Skipper-CCDs

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Snowmass 2022

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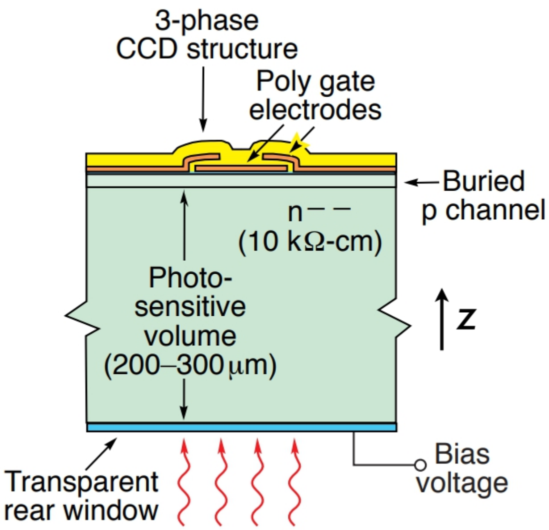
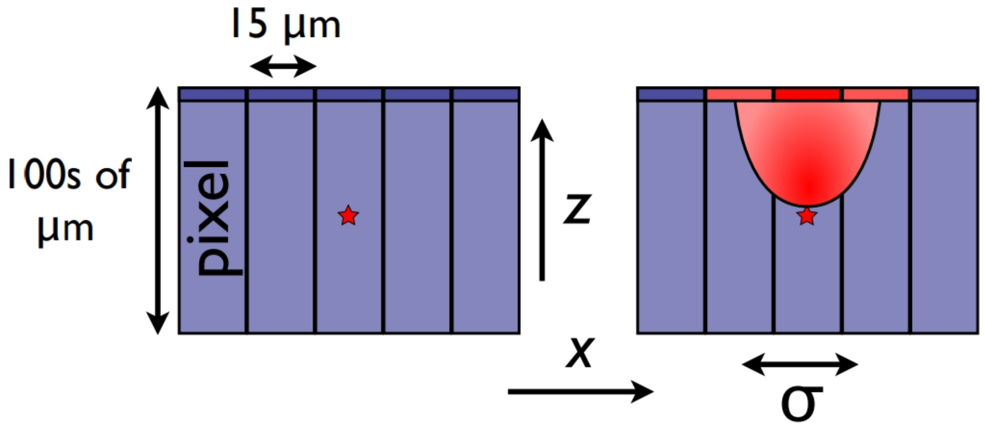
Scientific Charge-Coupled Devices: structure and operation

CCDs are essentially an array of Metal-Oxide-Semiconductor capacitors

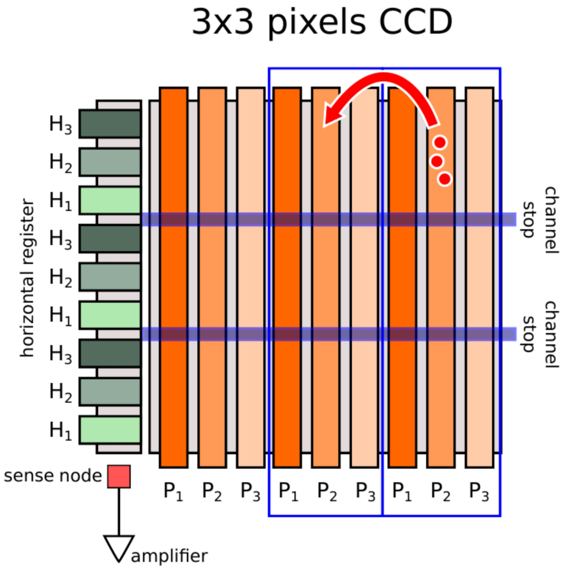


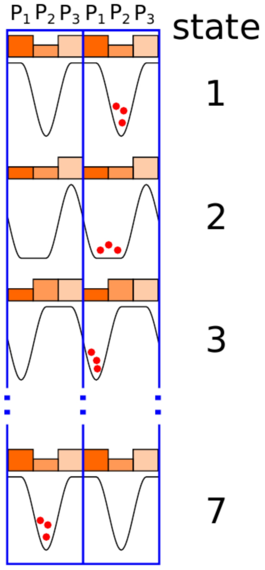
- Radiation interacting in the substrate produces e-h pairs (in Si, 1 e-h pair corresponds to ~3.8 eV)
- Charge is collected near the surface by applying V_{sub}

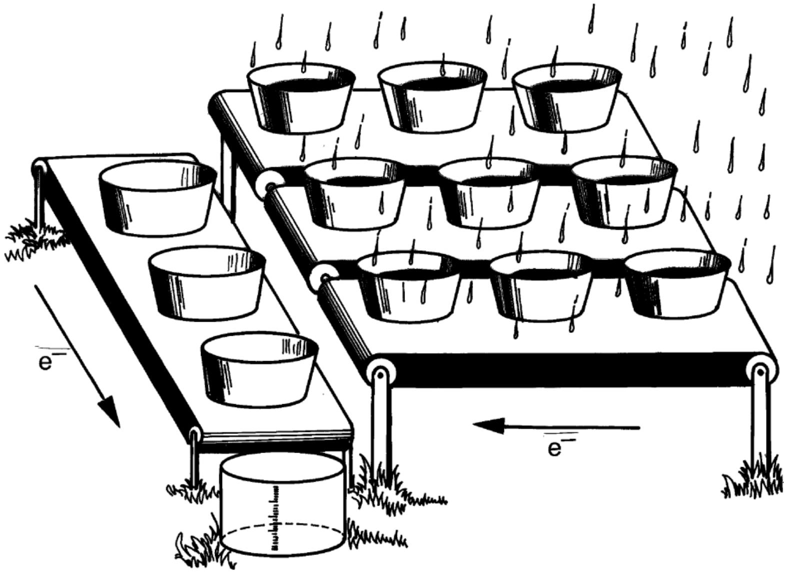


Scientific Charge-Coupled Devices: structure and operation

- Collected charge is then transferred along the surface by varying potential wells until reaching the readout stage

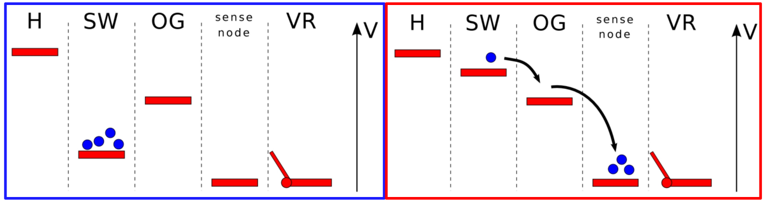


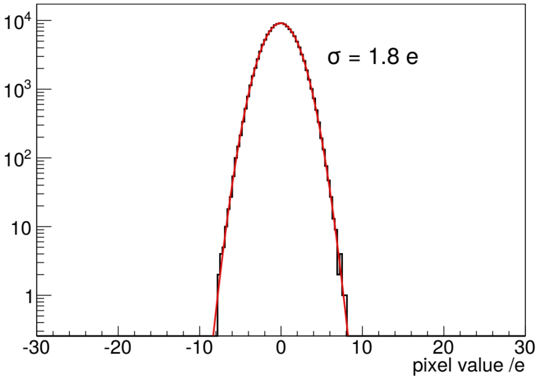


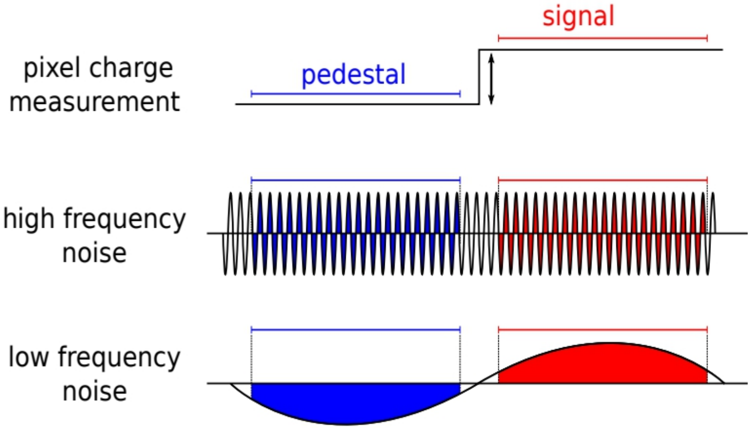


Standard CCDs: readout

- “Charge packets” are moved to the sense node, read and then discarded







Correlated Double Sampling to measure charge:

1. Pedestal integration
2. Signal integration
3. Charge = Signal - Pedestal

Sensitive to low frequency noise

Fermilab

Skipper CCDs

[1990ASPC....8...18J] → Very old idea!

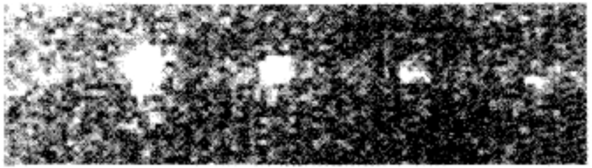
The CCD Skipper was invented to circumvent the 1/f noise problem and realize a square-root reduction in noise with increasing sample time thereby allowing sub-electron noise floors to be achieved. The principal function of Skipper technology is to allow the user to nondestructively measure the charge contained in a pixel multiple times (similar to CID operation) using a "floating gate" amplifier. The samples collected for a given pixel are then averaged together off-chip reducing the random noise of the on-chip amplifier by the square-root of the number of samples taken. For example, if a pixel is sampled 100 times, the random noise associated with the on-chip amplifier is diminished by a factor of ten.

→

- Multiple (N) non-destructive measurements of same “charge packet”
- The only modification is done in the readout stage! (floating sense node)

The ultimate test for the Skipper CCD, yet to be achieved, is to detect the single photo-electron. Skipper cameras have been constructed which employ ultra high gain, in excess of 100 ADC counts per electron. Assuming that the noise can be lowered to 0.2 e- rms using multiple sampling, there is no fundamental reason why the photo-electron can't be detected. It will be interesting to see if the CCD can accomplish this feat in the near future.

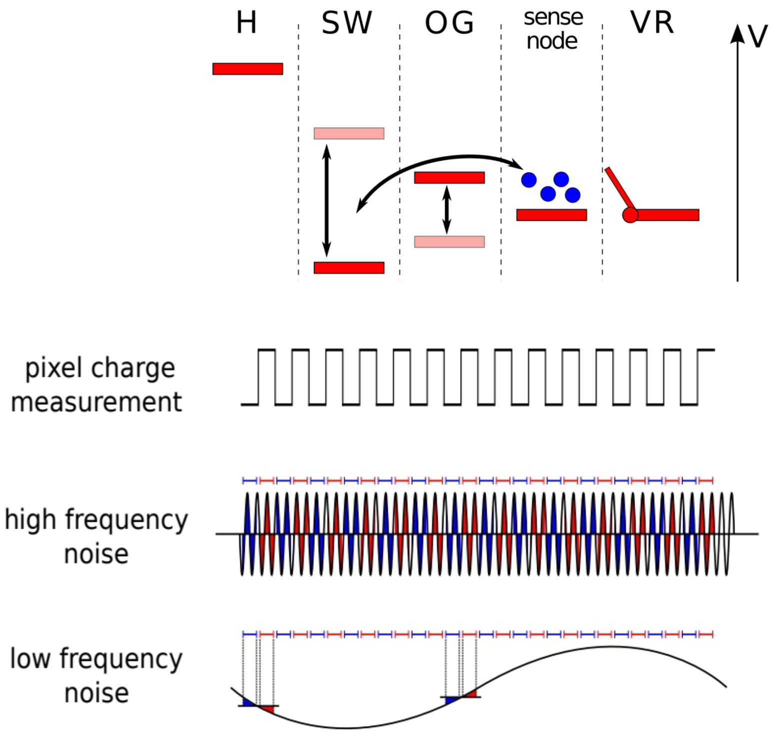
READ NOISE = 7.6 e^- rms



READ NOISE = 0.97 e^- rms

N_S = 64

Skipper CCDs: readout



- “Charge packets” are moved back and forth without being corrupted nor distroyed

1. Pedestal integration
2. Signal integration
3. Charge = Signal - Pedestal
4. Repeat N times
5. Pixel value = average of all samples

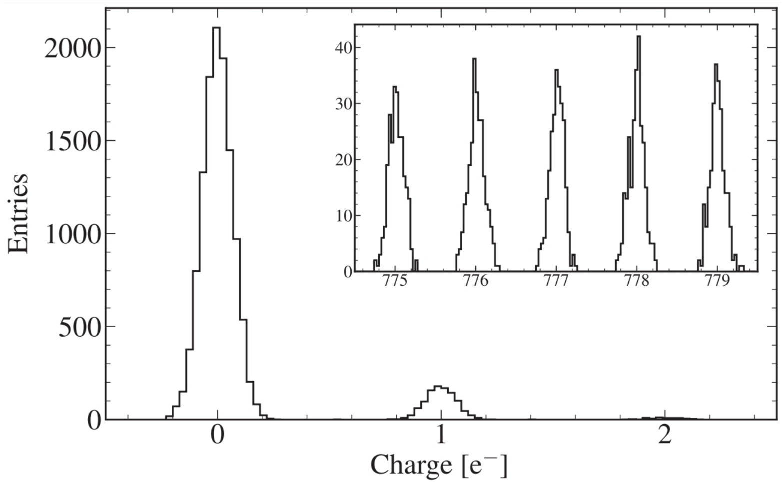
Noise is reduced as $\sigma = \frac{\sigma_1}{\sqrt{N}}$

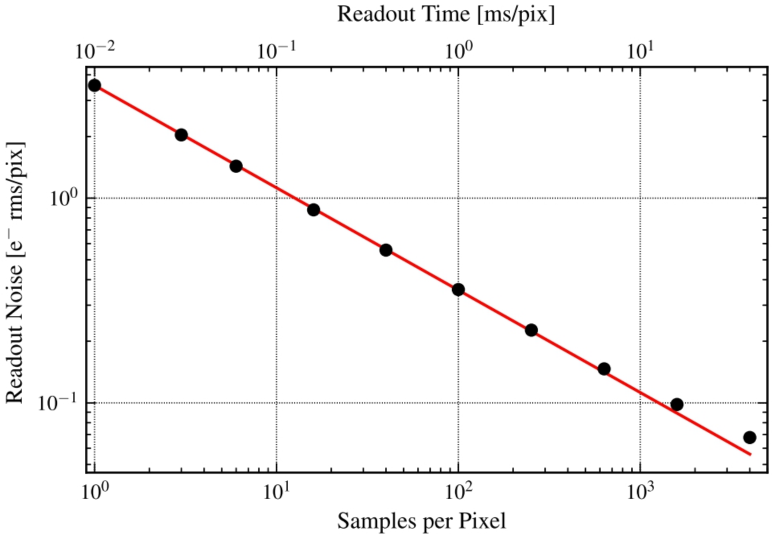
Low-frequency noise can also be reduced!

Skipper CCDs

The technology first demonstrated a good performance in 2017 using a detector designed by Stephen Holland (LBNL) allowing to count electrons in a wide dynamic range!

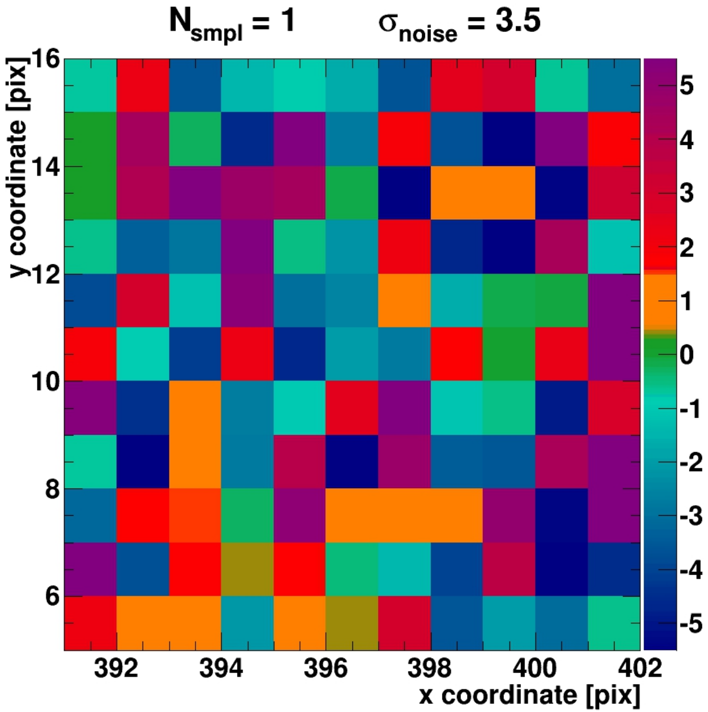
[10.1103/PhysRevLett.119.131802]



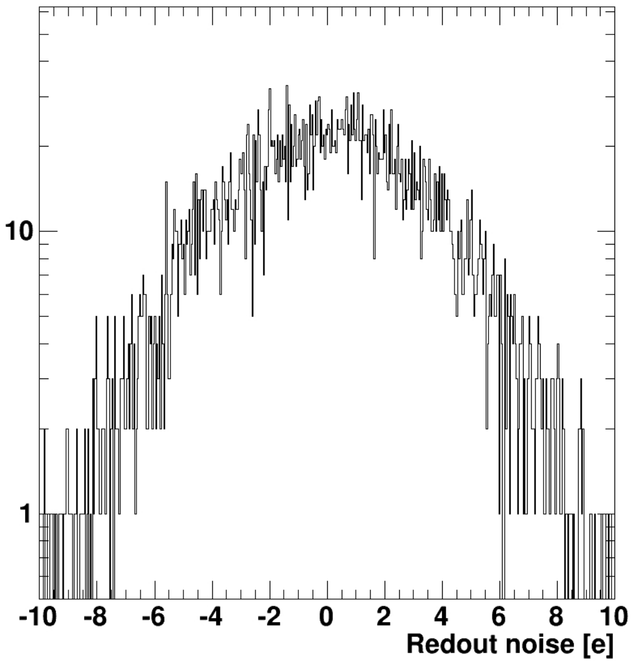


The price to pay is readout time, but this can be optimized depending on your interests*

Skipper CCDs



Taken from real data!



Skipper CCDs: smart readout

[10.1103/PhysRevLett.127.241101]

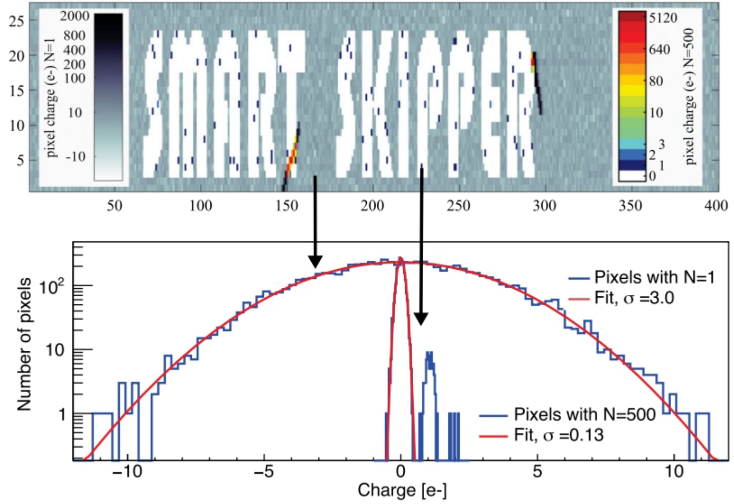


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

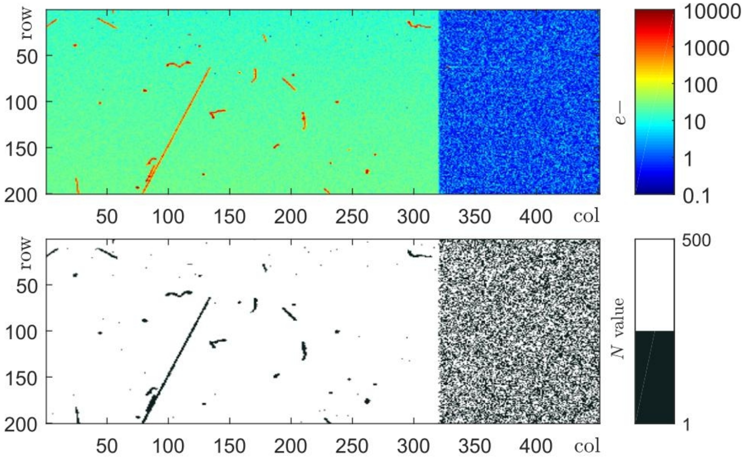


FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

Skipper CCDs: applications

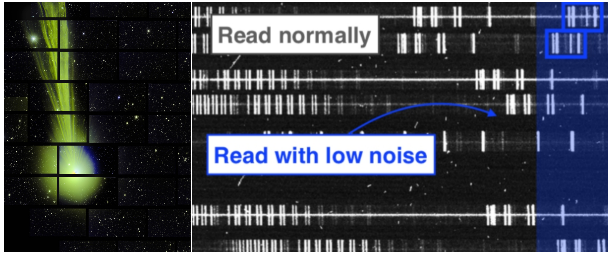
These are great detectors to study physical processes where a low-energy deposition takes place!

Plus, they have all the attractive features of CCDs, e. g., high quantum efficiency (>90%), great spatial resolution (15 µm x 15 µm pixels), high charge transfer efficiency, low dark current, etc.

Particle physics

Direct dark matter search
Low-energy neutrinos (CEνNS)

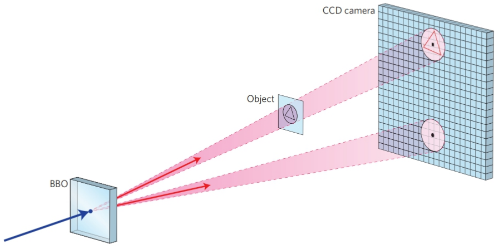
Astronomy



Faint sources
Short duration transients

[10.1117/12.2562403]

Quantum imaging

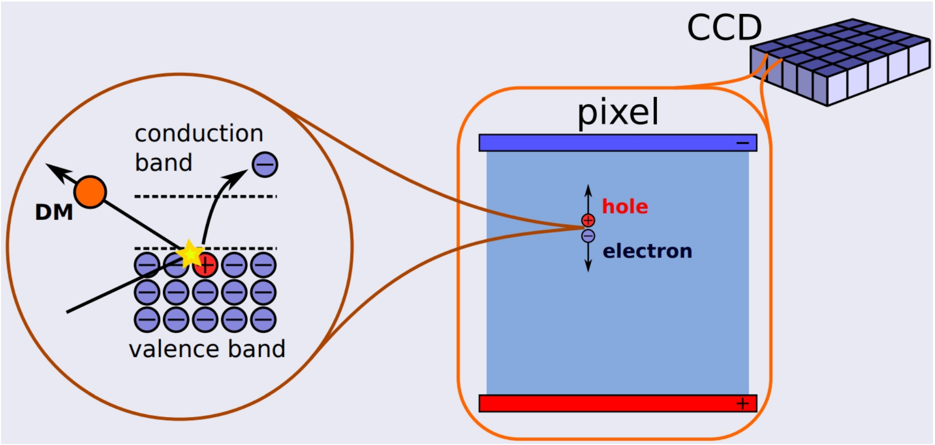


Agustina Magnoni talk!

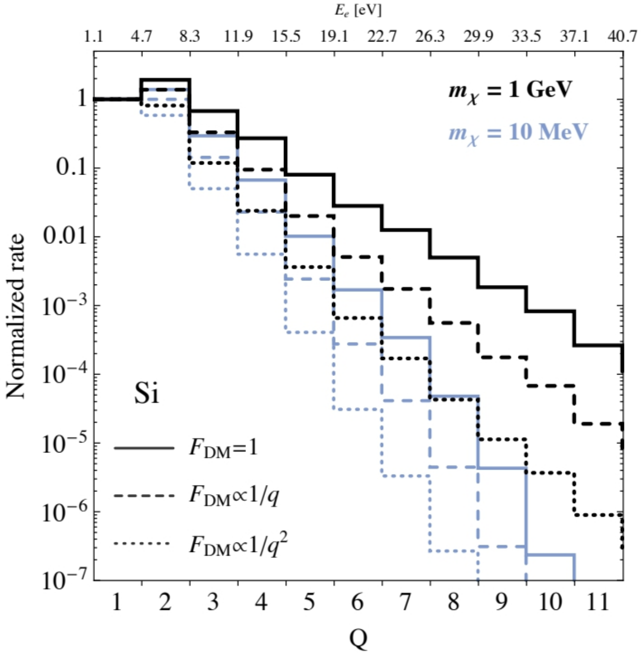
Direct dark matter search with skipper CCDs

DM-electron scattering:
m_χ in the MeV-GeV range → energy transfer is a few eV

DM absorption:
Bosonic DM at the eV scale → energy transfer equals m_χ



Sensitivity depends entirely on 1e- rate



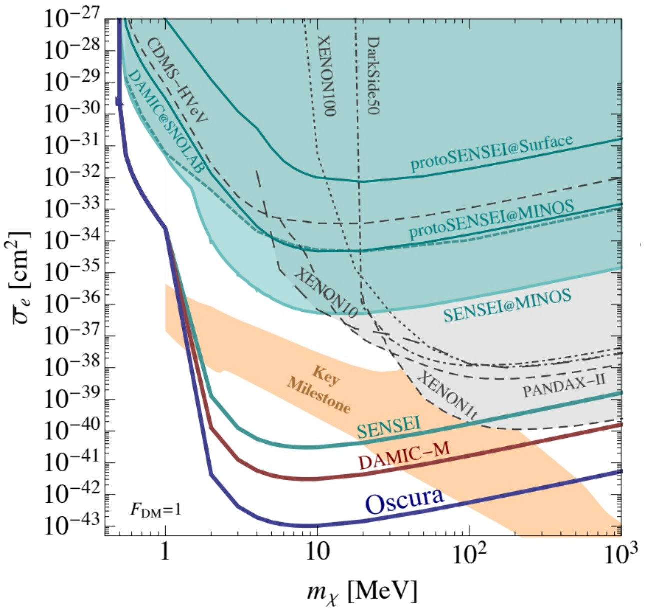
[10.1007/JHEP05(2016)046]

Fermilab

Direct dark matter search with skipper CCDs

[10.1103/PhysRevLett.125.171802]

World best limits for light dark matter candidates with this technology (SENSEI with ~2 g!)



DM-e- scattering (heavy mediator)

Ongoing program:

Experiment	Mass	Background	Year commissioning
DAMIC @ SNOLAB	~20 g	5 dru	12/2021
DAMIC-M (proto)	~10 g	1 dru	11/2021
SENSEI-100	~100 g	5 dru	2022
DAMIC-M	~1 kg	0.1 dru	2023
OSCURA	10 kg	0.01 dru	~2027

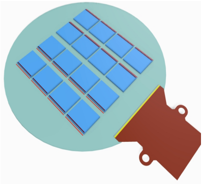
We know how to build experiments with skipper CCDs.
The challenge is going from 100 g to 10 kg (50 CCDs ➔ 24,000 CCDs)

Multi-kg experiments with skipper CCDs

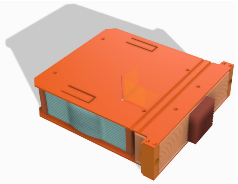
New ideas on sensor packaging, cryogenics and electronics are needed.

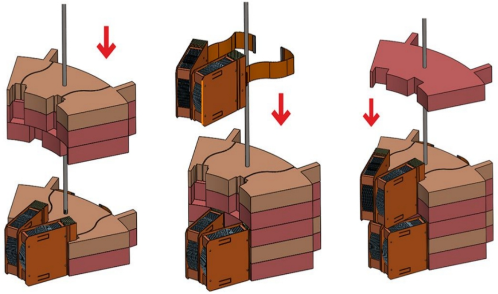
OSCURA's overall envisioned design [arXiv:2202.10518]

Multi-Chip Module
(16 skipper CCDs)

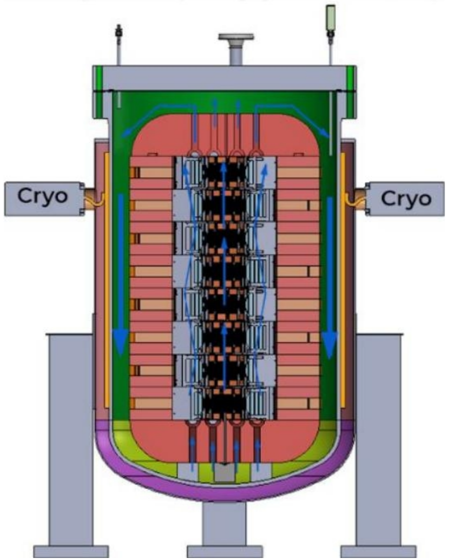


Super Module
(16 MCMs)



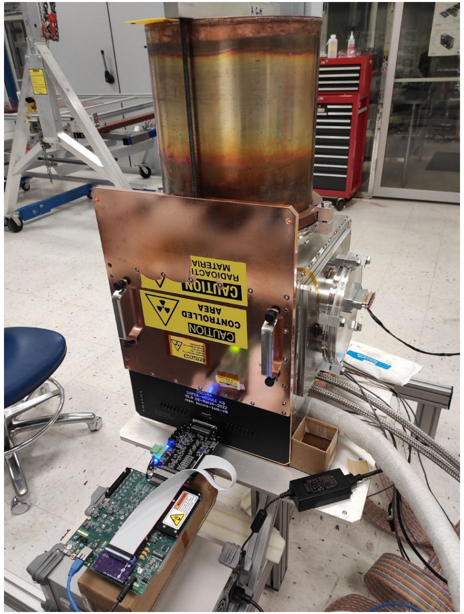


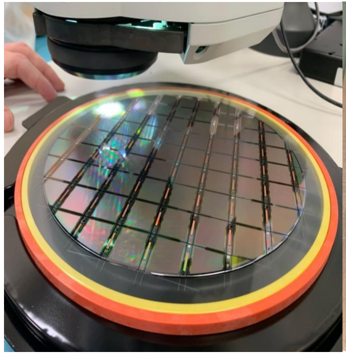
LN_2 pressure vessel

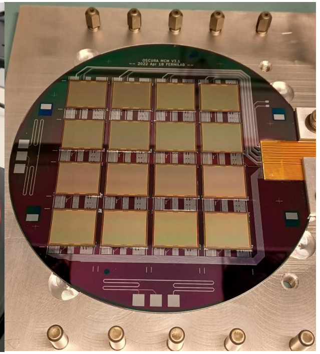


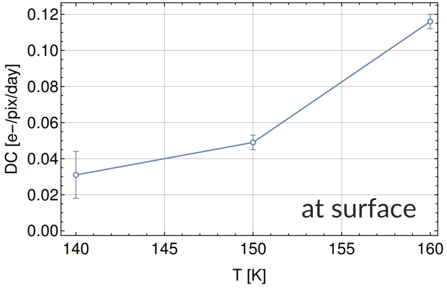
Multi-kg experiments with skipper CCDs

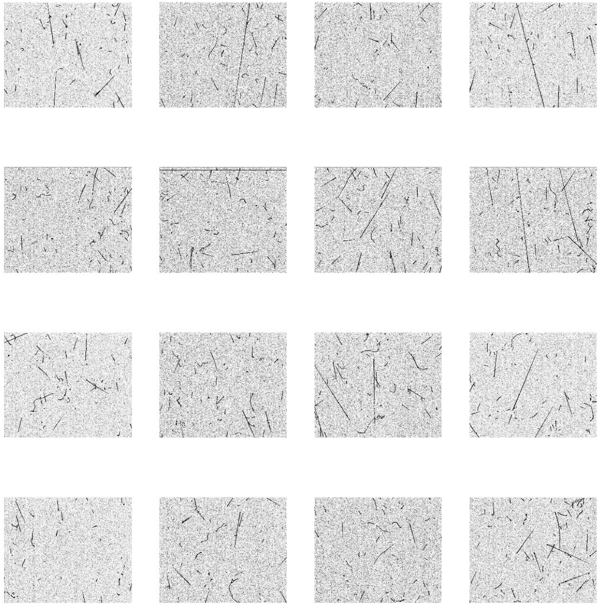
Great progress has been achieved during last year... stay tuned!







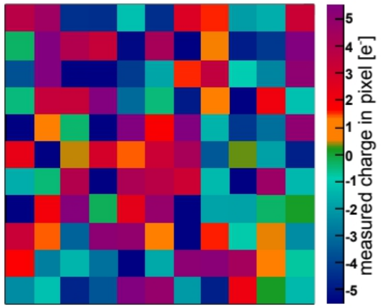




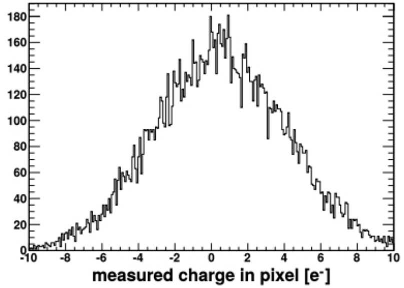
THANK YOU!

Standard vs skipper

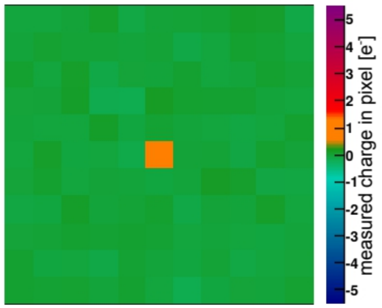
Standard CCD mode: charge in each pixel is measured once



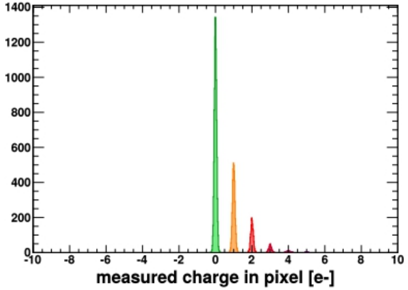
Readout-noise: 3.5 e RMS



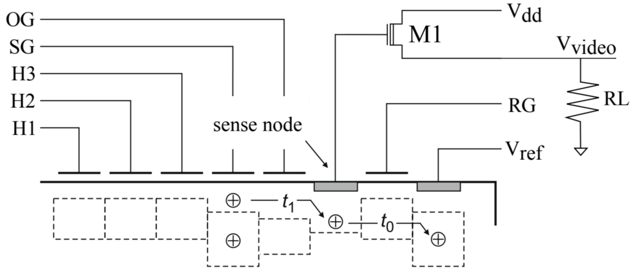
New Skipper CCD: charge in each pixel is measured multiple times



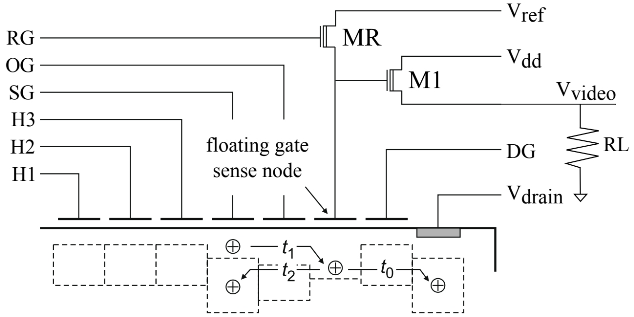
Readout-noise: 0.06 e RMS



Standard CCD



Skipper CCD



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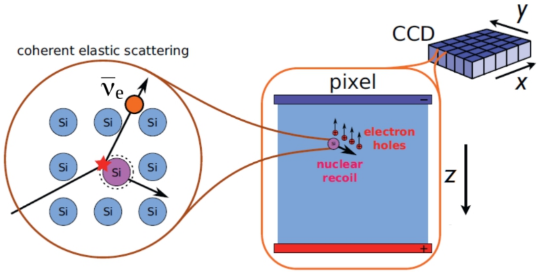
Coherent Elastic Neutrino Nucleus Scattering with skipper CCDs



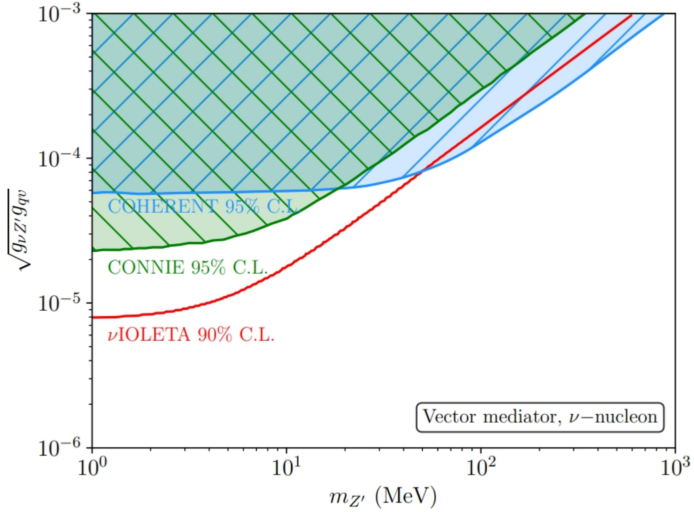
In Si, for E_ν = 2 MeV, E_R ~300 eV

Reactor neutrinos are a great source!

- E_ν< 4 MeV and high flux ~10^{20} ν/s

- Standard CCDs have demostrated to be competitive constraining BSM physics (CONNIE) [10.1007/JHEP04(2020)054]
- Skipper CCDs can extend the reach of these searches (νIOLETA)

[10.1007/JHEP02(2022)127]



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