The SENSEI Experiment: Origin and characterization of single-electron events

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TU Wien / HEPHY

for the SENSEI* Collaboration
2023 EXCESS@TAUP

*Sub-Electron-Noise Skipper-CCD Experimental Instrument

The SENSEI Collaboration

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- L. Barak, E. Etzion, A. Orly, T. Volansky, Y. Korn
- A. Desai, T.-T. Yu
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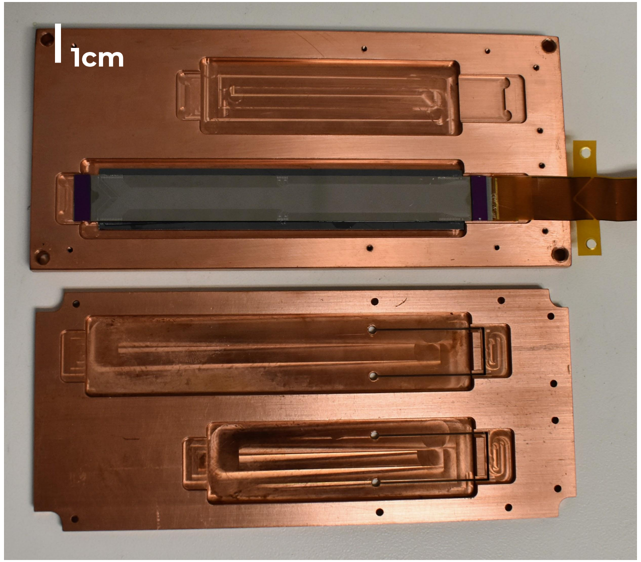
- I. Lawson, S. Luoma, S. Scorza
- I. M. Bloch
- S. Holland

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

The SENSEI Experiment

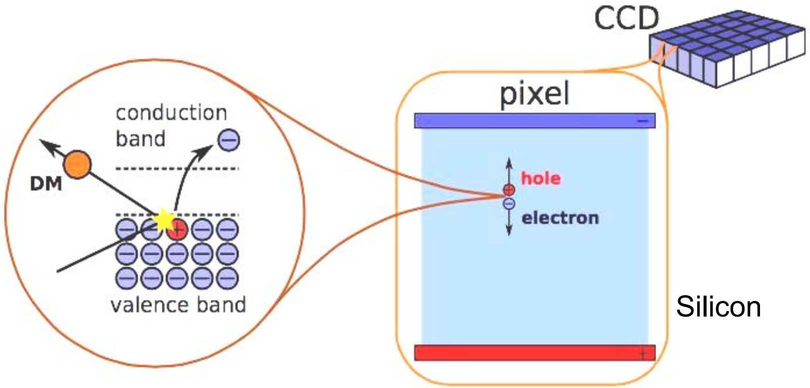


- Si Skipper Charge-Coupled Devices (SENSEI, DAMIC, DAMIC-M, OSCURA)
- Probes sub-GeV DM via **e- recoil** and (~eV) DM **absorption**
- Sub-electronic (**~0.1 e-**) readout noise
- Energy threshold as low as **~1.1 eV** (Silicon bandgap)
- Lowest single-electron rate (**~1e-4 e-/pix/day**) in Silicon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

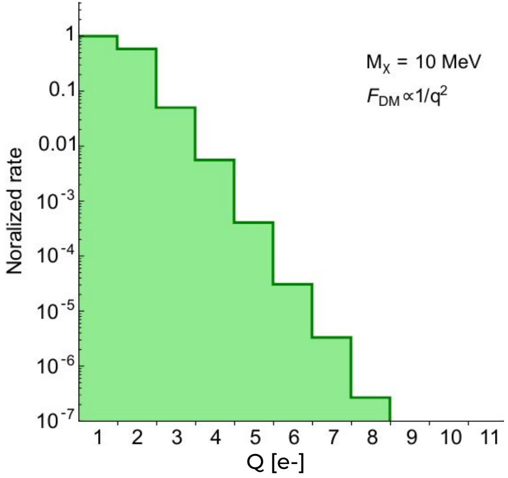
Electron recoils for sub-GeV DM in Skipper-CCDs

- DM candidates:
  - Sub-Gev DM-e^- scattering
  - Dark photon absorption
  - mCP (***new!*** arXiv:2305.04964)

- Silicon SCCDs as **ionization** detectors
  - Energy transfer via electron recoil (or absorption)
  - Ionized h^+ are captured and stored by SCCD.
  - Signal is readout afterwards.



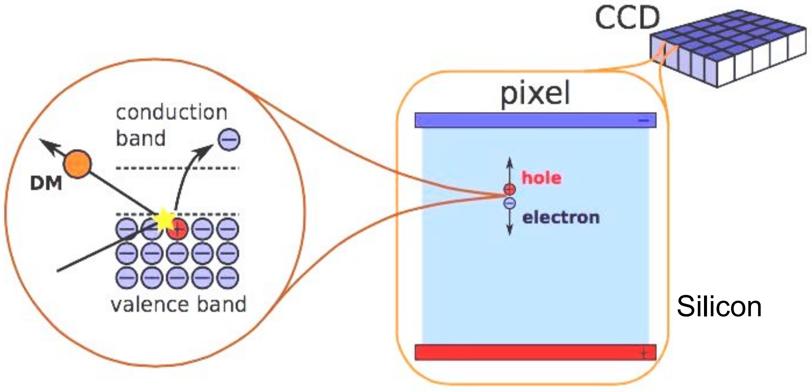
Expected spectrum for e- recoil

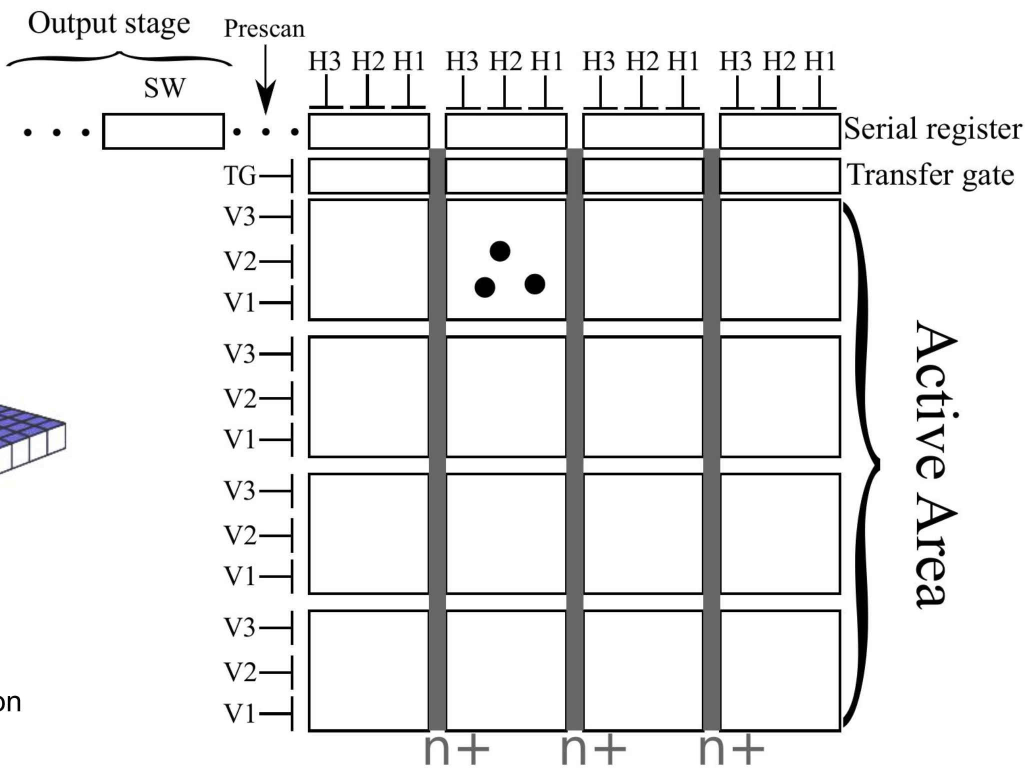


R. Essig et al, JHEP 05 (2016), 046

CCD basics

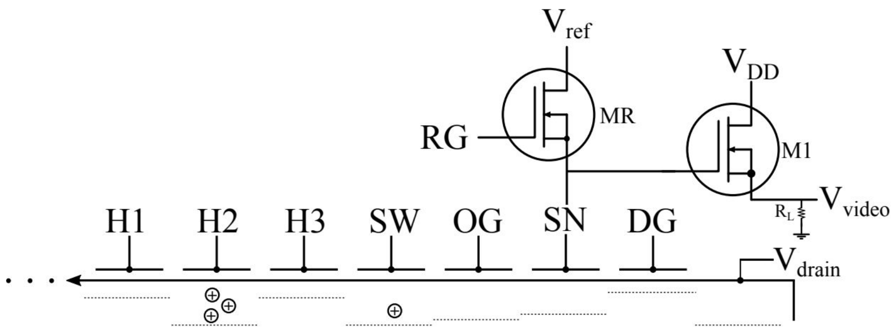
- **CCD = pixelated silicon array**
- **Collect, store and read**
- **~2/2.5g** per device
- ~5.5Mpixels of **15x15**x675 μm^3 each





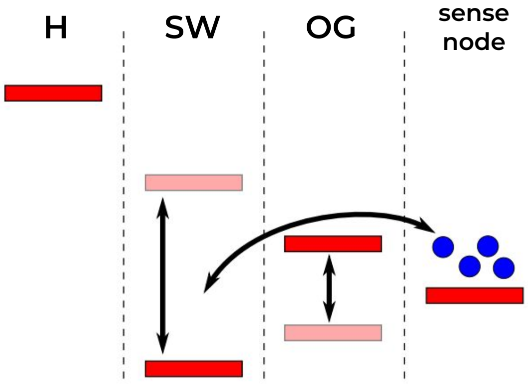
Skipper-CCD basics

- 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 non-destructive readout**

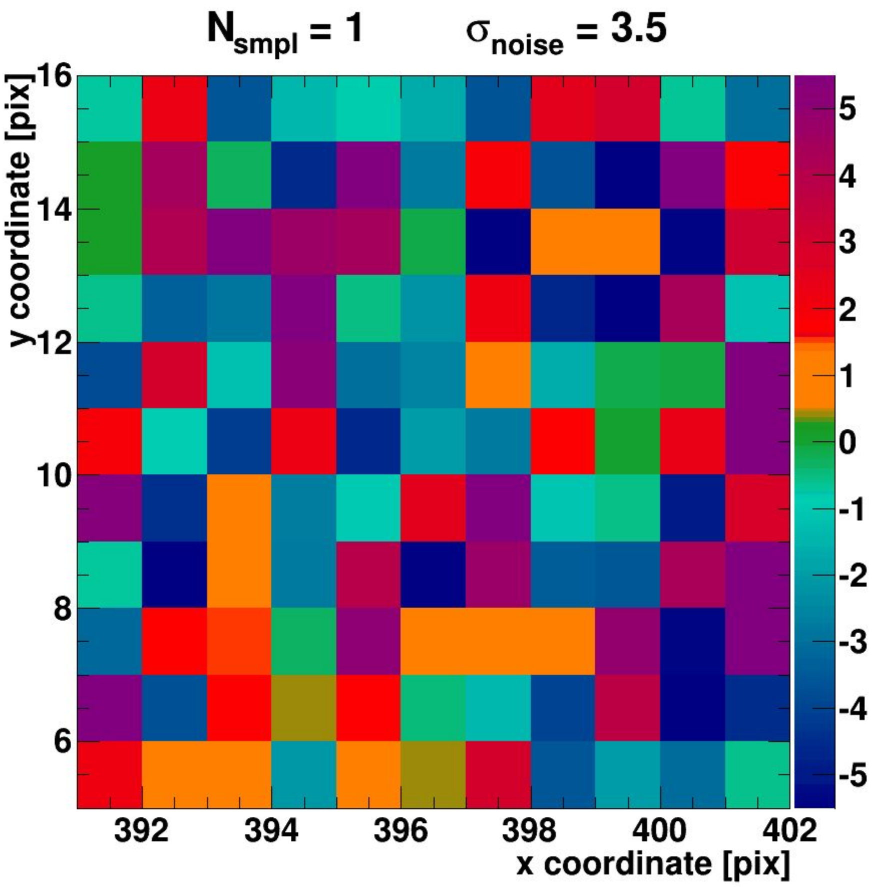


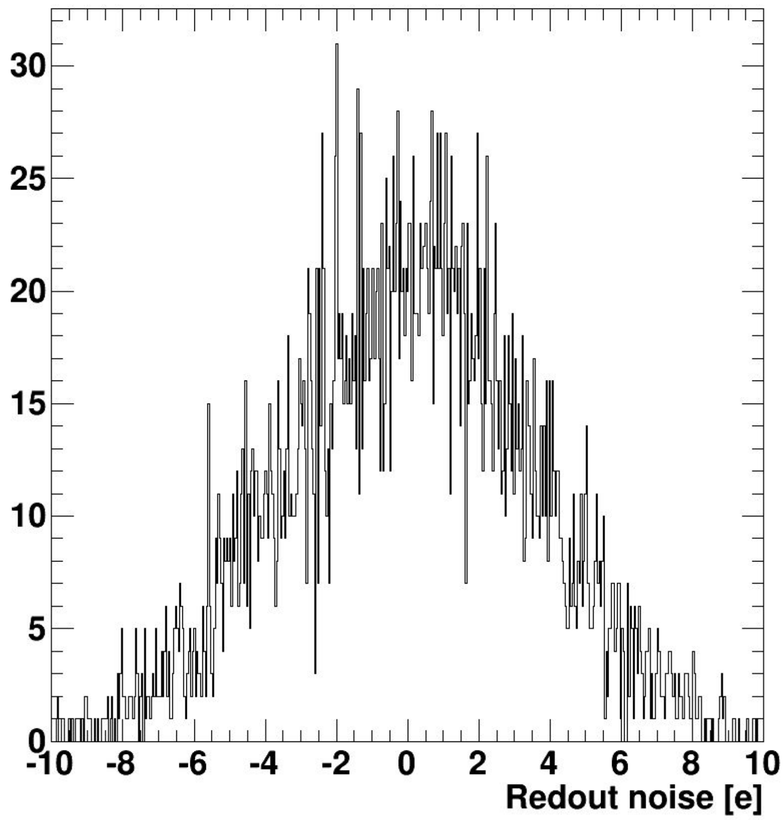
Skipper-CCD output stage

The Skipper technology



Skipper-CCD basics





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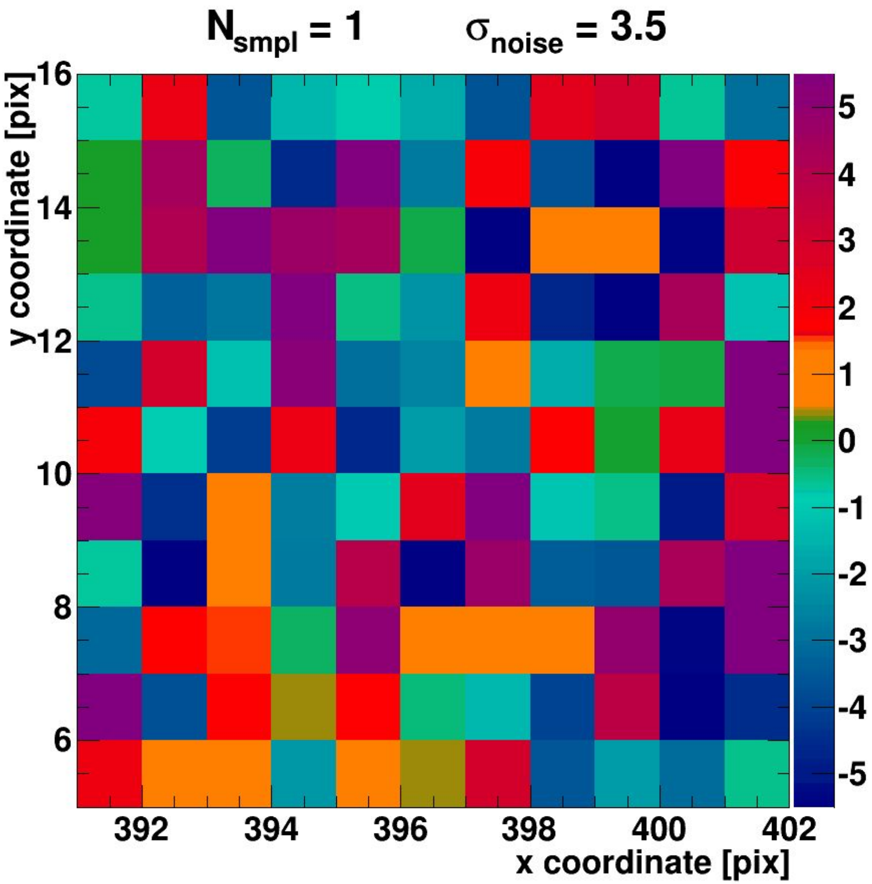
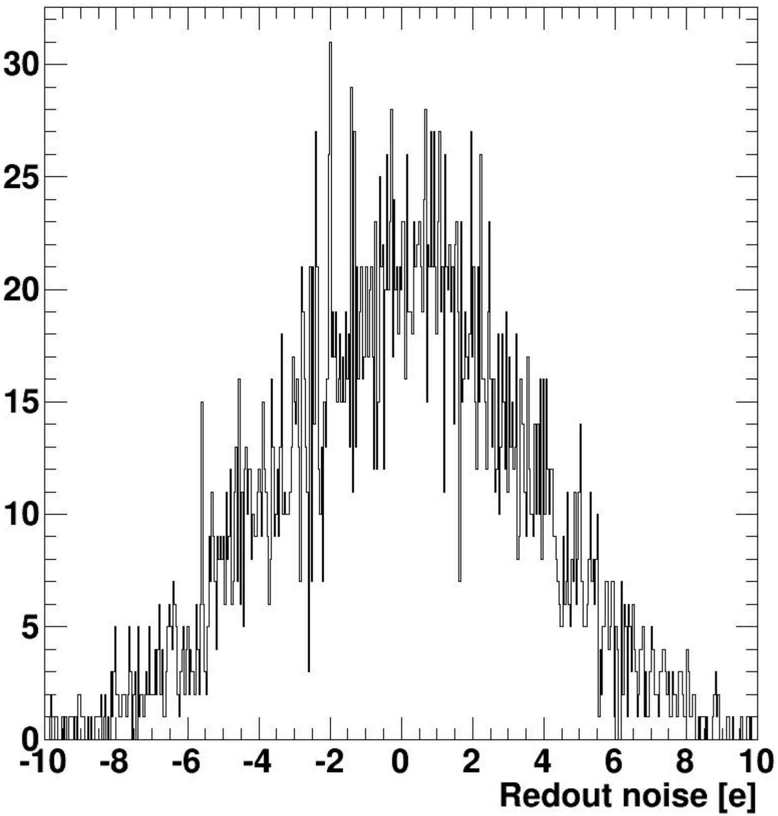
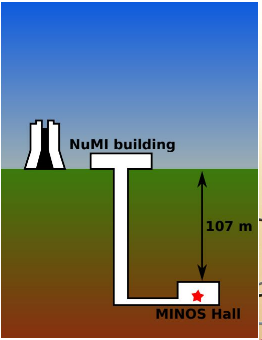
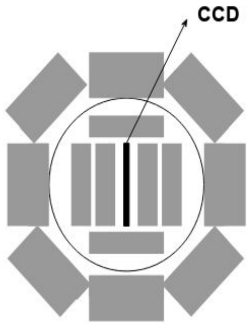


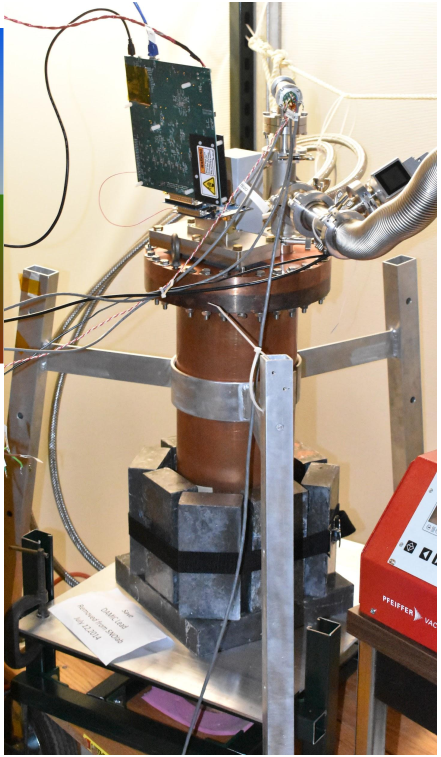


Locations: where is SENSEI?

Fermilab





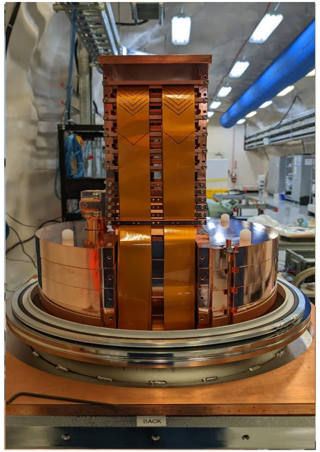


→ **107** meters underground

→ 1 device (**2 grams**) installed

→ Same site as dev site

SNOLAB



Final location ←

2 kilometers underground ←

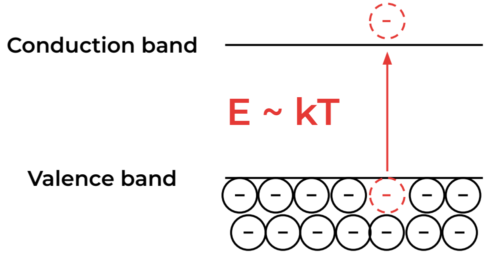
6 devices (**15g**) installed * ←

Near dev site (Canada) ←

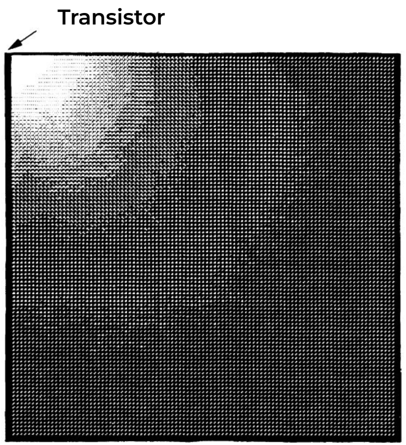
* 40 grams after new visit (see next slides!)

Single Electron Event (SEE) contributions

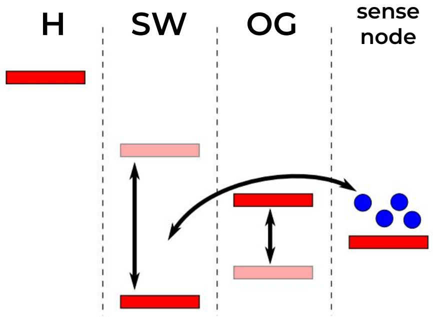
Dark current



Amplifier light



Spurious charge



Single Electron Event (SEE) contributions

Dark current	**Amplifier light**	**Spurious charge**

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

Dark current

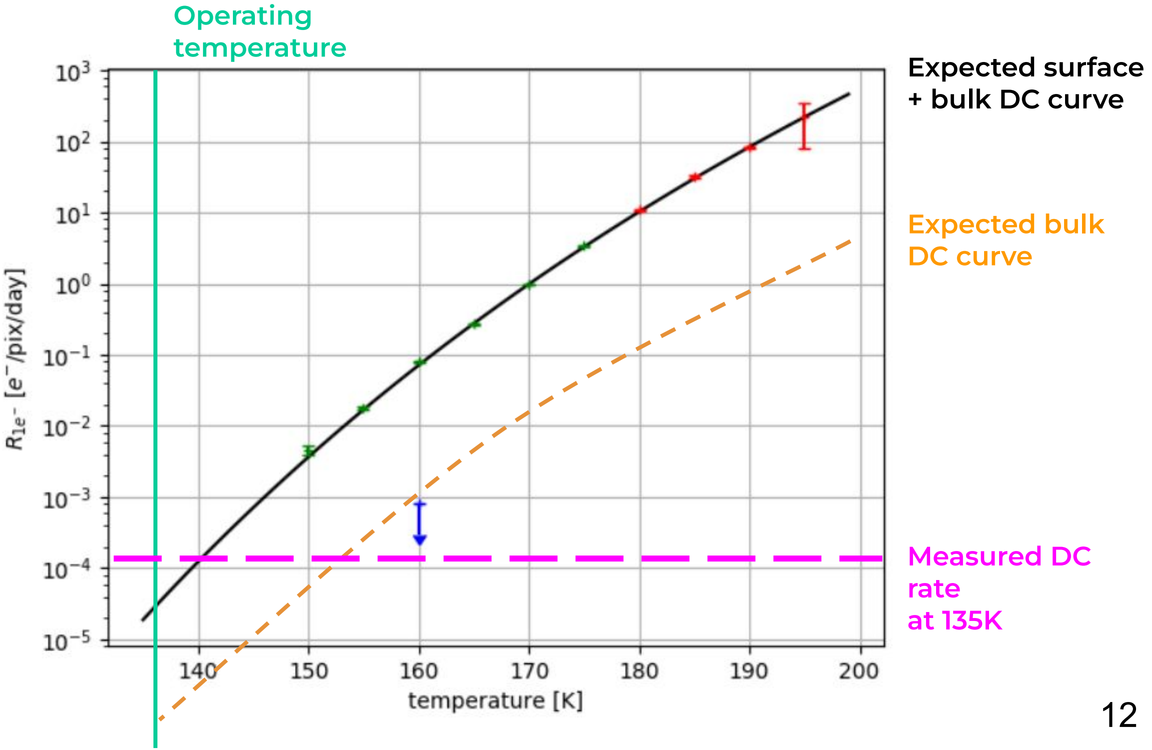
→ Dark current rate (presumably from thermal agitation) is higher than the expected (theoretical) at 135K

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

Dark Current

=

(Surface + Bulk) Dark Current



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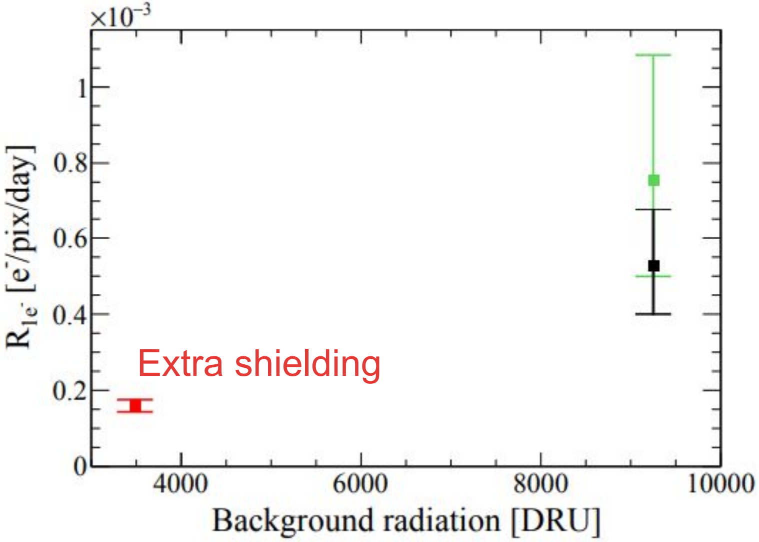
→ Origin? Du, Egana, Essig and Sholapurkar (2011.13939) proposed the source of this discrepancy may come from the interaction of high energy events with the CCD as it is was hinted in SENSEI2020@MINOS:



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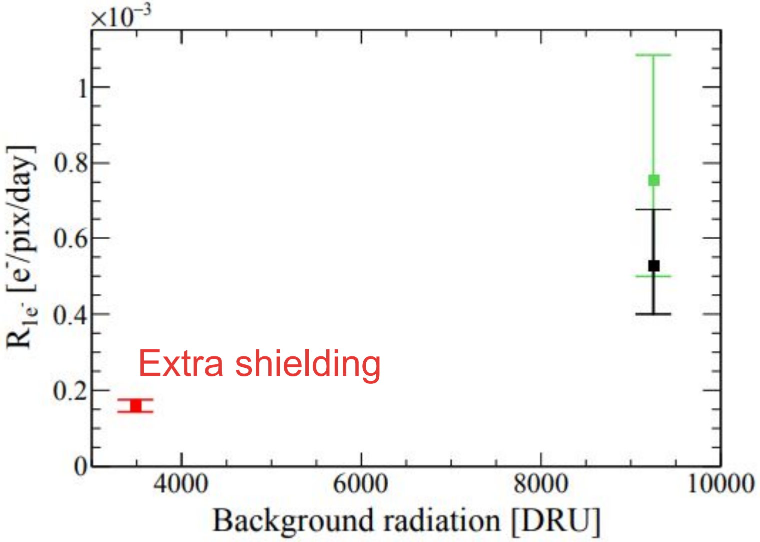
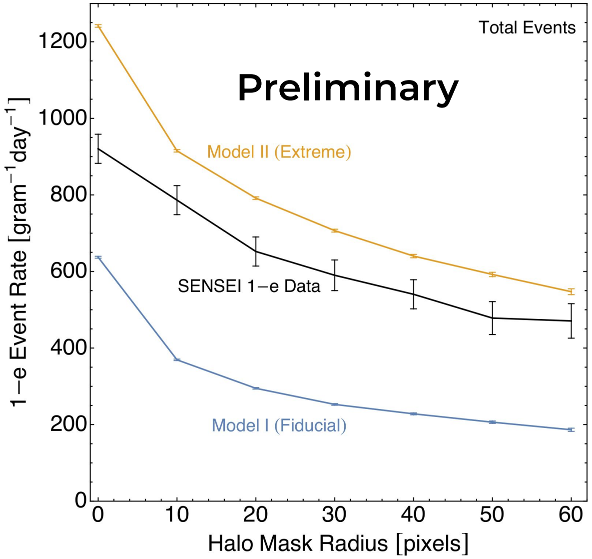
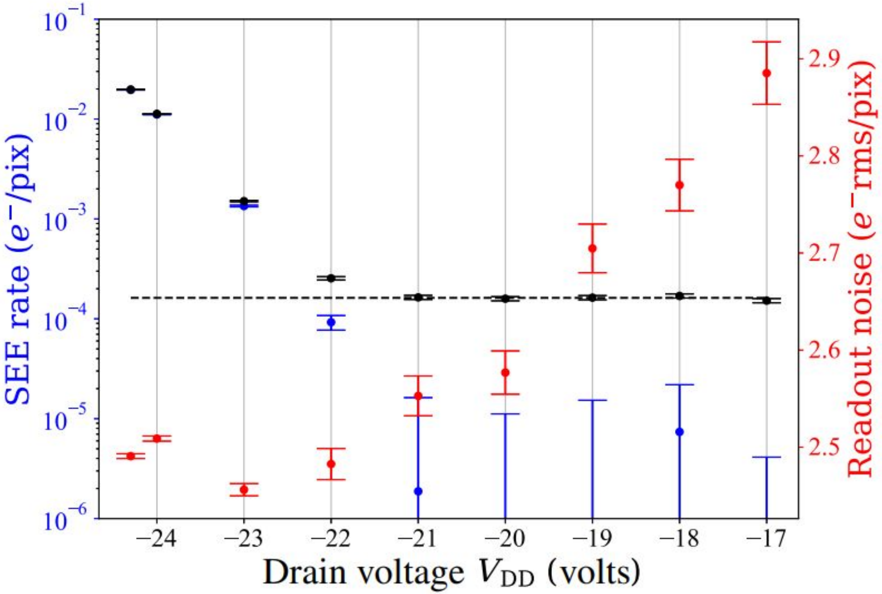


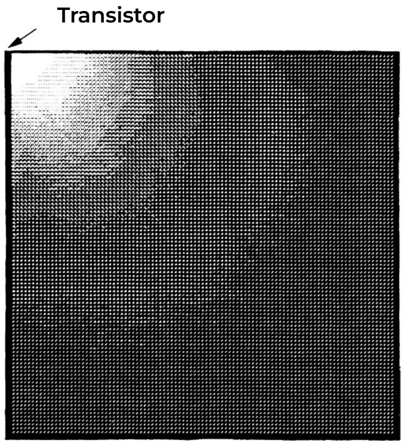


Credits to Essig et al.

Amplifier light study

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

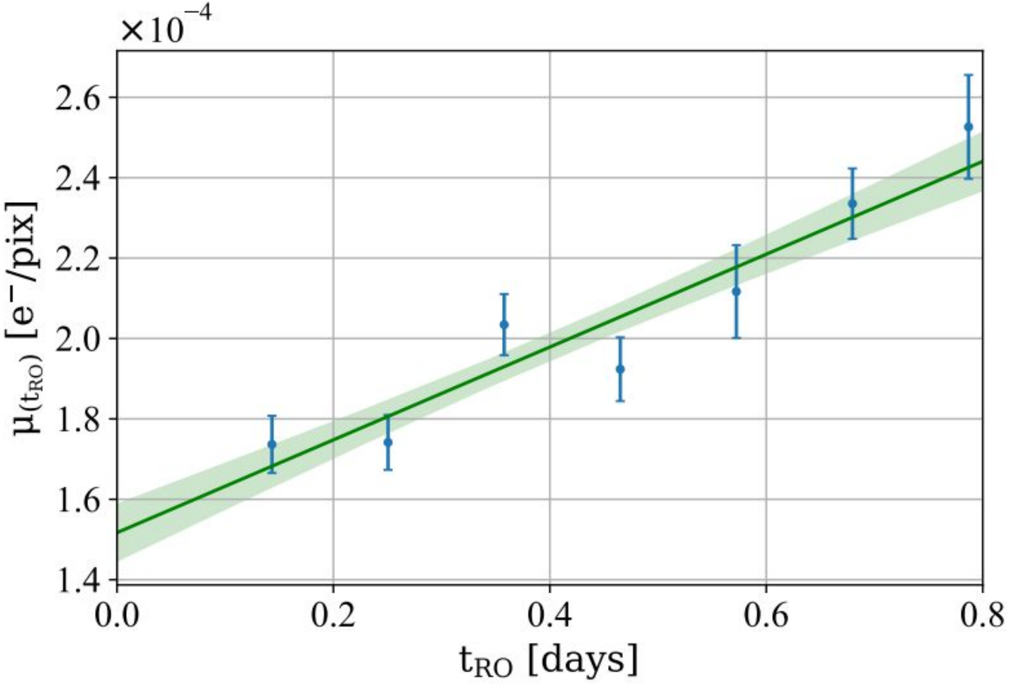




V_{DD}	λ_{AL} $(10^{-4}\ e^-/\text{pix/day})$
-21	(0.36 ± 0.18)
-22	(19.91 ± 1.26)

Determination of contributions

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



Determination of contributions

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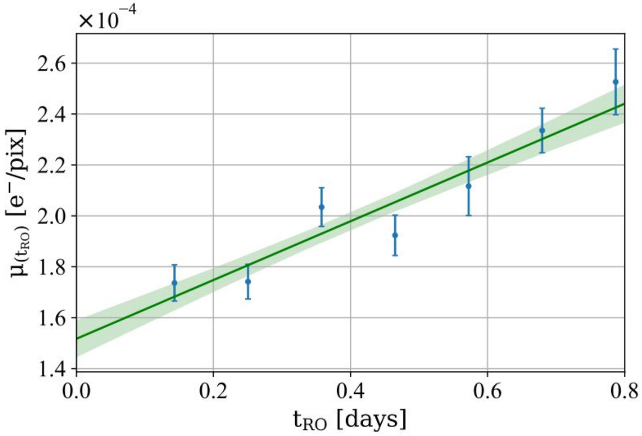
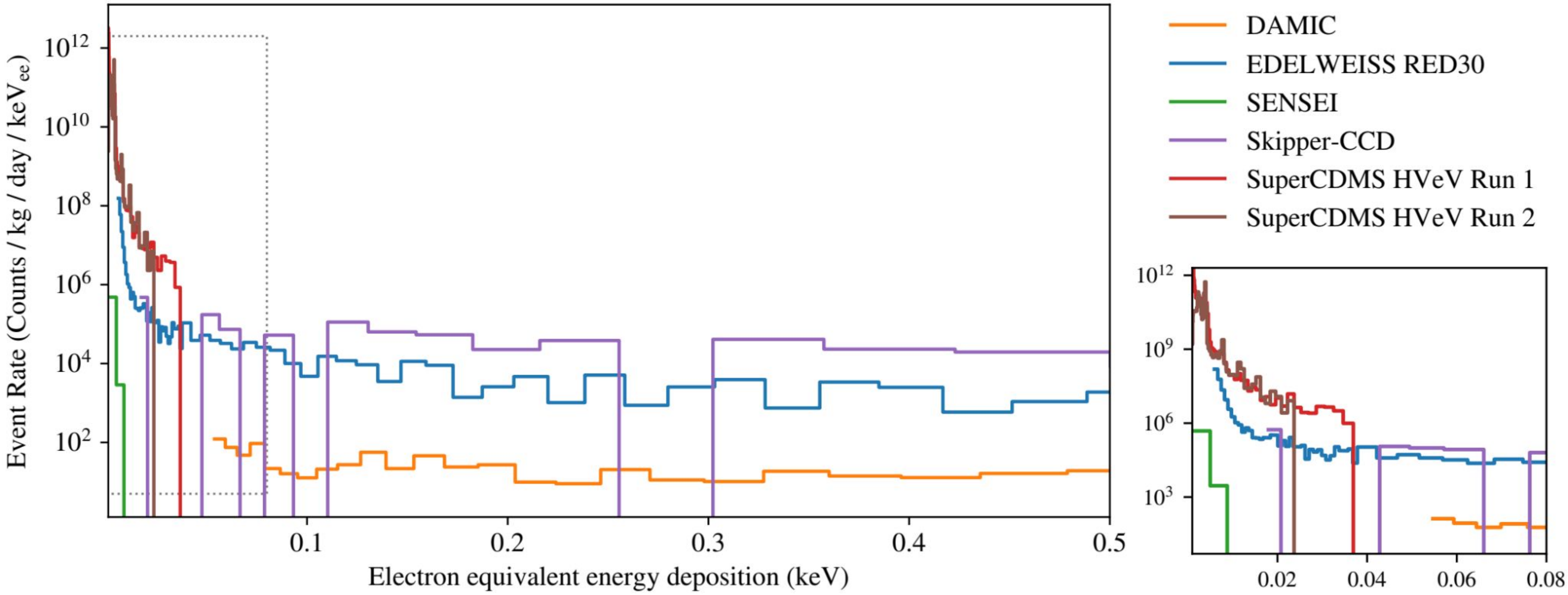


V_{DD}	External Shield	λ_{DC}	λ_{AL}	μ_{SC}
-21	Yes	(1.59 ± 0.16) 10^{-4} e^-/pix/day	(0.36 ± 0.18) 10^{-4} e^-/pix/day	(1.52 ± 0.07) 10^{-4} e^-/pix

Last report @ EXCESS Feb 2022

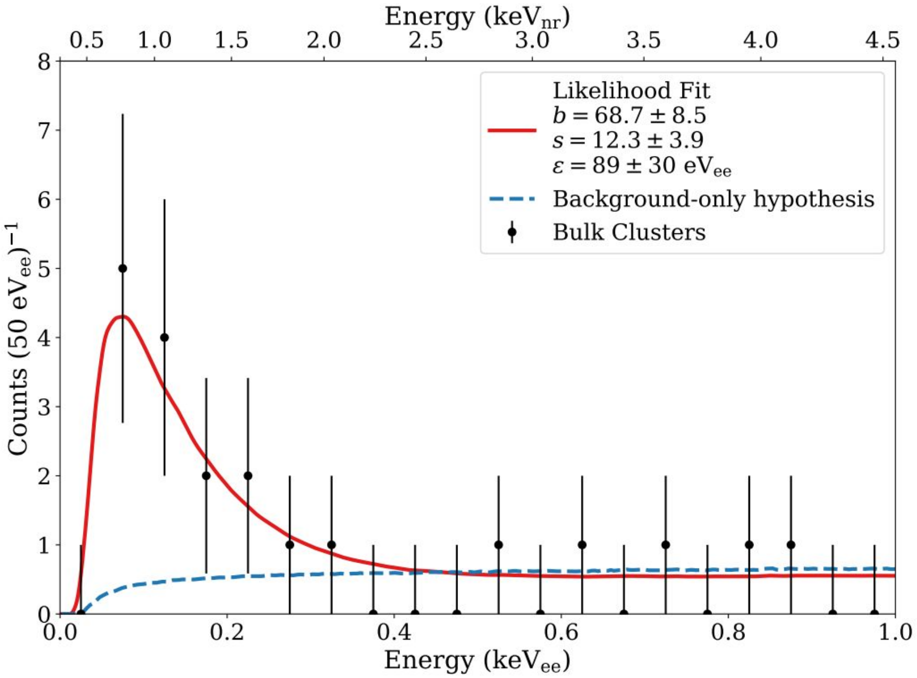


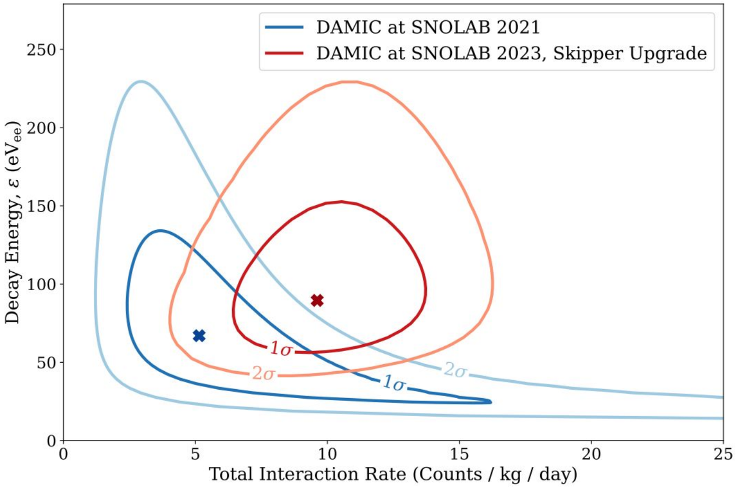
→ This is the result presented for 2020@MINOS run, new update coming soon for SNOLAB first run.

→ No excess reported but take in mind single-electron event resolution + particle discrimination.

→ Spatial correlation of high energy events (>O(100keV)) with 1e- events: cherenkov radiation / radiative recombination (arXiv:2011.13939). Talk with Daniel!

SCCD EXCESS @ SNOLAB





→ No exponential rise with lower-energies: rejection of surface events discards first-bin events.

→ Not explained (yet) by any background model.

→ SENSEI@SNOLAB (and DAMIC-M@LSM) will probe this excess very soon.

Second science run @ SNOLAB

Latest results from the SENSEI experiment on sub-GeV dark matter searches

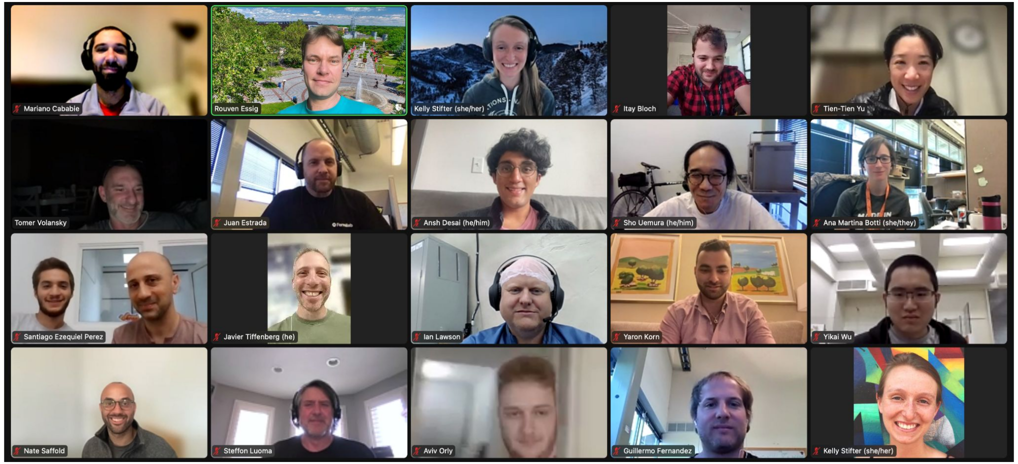
31 ago 2023, 14:45
15m
Hörsaal 3 lecture hall (University of Vienna)

Parallel talk | Dark matter and its ... | Dark matter and its det...

Ponente

Ana Martina Botti (Fermilab)

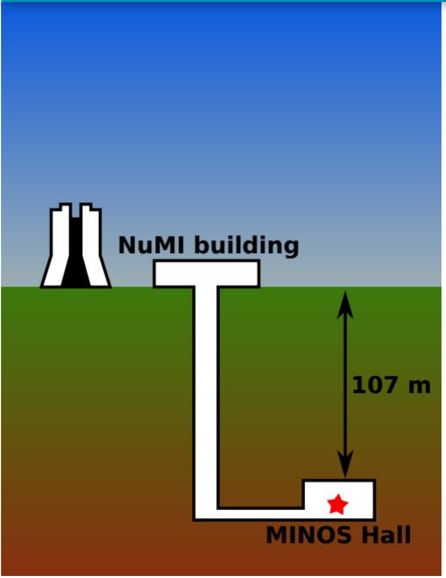
- Detailed results
- mCP exclusion limits
- Last SNOLAB visit



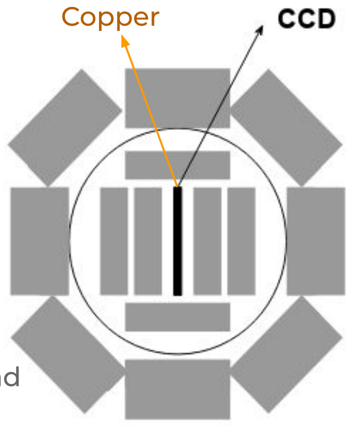
Thank you!
Any questions?

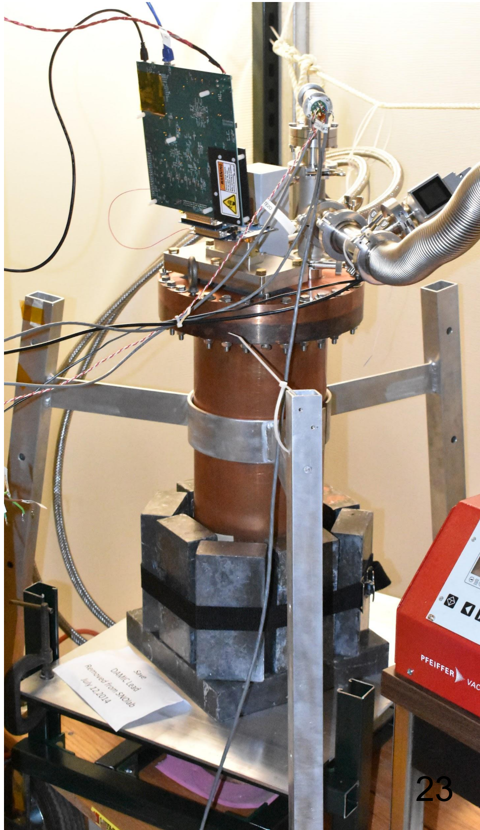
BACK UP SLIDES

MINOS2020 setup: location and shielding

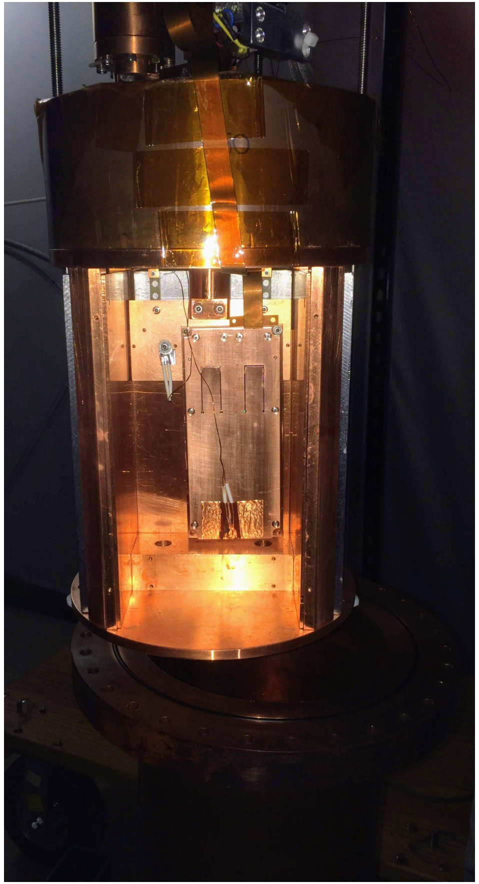


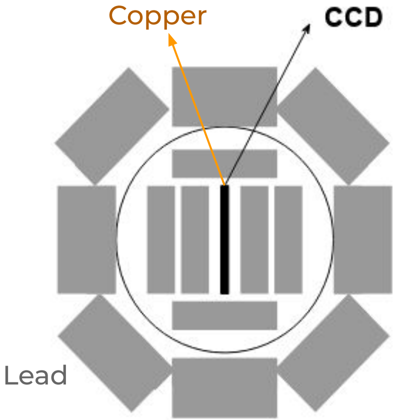
- Underground site reduces **muon** environmental radiation
- Inner (1" each) and outer (2" each) lead bricks reduces **gamma** environmental radiation
- Copper module for **IR** radiation
- Temperature at **135K** and high-vacuum regime.
- Operated with specifically designed readout electronics (**LTA - Low Threshold Acquisition board**)

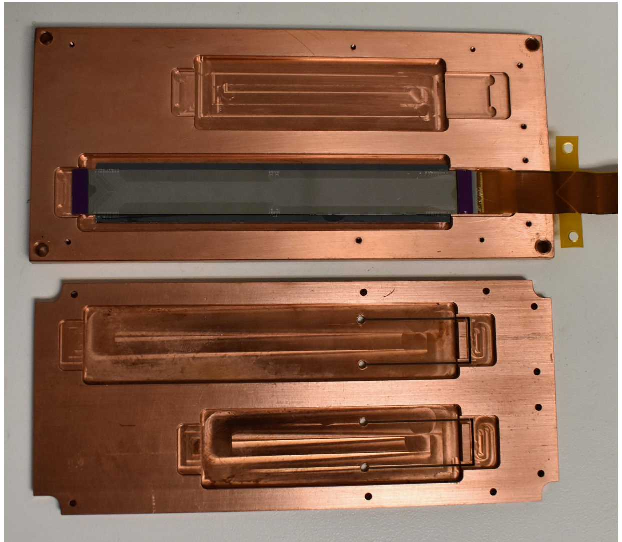


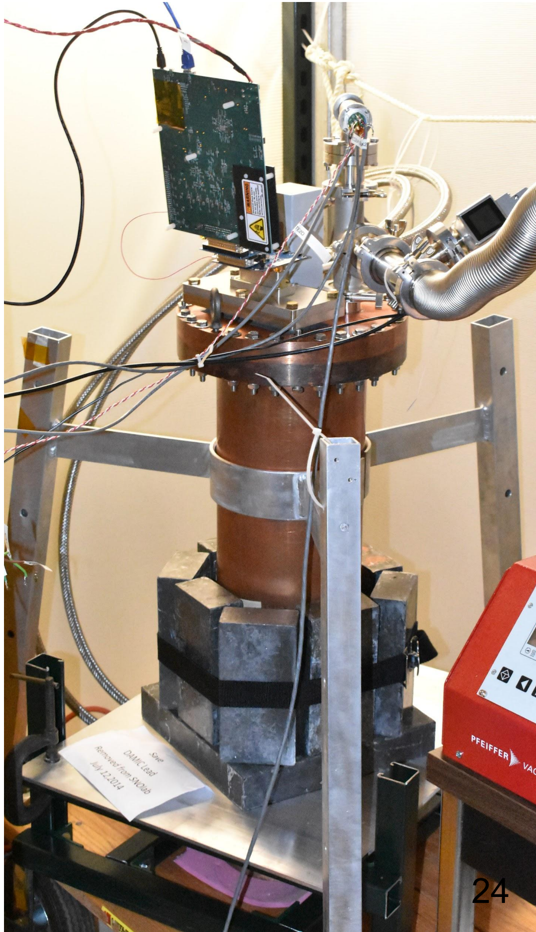


MINOS shielding

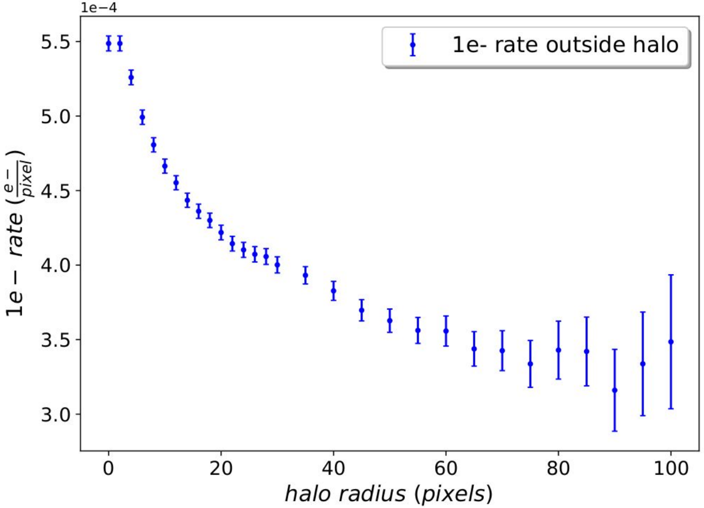






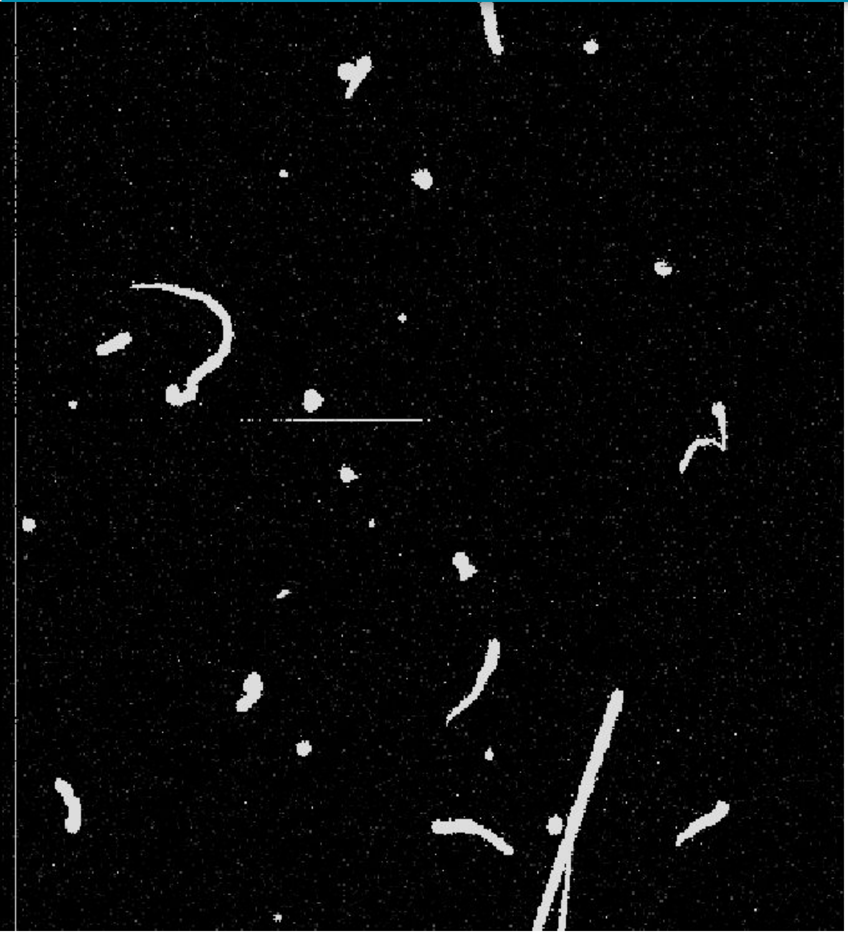


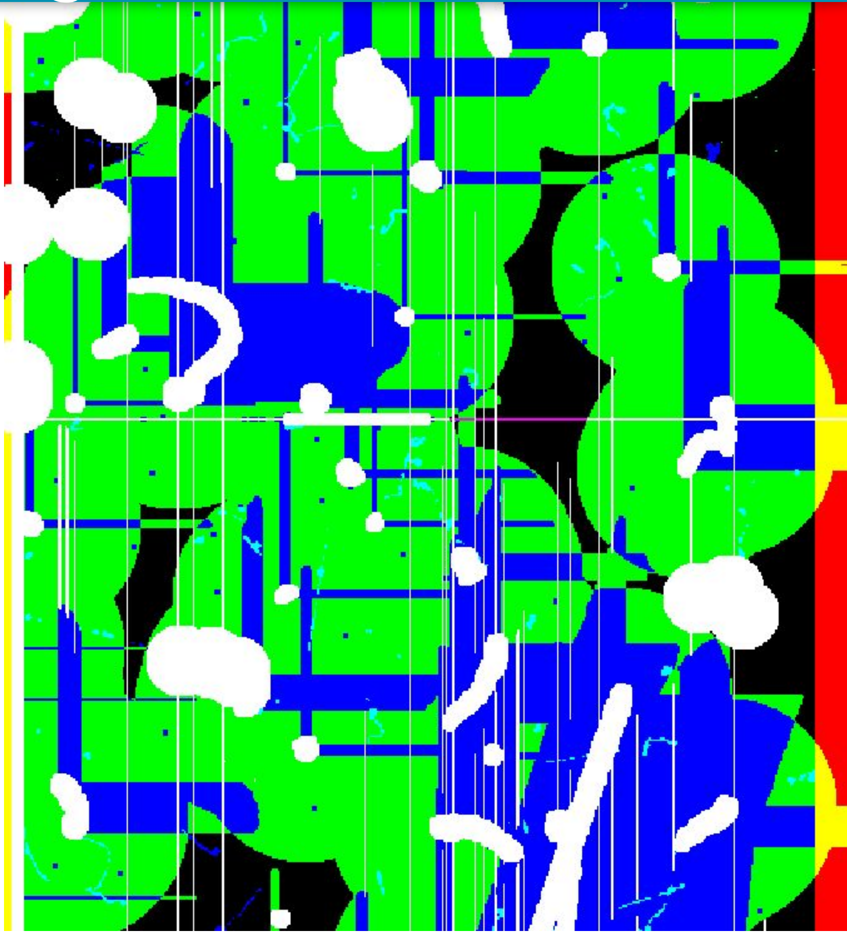
Single electron event rate



- Spatial correlation between high energy events (>360eV) and 1e- events.

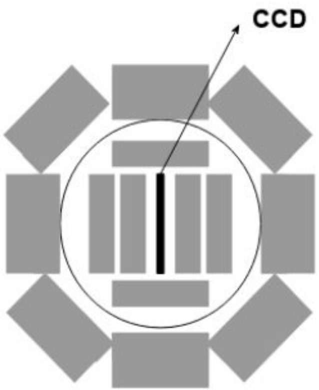
Sample image

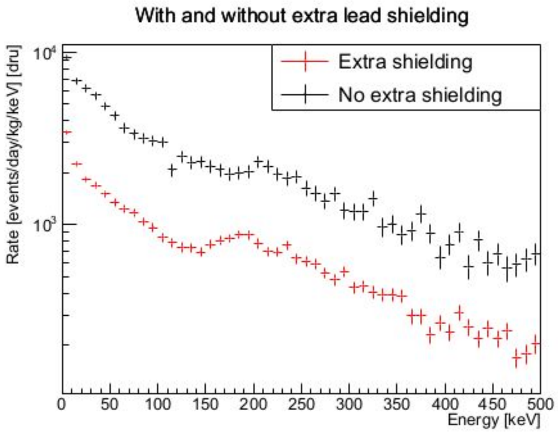


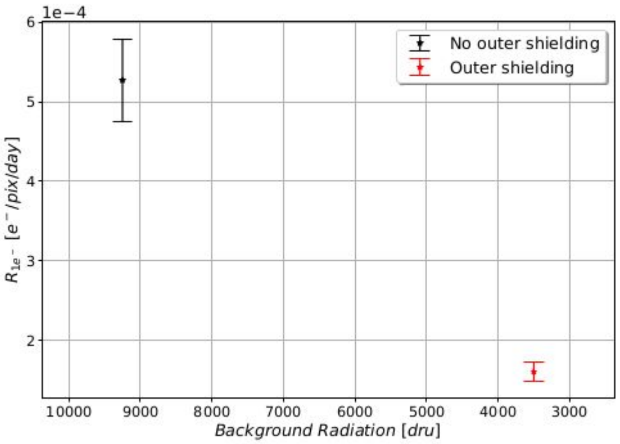


1e- rate vs. shielding

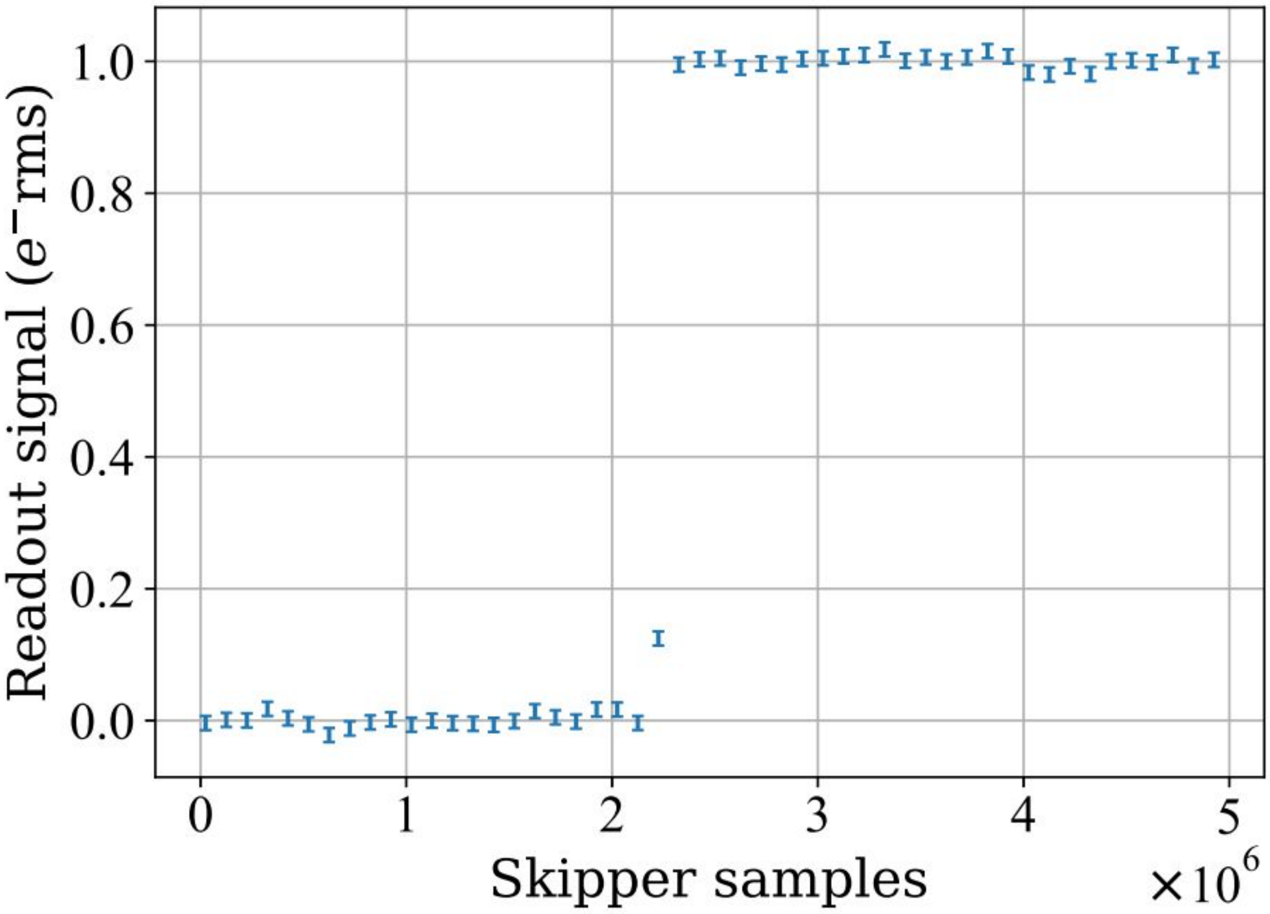
- We have data with and without the outer ring of lead bricks
- Factor of 3 reduction in the rate of high-energy tracks → factor of 3 reduction in the $1e^-$ rate
  - There is some mechanism by which ionizing radiation generates charge uniformly in our CCD
  - Better shielding will very likely further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







SC@Sense node

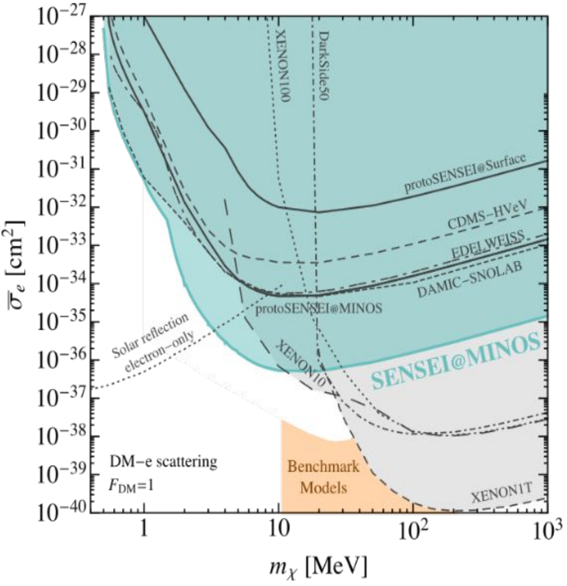


(1.1+-0.2) 10^{-5} e-/pix

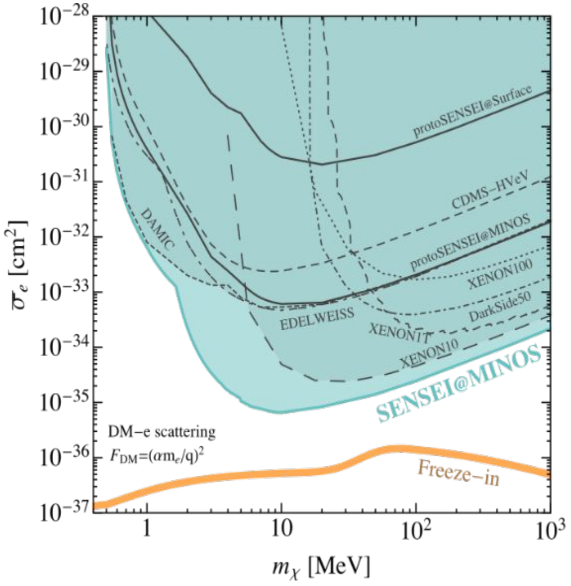
~3×10^{-6} e-/pix

Latest Results: SENSEI@MINOS

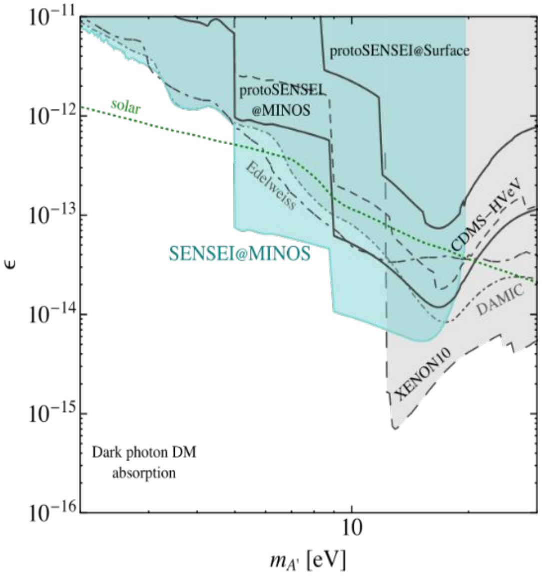
Heavy mediator e- scattering



Light mediator e- scattering

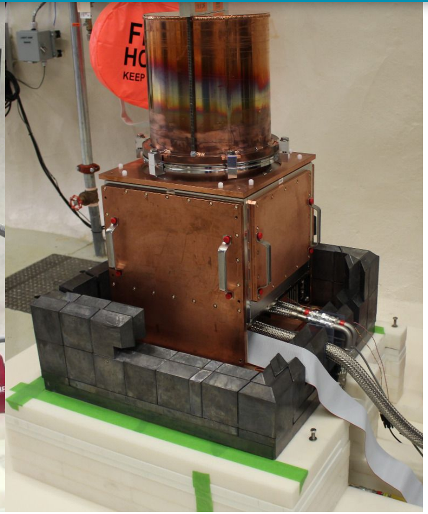


Absorption



SENSEI@SNOLAB

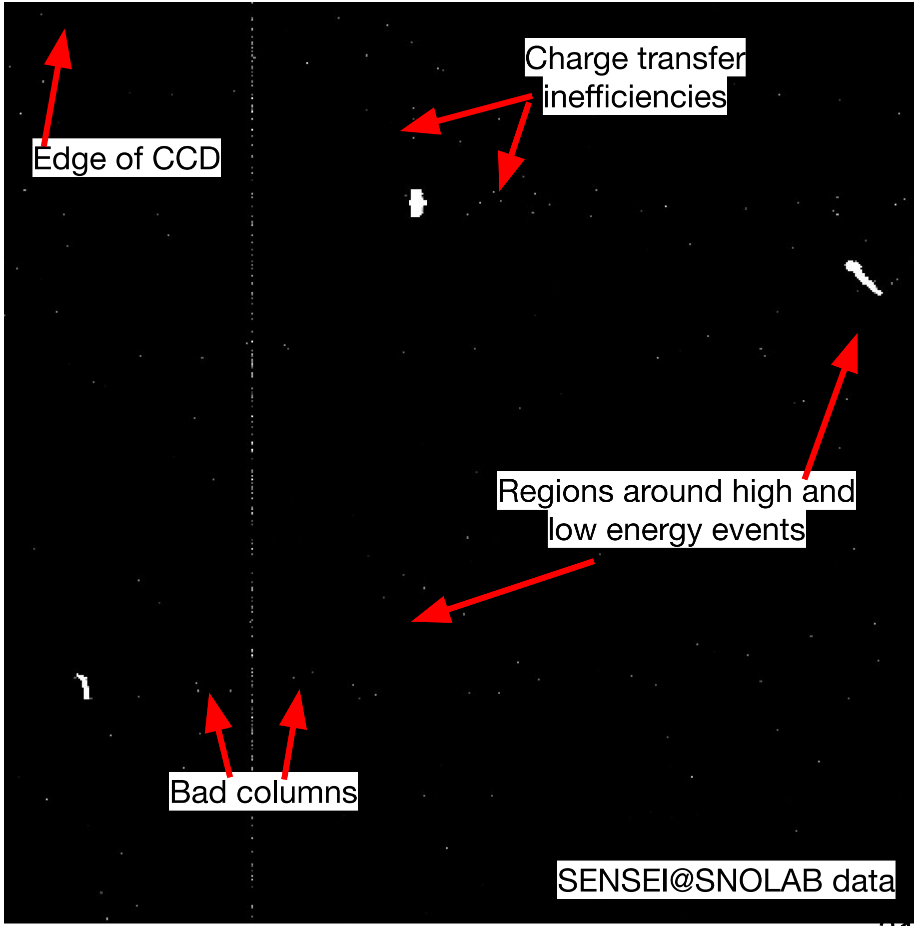
- **Extraordinary** support from SNOLAB during COVID-19 pandemic
  - 6 CCDs (**15g**) deployed.
  - 2km of granite, 3” of lead, 20” of polyethylene and water



- First science run of SENSEI@SNOLAB
  - 6 months of data-taking: 129 images, no binning, 50% blinded
  - 300 Skipper samples → 0.14e- noise
  - 1 e- density (after cuts): $\sim 2 \times 10^{-4}$ e-/pixel

SENSEI@SNOLAB: event selection criteria

- Electronic noise
- Crosstalk
- Edges of CCDs
- Bad pixels/columns
- Serial register hits
- Bleeding (CTI)
- High-energy halo
- Low-energy halo



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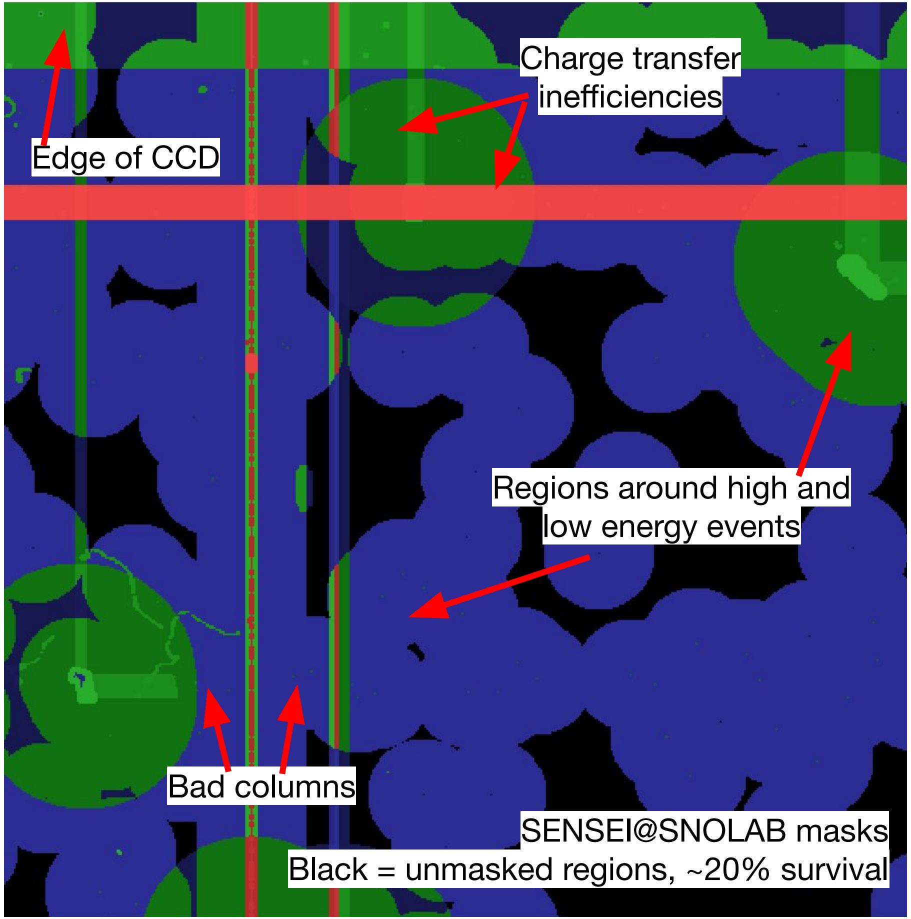
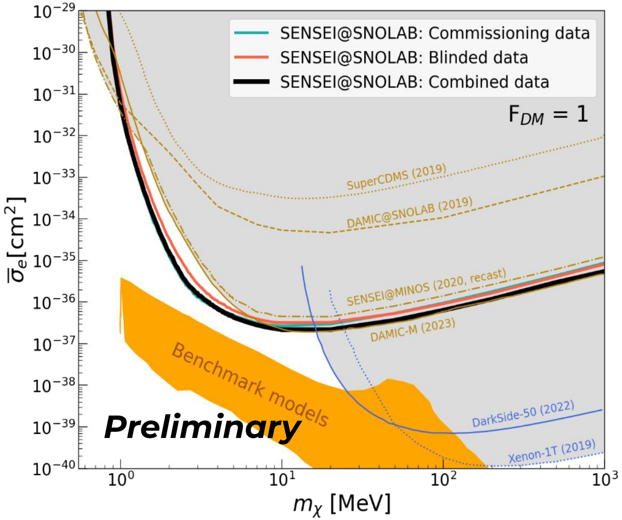
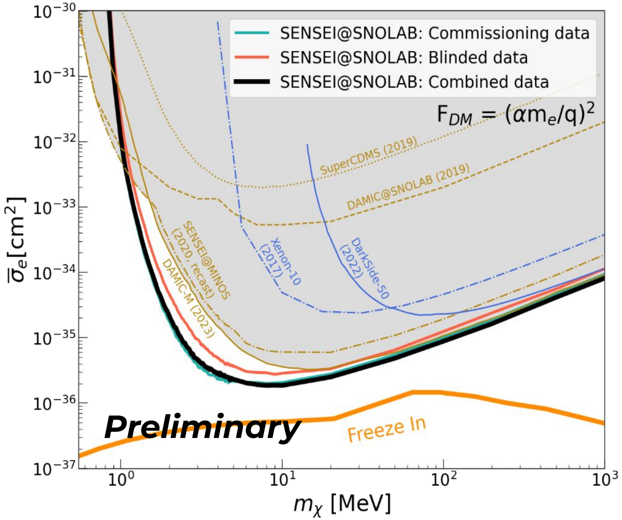


SENSEI@SNOLAB: results

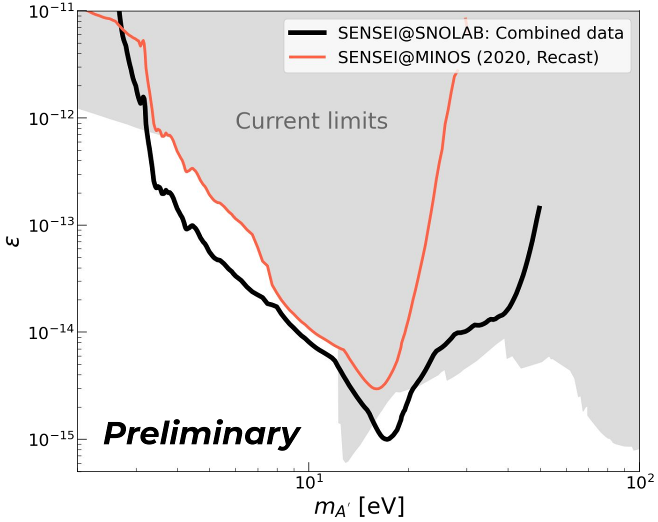
Heavy mediator e- scattering



Light mediator e- scattering



Absorption

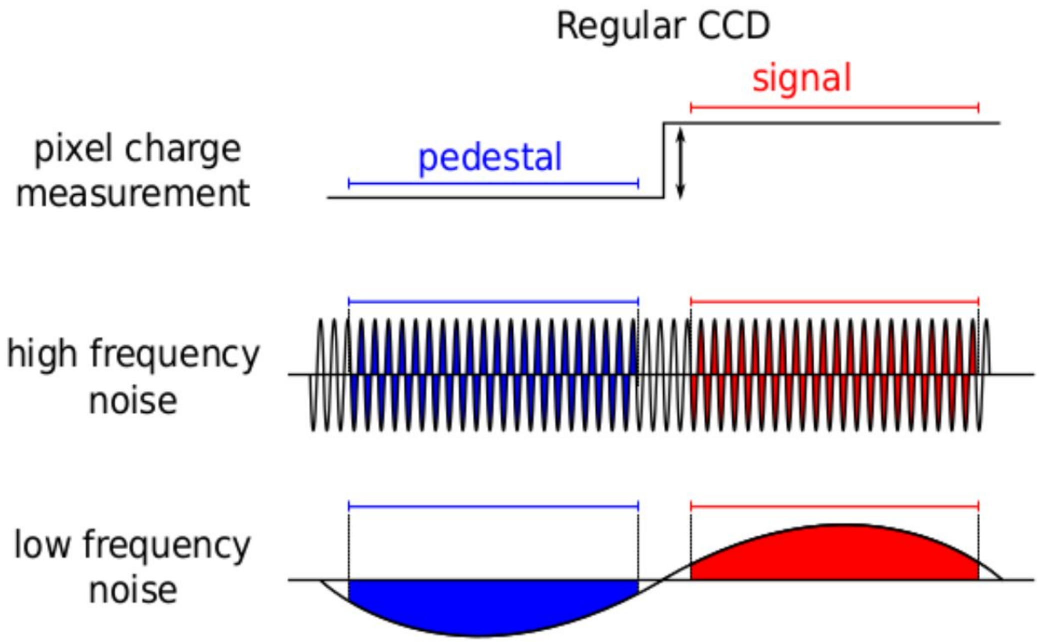


Skipper-CCD basics

- 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



Skipper-CCD basics

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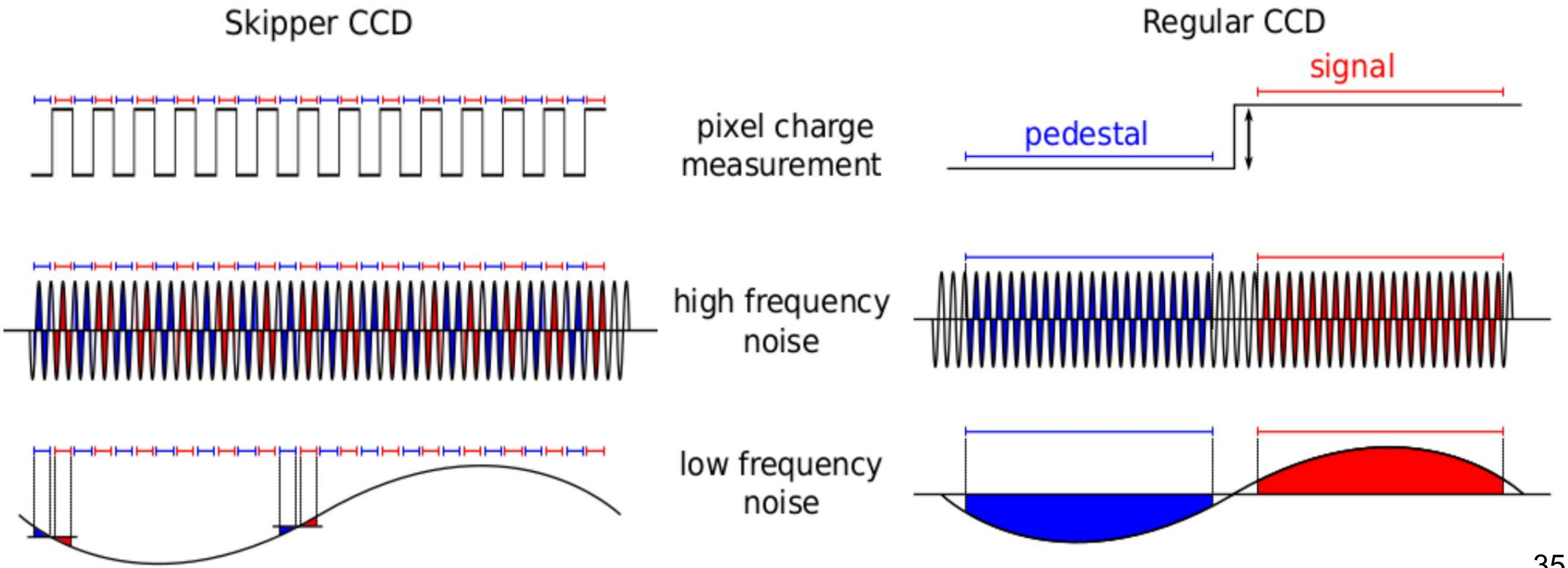
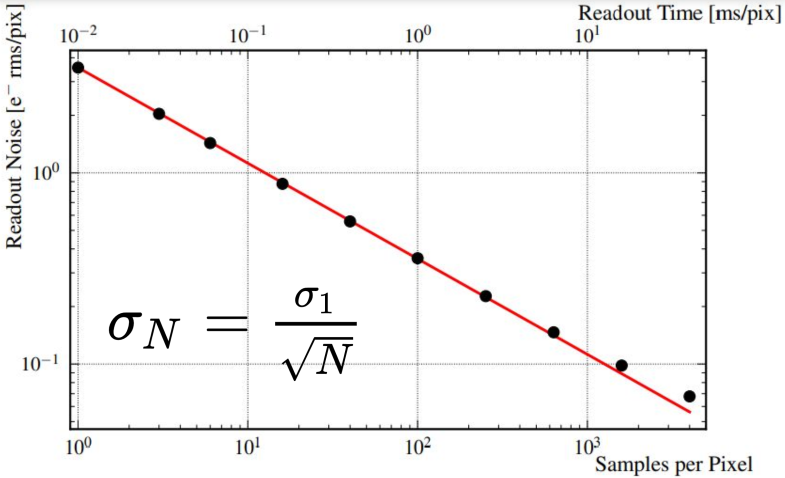
  Then it is **drained** and charge is **lost**.

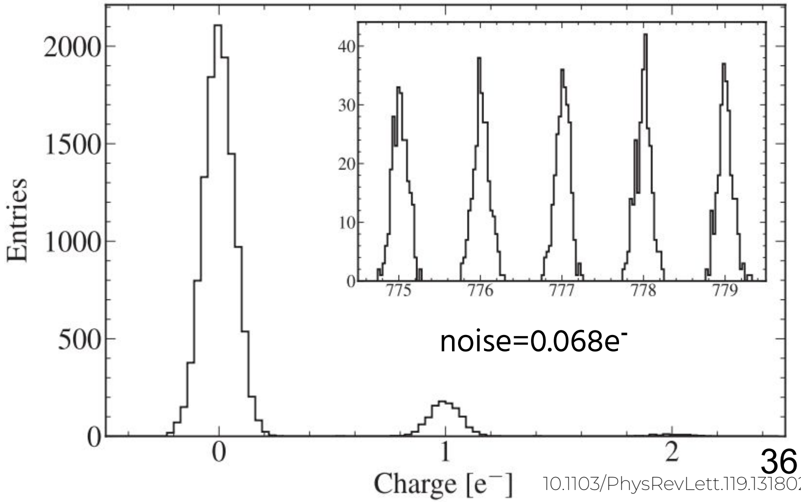
- Longer integration reduces noise but cannot reduce **1/f** noise.



Skipper-CCD basics

- *Skipper* technology allows to read repeatedly the *same pixel* to achieve **sub-electron noise**
- ~2e- noise goes to**<0.1e⁻** using the *skipper* technology
- Low energy threshold down to **~1.1eV** (Si band gap)
- Capability of unambiguously **count clusters** of few electrons
- 15x15 μm² pixels allow for **spatial resolution** of events



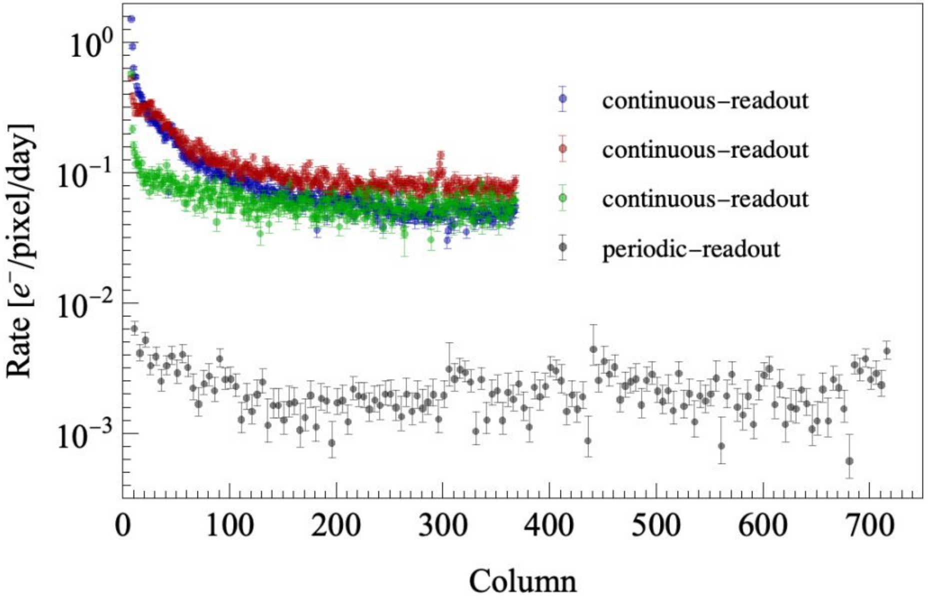


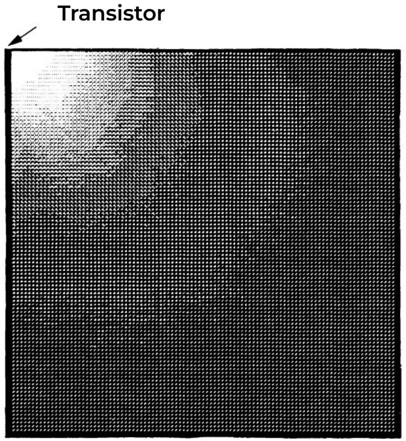
10.1103/PhysRevLett.119.131802

Amplifier light

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

→ In SENSEI 2019 this effect was a mayor SEE contributor





Amplifier light study

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

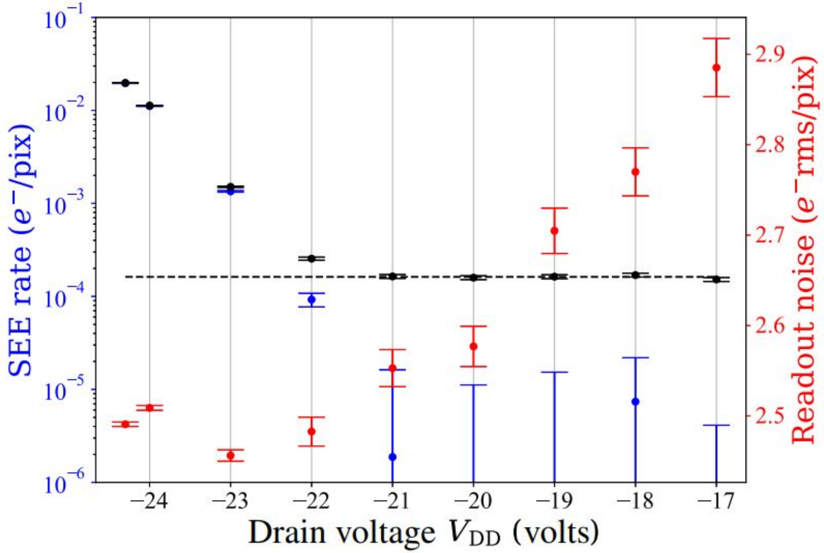
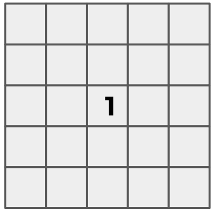


FIG. 5. SEEs per pixel (left axis) and single-sample readout noise (red, right axis) as a function of the drain voltage of the $M1$ transistor (V_{DD}). In black, we show the SEEs per pixel collected for each voltage ($\mu_{(t_{ro})}$) and in blue the AL contribution (μ_{AL}), estimated from Eq. (6).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

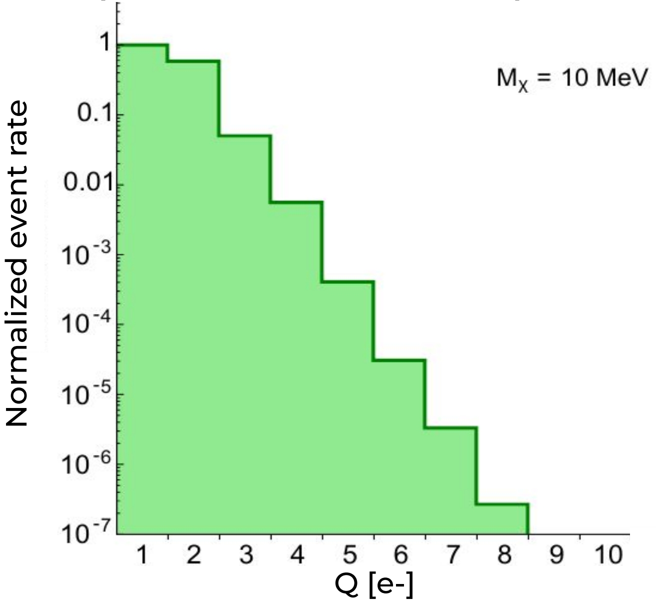
V_{DD}	λ_{AL} (10^{-4} e^-/pix/day)
−21	(0.36 ± 0.18)
−22	(19.91 ± 1.26)

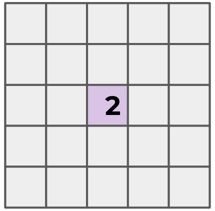
Why are SEEs relevant?

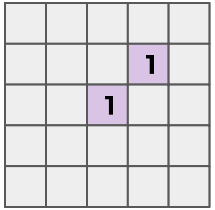
⇛ Because of spatial random coincidence of SEEs can generate higher energy events



Expected electronic recoil spectrum







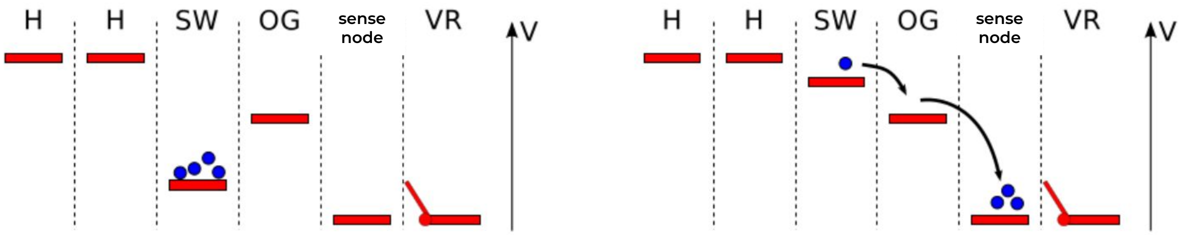
R. Essig et al, JHEP 05 (2016), 046

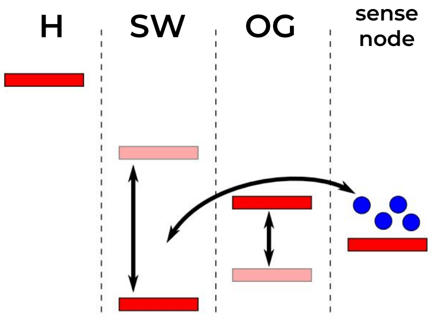
Skipper-CCD basics

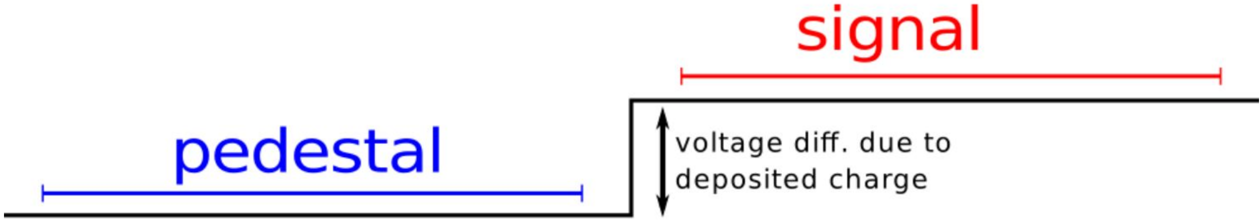
- In a conventional CCD, charge is moved to the sense node and readout **once**.
  Then it is **drained** and charge is **lost**.

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

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







Single Electron Event (SEE) contributions

Contribution (e^-/pix)		Time dependence: Linear – Exposure	Time dependence: Linear – Readout	Time dependence: Independent	Spatial distribution
Dark current	Intrinsic	$\lambda_{DC}\, t_{EXP}$	$\frac{\lambda_{DC}}{2}\, t_{RO}$	-	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