

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

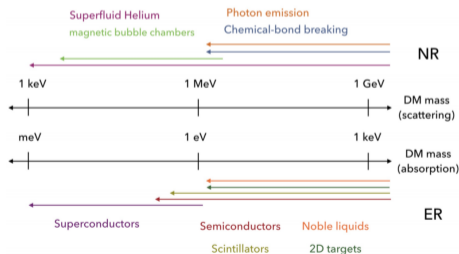
Sho Uemura

Tel Aviv University
for the SENSEI Collaboration

SU was supported in part by the Zuckerman STEM Leadership Program

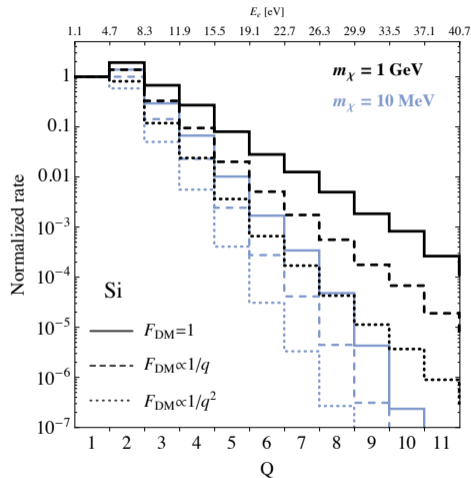
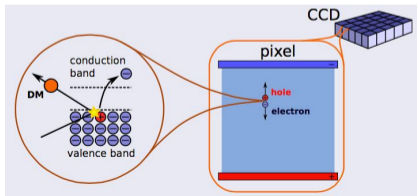
The search for sub-GeV dark matter

- 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



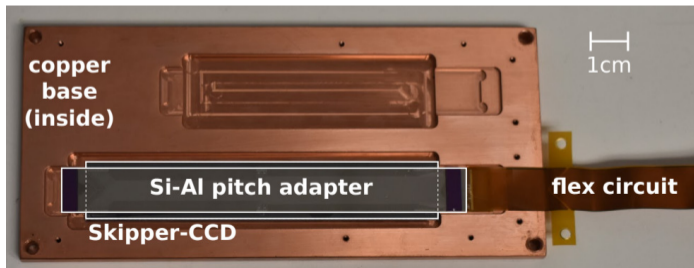
Electron recoils in silicon

- We look for DM interactions with electrons in silicon
 - ▶ DM-electron scattering: m_χ 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_χ
- Energy transfer creates ionization, and we measure the number of electron-hole pairs



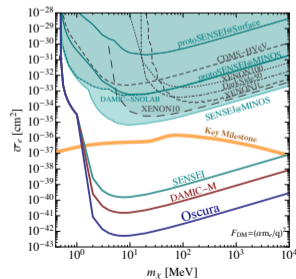
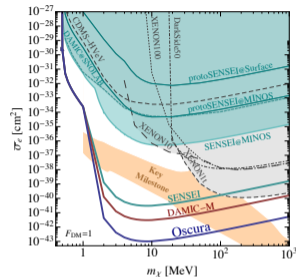
Strategy

- 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:

- F. Chierchie, M. Cababie, G. Cancelo, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez-Moroni, D. Rodrigues, M. Sofo-Haro, L. Stefanazzi, J. Tiffenberg

Stony Brook:

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

Tel-Aviv:

- L. Barak, I. Bloch, E. Etzion, A. Orly, S. Uemura, T. Volansky

U. Oregon:

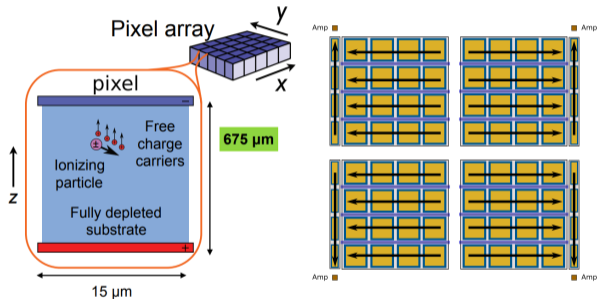
- T.-T. Yu

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& leveraging R&D support from Fermilab



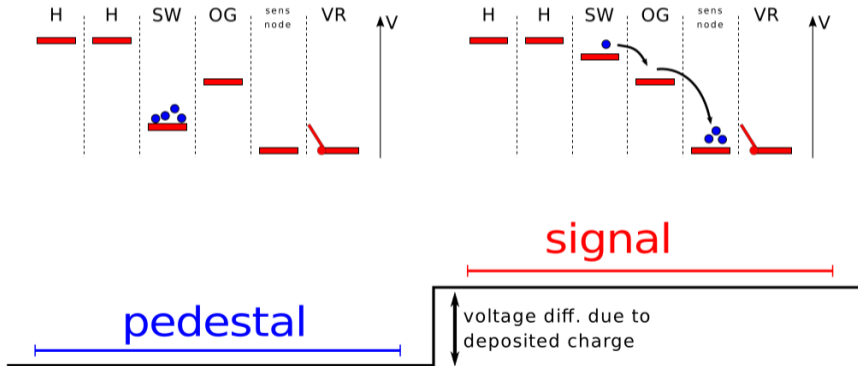
CCDs

- 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 $\sim 2e^-$



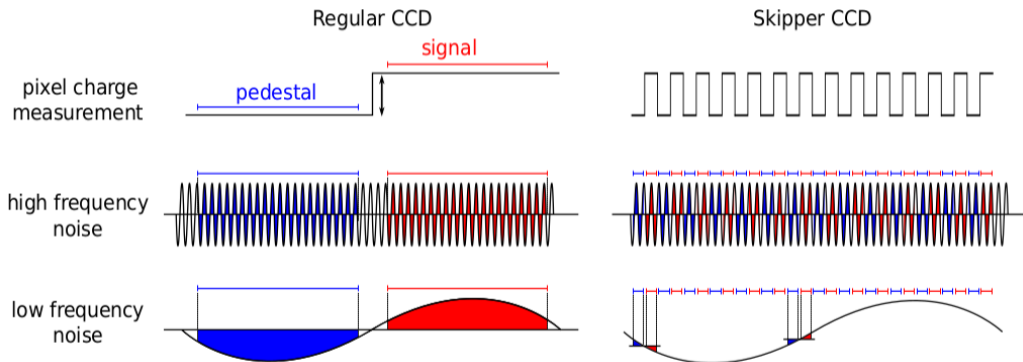
Skipper readout

- 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!



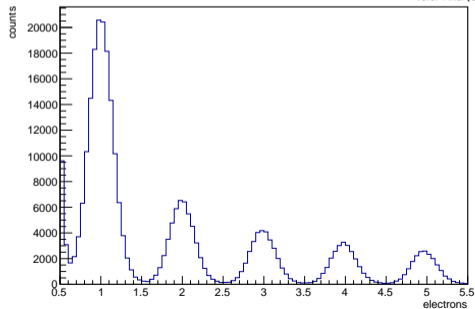
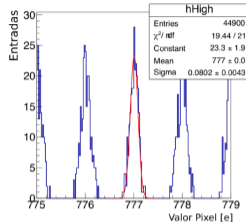
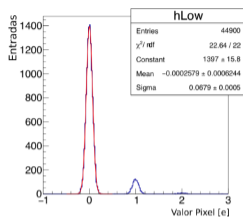
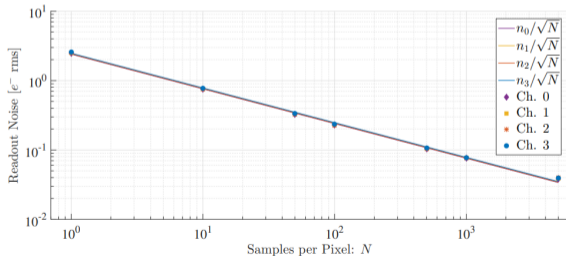
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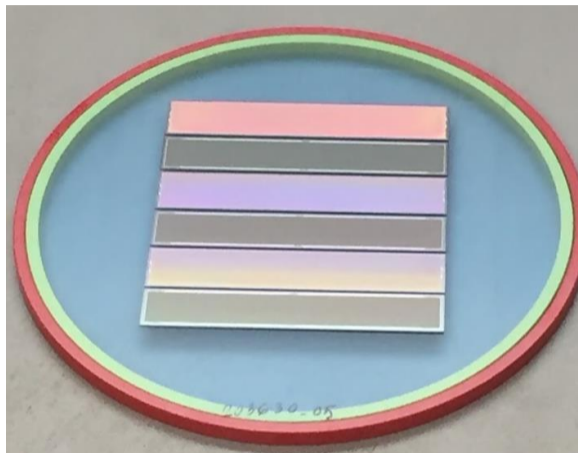
Sub-electron readout noise

- 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



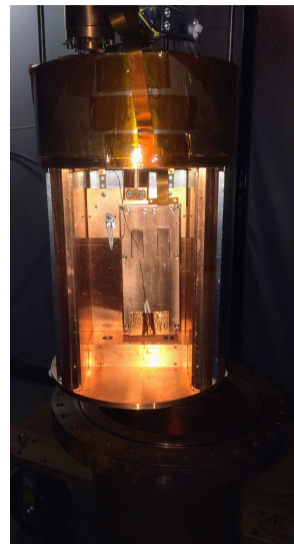
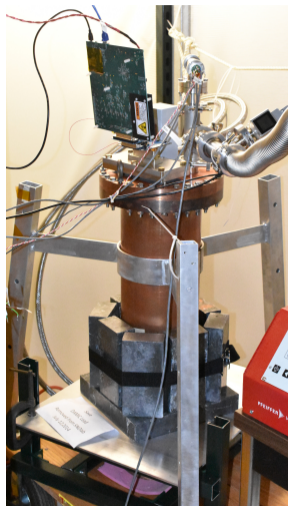
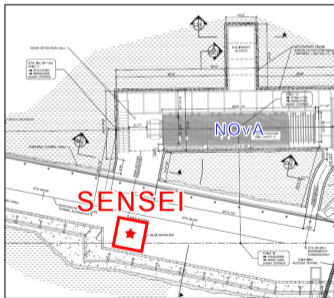
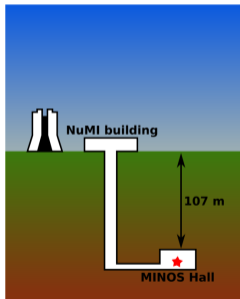
The SENSEI CCDs

- High-resistivity silicon 675 μm thick, $1.59 \times 9.42 \text{ cm}^2$
- 6144×886 pixels, 15 μm pitch (1.925 grams active)
- The first dedicated production of Skipper CCDs for dark matter



MINOS setup

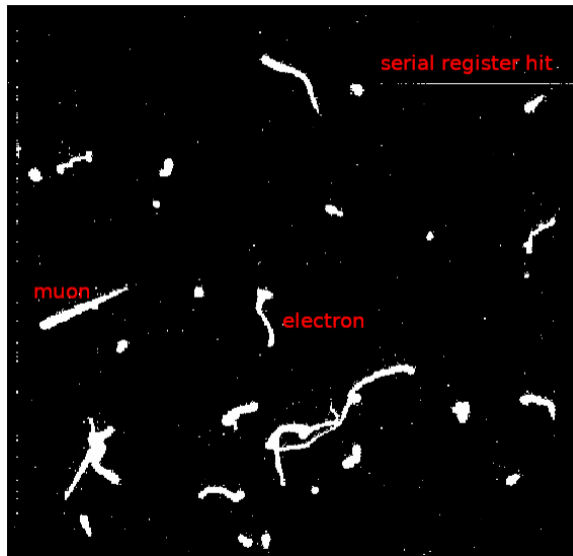
- Shallow underground site (MINOS cavern at Fermilab), simple lead shield
- CCD at 135 K, biased at 70 V



Images!

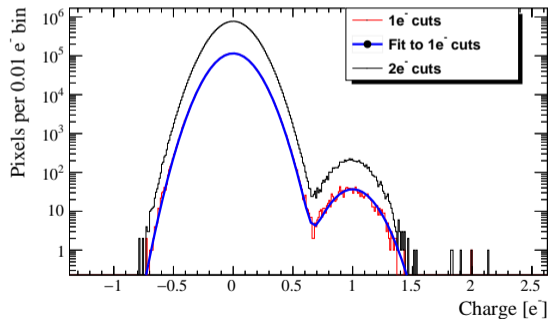
- This is 1/6th of one quadrant
- 20 hours exposure, 5.15 hours readout
 - ▶ During readout, the image continues to accumulate hits and charge
- 22 images in the blinded dataset

Search	Exposure post-cuts
$1e^-$	1.38 gram-days
$2e^-$	9.17 gram-days
$3e^-$	11.87 gram-days
$4e^-$	11.70 gram-days



Searches and backgrounds

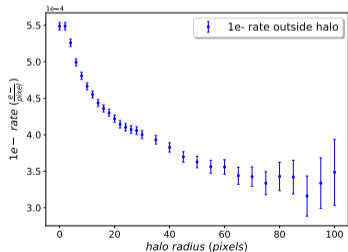
- Single-electron: background-dominated
- Multiple electrons (single-pixel or cluster): low-background
 - ▶ Coincidence of $1e^-$ processes
 - ▶ True multi- e^- processes



- $1e^-$ 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

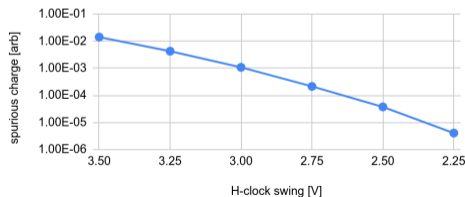
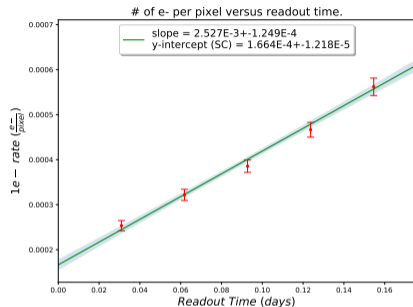
Localized charge from high-energy events

- 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 $3.188(90) \times 10^{-4} e^-/\text{pixel}$



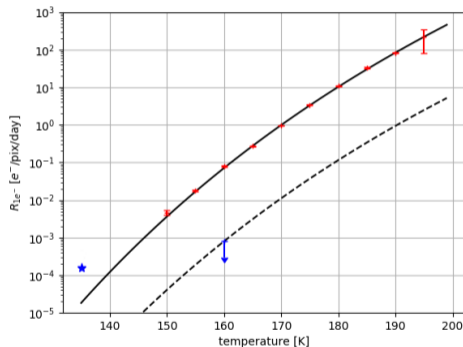
Spurious charge

- Measurements with shorter exposures show a limiting value for the CCD charge:
 $1.66(12) \times 10^{-4} e^-/\text{pixel}$
 - ▶ Half of the $1 e^-$ 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 $1.59(16) \times 10^{-4} e^-/\text{pixel}/\text{day}$



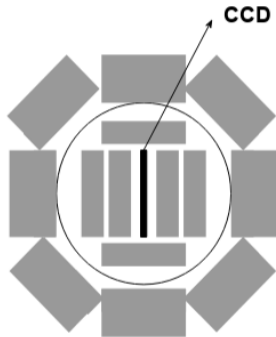
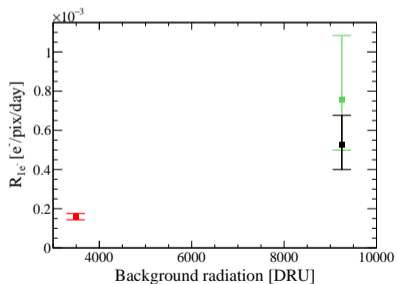
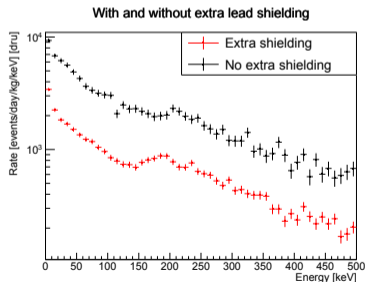
Intrinsic dark current

- Subtracting the exposure-independent charge, our $1e^-$ rate is $1.59(16) \times 10^{-4} e^-/\text{pixel}/\text{day}$
- 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 $\ll 1 \times 10^{-5} e^-/\text{pixel}/\text{day}$ 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



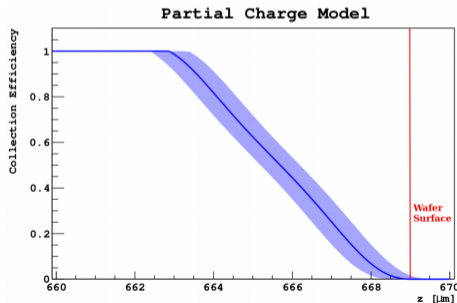
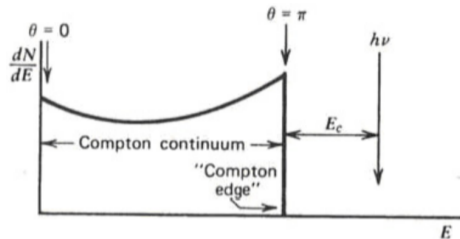
$1e^-$ rate vs. shielding

- 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 $1e^-$ rate
 - ▶ Radiation generates charge in halos, in loose clusters, and uniformly
 - ▶ Better shielding will very likely further reduce our $1e^-$ rate



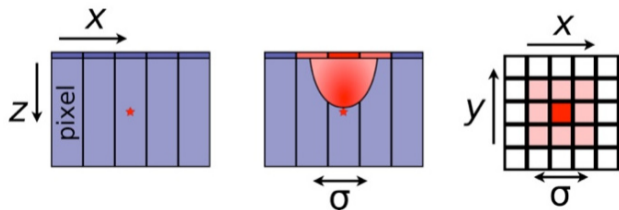
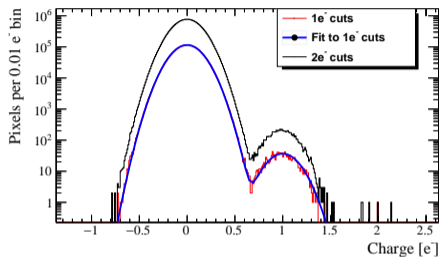
Multi- e^- backgrounds

- 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



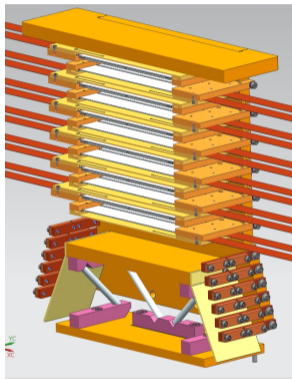
Multi- e^- searches

- We observe 5 $2e^-$ pixels and no 3, $4e^-$ 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, $4e^-$ to form a contiguous cluster
- Now we can put limits on the rate of events



	90% CL
$1e^-$	525.2 events/g-day
$2e^-$	4.449 events/g-day
$3e^-$	0.255 events/g-day
$4e^-$	0.253 events/g-day

- 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

