Characterizing Long-Lived Charge Traps in Skipper-CCDs

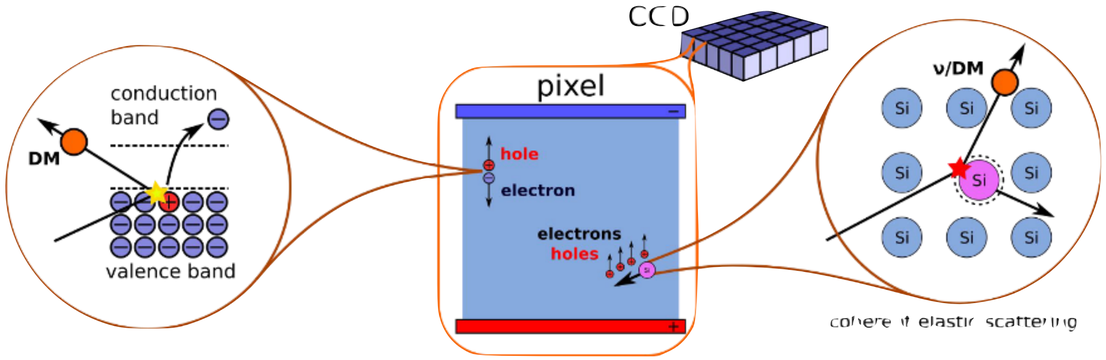
Ansh Desai

Based on: *arXiv:2610.22418*

adesai@uoregon.edu · Sub-Electron-Noise Skipper-CCD Experimental Instrument · https://sensei-skipper.github.io/

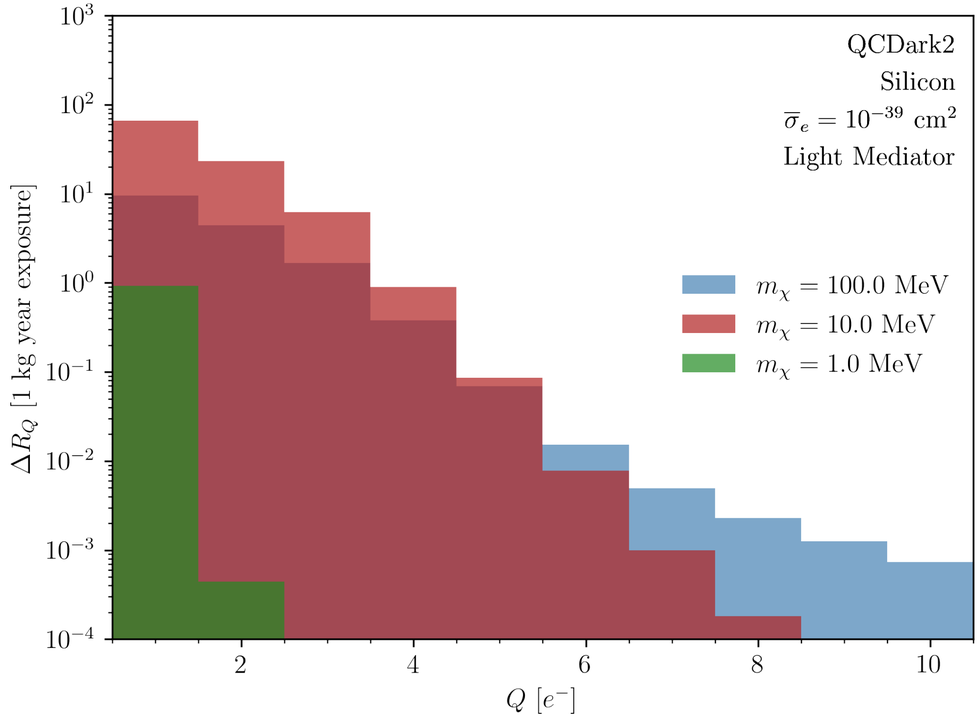
Skipper-CCDs for Dark Matter

QCDark2: Dreyer et al.
arXiV:2603.12326



DM-electron Scattering

DM-Nucleus Scattering

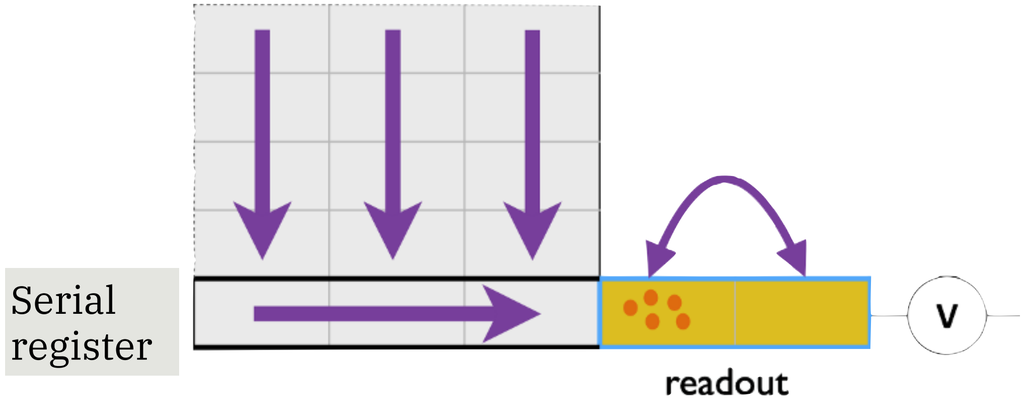


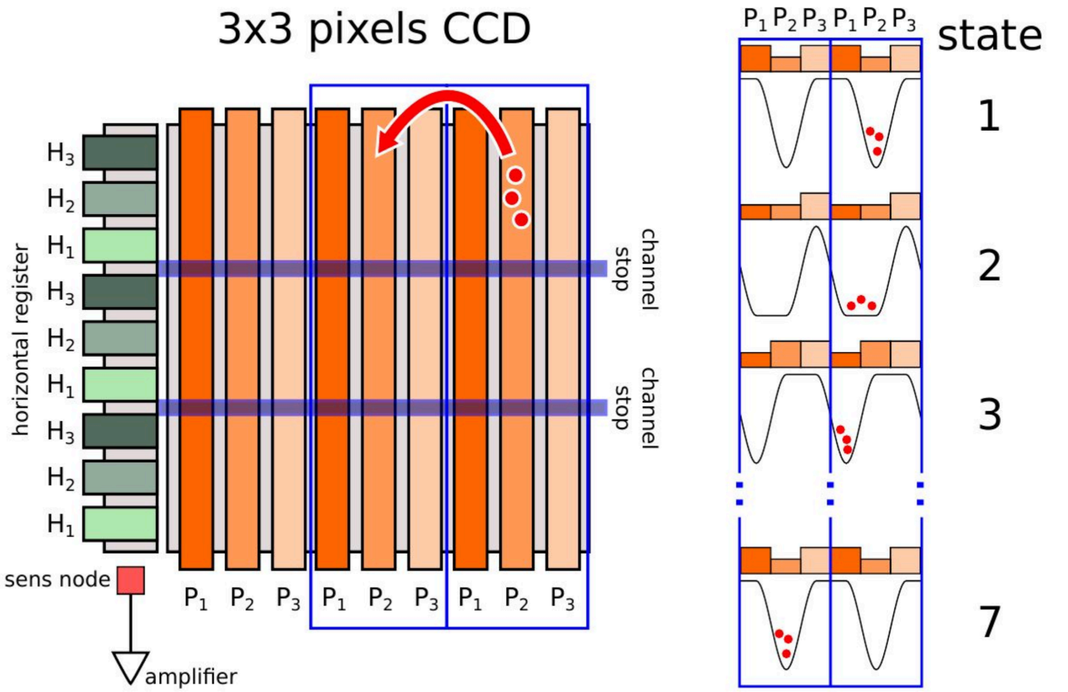
- Skipper-CCDs act as pixelated ionization detectors with single-electron resolution
- DM signals are of order few e^- with a rapidly falling spectrum

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Skipper-Readout

- Skipper-CCDs allow for reduction of both high and low frequency noise
- This is done through repeated non-destructive measurements at the sense node
- All measurements averaged — gives sub-electron resolution
- Time for readout for an unbinned image is ~7h

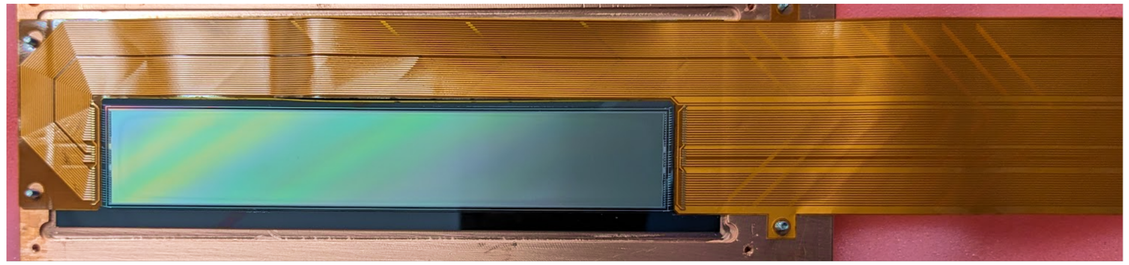




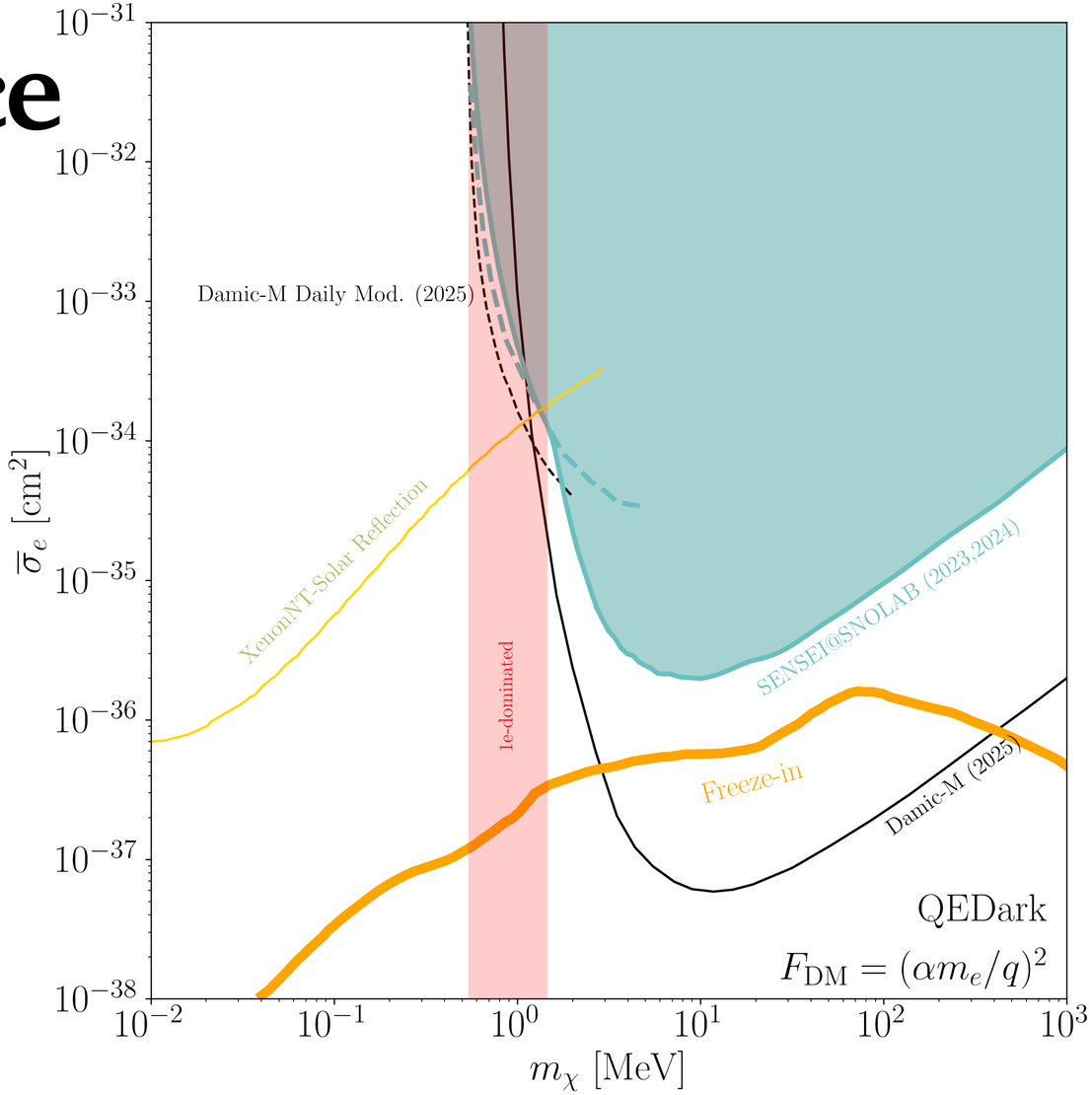


Skipper-CCD Performance

- Skipper-CCDs are currently the leading technology for MeV-scale DM
- Intrinsic background of single-electron events — causes pileup backgrounds
- Understanding these events is key to improving the performance of these detectors



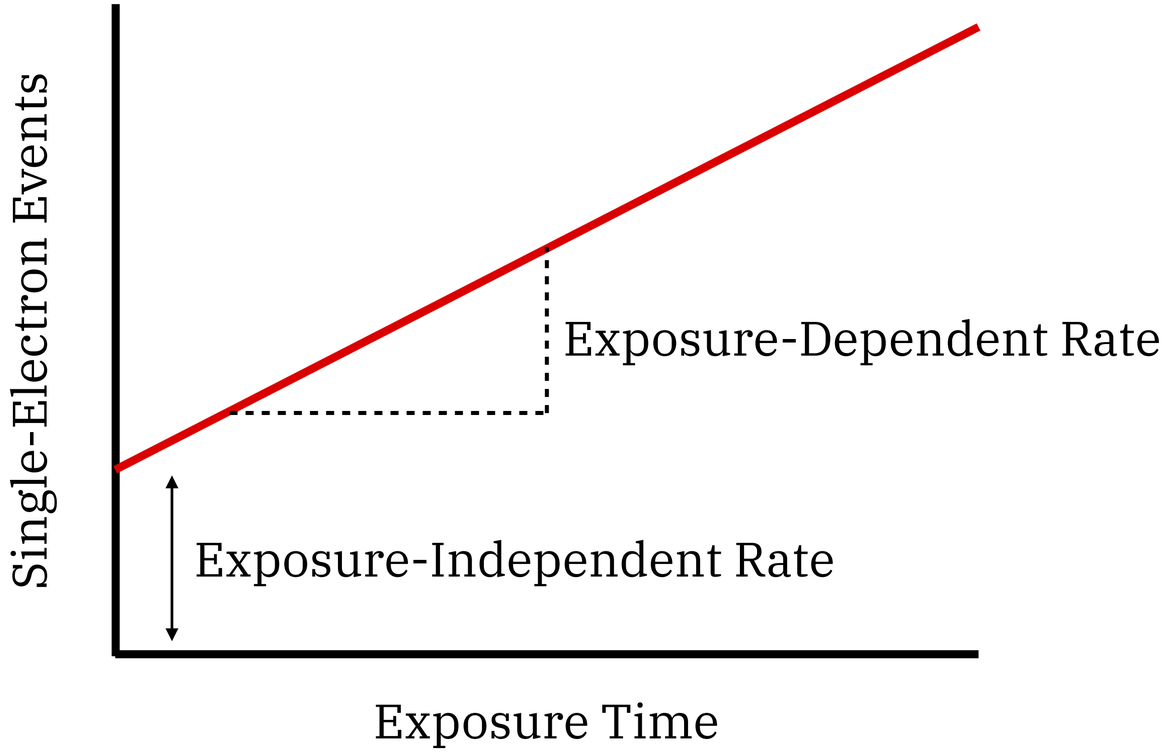
6144×1024 pixels



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Single-Charge Backgrounds

- We typically separate the single-electron backgrounds into two components
- **Exposure-dependent rate:**
  - Dark current
  - Radiation-induced charge
- **Exposure-independent rate:**
  - Spurious charge — recently studied in detail in *arXiv:2605.30281*



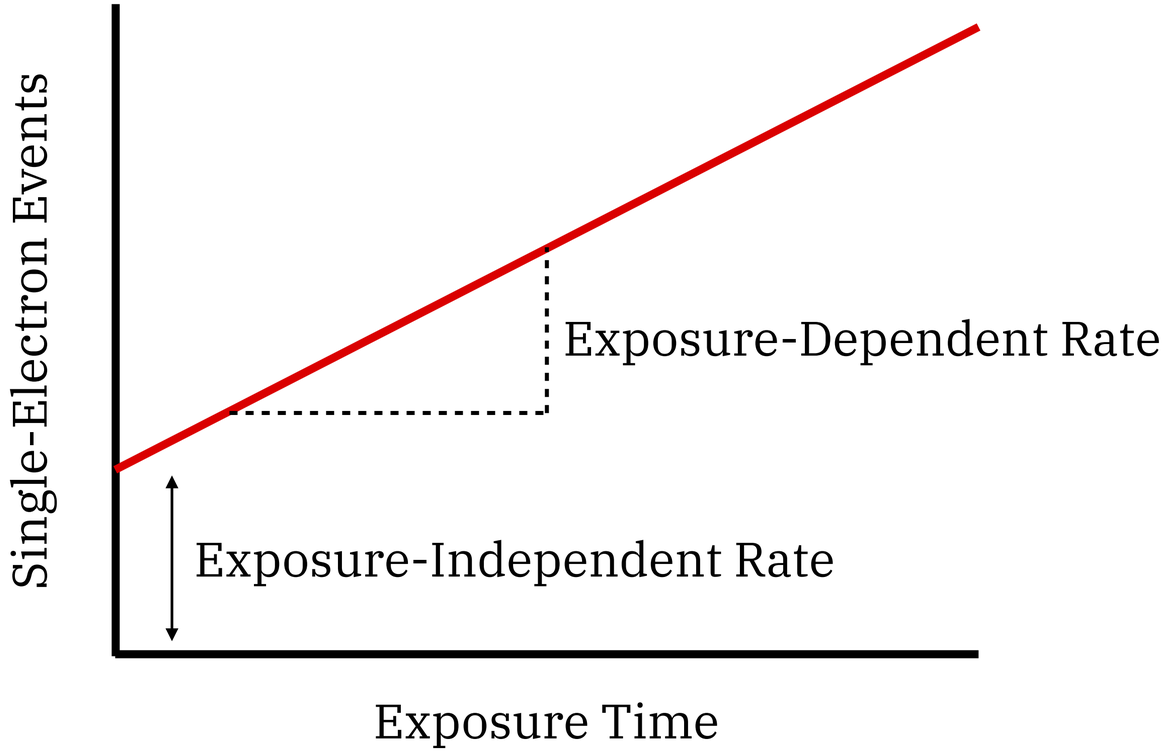
Single-Charge Backgrounds

- Current values: (best in any NIR/UV photodetector)
- **Exposure-dependent rate:**

$$(1.4 \pm 0.1) \times 10^{-5}\ \mathrm{e^-/pix/day}$$

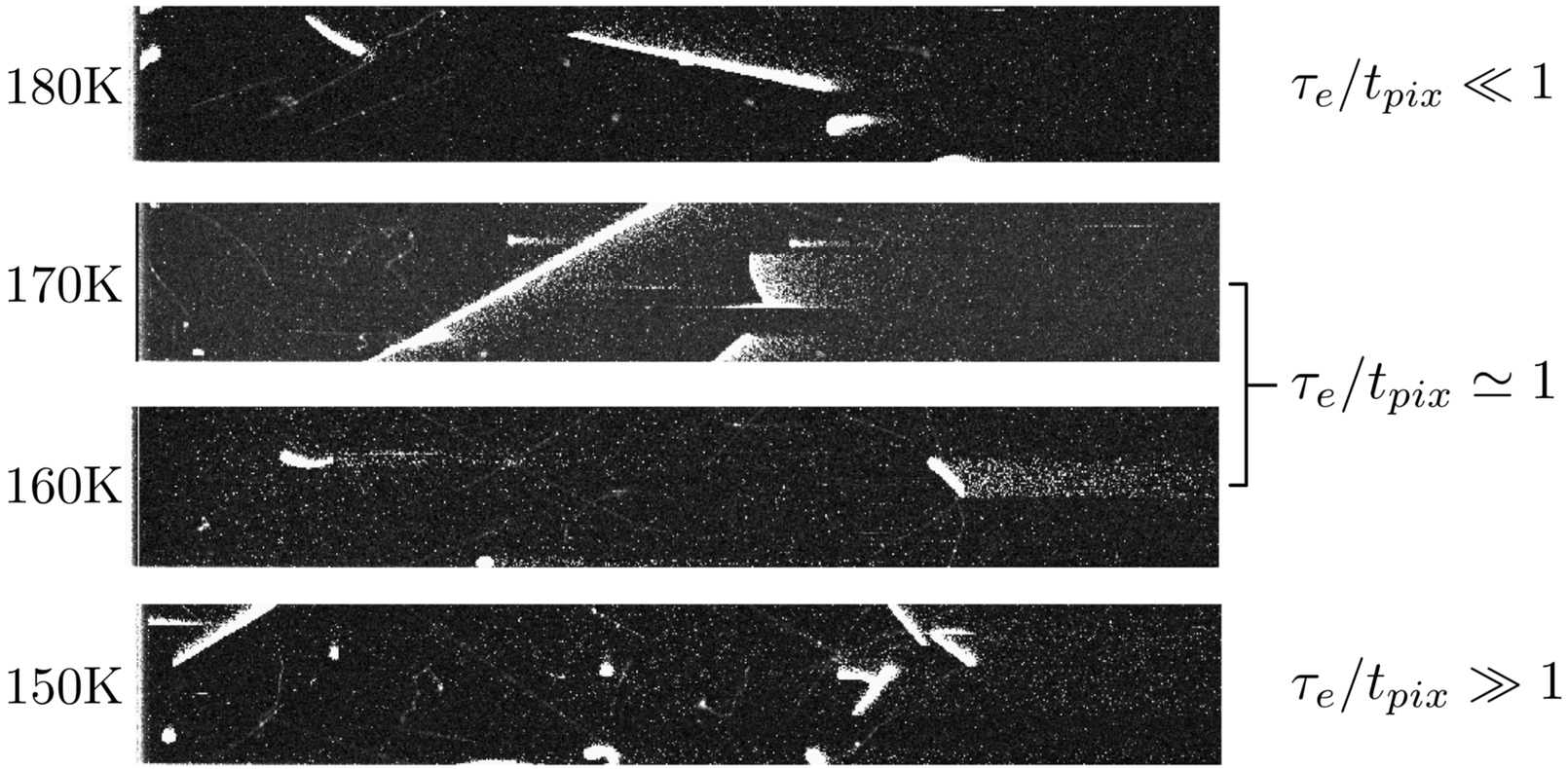
- **Exposure-independent rate:**

$$(6.9 \pm 0.8) \times 10^{-5}\ \mathrm{e^-/pix/image}$$



Charge Traps

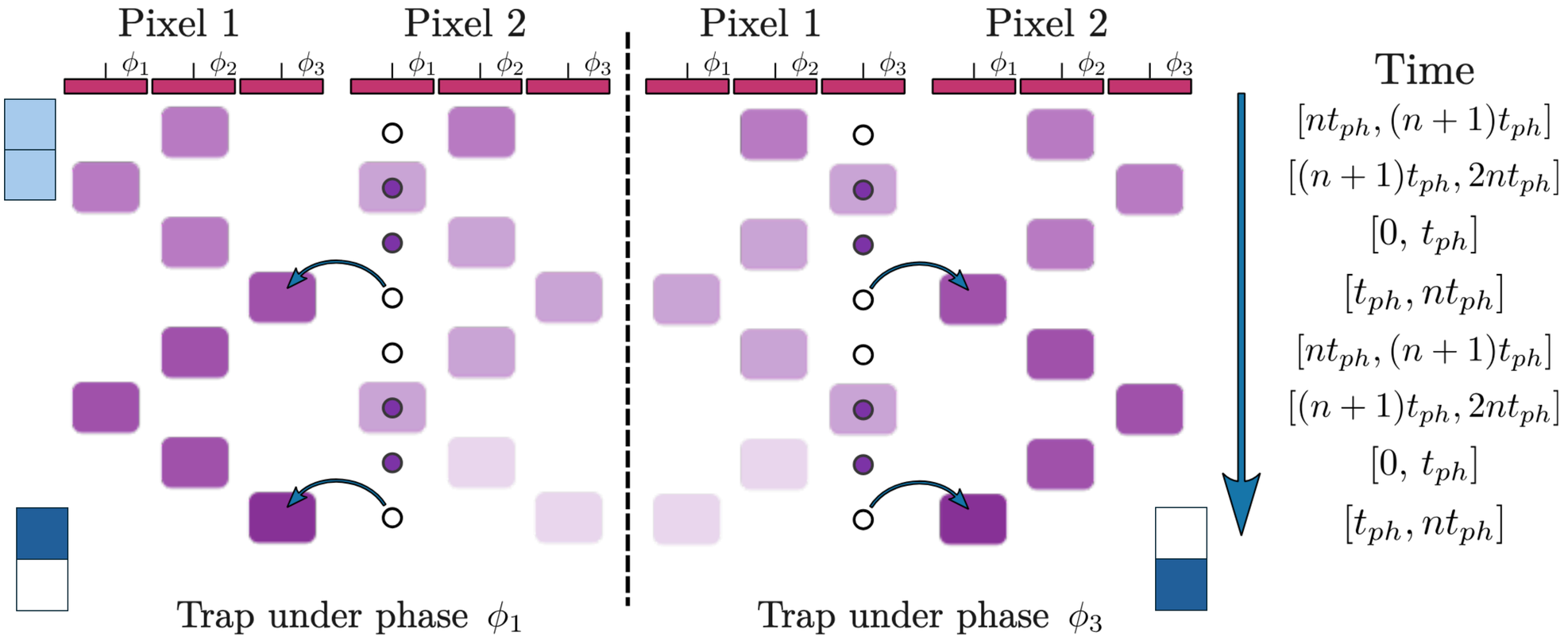
- One possible source of **exposure-dependent charge**
- Defects from contaminants during fabrication or vacancies — observed in other silicon sensors
- Depending on the emission time of a trap at operating temperatures, these can produce seemingly-uncorrelated single-electron events



t_{pix} = Readout time between consecutive pixels

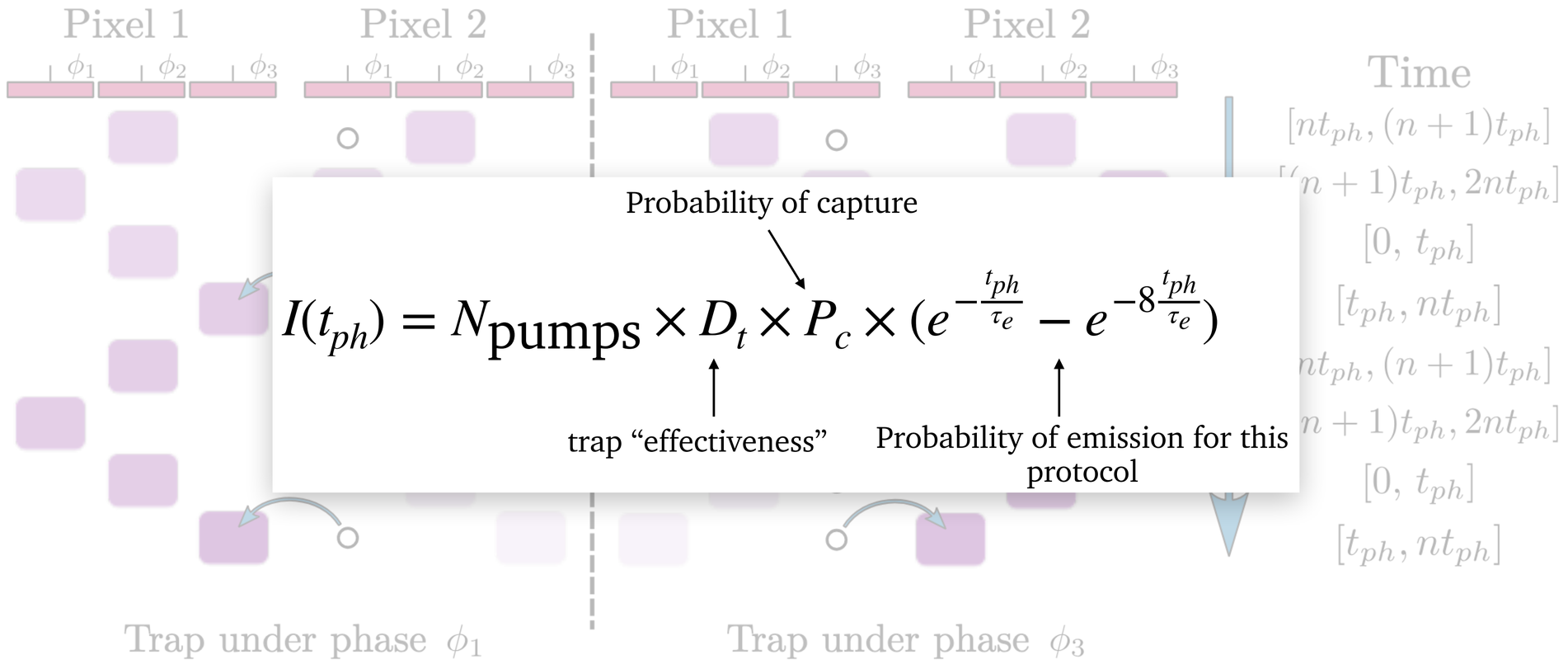
τ_e = trap emission time

Searching for Traps



Can identify traps in the edge phases of the pixel through “pocket pumping”
Traps will appear as “dipoles”

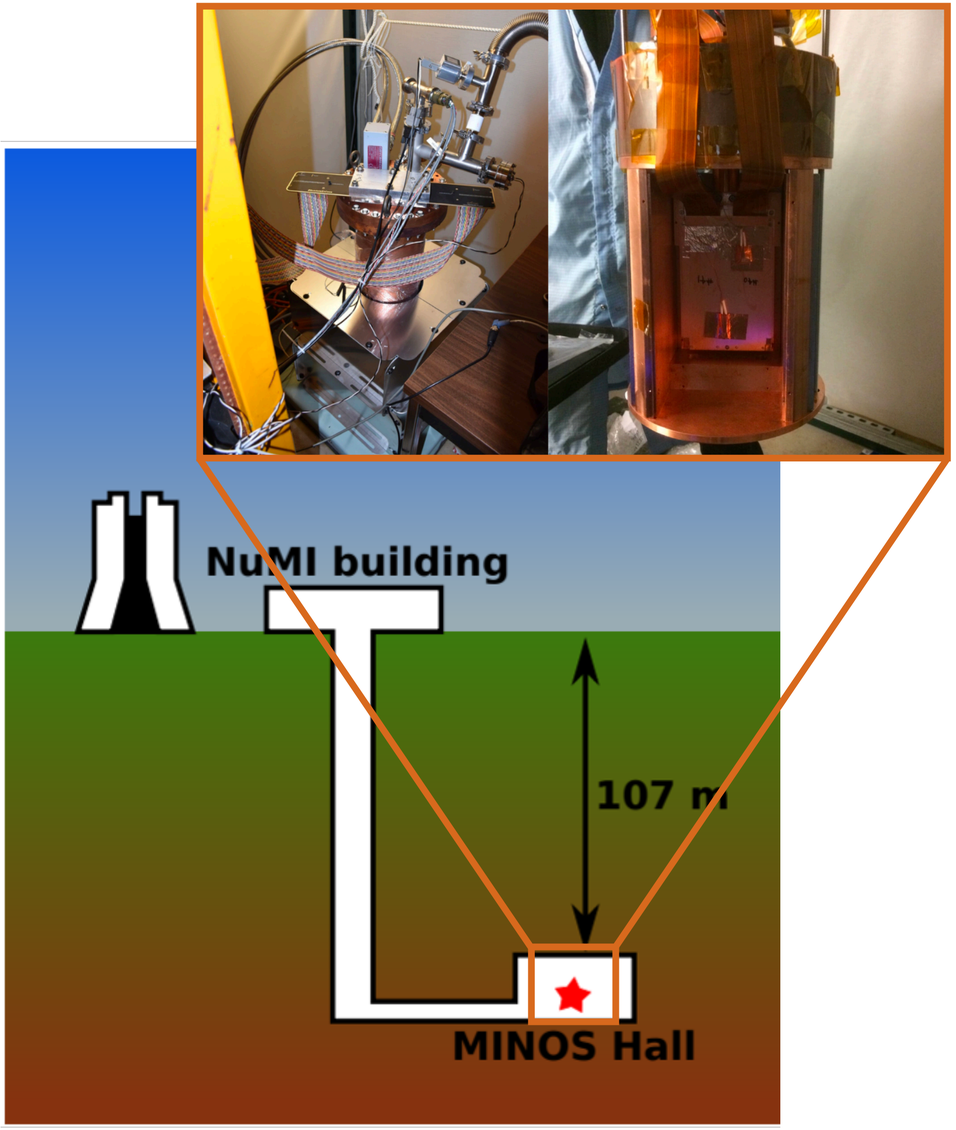
Searching for Traps



Intensity of the dipole is modeled by Shockley-Read-Hall Theory —*PhysRev.87.835*

Measurement Motivation

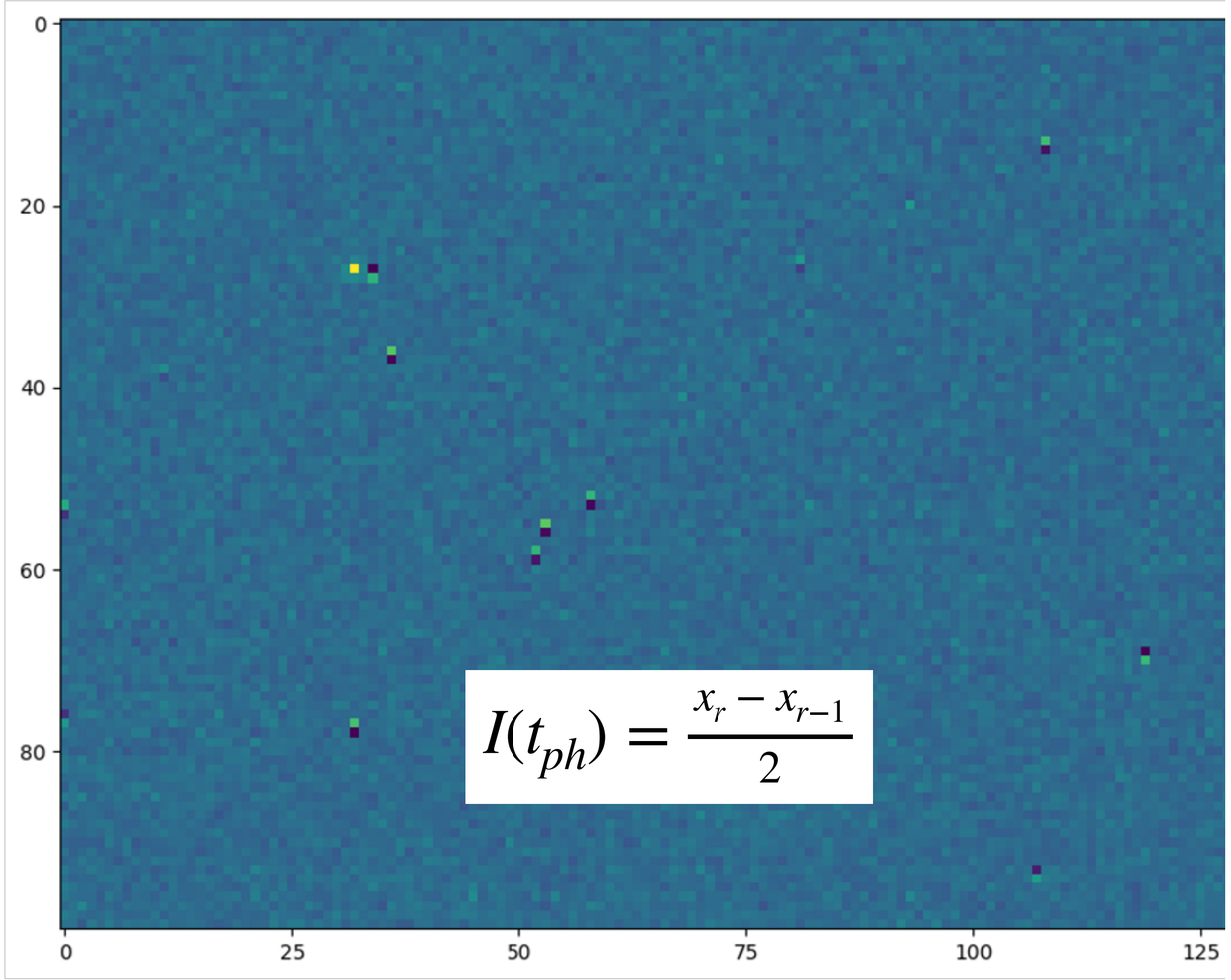
- Shockley-Read-Hall also provide a model for understanding how the trap emission time scales with temperature
- To probe very long-lived traps ($\tau_e(135\ \mathrm{K}) \geq 10^3$ s) you need to take long measurements at high temperature — requiring a shielded environment
- We took long measurements in the SENSEI setup in the MINOS underground cavern
- Measuring these requires method for generating a flat field of charge — **new method developed to take advantage of spurious charge to perform in-situ charge generation and calibration** — described in *arXiv:2605.30281*



Trap Identification

- Using 1 CCD underground in MINOS we took 36 – 50 images ($t_{ph} \in (50\,\mu s, 1.03\,s)$) for temperatures in the range ($T \in (125\,K, 210\,K)$)

* For each image we
  * Subtract median of charge from the image
  * Multiply adjacent rows of charge and identify negative values — evidence of a dipole
  * Intensity is logged as the half the difference of charge in the two pixels



Trap Fitting

- We then fit the intensity curve $I(t_{ph})$ for every identified dipole at a given temperature T — this gives you the emission time τ_e at that temperature
- By combining these fits for different temperatures you can fit the trap energy E and cross-section σ by fitting $\tau_e(T)$
- Several goodness of fit criteria applied — minimum four intensity curves must be fit to call a trap characterized

Amplitude term A absorbs $N_{\text{pumps}}, D_t, P_c$

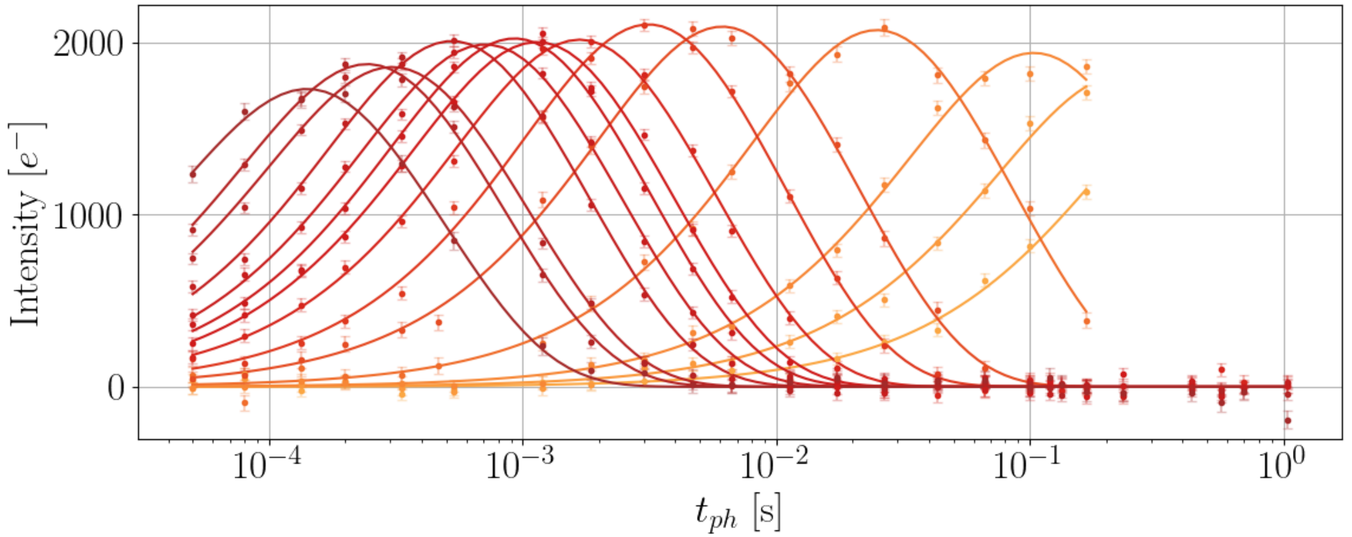
$$I(t_{ph}) = A \times (e^{-\frac{t_{ph}}{\tau_e}} - e^{-8\frac{t_{ph}}{\tau_e}}) + I_0$$

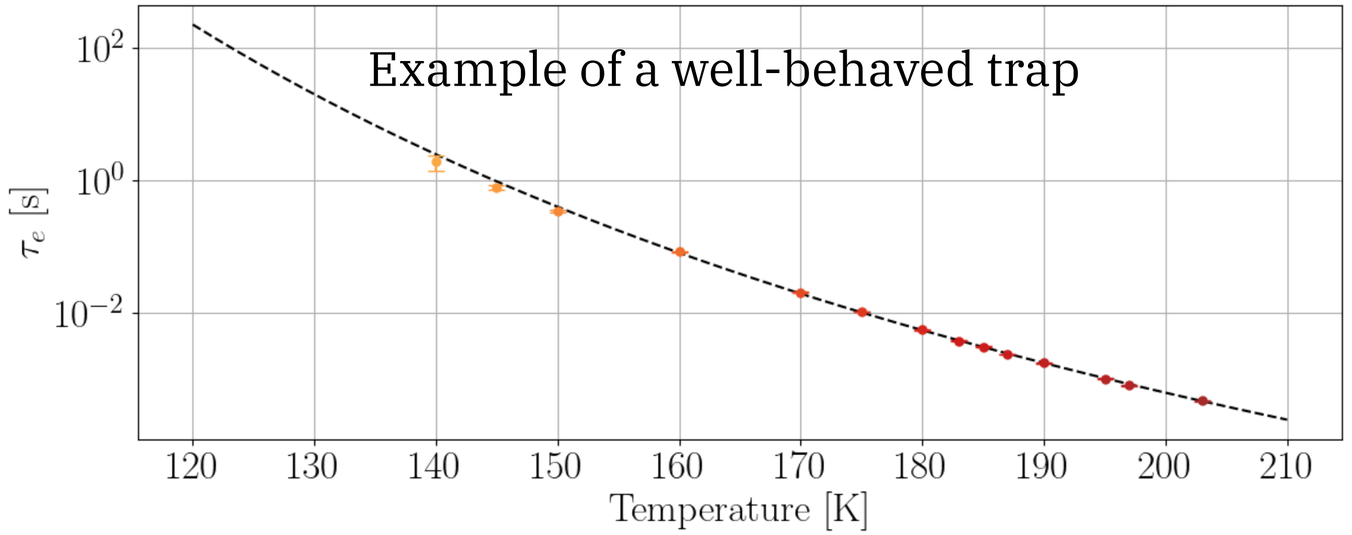
Pedestal term to help fitting in the presence of high dark current

$$\tau_e(T) = \frac{h^3 c^2}{2\sqrt{3}\, 2\pi^{3/2}\, m_e} \times \frac{1}{\sigma\,(k_b T)^2} \times e^{\frac{E}{k_b T}}$$

Trap Fitting

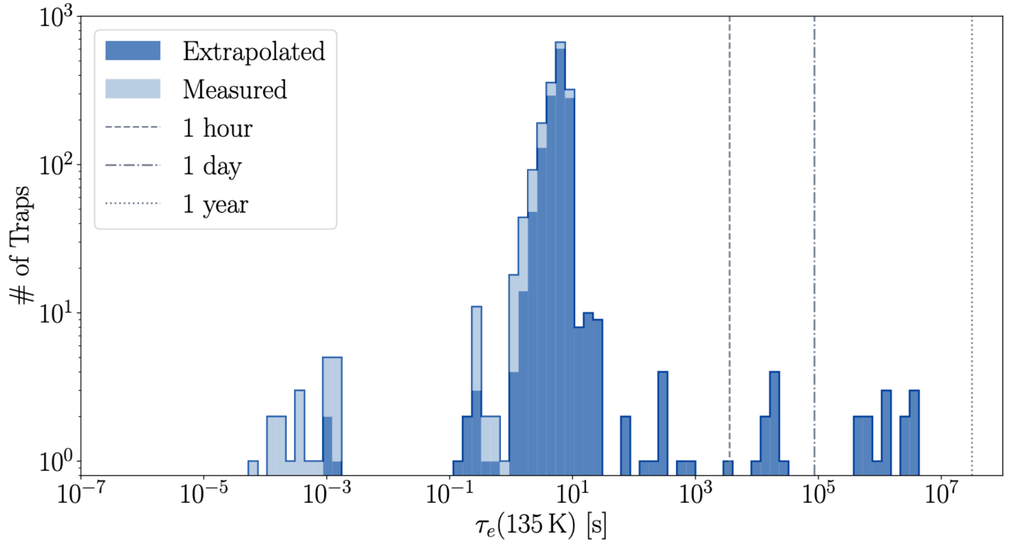
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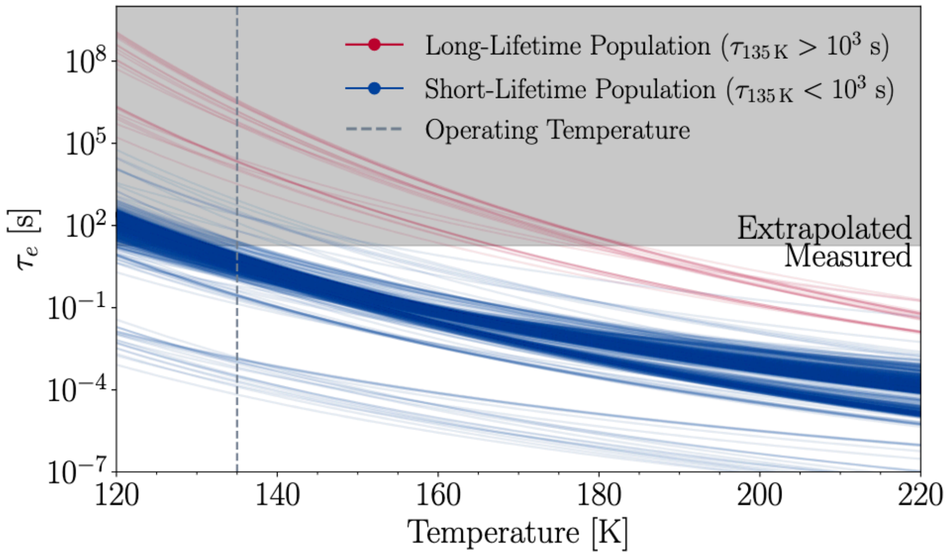


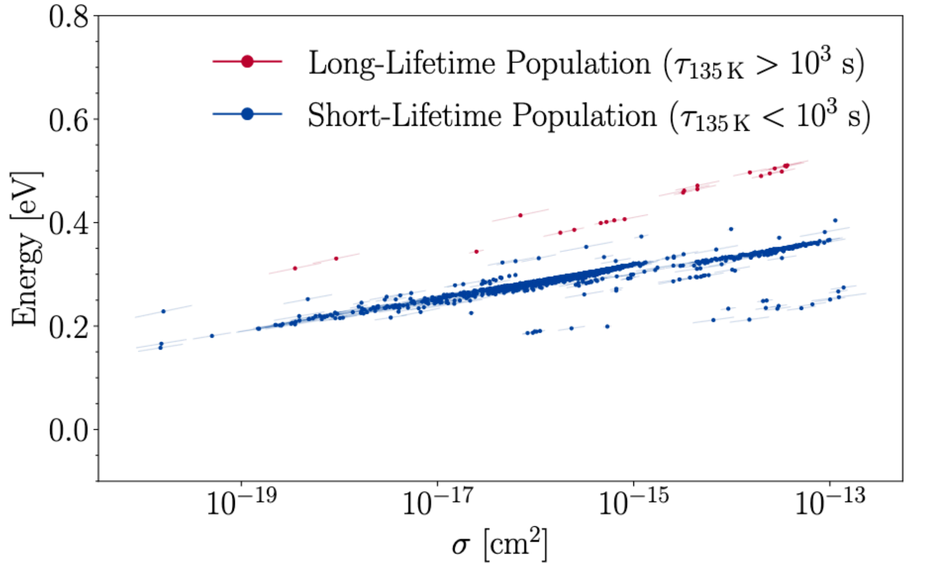


Characterized Trap Population

- After all selections, 1787 genuine traps are identified and characterized from 9333 candidates
- We then use the measurements at high temperatures to extrapolate the emission times at operating temperatures of 135K

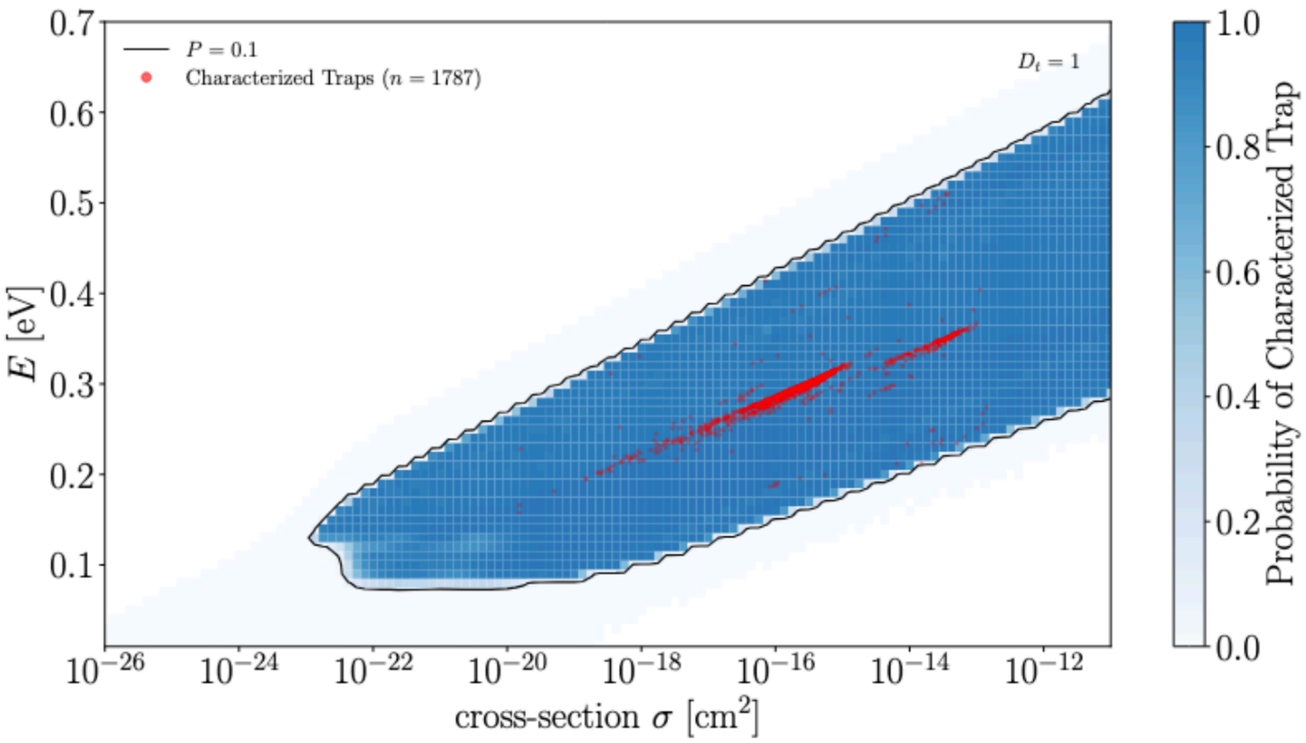






Completeness of Measurement

- To assess the strength of this measurement we simulate traps with various energies and cross-sections
- Probability of capture can be calculated using occupancy probability based on the pumping procedure, we choose $D_t = 1$ for maximally capturing traps
- We can then predict the intensity for a simulated dipole for different temperatures by injecting it into empty parts of real data and propagate it through our selections,
- The probability of detection is defined as repeating this for a physical trap 100 times and see how often it passes selections



Are these traps dangerous?

CCD Readout

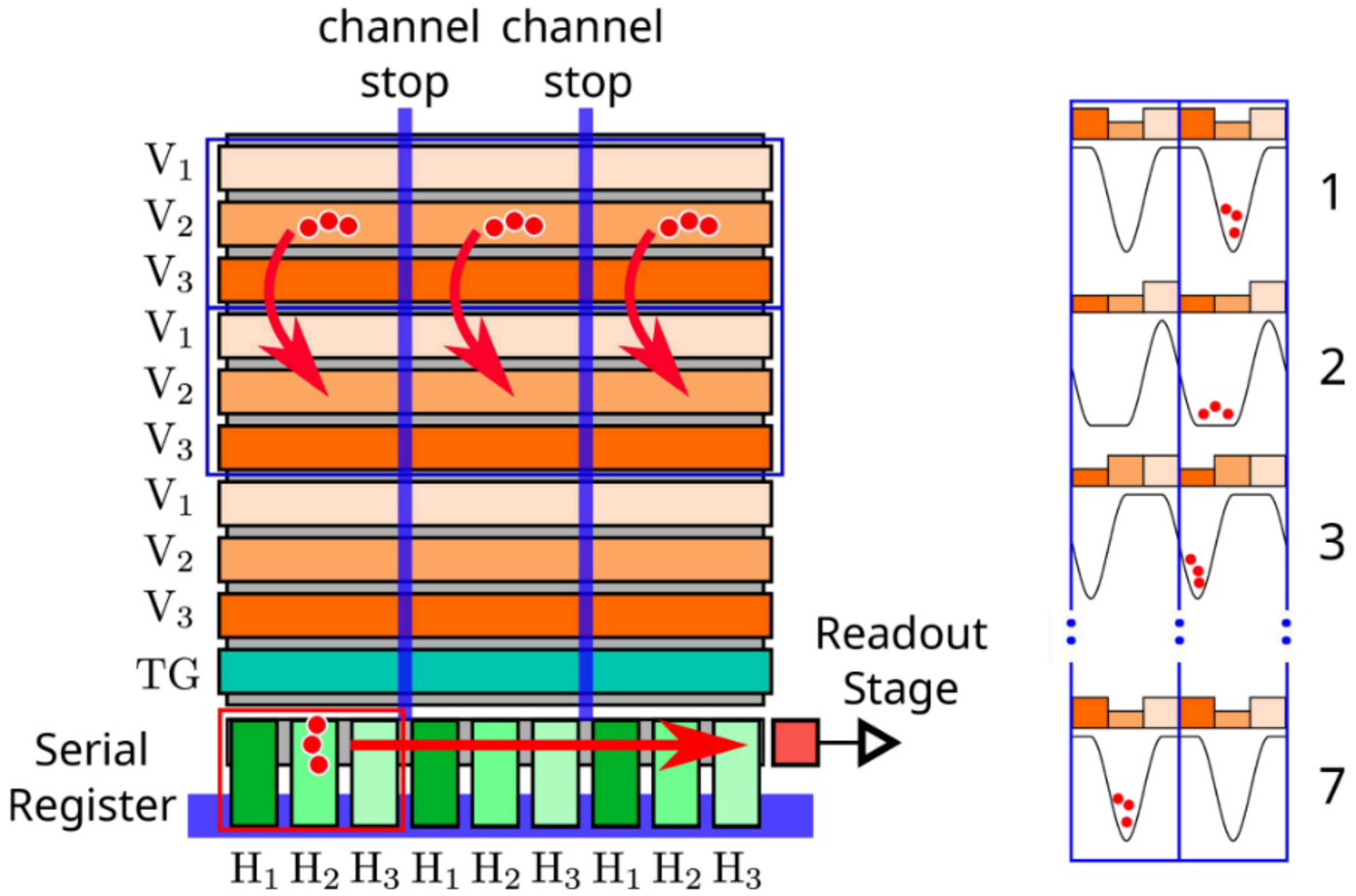
- Traps can capture during the short overlap when charge shifts over V_1 or V_3 which **only happens during readout**

$$P_e = 1 - e^{-\frac{t_r}{\tau_e}}$$

$$P_c = 1 - e^{\lambda_c dt}$$

$$\lambda_c = \sigma v_{th} \frac{q}{V_p} = \sigma \sqrt{\frac{3k_b T}{0.41 m_e}} \frac{q}{V_p}$$

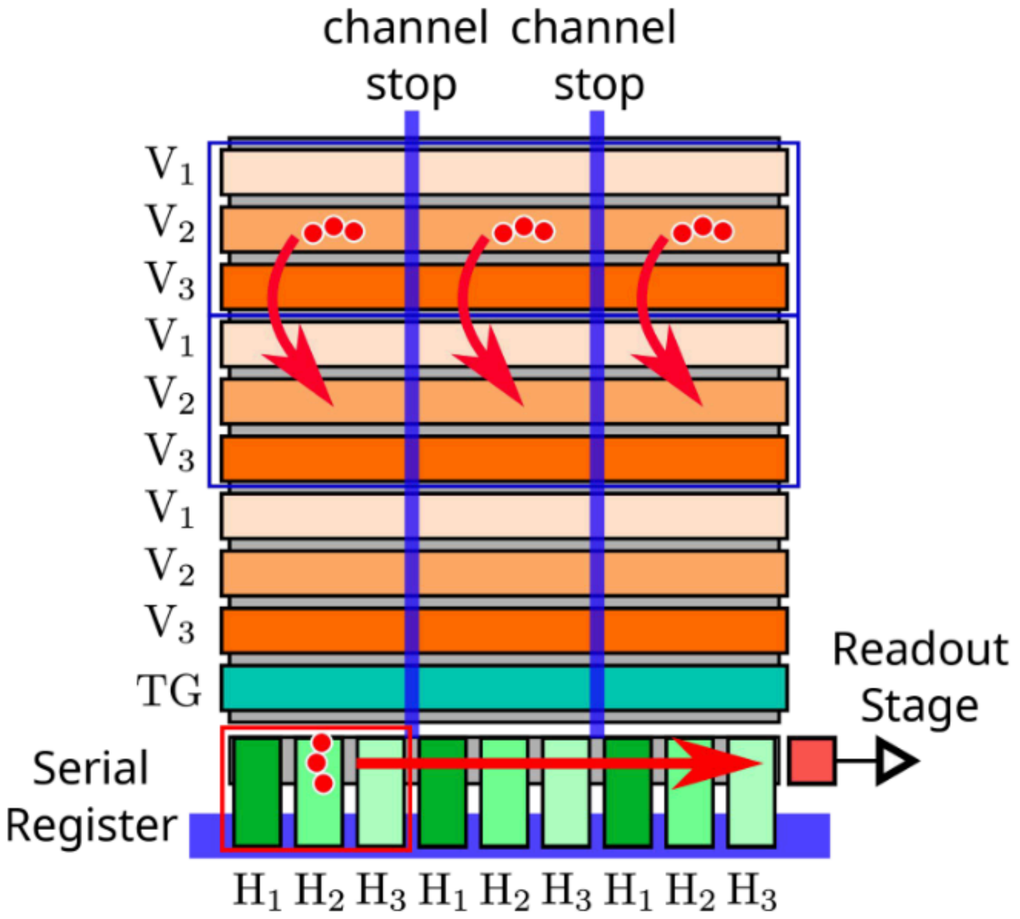
$$dt = 80\,\mu\text{s}$$

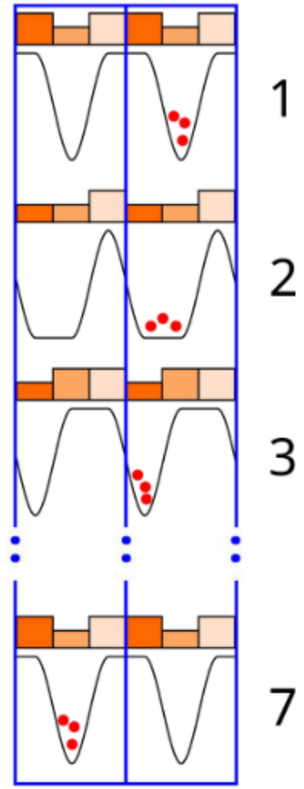


t_r refers to how long the charge is in phase V_2 during readout

Readout Simulation

- We simulate this exact readout with a new simulation code for two operating conditions corresponding to actual SENSEI@SNOLAB data-taking procedures
- We initialize a CCD with randomly distributed traps sampling from the measured energies and cross-sections
- We also assume the CCD has an intrinsic exposure-independent and exposure-dependent rate, values chosen were measured in previous runs

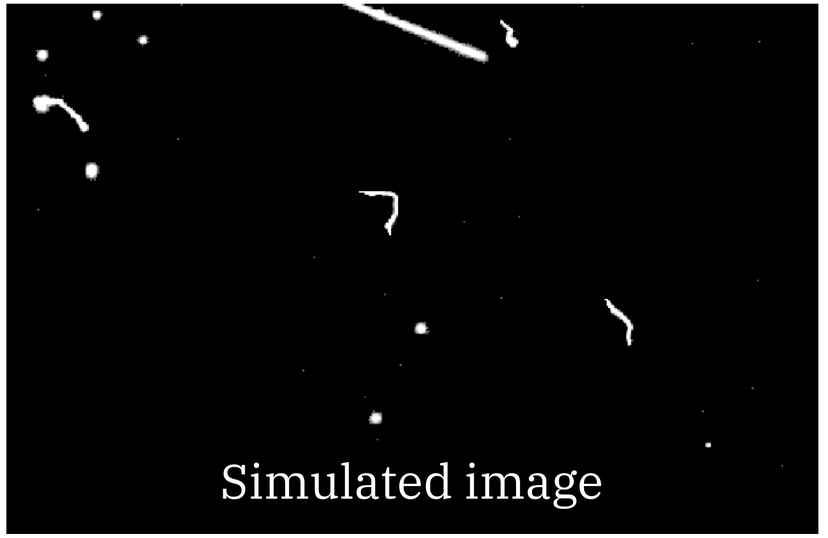




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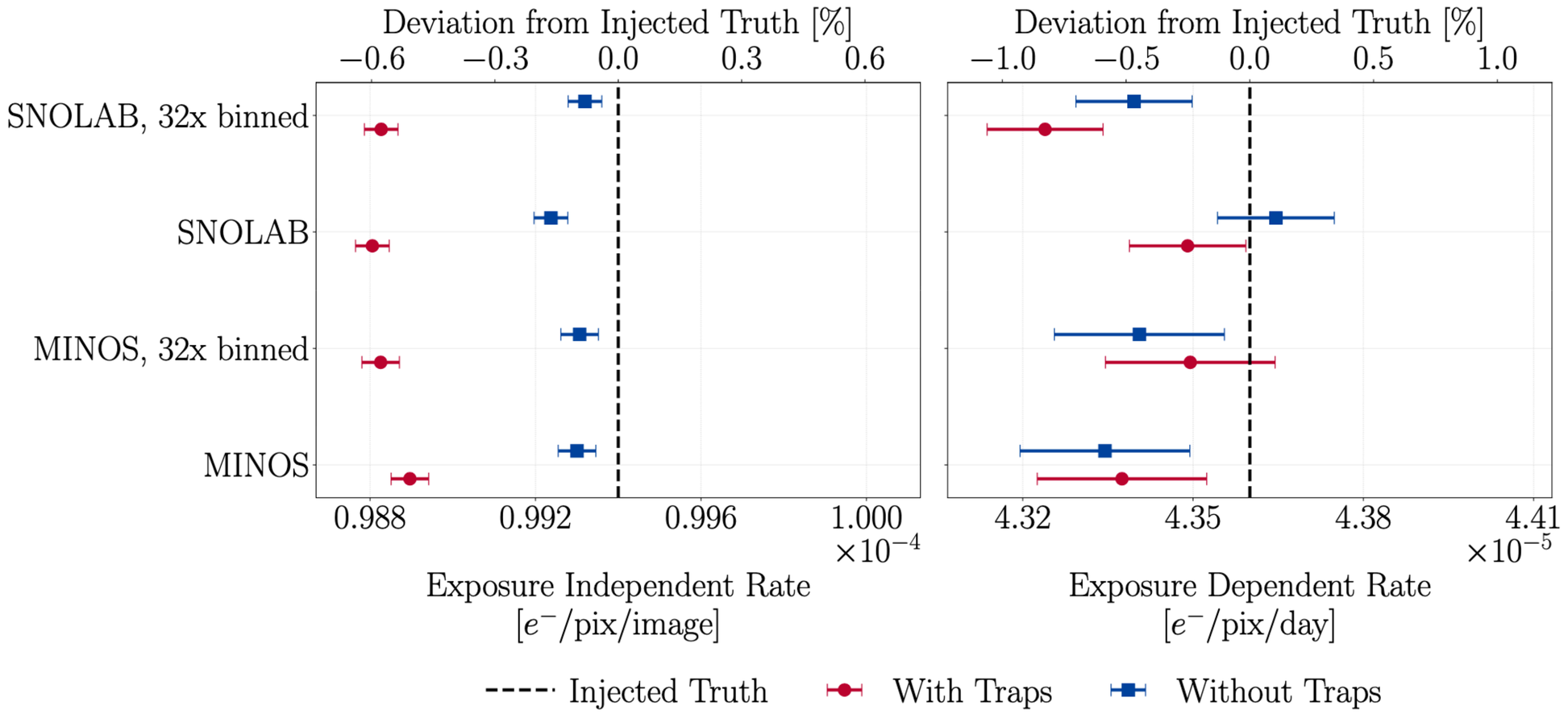
Simulation Analysis

- One “trial” means 500 images in order with exposures 0h, 4h, 6h 10h, and 20h.
- Then two copies of the image are “read out”, one with traps and one without
- We then apply SENSEI masks that were designed to target exposure-dependent backgrounds — hot column/pixel, halo, and bleed
- After each image a clear is performed where charge is cycled out for 3 hours
- This is done for 100 “trials” — then the exposure-dependent charge is fit as a function of exposure


Simulated image


Simulated with masks

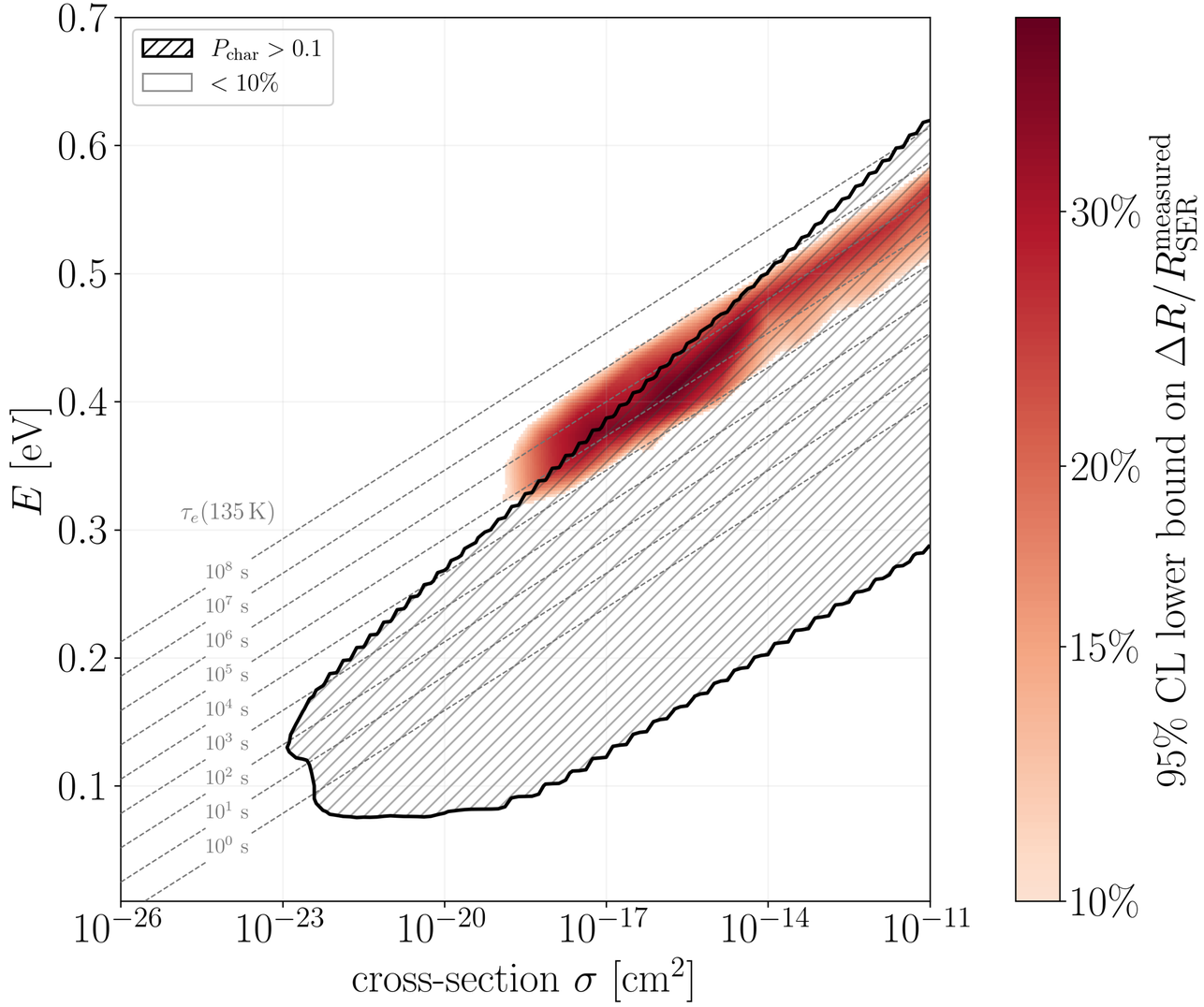
Results



Deviations are sub-percent — **this population is negligible for the single-electron rate**

What about a hidden population?

- We take ~2000 traps sampled from a point on the (E, σ) plane and run them through the same simulation — repeat for a grid of points
- A point is classified as “dangerous” when the 95% confidence lower bound on the trap-induced rate exceeds 10% of the measured single-electron rate measured at SNOLAB
- Many of these dangerous traps were probed by this measurement — but new techniques will have to be studied to fully exclude this population



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Conclusions

- We identified 1787 charge traps in a SENSEI CCD at MINOS
- The new charge-generation technique and access to shielded measurements allowed us to probe traps with emission times $\tau_e \geq 10^3$ s, a region not previously accessible with this measurement
- We studied the impact of these traps on the single-electron rate, and found the observed population contributes negligibly
- We also studied hypothetical traps that would be dangerous, and compared this to where we are confident our measurement holds
- **Future**: dangerous populations are not fully excluded — different procedure must be investigated in order to study these traps
- **Future**: modifying the pumping procedure can measure traps under the center phase, which we ignored in this work

Thank you for your attention!

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Backup

Dipole Detection Algorithm

- Estimate average charge spread σ_{MAD} using median absolute deviation
- Subtract median charge of image from every pixel
- Corrected pixel charge in row r (x_r) is multiplied by charge in the same column in the previous row (x_{r-1})
- If the product $x_r x_{r-1} < -(3\sigma_{MAD})^2$ it is tracked
- If the dipole appears in multiple images with the same orientation -> trap candidate
- Duplicates are filtered through dealiasing

Intensity and Energy Cross-Section Fitting

- For every identified trap the fitted amplitude A must be at least 3 times its fit uncertainty to reject signals with weak pumping strength
- We impose requirements on the fitted emission time τ_e to have relative fit uncertainty to reject curves with an insufficiently constrained peak
- We then require the goodness-of-fit test statistic for the fit, and also require that the fit eats a straight line fit by a sufficient margin
- We similarly impose requirement son the fitted cross-section and the goodness of fit so we get good energy and cross-section measurements
- Traps that don’t appear for at least four temperatures are also rejected

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Trap Identification

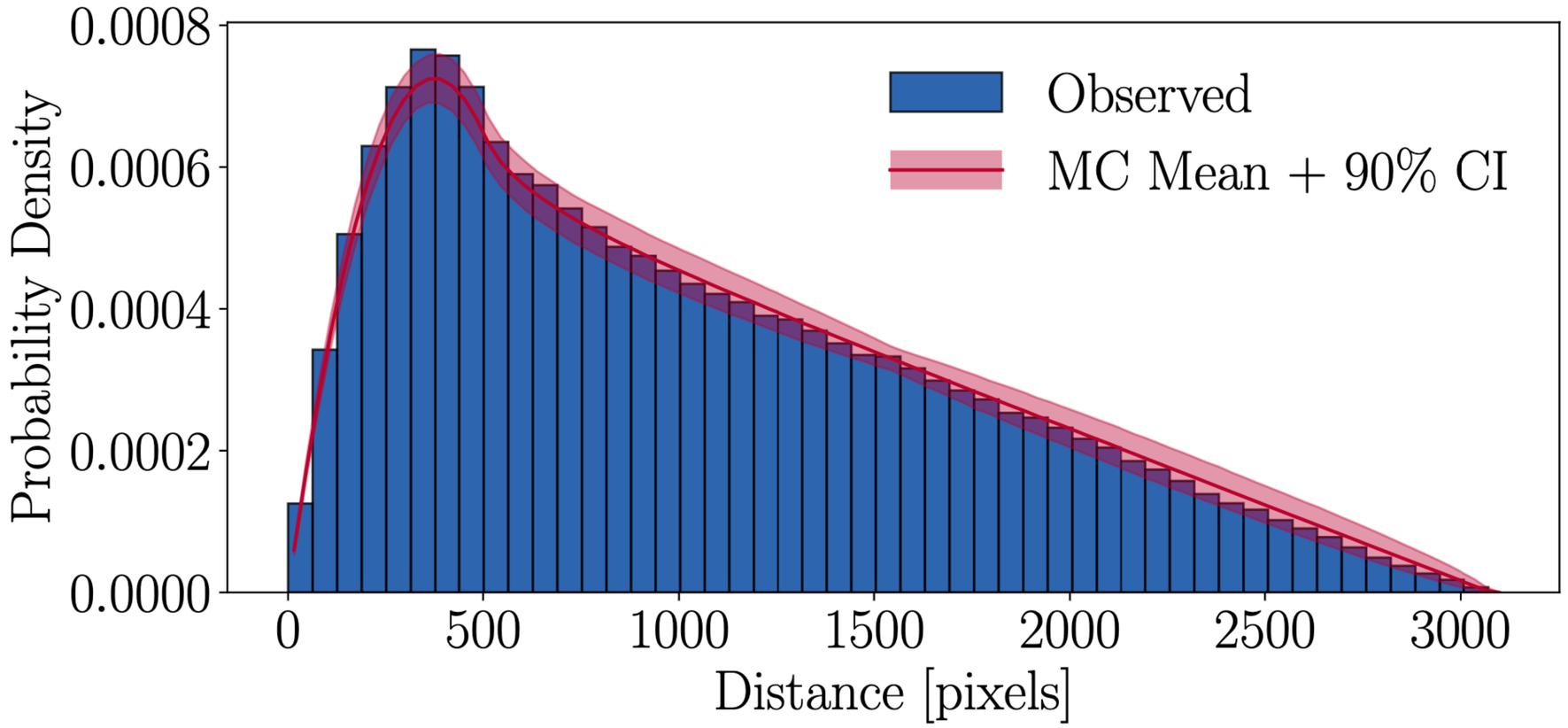
- Tricky to identify sources of defects, likely a combination of multiple defects like Silicon divacancy, heavy metals, etc

Table 1. Energy levels and majority carrier capture cross sections measured for defect states observed in silicon samples quenched from 1175 °C.

Dopant	Energy level (eV)	Cross-section (cm^2)	Si
Au	$E_c - 0.28$ (electron trap)	10^{-17}	n- and p-type
Fe	$E_v + 0.32$ (hole trap)	2×10^{-15}	p-type
Ni	$E_v + 0.33$ (hole trap)	10^{-20}	p-type
Fe	$E_v + 0.39$ (hole trap)	3×10^{-17}	p-type
Fe	$E_v + 0.40$ (hole trap)	10^{-18}	p-type
Undoped	$E_v + 0.43$ (hole trap)	6×10^{-18}	p-type
Au, Ag	$E_v + 0.48$ (hole trap)	4×10^{-17}	p-type
Cu	$E_v + 0.53$ (hole trap)	2×10^{-16}	p-type

Defects in Oscura sensors studied in *arXiv:2406.18502*

Distance Between Traps



Trap Capture Physics

- For a genuine trap P_c is dependent on the capture and occupancy evolution during the pumping sequence, which is based on the capture rate $\lambda_c = \dfrac{\sigma v_{th}(T) n_e}{V_p}$
- $V_p \approx 1\,\mu$m by using the pixel geometry and taking some reasonable values
- Steady state occupation is then: $p_\infty = \dfrac{\lambda_c}{\lambda_c + \lambda_e}$ and thus the exact mean occupancy over N_{pumps} is

$$P_{\text{eff}}(t_{\text{ph}}) = p_\infty \left(1 - e^{-7 t_{\text{ph}}(\lambda_c + \lambda_e)}\right) \times \frac{1}{N_{\text{pumps}}} \sum_{k=0}^{N_{\text{pumps}}-1} \left(N_{\text{pumps}} - k\right) \times \left(e^{-7 t_{\text{ph}}(\lambda_c + \lambda_e)} e^{-9 t_{\text{ph}} \lambda_e}\right)^k$$

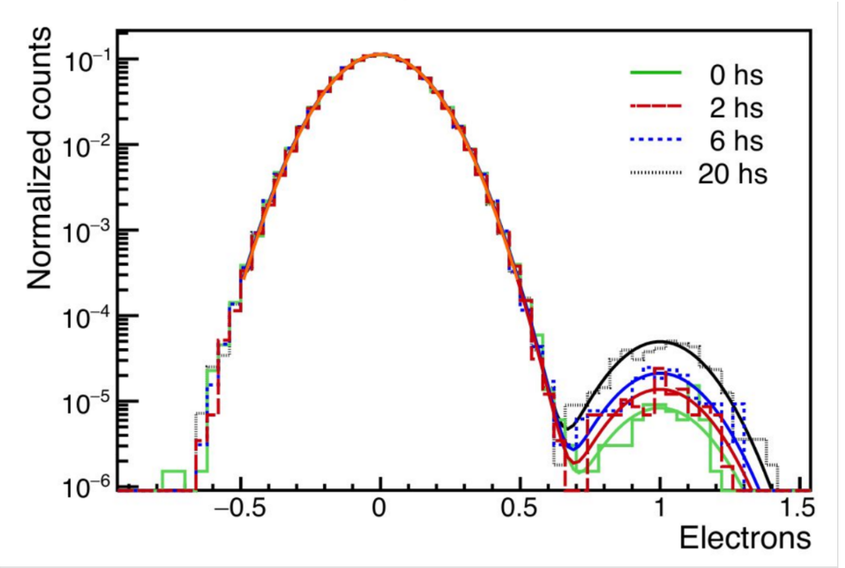
$$I_{\text{phys}}(t_{\text{ph}}) = o D_t N_{\text{pumps}} P_{\text{eff}} \times \left[e^{-t_{\text{ph}}/\tau_e} - e^{-8 t_{\text{ph}}/\tau_e}\right]$$

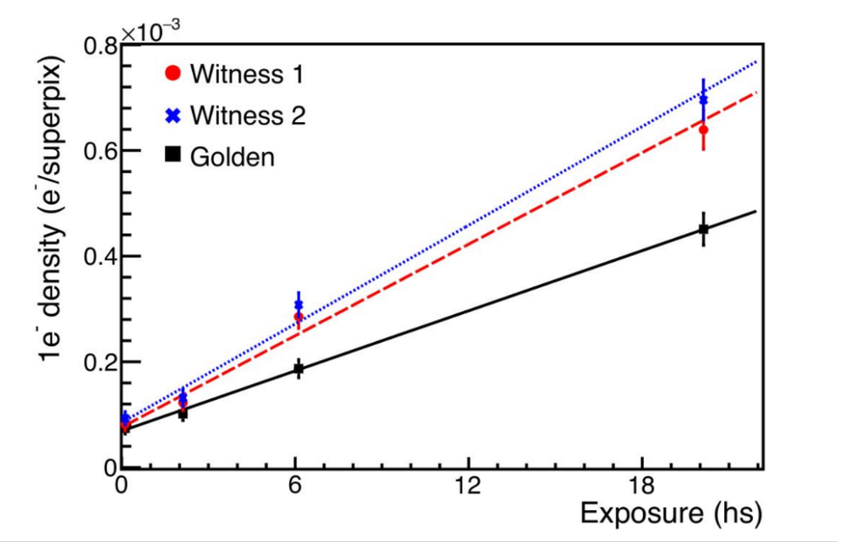
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The SENSEI Collaboration
Phys.Rev.Lett. 134 (2025) 16, 161002

SENSEI Run 2

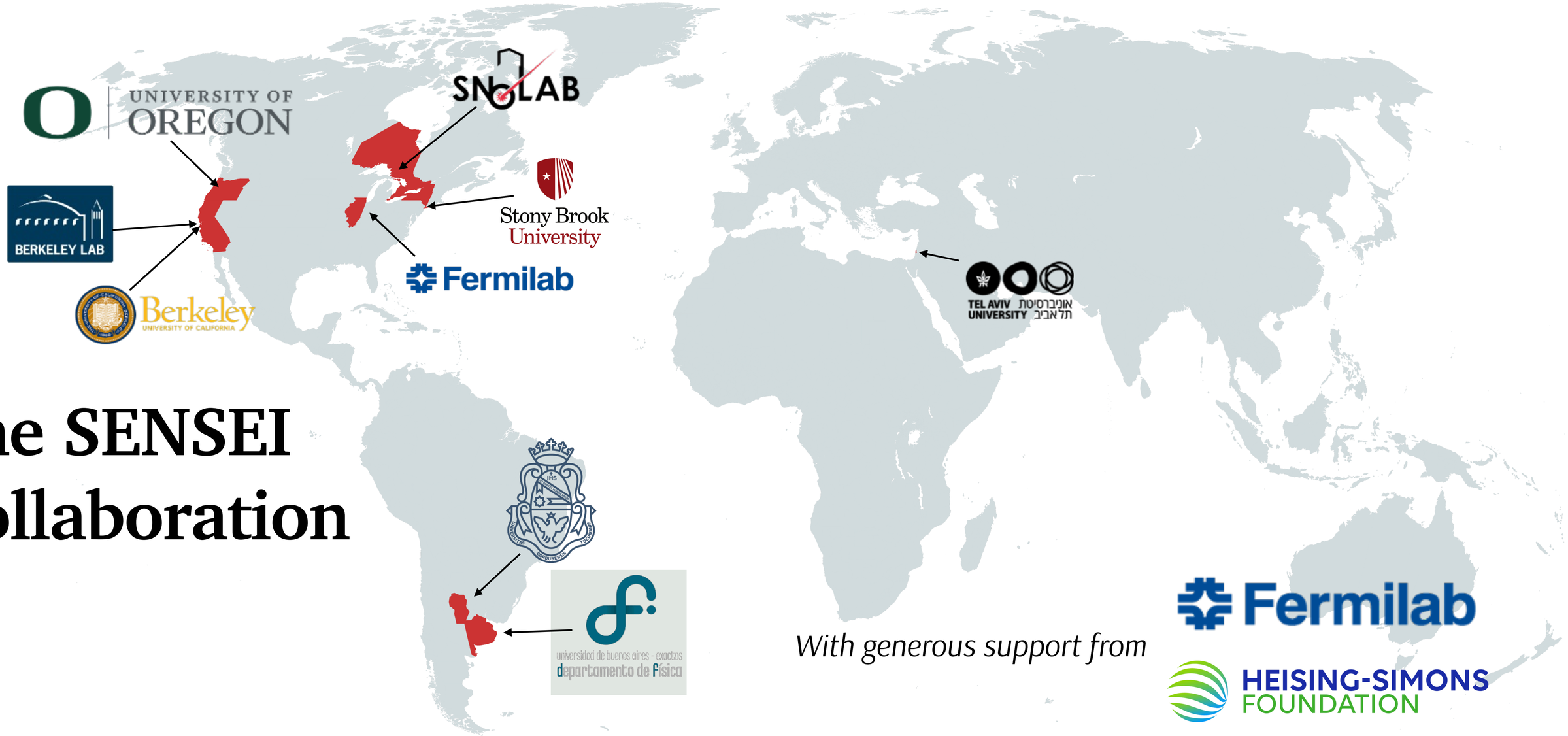
- Fitting double gaussian gives you single-electron density for each exposure
- Plotting single-electron density as a function of exposure gives measurement of exposure dependent single-electron rate
- We used the best MINOS numbers for this study in simulation





MINOS CCD 2	Exposure Dependent Rate ($\times 10^{-5} e^-$/pix/day)	Exposure Independent Rate ($\times 10^{-5} e^-$/superpix/image)
Quadrant 1	8.19	12.23
Quadrant 2	**4.36**	**9.94**
Quadrant 3	6.88	7.53
Quadrant 4	8.23	6.52

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The SENSEI Collaboration

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