One Electron at a Time
Skipper-CCD and beyond

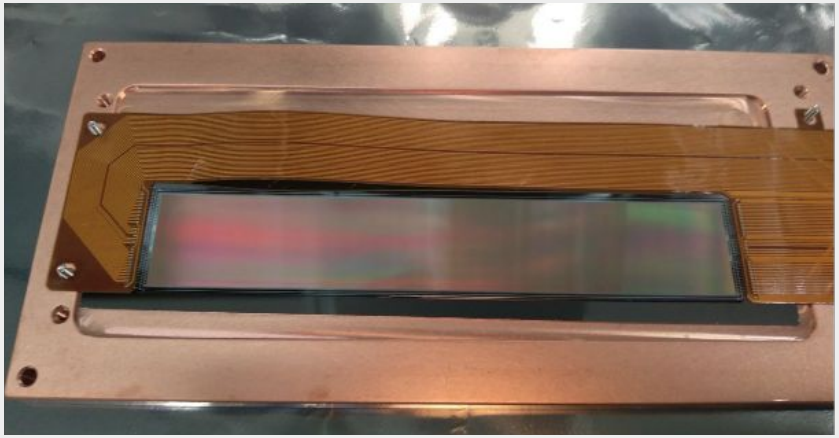

Image: SENSEI skipper-CCD sensor

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Nov 4th, 2025

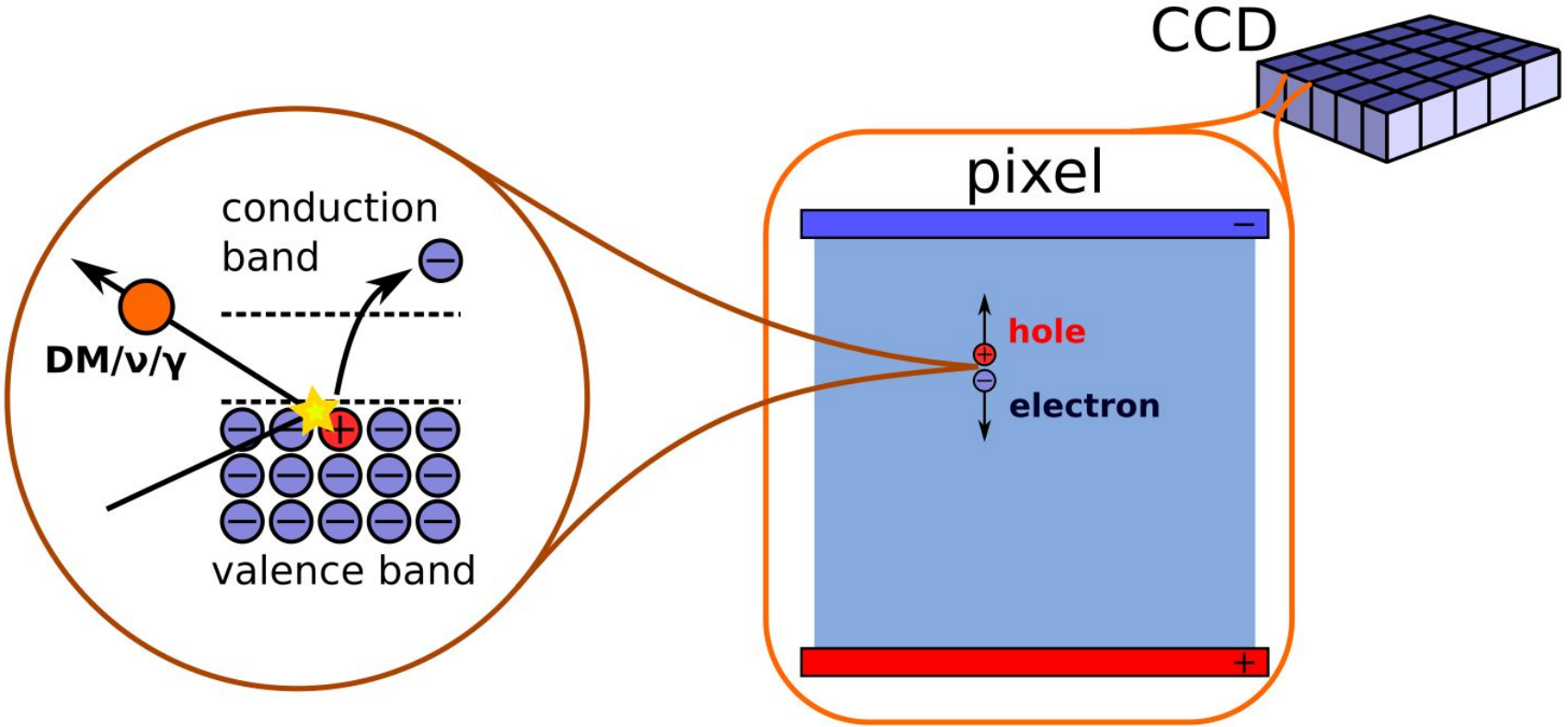
Astroparticle Symposium 2025

* Fermi National Accelerator Laboratory, and LAMBDA at the University of Buenos Aires

Disclaimer

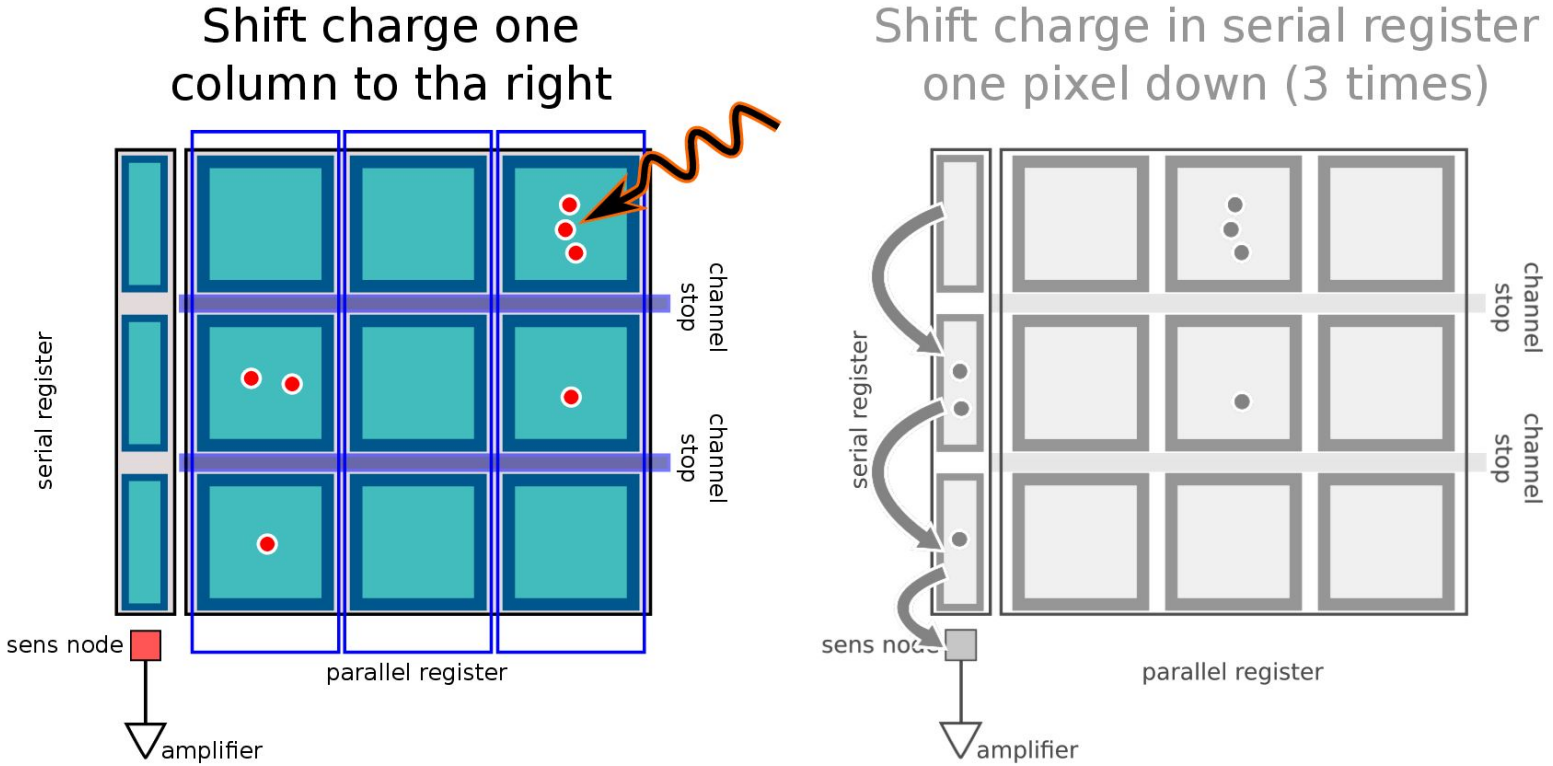
- This is a super-fast overview of topics to motivate discussion (please ask me about any details during the breaks)
- These are very long stories told short
- All this work is the product of many collaborations (and people)

CCDs as particle detectors



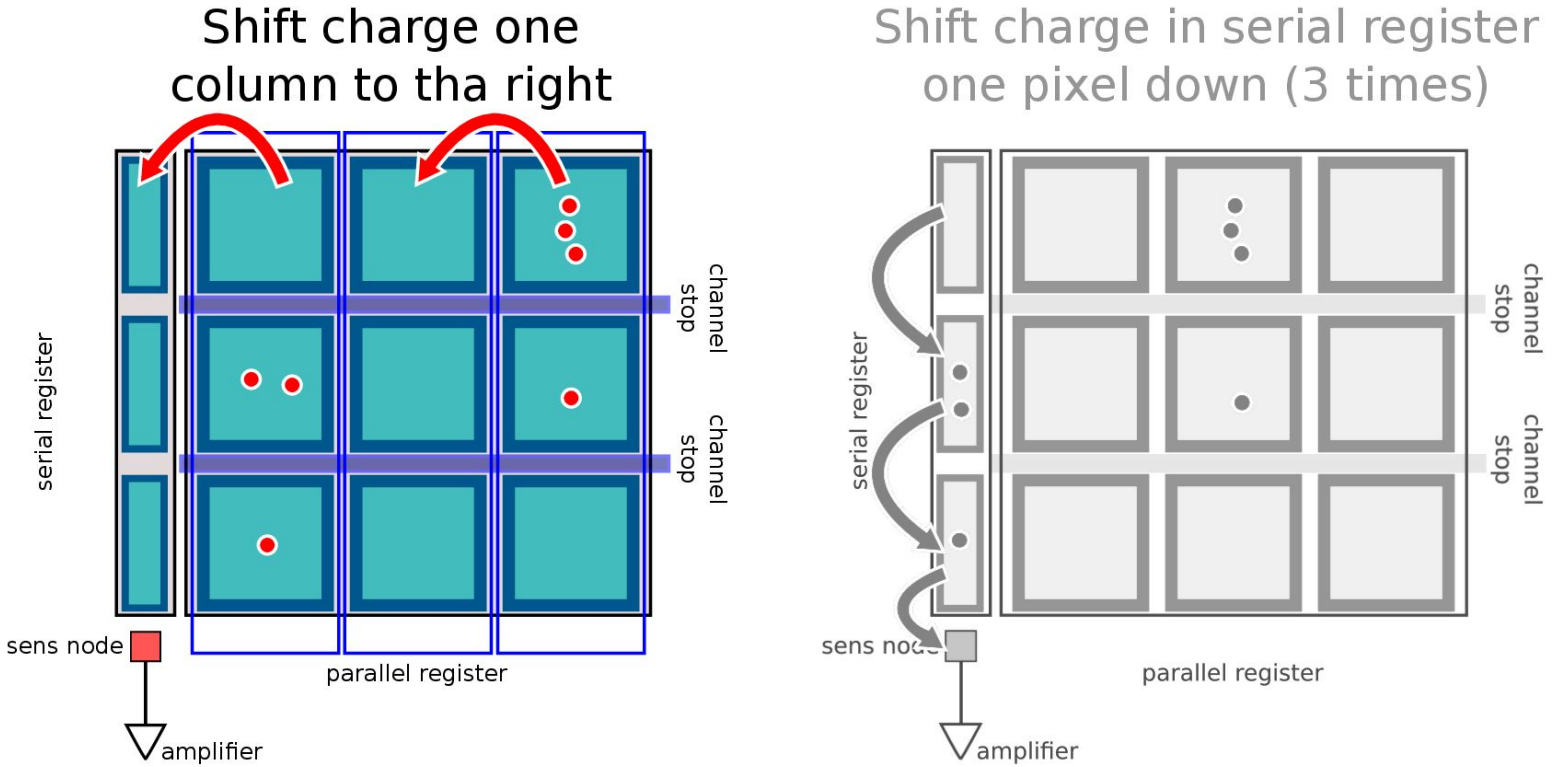
CCDs as particle detectors

3x3 pixels CCD

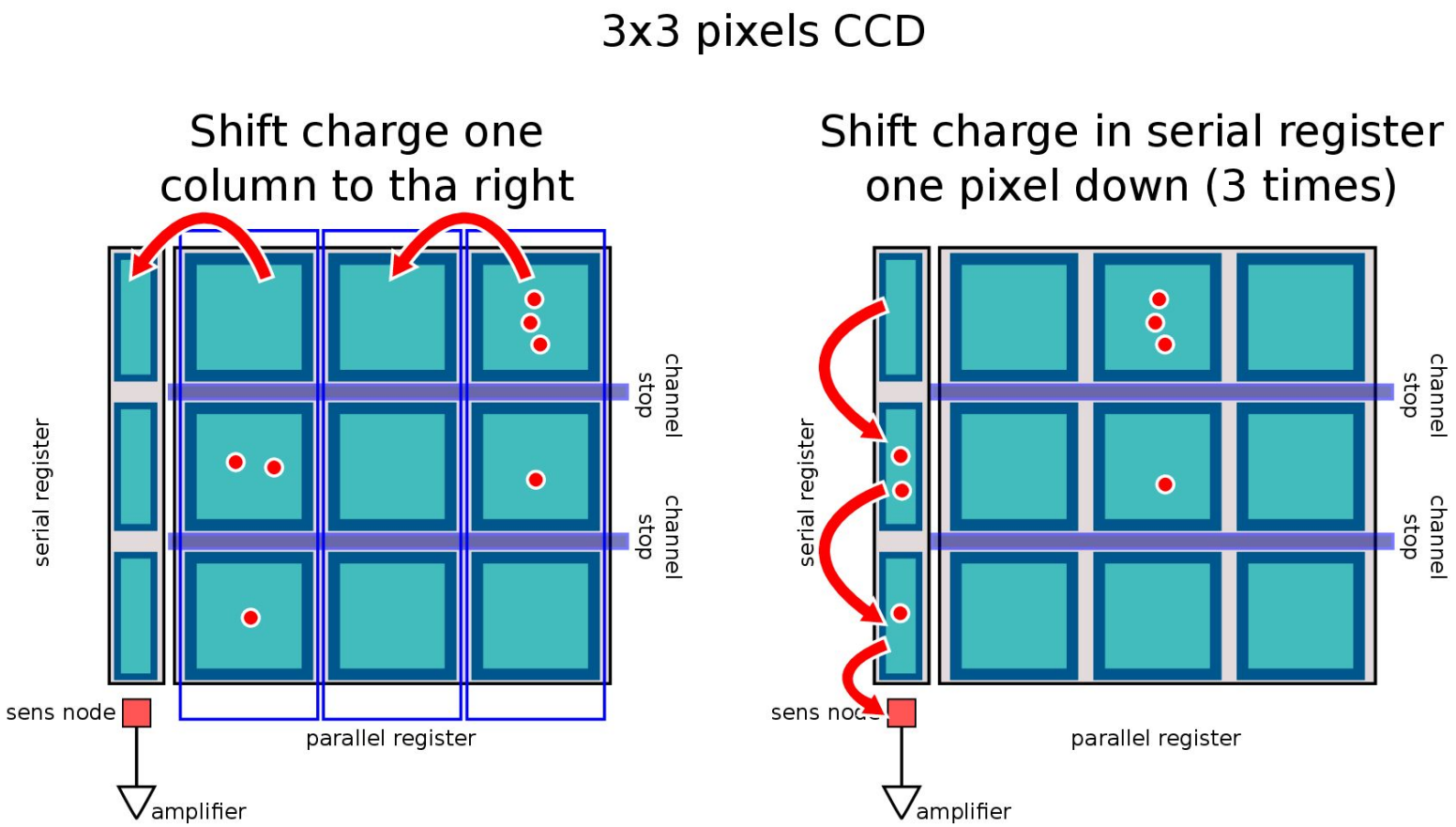


CCDs as particle detectors

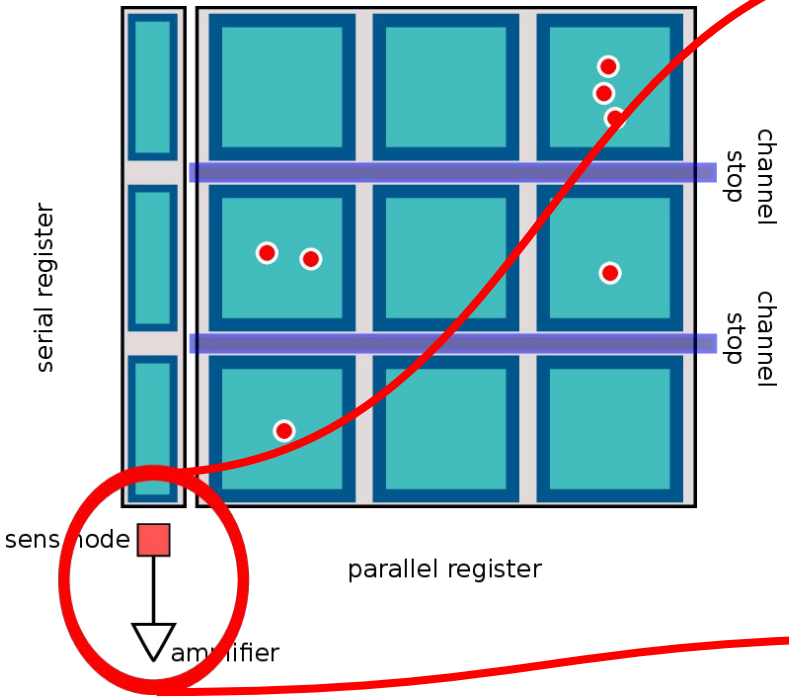
3x3 pixels CCD



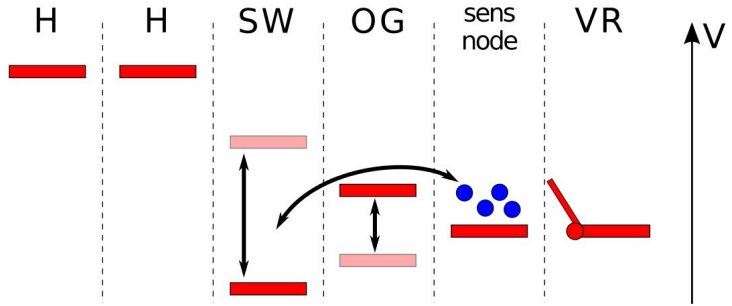
CCDs as particle detectors



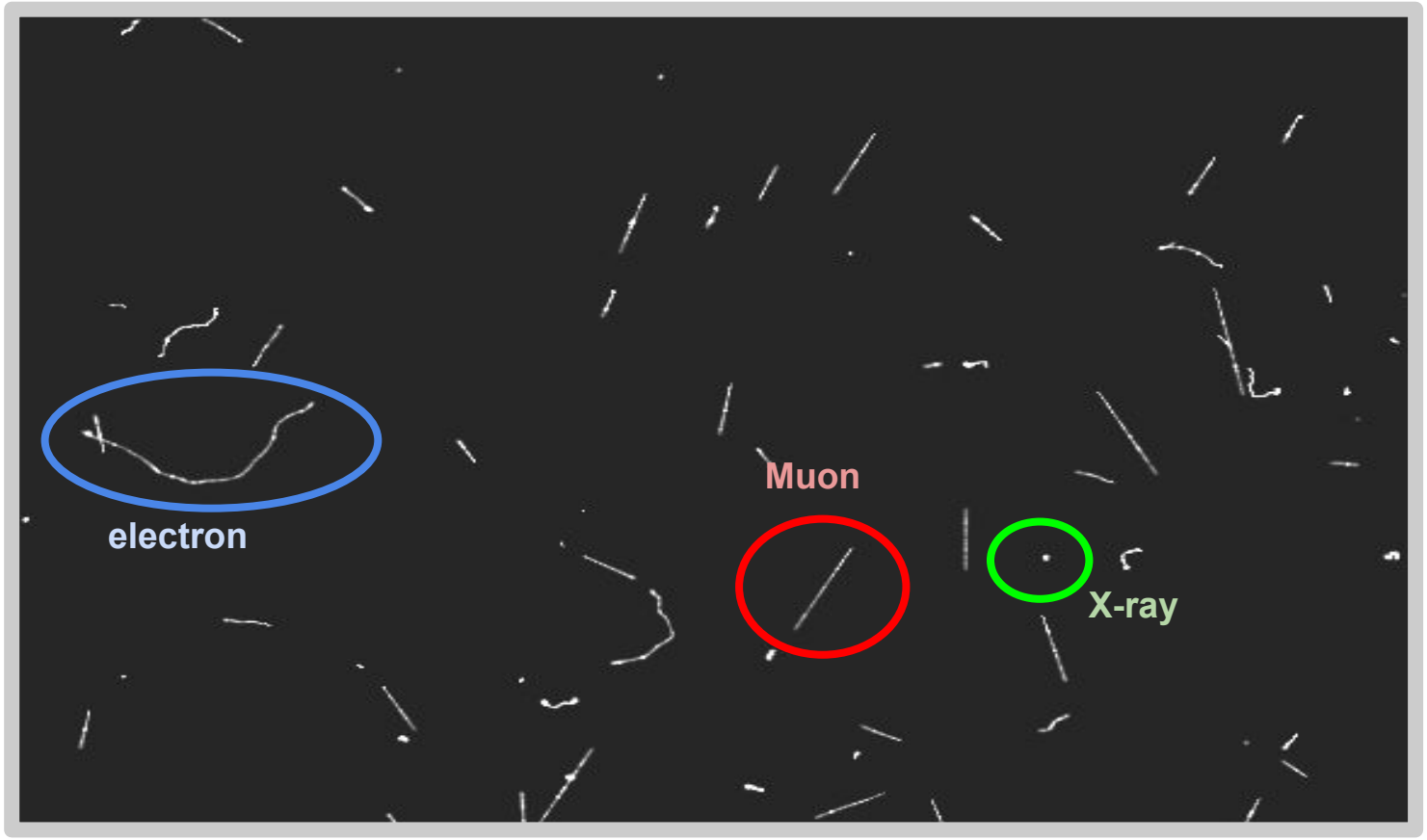
The Skipper-CCD



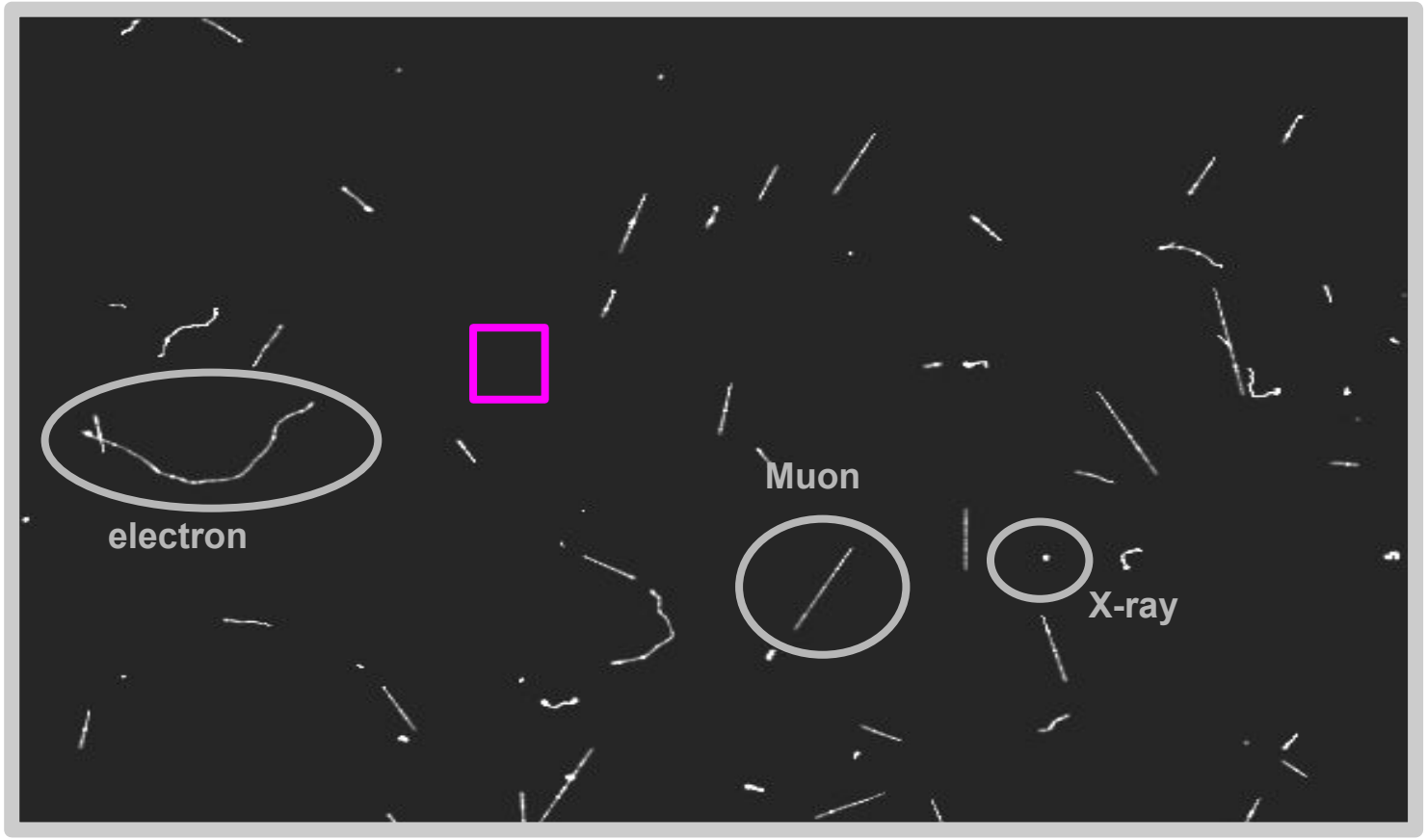
- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



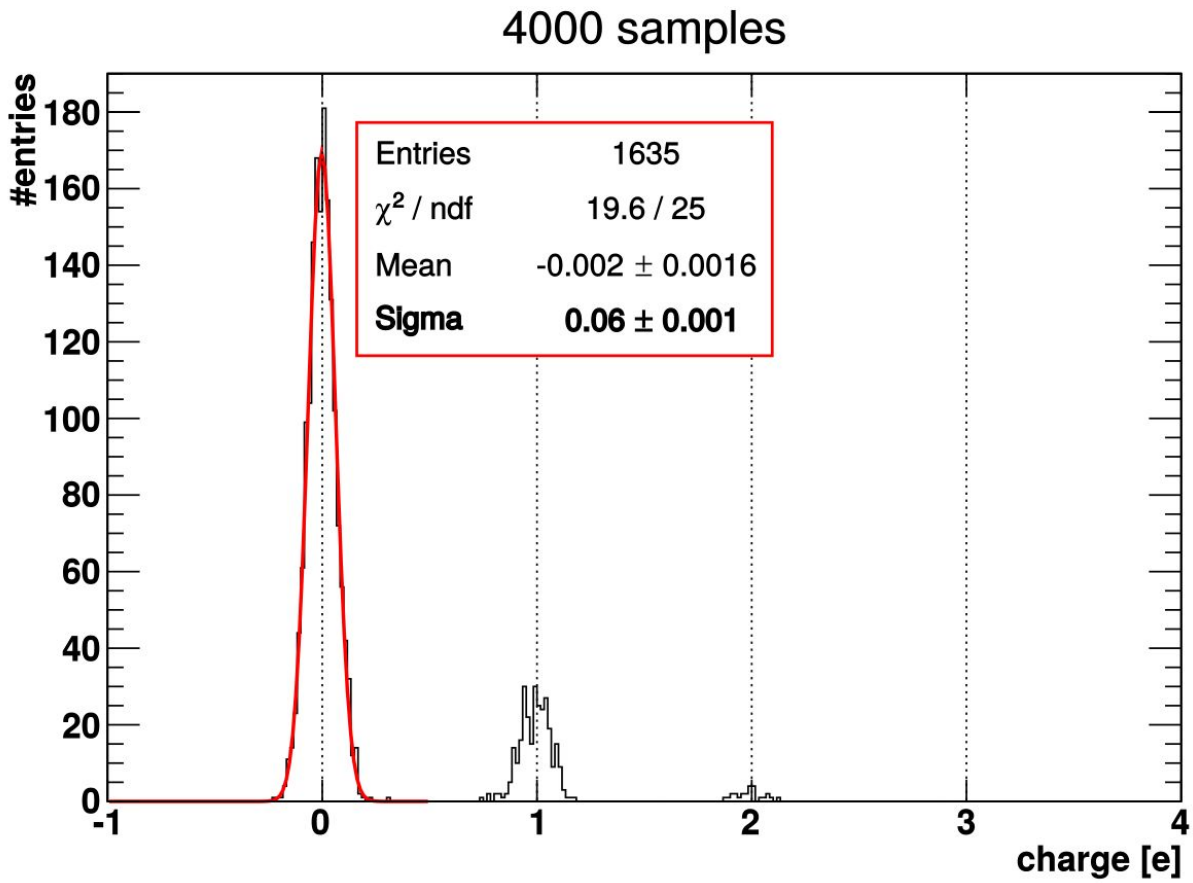
CCDs as particle detectors



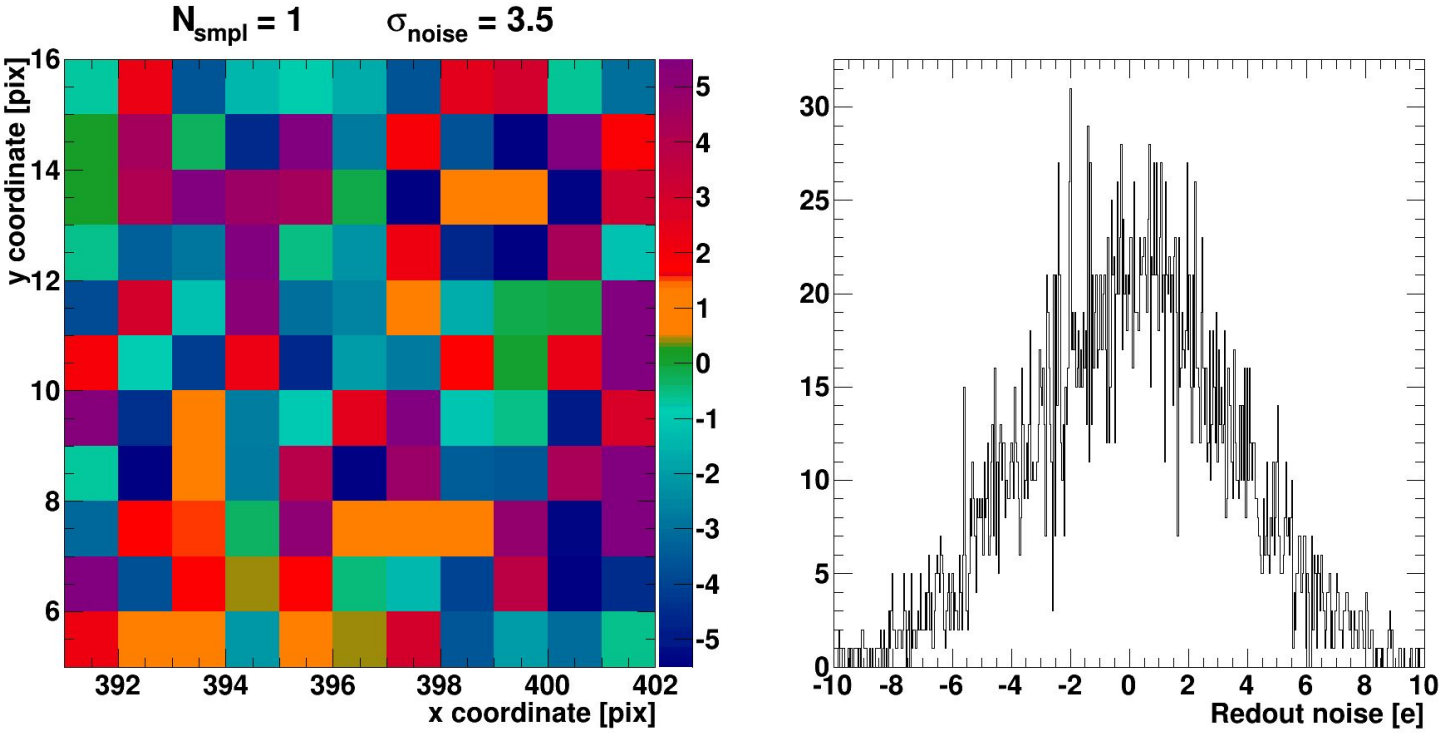
CCDs as particle detectors



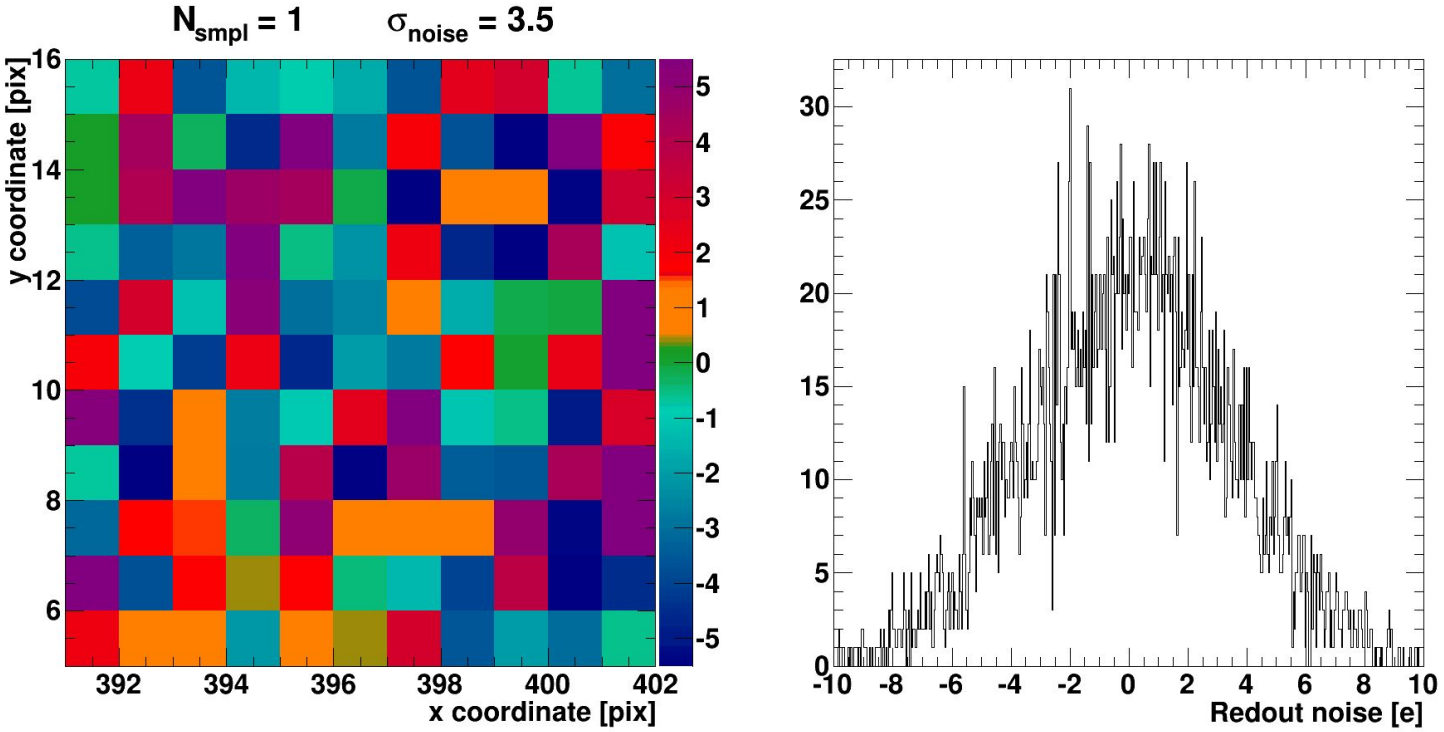
Counting electrons



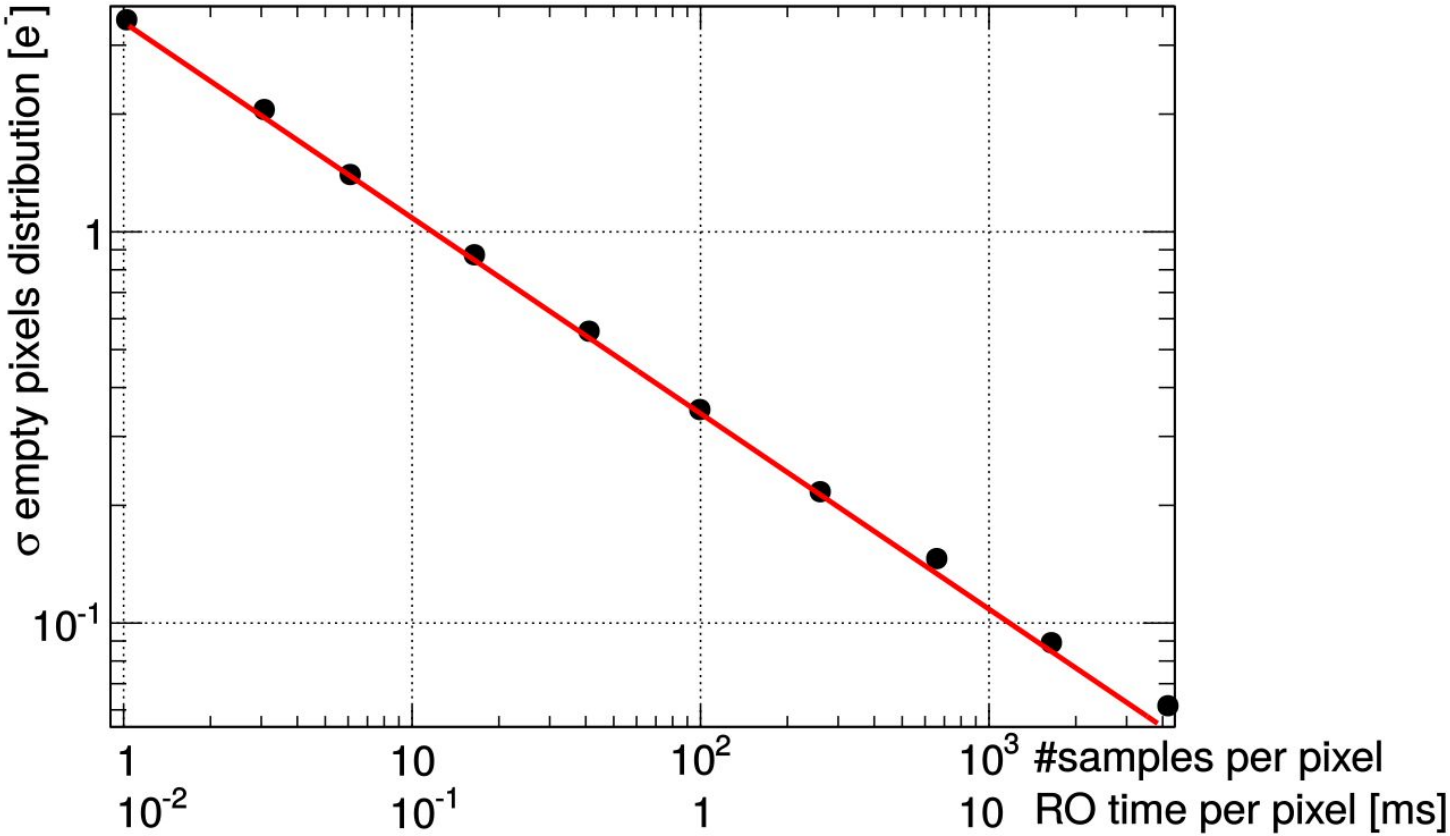
Counting electrons



Counting electrons

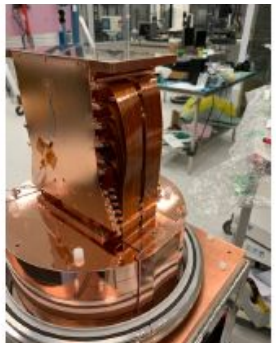


Noise vs RO time



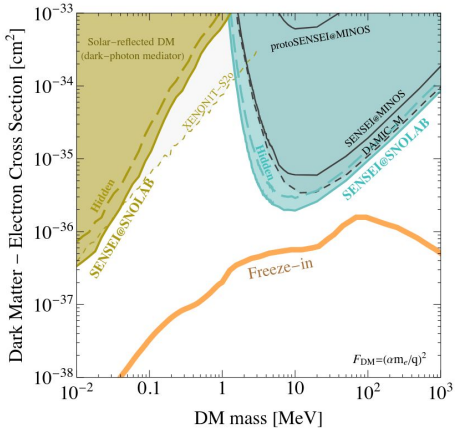
The SENSEI Experiment

‘17	‘18	‘19	‘20	‘21-’23	‘24	‘25
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**) + 2nd science run + started very promising 3rd run but CC died :(	**3rd** run with new cryocooler

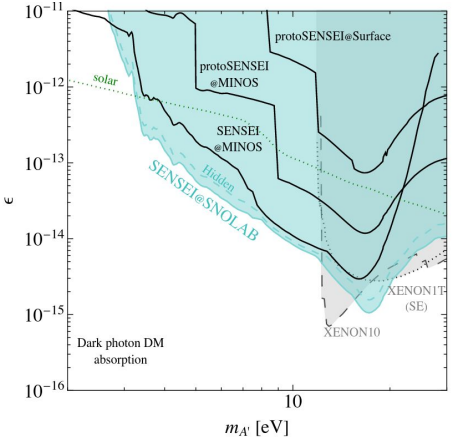



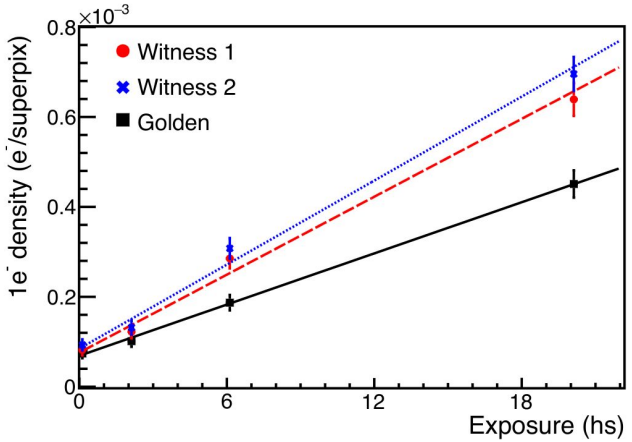

The sensei Experiment

Light mediator



Absorption





Phys. Rev. Lett. 121.6 (2018) 061803.
Phys. Rev. Lett. 122.16 (2019) 161801
Phys. Rev. Lett. 125, 171802 (2020)
Phys. Rev. Lett. 134 (2025) 011804
Phys. Rev. Lett. 134 (2025) 161002

- ➔ **First** experiment using **skipper CCDs**
- ➔ Numerous advances on Skipper-CCD **operation and single-electron reduction**
- ➔ **Lowest dark current** record **(1 e-/pix/200 years)**
- ➔ Lowest ever in Silicon (or NIR/UV photodetector)

Milli-charged particles (mCP) @ SENSEI and LHC

sensei

No spoilers here

See Santiago Perez talk
(the next one!)

The DAMIC-M experiment

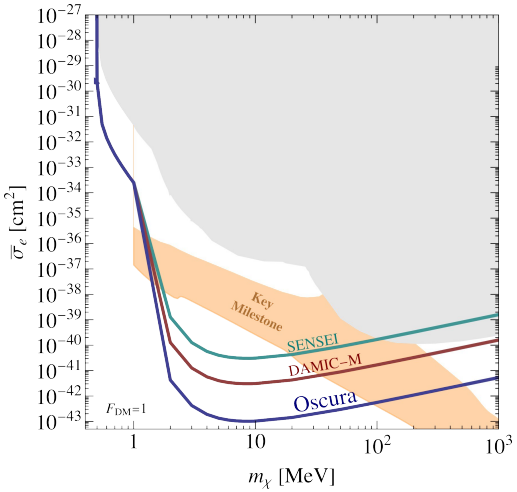
Still no spoilers here

See Nicolas Avalos talk
(just one presentation away!)

Scaling-up.. Oscura

SENSEI 100g → **DAMIC-M 1kg** → **OSCURA 10kg**

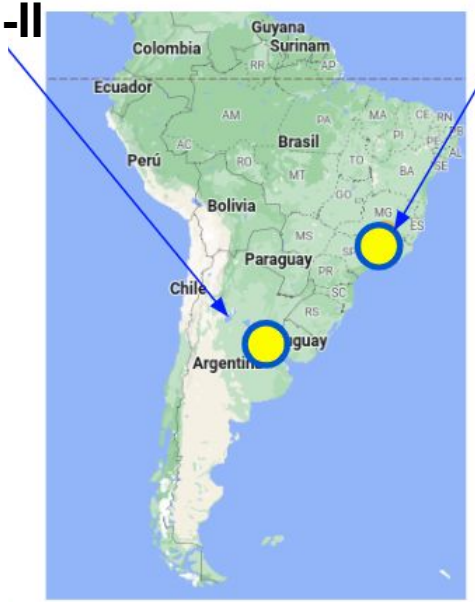
- ➔ **Skipper-CCDs are constantly producing world-leading limits on light DM candidates since 2018**
- ➔ We are pushing towards more mass and less backgrounds.
- ➔ **Oscura** will have be the ultimate DM skipper-CCD detector, **joining expertise from all ongoing efforts**.



arXiv: 2304.04401

Skipper-CCDs @ Nuclear reactors & Space

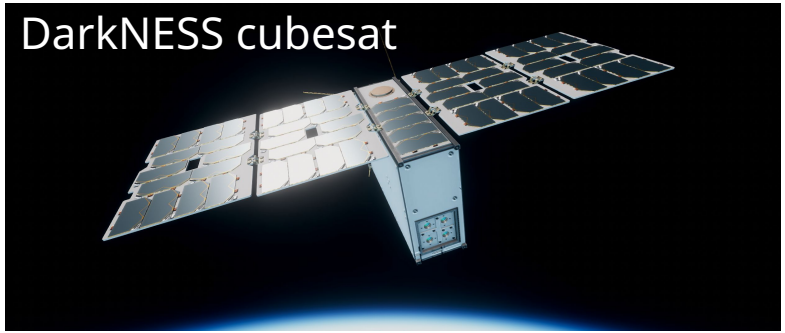
Atucha-II



CONNIE

Search for Reactor-Produced Millicharged Particles with Skipper-CCDs at the CONNIE and Atucha-II Experiments

Phys. Rev. Lett. 134, 071801 – 19 February, 2025



A wide angle X-ray observatory and SIDM search

Funded by the **Heising-Simons** foundation, **R&D** from **Fermilab & UIUC.** To be launch by **Firefly Aerospace**

HEISING-SIMONS FOUNDATION

DarkNESS: A skipper-CCD nanosatellite for dark matter searches

Advances in Space Research Volume 76, Issue 8 - 15 October, 2025

Where can we improve

- Can we read faster?
- Can we suppress the remaining dark counts?

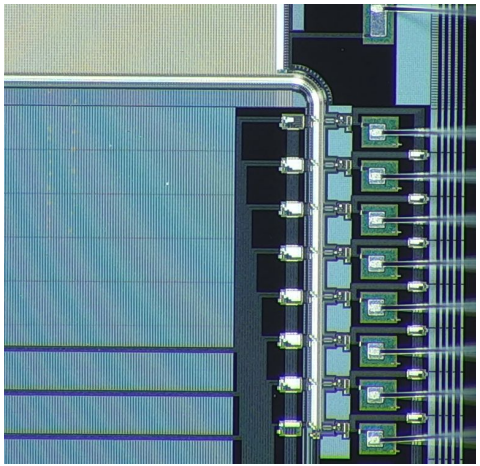
Where can we improve

- Can we read faster? Yes, we can
- Can we suppress the remaining dark counts?

The need for speed

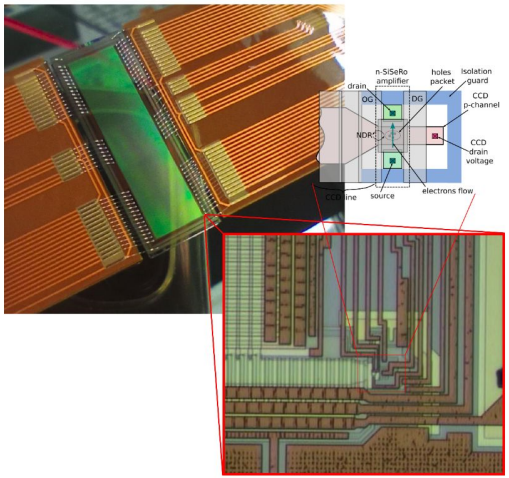
New generations with fast(er) read-out @ FNAL

MAS-CCD ~*O*(100) faster



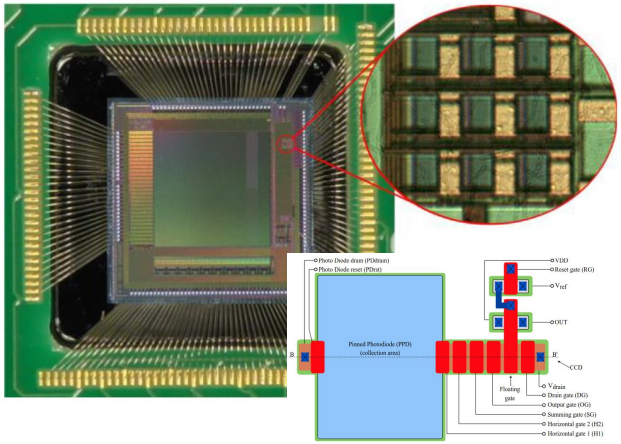
IEEE Transactions on Electron Devices, vol. 71, no. 6, pp. 3732-3738 (2024).

Sisero-CCD ~*O*(100)



Phys. Rev. Lett. 133, 121003

Skipper-CMOS ~*O*(10000)



IEEE Transactions on Electron Devices, vol. 71, no. 11, pp. 6843-6849,2024

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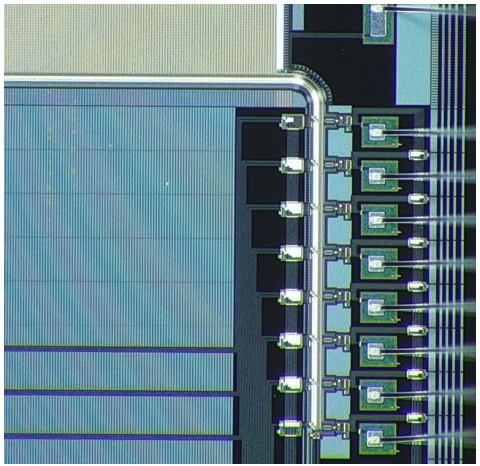

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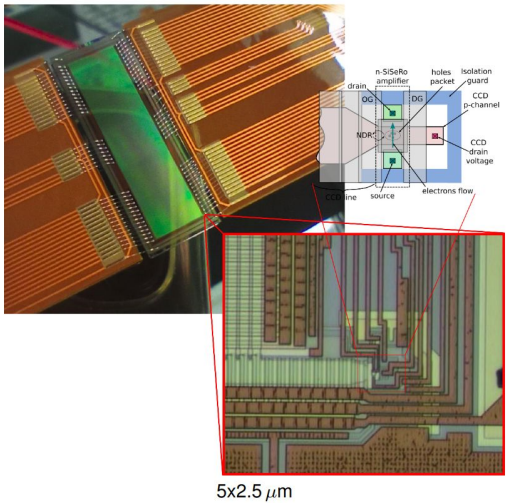
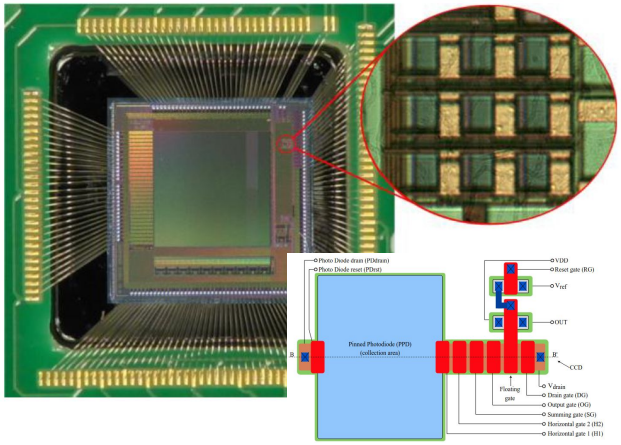
Sisero-CCD ~*O*(100)



5x2.5 μm

Phys. Rev. Lett. 133, 121003

Skipper-CMOS ~*O*(10000)



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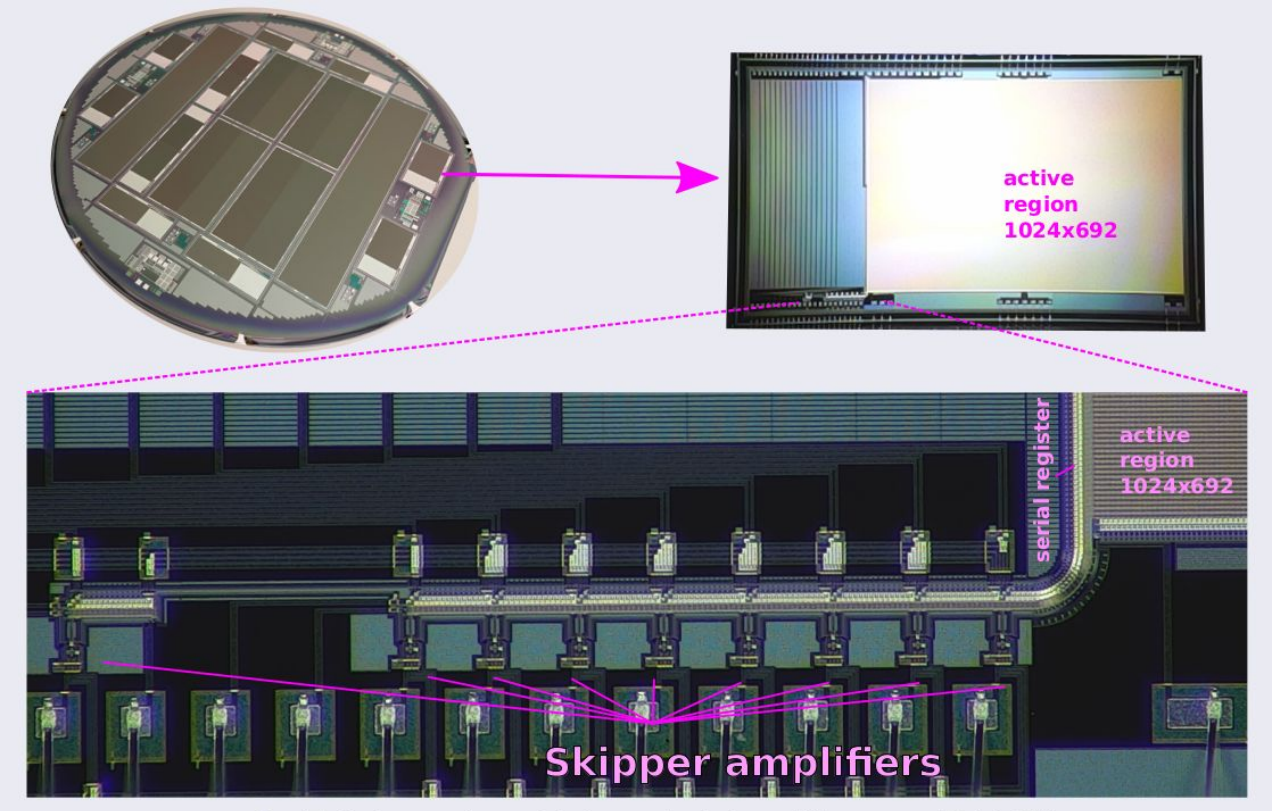
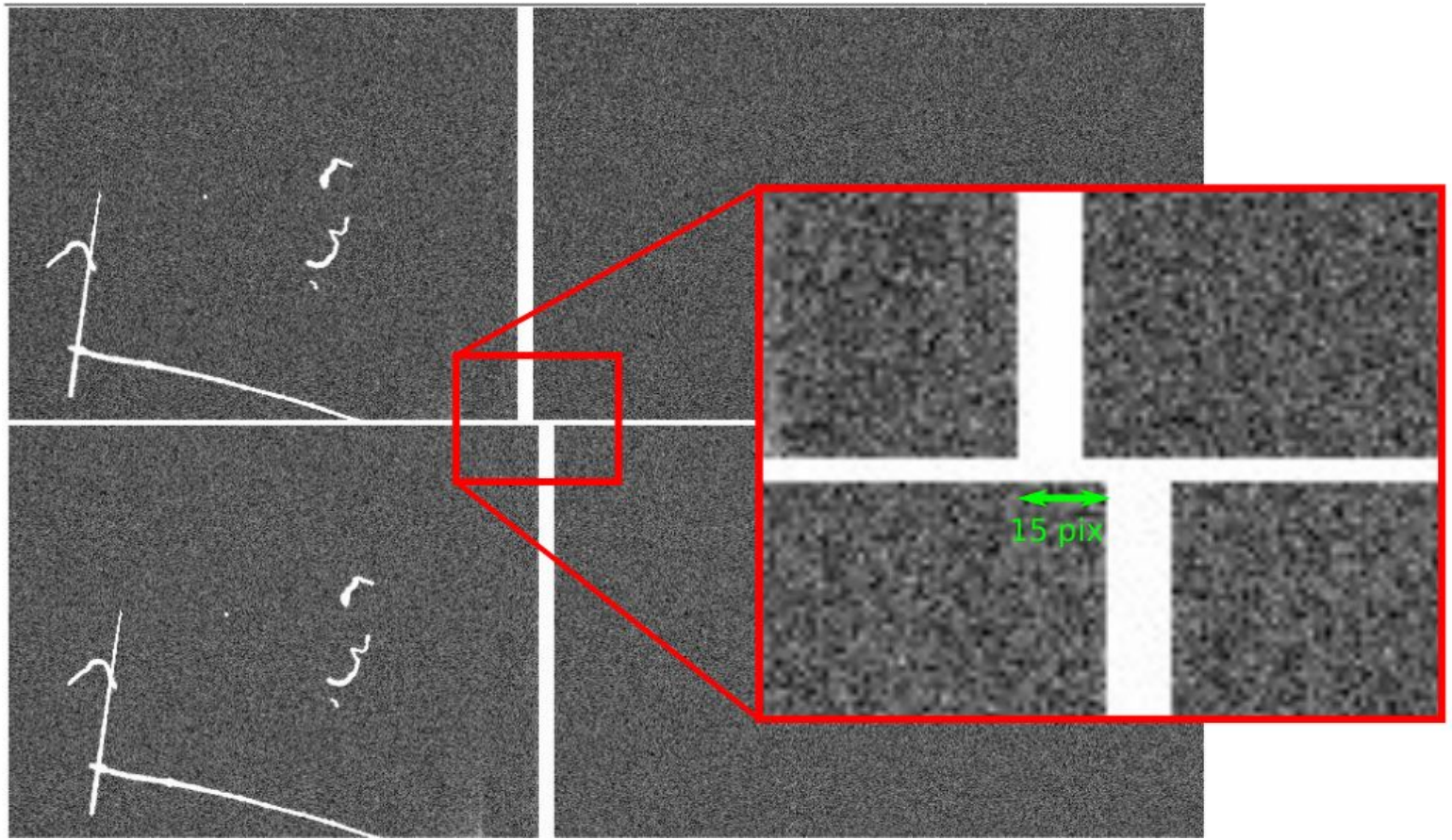
The MAS-CCD: first prototype, fabricated on 2021



The MAS-CCD was developed as a collaborative endeavor between LBNL and Fermilab.

The MAS-CCD



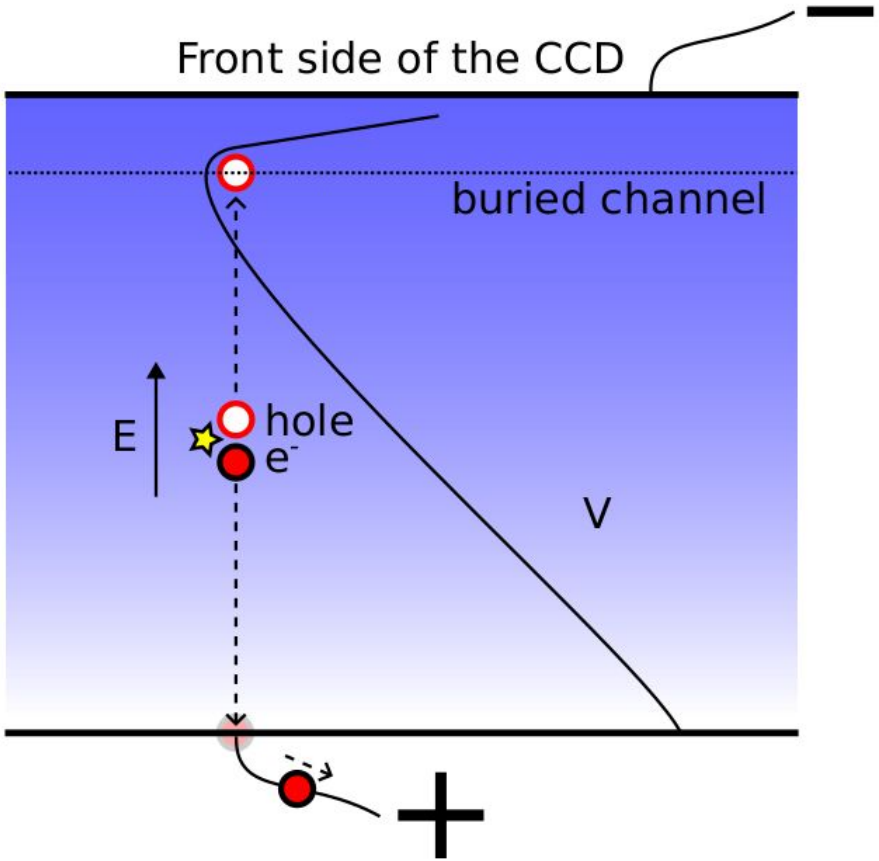
The MAS-CCD take home message

- It just works!
- Readout speed increases linearly with the number of readout stages
- 64 channel version in fabrication
- Identified as the leading technology for DESI-II and other future spectrographic surveys

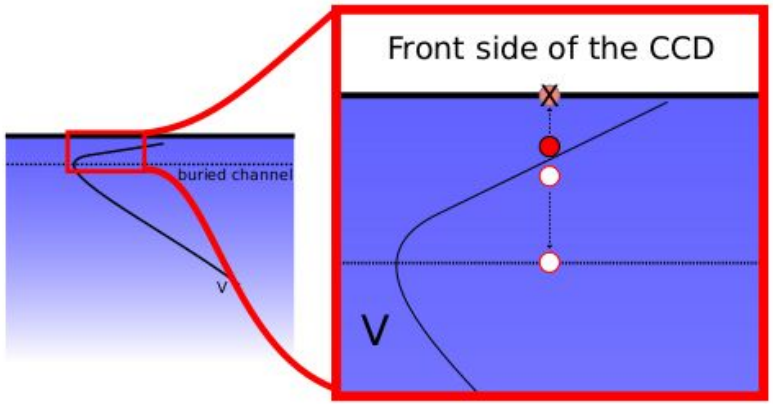
Where can we improve

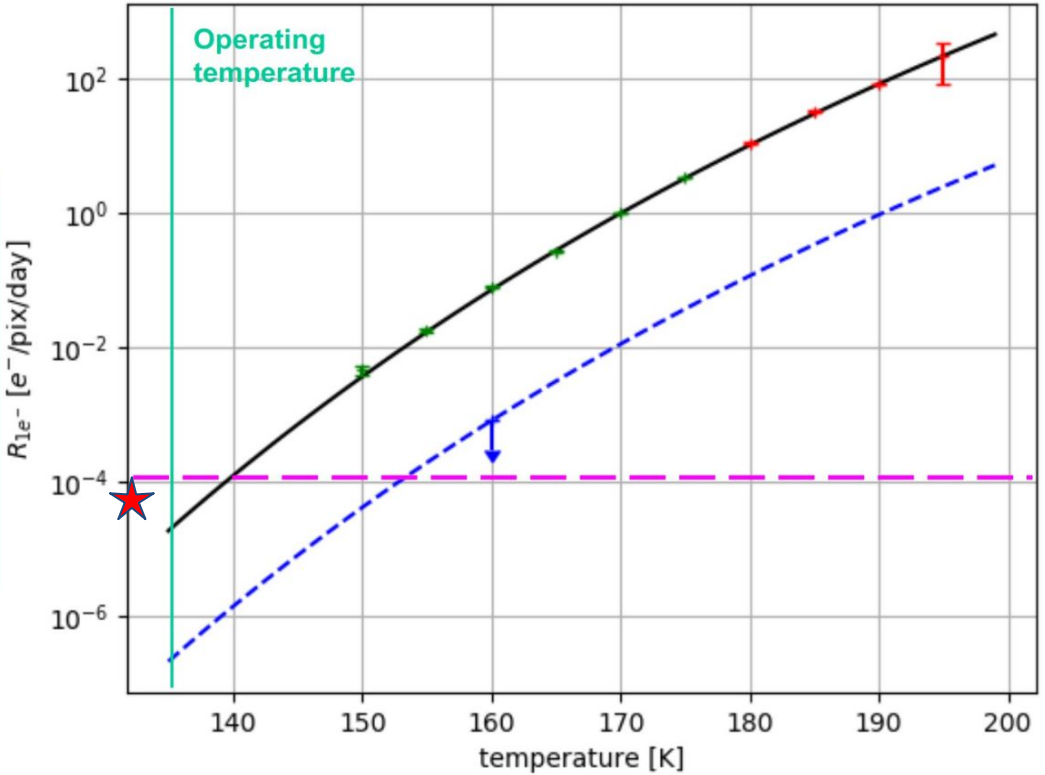
- Can we read faster? Yes, we can
- Can we suppress the remaining dark counts? Maybe!

Buried channel CCDs

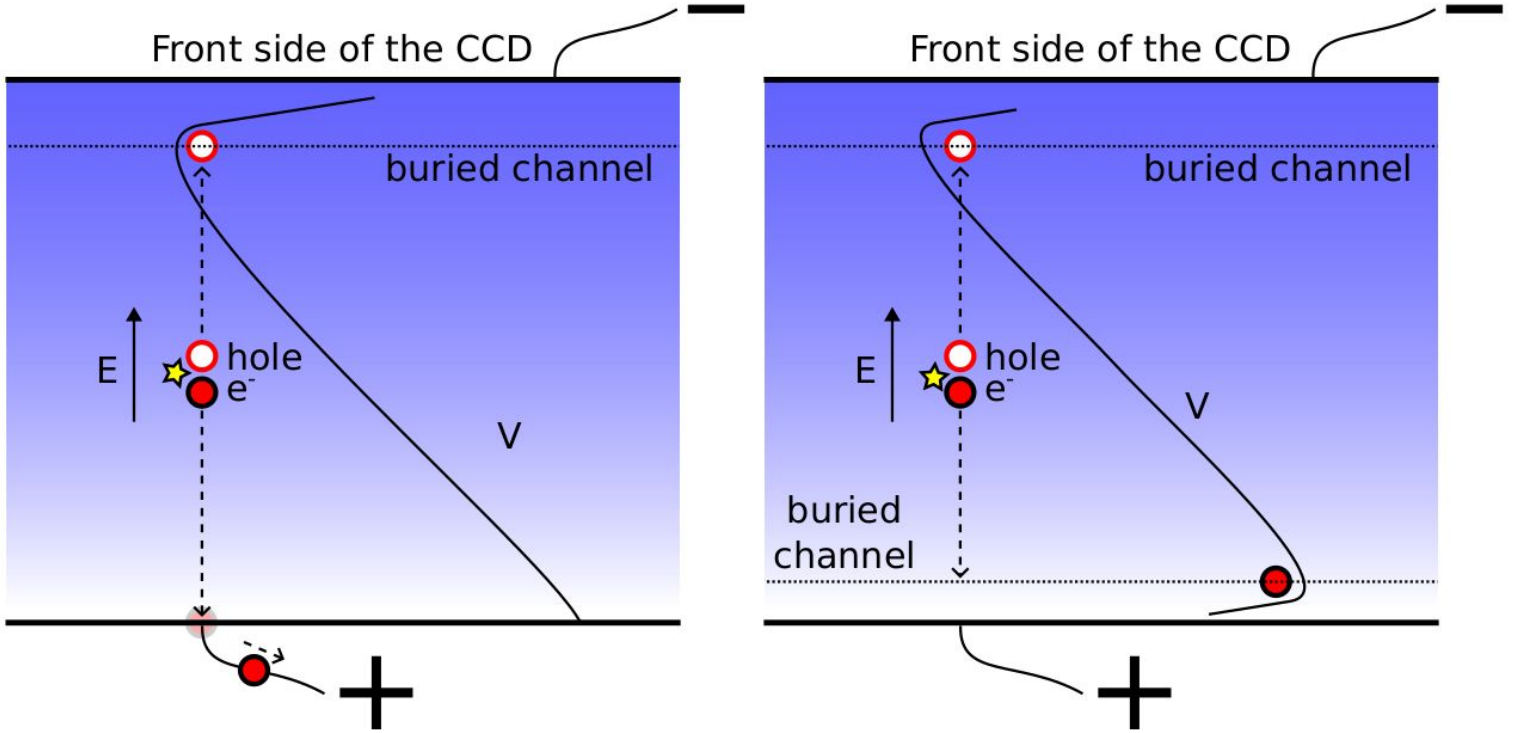


Dark counts: surface events

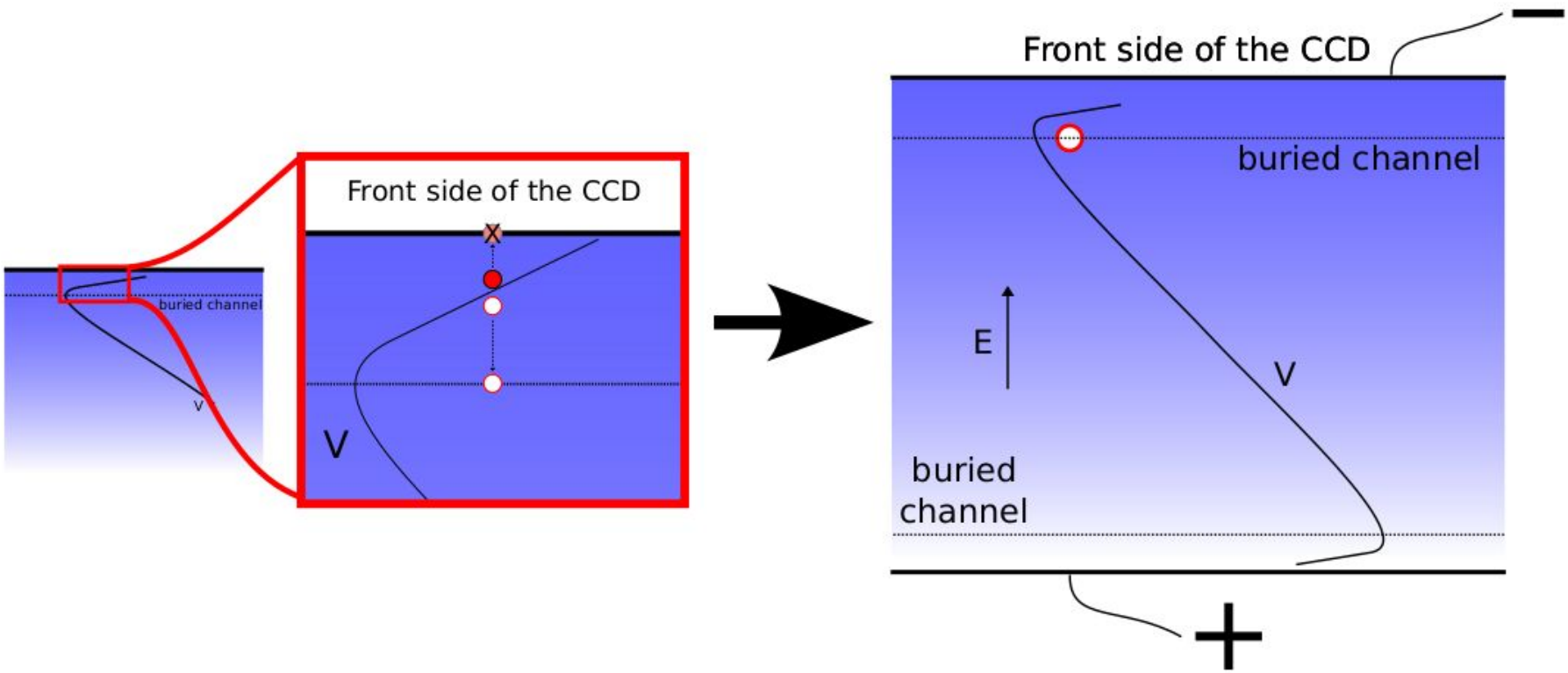




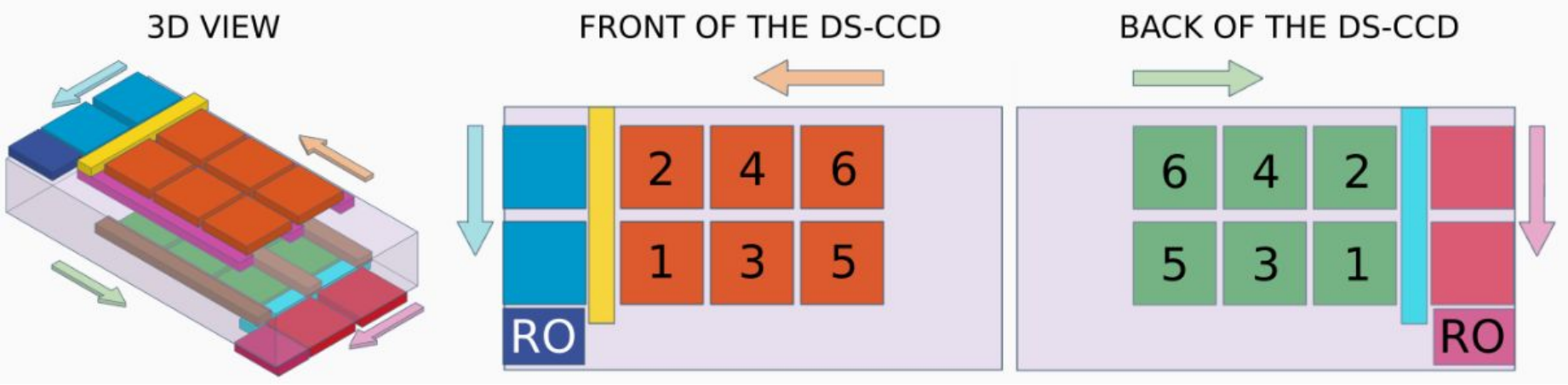
The Dual-side CCD (DCCD)



DCCD: Surface Dark Counts suppression

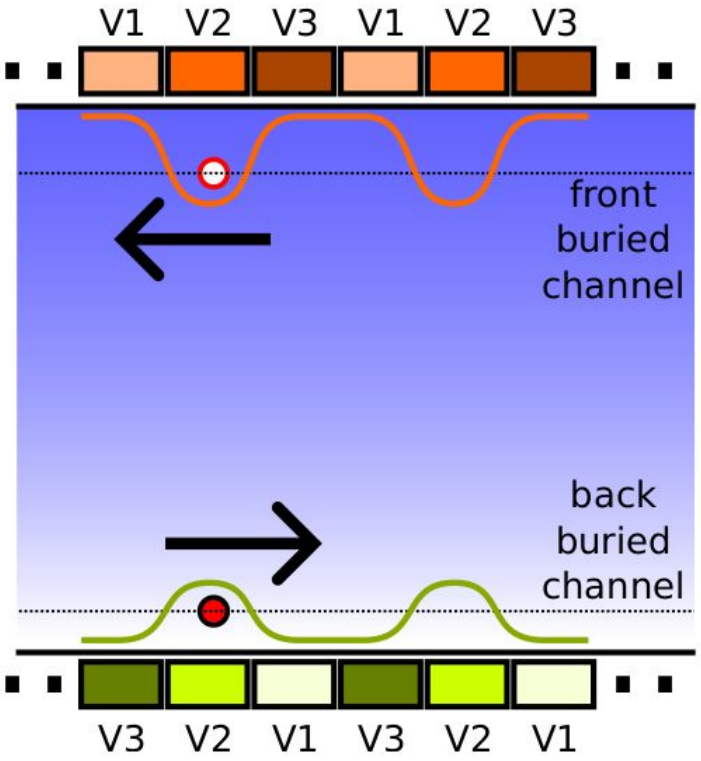


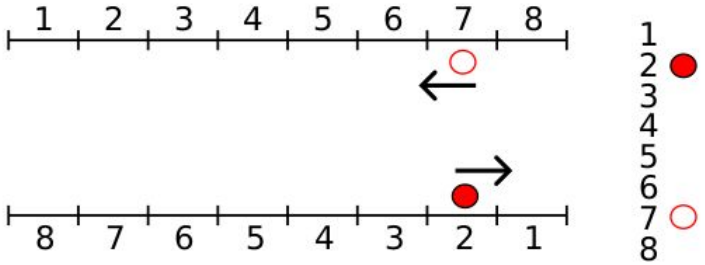
DCCD: basic concept



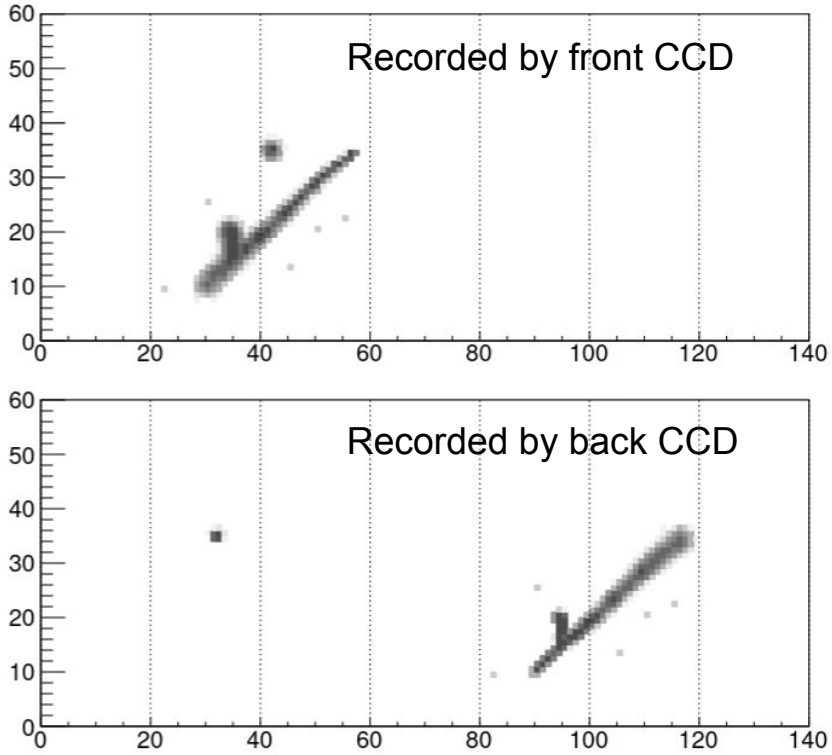
If the front and back active area are read in opposite directions we can disambiguate the position and timing of the interaction!

DCCD: position disambiguation and time resolution

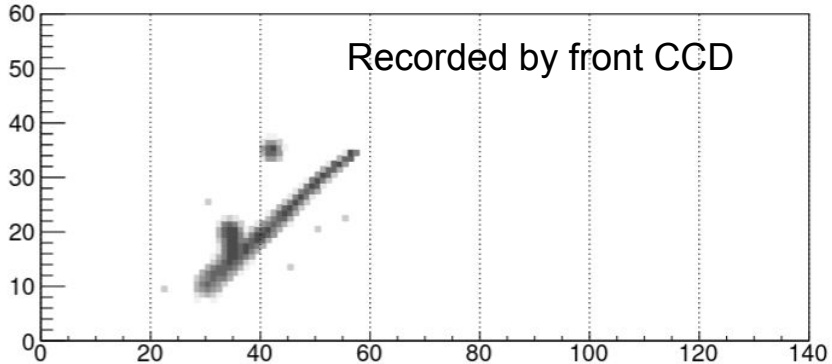


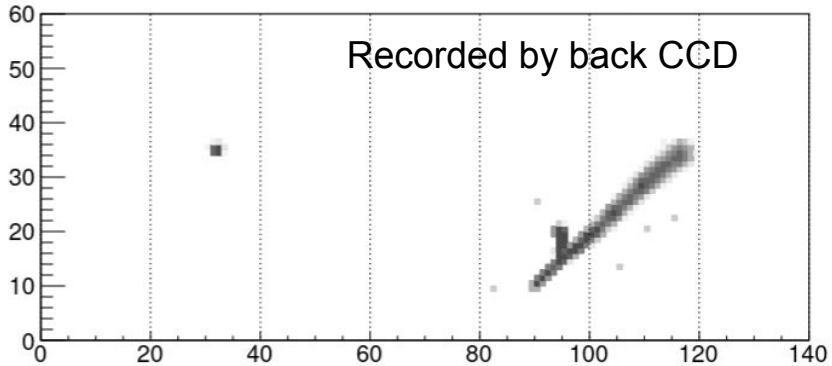


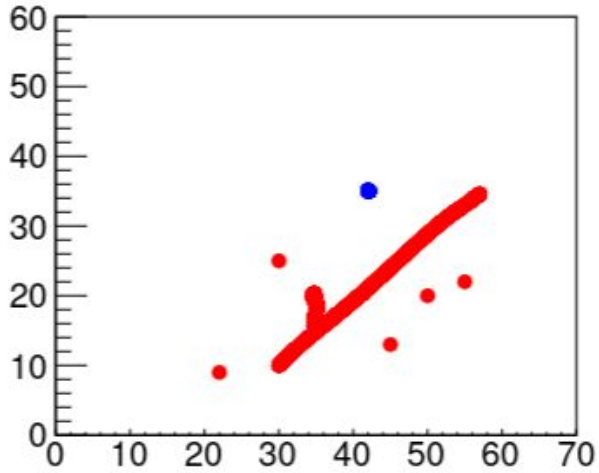
DCCD: timing reconstruction simulation



DCCD: timing reconstruction simulation







Timing resolution is given by the amount of time that takes to read a single line (1 ms to 1s)

Summary

- Skipper-CCDs are now mainstream in rare-events searches (and imaging)
- New demonstrated spin-offs with faster RO are ready (or coming soon)

- **DCCD could be the next lamppost**
  - ➔ Rejection of the surface DC by 2 orders of magnitude
  - ➔ Timing! Active veto (internal and external)
  - ➔ And more:
    - Rejection of charge transfer inefficiency events
    - Rejection of all serial register events
    - Fiducialization of hot areas (light from RO transistor)