Skipper-CCDs and the SENSEI Search for Sub-GeV Dark Matter

Sho Uemura

Tel Aviv University
for the SENSEI Collaboration

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The search for sub-GeV dark matter

- Direct-detection experiments have focused on WIMP DM down to $O(\text{GeV})$
  - Well motivated ("WIMP miracle"), experimentally accessible (nuclear recoils)
- New complementary searches for lower masses
  - New theoretical interest in dark sectors
  - New technologies with lower thresholds
- One promising direction: Skipper-CCDs for electron recoil, with thresholds near the silicon bandgap
  - Many others, both for NR and ER — refer back to M-C. Piro Monday talk
- The DM results I show are for the 2020 test run of SENSEI (arXiV:2004.11378), but the program is just getting started
Electron recoils in silicon

- We look for DM interactions with electrons in silicon
  - DM-electron scattering: $m_\chi$ in the MeV-GeV range
    - Energy transfer is a few eV, good match to semiconductor band gap
  - DM absorption: bosonic DM at the eV scale
    - Energy transfer equals $m_\chi$
- Energy transfer creates ionization, and we measure the number of electron-hole pairs
Strategy

- **Challenges:**
  1. Unambiguously ID $1e^-, 2e^-$ events
  2. Minimize background sources of charge
  3. Minimize coincidence background

- **Our starting point is the CCD**
  - Mature technology, used for DM in DAMIC
  - Achieves #3 through pixel segmentation

- **Same physics as EDELWEISS, CDMS HV — very different detector**
CCD searches for dark matter

- DAMIC (40 g, complete): first CCD DM experiment
- SENSEI ($O(100)$ g starting 2021): first DM experiment with Skippers
  - Several physics results (most recent 2020) from prototypes and test runs; full-scale experiment under construction
  - Active mass and radiopurity similar to DAMIC
- DAMIC-M ($O(1)$ kg starting 2023): next-generation Skipper experiment
  - Scaling up in mass, with corresponding improvement in radiopurity
- Oscura ($O(10)$ kg, in development): large-scale
  - Major R&D for readout, cooling, integration
The SENSEI Collaboration

Fermilab:

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

Tel-Aviv:

U. Oregon:
- T.-T. Yu

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& leveraging R&D support from Fermilab
CCDs

- Holes drift through the substrate and collect in pixels near the surface.
- Charge packets are shifted to a shared amplifier (1 per quadrant) for readout.
- All CCDs for DM are designed by LBNL MSL, based on fully-depleted CCD designs proven in astronomy.
  - High-efficiency charge collection and transport, low dark current.
  - Thickness limited only by commercial foundry capabilities.
- Conventional CCDs are limited to noise of $\sim 2e^-$. 
Skipper readout

- In a conventional CCD, charge moved to the sense node must be drained
  - You can integrate longer, but you cannot beat the $1/f$ noise
- The Skipper amplifier lets you make multiple measurements!

![Diagram of Skipper readout]
Skipper readout

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Regular CCD

Pixel charge measurement

Skipper CCD

High frequency noise

Low frequency noise

pedestal
Sub-electron readout noise

- Skipper noise scales as $1/\sqrt{N}$: trade resolution for speed
  - For the 2020 DM search we operated at $N = 300$ (13 ms/pixel), noise of $\sim 0.14e^-$
- We can count single electrons: self-calibrating charge measurement with zero noise
The SENSEI CCDs

- High-resistivity silicon 675 $\mu$m thick, $1.59 \times 9.42$ cm$^2$
- $6144 \times 886$ pixels, 15 $\mu$m pitch (1.925 grams active)
- The first dedicated production of Skipper CCDs for dark matter
MINOS setup

- Shallow underground site (MINOS cavern at Fermilab), simple lead shield
- CCD at 135 K, biased at 70 V
Images!

- This is 1/6th of one quadrant
- 20 hours exposure, 5.15 hours readout
  - During readout, the image continues to accumulate hits and charge
- 22 images in the blinded dataset

<table>
<thead>
<tr>
<th>Search</th>
<th>Exposure post-cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1e^-$</td>
<td>1.38 gram-days</td>
</tr>
<tr>
<td>$2e^-$</td>
<td>9.17 gram-days</td>
</tr>
<tr>
<td>$3e^-$</td>
<td>11.87 gram-days</td>
</tr>
<tr>
<td>$4e^-$</td>
<td>11.70 gram-days</td>
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</tbody>
</table>
Searches and backgrounds

- Single-electron: background-dominated
- Multiple electrons (single-pixel or cluster): low-background
  - Coincidence of $1e^-$ processes
  - True multi-$e^-$ processes

- $1e^-$ processes
  - Local sources of charge: high-energy clusters (ionizing radiation), amplifier luminescence, CCD defects
  - Spatially uniform sources of charge
    - Spurious charge: charge generated during readout
    - Intrinsic dark current: charge generated during exposure by thermal excitation
  - Skippers give us new insight into these processes: paper in prep

- Multi-$e^-$ processes: rare but irreducible
  - Compton scattering
  - Partial charge collection
Localized charge from high-energy events

- **Bleeding**: charge “left behind” by charge transfer
- **Halo**: excess of charge near high-charge pixels
  - Probably near-bandgap photons from Cherenkov radiation and electron-hole recombination (see arXiv:2011.13939)
- **Loose clusters**: regions with high charge density
  - May be Cherenkov photons (reflected, or generated outside of CCD)
- After cuts, charge density of $3.188(90) \times 10^{-4} \, e^-/\text{pixel}$
Spurious charge

- Measurements with shorter exposures show a limiting value for the CCD charge: $1.66(12) \times 10^{-4}$ $e^-$/pixel
  - Half of the $1e^-$ events we see are due to spurious charge!
  - Optimization of the CCD voltage waveforms will reduce this background in future runs
- Subtracting the exposure-independent charge, our $1e^-$ rate is $1.59(16) \times 10^{-4}$ $e^-$/pixel/day
Intrinsic dark current

- Subtracting the exposure-independent charge, our 1e- rate is $1.59(16) \times 10^{-4}$ $e^-$/pixel/day.
- Intrinsic dark current is the usual suspect:
  - Thermal generation of electron-hole pairs, mediated by lattice defects.
- However:
  - Extrapolation from higher temperatures (dashed black line) predicts $\lesssim 1 \times 10^{-5}$ $e^-$/pixel/day at our operating temperature of 135 K.
    - Suppressing surface dark current gets us from red data points to blue.
- High-quality silicon has made this a subdominant background.
1\text{e}^- \text{ rate vs. shielding}

- We have data with and without the outer ring of lead bricks
- Factor of 3 reduction in the rate of high-energy tracks $\rightarrow$ similar reduction in the 1\text{e}^- rate
  - Radiation generates charge in halos, in loose clusters, and uniformly
  - Better shielding will very likely further reduce our 1\text{e}^- rate
Multi-\( e^- \) backgrounds

- At the low-energy end of the Compton spectrum, a gamma ray can create arbitrarily small-energy electron recoils
  - DAMIC and SENSEI efforts to measure this spectrum and compare to theory

- Depending on details of processing, some CCDs have a highly-doped backside layer with partial charge collection: this can create low-charge events
  - DAMIC and SENSEI are affected, but future CCDs will not have this layer
Multi-$e^-$ searches

- We observe 5 $2e^-$ pixels and no 3, 4$e^-$ clusters (adjacent nonempty pixels)
- Some multi-$e^-$ events will be lost when they diffuse
  - We calibrate the diffusion width using muon tracks and simulate the geometric efficiencies: 22.8% for $2e^-$ to stay in one pixel, 76.1%, 77.8% for 3, 4$e^-$ to form a contiguous cluster
- Now we can put limits on the rate of events

<table>
<thead>
<tr>
<th>Charge bin</th>
<th>$1e^-$ cuts</th>
<th>90% CL</th>
</tr>
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<tbody>
<tr>
<td>$1e^-$</td>
<td>525.2 events/g-day</td>
<td></td>
</tr>
<tr>
<td>$2e^-$</td>
<td>4.449 events/g-day</td>
<td></td>
</tr>
<tr>
<td>$3e^-$</td>
<td>0.255 events/g-day</td>
<td></td>
</tr>
<tr>
<td>$4e^-$</td>
<td>0.253 events/g-day</td>
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Limits from SENSEI@MINOS

- New record lows for semiconductor detectors and DM searches at these thresholds
- The derived DM constraints are also world-leading
  - Left to right: $F_{DM} = 1$ scattering (heavy mediator), $F_{DM} = (\alpha m_e/q)^2$ scattering (light mediator), absorption
SENSEI@SNOLAB

- We are building the full-scale SENSEI experiment, deep underground at SNOLAB with a low-background shield
- Installation in progress by SNOLAB team
Backup: CCD amplifiers

- Floating diffusion: standard CCD amplifier
- Floating gate: used in our Skippers
  - Enables nondestructive readout at the cost of S/N
- SiSeRO: under development by MIT-LL
  - Best of both worlds: nondestructive, and excellent S/N
  - Possible option for Oscura

![Diagram of CCD amplifier components]

- Floating gate
- Output gate
- Summing well
- SiSeRO
- pMOSFET
- Charge packet
- CCD channel

Sho Uemura
SENSEI
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