipper mode. The effect of a low-frequency noise waveform is much smaller in skipper mode because the waveform changes very little during the short CDS sequence.

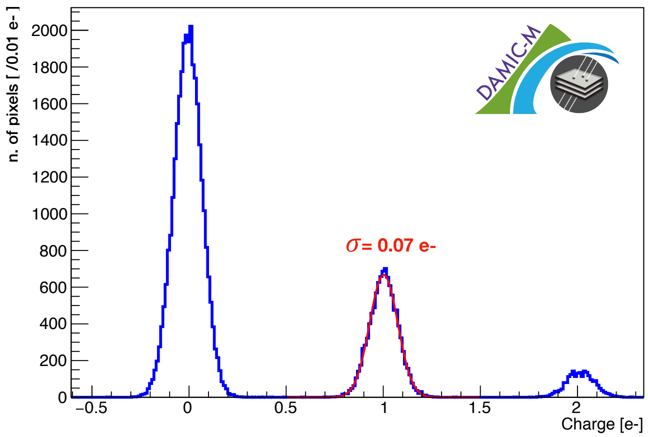

Figure 4: Pixel charge distribution of a DAMIC-M skipper CCD. Peaks corresponding to pixels with zero, one and two charges are clearly distinguished. A Gaussian fit to the charge distribution yields a resolution of 0.07 electrons [23].

measurements the white noise is reduced by 1/√N. Most importantly, the effect of low-frequency 1/f noise is drastically reduced, since the integration time of each measurement is much shorter than in the conventional readout. Single electron resolution can then be achieved, as recently demonstrated by the DAMIC-M experiment with large-size CCDs [23], see Fig. 4.

We note that while many other concepts and target materials have been considered in the literature for detecting sub-GeV DM-electron interactions (see [4] for summaries), skipper-CCDs are currently the only demonstrated technology to probe low-energy electron recoils without significant backgrounds [5, 21, 22], and without any events containing three or more electrons.

In addition, to its unprecedented charge resolution, a skipper-CCD experiment presents some other unique advantages for a zero-background multi-kg detector compared to other proposed sub-GeV DM direct-detection technologies:

- Very low leakage current, $< 10^{-21}$ A/cm^2 at the operating temperature of 140 K [28]; fluctuations of a background dark current may significantly limit the detector sensitivity [29]
- Excellent spatial resolution
- Background identification and rejection, 3D reconstruction for surface events, follow up of radioactive decay chains using spatial correlation of events.

Technical details of the proposed detector can be found in the contribution to the working group GT08 *Toward a 10-kg skipper-CCD sensor*. Briefly, we mention the main technical challenges that will need to be addressed by a dedicated R&D effort:

1. A new method needs to be developed for the fabrication of the large number of skipper-CCDs required by the 10 kg experiment. The foundry currently used for the skipper-CCD fabrication will discontinue the production line for these sensors. This challenge also represents a new opportunity for migrating the fabrication of skipper-CCDs into the more modern CMOS technology.

2. The second technical challenge is related to the low noise readout needed for a skipper-CCD experiment with 10 kg of active mass. This readout system requires several thousand channels, comparable in size with that of the largest CCD cameras ever built for astronomy, but with more stringent noise requirements.

3. Finally, the 10 kg skipper-CCD experiment requires a background more than an order of magnitude lower than planned for SuperCDMS at SNOLAB [30]. This requirement comes from a goal of zero ionization events in the 2-10 e- signal range.

The IN2P3 is already invested in the search for dark matter using the skipper CCDs technology, with the DAMIC-M experiment to be installed at the Laboratoire Souterrain de Modane. Strong expertise in the areas required for the development of a 10 kg skipper-CCD detector exists at the IN2P3, notably in CMOS technologies and in read-out electronics (with dedicated chips developed for LSST and DAMIC-M), in low-background techniques, and in simulations and data analysis. We foresee a close collaboration with international partners for this ambitious project. In particular, we have strong connections with groups in the US (FERMILAB, University of Chicago, University of Washington and PNNL) who have already submitted a proposal to the DOE program "Dark Matter New Initiatives" for the development of 10 kg skipper-CCD experiment.

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