Characterization of Single-Electron Events Using a Skipper-CCD

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Characterization of SEEs with a SCCD

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SENSEI: Characterization of Single-Electron Events Using a Skipper Charge-Coupled Device

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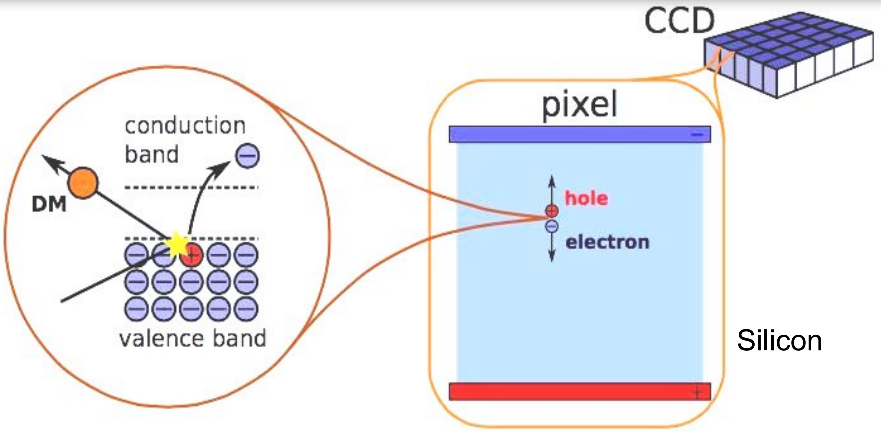
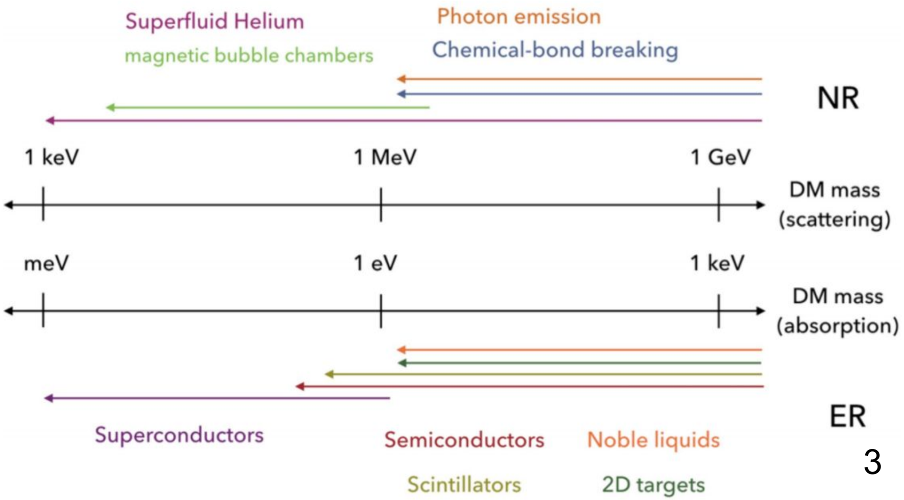
Electron recoils for sub-GeV DM in Skipper-CCDs

- Benchmark models:
  - DM-e$^-$ scattering, DM absorption
- Silicon Skipper-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

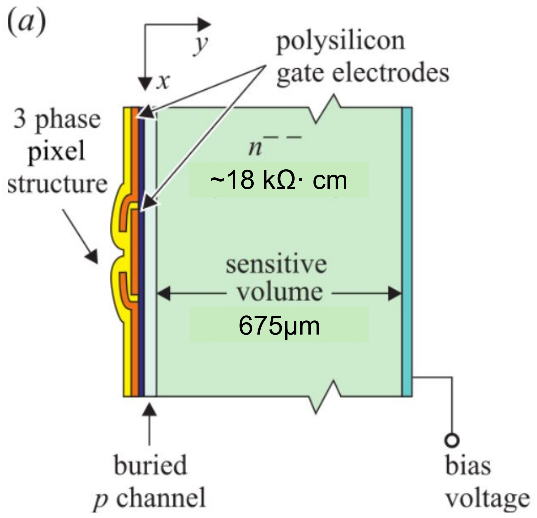
  (~eV on DM absorption)

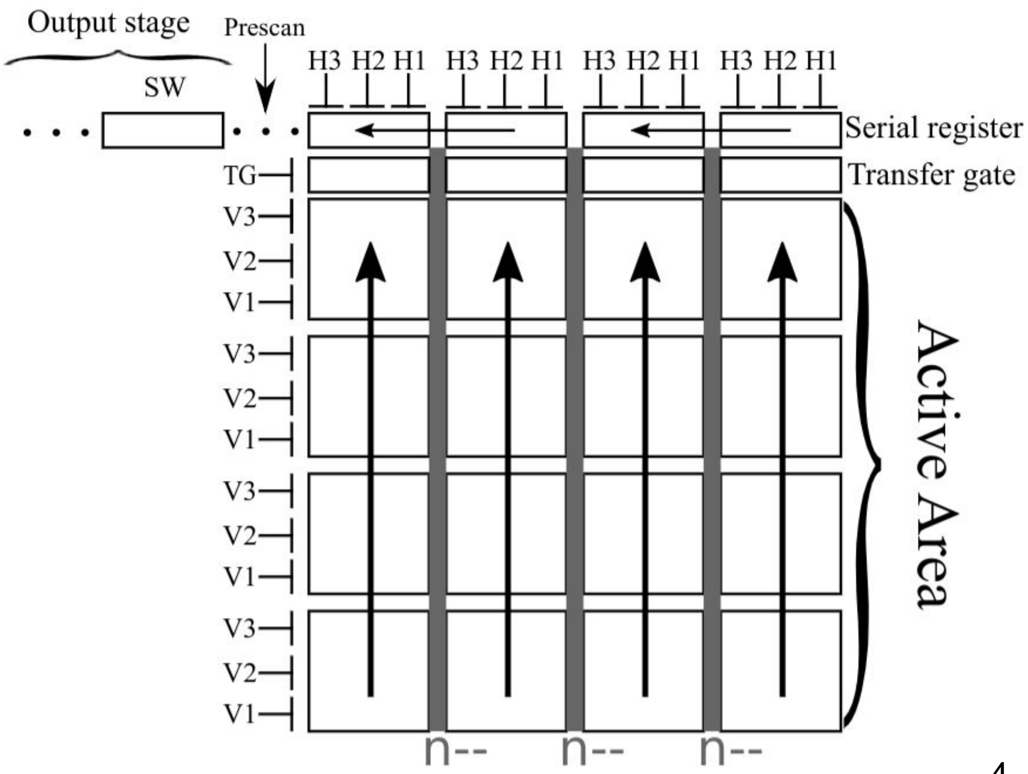




CCD basics

- **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

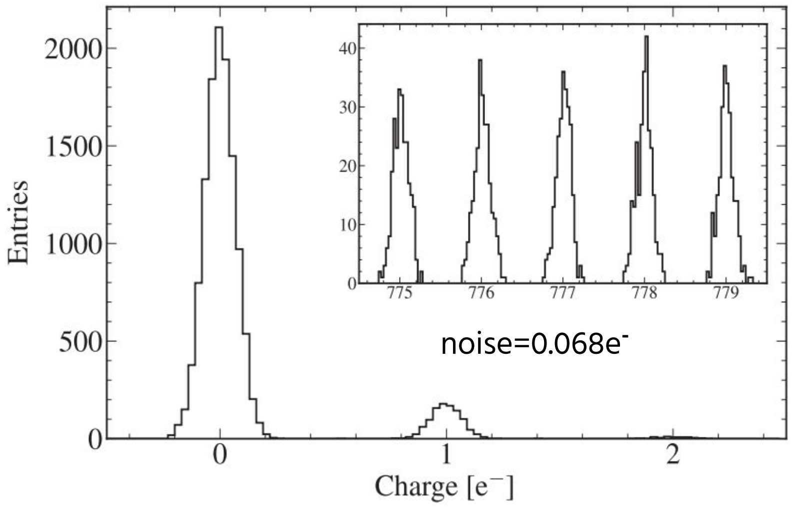




Skipper-CCD basics

- 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**



- **Low energy** threshold **down to** 1.2eV (Si band gap)

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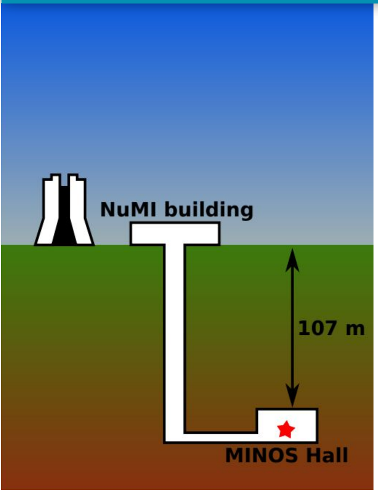
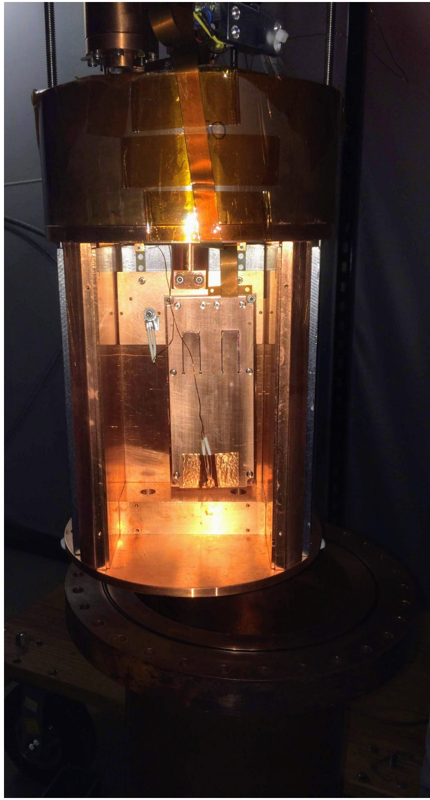
MINOS setup: location and shielding

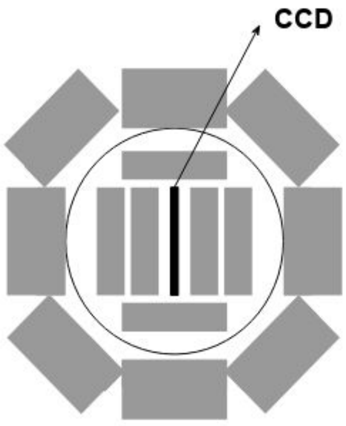


- Setup **~107m below surface** at shallow underground MINOS site @FNAL to reduce environmental background radiation.

- Inner (1" each) and outer (2" each) **lead bricks** reduces environmental gamma radiation



- Operated at **135K** and high-vacuum regime to reduce dark current without generating CTI



DOI: 10.1103/PhysRevLett.125.171802

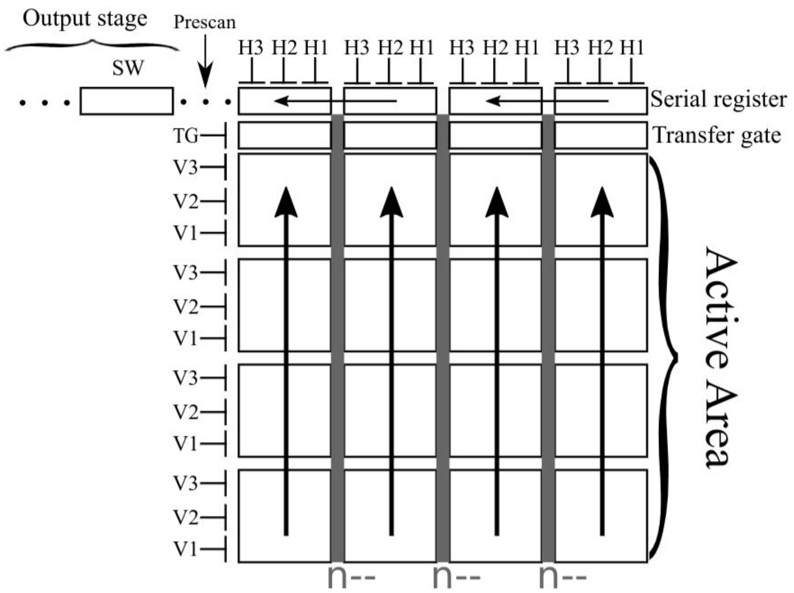
Data-taking cycle

➤ Data-taking cycle was divided into 3 phases: **Cleaning**, **Exposure** and **Readout**.

- **Cleaning**: voltages are changed so surface traps energy levels or interface states are filled (“reset”). This way they do not contribute to DC. CCD is readout in order to erase charges this “reset” leaves.

- **Exposure**: voltages keep fixed. Note bias voltage in output transistor is set to 0V so no amplifier light is emitted.

- **Readout**: signal is collected.



Basic model

- Data-taking cycle was divided into 3 phases: **Cleaning**, **Exposure** and **Readout**.
- We will define three type of events based on these three phases:
  - μ_{EXP}: rate of SEEs produced during Exposure
  - μ_{RO}: rate of SEEs produced during Readout
  - μ_{SC}: rate of SEEs produced by the change in the voltages as charge gets transferred ("clocking") during both Readout and Cleaning but does not scale with time (exposure-independent events).

$$\mu_{(t_{EXP}, t_{RO})} = \mu_{(t_{EXP})} + \mu_{(t_{RO})} + \mu_{SC}$$

$$\mu_{(t_{EXP}, t_{RO})} = \lambda_{EXP}\, t_{EXP} + \lambda_{RO}\, t_{RO} + \mu_{SC}$$

SEE contributions

- We will differentiate three types of SEE events

  - **Dark current**. SEEs that are uniformly generated across the CCD and that scale linearly with time. They are produced during both Exposure and Readout.

  - **Amplifier light**. SEEs generated from the interaction of amplifier light with the pixels of the CCD. They are localized near the amplifier and scale linearly with time. They are produced during Readout.

  - **Spurious charge**. SEEs generated due to clocking of pixels. They are produced during Readout but do not scale with time. They are spread uniformly across the CCD.

All in all

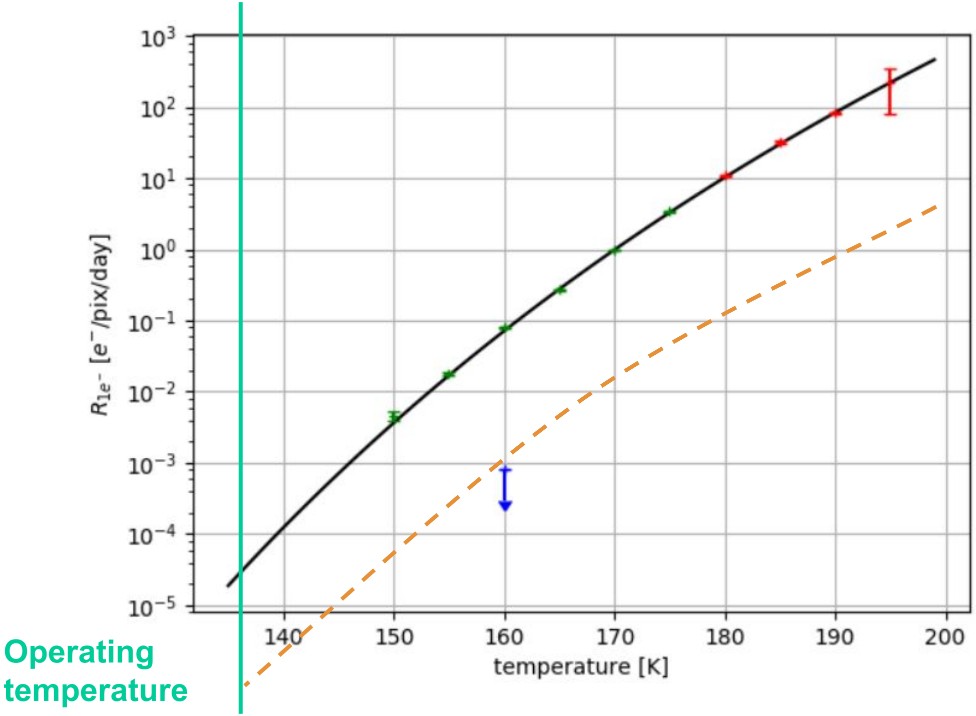
<table>
<tr><th colspan="2" rowspan="3">Contribution
(e^-/pix)</th><th colspan="3">Time dependence</th><th rowspan="3">Spatial distribution</th></tr>
<tr><th colspan="2">Linear</th><th rowspan="2">Independent</th></tr>
<tr><th>Exposure</th><th>Readout</th></tr>
<tr><td rowspan="2">Dark current</td><td>Intrinsic</td><td rowspan="2">$\lambda_{DC}\, t_{EXP}$</td><td rowspan="2">$\frac{\lambda_{DC}}{2}\, t_{RO}$</td><td rowspan="2">-</td><td>Uniform</td></tr>
<tr><td>Extrinsic</td><td>Uniform</td></tr>
<tr><td colspan="2">Amplifier-light current</td><td>-</td><td>$\lambda_{AL}\, t_{RO}$</td><td>-</td><td>Localized</td></tr>
<tr><td colspan="2">Spurious charge</td><td>-</td><td>-</td><td>μ_{SC}</td><td>Uniform</td></tr>
</table>

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

Dark current

→ Even though sub-electron readout noise allowed us to take a closer look into SEEs and DC, we've 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

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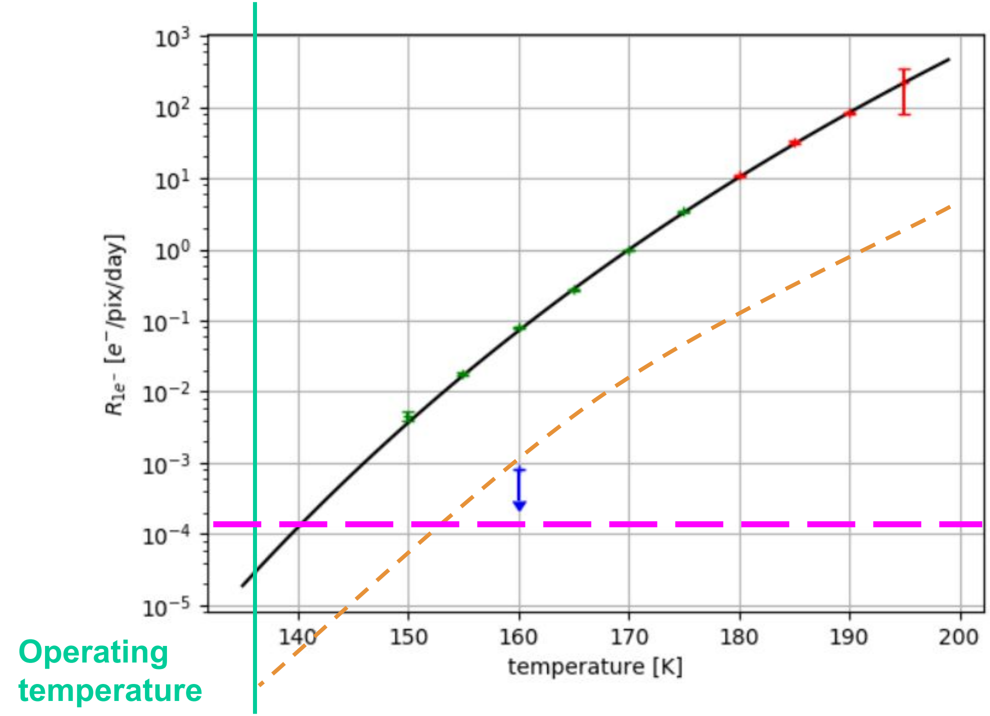

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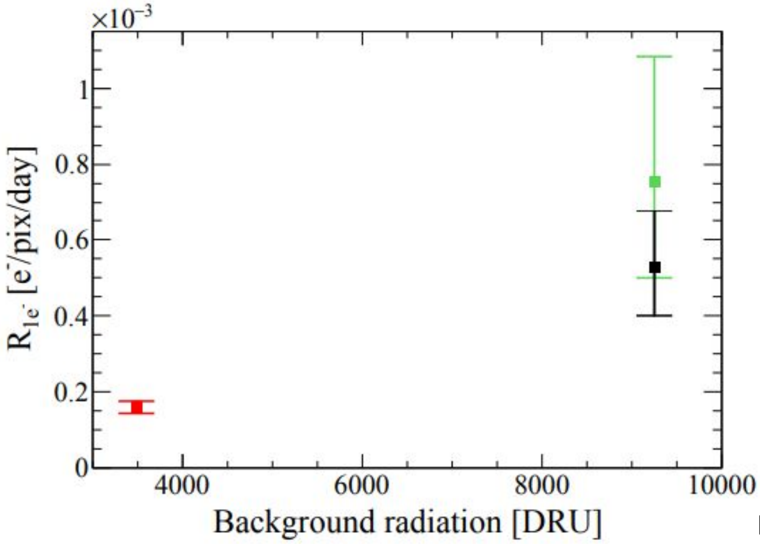
→ Origin? Essig et al. (2011.13939) proposed the source of this discrepancy may come from the interaction of high energy events with the CCD as it is was hinted in SENSEI 2020:



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Dark current

→ Because of this, we suggested introducing the concept of **extrinsic** DC as SEE that appear to be usual DC (uniform in space, linear in time) but seem to come from an **interaction between the environment and the CCD**.

→ We will refer to SEE that come from thermal agitation as **intrinsic** DC.

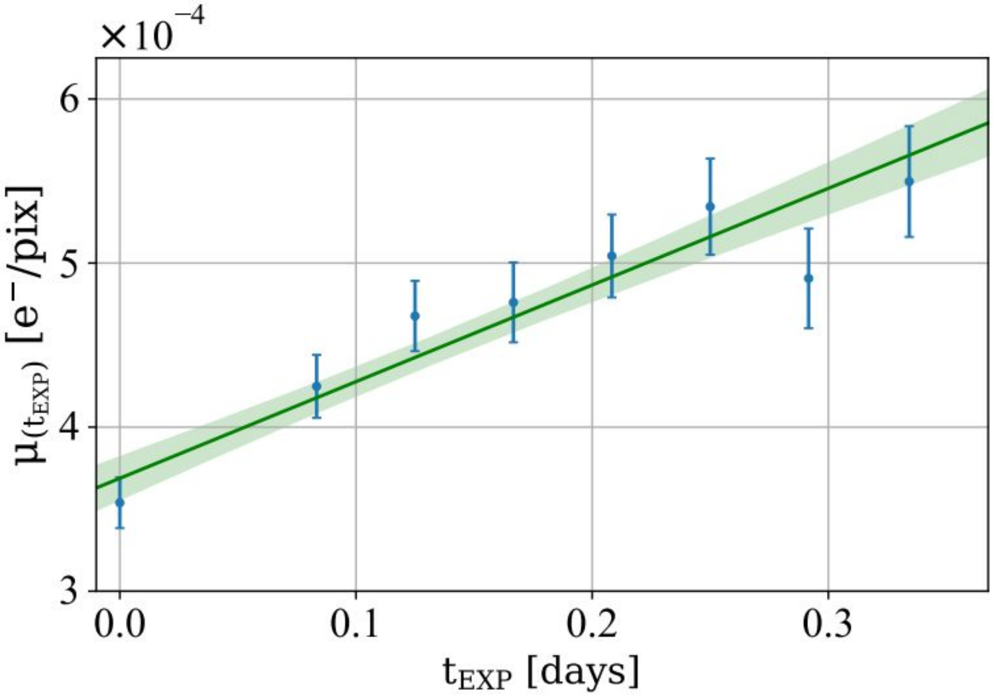
→ Hints were found, still unable to make direct measurement or test a model.

→ This work does not report a value for both extrinsic and intrinsic DC, without discriminating between them.

Dark current: λ_{DC}

→ **Determination of λ_{DC}**. Fix READOUT time, change EXPOSURE time.

$$\mu(t_{EXP}) = \lambda_{DC}\ t_{EXP} + (\mu_{RO} + \mu_{SC})$$

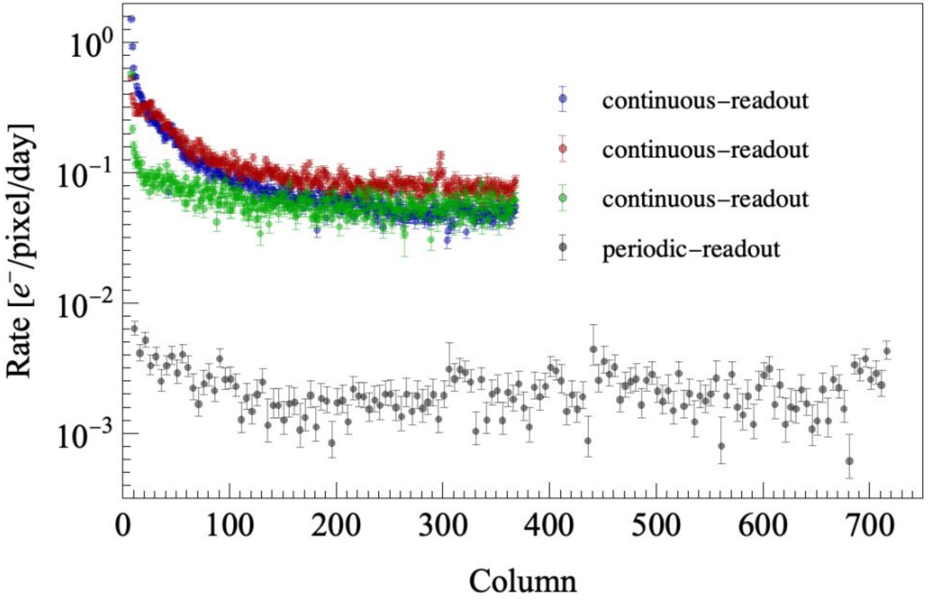


External Shield	λ_{DC} (10^{-4} e^-/pix/day)
Yes	(1.59 ± 0.16)
No	(5.89 ± 0.77)

Amplifier light

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

→ In SENSEI 2019 this effect was a huge SEE contributor



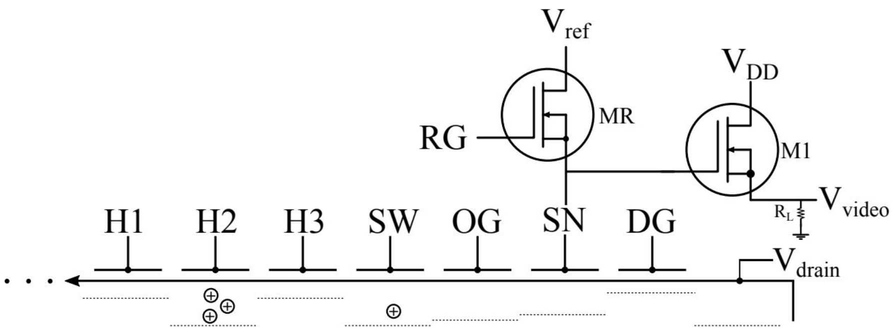


FIG. 2. Schematic illustration of a Skipper-CCD readout stage. H1, H2 and H3 are the last horizontal clocks in the serial register before the Summing Well (SW).

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Amplifier light study

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

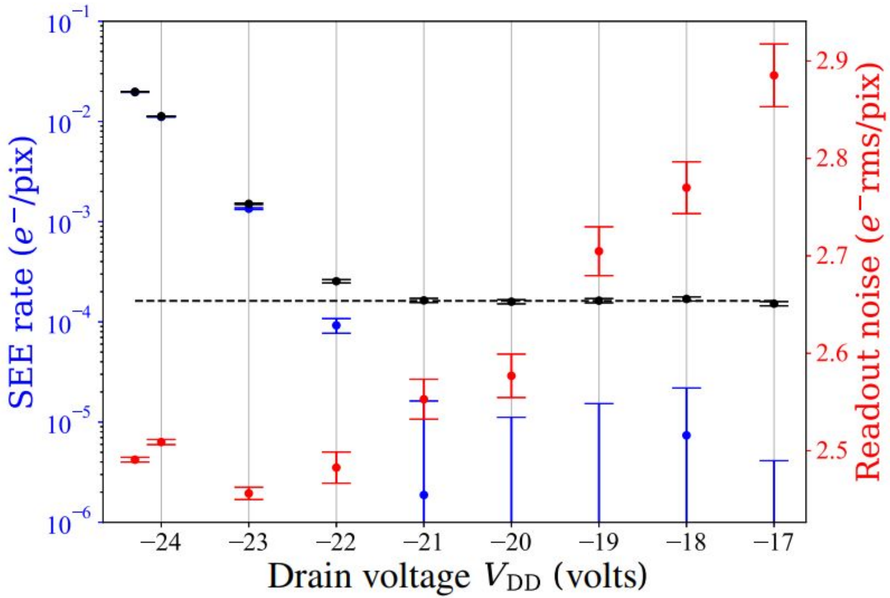


FIG. 5. SEEs per pixel (left axis) and single-sample readout noise (red, right axis) as a function of the drain voltage of the $M1$ transistor (V_{DD}). In black, we show the SEEs per pixel collected for each voltage ($\mu_{(t_{ro})}$) and in blue the AL contribution (μ_{AL}), estimated from Eq. (6).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

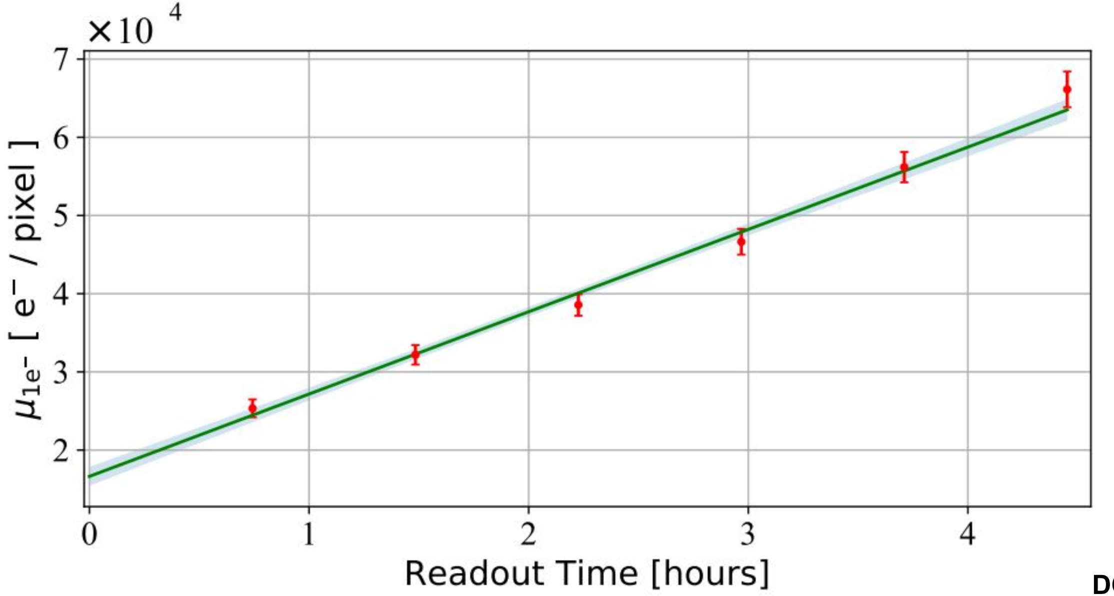
Spurious charge

→ SEE generated from **clocking** of pixels.

→ Depends mostly on **voltage swings** and **clock shaping**. Increases with lower temperatures.

→ Low energy background to possible DM signal (reduction and characterization)

→ In SENSEI2020,



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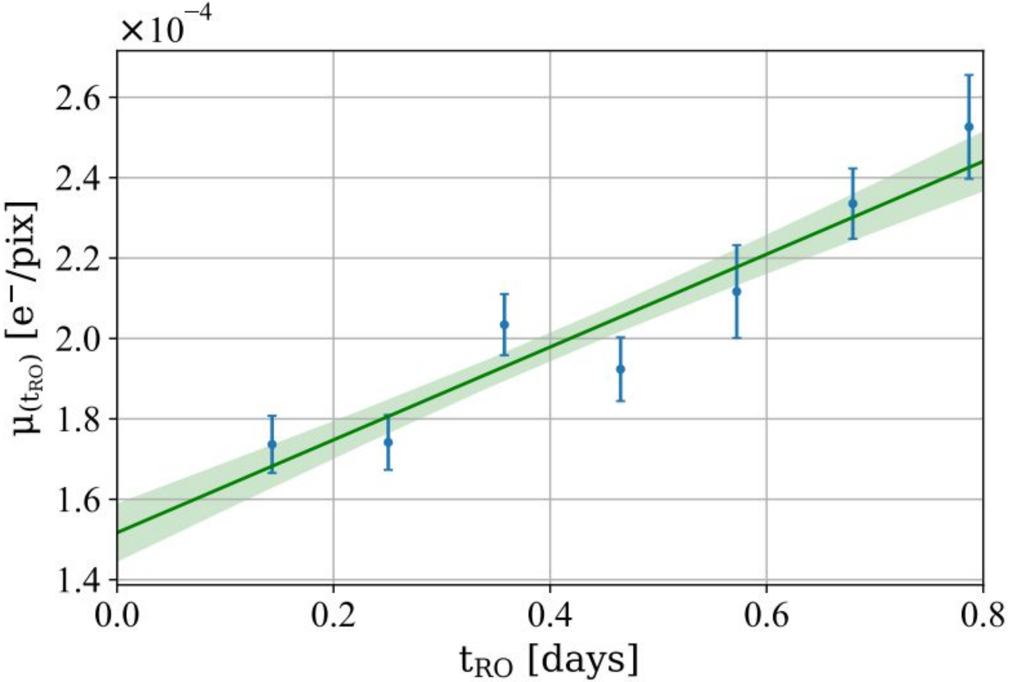
Transfer curves: λAL and μsc

→ **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)

All contributions: results

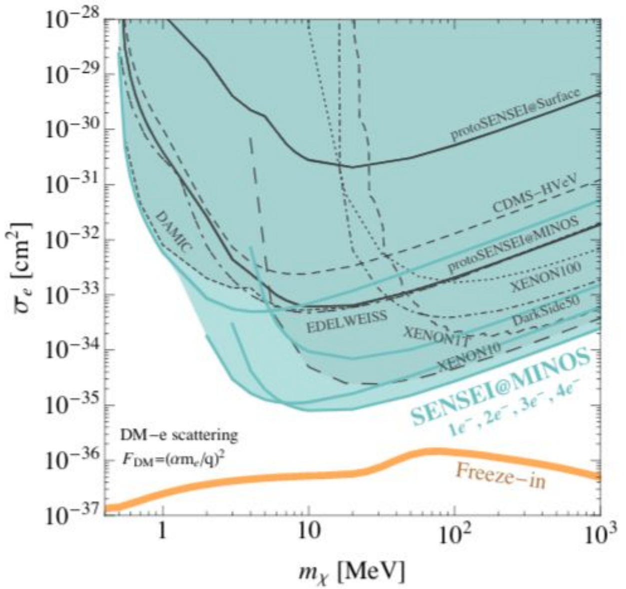
V_{DD}	External Shield	λ_{DC}	λ_{AL}	μ_{SC}
-21	Yes	(1.59 ± 0.16) $10^{-4}\ e^-/\mathrm{pix/day}$	(0.36 ± 0.18) $10^{-4}\ e^-/\mathrm{pix/day}$	(1.52 ± 0.07) $10^{-4}\ e^-/\mathrm{pix}$

→ Considering λ_{AL} negligible, in a 24 hours exposure image (typical science run) we would have the same amount of SEE coming from DC than from SC.

→ SC can be further reduced by **pixel binning** and **swing shaping**.

→ This limiting factor in DC may come from both **extrinsic** and **intrinsic** contributions.

→ Origin of remaining DC is being investigated at the moment.



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THANKS!