The SENSEI Experiment: An Ultrasensitive Search for Sub-GeV Dark Matter

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IFIBA - CONICET/FNAL
for the SENSEI* Collaboration

@ 2022 IDM

*Sub-Electron-Noise Skipper-CCD Experimental Instrument

The SENSEI Collaboration

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- L. Barak, I. M. Bloch, E. Etzion, A. Orly, T. Volansky
- T.-T. Yu
- M. Cababie, D. Rodrigues
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Fermilab

Stony Brook University

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

UNIVERSITY OF OREGON

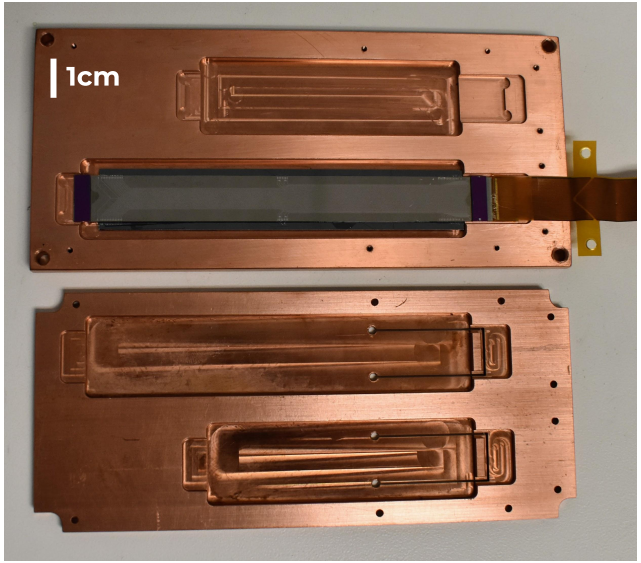
IFIBA UBA CONICET

SNOLAB

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

HEISING-SIMONS FOUNDATION

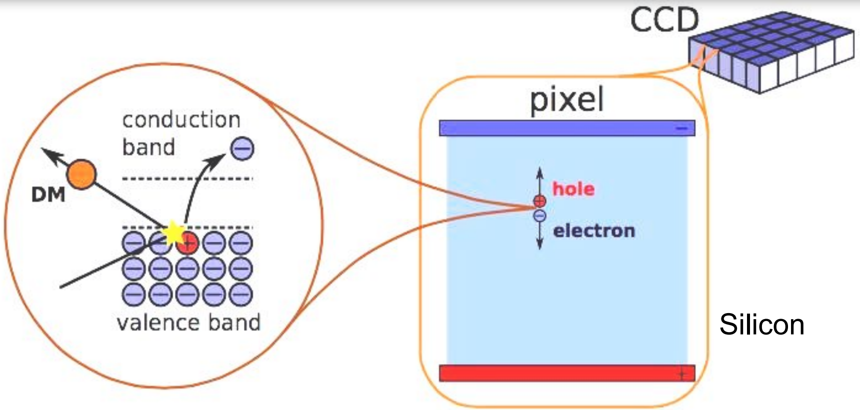
The SENSEI Experiment

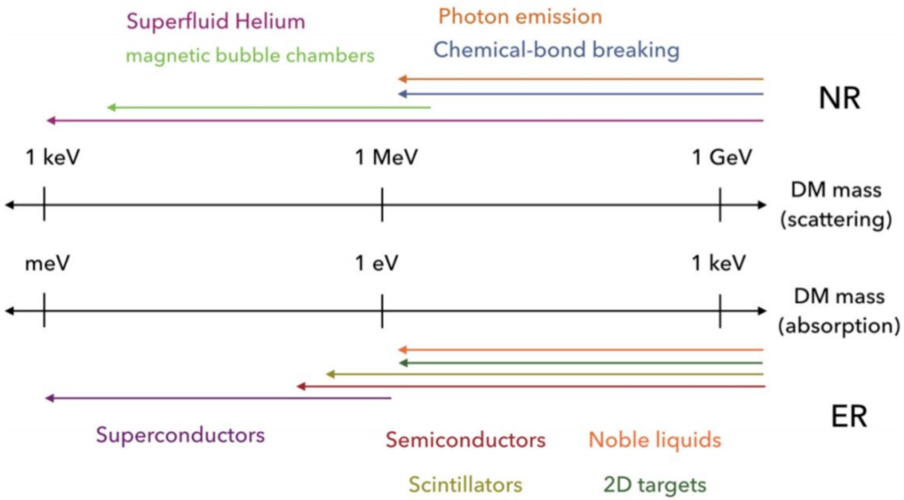


- **New generation** Si Charge-Coupled Devices (DAMIC, DAMIC-M, OSCURA)
- Probes sub-GeV DM via **e- recoil** and (~eV) DM **absorption**
- Sub-electronic (**~0.1 e-**) readout noise
- Energy threshold as low as **~1.1 eV** (Silicon bandgap)
- Lowest dark current (**~1e-4 e-/pix/day**) in Silicon semiconductors
- Developed by **LBNL** MicroSystems Lab Energy

Electron recoils for sub-GeV DM in Skipper-CCDs

- Benchmark models:
  - DM-e⁻ scattering, DM absorption
- Silicon CCDs as ionization detectors
  - DM-e⁻ interaction (or absorption)
  - Energy transfer via electron recoil
  - Ionized h^+ are captured by potential well
  - Signal is readout after exposure is finished.
- DM range mass: 1-1000 MeV
  (~eV on DM absorption)





arXiv:1707.04591

Electron recoils for sub-GeV DM in Skipper-CCDs

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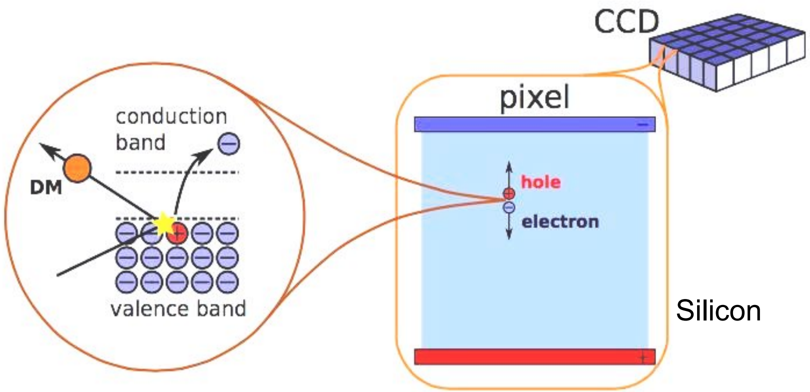
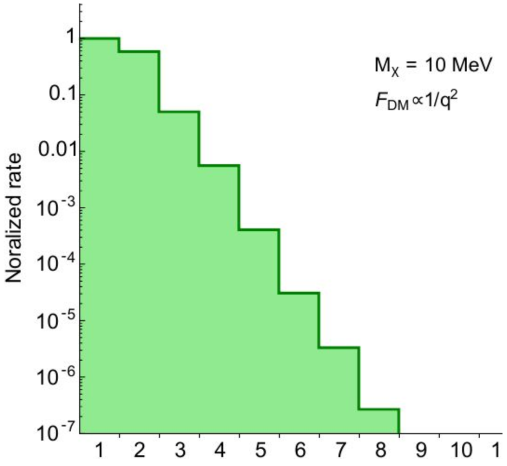
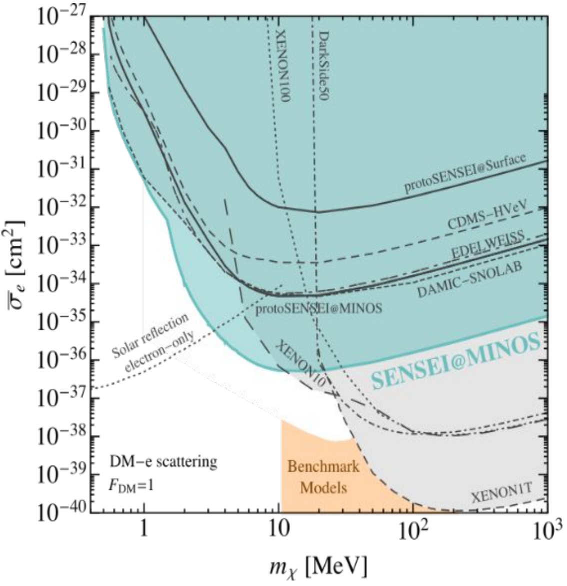




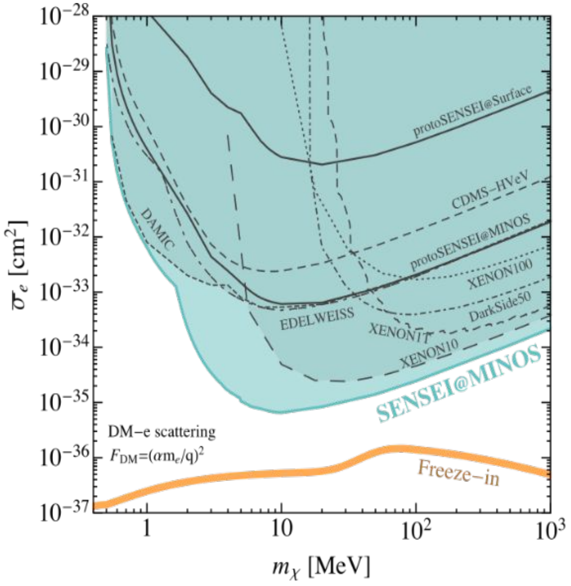
R. Essig et al, JHEP 05 (2016), 046

Latest Results: SENSEI@MINOS

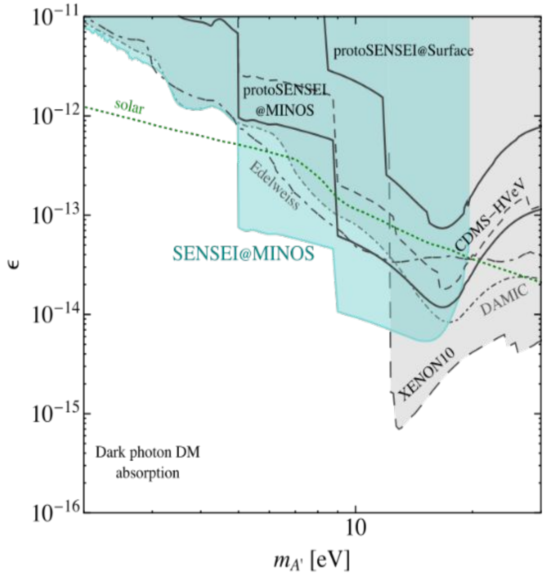
Heavy mediator e- scattering



Light mediator e- scattering

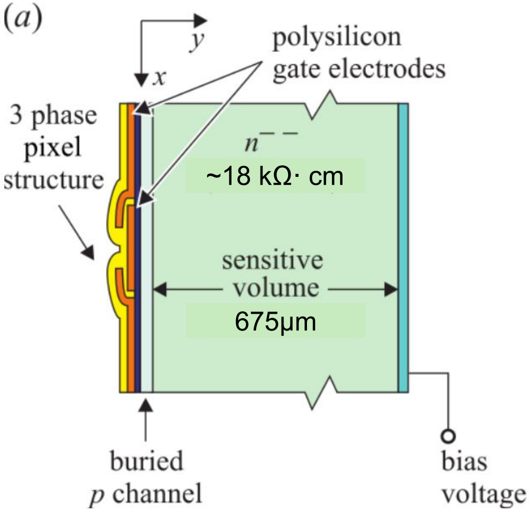


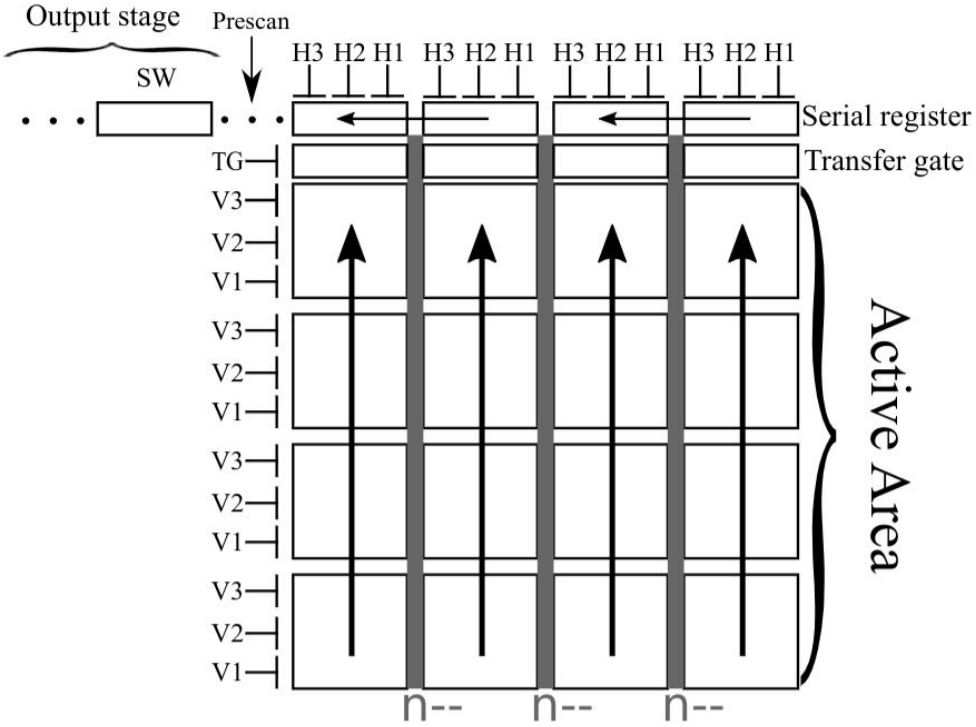
Absorption



CCD basics

- **CCD = pixelated silicon array**
- **~2g** per device of high-resistivity fully-depleted silicon
- **>99.9%** charge collection and transfer efficiency
- **~5.5Mpixels** of 15x15x675 μm^3 each





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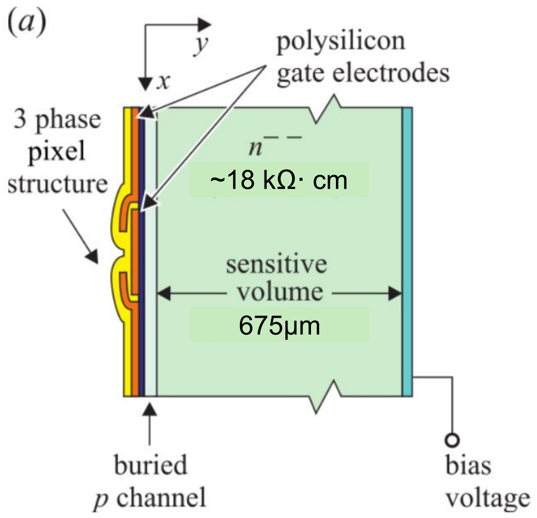
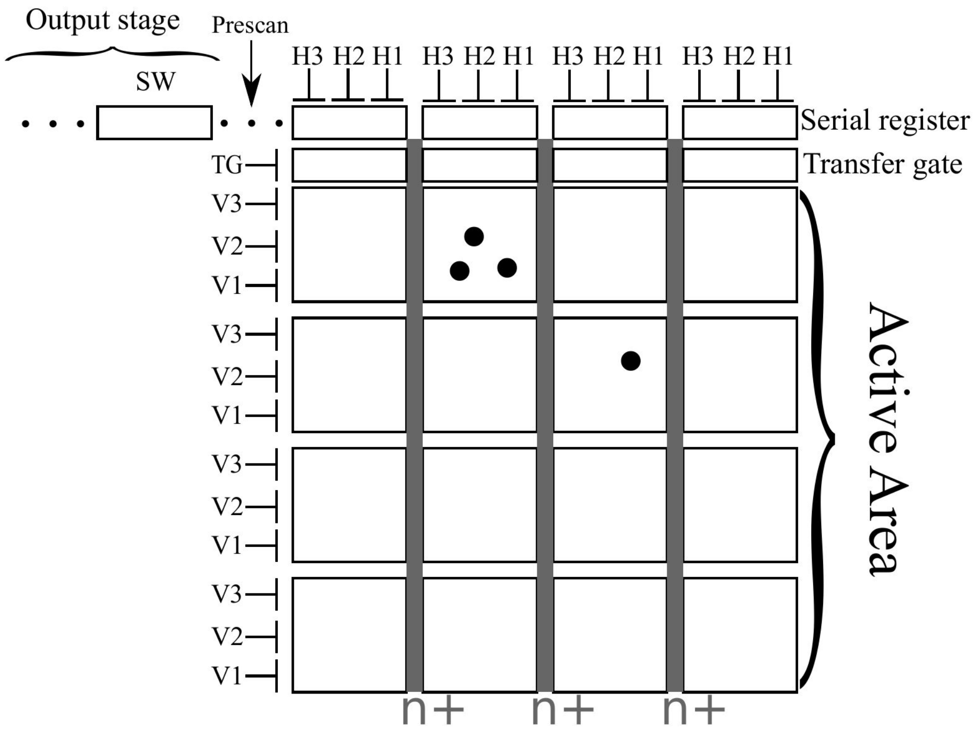




Skipper-CCD basics

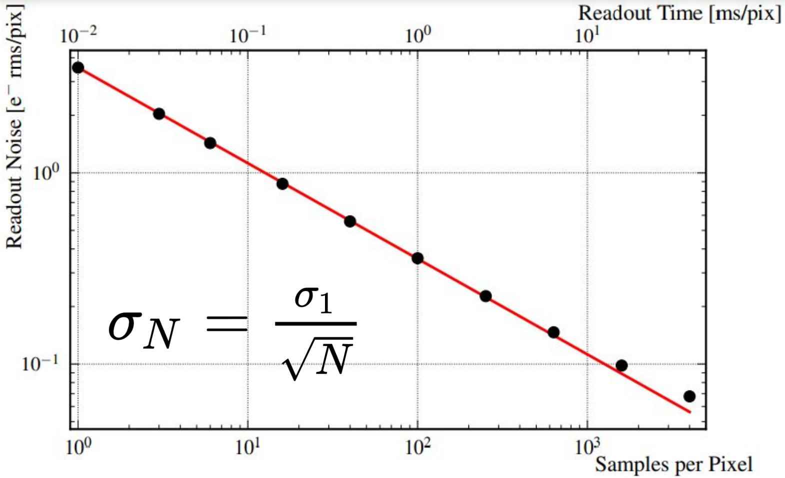
- DM range **mass**: 1-1000 MeV (~eV on DM absorption)
  - Very small **signals**
    - Very low energy **threshold**

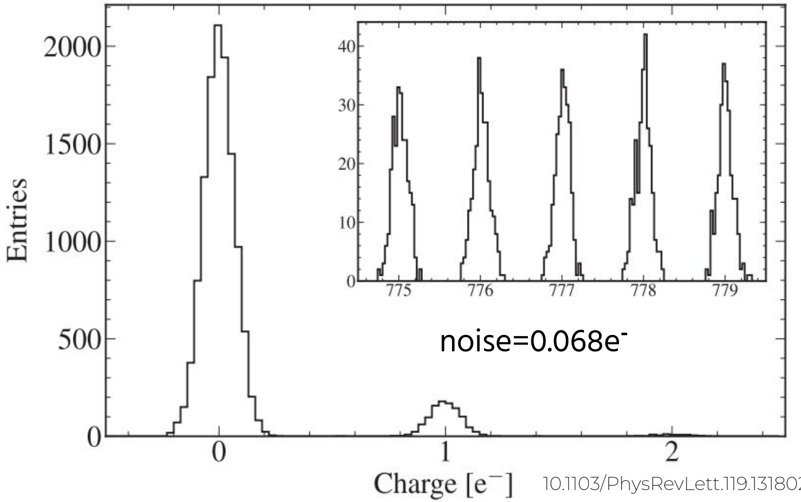
- *Skipper* technology allows to read repeatedly the *same pixel* to achieve **sub-electron noise**

- ~2e$^-$ readout noise and **<0.1e$^-$** using *skipper* technology

- Low energy threshold down to **~1.1eV** (Si band gap)

- Capability of unambiguously **count clusters** of few electrons





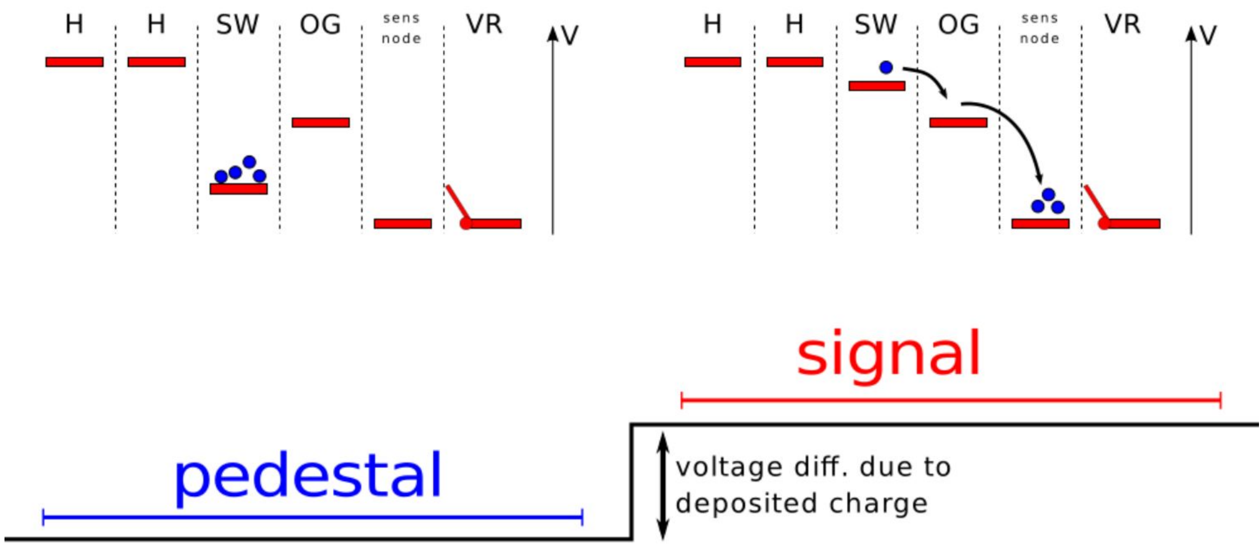
10.1103/PhysRevLett.119.131802

Skipper-CCD basics

- In a conventional CCD, charge is moved to the sense node and readout **once**.
  Then it is **drained** and charge is **lost**.

- Longer integration reduces noise but cannot reduce **1/f** noise.

- Skipper-CCD moves charges towards and backwards the floating sense node to achieve multiple readout



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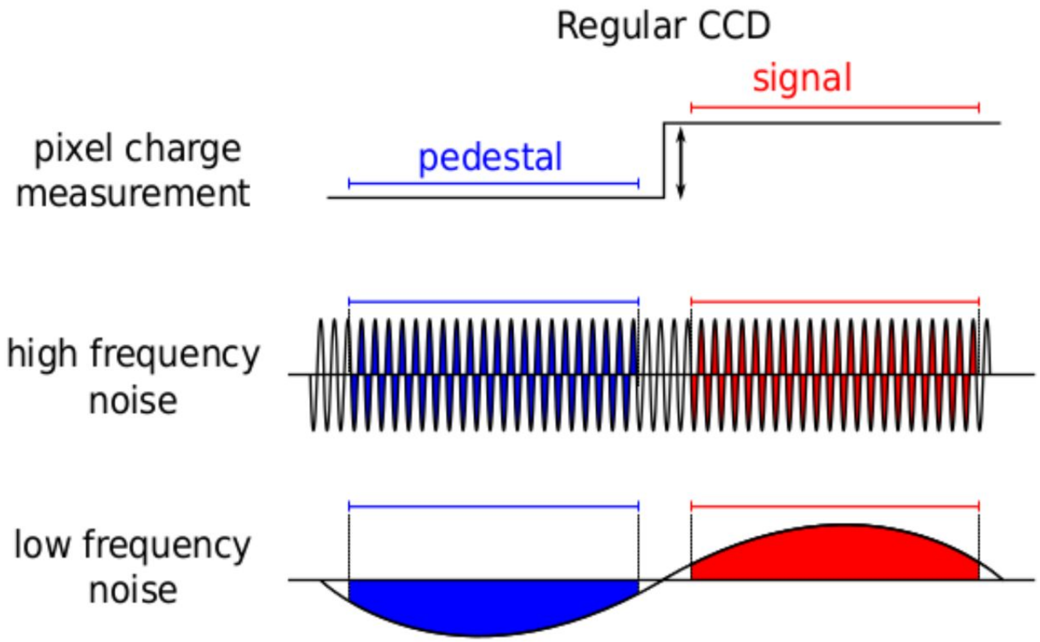

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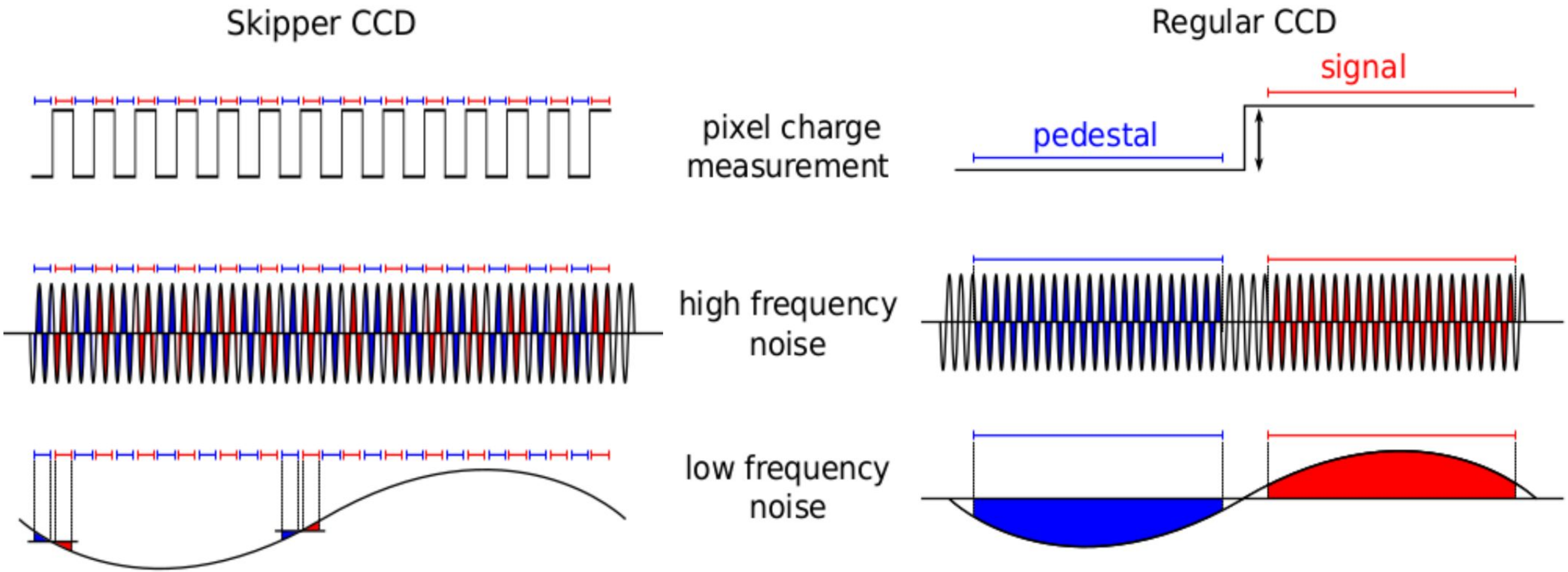
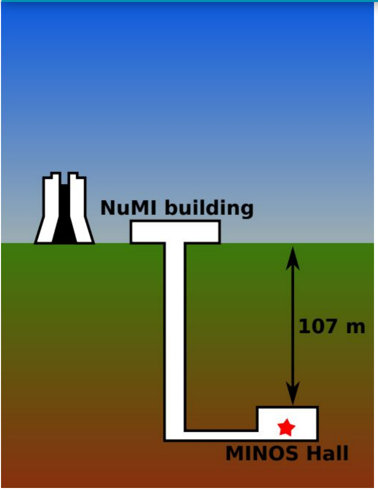
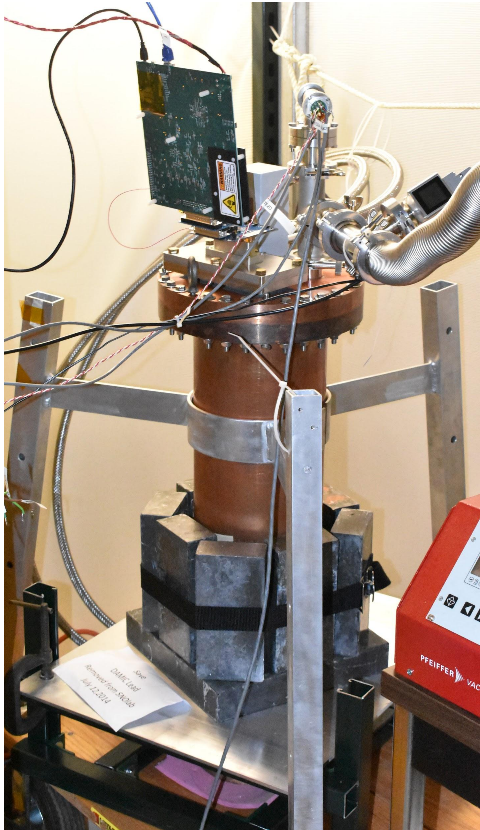


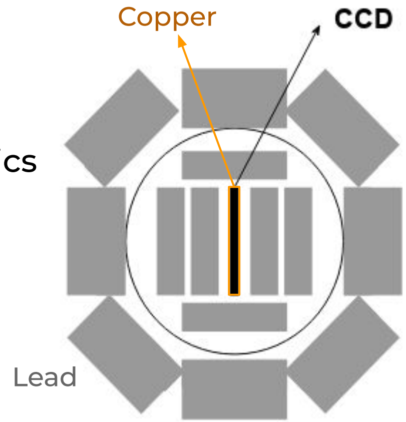
MINOS2020 setup: location and shielding



- Setup **~107m below surface** at shallow underground MINOS site @FNAL.
- Underground site reduces **muon** environmental radiation
- Inner (1" each) and outer (2" each) lead bricks reduces **gamma** environmental radiation
- Copper module for **IR** radiation



- Temperature at **135K** and high-vacuum regime to reduce dark current without generating CTI
- Operated with specifically designed readout electronics (**LTA - Low Threshold Acquisition board**)



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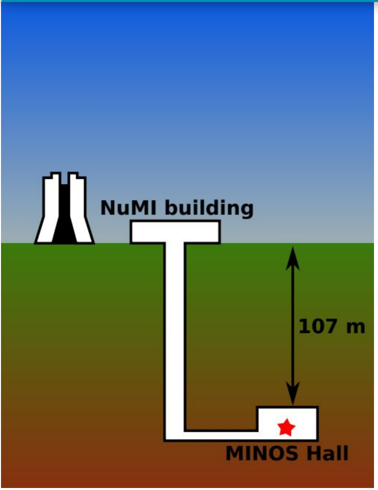

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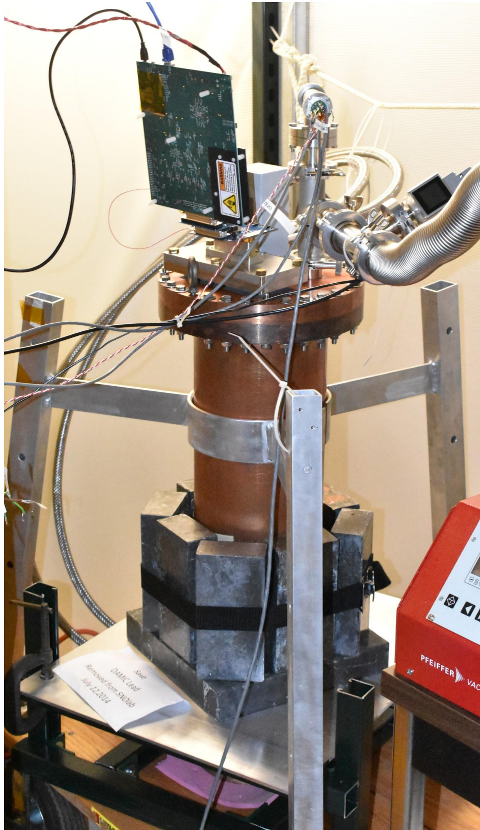

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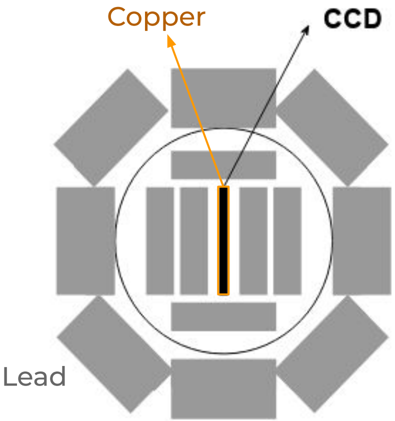
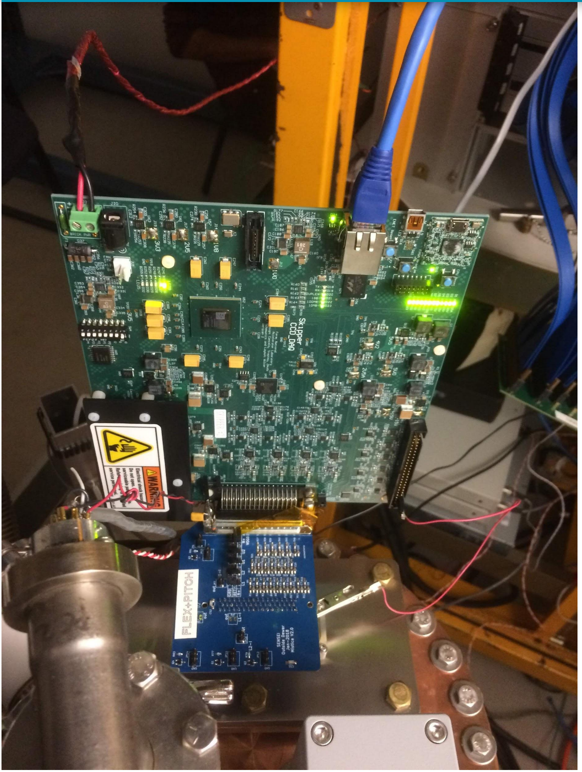
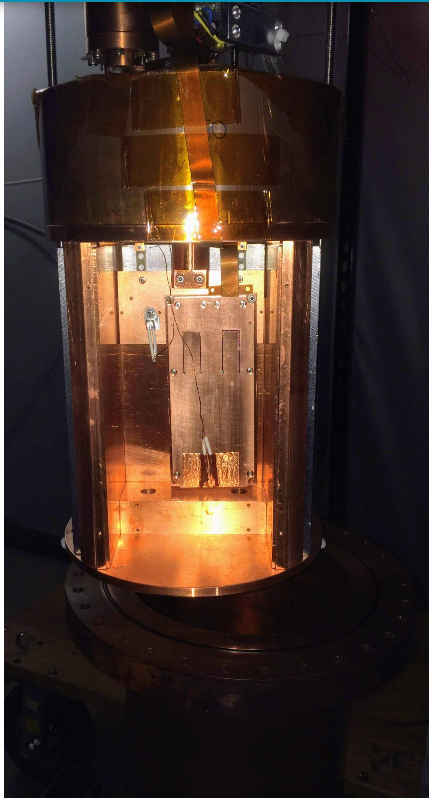


Electronics | Inside the Vessel



- Shielding design adapted from DAMIC: **cylindrical vacuum vessel** with lead “plugs” above and below the CCD
- Operated with specifically designed readout electronics (**LTA - Low Threshold Acquisition board**)
- LTA boards admit multiple reading of multiple CCDs synchronously which enables **scaling**



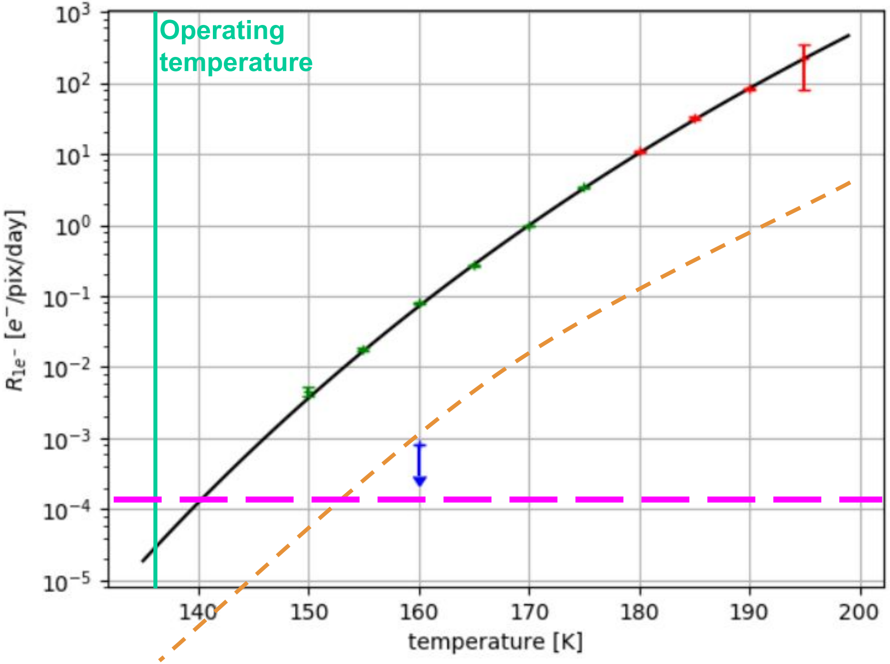
Single Electron Event (SEE) contributions

Contribution (e^-/pix)		Time dependence: Linear – Exposure	Time dependence: Linear – Readout	Time dependence: Independent	Spatial distribution
Dark current	Intrinsic	$\lambda_{\mathrm{DC}}\, t_{\mathrm{EXP}}$	$\frac{\lambda_{\mathrm{DC}}}{2}\, t_{\mathrm{RO}}$	-	Uniform
	Extrinsic				Uniform
Amplifier-light current		-	$\lambda_{\mathrm{AL}}\, t_{\mathrm{RO}}$	-	Localized
Spurious charge		-	-	μ_{SC}	Uniform

$$\mu_{(t_{EXP},t_{RO})} = \lambda_{DC}\, t_{EXP} + \left(\frac{\lambda_{DC}}{2} + \lambda_{AL}\right) t_{RO} + \mu_{SC}$$

→ Even though sub-electron readout noise allowed us to take a closer look into SEEs and DC, it was found in 2020 that our DC rate is way higher than the theoretical one at 135K:

$$1.6 \times 10^{-4} e-/pix/day >>\sim 1 \times 10^{-6} e-/pix/day$$



Dark Current = (Surface + Bulk) Dark Current

DOI: 10.1103/PhysRevLett.125.171802

Dark current

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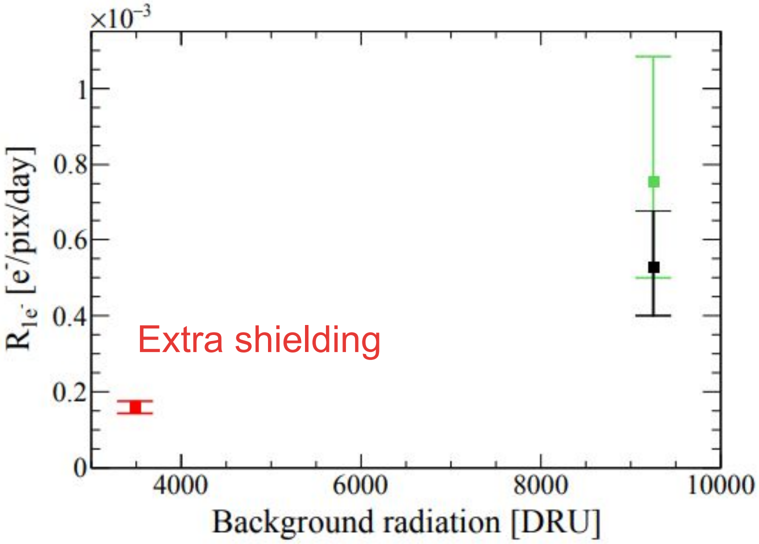
$$1.6 \times 10^{-4} e - /pix/day >>\sim 1 \times 10^{-6} e - /pix/day$$

→ Origin? Essig et al. (2011.13939) proposed the source of this discrepancy may come from the interaction of high energy events with the CCD as it is was hinted in SENSEI2020@MINOS:



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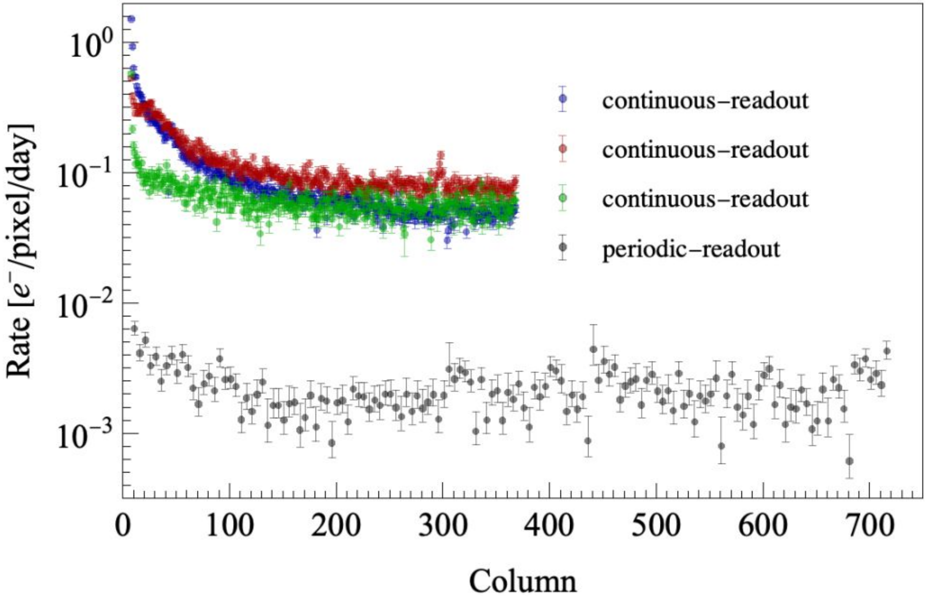
Amplifier light

→ Increases linearly with time but spatially localized near the readout stage.

→ In SENSEI 2019 this effect was a huge SEE contributor



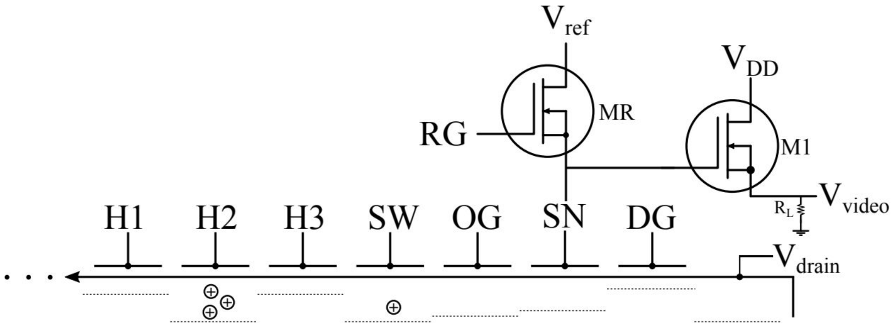


FIG. 2. Schematic illustration of a Skipper-CCD readout stage. H1, H2 and H3 are the last horizontal clocks in the serial register before the Summing Well (SW).

DOI: 10.1103/PhysRevLett.122.161801

Amplifier light study

→ How does M1 output transistor bias voltage affect light emission and readout noise?

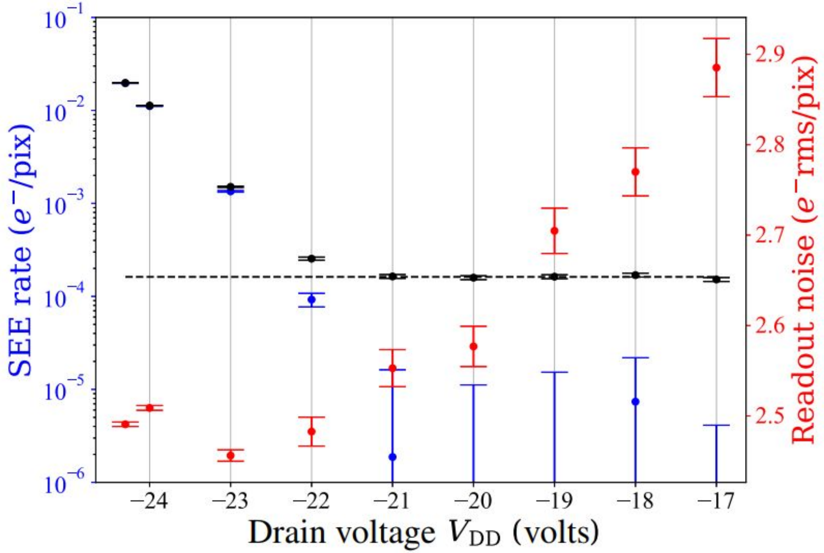


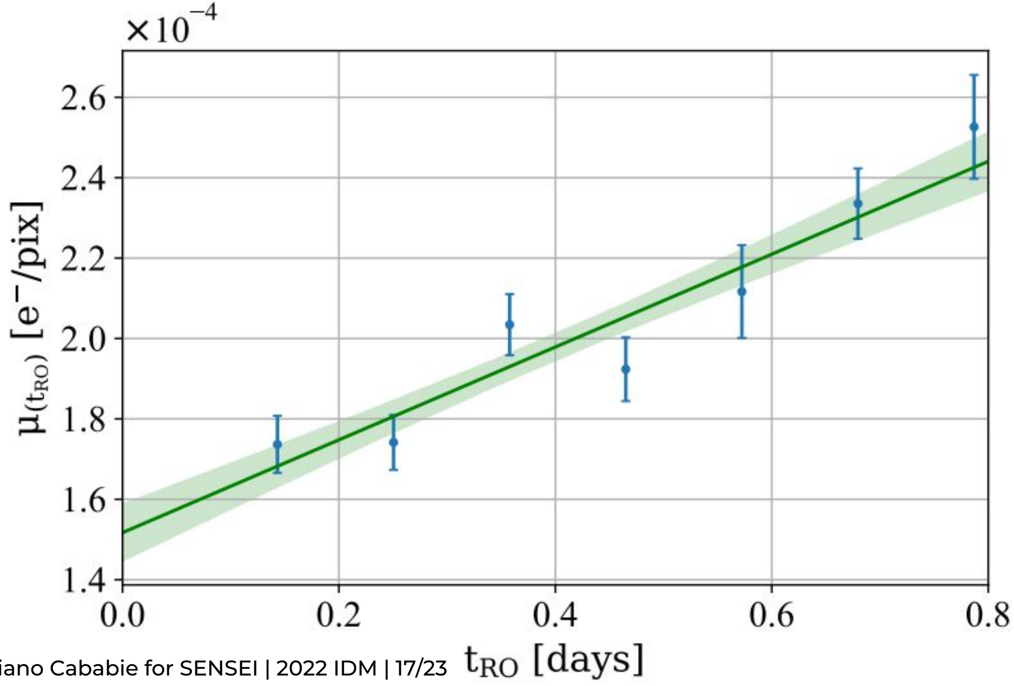
FIG. 5. SEEs per pixel (left axis) and single-sample readout noise (red, right axis) as a function of the drain voltage of the $M1$ transistor (V_{DD}). In black, we show the SEEs per pixel collected for each voltage ($\mu_{(t_{ro})}$) and in blue the AL contribution (μ_{AL}), estimated from Eq. (6). The black dashed line shows the estimation for μ_{SC}. Images are taken from dataset B.

V_{DD}	λ_{AL} (10^{-4} e^-/pix/day)
−21	(0.36 ± 0.18)
−22	(19.91 ± 1.26)

λ_{AL} and μ_{SC}

→ **Determination of λ_{AL} and μ_{SC}.** Change READOUT time, set EXPOSURE time to 0.

$$\mu(t_{RO}) = \left(\frac{\lambda_{DC}}{2} + \lambda_{AL}\right) t_{RO} + \mu_{SC}$$



V_{DD}	μ_{SC} (10^{-4} e^-/pix)
−21	(1.52 ± 0.07)
−22	(1.59 ± 0.12)

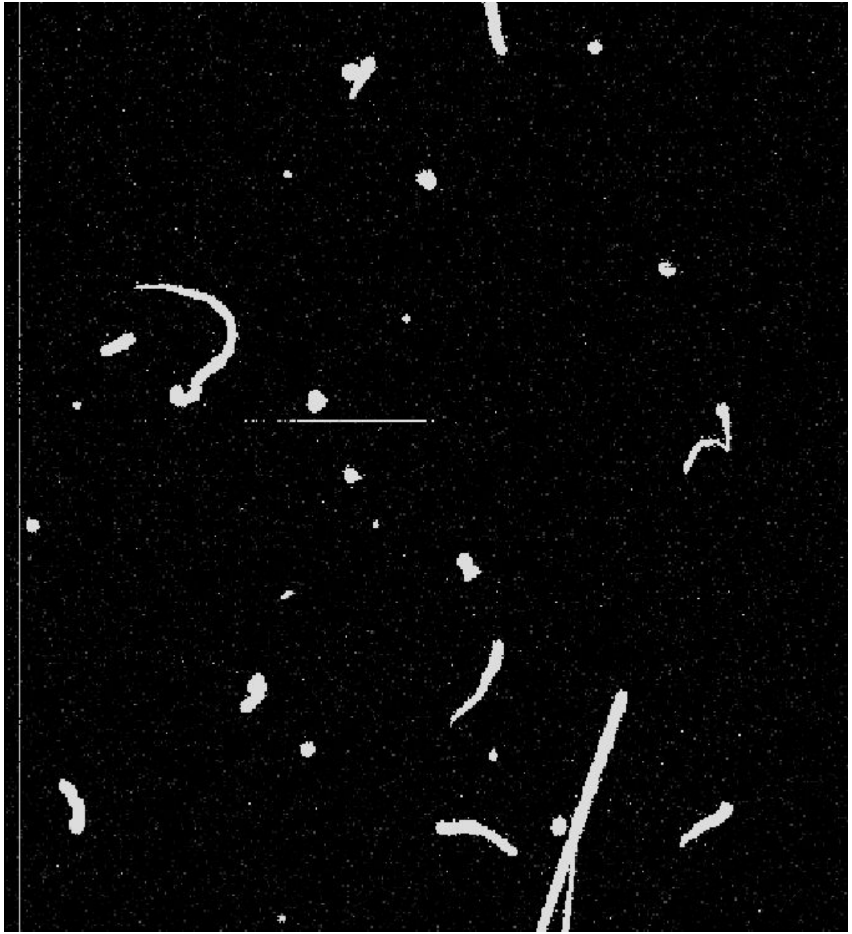
Single Electron Event (SEE) contributions

Contribution (e^-/pix)		Time dependence			Spatial distribution
		Linear		Independent	
		Exposure	Readout		
Dark current	Intrinsic	$\lambda_{DC}\, t_{EXP}$	$\frac{\lambda_{DC}}{2}\, t_{RO}$	-	Uniform
	Extrinsic				Uniform
Amplifier-light current		-	$\lambda_{AL}\, t_{RO}$	-	Localized
Spurious charge		-	-	μ_{SC}	Uniform

V_{DD}	External Shield	λ_{DC}	λ_{AL}	μ_{SC}
-21	Yes	(1.59 ± 0.16) 10^{-4} e^-/pix/day	(0.36 ± 0.18) 10^{-4} e^-/pix/day	(1.52 ± 0.07) 10^{-4} e^-/pix

DM search: quality cuts

- Bad pixels/columns
- Serial register hits
- Bleeding (CTI)
- Halo (SEE around tracks)
- Loose clusters (≥2e- analysis)



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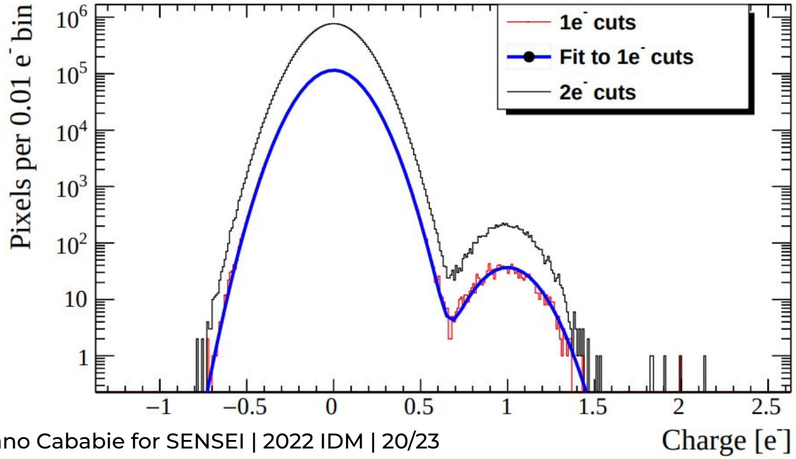
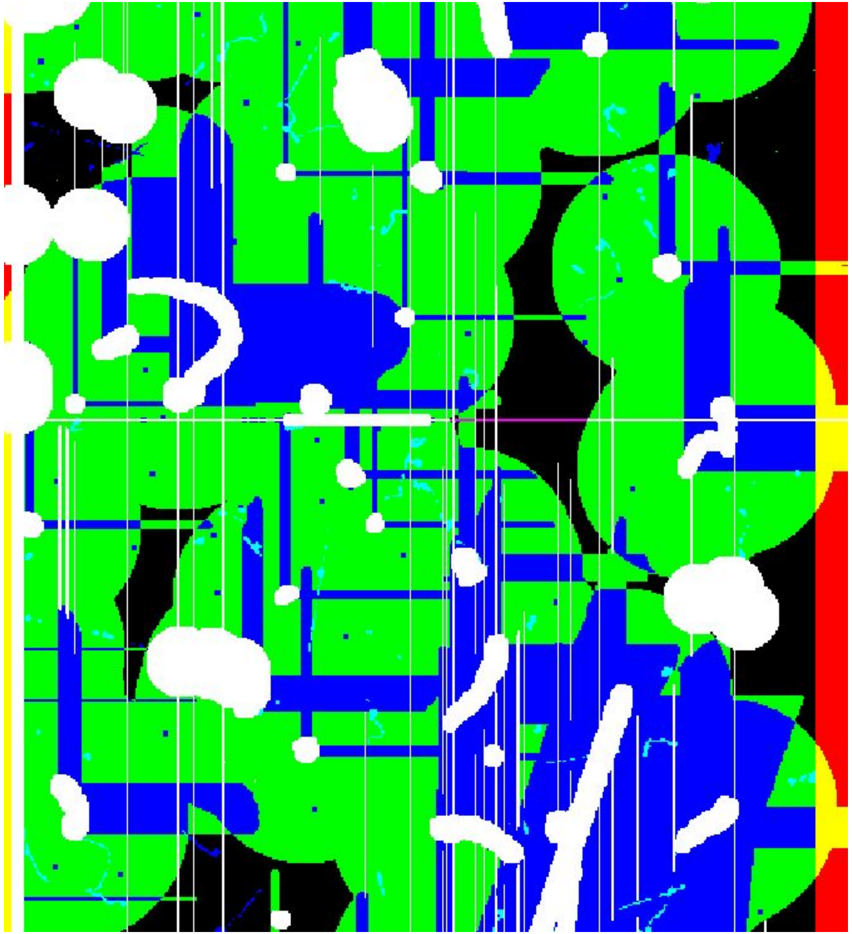


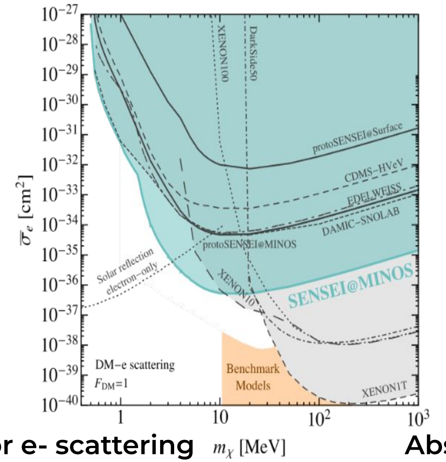


DM search: 2020 results

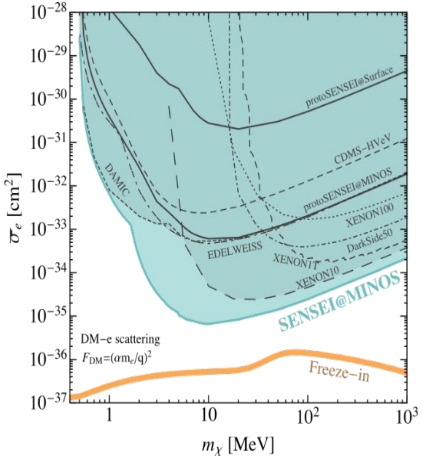
Open-data available in SENSEI papers

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 [g-day]$^{-1}$	525.2(*)		4.449		0.255		0.253	

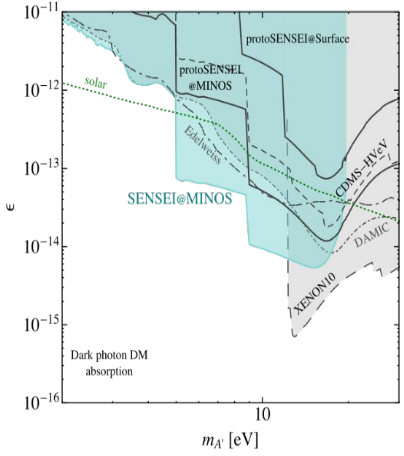
Heavy mediator e- scattering



Light mediator e- scattering



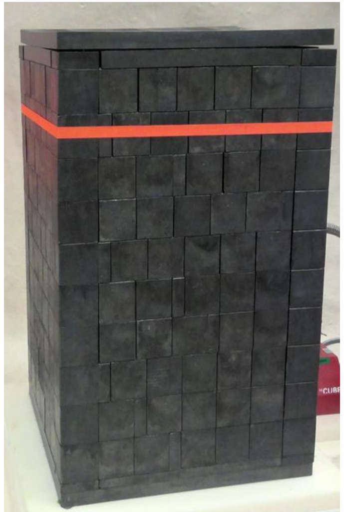
Absorption

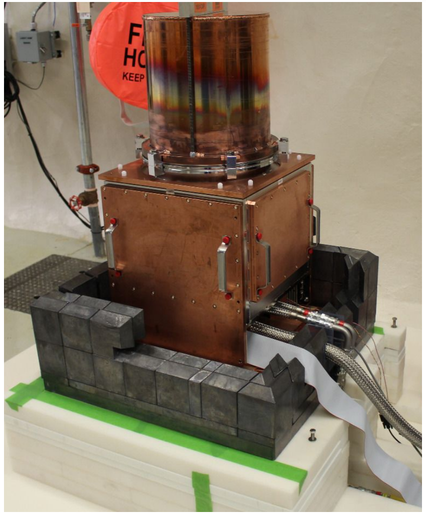


SENSEI@SNOLAB

- We're looking forward to new data from SNOLAB!
    - MINOS (standard shield): 10000 dru
    - MINOS (extra shield): 3000 dru
    - SNOLAB (final setup goal): **5 dru**

- ****Extraordinary**** support from SNOLAB during COVID-19 pandemic





- Commissioning of SENSEI@SNOLAB
    - 12 CCDs (**25g**) deployed.
    - Performance test runs.
    - People on-site last week!

- Final mass: **100g**

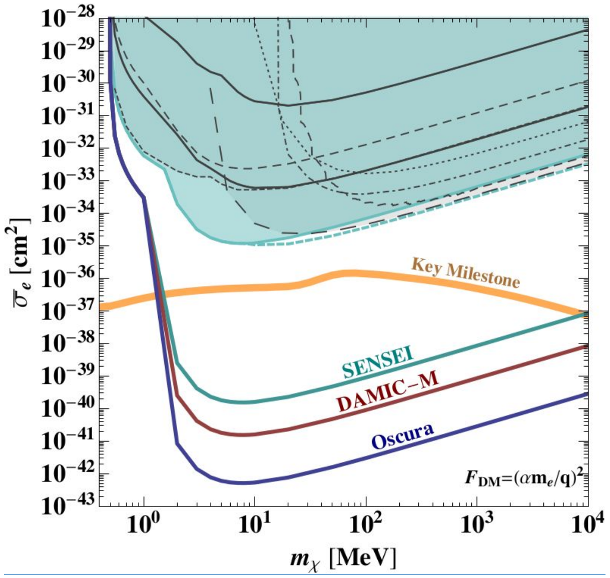
Just the beginning...

SENSEI
- 100g
- 2023

DAMIC-M
- 1kg
- ~2024

OSCURA
- 10kg
- ~2027

Light mediator e- scattering



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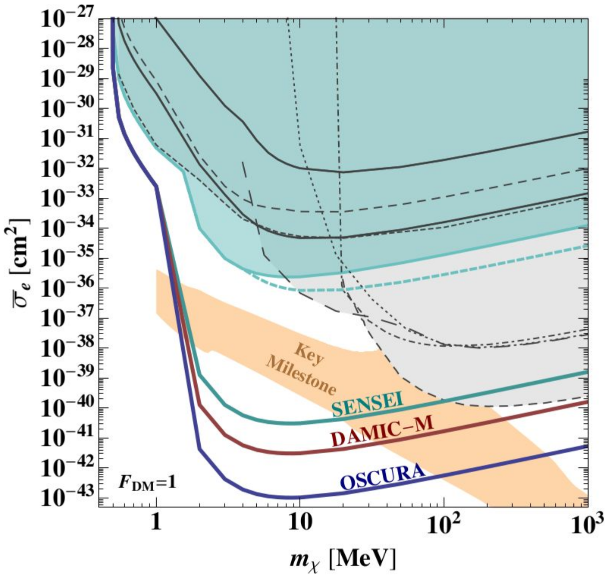
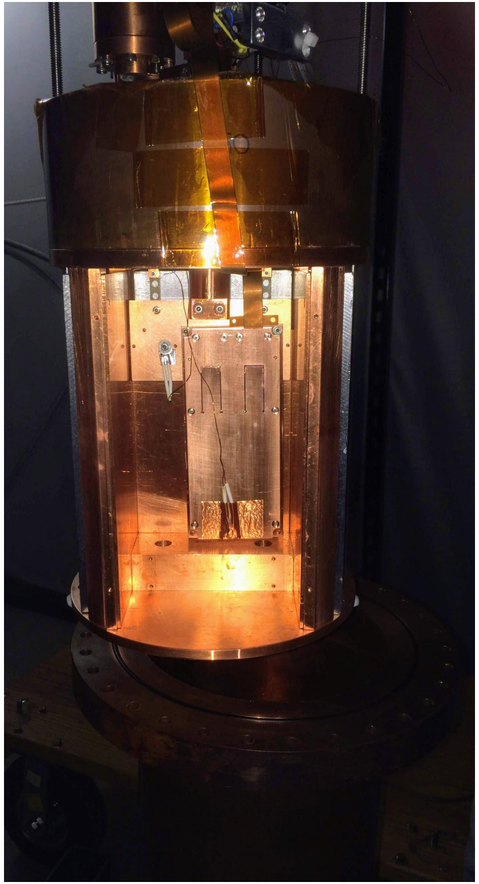
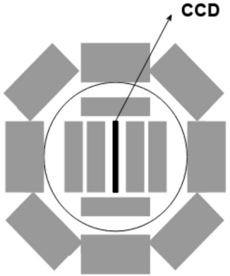


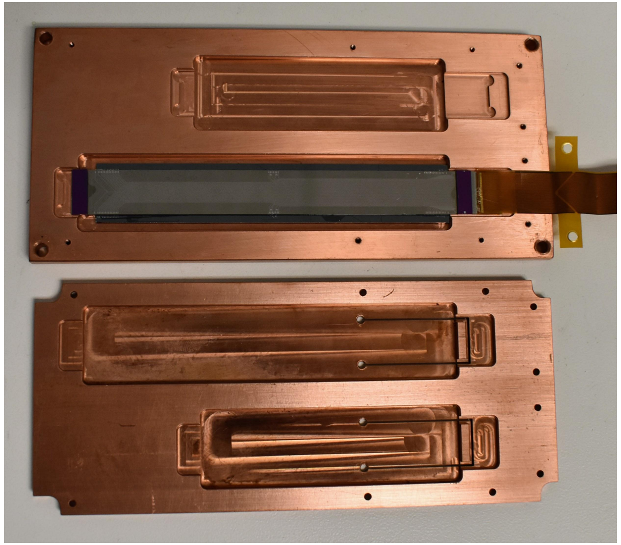
Thank you!
Any questions?

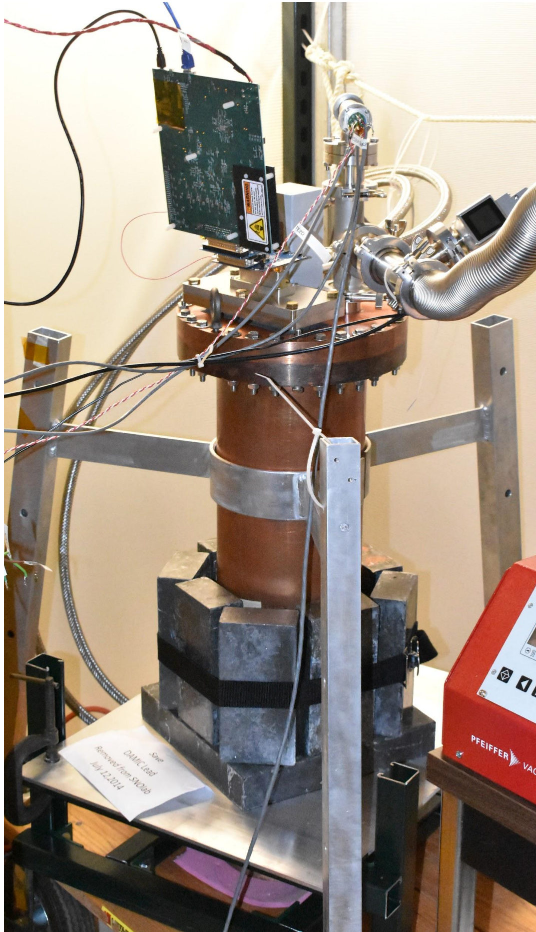
BACK UP SLIDES

MINOS shielding



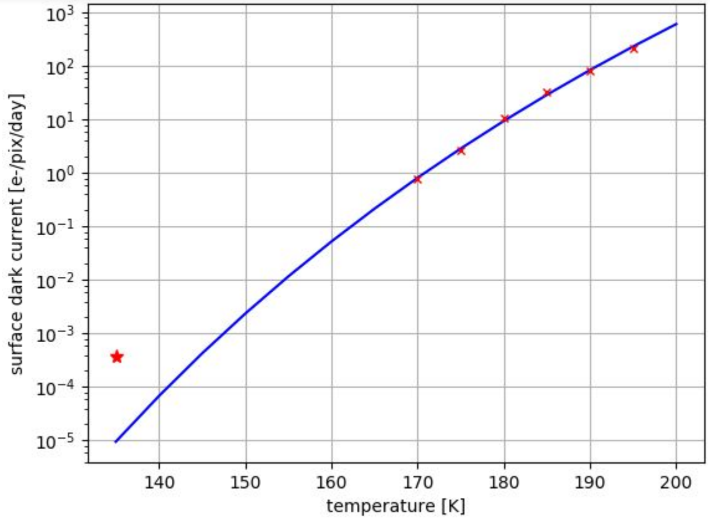




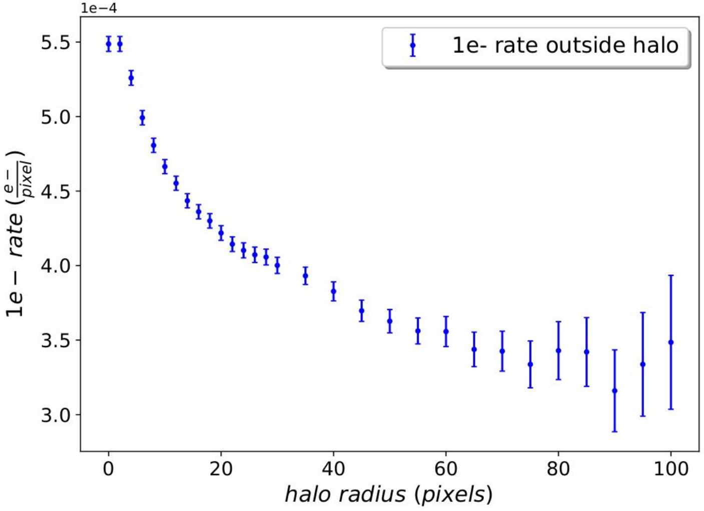


Our last result: single electron event rate

- A 1e- rate excess is found extrapolating from higher temperatures **assuming only surface DC**.

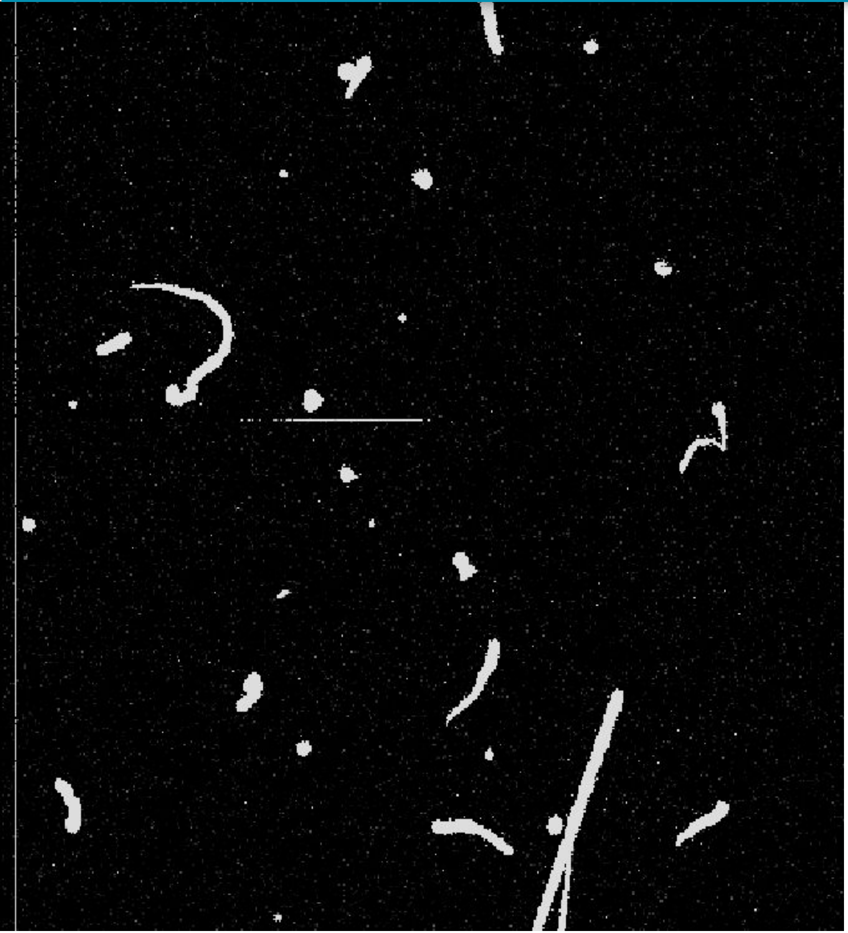


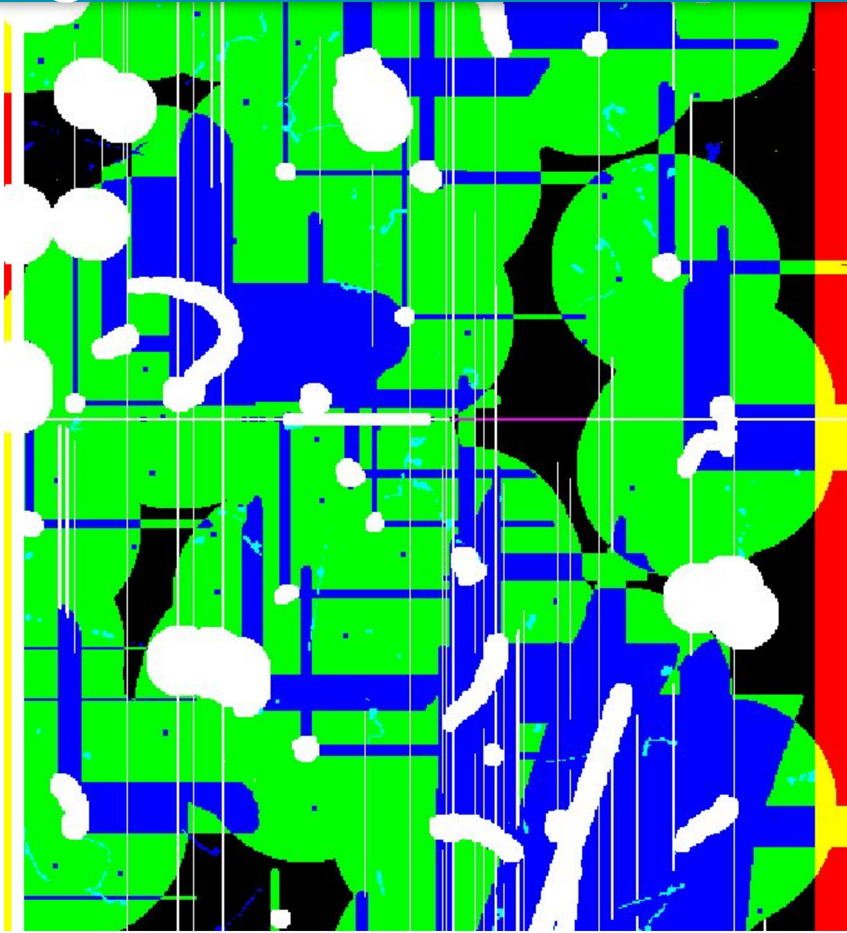
- Extrinsic or intrinsic sources?
  - RO stage luminescence, other DC
  - Diffusive light, related to high energy events



- Spatial correlation between high energy events (>360eV) and 1e- events.
- Low-energy photons? From copper module, CCD or both?
- Can we mask it up to 100%?

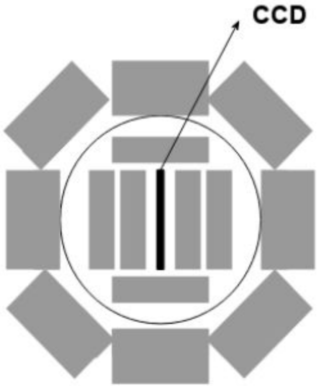
Sample image

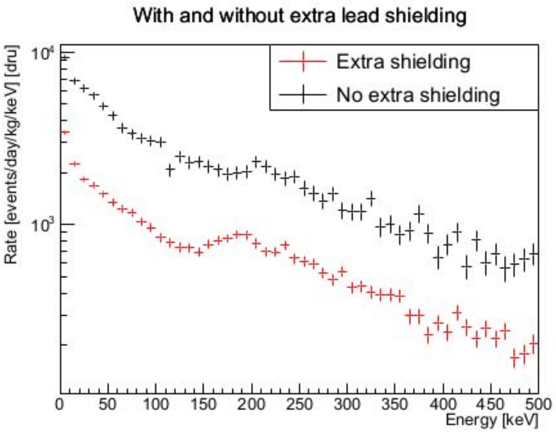


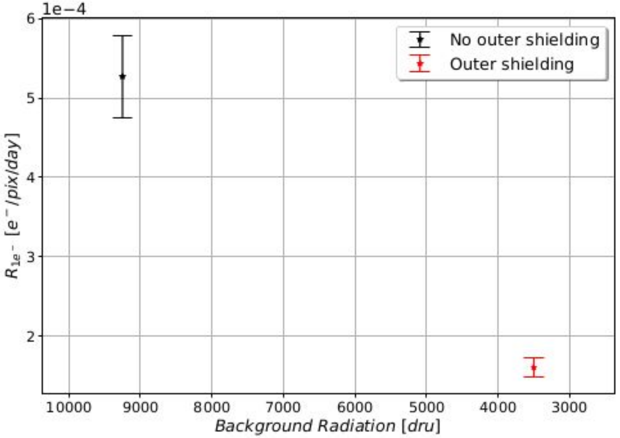


1e- rate vs. shielding

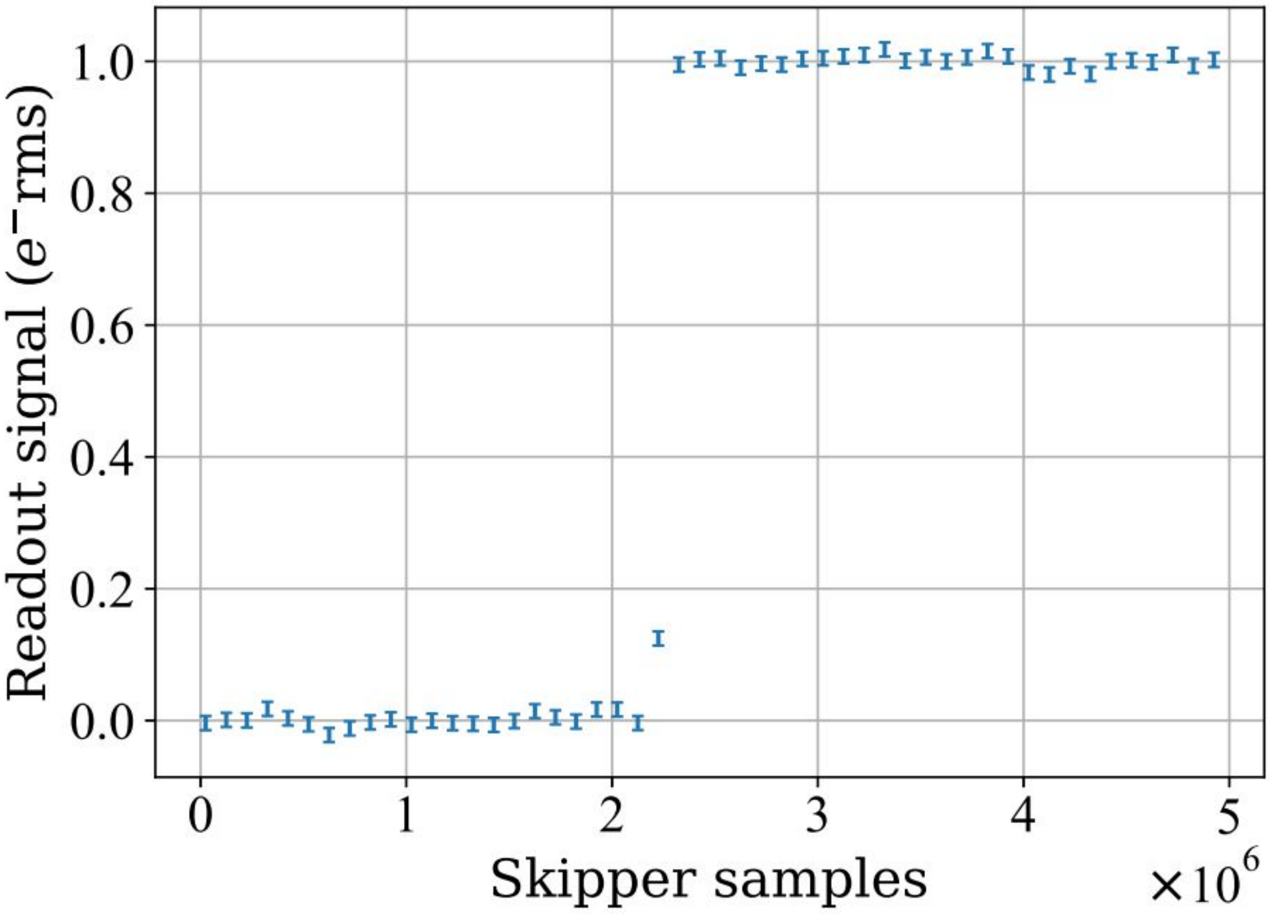
- We have data with and without the outer ring of lead bricks
- Factor of 3 reduction in the rate of high-energy tracks $\rightarrow$ factor of 3 reduction in the $1e^-$ rate
    - There is some mechanism by which ionizing radiation generates charge uniformly in our CCD
    - Better shielding will very likely further reduce our $1e^-$ rate







SC@Sense node



(1.1+-0.2) 10^{-5} e-/pix

~3×10^{-6} e-/pix

SENSEI@SNOLAB