SENSEI

performance, results, and prospects for sub-GeV dark-matter searches

A. M. Botti* for the SENSEI† collaboration

Conference on Science at SURF

May 11-13, 2022

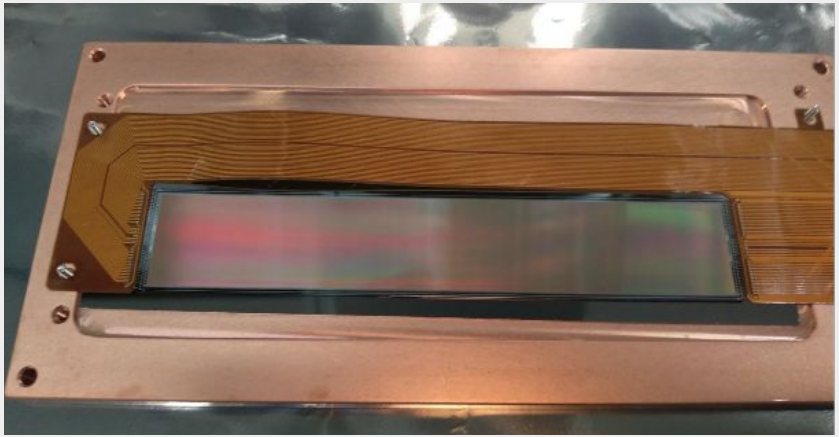

Image: SENSEI sensor

* Fermi National Accelerator Laboratory · abotti@fnal.gov

† Sub-Electron-Noise Skipper-CCD Experimental Instrument · https://sensei-skipper.github.io

The ensei Collaboration*

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***as in its last publication**

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[3] Also CAB, CNEA-CONICET-IB

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

The oensei Experiment

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

New generation Charge Couple Devices **(CCD)**

Developed at **LBNL** MicroSystems Lab

Energy threshold **~ 1.1 eV** (Si bandgap)

Readout noise **~ 0.1 e^-**

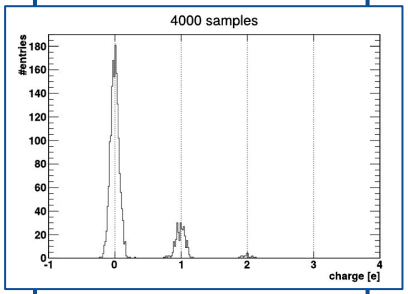
Main goals

- First DM detector with Skipper-CCDs
- Validate technology for DM and ν detection
- Probe DM masses at the MeV scale (e - recoil)
- Probe axion and hidden-photon DM masses > 1 eV (absorption)

The sensei Experiment

2017

Demonstrate sub-electron resolution



Tiffenberg, Javier, et al. Physical Review Letters 119.13 (2017): 131802.

2018

DM search with **proto-SENSEI** (0.1 g) at **surface**

2019

DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)

2020

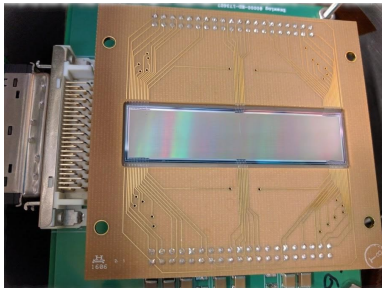
DM search with **science grade** (~2 g) at **MINOS**

Ongoing

Production (100g) + commissioning at **SNOLAB** (6000 m.w.e.)

First Skipper-CCD prototypes

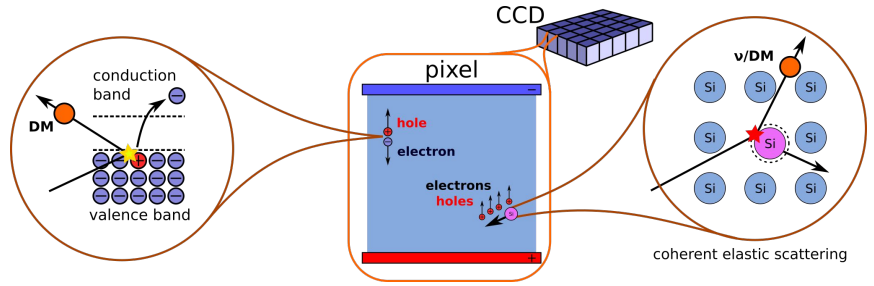
- Prototype designed at LBNL MSL
- 200 & 250 µm thick, 15 µm pixel size
- Two sizes 4k × 1k (0.5gr) & 1.2k × 0.7k pixels
- Parasitic run, optic coating and Si resistivity ~10kΩ
- 4 amplifiers per CCD, three different RO stage designs



Instrument:

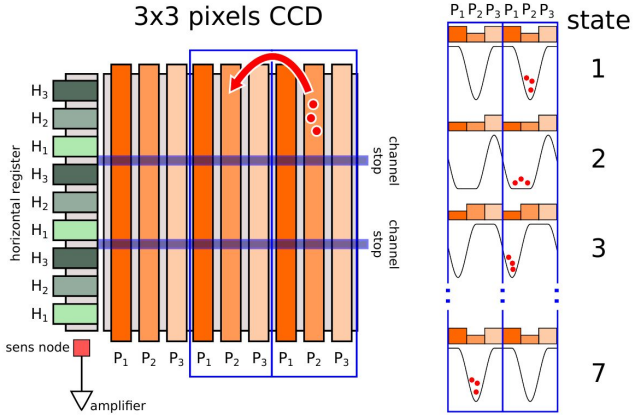
· System integration done at Fermilab
· Custom cold electronics
· Firmware and image processing software
· Optimization of operation parameters

Charge-coupled devices (CCD)



DM-electron scattering

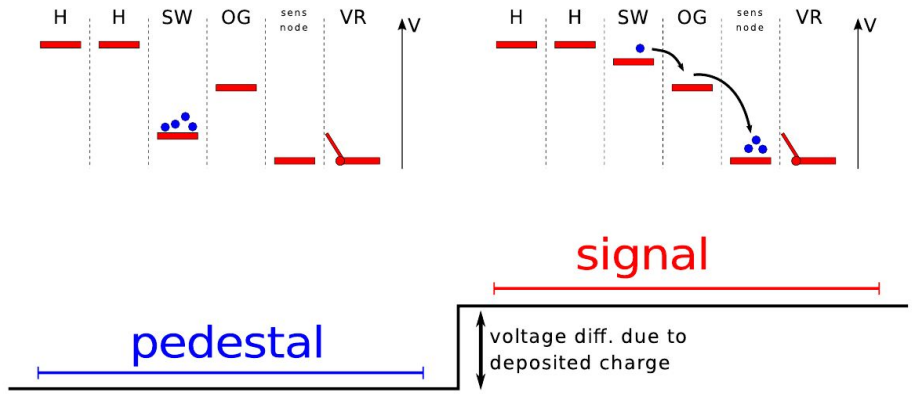
DM-Nucleus scattering



CCD read-out

Charge estimation:

1. **pedestal** integration
2. **signal** integration
3. **charge** = **signal** - **pedestal**

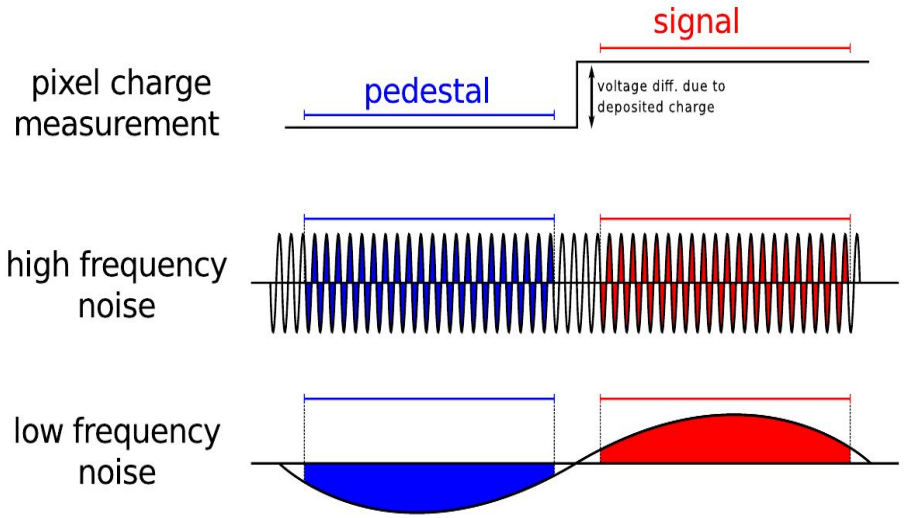


CCD read-out noise

Traditional **CCD**: **charge** transferred to sense node and read **once**

Pedestal and **signal** integration reduces **high-frequency** noise.

But not **low frequency**...

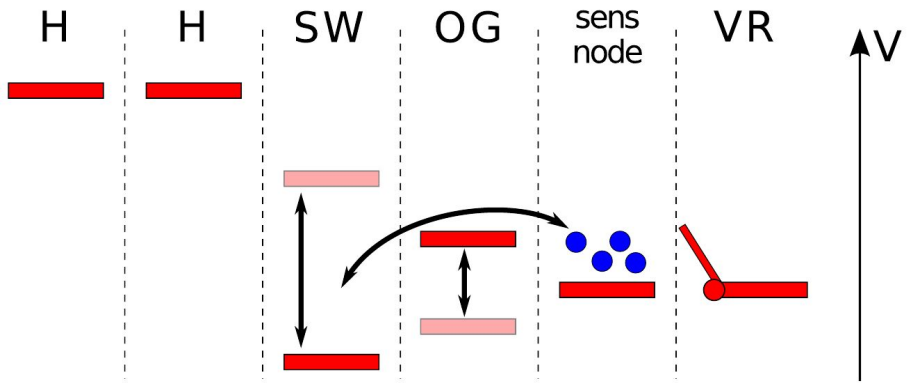


Skipper CCD read-out

Multiple sampling of same pixel without corrupting the **charge** packet.

Pixel value = **average** of all samples

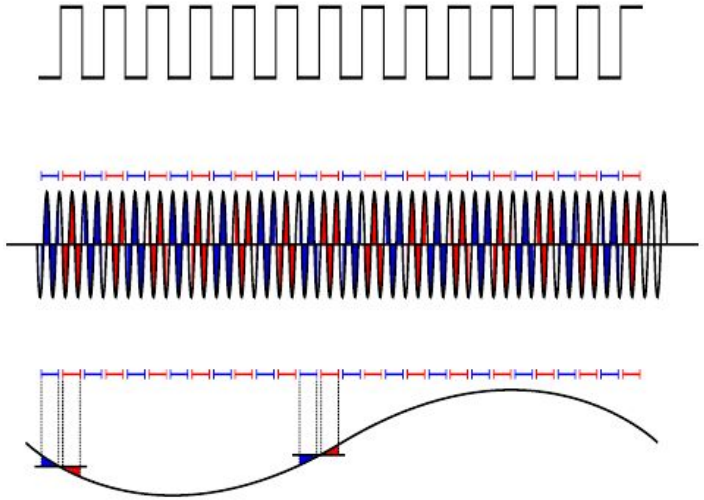
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



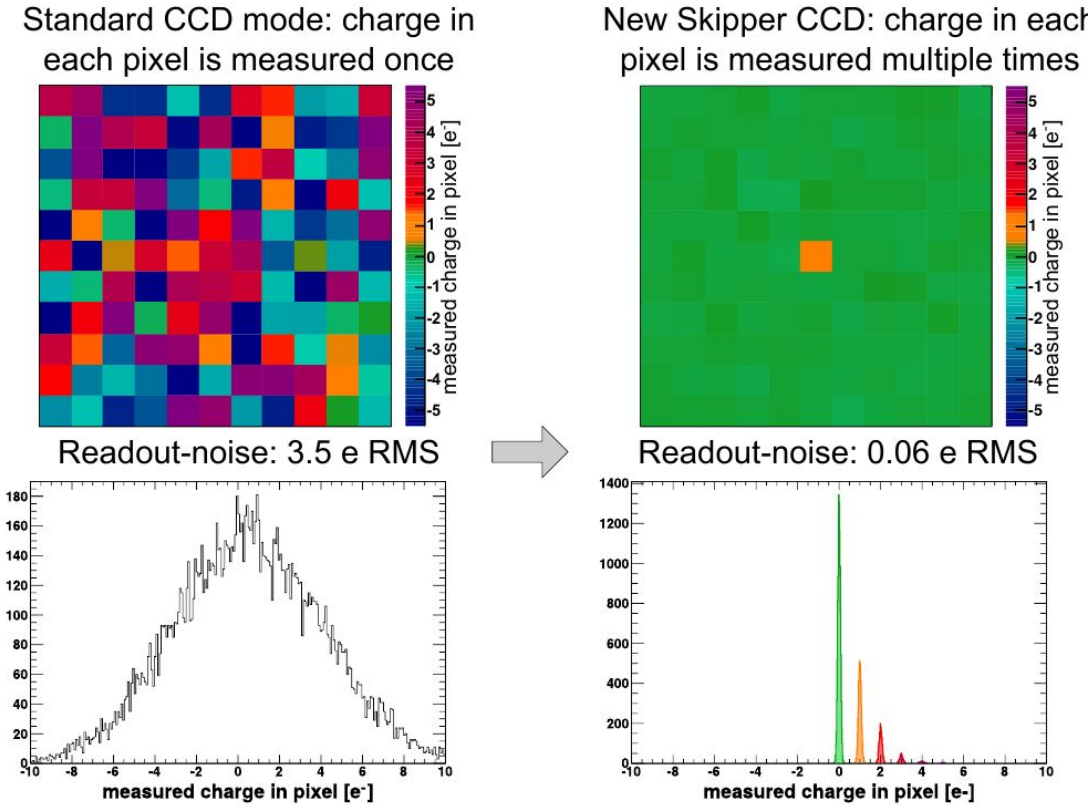
Skipper CCD read-out

1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.
4. **Repeat** N times.
5. **Average** all samples.

Then, the low-frequency noise is reduced



Skipper-CCD read-out noise



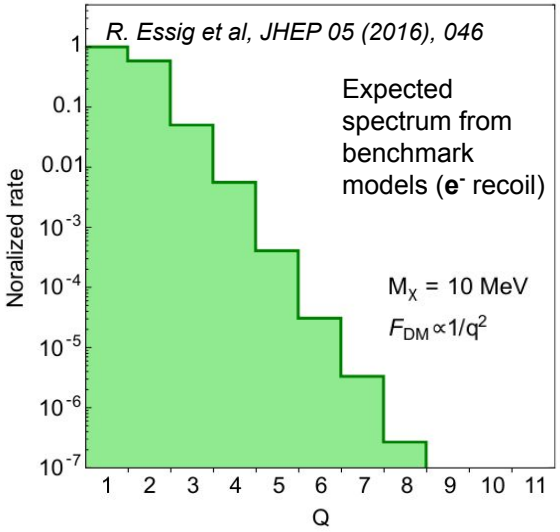
Skipper-CCDs for dark matter

Light-**DM** mass range:
- 1-1000 MeV for **e**$^-$ recoil
- 1~1000 eV for **absorption**
- 0.5~1000 MeV **Nucleus** recoil (Migdal effect)

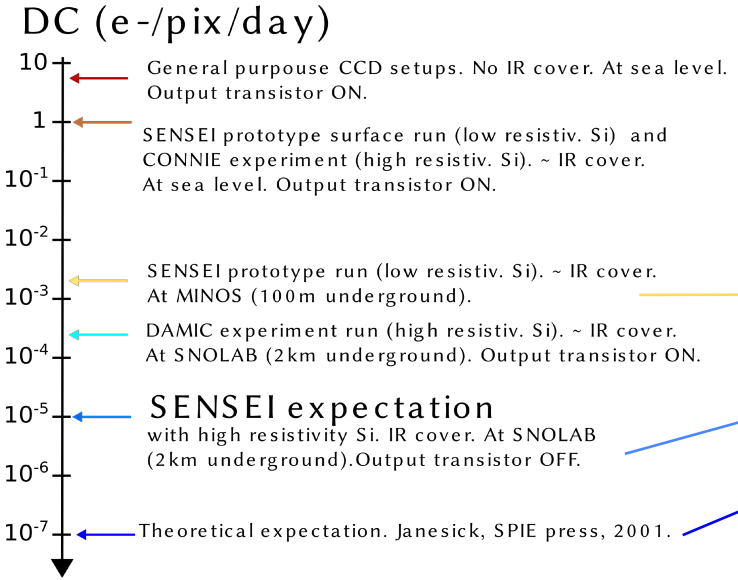
Sensitivity to **1,2,3 e**$^-$ signals needed: **Skippers** can do this!
But only if we understand and control **backgrounds**

Environmental background:
- Air-shower **muons** → go **underground**
- **Soil** radioactivity/environmental **radiation** → **shielding**

Detector noise:
- Dark counts → CCD **operation**
- Defects in crystal lattice → quality **cuts**
- Other spurious charge → CCD **operation** + quality **cuts**



Expected background



Dark Current $[e^- pix^{-1} day^{-1}]$	$\geq 1e^-$ [pix]	$\geq 2e^-$ [pix]	$\geq 3e^-$ [pix]
10^{-3}	1×10^8	3×10^3	7×10^{-2}
10^{-5}	1×10^6	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^4	3×10^{-5}	7×10^{-14}

Background estimations for 1 year and 100 g.

Blue: discovery channel (background free)
Red: modulation or limits

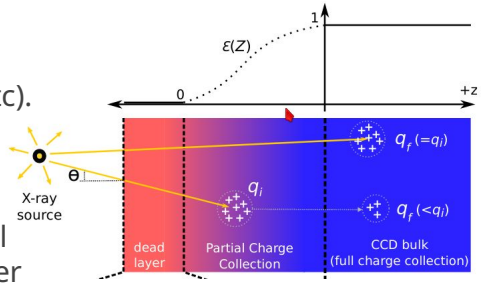
Background sources

Detector

- Dark current
- Spurious charge
- Amplifier light

Environment

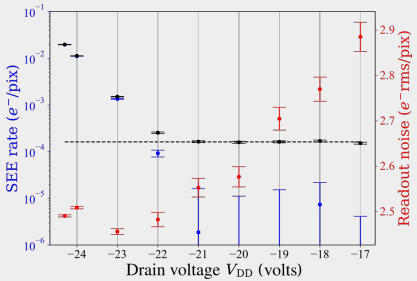
- High-energy events (muons, electrons, etc).
- Halo and transfer inefficiency from high-energy events
- Interactions in partial charge collection layer
- Compton scattering



G. Fernandez Moroni, Phys. Rev. Applied 15, 064026 (2021)

Single electron rate reduced by optimizing operation parameters

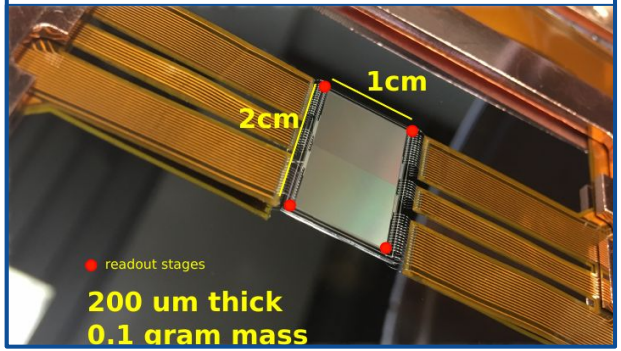
- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while not reading



The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

The SENSEI Experiment

2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



The SENSEI Collaboration
Physical Review Letters 121.6 (2018): 061803.

The SENSEI Collaboration
Physical review letters 122.16 (2019): 161801.

The SENSEI Experiment

2017	2018	2019	2020	Ongoing
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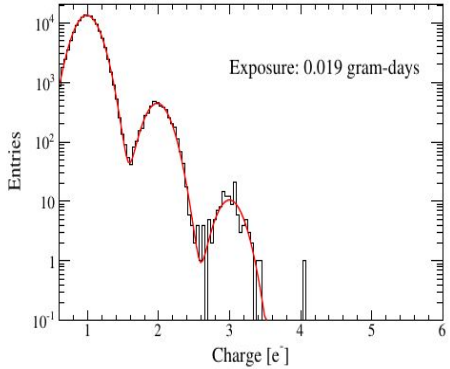
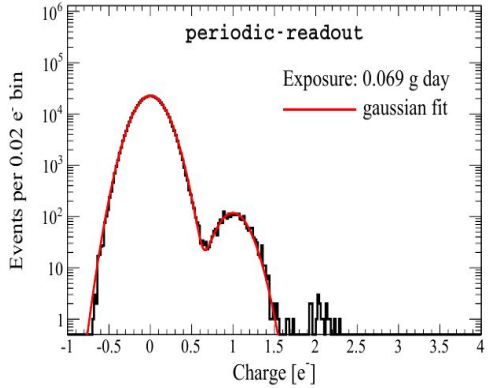
The SENSEI Collaboration Phys. Rev. Lett. 125, 171802 (2020)

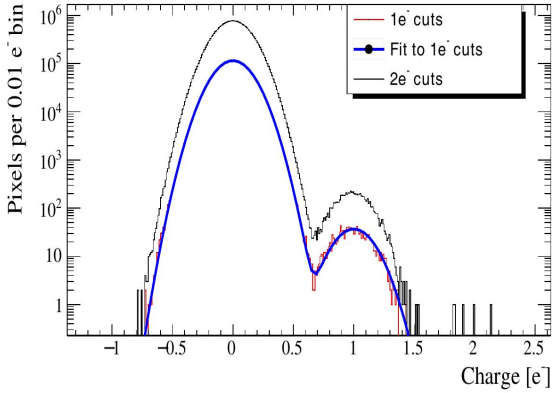
From prototype to science grade



Active mass ~ **0.1 g**
0.019 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **1.14 e-/pixel/day**

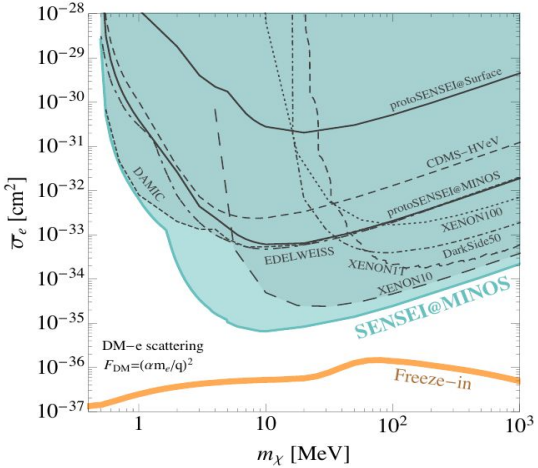


Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**

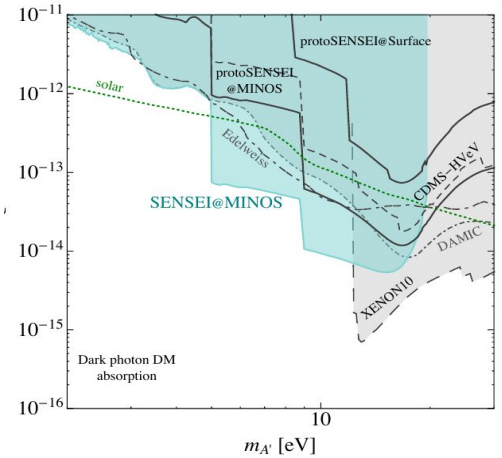


Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
DC ~ **1.6×10^{-4} e-/pix/day**

Latest results



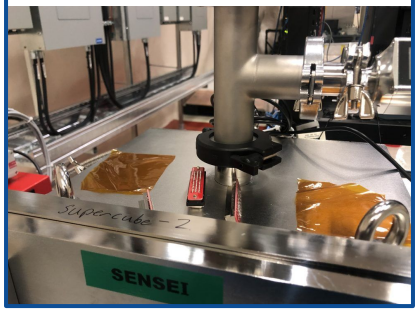
***Light** mediator*
***e**- scattering*



Absorption

The sensei Experiment

2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



SENSEI @ SNOLAB

- Science-grade skipper-CCDs achieved
- Packaging and electronics also achieved
- Phase 1 system @ SNOLAB
- Vessel delivered to SNOLAB
- First CCDs deployed

Towards a **100 g** skipper-CCD detector:

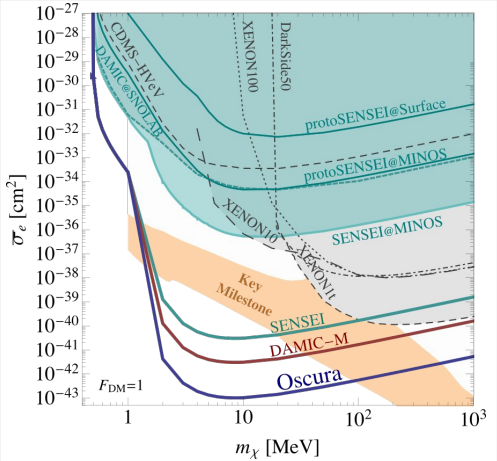
- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB**

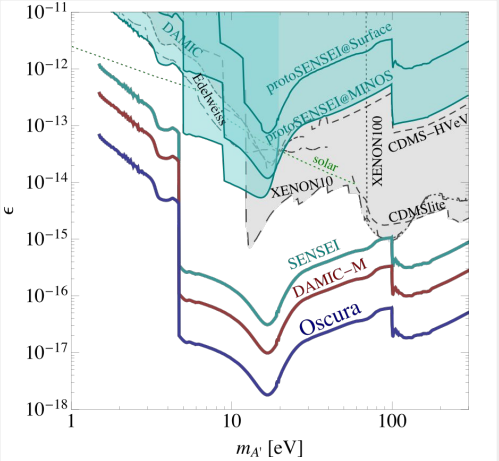
➔ **10000** dru (MINOS standard shield): proto-SENSEI
➔ **3000** dru (MINOS extra shield): first science grade skipper
➔ **5 (ultimate goal)** dru (SNOLAB): SENSEI 100 g

Perspectives: beyond sensei

2021	2024	2027
SENSEI 100g	DAMIC-M 1kg	OSCURA 10kg

The Oscura Experiment
arXiv: 2202.10518



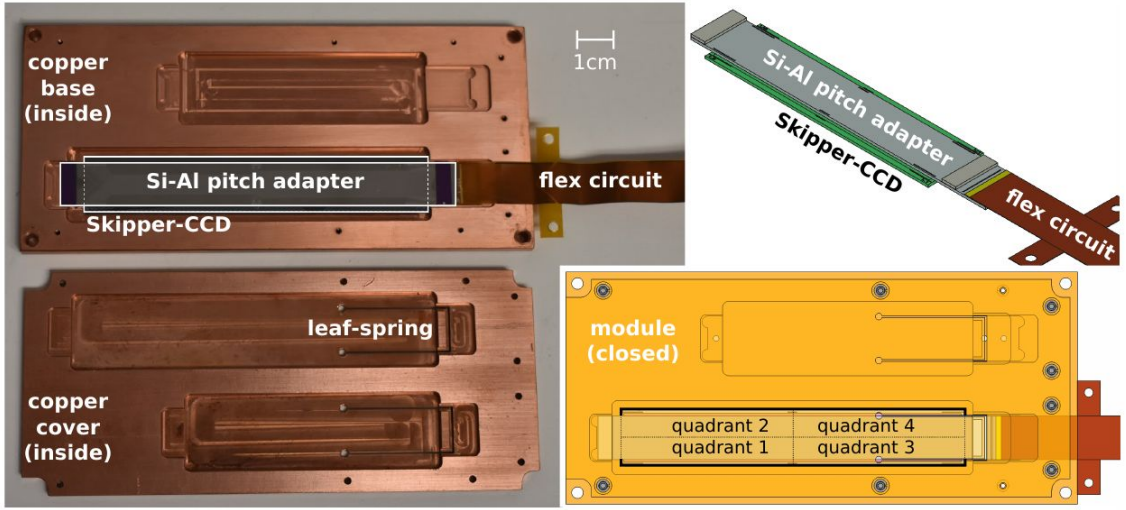


Summary

- **SENSEI**: first dedicated experiment searching for **e-DM** interactions.
- **protoSENSEI** at the **surface** and **MINOS** produced first physics.
- First **scientific grade skipper-CCD** achieved.
- Best constraints on **DM-e-** scattering for light mediator and heavy mediator, up to **10 MeV**.
- Best constraints for **DM absorption** on electrons for mass **5~12.8 eV**.
- **Production** of full **100 g** detector fully funded and ongoing.
- **SENSEI** experiment will collect almost **2 million** times the exposure of the first run in ~ **2-3 years**, probing large regions of uncharted territory populated by benchmark models
- **generations** of **skipper-CCD** experiments foreseen for DM searches in the next ~ 7 years

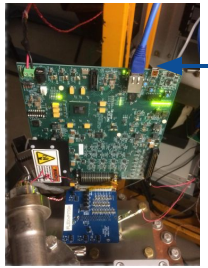
New device

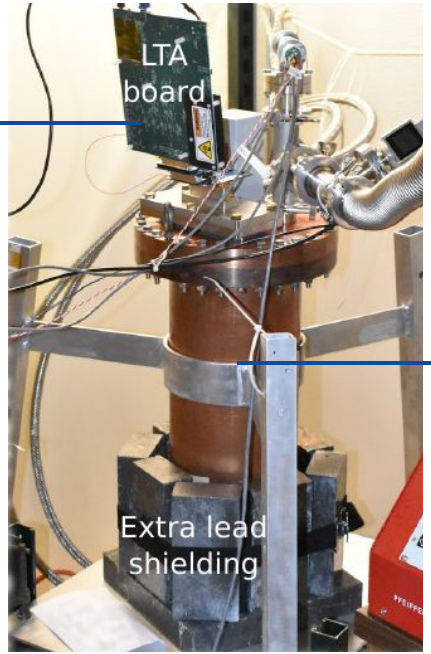
- First skipper-CCD optimized for DM detection
- 5.5 Mpix of 15 μm
- 675 μm thick
- Active mass ~ 2 g
- 20 kΩ
- 4 amplifiers
- T ~ 135 K + vacuum



Setup @ MINOS

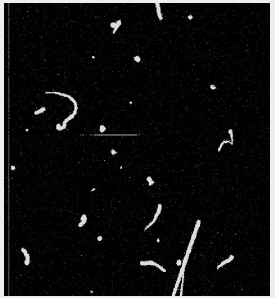
- 230 m.w.e.
- Previous vessel + extra shielding
- T ~ 135 K + vacuum
- LTA board



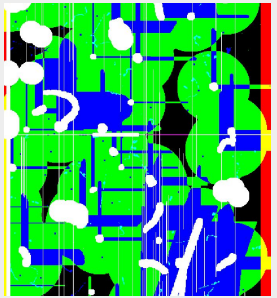


Quality cuts

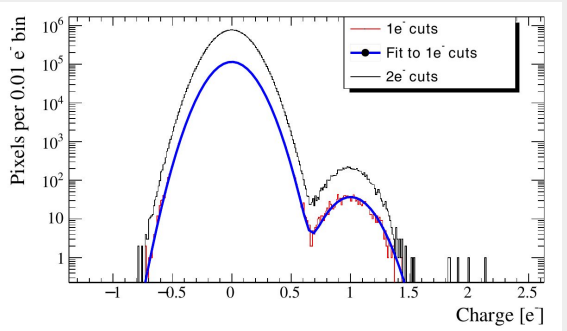
N_e / Cuts	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	0.69	35	0.69	7
6. Edge	0.70	25585	0.90	70	0.93	8	0.93	2
7. Bleeding Zone	0.60	11317	0.79	36	0.87	7	0.87	2
8. Bad Pixel/Col.	0.98	10711	0.98	24	0.98	2	0.98	0
9. Halo	0.18	1335	0.81	11	~ 1	2	~ 1	0
10. Loose Cluster	N/A		0.89	5	0.84	0	0.84	0
11. Neighbor	~ 1	1329	~ 1	5	N/A			
Total Efficiency	0.069		0.105		0.341		0.349	
Eff. Efficiency	0.069		0.105		0.325		0.327	
Eff. Exp. [g-day]	1.38		2.09		9.03		9.10	
Observed Events	$1311.7^{(*)}$		5		0		0	
90%CL $[\text{g-day}]^{-1}$	$525.2^{(*)}$		4.449		0.255		0.253	



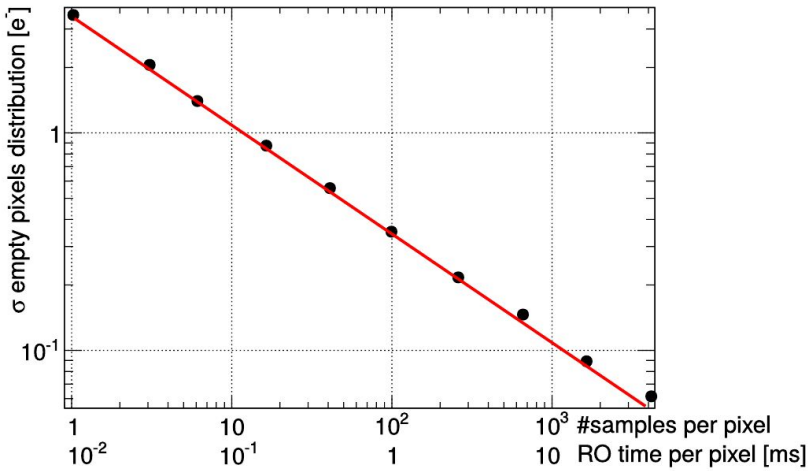
Example image

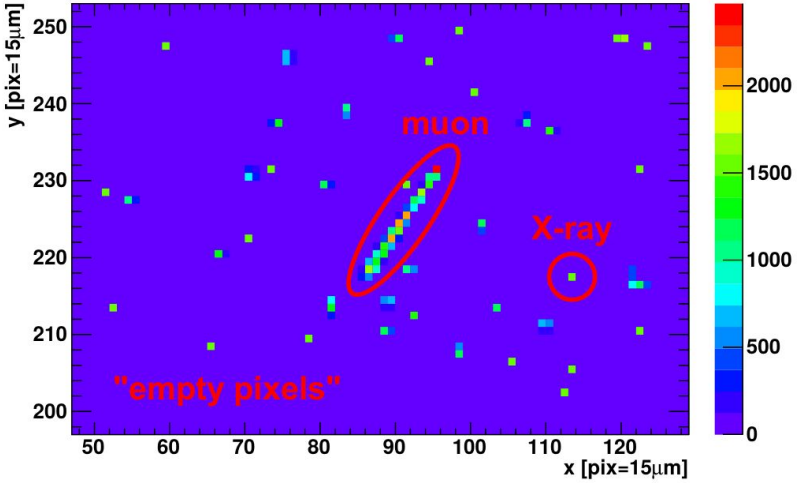


Masking

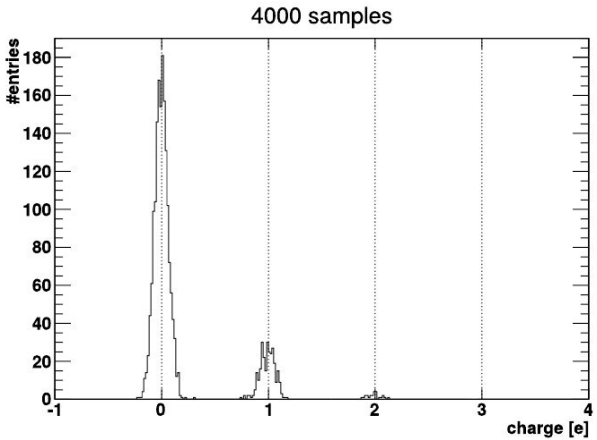


Skipper-CCD read-out noise

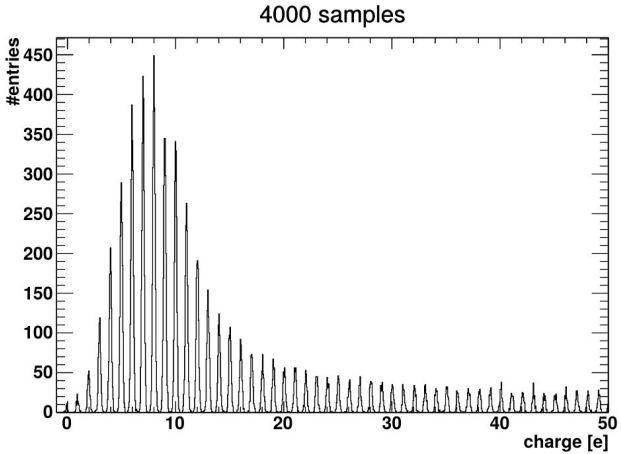




Skipper-CCD resolution



(Almost) Empty CCD



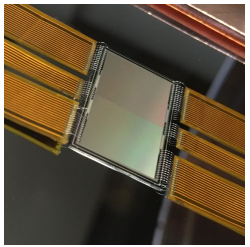
Front-illuminated CCD

proto-SENSEI

R&D sensor:

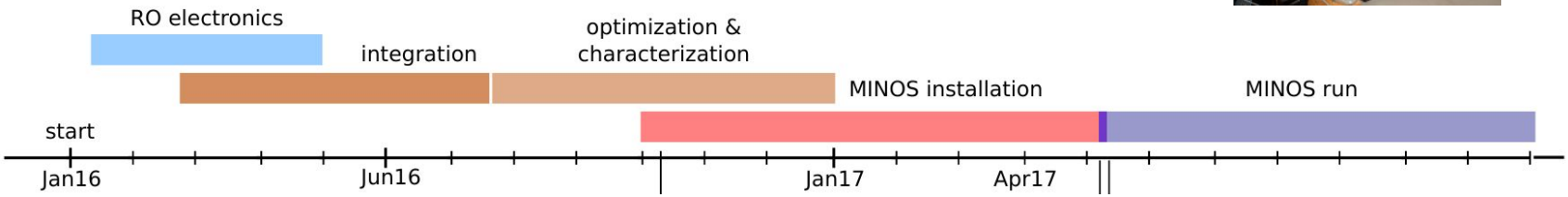
- **optimize** operation parameters
- develop **packaging** and **shielding**
- Characterize **background/noise**
- first physics **results**!

New package Commissioned at surface

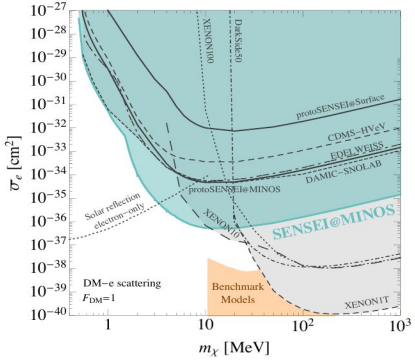


Underground clean room

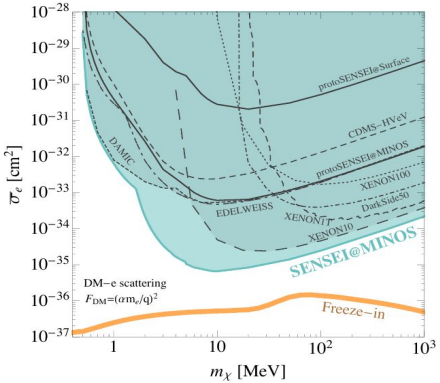
Deploy at MINOS + data taking



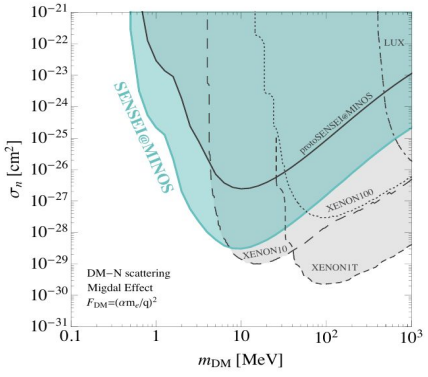
Latest results



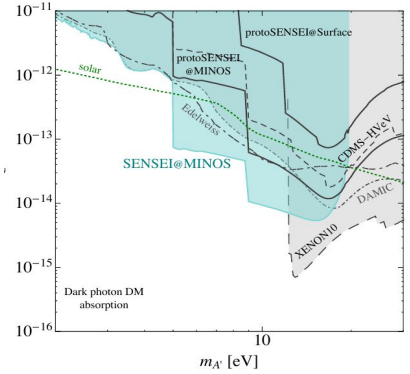
Heavy *mediator*
e$^-$ *scattering*



Light *mediator*
e$^-$ *scattering*



Light *mediator*
Nucleus *scattering*



Absorption