The SENSEI Experiment: An Ultrasensitive Search for Sub-GeV Dark Matter

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IFIBA - CONICET/FNAL
for the SENSEI* Collaboration

@ 2021 SNOLAB User Meeting

***S**ub-**E**lectron-**N**oise **S**kipper-CCD **E**xperimental **I**nstrument

The SENSEI Collaboration

Sensei

Fermilab

Stony Brook University

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

UNIVERSITY OF OREGON

IFIBA UBA CONICET

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Tel-Aviv:

- L. Barak, I. Bloch, E. Etzion, A. Orly, S. Uemura, T. Volansky

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- T.-T. Yu

Fully funded by Heising-Simons Foundation

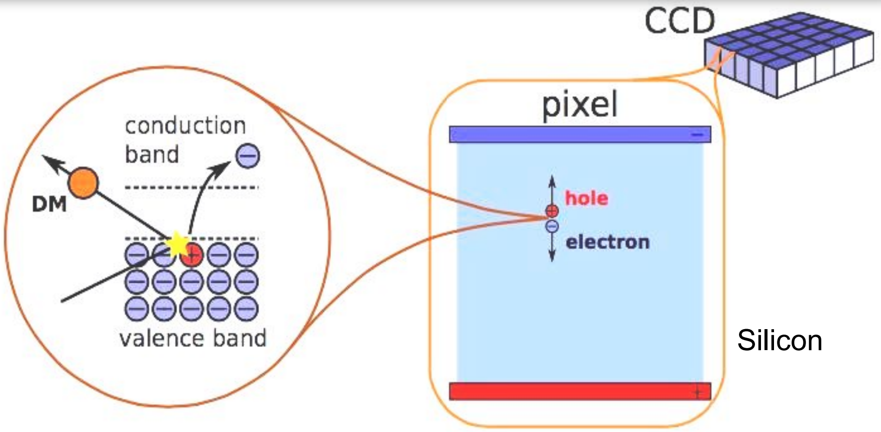
& leveraging R&D support from Fermilab

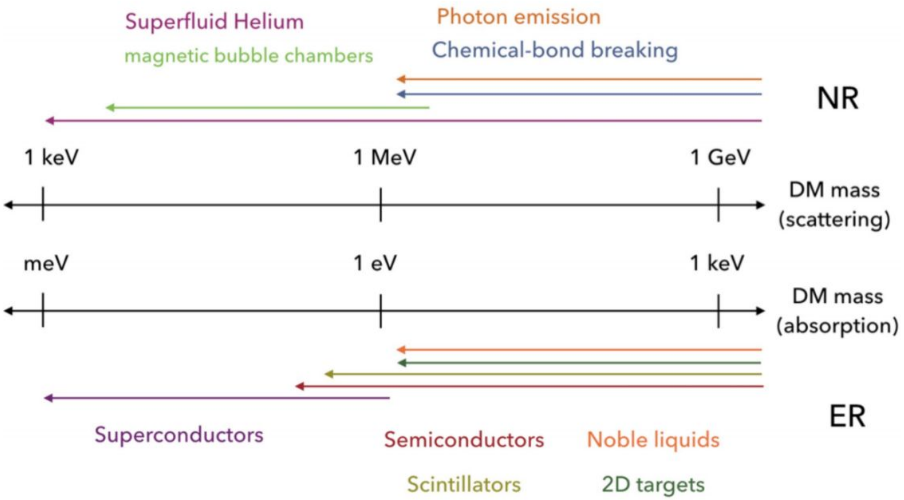
HEISING-SIMONS FOUNDATION

Electron recoils for sub-GeV DM in Skipper-CCDs

- Benchmark models:
  - DM-e⁻ scattering, DM absorption
- Silicon CCDs as **ionization** detectors
  - DM-e⁻ interaction (or absorption)
  - Energy transfer via **electron recoil**
  - Ionized h^+ are **captured** by potential well
  - Signal is readout **after** exposure is finished.
- DM range **mass**: 1-1000 MeV

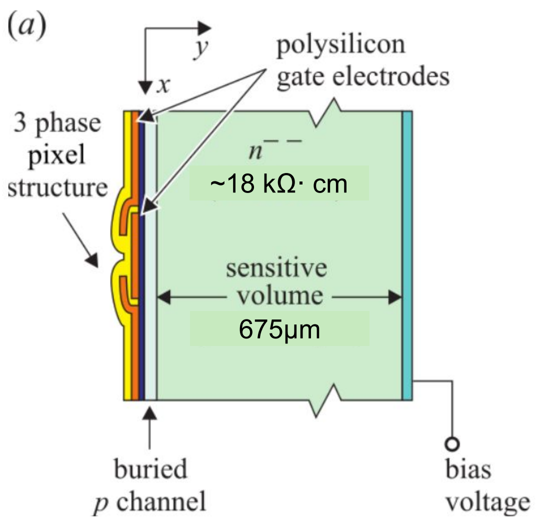
  (~eV on DM absorption)

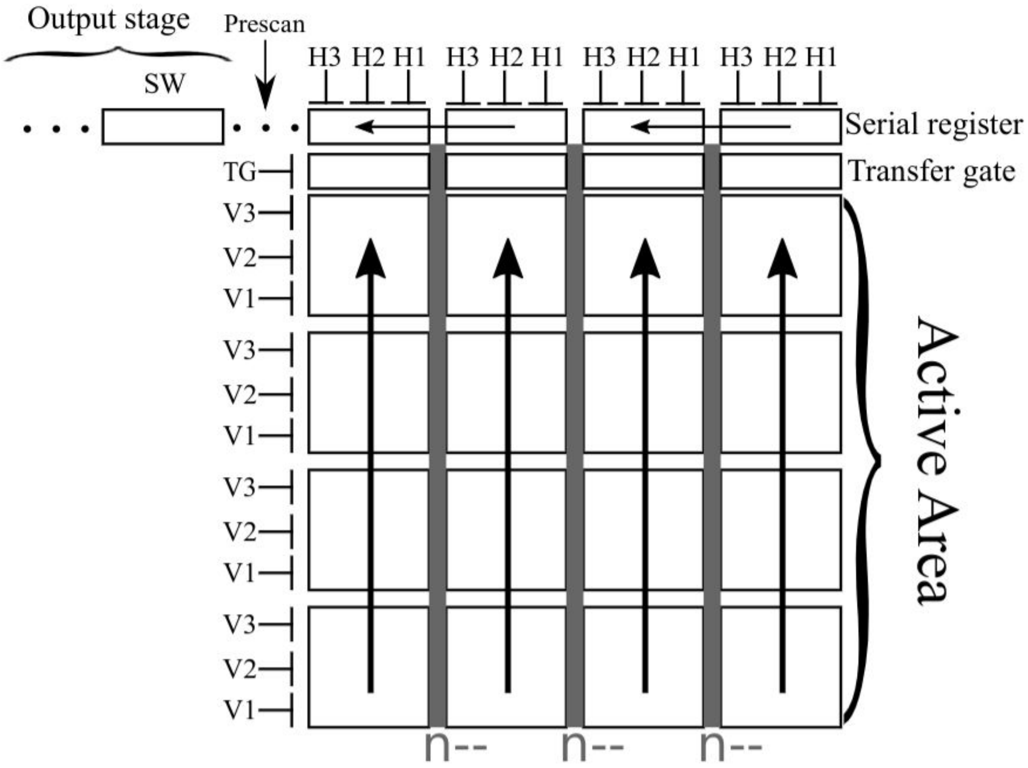




CCD basics

- **CCD = pixelated silicon array**
- ~**2g** per device of high-resistivity fully-depleted **silicon**
- >**99.9%** charge collection and transfer efficiency
- ~**5.5Mpixels** of 15x15x675 μm^3 each





Skipper-CCD basics

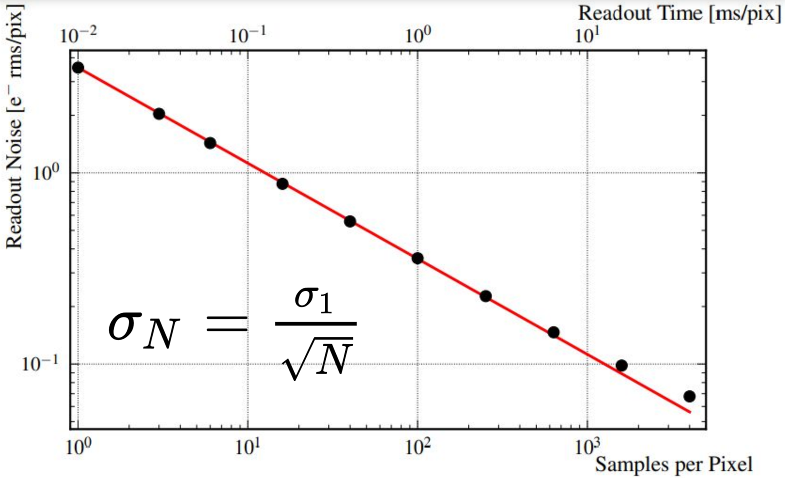
- DM range **mass**: 1-1000 MeV (~eV on DM absorption)
    - Very small **signals**
        - Very low energy **threshold**

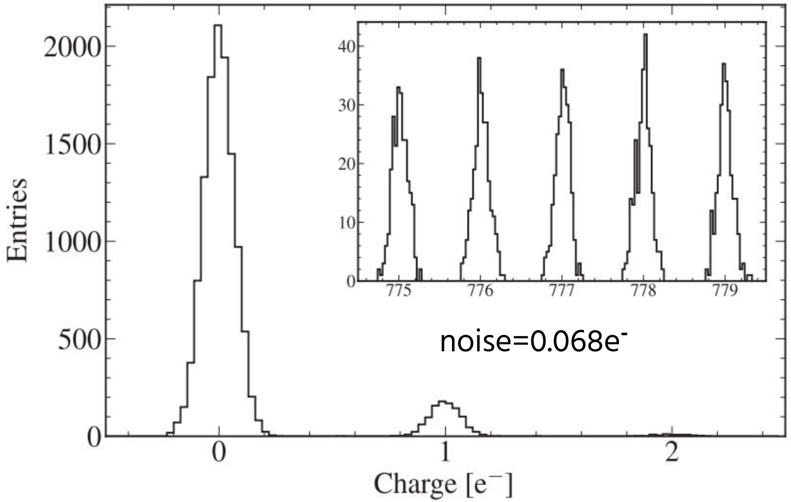
- *Skipper* technology allows to read repeatedly the *same pixel* to achieve **sub-electron noise**

- ~2e⁻ readout noise and **<0.1e⁻** using *skipper* technology

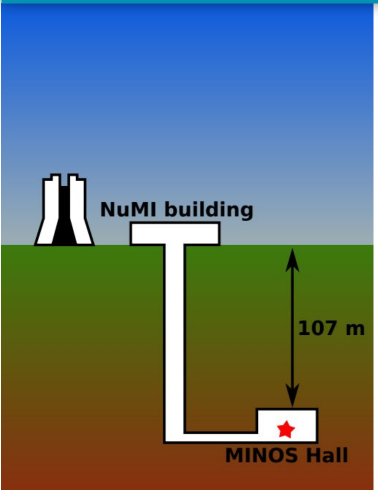
- **Low energy** threshold **down to** 1.2eV (Si band gap)

- **Unambiguously count** cluster of few electrons

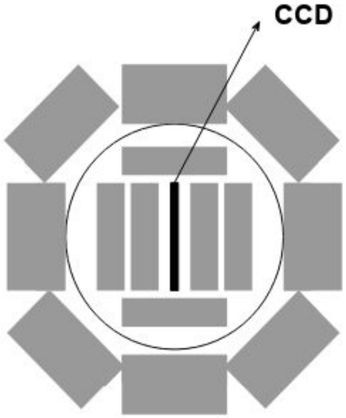


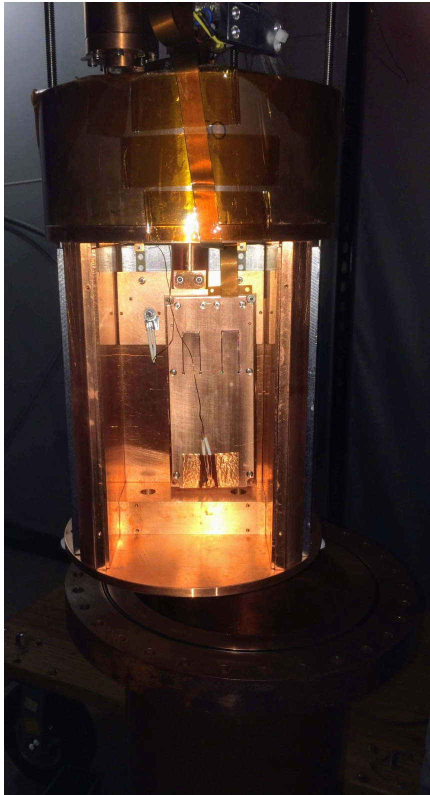


MINOS setup: location and shielding



- Setup **~107m below surface** at shallow underground MINOS site @FNAL.
- This reduces muon environmental background radiation
- Inner (1" each) and outer (2" each) lead bricks reduces environmental gamma radiation
- Operated at **135K** and high-vacuum regime to reduce dark current without generating CTI

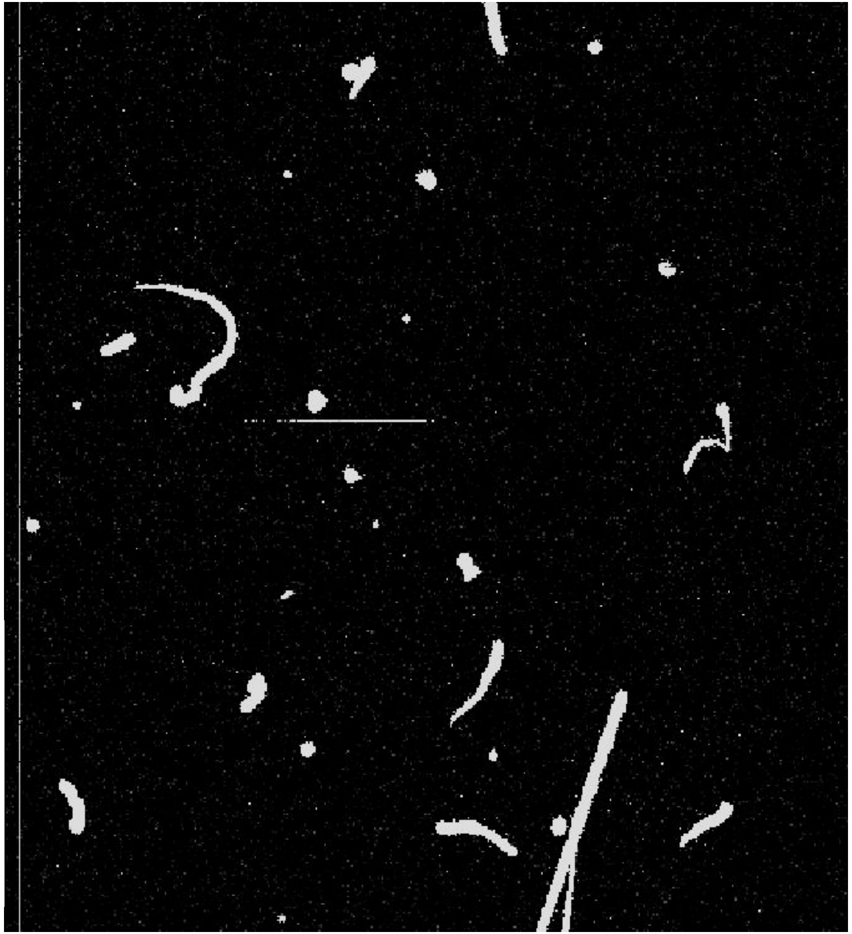




MINOS 2020 result: quality cuts

- Bad pixels/dark spikes
- Serial register hits
- Bleeding (CTI)
- Halo (low energy events near high energy events)
- Loose clusters (≥2e- analysis)
- Others

Search	Exposure post-cuts
$1e^-$	1.38 gram-days
$2e^-$	9.17 gram-days
$3e^-$	11.87 gram-days
$4e^-$	11.70 gram-days



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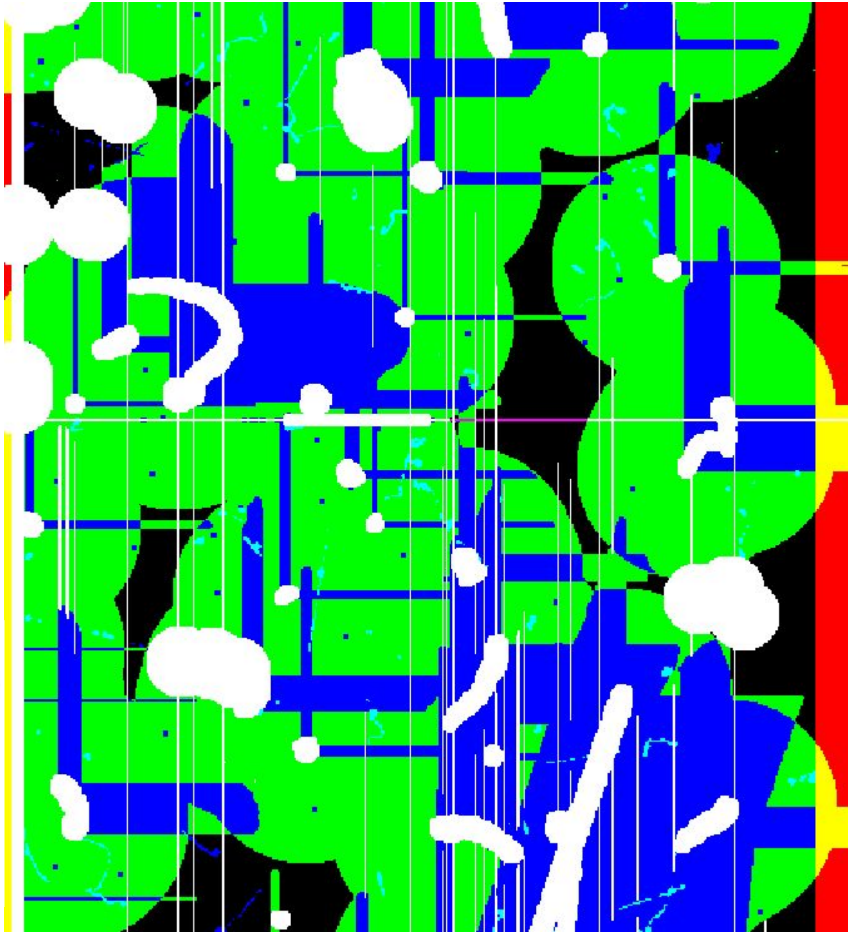
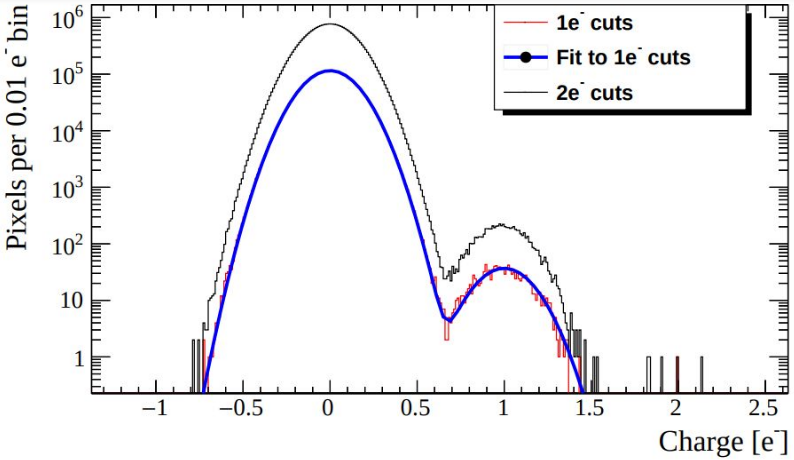


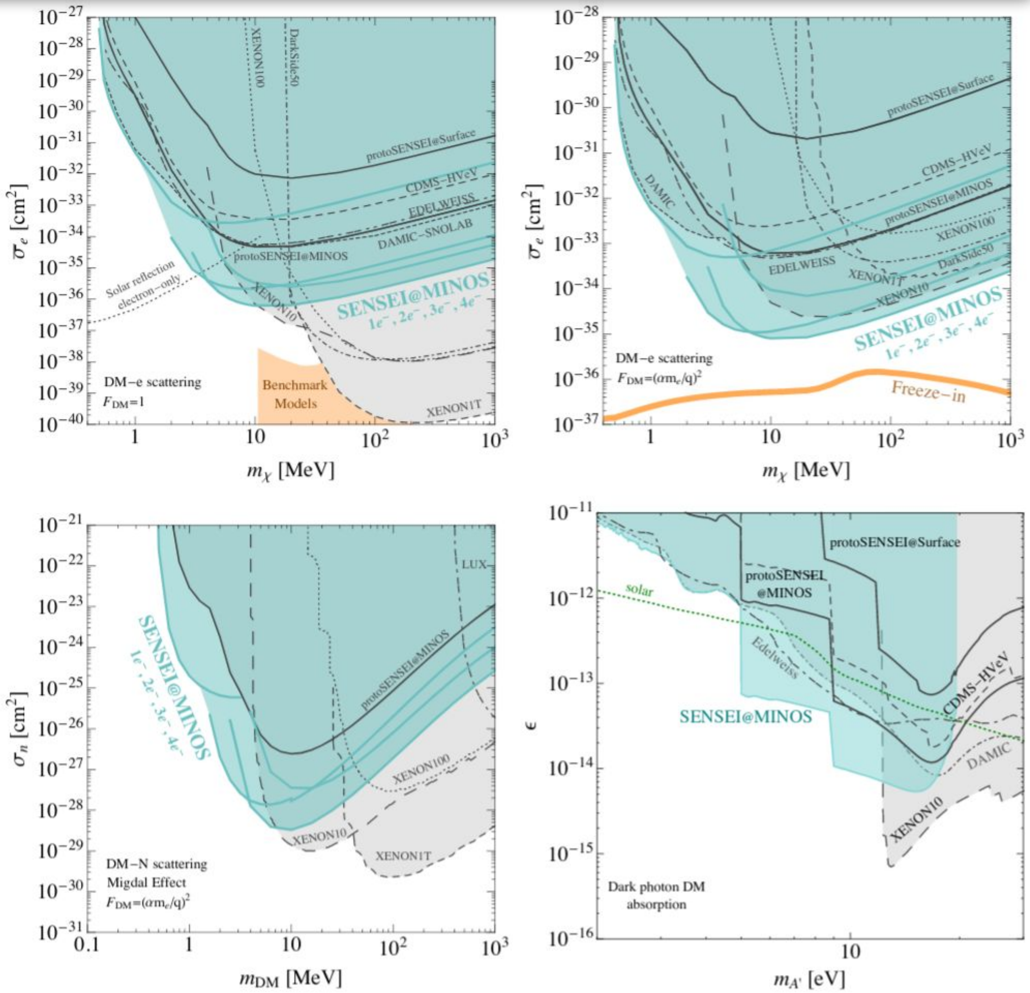
MINOS 2020 result: data and some specifics



- Blinded dataset of 22 images, Feb 25 - Mar 20, 2020
  - →**20hs** exposure + **6hs** readout (each)
  - →Total exposure: **19.926 gram-days**
- 300 *skipper* samples → **0.14e⁻** readout noise
- **x20 more mass** than 2019 (x10-15 effectively)
- Background as low as ~3400 events/kg/keV/day (**~3 times** less than 2019)
- Single-electron event rate as low as ~1.6×10^{-4} e⁻/pixel/day or ~**450 events/gram/day** (**~20 times** less than 2019)
- x(**8-35**) more effective exposure (depending on e⁻ channel)

MINOS 2020 result: limits on DM

- World-leading constraints on **DM-e⁻ scattering** for light mediator (top right) and heavy mediator (top left), up to 10 MeV.
- World-leading constraints for **DM-nucleus scattering** (bottom left) through light mediator from 600 keV to 5 MeV (Migdal Effect [5]).
- World-leading constraints for **DM absorption on electrons** (bottom right) from 1.2 to 12.8 eV.

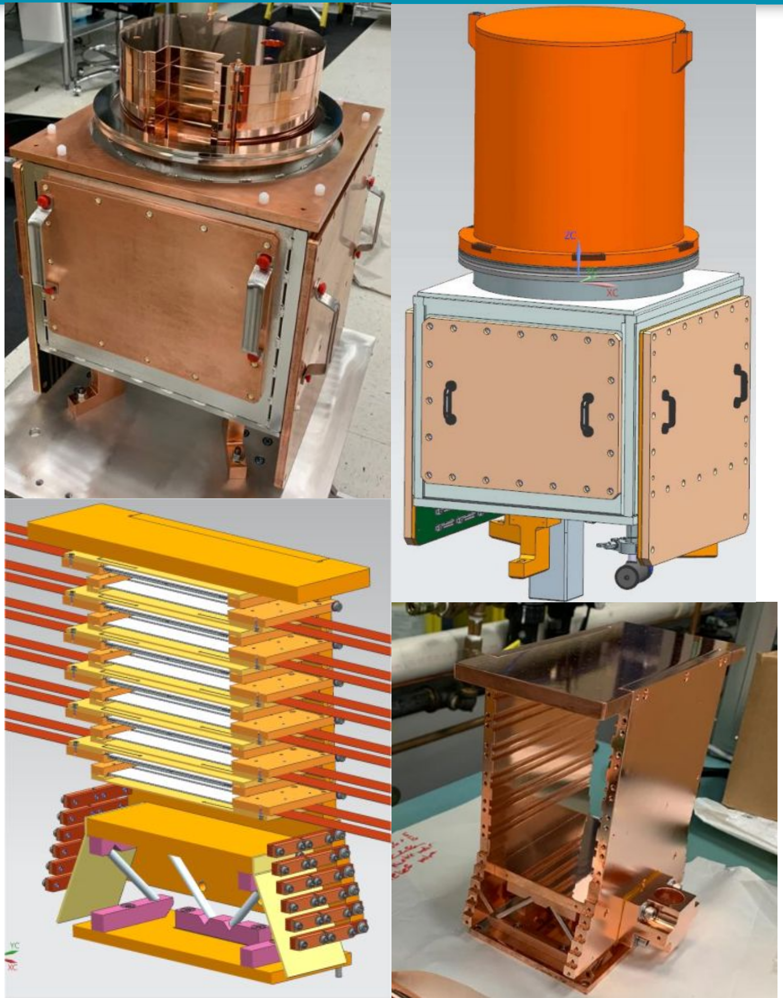


Perspectives: SNOLAB

- "Phase 1" system **fully operational** since December 2019 @SNOLAB

- Status@FNAL: **production** (in progress)
    - Packaging and testing detectors

- SENSEI Vessel is at SNOLAB, going through commissioning.

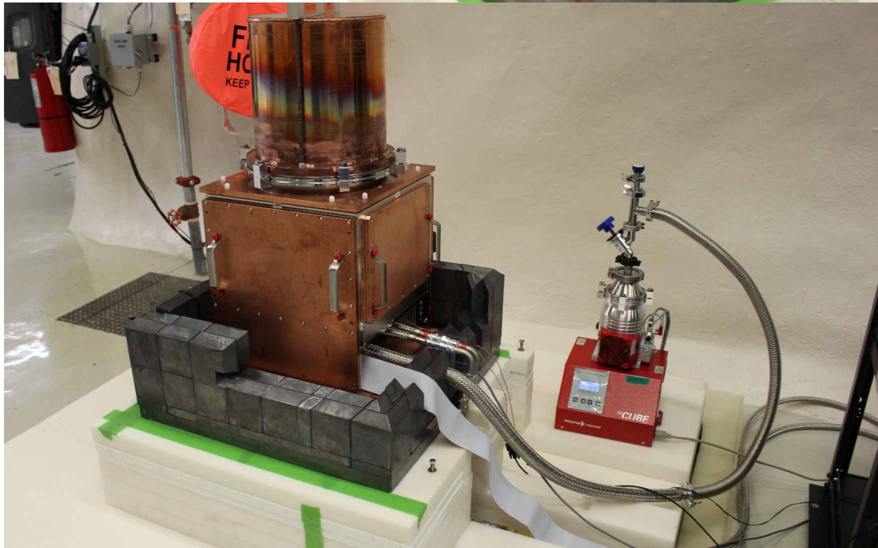


Perspectives: SNOLAB

- We're looking forward to DM data at SNOLAB!
    - MINOS (standard shield): 10000 dru
    - MINOS (extra shield): 3000 dru
    - SNOLAB (final setup): **5 dru**.

- Commissioning of VESSEL@SNOLAB
    - Vacuum test
    - Cold test ← **We are here**
    - CCD installation
    - Data taking

- Extraordinary support from SNOLAB



Perspectives: SNOLAB

- Detectors from production@FNAL going to SNOLAB.

- Deployment in **stages**, increasing mass. Results will be presented **gradually**.
  - First batch of science grade sensors to be deployed soon (~10g)

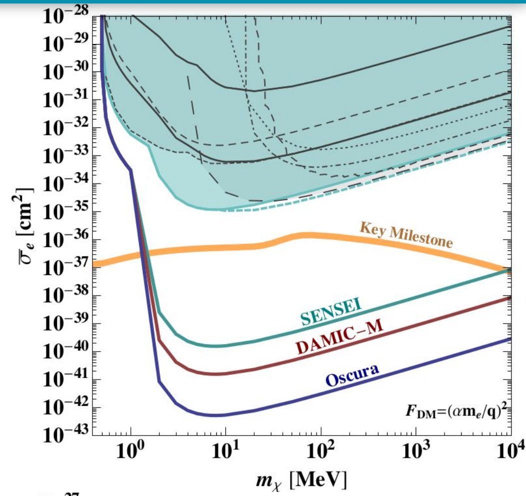
- Final mass: **100g**

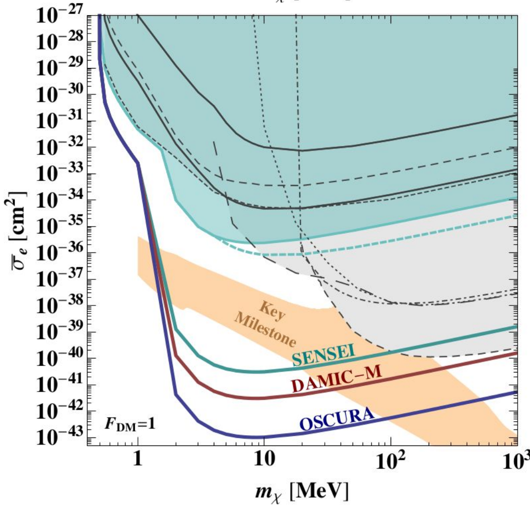
- Stay tuned!

SENSEI
- 100g
- 2021

DAMIC-M
- 1kg
- ~2024

OSCURA
- 10kg
- ~2027

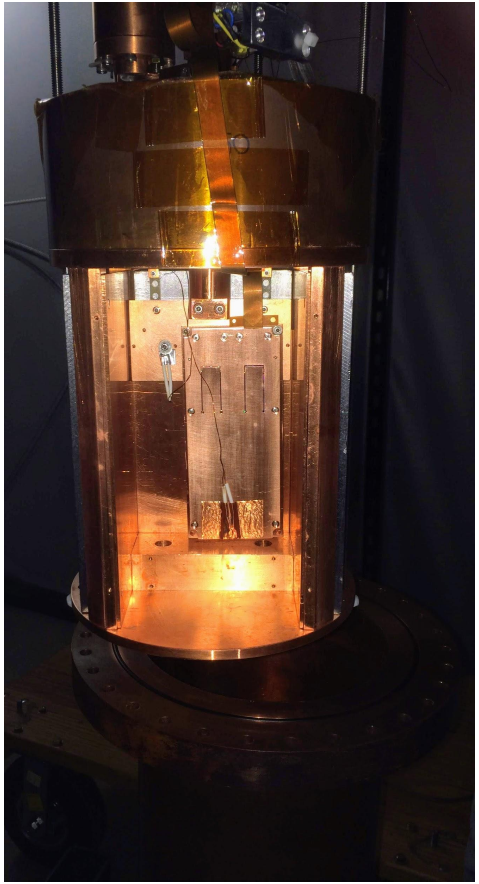


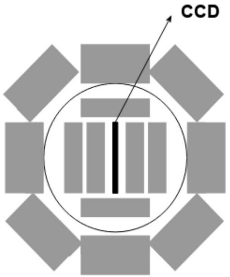


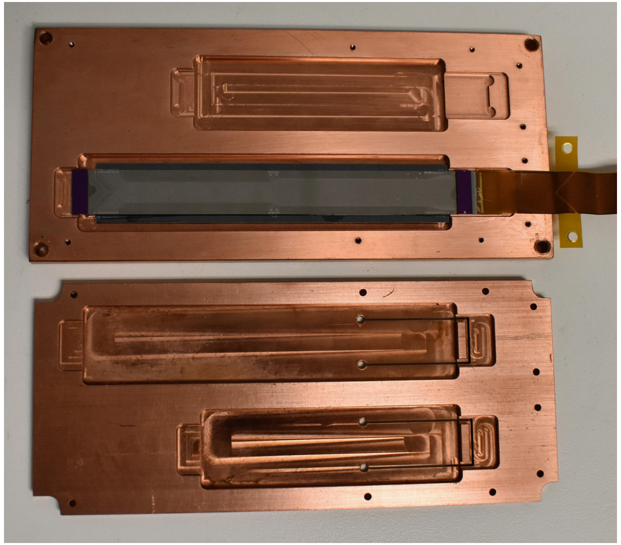
THANK YOU!

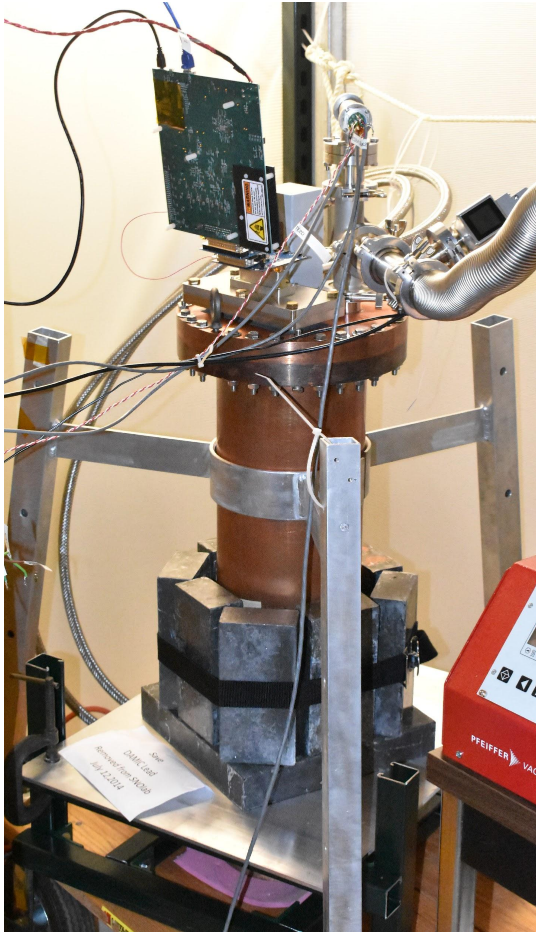
BACK UP SLIDES

MINOS shielding









References

[1] Tiffenberg, Javier, et al. "Single-electron and single-photon sensitivity with a silicon Skipper CCD." Physical Review Letters 119.13 (2017): 131802.

[2] Crisler, Michael, et al. "SENSEI: first direct-detection constraints on sub-GeV dark matter from a surface run." Physical Review Letters 121.6 (2018): 061803.

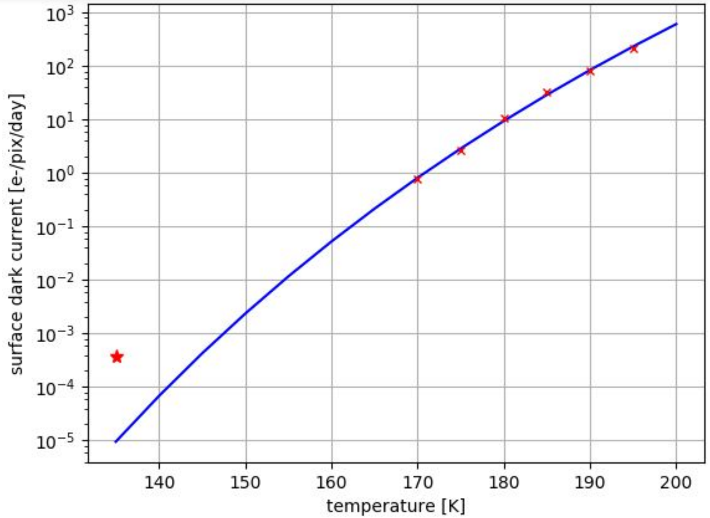
[3] Abramoff, Orr, et al. "SENSEI: Direct-detection constraints on sub-GeV dark matter from a shallow underground run using a prototype skipper CCD." Physical review letters 122.16 (2019): 161801.

[4] Barak, Liron, et al. "SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD." arXiv preprint arXiv:2004.11378 (2020).

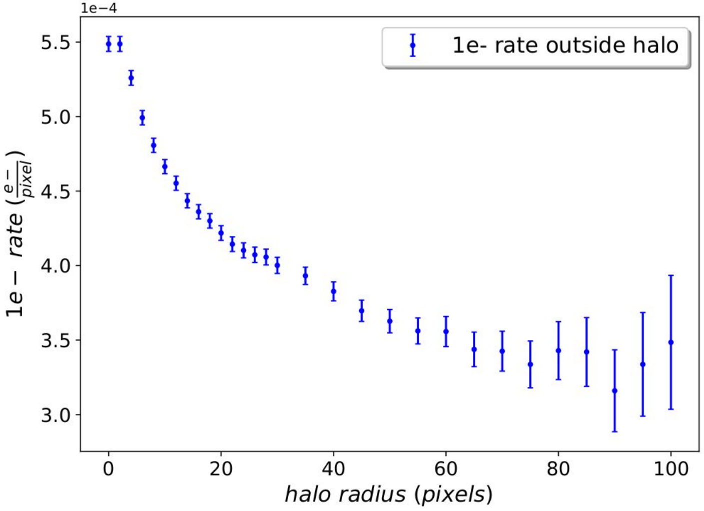
[5] Essig, Rouven, et al. "Relation between the Migdal Effect and Dark Matter-Electron Scattering in Isolated Atoms and Semiconductors." Physical Review Letters 124.2 (2020): 021801.

Our last result: single electron event rate

- A 1e- rate excess is found extrapolating from higher temperatures **assuming only surface DC**.

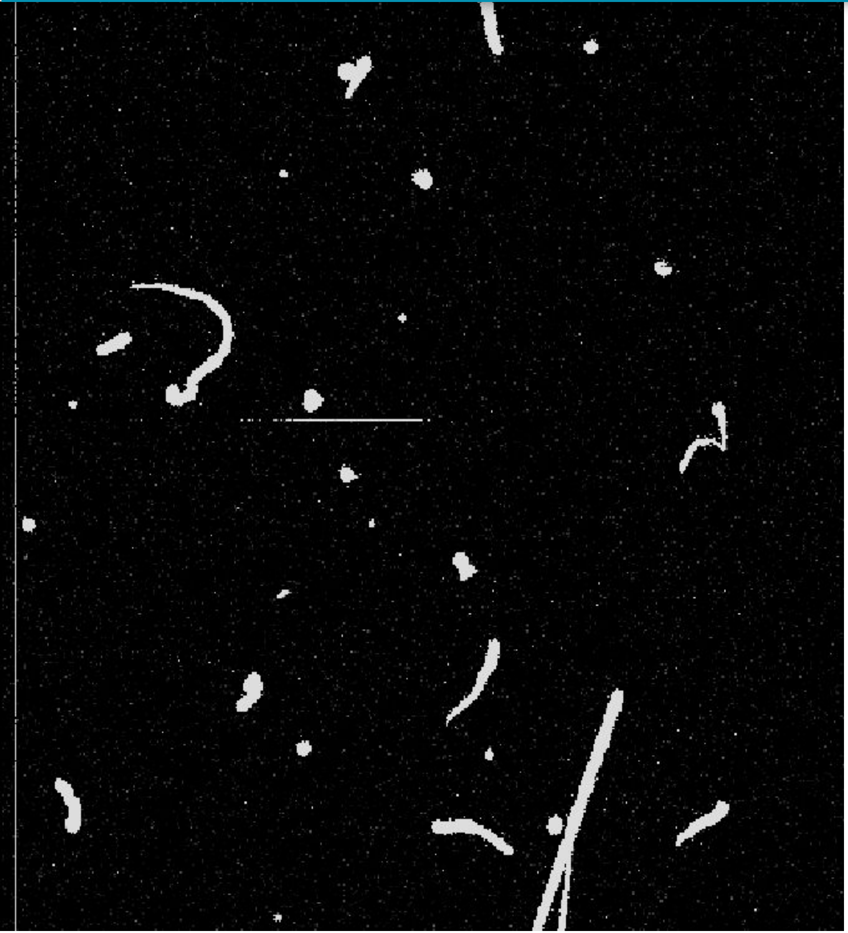


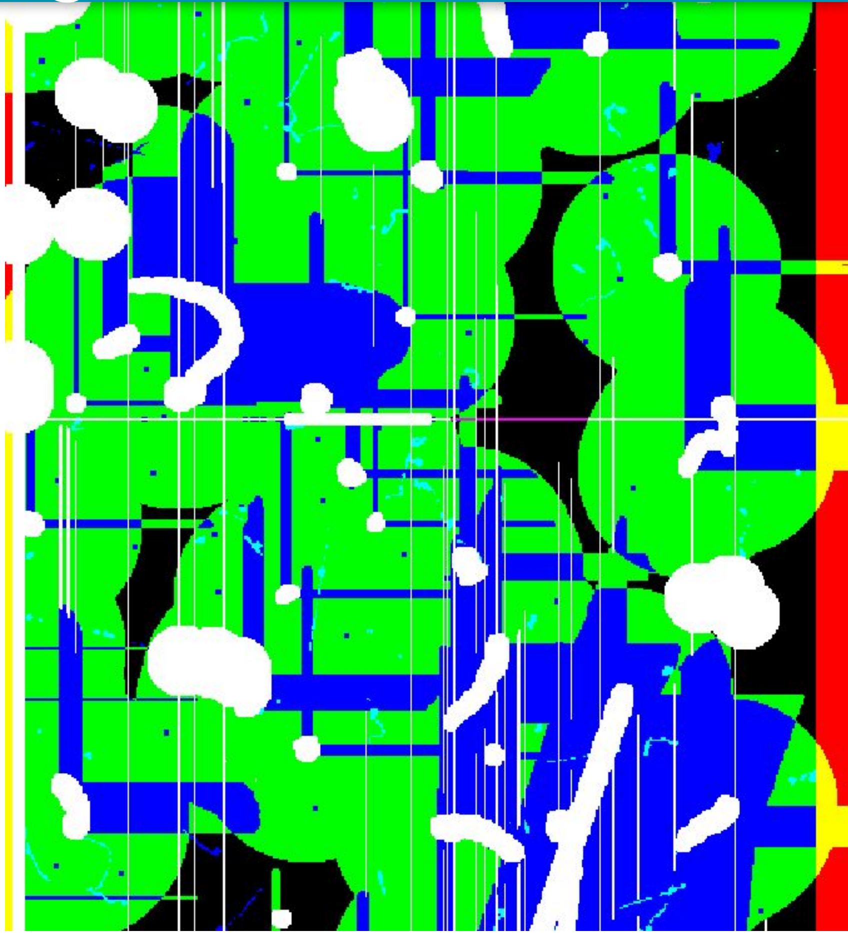
- Extrinsic or intrinsic sources?
  - RO stage luminescence, other DC
  - Diffusive light, related to high energy events



- Spatial correlation between high energy events (>360eV) and 1e- events.
- Low-energy photons? From copper module, CCD or both?
- Can we mask it up to 100%?

Sample image





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 $\rightarrow$ factor of 3 reduction in the $1e^-$ rate
  - There is some mechanism by which ionizing radiation generates charge uniformly in our CCD
  - Better shielding will very likely further reduce our $1e^-$ rate