Searching for Sub-GeV Dark Matter with SENSEI

Sho Uemura

Tel Aviv University
for the SENSEI Collaboration

SU was supported in part by the Zuckerman STEM Leadership Program

New results from SENSEI

- SENSEI has delivered world-leading results in low-threshold DM direct detection
  - 2017: Demonstration of 0.068 e^{-} noise in prototype
  - 2018: DM search, surface run of prototype
  - 2019: DM search, underground run of prototype

2021 New Horizons in Physics Prize (3)

- **Rouven Essig**, Stony Brook University
  Javier Tiffenberg, Fermilab
  Tomer Volansky, Tel Aviv University
  Tien-Tien Yu, University of Oregon

  Citation: For advances in the detection of sub-GeV dark matter especially in regards to the SENSEI experiment.

- Today we present results from the 2020 SENSEI run
  - First DM search with a science-grade SENSEI CCD
  - Paper in PRL — see arXiV 2004.11378
  - Next step: full-scale experiment deep underground

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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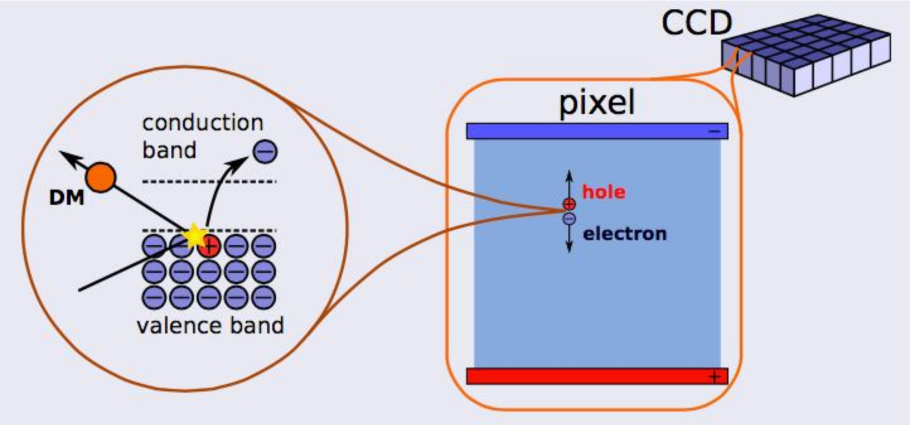
& leveraging R&D support from Fermilab

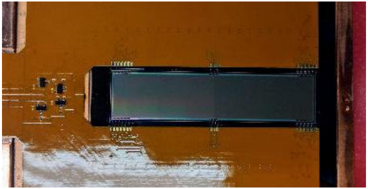
Electron recoils for sub-GeV dark matter

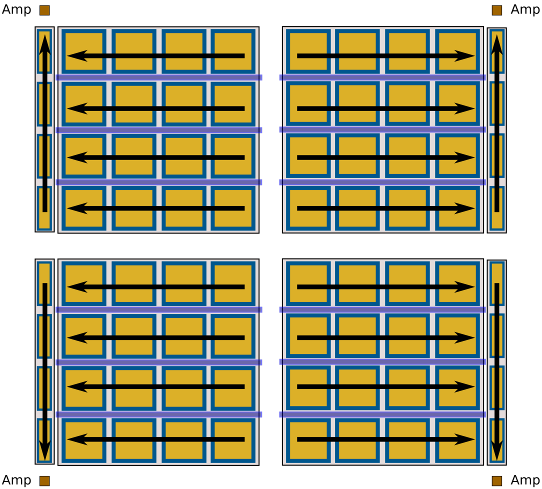
- We look for DM interactions with the electrons in a CCD
  - Benchmark models: DM-electron scattering, absorption
  - Mass range and sensitivity strongly depend on the energy threshold
- Silicon bandgap gives us sensitivity to 1.2 eV excitations — if we can capture and resolve a single electron



CCDs

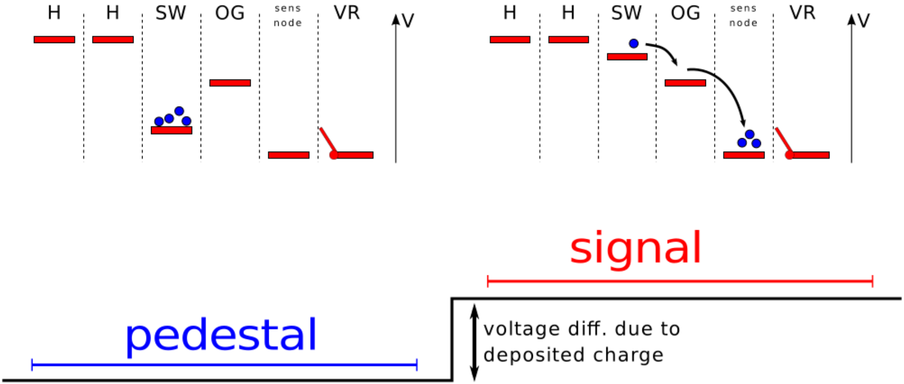
- CCDs can read millions of charge packets with minimal loss
  - The result of decades of R&D in imaging CCDs
- Conventional CCDs are limited to noise of $\sim 2e^{-}$





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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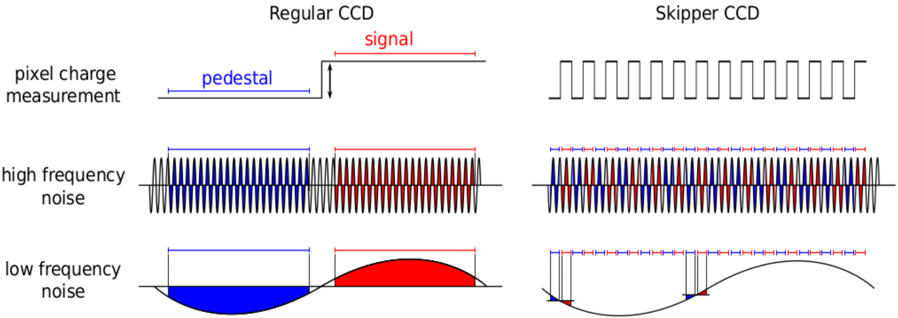
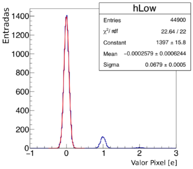
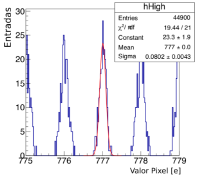
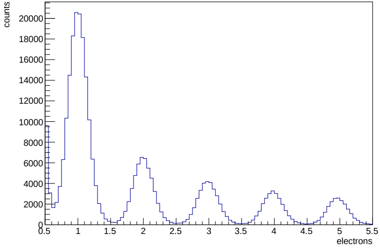


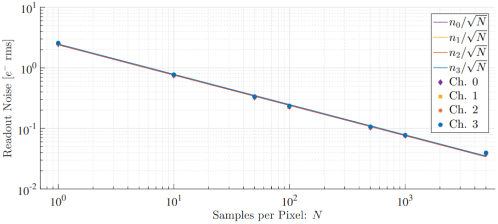
Sub-electron readout noise

- Skipper noise scales as $1/\sqrt{N}$
  - For the dark matter search we operate at $N = 300$, noise of $\sim 0.14e^{-}$
- We can count single electrons: self-calibrating charge measurement with zero noise
  - Other applications, such as a very clean measurement of the Fano factor in silicon



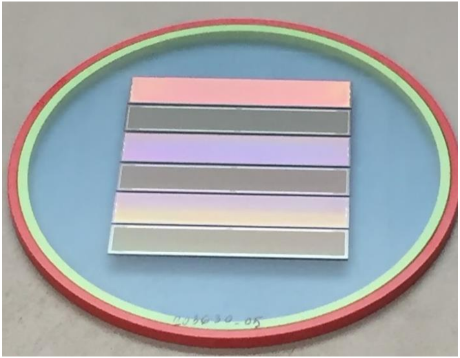






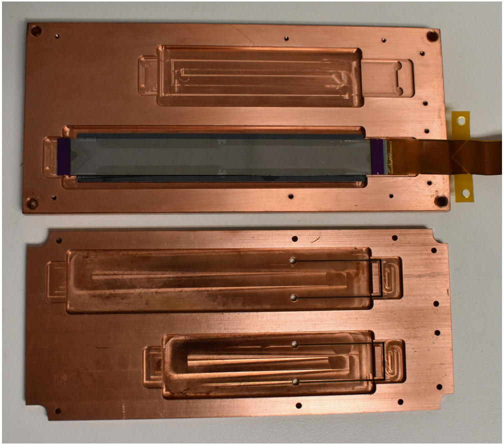
Our CCDs

- 6144×886 pixels (divided in quadrants), 15 μm pitch
- High-resistivity silicon 675 μm thick, 1.59×9.42 cm^2
- Designed by LBNL MSL, fabricated by DALSA
- The first dedicated production of Skipper CCDs for dark matter
  - 1.925 grams of active mass, up from 0.0947 in protoSENSEI
  - Orders of magnitude improvement in dark current and amplifier luminescence



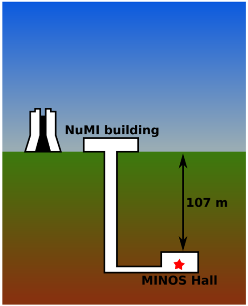
CCD package

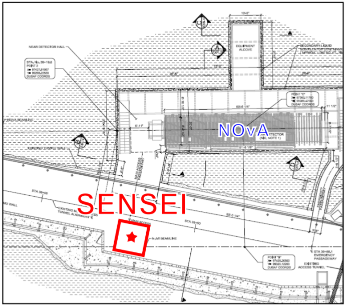
- Densely packable and minimizes radioactive contamination
- Silicon pitch adapter serves multiple functions:
  - Electrical interface to flex cable
  - Mechanical support, with perfectly matched thermal expansion
  - Thermal connection to copper tray through machined leaf spring

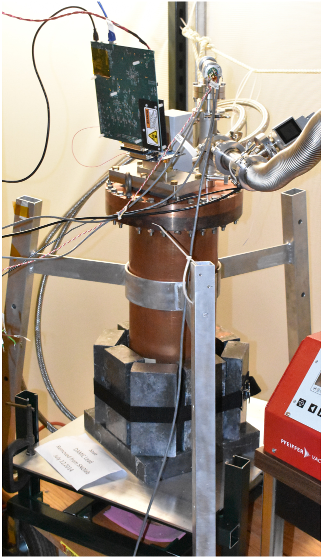


MINOS setup

- Shallow underground site (MINOS cavern at Fermilab) reduces muon rate from cosmic rays; lead shielding reduces gamma rate from ambient radioactivity
- Cryocooler and insulating vacuum keep the CCD cold to minimize dark current

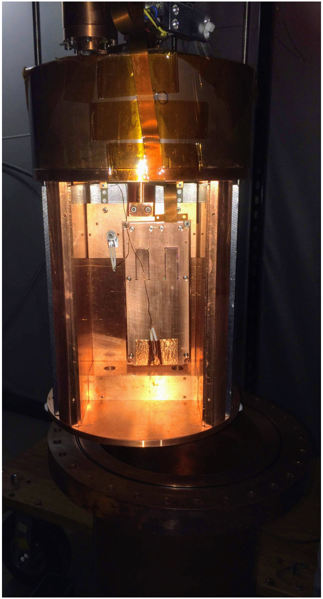






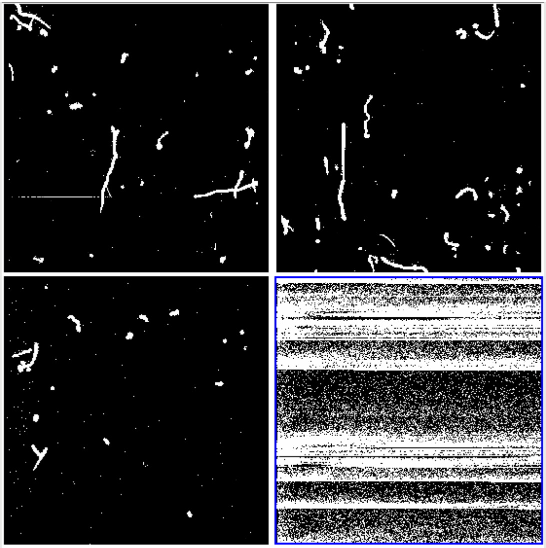
Inside the cryostat

- Shielding design adapted from DAMIC: cylindrical vacuum vessel with lead "plugs" above and below the CCD
- CCD at 135 K, biased at 70 V



The dataset

- 20 hours exposure, 6 hours readout
- Analysis developed using 7 commissioning images
- Blinded dataset of 22 images, Feb. 25 — Mar. 20
- One quadrant is damaged, one has a light leak: we use the first two quadrants (19.93 gram-days) for the $1/2e^-$ searches, and add part of the third quadrant for $3/4e^-$ (total 27.82 gram-days)



Images!

- This is 1/5th of one quadrant
- Muons: straight tracks
- Electrons: curly tracks
- X-rays: round clusters

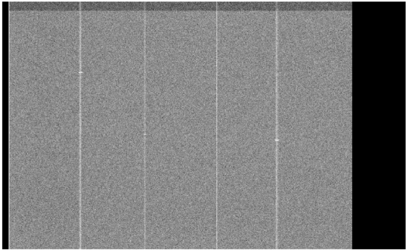
Searches and backgrounds

- Single-pixel searches (we exclude any pixel with a nonempty neighbor):
  - Single-electron: background-dominated
  - Two-electron: low-background
- Three-, four-electron clusters (we combine adjacent pixels): zero-background

- Local sources of charge: high-energy clusters (ionizing radiation), CCD defects
- Spatially uniform sources of charge
  - Spurious charge: charge generated during readout
  - Dark current: charge generated during exposure by thermal excitation
  - Others?

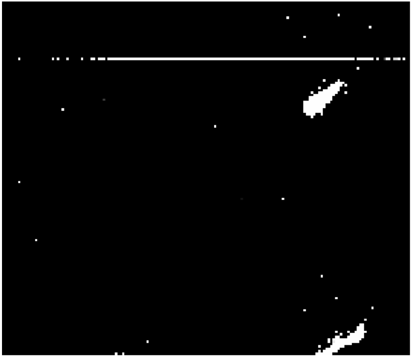
Cuts: bad pixels/dark spikes

- Surface defects on the CCD can create pixels with high dark current
- We identify these with special high-temperature runs and by stacking images, and mask them out



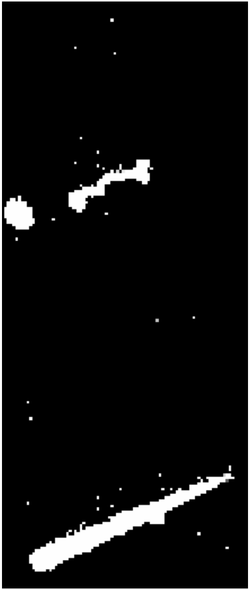
Cuts: serial register hits

- Tracks that cross the serial register during readout can produce lines of charge in the image
- We mask out isolated horizontal lines of charge



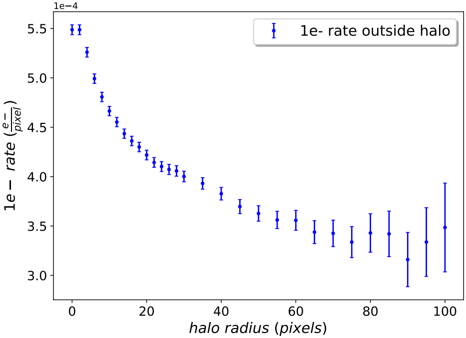
Cuts: bleeding

- Some charge may be left behind when we transfer charge from one cell to the next
  - Surface defects can create traps that increase the bleeding tails in specific columns
- We mask out bleed regions above and to the right of high-charge pixels
- We identify high-bleed columns by looking for excess charge above high-charge pixels



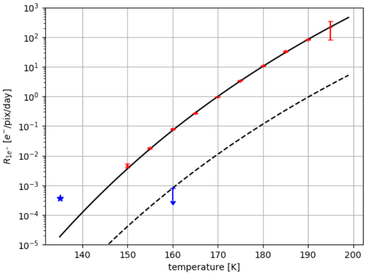
Cuts: halo

- We see an excess of charge near high-charge pixels, even after masking out bleed regions
  - Likely near-bandgap photons from Cherenkov radiation and electron-hole recombination (see arXiV:2011.13939)
- We apply a tight cut (>60 pixels from any high-charge pixel) for the $1e^-$ analysis, looser (>20 pixels) for the $2/3/4e^-$ analyses



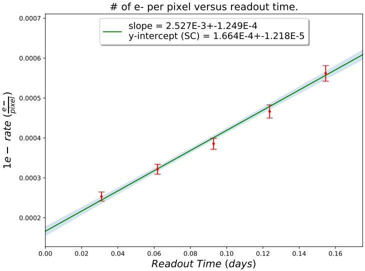
$1e^-$ rate

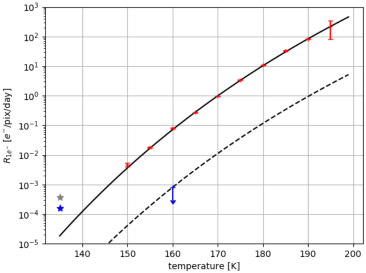
- We see $3.188(90) \times 10^{-4}$ e^-/pixel in our images, from a total exposure of 1.380 gram-days
  - If all exposure-dependent, this is a $1e^-$ rate of $3.363(94) \times 10^{-4}$ e^-/pixel/day
- Is this all dark current? Unlikely!
  - Extrapolation from higher temperatures (dashed black line) predicts $\ll 1 \times 10^{-5}$ e^-/pixel/day at our operating temperature of 135 K
    - ★ Suppressing surface dark current gets us from red data points to blue



Spurious charge measurement

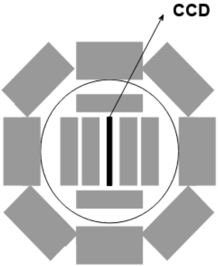
- Measurements with shorter exposures show a limiting value for the CCD charge: $1.66(12) \times 10^{-4}\ e^{-}$/pixel
  - Half of the $1e^{-}$ rate we see is due to spurious charge!
  - Optimization of the CCD voltage waveforms will reduce this background in future runs
- Subtracting the exposure-independent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

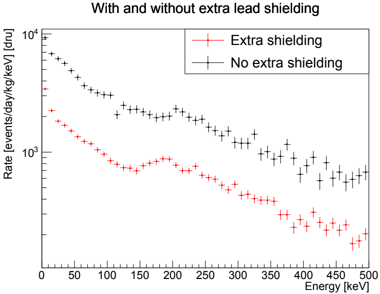


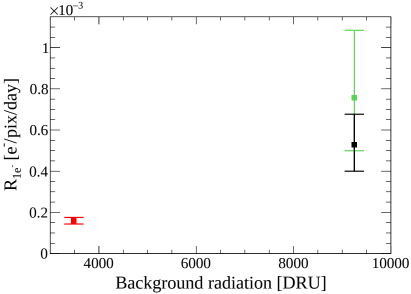


$1e^{-}$ rate vs. shielding

- 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
  - Ionizing radiation generates charge both locally (halo) and uniformly in our CCD
  - Better shielding will very likely further reduce our $1e^{-}$ rate

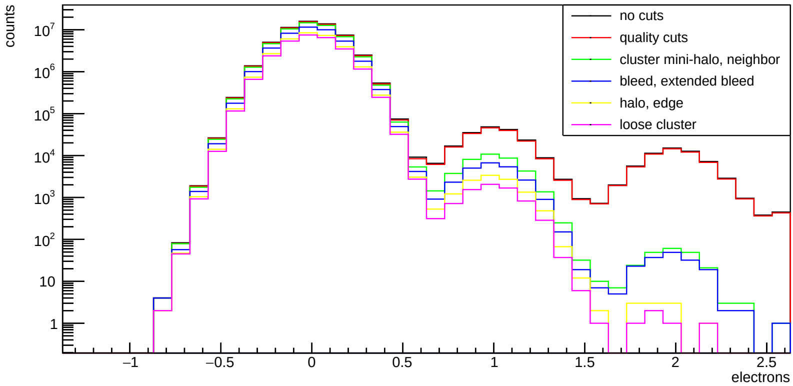






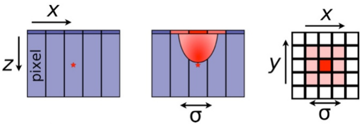
2/3/4e^- rate

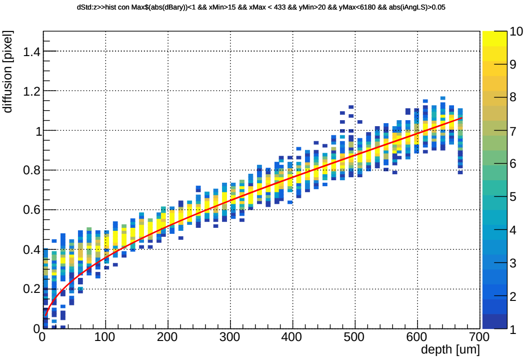
- For these searches, we use a smaller halo radius (to preserve exposure) but apply an additional “loose cluster” cut to remove regions with higher charge density
- After all cuts, we see 5 pixels with 2e^-
- We see no 3e^- or 4e^- clusters

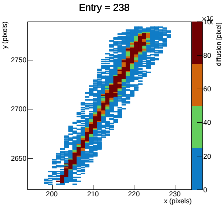


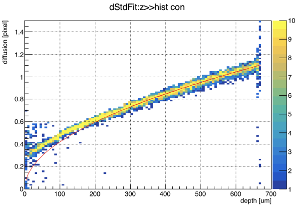
Charge diffusion

- What is the probability for both electrons from a DM interaction to end up in the same pixel?
- We use muon tracks to measure diffusion as a function of depth
- 22.8% for $2e^-$ to stay in one pixel
- 76.1%, 77.8% for 3, $4e^-$ to form a contiguous cluster







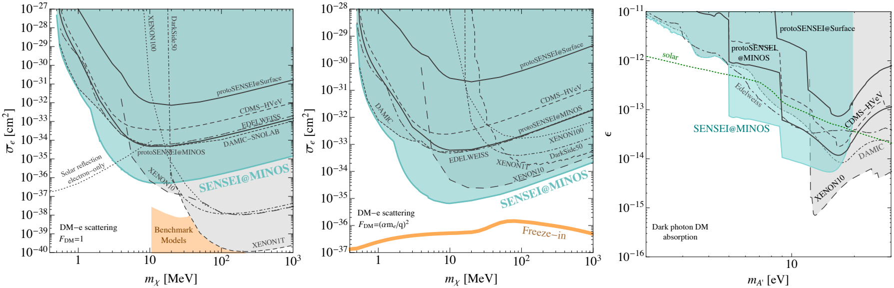


Limits

- New record lows for semiconductor detectors and DM searches at these thresholds

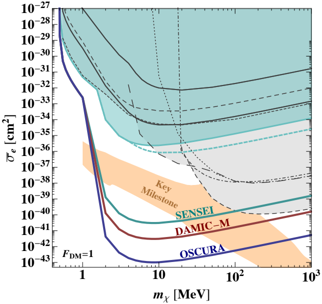
	90% CL
$1e^-$	525.2 events/g-day
$2e^-$	4.449 events/g-day
$3e^-$	0.255 events/g-day
$4e^-$	0.253 events/g-day

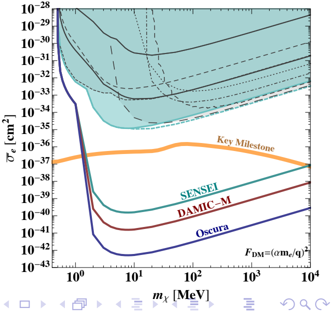
- The derived DM constraints are also world-leading
  - Left to right: $F_{DM} = 1$ scattering (heavy mediator), $F_{DM} = (\alpha m_e/q)^2$ scattering (light mediator), absorption



The future of Skippers

- We expect significant improvements in all measurement channels:
  - $1e^-$: better shielding $\rightarrow$ lower $1e^-$ rate
  - $2e^-$: reduced spurious charge $\rightarrow$ shorter exposures $\rightarrow$ lower coincidence rate
  - $3, 4e^-$: increased detector mass
- SENSEI@MINOS demonstrates that Skipper CCDs have the performance we need to reach theory targets
  - SENSEI@SNOLAB: 100 grams
  - DAMIC-M: 1 kg
  - Oscura: 10 kg





SENSEI@SNOLAB

- We are building the full-scale SENSEI experiment, deep underground at SNOLAB with a low-background shield
- "Phase 1" system is operating at SNOLAB, full experiment is ready for installation