Optical Single Photon Detection with Skipper-CCDs

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BREAD Collaboration Meeting

October 4-6, 2023

Fermilab

Charge-Coupled Devices (CCDs)

[10.1103/RevModPhys.82.2307]

Invented in 1969

The Nobel Prize in Physics 2009

Willard S. Boyle and George E. Smith

Bell Laboratories, Murray Hill, NJ, USA

"for the invention of an imaging semiconductor circuit – the CCD sensor"

FIG. 14. (Color online) W. S. Boyle and G. E. Smith, 1970.

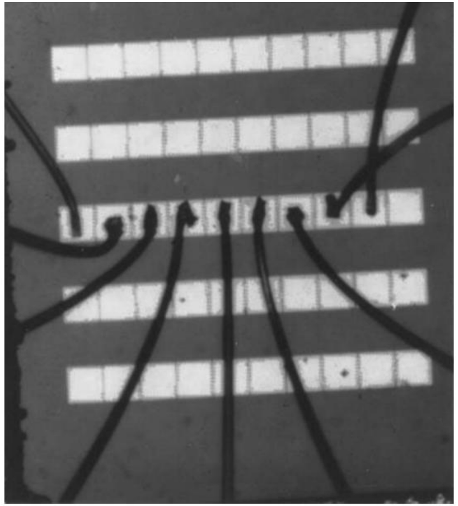


FIG. 7. The first CCD device.

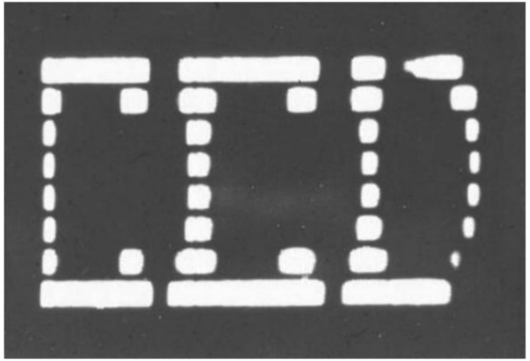
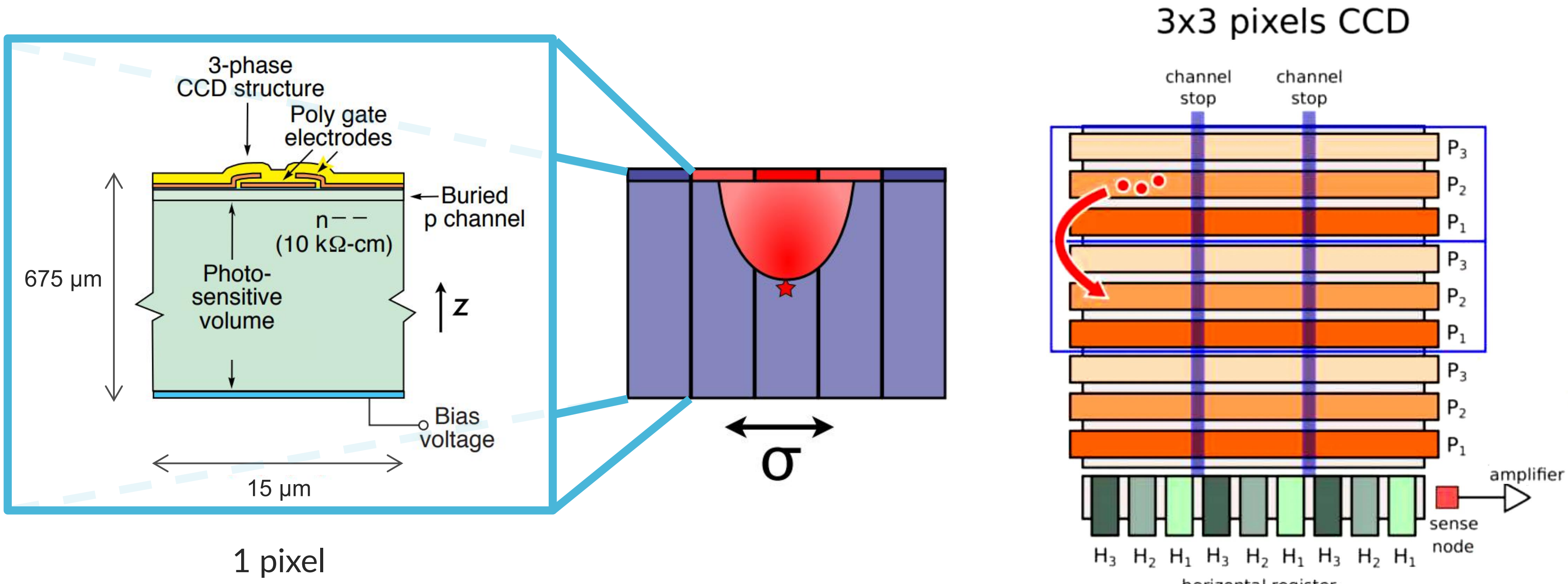


FIG. 9. Oscilloscope display of the output of the 8-bit device used as an imager.

CCDs: silicon ionization sensors

CCDs are an array of Metal-Oxide-Semiconductor capacitors
Ionizing radiation produces e-h pairs (In silicon, 1 e-h pair ~ 3.75 eV)
Charge is collected near the surface, transferred along the device until the readout stage



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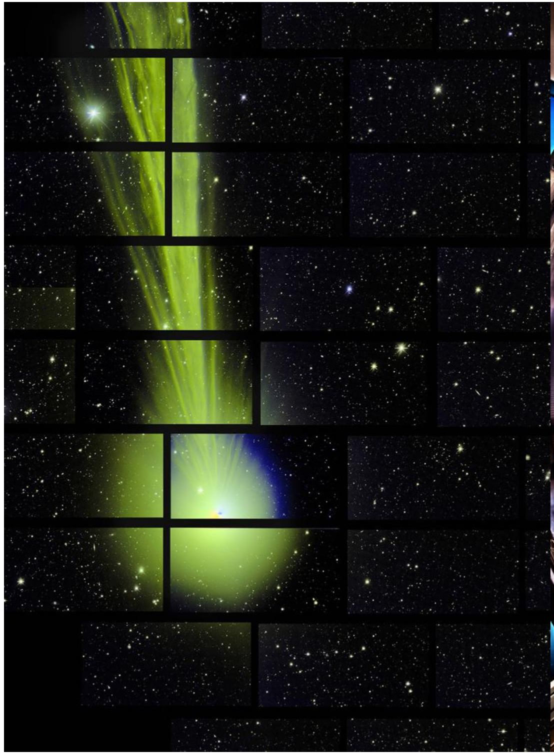
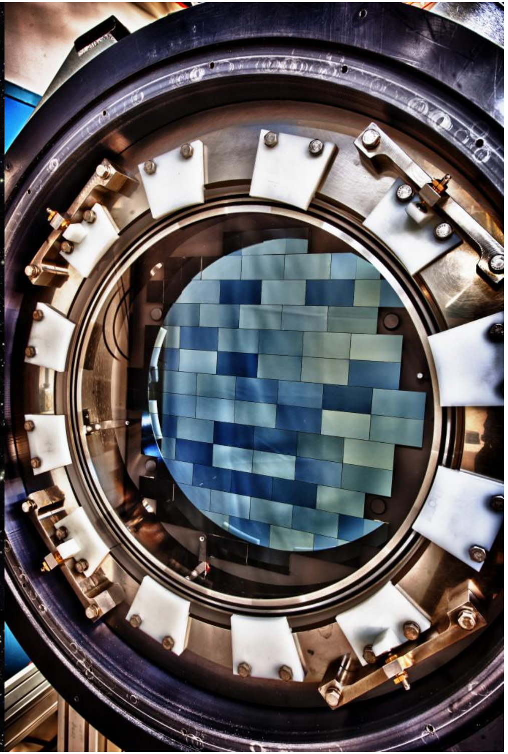
CCDs: imaging detectors

In astronomy, CCDs have been widely used since their invention





www.darkenergysurvey.org

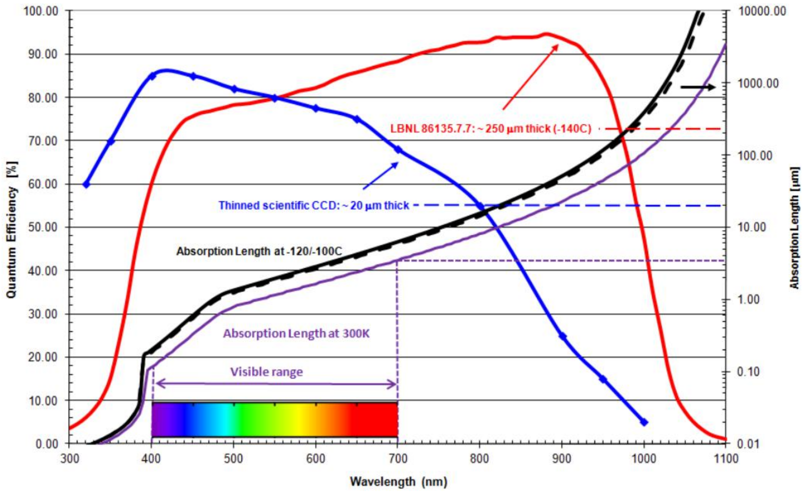
LBNL developed thick CCDs for DECam to increase quantum efficiency at IR

Steve Holland, Engineer/Extraterrestrial Rock Star

***Asteroid #40981** (1999 TL284)
Presented to: Stephen Holland, *CCD Developer Extraordinaire*

BERKELEY LAB

[10.1109/TED.2002.806476]



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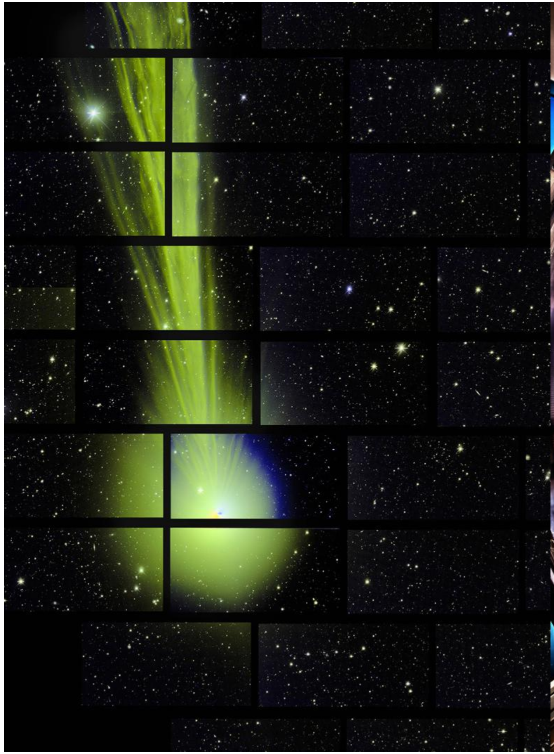

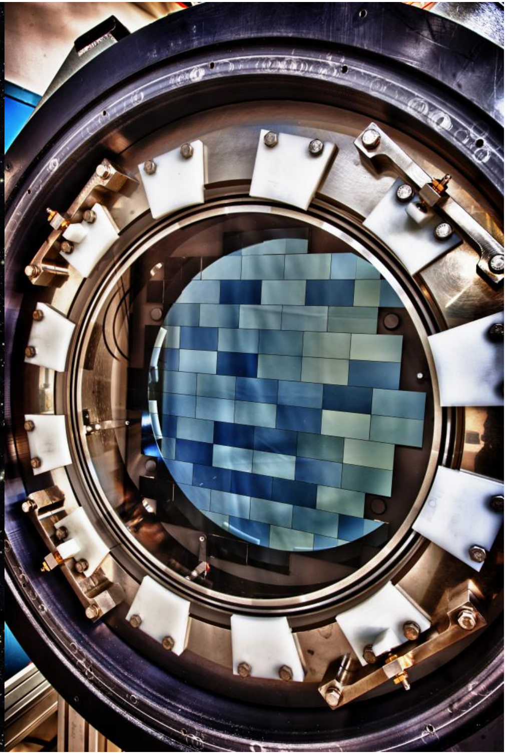

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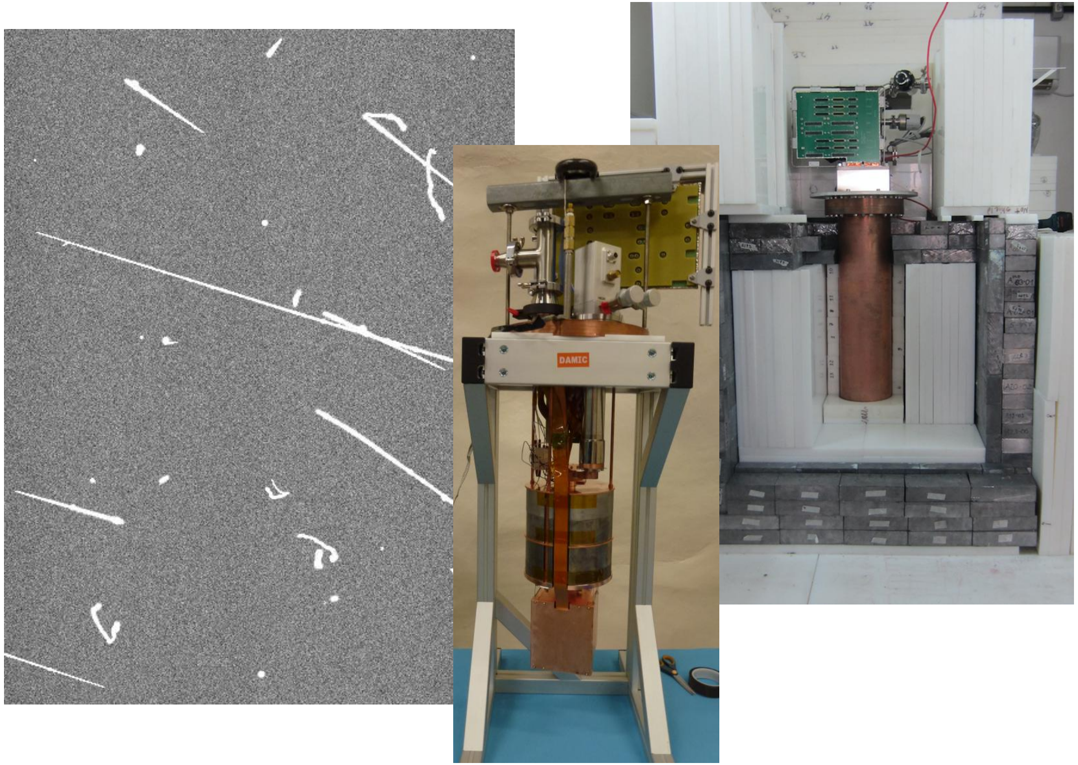
- Great spatial resolution (15 μm pixels)
- High charge transfer efficiency (~10^5)
- Low energy sensitivity (1 e-h pair ~ 3.75 eV)
- Low instrumental backgrounds (~ e^-/pix/day)
- Low readout noise (~ e^-)

CCDs: particle detectors

CCD group @ FNAL uses CCDs to study low-energy particle interactions (dark matter, neutrinos, etc.)



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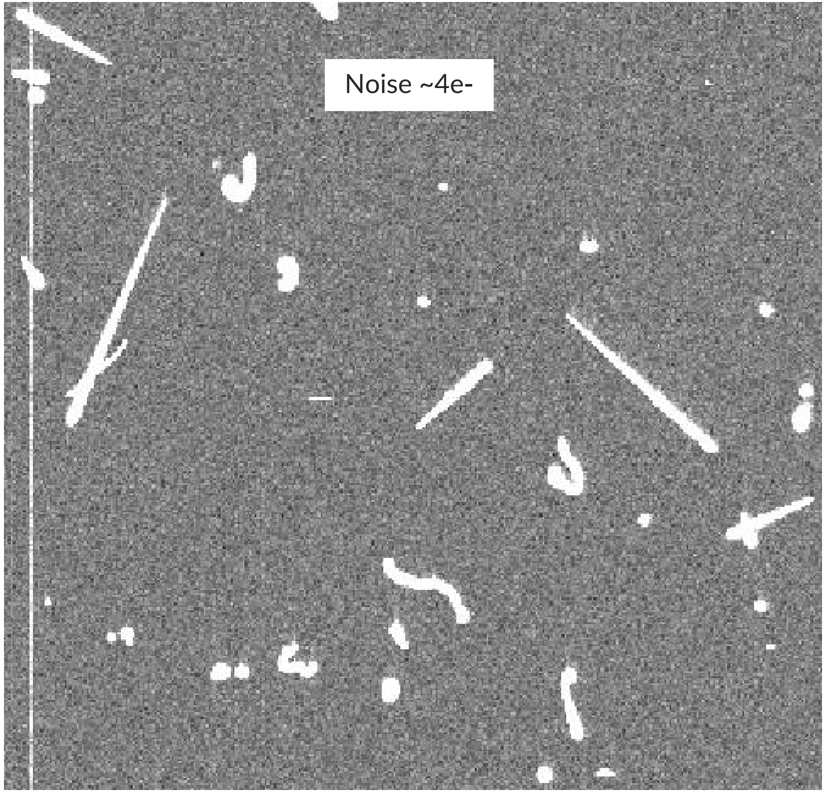
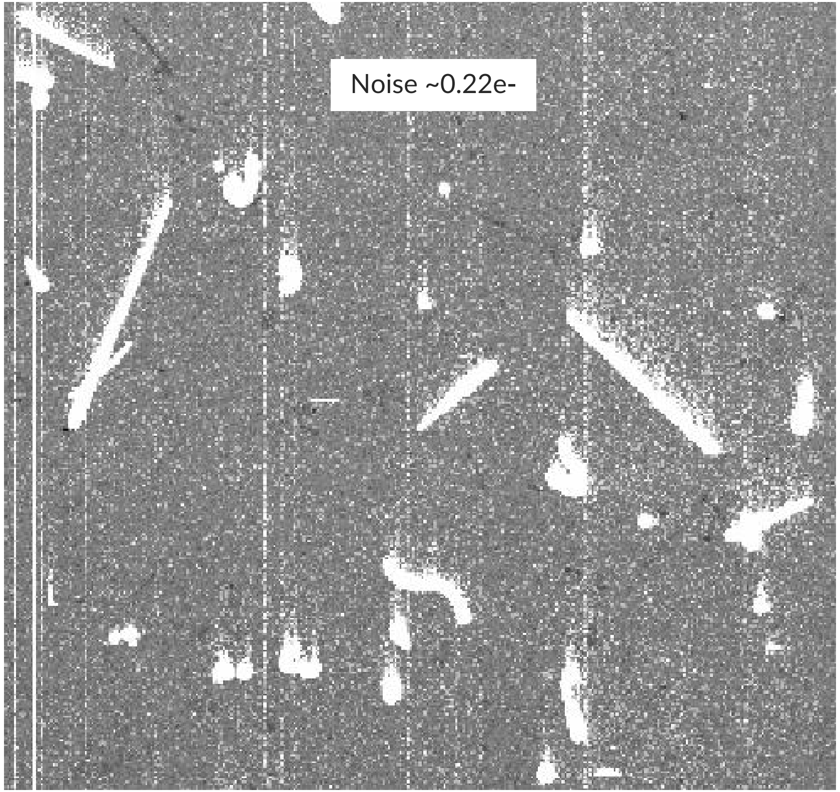
↓

Deeply studied and minimized
Further understood with the new generation
skipper-CCDs

Skipper-CCDs: window to truly understand “dark counts”

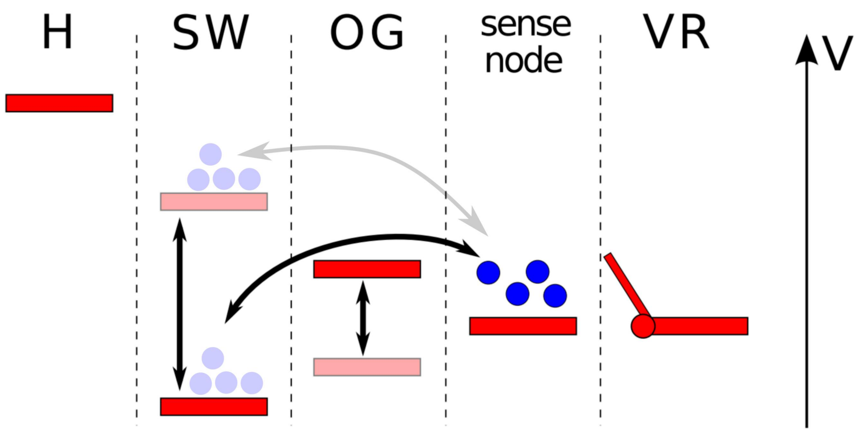
Achieving sub-electron noise allows to deeply explore what is invisible with standard CCDs (pixels below noise)





Skipper-CCDs: electron-counting silicon sensors

Skipper output stage allows to perform multiple non-destructive measurements of same charge packet

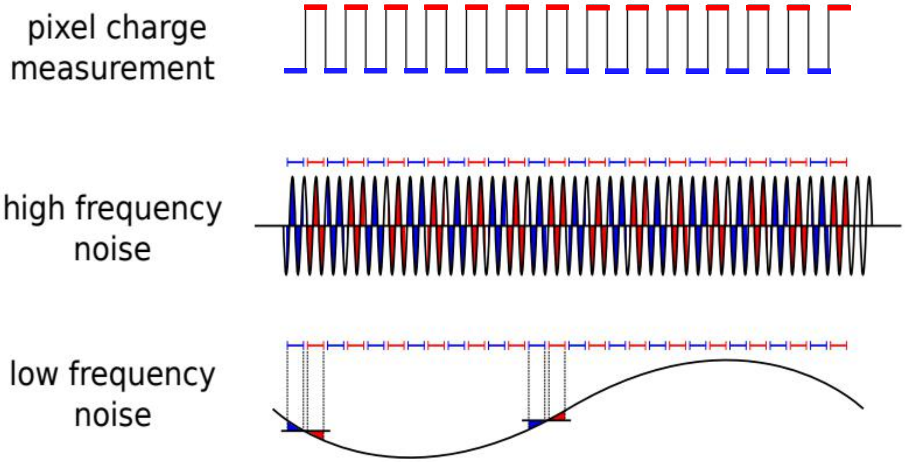


Sub-electron noise can be achieved by averaging pixel samples off-chip

$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

Correlated Double Sampling to measure charge:

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



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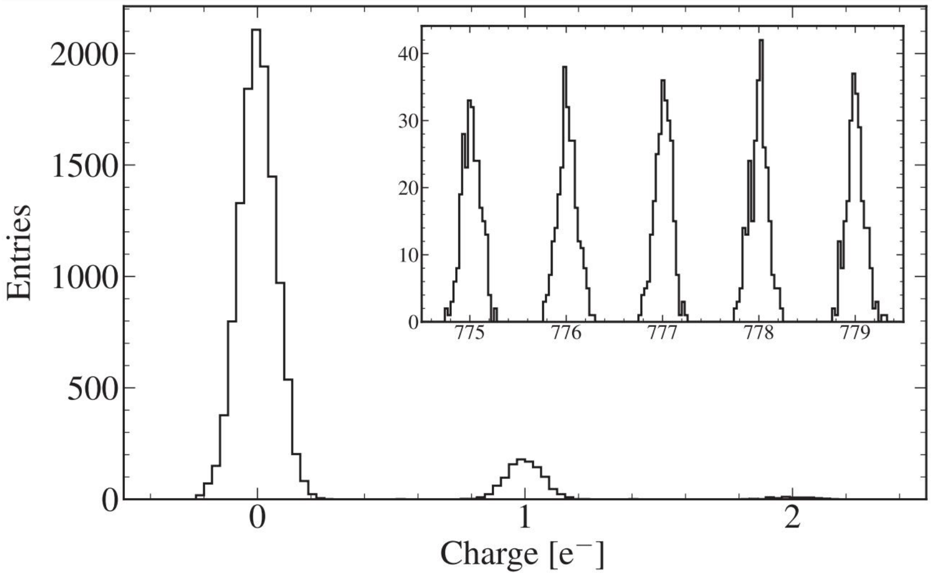
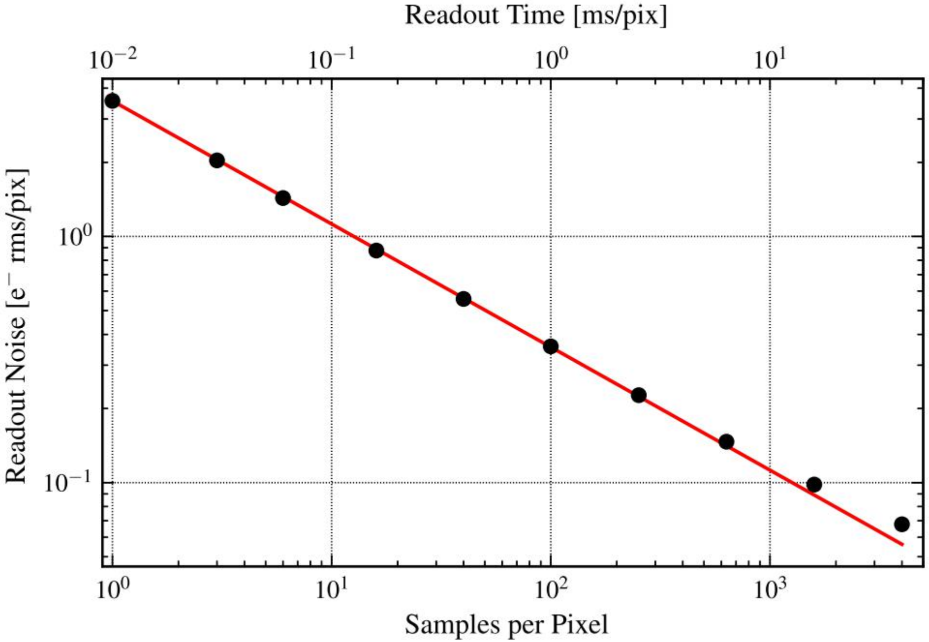
Skipper-CCDs: electron-counting silicon sensors

Count single electrons in a wide dynamic range: self-calibrating charge measurement
Trade-off between charge resolution and readout time





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Skipper-CCDs: smart readout

Two approaches during DAQ: Region-of-interest (ROI) and Energy-of-interest (EOI)
Decreases overall sensor readout time

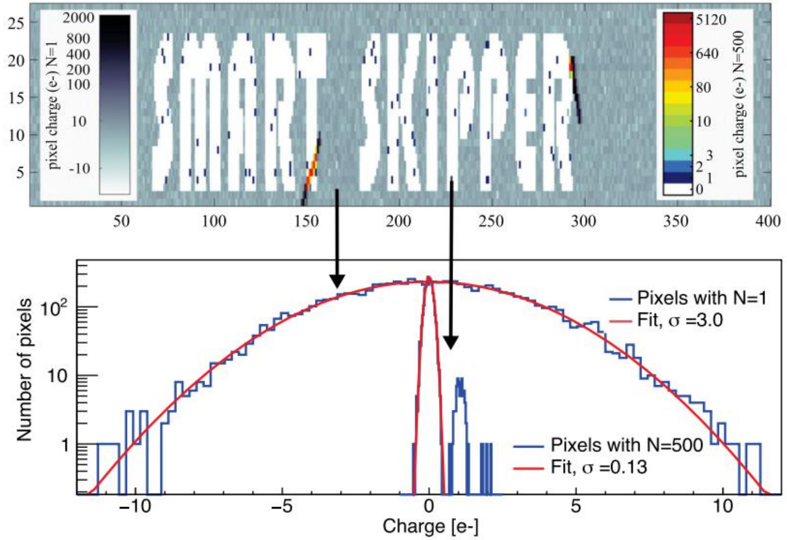


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

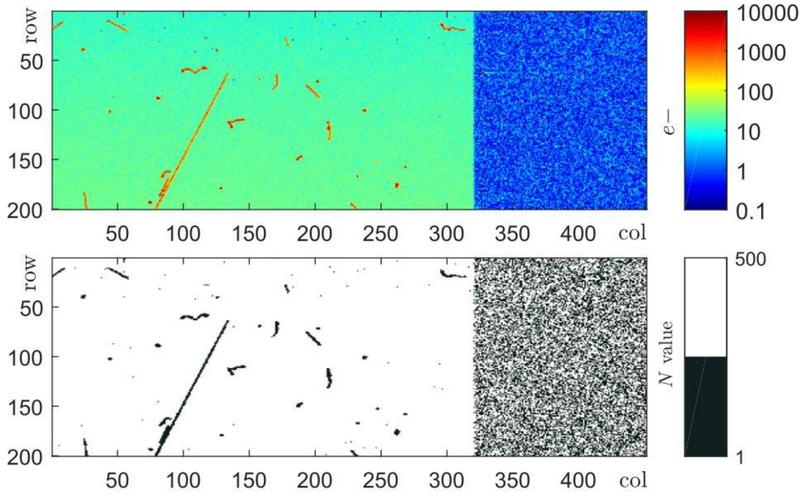


FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

[10.1103/PhysRevLett.127.241101]

Skipper-CCDs: ultra-low instrumental background

[10.1088/1748-0221/18/08/P08016]

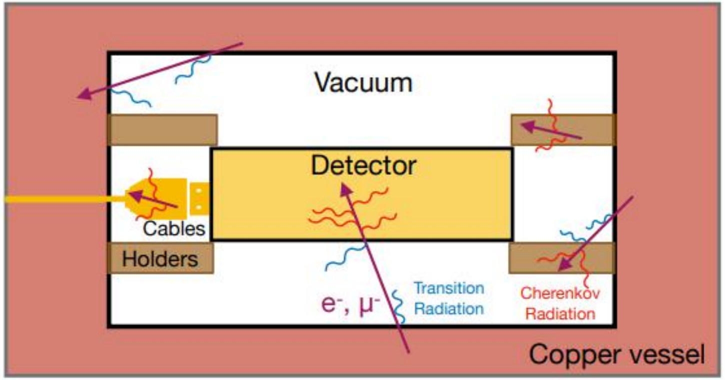
Optimization for dark matter searches achieved lowest 1e- rate in silicon (~10^{-4} e-/pix/day - SENSEI @ MINOS)
We can say we understand it fairly well

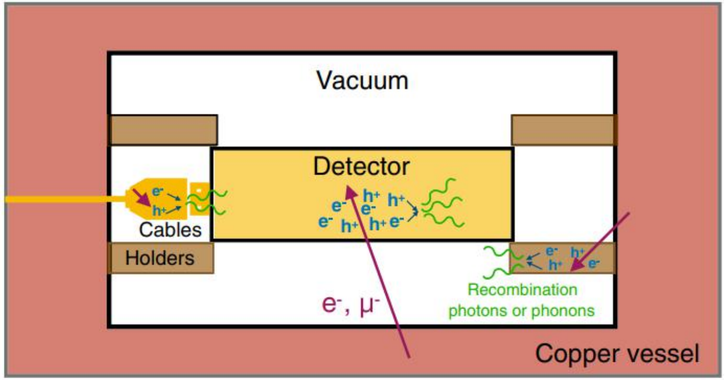
*for a 30 kg-year exposure

Parameter	No events with 2e- or more*	No events with 3e- or more*	Prototype	Best achieved	Units
Dark current	1×10^{-6}	1.6×10^{-4}	3×10^{-2}	1.6×10^{-4} ✓	e^-/pix/day
Readout time (full array)	< 2	< 5	3.4 (4.2)	3.4 ✓	hours
Pixel readout rate	> 188	> 76	111 (89)	111 ✓	pix/s
Readout noise	< 0.16	< 0.20	0.19 (0.20)	0.19 ✓	e^- RMS
Spurious charge	$< 4 \times 10^{-11}$	$< 6 \times 10^{-9}$	7.2×10^{-7}	1.4×10^{-8}	e^-/pix/transfer
Trap density ($\tau > 5.3$ ms)	< 0.12		< 0.015	< 0.0003 ✓	traps/pix
Charge transfer inefficiency	$< 10^{-5}$		$< 5 \times 10^{-5}$	$< 10^{-5}$ ✓	1/transfer
VIS/NIR light blocking	$> 90\%$		95%	95% ✓	

Experiments are mainly limited by **external background**

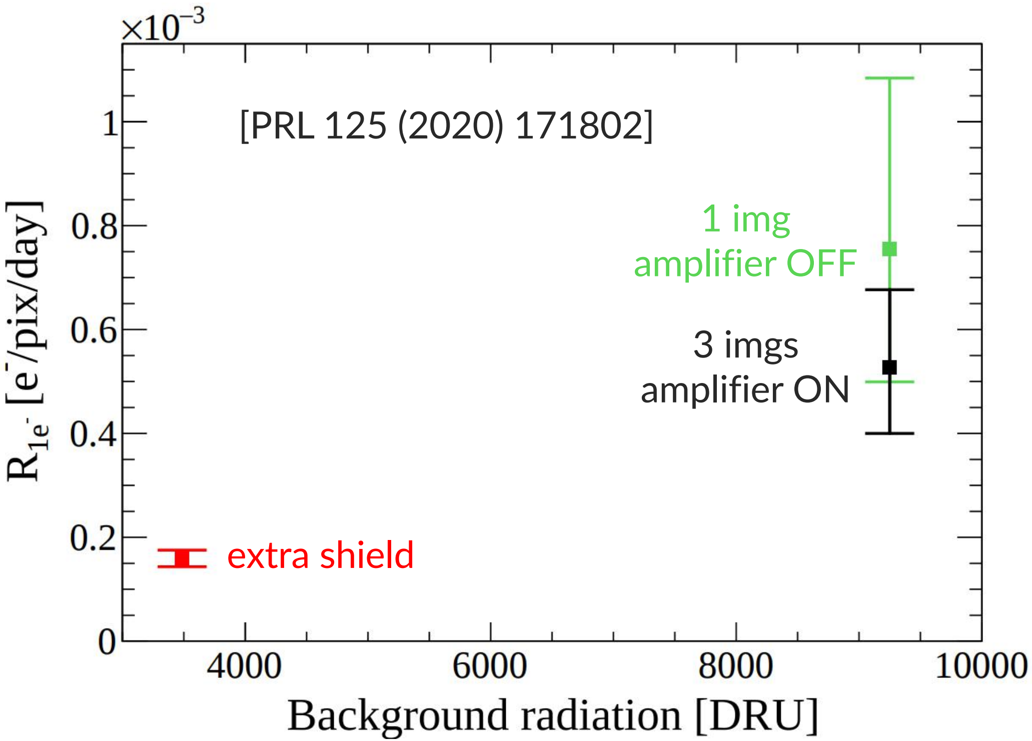
Low-energy background from high-energy events



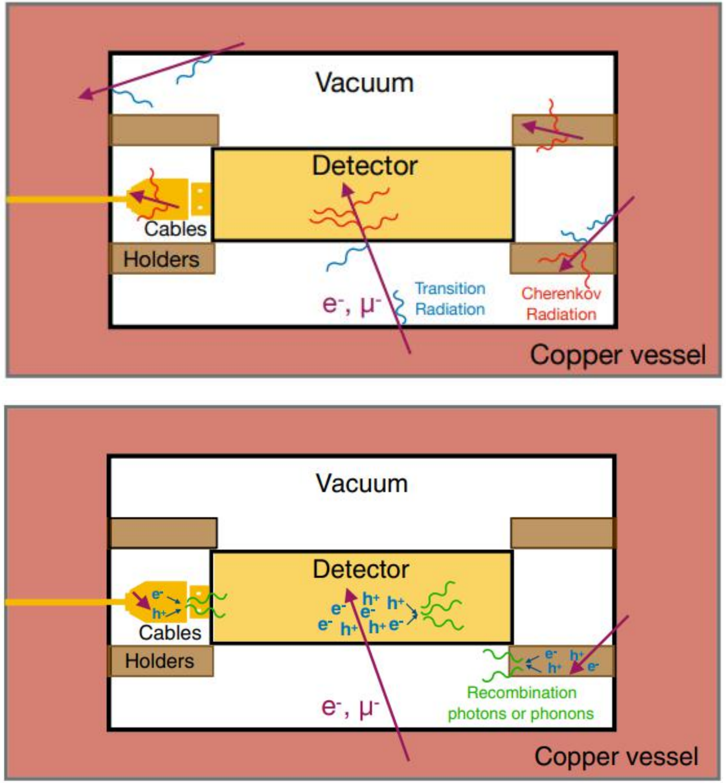


[PRX 12 (2022) 011009]

High-energy radiation interacting with setup results in low-E photons which can produce single-e- depositions

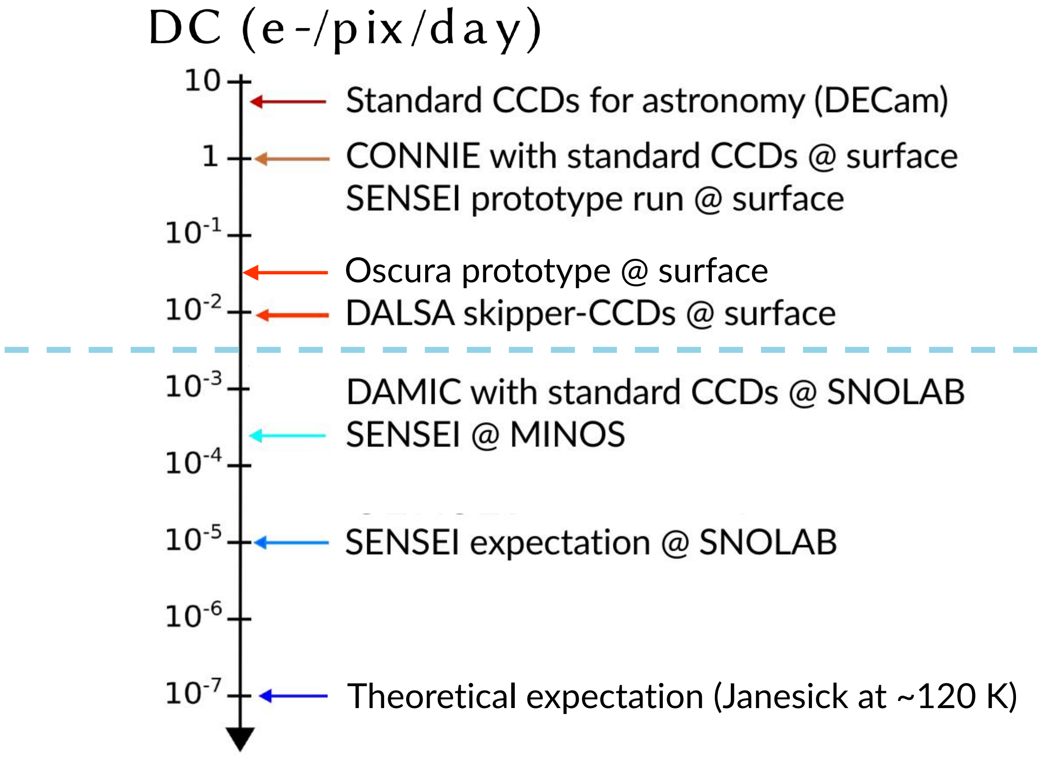


Low-energy background from high-energy events



[PRX 12 (2022) 011009]

Main "dark counts" contribution



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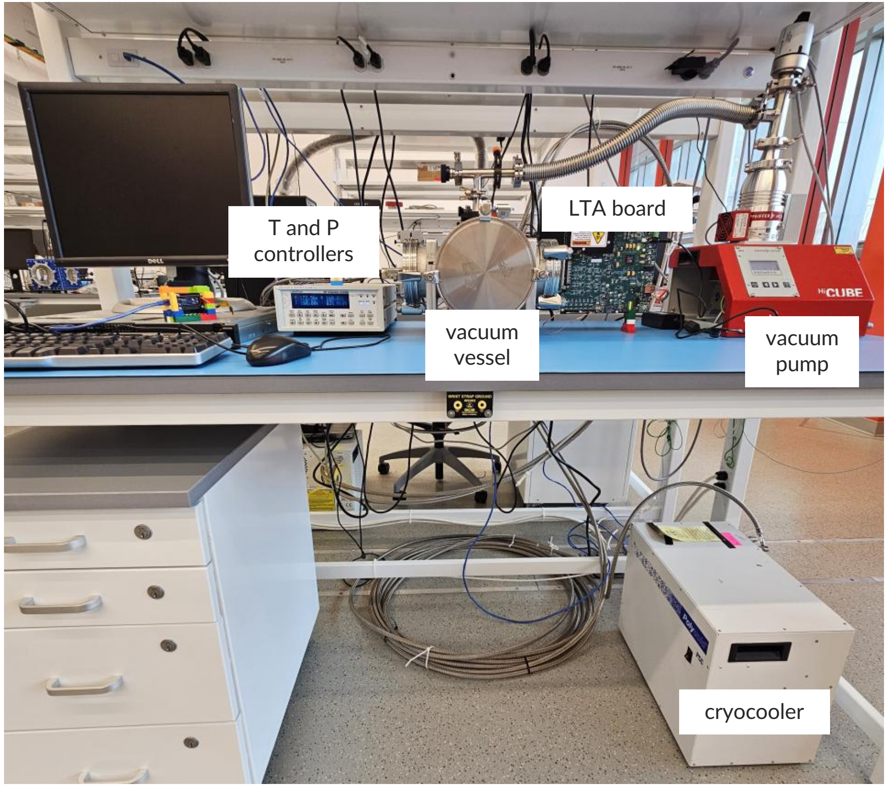
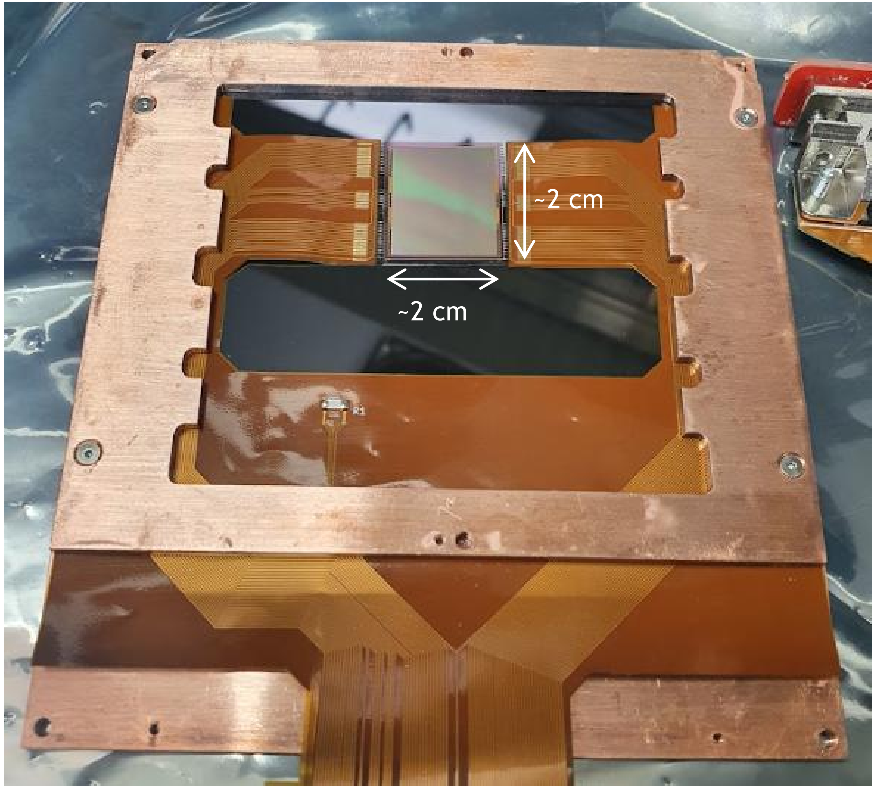
Skipper-CCDs: single-module operation station

CCDs operate inside vacuum (~e-6 mbar) at temperatures around ~140 K



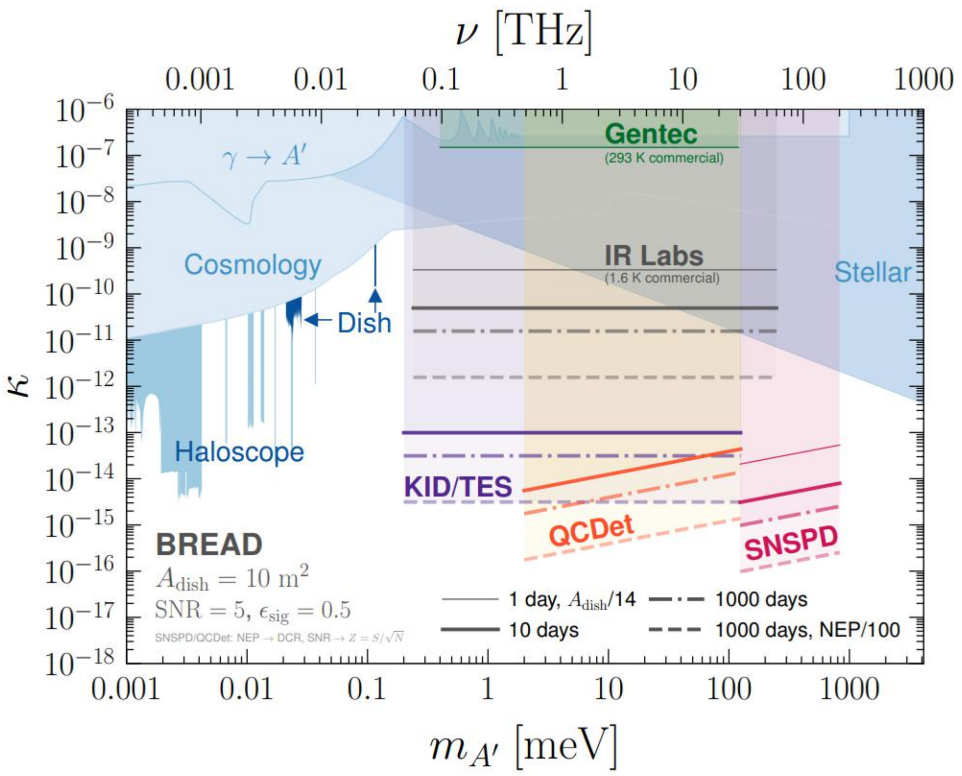


Skipper-CCDs + BREAD

[arxiv:2111.12103]

$$\begin{Bmatrix} \left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2 \end{Bmatrix} = \begin{Bmatrix} \frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_\mathrm{ext}}\right)^2 \\ 11.9\frac{2/3}{\alpha^2_\mathrm{pol}}\frac{m_{A'}}{\mathrm{meV}} \end{Bmatrix} \left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2} \times \frac{10\,\mathrm{m}^2}{A_\mathrm{dish}}\frac{Z}{5}\frac{0.5}{\epsilon_s}\left(\frac{\mathrm{DCR}}{10^{-2}\,\mathrm{Hz}}\right)^{1/2}\frac{0.45\,\mathrm{GeV/cm}^3}{\rho_\mathrm{DM}}. \qquad (11)$$

Sensitivity for dark photons



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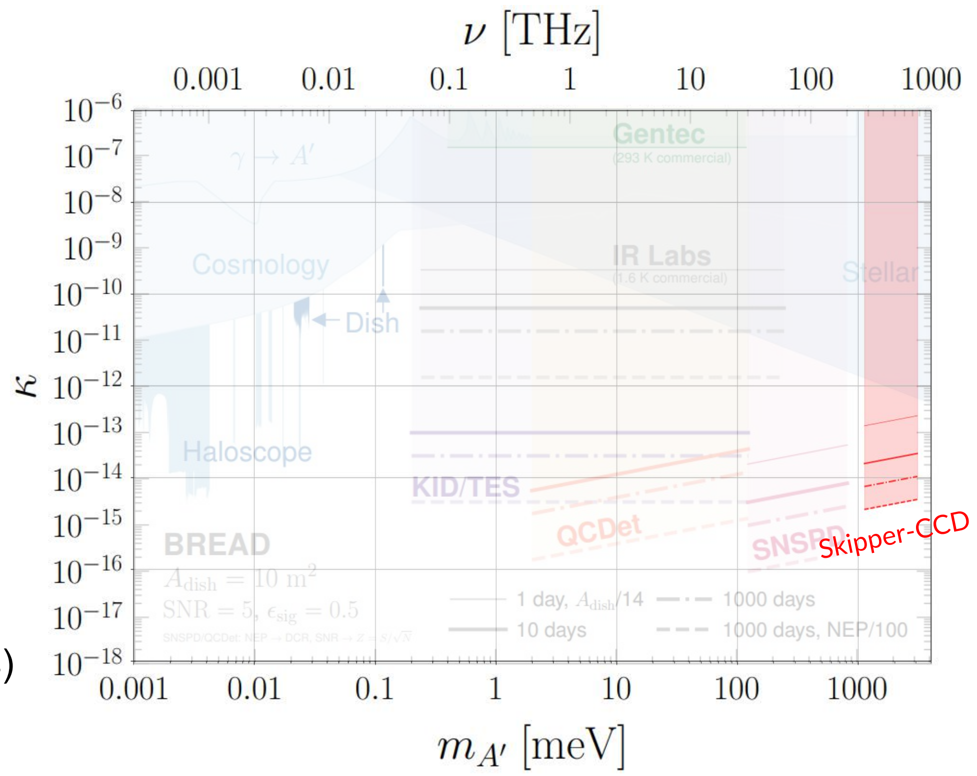

For skipper-CCDs:

$m_{A'}$ = [1127, 3100] meV → [1100, 400] nm
DCR in 2x2 mm^2 spot ≈ 2x10^{-3} Hz → 10^{-2} e-/pix/day
ε_s > 50% (back-illuminated sensor is better)
α^2_{pol} = 2/3 (skipper-CCDs sensitive to all polarizations)

Skipper-CCDs + BREAD

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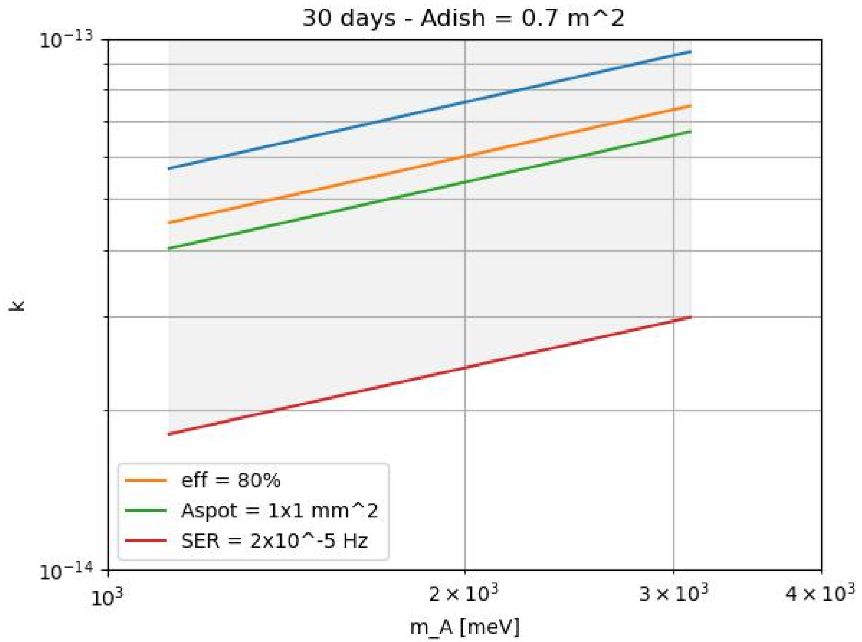

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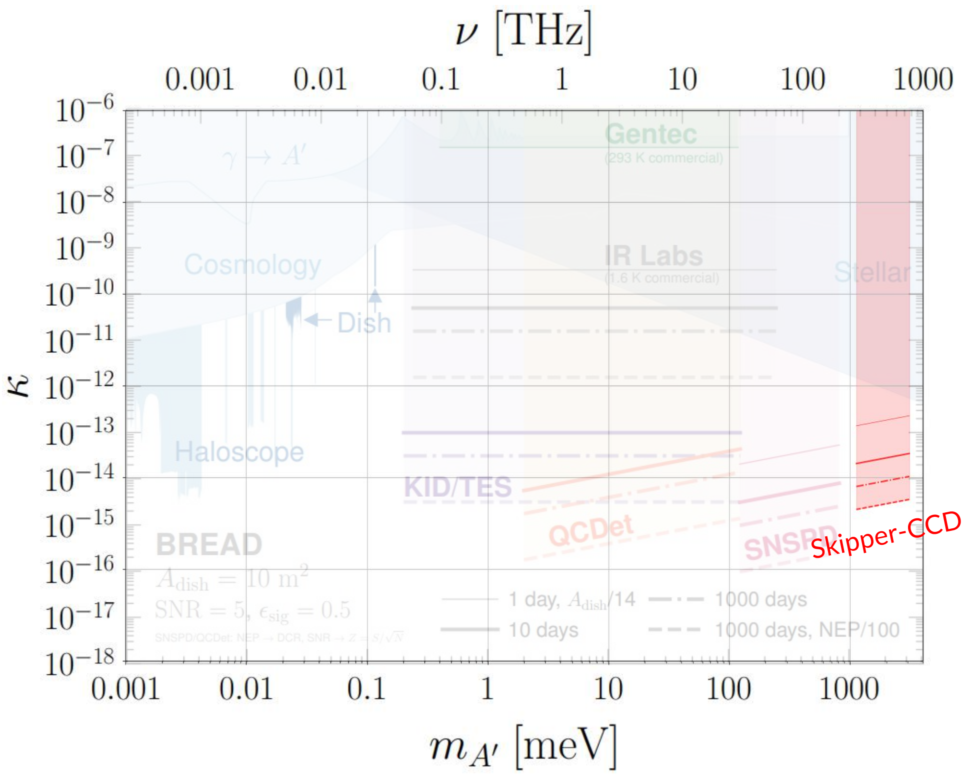

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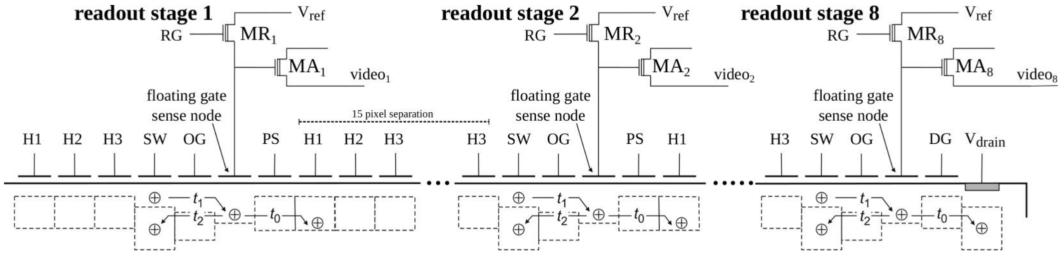
Fast-readout technologies with single-electron resolution

New Initiatives Grant

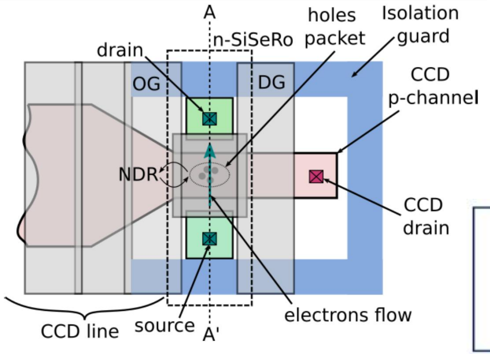
Multi-Amplifier Sensing (MAS) CCDs

[10.1002/asna.20230072] [arXiv:2308.09822]



CCDs with n-Sisero stage

[10.1109/TED.2022.3233288]



[indico.fnal.gov/event/58707]

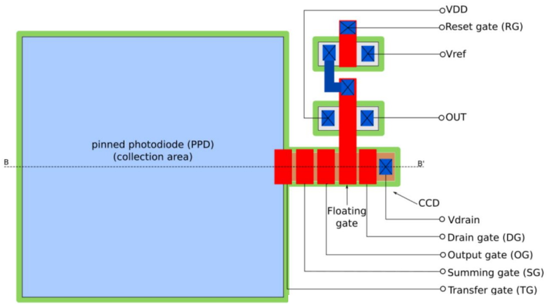
Instituto Balseiro

UNC

SLAC NATIONAL ACCELERATOR LABORATORY

Skipper-in-CMOS

[B. Parpillon @ CPAD 2022]



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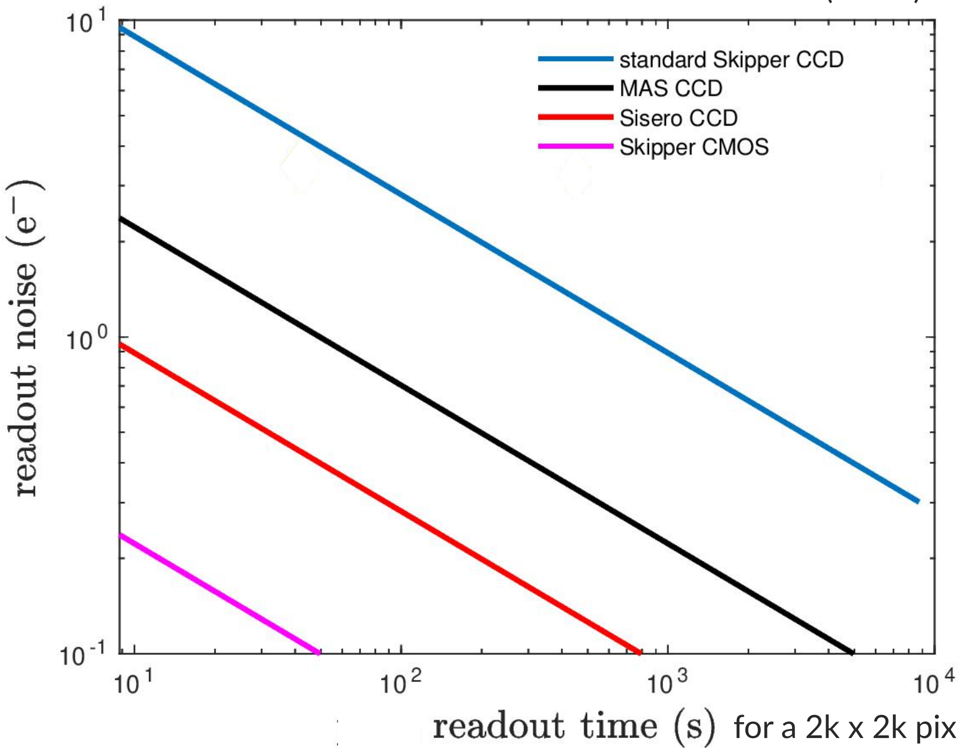
Fast-readout technologies with single-electron resolution

Improve readout time, compared to skipper-CCDs, without losing electron-counting capability
Could help reduce external backgrounds

Plot from G. Fernandez Moroni (FNAL)



for a 2k x 2k pix sensor

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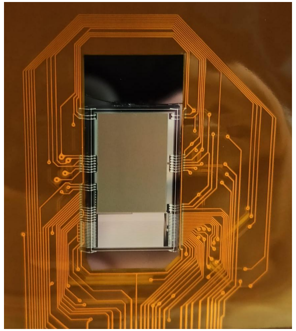
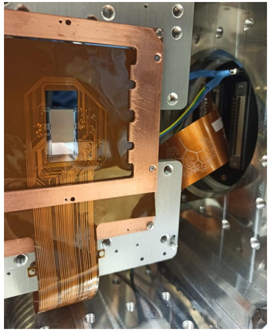
Fast-readout technologies with single-electron resolution

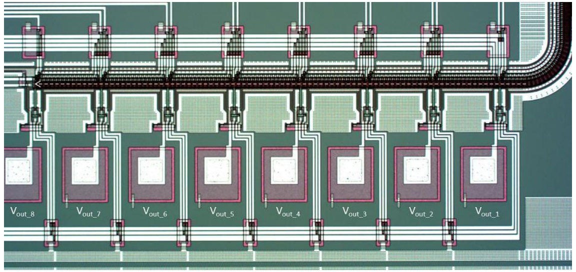
First prototypes are being tested at SiDet!

Multi-Amplifier Sensing (MAS) CCDs

[10.1002/asna.20230072]
[arXiv:2308.09822]

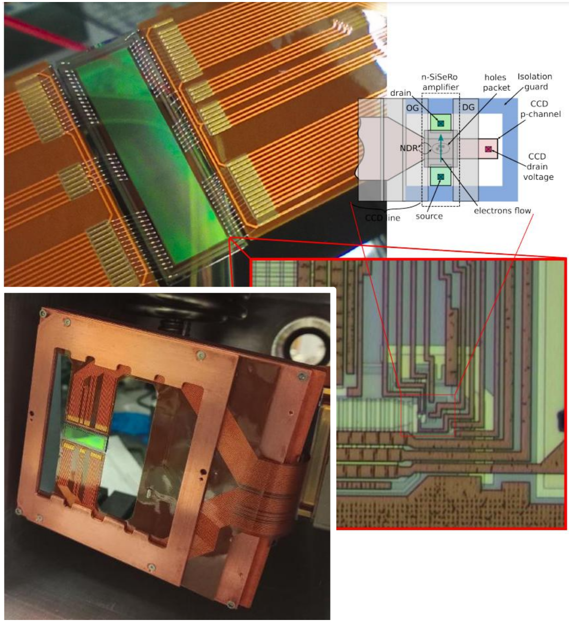






CCDs with n-Sisero stages

[10.1109/TED.2022.3233288]
[indico.fnal.gov/event/58707]



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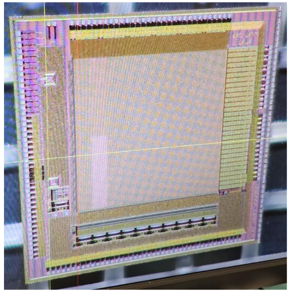

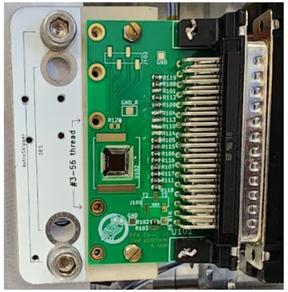

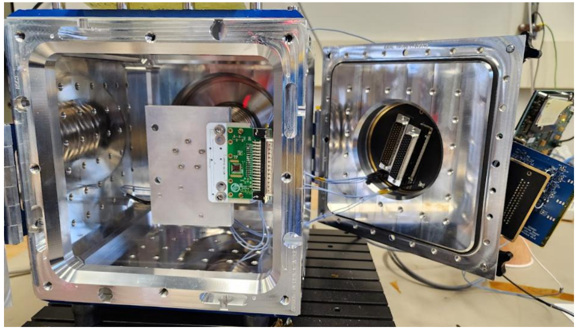

Stay tuned for results!

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Take-home messages

- Electron-counting skipper-CCD technology allows to study faint signals
- Thick and back-illuminated CCDs have a high quantum efficiency at near-IR wavelenghts
- Skipper-CCD operation setups are quite simple
- Experiments are mainly limited by external backgrounds (instrumental backgrounds are low)
- Skipper-CCDs + BREAD could explore dark photon masses above ~1 eV
- Emerging fast-readout semiconductor technologies with single-electron resolution are being developed (useful to further reject external backgrounds)

Thank you!

[https://www.astronomy.ohio-state.edu/weinberg.21/Rap/index.html]

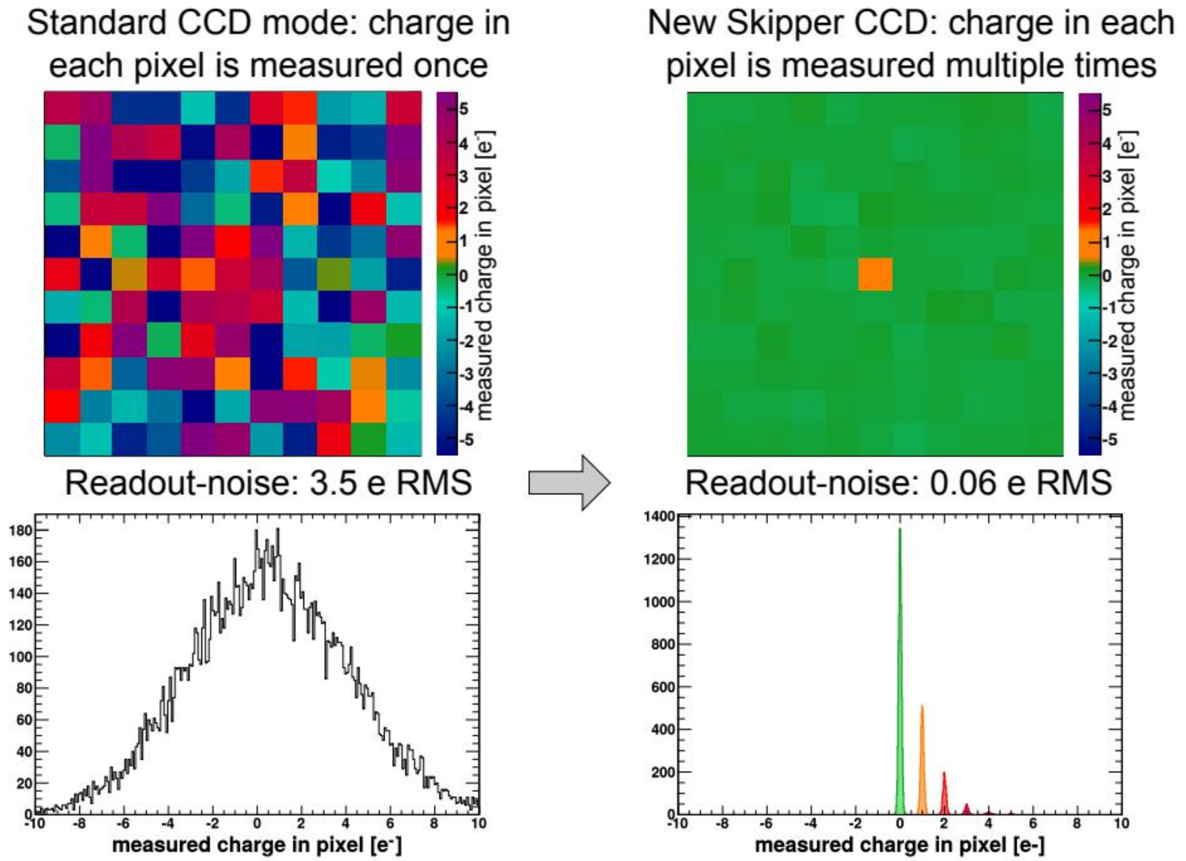
The Dark Matter Rap: A Cosmological History
by David Weinberg, ©1992
Lyrics updated 2023

...

WIMPy, fuzzy, warm, dark atomic, superlight,
so hard to find it feels like they are hiding out of spite.
So we huddle deep in mines with the world's supply of xenon
seeking scintillating flashes of the insight we are keen on.
Mic silicon-germanium to listen in for phonons.
Build hyper-volume radios, tuning in for axions.
We search the skies for gamma-rays from WIMP annihilation,
those tiny sparks that light the dark in EM radiation.
We smash together protons, search for tracks in the debris,
to prove we made our own DM within the LHC.
The search is ever-popular, as many realize
that the detector of dark matter may well win the Nobel Prize.

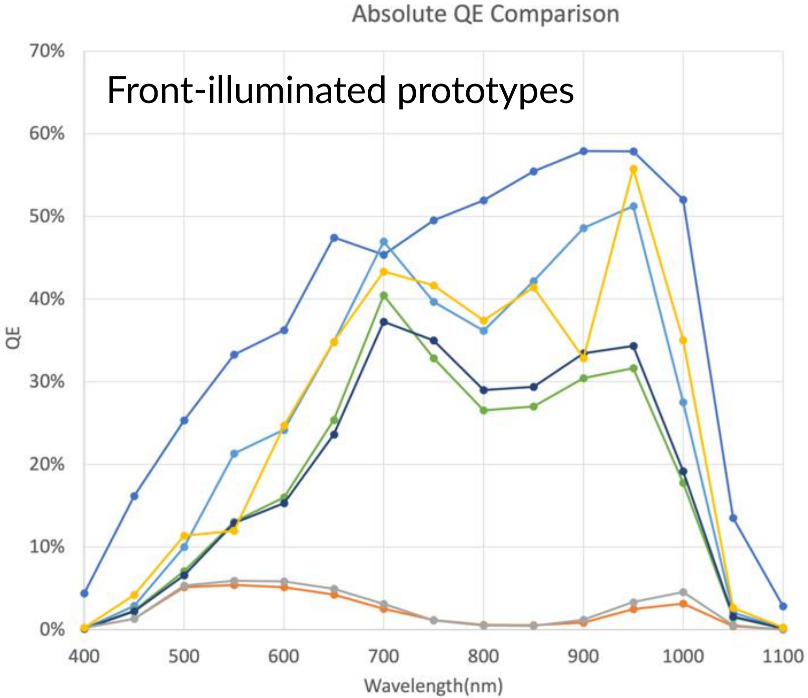
So now you've heard my lecture, and it's time to end this session
with the standard closing line: Thank you, any questions?

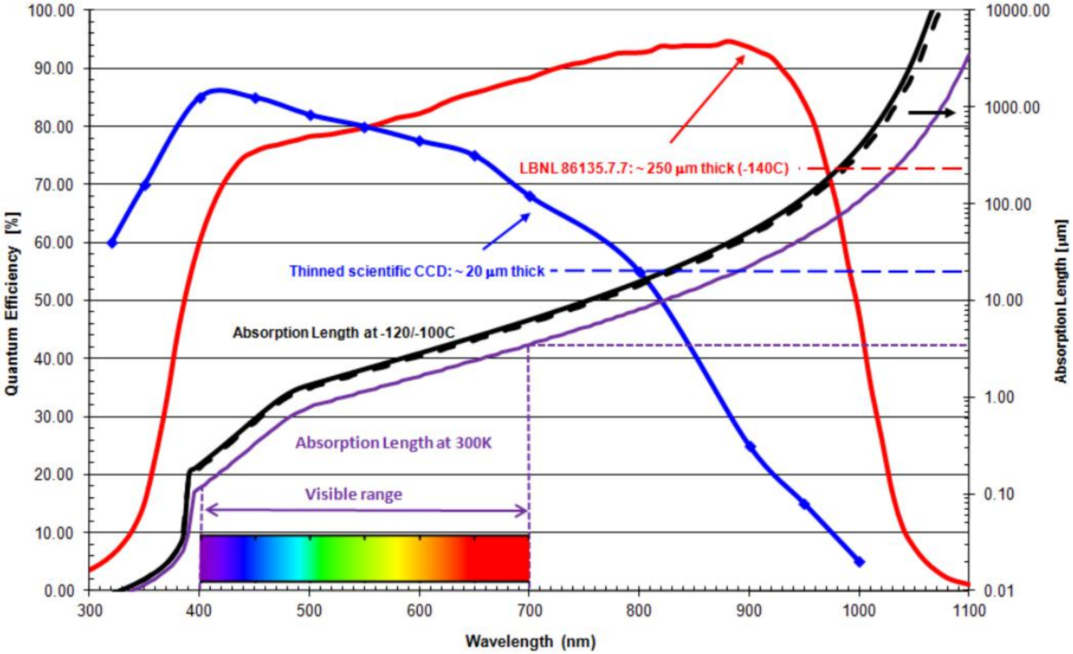
Skipper-CCDs: readout noise



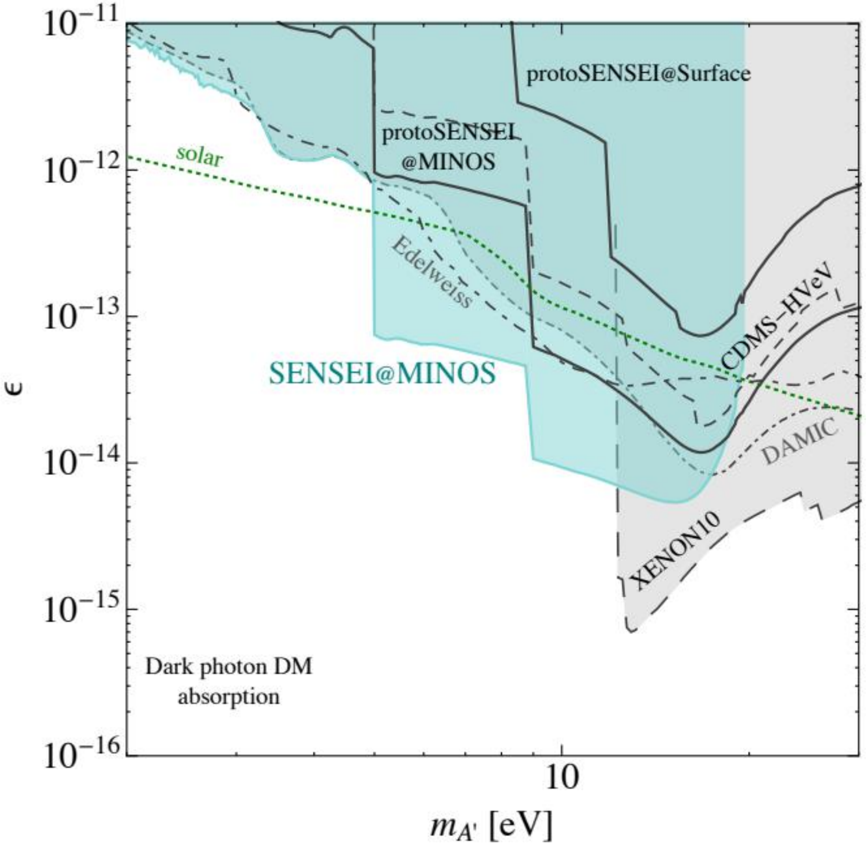
Skipper-CCDs: Quantum efficiency

[10.1103/PhysRevLett.125.171802]





SENSEI: Sensitivity to DM absorption on electrons [10.1103/PhysRevLett.125.171802]



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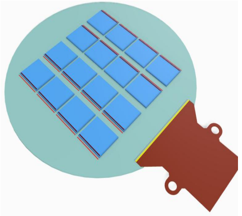
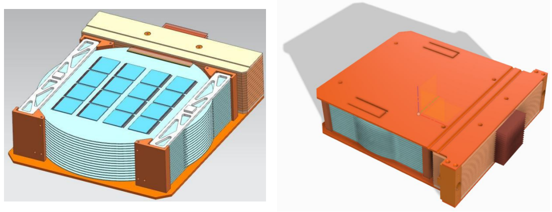
Oscura: First multi-kg (10-kg) skipper-CCD detector

[arXiv:2202.10518]

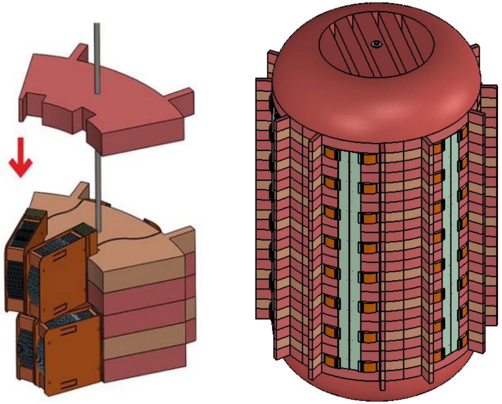
Multi-Chip Module (16 skipper-CCDs)



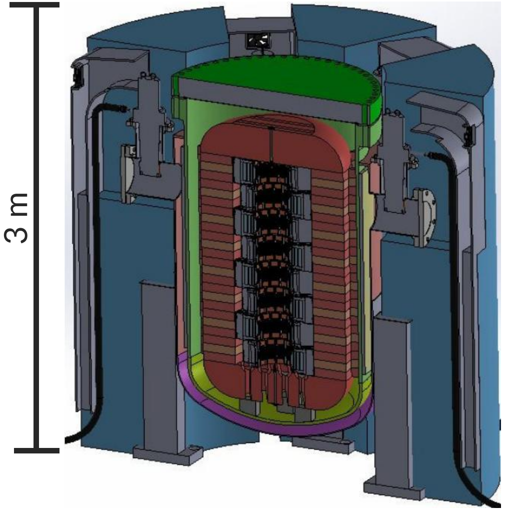
Super Module (16 MCMs)



Detector payload in 6 columnar slices
(96 Super Modules)



LN_2 pressure vessel (450 psi) @ SNOLAB



DM New Initiatives

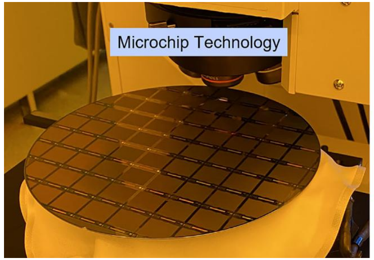
Oscura conducted a major R&D:

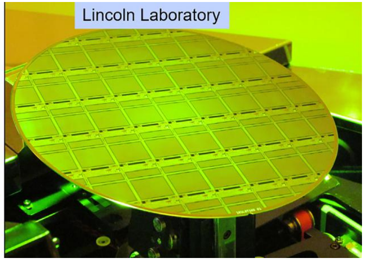
- Mass production of science-grade skipper-CCDs
- New sensors packaging and cryogenics for multi-kg detectors
- Cold front-end electronics for thousands of readout channels
- Low radiation background design

Oscura: Sensors and MCMs fabrication

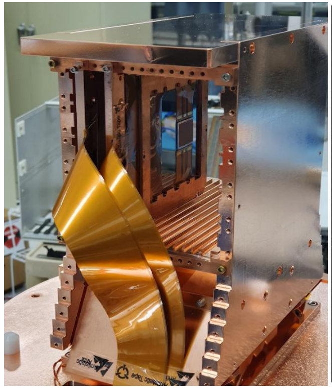
Success!

Fabrication of sensors at two NEW foundries: Microchip Technology Inc. and MIT Lincoln Lab





[10.1002/asna.20230072] [NIMA 1046 (2023), 167681]



Skipper-CCD mounted in cryostat

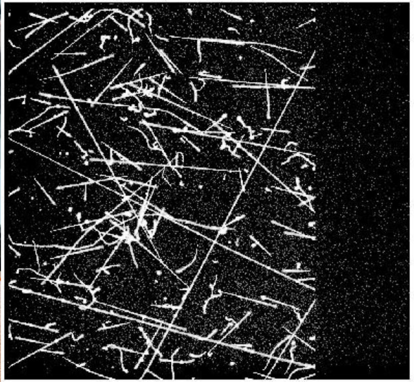
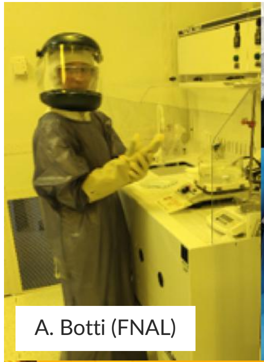
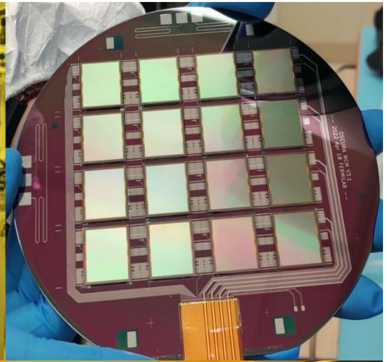


Image from prototype CCD

My work → [arXiv:2304.04401]

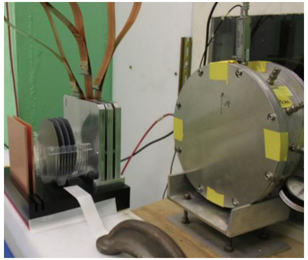
Fabrication of silicon MCMs at Argonne National Lab in collaboration with FNAL



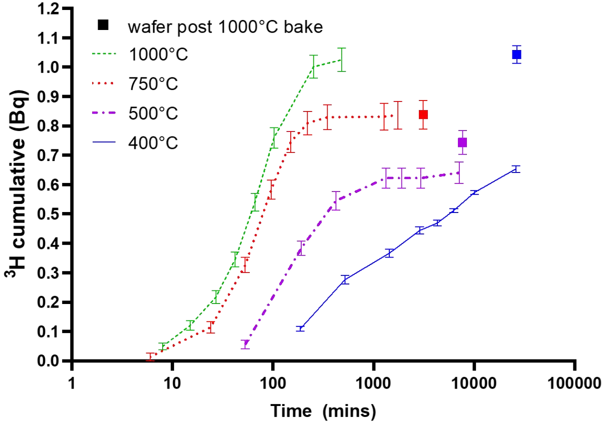


Oscura: Radiation background control

Goal: 0.01 dru → Pathfinder experiments paving the way
Decisions driven by simulations



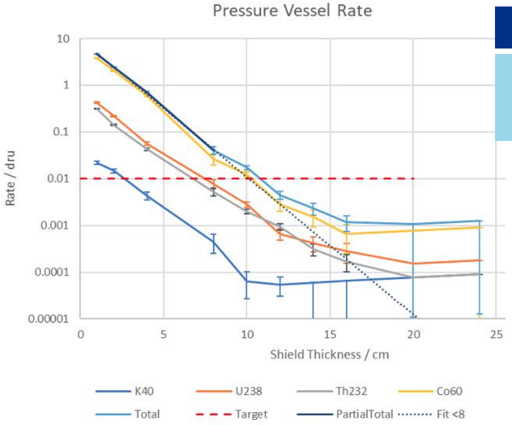
[PRD 102, 102006]



Sources:

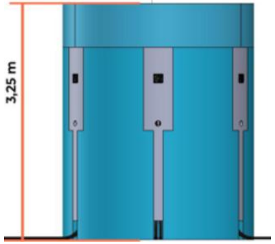
- Cosmogenic activation of Si and Cu
  - ^{3}H in Si: Main bkgd (2 mdru/day at sea level)
    → <5 days on surface
    Can be baked out during fab! ("total" removal at 1000°C)

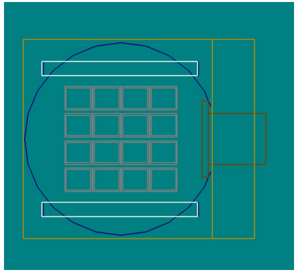
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [arXiv:2303.10862]
  - Simulations of ^{238}U, ^{232}Th and ^{40}K
  - → 4cm of cable visible to CCDs (with 15 ppt)
  - → Electronics behind inner shield (width>10cm)



DAMIC-M cable	^{238}U [ppt]	^{232}Th [ppt]
Commercial	2670 +/- 30	270 +/- 60
Customed	**31 +/- 1**	**11 +/- 1**

- External backgrounds
  - Outer shield: polyethylene
  - Inner shield: ancient lead and electroformed copper

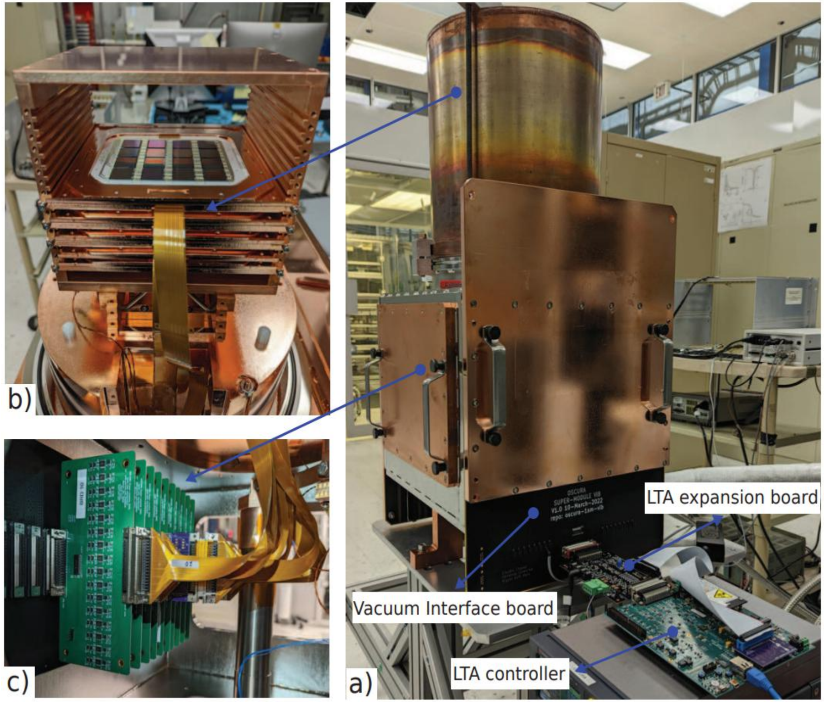


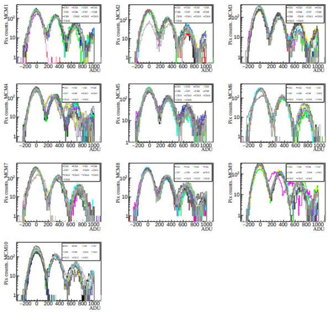


Oscura: Massive testing setup with 160 skipper-CCDs

[JINST 18 P01040]

Copy of SENSEI-100 vessel with 10 prototype ceramic MCMs and the discrete readout electronics
Largest ever built instrument with skipper-CCDs controlled by 1 LTA → Demonstrates electronics solution

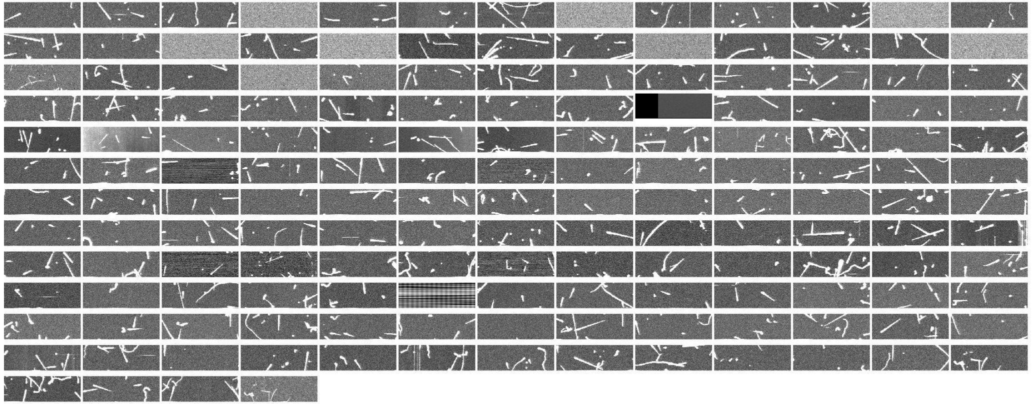




~90% of the sensors working without a preselection! This is a BIG deal!*

*LSST, the largest "astronomical camera" has 189 CCDs!

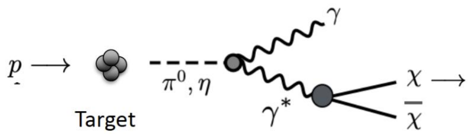
Setup is being used to develop analysis software and could be used for early science



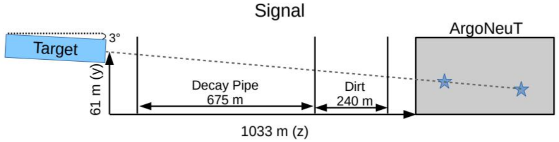
Oscura: Early science (DM production)

[arXiv:2304.08625]

With a 10% mass load (32-layer tracker), **search for millicharged particles** produced at the NuMI beam at FNAL

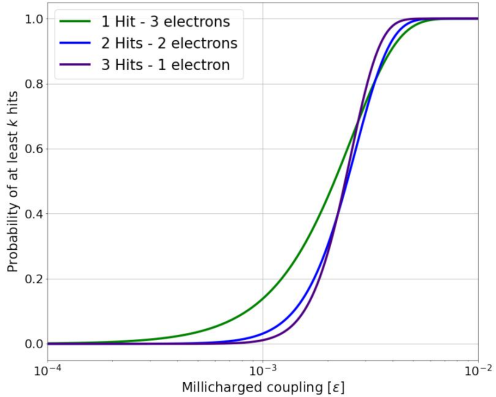


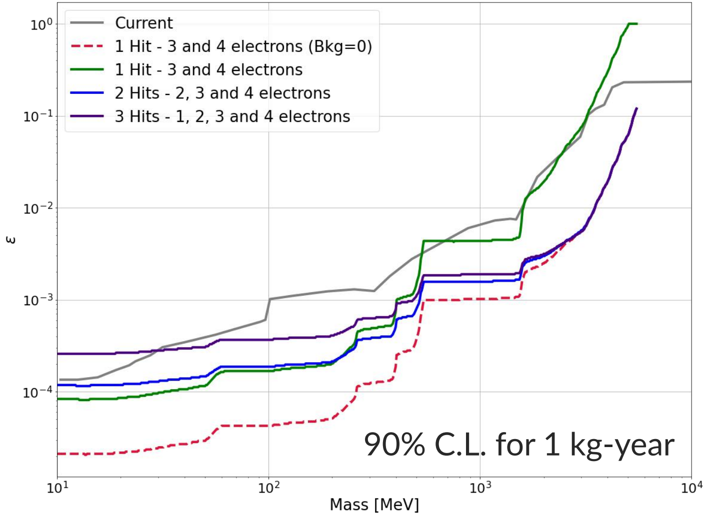
[PRL 124, 131801 (2020)]

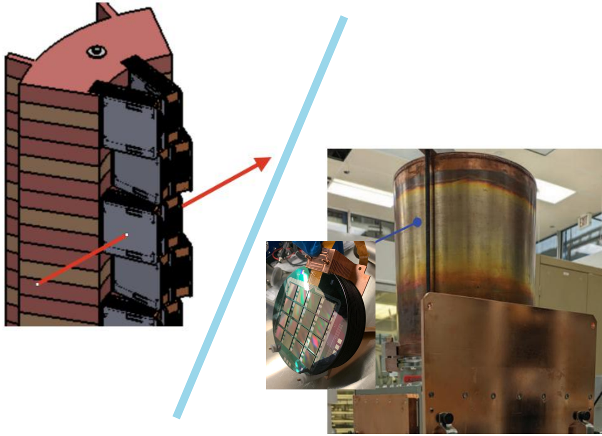


Multiple-hit search could reduce bkgds
Exclusion limits are promising!

mCPs skipper-CCD detector:
- Large-mass setup (tracker?)
- Location @ accelerator facilities







Number of fake tracks per day produced by random coincidences of uncorrelated single pixel hits

Threshold	doublets ($b=2$)	triplets($b=3$)	p_{bkg}
$1e^-$	3822	11.4	3×10^{-4}
$2e^-$	0.031	2.72×10^{-7}	$8.6 \times 10{-}7$
$3e^-$	9.06×10^{-5}	4.17×10^{-11}	4.6×10^{-8}