The next decade in the Direct Detection of sub-GeV Dark Matter

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Cosmic Controversies, Chicago, Oct 7, 2019
Traditional Direct Detection strategy:

look for nuclear recoils from elastic WIMP-nucleus scattering
Constraints & projections from elastic nuclear recoils

- dozens of experiments over last several decades
- WIMP searches well-established with multi-ton-scale experiments taking data soon
- How probe lower masses?

Limit plotter: Saab & Figueroa

large regions of unexplored parameter space!
Several Well-Motivated Hidden-sector DM Candidates

Can obtain relic abundance from freeze-out, an initial asymmetry, freeze-in, SIMP, ELDER…

need to probe nuclear and electron interactions

Limit plotter: Saab & Figueroa
Probing sub-GeV DM w/ elastic nuclear recoils

$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{X,N}^2 \nu_X^2}{m_N} \approx \frac{2m_X^2 \nu_X^2}{m_N}$

- will soon have phonon detectors w/ O(1 eV) sensitivity
- probe 20-50 MeV DM

**signals from recoiling nucleus**

**heat/phonons**

**electronic excitations**

- e.g. M. Pyle et.al. (DoE BRN report)
- Hertel, Biekert, Lin, Velan, McKinsey (Superfluid $^4$He)
Probing sub-GeV DM w/ elastic nuclear recoils

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\[ E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu^2_{xN}v_x^2}{m_N} \approx \frac{2m^2_xv_x^2}{m_N} \]

- ultimate sensitivity, to a single ~1 meV phonon, probes 1 MeV DM

Maximum \( E_R \) [eV]

- Xe
- Si
- He

Signals from recoiling nucleus

heat/phonons

electronic excitations

Dark Matter Mass [MeV]

probe 20-50 MeV DM
Probing sub-GeV DM w/ elastic nuclear recoils

\[ E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_X^2}{m_N} \approx \frac{2m_{\chi}^2 v_X^2}{m_N} \]

\[ E_{kin} \gg E_R \]
To probe DM $\ll$ GeV, look for signals from “inelastic” processes

- Can transfer $O(1)$ of $E_{\text{kin}}$
- A detector sensitive to:
  - 1 eV, probes $\sim$500 keV DM (already demonstrated!)
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Some Inelastic Processes giving $E_{\text{max}} \sim (1/2) m_{\chi} v_{\chi}^2$

Electron excitation/ionization in e.g. noble-liquids or semiconductors (DM-electron scattering)

![Diagram of electron excitation/ionization in noble liquids and semiconductors]

- **noble liquids**
  - $E_{\text{binding}} \sim 10 \text{ eV}$
  - $m_{\text{threshold}} \sim 5 \text{ MeV}$

- **semiconductors**
  - $E_{\text{binding}} \sim 1 \text{ eV}$
  - $m_{\text{threshold}} \sim 500 \text{ keV}$

Typically produces a signal of only **one** to a **few** electrons

Some Inelastic Processes giving $E_{\text{max}} \sim (1/2)m_\chi v_\chi^2$

Electron excitation/ionization in e.g. noble-liquids or semiconductors (DM-electron scattering)

Measuring small ionization signals is already demonstrated!

two-phase TPCs (XENON10/100/1T, DarkSide-50)

Skipper-CCDs (SENSEI)
TES (SuperCDMS)
DEPFET (DANAE)

Planned experiments include

SENSEI (100 g)
DAMIC-M (1 kg)
10 kg Skipper-CCD detector
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Electrons from Migdal effect (DM-nucleus scattering)

A detector sensitive to small ionization signals will be sensitive to both DM-e and DM-N interactions (w/ same mass threshold)

e.g. Vergados, Ejiri 2004; Ibe, Nakano, Shoji, Suzuki 2017

Fig. credit: Dolan, Kahlhoefer, McCabe RE, Pradler, Sholapurkar, Yu Baxter, Kahn, Krnjaic
Some Inelastic Processes giving $E_{\text{max}} \sim (1/2)m_{\chi}v_{\chi}^2$

**Molecular Excitations (DM-nucleus scattering)**

RE, Perez-Rios, Ramani, Slone (2019)

Excited molecule relaxes to ground state emitting **multiple** photons of energy $O(100-250 \text{ meV})$; detect w/ ultrasensitive photodetectors

probe spin-independent **and** spin-dependent interactions
Some Inelastic Processes giving $E_{\text{max}} \sim (1/2)m_{\chi}v_{\chi}^2$

Create optical phonons in polar materials, e.g. GaAs, sapphire (DM-phonon scattering)

probe sub-MeV DM if have sensitivity to 10’s of meV of phonons

Knapen, Lin, Pyle, Zurek
Griffin, Knapen, Lin, Zurek
The next decade in sub-GeV DM direct-detection
from DoE High-Energy Physics Basic Research Needs Report

nuclear couplings

New detection concepts & technological advances enable exploration of vast new regions of parameter space

- solid: ready for development
- dashed: short-term R&D
- dotted: long-term R&D

(doesn’t include projections for e.g. Migdal effect)
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from DoE High-Energy Physics Basic Research Needs Report

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The next decade in sub-GeV DM direct-detection

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Some experiments ready soon:

Skipper-CCD on balloon/satellite
(see backup slides)

LBEC (liquid Xe)
(see backup slides)

SENSEI
(silicon Skipper CCDs)
The SENSEI Collaboration

“Sub-Electron-Noise Skipper-CCD Experimental Instrument”

Fermilab:

Stony Brook:
• N. Bachhawat, L. Chaplinsky, R. Essig, D. Gift, Dawa, S. Munagavalasa, A. Singal

Tel-Aviv:

U. Oregon:
• T.-T. Yu

Fully funded by Heising-Simons Foundation & Fermilab
Detection Concept

silicon Skipper-CCD

~million pixels

developed in collaboration between FNAL & LBNL MicroSystems Lab
DM typically creates only one or a few electrons per pixel
Detection Concept

DM typically creates only one or a few electrons per pixel

silicon Skipper-CCD

~million pixels
Detection Concept

DM typically creates only one or a few electrons per pixel.

Silicon Skipper-CCD

Repeatedly measure charge to achieve sub-electron readout noise.

~million pixels
Detection Concept

DM typically creates only one or a few electrons per pixel.

silicon Skipper-CCD

~million pixels

repeatedly measure charge to achieve sub-electron readout noise
DM typically creates only one or a few electrons per pixel

repeatedly measure charge to achieve sub-electron readout noise

silicon Skipper-CCD

~million pixels
Detection Concept

DM typically creates only one or a few electrons per pixel.

repeatedly measure charge to achieve sub-electron readout noise

silicon Skipper-CCD

~million pixels

DM

conduction band

valence band

pixel

hole

electron

CCD
Can count individual electrons, w/ ~zero noise

Si: traditional CCD

Si: Skipper-CCD

Can count individual electrons, w/ ~zero noise

Si: traditional CCD

Si: Skipper-CCD

rms noise $\sim 3\ e^-$
(single measurement)

rms noise $\sim 0.06\ e^-$!
(repeated measurements)

successfully demonstrated by SENSEI in a Fermilab LDRD project

enables a super-sensitive search for DM
SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL

• tiny exposures:
surface: ~0.02 gram-days
MINOS: ~0.246 gram-days
SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration, 1804.00088 & 1901.10478, PRL

• tiny exposures:
surface: ~0.02 gram-days
MINOS: ~0.246 gram-days

DAMIC@SNOLAB
(w/ ordinary CCDs w/ high-quality silicon, 200 gram-days)

1907.12628
SENSEI projection for 100 g of science-grade Skipper-CCDs

• orange: “freeze-in DM”

SENSEI: 100 g @ SNOLAB (funded, 2020)

new sensors are already being tested

[see backup slides for other models like SIMP, ELDER, freeze-out, asymmetric]
SENSEI & other planned Skipper-CCD detectors

SENSEI: 100 g @ SNOLAB (funded, 2020)

DAMIC-M: 1 kg @ Modane (funded, 2023)

10 kg Skipper-CCD (R&D funding announced last week by DoE)

J. Estrada, A. Chavarria, RE, B. Loer, P. Privitera; M. Crisler, M. Fernandez-Serra, R. Saldanha, J. Tiffenberg
SENSEI & LBECA have sensitivity also to **Nuclear Interactions from Migdal effect**

XENON10 sets best limit between 5 to 30 MeV

SENSEI & LBECA expected to improve by orders of magnitude

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RE, Pradler, Sholapurkar, Yu

see also Baxter, Kahn, Krnjaic
Summary

• A much wider class of DM models are now actively being considered compared to ~10 years ago, including several well-motivated sub-GeV DM candidates.

• Direct detection of sub-GeV DM is now possible, with several competing proposals.

• SENSEI and other experiments have first results and will probe vast new regions of uncharted territory in next few years.
Thank you!
SENSEI sensitivity to Benchmark Models

mediator: “heavy” dark photon

Models:
- thermal scalar
- asymmetric fermion
- SIMP
- ELDER

\[ \sigma_e [\text{cm}^2] \]
\[ m_\chi [\text{MeV}] \]
\[ F_{DM} = 1 \]
\[ m_{A'} = 3 m_\chi \]

Beam dump Collider WIMP–DD Searches
Best current constraints on DM-e\(^{-}\) scattering >5 MeV from liquid xenon detectors

\[ \sigma_{e} < \text{[cm}^2\text{]} \]

\[ m_\chi \text{[MeV]} \]

RE, Mardon, Volansky, 2011
RE, Manalaysay, Mardon, Sorensen, Volansky, 2012
RE, Volansky, Yu 2017
DarkSide-50, 2018
XENON1T, 2019
The LBECA Collaboration

“Low Background Electron Counting Apparatus”

LBNL:
• P. Sorensen

LLNL:
• A. Bernstein, S. Pereverzev, J. Xu

Purdue
• F. M. Clark, A. Kopec, R. Lang

Stony Brook:
• R. Essig, M. Fernandez-Serra, C. Zhen

UC San Diego:
• K. Ni, J. Long, J. Ye

R&D partially funded by US DoE
Proposed Experiment: LBECA

“Low Background Electron Counting Apparatus”

Goal:
100 kg liquid xenon detector w/o backgrounds that have plagued previous detectors

partially funded by DoE Detector R&D program

Bernstein, Clark, RE, Fernandez-Serra, Kopec, Lang, Long, Ni, Pereverzev, Sorensen, Xu, Ye, Zhen…
Detection Concept

• delayed e⁻ extraction across liquid-gas interface
• photoionization of negatively charged impurities
• exposed metal surfaces

Sensitive to single electrons!

But large backgrounds:

LBECa: a ~100 kg detector, ideally w/o these backgrounds
Current bounds on DM w/ large interactions

assumes dark photon mediator

Surface data (from prototypes by SENSEI & CDMS-HV) are most constraining at high cross sections
A Skipper-CCD on a satellite or balloon can probe DM with even larger interactions.

Balloon- & satellite-borne detector being explored in collaboration w/ scientists at FNAL & JPL.
Is there a DM model w/ such large interactions?

Maybe…

a subdominant component of DM interacting w/ ultralight dark photon?

see also 1908.06986, in which subdominant millicharged DM interacts w/ CDM, opening up more parameter space to explain EDGES

Liu, Outmezguine, Redigolo, Volansky