Results from sub-GeV dark matter searches with SENSEI

Kelly Stifter, for the SENSEI collaboration

PHENO 23 conference

5/8/2023

The SENSEI collaboration

Fermilab: A. M. Botti, G. Cancelo, F. Chierchie, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez Moroni, N. Saffold, M. Sofo Haro, L. Stefanazzi, K. Stifter, J. Tiffenberg, S. Uemura

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

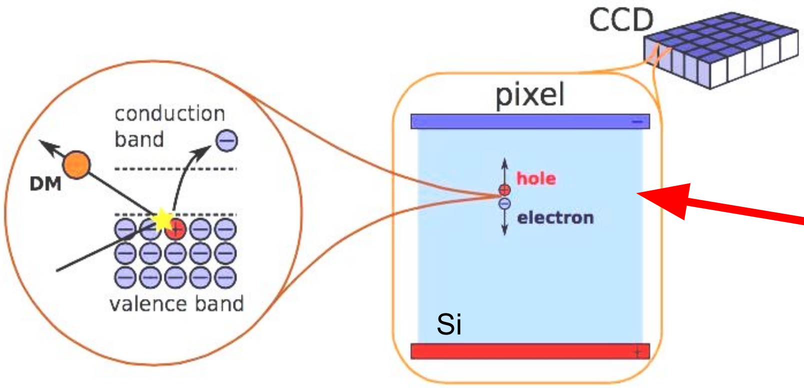
LBNL: S. Holland

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):



Pixelated silicon substrate

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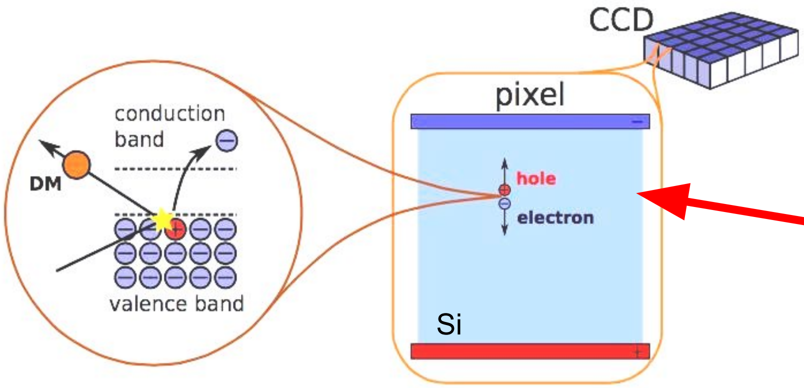

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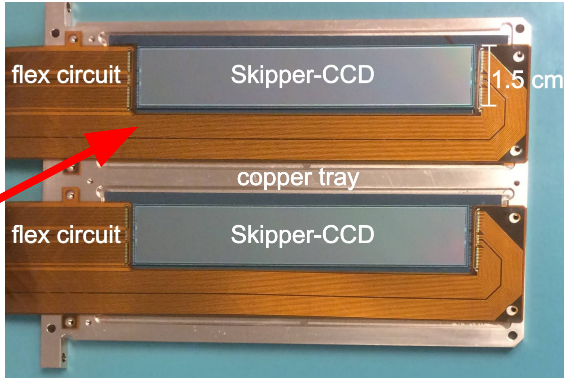

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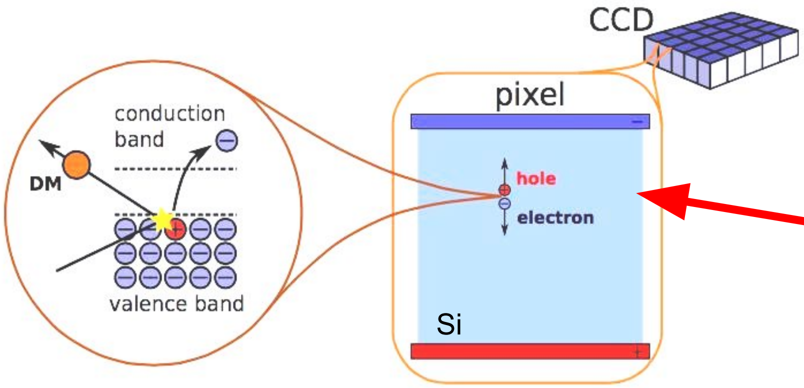
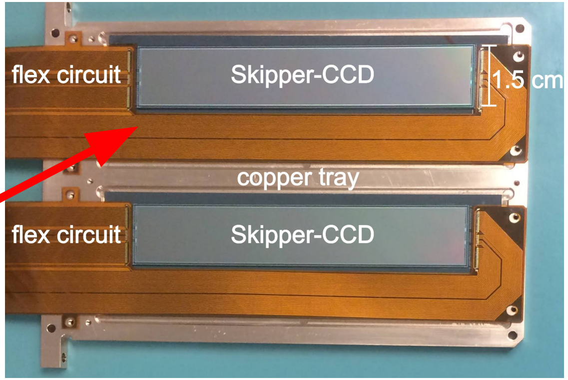
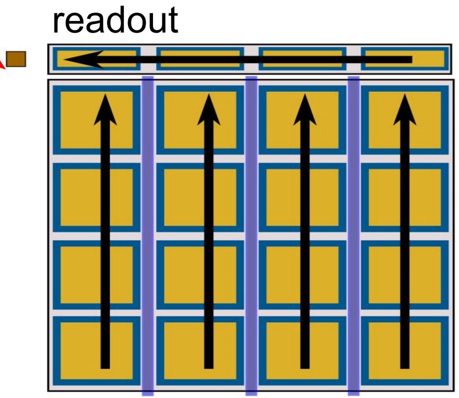


Pixelated silicon substrate read out with repeated, non-destructive measurements





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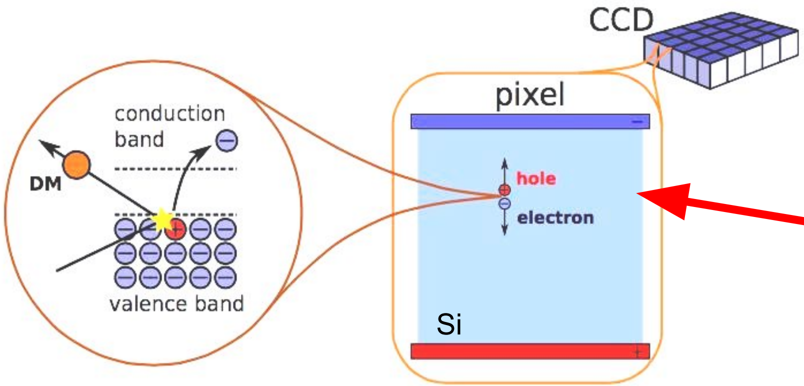
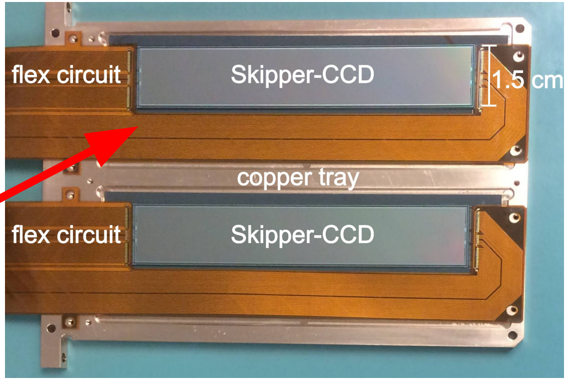
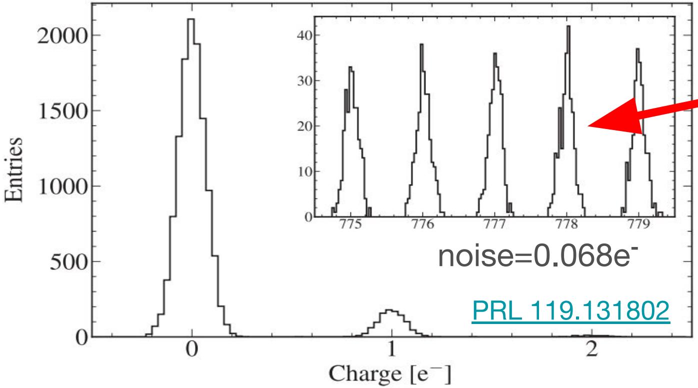
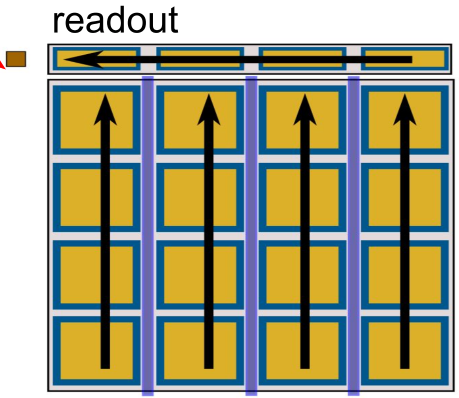




Pixelated silicon substrate read out with repeated, non-destructive measurements, gives 1e^- resolution (see back up for details)





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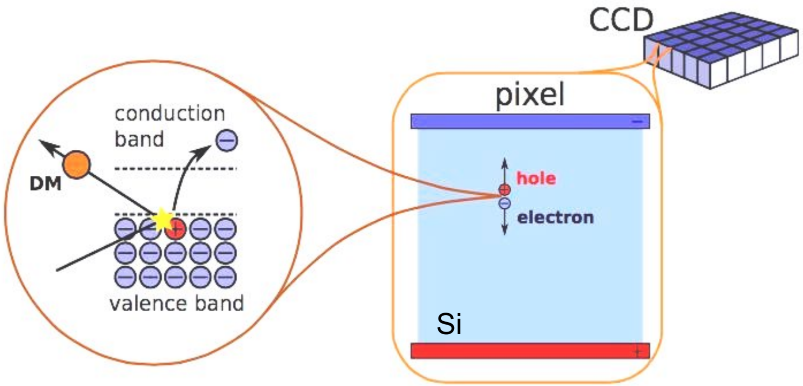
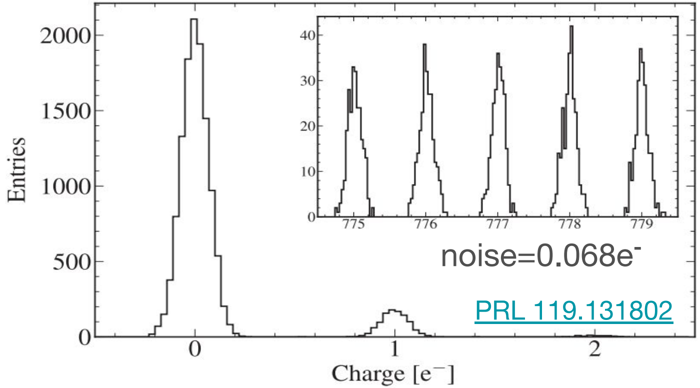




Specifications:

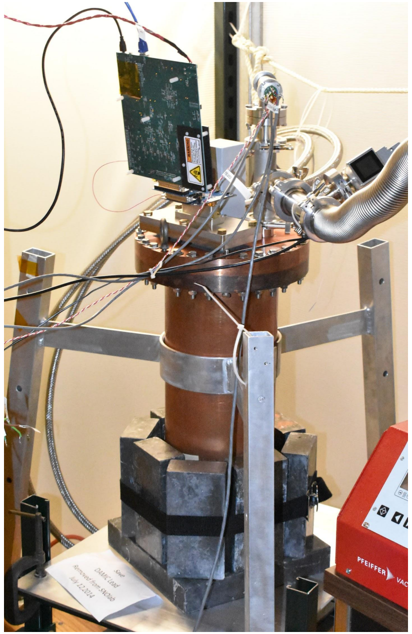
- Energy threshold of Si bandgap (~1.1 eV)
- Low dark current (~10^{-4} e^-/pix/day)
- Sub-electron (~0.1e^-) readout noise

Access to low-mass searches:

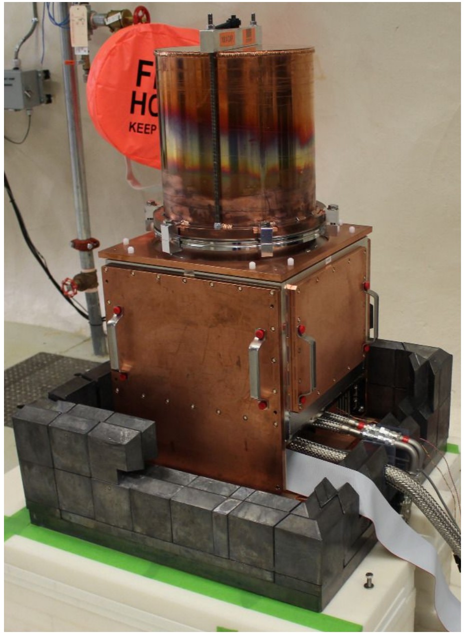
- Electron scattering of 1-1000 MeV DM
- Nuclear scattering of 1-1000 MeV DM via Migdal effect
- Absorption of 1-1000 eV DM
- Scattering of milli-charged particles
- Etc…

Current status: two science-capable SENSEI setups

SENSEI@MINOS



SENSEI@SNOLAB



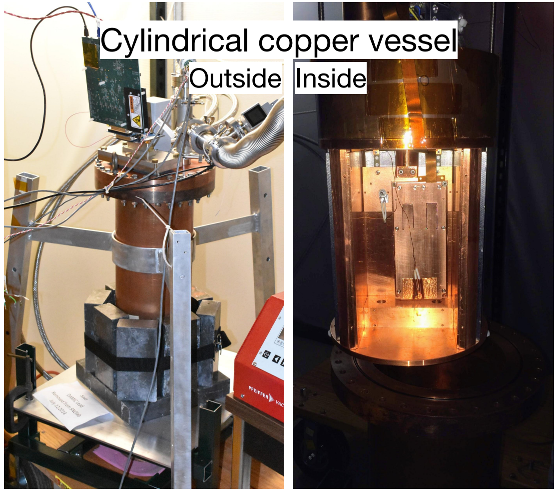
Will show new results/data from *both* detectors today

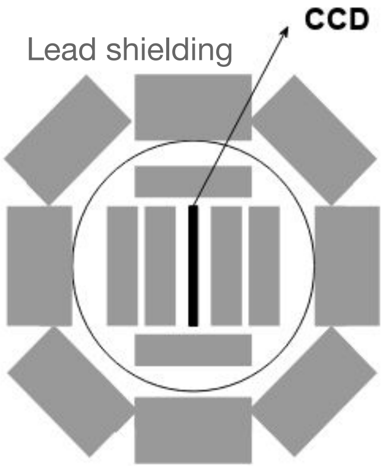
SENSEI@MINOS

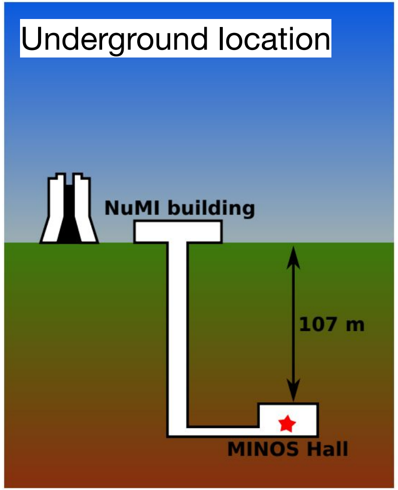
One CCD module installed in copper cryostat: ~1.925 g, operated at 135 K

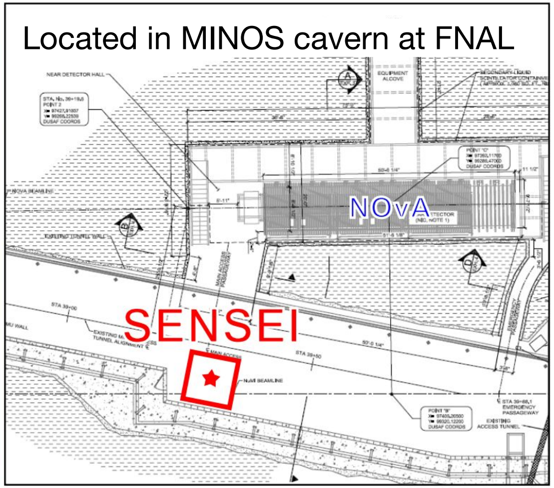
Shielding: inner and outer layers of lead shielding, underground site at FNAL in MINOS cavern (~107 m)

Intersects with NuMI beamline



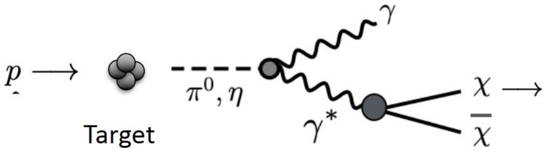




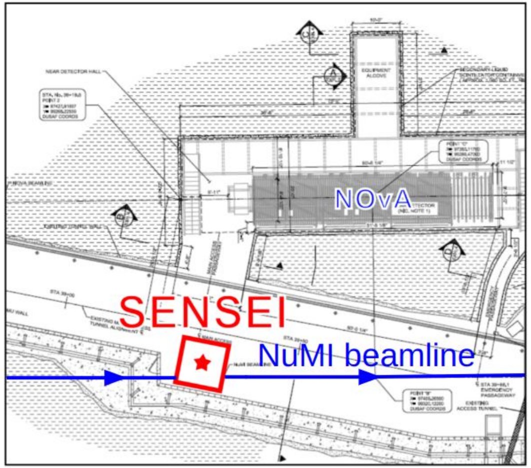


Millicharged particle (mCP) search in SENSEI@MINOS

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



arXiV:1902.03246



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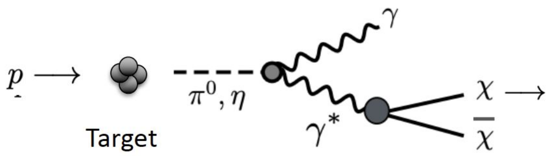

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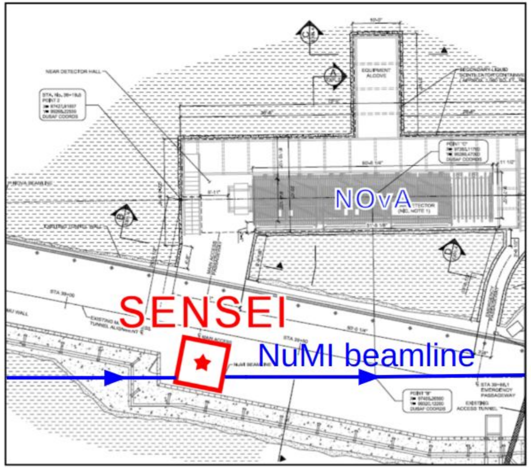
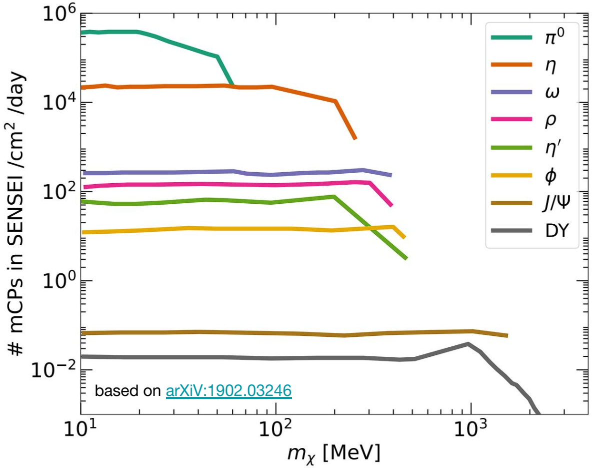


Using production rates accepted by SENSEI@MINOS…



… and data from SENSEI@MINOS:

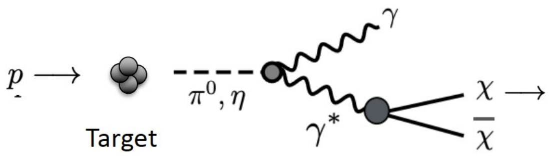
	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Eff. Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exp. [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Obs. Events	1311.7	5	0	0	0	0

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

Millicharged particle (mCP) search in SENSEI@MINOS

Paper submitted TODAY

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



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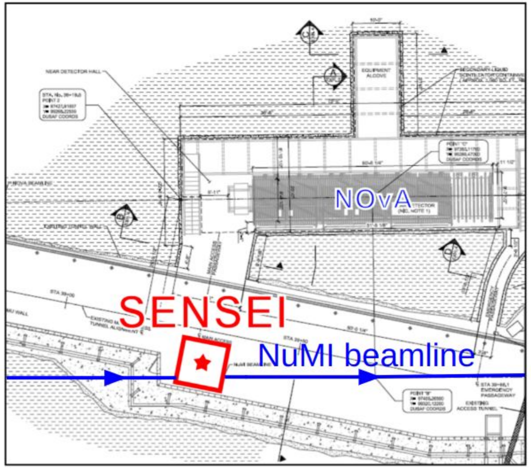

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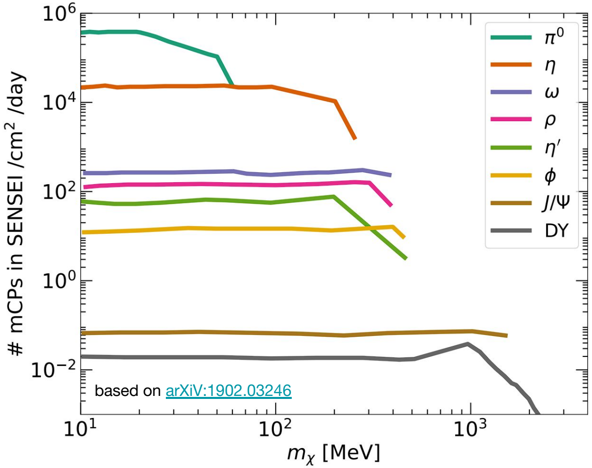

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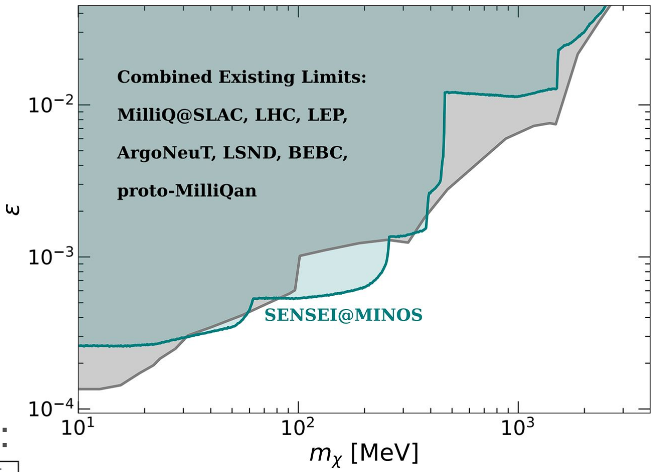
World-leading limits from 30 – 380 MeV:



Significant potential for future mCP searches with CCDs!

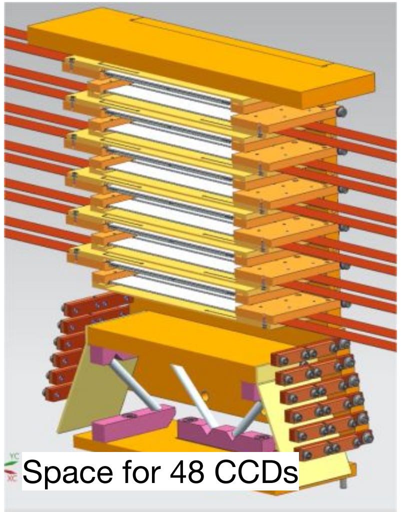
arXiV:2304.08625

SENSEI@SNOLAB

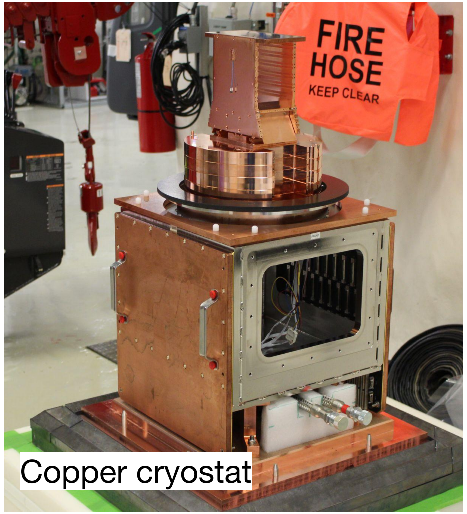
CCDs installed in copper cryostat: 6 CCDs (~13 g) operating (out of eventual ~100g), 6144 × 1024 pixels, 15 μm pitch, 675 μm thick

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

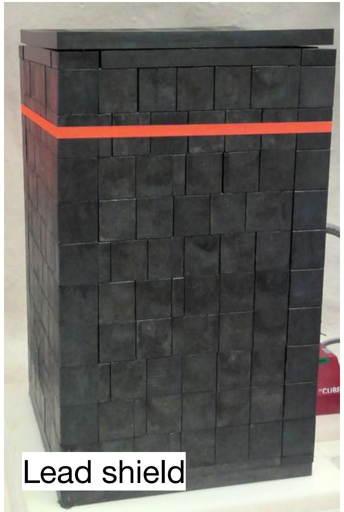
Installation: 4-7/2021, **Commissioning:** 10/2021-8/2022, **Science:** 9/2022-4/2023



Space for 48 CCDs



Copper cryostat



Lead shield

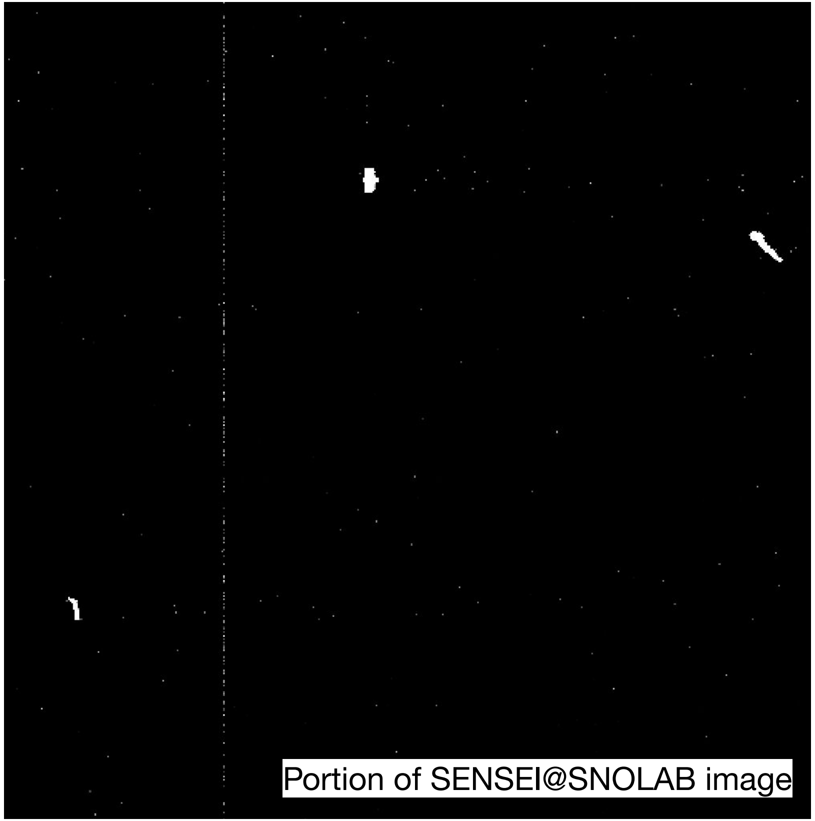
Polyethylene shield with part of installation team

Data collection, reconstruction, and analysis

20 hour exposures: 129 images, no binning, ~50% hidden for bias mitigation

For each image:

1. Data quality cuts to remove anomalous images
2. Cluster any contiguous pixels ≥1 e^-
3. Apply masks to images to remove known backgrounds
4. Remove clusters with pixels overlapping a mask
5. Remove high-background cluster shapes



Portion of SENSEI@SNOLAB image

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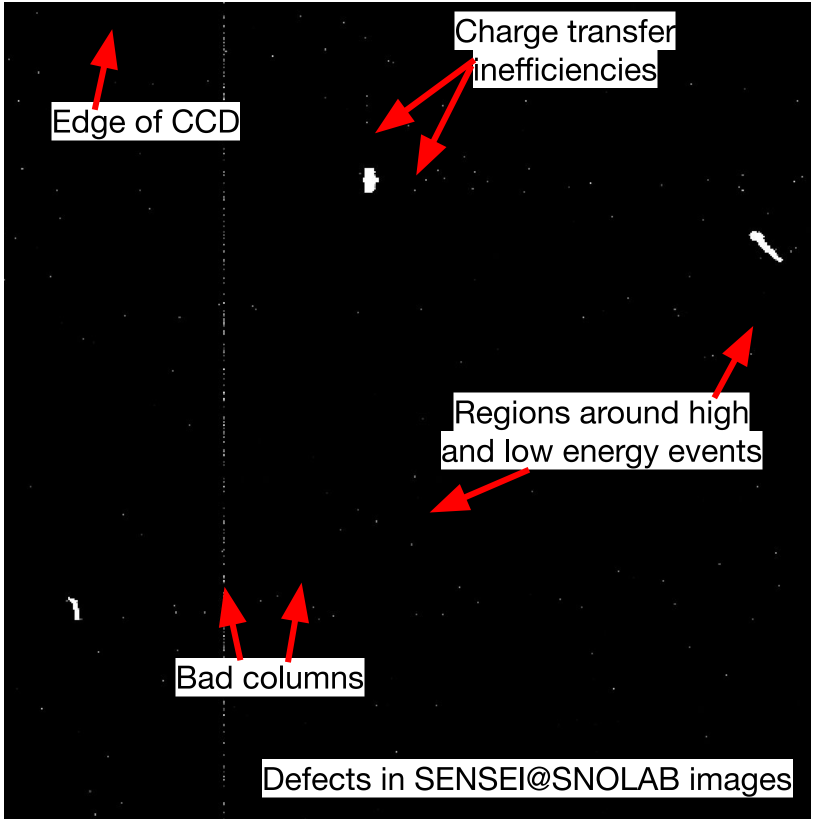

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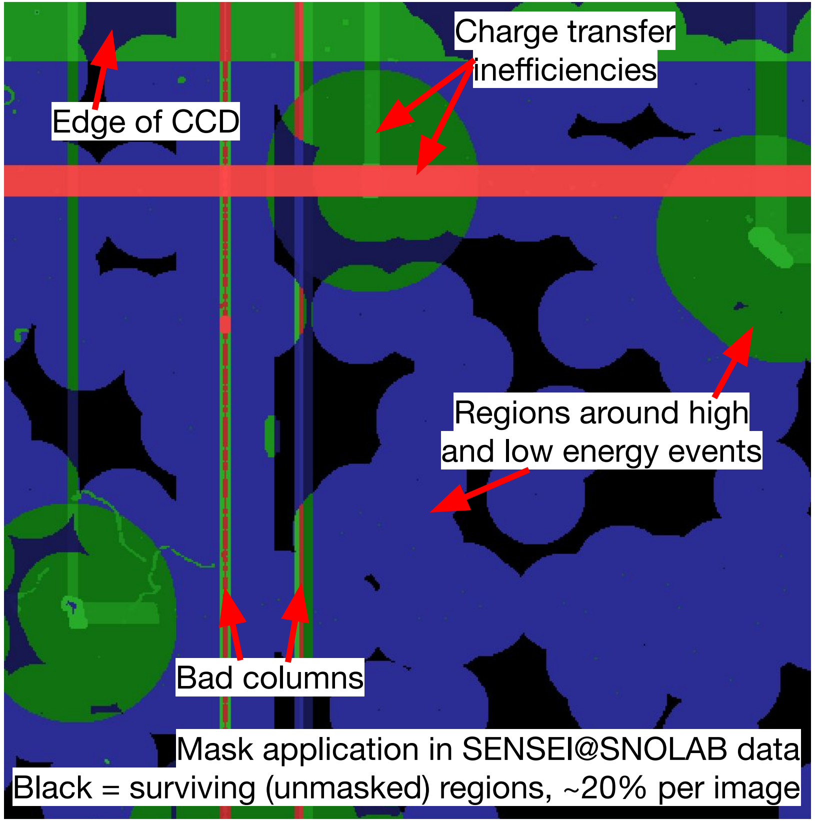


Dark matter limit setting

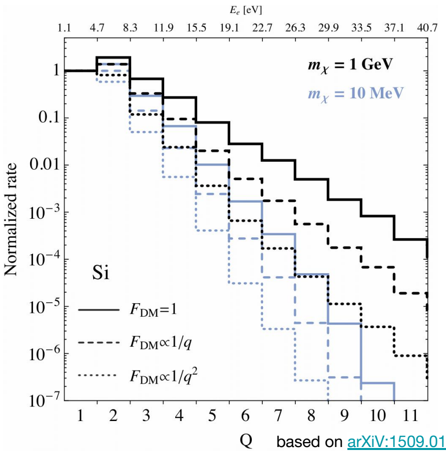
Signal model: generate expected DM events per electron channel using QEdark (upper right) and other calculations given astrophysical parameters from PhystatDM and ionization model (lower right)

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

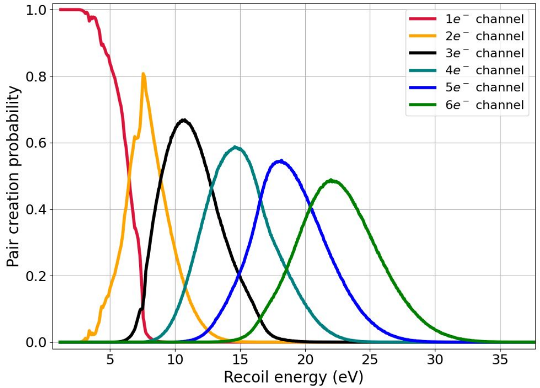
Exposure: determine effective exposure for each bin using Monte Carlo simulation given actual masks and charge diffusion parameters measured in SENSEI@MINOS

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

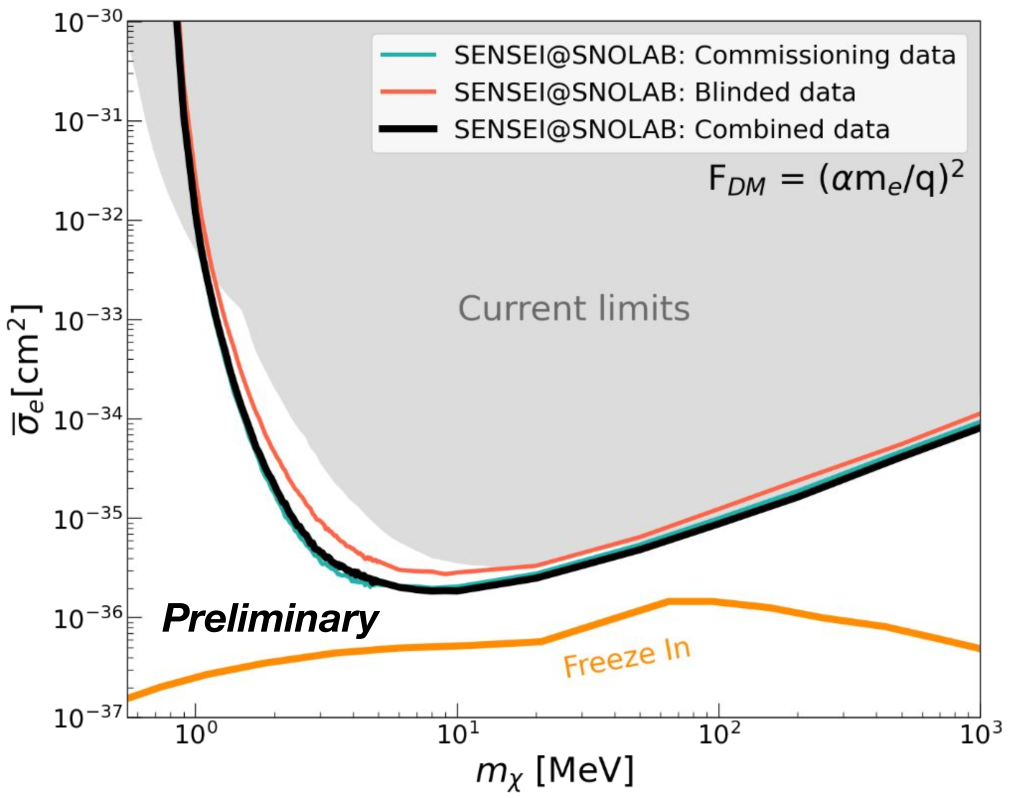
Dark matter-electron scattering limits

Data: 45 unblinded commissioning images, 37 hidden images, 2-10 e^- channels

Exposure: combined datasets amount to ~70 g-days per electron channel with current masks

Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

Paper in preparation to present full results



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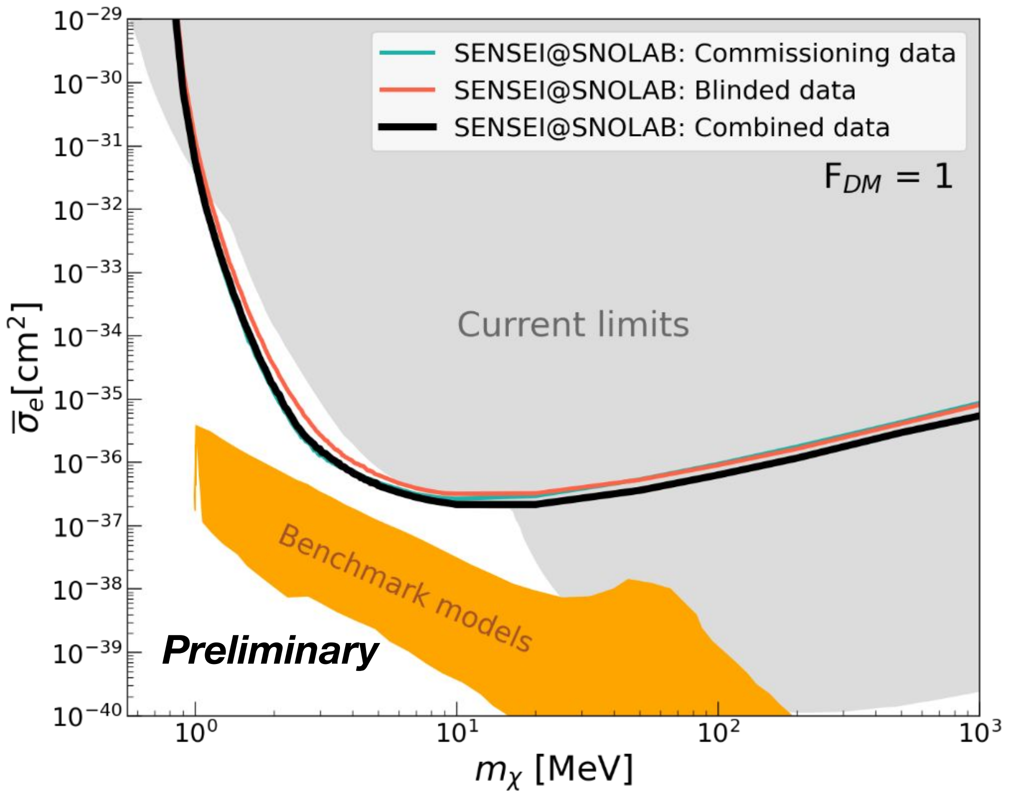

Dark matter absorption limit

Data: 45 unblinded commissioning images, 37 hidden images, 2-10 e^- channels

Exposure: combined datasets amount to ~70 g-days per electron channel with current masks

Two limits: combined commissioning + blinded exposure, recast 2020 results w/ new ionization model, limit-setting procedure from arXiV:1608.02123

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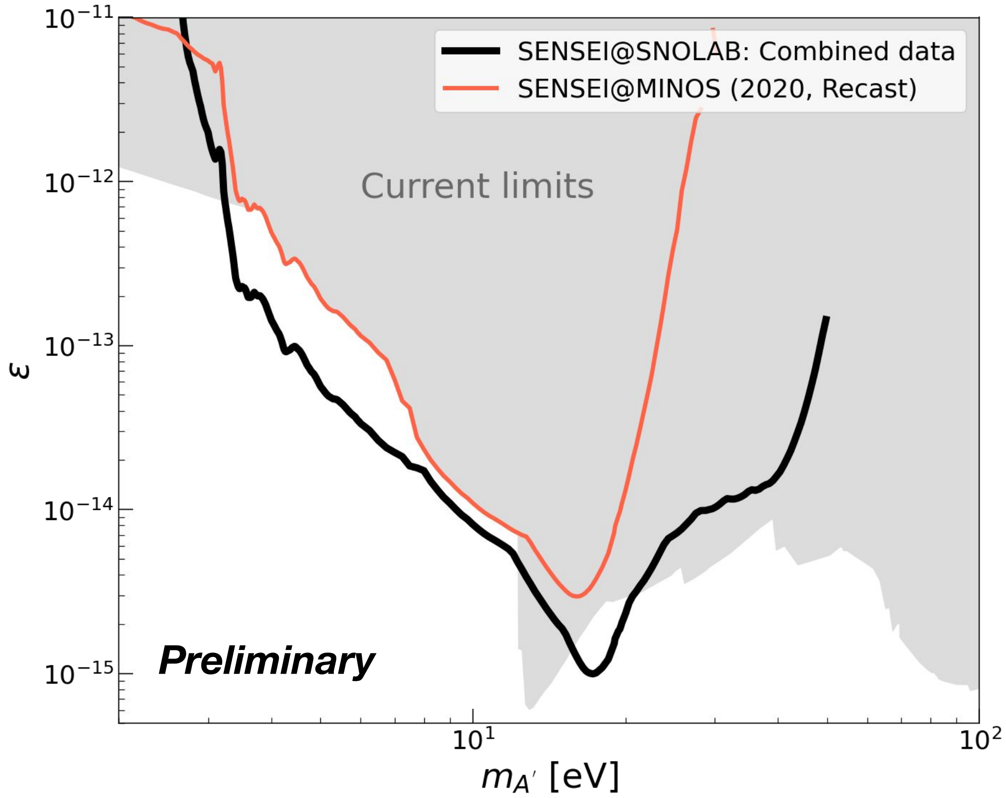


Future SENSEI plans

Ongoing hardware intervention at SNOLAB to:

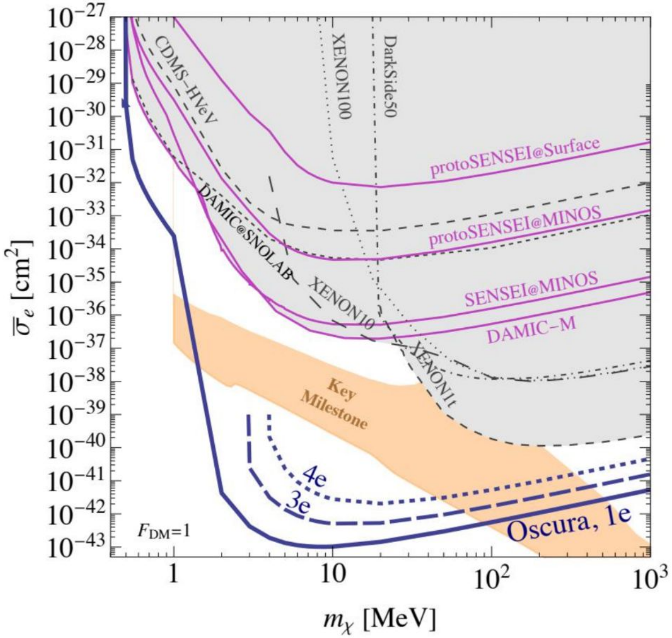
- Repair failing cryocooler
- Install additional CCDs
- Improve noise environment

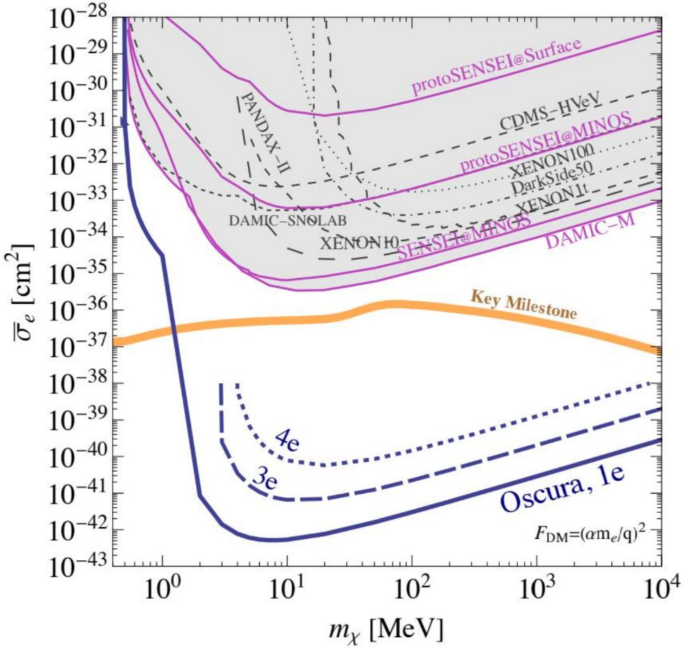
Followed by commissioning, and start of Science Run 2

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

- 1 e^- studies
- Alternate interactions, including Migdal, solar reflection, etc.
- Alternate signatures, including daily modulation

More to come from Skipper-CCDs!



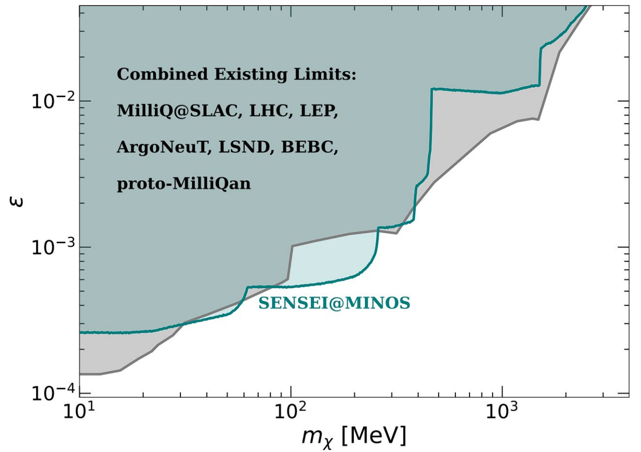


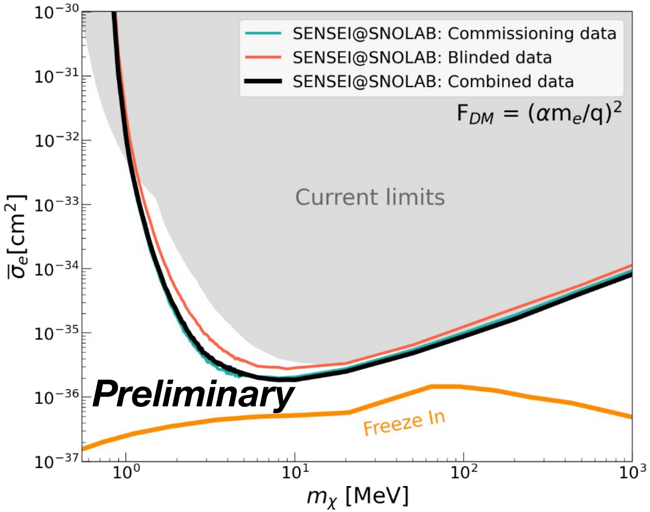
Oscura experiment plans to deploy 10 kg skipper-CCD array to provide unprecedented sensitivity to sub-GeV DM

See arXiV:2304.04401, arXiV:2304.08625, B. Cervantes's UCLA DM 2023 talk

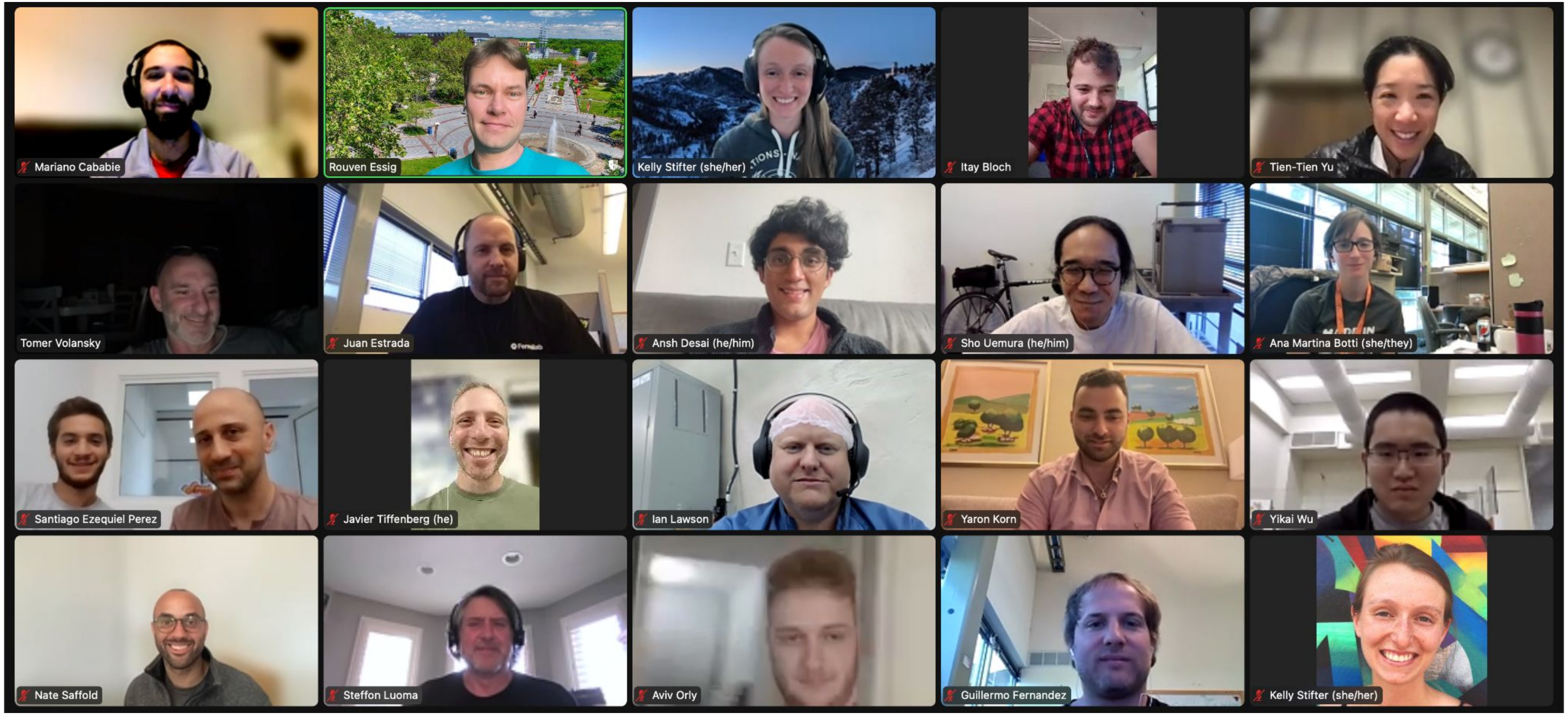
Conclusions

- **The SENSEI collaboration has two detectors utilizing Si Skipper-CCDs to perform world-leading science:**
  - SENSEI@MINOS has set new, world-leading limits on millicharged particles from 30 – 380 MeV
  - SENSEI@SNOLAB completed its first science run, and set world-leading limits on sub-GeV dark matter interacting with electrons
- **Many more exciting results to come, paving the way for the next generation of CCD experiments**





Thanks for listening!



SENSEI collaboration at unblinding meeting

Thanks to my collaborators for all their hard work that helped us reach these milestones!

Back up

The search for sub-GeV dark matter

- Direct detection experiments have historically focused on WIMP DM with masses down to O(GeV)
  - Well motivated (“WIMP miracle”), experimentally accessible (nuclear recoils)
- New complementary searches for low masses
  - Theoretical interest in dark sectors
- Need technologies with lower thresholds
  - One promising direction: **Skipper-CCDs for electron recoil**, with thresholds near the silicon bandgap

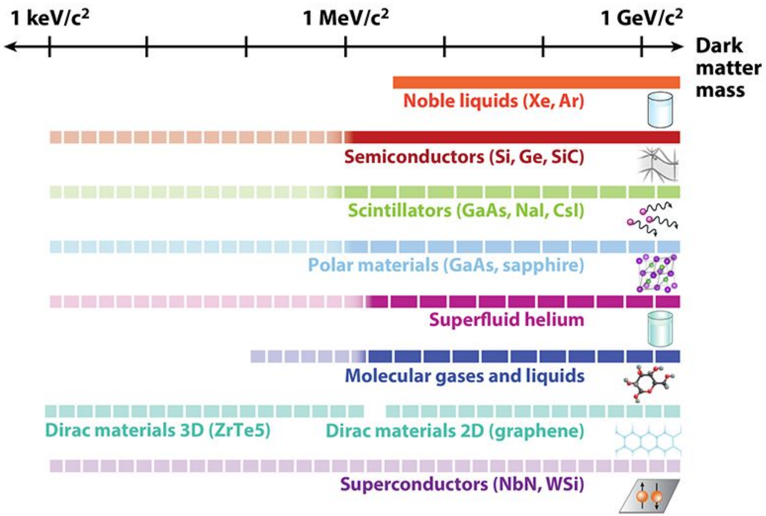
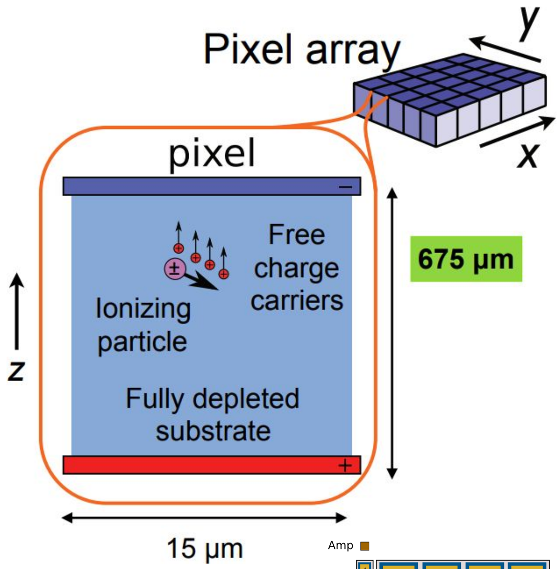
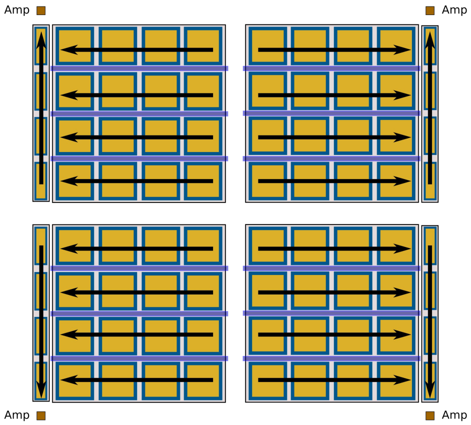


Image Credit: R. Essig, SBU; C. Cain, APS

Charge coupled devices (CCDs)

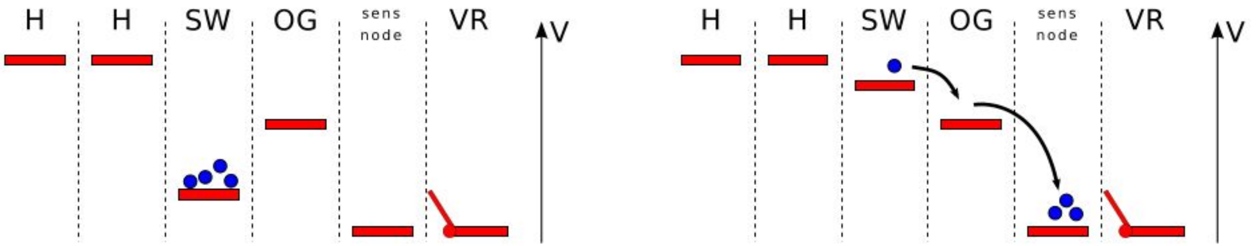
- Charge coupled devices (CCDs) are integrated circuits that produce images of the energy depositions in a pixelated Si substrate
- Holes drift through substrate and collect in pixels near the surface
- Charge packets are shifted to a shared amplifier (1 per quadrant) for readout
- CCDs for DM are designed 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 capabilities of commercial foundries

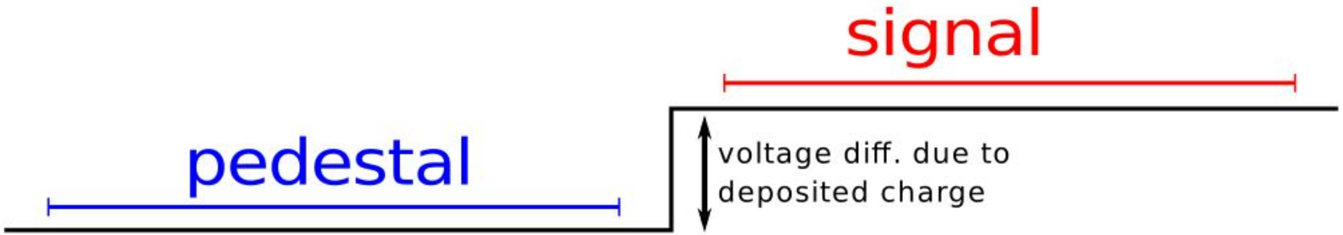




Skipper readout

- Conventional CCDs are limited to noise of ~2e^-
  - 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 non-destructive measurements!





For review, see: [arXiV:1106.1839](https://arxiv.org/abs/1106.1839)

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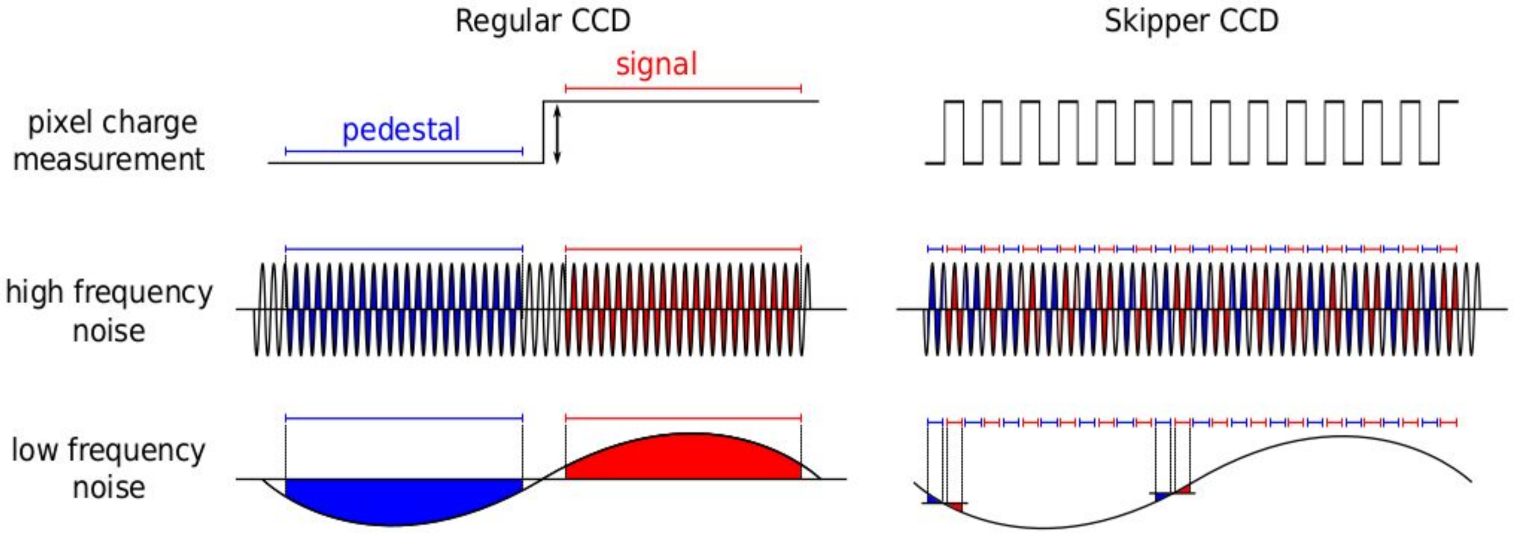

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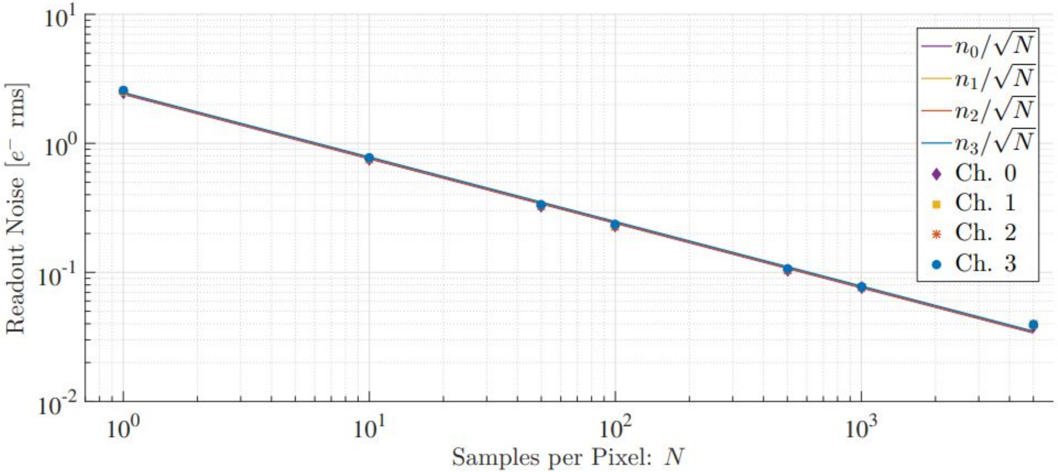
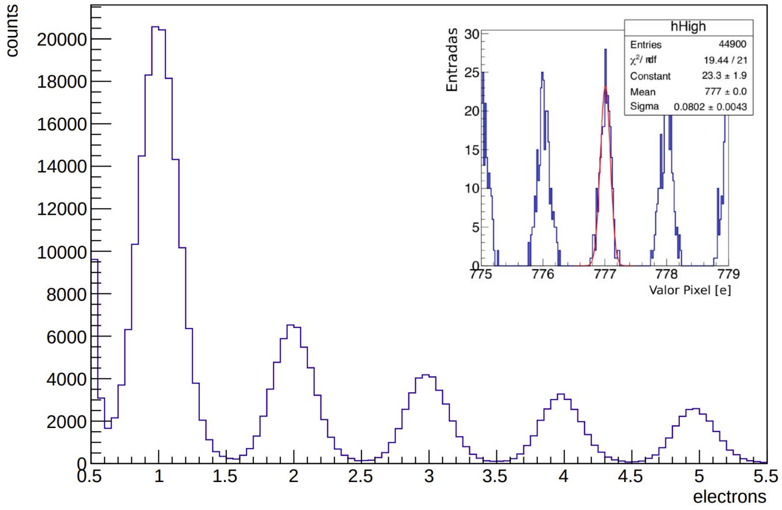
Sub-electron readout noise in Skippers

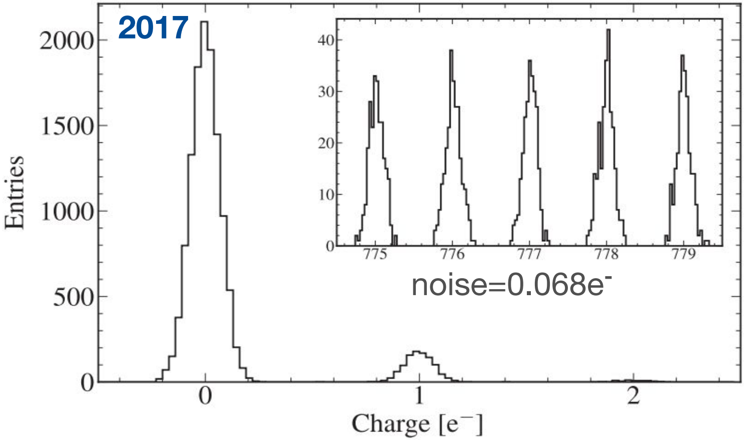
- Skipper noise scales as $1/\sqrt{N}$:
  - Trade charge resolution for speed
- We can count ***single electrons***: self-calibrating charge measurement across wide energy range

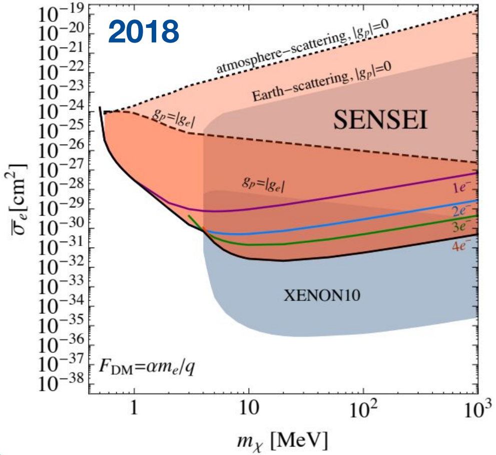


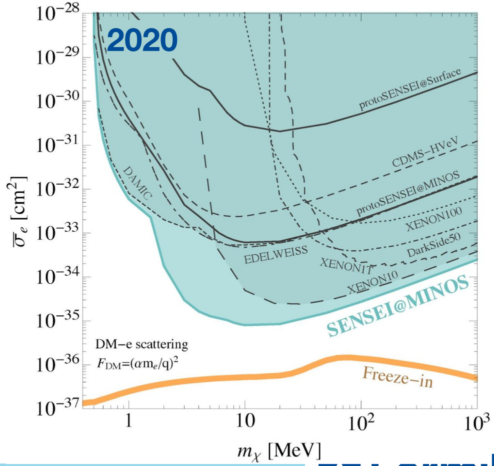


History of SENSEI results

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]







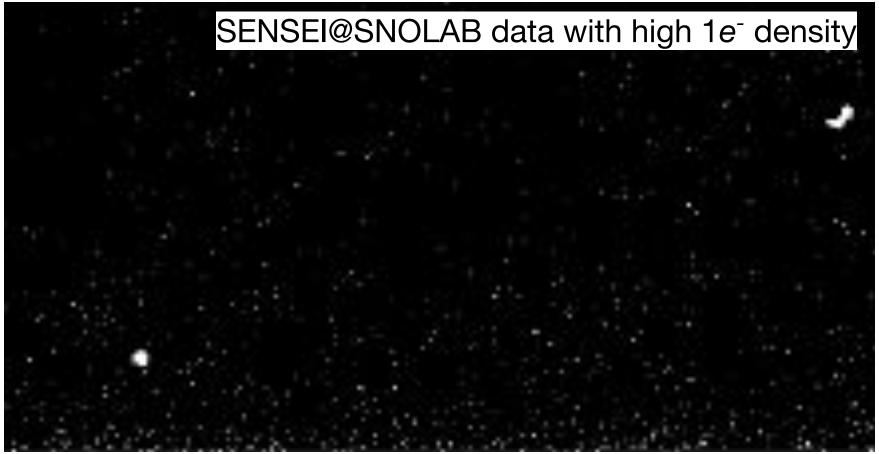
SENSEI@SNOLAB data selection

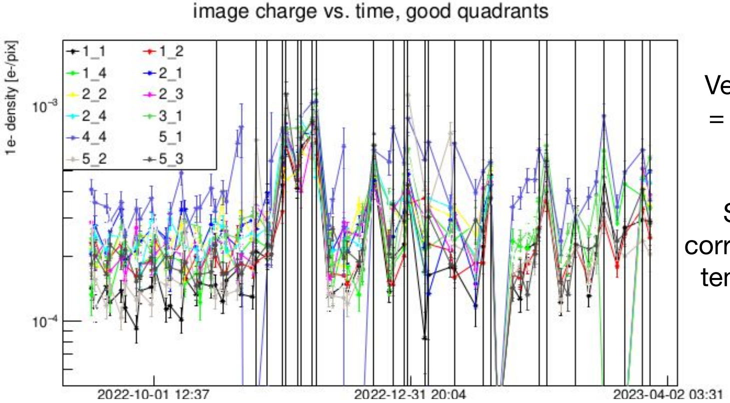
Remove quadrants of CCDs that exhibit unusual behavior:

- 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

CCDs are operating well

20 hour exposures: 129 images, 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

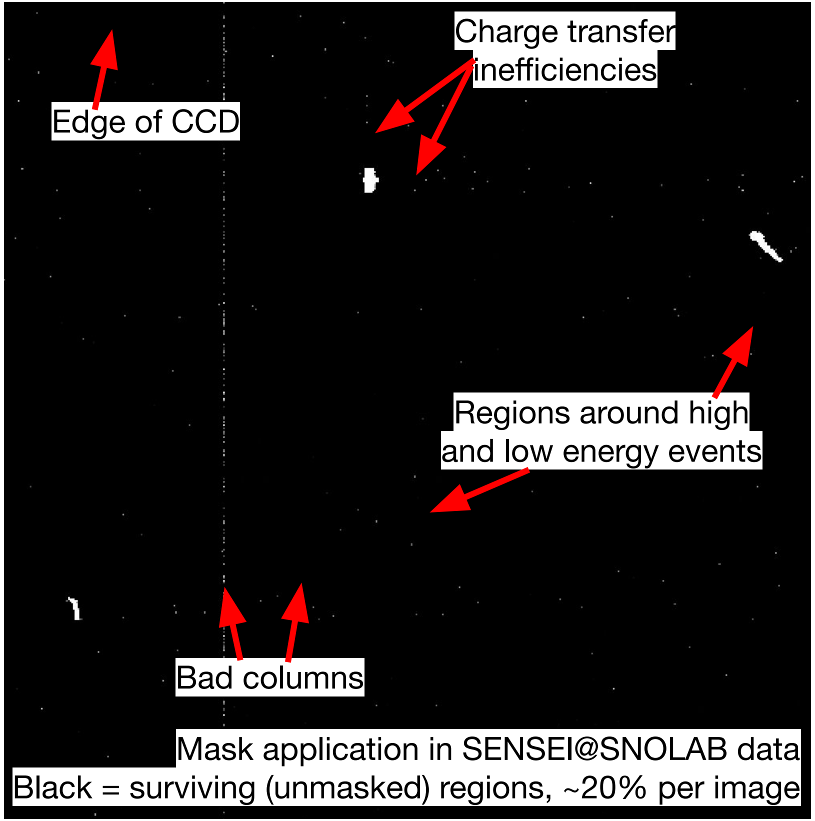
1 e^- density (after cuts): **~2 x 10^{-4} e^-/pixel**

- No dark rate measurement performed

Cluster reconstruction + selection

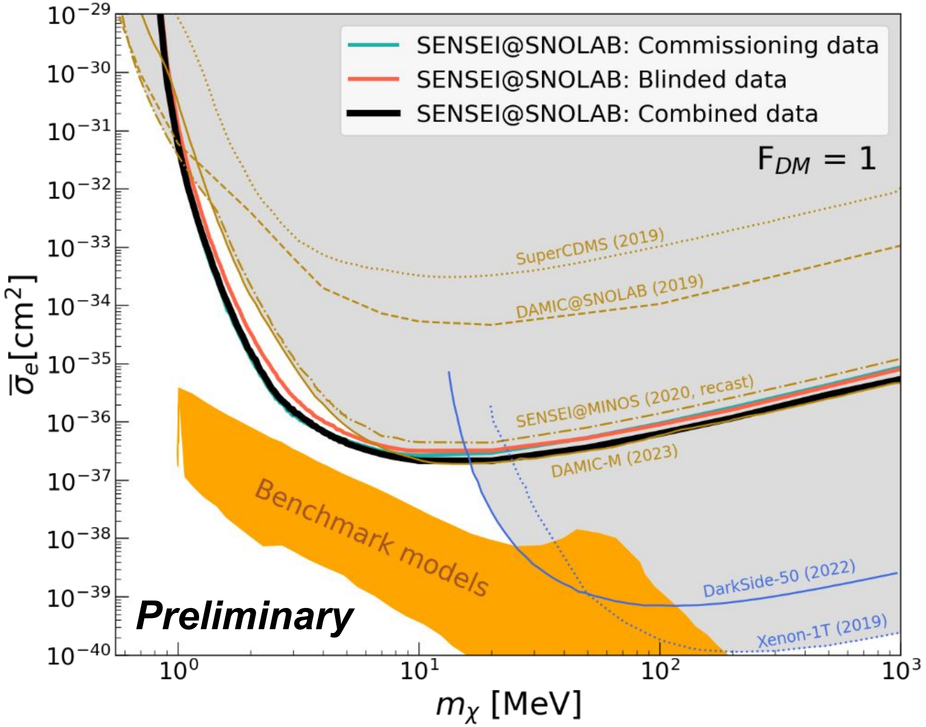
For each image:

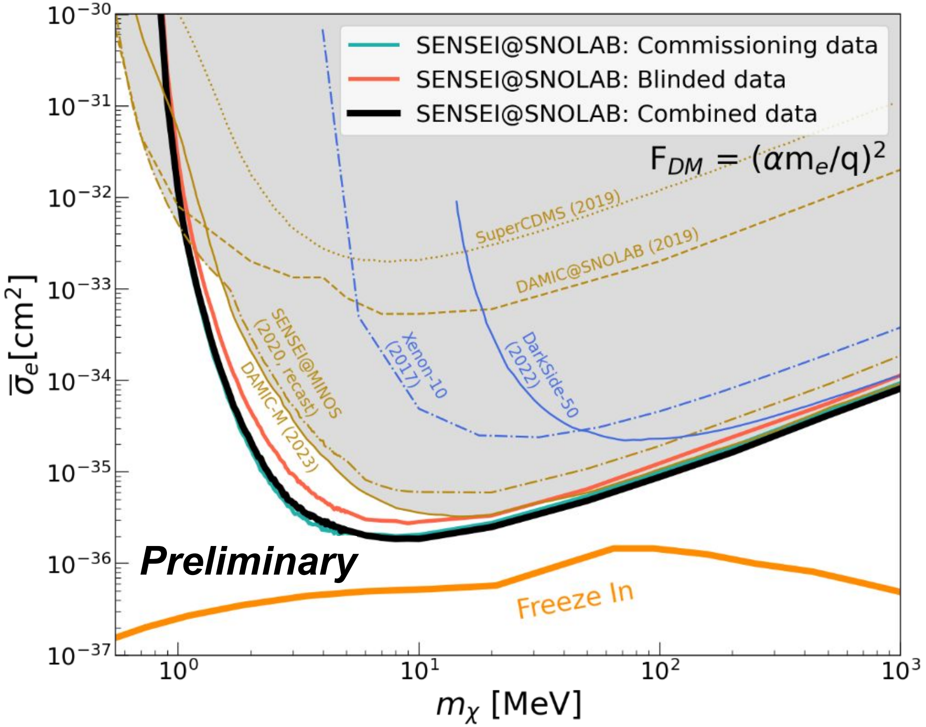
1. **Data quality cuts to remove anomalous images**
2. **Cluster any contiguous pixels ≥1 e^-**
3. **Apply masks to images to remove known backgrounds**
   - Electronic noise
   - Cross-talk
   - Edges of CCDs
   - Bad pixels and columns
   - Serial register events
   - Charge transfer inefficiencies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



Mask application in SENSEI@SNOLAB data
Black = surviving (unmasked) regions, ~20% per image

Detailed SENSEI@SNOLAB limit plots

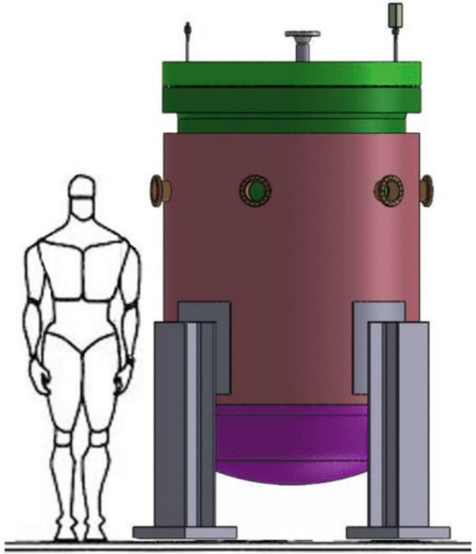




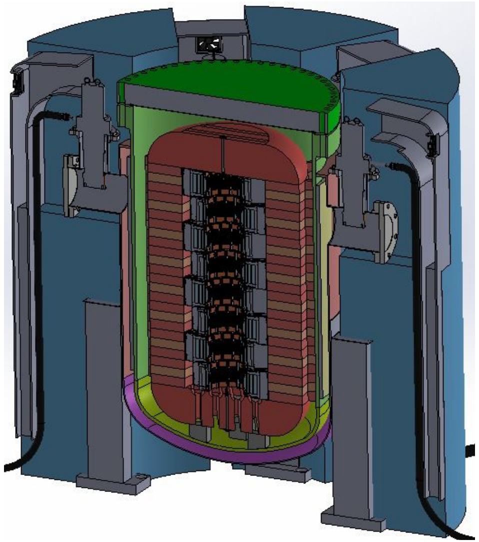
SENSEI@SNOLAB 90% exclusion limits on dark matter interacting with electrons

Oscura: 10 kg Skipper-CCD experiment

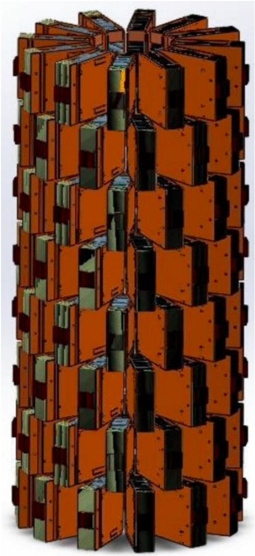
- Science goal: electron recoil low-mass direct DM search (1 MeV-1 GeV)
- Technology: skipper-CCD array at underground lab (planning for SNOLAB)
- R&D: scale the existing technology towards a 10 kg experiment
- Oscura review paper: arXiv:2202.10518



10 kg vessel



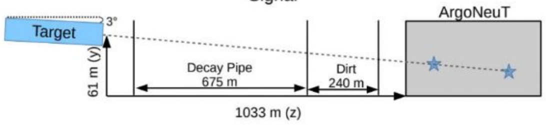
10 kg vessel

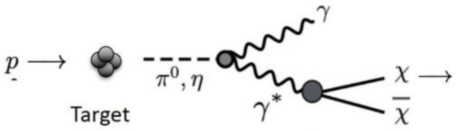


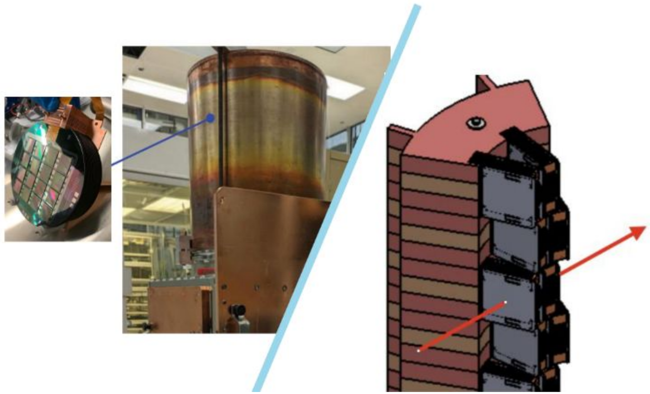
Detector payload

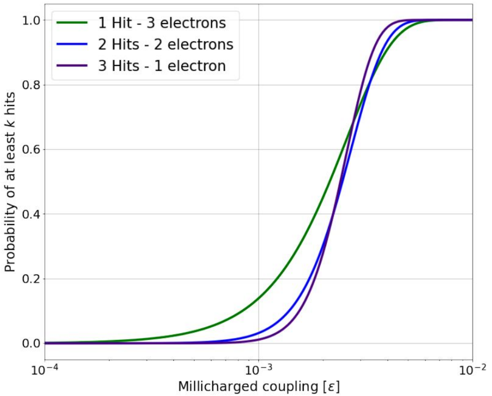
Oscura: Early Science (mCP search)

[PRL 124, 131801 (2020)]







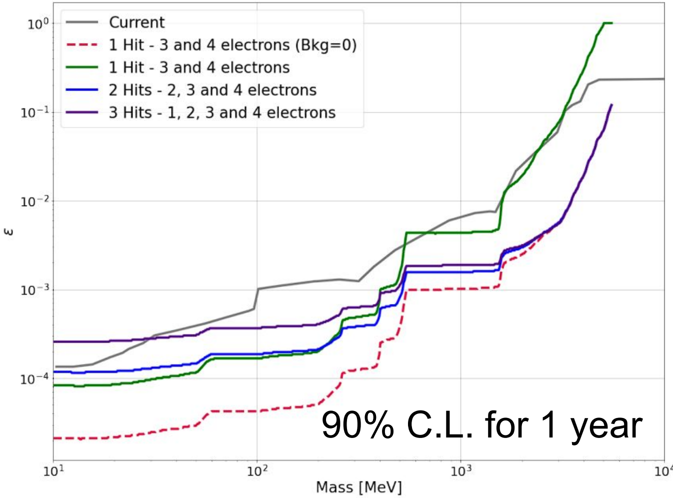


Number of fake tracks per day produced by random coincidences of uncorrelated single pixel hits

Threshold	doublets $(b=2)$	triplets$(b=3)$	p_{bkg}
$1e^-$	3822	11.4	3×10^{-4}
$2e^-$	0.031	2.72×10^{-7}	$8.6 \times 10{-}7$
$3e^-$	9.06×10^{-5}	4.17×10^{-11}	4.6×10^{-8}

If doing tracking, we are essentially background-free!

Essential items:
- Large-mass setup → Massive setup / SM
- Location @ MINOS → MOSKITA



Exclusion limits are promising!

Adapted from arXiV:2304.04401, arXiV:2304.08625, B. Cervantes's UCLA DM 2023 talk