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

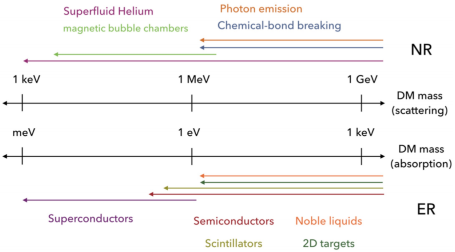
Sho Uemura

Tel Aviv University
for the SENSEI Collaboration

SU was supported in part by the Zuckerman STEM Leadership Program

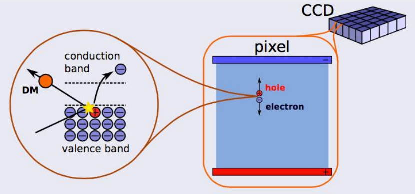
The search for sub-GeV dark matter

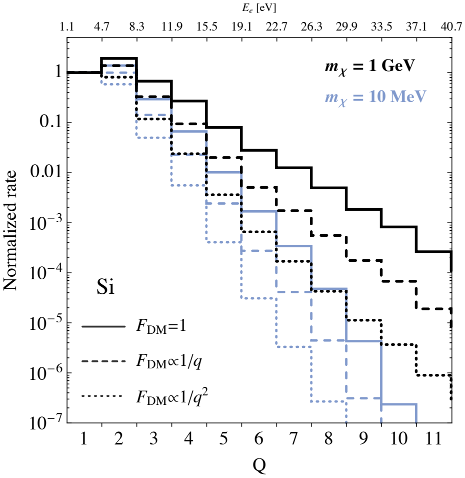
- Direct-detection experiments have focused on WIMP DM down to $O(\mathrm{GeV})$
  - Well motivated ("WIMP miracle"), experimentally accessible (nuclear recoils)
- New complementary searches for lower masses
  - New theoretical interest in dark sectors
  - New technologies with lower thresholds
- One 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

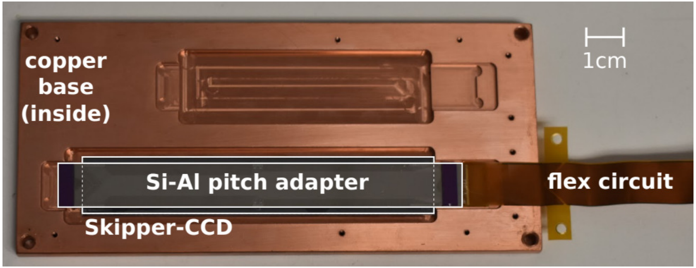
- We look for DM interactions with electrons in silicon
  - DM-electron scattering: m_χ in the MeV-GeV range
    - ★ Energy transfer is a few eV, good match to semiconductor band gap
  - DM absorption: bosonic DM at the eV scale
    - ★ Energy transfer equals m_χ
- Energy transfer creates ionization,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





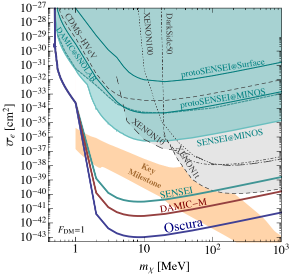
Strategy

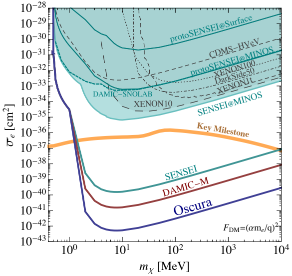
- Challenges:
  1. Unambiguously ID $1e^-$, $2e^-$ events
  2. Minimize background sources of charge
  3. Minimize coincidence background
- Our starting point is the CCD
  - Mature technology, used for DM in DAMIC
  - Achieves #3 through pixel segmentation
- Same physics as EDELWEISS, CDMS HV — very 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:

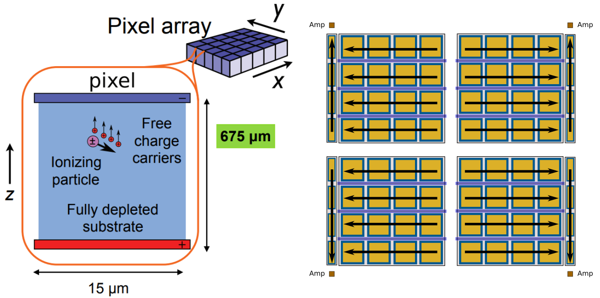
- T.-T. Yu

Fully funded by Heising-Simons Foundation

& leveraging R&D support from Fermilab

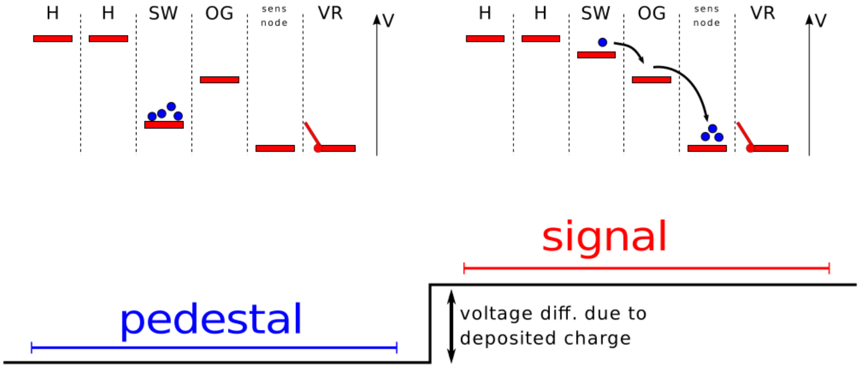
CCDs

- 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 $\sim 2e^-$



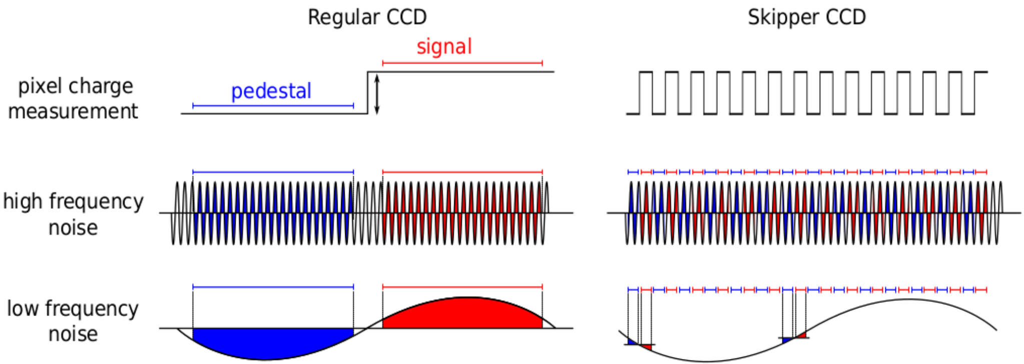
Skipper readout

- 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!



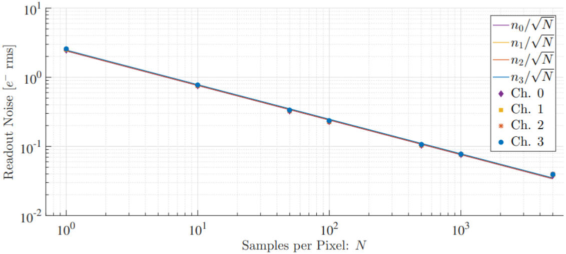
Skipper readout

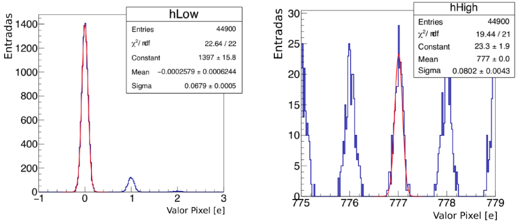
- In a conventional CCD, charge moved to the sense node must be drained
  - You can integrate longer, but you cannot beat the $1/f$ noise
- The Skipper amplifier lets you make multiple measurements!

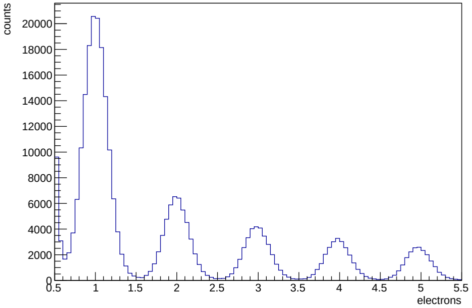


Sub-electron readout noise

- 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

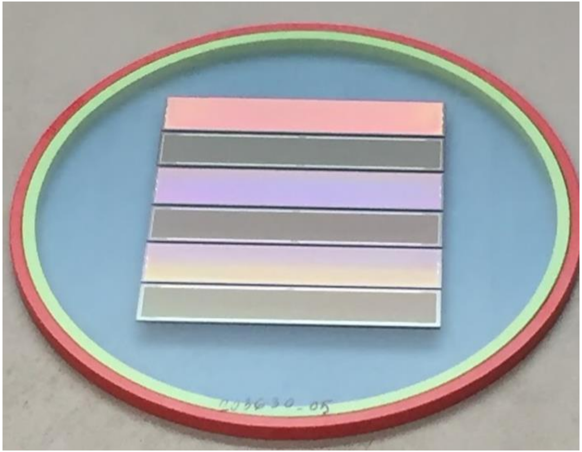






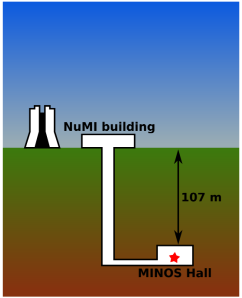
The SENSEI CCDs

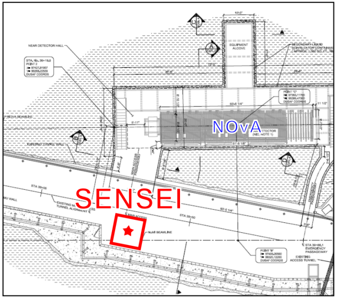
- High-resistivity silicon 675 μm thick, 1.59 $\times$ 9.42 cm^2
- 6144 $\times$ 886 pixels, 15 μm pitch (1.925 grams active)
- The first dedicated production of Skipper CCDs for dark matter

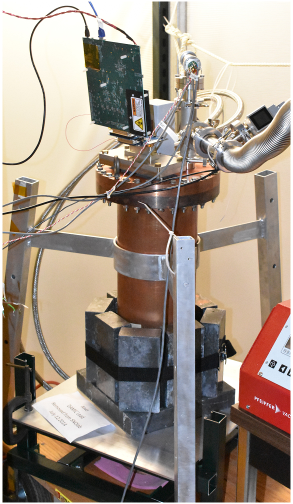


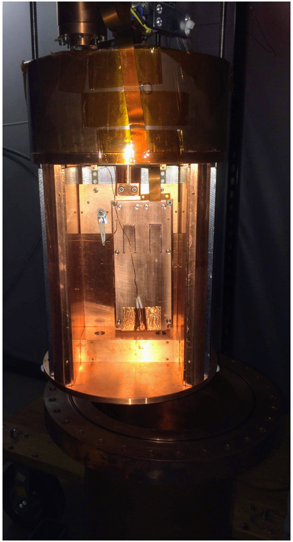
MINOS setup

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





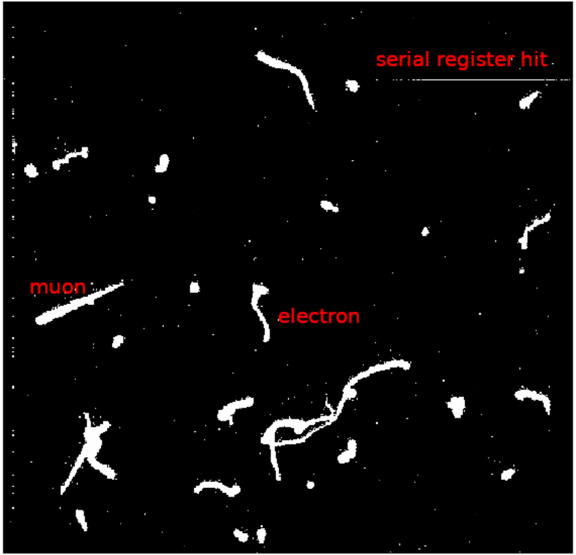




Images!

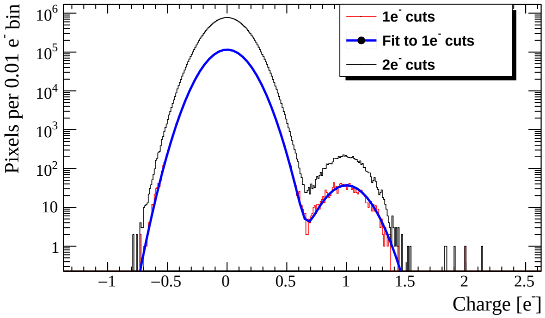
- This is 1/6th of one quadrant
- 20 hours exposure, 5.15 hours readout
  - During readout, the image continues to accumulate hits and charge
- 22 images in the blinded dataset

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

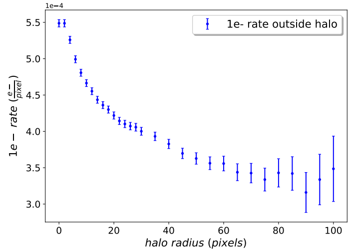
- Single-electron: background-dominated
- Multiple electrons (single-pixel or cluster): low-background
  - Coincidence of $1e^-$ processes
  - True multi-e^- processes

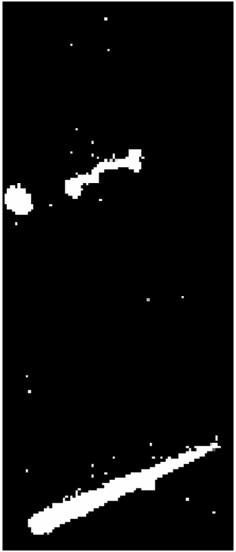


- $1e^-$ processes
  - Local sources of charge: high-energy clusters (ionizing radiation), amplifier luminescence, CCD defects
  - Spatially uniform sources of charge
    - Spurious charge: charge generated during readout
    - Intrinsic dark current: charge generated during exposure by thermal excitation
  - 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

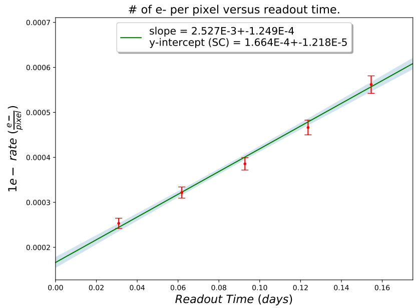
- Bleeding: charge “left behind” by charge transfer
- Halo: excess of charge near high-charge pixels
  - Probably near-bandgap photons from Cherenkov radiation and electron-hole recombination (see arXiV:2011.13939)
- Loose clusters: regions with high charge density
  - May be Cherenkov photons (reflected,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

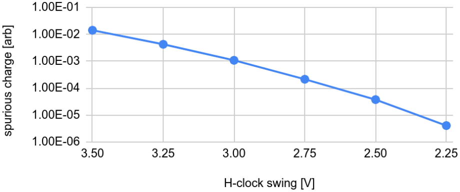




Spurious charge

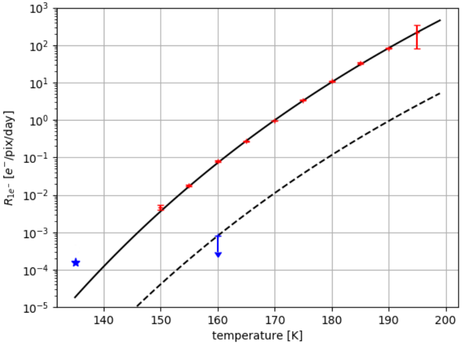
- Measurements with shorter exposures show a limiting value for the CCD charge: $1.66(12) \times 10^{-4}$ e^{-}/pixel
  - Half of the $1e^{-}$ events we see are due to spurious charge!
  - Optimization of the CCD voltage waveforms will reduce this background in future runs
- Subtracting the exposure-independent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





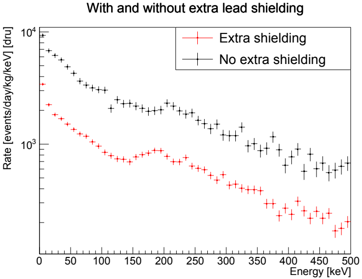
Intrinsic dark current

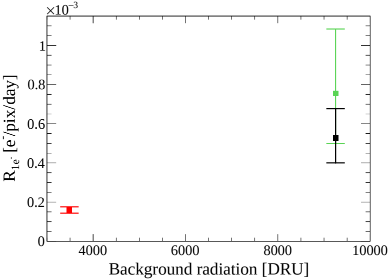
- Subtracting the exposure-independent charge, our 1e- rate is $1.59(16) \times 10^{-4}$ e^{-}/pixel/day
- Intrinsic dark current is the usual suspect
  - Thermal generation of electron-hole pairs, mediated by lattice defects
- However:
  - Extrapolation from higher temperatures (dashed black line) predicts $\ll 1 \times 10^{-5}$ 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

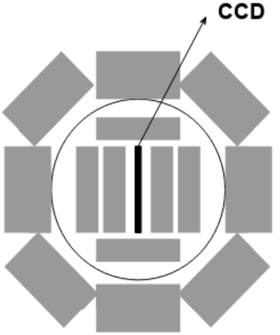


$1e^-$ rate vs. shielding

- 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

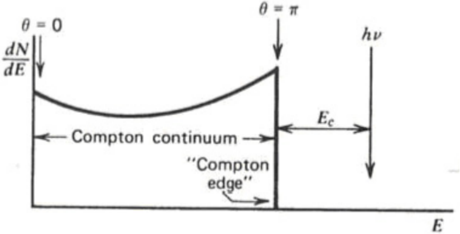


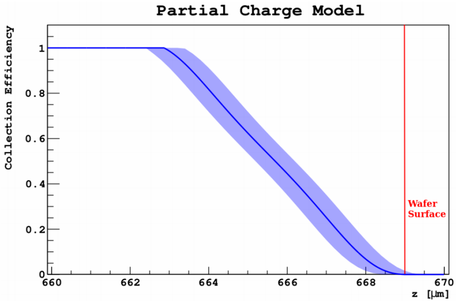




Multi-e^- backgrounds

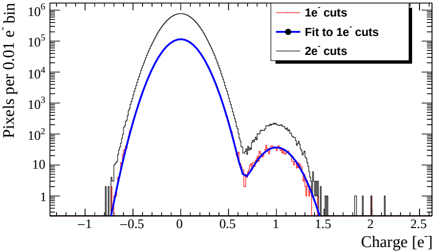
- At the low-energy end of the Compton spectrum, a gamma ray can create arbitrarily small-energy electron recoils
  - DAMIC and SENSEI efforts to measure this spectrum and compare to theory
- Depending on details of processing, some CCDs have a highly-doped backside layer with partial charge collection: this can create low-charge events
  - DAMIC and SENSEI are affected, but future CCDs will not have this layer

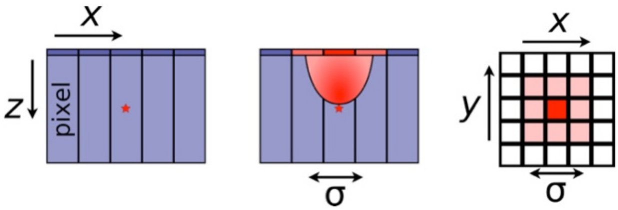




Multi-e^- searches

- 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

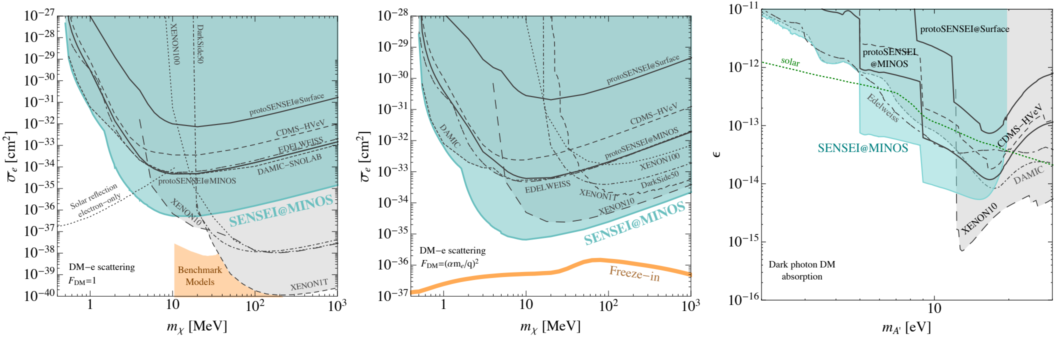




	90% CL
$1e^-$	525.2 events/g-day
$2e^-$	4.449 events/g-day
$3e^-$	0.255 events/g-day
$4e^-$	0.253 events/g-day

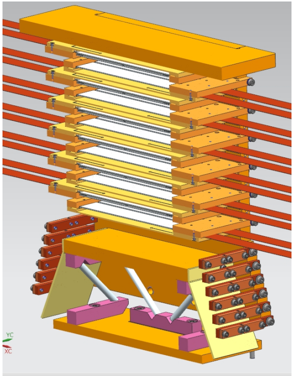
Limits from SENSEI@MINOS

- 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