The SENSEI† Experiment: sub-GeV dark matter searches with skipper-CCD

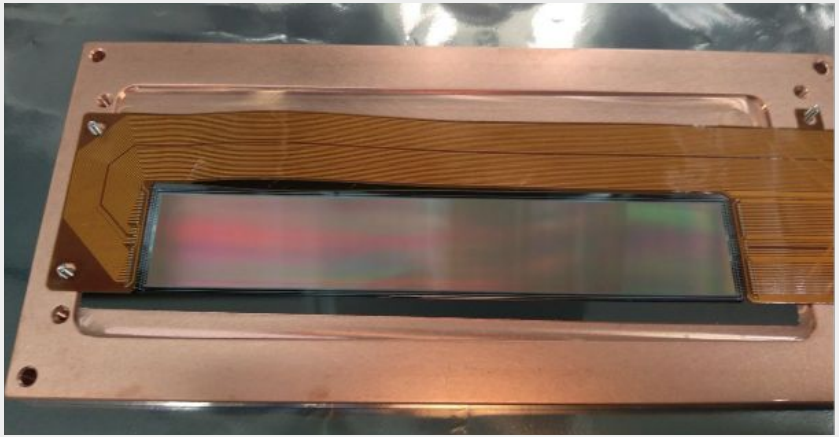


Image: SENSEI sensor

A. M. Botti* for the SENSEI† collaboration

18th International Conference on Topics in Astroparticle and Underground Physics, Vienna

August 31, 2023

* Fermi National Accelerator Laboratory · abotti@fnal.gov

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

The ensei Collaboration

- L. Barak, E. Etzion, Y. Korn, A. Orly, T. Volansky
- 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
- M. Cababie, D. Rodrigues, S. Perez
- P. Adari, R. Essig, A. Singal, Y. Wu
- A. Desai, T.-T. Yu
- I. Lawson, S. Luoma, S. Scorza
- I. M. Bloch
- S. Holland

[1] Also Fermilab
[2] Also U. Chicago
[3] Also CAB, CNEA-CONICET-IB

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

The SENSEI Experiment

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

New generation Charge Coupled Devices **(CCD)**
LBNL MicroSystems Lab Energy threshold **~ 1.1 eV**
(Si bandgap) and 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)

Skipper-CCD for rare-event searches: number of contributions accepted **@ TAUP**

Skipper-CCD demonstrated **@ FNAL**

Year	2017	2019	2021	2023
Contributions	0	2	1	12

SENSEI. This talk

DAMIC-M. Next talk

OSCURA. Estrada et al.

CONNIE Aguilar-Arevalo et al.

Packages Botti, et al.

Electronics Chavez, et al.

Atucha Cababie et al.

DarkNESS Saffold et al.

DMSQUARE Avalos et al.

DAMIC Traina et al.

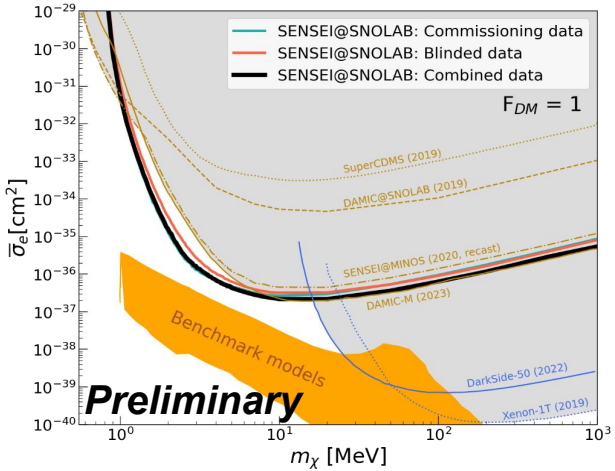
Background / calibration Smida et al.

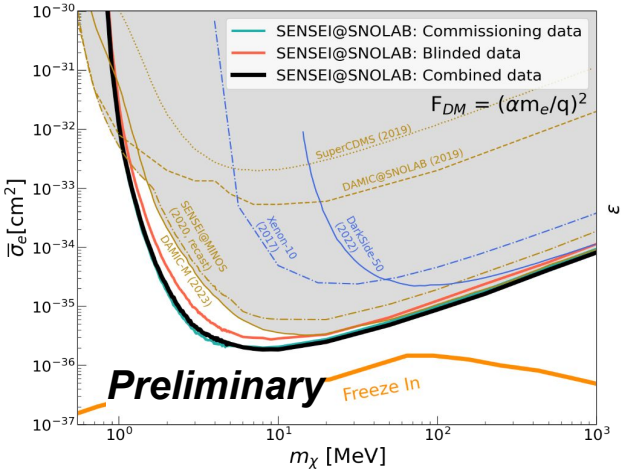
Outreach & Education Botti et al.

8 Experiments / collaborations showing skipper-CCD data

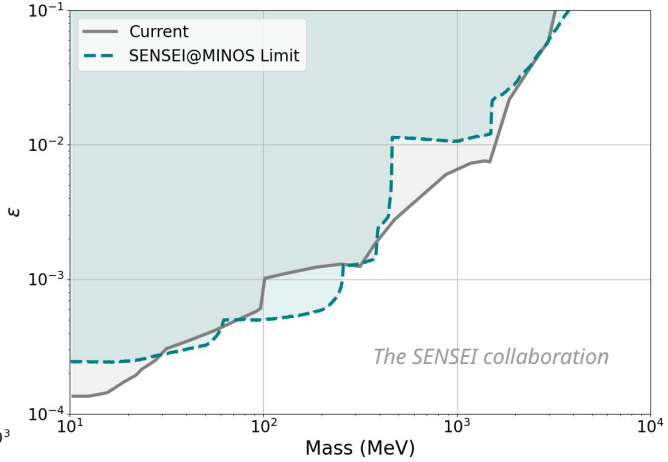
Latest results (2023)

SENSEI@SNOLAB





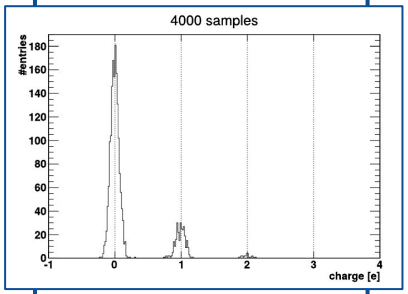
SENSEI@MINOS



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.)

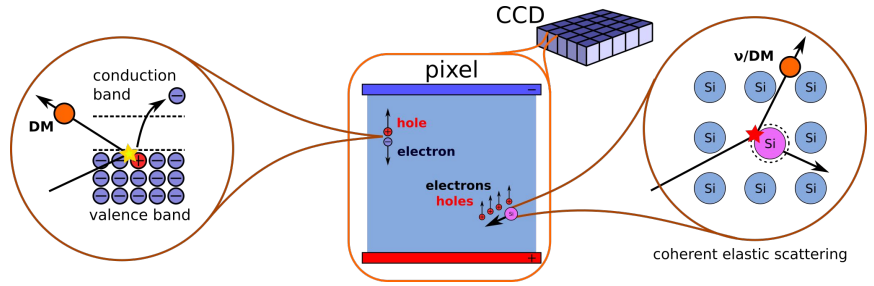
2020

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

Ongoing

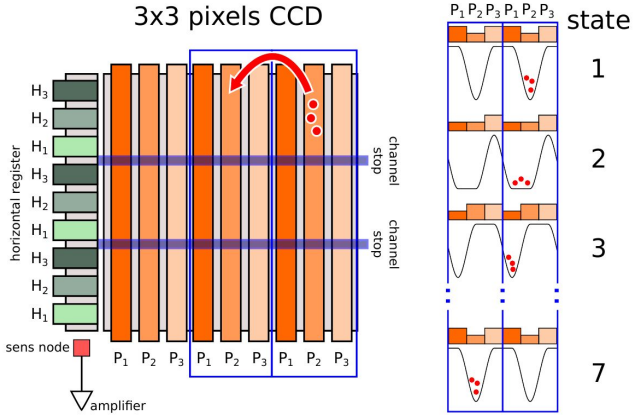
Production (100g) + commissioning at **SNOLAB** (6000 m.w.e.)

Charge-coupled devices (CCD)



DM-electron scattering

DM-Nucleus scattering



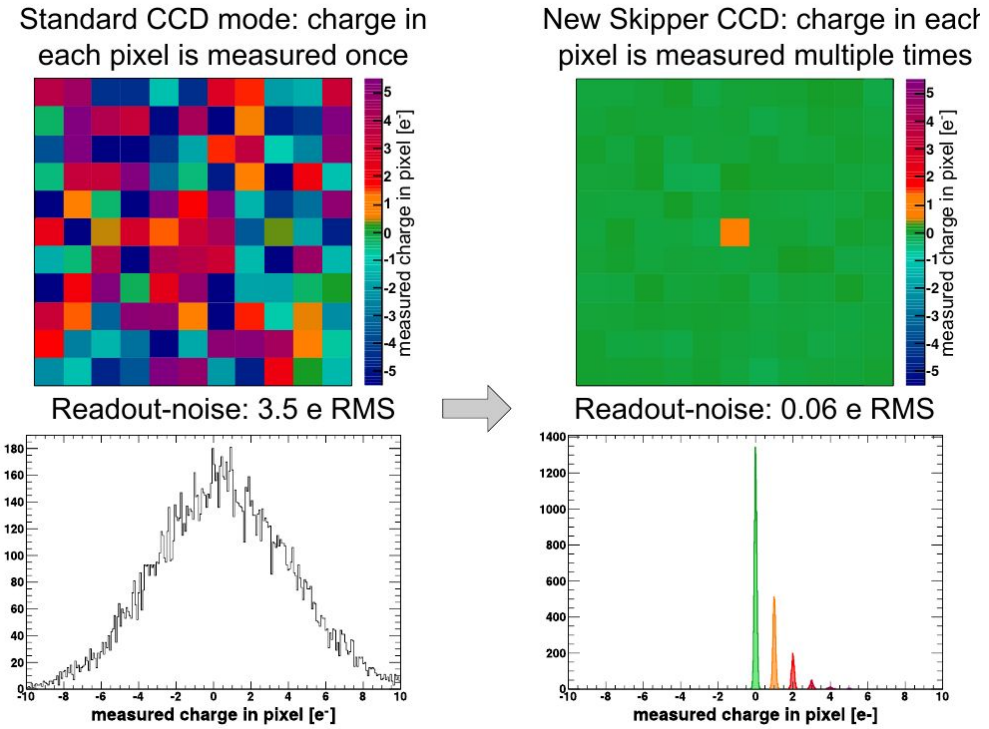
Covered at DM plenary talks K. Schaeffner

Skipper-CCD read-out noise

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

Then, both high- and low-frequency noise are reduced

Covered at DM plenary talks K. Schaeffner



Skipper-CCDs for dark matter

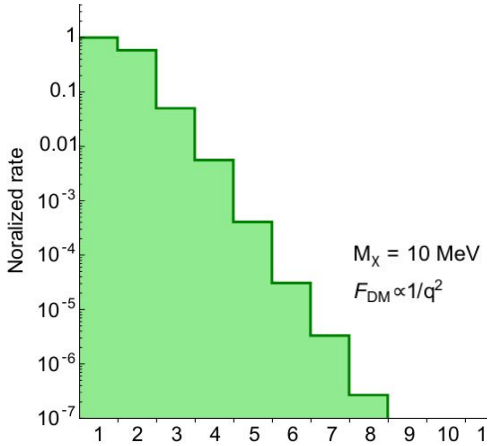
Light-**DM** mass range:
- 1-1000 MeV for **e**$^-$ recoil
- 1~1000 eV for **absorption**
- 0.5~1000 MeV **Nucleus** recoil (Migdal effect)

Sensitivity to **1,2,3 e**$^-$ signals needed: **Skippers** can do this!

But only if we understand and control **backgrounds...**

Covered at DM plenary talks M. Cirelli

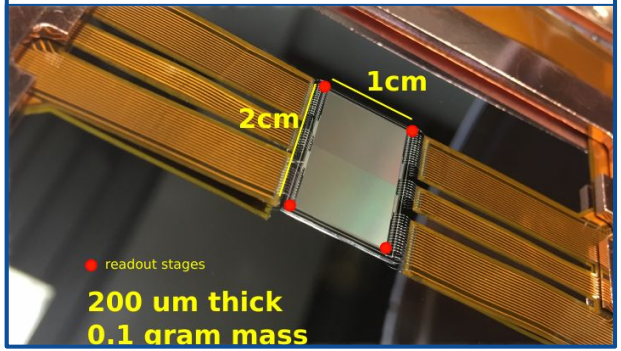
Expected spectrum from benchmark models (e$^-$ recoil)



R. Essig et al, JHEP 05 (2016), 046

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

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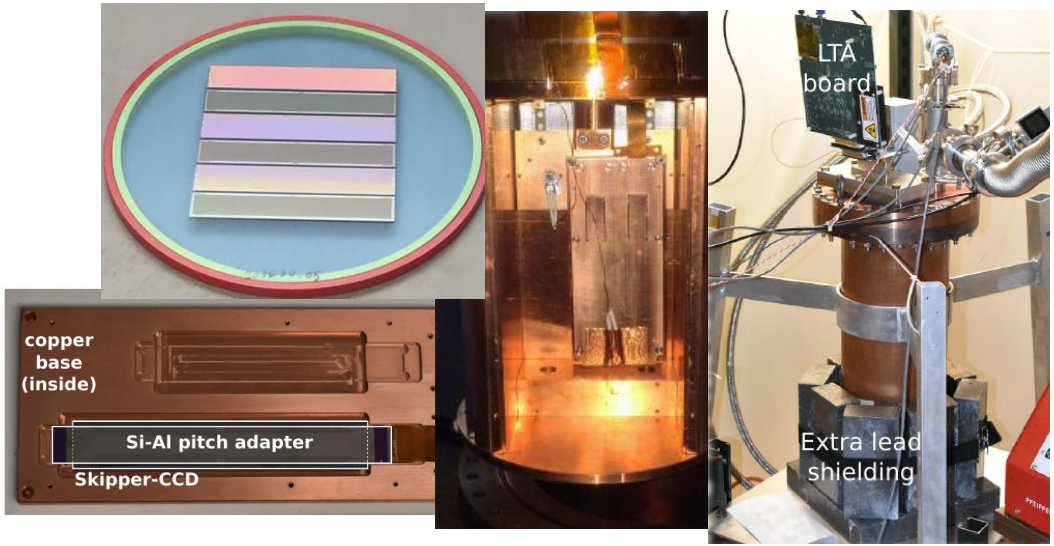
The SENSEI Collaboration
Phys. Rev. Lett. 125, 171802 (2020)

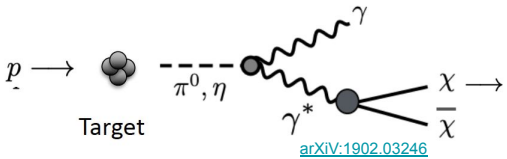
2020 New device @ MINOS

- 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

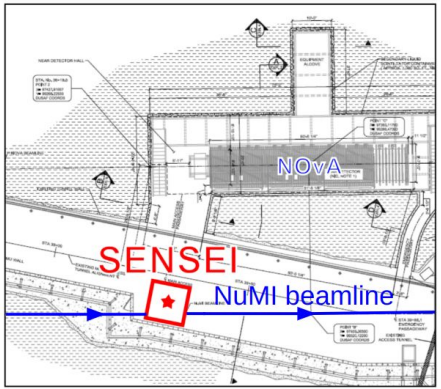


2023: Milli-charged particles @ MINOS

Proton collisions w/ fixed target -> mCPs collinear w/ NuMI beamline:

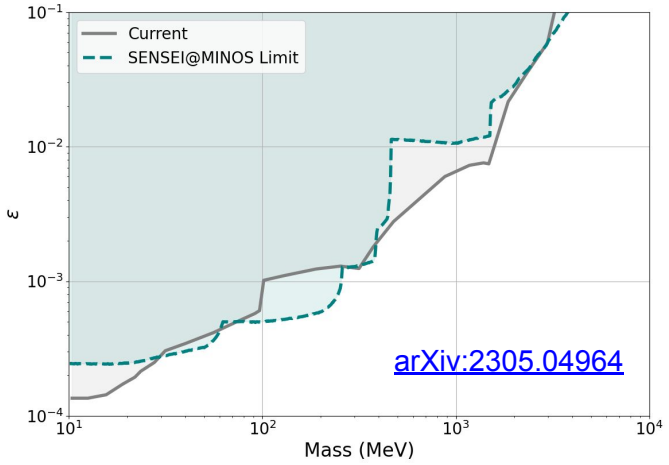


arXiV:1902.03246



Extension of previous analysis to 6e-

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
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



The SENSEI Experiment

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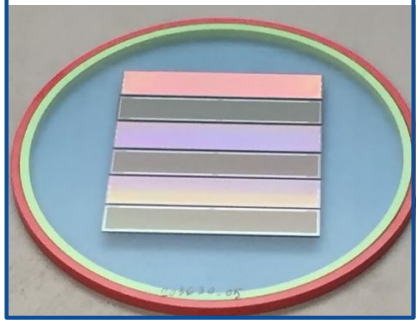


SENSEI @ SNOLAB

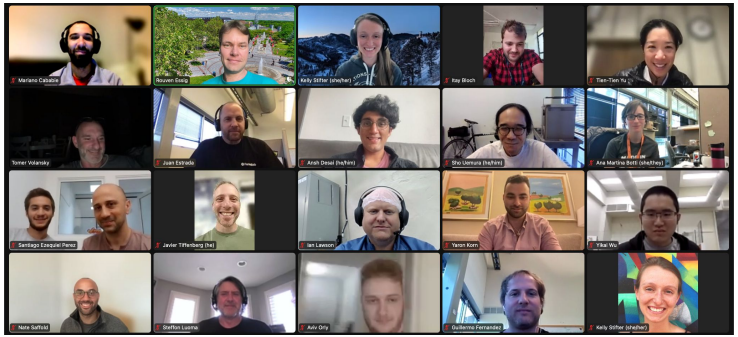
Towards a **100 g** science grade skipper-CCD detector:

- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB** (6000 m.w.e.)

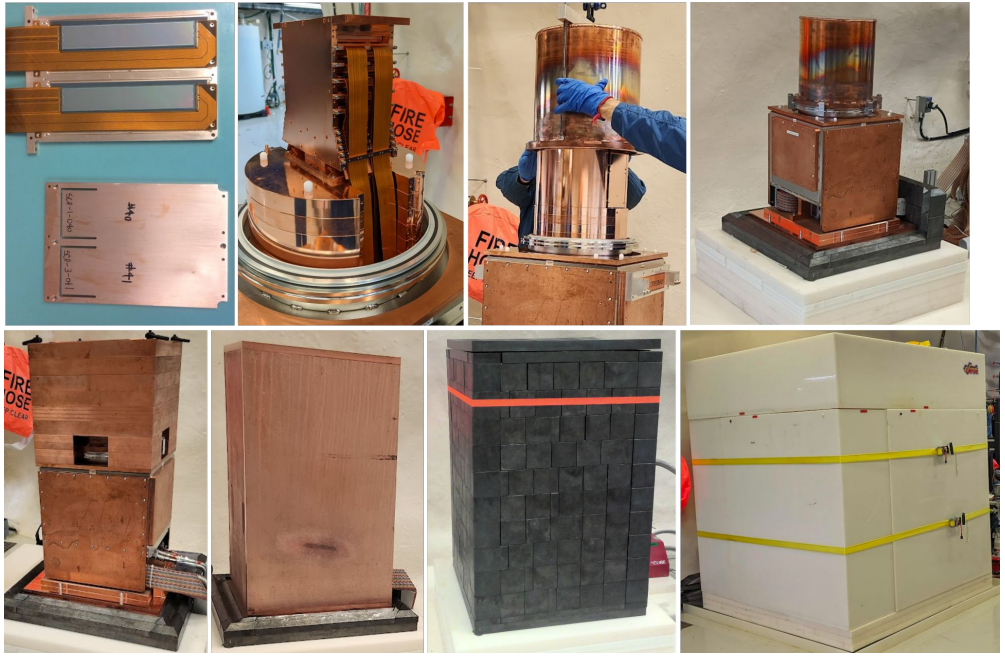
Vessel deployed during the pandemic by SNOLAB staff

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



SENSEI @ SNOLAB: Setup



Setup:

- Copper box for 12 copper tray
- Each tray for 2 (4) ~2g CCDs.
- Cold copper box
- 6-in copper bricks and hat inner shield
- Vacuum pump (< 2x10^-4 mbar)
- Cryocooler + heater (~140 K)
- 2 layer of copper outer shield
- 3-in lead
- 42-inch polyethylene and water shield

SENSEI @ SNOLAB: First science run

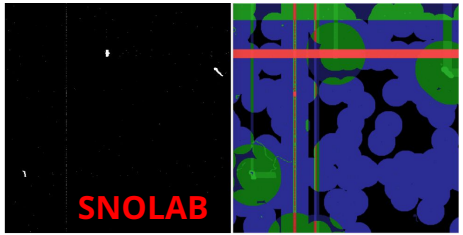
Setup:

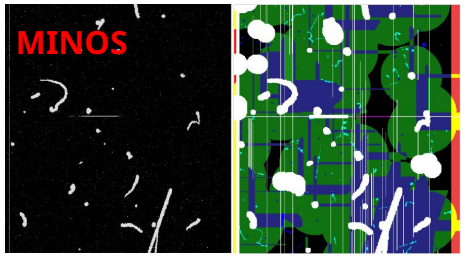
- 6 CCDs (~13 g),
- 6144 × 1024 pixels
- 15 μm pitch, 675 μm thick
- Installation: 4-7/2021
- Commissioning: 10/2021-8/2022
- Science: 9/2022-4/2023

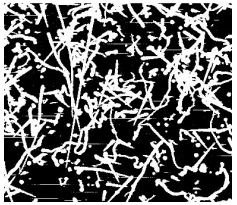
Operations:

- 20 hour exposures
- 129 images (~50% blinded)
- 7.3 hours readout, noise of ~0.14 e-
- Temperature variations of 135 K-155 K
- 1 e- density (after cuts): ~2 x 10-4 e-/pixel

SENSEI @ SNOLAB: quality cuts



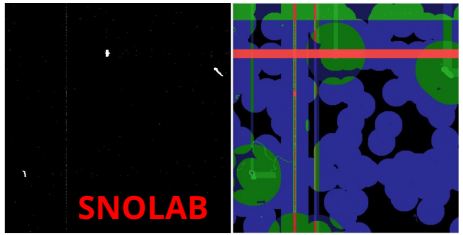


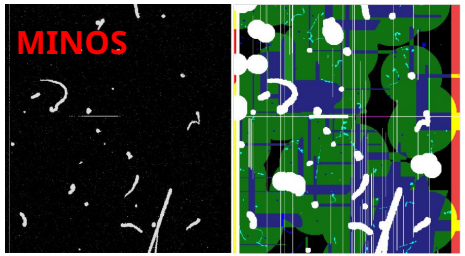


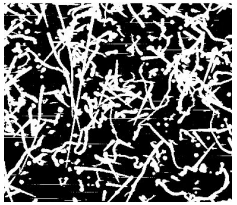
SURFACE (~20 less exposure)

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

SENSEI @ SNOLAB: quality cuts



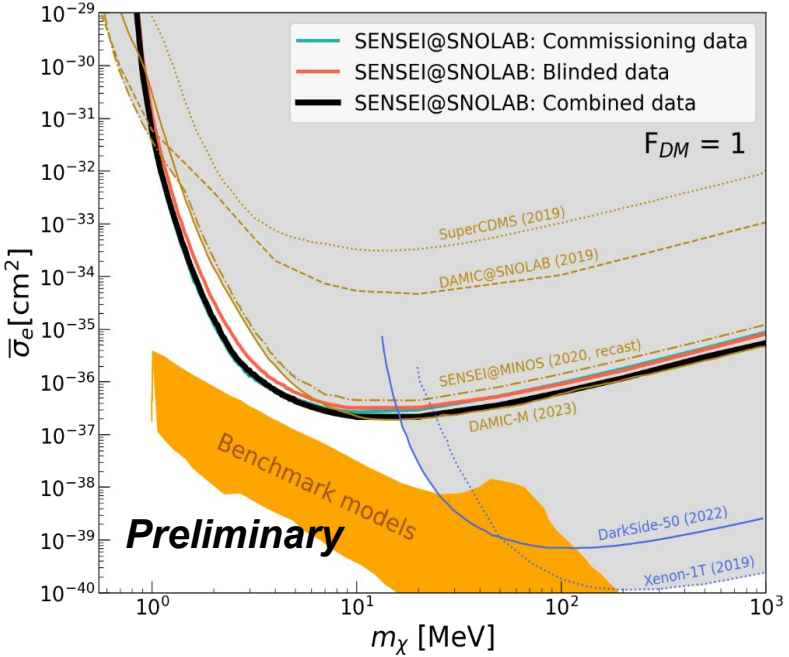


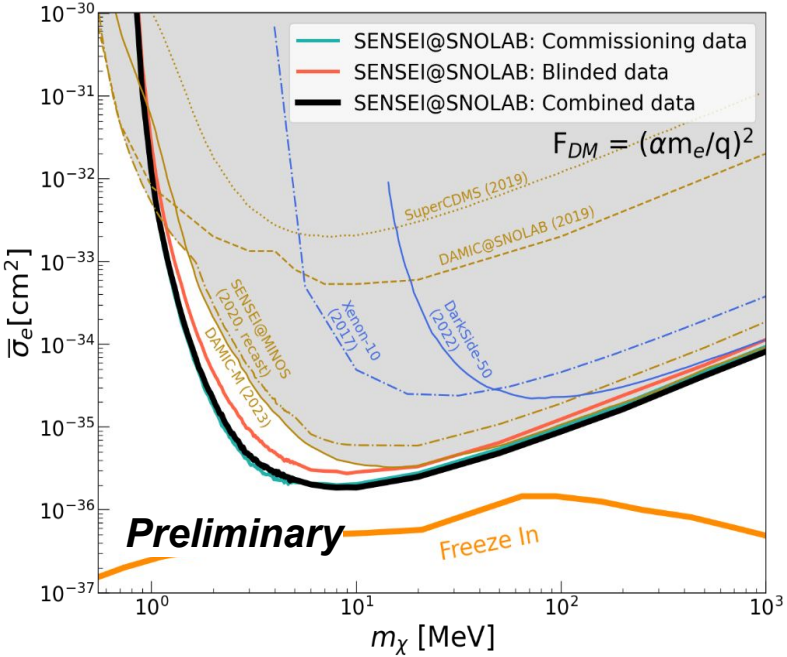


SURFACE (~20 less exposure)

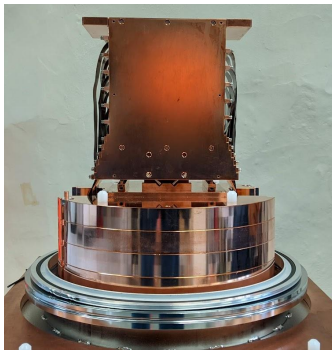
- 45 unblinded commissioning images,
- 37 blinded images
- 2-10 e- channels
- Combined datasets: ~70 g-days per electron channel with cuts
- Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

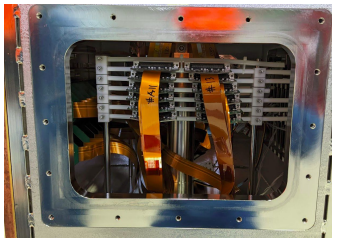
SENSEI @ SNOLAB: First results

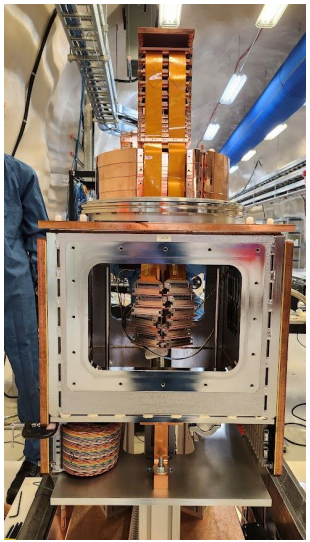




SENSEI @ SNOLAB: Second science run







- 19 CCDs (~ 40 g)
- Improved support
- Shield fully deployed
- Data acquisition starting soon

Open data

Data available in SENSEI papers:

- *Physical Review Letters 121.6 (2018): 061803.*
- *Physical review letters 122.16 (2019): 161801.*
- ***Phys. Rev. Lett. 125, 171802 (2020)***
- ***arXiv:2305.04964***
- ***SNOLAB paper in preparation***

Contact us if anything else is needed

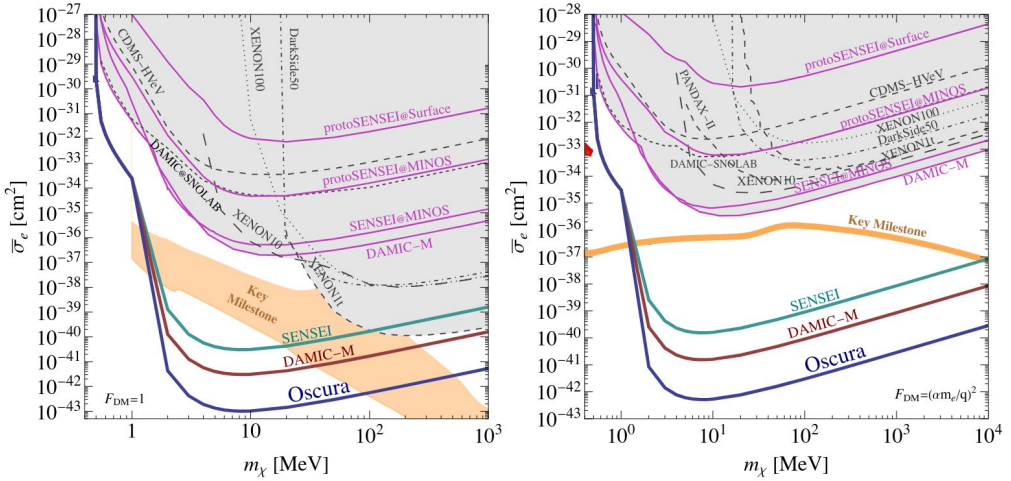
N_e / Cuts	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	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	

Perspectives DM with skippers

SENSEI 100g — 2021

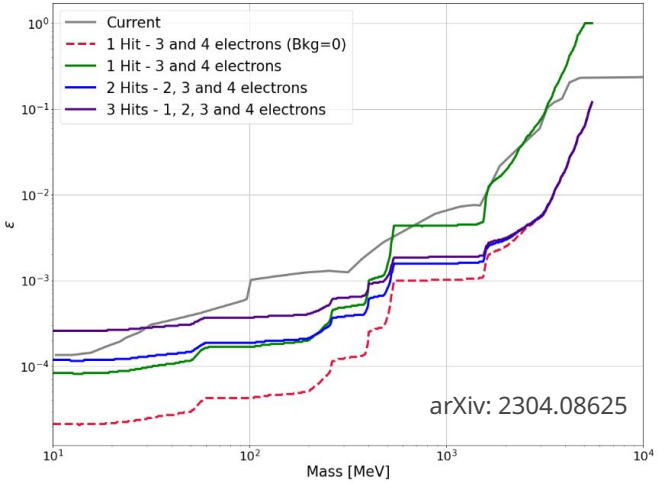
DAMIC-M 1kg — 2024

OSCURA 10kg — 2027



arXiv: 2304.04401

Perspectives mCP with skippers



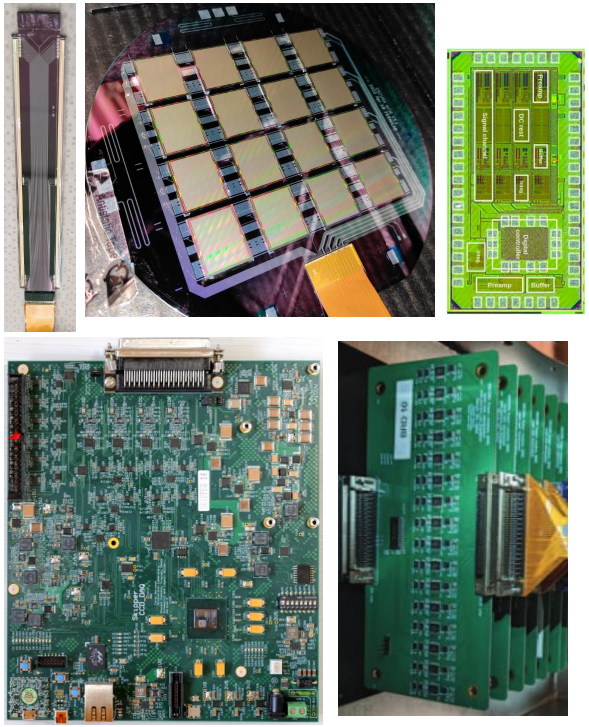
From SENSEI to OSCURA

arxiv: 2210.16418
arxiv: 2304.13088
arxiv: 2108.09389
arxiv:2004.07599
PoS(444)1397

OSCURA is expanding SENSEI concept to scale from 100 g to 10 kg

SENSEI:	**OSCURA**:
• **200** channels / **50** CCDs	• **24000** channels / **24000** CCDs
• **1** Low-threshold acquisition **board** per **1 CCD**	• **1** Low-threshold acquisition **board** + ACDS and mux in **ASIC** per **4000 CCDs** *Current **OSCURA** electronics can read whole **125g** with **1 channel** and whole **2 kg** with **1 board*** • **1** Silicon **pitch adapter** per **16 CCDs**
• **1** Silicon **pitch adapter** per **1 CCD**	

+ SENSEI expertise on sensor design and fabrication, operations, testing, debugging, theory, processing and analysis software



From SENSEI to OSCURA

arxiv: 2210.16418
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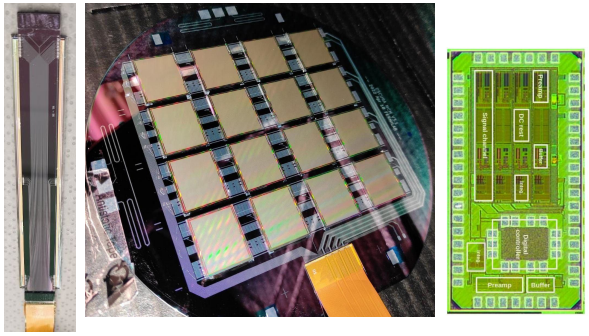

Check **R. Smida DAMIC-M** talk on **backgrounds**

Summary

- **SENSEI**: first dedicated experiment searching for **e-DM** interactions with skipper-CCDs.
- **protoSENSEI** at the **surface** and **MINOS** produced first physics.
- First **scientific grade skipper-CCD** achieved.
- New limit with MINOS data for **mCP**. Best constraints around **100 MeV**
- Best constraints on **DM-e-** scattering for light mediator (**1-1000 MeV)** and heavy mediator (**1-10 MeV)**
- **Absorption** and **Migdal** limits coming

- **Production** of full **100 g** detector fully funded
- **2nd** science run at **SNOLAB** with **40 g** starting soon
- **generations** of **skipper-CCD** experiments foreseen for cosmic DM searches in the next ~ 7 years
- **New efforts** to build particle **trackers** at **beams** for **mCPs**

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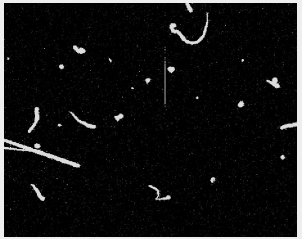
- Combined datasets: ~70 g-days per electron channel with cuts
- Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

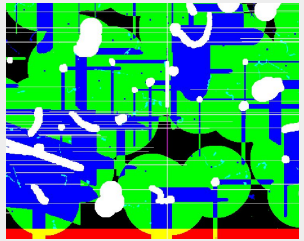
- Signal model: expected DM events per electron channel with QEdark, PhystatDM (arxiv:2105.00599f) and ionization model (arxiv:2004.10709)
- Split each electron channel into bins based on geometry
- Effective exposure with Monte Carlo given masks and charge diffusion
- Calculate expected coincidence background in each bin given measured 1e- density
- Limit: combined likelihood over all bins to set 90% C.L. upper limits

Quality cuts

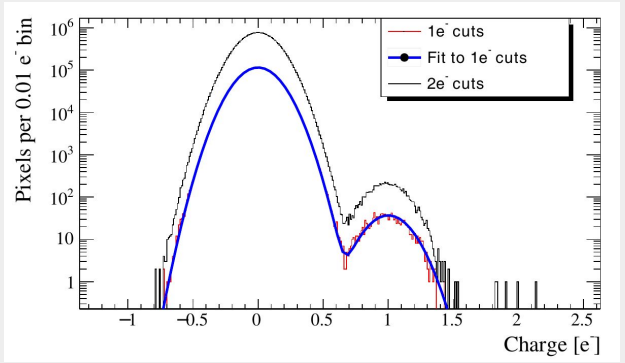
N_e / Cuts	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	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	



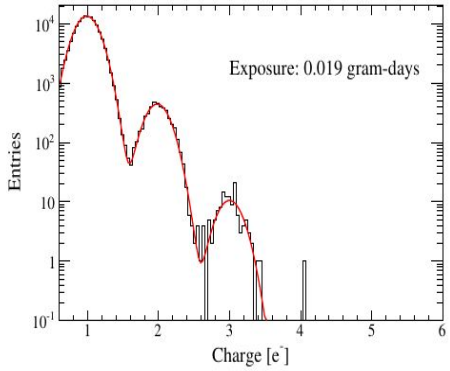
Example image



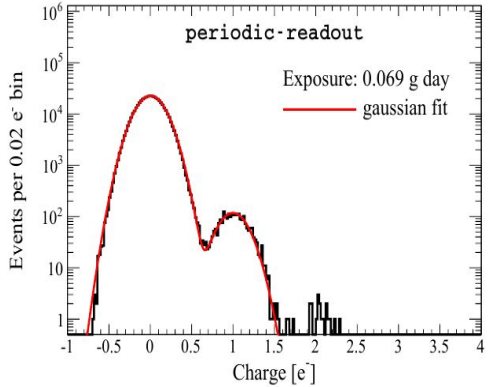
Masking



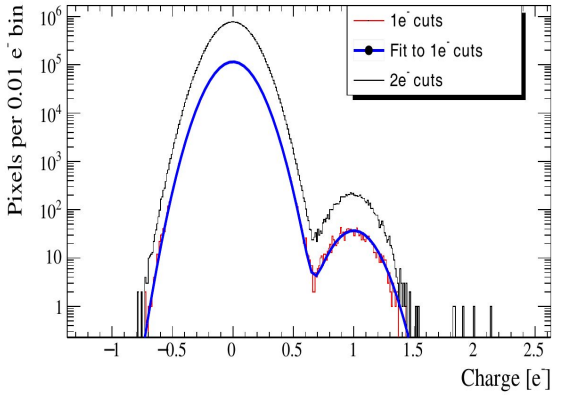
Summary: from prototype to science grade



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



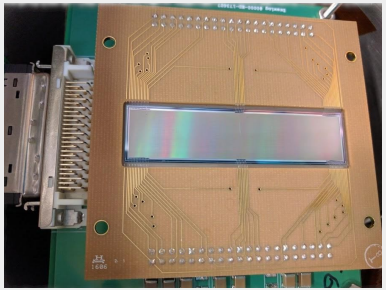
Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**



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

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:

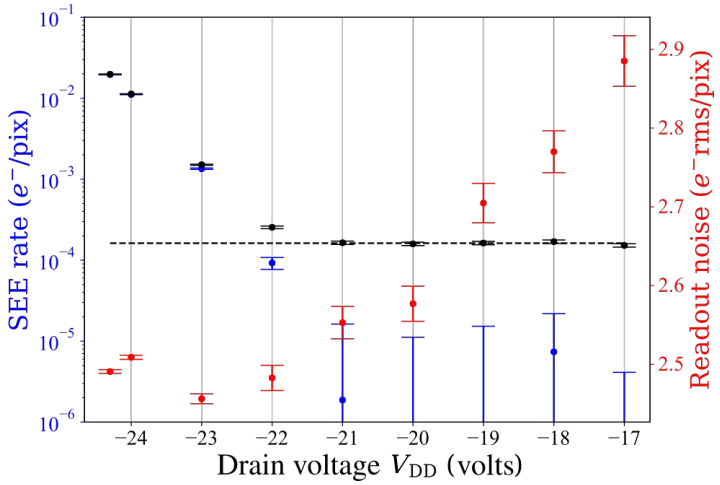
· System integration done at Fermilab
· Custom cold electronics
· Firmware and image processing software
· Optimization of operation parameters

Background sources: detector

Exposure dependent
- Dark current (10^{-5} e^-/pix/day at 135 K)
- Amplifier light (10^{-1} to 10^{-5} e^-/pix/day)

Exposure independent
- Spurious charge (10^{-2} to 10^{-5} e^-/pix/image)

Single electron rate reduced by optimizing operation parameters
- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure



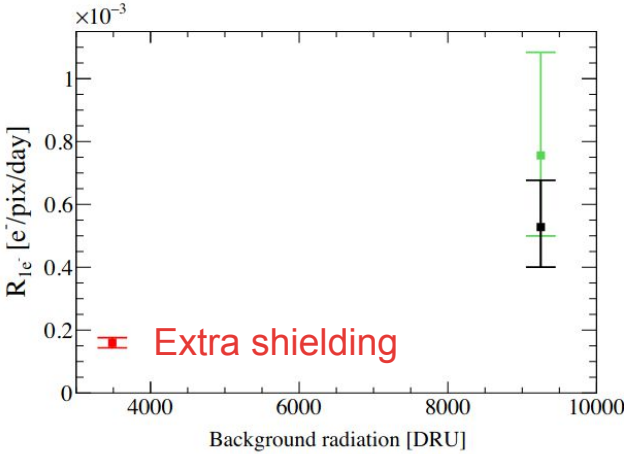
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Background sources: environment

High-energy:
- Air shower muons
- Nuclear decays
- x/ɣ-rays

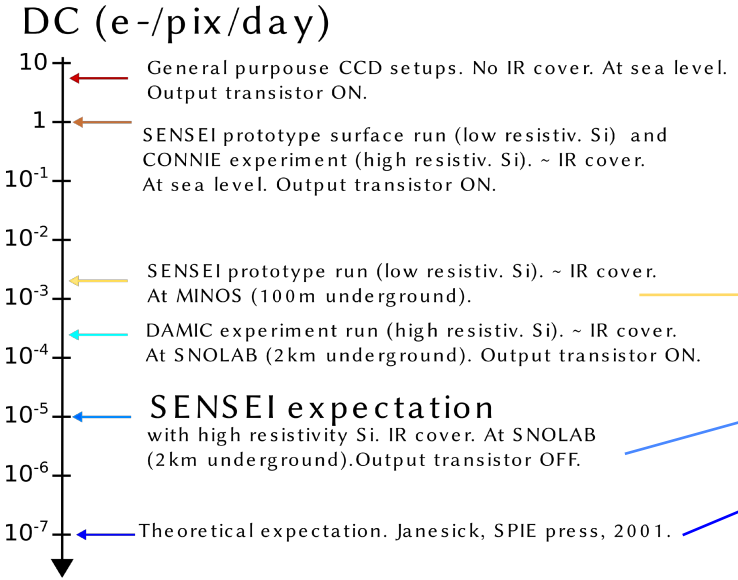
Low-energy:
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency

Environmental background is reduced with shielding, and removed from data with quality cuts



The SENSEI Collaboration - Phys. Rev. Lett. 125, 171802 (2020)

Background goal

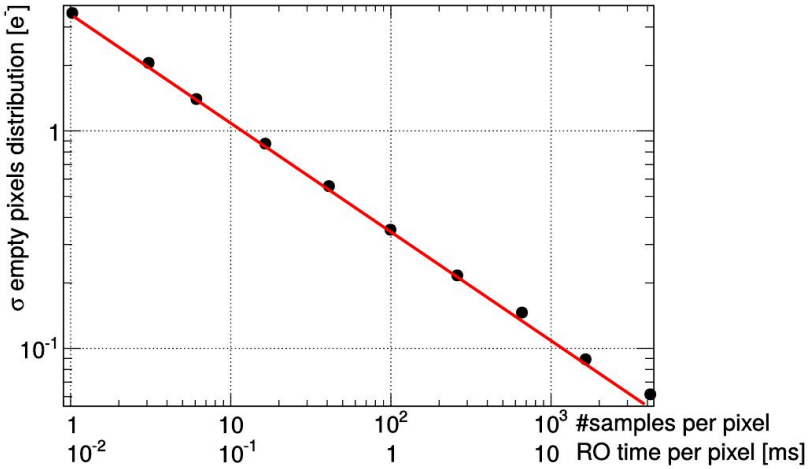


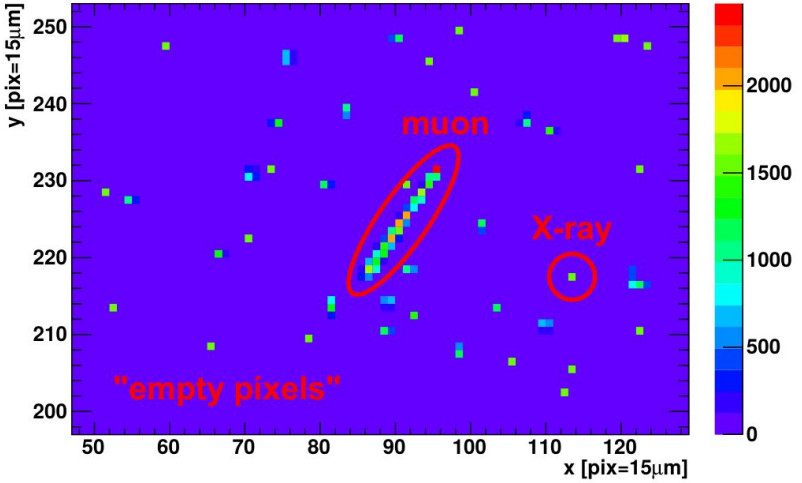
Dark Current $[e^{-}pix^{-1}day^{-1}]$	$\geq 1e^{-}$ [pix]	$\geq 2e^{-}$ [pix]	$\geq 3e^{-}$ [pix]
10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

Background estimations for 1 year and 100 g.

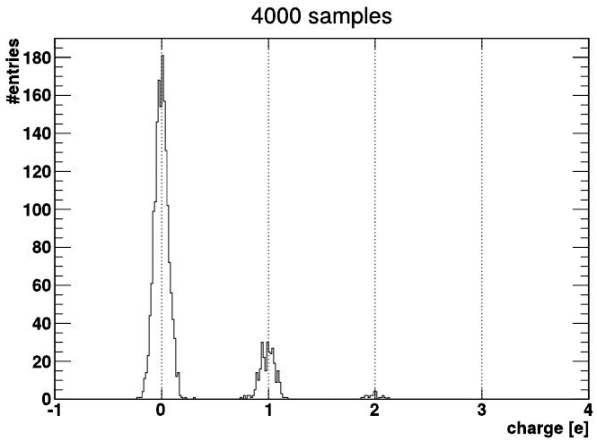
Blue: discovery channel (background free)
Red: modulation or limits

Skipper-CCD read-out noise

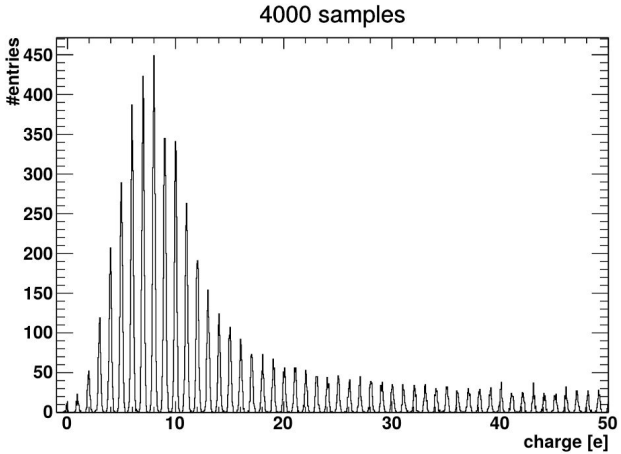




Skipper-CCD resolution



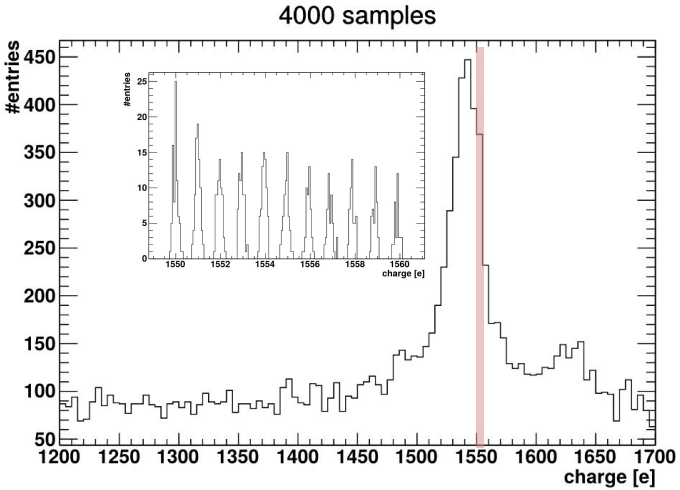
(Almost) Empty CCD



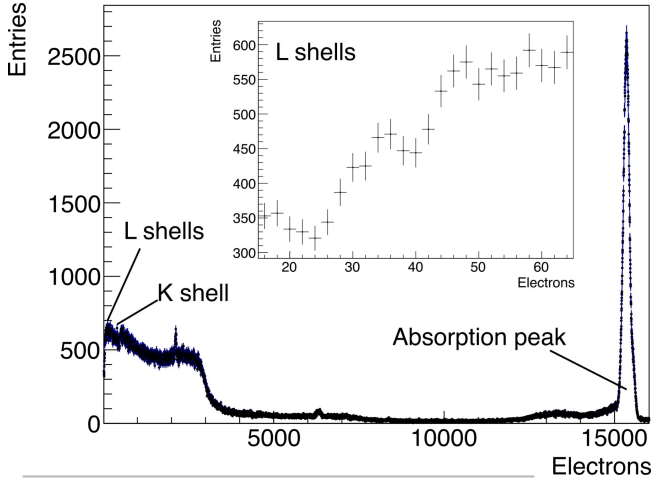
Front-illuminated CCD

Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511



Charge per event for 55Fe x-ray source



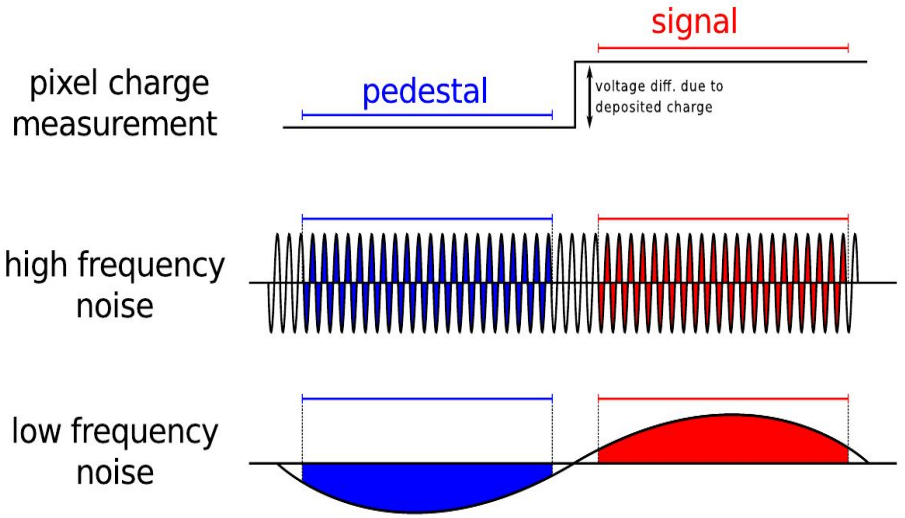
Compton scattering spectrum in Silicon with 241Am γ-ray source

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**...

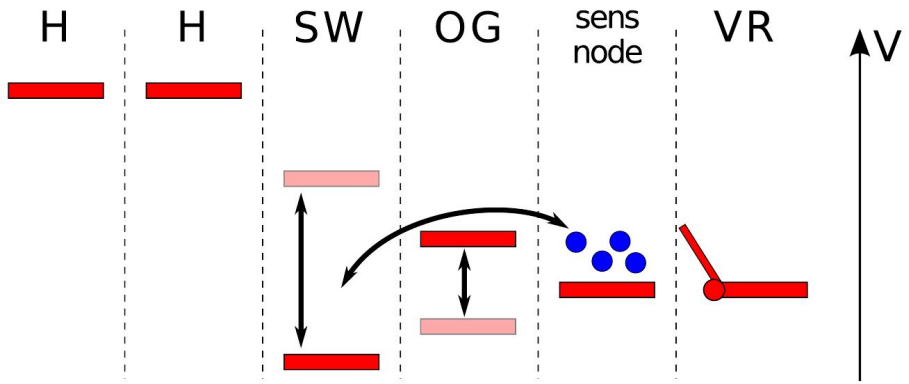


Skipper CCD read-out

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

Pixel value = **average** of all samples

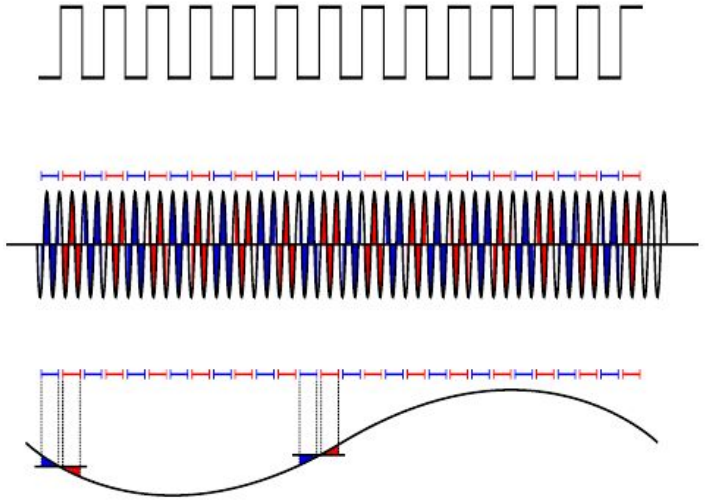
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



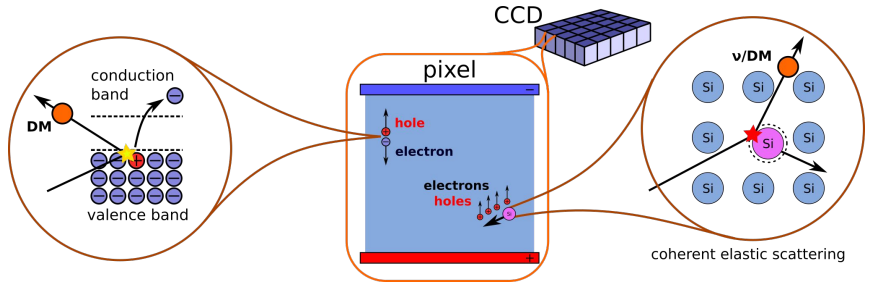
Skipper CCD read-out

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

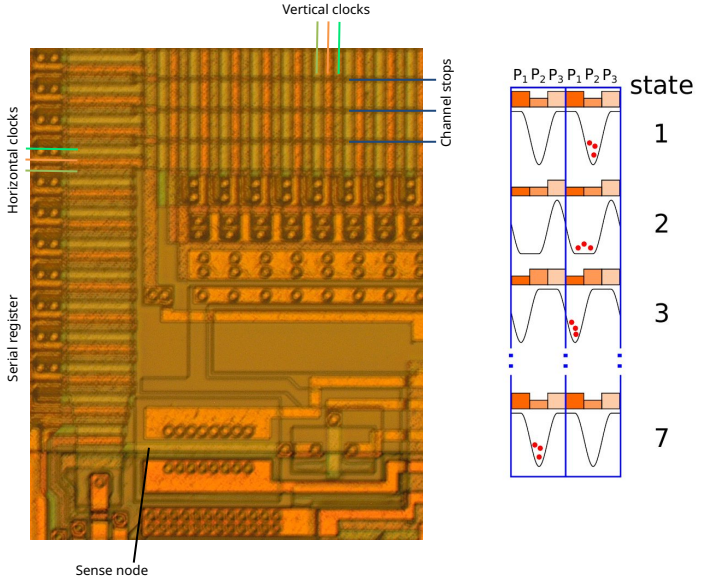


Charge-coupled devices (CCD)

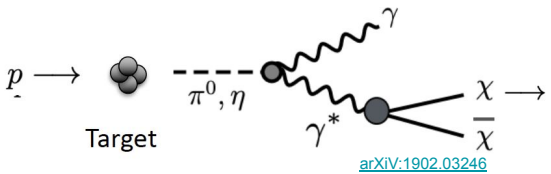


DM-electron scattering

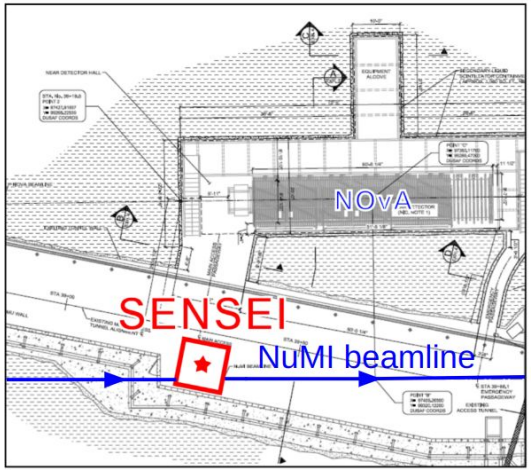
DM-Nucleus scattering



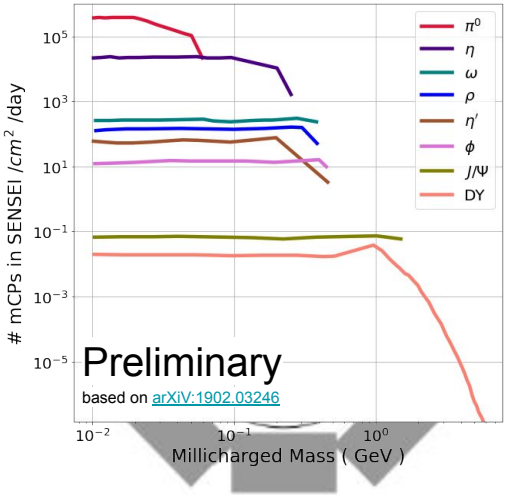
Proton collisions w/ fixed target can produce mCPs collinear w/ NuMI beamline:



arXiV:1902.03246



Using production rates accepted by SENSEI@MINOS…

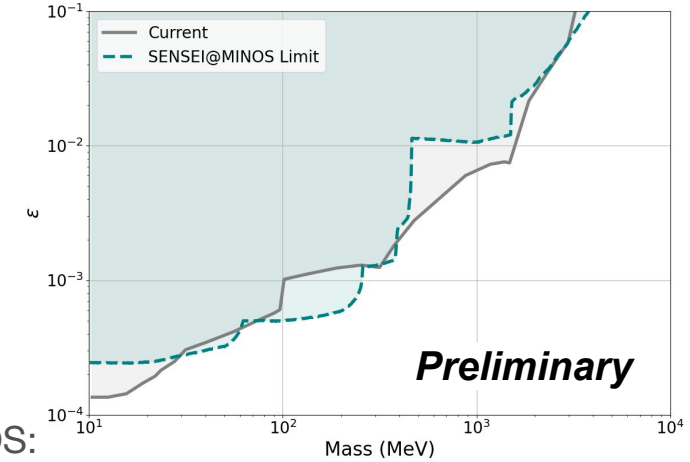


… and data from SENSEI@MINOS:

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
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 $6e^-$ (PRELIMINARY)

World-leading limits around 100 MeV:



Significant potential for future mCP searches with CCDs!