

New Sub-GeV Dark Matter Results from SENSEI

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for the SENSEI Collaboration

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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
- Today we present results from this spring's 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

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.



The SENSEI Collaboration



Fermilab:

- F. Chierchie, M. Cababie, G. Canelo, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez-Moroni, D. Rodrigues, M. Sofu-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:

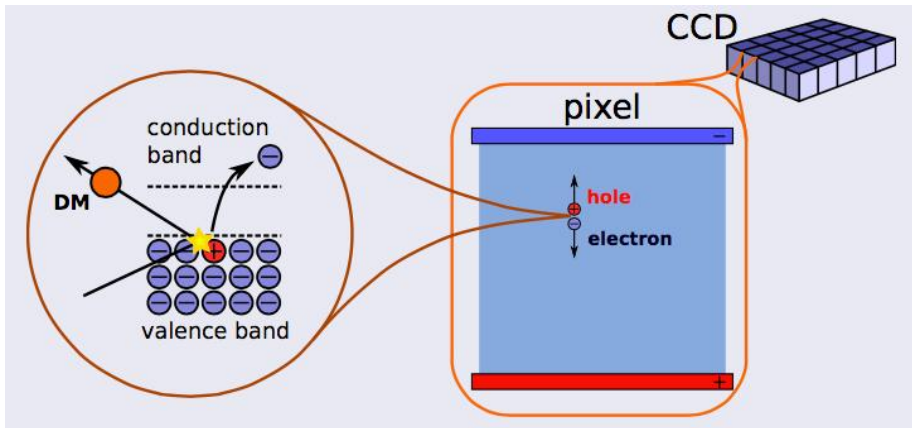
- T.-T. Yu

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& leveraging R&D support from Fermilab



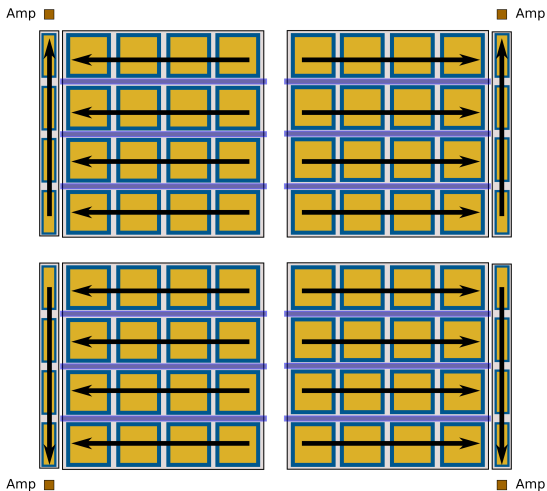
Electron recoils for sub-GeV dark matter

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



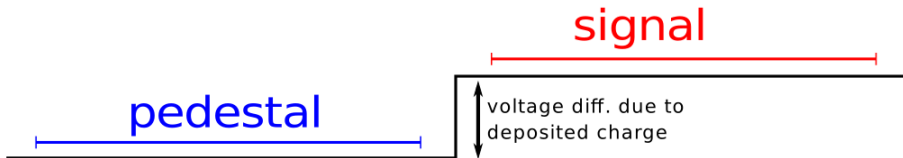
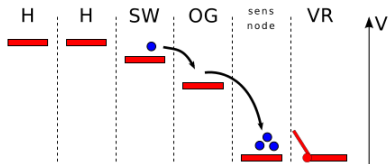
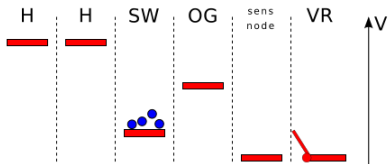
CCDs

- 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 $\sim 2e^-$



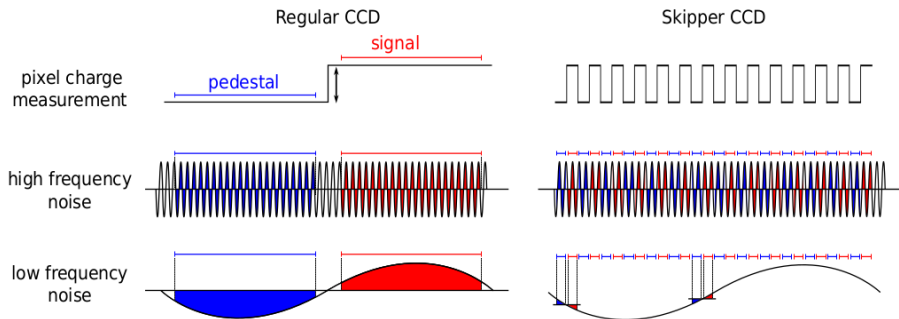
Skipper readout

- 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!



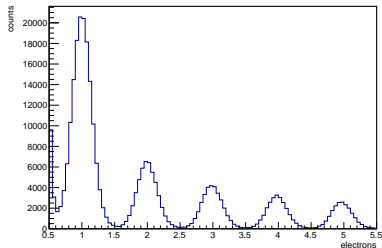
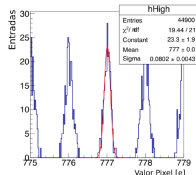
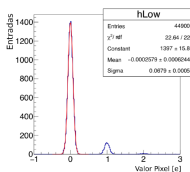
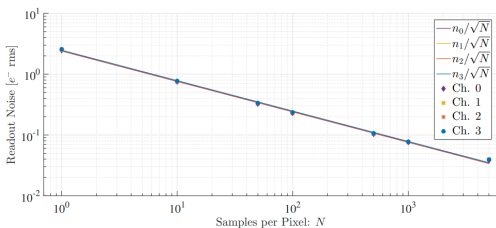
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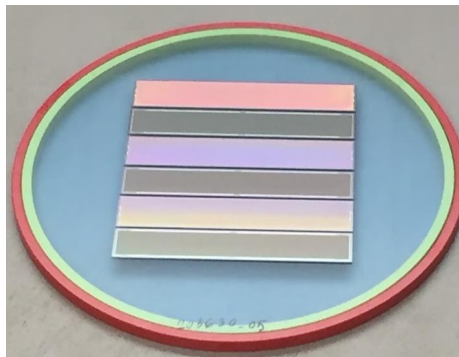
Sub-electron readout noise

- 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



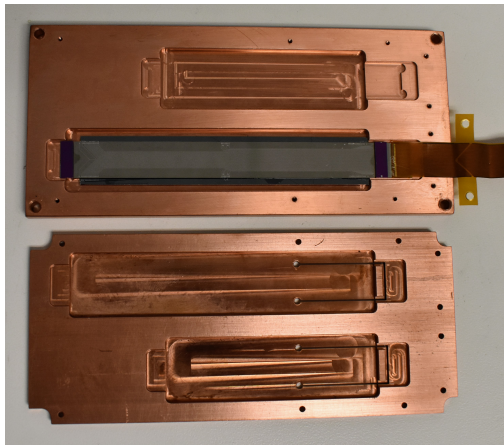
Our CCDs

- 6144×886 pixels (divided in quadrants), $15 \mu\text{m}$ pitch
- High-resistivity silicon $675 \mu\text{m}$ thick, $1.59 \times 9.42 \text{ cm}^2$
- 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



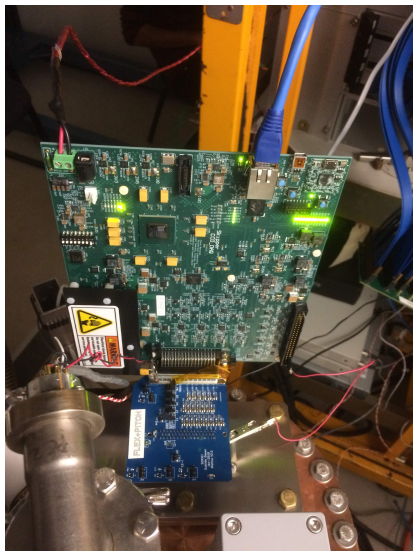
CCD package

- 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



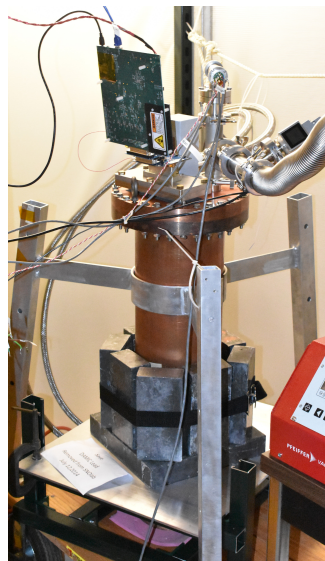
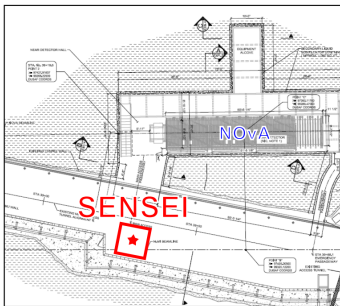
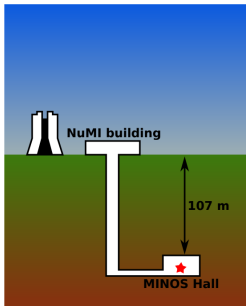
LTA readout board

- “Low Threshold Acquisition” — single-board readout system for Skipper CCDs
- Compared to previous solutions: compact, flexible, scalable, reliable
- One LTA board reads one CCD; multiple LTAs can be run synchronously for multi-CCD systems



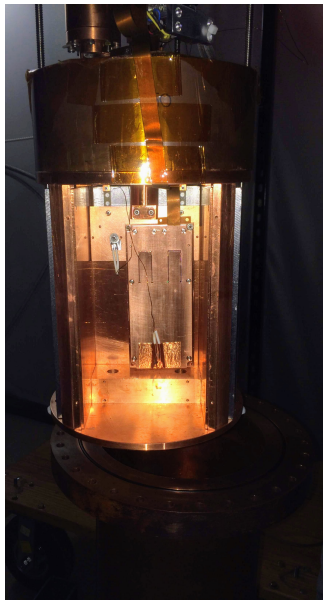
MINOS setup

- 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



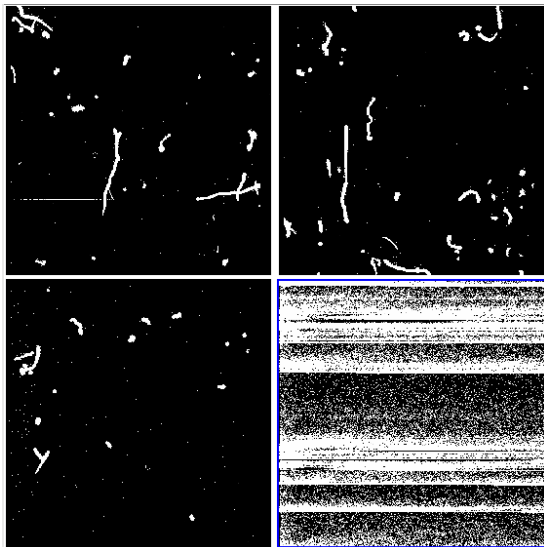
Inside the cryostat

- 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

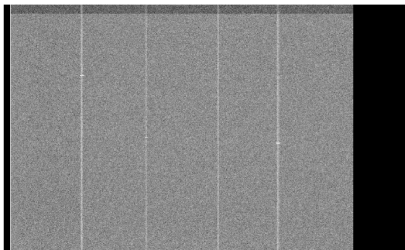


Searches and backgrounds

- 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?

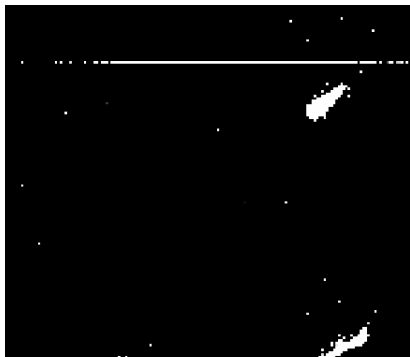
Cuts: bad pixels/dark spikes

- 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



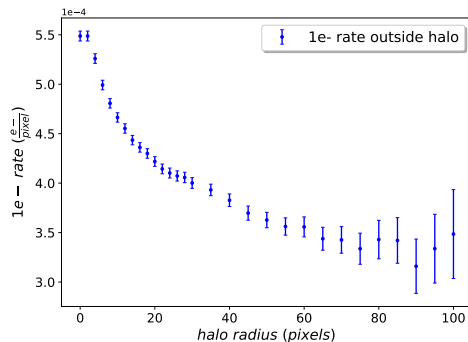
Cuts: bleeding

- 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



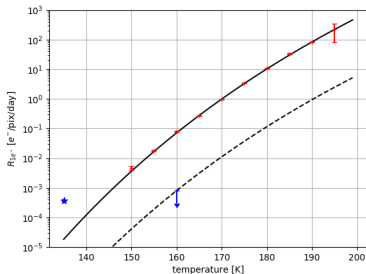
Cuts: halo

- We see an excess of charge near high-charge pixels, even after masking out bleed regions
 - ▶ We are investigating possible mechanisms
- We apply a tight cut (>60 pixels from any high-charge pixel) for the $1e^-$ analysis



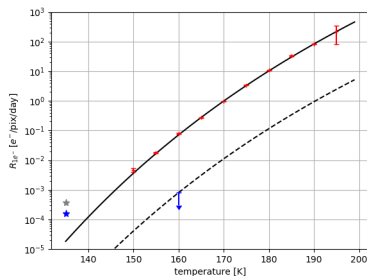
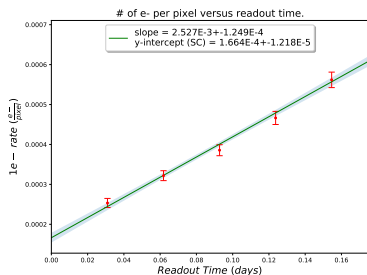
$1e^-$ rate

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



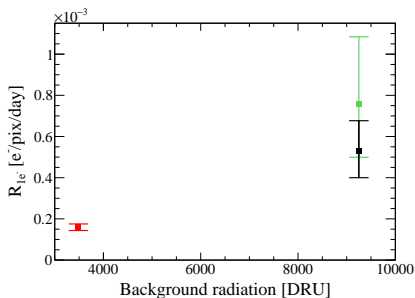
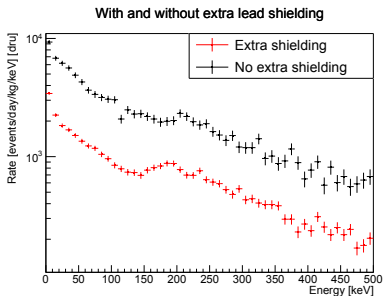
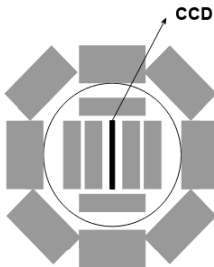
Spurious charge measurement

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



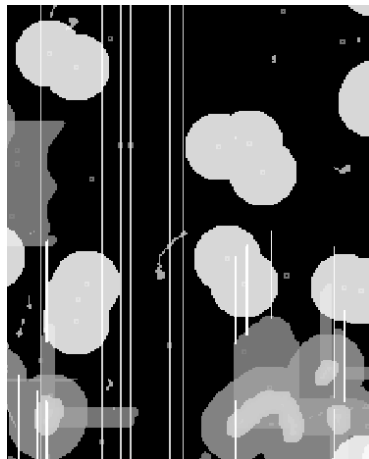
$1e^-$ rate vs. shielding

- 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



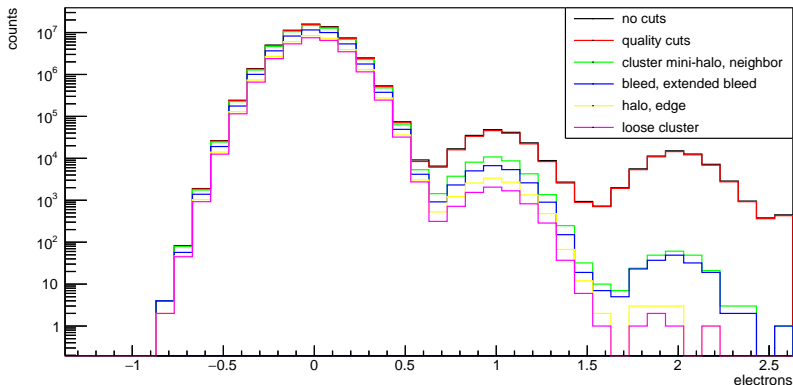
Cuts: loose clusters

- For the $2/3/4e^-$ searches, we use a smaller halo cut (to preserve exposure) but apply additional cuts to remove regions with higher charge density
- If two $1e^-$ pixels are within 20 pixels of each other, we remove a radius-20 circle around both
 - ▶ This cut kills half of the $2e^-$ events with a 11% loss of exposure



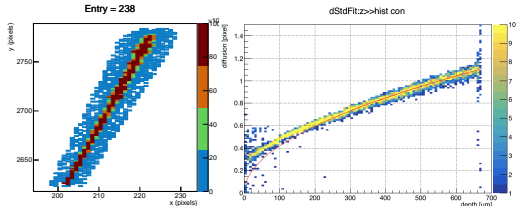
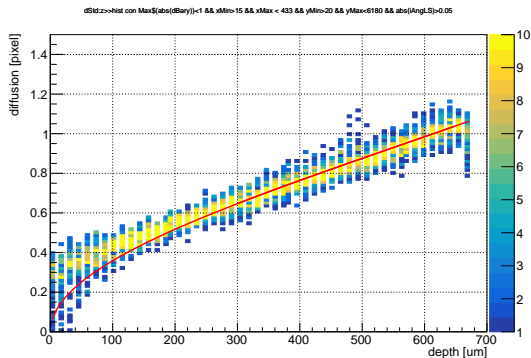
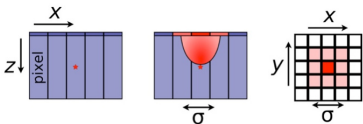
2/3/4e⁻ rate

- 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



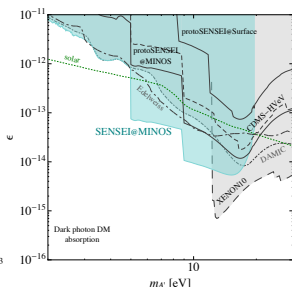
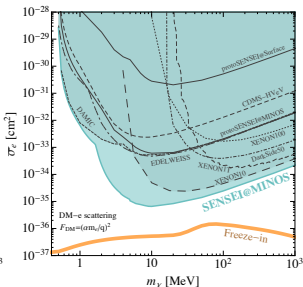
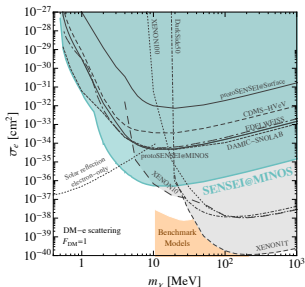
Limits

- 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 |

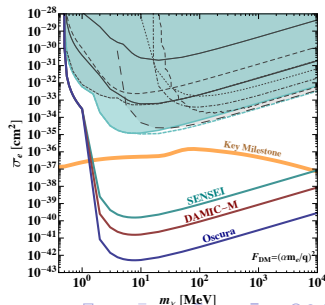
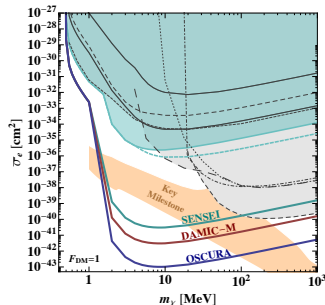
- The derived DM constraints are also world-leading

- ▶ 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

