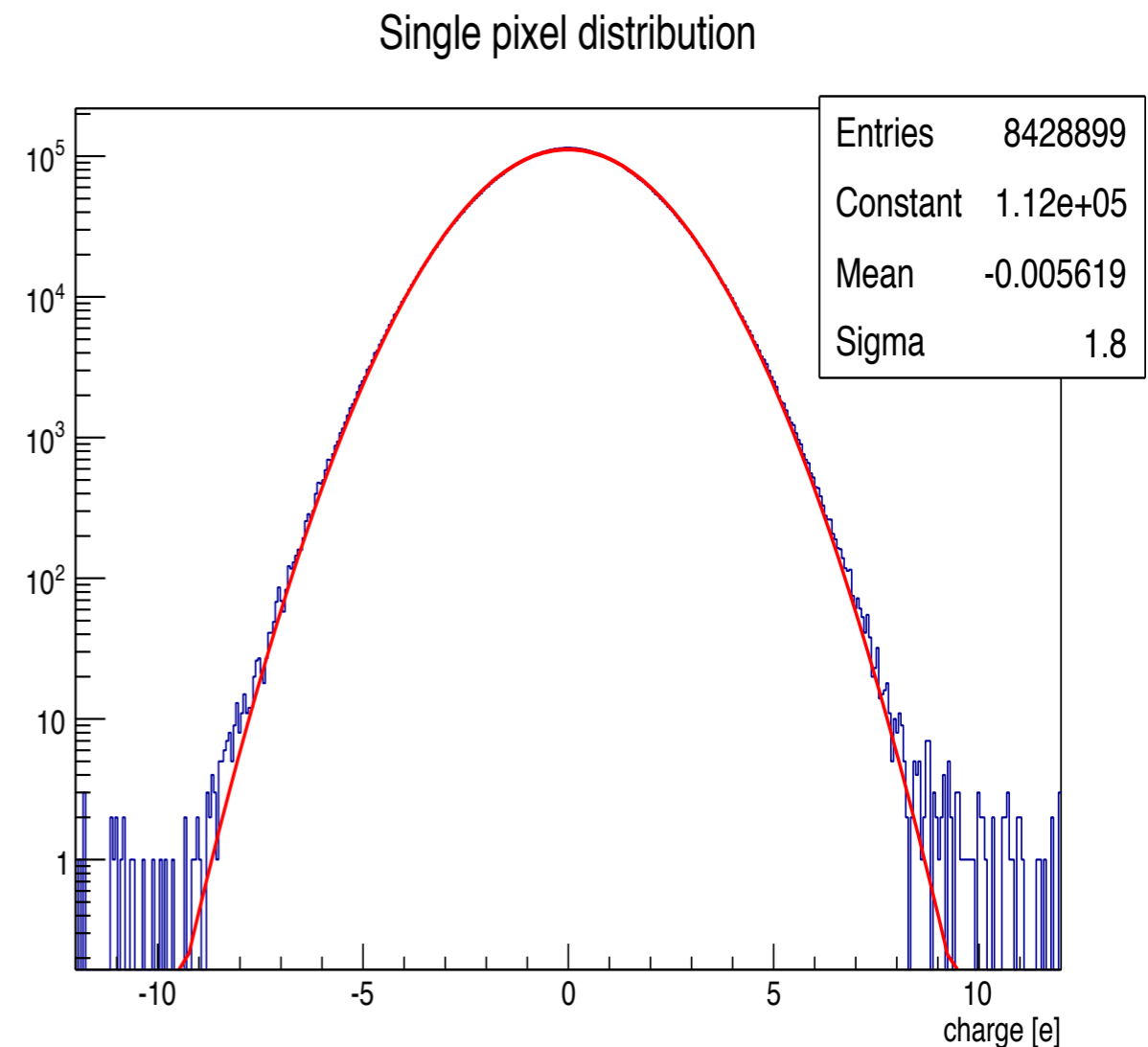
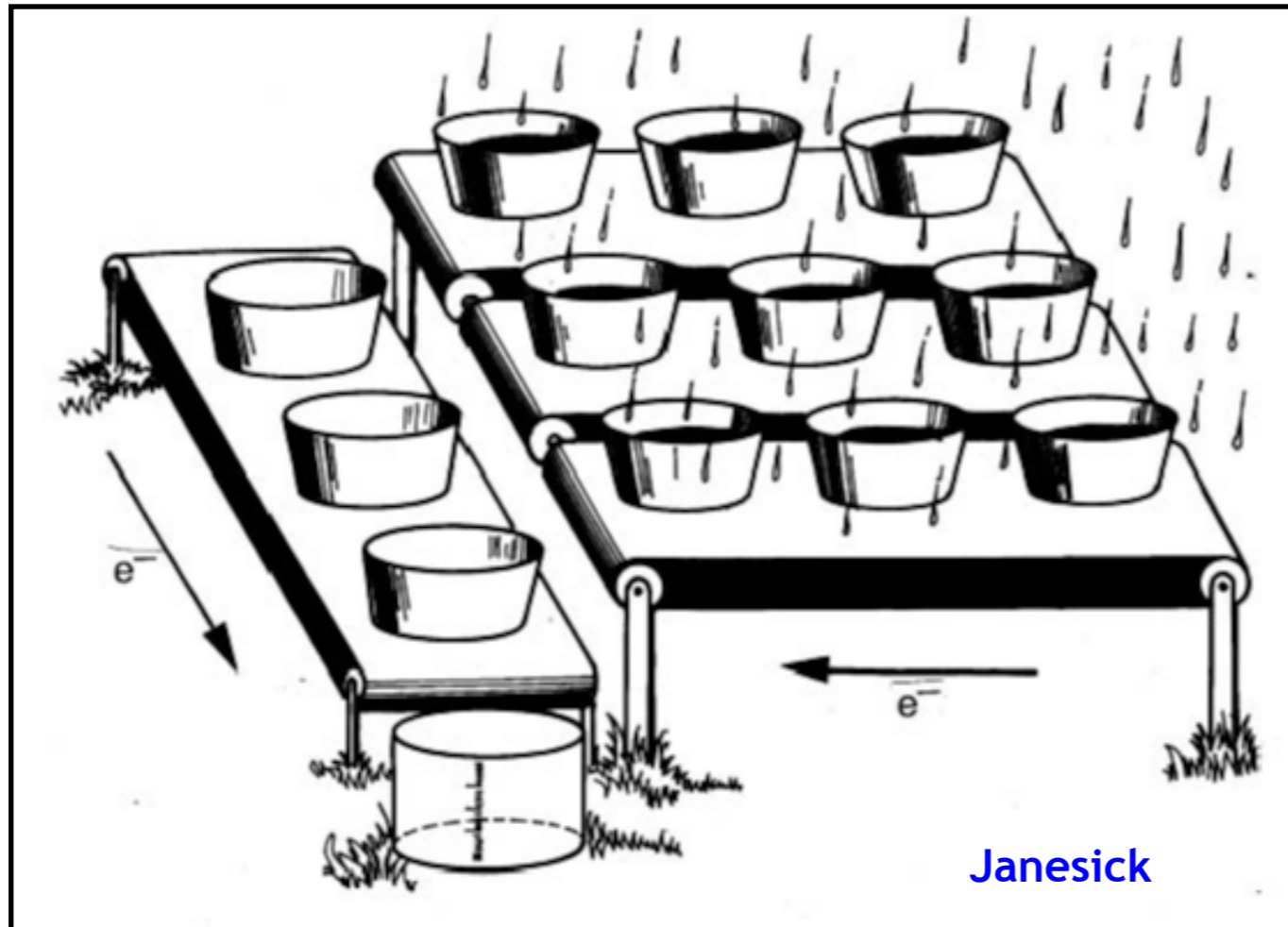
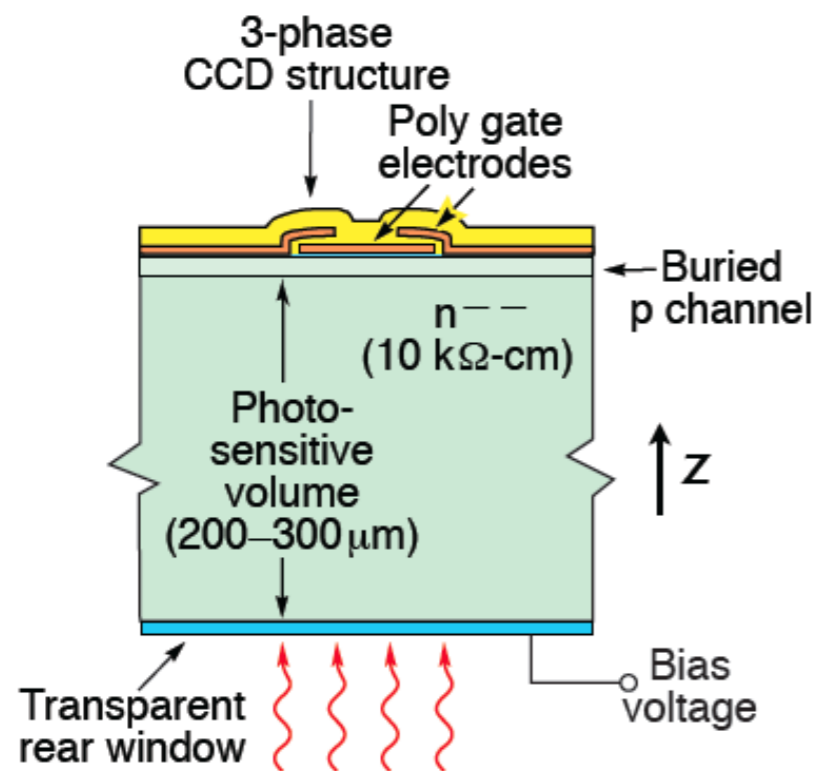


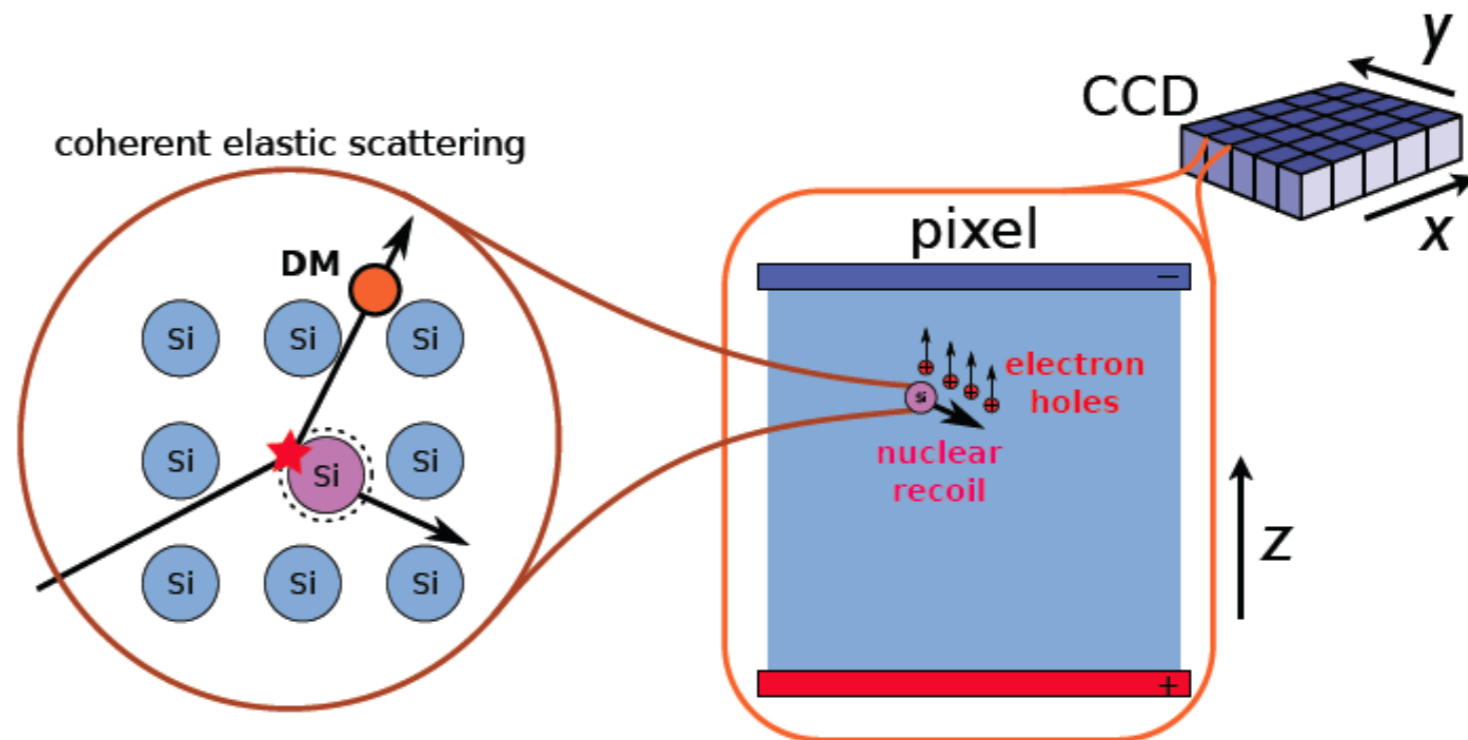
Charge-Coupled Device (CCD)



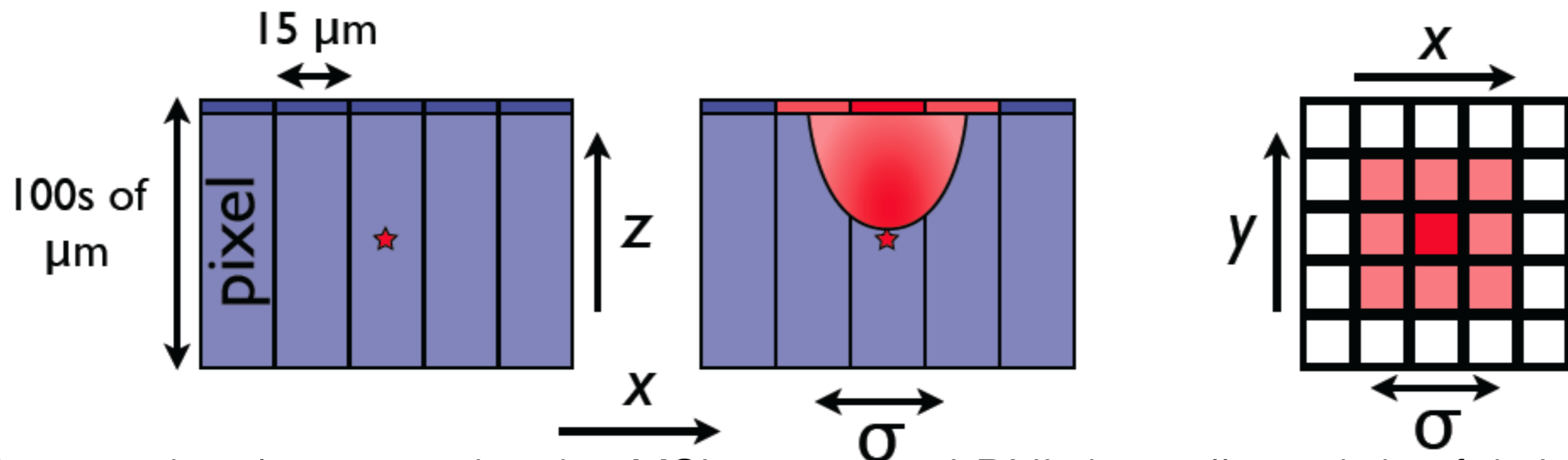
Charge coupling makes the detectors ideal for low noise measurements, typical noise for scientific CCDs is $2e^-$ RMS (7.2eV). Very recent work pushing this to “0” noise.



(a) A CCD pixel

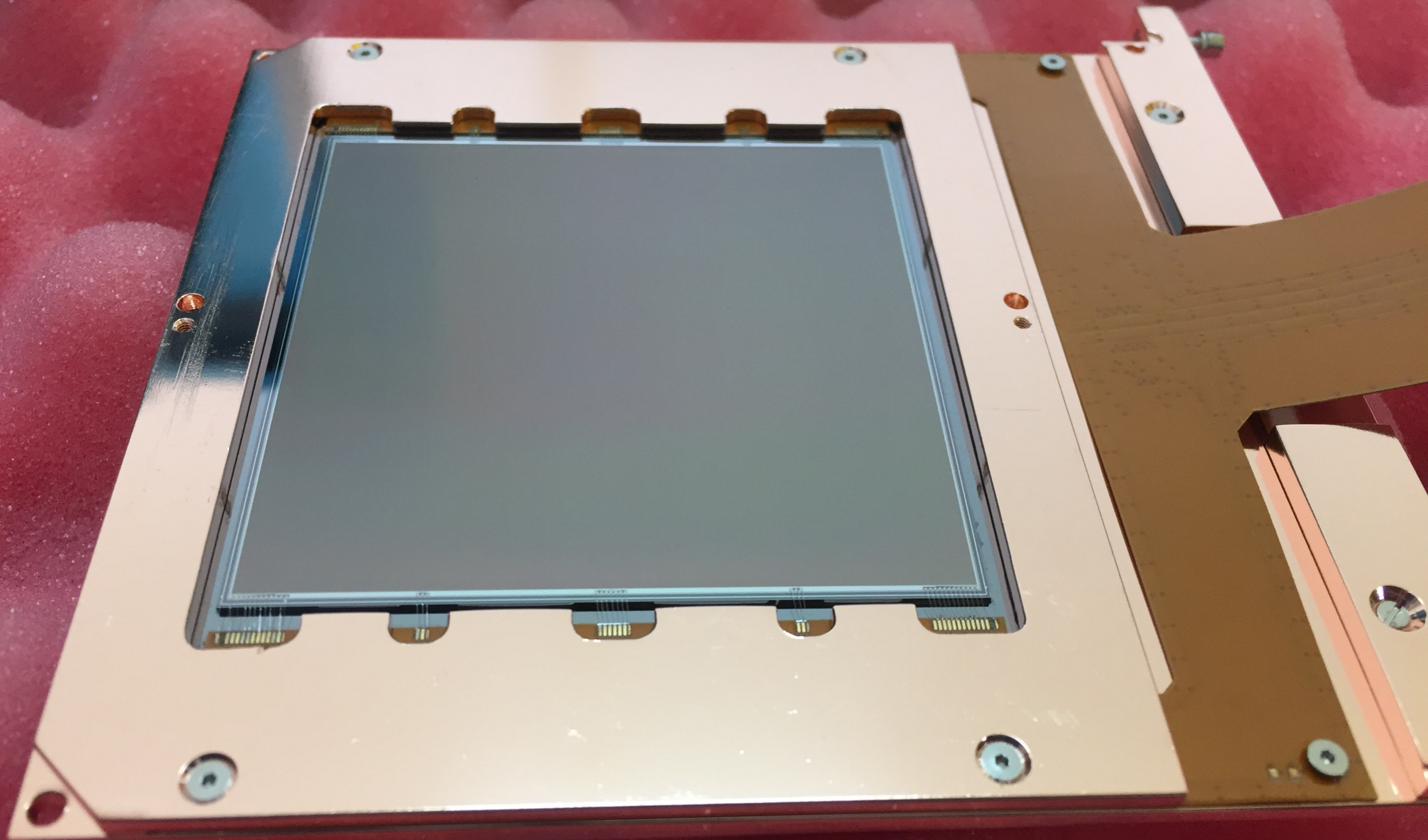


(b) WIMP detection principle



Recent developments by the MSL group at LBNL has allowed the fabrication for “massive” CCDs. 675 μm is now possible.

CONNIE-DAMIC 2016 sensors



4 amplifiers
2e- noise
low background package

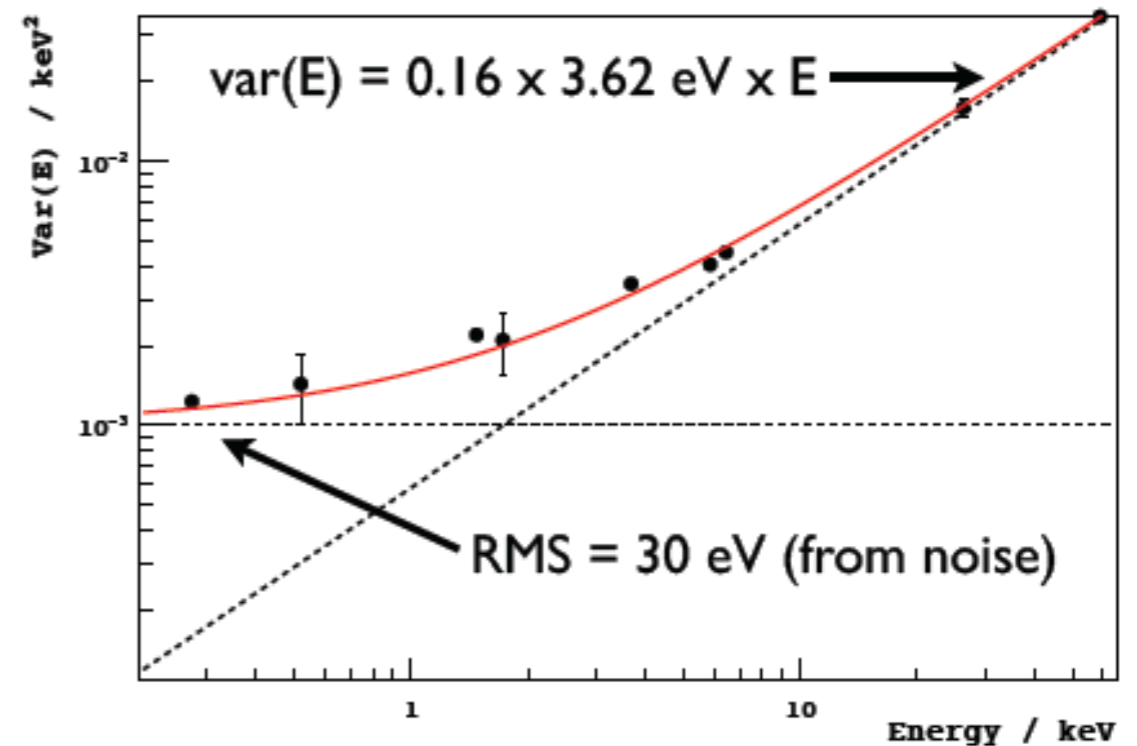
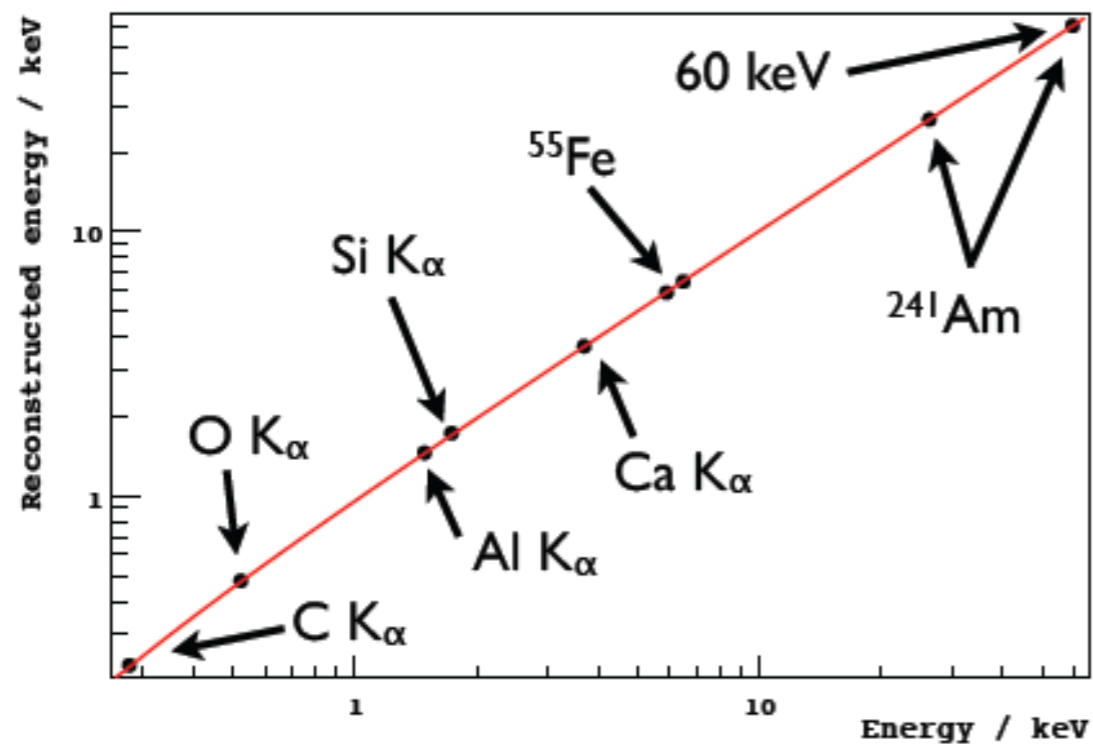
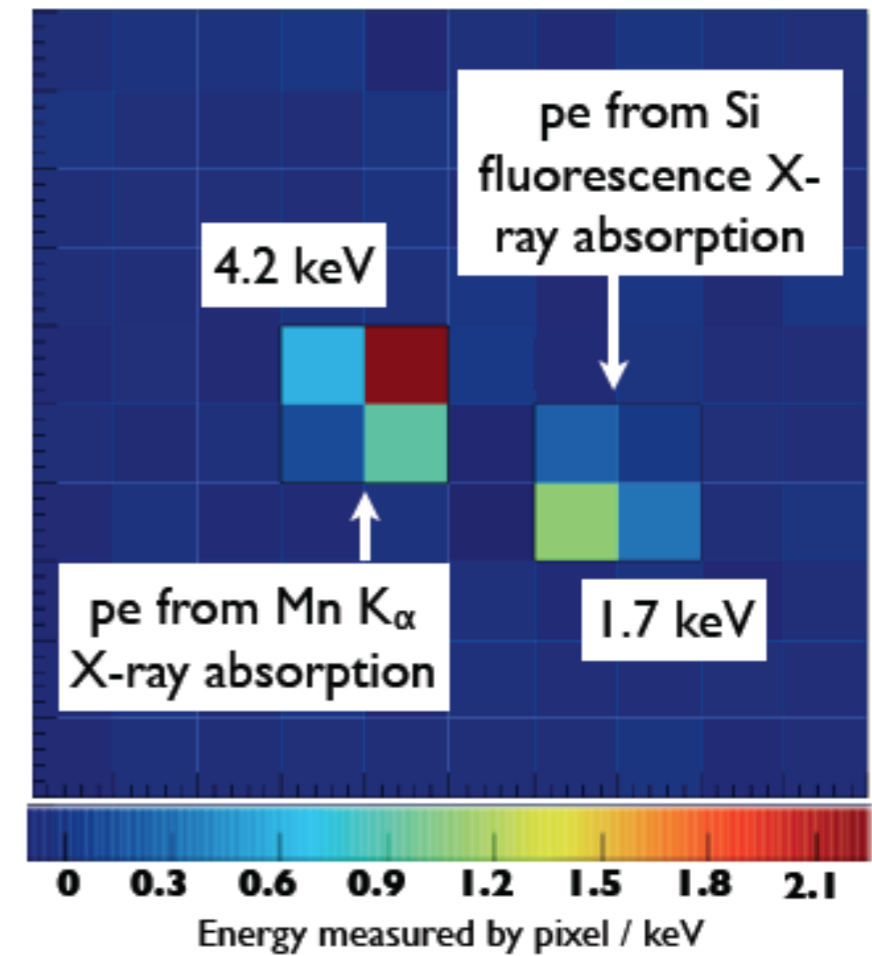
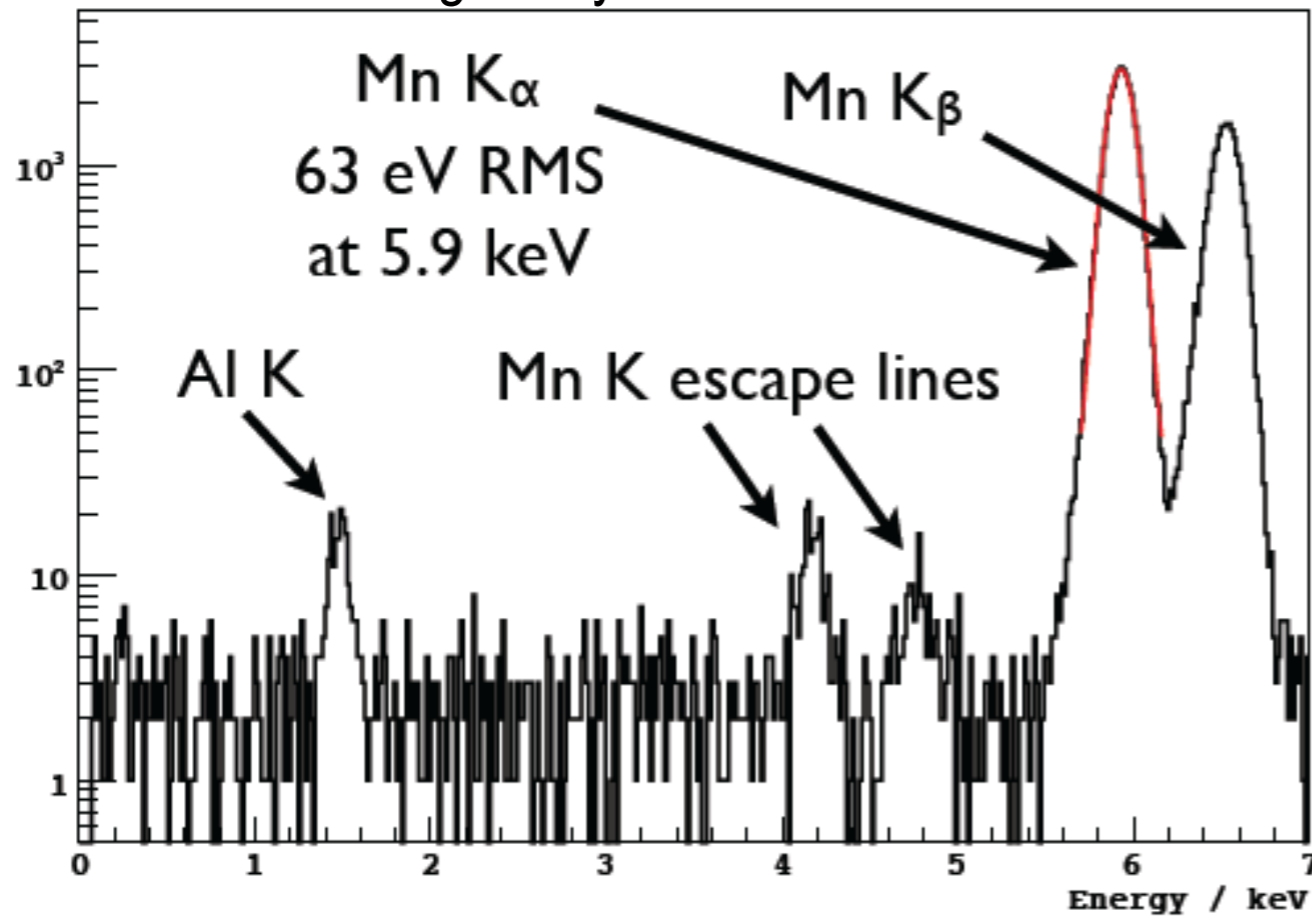
16 Mpix — 6g

Particle identification in a CCD image



muons, electrons and diffusion limited hits.

Calibration using X-rays



DAMIC Collaboration

2014

Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment

A. Aguilar-Arevalo^a, D. Amidei^b, X. Bertou^c, D. Bole^b, M. Butner^{d,j}, G. Canelo^d, A. Castañeda Vázquez^a, A.E. Chavarria^a, J.R.T. de Mello Neto^f, S. Dixon^e, J.C. D'Olivo^g, J. Estrada^h, G. Fernandez Moroniⁱ, K.P. Hernández Torres¹, F. Izraelevitch^d, A. Kavner², B. Kilminster³, I. Lawson¹², J. Liao¹¹, M. López², J. Molina⁷, G. Moreno-Granados², J. Peña², P. Privitera⁶, Y. Sarkis¹, V. Scarpine^d, T. Schwarz⁶, M. Sofo Haro³, J. Tiffenberg⁴, D. Torres Machado⁸, F. Trillaud¹, X. You⁸ and J. Zhou⁶

^a Universidad Nacional Autónoma de México, México D.F., México

^b University of Michigan, Department of Physics, Ann Arbor, MI, United States

^c Centro Atómico Bariloche - Instituto Balseiro, CNEA/CONICET, Argentina

^d Fermi National Accelerator Laboratory, Batavia, IL, United States

^e Kavli Institute for Cosmological Physics and The Enrico Fermi Institute, The University of Chicago, Chicago, IL, United States

^f Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil

^g Universität Zürich Physik Institut, Zurich, Switzerland

^h SNOLAB, Lively, ON, Canada

ⁱ Facultad de Ingeniería - Universidad Nacional de Asunción, Paraguay

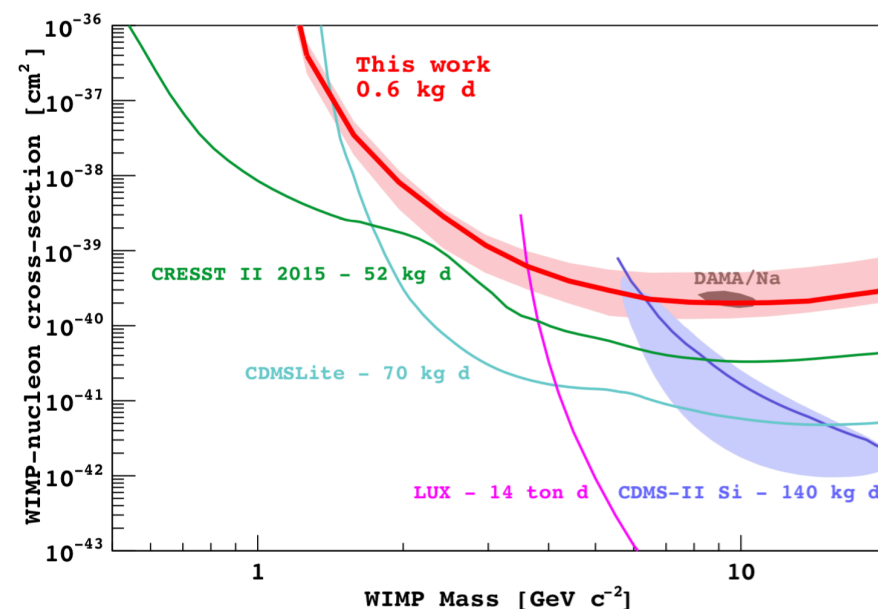
^j Northern Illinois University, DeKalb, IL, United States

2016

Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB

A. Aguilar-Arevalo¹, D. Amidei², X. Bertou³, M. Butner^{4,5}, G. Canelo⁴, A. Castañeda Vázquez¹, B.A. Cervantes Vergara¹, A.E. Chavarria⁶, C.R. Chavez⁷, J.R.T. de Mello Neto⁸, J.C. D'Olivo¹, J. Estrada⁴, G. Fernandez Moroni^{4,9}, R. Gañor¹⁰, Y. Guardincerri⁴, K.P. Hernández Torres¹, F. Izraelevitch⁴, A. Kavner², B. Kilminster¹¹, I. Lawson¹², A. Letessier-Selvon¹⁰, J. Liao¹¹, V.B.B. Mello⁸, J. Molina⁷, J.R. Peña⁶, P. Privitera⁶, K. Ramanathan⁶, Y. Sarkis¹, T. Schwarz², C. Sengul⁶, M. Settimo¹⁰, M. Sofo Haro³, R. Thomas⁶, J. Tiffenberg⁴, E. Tiouchichine³, D. Torres Machado⁸, F. Trillaud¹, X. You⁸ and J. Zhou⁶

(DAMIC Collaboration)



First Direct-Detection Constraints on eV-Scale Hidden-Photon Dark Matter with DAMIC at SNOLAB

A. Aguilar-Arevalo¹, D. Amidei², X. Bertou³, M. Butner^{4,5}, G. Canelo⁴, A. Castañeda Vázquez¹, B.A. Cervantes Vergara¹, A.E. Chavarria⁶, C.R. Chavez⁷, J.R.T. de Mello Neto⁸, J.C. D'Olivo¹, J. Estrada⁴, G. Fernandez Moroni^{4,9}, R. Gañor¹⁰, Y. Guardincerri⁴, K.P. Hernández Torres¹, F. Izraelevitch⁴, A. Kavner², B. Kilminster¹¹, I. Lawson¹², A. Letessier-Selvon¹⁰, J. Liao¹¹, A. Matalon⁶, V.B.B. Mello⁸, J. Molina⁷, P. Privitera⁶, K. Ramanathan⁶, Y. Sarkis¹, T. Schwarz², M. Settimo¹⁰, M. Sofo Haro³, R. Thomas⁶, J. Tiffenberg⁴, E. Tiouchichine³, D. Torres Machado⁸, F. Trillaud¹, X. You⁸ and J. Zhou⁶

(DAMIC Collaboration)

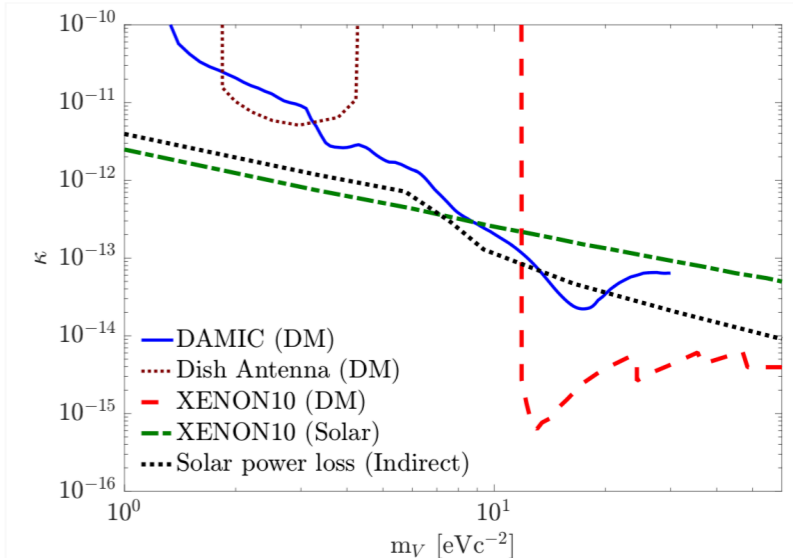


FIG. 5. Exclusion plot (90% C.L.) for the hidden-photon kinetic mixing κ as a function of hidden photon mass m_V from the dark matter search presented in this Letter (solid line). The exclusion limits from other direct searches for hidden-photon dark matter in the galactic halo with a dish antenna (thin dotted line) [13] and with the XENON10 experiment (dashed line) [5] are shown for comparison. A limit from a direct search with the XENON10 experiment for hidden photons radiated by the Sun (dot-dashed line) [5] and an indirect constraint from the upper limit of the power lost by the Sun into invisible radiation (thick dotted line) [14] are also presented.

arXiv:1907.12628
on e-recoil DM (in a few slides)

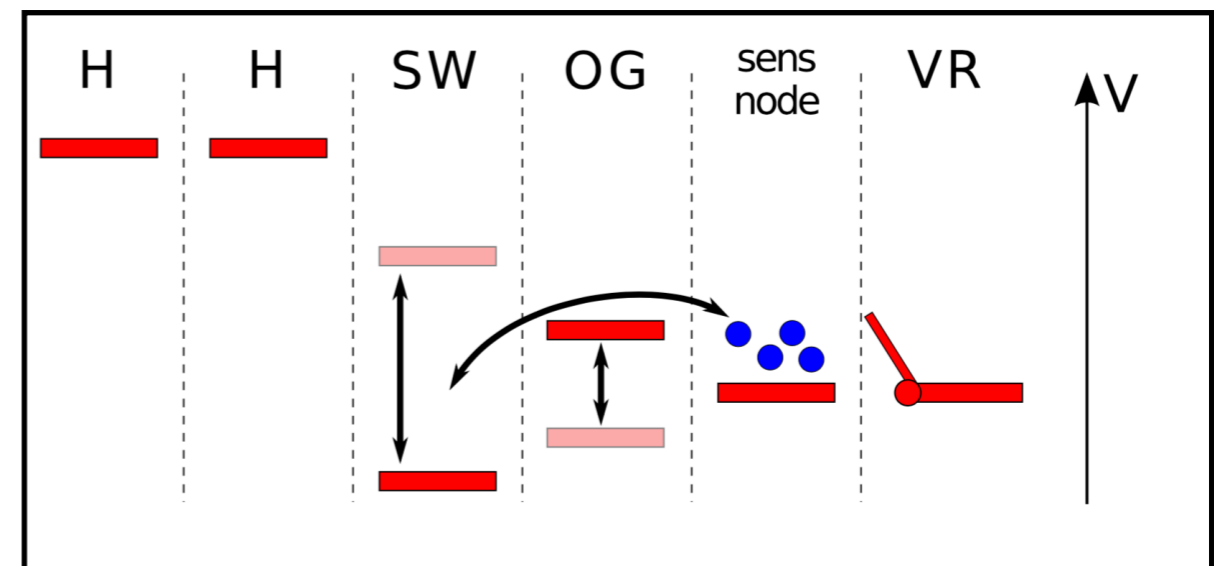
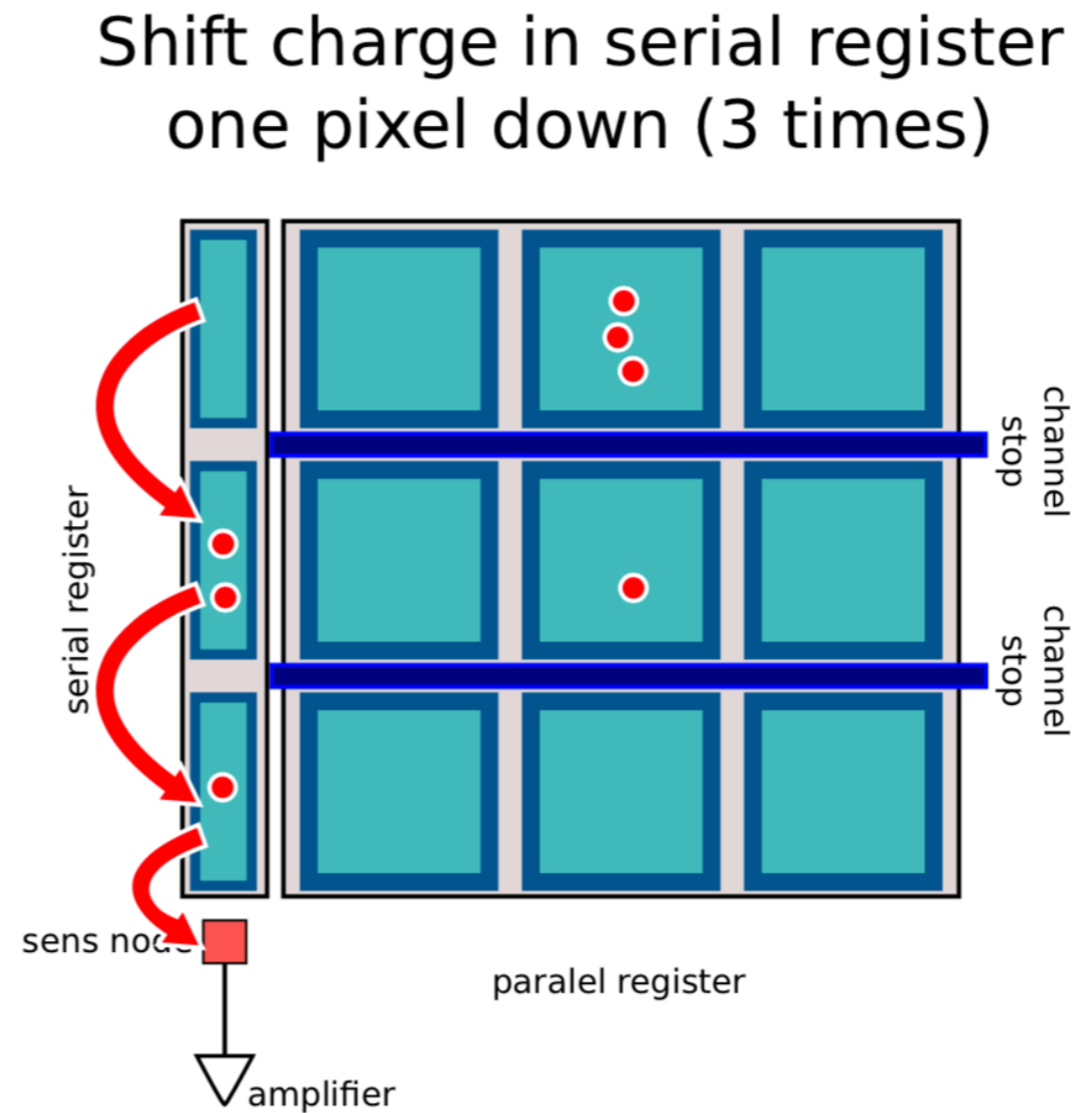
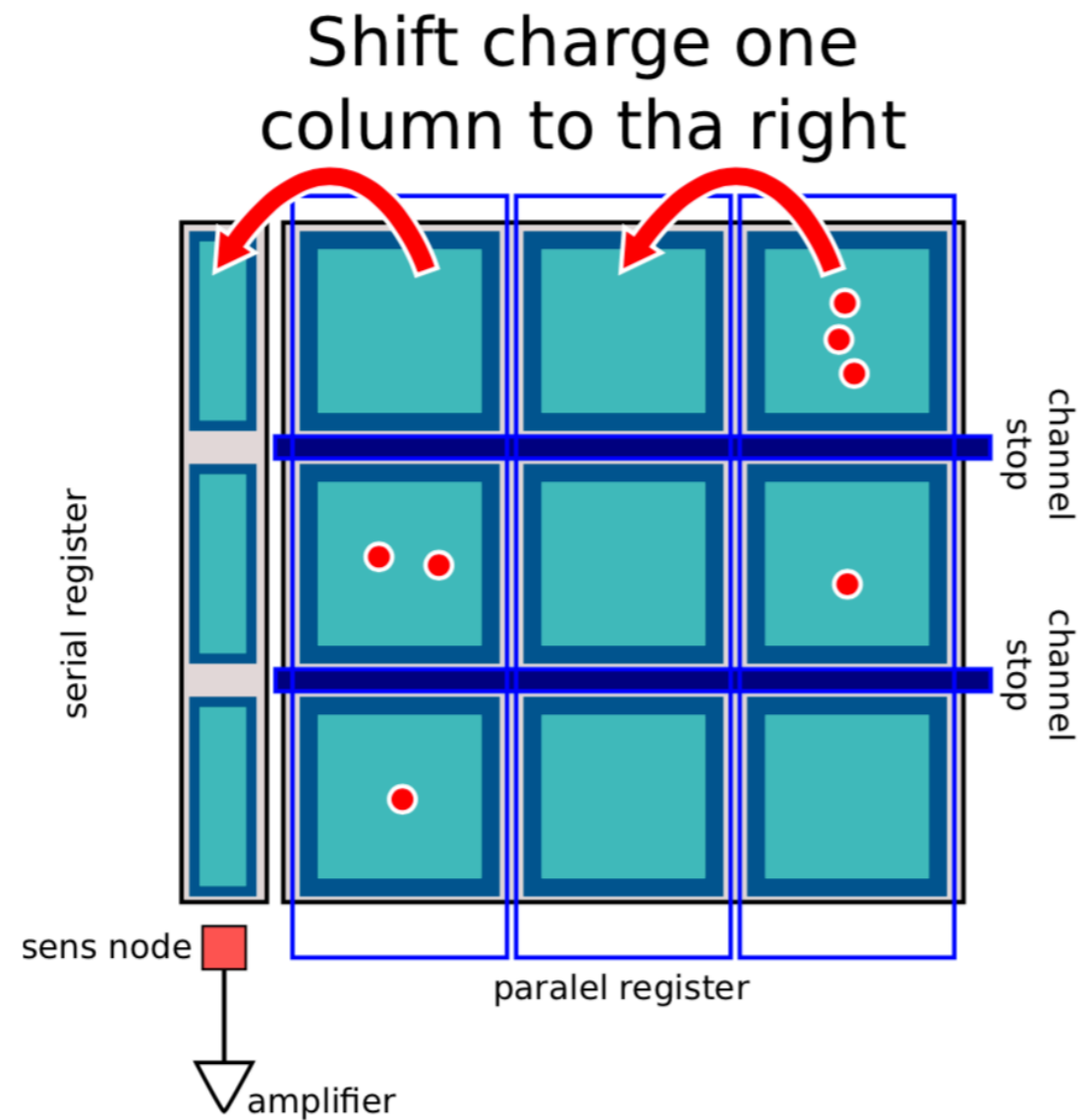


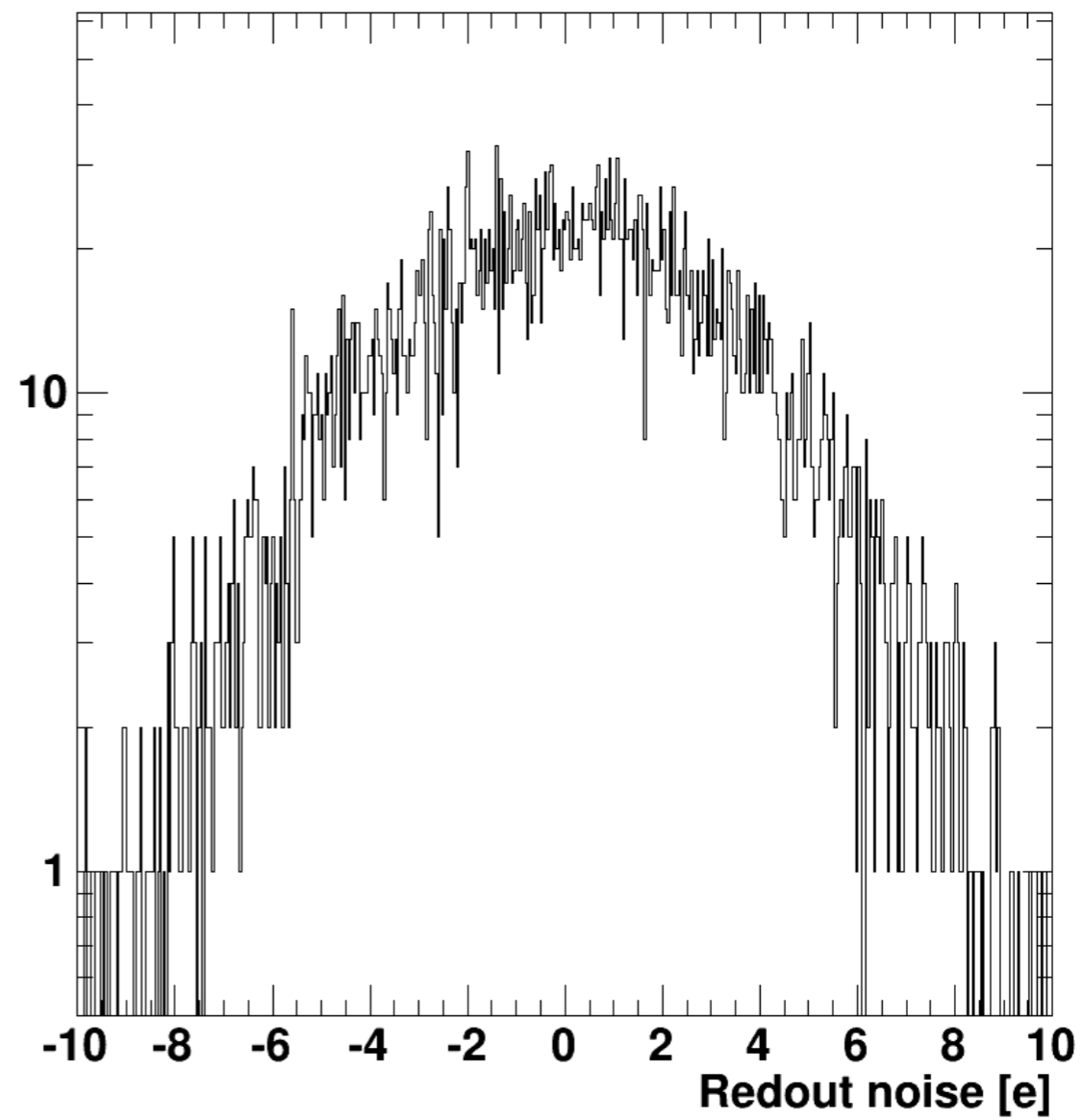
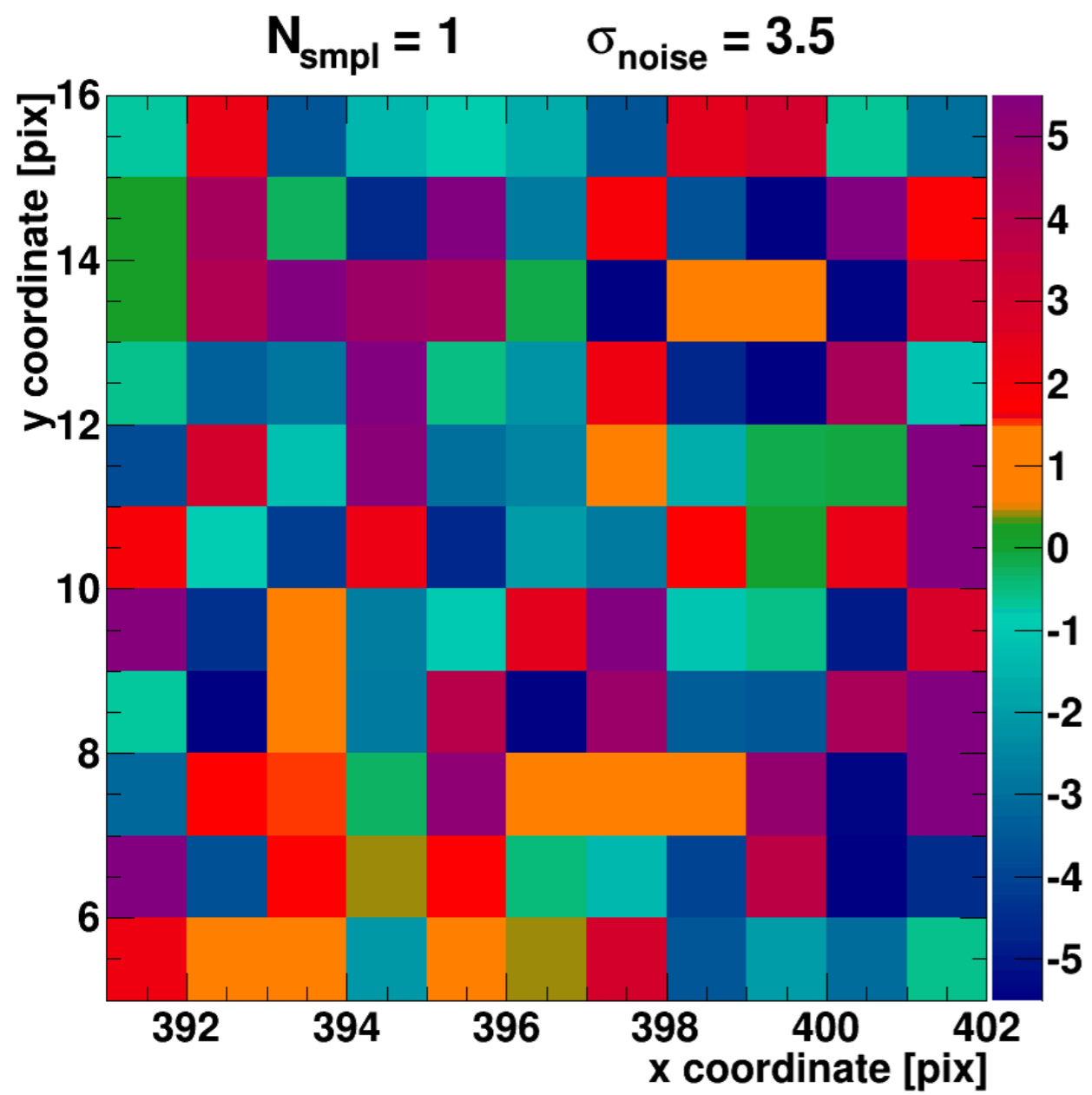
standard model process
never observed

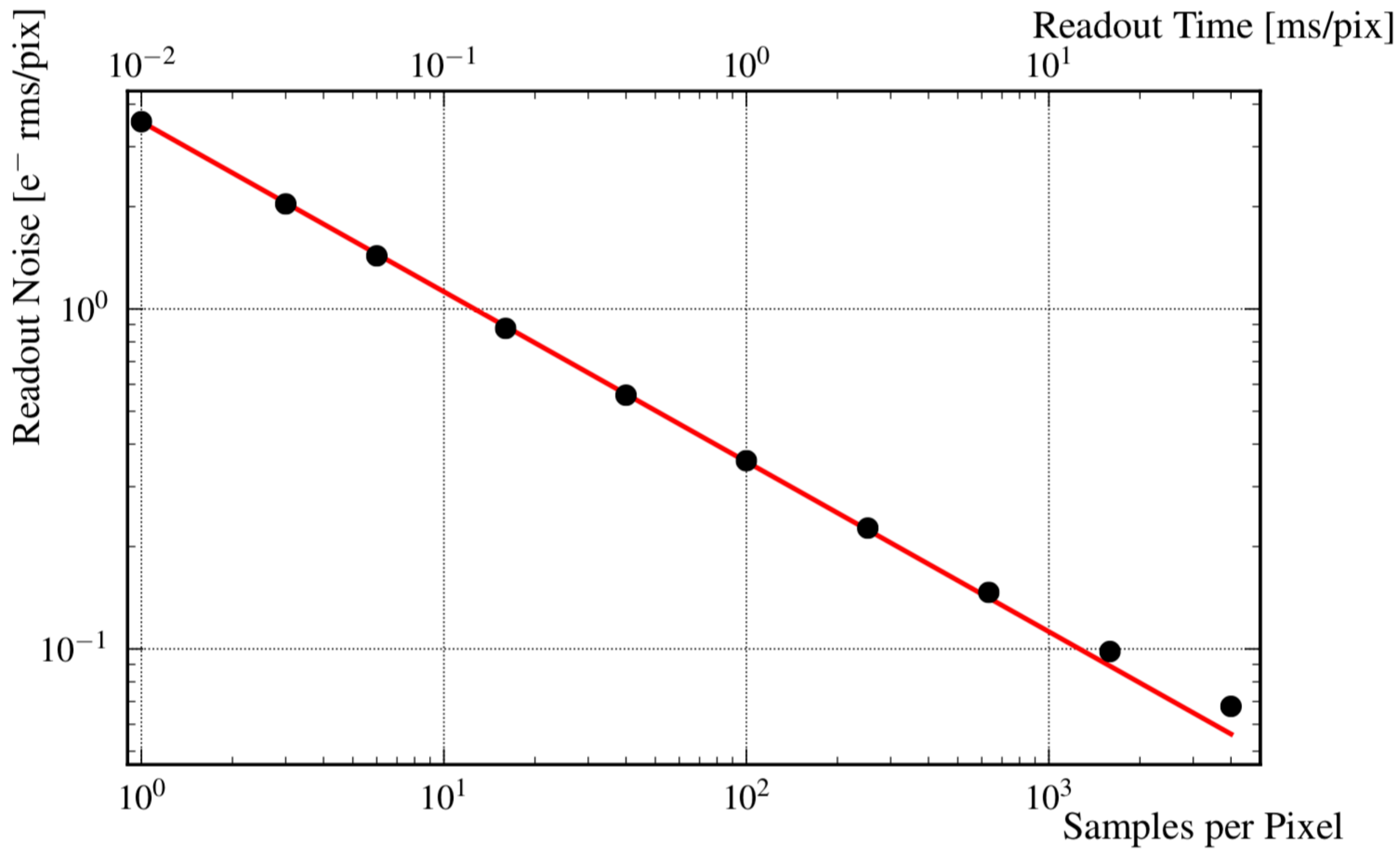
a window to new
physics in the
low energy
neutrino sector

$$\frac{d\sigma}{dT_A} = \frac{G_F^2}{4\pi} m_A [Z(1 - 4 \sin^2 \theta_W) - N]^2 \left[1 - \frac{m_A T_A}{2E_\nu^2} \right]$$

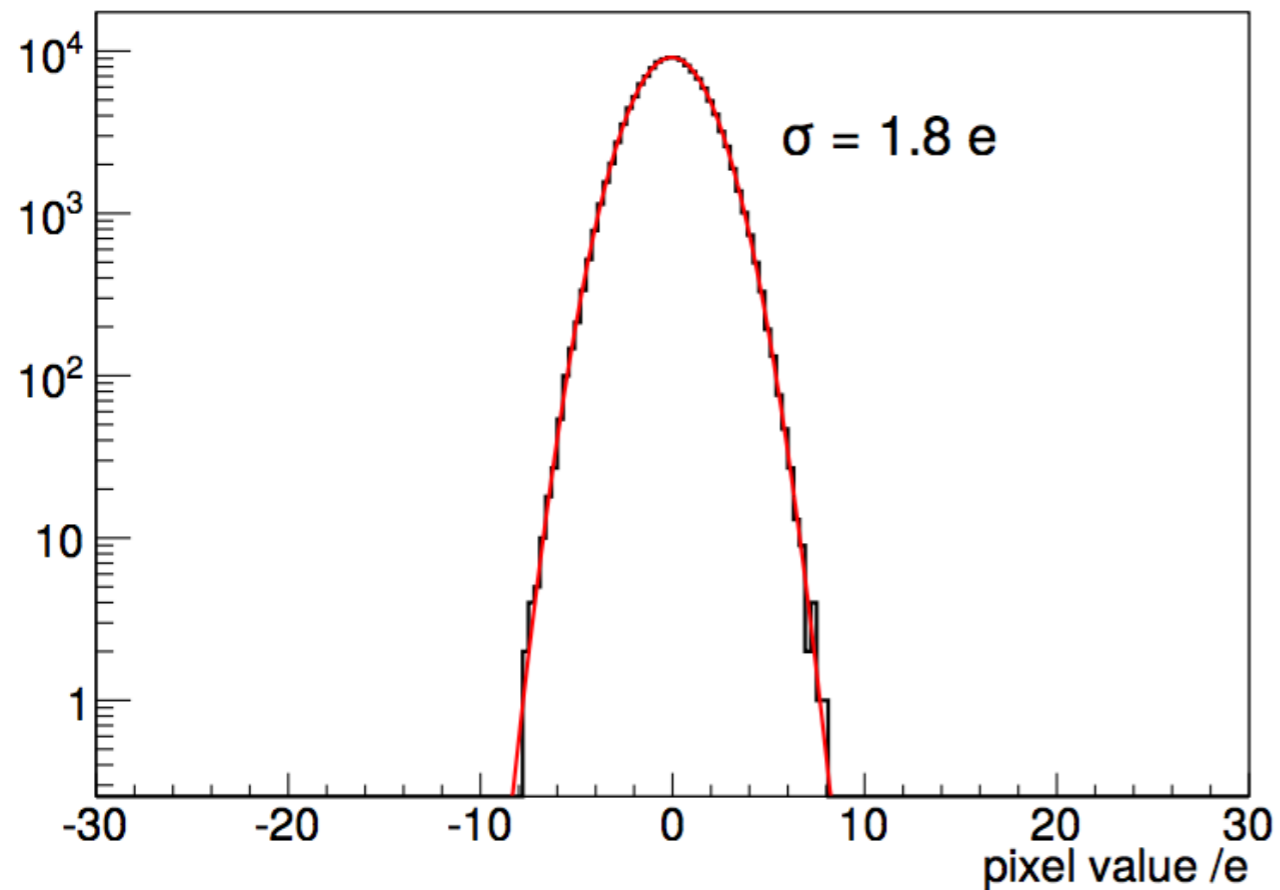
The skipper-CCD is a modification of the output stage of a CCD (Janesik et al -1990). It allows for multiple non-destructive readout of the charge in a pixel.



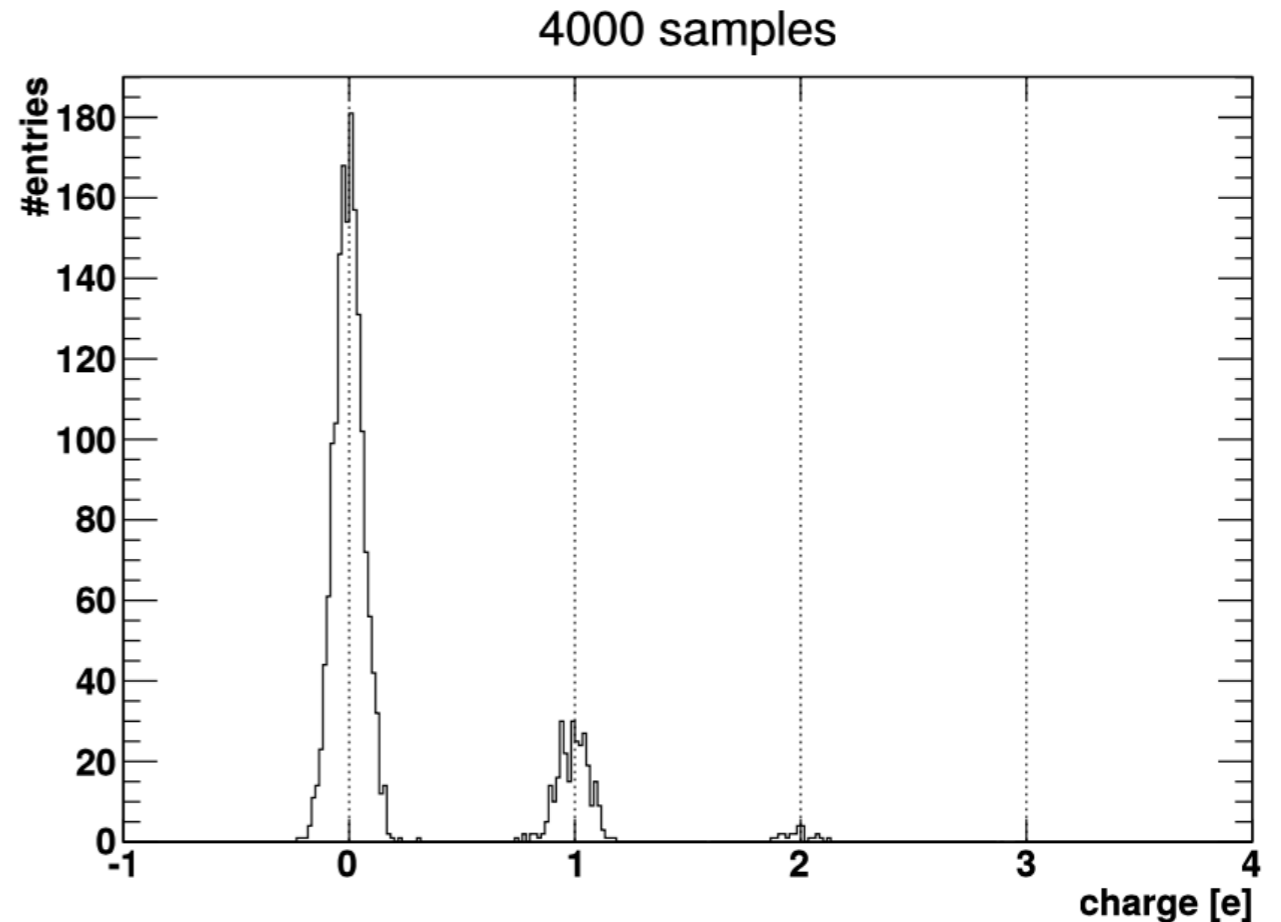




CONNIE now

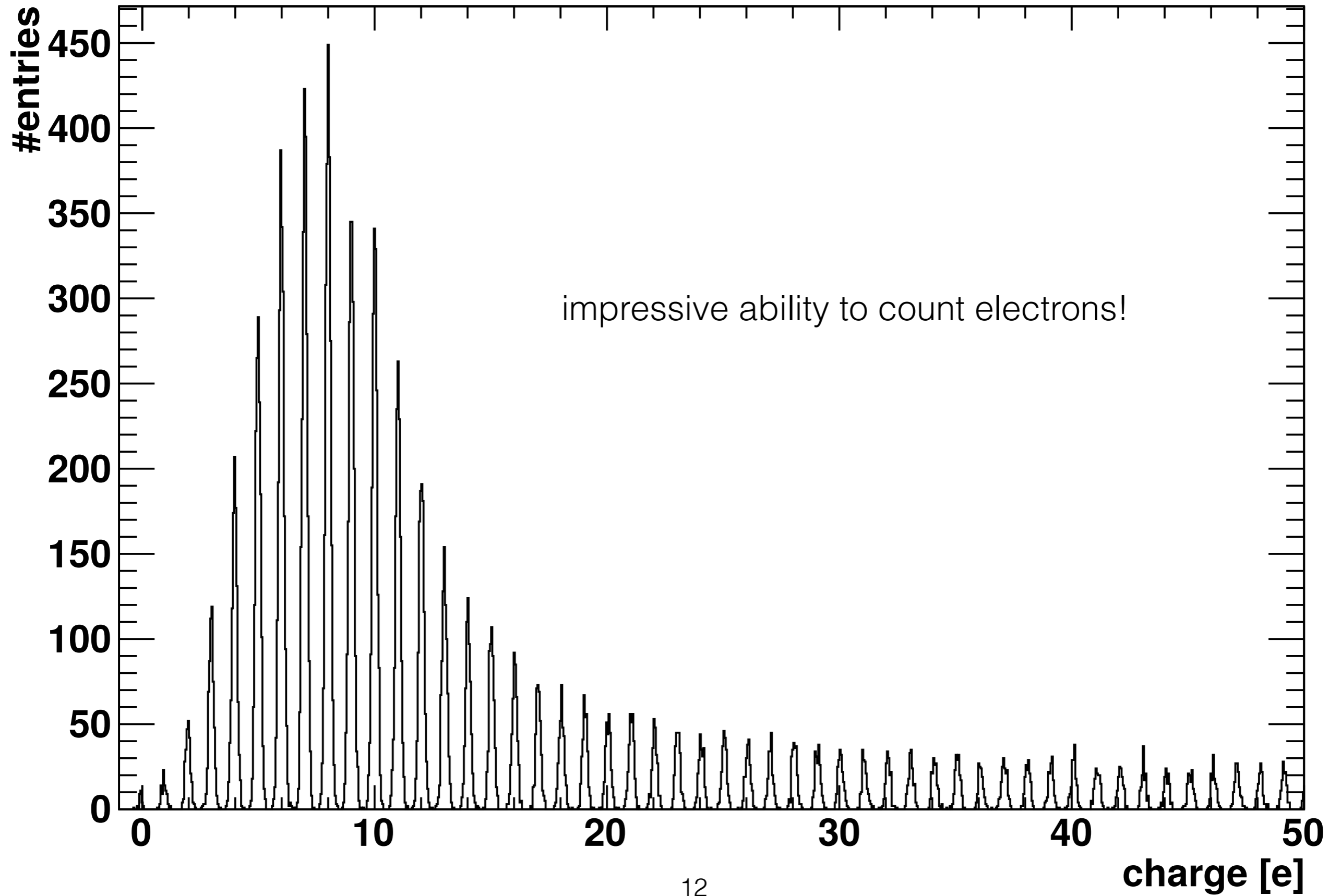


skipper CCD

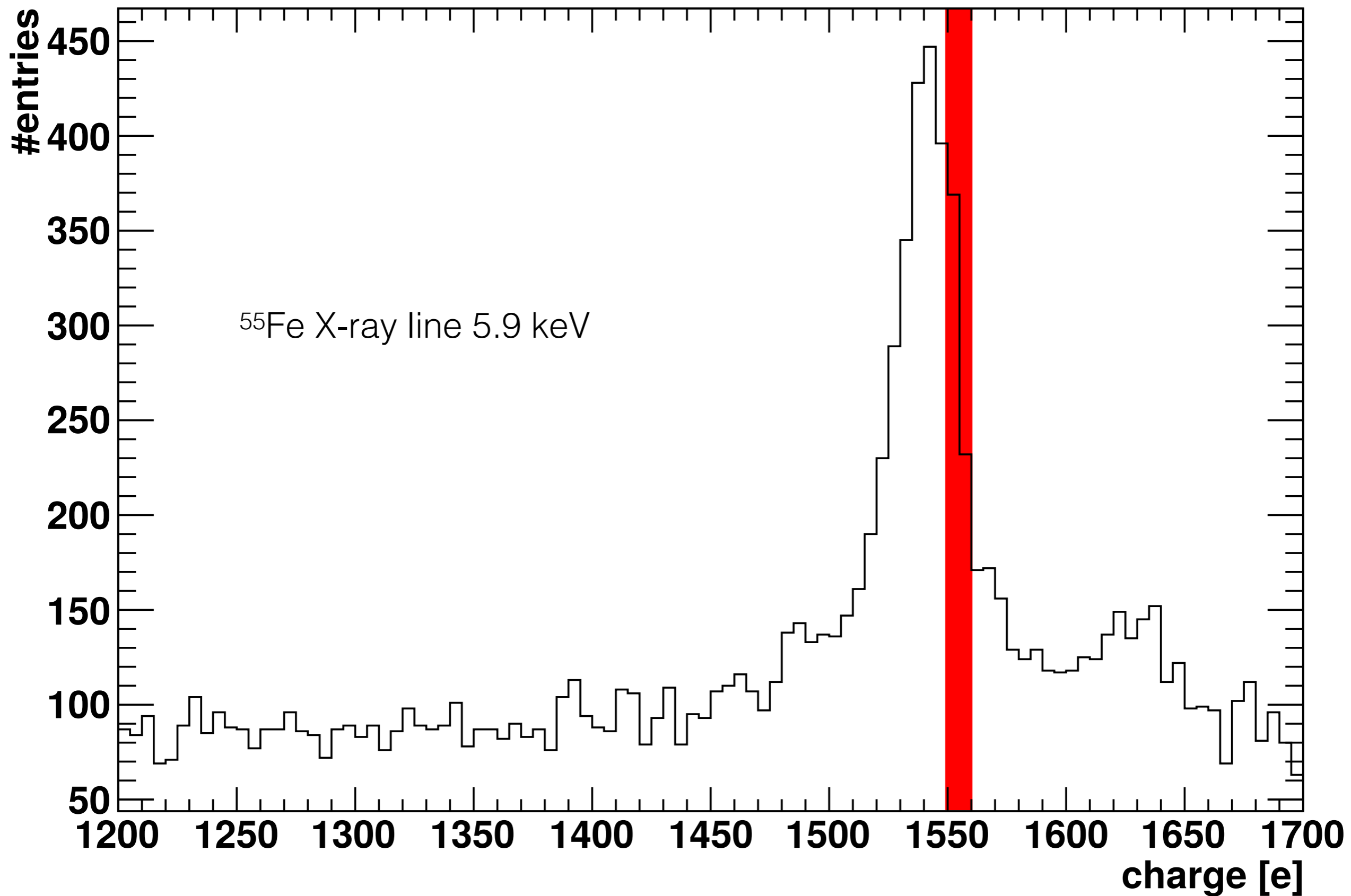


Designed ~30 years ago, but technology first demonstrated summer 2017 by Javier Tiffenberg et al (arXiv:1706.00028) allows reduction of the threshold by another factor of 2. The plan is to install a couple of these detectors in CONNIE also. Will need a new ionization efficiency measurement. Detector designed by Steve Holland (LBNL).

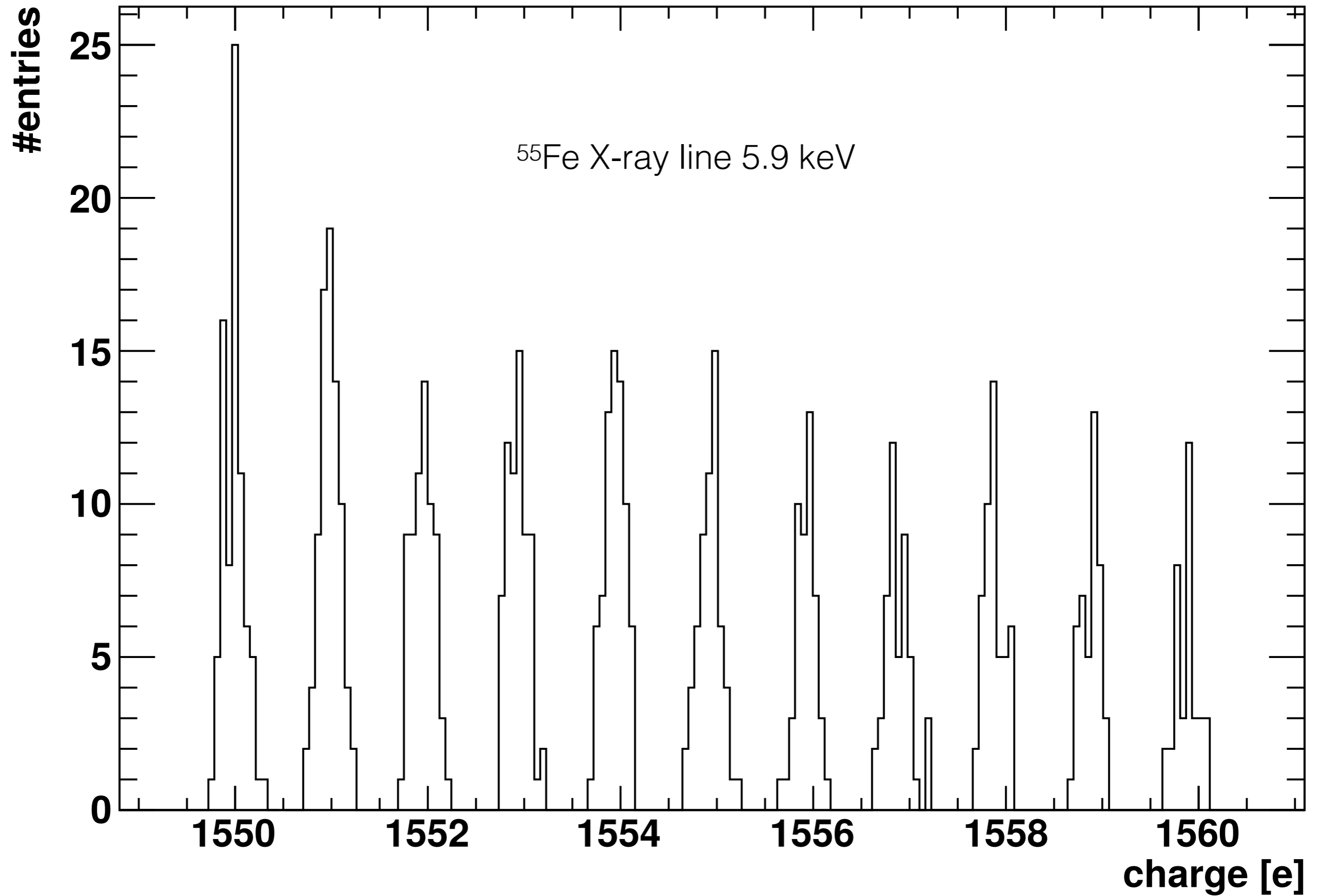
4000 samples

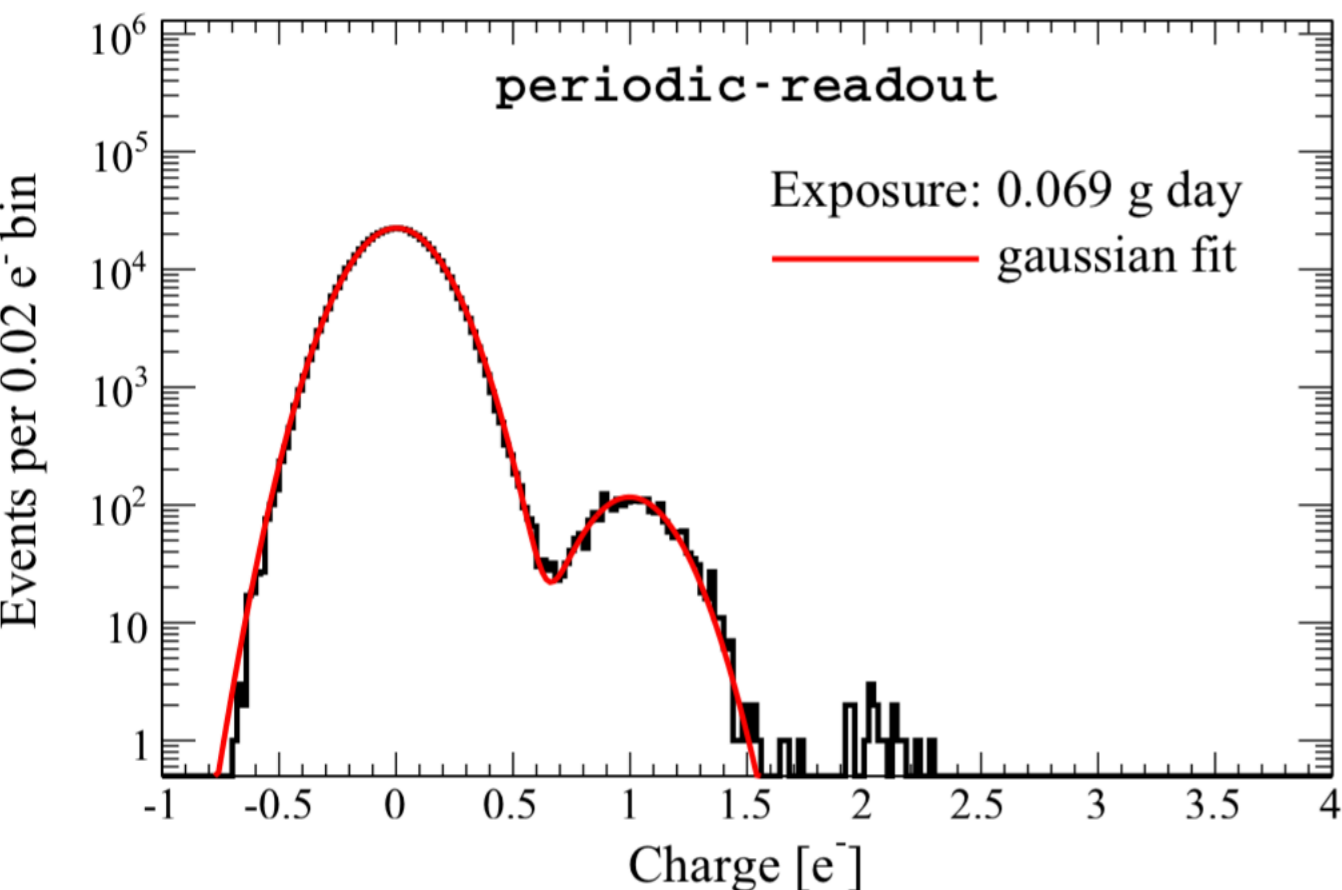


4000 samples



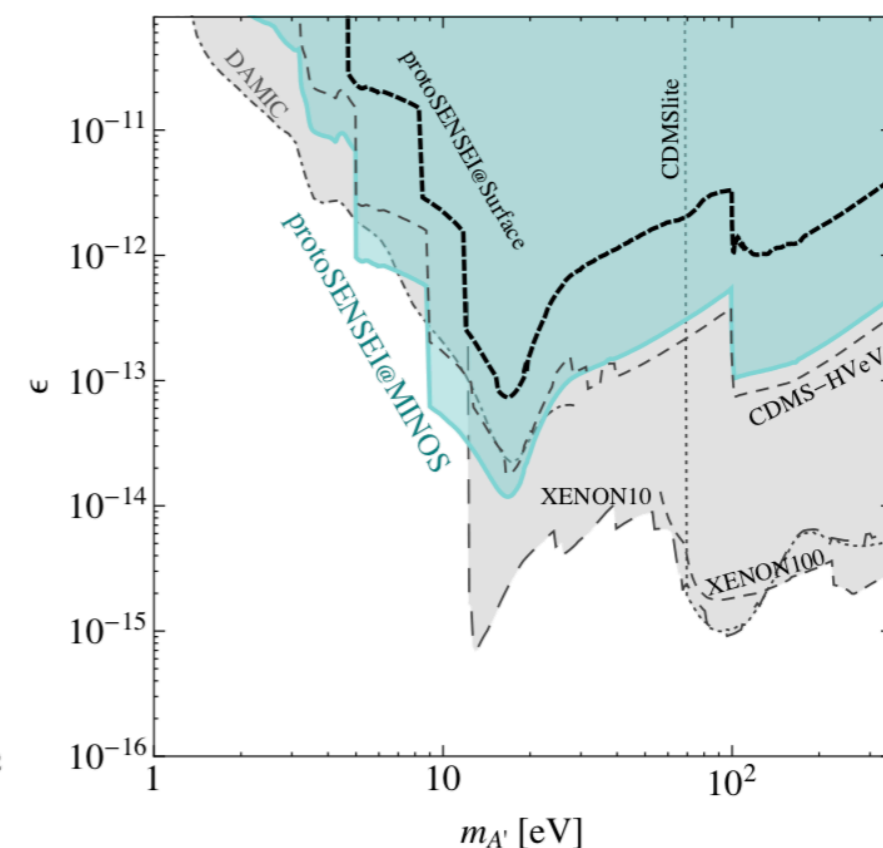
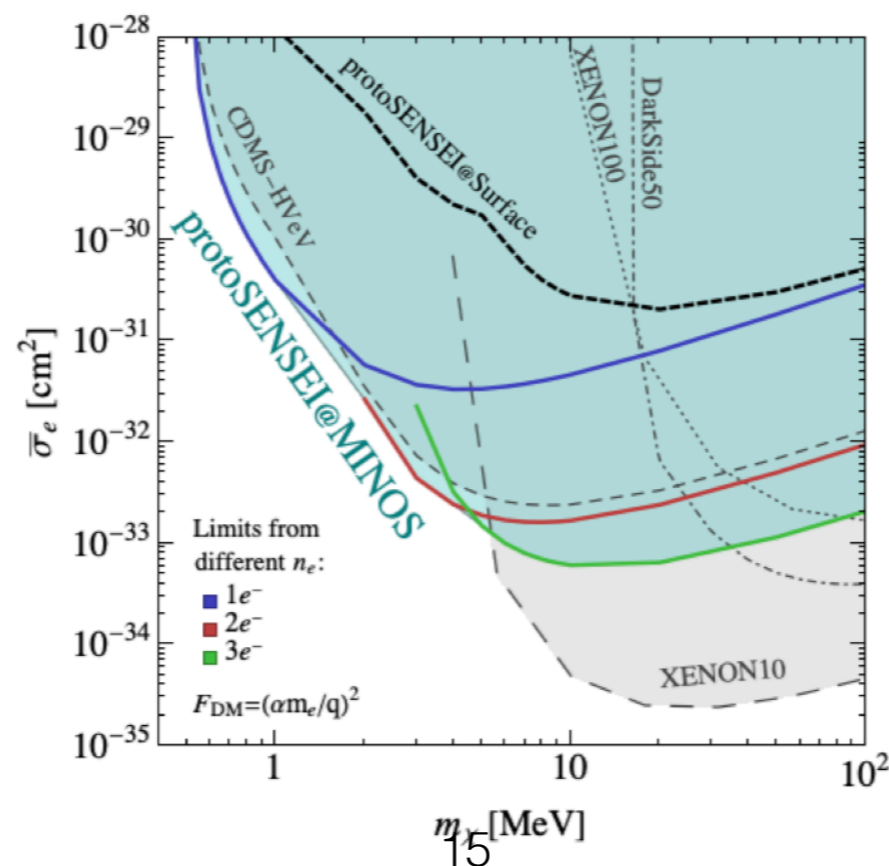
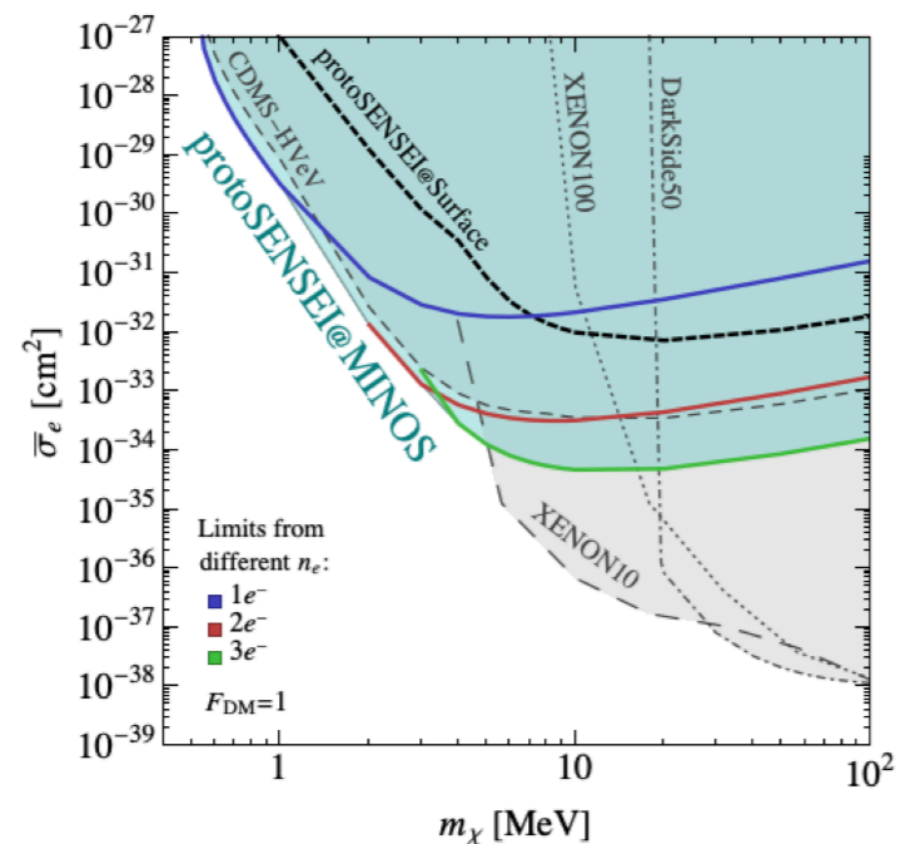
4000 samples





with a very modest exposure we are leading the world in the search for e-recoil dark sector particles.

dark rate : 3.68×10^{-3} events/pixel/day



skipper for treaty verification

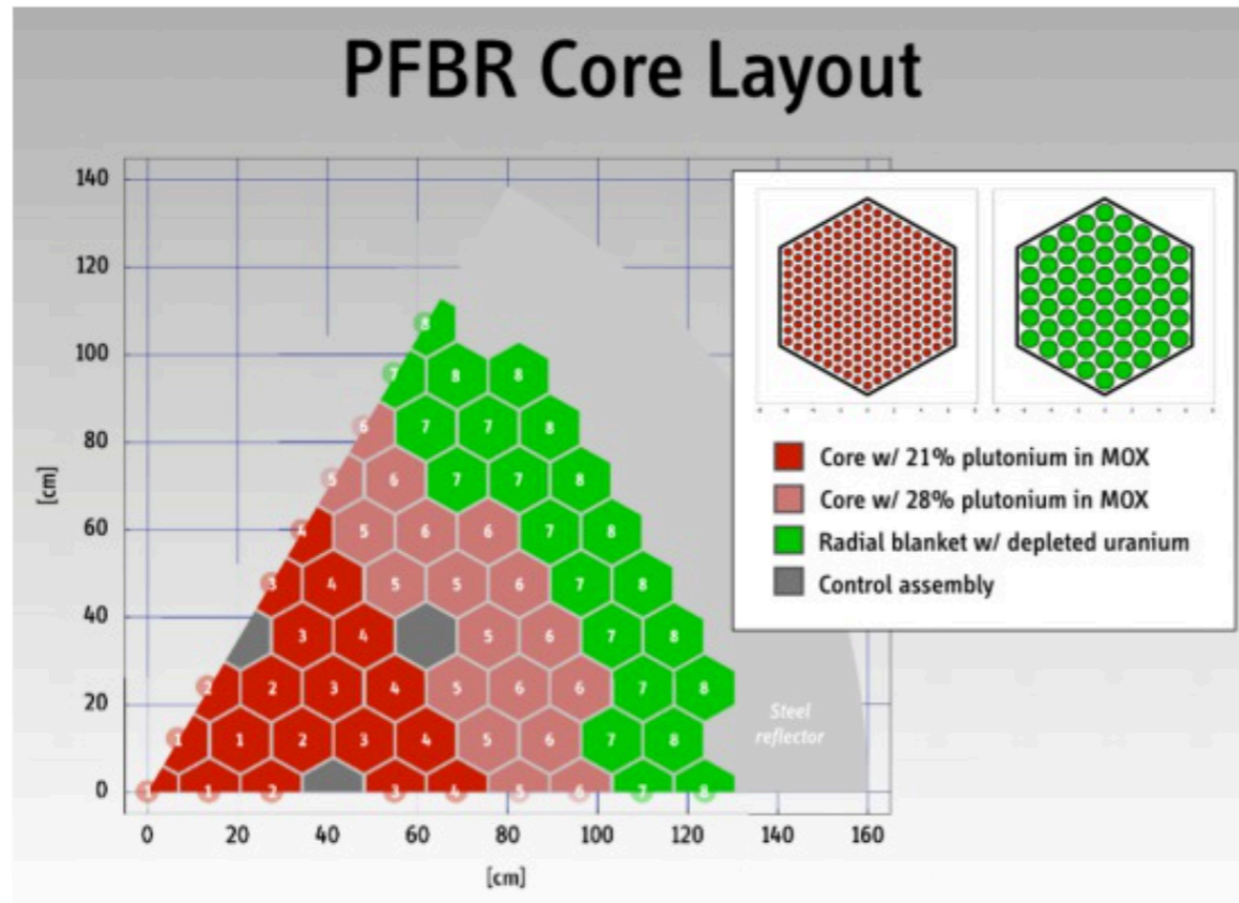


Image: Glaser *et. al*, Science & Global Security 15 (2007)

keV fast neutrons drive core fission (red hexagons) and neutron capture in a surrounding blanket (green hexagons) of natural or depleted uranium where Pu-239 breeding can occur

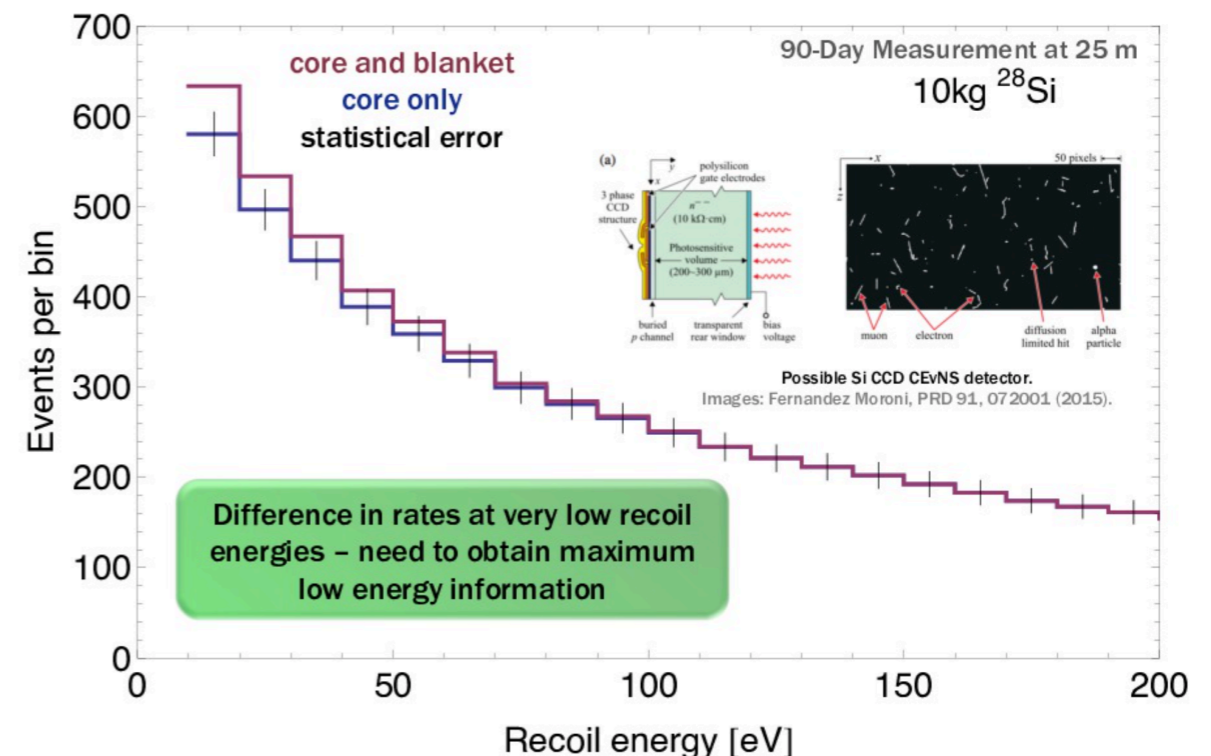
Model and data taken from:
A. Glaser and M. V. Ramana, Science & Global Security 15 (2007)

Achieved: Proof of Principle

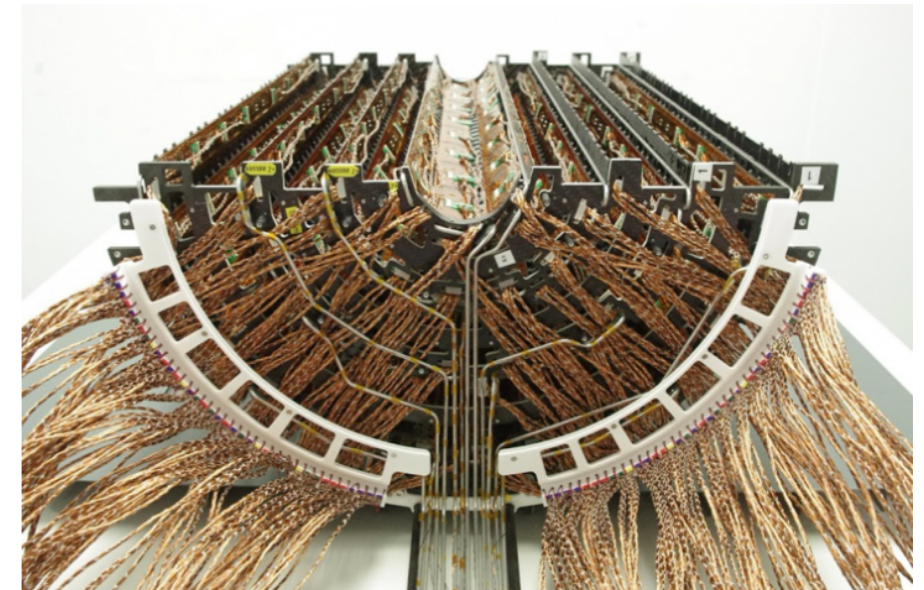
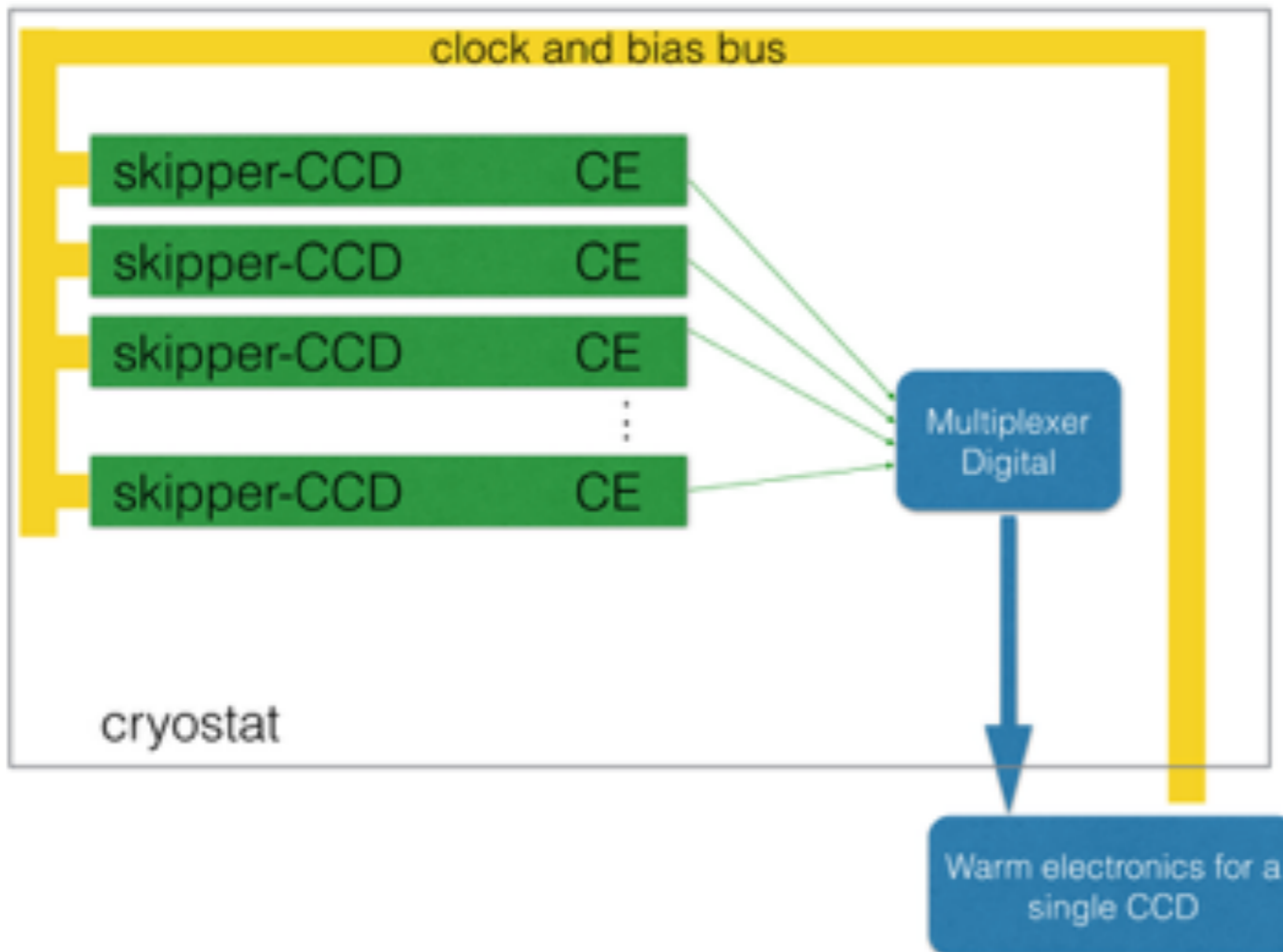
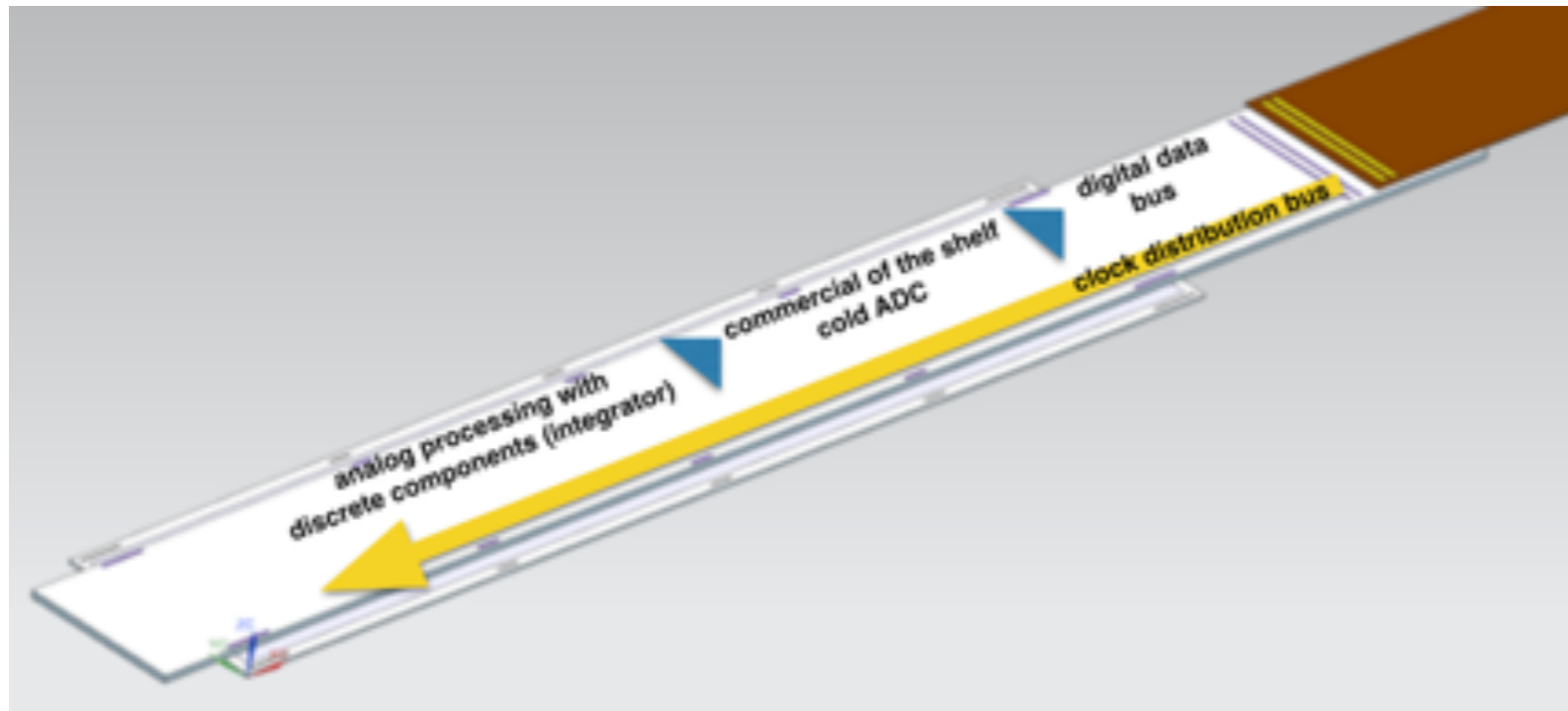
- On-going R&D on silicon-based charge coupled devices (CCDs) shows detector masses of 17-kg with 20 eV threshold may be possible in the near future¹
- Can detect the presence of a breeding blanket at a PFBR-type fast reactor at 95% confidence level within 90 days using a 36-kg ^{28}Si CENNS detector with a threshold of 30 eV²

¹G. Fernandez Moroni, J. Estrada, E. E. Paolini, *et al.*, Phys. Rev. D 91, 072001 (2015); ²Cogswell and Huber INMM Proceedings 2015

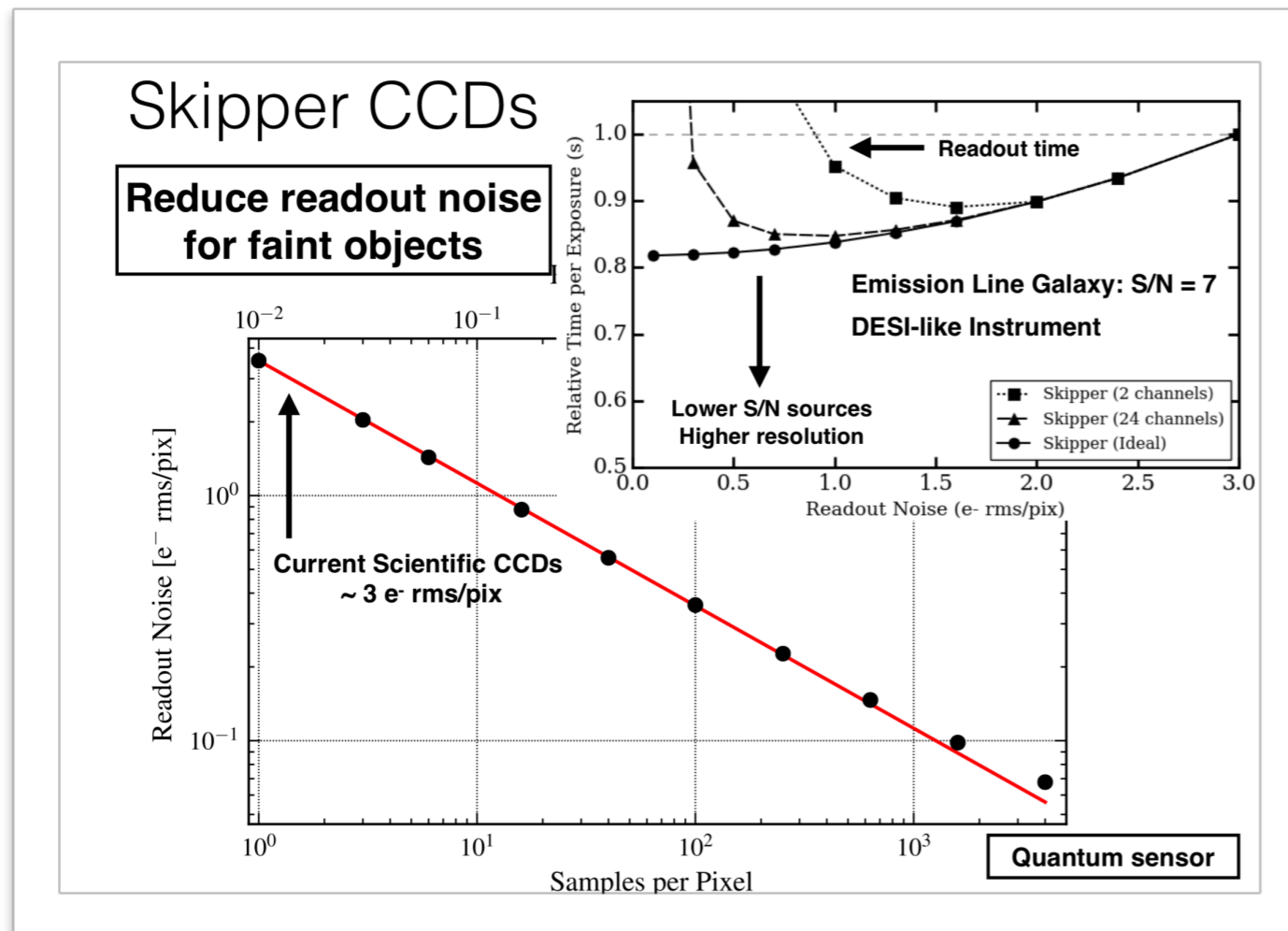
Interaction Rates for 10 kg of ^{28}Si



10 kg skipper Detector (4000sensors)



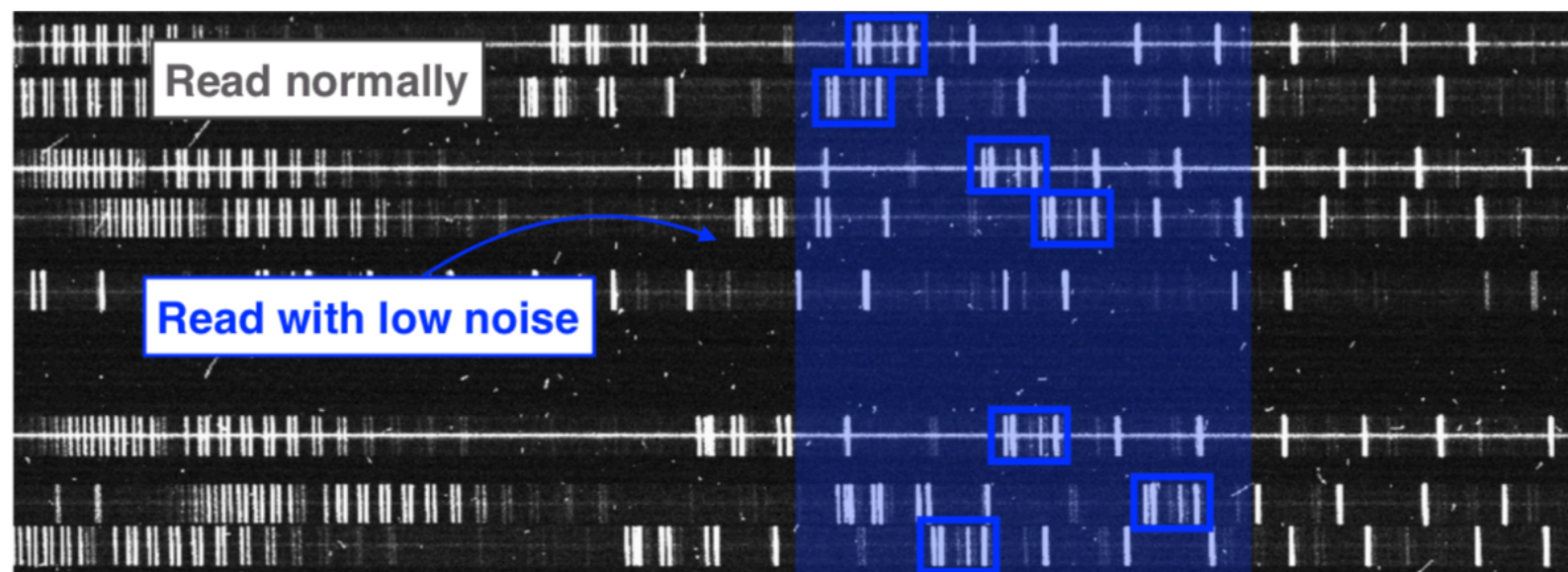
skipper for cosmic surveys



new skipper-CCD technology could improve the efficiency of a survey spectrograph reducing readout time.

Signal to noise could be tuned to optimizing readout time (target specific pixels for low noise).

(A.Drilica-Wagner)



Quantum Imaging

Nature 2012

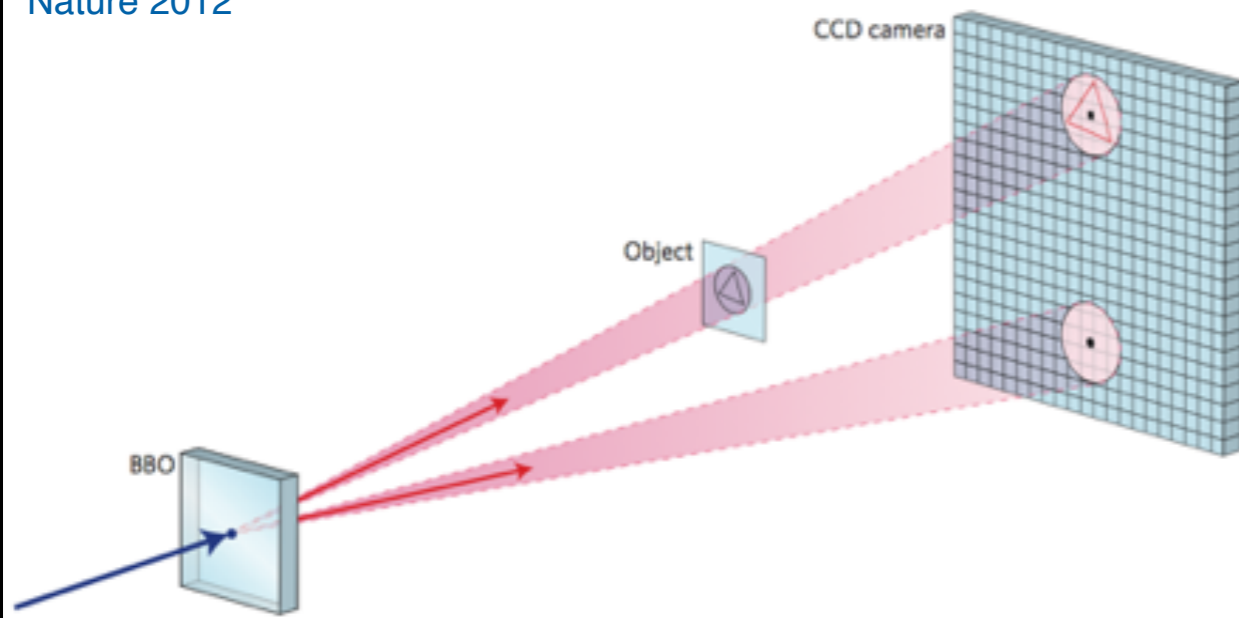
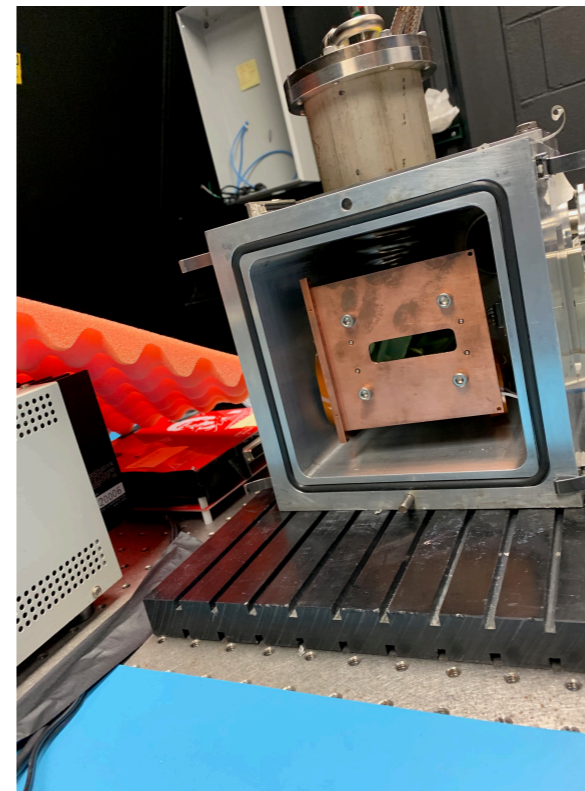
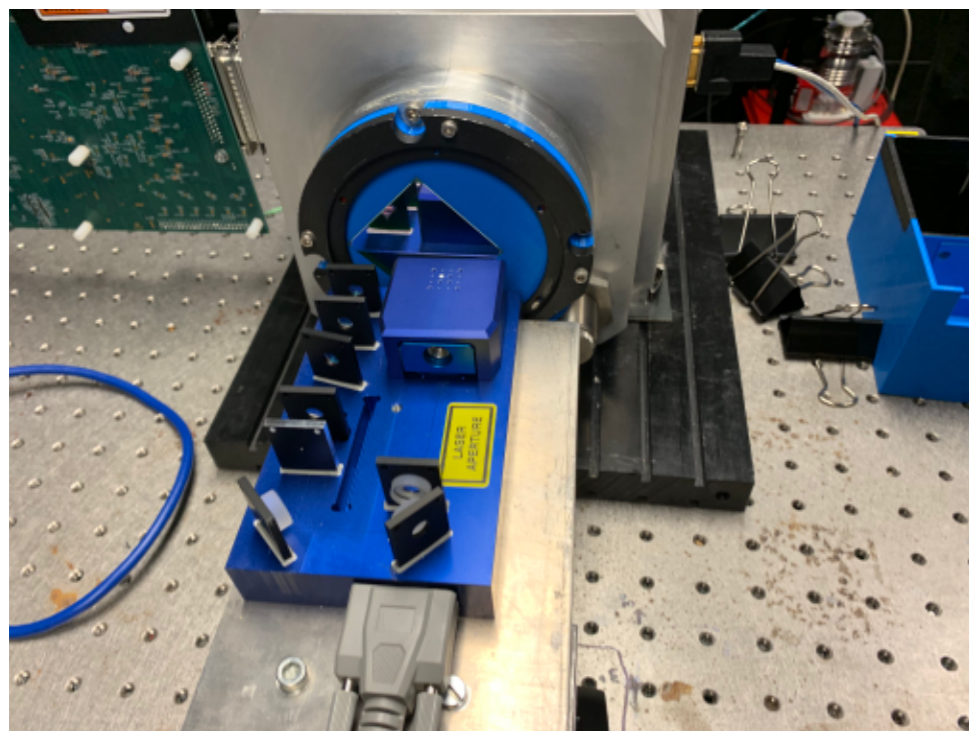


Figure 1 | The differential quantum imaging experiment of Brida and colleagues. The β -barium borate (BBO) crystal converts one laser photon into two photons that are quantum correlated in momentum and position. These non-classical correlations are used for the improved differential imaging of a weakly absorbing object.

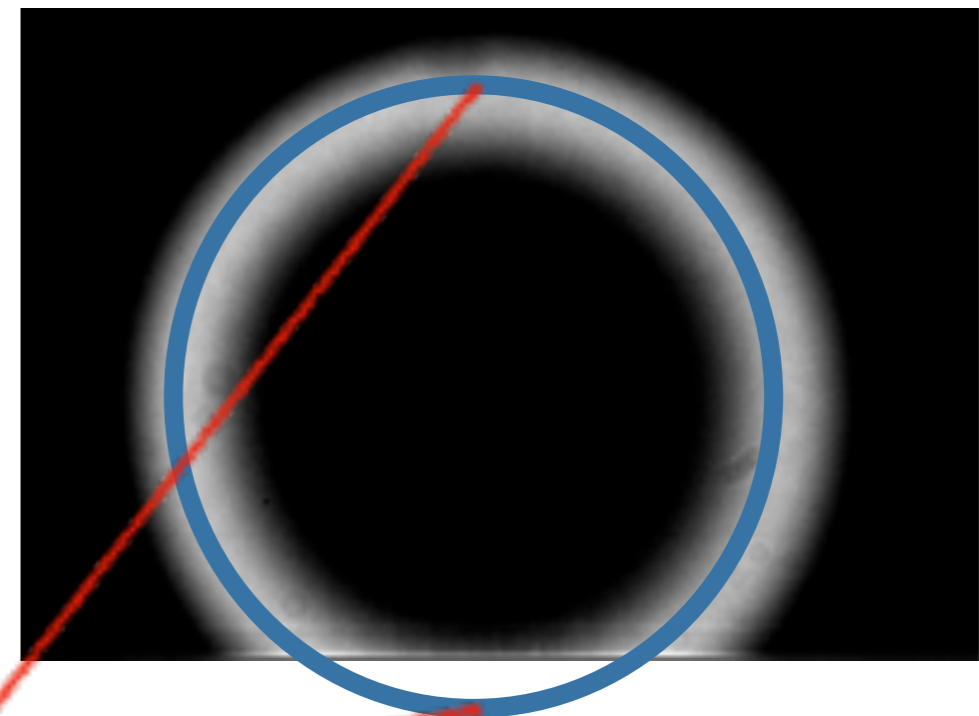


Skipper-CCD
packaged for imaging
(back illuminated) at
Sidet

Ring of entangled
photons on Skipper-CCD



Source of entangled photons at Sidet



BBO crystal

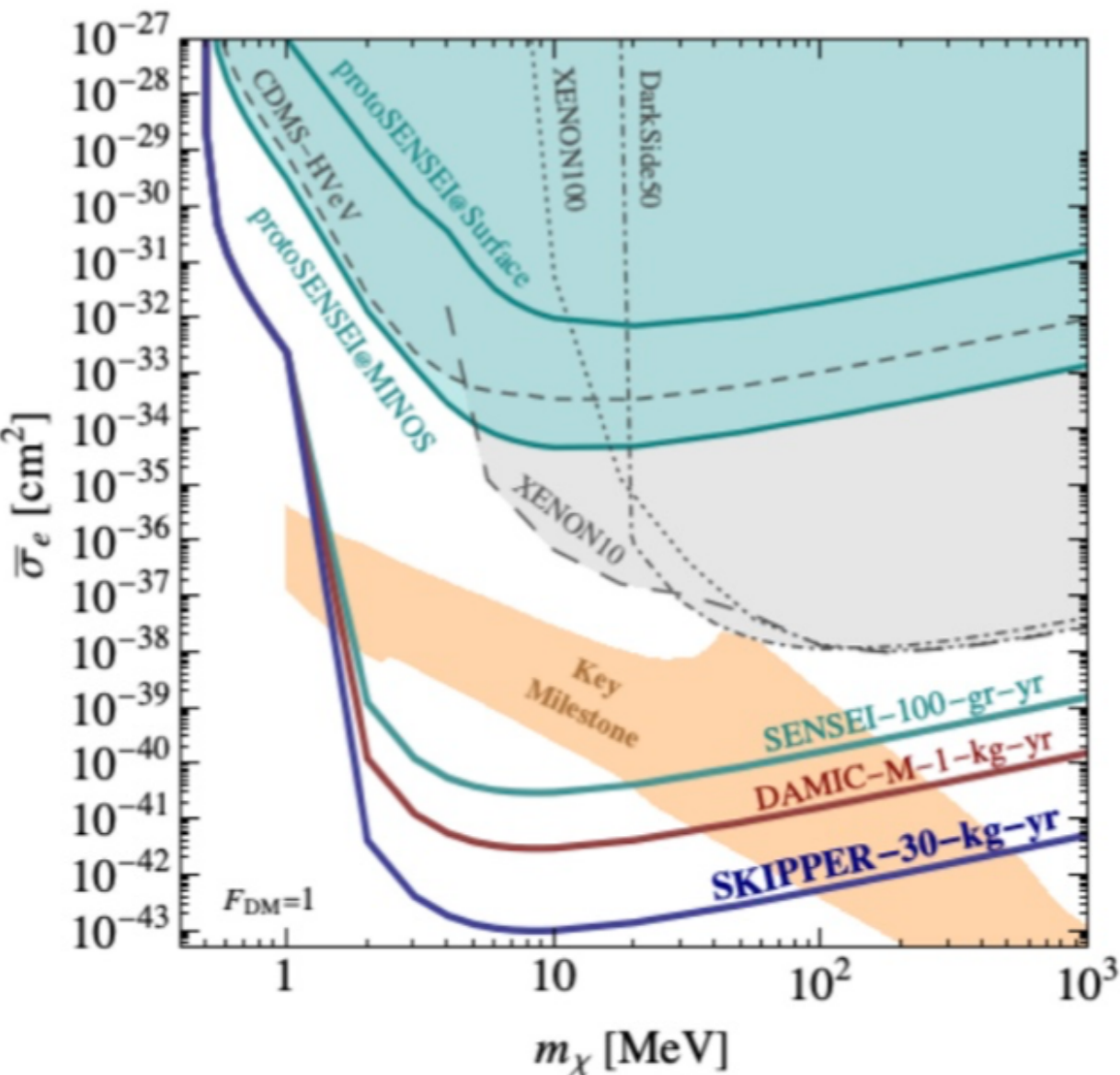
Pair of 810 nm *entangled photons*

405 nm laser

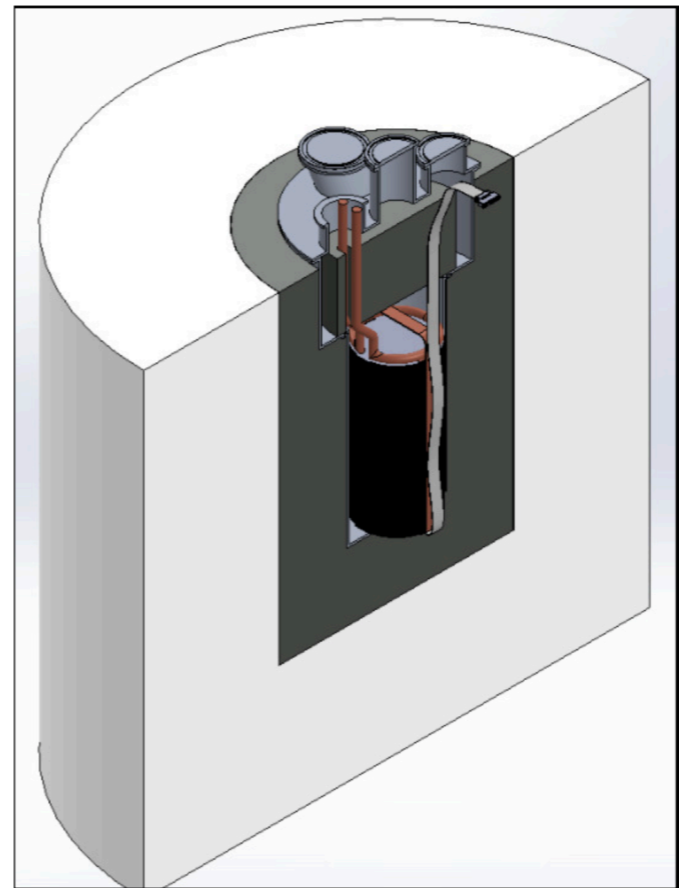
Thanks UIUC for support/ideas (Prof.Kwiat)
 Fermilab

Oscura 4 year R&D effort “DOE Dark matter New Initiatives” . FNAL, LBNL, PNNL, U.Chicago, U.Washington, Stony Brook University.

Fermilab is leading the effort to develop the a skipper-CCD dark matter detector with active mass of 10 kg of Silicon.



Taking the skipper-CCDs to their full potential as dark matter detectors.

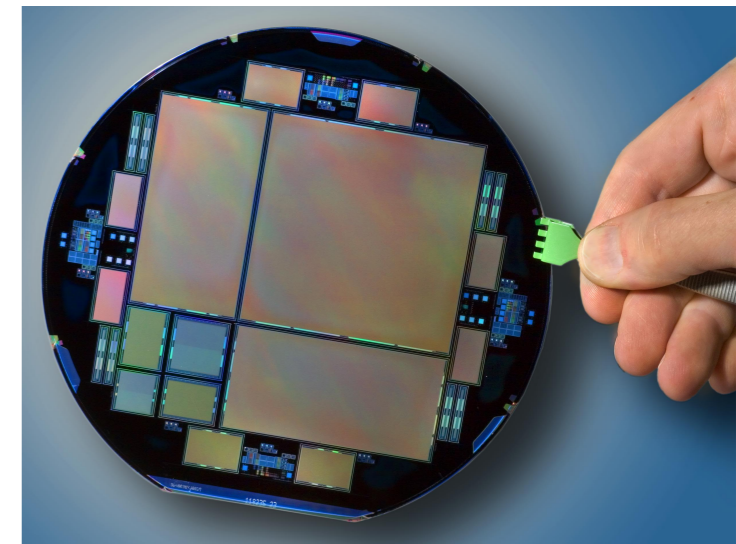


Fabrication of skipper-CCDs is needs to be adapted to the changes in the semiconductor industry. We have identified new industrial partners for this, and will be testing them over the next year.

24 Gigapixel digital camera for dark matter!

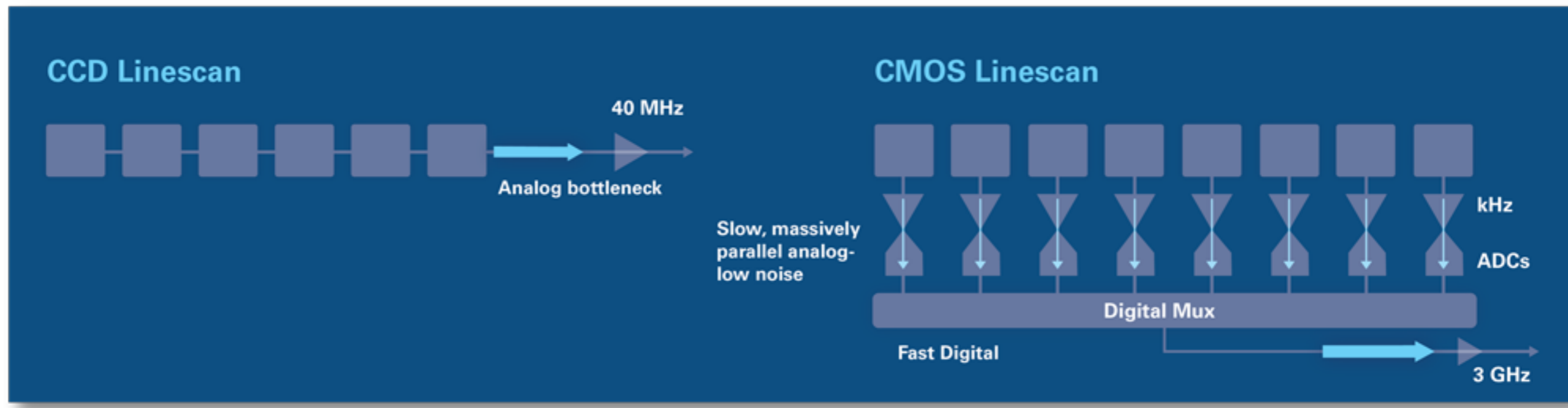
Cooling, readout, packaging and testing of the required 4000 skipper-CCD sensors require engineering solutions that are not available yet for scientific CCDs.

Radiation background required is ~ 10 lower than state of the art experiments.



Big challenge: modern way to fabricate skippers!

non-destructive, low noise readout on CMOS is very close to reality (BES, X-ray astronomy)



future skipper-CCDs

Ongoing:

- SENSEI (100g operating at SNOLAB) — small version currently at FNAL
- DAMIC-M (~1kg operating at Modane)

R&D:

- FNAL-LDRD : technology for 10kg detector
- FNAL-LDRD : demonstration in astronomical instrument
- QIS : skipper quantum imaging
- soon... test at nuclear reactor(Guillermo)
- ECA-Tiffenberg : towards development of 10kg neutrino detectors
- OSCURA :10 kg experiment for Dark Matter [DOE DMNI]

Groups:

Labs in US: LBNL, FNAL, PNNL

Univ. in US: U. of Chicago, U. of Washington, Stony Brook University, U. of Michigan (DAMIC)

Several international partners in Europe and the Americas

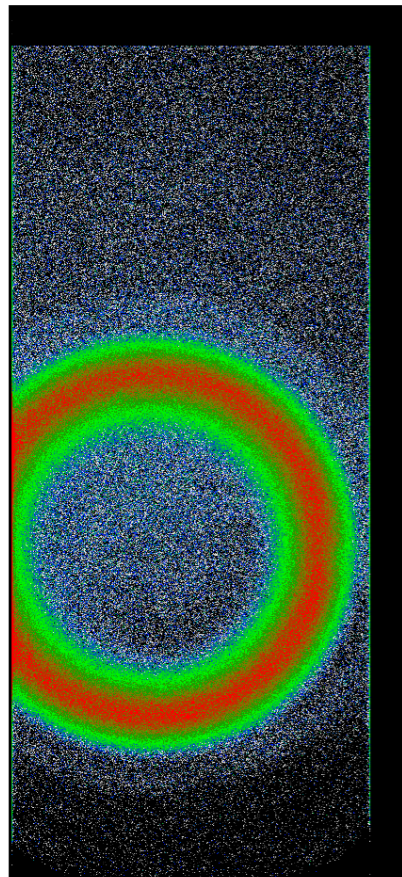
Technology development by DOE with significant impact on the field (and outside the field).

Should support the projection of this technology into the future with skipper-CCDs and skipper-CCDs-in-CMOS.

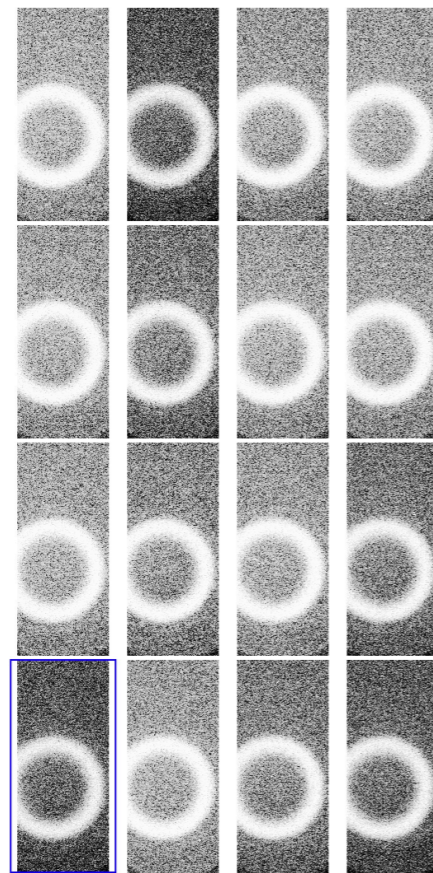
hopefully I convinced you that skipper-CCD are
great for Dark Matter, neutrinos, quantum
imaging, cosmic surveys

is there a way to get similar performance in a
CMOS process

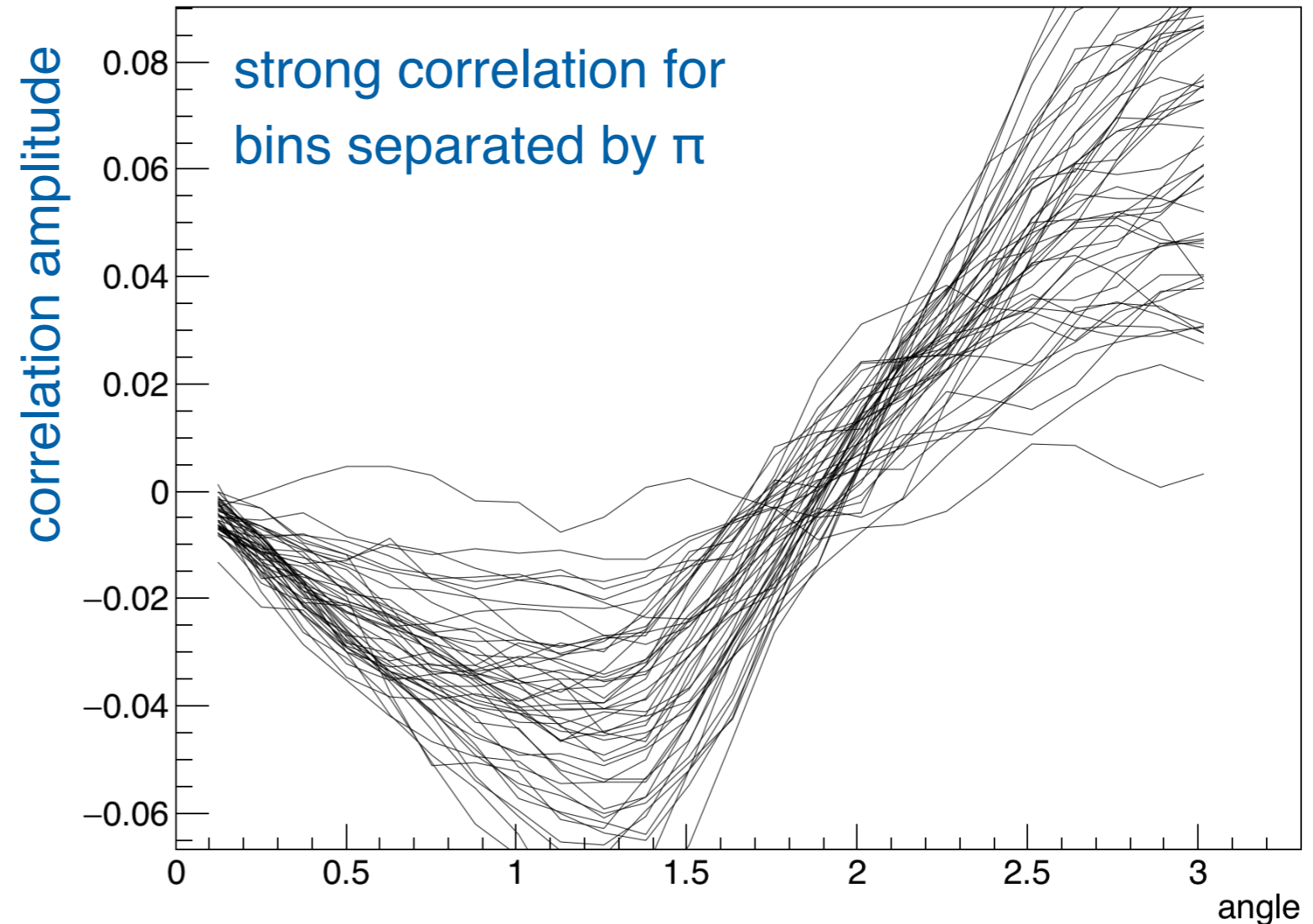
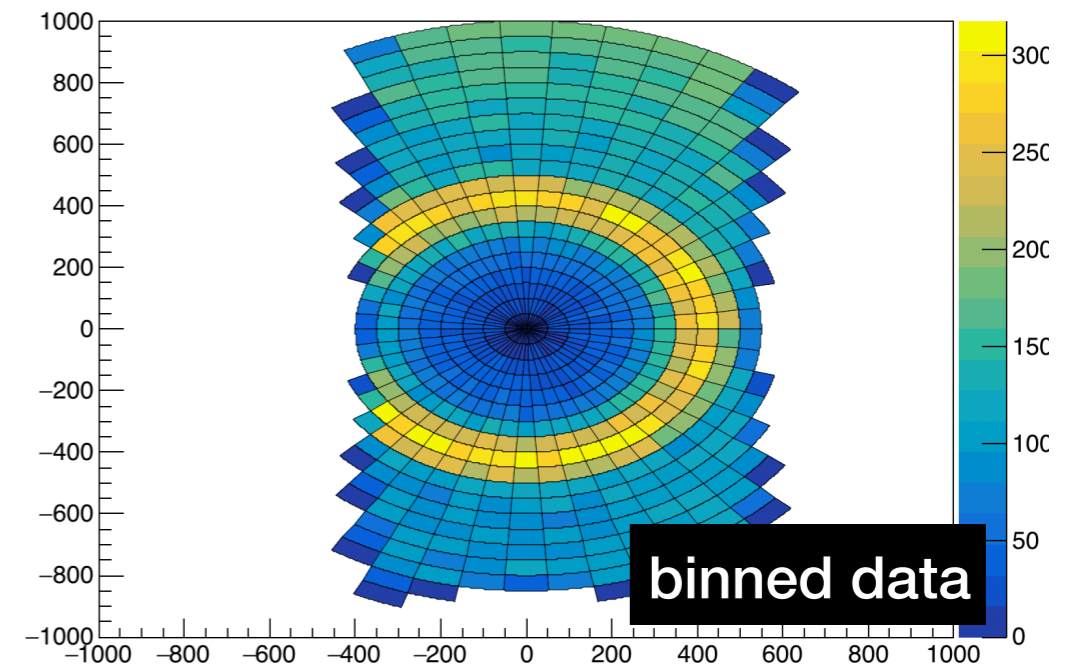
Modeled the ring of entangled photons and calculated correlation function as a function of angle.



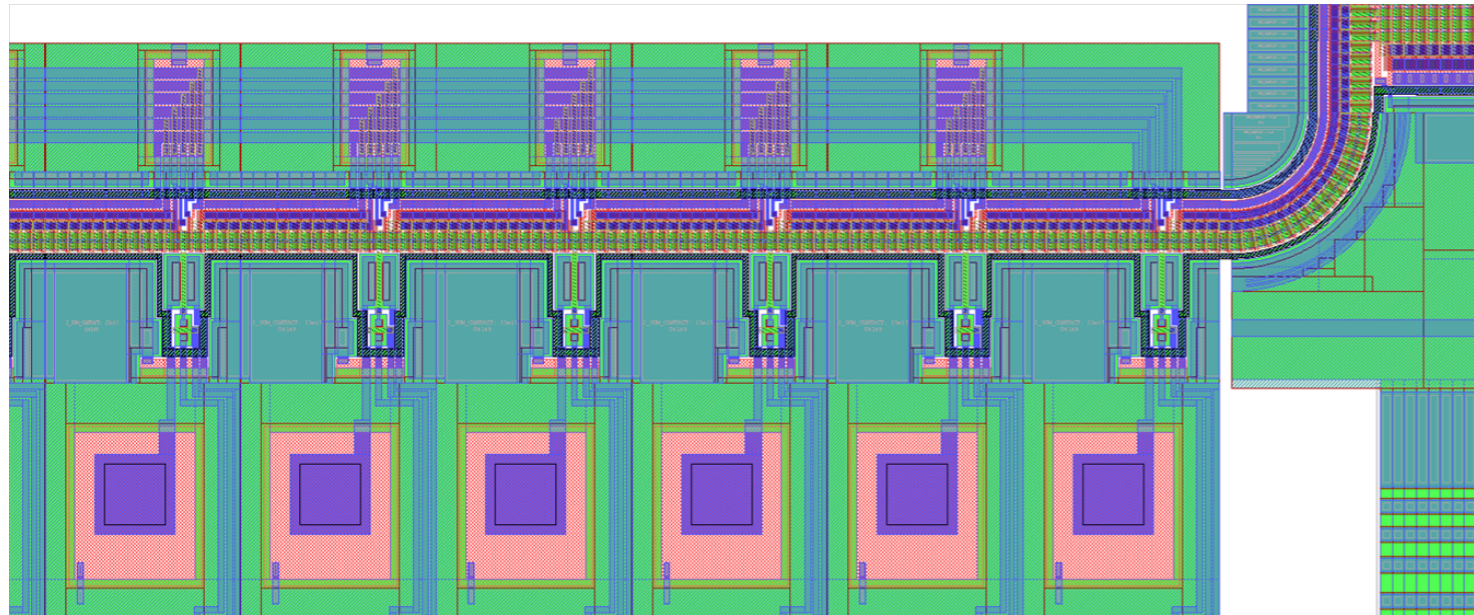
single image



measure
image-to-
image
fluctuations

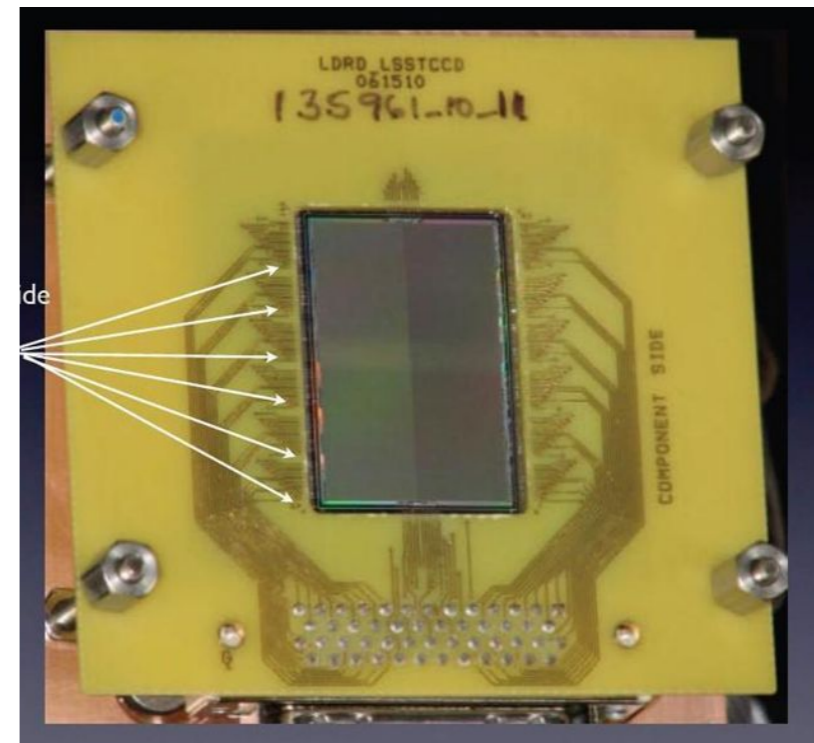


Over the last year FNAL has worked with LBNL to develop skipper-CCDs optimized for quantum imaging (fast low noise readout). Contract for fabrication in place!

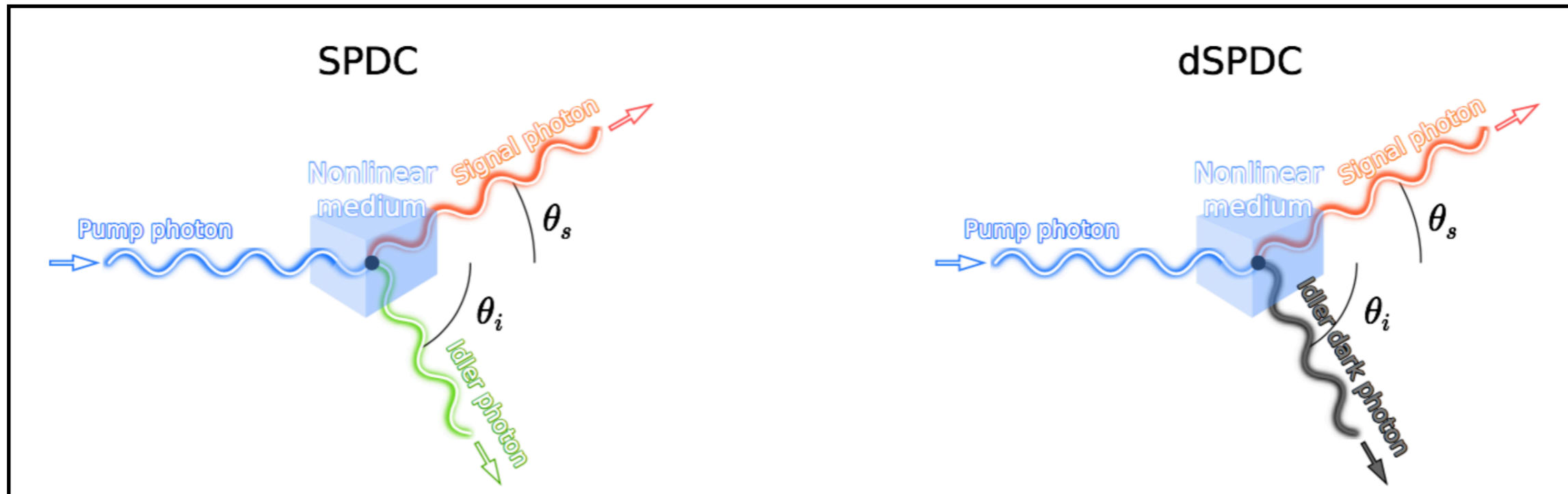


Several amplifiers in line, for simultaneous sampling multiple sampling of the charge of a pixel. New way of skipper readout.

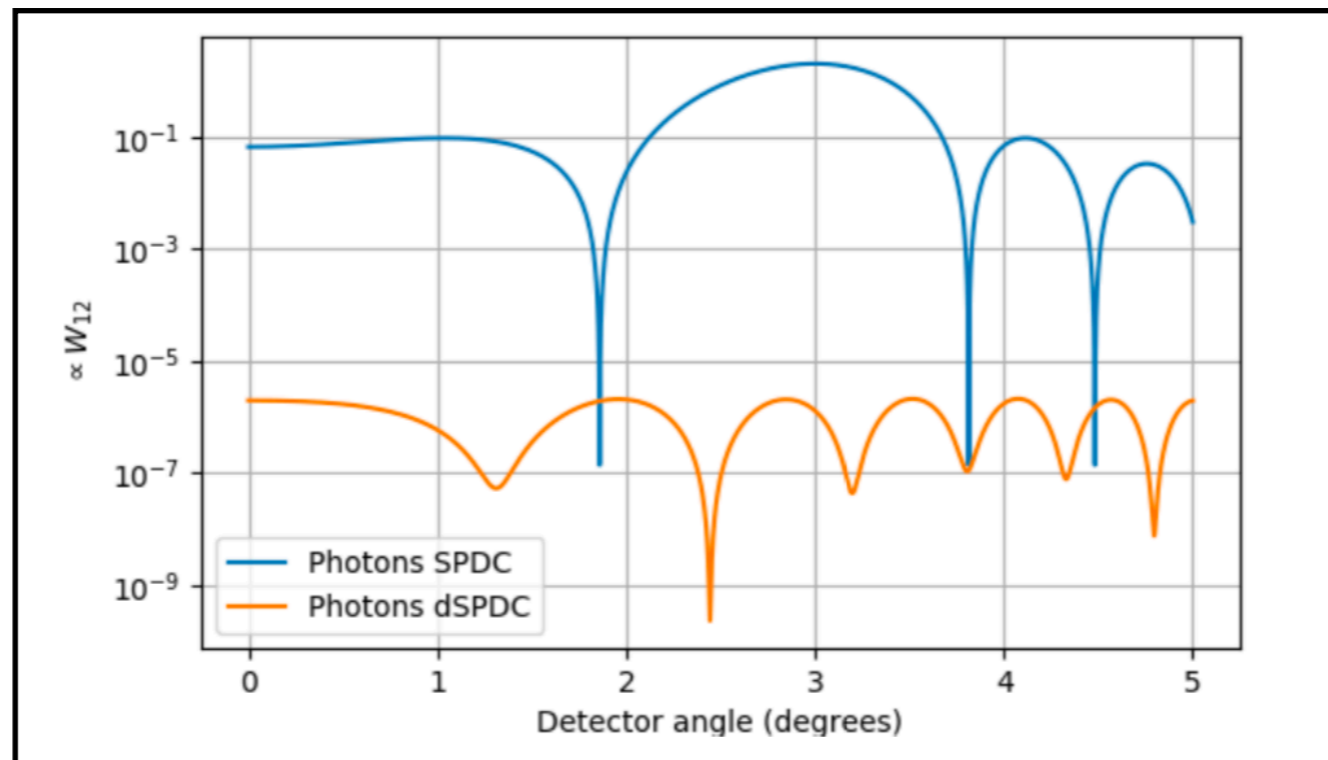
Repurposing a previous design that LBNL developed for astronomy, we are also developing a skipper-CCD with 16 amplifiers in parallel. Larger format, fast readout.



In the same way we produce a pair of entangled photons, we could produce an entangled pair with one dark photon.



Because of the change of kinematics, the angular distribution of the visible photons changes when a dark photon is produced.



exploring a design of an experiment to look for dark photons using this concept.

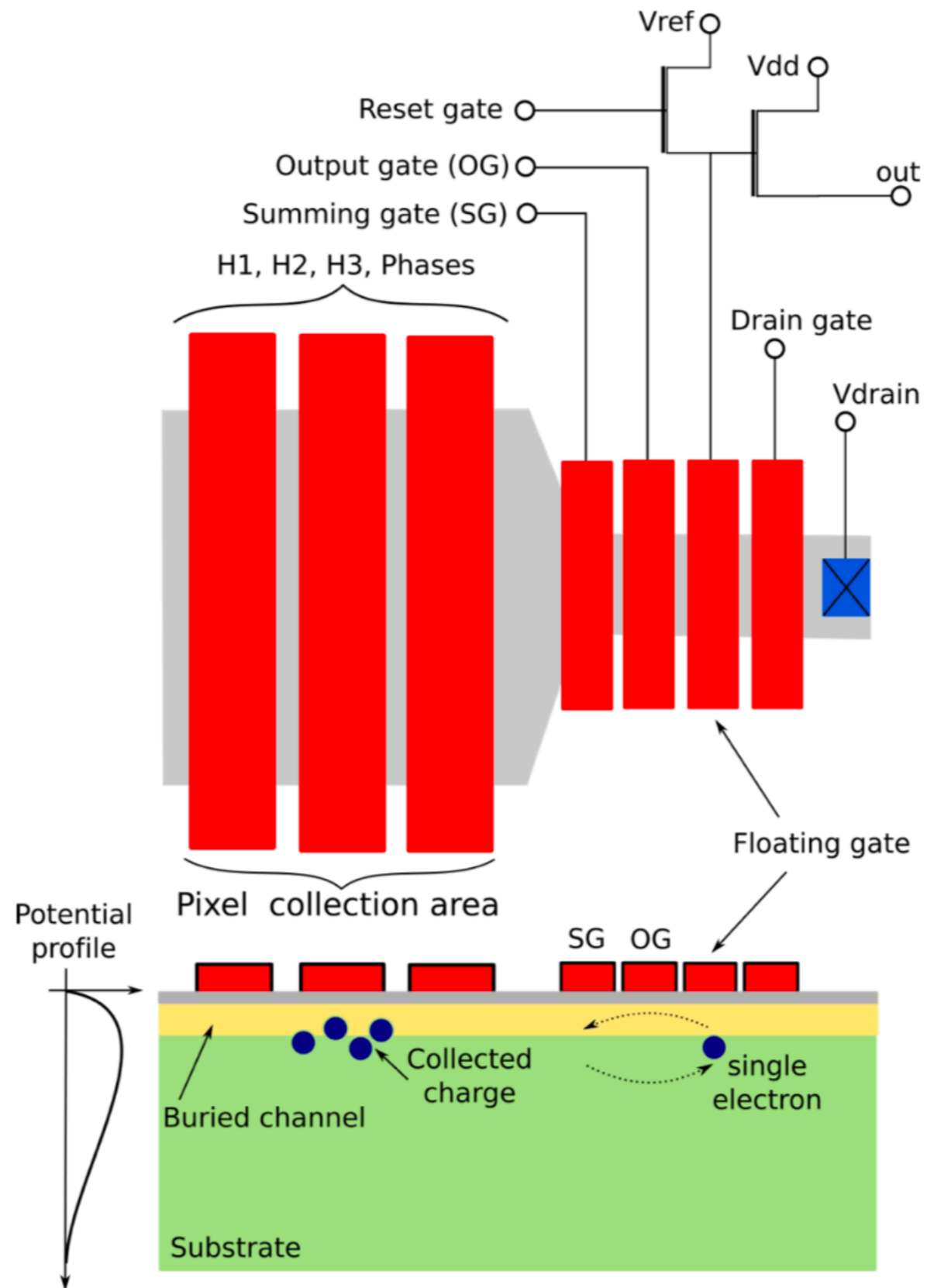


Figure 1.: Simplified diagram of a single-pixel skipper-CCD fabricated in a CMOS process.

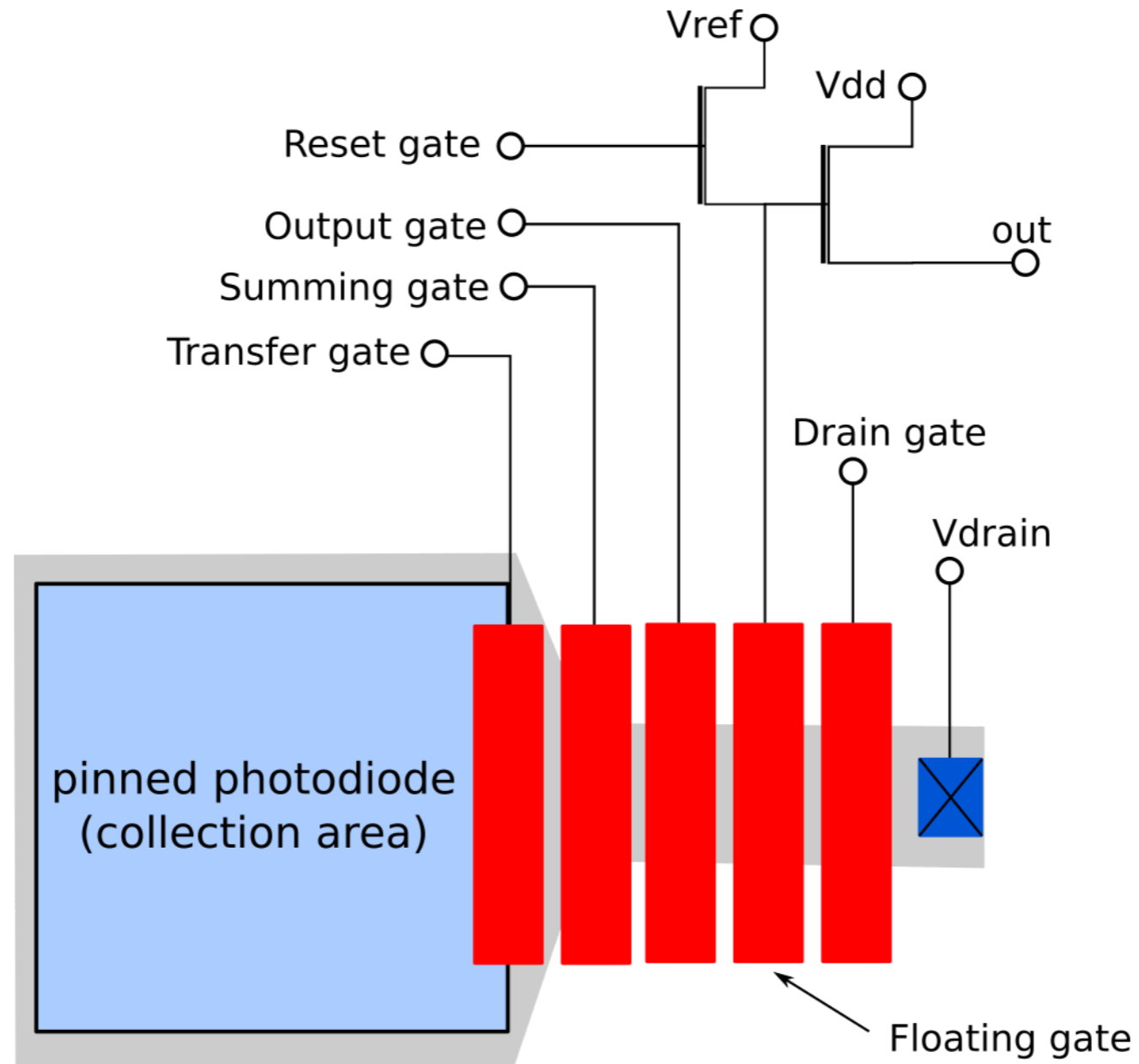


Figure 2. Simplified diagram of a pixel, fabricated in a CMOS process, with skipper-CCD readout