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

A. M. Botti* for the SENSEI† collaboration

15th International Workshop on the Identification of Dark Matter 2024 · L'Aquila

July 10th, 2024

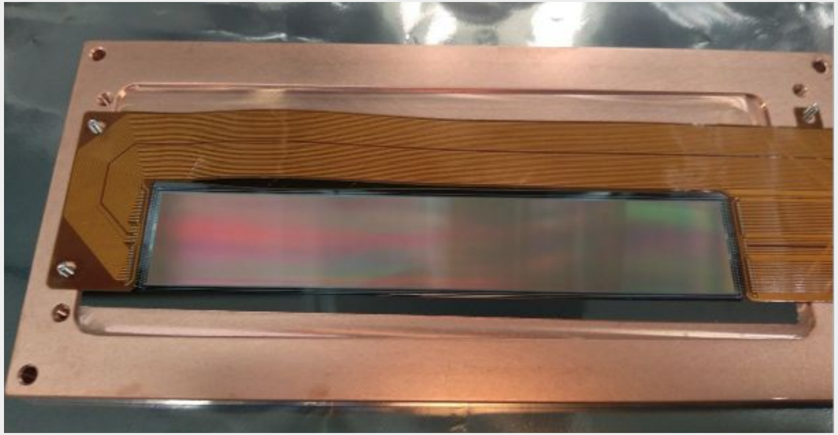
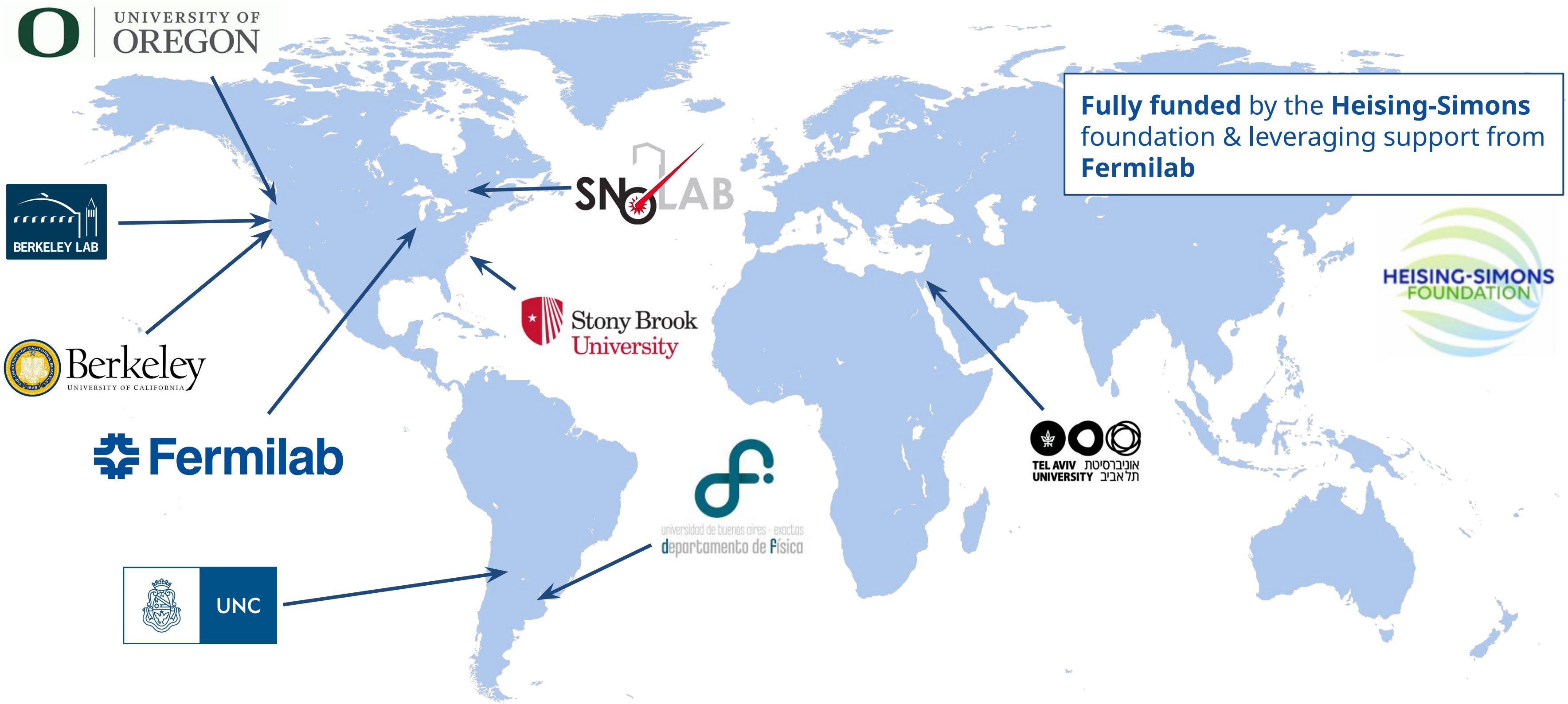


Image: SENSEI sensor

* Fermi National Accelerator Laboratory · abotti@fnal.gov

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

The Sensei Collaboration



Fully funded by the **Heising-Simons** foundation & leveraging 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$^-$**

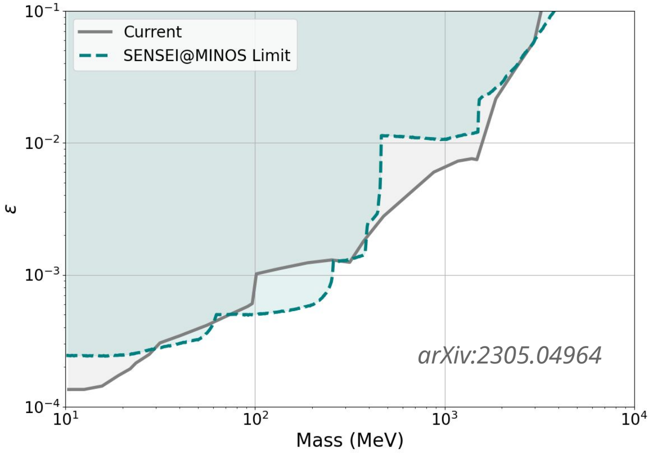
Main goals

- **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)

Current and Latest results

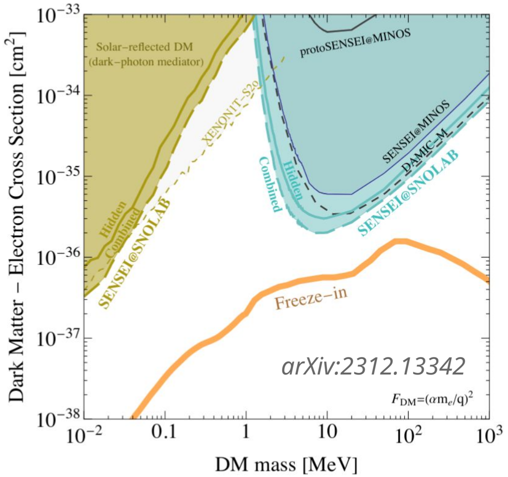
SENSEI@MINOS 2023

Milicharge



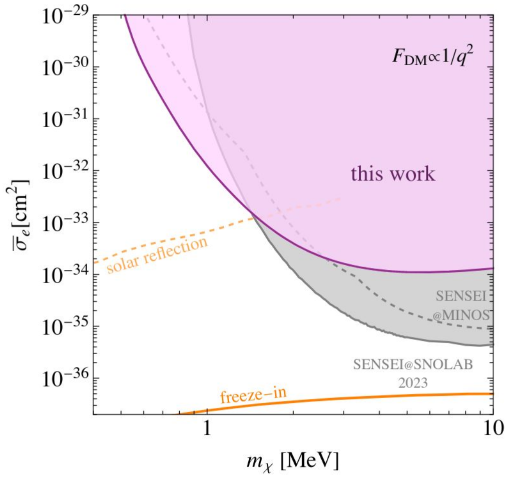
SENSEI@SNOLAB 2023

Light mediator



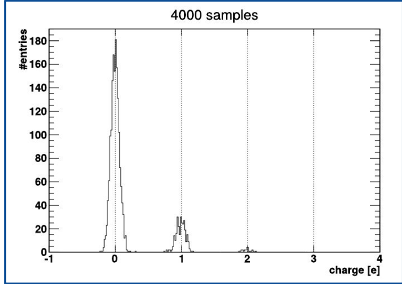
SENSEI@SNOLAB 2024

Light mediator



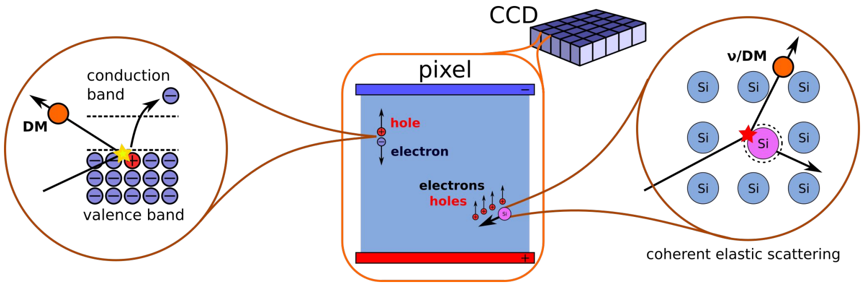
The SENSEI Experiment

‘17	‘18	‘19	‘20	‘21-’23	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 (12g) at **SNOLAB** (6000 m.w.e.) + 1st science run	**2nd** commissioning (**40g**) + science run



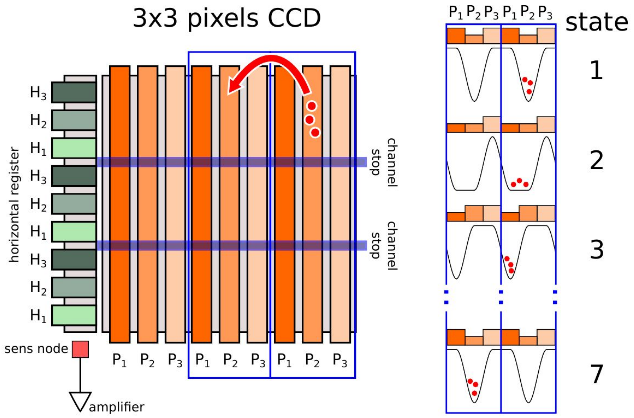
Tiffenberg, Javier, et al. Physical Review Letters 119.13 (2017): 131802.

Charge-coupled devices (CCD)

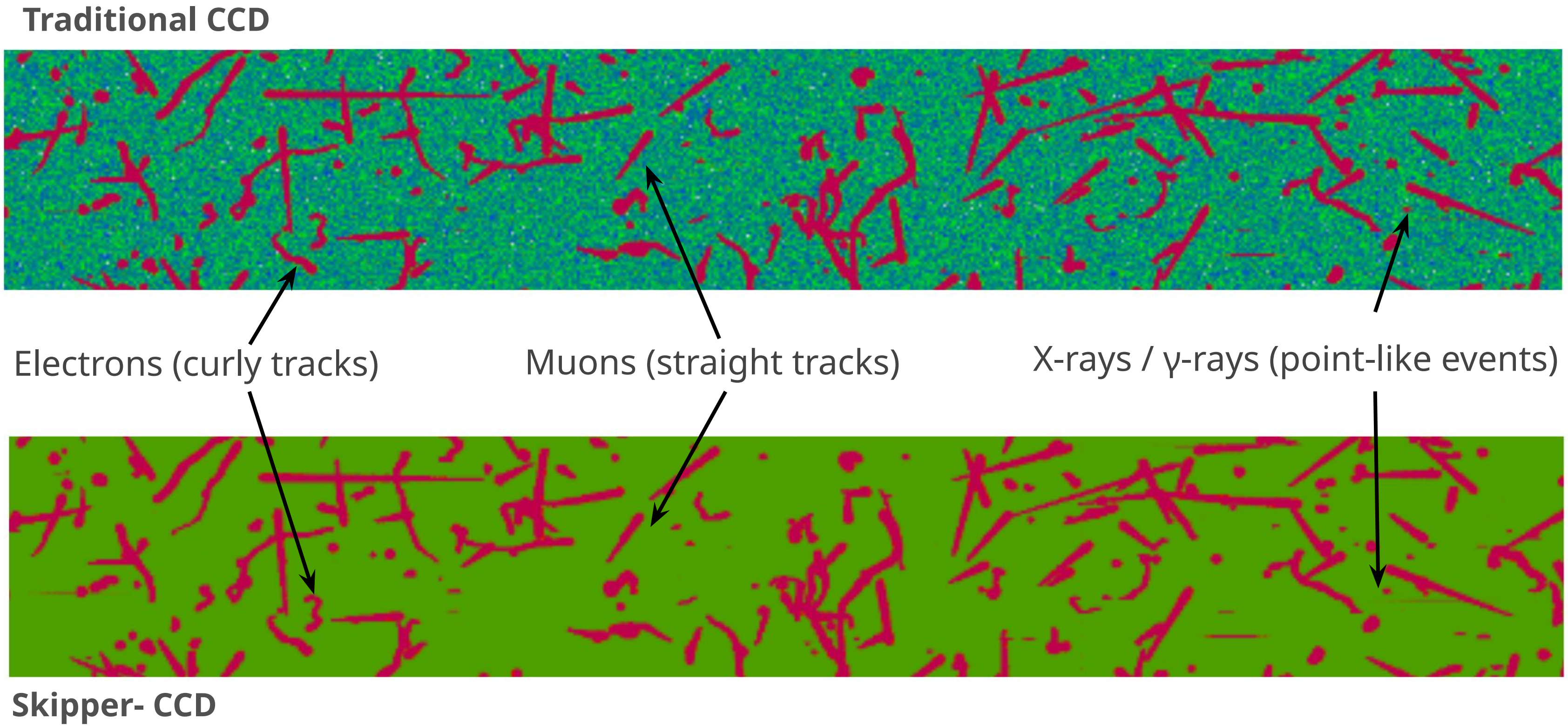


DM-electron scattering

DM-Nucleus scattering

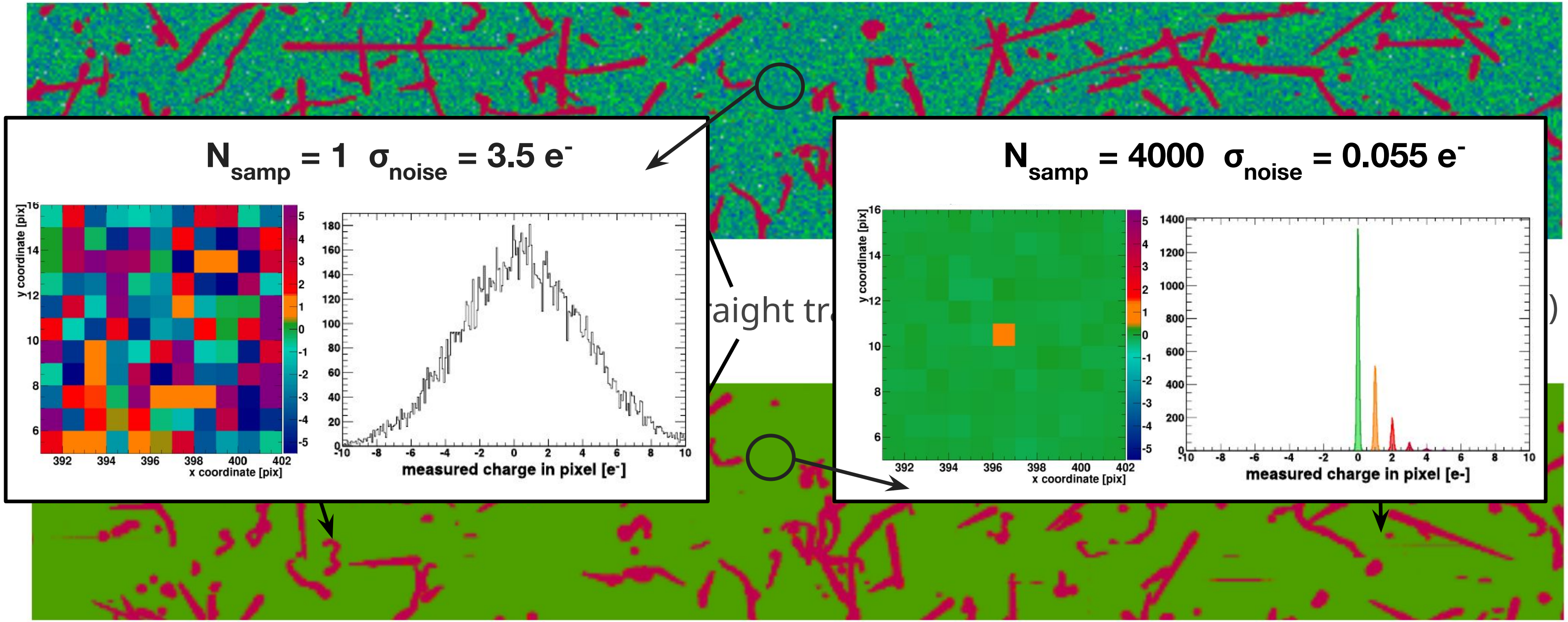


Example images (real data!)



Example images (real data!)

Traditional CCD



Skipper- CCD

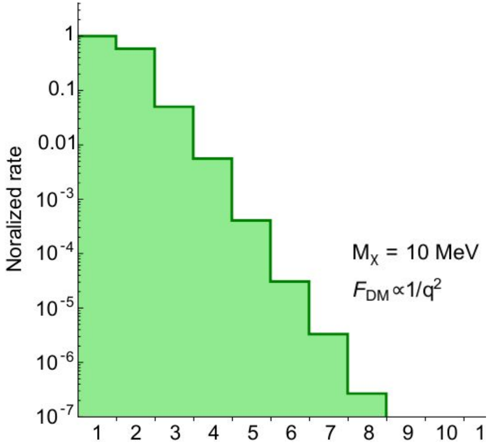
Skipper-CCDs for dark matter

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

The sensei Experiment

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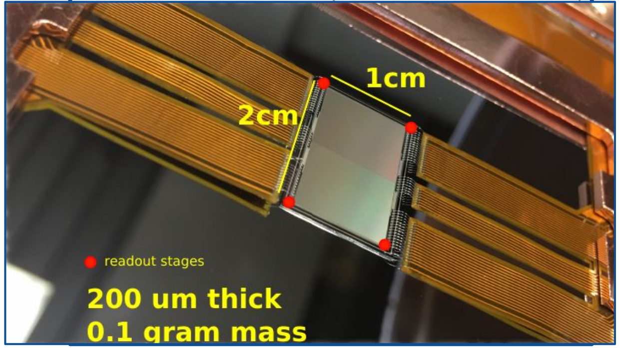

The SENSEI Collaboration
Physical Review Letters 121.6 (2018): 061803.

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

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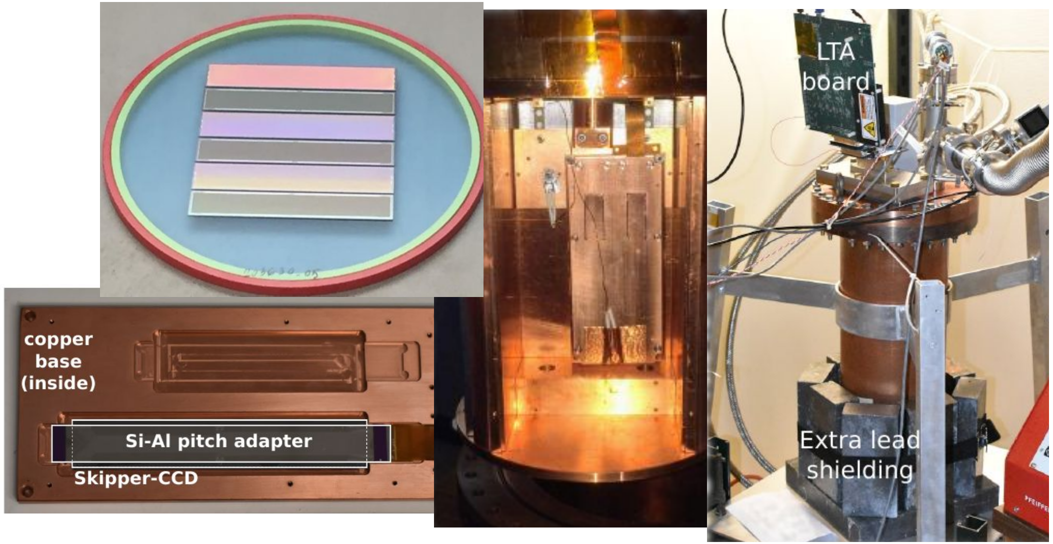
The SENSEI Collaboration Phys. Rev. Lett. 125, 171802 (2020)

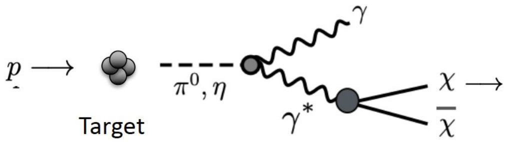
2020 New device @ MINOS

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

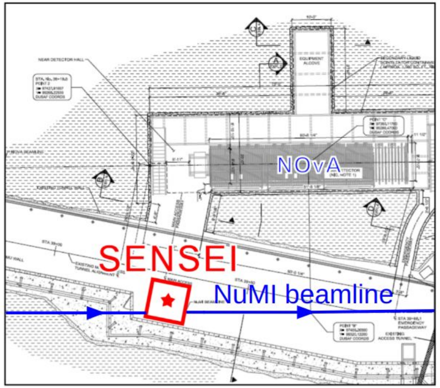


2023: Milli-charged particles @ MINOS

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

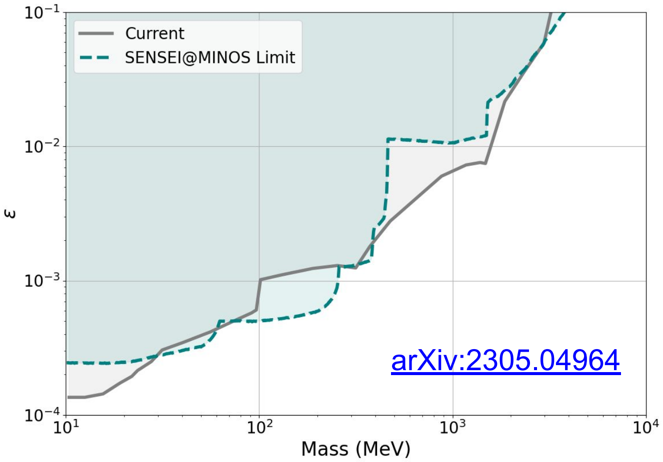


arXiV:1902.03246



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



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arXiv:2312.13342

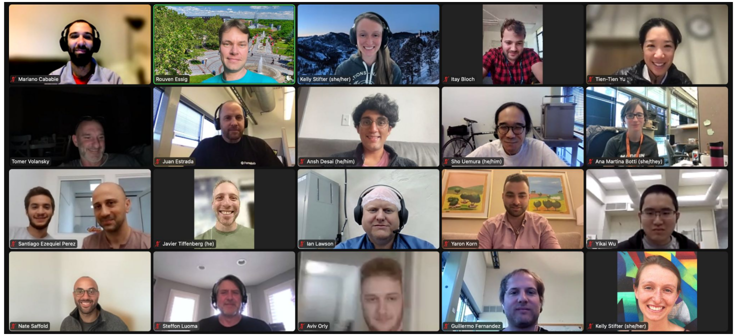
SENSEI @ SNOLAB: Setup

- Cold copper box for 12 copper tray
- Each tray for 2 (4) ~2g CCDs.
- 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

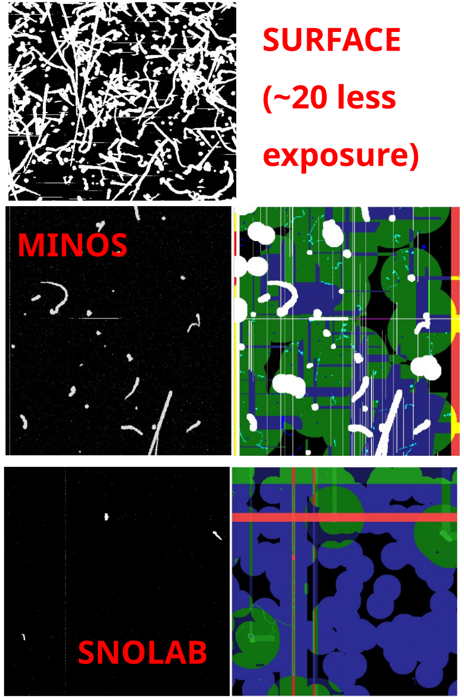
SENSEI @ SNOLAB: 1st run

Setup and operations:

- 6 CCDs (~13 g)
- 6144 × 1024 pixels
- 15 μm pitch, 675 μm thick
- Run: 9/2022-4/2023
- 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

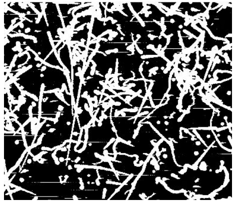


SENSEI @ SNOLAB: quality cuts



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

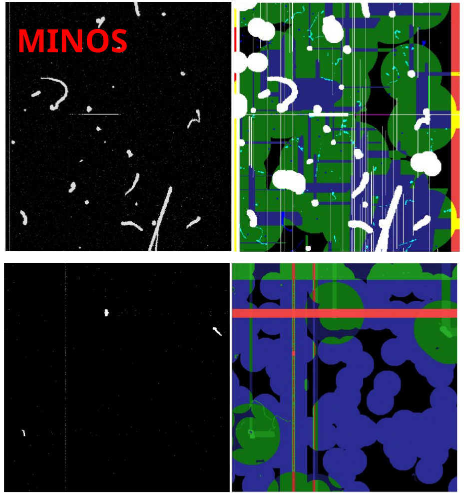
SENSEI @ SNOLAB: quality cuts



SURFACE

(~20 less

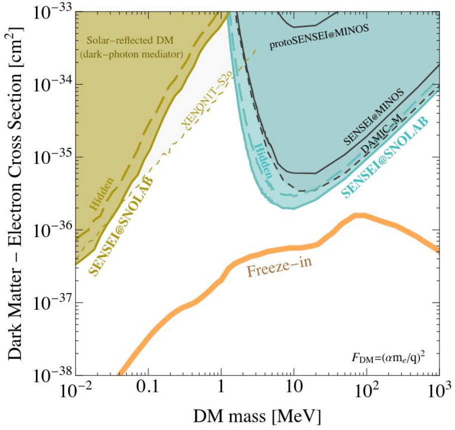
exposure)



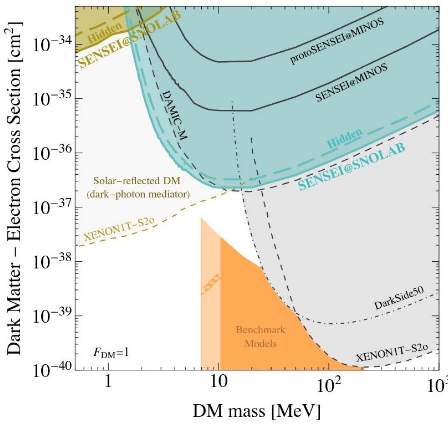
- 45 unblinded commissioning images,
- 37 blinded images
- 2-10 e- channels
- Combined datasets: ~70 g-days per electron channel with cuts
- Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

SENSEI @ SNOLAB: First results

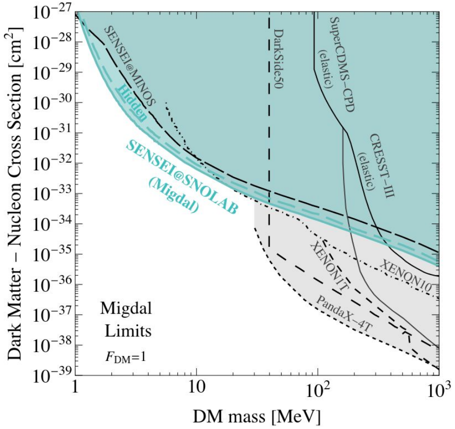
Light mediator



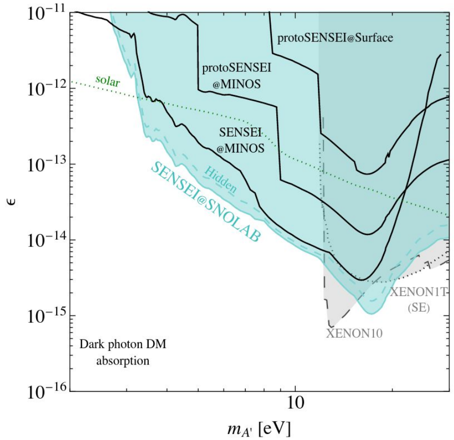
Heavy mediator



Heavy mediator (migdal)



Absorption



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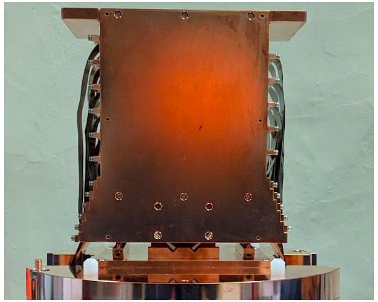
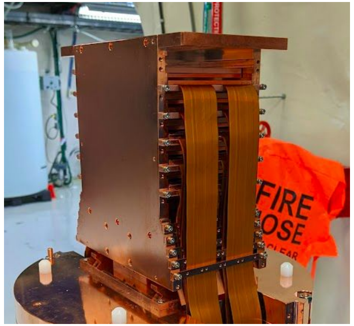
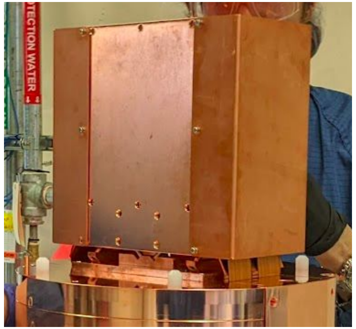
SENSEI @ SNOLAB: Second science run



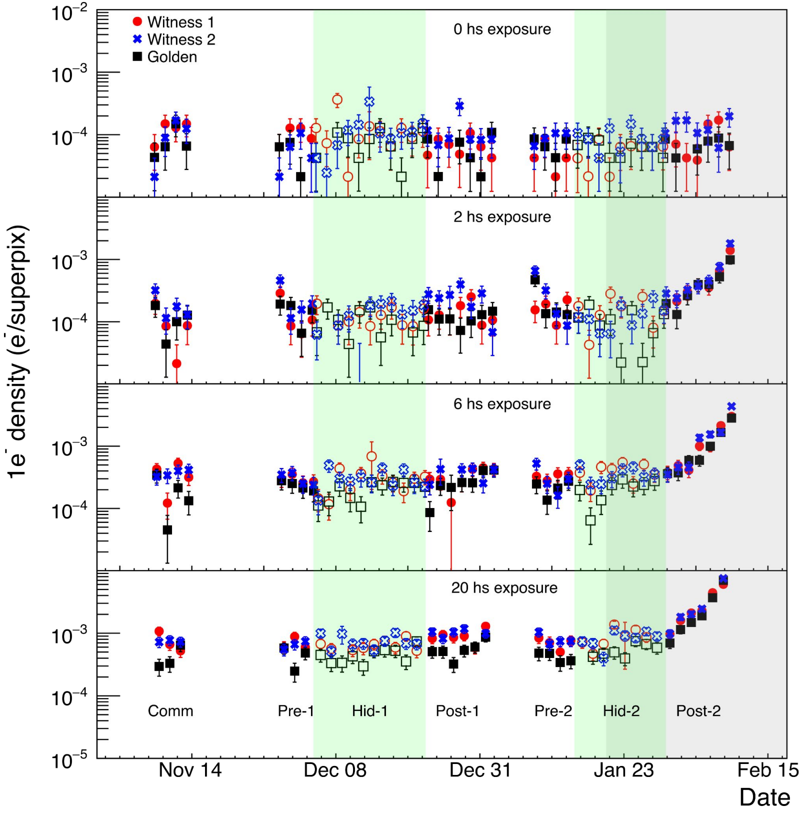




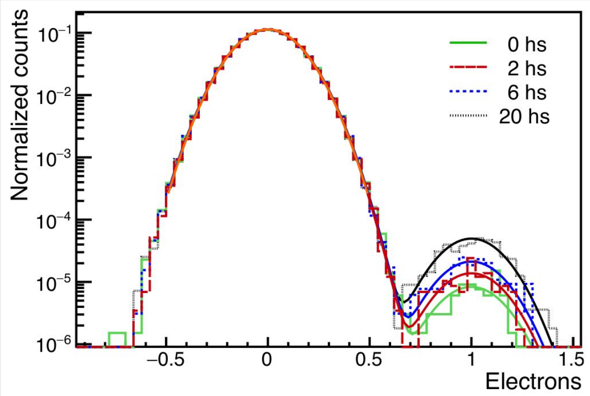
Setup and operations:

- Dedicated run for **1e⁻** events
- **19 CCDs** with new copper trays
- **101 Commissioning** (unblinded) images
- **77 Hidden** (blinded) images
- **0, 2, 6, 20 hour** exposures
- Binned data (**1superpix = 32 pix**)
- ~ 14 m readout, noise of ~0.14 e-
- Temperature ~ 140 K

SENSEI @ SNOLAB: 1e- density



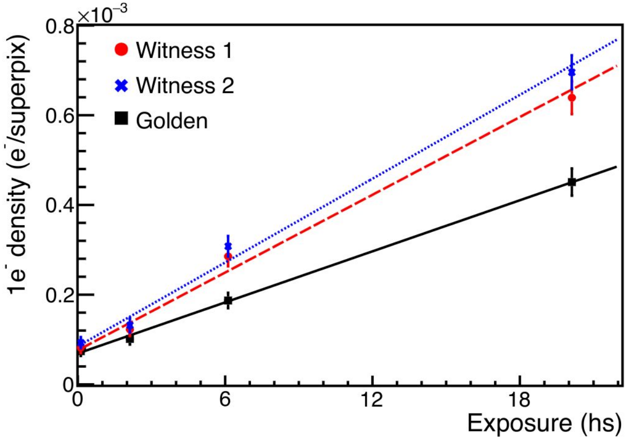
- Optimized cuts with respect to first run (no low-E mask for example)
- **19 hidden** images selected
- Cut efficiencies: **(85~97)%**



SENSEI @ SNOLAB: rates

- Golden quadrant: **(1.4 ± 0.1) x10^{-5} e-/pix/day**
- Witness quadrants: **(2.2 ± 0.1) x10^{-5} e-/pix/day**
- Lowest ever in Silicon (or NIR/UV photodetector)
- **1 order of magnitude improvement** with respect to last published result (SENSEI 2020)
- SENSEI original goal: **1.0 x 10^{-5} e-/pix/day**
- Rest of quadrants are still hidden

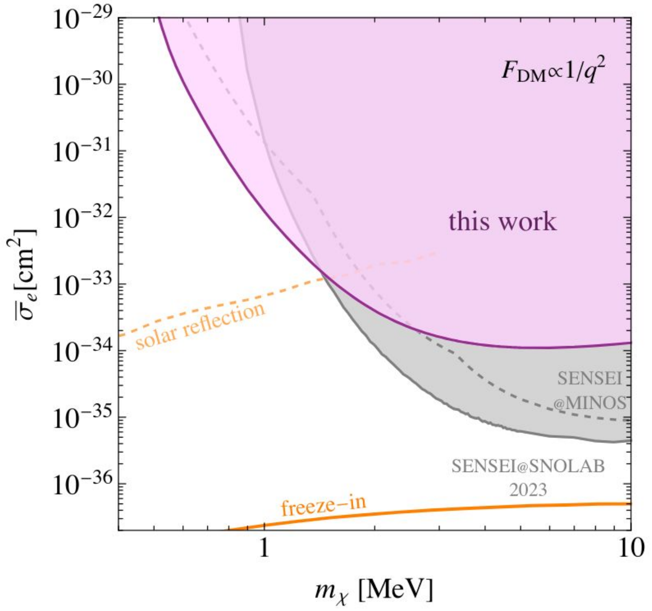
New records!!!



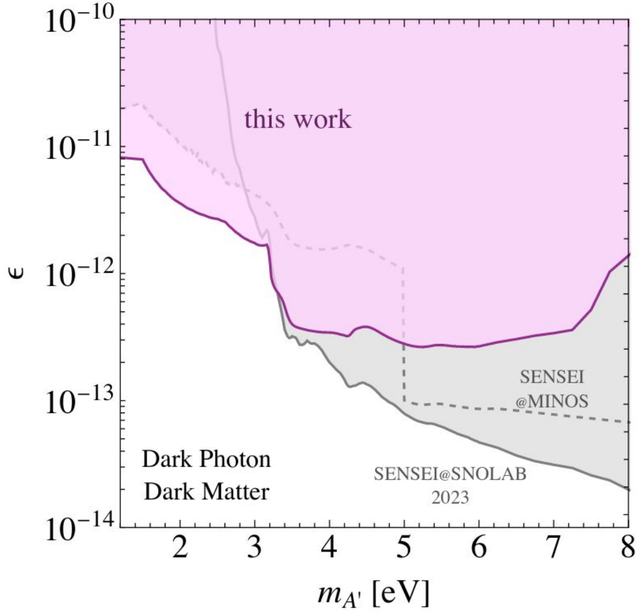
Quadrant .	Exp. indep. $\times 10^{-6}$ e^-/pix/image	Exp. dep $\times 10^{-5}$ e^-/ pix/day	90% U.L. $\times 10^{-5}$ e^-/ pix/day
Golden	2.17 ± 0.26	1.39 ± 0.11	1.53
Witness 1	2.39 ± 0.30	2.13 ± 0.13	2.30
Witness 2	2.72 ± 0.32	2.23 ± 0.14	2.41

SENSEI @ SNOLAB: 2nd run 1st results

Light mediator



Absorption



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***
- ***arXiv:2312.13342***
- ***1e- paper in preparation with data release***

Contact us if anything else is needed

	Efficiencies	All data			Hidden data		
Shape	Diff./ID/Geom.	Expo.	Ev.	Bkgd.	Expo.	Ev.	Bkgd.
2e2p, h	0.15/0.96/0.94	13.58	10	10.66	6.12	6	4.75
2e2p, v	0.18/0.96/0.94	16.21	13	12.65	7.36	6	5.61
2e2p, d	0.19/0.96/0.93	17.82	32	25.31	7.65	18	11.22
2e, all	**0.51/0.96/0.94**	**46.61**	**55**	**48.62**	**21.13**	**30**	**21.57**
3e2p	0.33/0.98/0.96	30.87	3	0.01	14.01	2	0.01
3e3p	0.31/0.94/0.90	26.84	1	0.06	12.21	0	0.03
3e, all	**0.64/0.96/0.93**	**57.71**	**4**	**0.07**	**26.22**	**2**	**0.03**
4e2p	0.21/0.98/0.96	19.51	0	0.00	8.85	0	0.00
4e3p	0.31/0.96/0.92	27.60	0	0.00	12.55	0	0.00
4e4p	0.19/0.93/0.88	15.93	0	0.00	7.25	0	0.00
4e, all	**0.71/0.96/0.92**	**63.03**	**0**	**0.00**	**28.66**	**0**	**0.00**
5e, all	0.75/0.95/0.91	65.56	0	0.00	29.84	0	0.00
6e, all	0.78/0.95/0.90	67.31	0	0.00	30.63	0	0.00
7e, all	0.80/0.95/0.89	68.53	0	0.00	31.19	0	0.00
8e, all	0.82/0.95/0.89	69.52	0	0.00	31.67	0	0.00
9e, all	0.84/0.94/0.88	70.30	0	0.00	32.02	0	0.00
10e, all	0.85/0.94/0.88	70.89	0	0.00	32.30	0	0.00

Perspectives light-DM with skippers

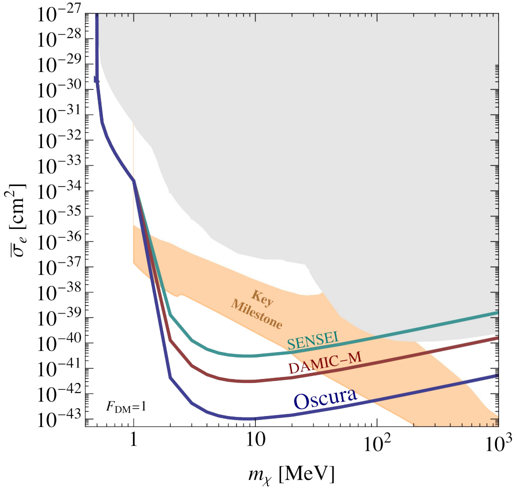
SENSEI 100g

DAMIC-M 1kg

OSCURA 10kg

See B. Cervantes talk this Thursday

See D. Norcini talk in this session



arXiv: 2304.04401

Perspectives light-DM with skippers

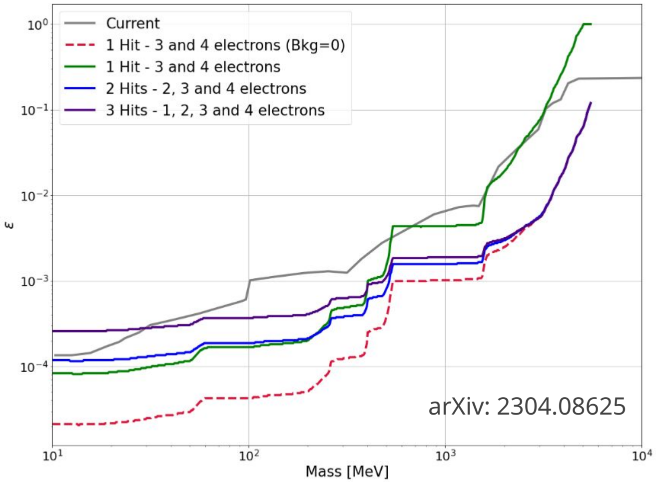
SENSEI 100g

DAMIC-M 1kg

OSCURA IT 1kg

OSCURA 10kg

See S. Perez talk this Thursday



Perspectives light-DM with skippers

DARKNESS 2g in space

SENSEI 100g

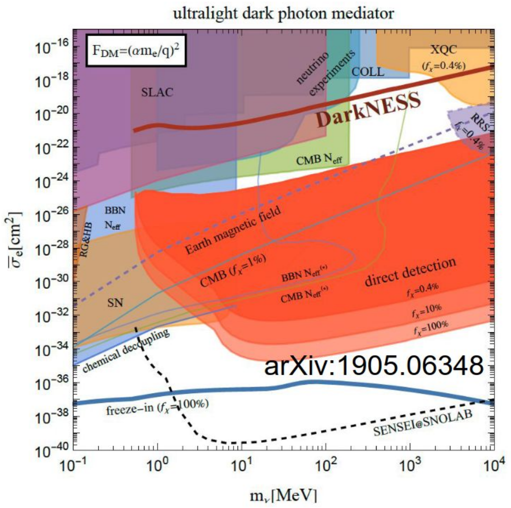
DAMIC-M 1kg

OSCURA IT 1kg

OSCURA 10kg

See N. Saffold talk on Thursday

See Poster #130 this afternoon



Perspectives light-DM with skippers

DARKNESS 2g in space

SENSEI 100g

DAMIC-M 1kg

OSCURA IT 1kg

OSCURA 10kg

Summary

- New 1e- rate record of **(1.4 ± 0.1) x10-5 e-/pix/day**
- Limit with **MINOS** data for **mCP. Best constraints around 100 MeV.**
- Best constraints from **SNOLAB** on **DM-e- direct scattering** for **light mediator (1-1000 MeV), heavy mediator/Migdal around (1-10 MeV), and Absorption (1-10 eV)**

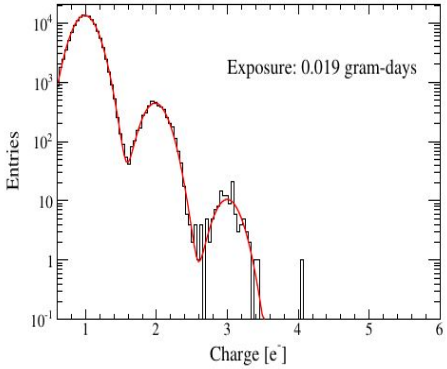
- **Unbinned** data with different exposures to study **2, 3 , 4 e- channels** with improved analysis coming
- **Strategies to further push background** foreseen: different form factor, package, IR shield, etc
- Renewed support from H-S and new cryocooler
- **generations of skipper-CCD experiments** foreseen for cosmic DM searches in the next ~ 7 years
- **New efforts** to build particle trackers at **beams** for mCPs and **satellites** for SIMPs

SENSEI @ SNOLAB: First results

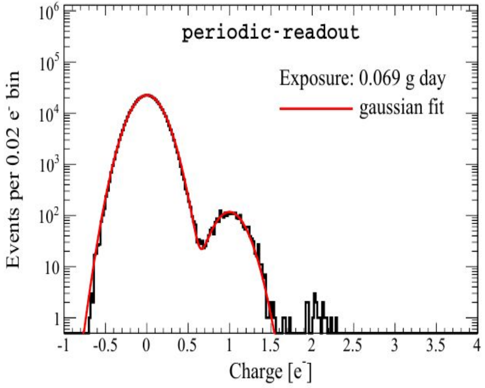
- 45 unblinded commissioning images,
- 37 blinded images
- 2-10 e- channels
- Combined datasets: ~70 g-days per electron channel with cuts
- Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

- 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

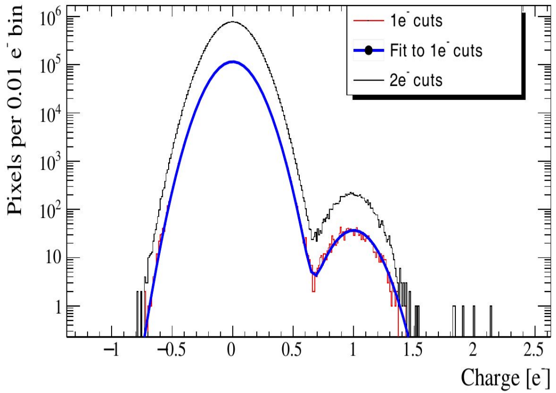
Summary: from prototype to science grade



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**

Background sources: detector

Exposure dependent

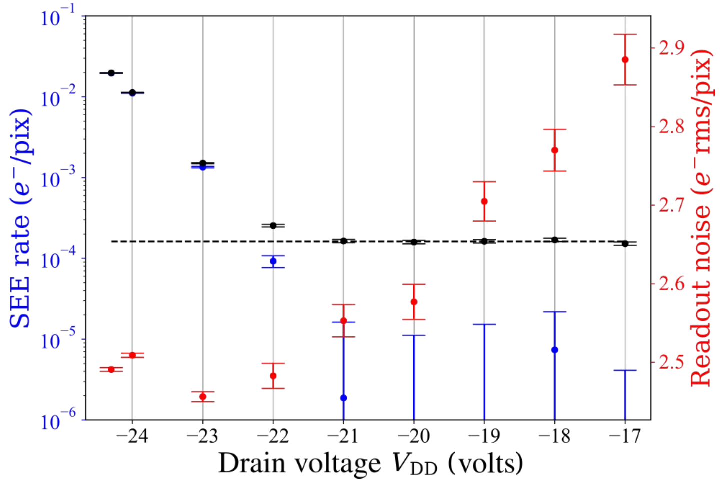
- Dark current (10^{-5} e^{-}/pix/day at 135 K)
- Amplifier light (10^{-1} to 10^{-5} e^{-}/pix/day)

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



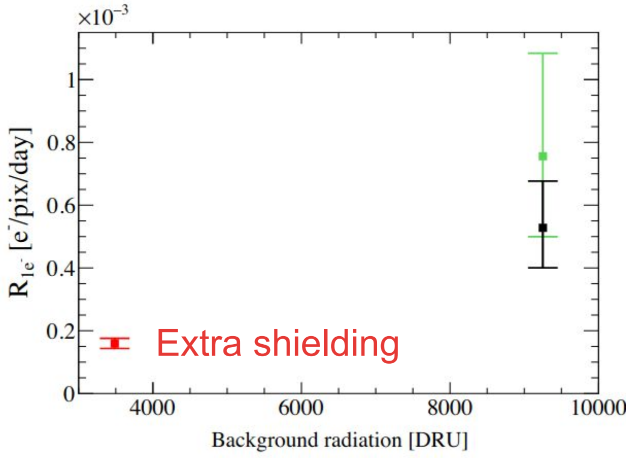
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Background sources: environment

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

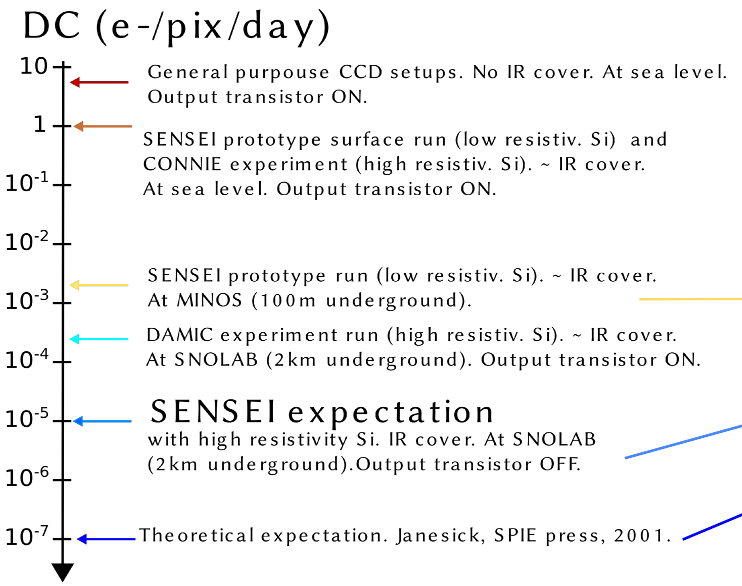
Low-energy:
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency

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



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

Background goal

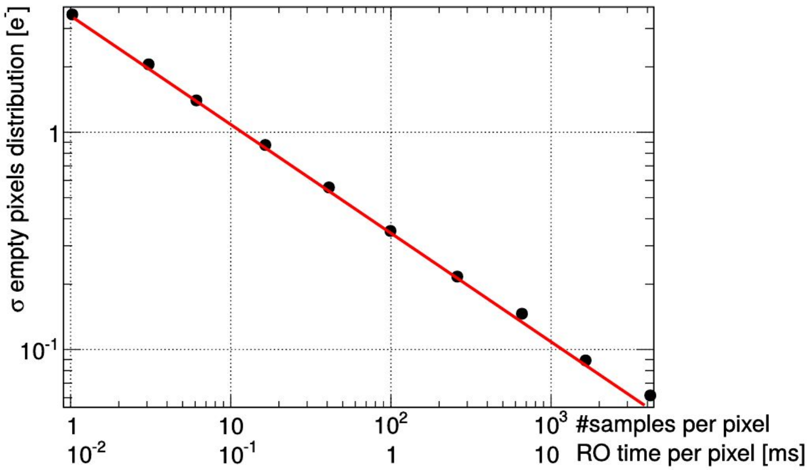


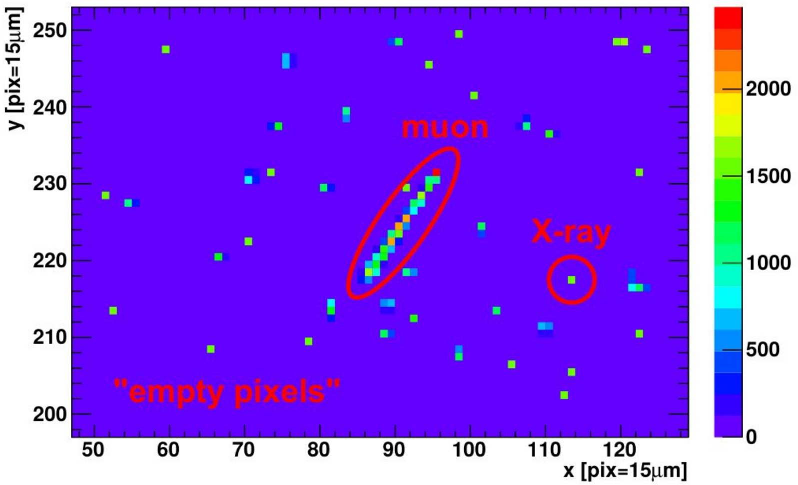
Dark Current [$e^{-}pix^{-1}day^{-1}$]	$\geq 1e^{-}$ [pix]	$\geq 2e^{-}$ [pix]	$\geq 3e^{-}$ [pix]
10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

Background estimations for 1 year and 100 g.

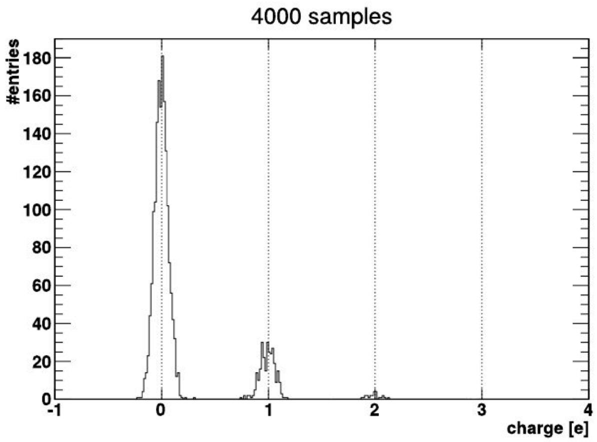
Blue: discovery channel (background free)
Red: modulation or limits

Skipper-CCD read-out noise

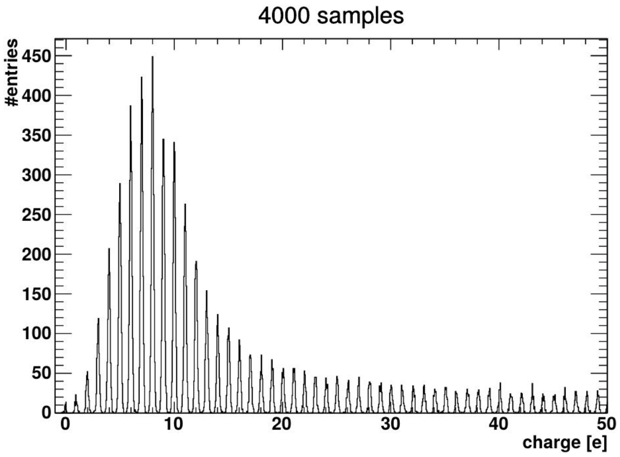




Skipper-CCD resolution



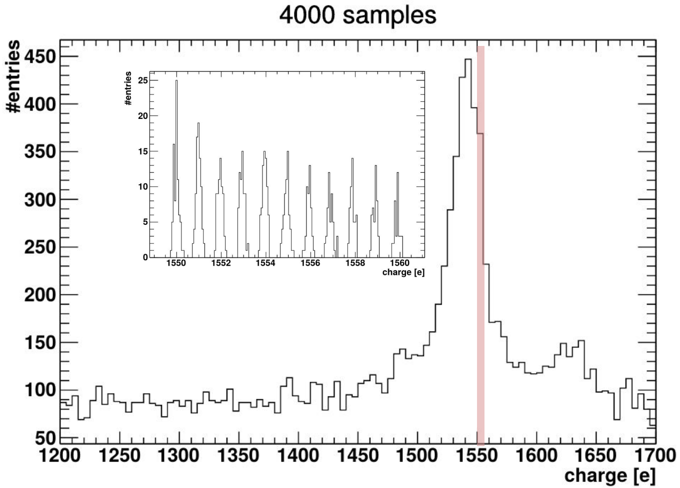
(Almost) Empty CCD



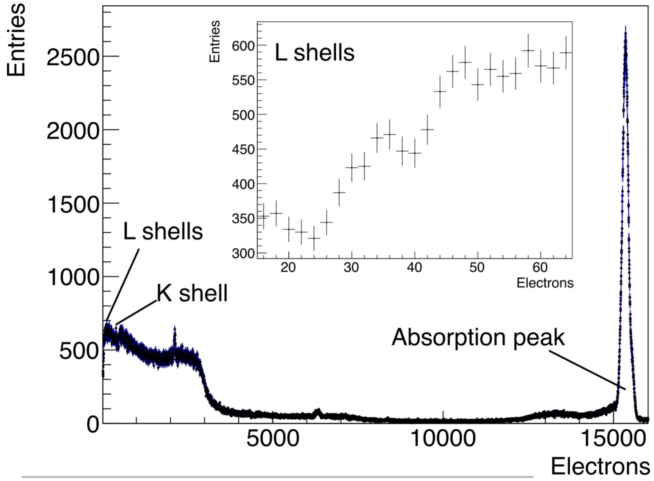
Front-illuminated CCD

Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511



Charge per event for 55Fe x-ray source



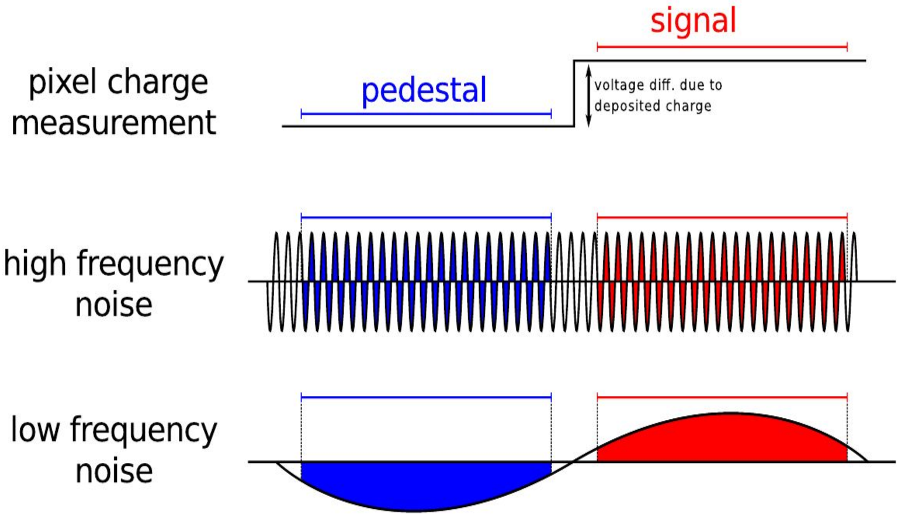
Compton scattering spectrum in Silicon with 241Am γ-ray source

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**…

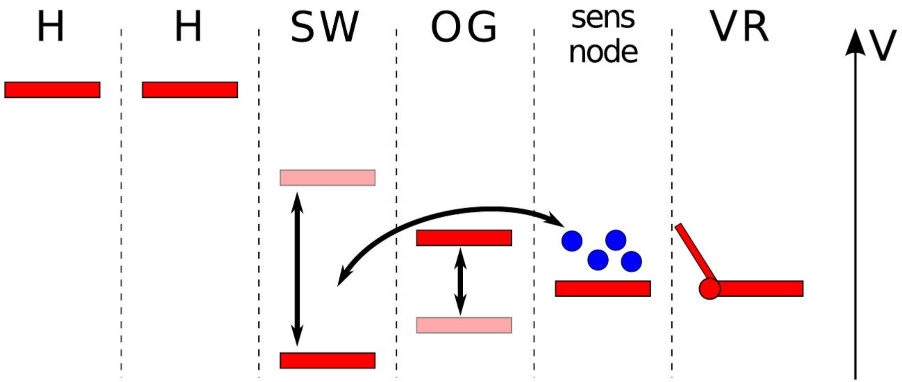


Skipper CCD read-out

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

Pixel value = **average** of all samples

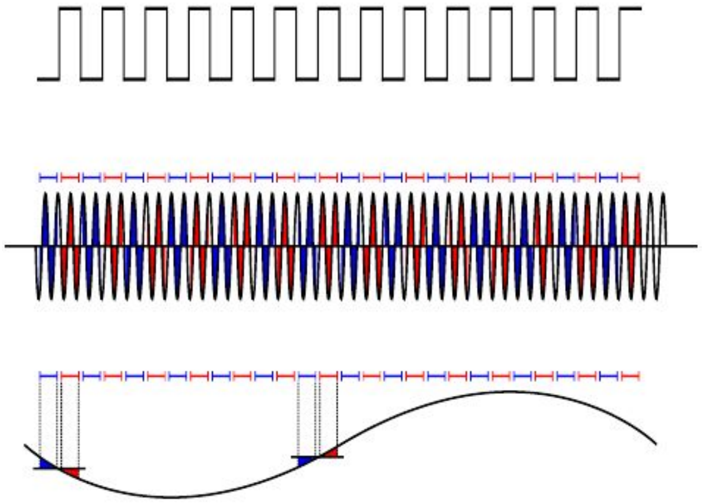
Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)



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



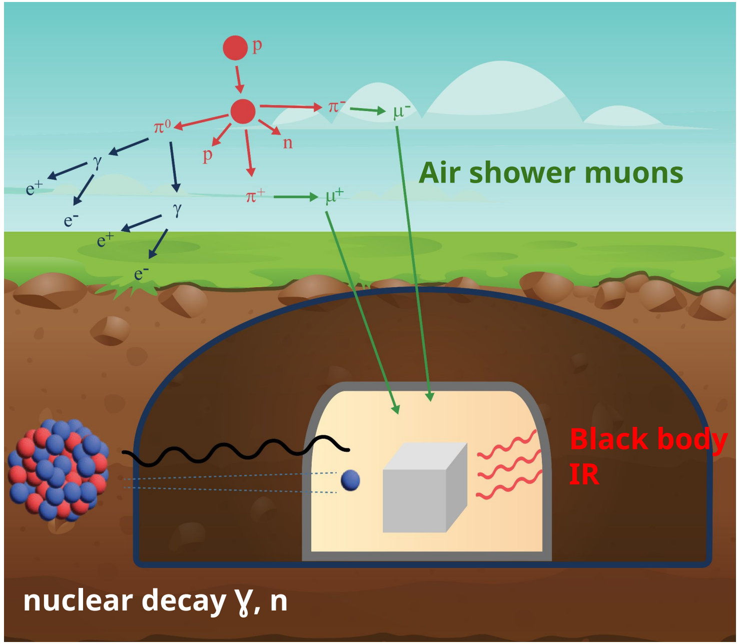
Background sources: environment

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

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

Shielding and quality cuts to remove environmental background.

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



Background sources: detector

Exposure independent

- Spurious charge (10^{-2} to 10^{-5} e^-/pix/image)
- Amplifier light (10^{-1} to 10^{-5} e-/pix/day)

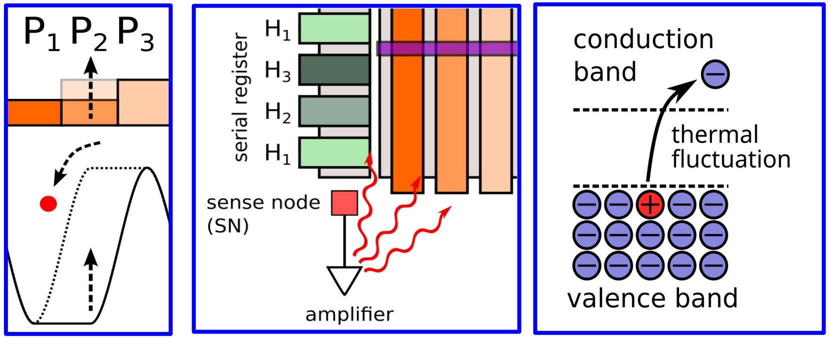
Exposure dependent

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

Single electron rate reduced by optimizing operation parameters

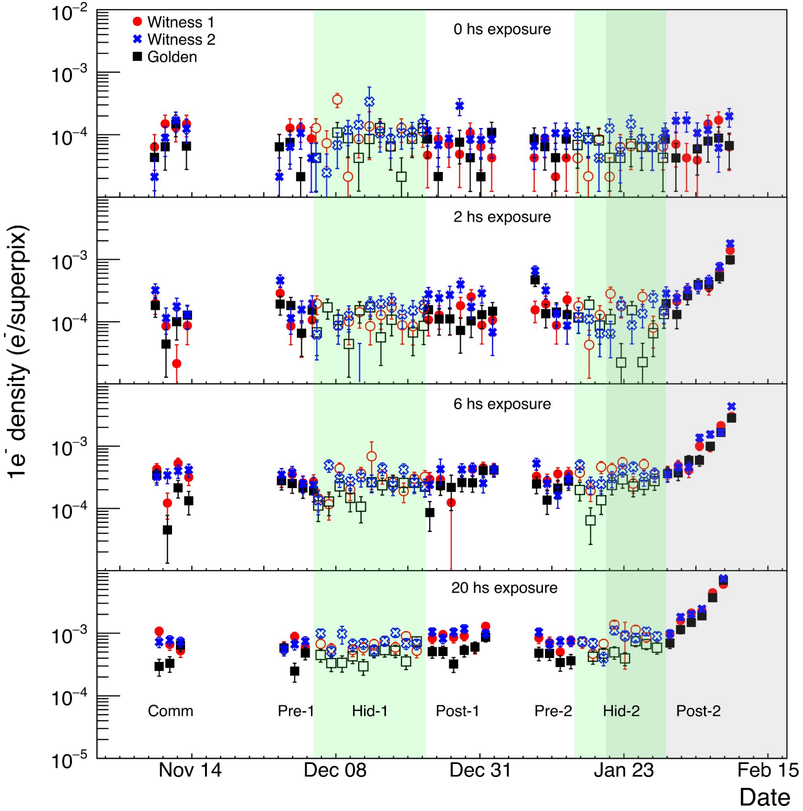
- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure
- Temperature control

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



Spurious charge **Amplifier light** **Dark current (DC)**

SENSEI @ SNOLAB: quality cuts



Blinded analysis

1. Choose **1 Golden** quadrant

2. Quality cuts with **commissioning** data:

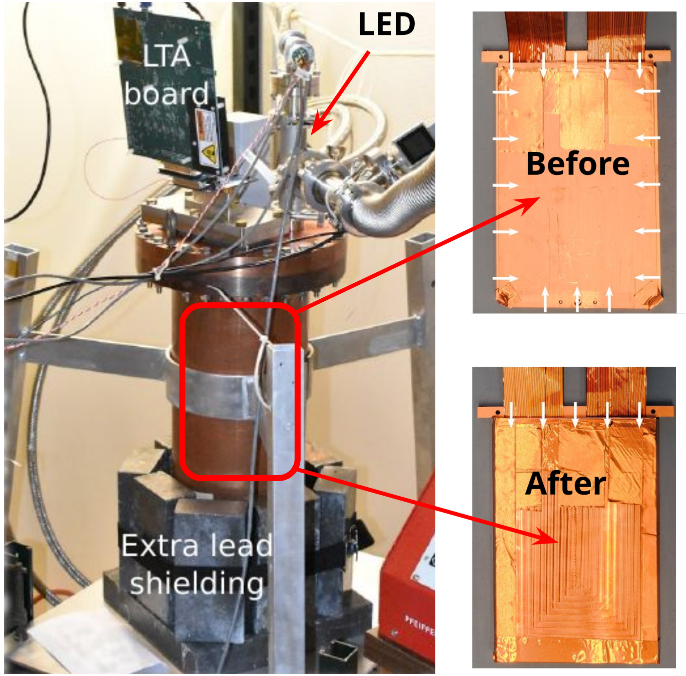
- Electronic noise
- Cross-talk
- Edges of CCDs
- Bad pixels and columns
- Hot image (3-sigma upper cut)
- Noisy image (refit after masking)
- Serial register events
- Charge transfer inefficiencies
- High-energy events halo

System / detector effects

Environmental background

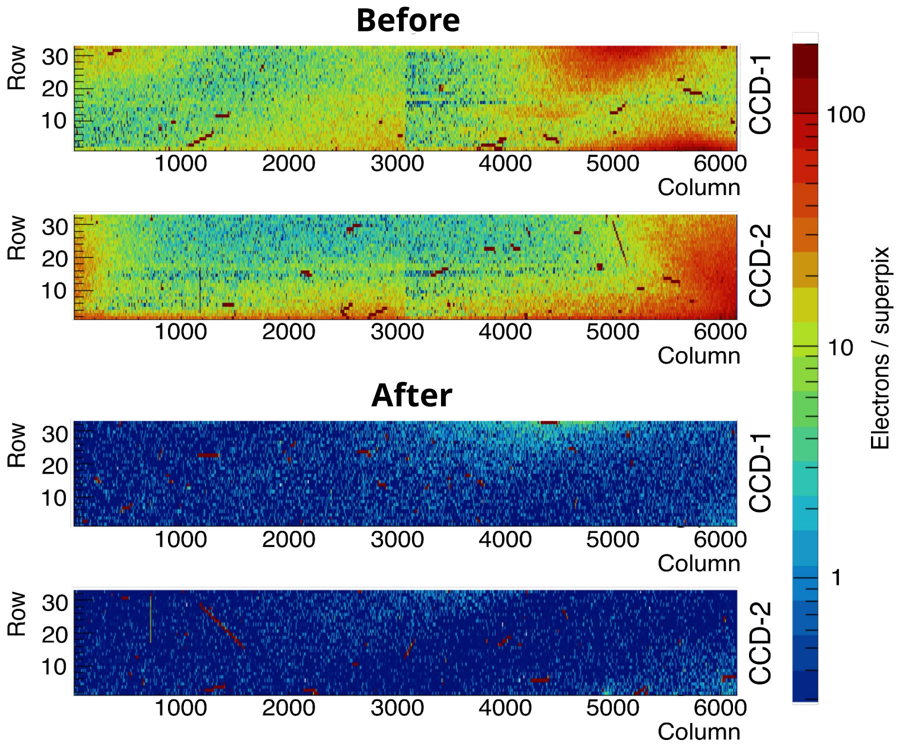
3. Choose **2 Witness** quadrants to assess cryocooler effect in hidden data

SENSEI @ MINOS: light-leak test setup



- Same CCDs as in SNOLAB
- 1 Cold copper tray with 2 CCDs
- **No cold box** around tray
- 6 hs exposure with **LED on**
- No cold box around tray
- Run 1 with **old tray**
- Run 2 with **new tray** and extra tape
- Run with 0, 2 and 6 hs exposure
- Same operation parameters and quality cuts as in SNOLAB

SENSEI @ MINOS: light-leak test result



- Best previous result :

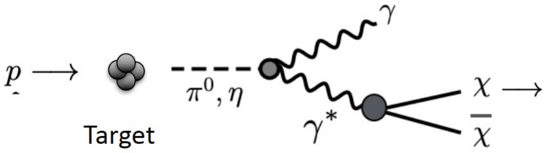
  ~8 x 10^{-5} e-/pix/day (not published)
- New best result:

  (3.4 ± 0.1) x 10^{-5} e-/pix/day
- Improvement of factor 2 with light-tight tray

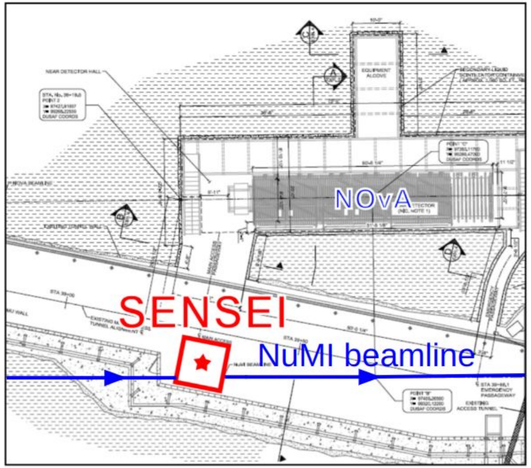
Exposure-dependant rates in **x 10^{-5} e-/pix/day**

CCD-1	3.43 ± 0.13	4.27 ± 0.14
	7.79 ± 0.21	7.38 ± 0.22
CCD-2	9.04 ± 0.27	4.10 ± 0.16
	6.47 ± 0.19	7.14 ± 0.25

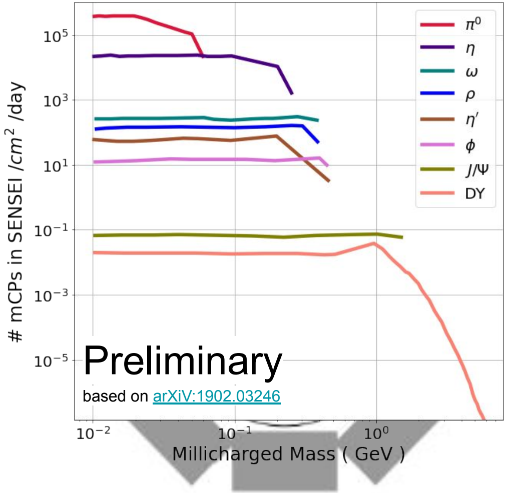
Proton collisions w/ fixed target can produce mCPs collinear w/ NuMI beamline:



arXiV:1902.03246



Using production rates accepted by SENSEI@MINOS…

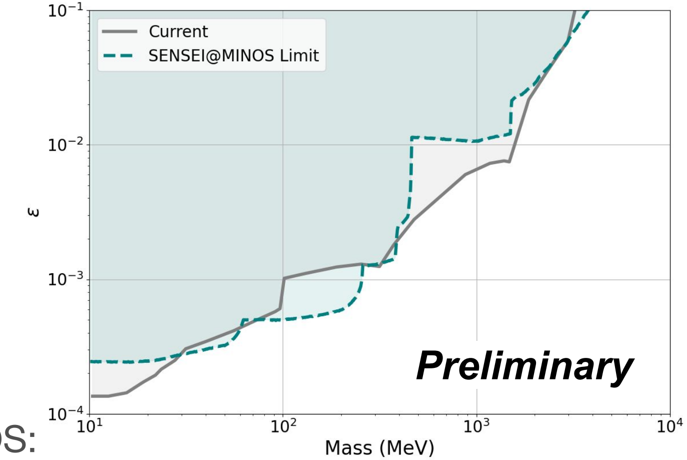


… and data from SENSEI@MINOS:

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