Searching for sub-GeV dark matter with SENSEI

A. M. Botti* for the SENSEI† collaboration

ICHEP 2022

July 6-13, 2022

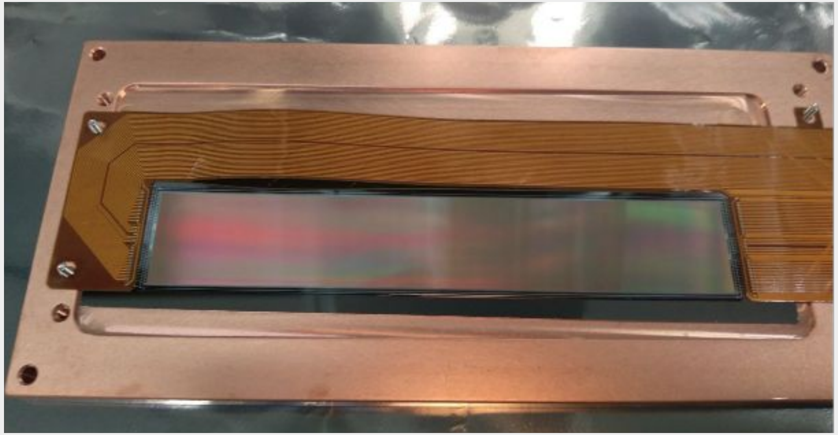


Image: SENSEI sensor

* Fermi National Accelerator Laboratory · abotti@fnal.gov
† Sub-Electron-Noise Skipper-CCD Experimental Instrument · https://sensei-skipper.github.iowww

The SENSEI Collaboration

L. Barak, I. M. Bloch, E. Etzion, A. Orly, T. Volansky

A. M. Botti, G. Cancelo, F. Chierchie[3], M. Crisler, A. Drlica-Wagner[2], J. Estrada, G. Fernandez Moroni[2], M. Sofo Haro[4], L. Stefanazzi, S. Uemura, J. Tiffenberg

M. Cababie[1], D. Rodrigues[1]

L. Chaplinsky, R. Essig, D. Gift, S. Munagavalasa, A. Singal

T.-T. Yu

I. Lawson, L. Steffon, S. Scorza NEW!

[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

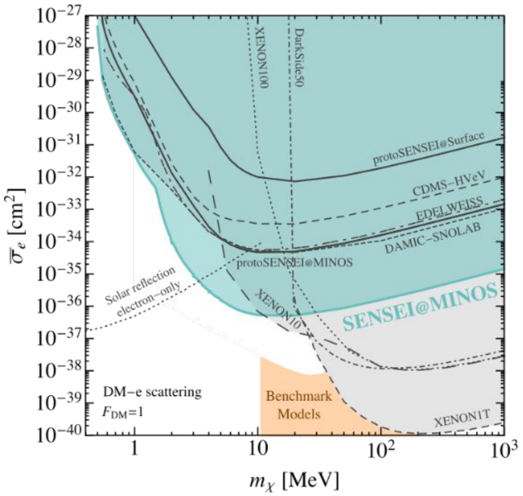
Sub-**E**lectron-**N**oise **S**kipper-CCD **E**xperimental **I**nstrument

New generation Charge Couple Devices **(CCD)**
LBNL MicroSystems Lab Energy threshold **~ 1.1 eV**
(Si bandgap) and readout noise **~ 0.1 e$^-$**

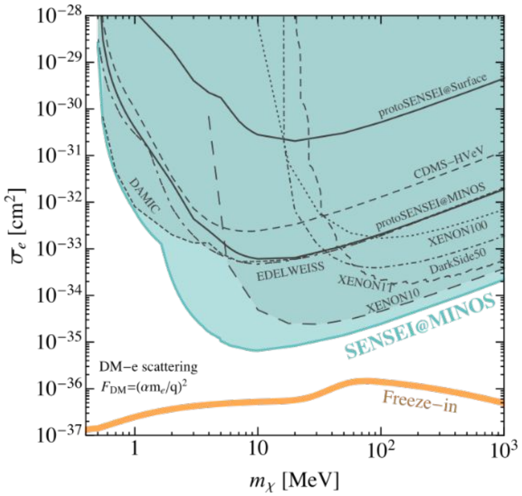
Main goals

- 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)

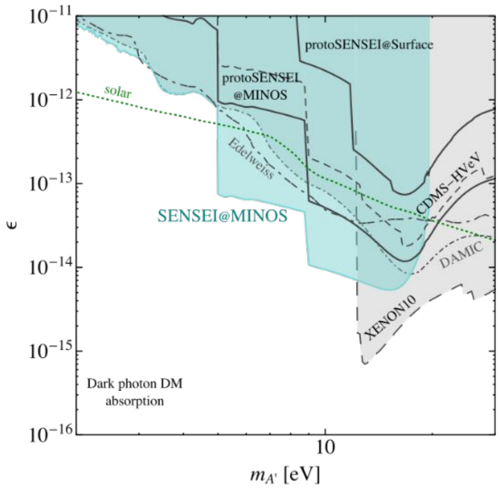
Latest results (2020)



Heavy mediator
e⁻ scattering



Light mediator
e⁻ scattering

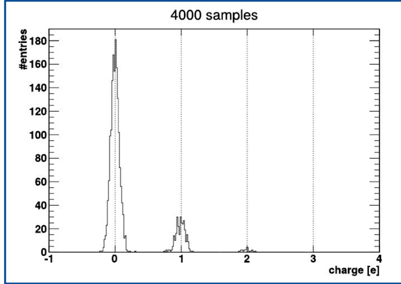


Absorption

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

The SENSEI Experiment

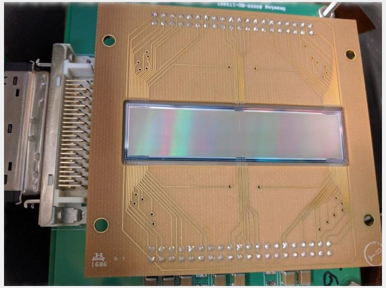
2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



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

First Skipper-CCD prototypes

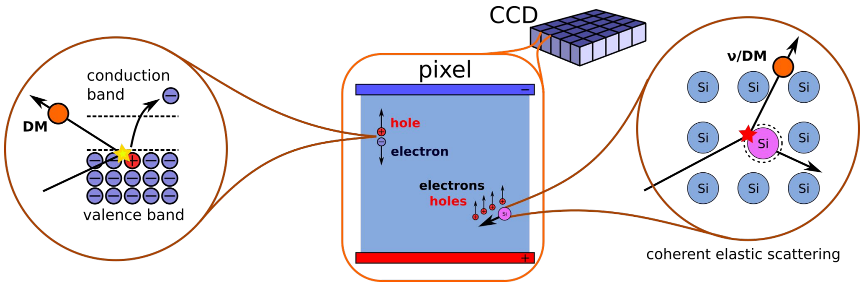
- Prototype designed at **LBNL MSL**
- 200 & 250 µm thick, 15 µm pixel size
- Two sizes 4k × 1k (0.5gr) & 1.2k × 0.7k pixels
- Parasitic run, optic coating and Si resistivity ~10kΩ
- 4 amplifiers per CCD, three different RO stage designs



Instrument:

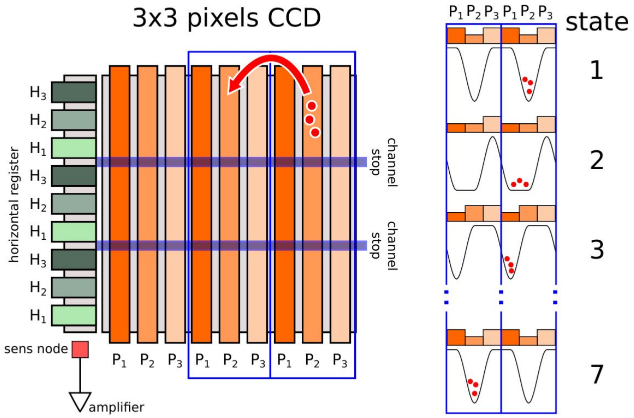
- System integration done at Fermilab
- Custom cold electronics
- Firmware and image processing software
- Optimization of operation parameters

Charge-coupled devices (CCD)



DM-electron scattering

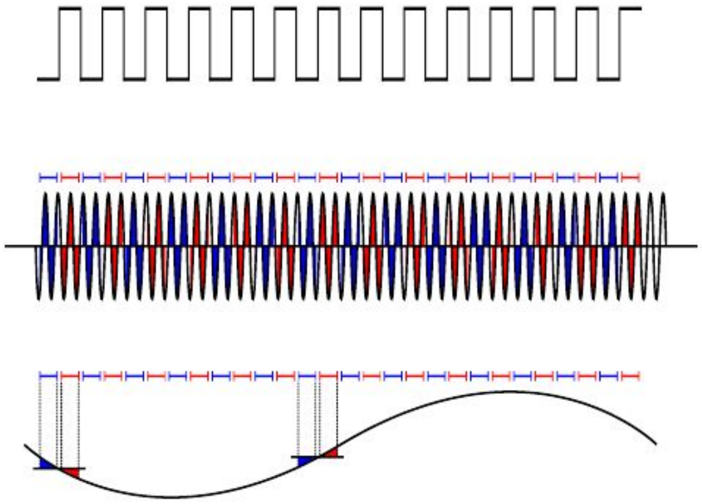
DM-Nucleus scattering



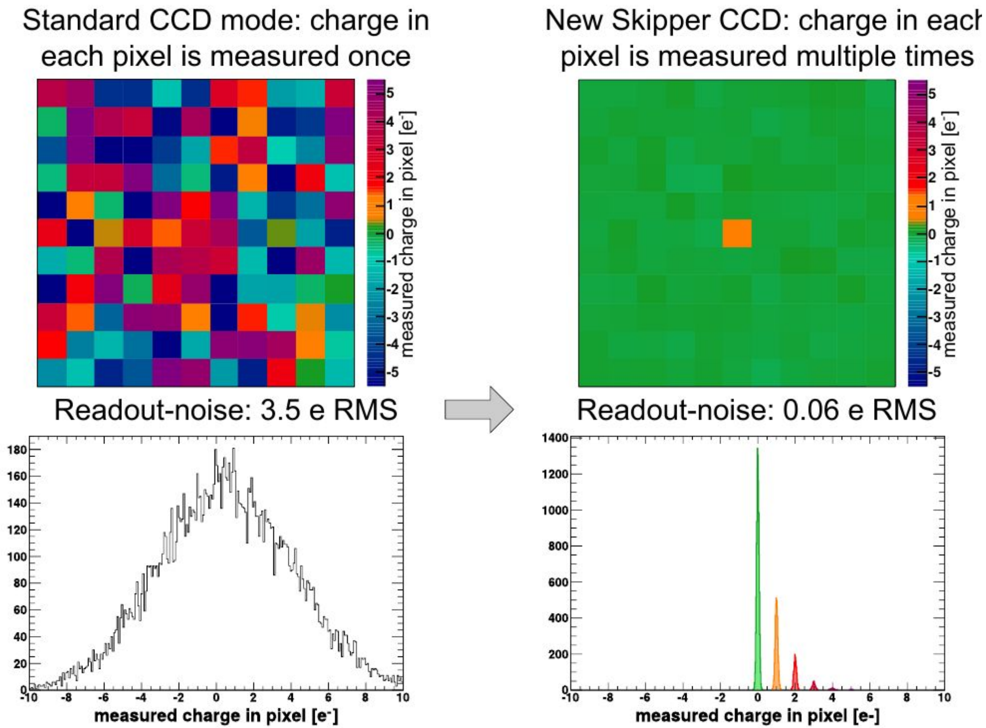
Skipper CCD read-out

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 is reduced



Skipper-CCD read-out noise



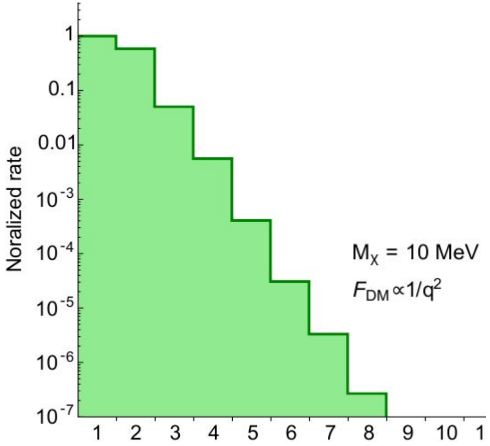
Skipper-CCDs for dark matter

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...**

Expected spectrum from benchmark models (e⁻ recoil)



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

Background sources: detector

Exposure independent

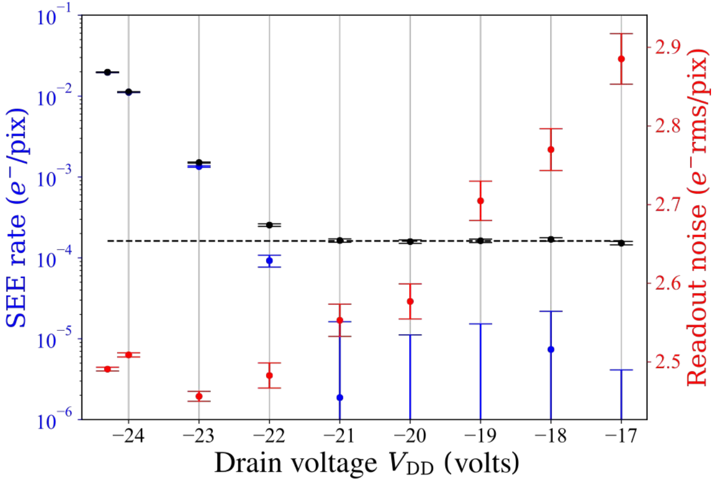
- Spurious charge (10^{-2} to 10^{-5} e^-/pix/image)

Exposure dependent

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

Single electron rate reduced by optimizing operation parameters

- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure



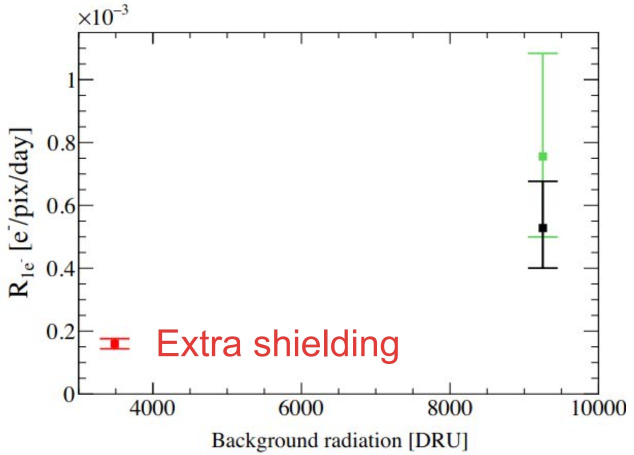
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Background sources: environment

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

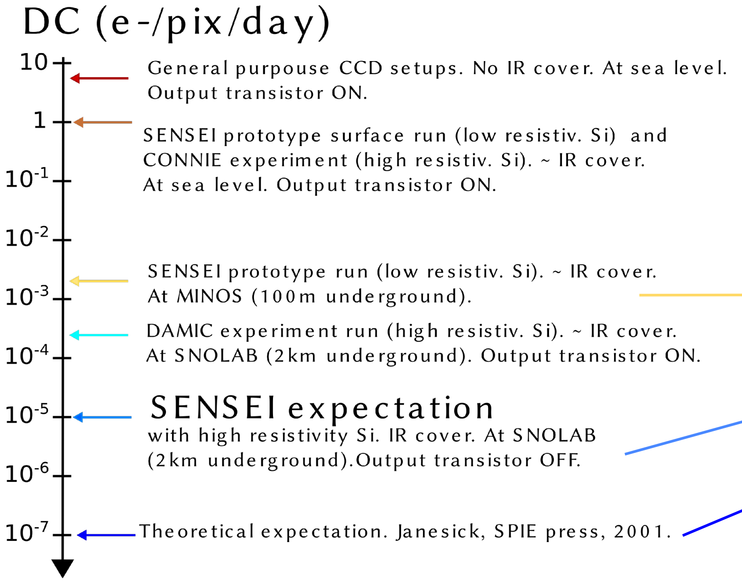
Low-energy:
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency

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

Latest SENSEI published result: **1.6×10^{-4} e-/pix/day**

The SENSEI Experiment

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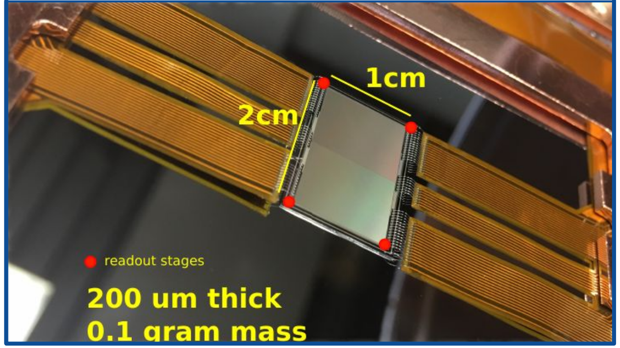

The SENSEI Collaboration
Physical Review Letters 121.6 (2018): 061803.

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

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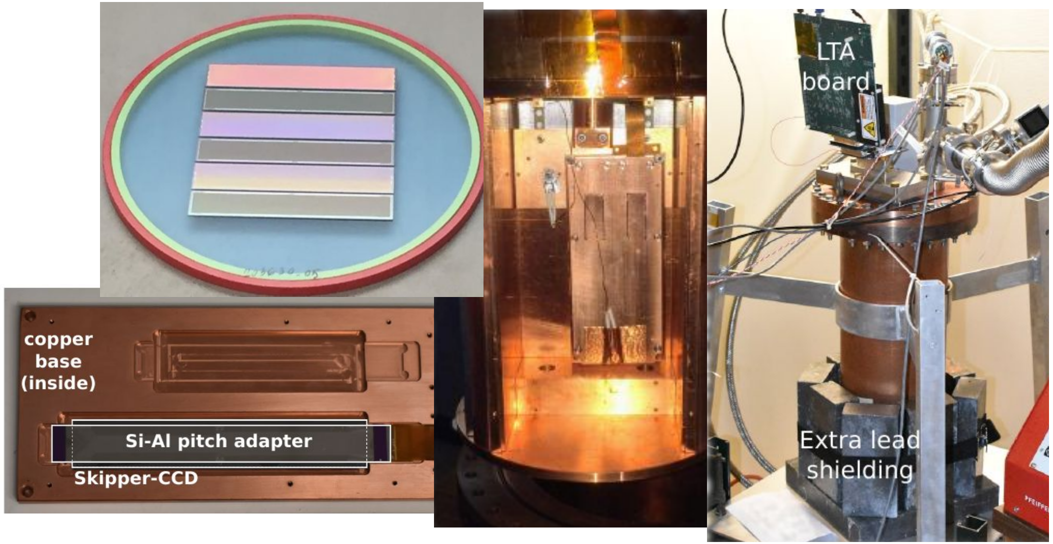
The SENSEI Collaboration Phys. Rev. Lett. 125, 171802 (2020)

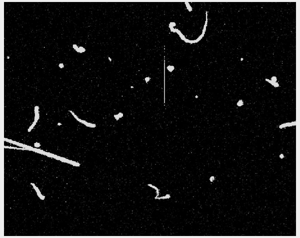
New device @ MINOS

- 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

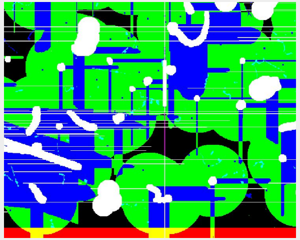


Quality cuts

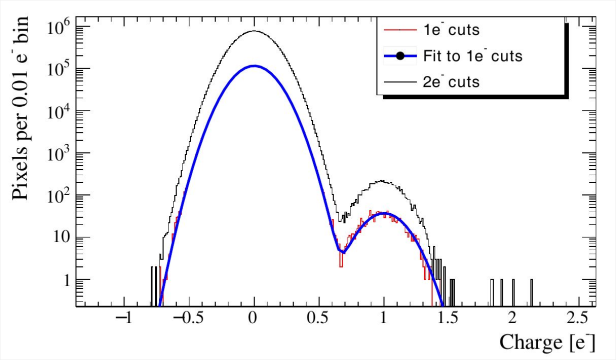
Cuts \ N_e	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301	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 [g-day]$^{-1}$	525.2$^{(*)}$		4.449		0.255		0.253	



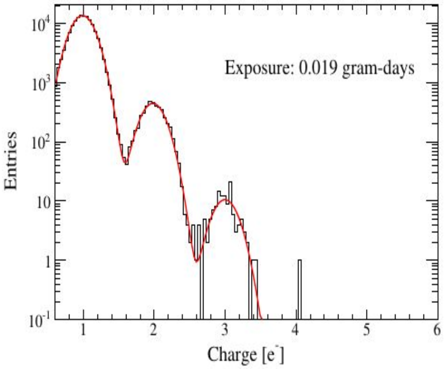
Example image



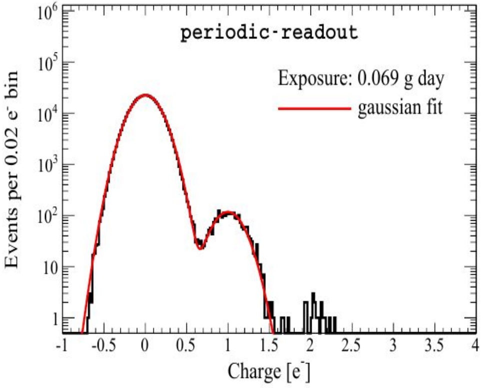
Masking



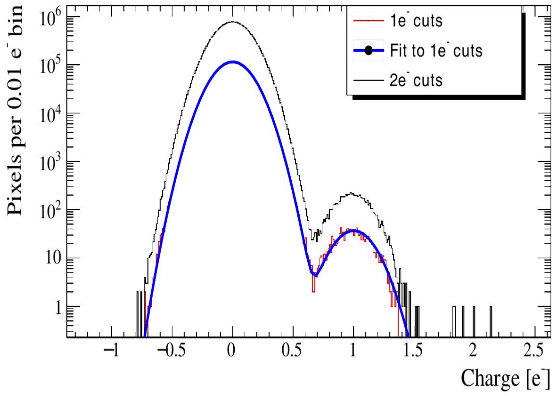
Summary: from prototype to science grade



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

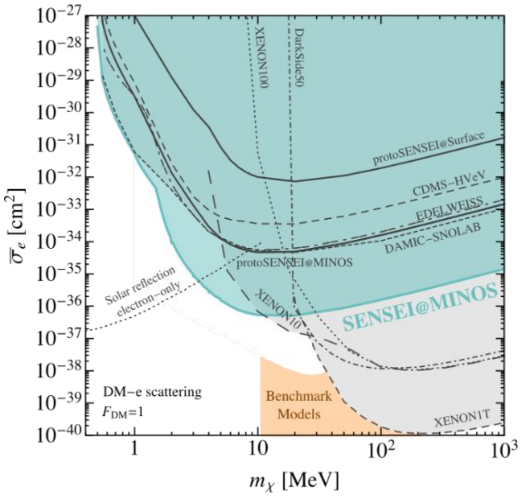


Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**



Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
SEE ~ **1.6x10^{-4} e-/pix/day**

Latest results (2020)



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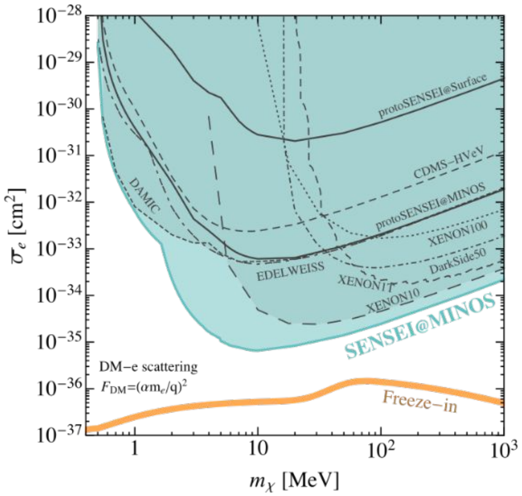
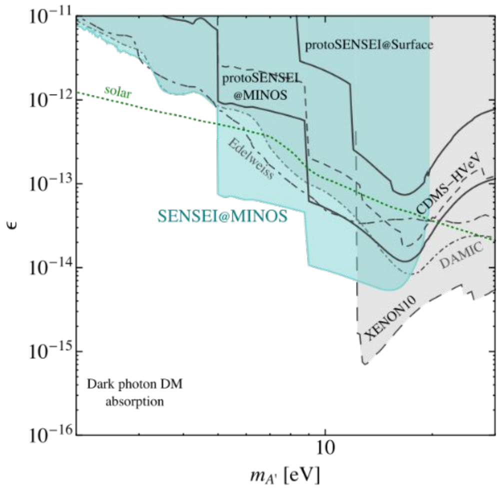


Light mediator
e⁻ scattering



Absorption

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

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)***

Contact us if anything else is needed

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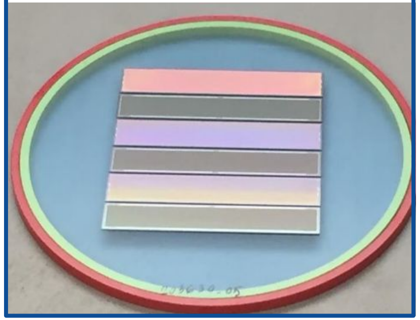


SENSEI @ SNOLAB

- Science-grade skipper-CCDs achieved
- Packaging and electronics also achieved
- Phase 1 system @ SNOLAB
- Vessel deployed at SNOLAB (during the pandemic!!!)
- First 10 CCDs deployed

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

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

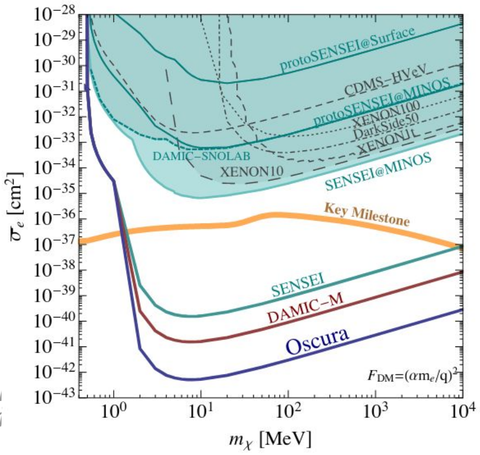
➔ **10000** dru (MINOS standard shield): proto-SENSEI
➔ **3000** dru (MINOS extra shield): first science grade skipper
➔ **5 (ultimate goal)** dru (SNOLAB): SENSEI 100 g

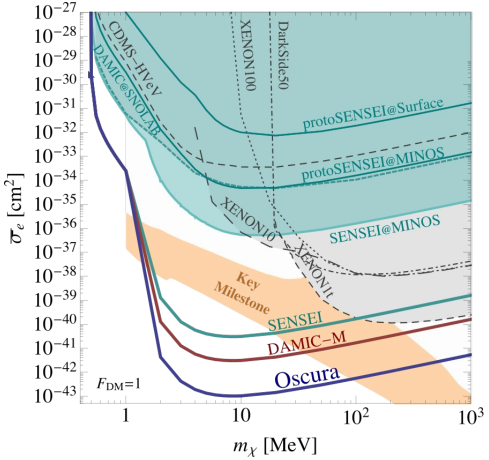
Perspectives: beyond SENSEI

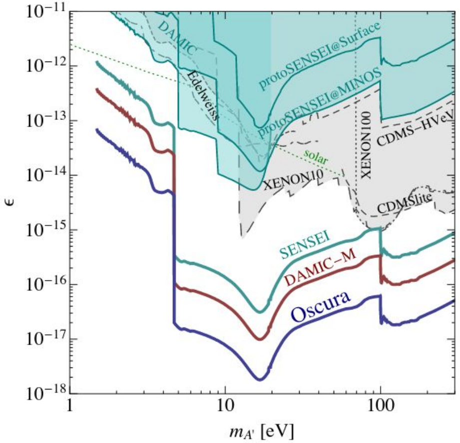
SENSEI 100g — 2021

DAMIC-M 1kg — 2024

OSCURA 10kg — 2027







The Oscura Experime
arXiv: 2202.1051

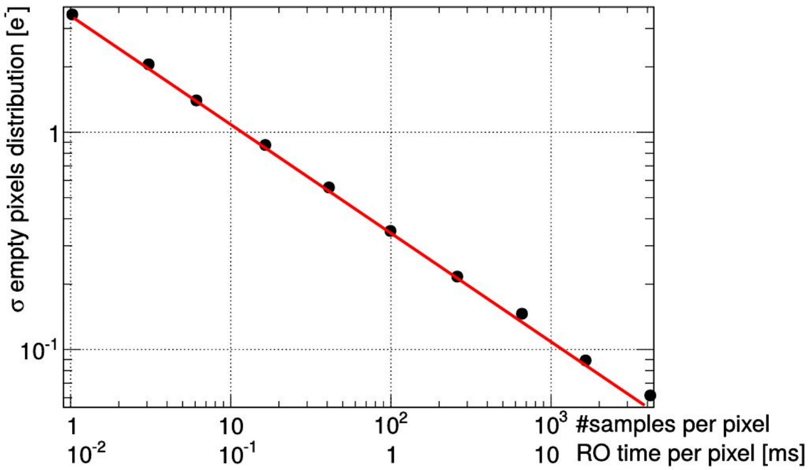
Summary

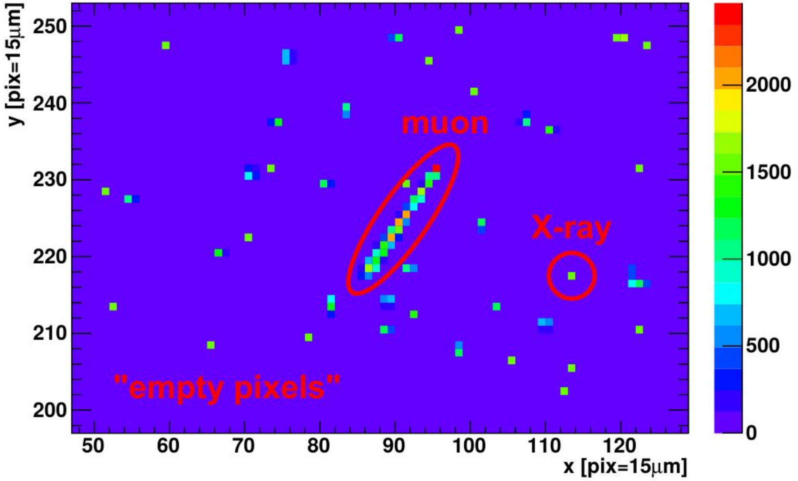
- **SENSEI**: first dedicated experiment searching for **e-DM** interactions.
- **protoSENSEI** at the **surface** and **MINOS** produced first physics.
- First **scientific grade skipper-CCD** achieved.
- Best constraints on **DM-e-** scattering for light mediator and heavy mediator, up to **10 MeV**.
- Best constraints for **DM absorption** on electrons for mass **5~12.8 eV**.

- **Production** of full **100 g** detector fully funded and ongoing.
- **Vessel** and **10 Skipper-CCDs** deployed at **SNOLAB during the pandemic** and taking data.
- **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 popular models
- **generations** of **skipper-CCD** experiments foreseen for DM searches in the next ~ 7 years

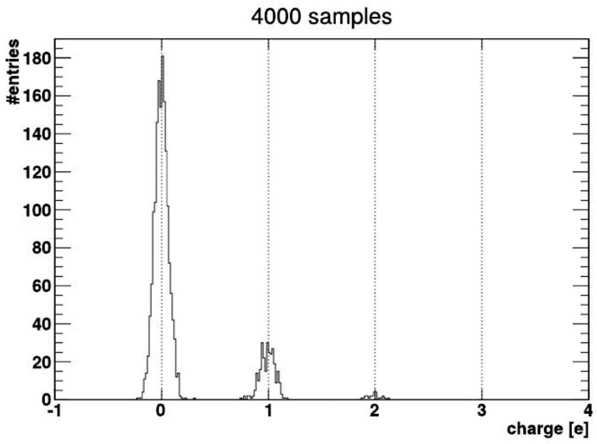
Backup slides

Skipper-CCD read-out noise

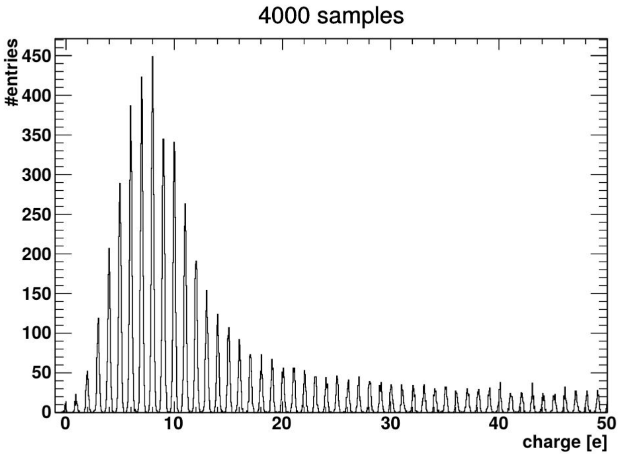




Skipper-CCD resolution



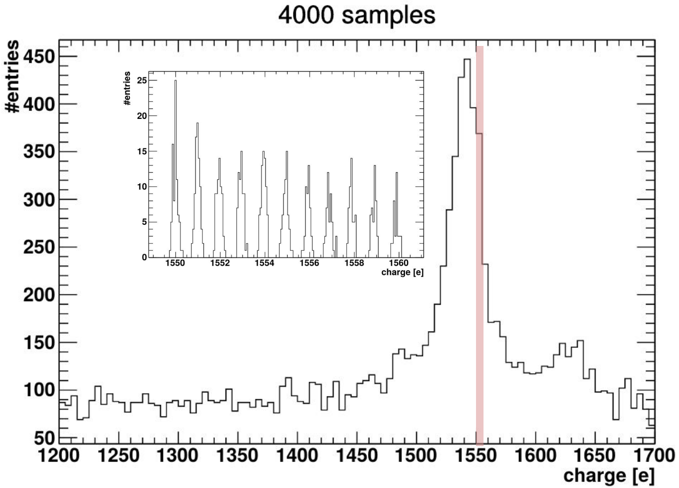
(Almost) Empty CCD



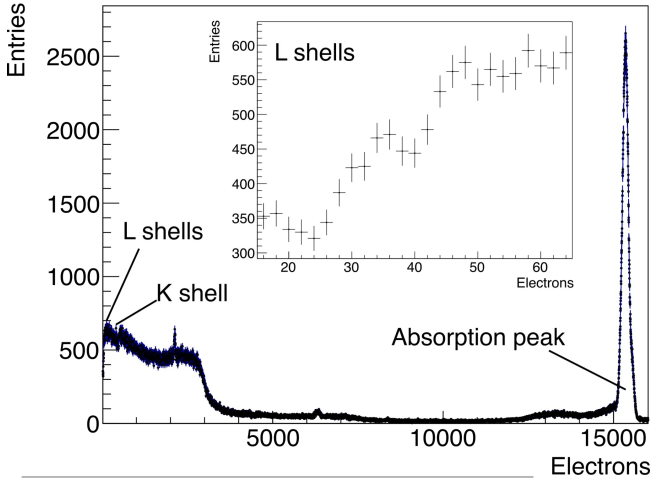
Front-illuminated CCD

Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511

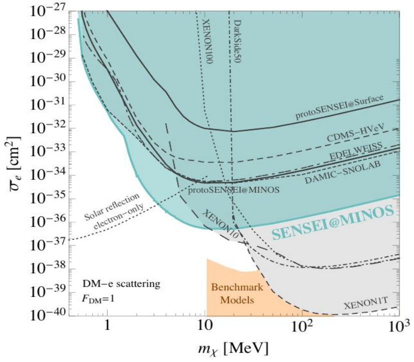


Charge per event for 55Fe x-ray source

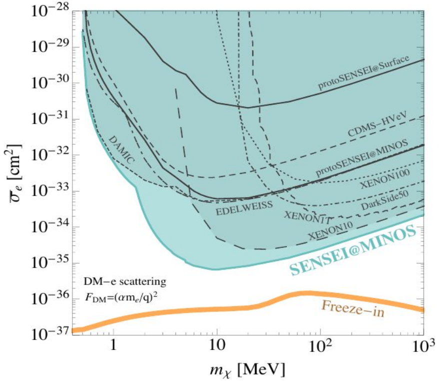


Compton scattering spectrum in Silicon with 241Am γ-ray source

Latest results



__Heavy__ mediator
__e__$^-$ scattering



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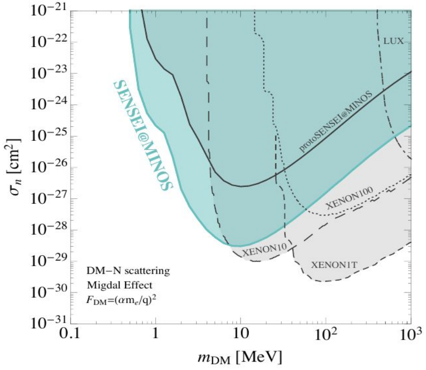

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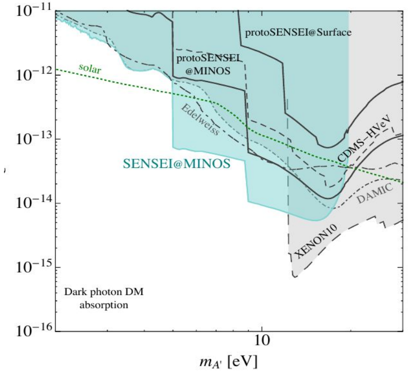

Absorption

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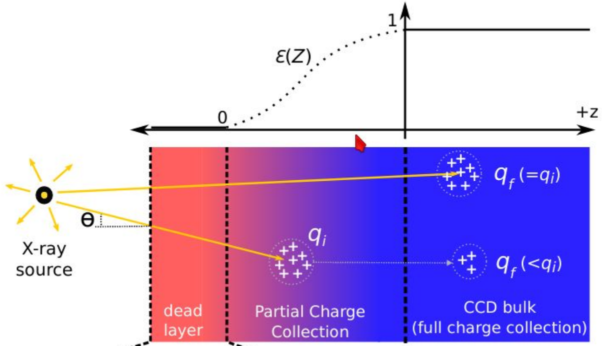
- Voltage configuration
- Amplifier off while not reading

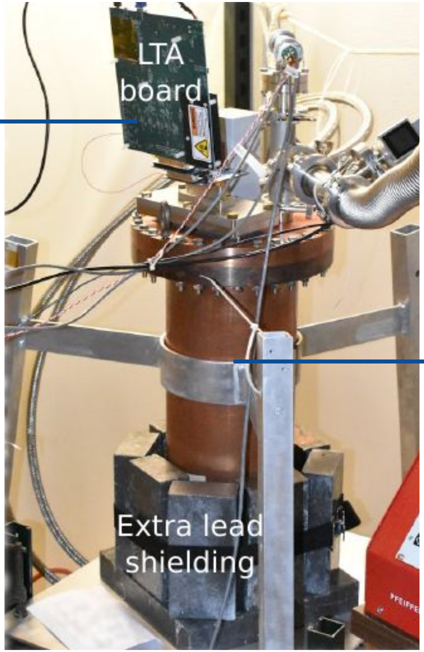


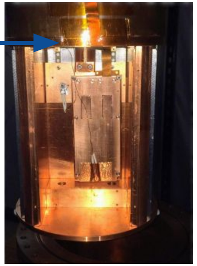
Unthinned CCD-A	2.2µm SiO_2	[0, ?] Si	~670µm Si
Thinned CCD-B	0.1 +0.04+0.02µm SiO_2+ZrO_2+In	[0, ?] Si	~200µm Si

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

Setup @ MINOS

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



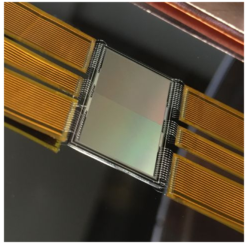


proto-SENSEI

R&D sensor:

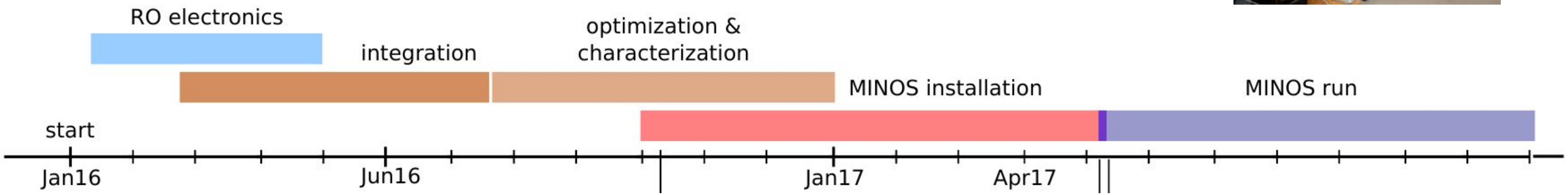
- **optimize** operation parameters
- develop **packaging** and **shielding**
- Characterize **background/noise**
- first physics **results**!

New package Commissioned at surface



Underground clean room

Deploy at MINOS + data taking



Proto-SENSEI runs

@ **surface**:

- Data from May 2017
- Sea level
- 3 mm copper shielding
- 18 images **continuous read**
- DC **1.14 e-/pixel/day**
- **0.019 gram-day** total exposure

@ **MINOS**:

- Data from 2018
- 230 m.w.e.
- **Cylindrical vacuum vessel** with 2” lead.
- Two readout modes (continuous & **periodic**)
- Single-electrons events **0.1~0.005 events/pix/day**
- **0.177 ~ 0.069 gram-day** total exposure

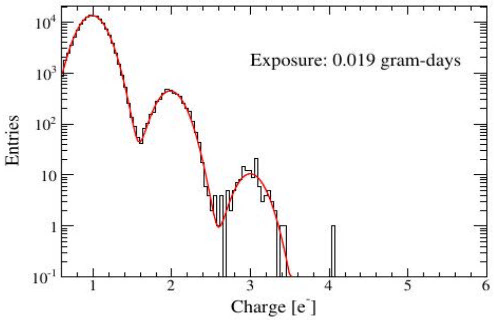
Device:

- 0.9 Mpix of 15 μm and 200 μm thick
- Active mass ~ 0.1 g
- 10 kΩ
- T ~ 130 K + vacuum
- 4 amplifiers
- 0.14 e- RO noise (800 samples)
- Operated with LTA board

Proto-SENSEI cuts

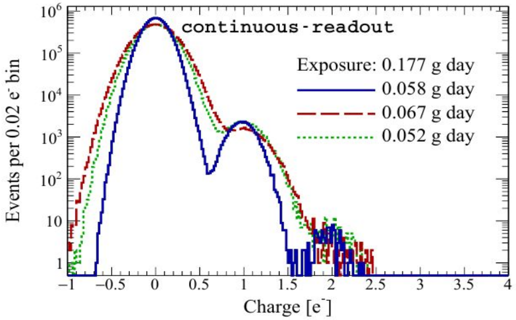
Cuts \ $N_{e,\min}$	1	2	3	4	5
1. DM within a single pixel	1	0.62	0.48	0.41	0.37
2. Nearest Neighbor	0.8	0.8	0.8	0.8	0.8
3. Noise	0.88	0.88	0.88	0.88	0.88
4. Bleeding	0.95	0.95	0.95	0.95	0.95
Total	0.67	0.41	0.32	0.27	0.24
Number of events	140,302	4,676	131	1	0

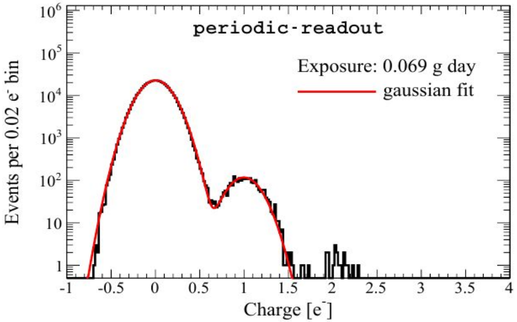
Surface run



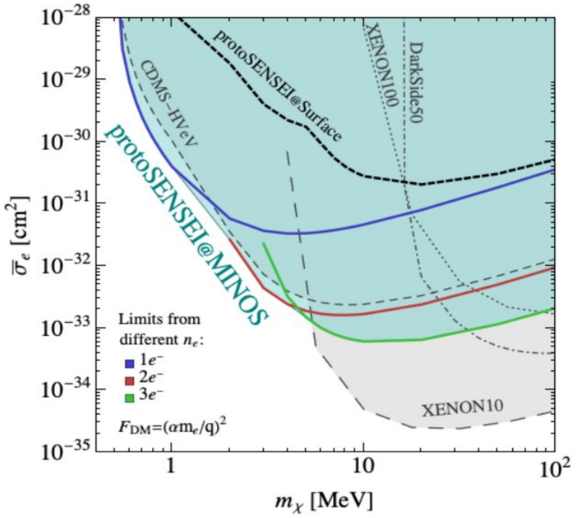
Cuts \ N_e	periodic			continuous		
	1	2	3	3	4	5
1. DM in single pixel	1	0.62	0.48	0.48	0.41	0.36
2. Nearest Neighbour	0.92			0.96		
3. Electronic Noise	1			~1		
4. Edge	0.92			0.88		
5. Bleeding	0.71			0.98		
6. Halo	0.80			0.99		
7. Cross-talk	0.99			~1		
8. Bad columns	0.80			0.94		
Total Efficiency	0.38	0.24	0.18	0.37	0.31	0.28
Eff. Expo. [g day]	0.069	0.043	0.033	0.085	0.073	0.064
Number of events	2353	21	0	0	0	0

MINOS run

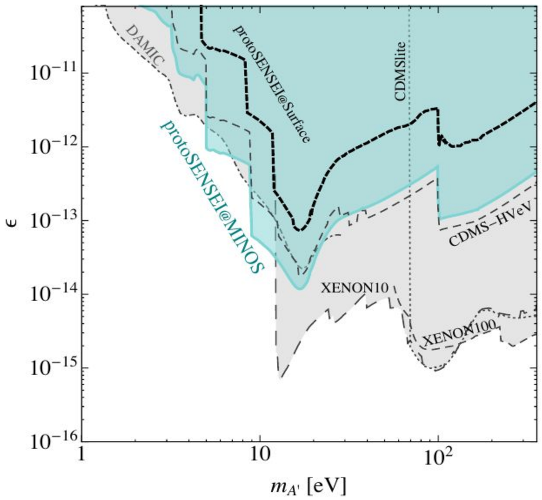




Proto-SENSEI results



***Ultralight** mediator*

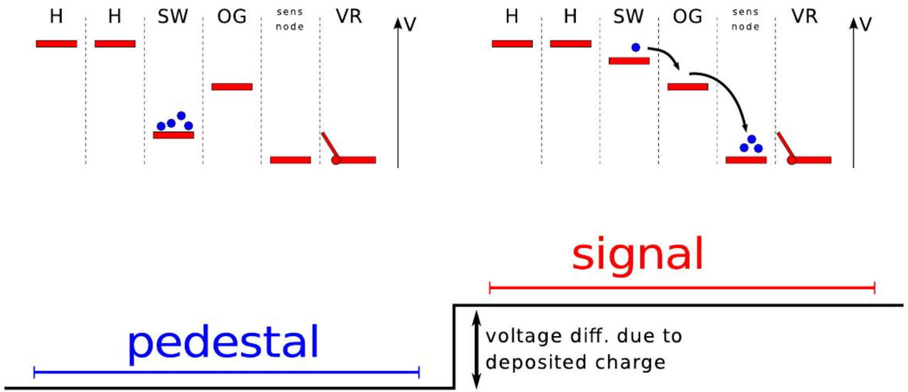


Absorption

CCD read-out

Charge estimation:

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

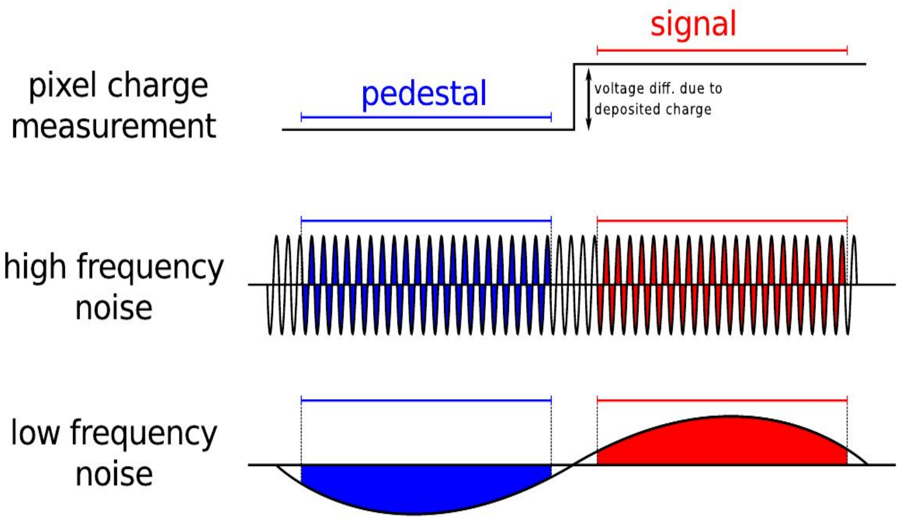


CCD read-out noise

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

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

But not **low frequency**…

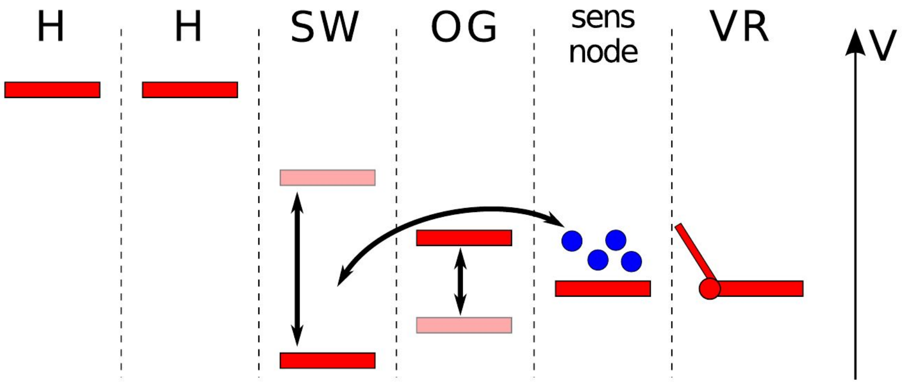


Skipper CCD read-out

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

Pixel value = **average** of all samples

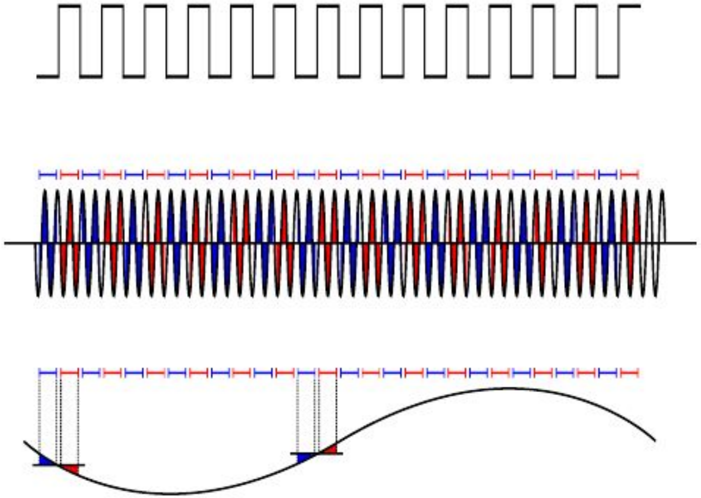
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)

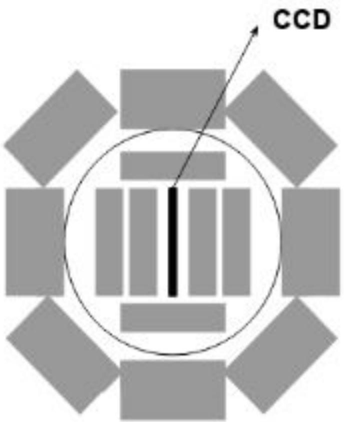


Skipper CCD read-out

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




CCD