Sub-GeV dark matter searches with SENSEI

Kelly Stifter, for the SENSEI collaboration

UCLA Dark Matter Conference

3/31/2023

The SENSEI collaboration

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Stony Brook: P. Adari, R. Essig, A. Singal, Y. Wu

Tel Aviv: L. Barak, E. Etzion, Y. Korn, A. Orly, T. Volansky

U. Oregon: A. Desai, T.-T. Yu

Buenos Aires: M. Cababie, S. Perez, D. Rodrigues

U.C. Berkeley: I. M. Bloch

SNOLAB: I. Lawson, S. Luoma, S. Scorza

LBNL: S. Holland

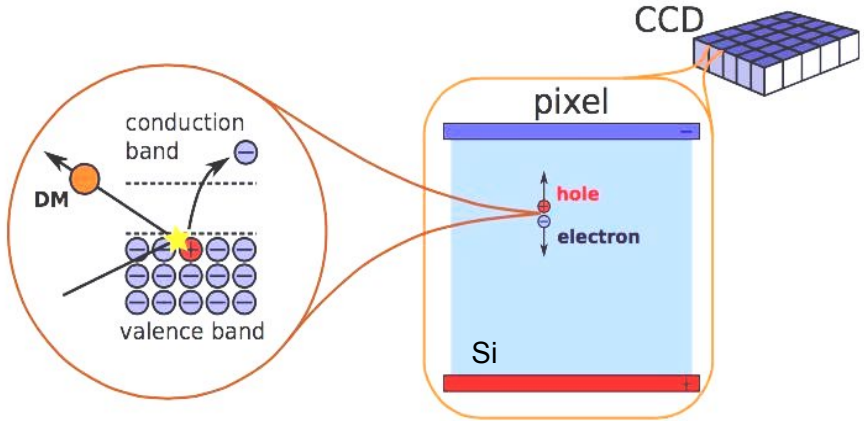
Fully funded by Heising-Simons Foundation + R&D support from Fermilab

The SENSEI* experiment

*Sub-Electron-Noise Skipper-CCD Experimental Instrument

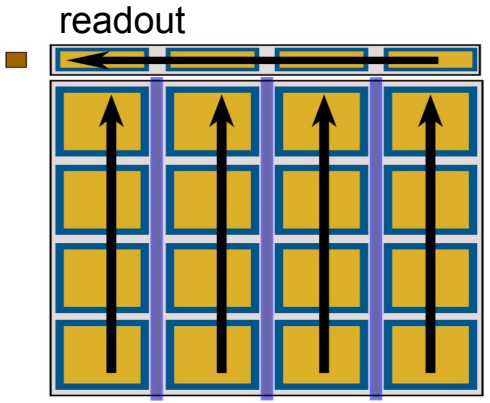
Silicon charge-coupled devices (CCDs) w/ Skipper amplification (designed by LBNL):

- Energy threshold of Si bandgap (~1.1 eV)
- Low dark current (~10^{-4} e^-/pix/day)
- Sub-electron (~0.1e^-) readout noise



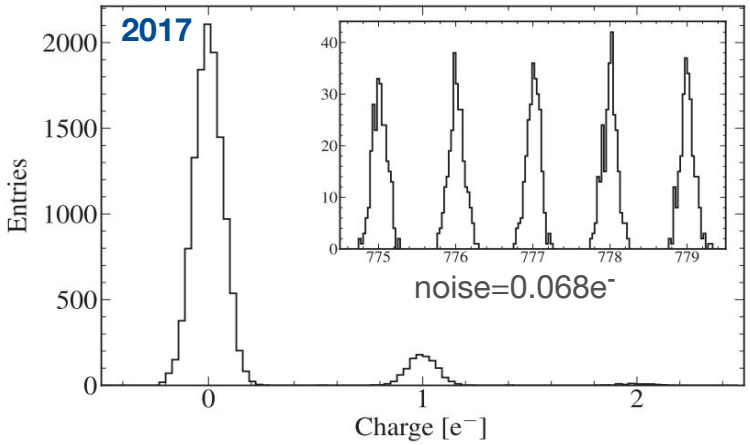
Access to low-mass searches:

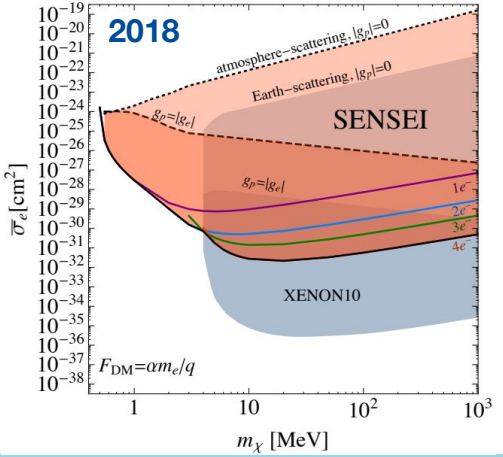
- Electron scattering of 1-1000 MeV DM
- Nuclear scattering of 1-1000 MeV DM via Migdal effect
- Absorption of 1-1000 eV DM
- Scattering of milli-charged particles
- Etc…

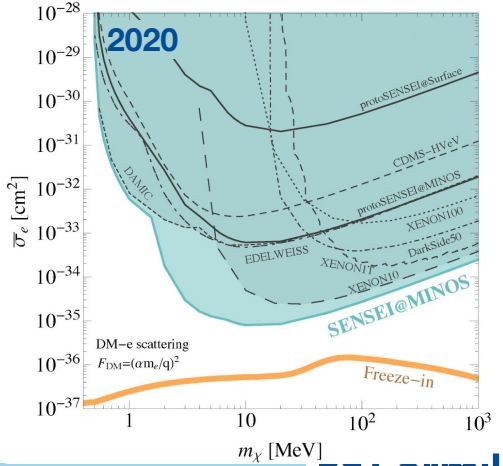


History of SENSEI results

2017	Demonstration of 0.068e^- noise in SENSEI prototype [PRL 119.131802]
2018	DM search with surface run of SENSEI prototype CCD [PRL 121.061803]
2019	DM search with underground run of SENSEI prototype CCD [PRL 122.161801]
2020	DM search with underground run of SENSEI science-grade CCD [PRL 125.171802]

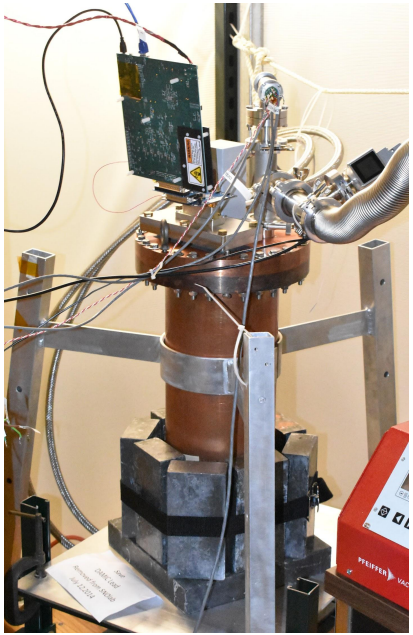




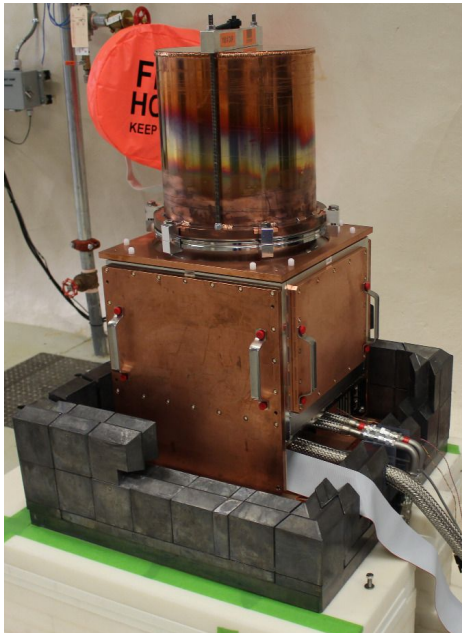


Current status: two science-capable SENSEI setups

SENSEI@MINOS



SENSEI@SNOLAB



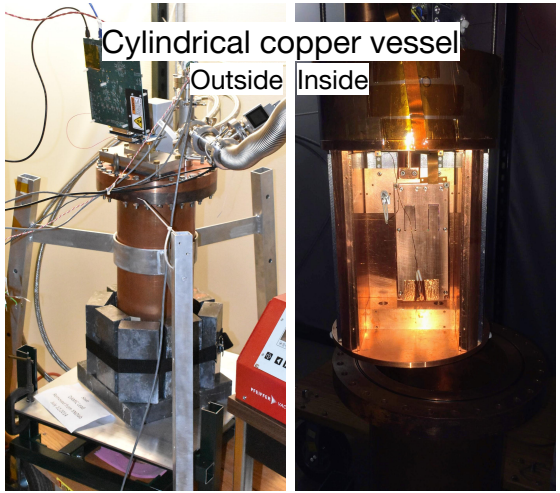
Will show new results/data from *both* detectors today

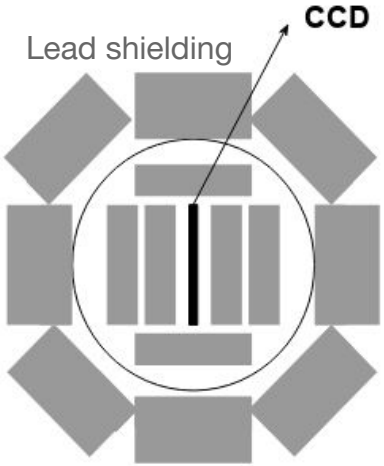
SENSEI@MINOS

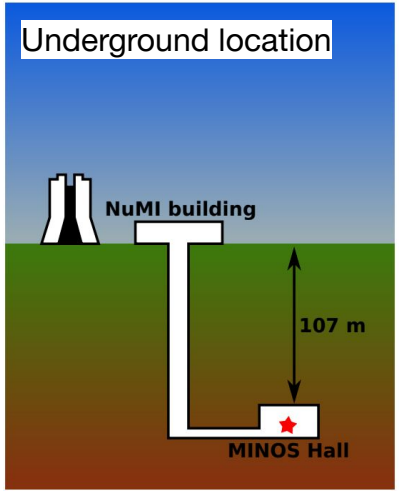
One CCD module installed in copper cryostat: ~1.925 g, operated at 135 K

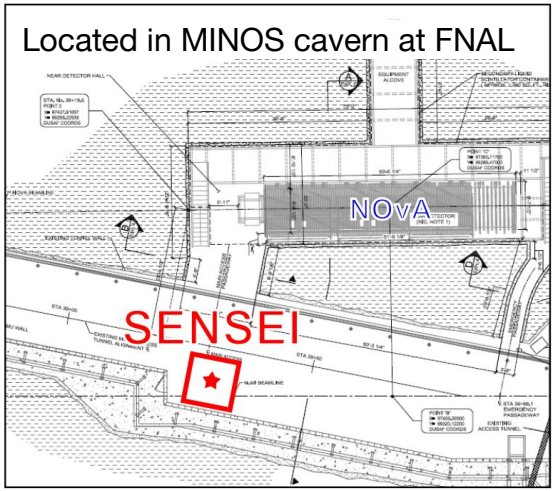
Shielding: inner and outer layers of lead shielding, underground site at FNAL in MINOS cavern (~107 m)

Intersects with NuMI beamline



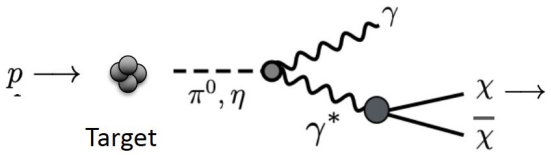




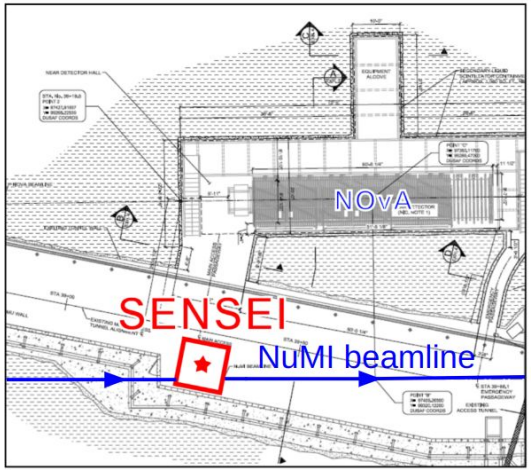


Milli-charged particle (mCP) search in SENSEI@MINOS

Proton collisions w/ fixed target can produce mCPs collinear w/ NuMI beamline:



arXiV:1902.03246



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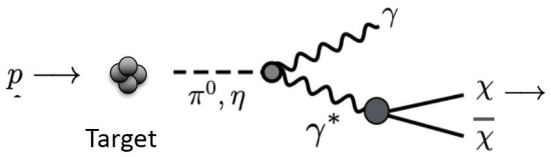

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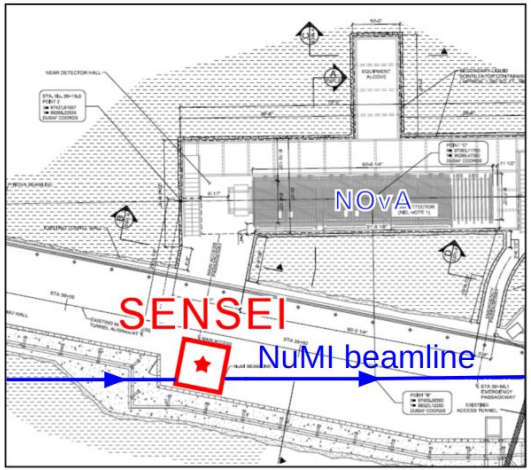
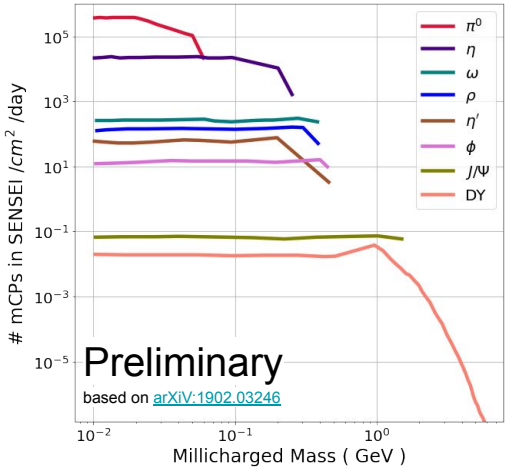


Using production rates accepted by SENSEI@MINOS…



… and data from SENSEI@MINOS:

N_e	1	2	3	4	5	6
Efficiency	0.069	0.105	0.325	0.327	0.288	0.276
Exp. [g-day]	1.38	2.09	9.03	9.10	8.02	7.69
Observed Events	1311.7	5	0	0	0	0

Using same analysis as PRL 125.171802, but extending up to 6e (PRELIMINARY)

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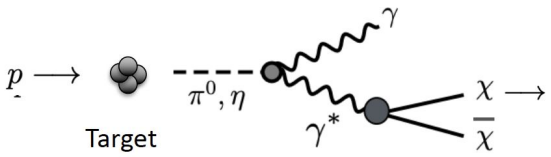

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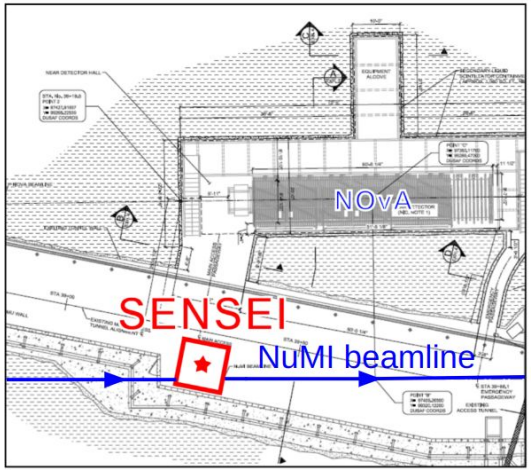

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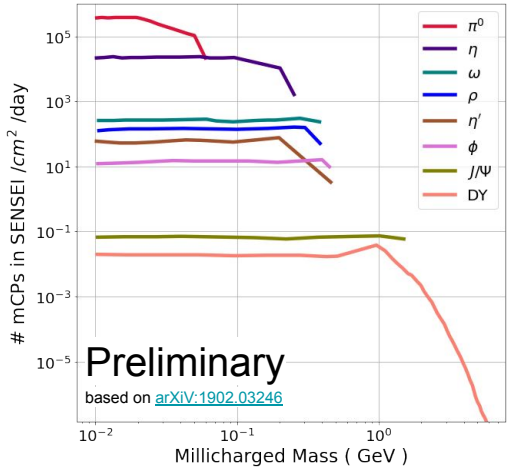

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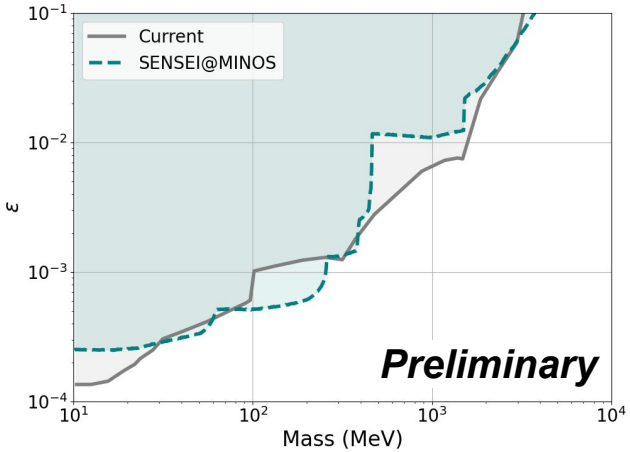
Paper forthcoming!

World-leading limits around 100 MeV:



Significant potential for future mCP searches with CCDs!

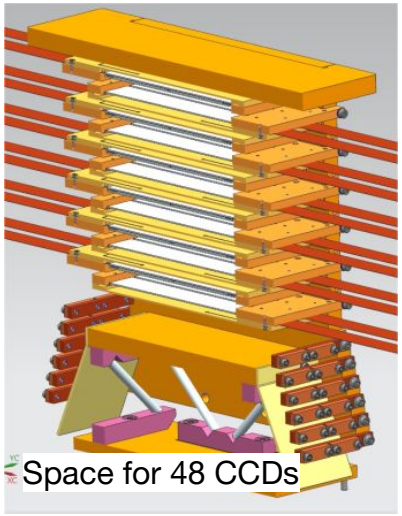
See Oscura talk by B. Cervantes

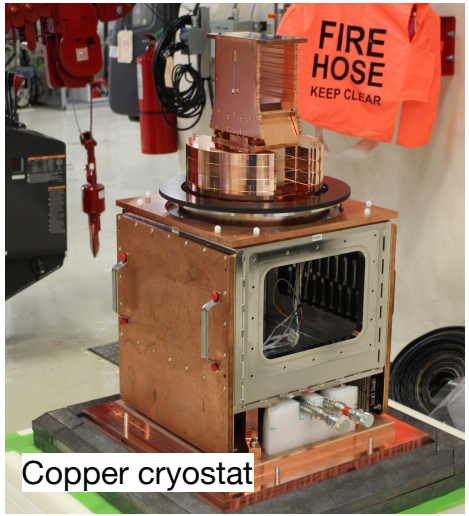
SENSEI@SNOLAB

CCDs installed in copper cryostat: 6 CCDs (~13 g) operating (out of eventual ~100g), 6144 × 1024 pixels, 15 μm pitch, 675 μm thick

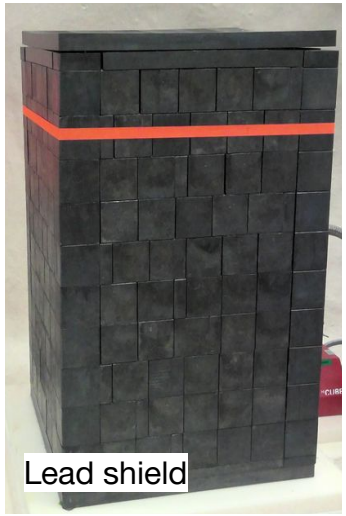
Shielding: 3” of lead, 20” of polyethylene and water, 2 km of granite overburden

Installation: 4-7/2021, **Commissioning:** 10/2021-8/2022, **Science:** 9/2022-present


Space for 48 CCDs



Copper cryostat


Lead shield


Polyethylene shield with part of installation team

CCDs are operating well

20 hour exposures: 122 images and counting, no binning, ~50% blinded for bias mitigation

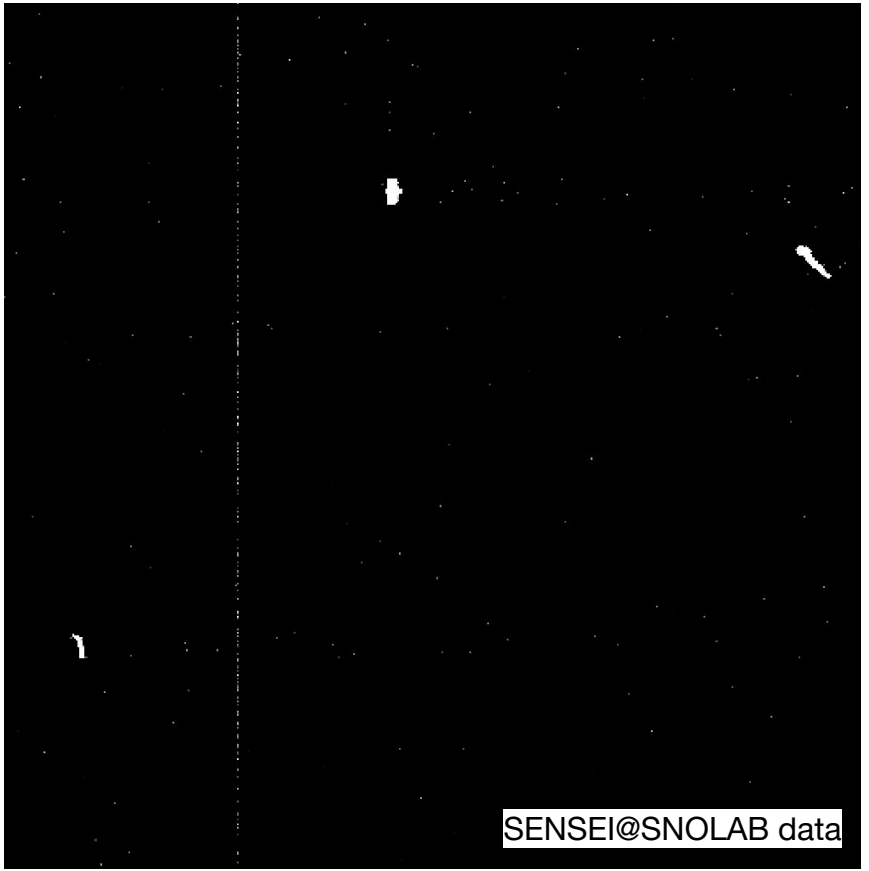
300 Skipper samples → 7.3 hours readout, noise of **~0.14 e^-**

3 hour "clear" following each image to sweep charge from active area

Temperature variations of **135 K-155 K** due to failing cryocooler

1 e^- density (after cuts): **~2 x 10^{-4} e^-/pixel**

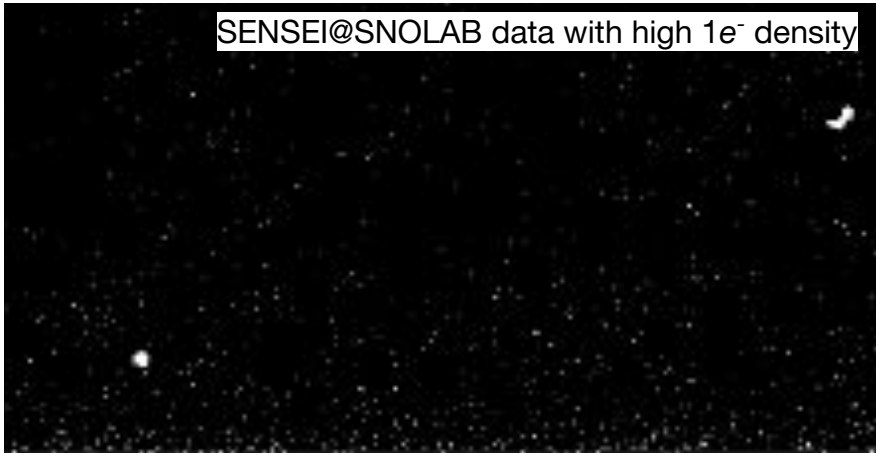
- No dark rate measurement performed



Data selection

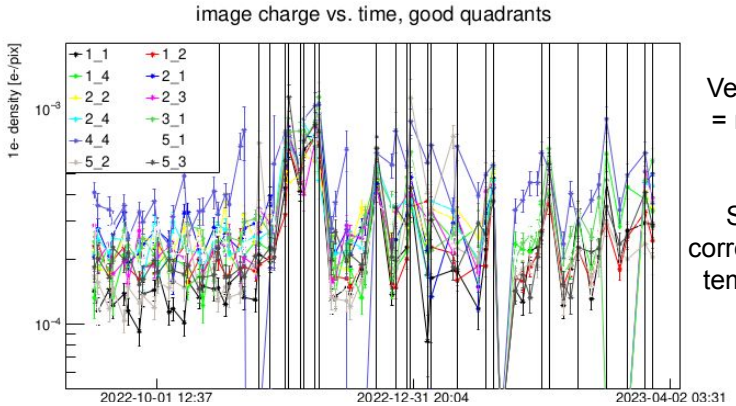
Remove quadrants of CCDs that exhibit unusual behavior:

- Consistently high 1 e^- density
- Low readout gain
- High electronic interference
- High charge transfer inefficiency



Remove images with unusually high 1 e^- density:

- Flag quads with p-value < X, where X is such that we expect to reject < 0.5 quads, remove images with > 1 rejected quads

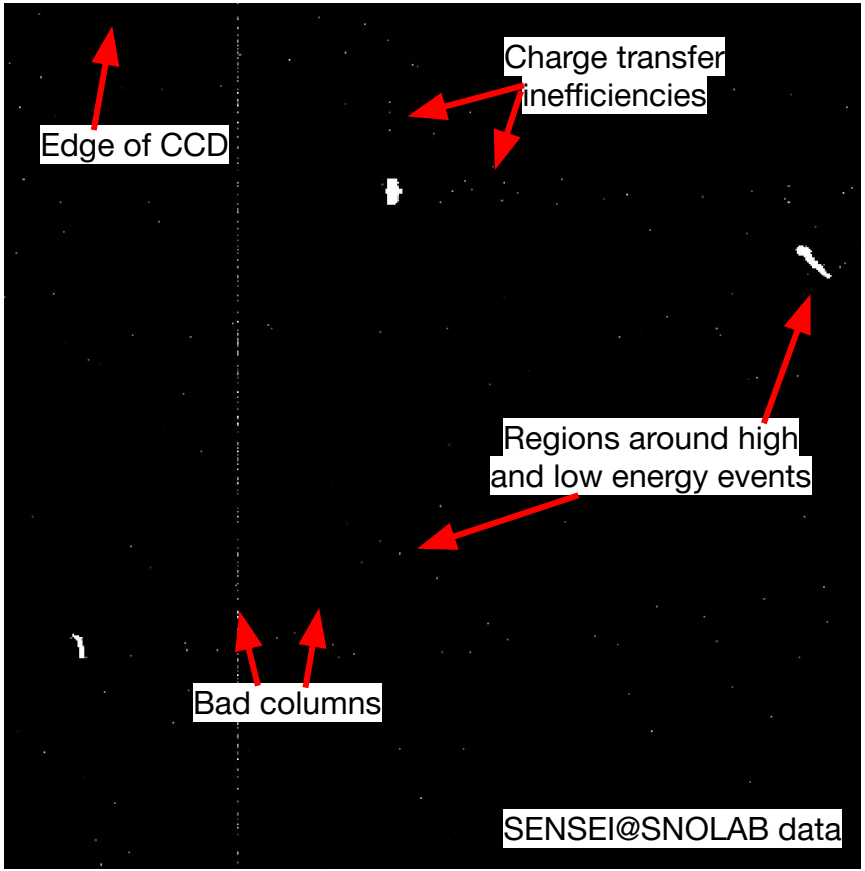


Vertical line = removed image

Strongly correlated with temperature

Cluster reconstruction + selection

1. **Cluster any contiguous pixels ≥1 e^-**
2. **Apply masks to images to remove:**
   - Electronic noise
   - Cross-talk
   - Edges of CCDs
   - Bad pixels and columns
   - Serial register events
   - Charge transfer inefficiencies (CTI, size varies by charge)
   - Region surrounding any ≥1e^- pixels (size varies by charge)
3. **Remove clusters with any pixels overlapping a mask**
4. **Remove individual high-background cluster shapes**



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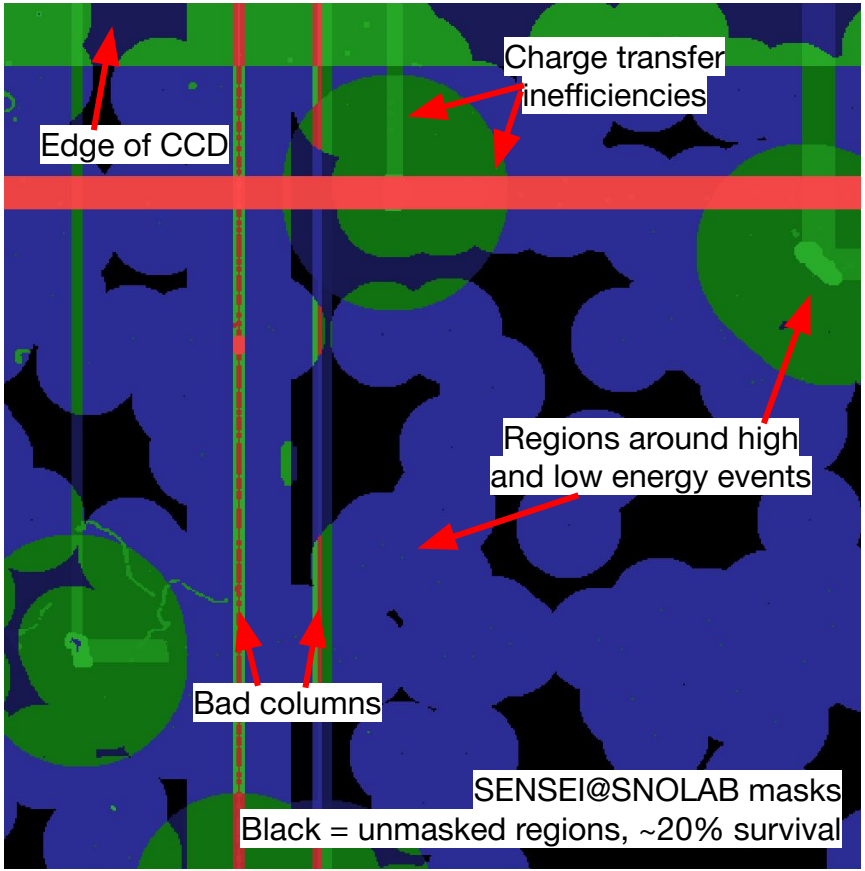


Dark matter-electron scattering limit setting

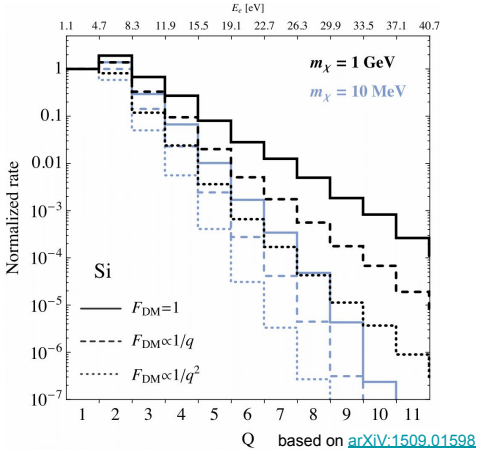
Signal model: generate expected DM events per electron channel using QEdark (upper right) and other calculations given astrophysical parameters from PhystatDM and ionization model (lower right)

Bin by shape: split each electron channel into bins based on number of pixels and/or shape of cluster

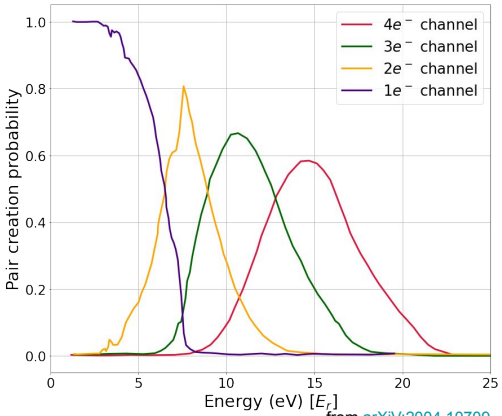
Exposure: determine effective exposure for each bin using Monte Carlo simulation given actual masks and charge diffusion parameters measured in SENSEI@MINOS

Backgrounds: calculate expected coincidence background in each bin given measured $1e^-$ density

Limit: Determine a combined likelihood over all bins to set 90% C.L. upper limits in cross section-DM mass parameter space



based on arXiV:1509.01598



from arXiV:2004.10709

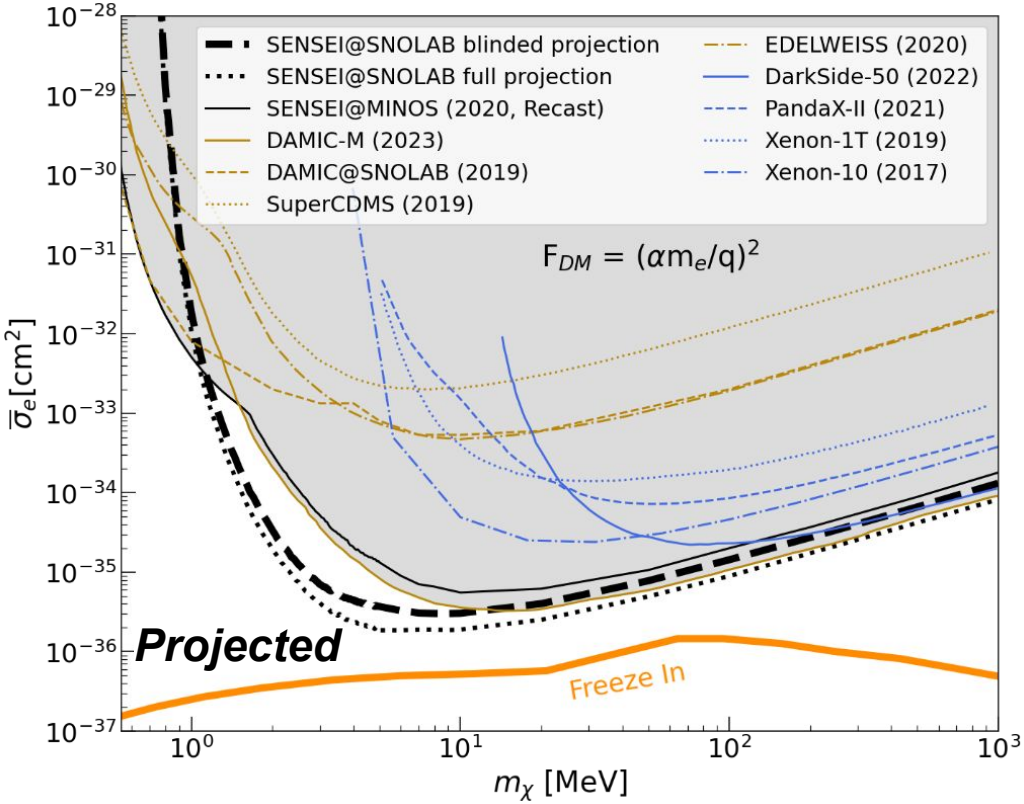
Projected dark matter-electron scattering limits

Data: 67 *unblinded* images (55 remain blinded), 2 -10 e^- channels

Exposure: amounts to ~35 g-days per electron channel with current masks

Two *projected* limits: unblinded rates ~scaled to blinded exposure, ~scaled to unblinded + blinded exposure

Full data will be released following unblinding



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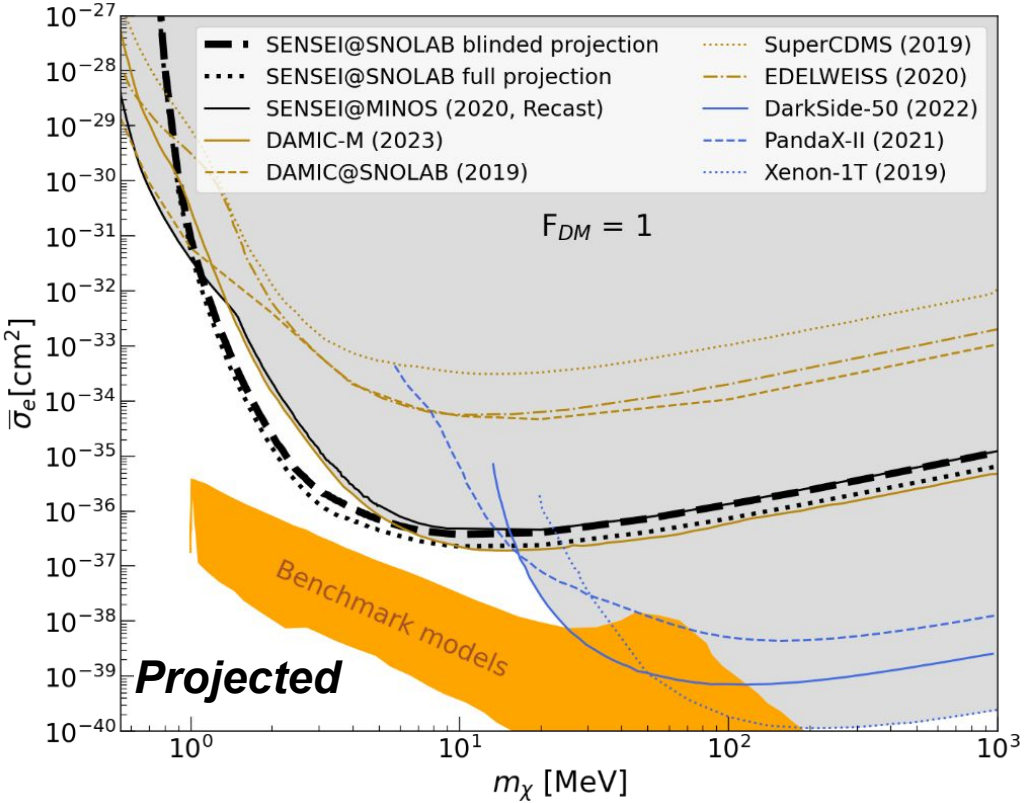


Future plans

End of Science Run 1: April 2023

Planned hardware intervention to:

- Repair cryocooler
- Install additional CCDs
- Improve noise environment

Followed by start of Science Run 2

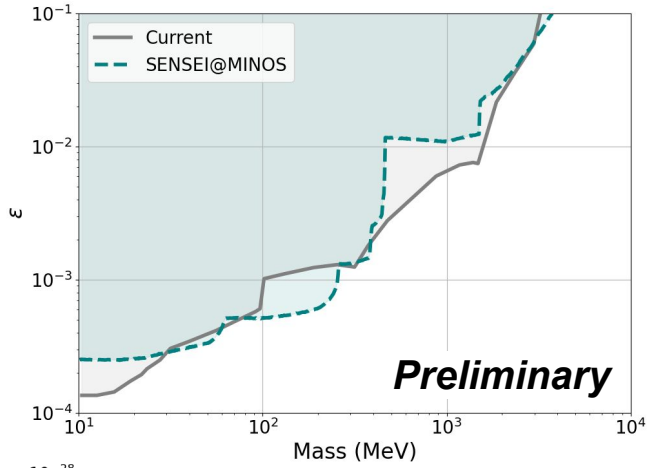
Results of Science Run 1 to appear soon

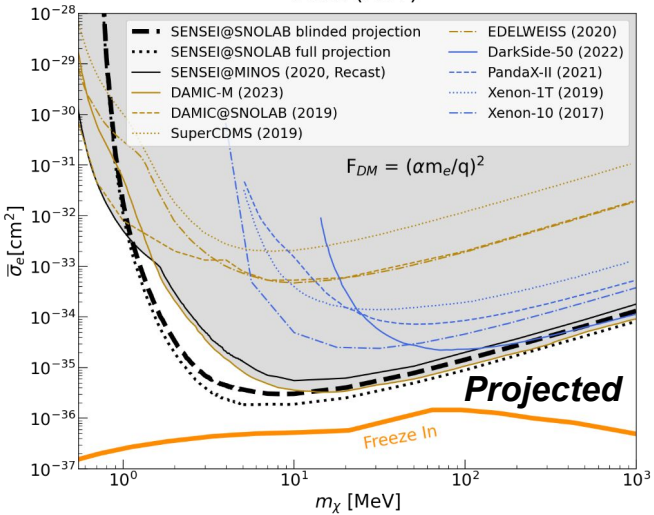
Pursuing additional measurements and analyses with both SNOLAB and MINOS data:

- 1 e^- studies
- Expanded energy range
- Alternate interactions, including Migdal, absorption, etc.
- Alternate signatures, including daily modulation

Conclusions

- **The SENSEI collaboration has two detectors utilizing Si Skipper-CCDs to perform world-leading science:**
  - SENSEI@MINOS has set new, world-leading limits on milli-charged particles around 100 MeV
  - SENSEI@SNOLAB is nearing the end of its first science run, and expects to probe new parameter space over a range of DM masses following upcoming unblinding
- **Many more exciting results to come, paving the way for the next generation of CCD experiments**





Fermilab