SENSEI† update on single-electron events

A. M. Botti* for the SENSEI† collaboration

EXCESS Workshop @ IDM, Rome

July 6, 2024

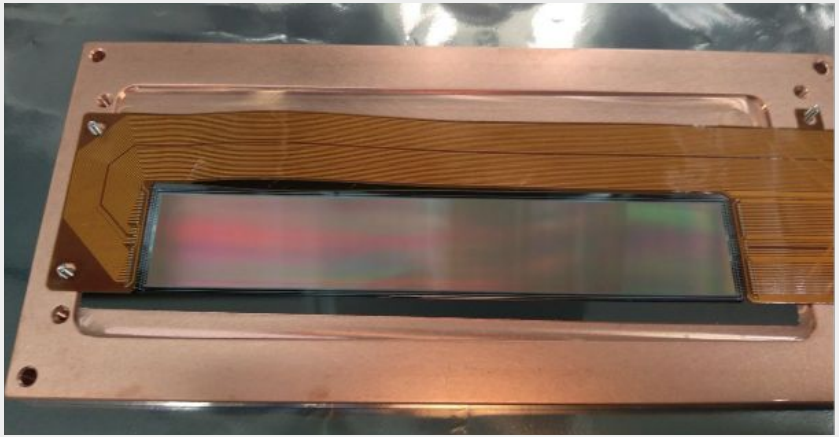
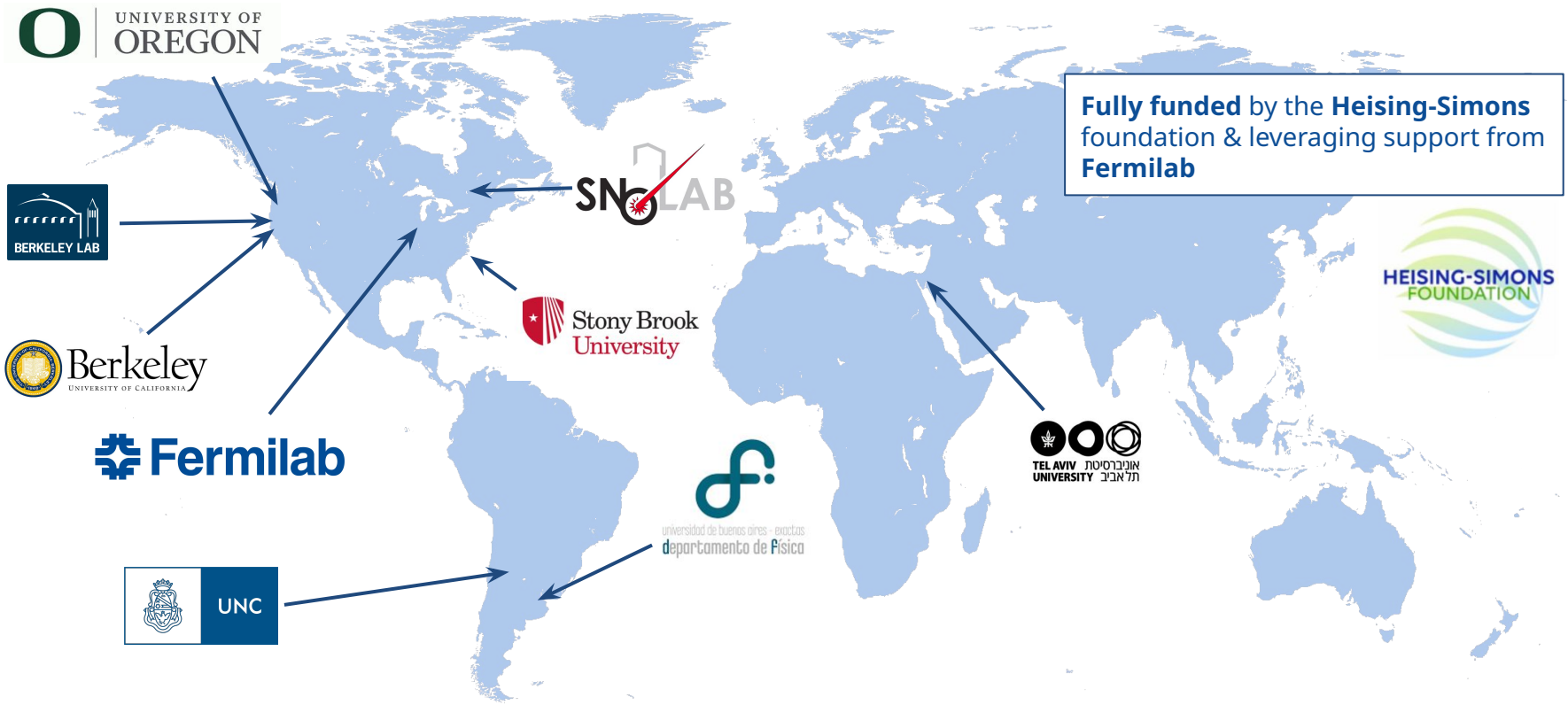


Image: SENSEI sensor

* Fermi National Accelerator Laboratory · abotti@fnal.gov

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

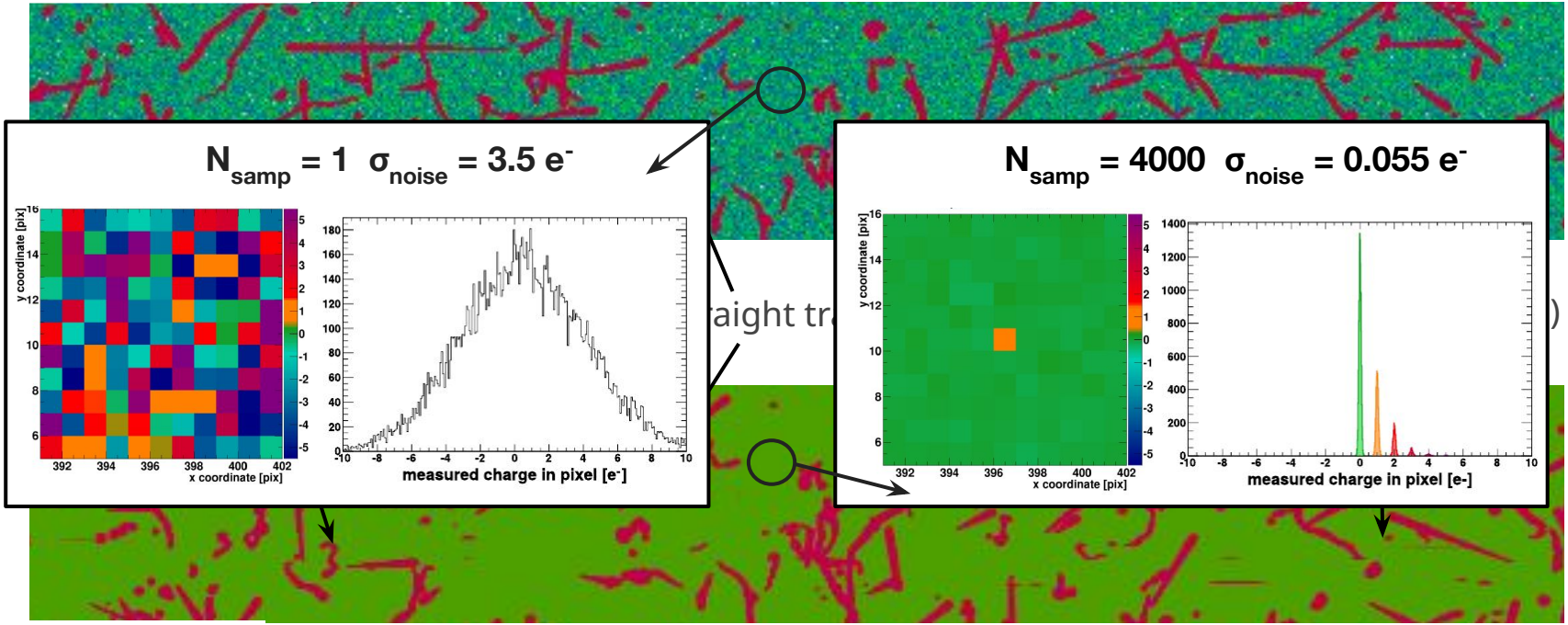
The ensei Collaboration



Fully funded by the **Heising-Simons** foundation & leveraging support from **Fermilab**

Example images (real data!)

Traditional CCD



Skipper- CCD

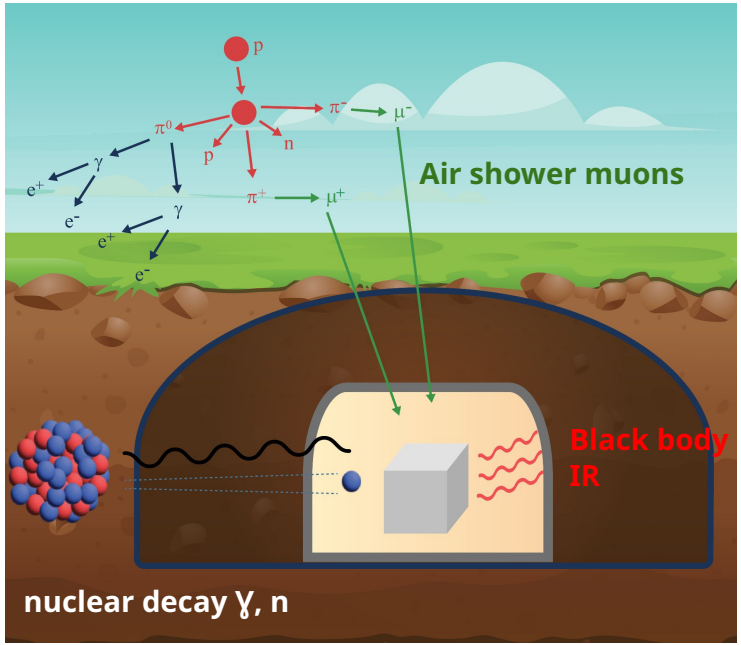
Background sources: environment

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)



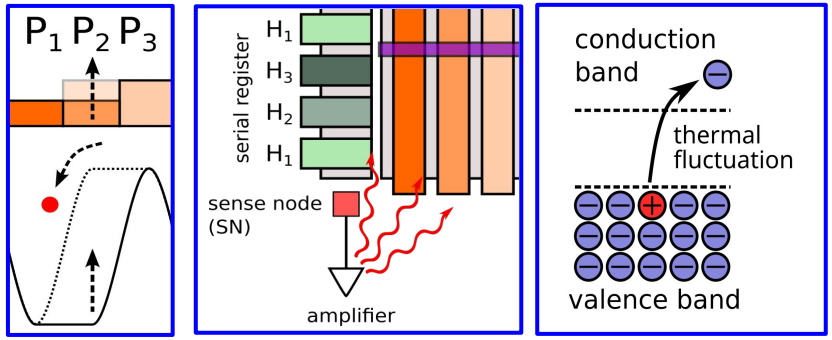
Background sources: detector

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

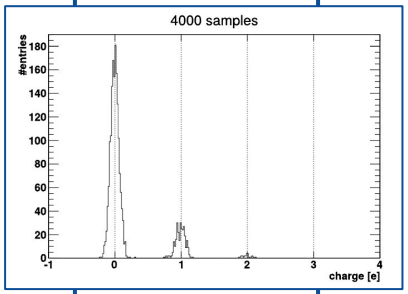
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)



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

The ensei 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.

The SENSEI Experiment

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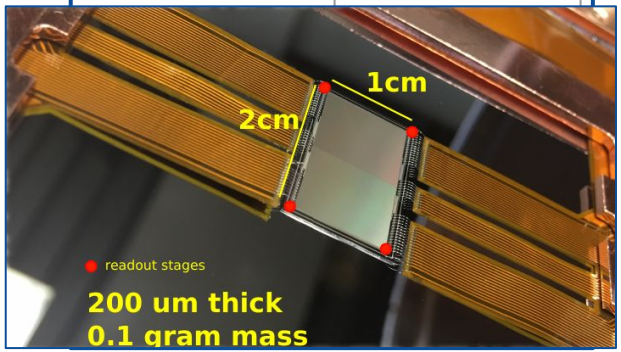

The SENSEI Collaboration
Physical Review Letters 121.6 (2018): 061803.

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

The SENSEI Experiment

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

Best published SEE rate < 1.6×10^{-4} e-/pix/day

The SENSEI Experiment

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arXiv:2312.13342

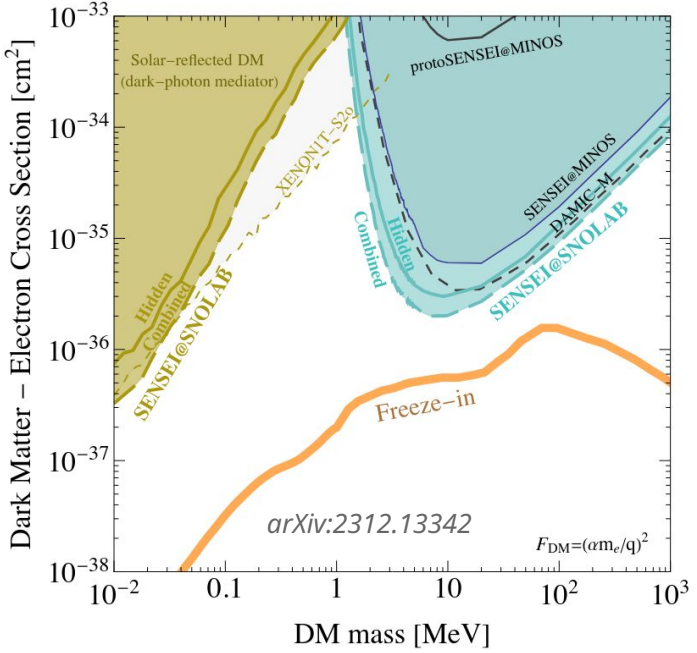
SENSEI @ SNOLAB: Setup

- 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: First science run

Setup and operations:

- 6 CCDs (~13 g) designed by S. Holland @ LBNL
- 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**



The SENSEI Experiment

‘17	‘18	‘19	‘20	‘21-’23	Ongoing
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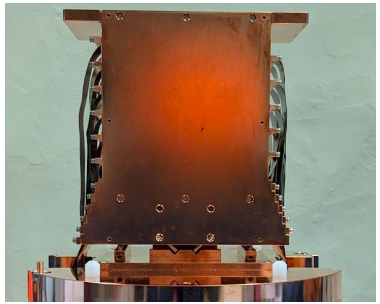
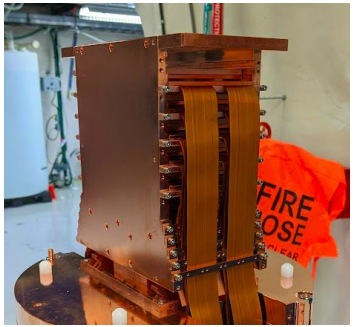
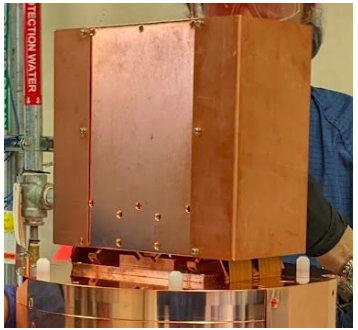
SENSEI @ SNOLAB: Second science run



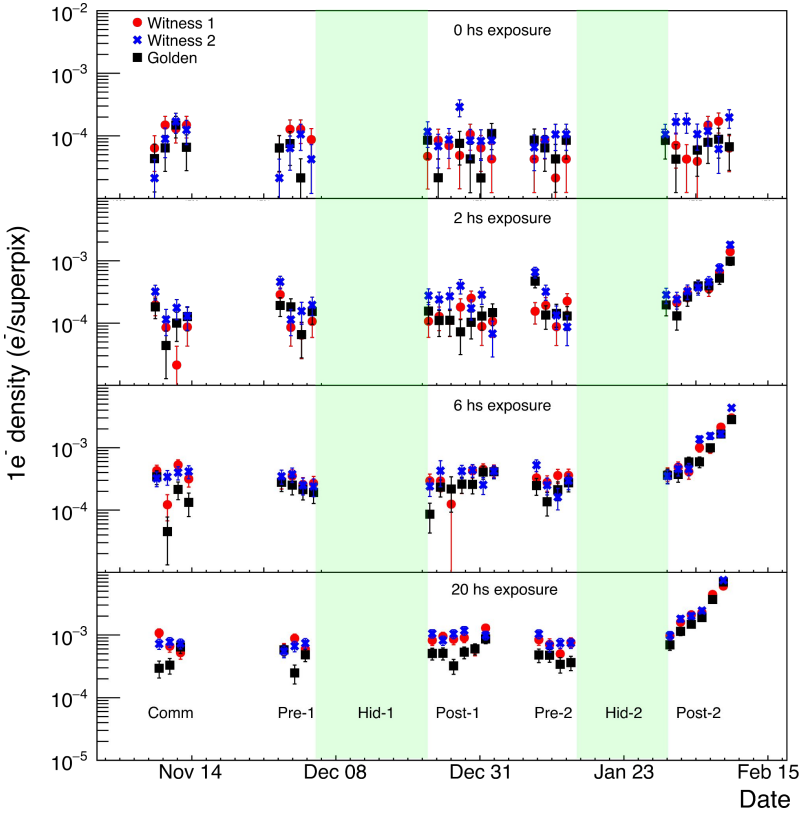




Setup and operations:

- **Dedicated run** for 1e^- events
- **22 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: quality cuts



Blinded analysis

1. Choose **1 Golden** quadrant

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

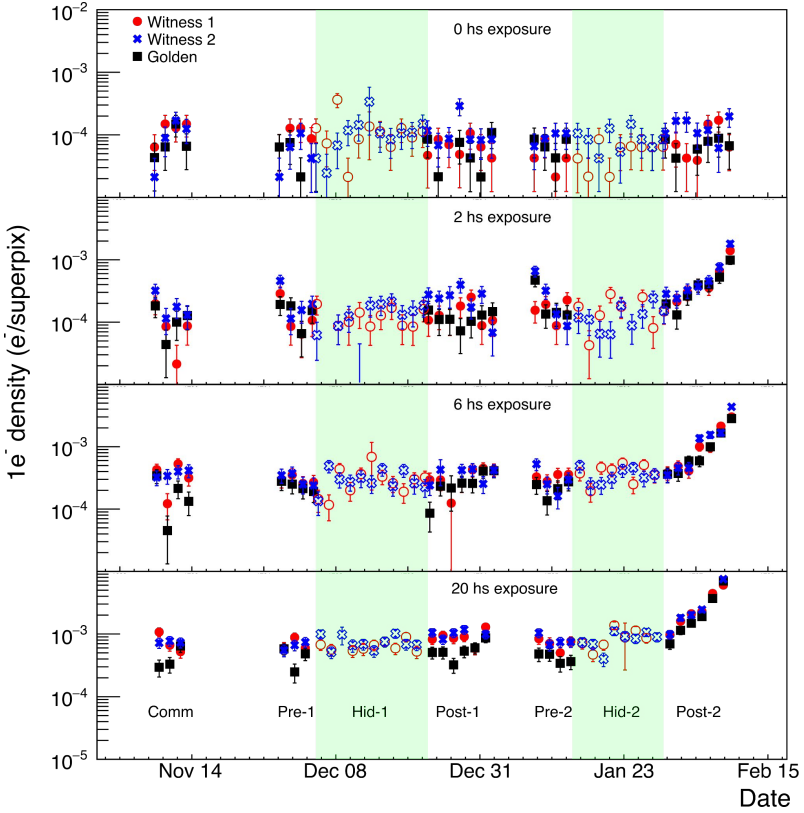
- Electronic noise
- Cross-talk
- Edges of CCDs
- Bad pixels and columns
- Hot image (3-sigma upper cut)
- Noisy image (refit after masking)
- Serial register events
- Charge transfer inefficiencies
- High-energy events halo

System / detector effects

Environmental background

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

SENSEI @ SNOLAB: quality cuts



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   - Edges of CCDs
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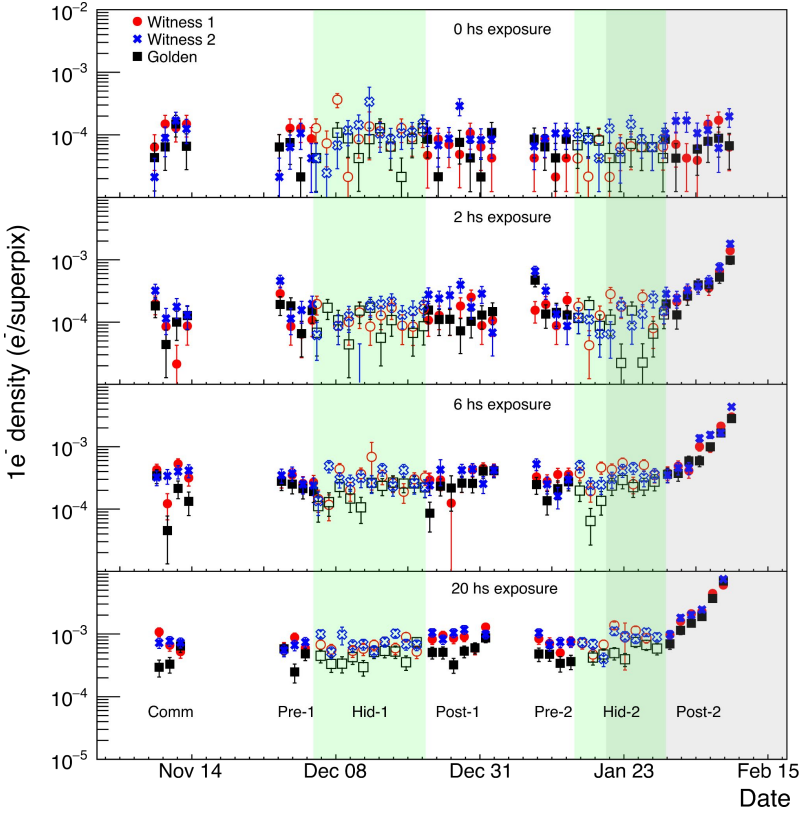

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System / detector effects

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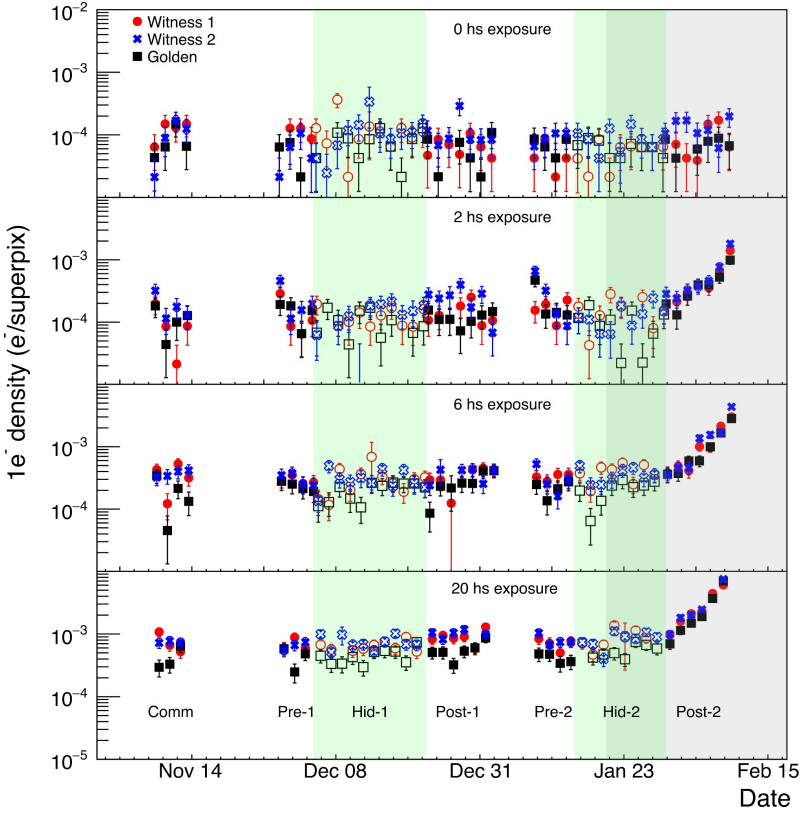
SENSEI @ SNOLAB: 1e- density

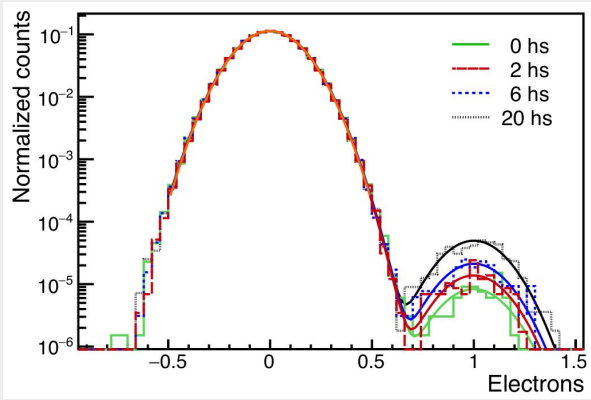


55 hidden images selected

Cut efficiencies: **(82~95)%**

Hot image: **0 Golden** - 1 Witness

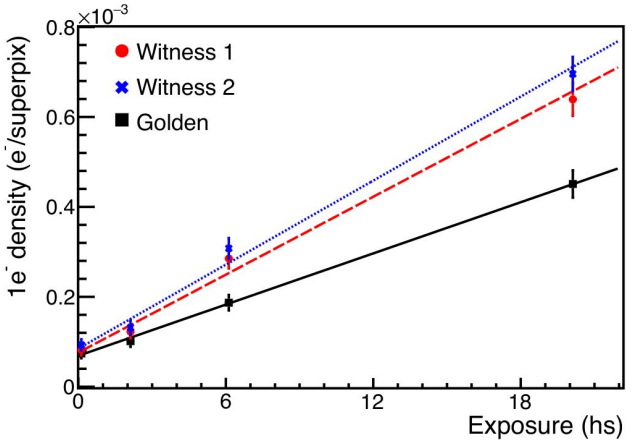
Noisy images: **0 Golden** - 0 Witness



SENSEI @ SNOLAB: rates

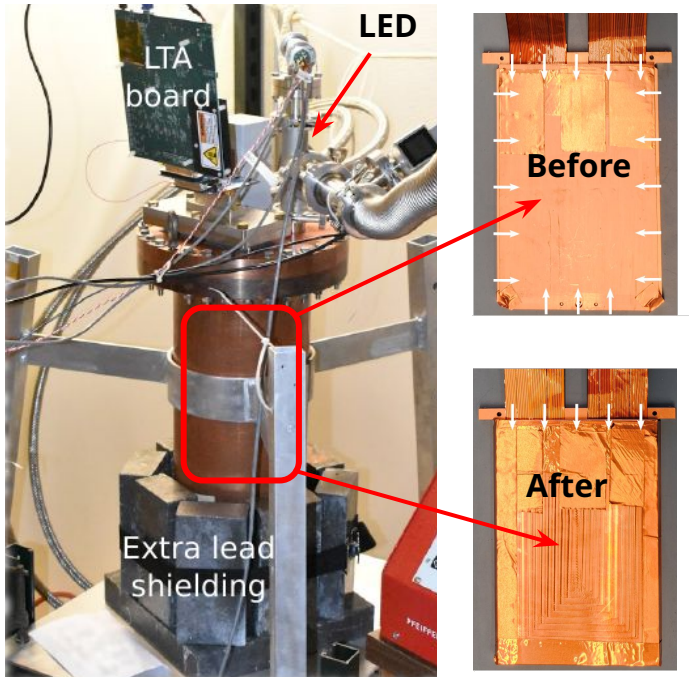
- Golden quadrant: **(1.4 ± 0.1) x10^{-5} e-/pix/day**
- Witness quadrants: **(2.2 ± 0.1) x10^{-5} e-/pix/day**
- Lowest ever in Silicon (or NIR/UV photodetector)
- SENSEI original goal: **1.0 x 10^{-5} e-/pix/day**
- Rest of quadrants are still hidden
- Significant improvement from SNOLAB 1st run
- What changed? Copper trays!

New records!!!



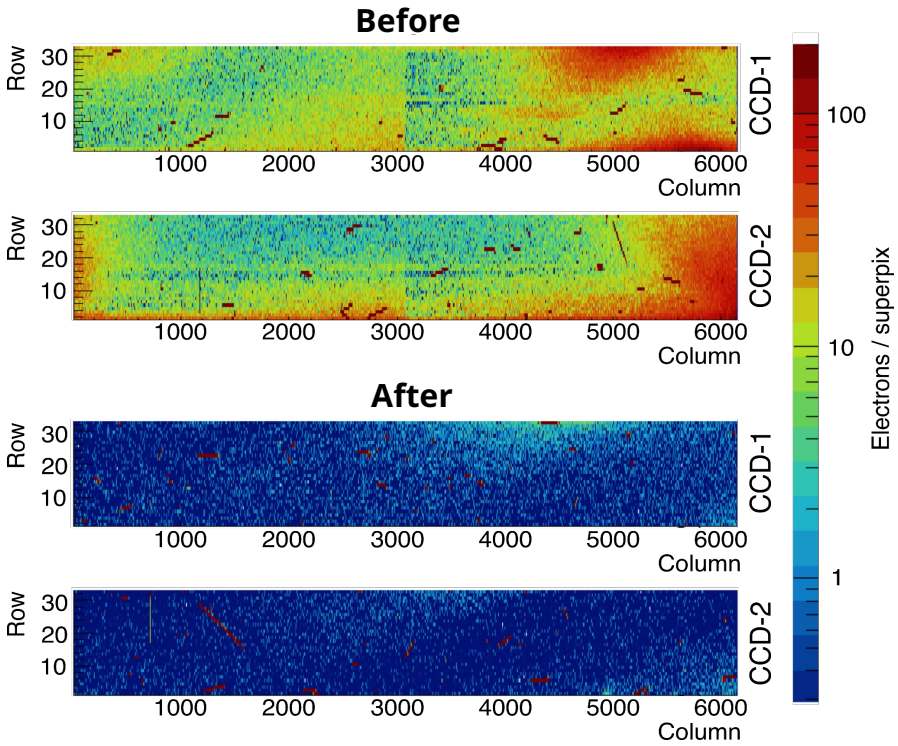
Quadrant .	Exp. indep. $\times 10^{-6}$ e^-/pix/image	Exp. dep $\times 10^{-5}$ e^-/pix/day	90% U.L. $\times 10^{-5}$ e^-/pix/day
Golden	2.17 ± 0.26	1.39 ± 0.11	1.53
Witness 1	2.39 ± 0.30	2.13 ± 0.13	2.30
Witness 2	2.72 ± 0.32	2.23 ± 0.14	2.41

SENSEI @ 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**

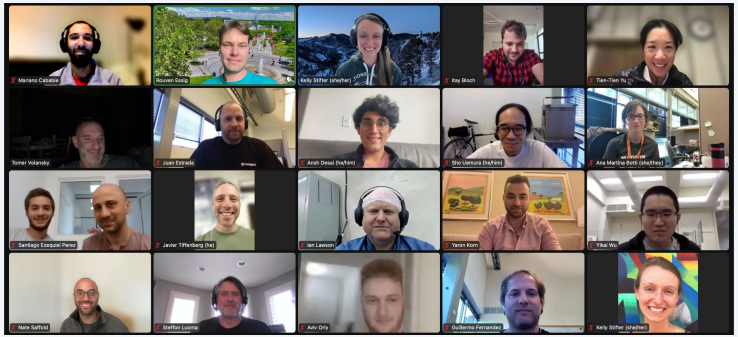
CCD-1	3.43 ± 0.13	4.27 ± 0.14
	7.79 ± 0.21	7.38 ± 0.22
CCD-2	9.04 ± 0.27	4.10 ± 0.16
	6.47 ± 0.19	7.14 ± 0.25

Summary and what's next?

- 1st **dedicated 1e- rate** measurement at **SNOLAB**: new world record of **(1.4 ± 0.1) x10^{-5} e-/pix/day**
- **MINOS** test support **light-leak** hypothesis
- **Paper** and **data release** coming soon

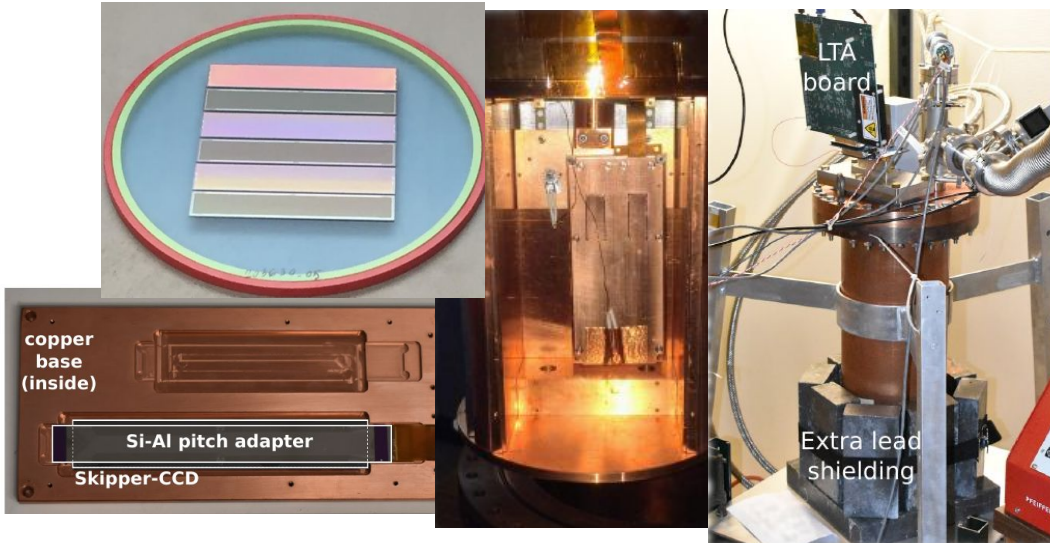
- New support from H-S
- New cryocooler coming.
- Unbinned measurement with different exposures to study 2, 3 , 4 e- channels with improved analysis
- Strategies to further push background: different form factor, package, IR shield, etc



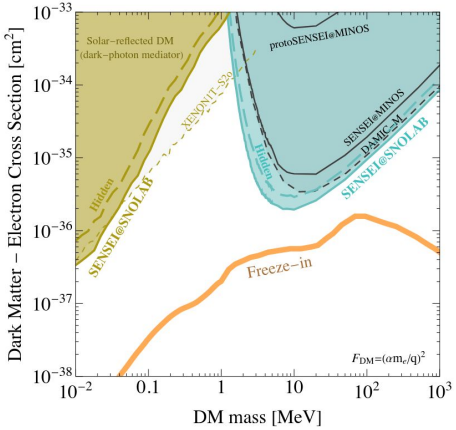
New device @ MINOS

- 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

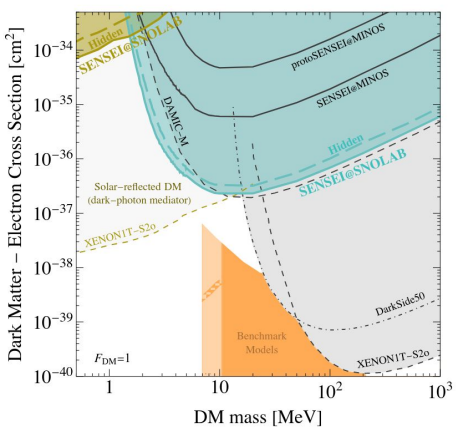


SENSEI @ SNOLAB: First results

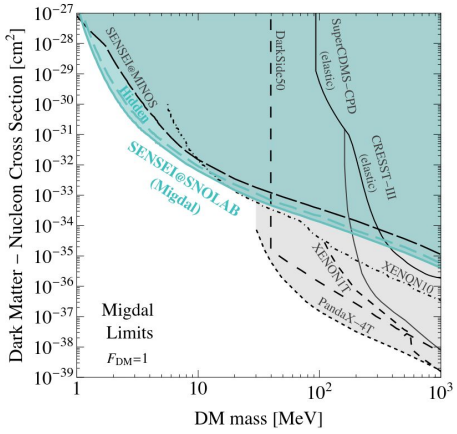
Light mediator



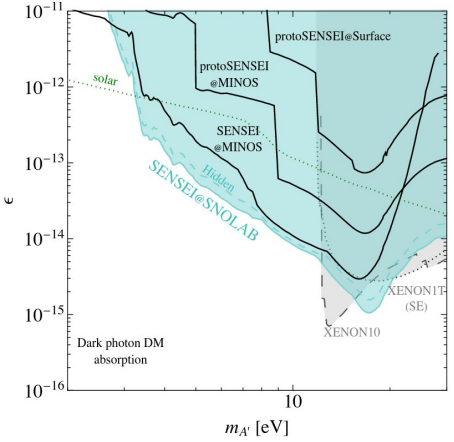
Heavy mediator



Heavy mediator (migdal)

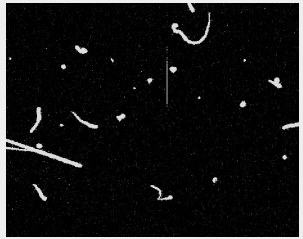


Absorption

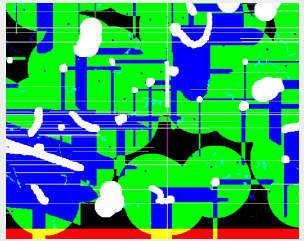


Quality cuts

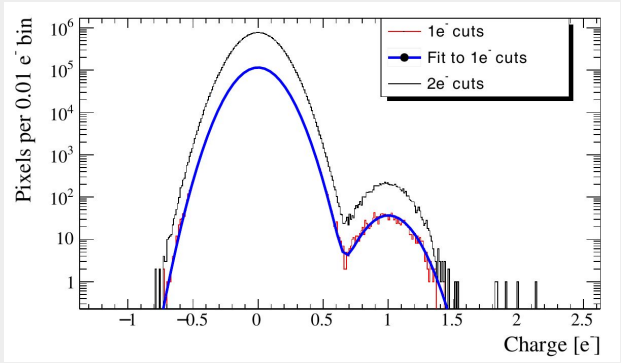
Cuts \ N_e	1		2		3		4	
1. Charge Diffusion	1.0		0.228		0.761		0.778	
	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev	Eff.	#Ev
2. Readout Noise	1	$> 10^5$	1	58547	1	327	1	155
3. Crosstalk	0.99	$> 10^5$	0.99	58004	0.99	314	0.99	153
4. Serial Register	~ 1	$> 10^5$	~ 1	57250	~ 1	201	~ 1	81
5. Low-E Cluster	0.94	42284	0.94	301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



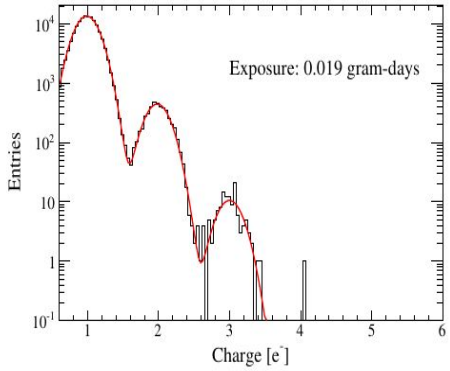
Example image



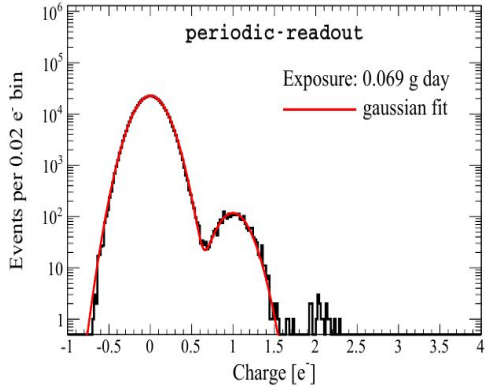
Masking



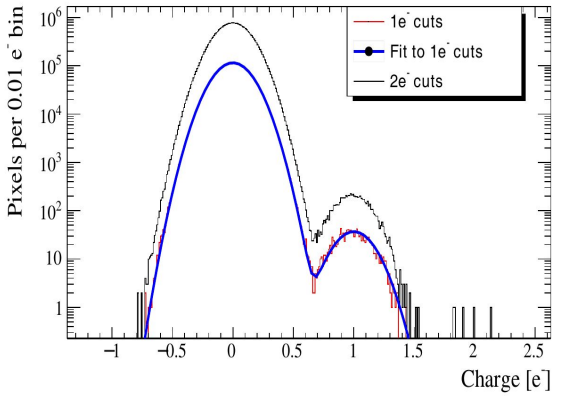
Summary: from prototype to science grade



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**



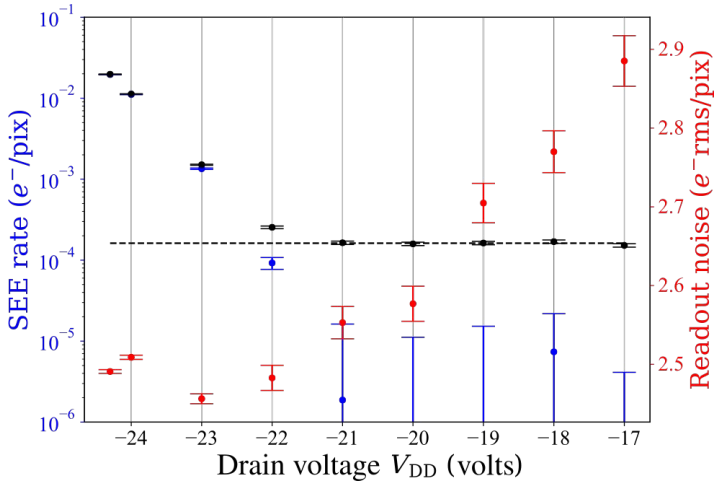
Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
SEE ~ **1.6×10^{-4} e-/pix/day**

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)

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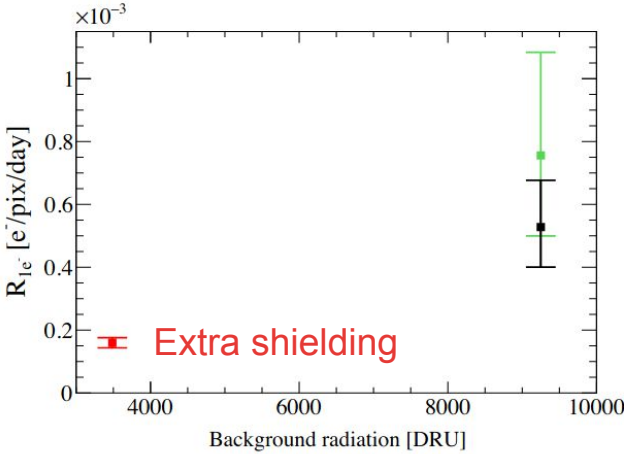
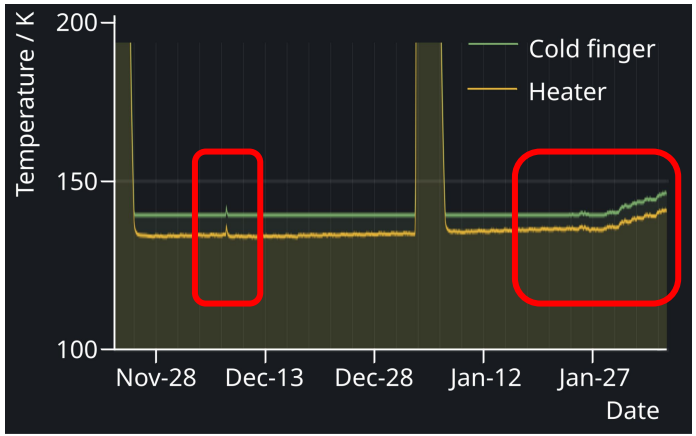
High-energy:
- Air shower muons
- Nuclear decays
- x/ɣ-rays

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

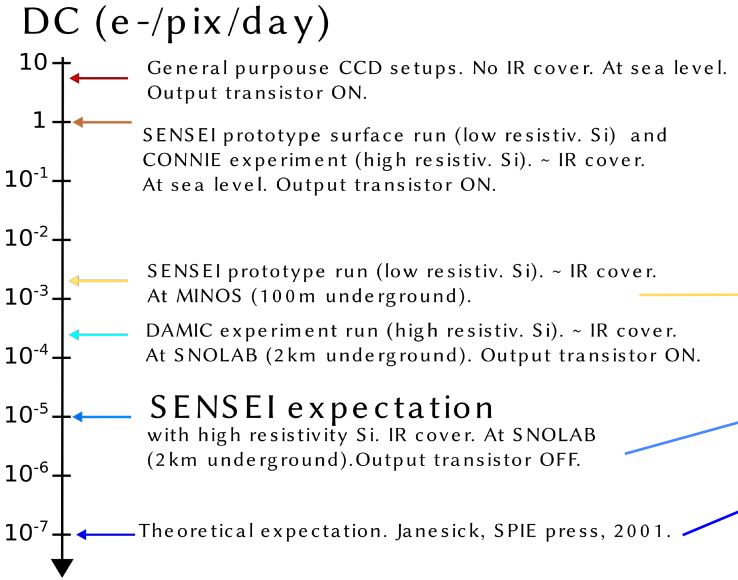
Environmental background is reduced with shielding, and removed from data with quality cuts



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


Temperature / K
200
150
100
Cold finger
Heater
Nov-28
Dec-13
Dec-28
Jan-12
Jan-27
Date

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