

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

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IFIBA - CONICET/FNAL
for the SENSEI* Collaboration
@ ICHEP 2020

The SENSEI Collaboration



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- 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

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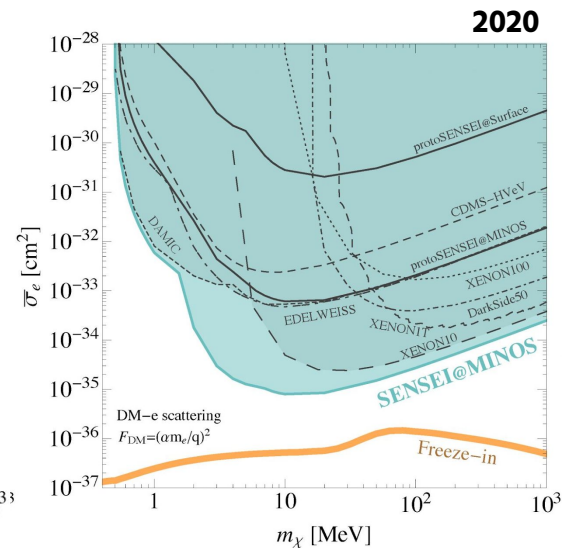
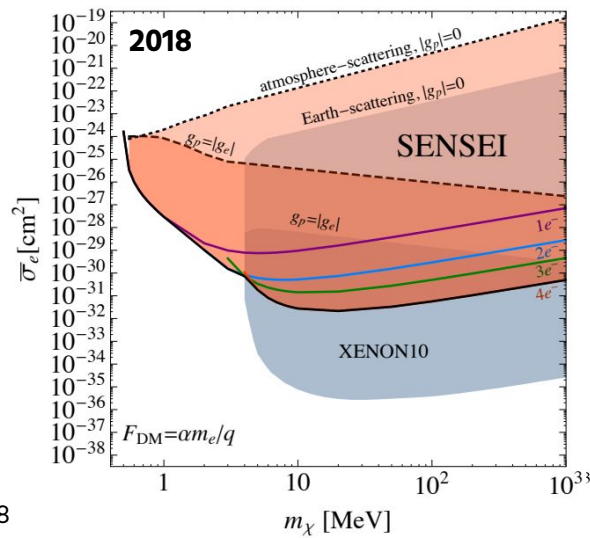
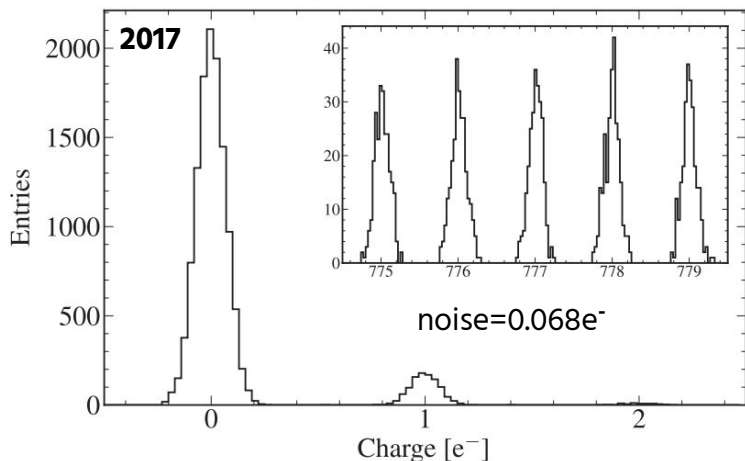
- T.-T. Yu

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



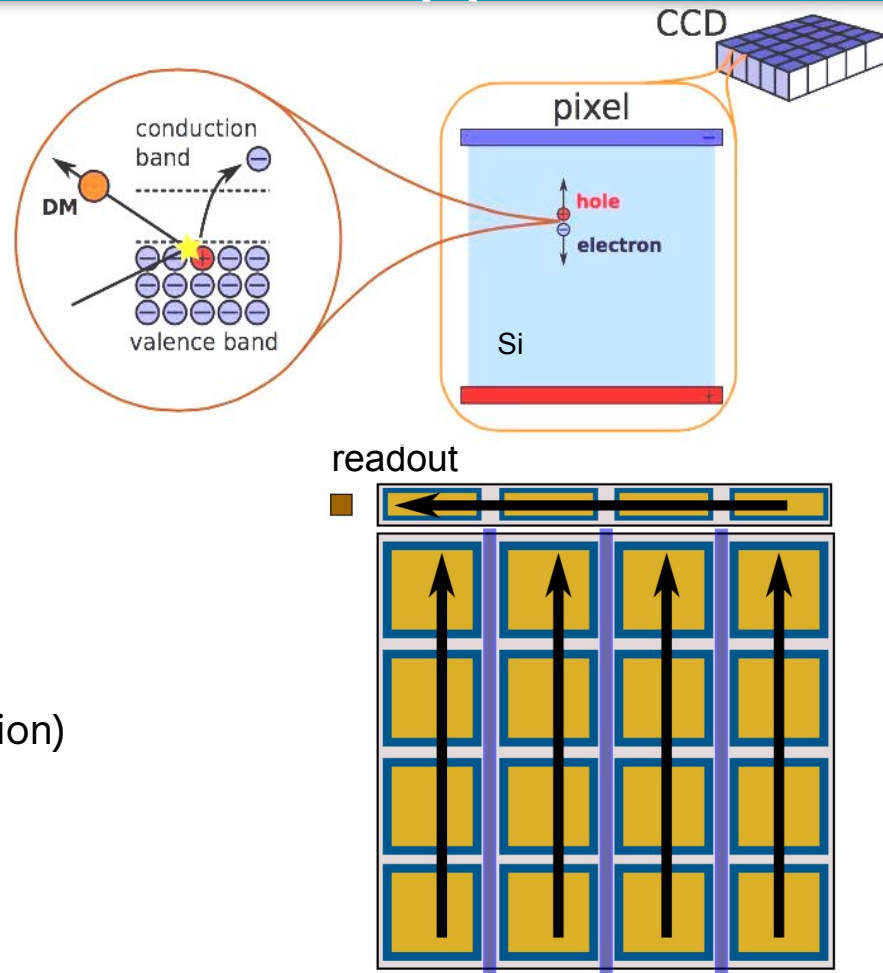
Recent news

2017	Demonstration of $0.068e^-$ noise in SENSEI prototype [1].
2018	DM search with surface run of SENSEI prototype [2].
2019	DM search with underground run of SENSEI prototype [3].
April 2020	DM search with underground run of SENSEI first science grade Skipper-CCD [4].



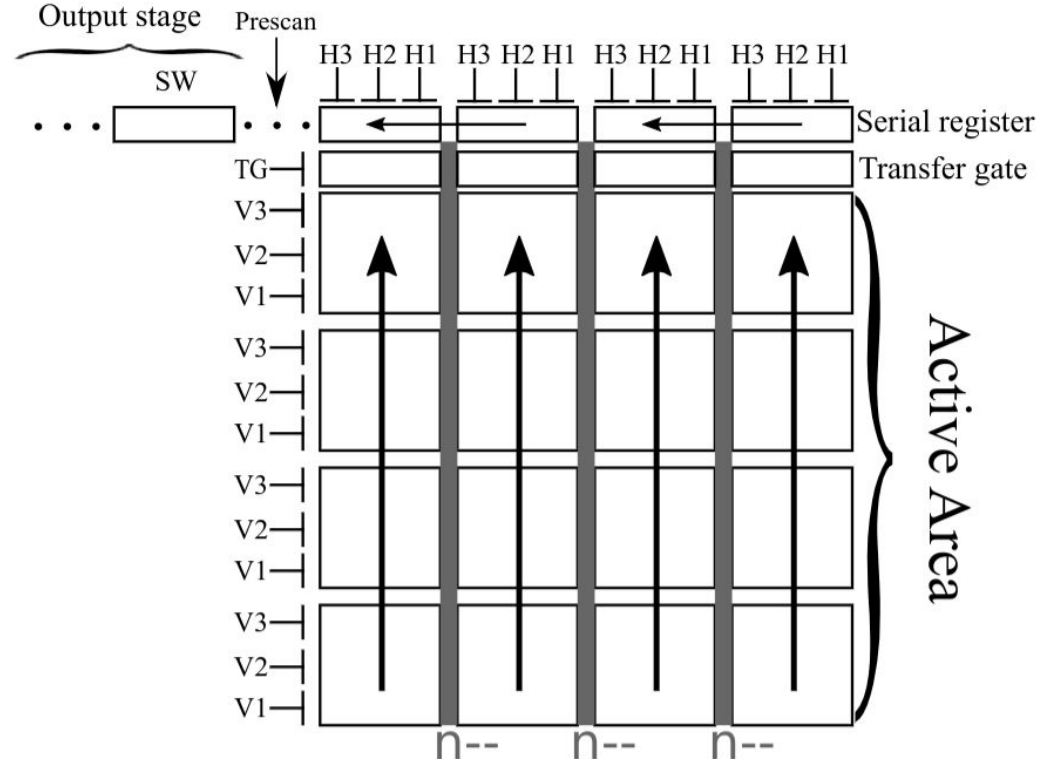
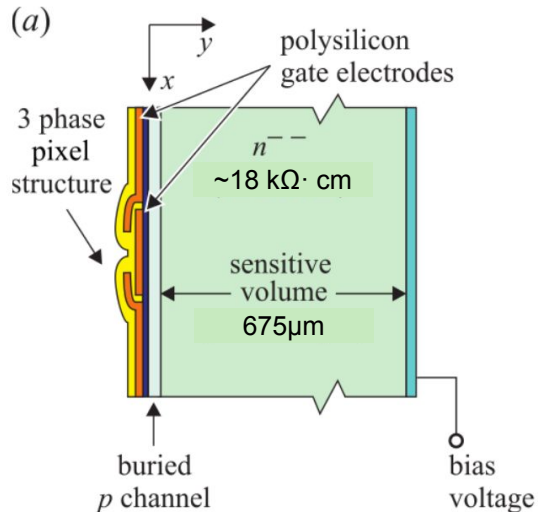
Electron recoils for sub-GeV DM in Skipper-CCDs

- ◆ 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 (\sim eV on DM absorption)



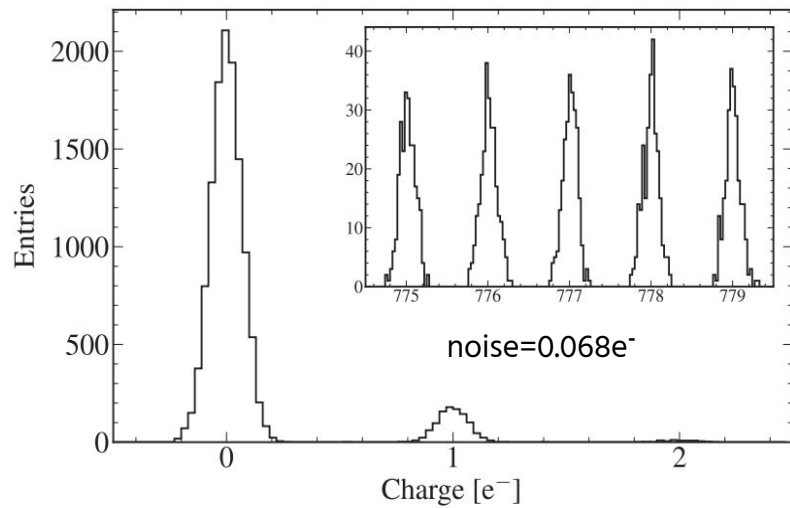
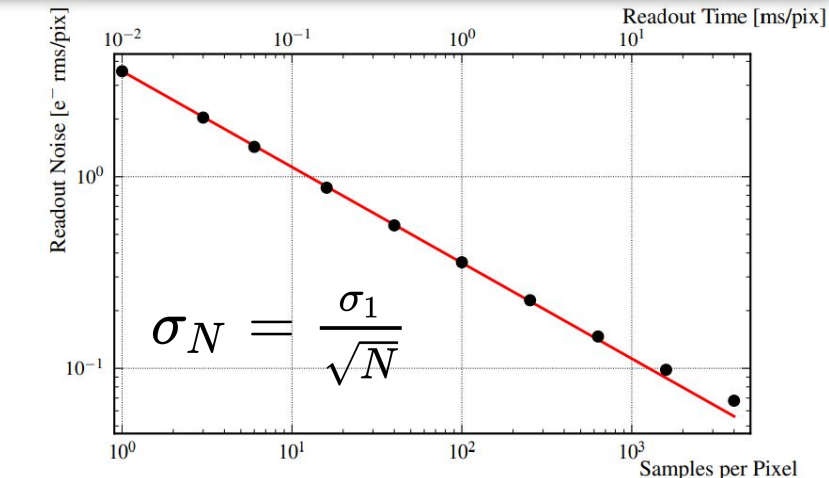
CCD basics

- ◆ **CCD = pixelated silicon array**
- ◆ **~2g** per device of high-resistivity fully-depleted **silicon**
- ◆ **>99.9%** charge collection and transfer efficiency
- ◆ **~5.5Mpixels** of $15 \times 15 \times 675 \mu\text{m}^3$ each



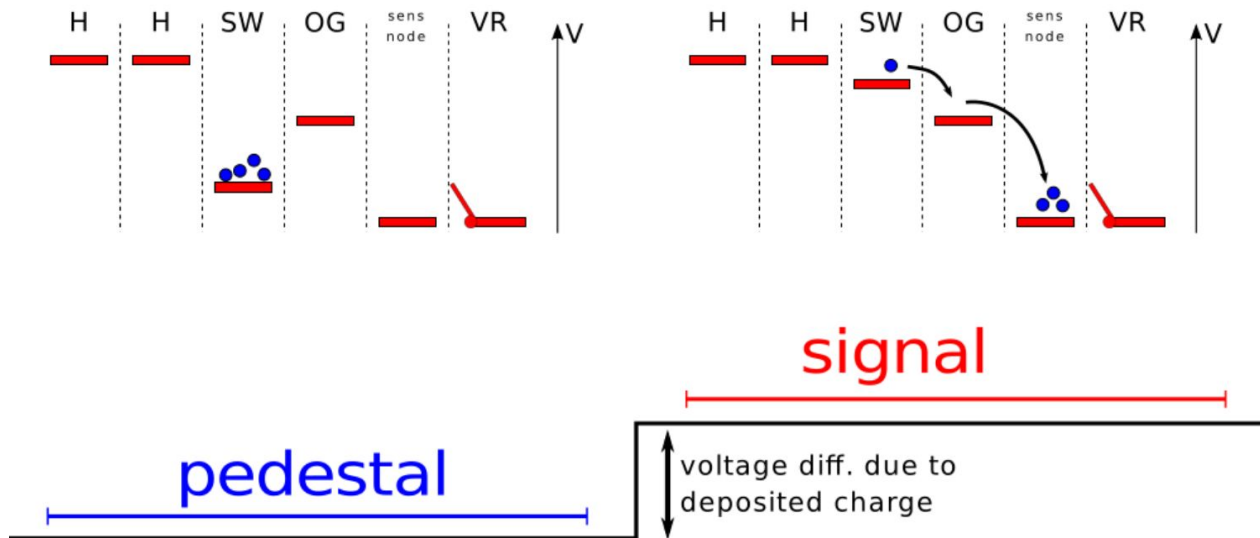
Skipper-CCD basics

- ◆ DM range **mass**: 1-1000 MeV (\sim 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**
- ◆ $\sim 2e^-$ readout noise and **$<0.1e^-$** using *skipper* technology
- ◆ **Low energy threshold down to 1.2eV** (Si band gap)



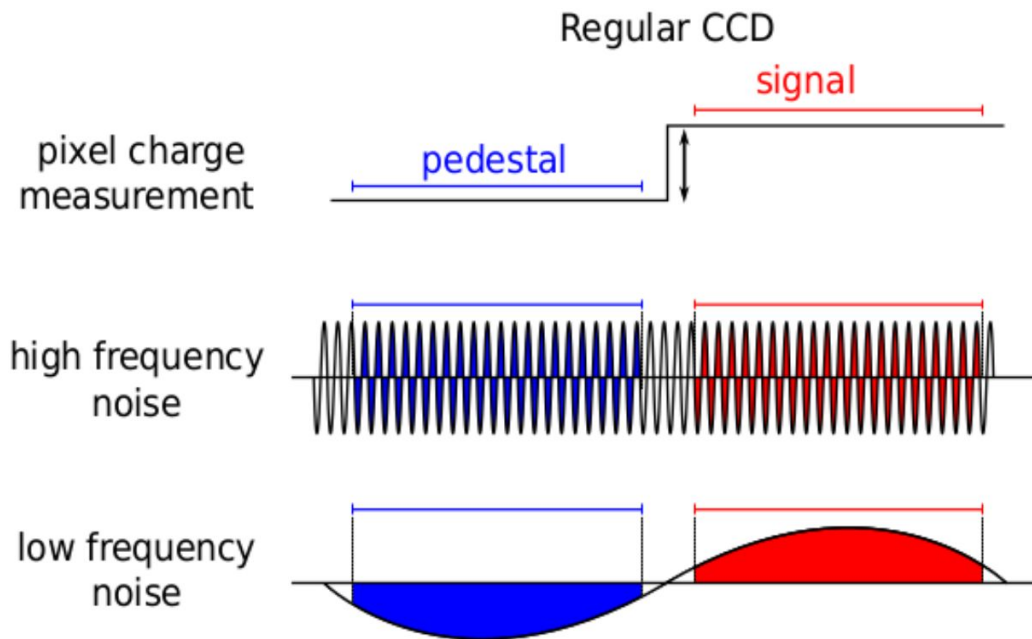
Skipper-CCD basics

- ◆ In a conventional CCD, charge is moved to the sense node and readout **once**. Then it is **drained** and charge is **lost**.
- ◆ Longer integration reduces noise but cannot reduce **1/f** noise.
- ◆ Skipper-CCD moves charges towards and backwards the floating sense node to achieve multiple readout



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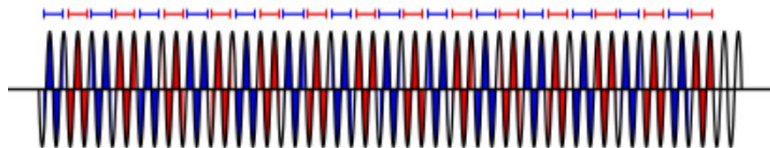
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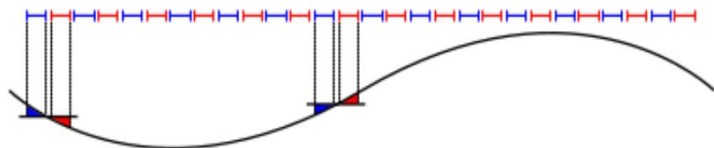
Skipper CCD



pixel charge measurement

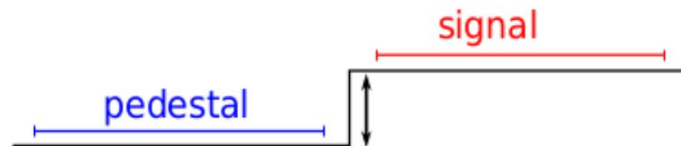


high frequency noise



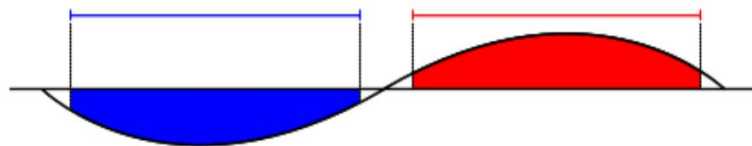
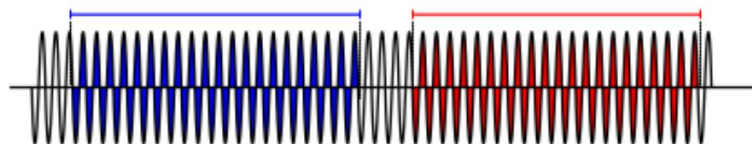
low frequency noise

Regular CCD

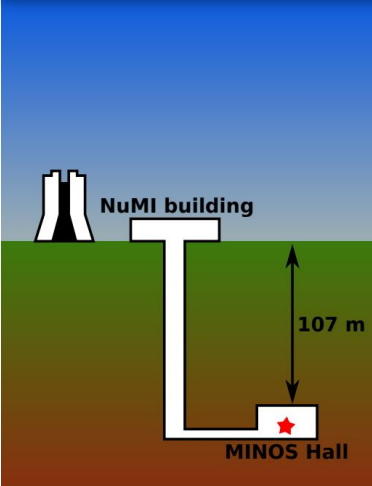


pedestal

signal

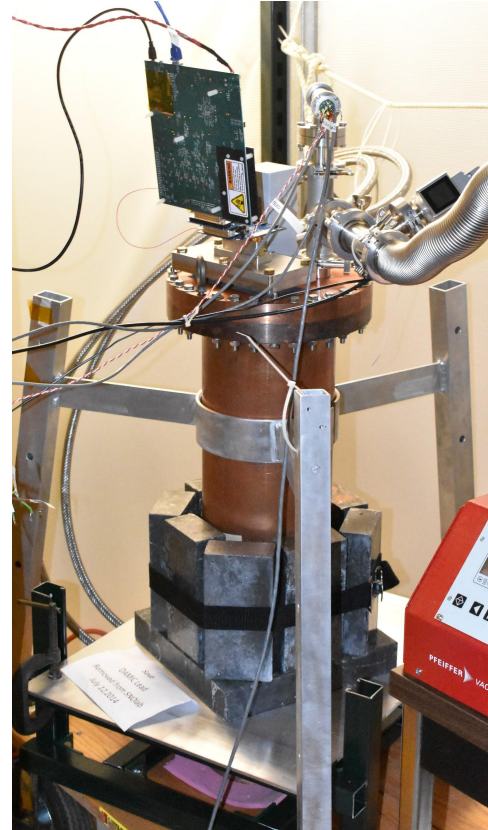
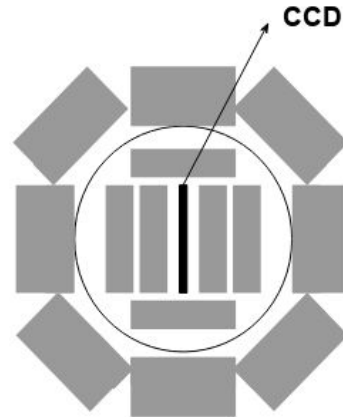


Our setup: location and shielding

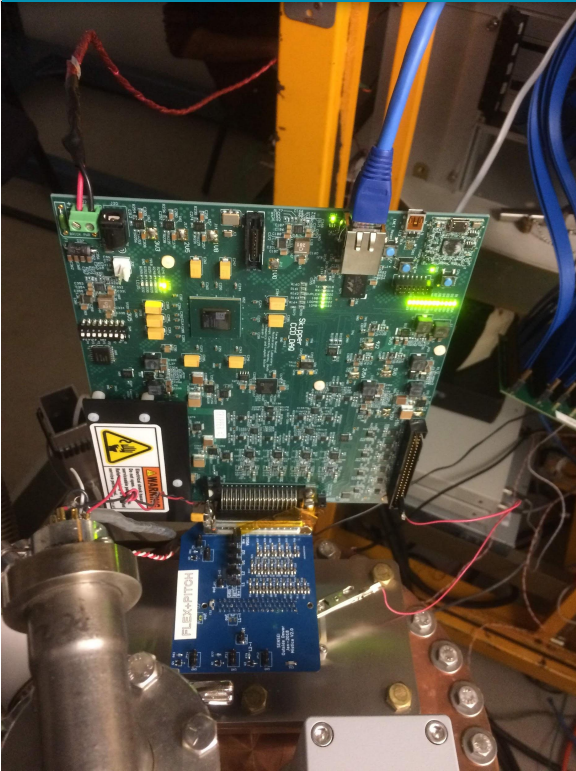


- ◆ Setup **~107m below surface** at shallow underground MINOS site @FNAL.
- ◆ This reduces muon environmental background radiation
- ◆ Inner (1" each) and outer (2" each) lead bricks reduces environmental gamma radiation

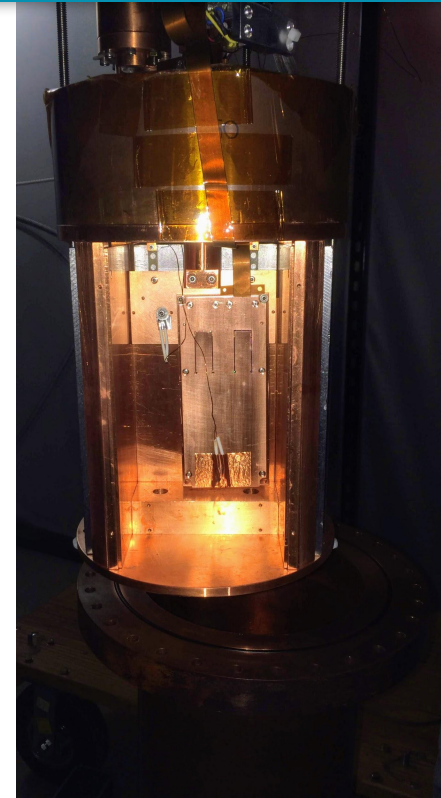
- ◆ Operated at **135K** and high-vacuum regime to reduce dark current without generating CTI



Electronics | Inside the Vessel



- ◆ Shielding design adapted from DAMIC: **cylindrical vacuum vessel** with lead “plugs” above and below the CCD
- ◆ Operated with specifically designed readout electronics (**LTA board**) (**Low Threshold Acquisition**)
- ◆ LTA boards admit multiple reading of multiple CCDs synchronously which enables **scaling**



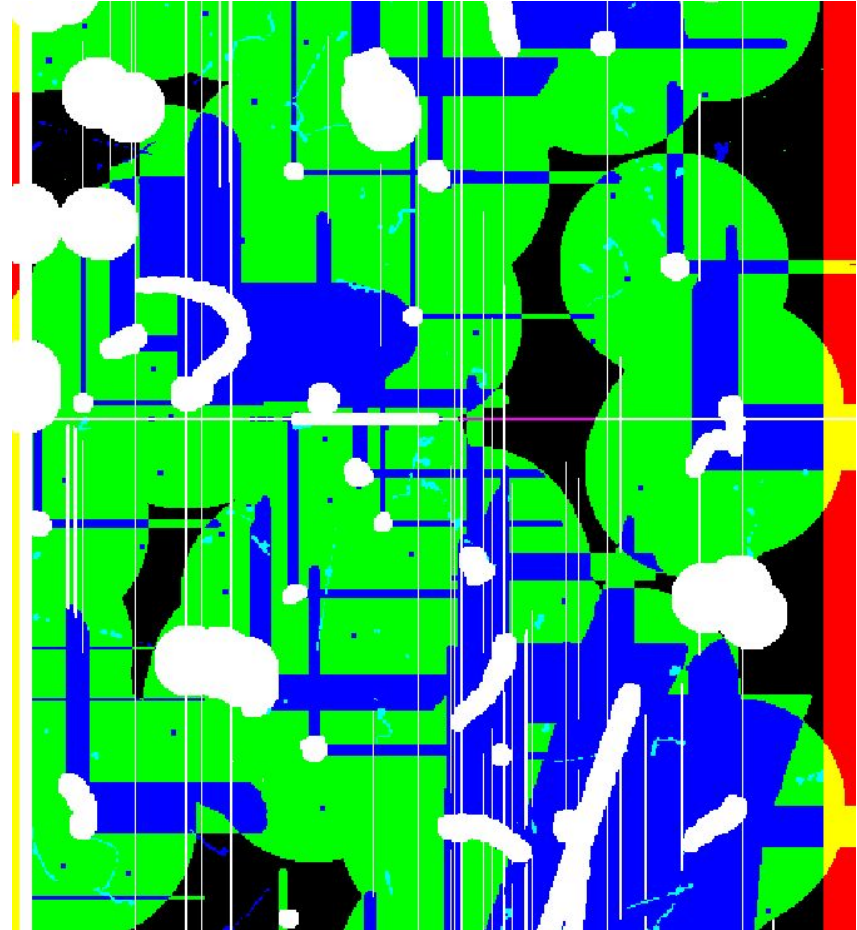
Our last result: quality cuts

- ◆ Bad pixels/dark spikes
- ◆ Serial register hits
- ◆ Bleeding (CTI)
- ◆ Halo (low energy events near high energy events) (**new!**)
- ◆ Loose clusters ($\geq 2e^-$ analysis)
- ◆ Others



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Our last result: data and some specifics

- ◆ Blinded dataset of 22 images, Feb 25 - Mar 20
 - **20hs** exposure + **6hs** readout (each)
 - Total exposure: **19.926 gram-days**

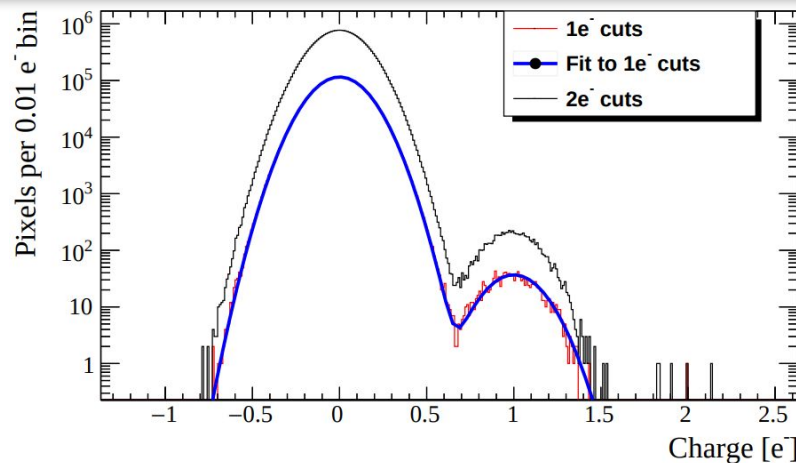
- ◆ 300 *skipper* samples → **0.14e⁻** readout noise

- ◆ **x20 more mass** than 2019 (x10-15 effectively)

- ◆ Background as low as ~3400 events/kg/keV/day (**~3 times** less than 2019)

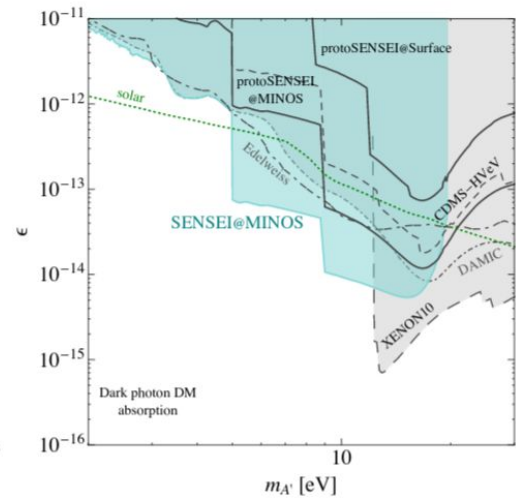
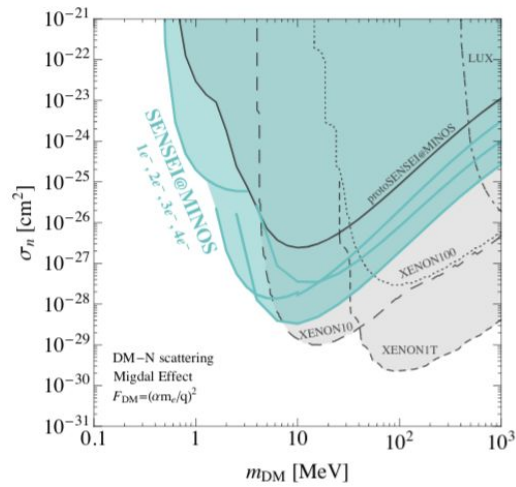
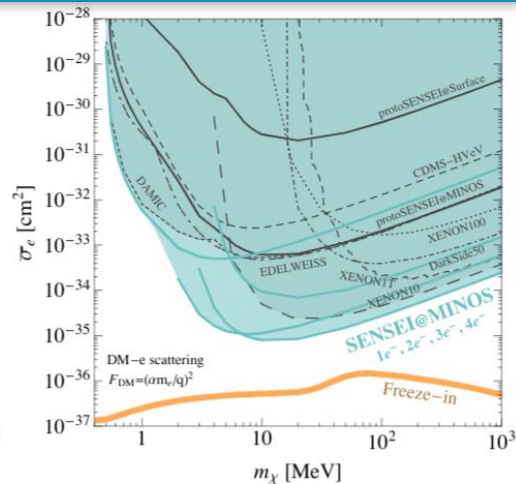
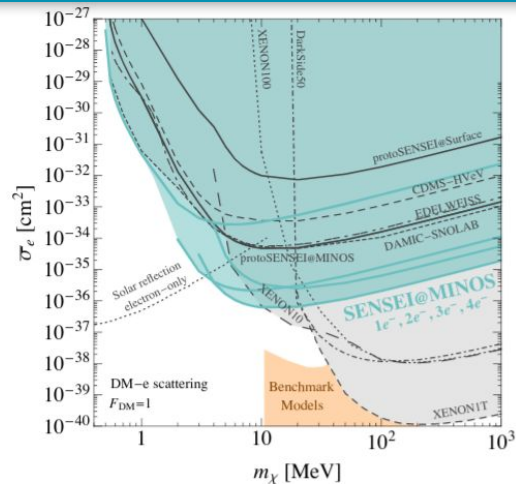
- ◆ ~~DC rate~~ Single-electron event rate as low as $\sim 1.6 \times 10^{-4}$ e⁻/pixel/day or **~450 events/gram/day** (**~20 times** less than 2019)

- ◆ x(**8-35**) more effective exposure (depending on e⁻ channel)



Our last 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.

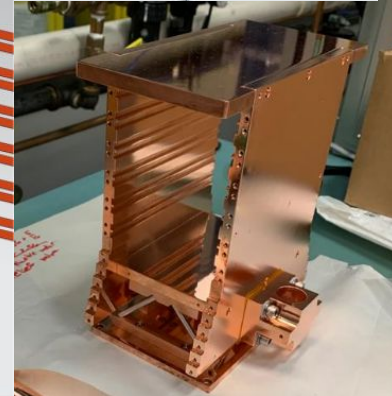
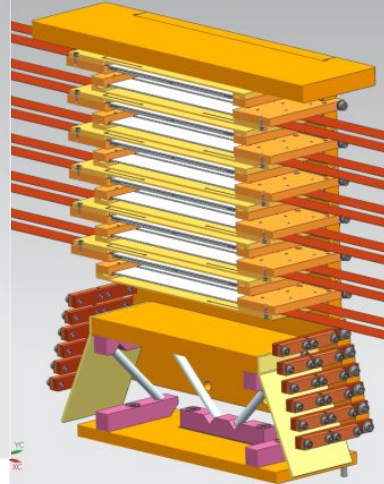
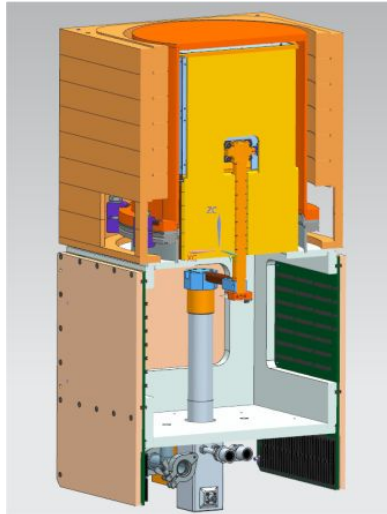
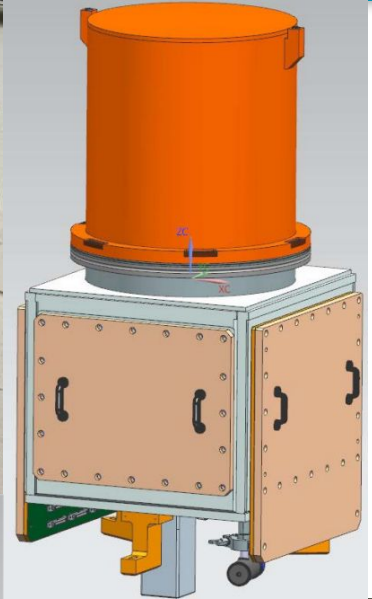
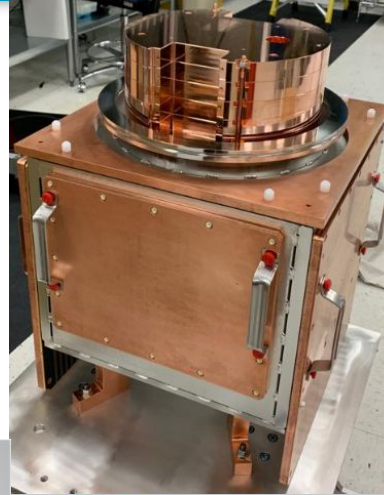


Perspectives

2017	Demonstration of 0.068e- noise in SENSEI prototype [1].
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April 2020	DM search with underground run of SENSEI first science grade Skipper-CCD [4].
2021	???

Perspectives

- ◆ We have our science detectors and they work!
Next step: **production** (in progress).
- ◆ We are assembling our vessel that will go to SNOLAB.
 - MINOS (standard shield): 10000 dru
 - MINOS (extra shield): 3000 dru
 - SNOLAB (final setup): **5 dru.**
- ◆ Vessel is at Fermilab, ready for testing prior to travel.



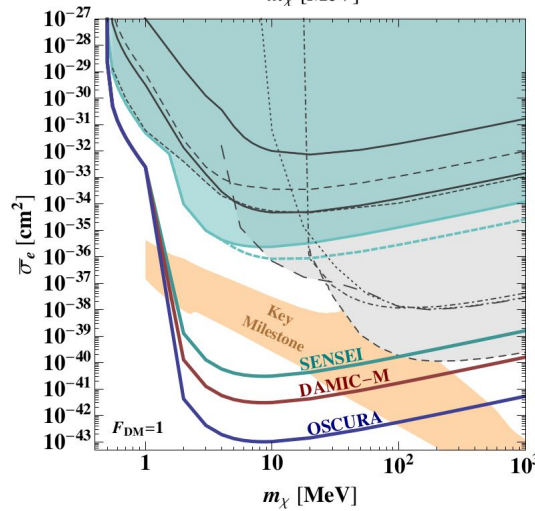
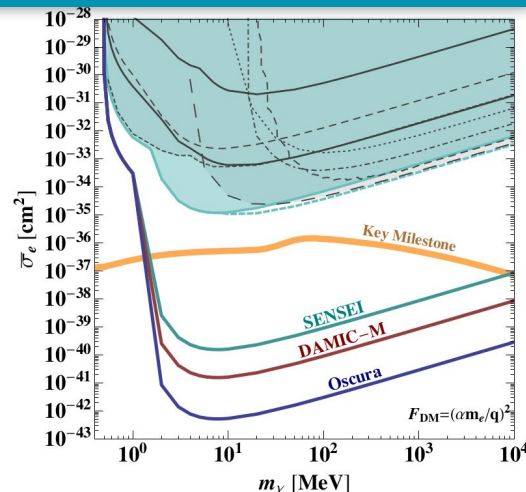
Perspectives

- ◆ “Phase 1” system **fully operational** since December @SNOLAB
- ◆ Final mass: **100g** (~2g now).
- ◆ Deployment in **stages**, increasing mass.
Results will be presented **gradually**.
- ◆ SENSEI should be deployed by ~~2020~~ end of 2020 beginning of 2021.

SENSEI
▶ 100g
▶ 2021

DAMIC-M
▶ 1kg
▶ ~2024

OSCURA
▶ 10kg
▶ ~2027



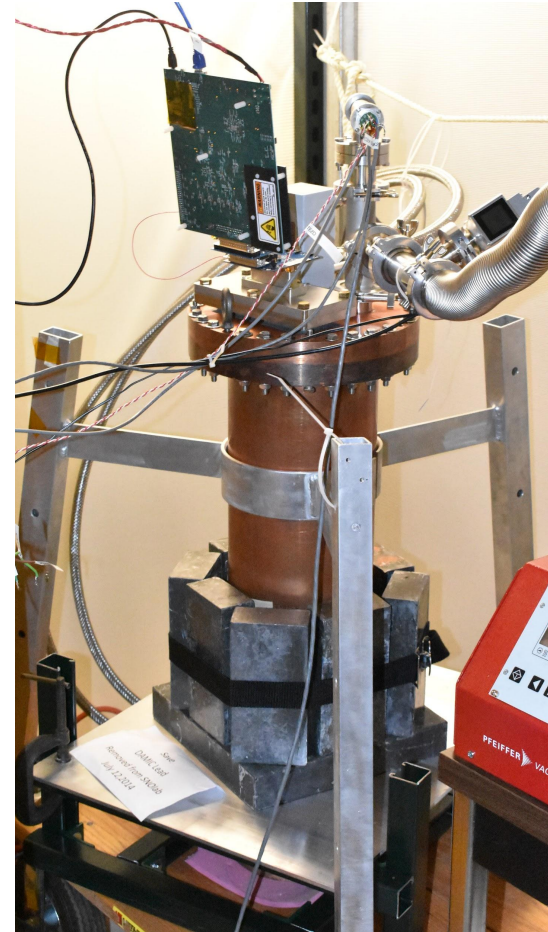
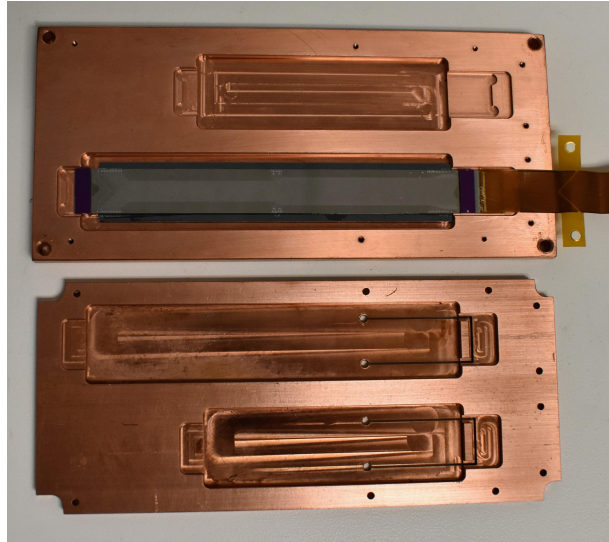
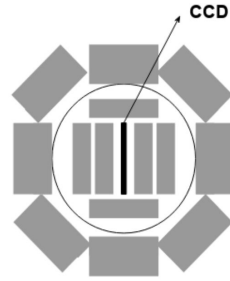
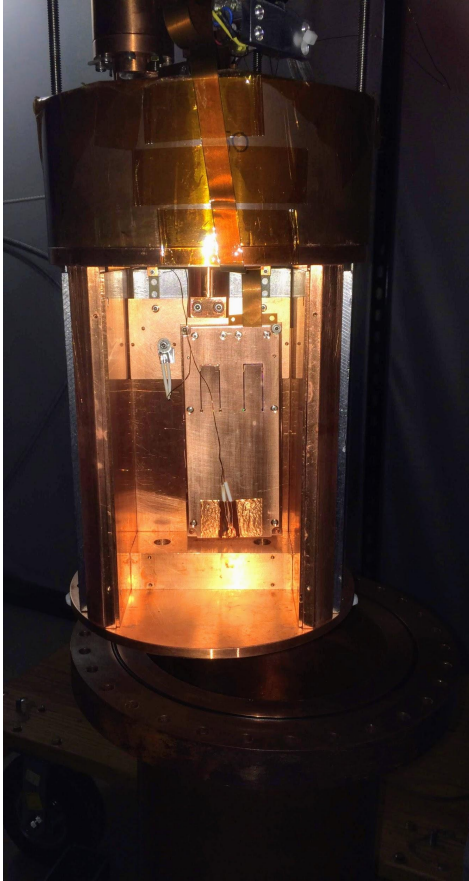
Sho Uemura,
Kevin Kuk
and
Guillermo Moroni
@SNOLAB
December 2019



THANK YOU!

BACK UP SLIDES

MINOS shielding



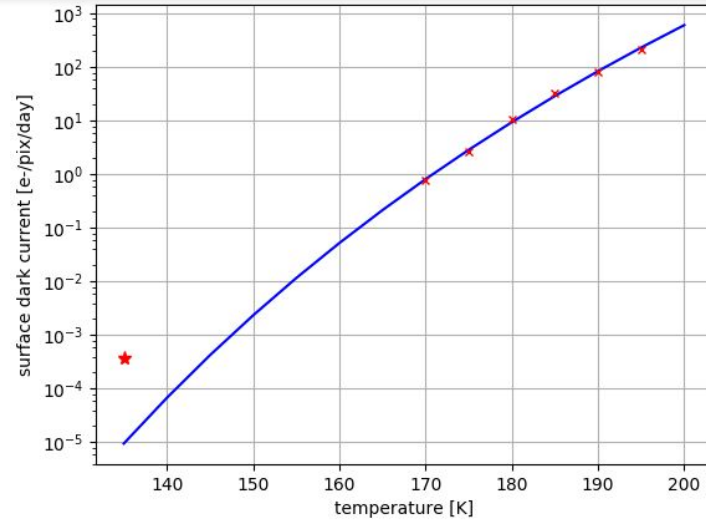
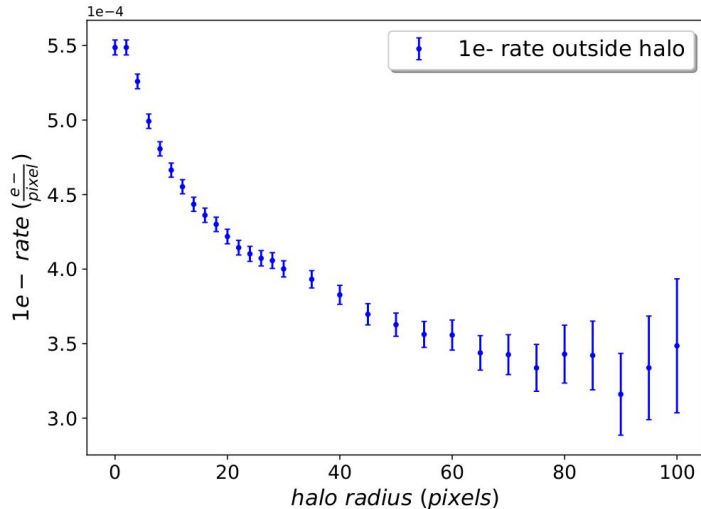
References

- [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

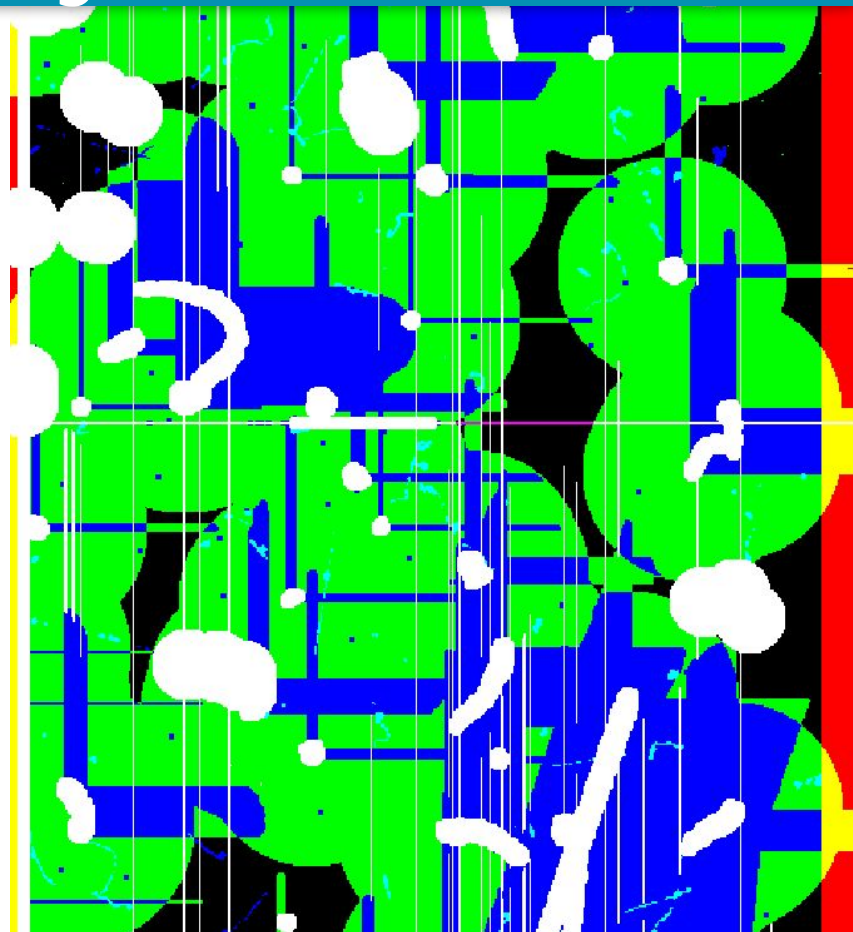
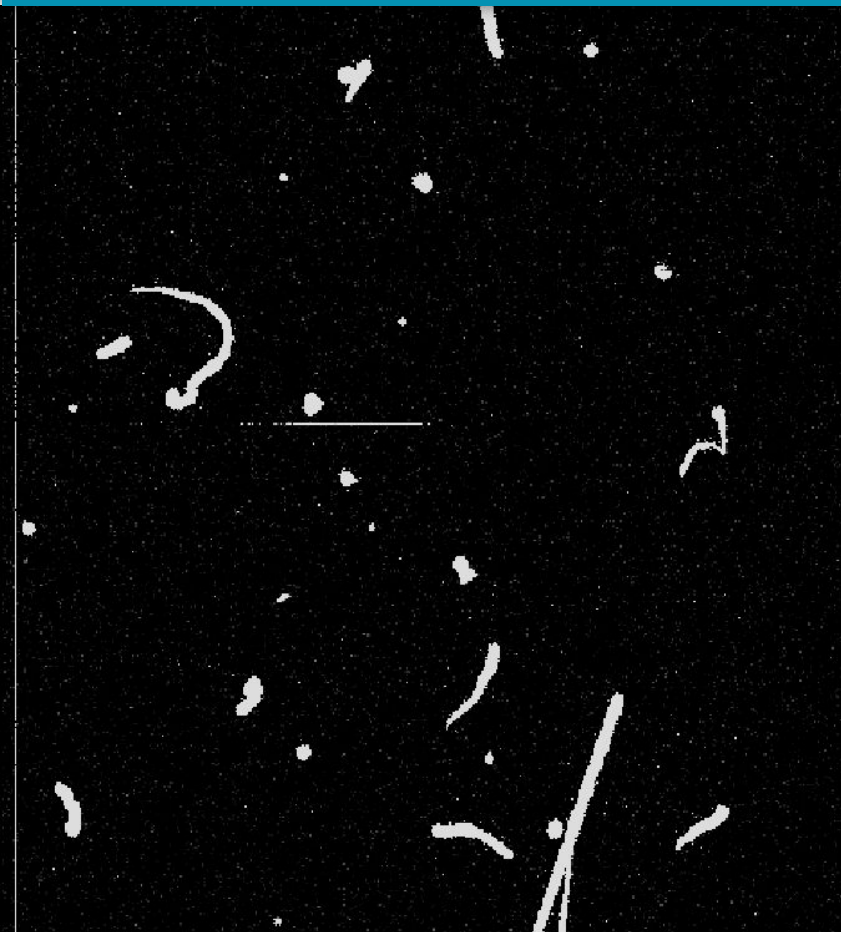
- ◆ A 1e- rate excess is found extrapolating from higher temperatures **assuming only surface DC**.
- ◆ Extrinsic or intrinsic sources?

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 → 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

