Position Sensitive Detectors in Astrophysics

Tools for dark energy and dark matter

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PSD13 - Oxford
05 Sep. 2023

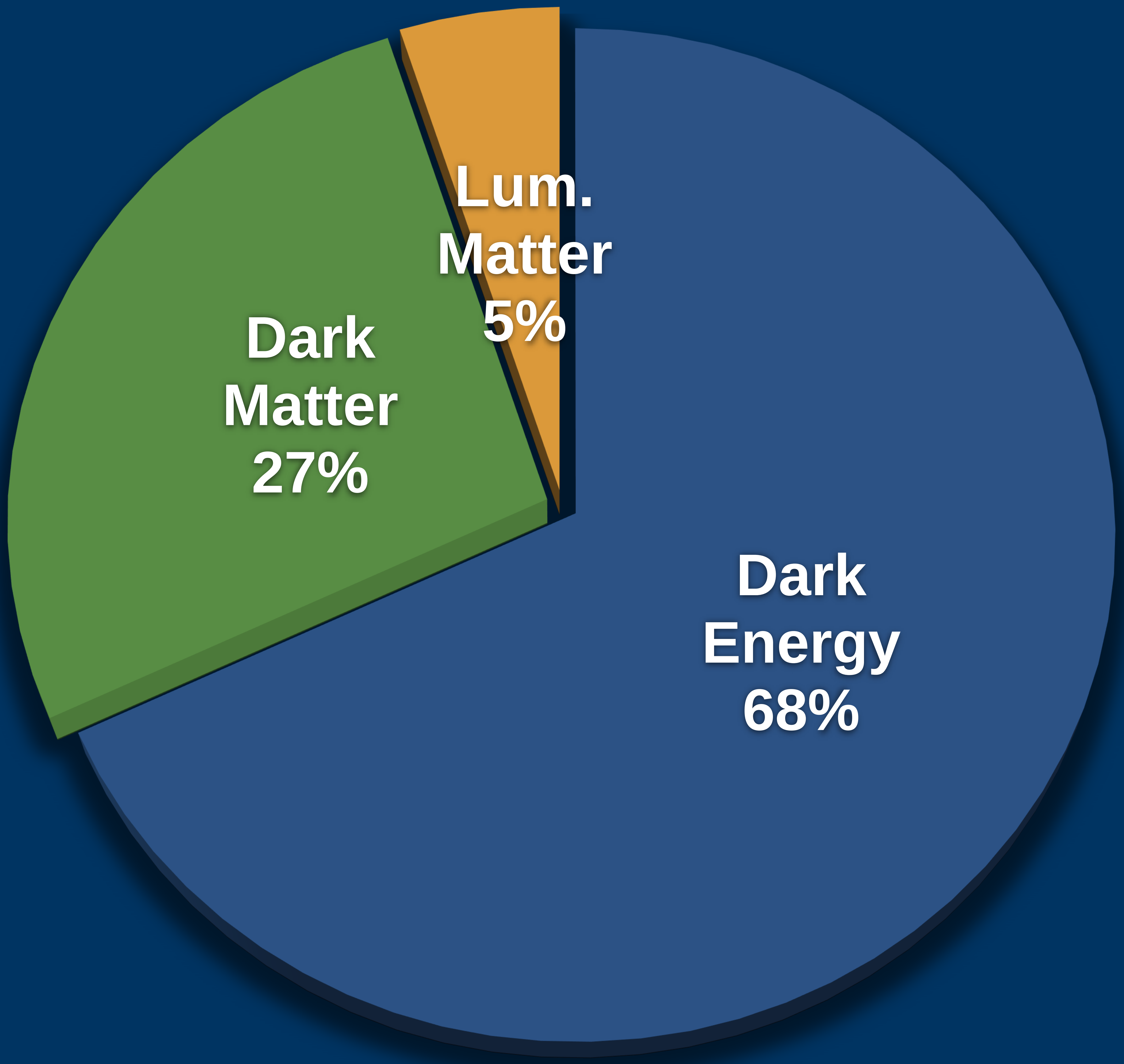
Race towards the development of instruments with more pixels, higher efficiency, faster readout, and lower noise.

Outlook

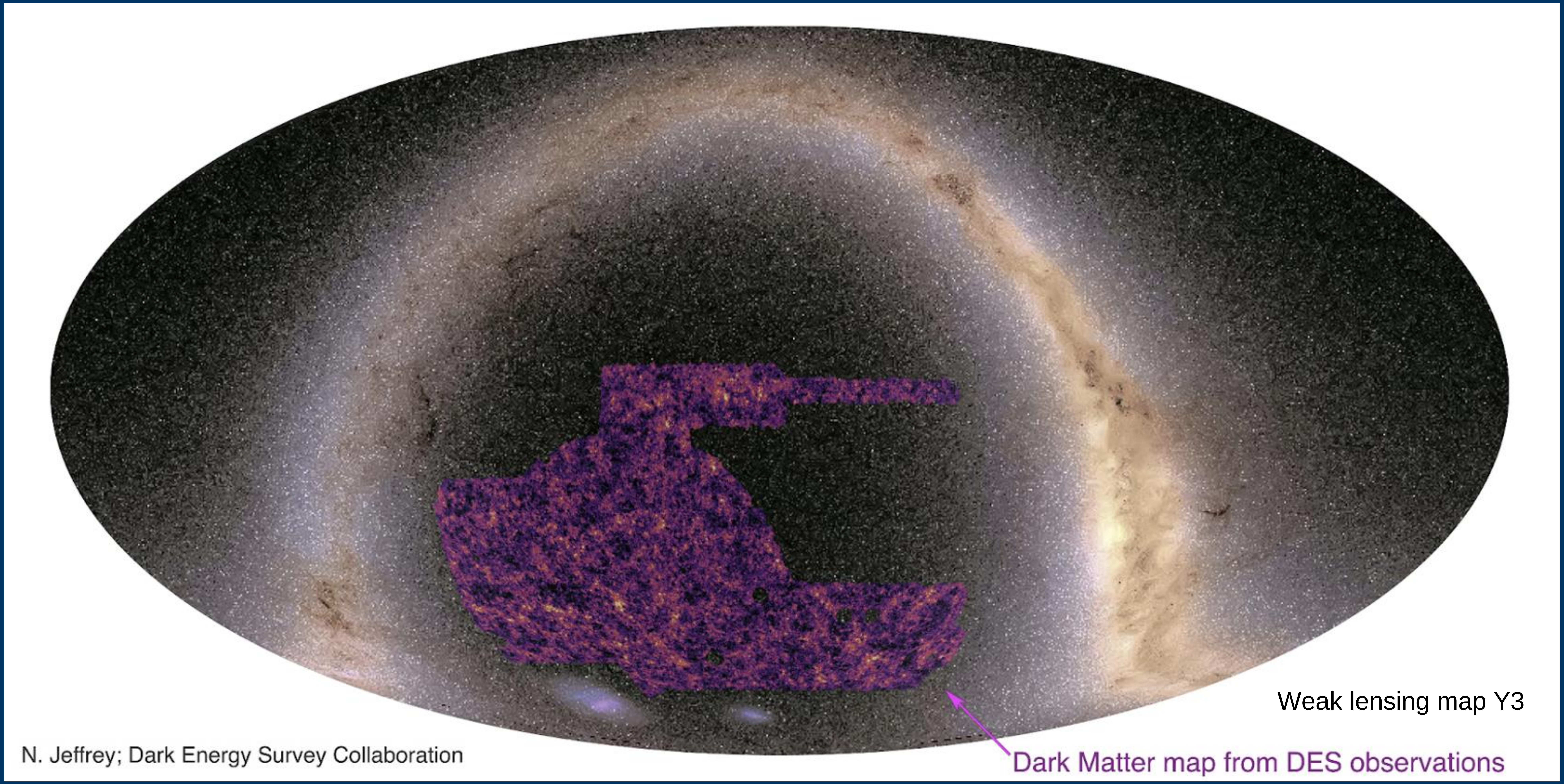
- Sensors in imaging surveys : DES,LSST,…
  - Sensors with good QE in VIS-NIR
- Applications for direct dark matter
- The skipper-CCD (zero noise)
  - SENSEI, DAMIC-M
  - Oscura
- New Technologies/Ideas with low noise.

- **Super exciting, but not included here:**
  - **All the superconducting technologies TES, MKID in CMB instruments.**
  - **Intensity mapping ideas (for cosmology).**

Science Driver

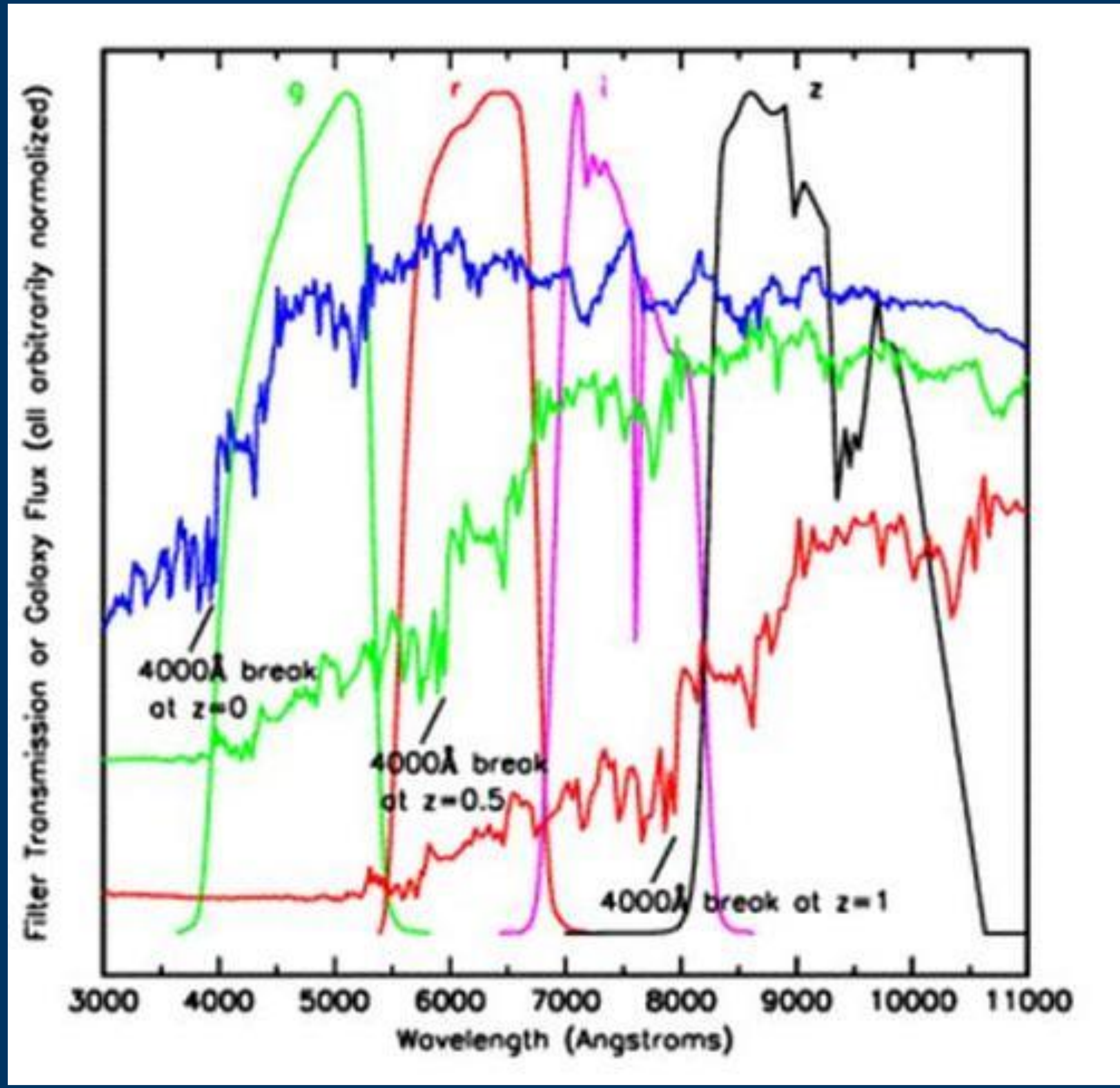


Methods : Cosmic Surveys

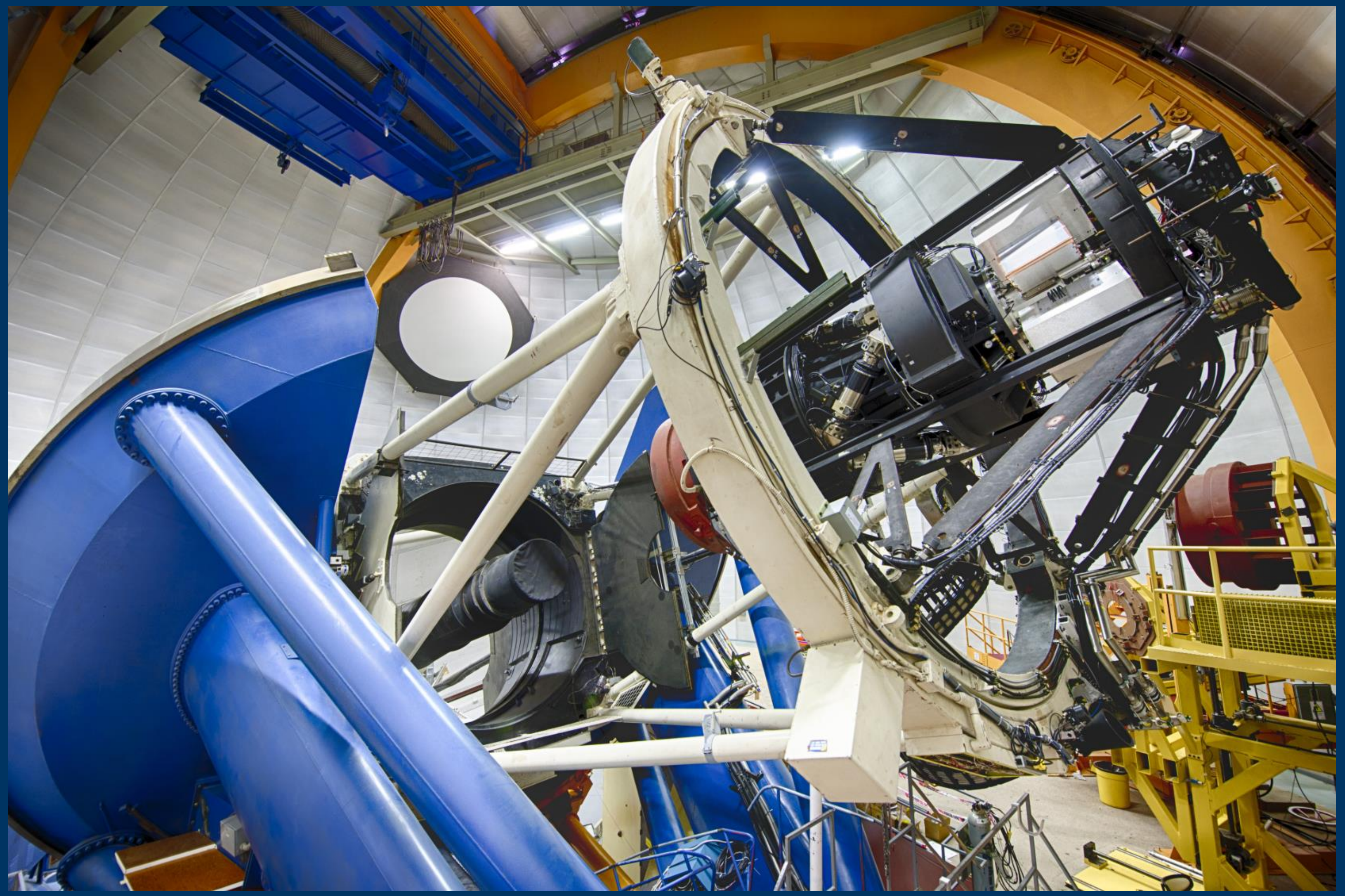


We try to answer these dark energy and dark matter question by performing precise mapping of visible objects (structure and geometry).

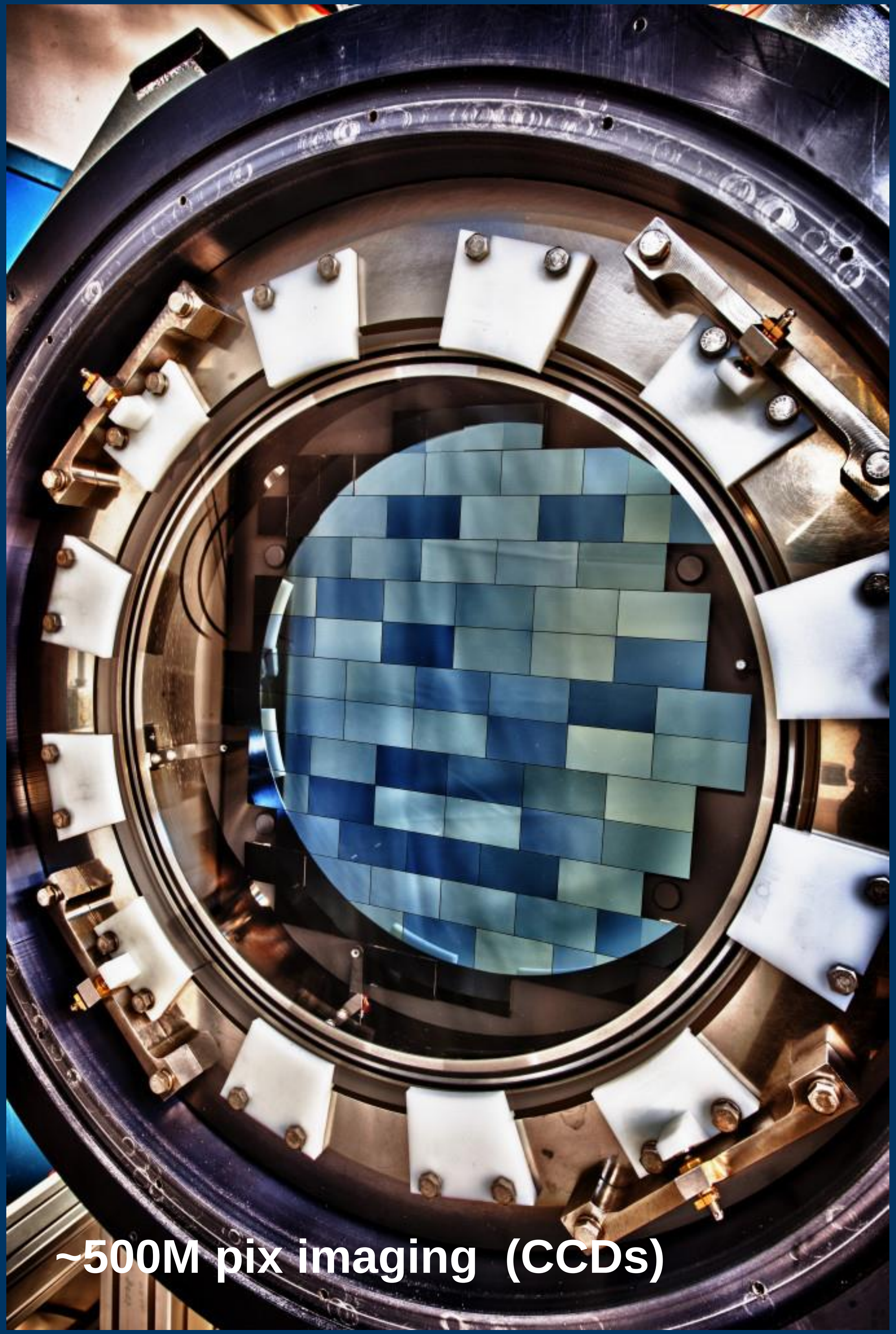
Imaging surveys in ~2010s (Dark Energy Survey)



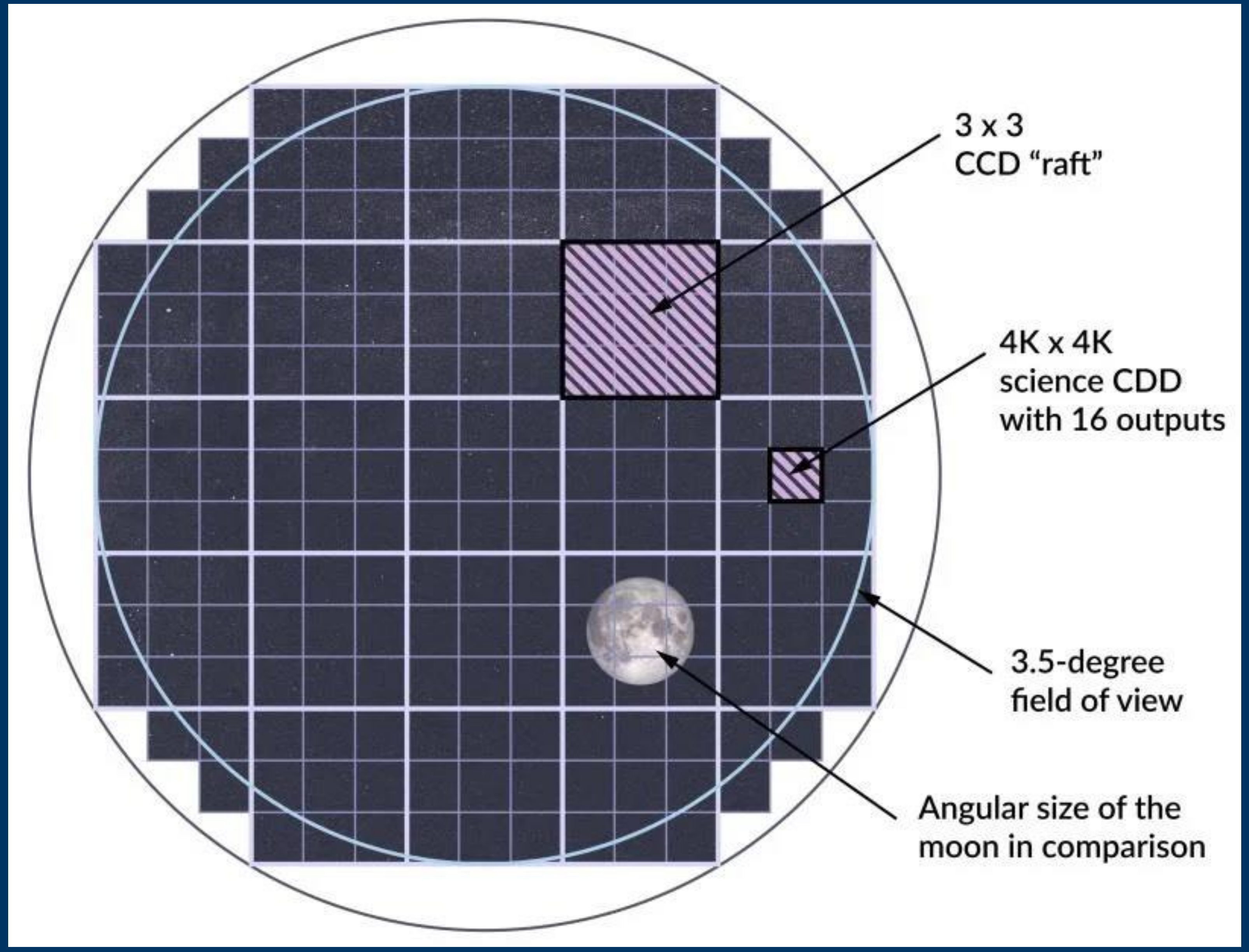
Dark Energy Camera

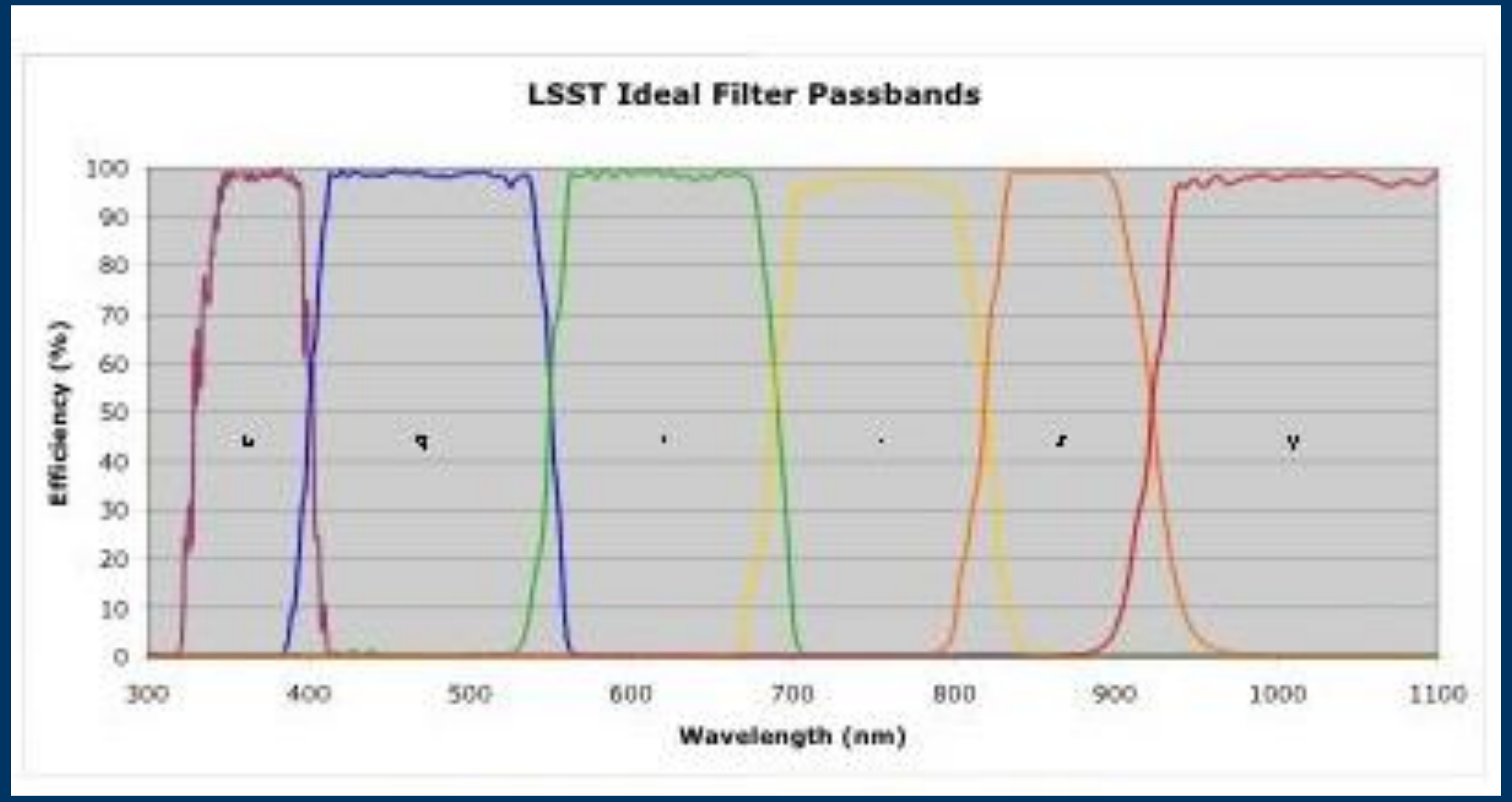


- DES surveyed a 5000 square degree area of the southern sky (roughly 1/8 of the total sky) over 525 nights.
- recorded over 300 million galaxies, most so faint that their light is around 1 million times fainter than the dimmest star that can be seen with the naked eye.
- DES also discovered and measured the brightness of thousands of supernovae by repeatedly targeting ten regions of the sky every six nights.



Imaging surveys in ~2020s (LSST)





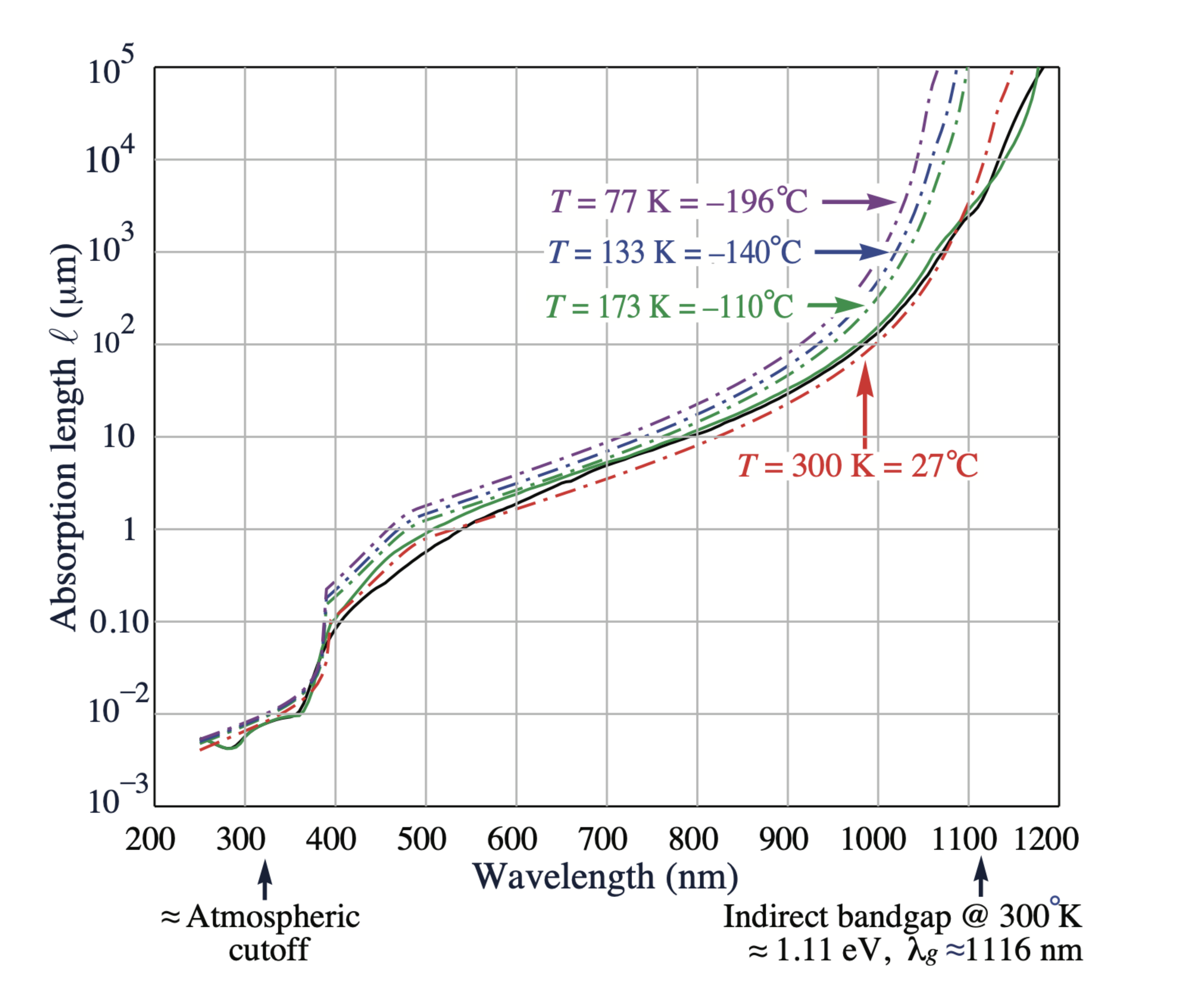
- 15-second exposure every 20 seconds
- 37 billions stars and galaxies
- **Larger camera ever constructed!**
- Moving to Chile soon.

~3,200M pix imaging (CCDs)

See also EUCLID discussion from yesterday…

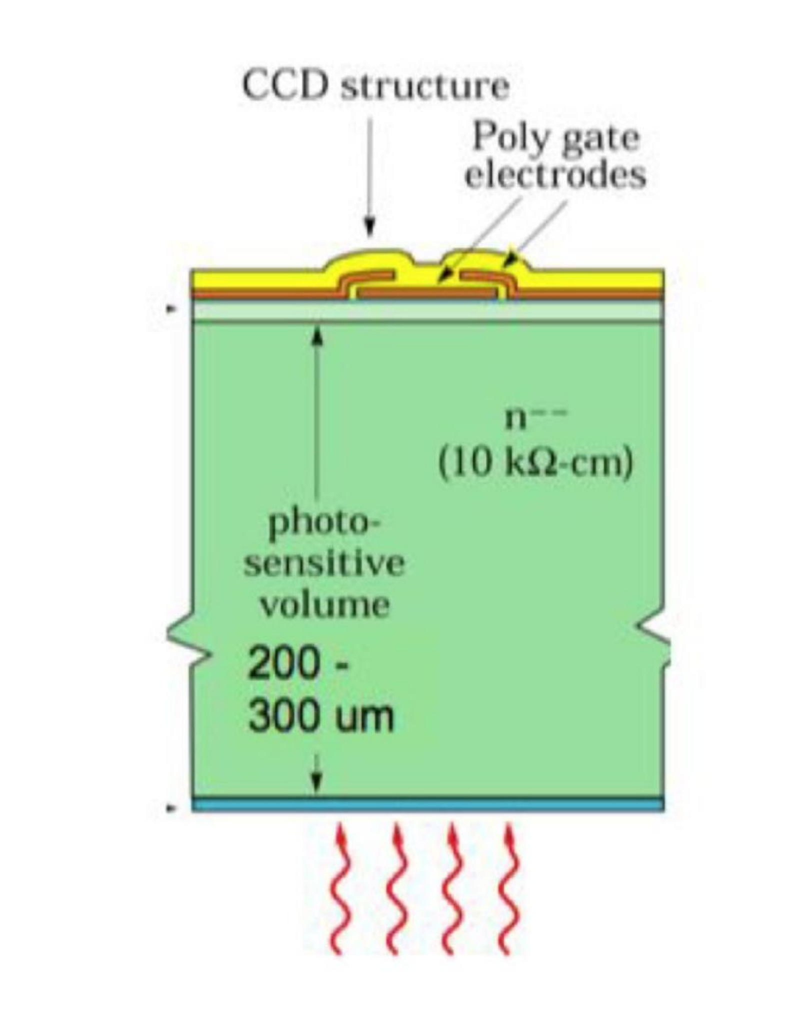
1um detection with silicon, means thick detectors.

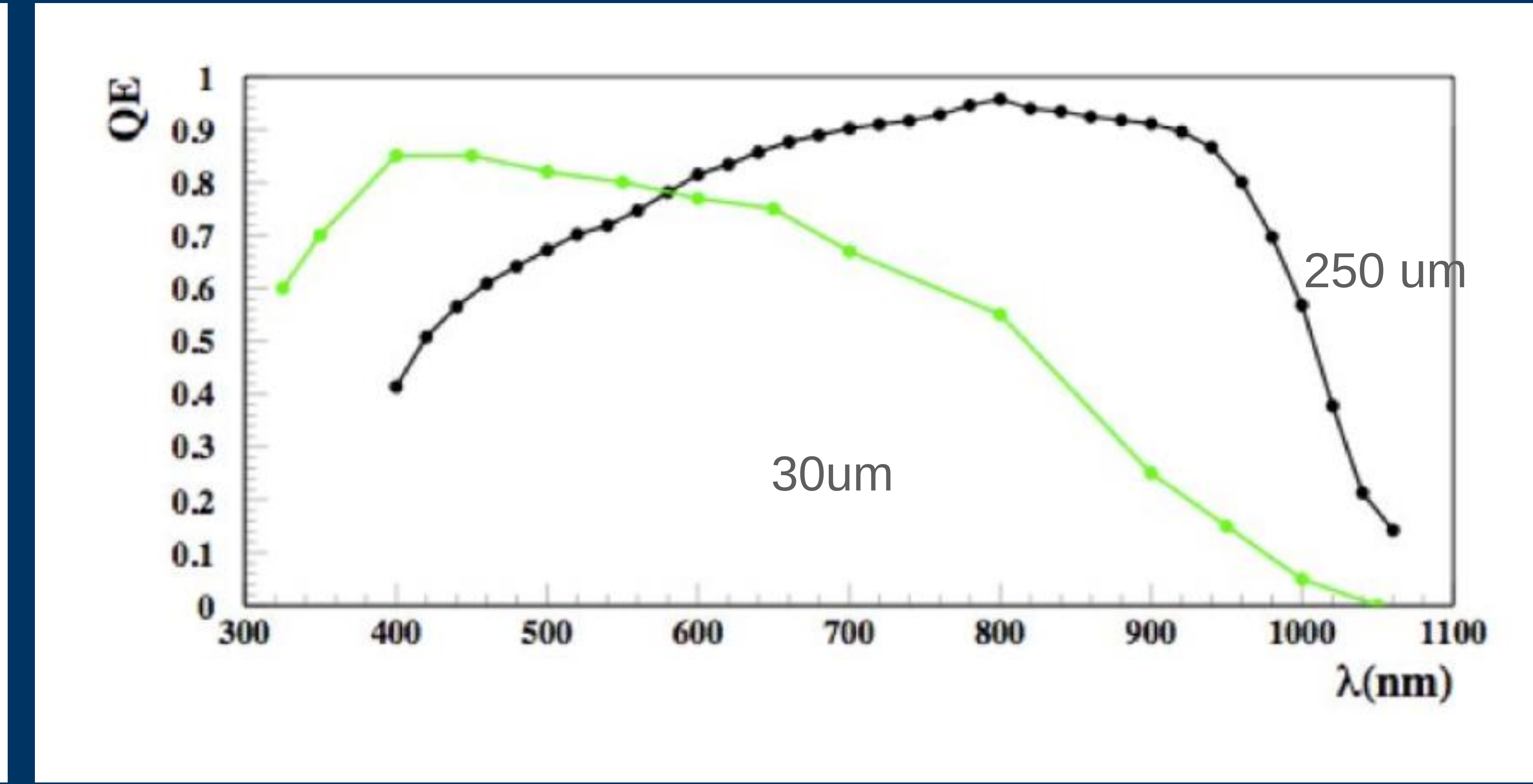
Key enabling technology



Journal of Applied Physics 122, 055301 (2017)

Holland, S., Groom, D., Palaio, N., Stover, R., & Wei, M. (2003), *IEEE Transactions on Electron Devices*, *50*(1), 225-238.





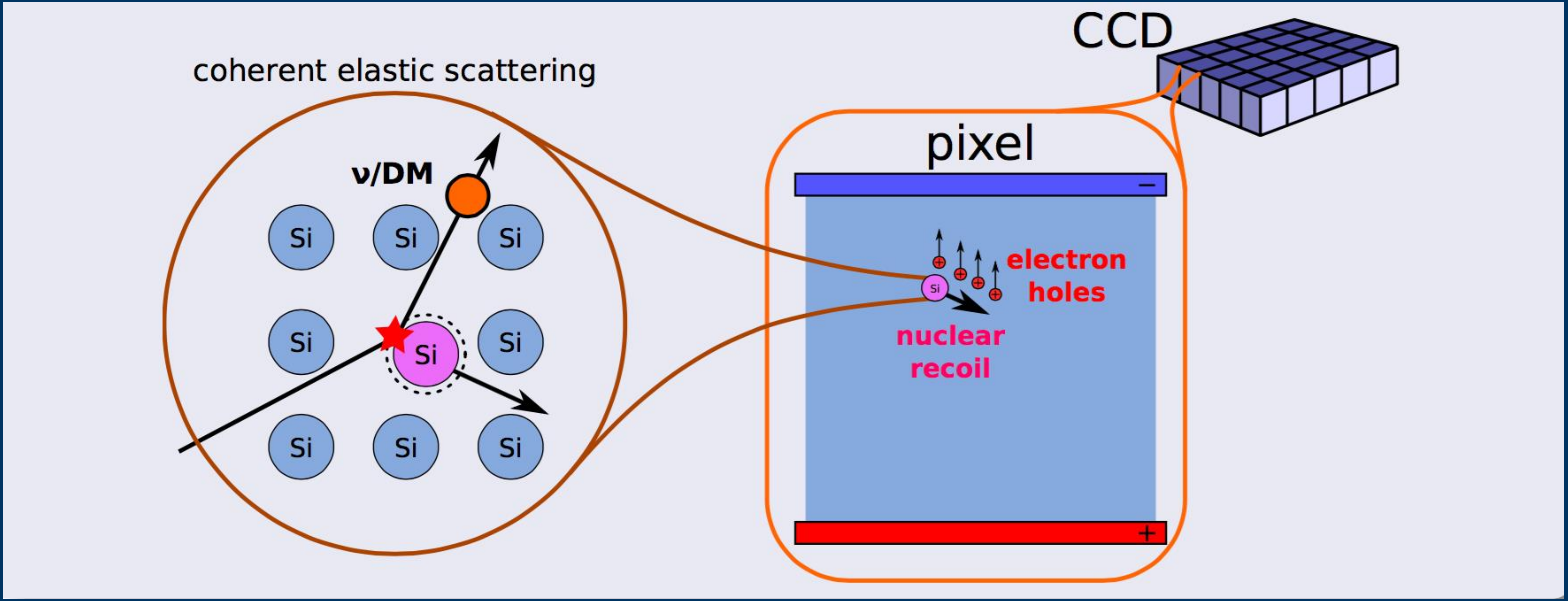
DECam used 250 um thick sensors (designed by S. Holland LBNL)
LSST uses 100 um (ITL + E2V)

Also extensive effort to improve optical entrance window, for the blue QE.

…new thicker sensors present new opportunities.

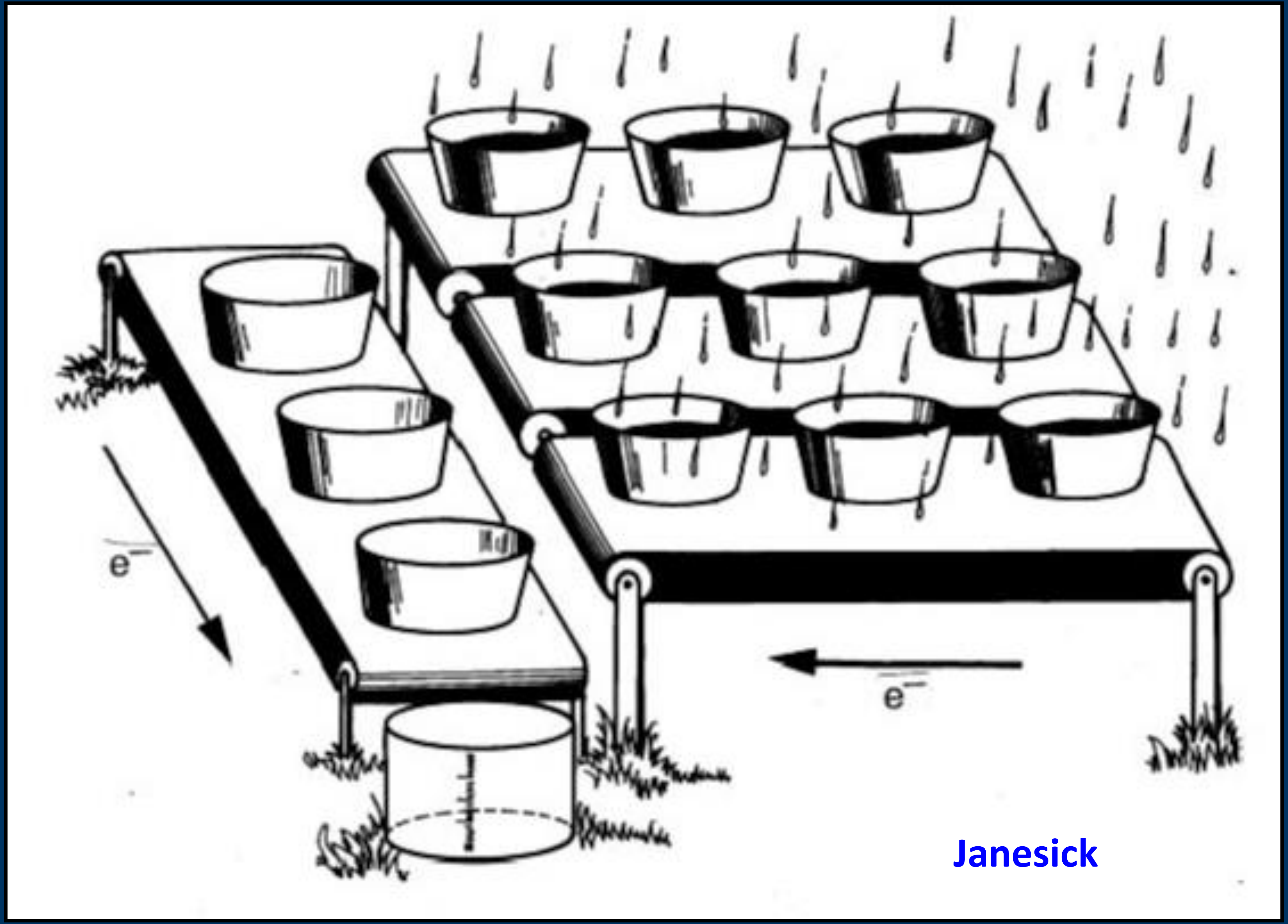
The dark matter problem

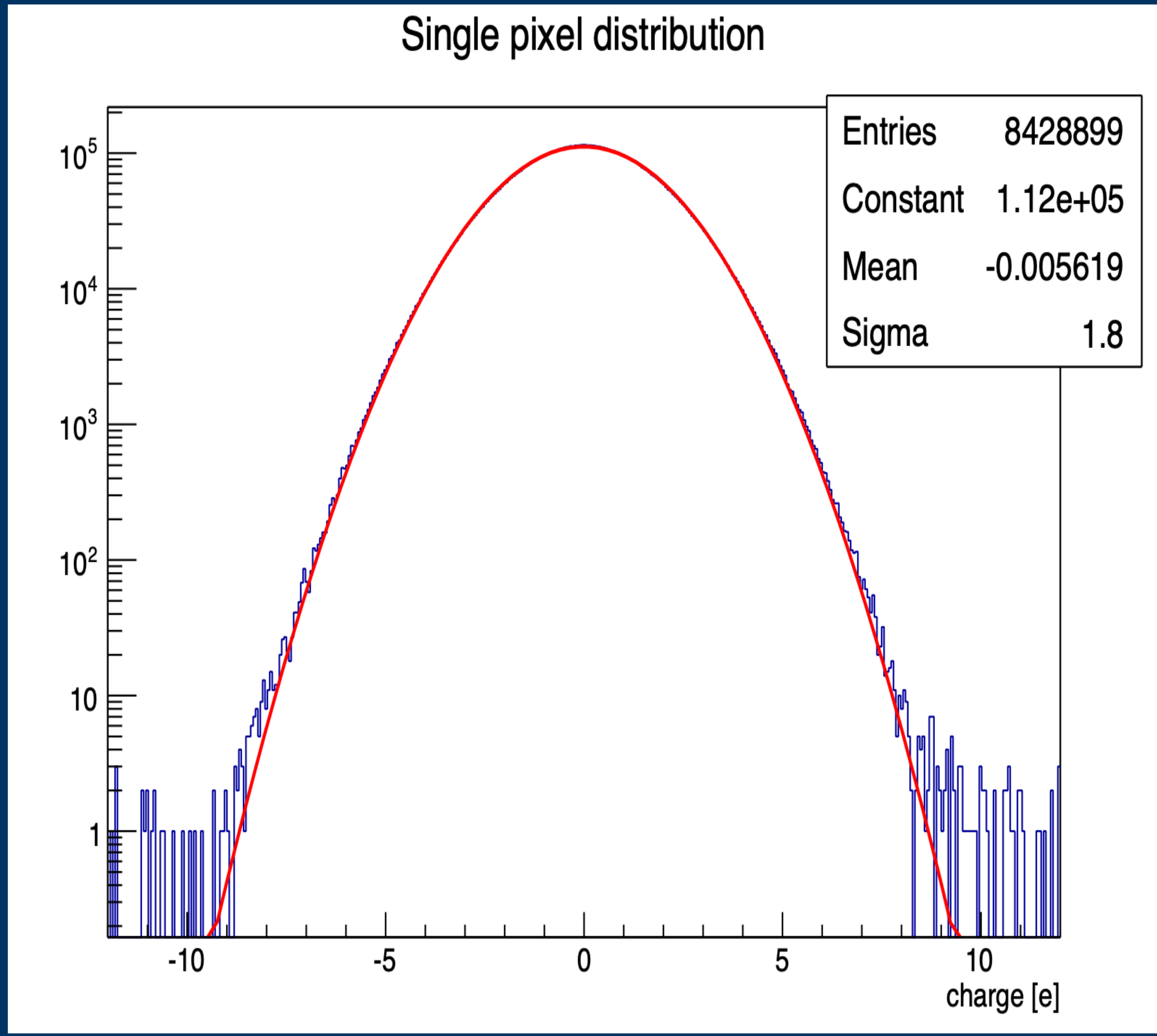
The dark matter problem with CCDs



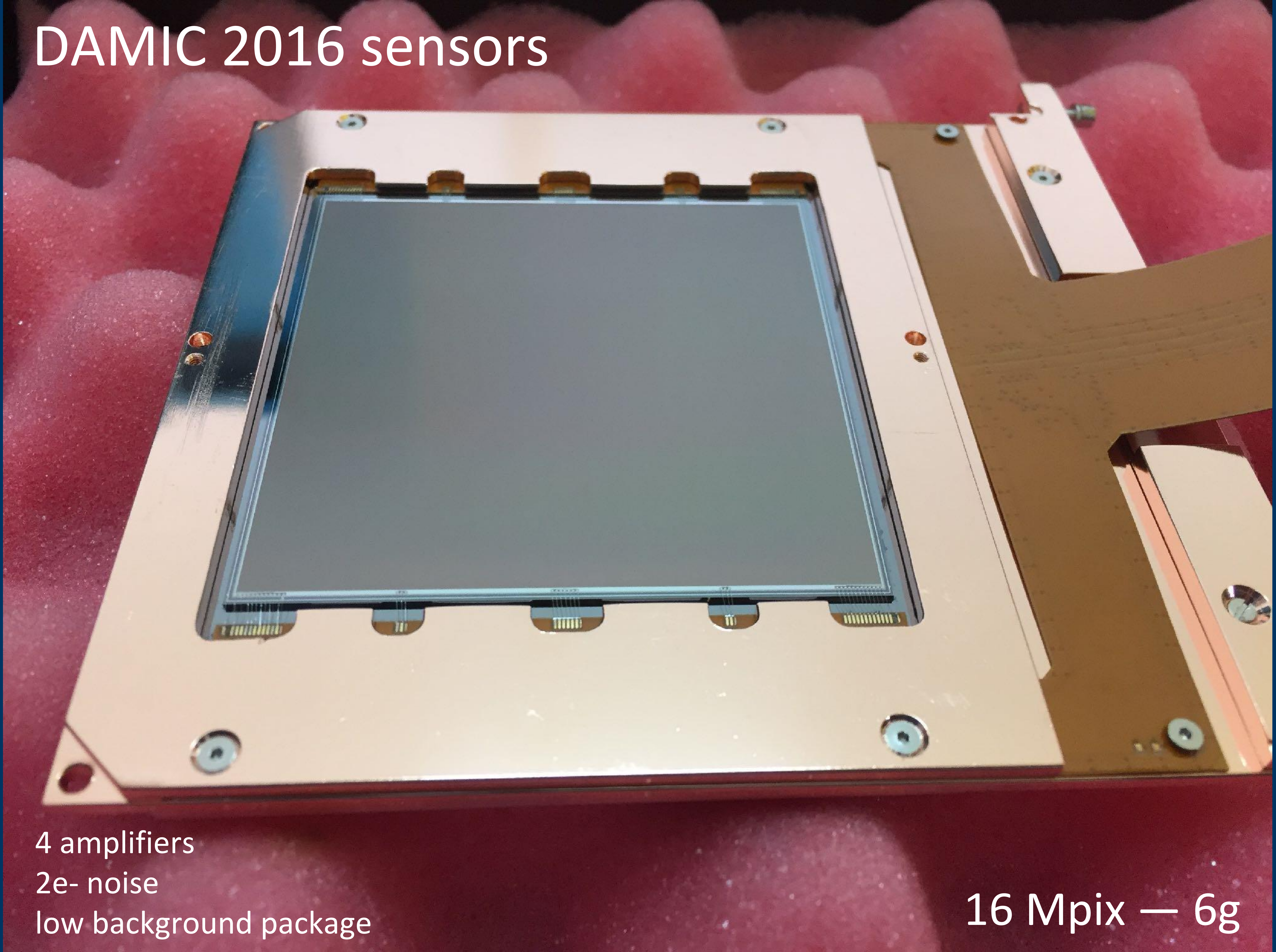
“Massive” sensors with low noise are good tool for a direct dark matter search…

Charge-Coupled Device (CCD)



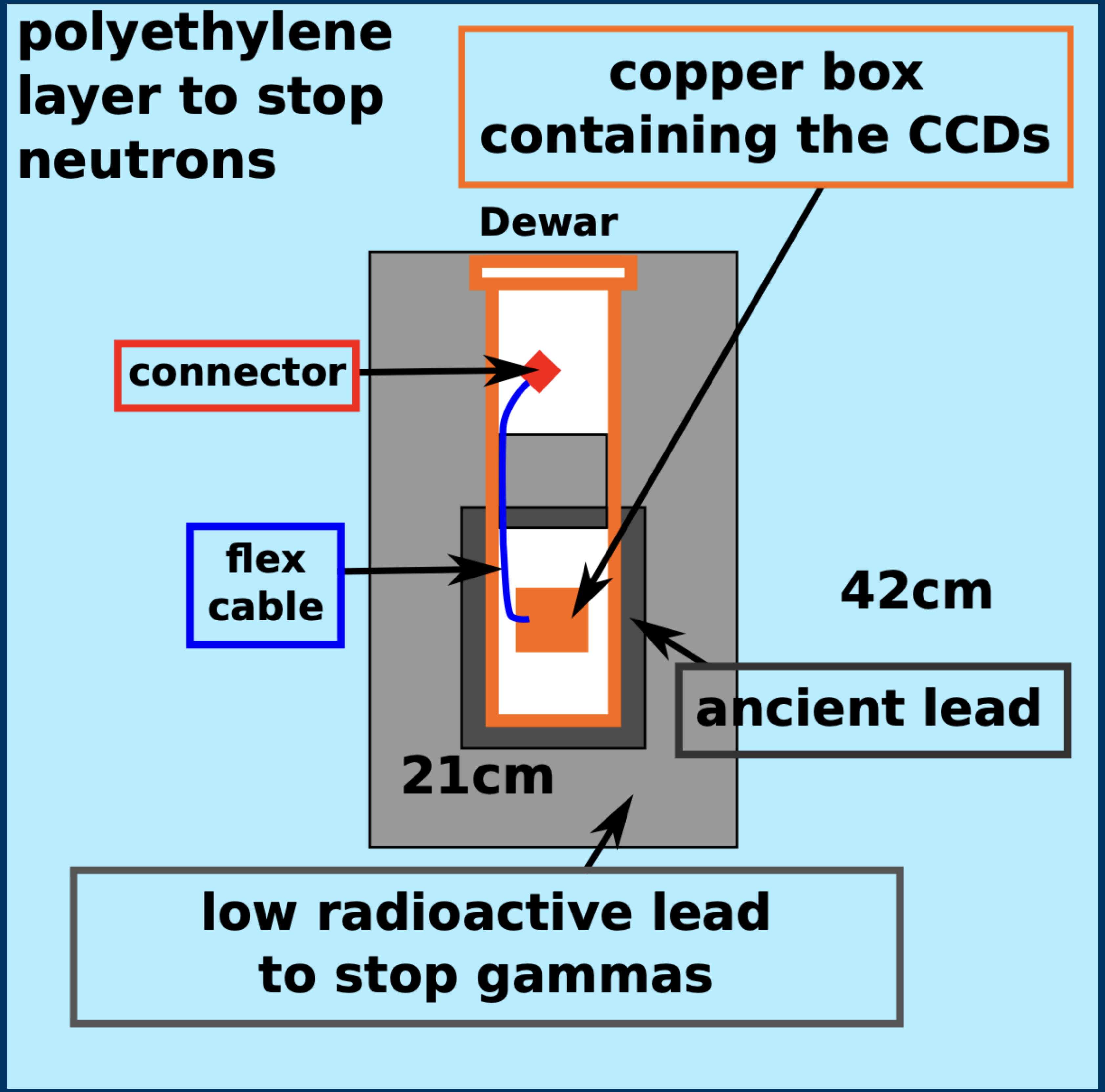


Charge coupling makes the detectors ideal for low noise measurements, typical noise for scientific CCDs is 2e- RMS (7.2eV).


DAMIC 2016 sensors
4 amplifiers
2e- noise
low background package
16 Mpix — 6g

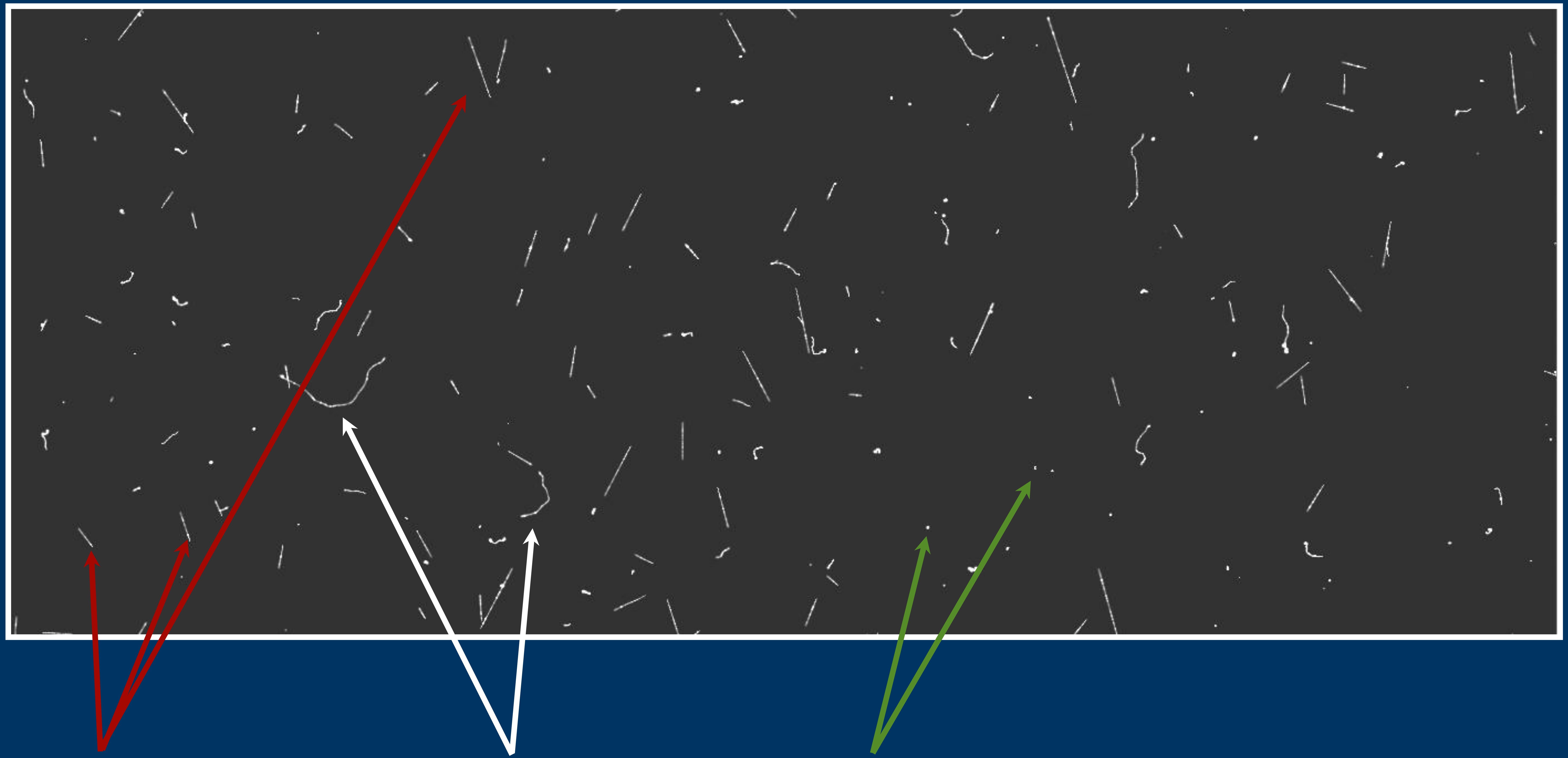
Go Deep : 2000 mts underground

And shield

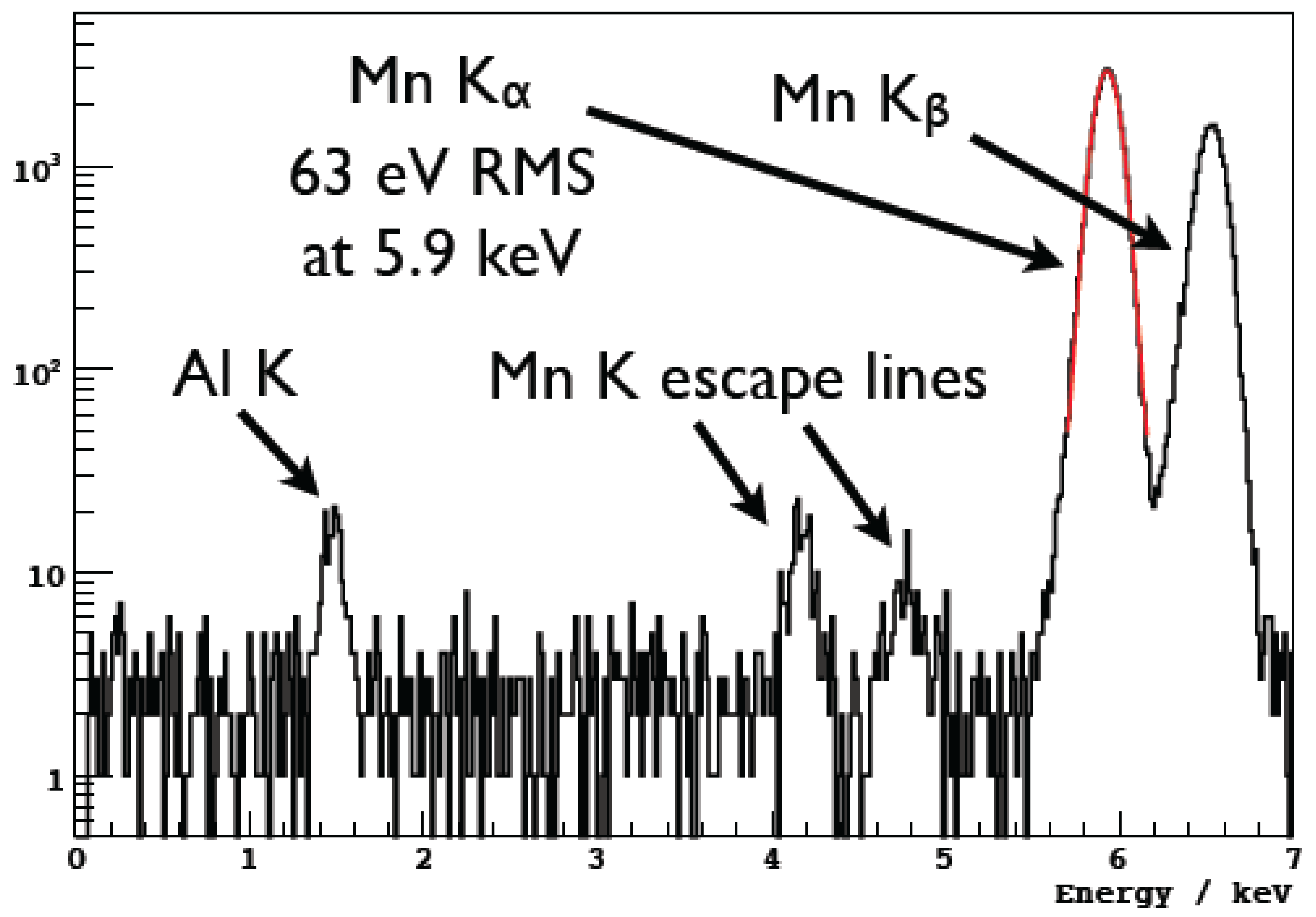


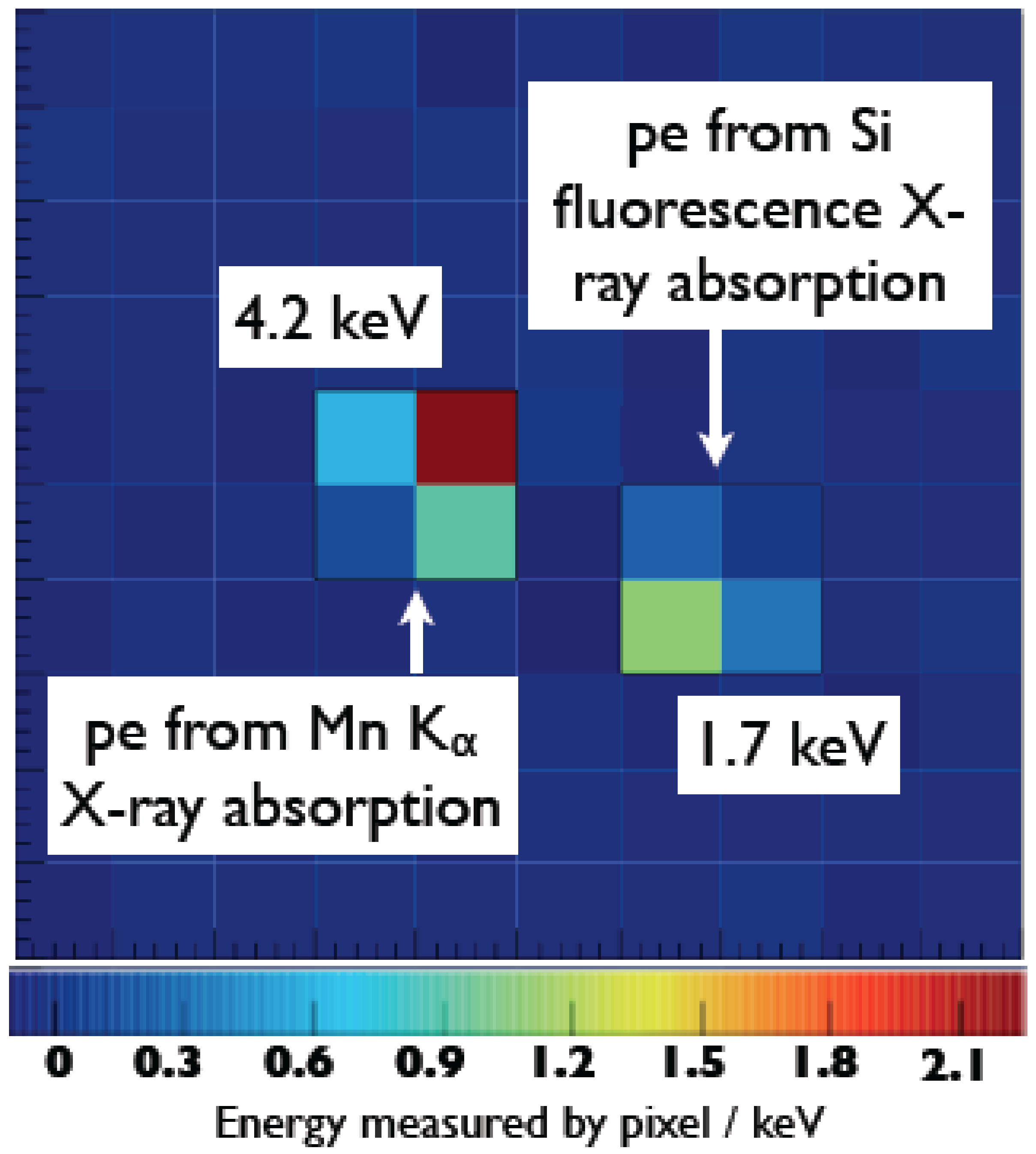
Sensors at ~140K

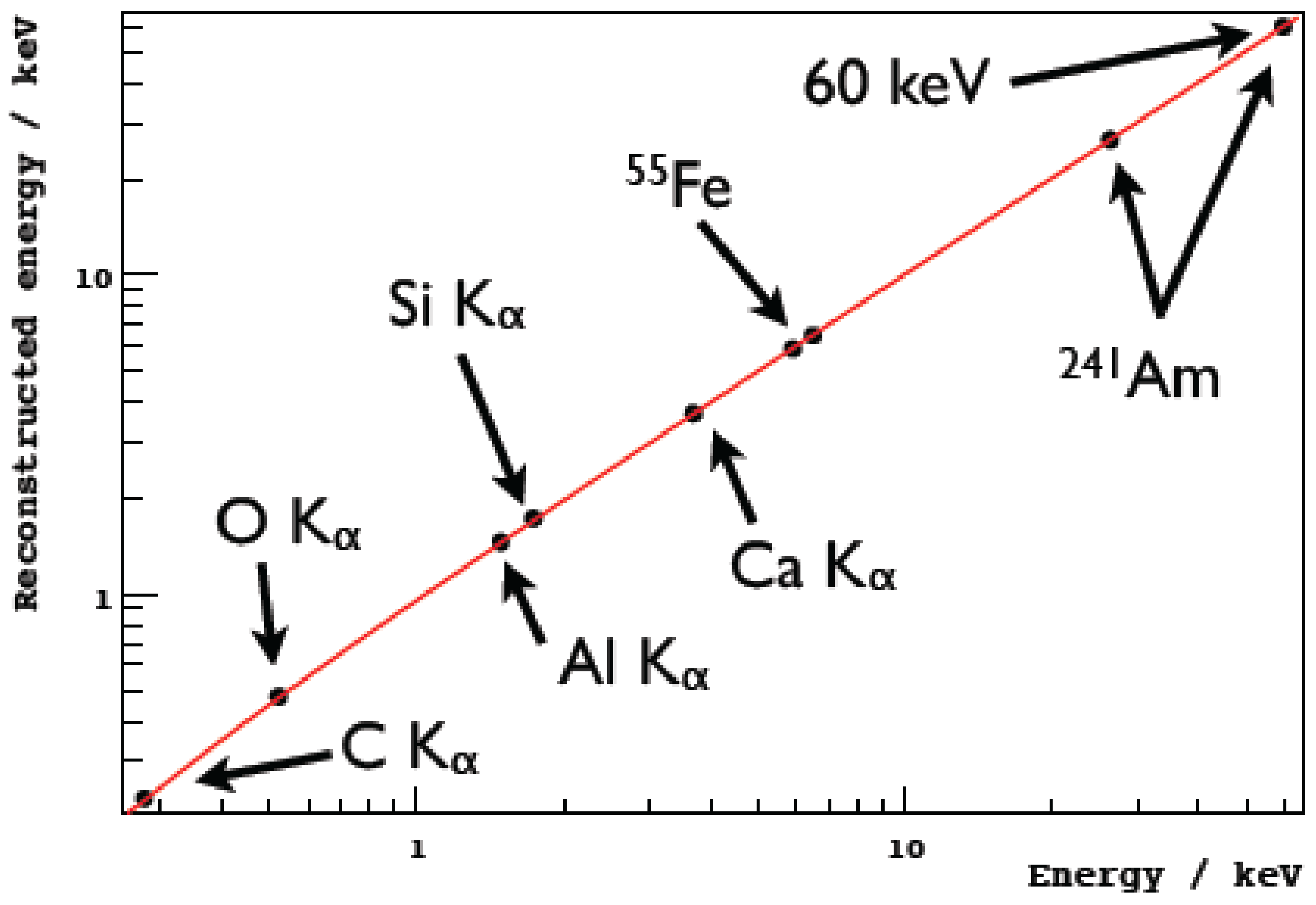
Particle identification in a CCD image

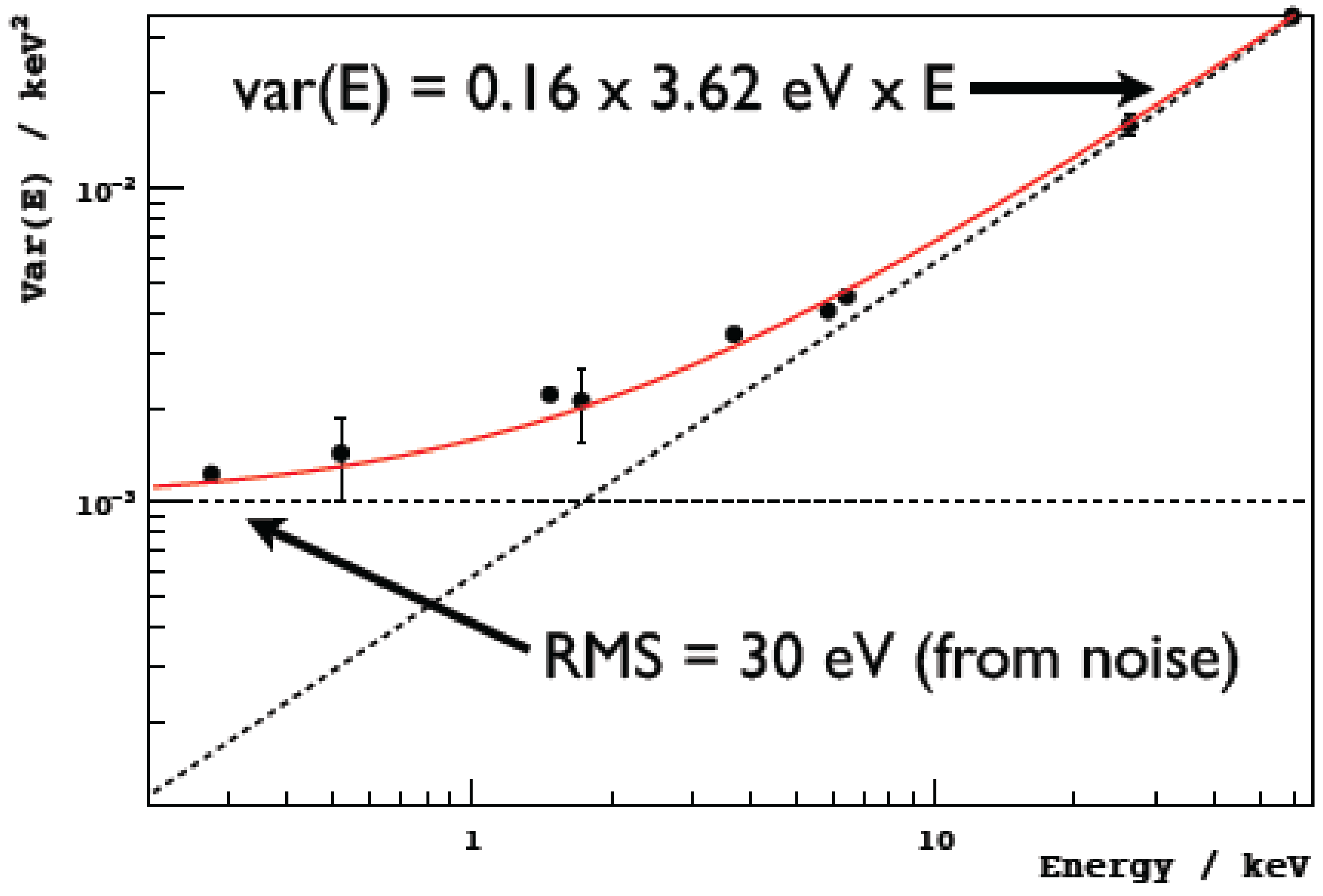


muons, electrons and diffusion limited hits.

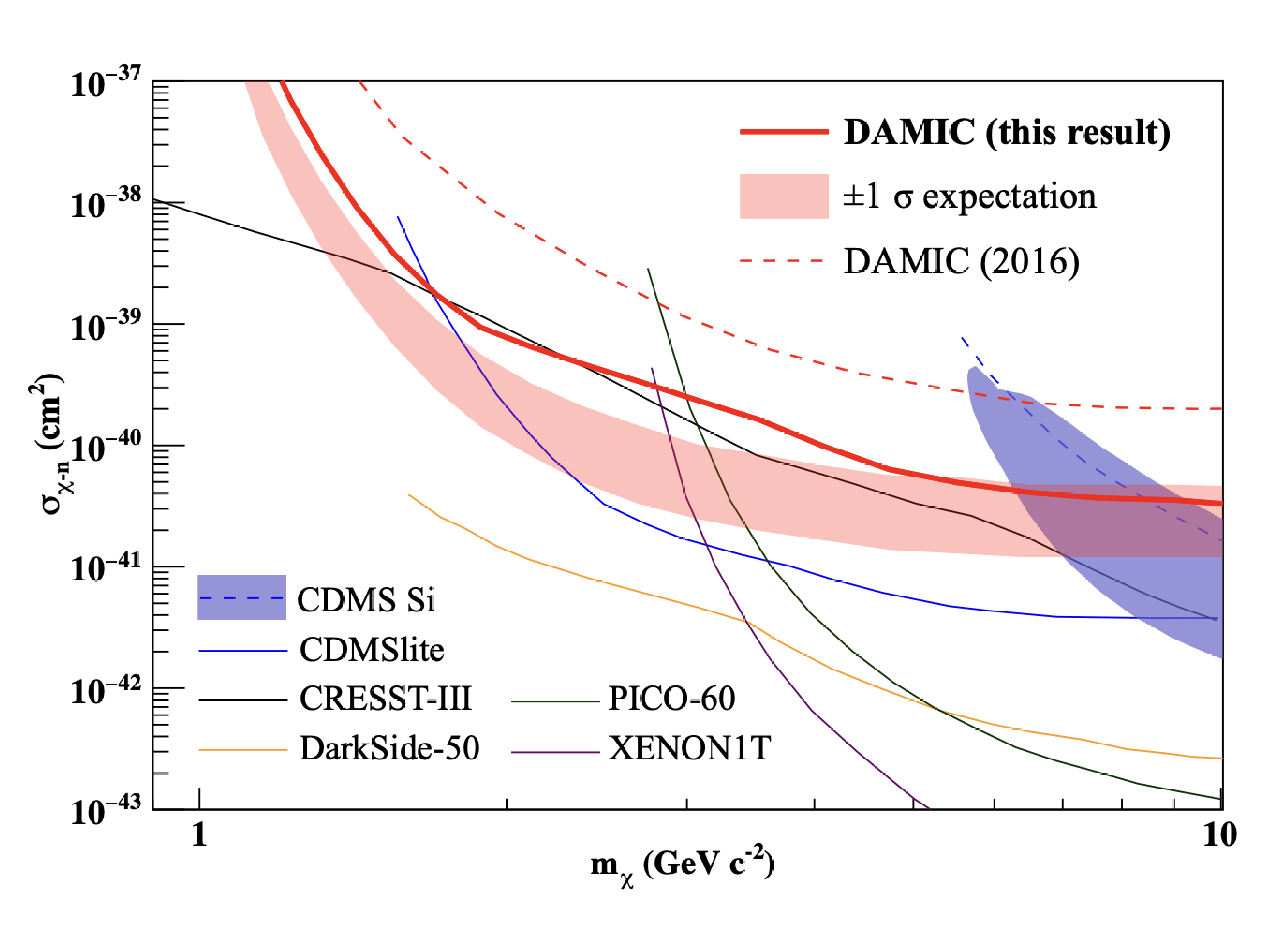

Mn Kα
63 eV RMS
at 5.9 keV
Mn Kβ
Al K
Mn K escape lines
Energy / keV


pe from Si
fluorescence X-
ray absorption
4.2 keV
pe from Mn Kα
X-ray absorption
1.7 keV
0 0.3 0.6 0.9 1.2 1.5 1.8 2.1
Energy measured by pixel / keV


60 keV
55Fe
241Am
Si Kα
O Kα
Ca Kα
Al Kα
C Kα
Reconstructed energy / keV
Energy / keV

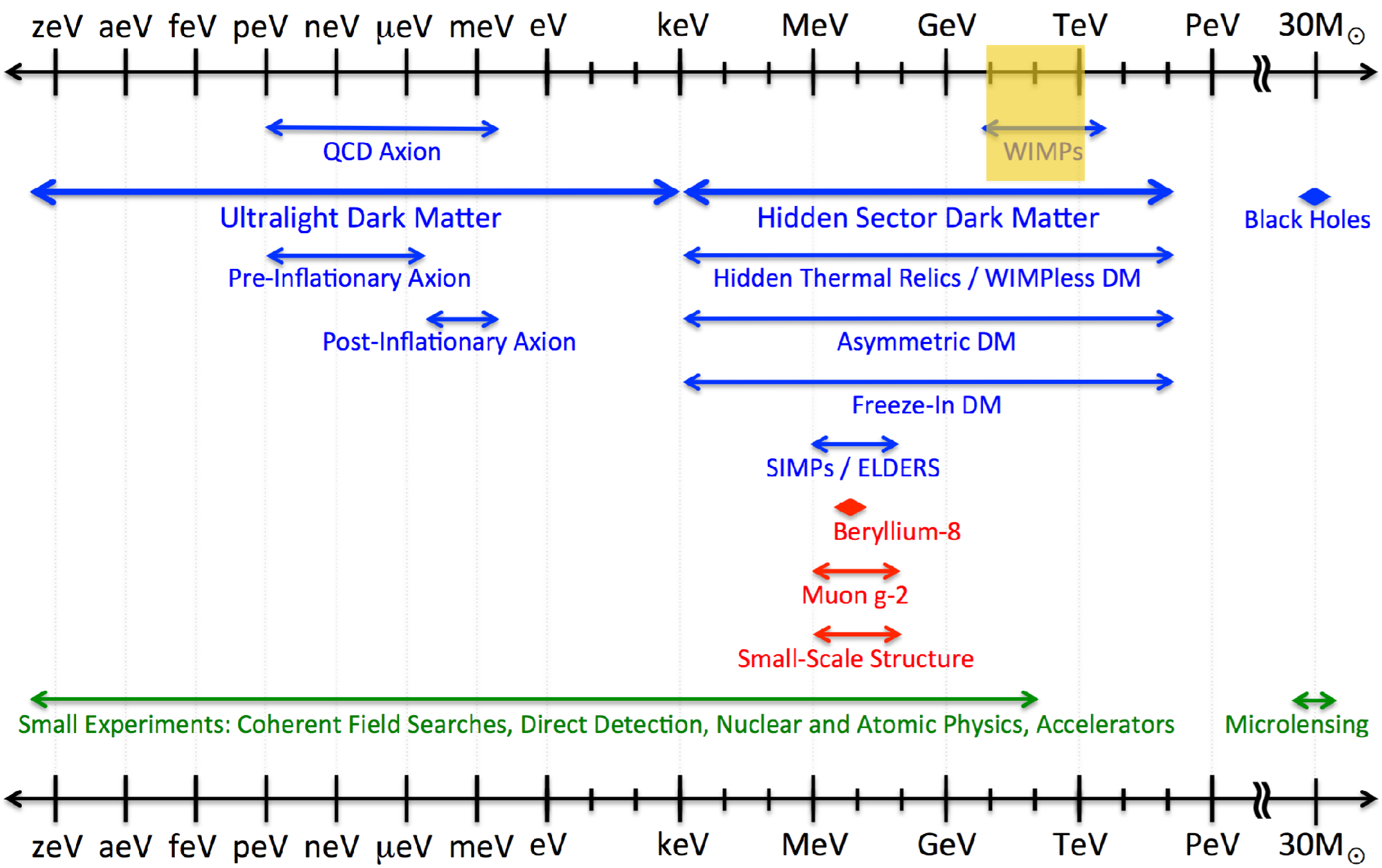

var(E) = 0.16 x 3.62 eV x E
RMS = 30 eV (from noise)
Var(E) / keV²
Energy / keV

DAMIC 2020 results summary : 11 kg-day

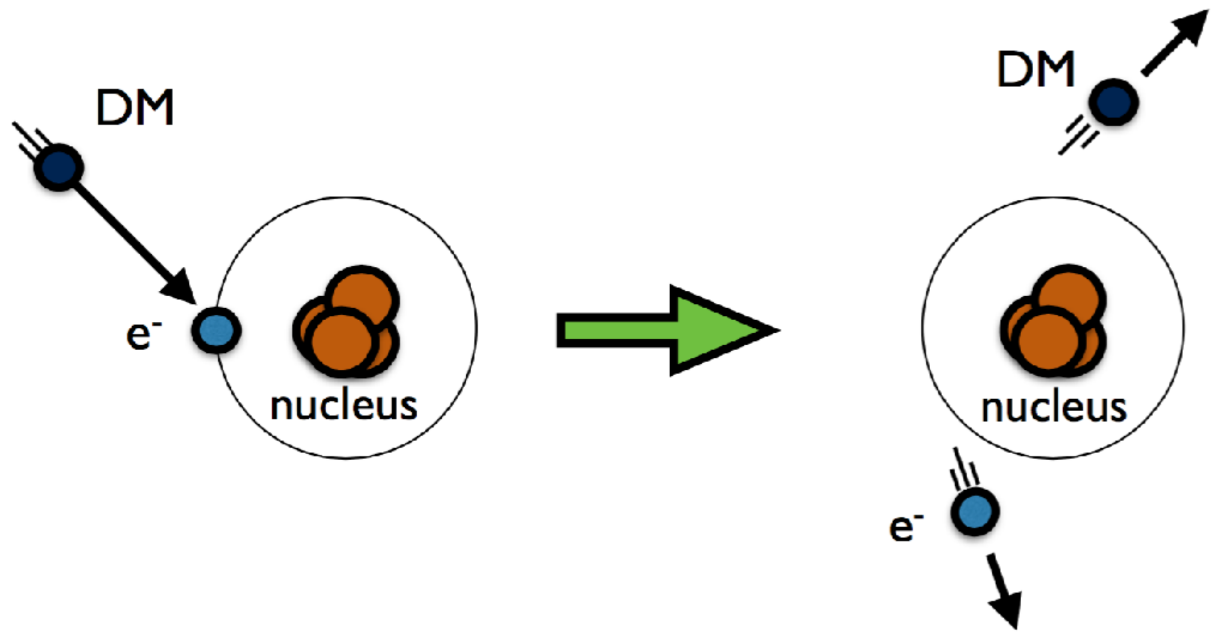


Phys. Rev. Lett. 125, 241803 (2020).

Around 2019… we started to look elsewhere for dark matter.



the “classic” search for wimps looks for nuclear recoil, but when looking at lower mass particles the e-recoil channel could be more competitive.



biding energy (~1 eV)

$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > \Delta E$$

Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

$$v_{\rm DM} \lesssim 800\ {\rm km/s} \implies m_{\rm DM} \gtrsim 300\ {\rm keV} \left(\frac{\Delta E}{1\ {\rm eV}}\right)$$

for outer shell e-

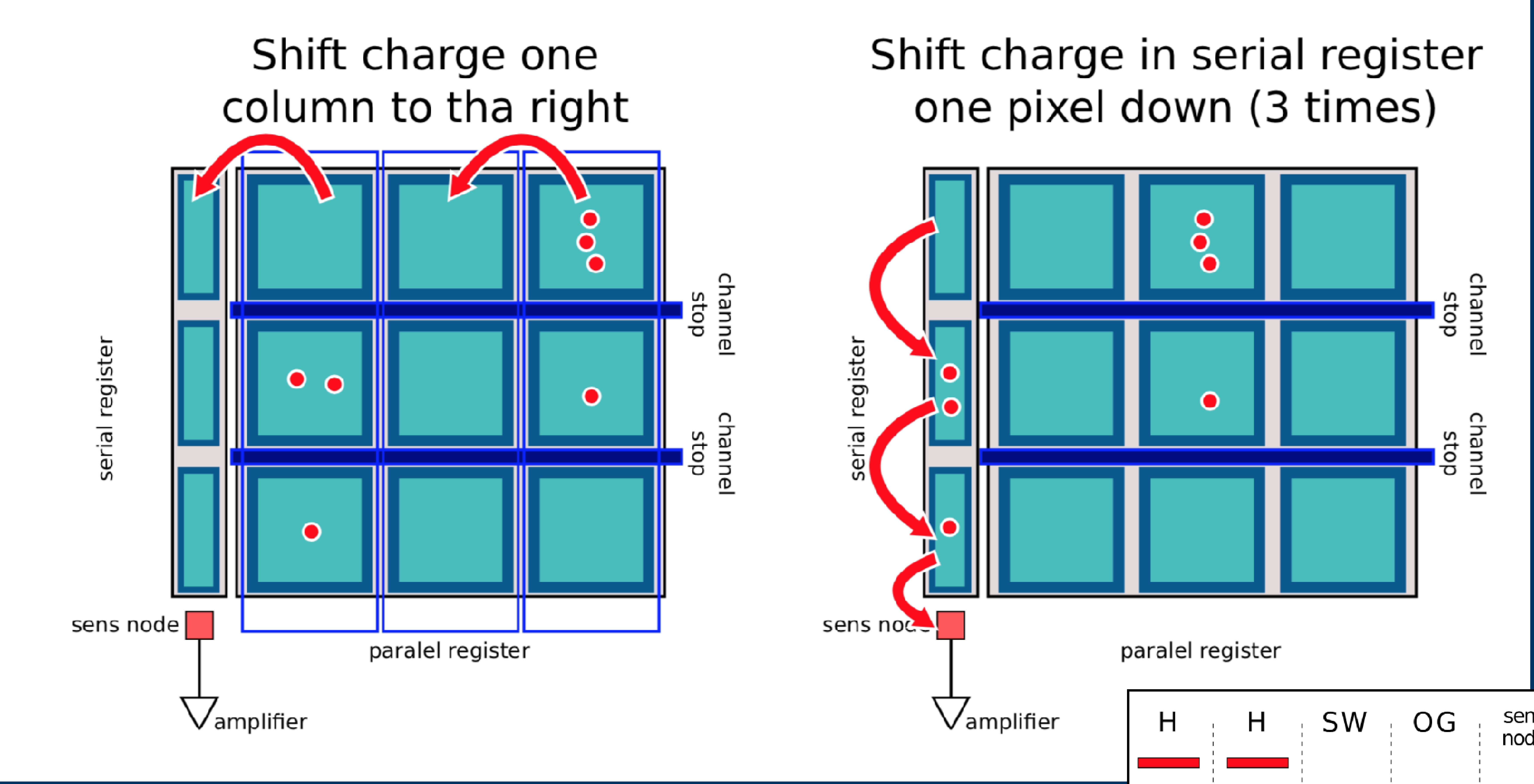
$$q_{\rm typ} \sim \alpha m_e \sim 4\ {\rm keV}$$

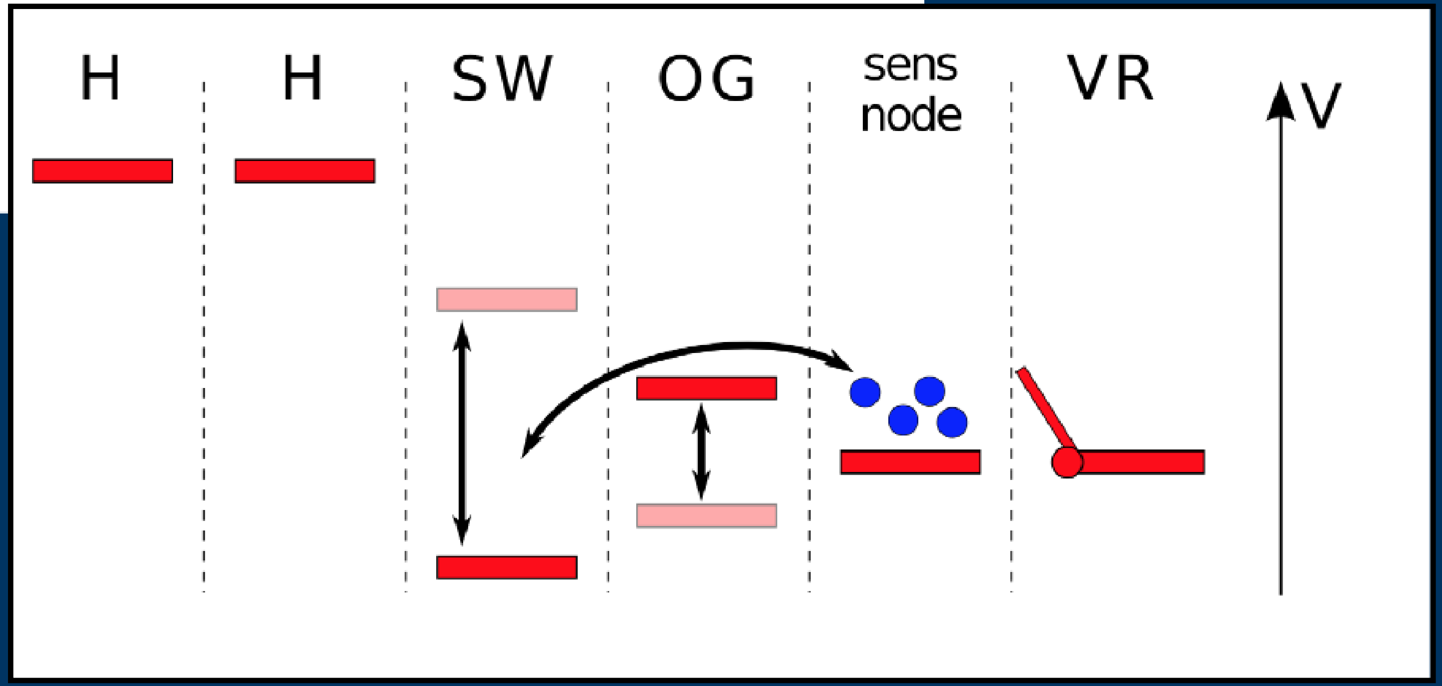
$$\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$$

typical recoil energy: $\Delta E \sim 4\ {\rm eV}$

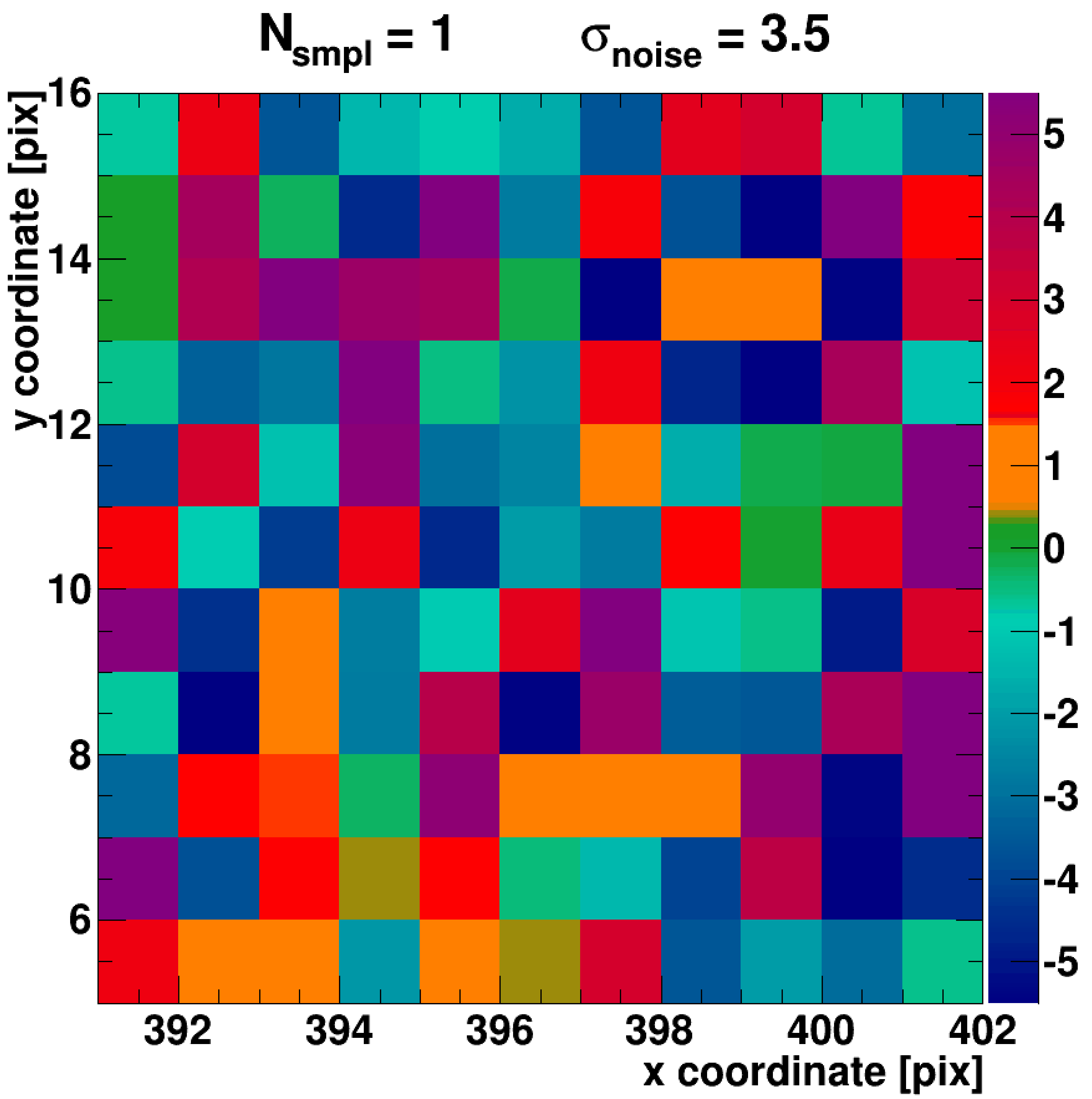
skipper-CCD a “new” tool to push for lower threshold in DM searches.

The skipper-CCD is a modification of the output stage of a CCD (Janesik et al -1990). It allows for multiple n

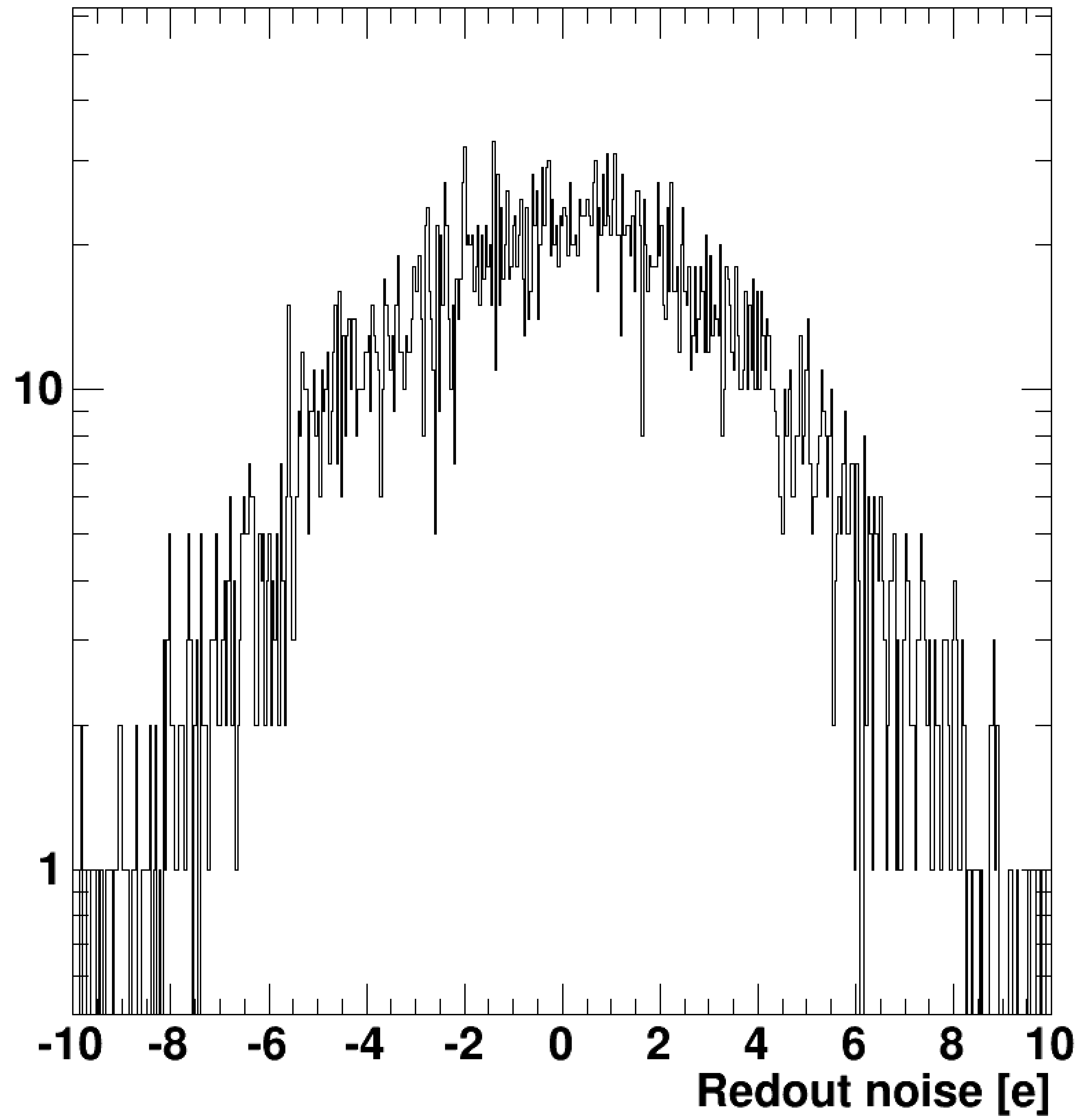




skipper-CCD

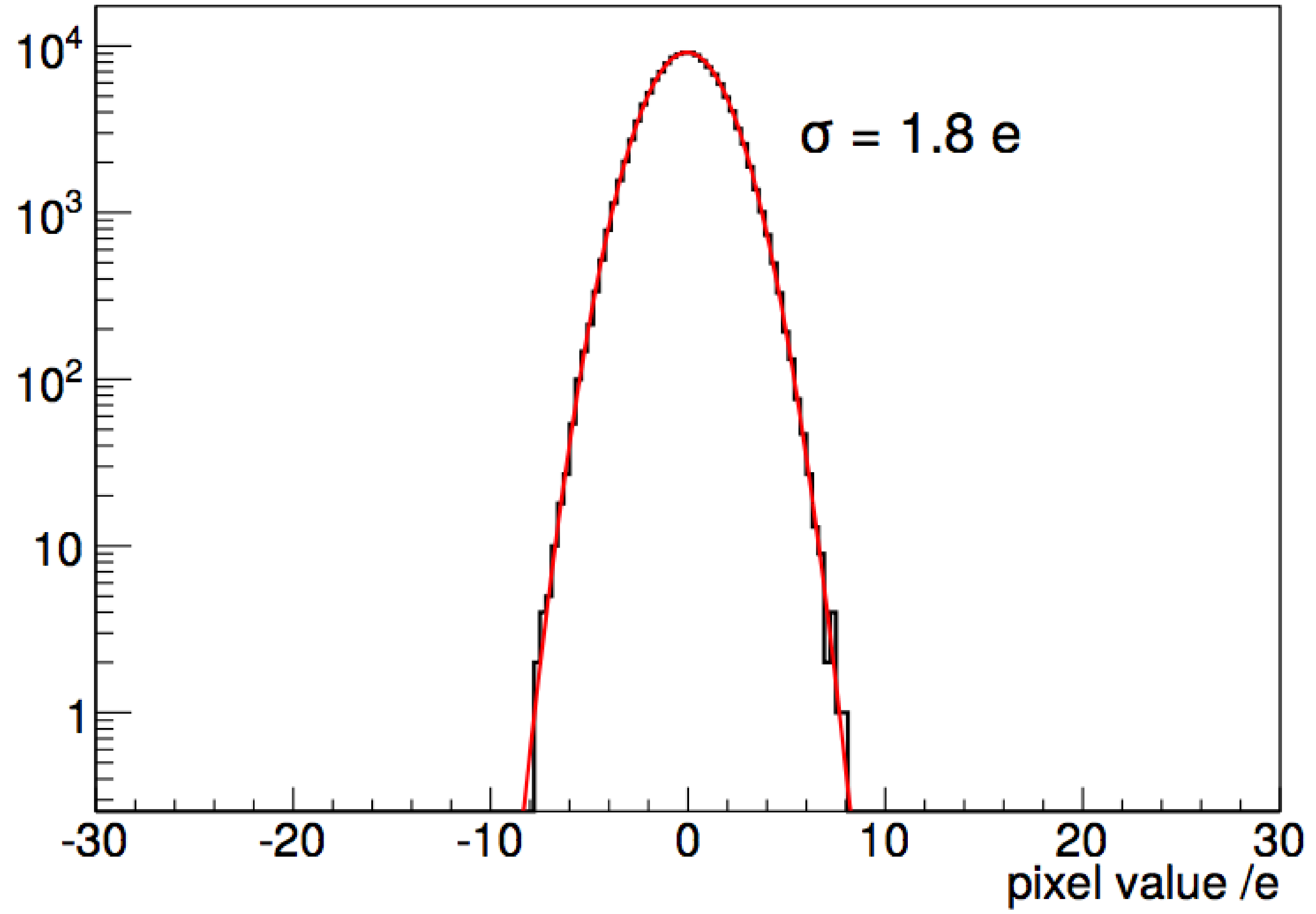


N_{smpl} = 1
σ_{noise} = 3.5
y coordinate [pix]
16
14
12
10
8
6
392
394
396
398
400
402
x coordinate [pix]
5
4
3
2
1
0
-1
-2
-3
-4
-5

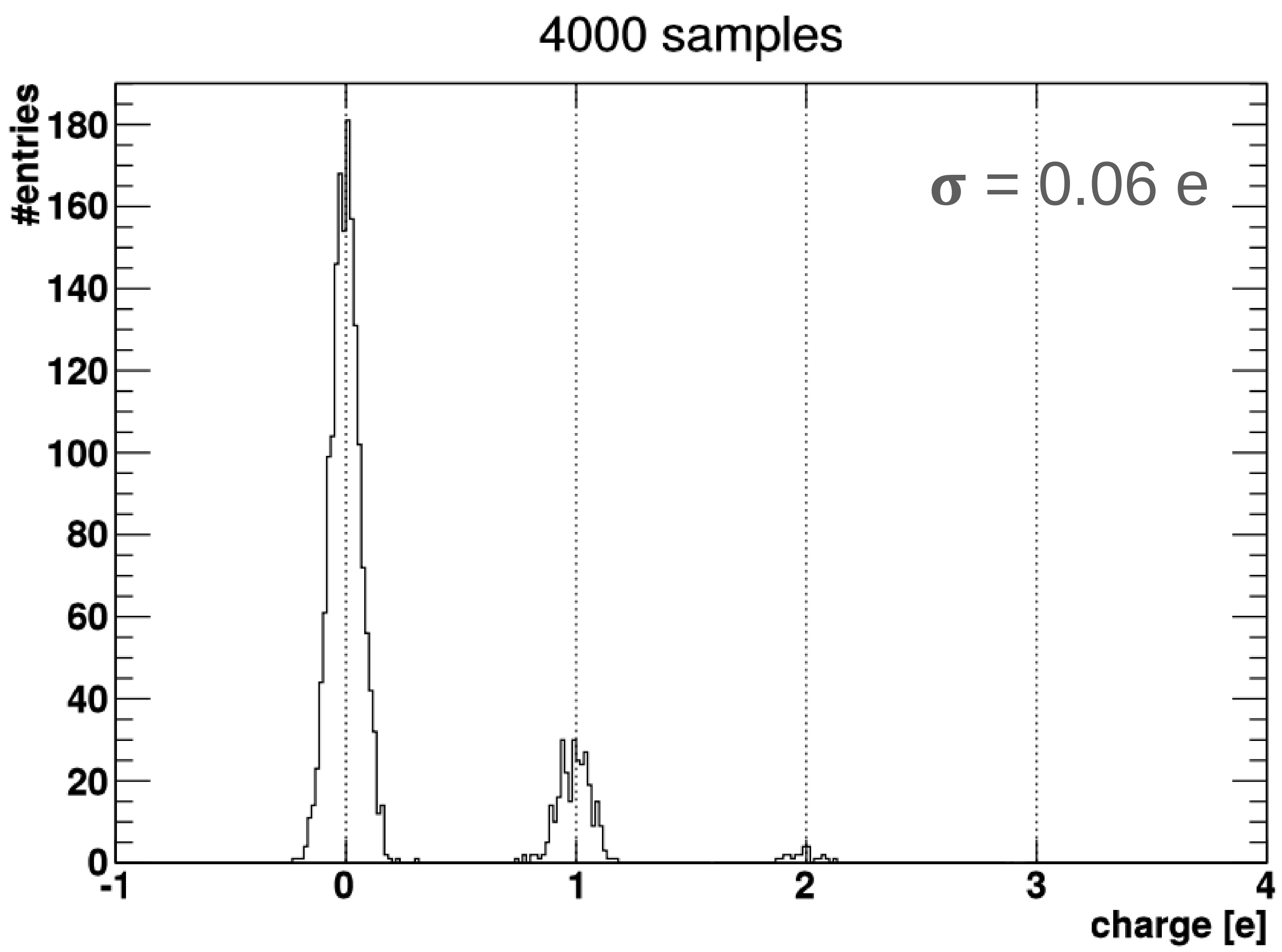


10
1
-10
-8
-6
-4
-2
0
2
4
6
8
10
Redout noise [e]

DAMIC 2016

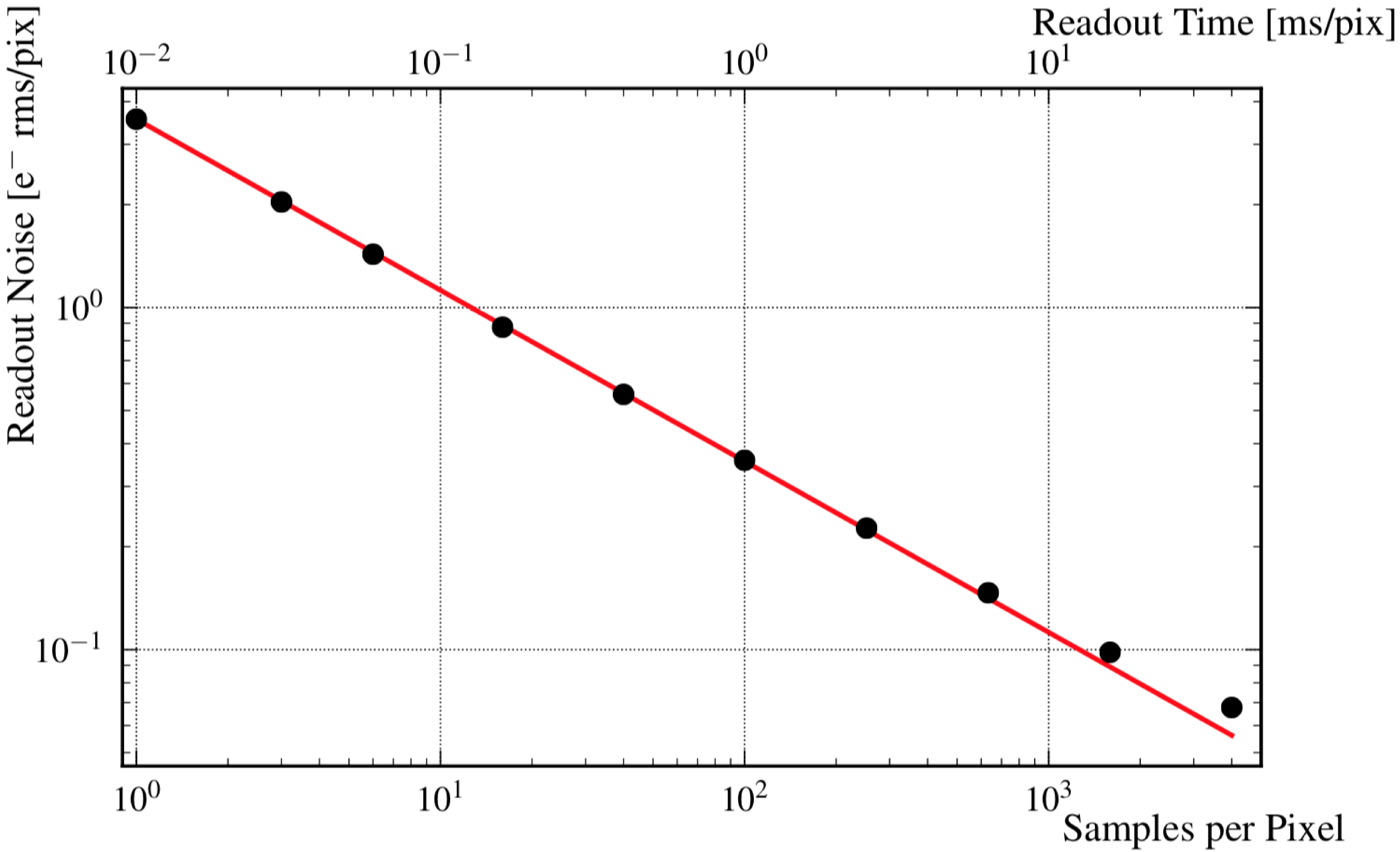


skipper CCD

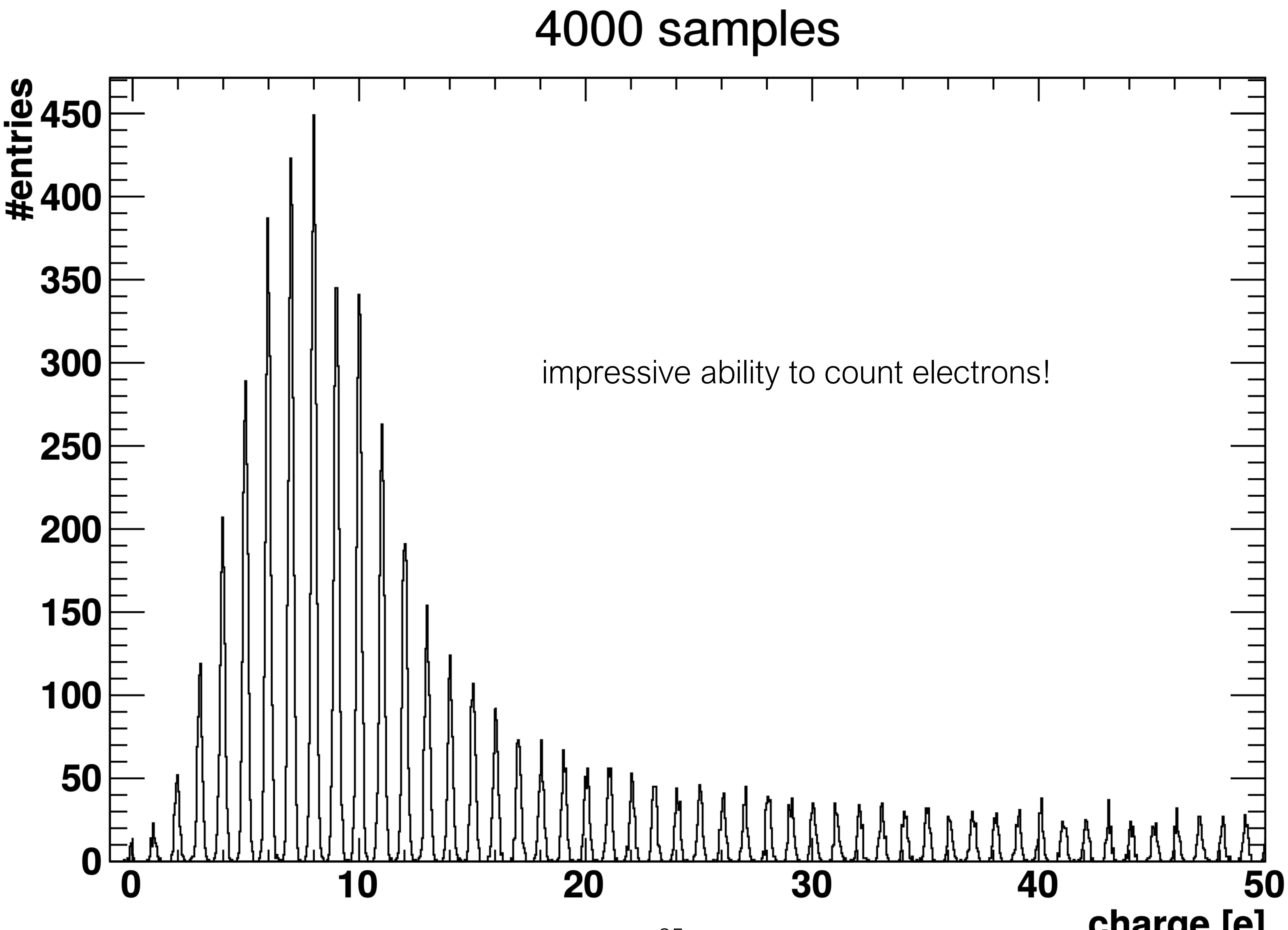


Phys. Rev. Lett. **119**, 131802 (2017)

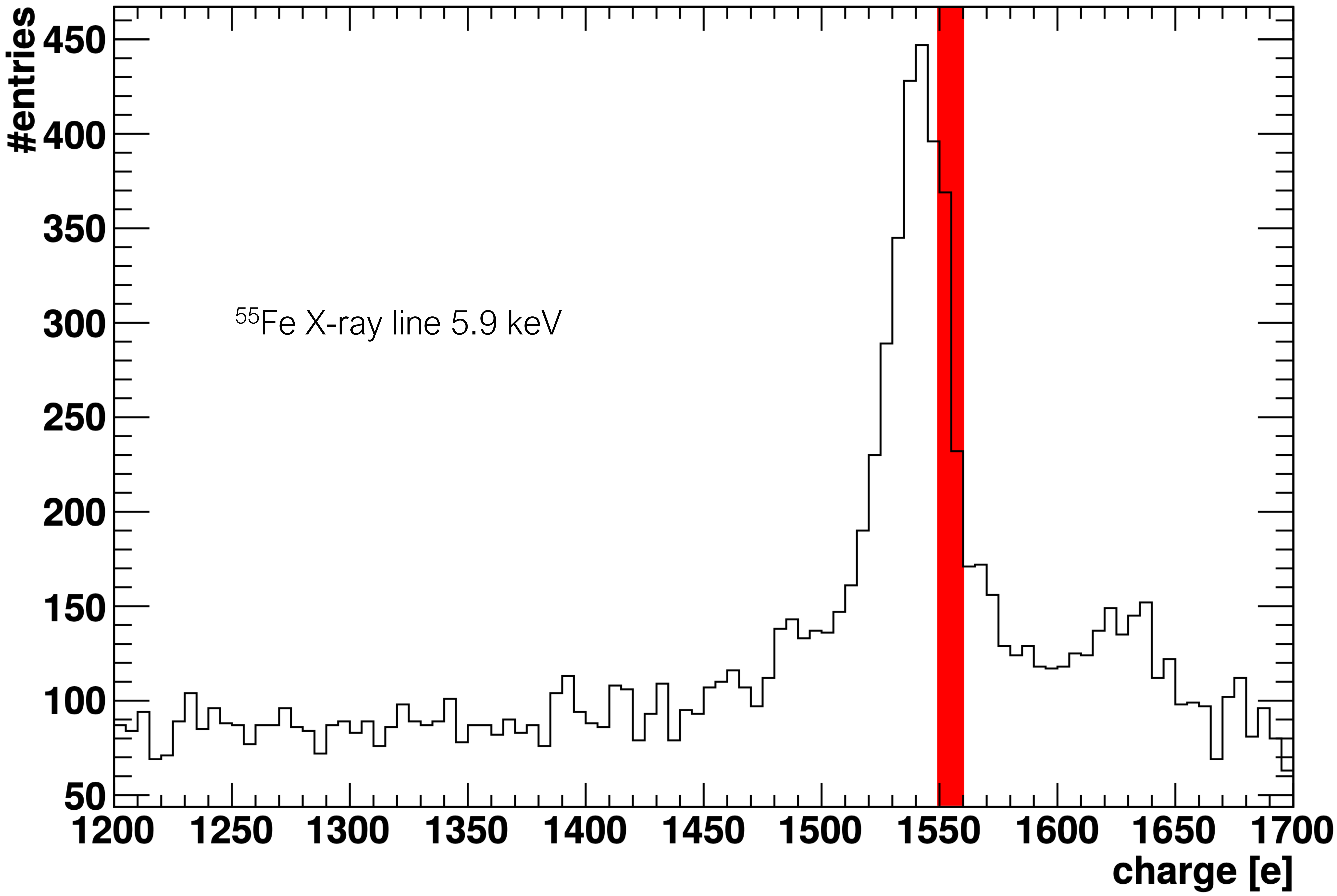
Designed ~30 years ago, but technology first demonstrated summer 2017 by Javier Tiffenberg et al allows reduction of the threshold by another factor of 10.



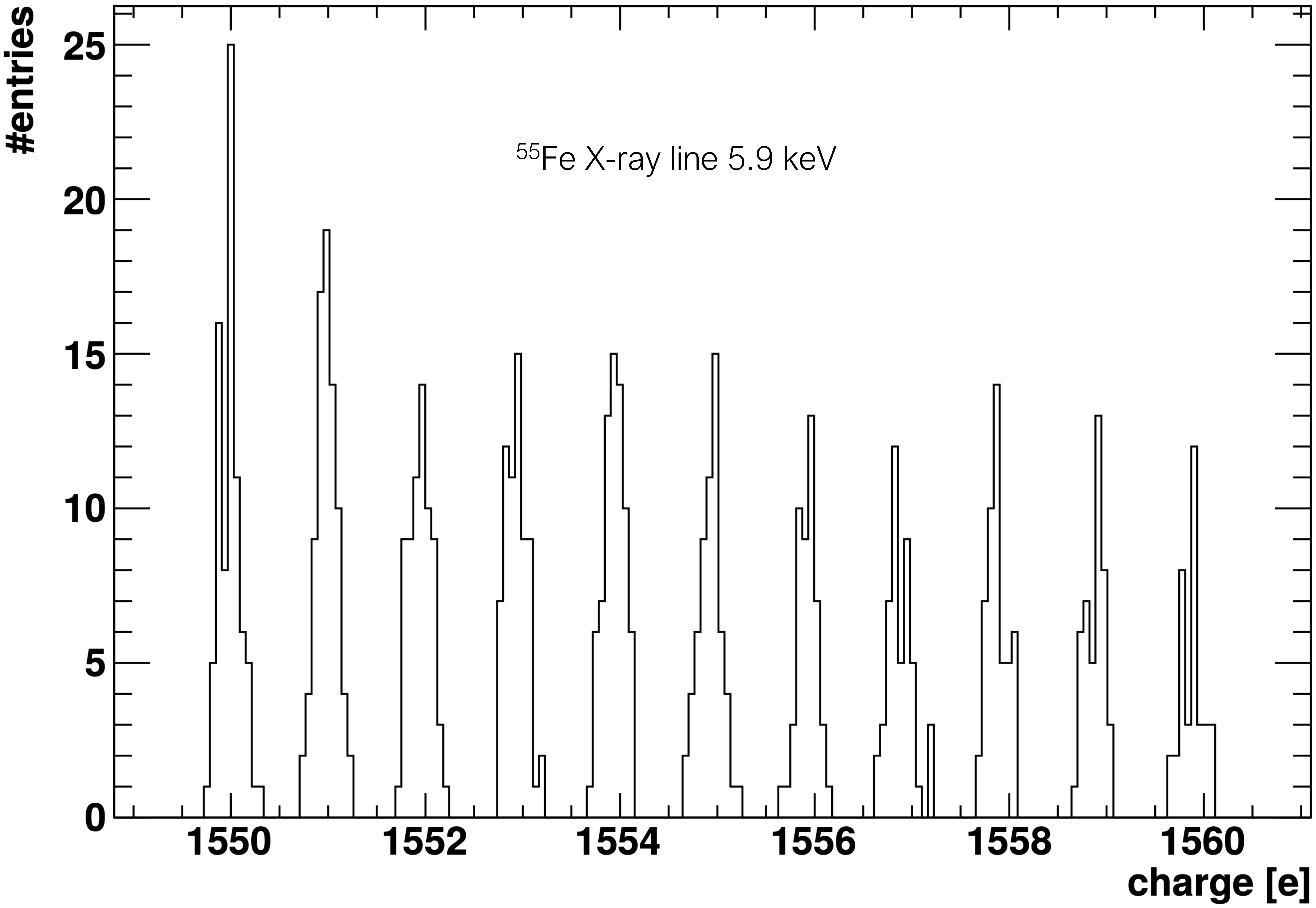
Readout Time [ms/pix]
10^{-2}
10^{-1}
10^{0}
10^{1}
Readout Noise [e^{-} rms/pix]
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Samples per Pixel


4000 samples
#entries
450
400
350
300
250
200
150
100
50
0
impressive ability to count electrons!
0
10
20
30
40
50
charge [e]

4000 samples

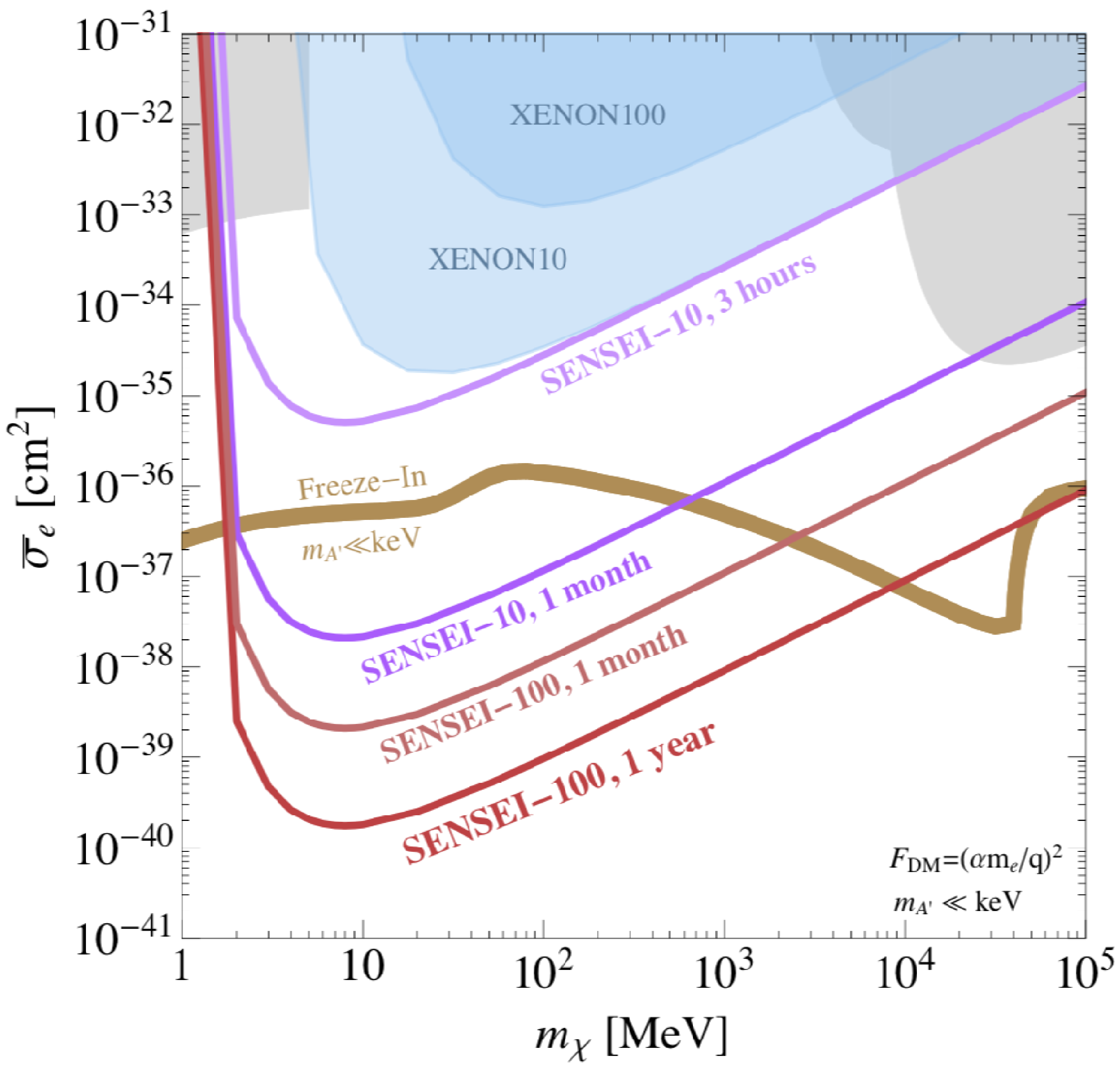


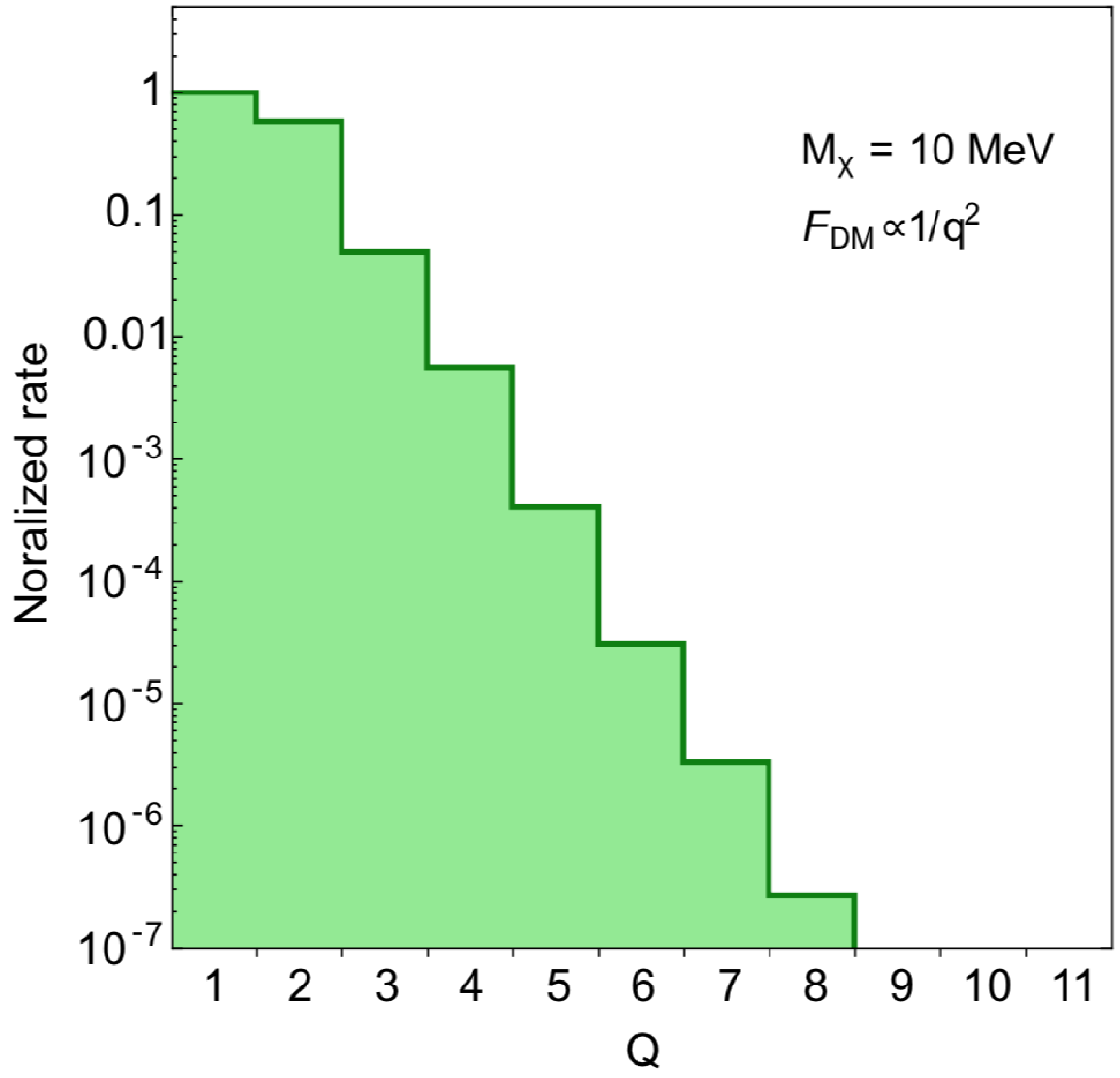
4000 samples

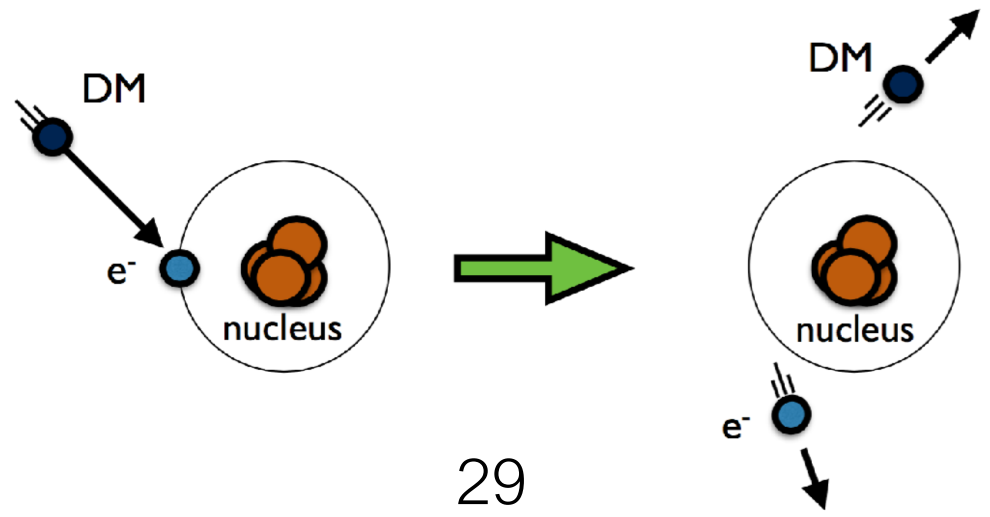


dark sector searches

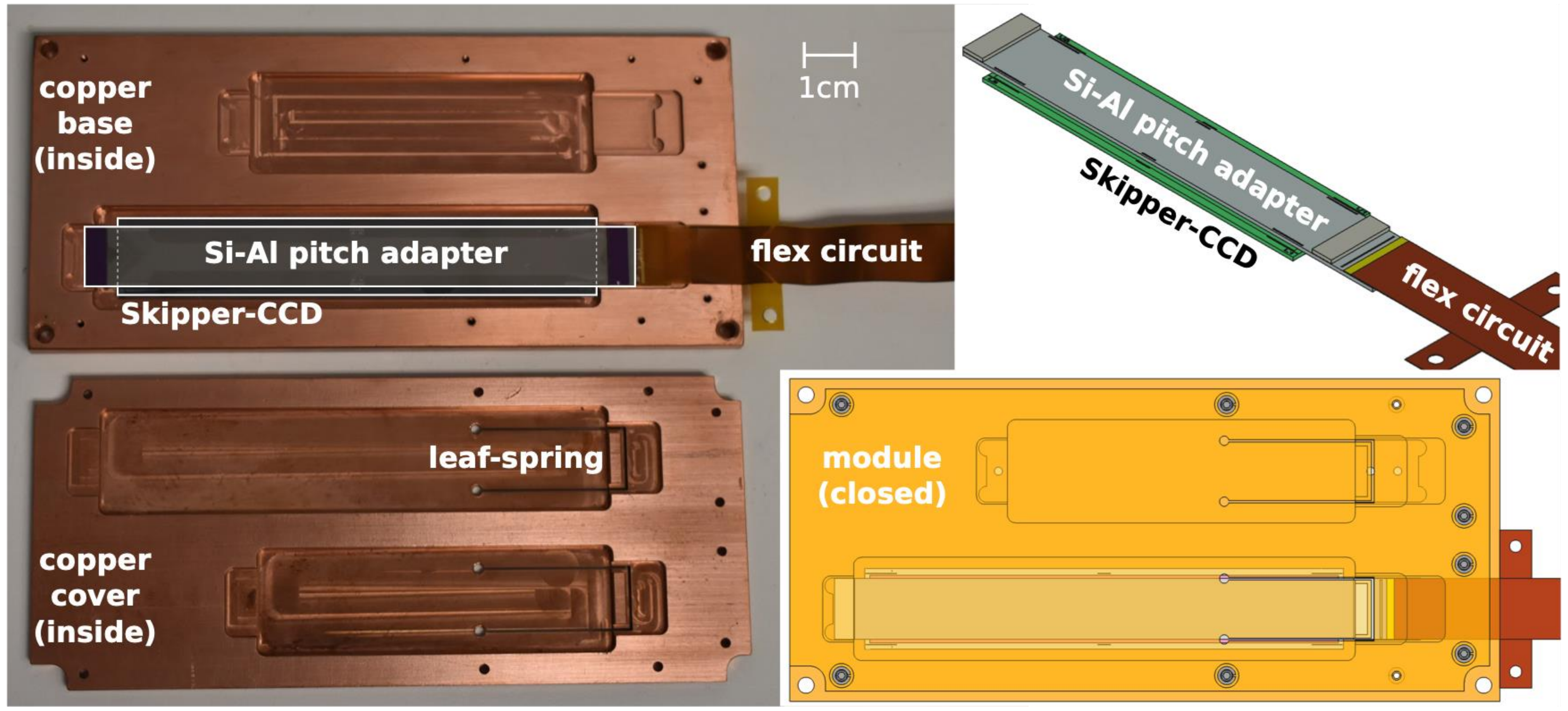
Once you can count electrons, you can search for electron recoils produced by very low mass dark matter (dark sector searches). As done with skipper-CCD in the **SENSEI experiment.**

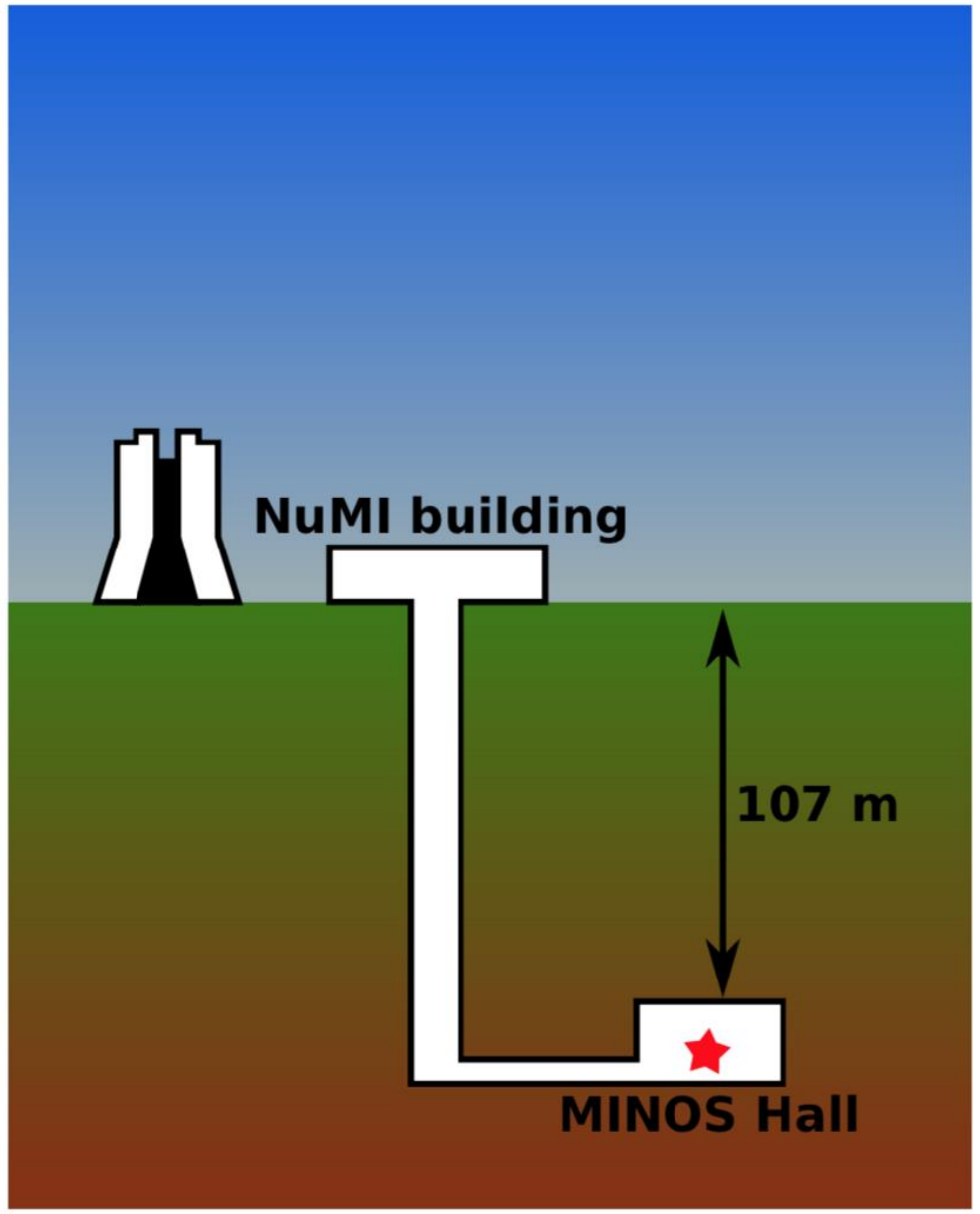


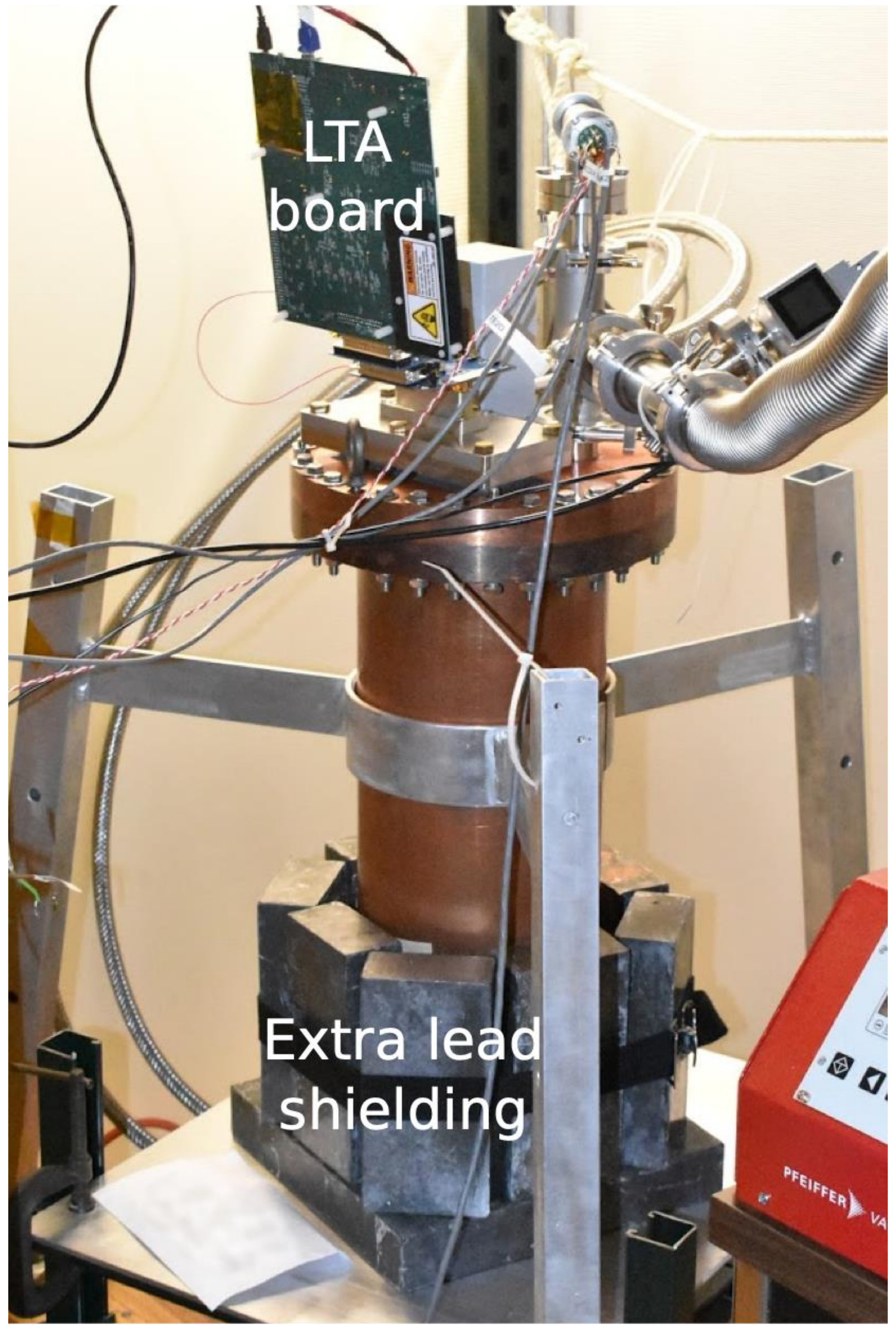


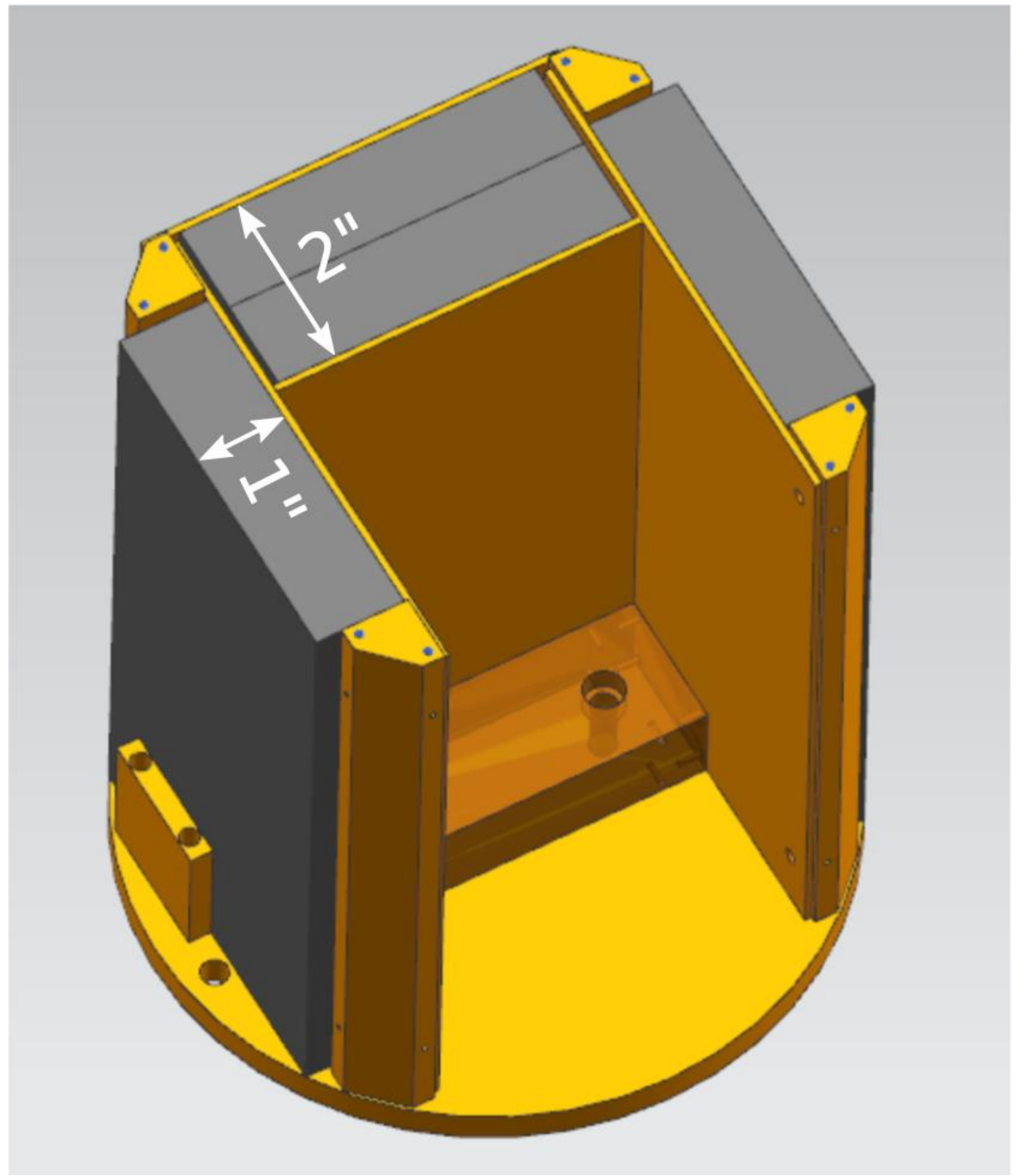


SENSEI 2020 results
arXiv:2004.11378



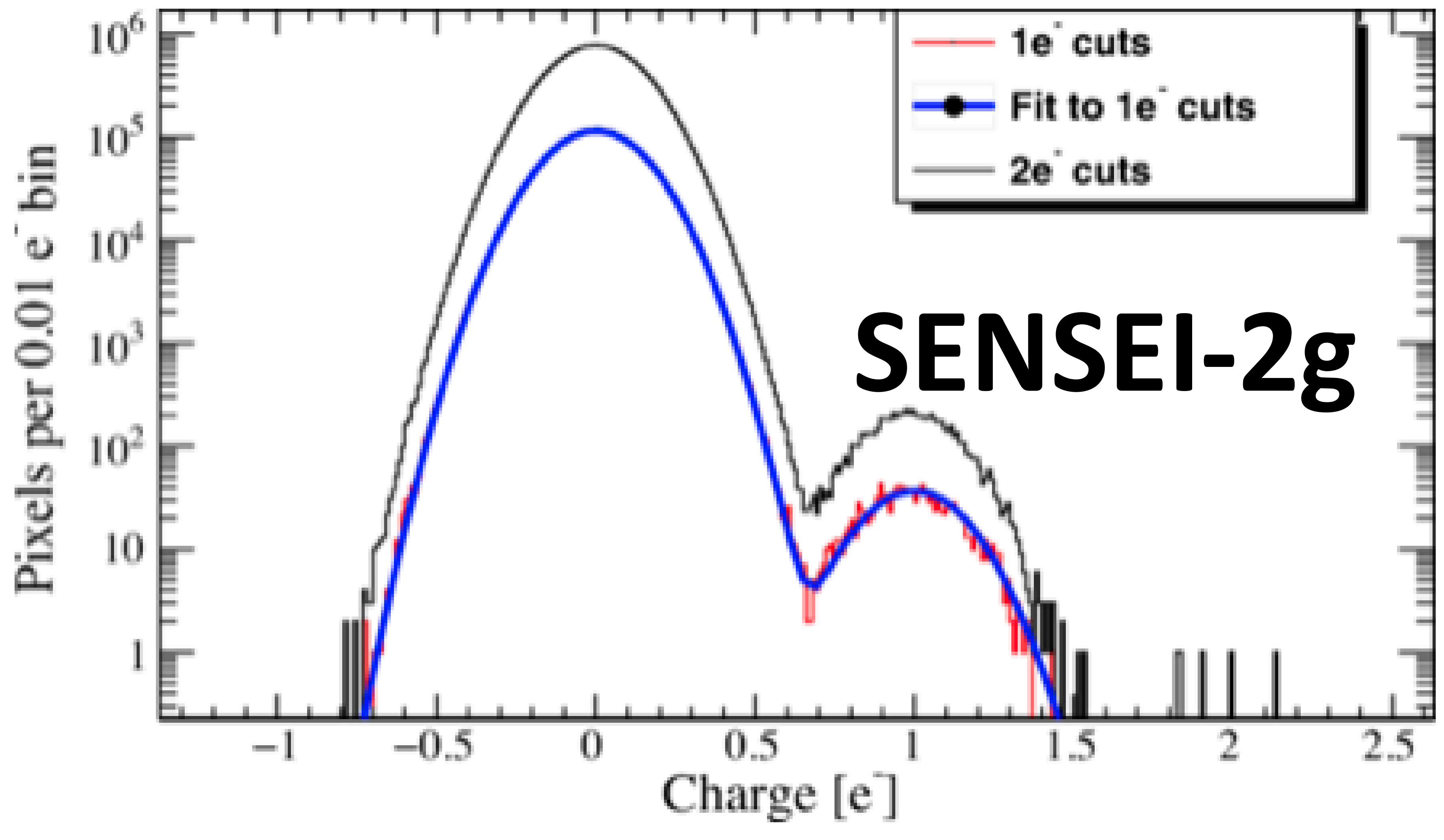


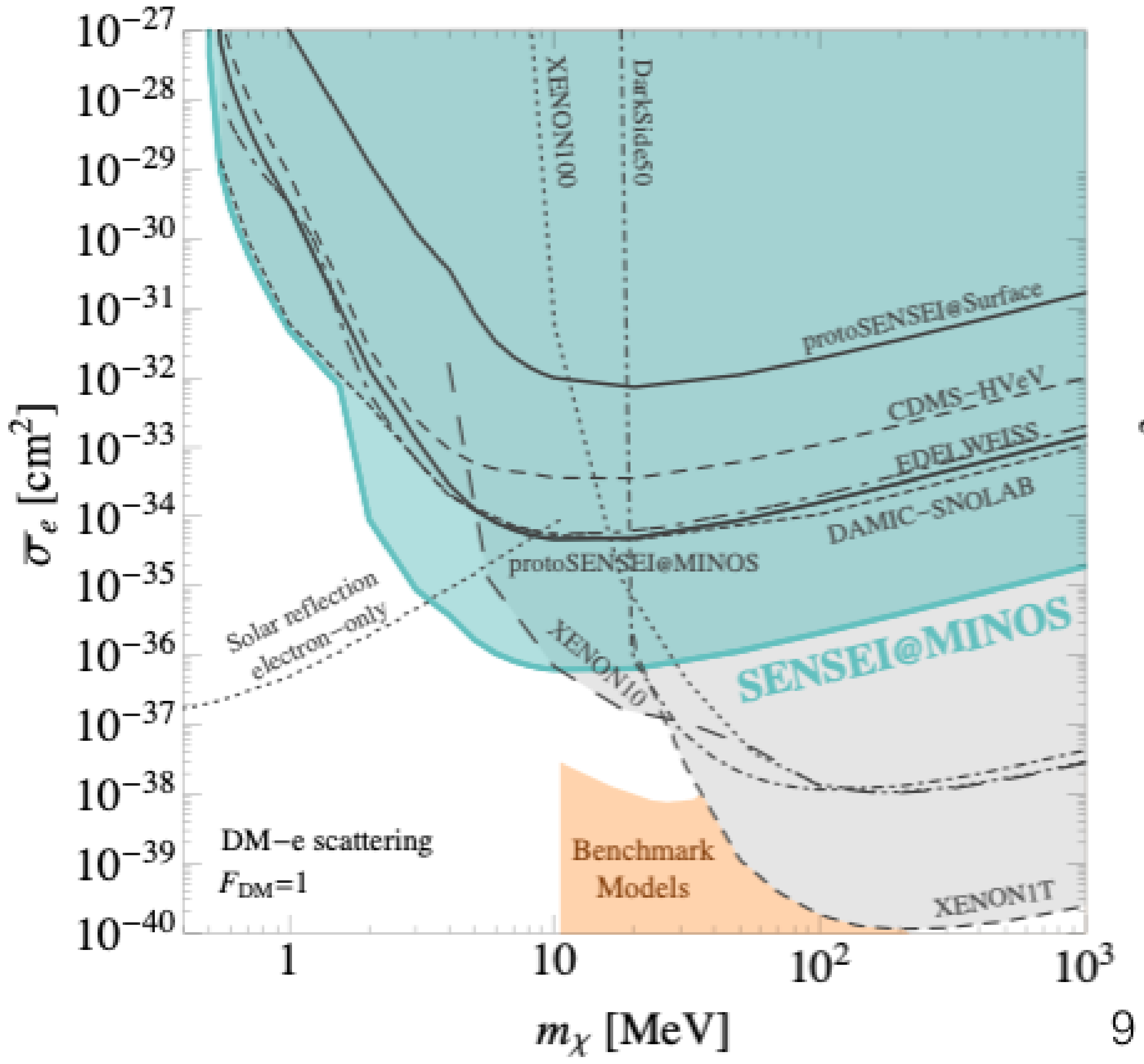




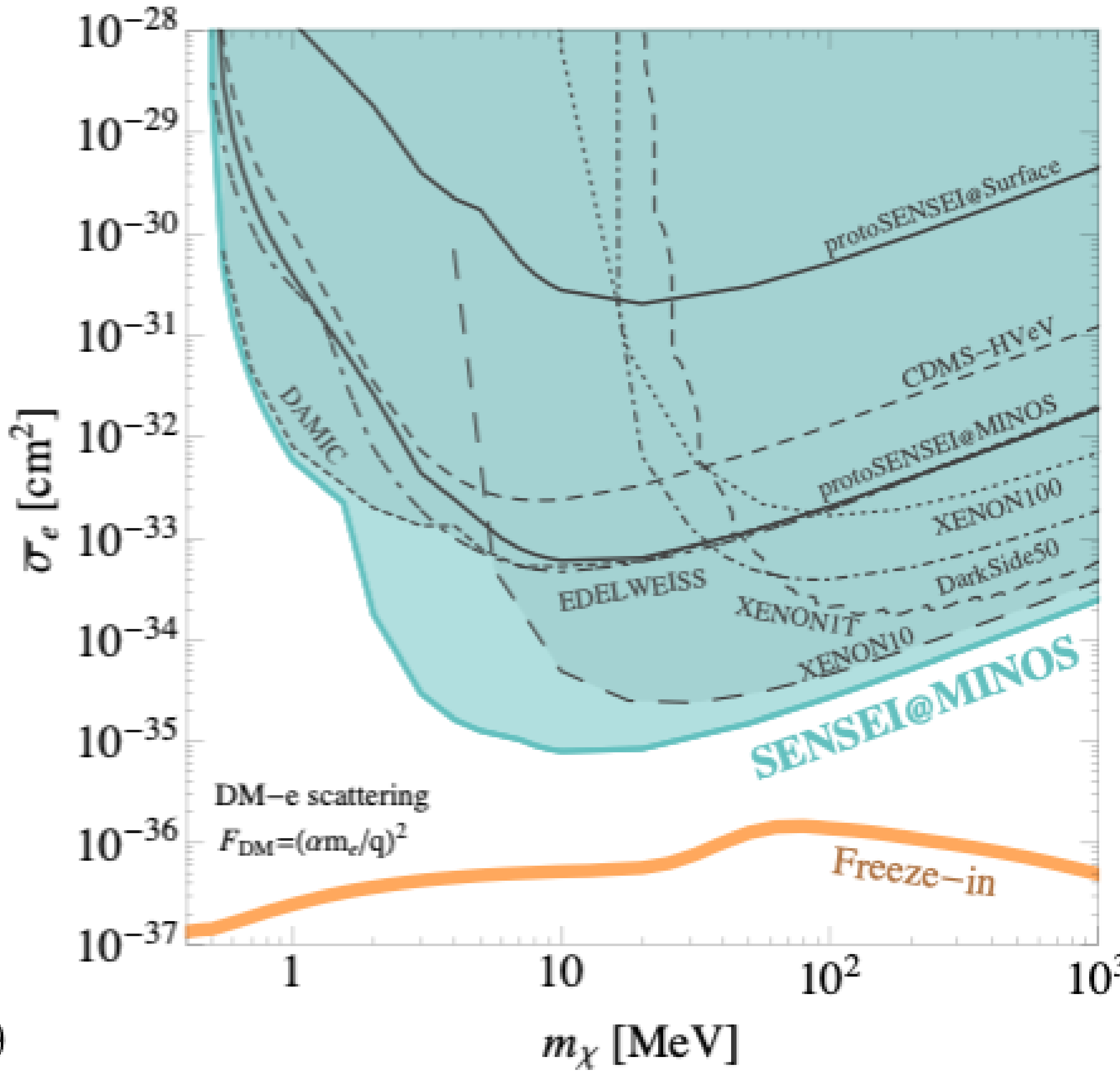
Skipper-CCD enabling technology

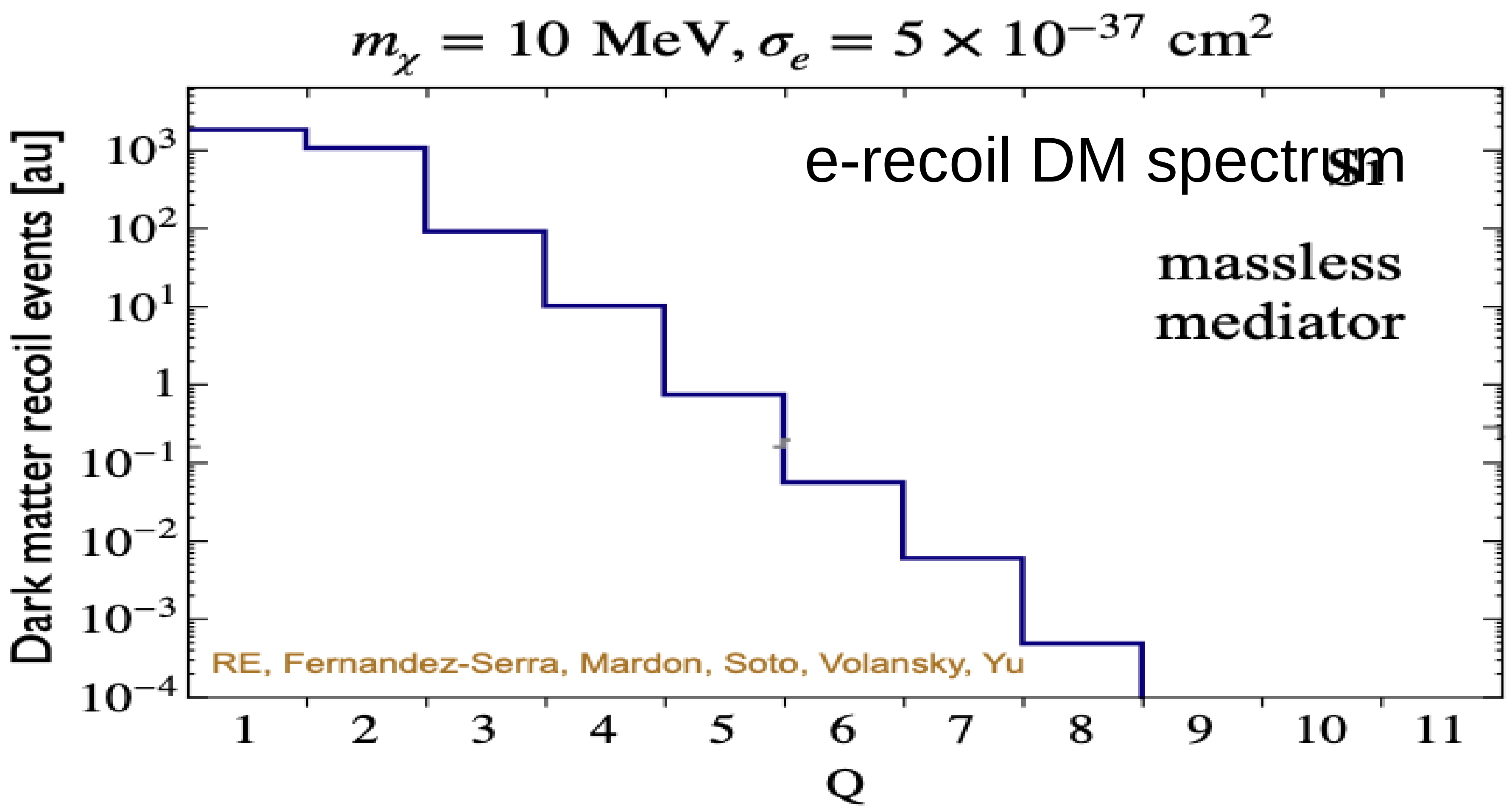
Skipper-CCD is an electron counting silicon detector device.





9





Rates:

- 1e- = 450 ev/g-day (1.6 10^{-4} e/pix/day)
- 2e- = 2.4 ev/g-day

Phys. Rev. Lett. **125**, 171802 – Published 20 October 2020

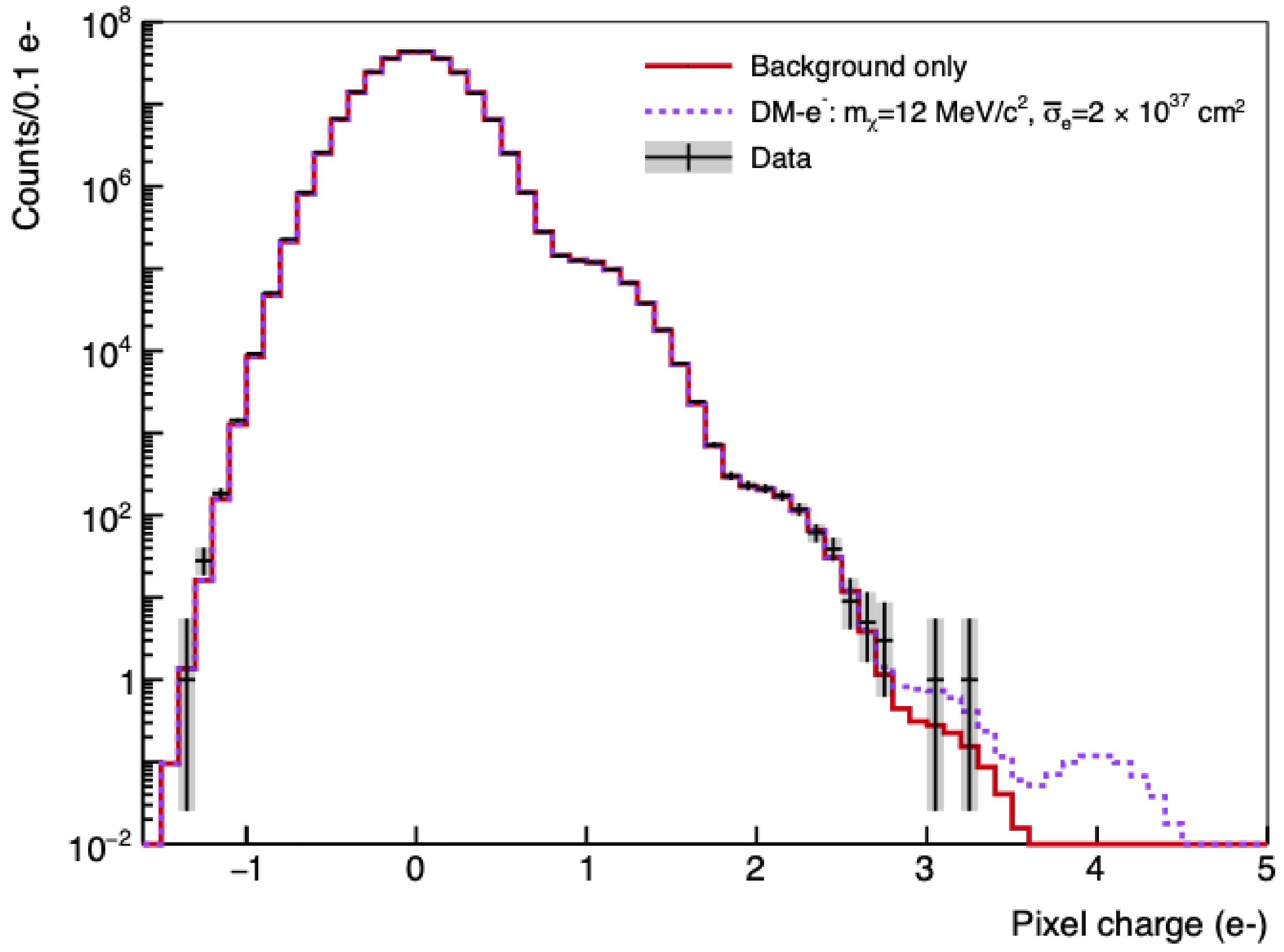
Update from DAMIC-M (@Modane)

Phys. Rev. Lett. **130**, 171003 – Published 28 April 2023

arXiv:2302.02372

Improvement over SENSEI 2020.

85 g-day 10 dru



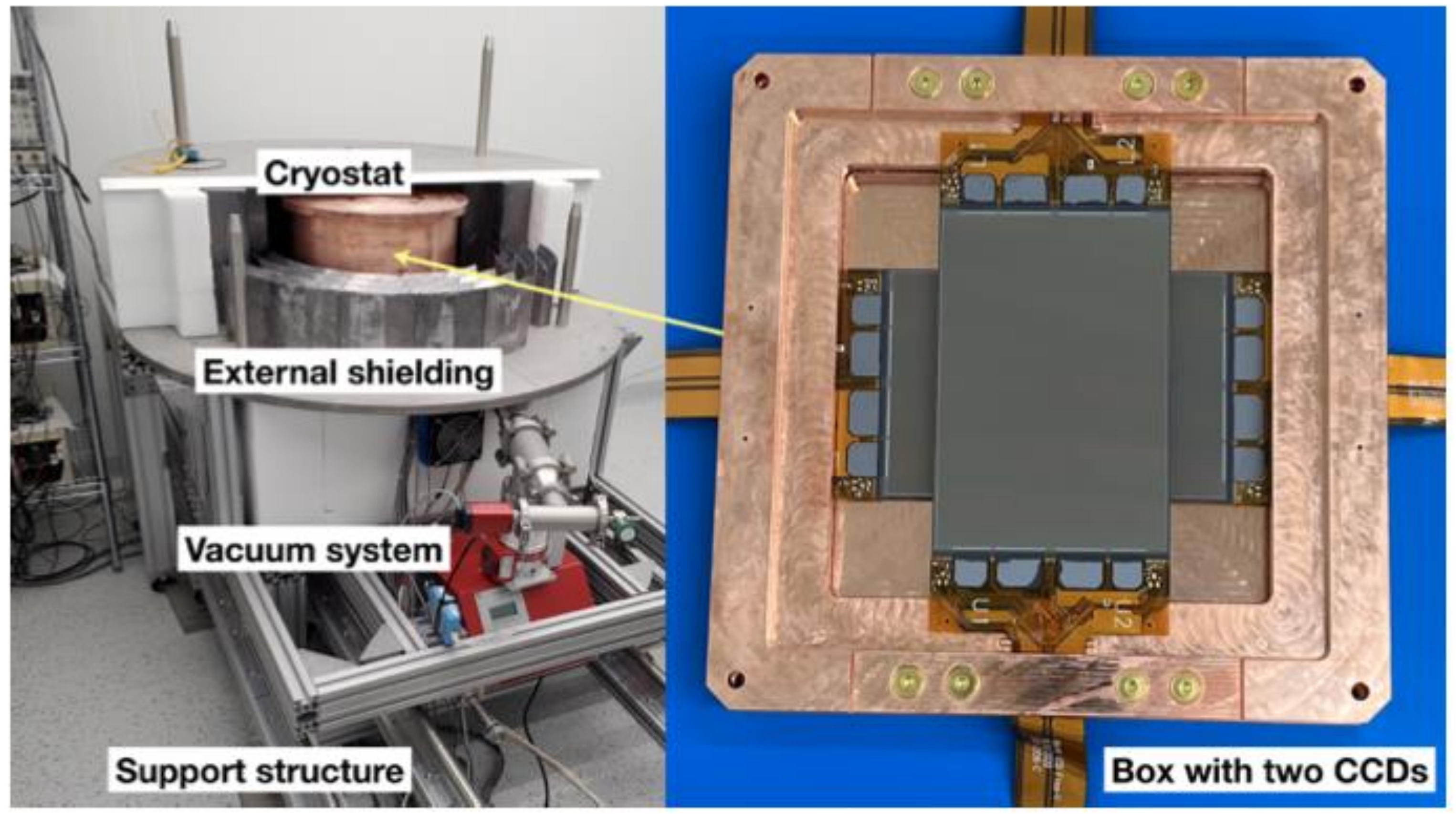
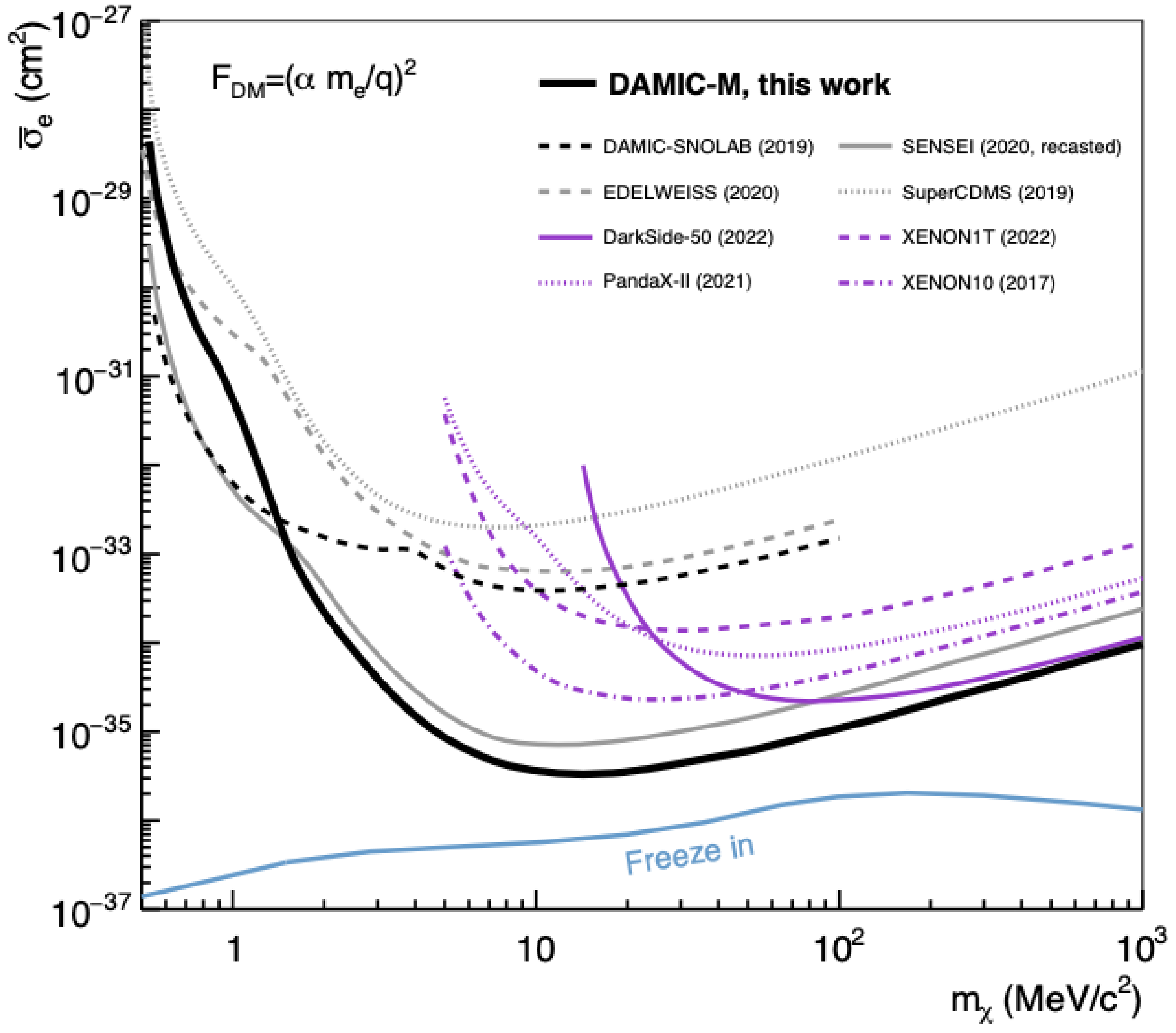
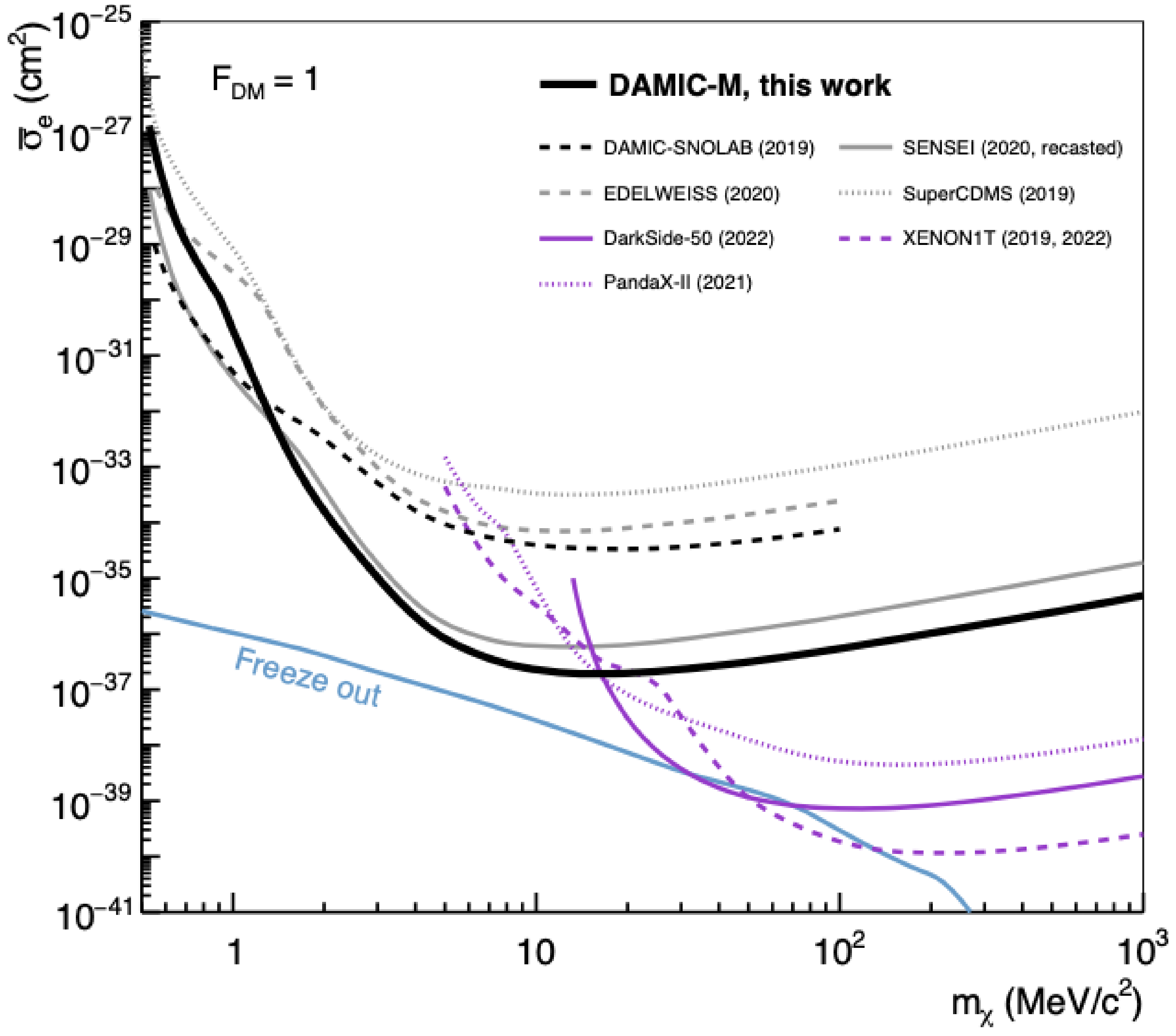


FIG. 1. The DAMIC-M Low Background Chamber installed underground at LSM: the two skipper CCDs are monted in a high-purity copper box (right); the box is placed inside the copper cryostat, visible here (left) during assembly of the external lead and polyethylene shielding.





Update from SENSEI-2023 (@SNOLAB)

Data: 45 *unblinded* commissioning images, 37 blinded images, 2-10 *e⁻* channels

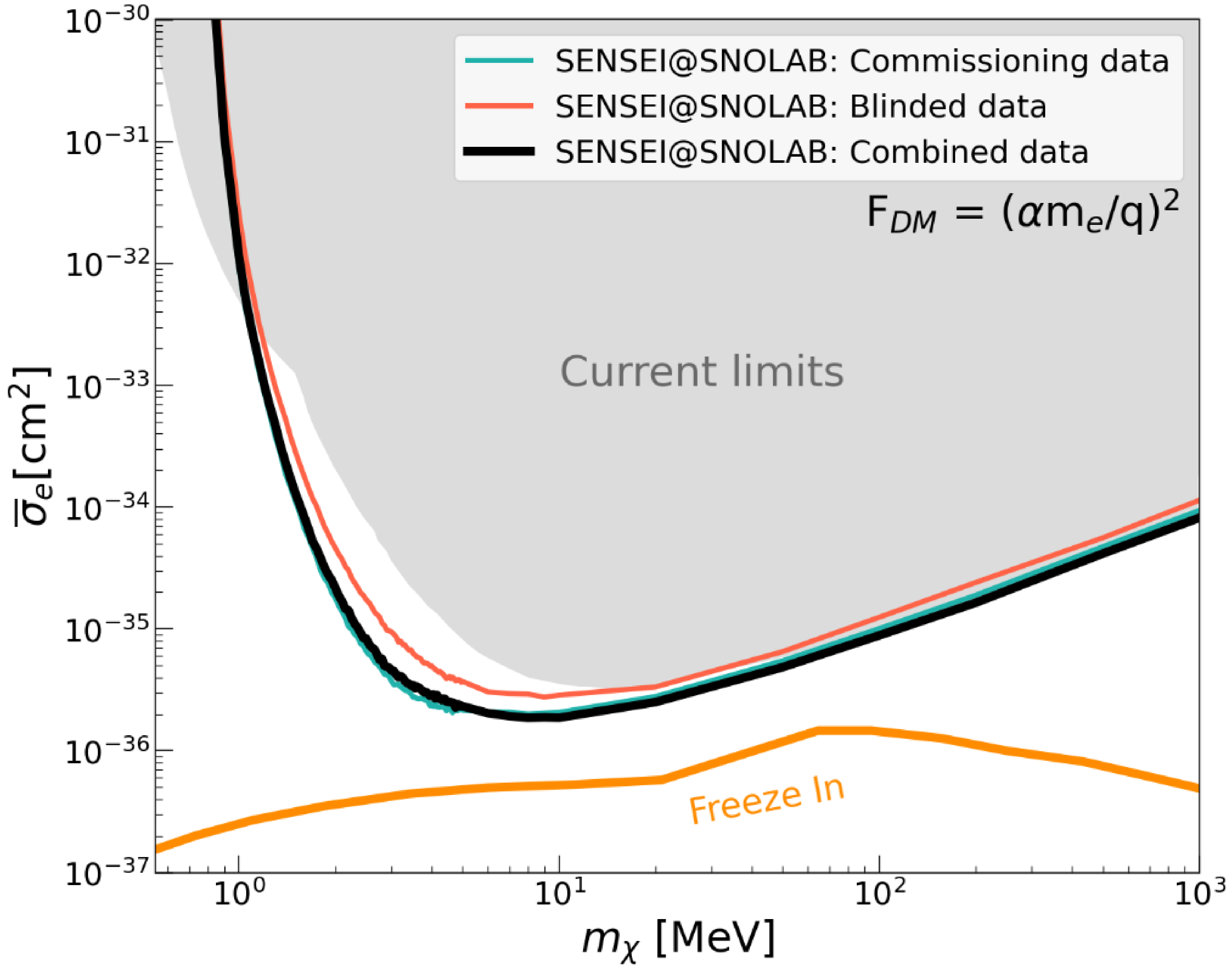
Exposure ~70 g-days per electron channel

Three limits: blinded dataset, commissioning dataset, and combined commissioning + blinded exposure

Paper in preparation to present full results

2023 April APS meeting

Improvement over DAMIC-M

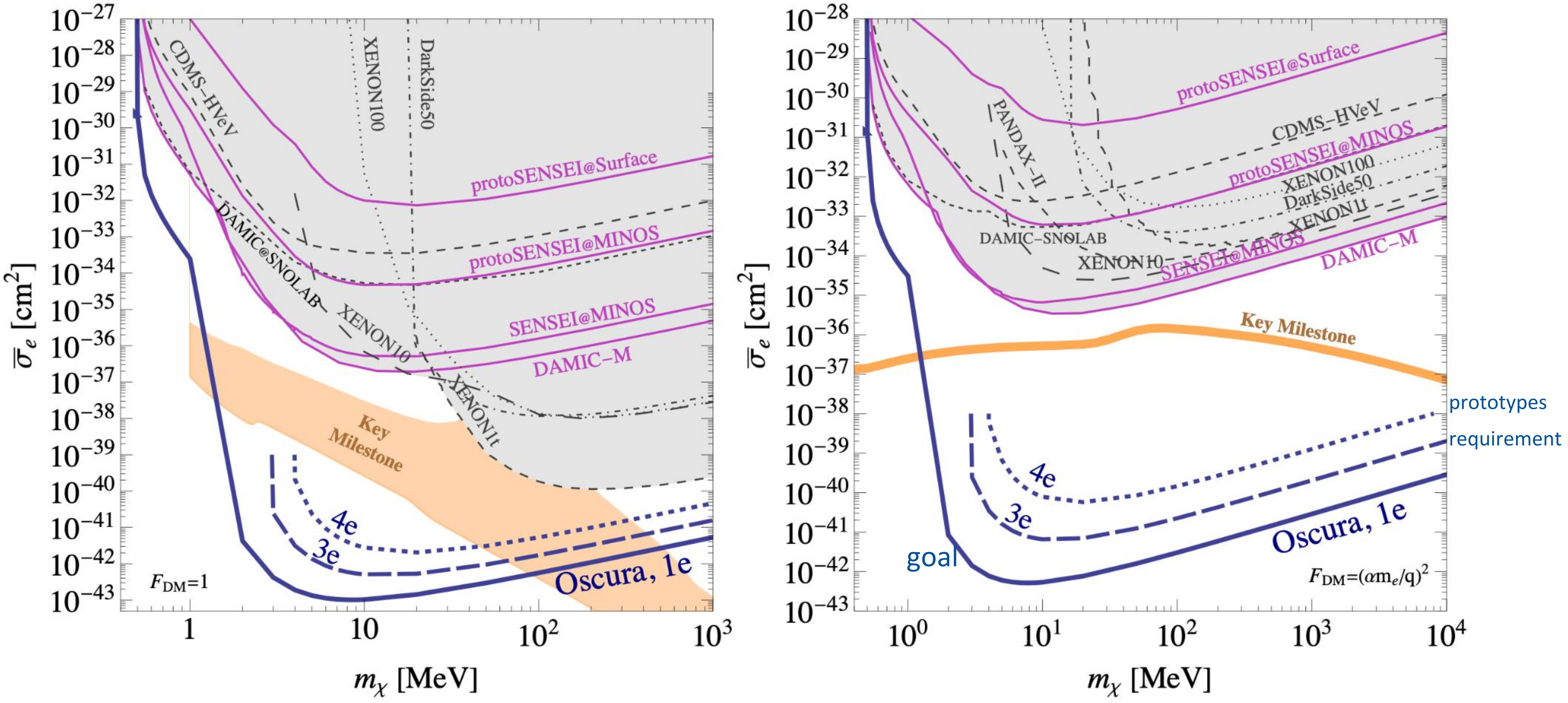


Skipper-CCD DM program : technology roadmap

Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10	3×10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	10	3×10^{-3}	late-2021
SENSEI-100	~0.1	50	10 (goal)		mid-2022
DAMIC-M	~1	200	0.1 (goal)		~2023
OSCURA	~10	20,000	0.01 (goal)	1×10^{-6} (goal)	~2028

Oscura is an ambitious program that brings together the DAMIC, SENSEI and DAMIC-M teams for the development of ultimate DM experiment with skipper-CCDs.

From sensor performance to science arXiv:2304.0440

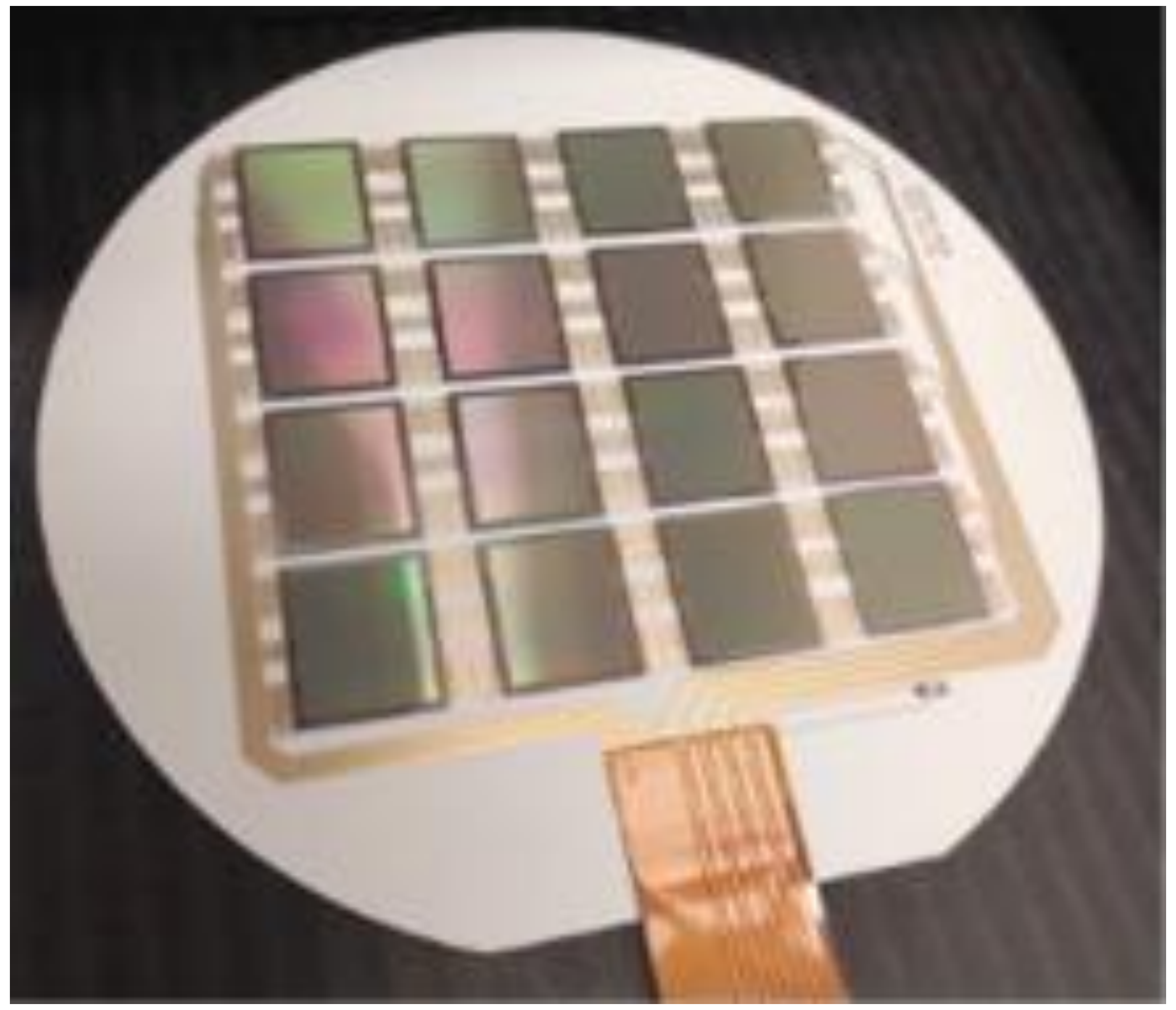


Completed R&D : electronics/packaging Multi Chip Module

Circuit layout

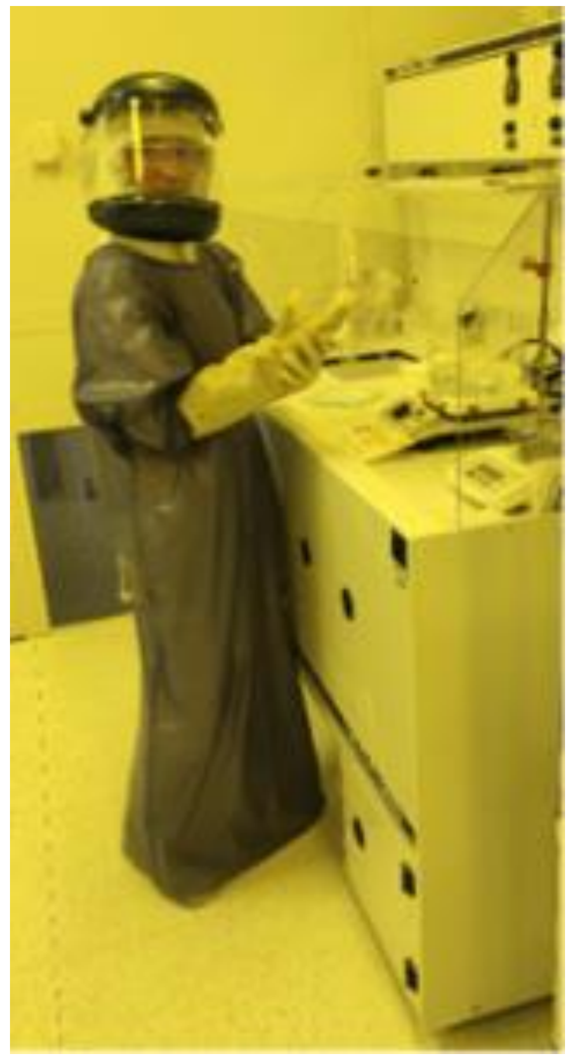
MCM concept 2021

Functional test cold



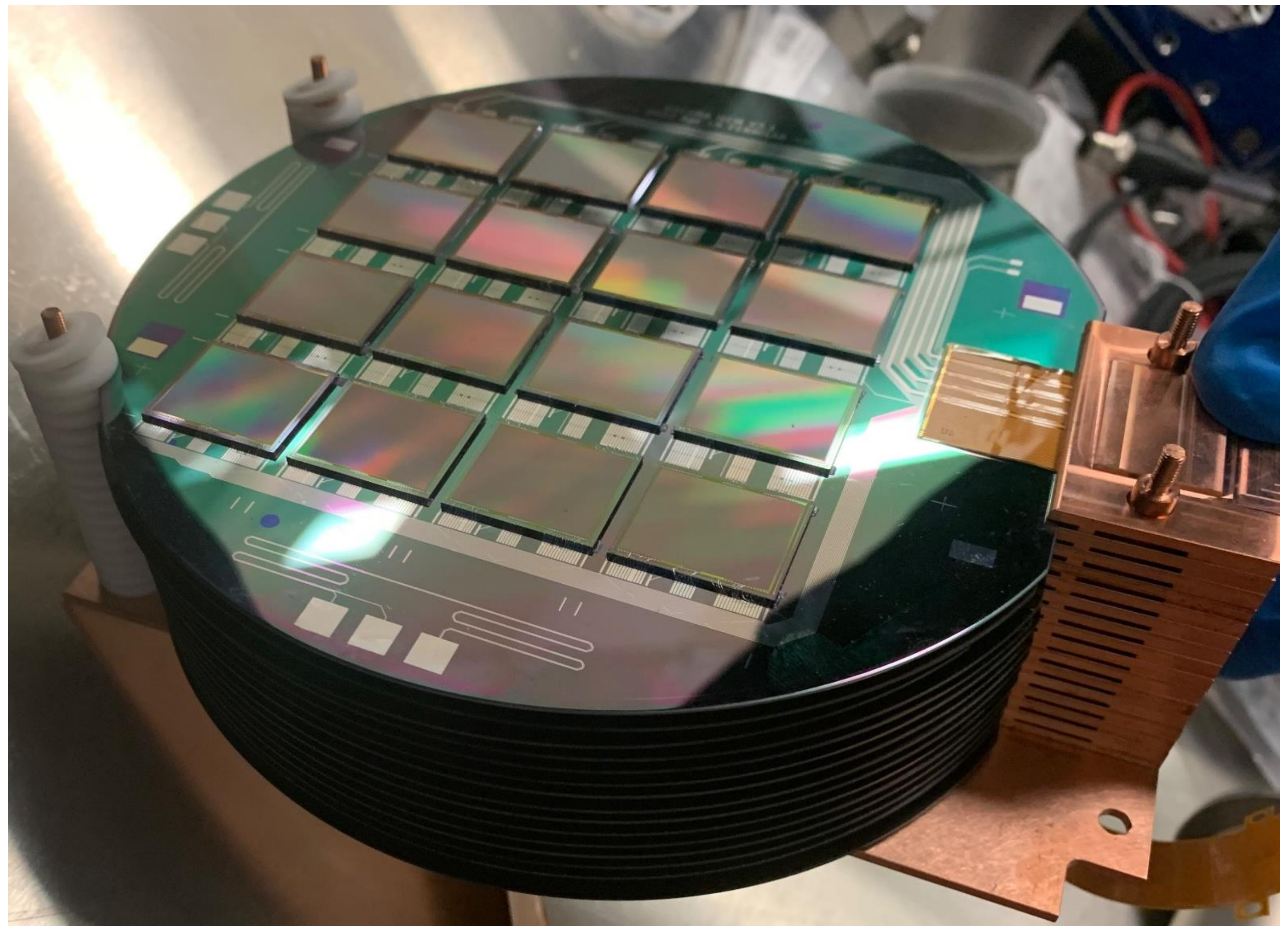
6” ceramic MCM 2022

Low background solution (Silicon)



6” Si MCM 2022 : fabs and ANL + FNAL

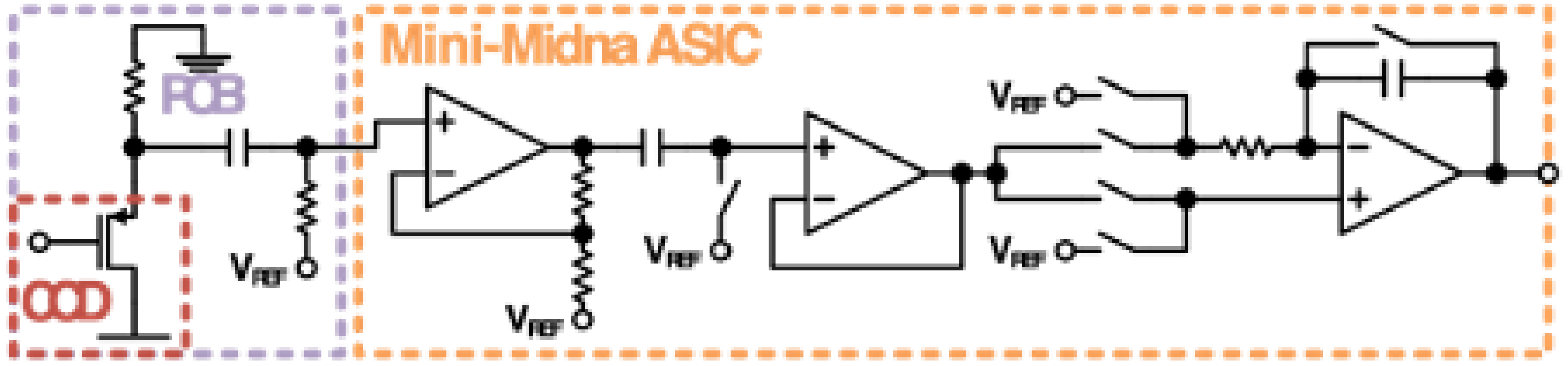
Mechanical prototype of the Oscura Supermodule with 130g of CCDs (16 MCMs)

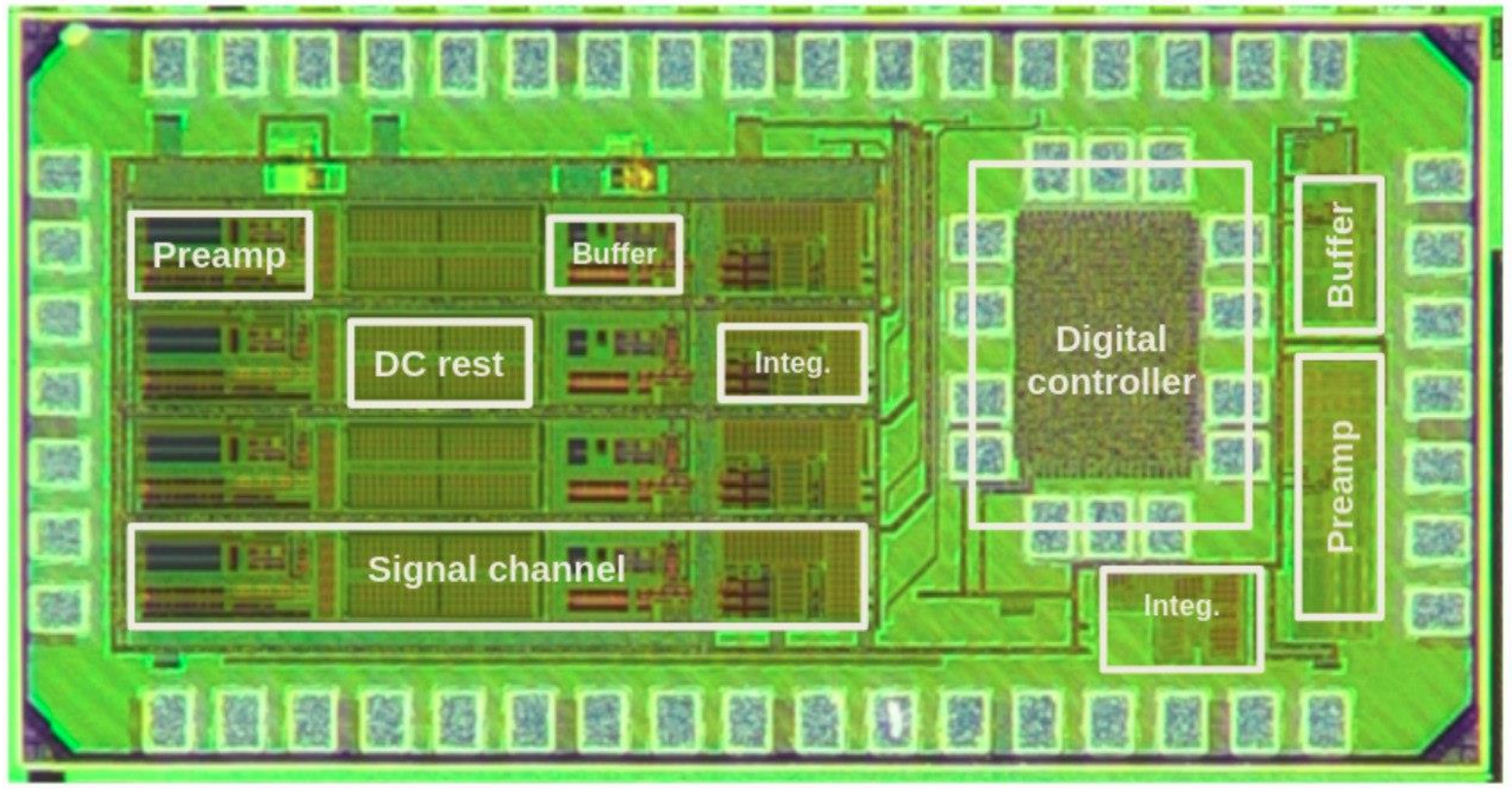


After a few iterations on the design of the Si-MCM we have now tested it, and are confident we can achieve the Oscura specs.

Completed R&D : electronics

Cold front end:



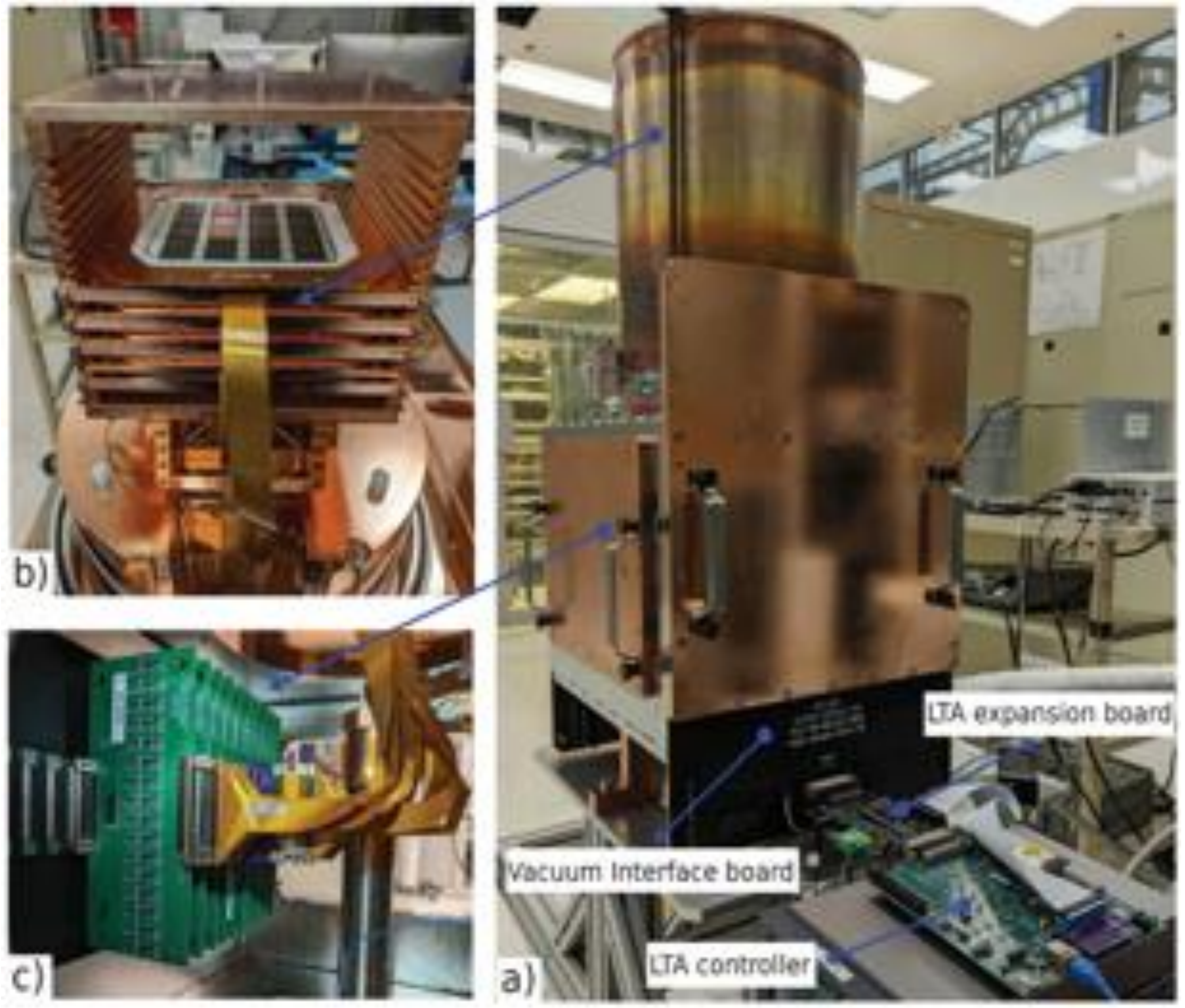


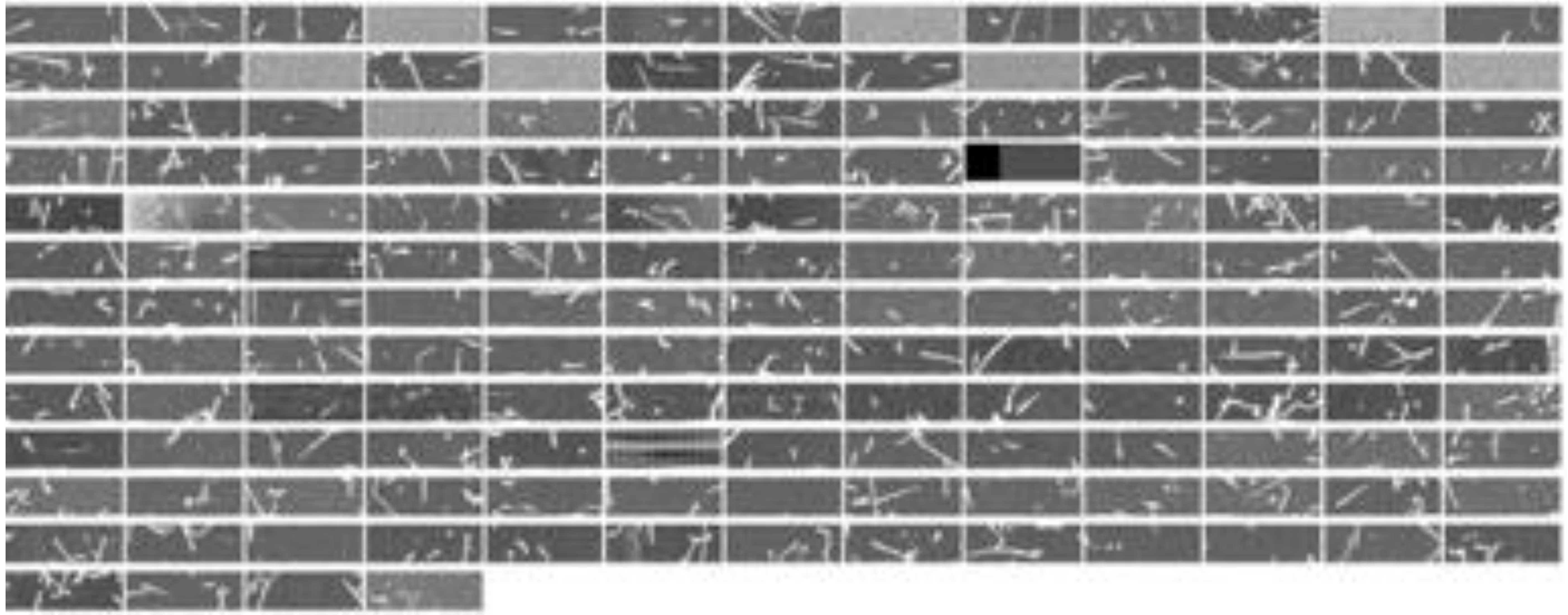
Designed, Fabricated and Tested the MIDNA ASIC. Cold front end electronics for skipper-CCD. 4-channel.

https://arxiv.org/abs/2304.13088

Back end : Designed and tested a multiplexer solution for the back end. Operated 160 CCDs with single readout channel.

Sensors 2022, 22(11), 4308

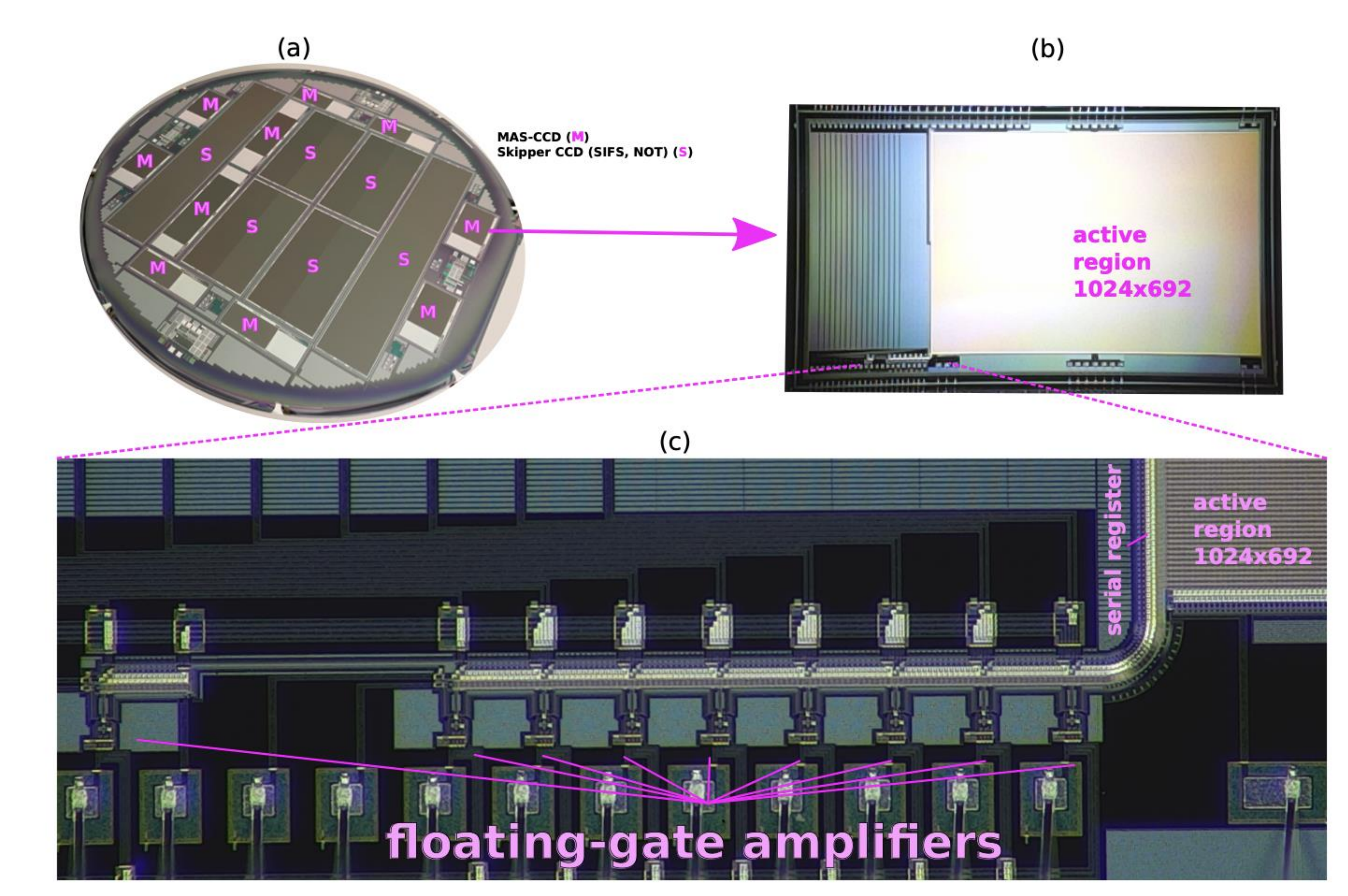


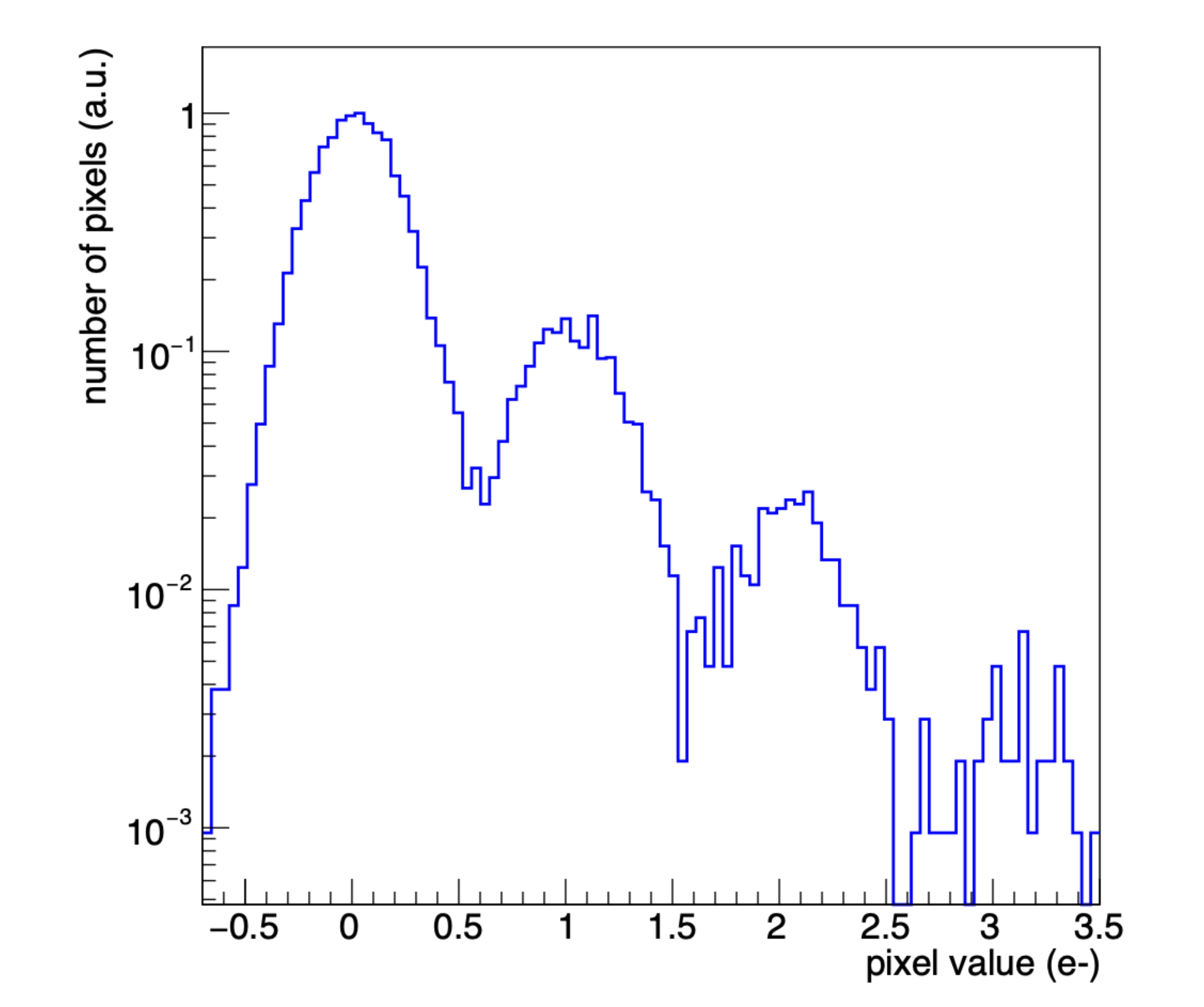


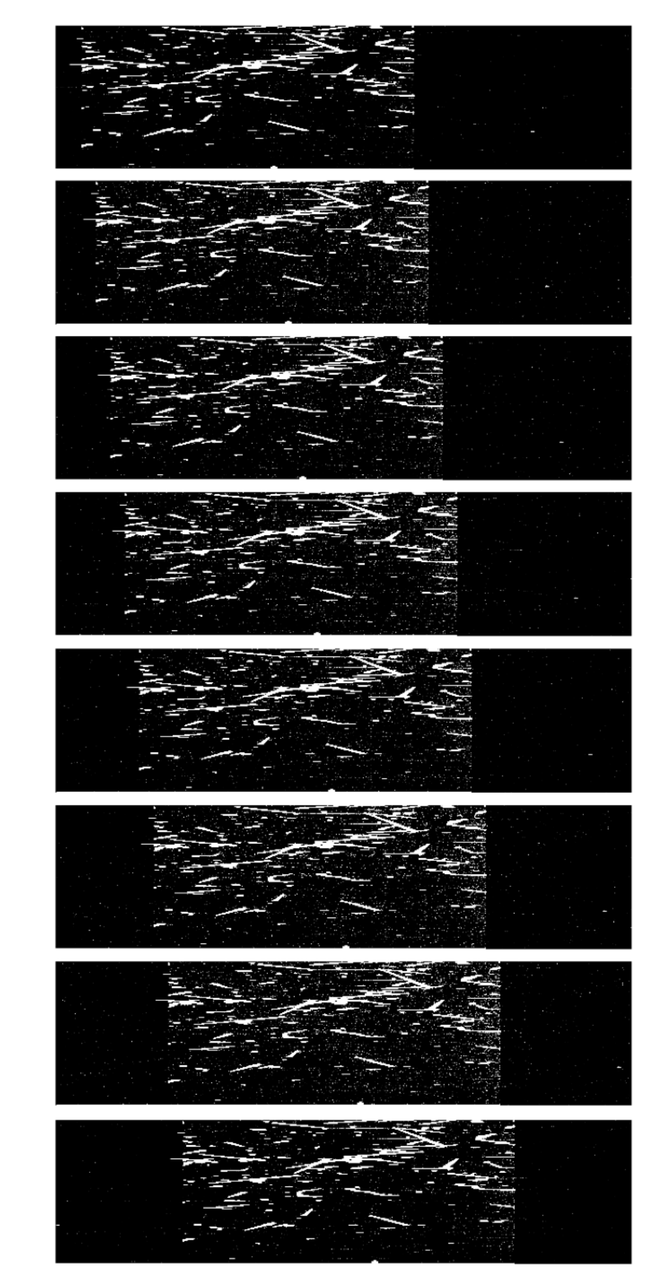
Next : Faster Non-destructive readout.

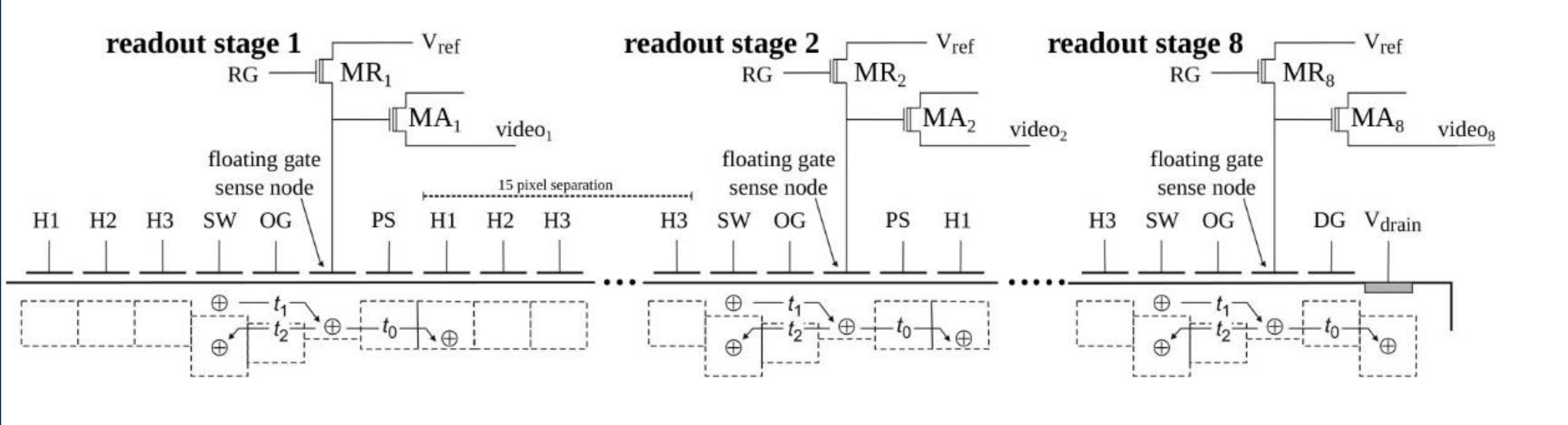
mas-CCD

arXiv:2308.09822







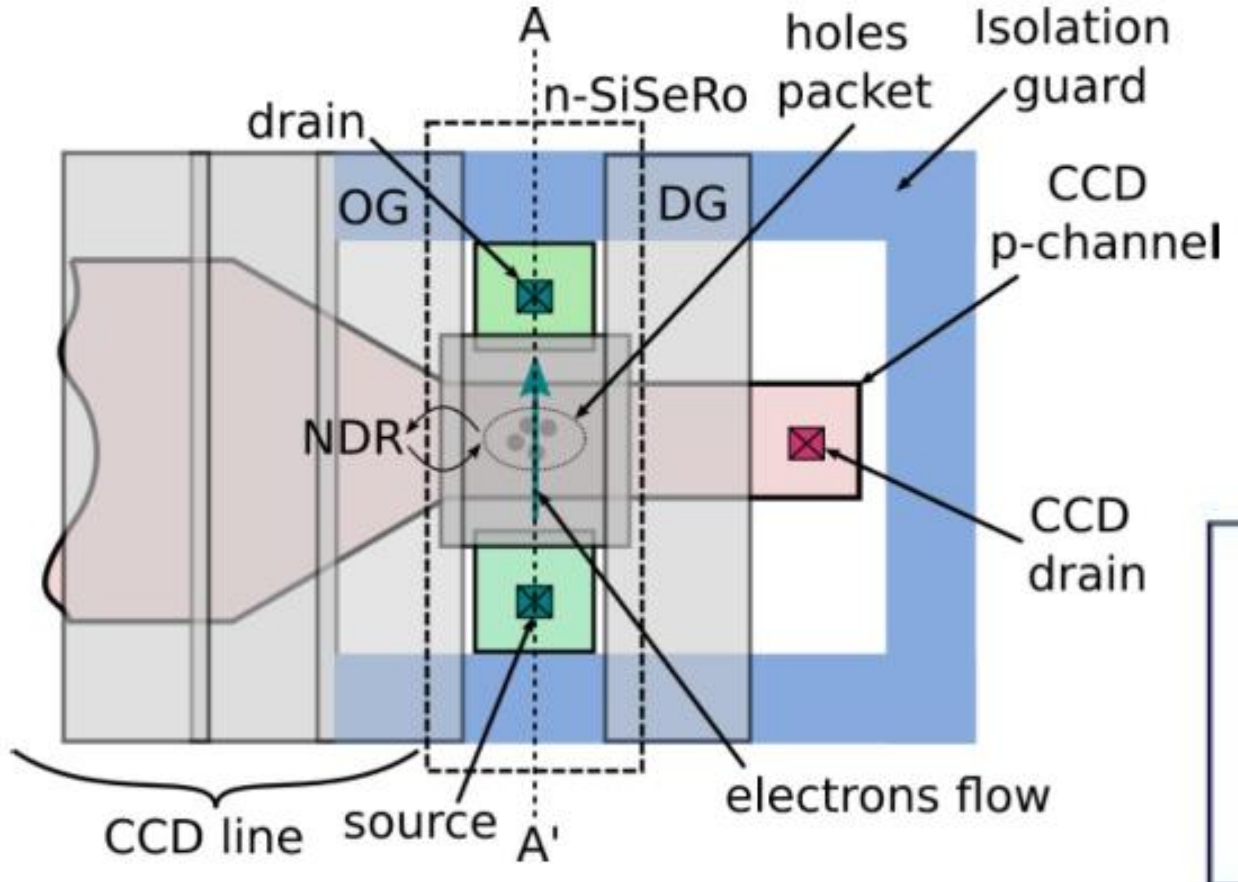


Others sensors in the works

CCDs with n-Sisero stages

[10.1109/TED.2022.3233288]

BERKELEY LAB



[indico.fnal.gov/event/58707]

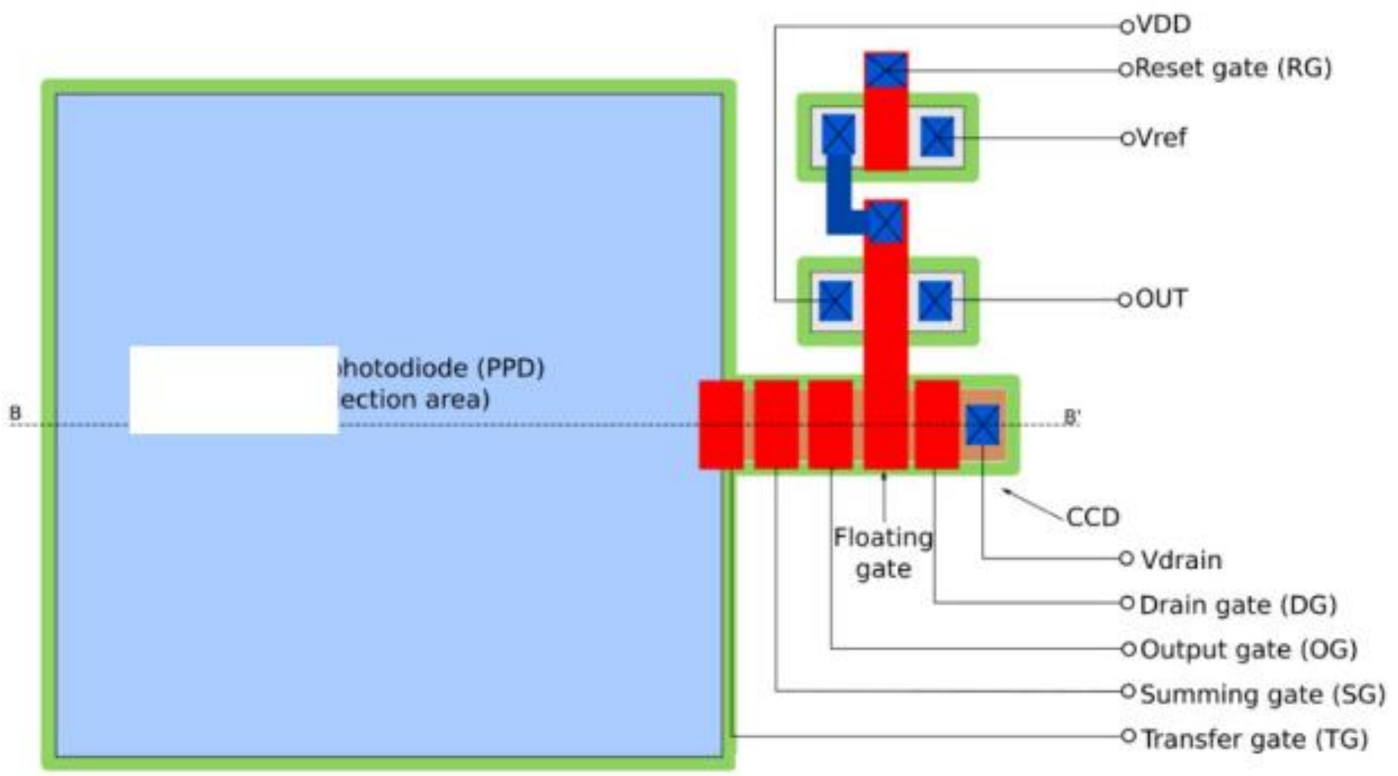
Instituto Balseiro

UNC

Skipper-in-CMOS

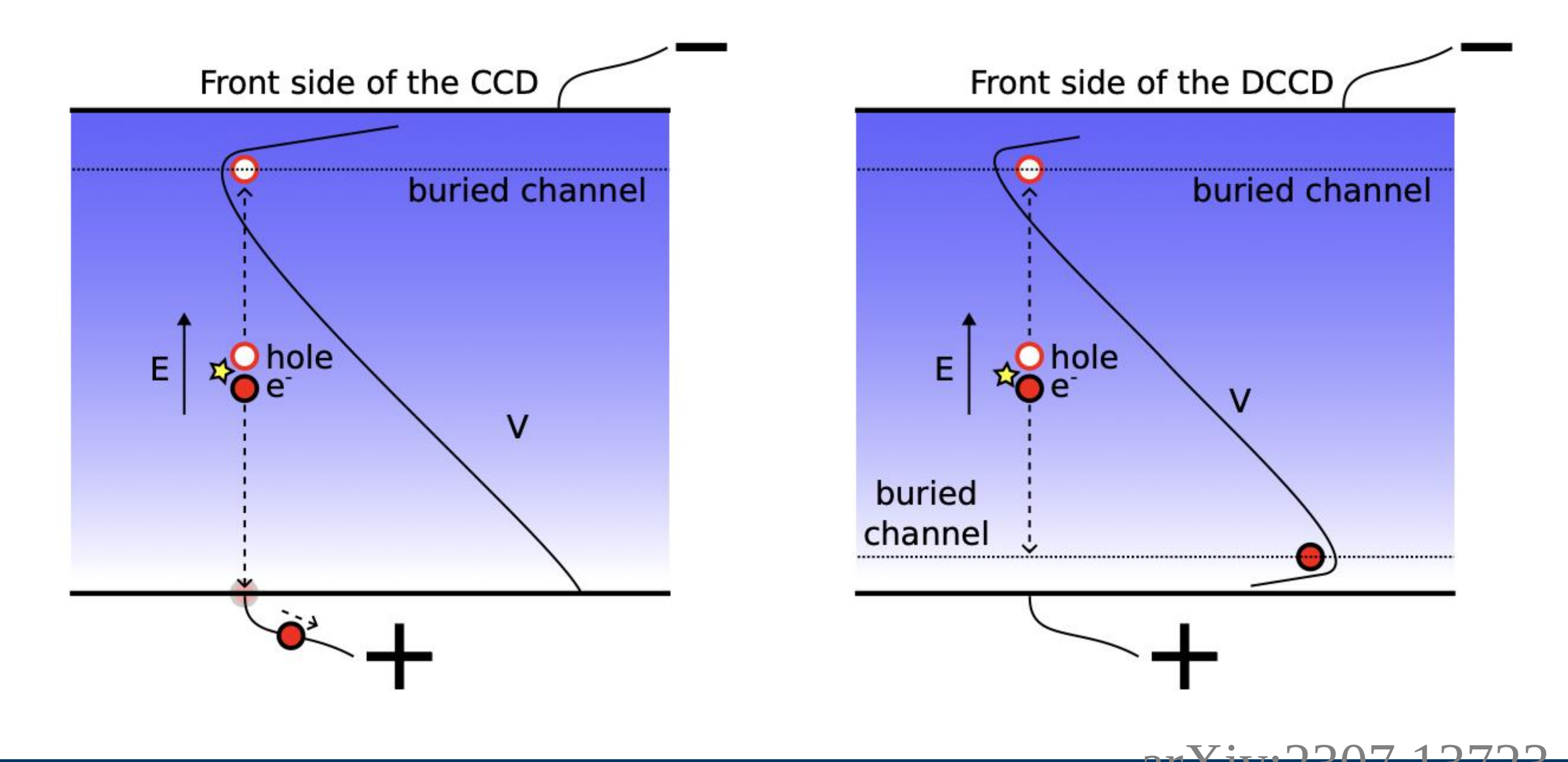
[B. Parpillon @ CPAD 2022]

SLAC NATIONAL ACCELERATOR LABORATORY



No paper with electron counting yet… but soon.

Double-sided CCD (no fab yet)



arXiv:2307.13723

Suppresses surface dark current, also provides timing.

Reading sides in opposite directions.

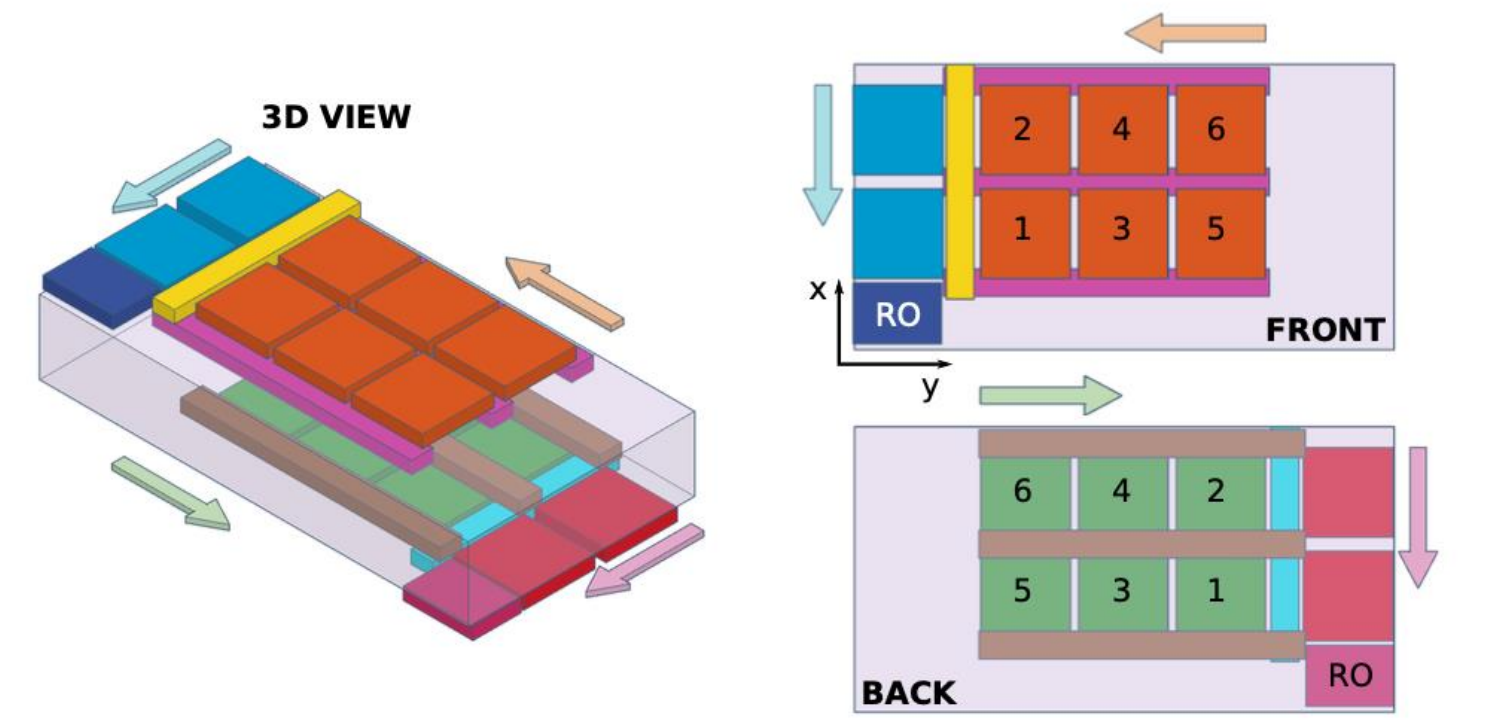


FIG. 4. View of a 3x2 pixels DCCD. Front and backside pixels are shown in dark orange and green, channel stops appear in magenta and brown, and gates are shown in blue and red, respectively. Arrows indicate the direction of charge transfer towards readout. The numbers indicate the pixel readout order on each side. The x is the coordinate along both SRs, and y along the VR of the front CCD.

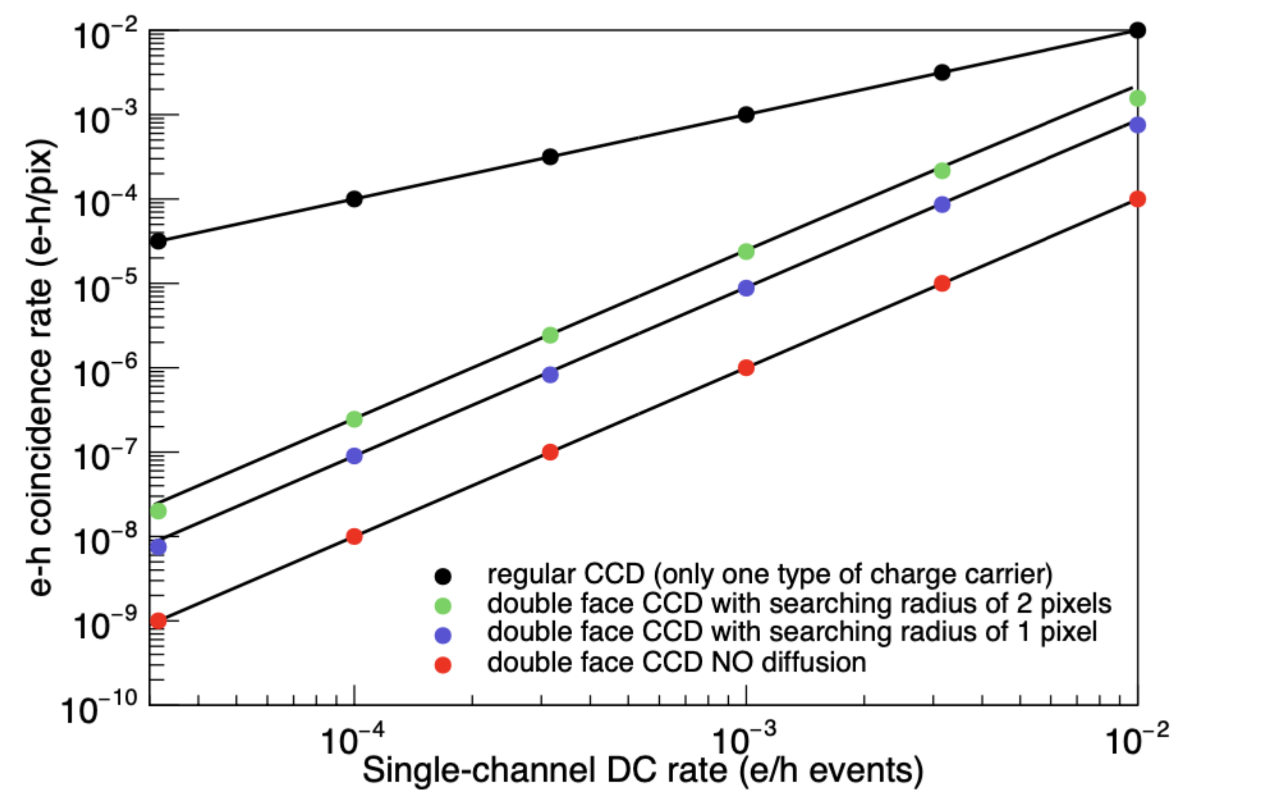


FIG. 5. Rate of coincident $e-h$ events versus the single-channel DC rate within an exposure time, assumed to be the same on both detector sides. Colored circles show the rates for different assumptions regarding bulk carrier diffusion. Black circles show the DC rates for a standard CCD. The plotted range of single-channel DCs represents realistic rates for day-long exposures [8]. The solid black lines are analytic calculations assuming an infinite CCD (see SM).

Now skipper-CCDs for cosmic surveys

It has now become evident that non-destructive readout (skippers) allow adaptive noise on the readout of spectroscopic data. This could have a huge impact in the noise limited cosmic spectroscopic surveys of the future. See arXiv:2103.07527 arXiv:2210.03665).

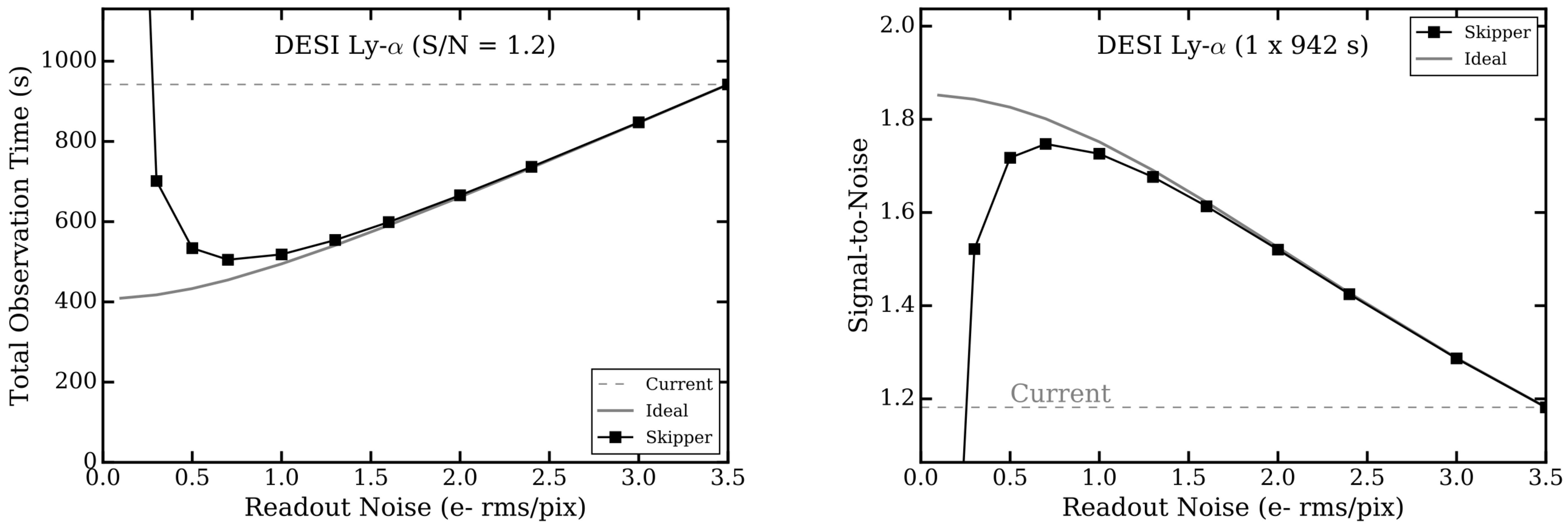


Figure 1: Expected improvement in DESI Lyman-α observations from reduced readout noise. The gray line shows the ideal case where readout noise is reduced without increasing readout time, while the black line shows the expected performance of a Skipper CCDs that reduces readout noise over 5% of the detector area. Left: Decrease in the required observation time (the sum of the exposure time and readout time) to reach a fixed S/N. Right: Increased S/N at fixed observation time as a function of readout noise.

First test of skipper-CCD in a telescope coming soon (SIFS at SOAR 4m, Alex Drlica-Wagner et al). These sensors could also play an important role in photon counting for future large space telescopes (working with NASA/GSFC)

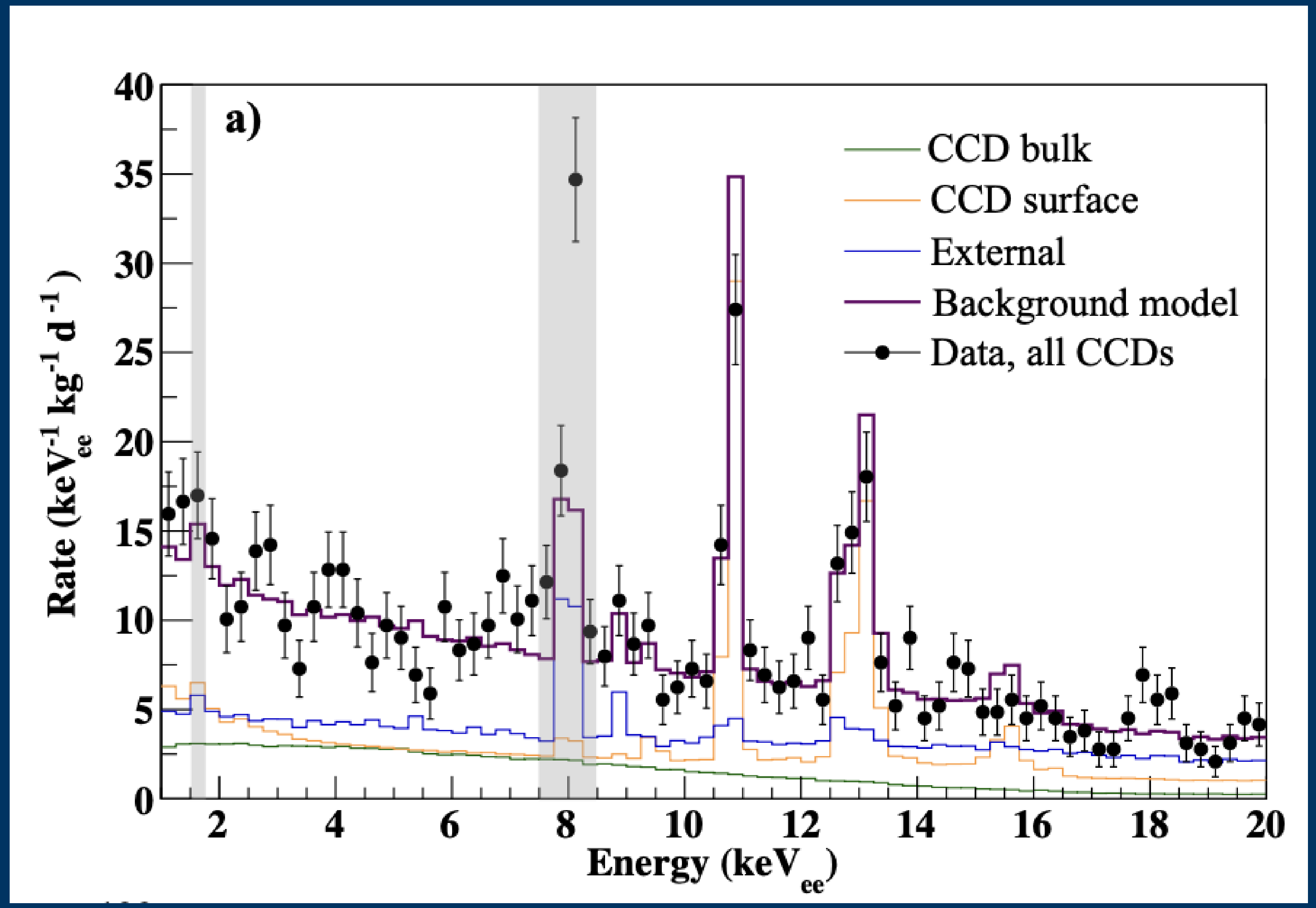
Conclusion

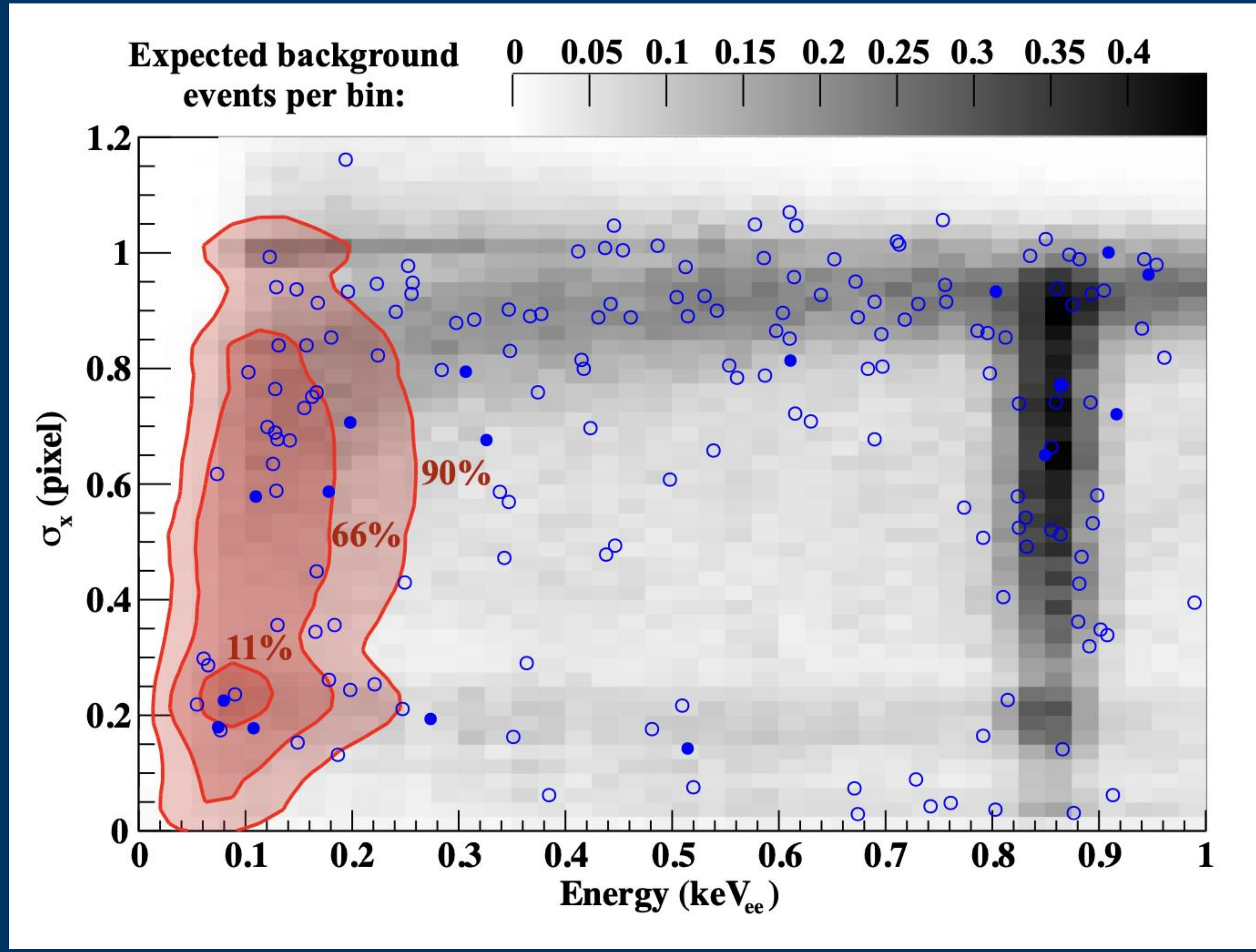
- Future looks exciting for silicon detectors with non destructive readout NDR (skipper-CCDs and more).
- Originally developed for astronomy, NDR has found extensive use in dark matter (and low threshold experiments, Quantum imaging).
- Recently commercial companies are starting to fabricate skipper-CCDs (STA).
- Now, with faster readout architectures, NDR is coming back to the telescopes in the ground and in space.

DAMIC : excess over expected background

Phys. Rev. Lett. 125, 241803 (2020)

Phys. Rev. D 105, 062003 (2022)





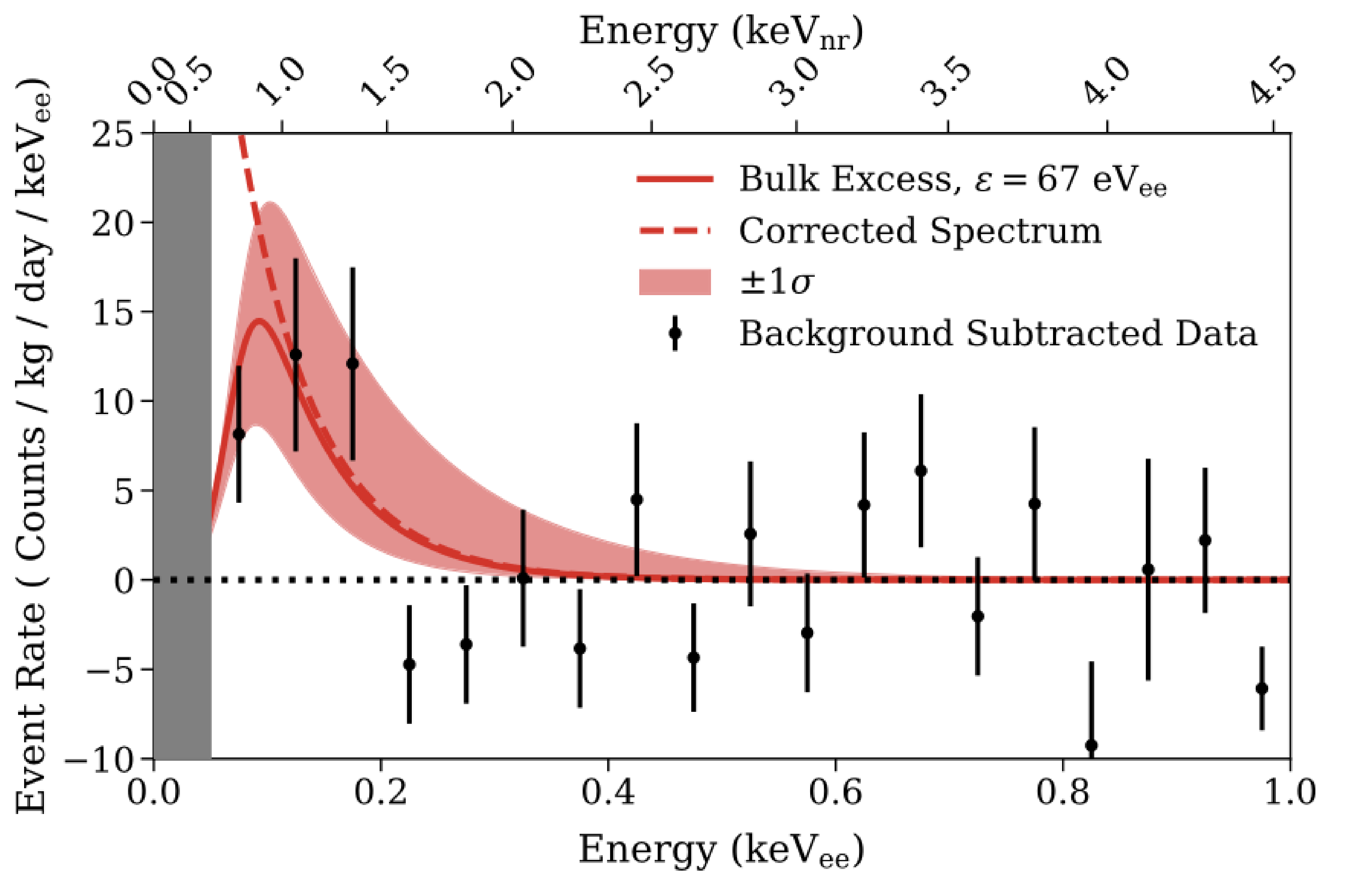
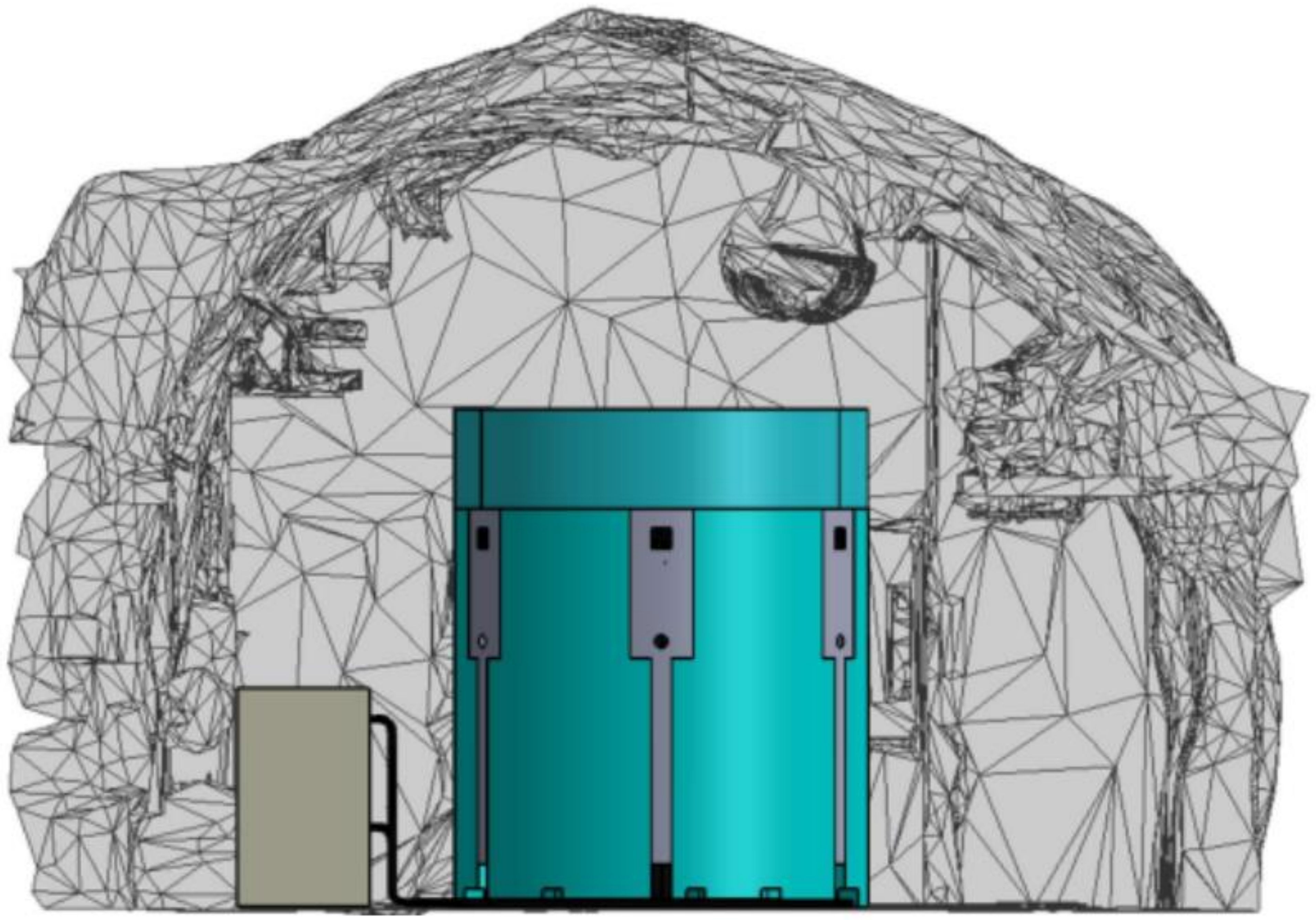


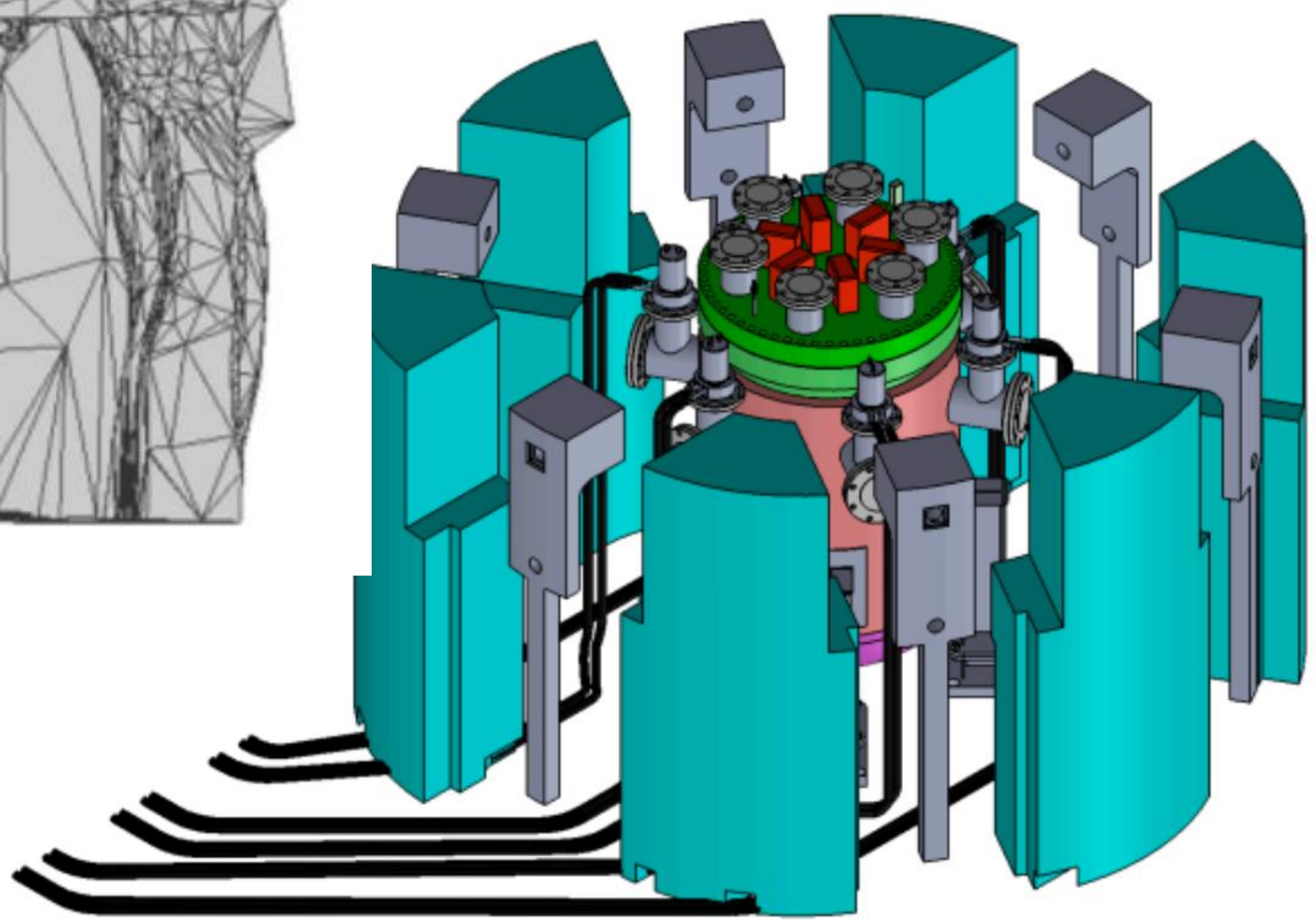
FIG. 14. Energy spectrum of the best-fit generic signal (red lines) overlaid on the background-subtracted data (markers). Both the fit spectrum that includes the detector response (solid line) and the spectrum corrected for the detection efficiency (dashed line) are provided. The red shaded region represents the 1-σ uncertainty from the likelihood-ratio tests. For reference, the equivalent nuclear recoil energy (keV$_{nr}$) is shown on the top axis; the ionization efficiency is taken from the direct calibration performed in Ref. [77].

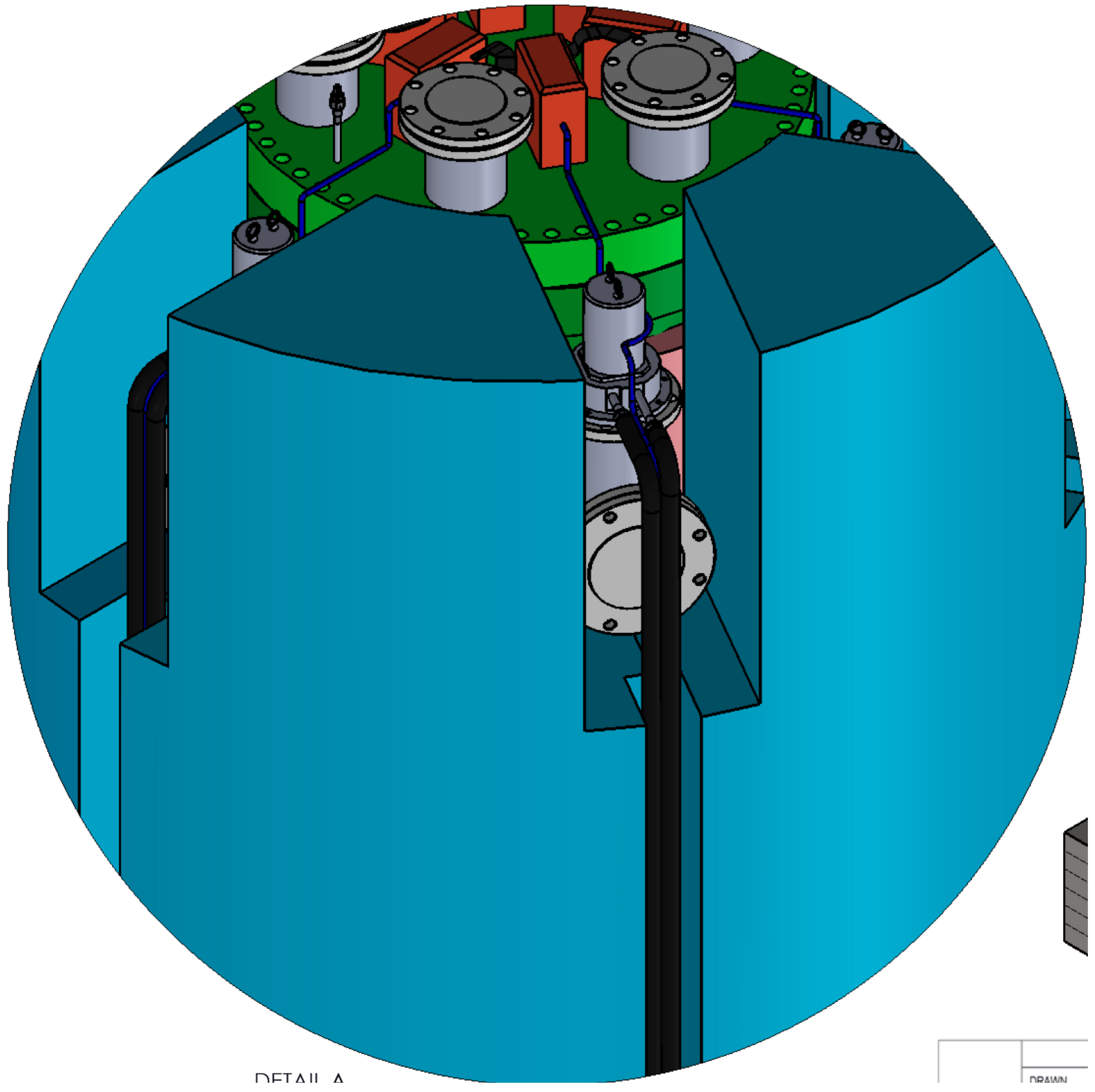
Design: outer shield and installation inside SNOLAB



In the SNOLAB drift

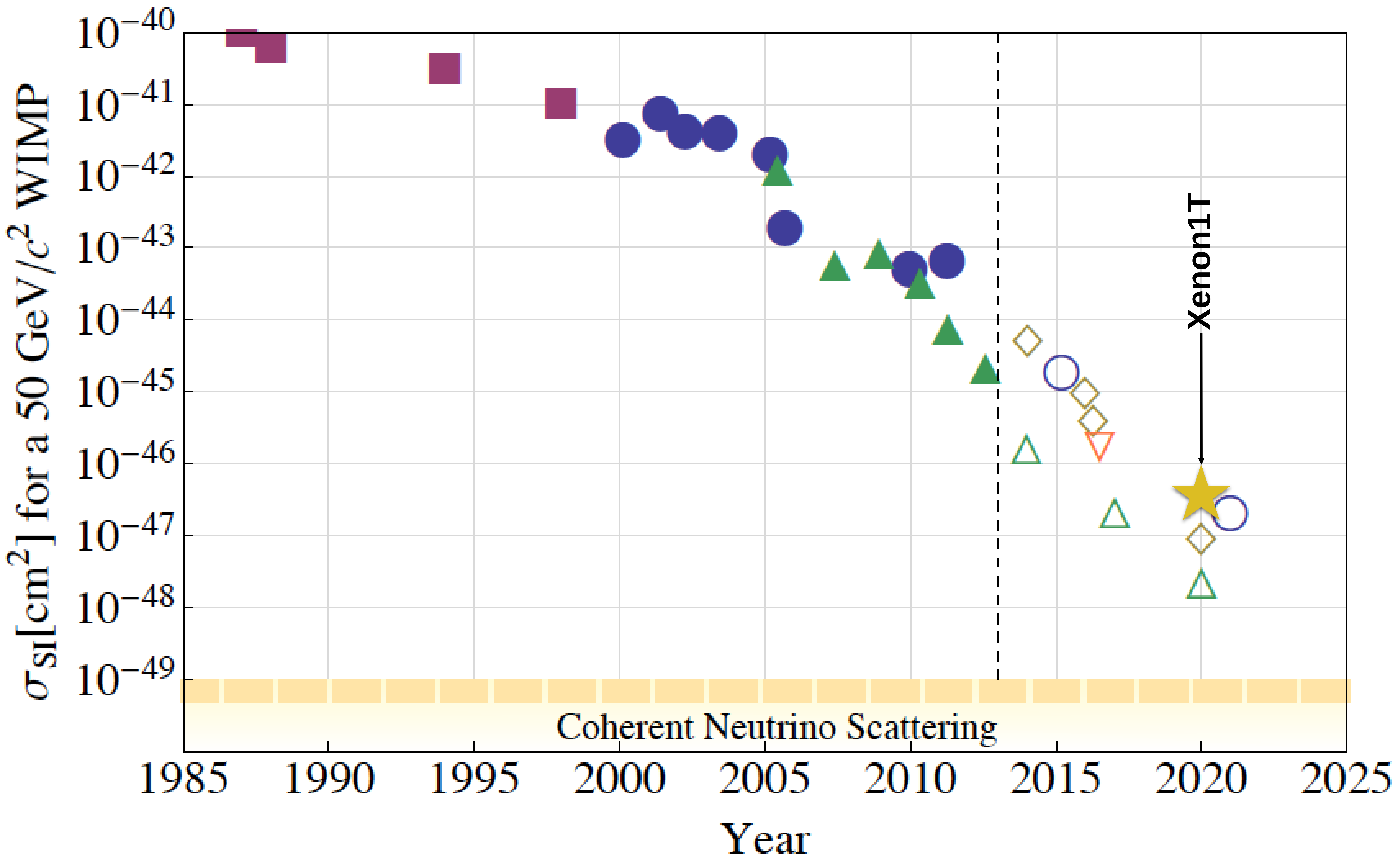
Outer shield assembly





Detail of helium lines

tremendous progress over 30 years



Snowmass report (2013)