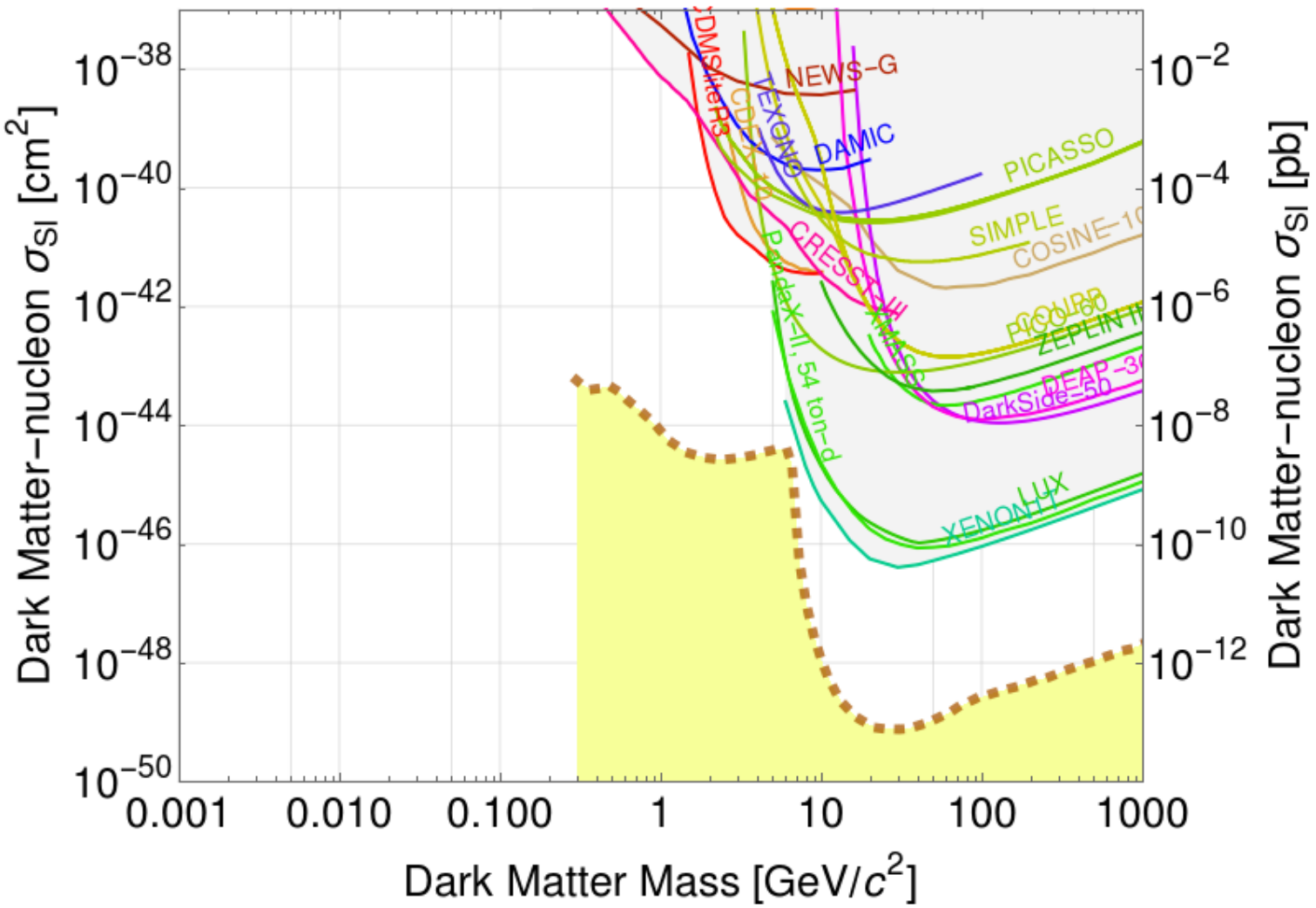
Counting electrons with the Skipper-CCD

Javier Tiffenberg

Fermi National Laboratory

Aug 2, 2019

Context & Motivation: Direct detection history

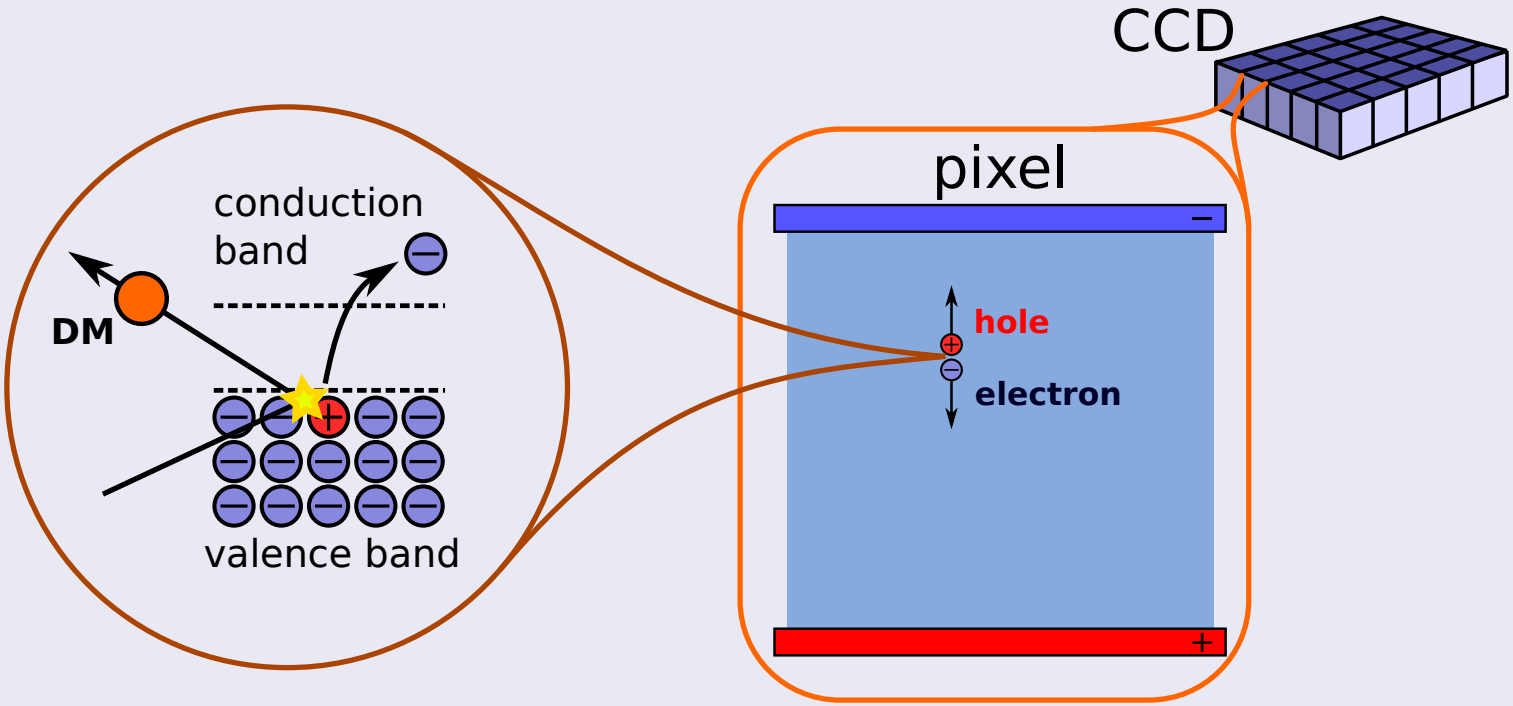


Dark Matter Limit Plotter v5.00, updated Feb 14, 2019.

Goal: lower the energy threshold to look for light DM candidates

Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

Idea: use electrons in the bulk silicon of a CCD as targets



This requires very low noise!

SENSEI LDRD Collaboration (2015)

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) using SkipperCCDs produced at LBL MSL

- **Fermilab:** Tiffenberg, Guardincerri, Sofo Haro
- **Stony Brook:** Rouven Essig
- **LBNL:** Steve Holland, Christopher Bebek
- **Tel Aviv University:** Tomer Volansky
- **CERN:** Tien-Tien Yu
- **Stanford University*:** Jeremy Mardon

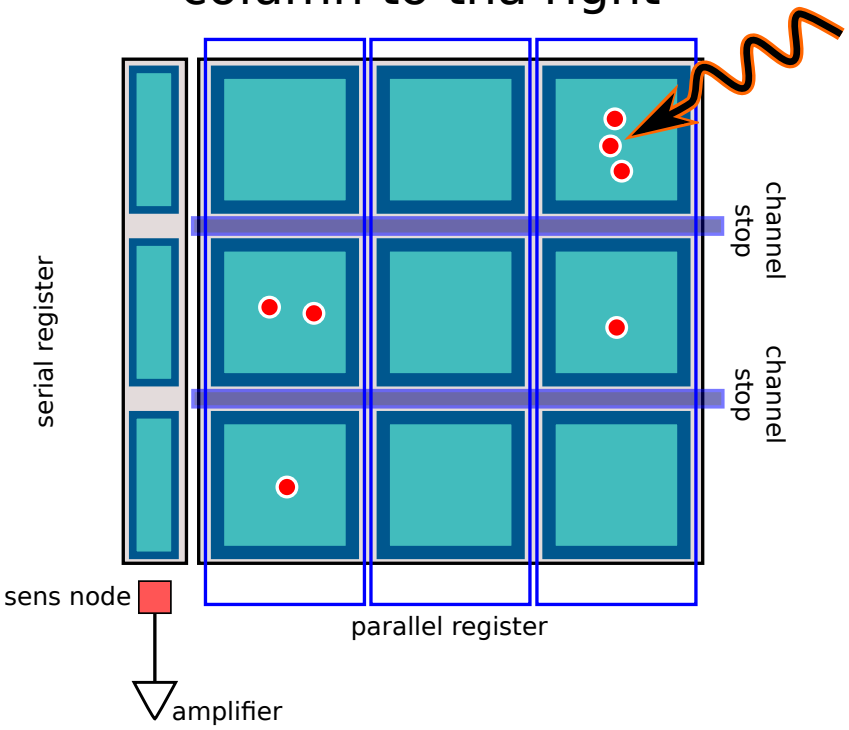
Main goals

- Build the first working detector using Skipper-CCDs.
- Validate the technology for DM and ν experiments.
- Probe DM masses at the MeV scale through electron recoil.
- Probe axion and hidden-photon DM with masses down to 1 eV.
- Single photon imaging with low dark counts.

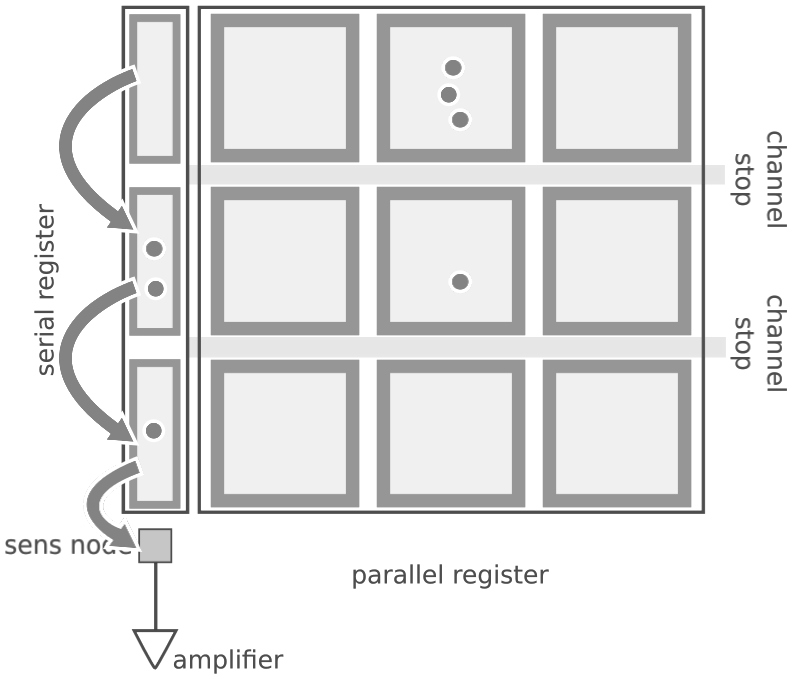
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



Shift charge in serial register one pixel down (3 times)



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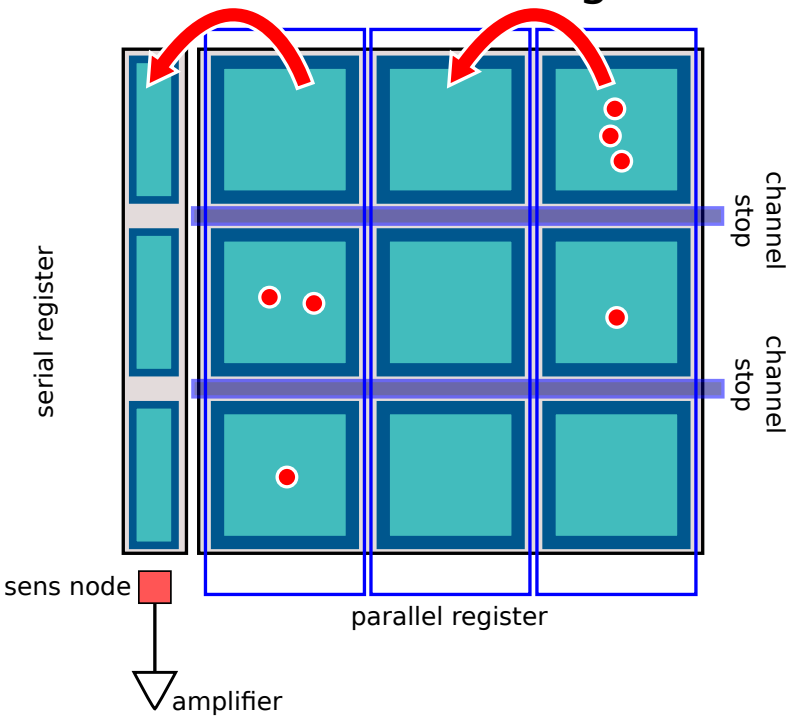

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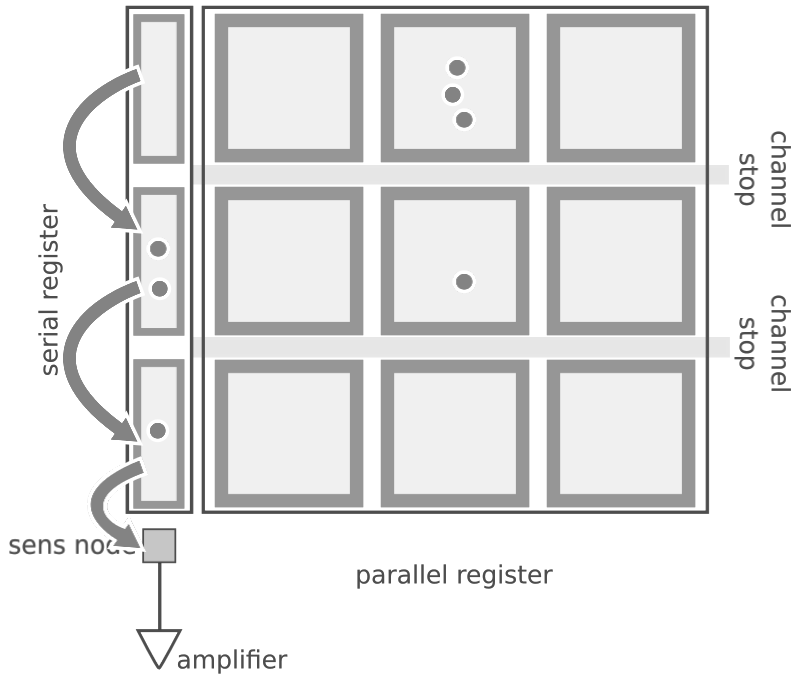

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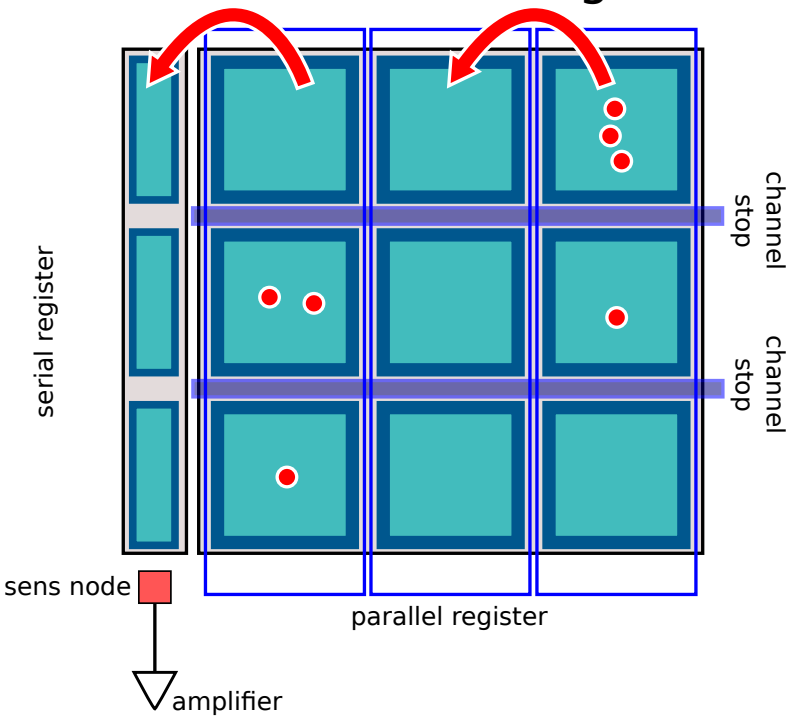

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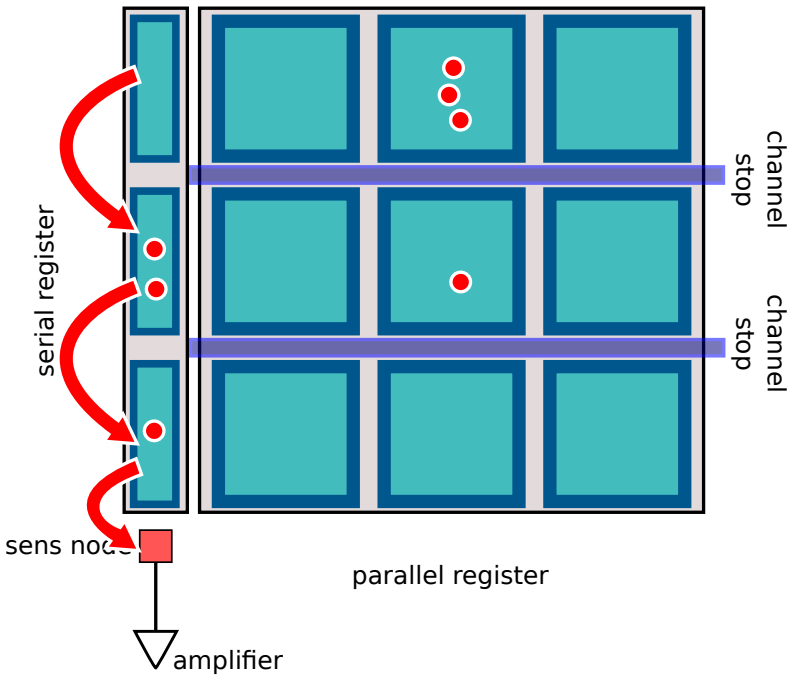
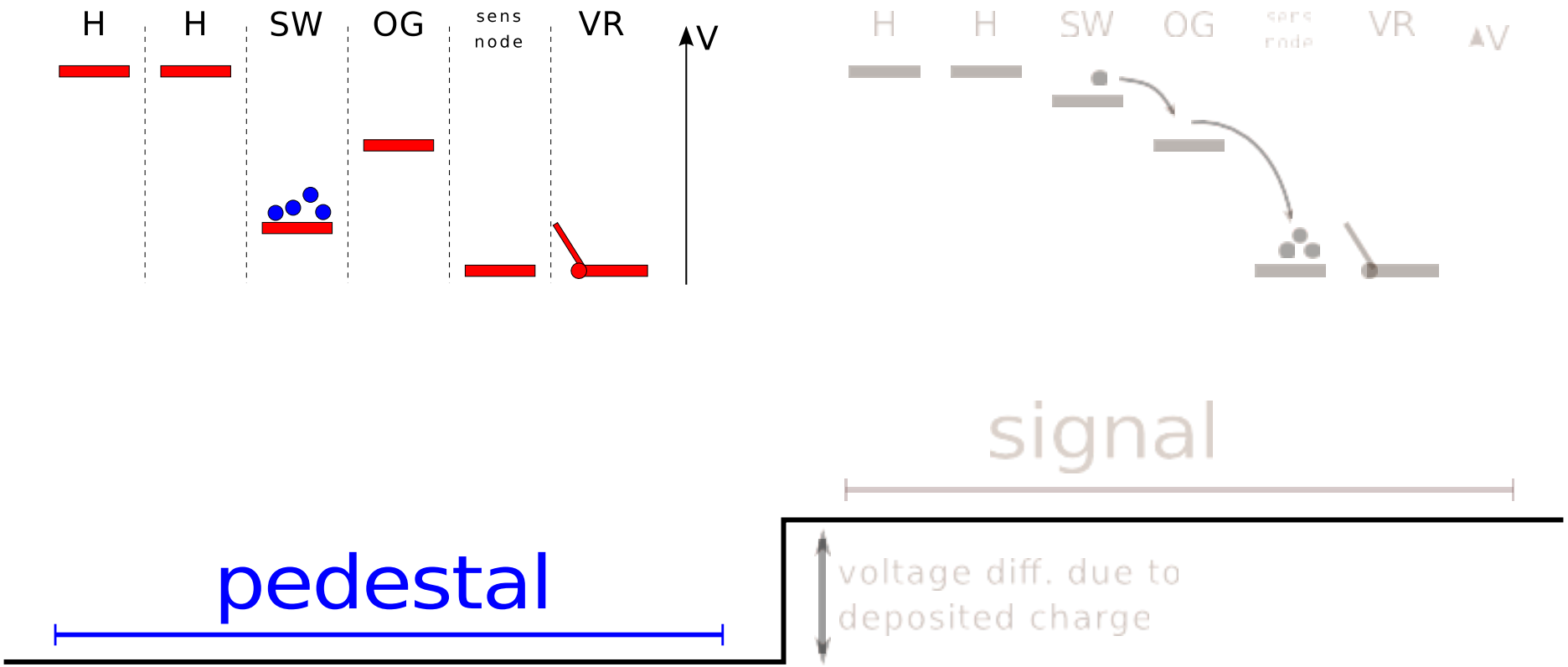
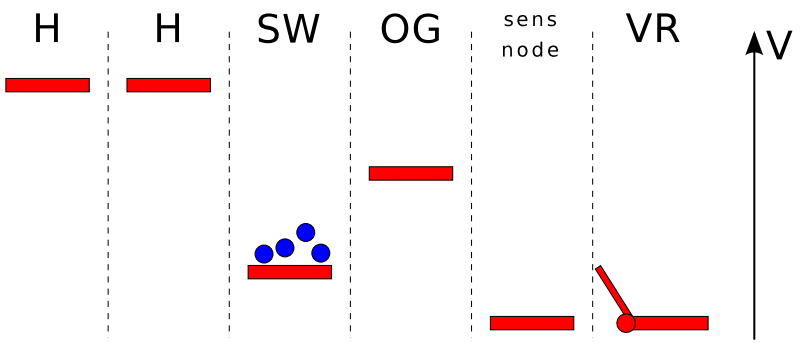


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

CCD: readout


H
H
SW
OG
sens node
VR
V
H
H
SW
OG
VR
V
signal
pedestal
voltage diff. due to deposited charge

CCD: readout


H
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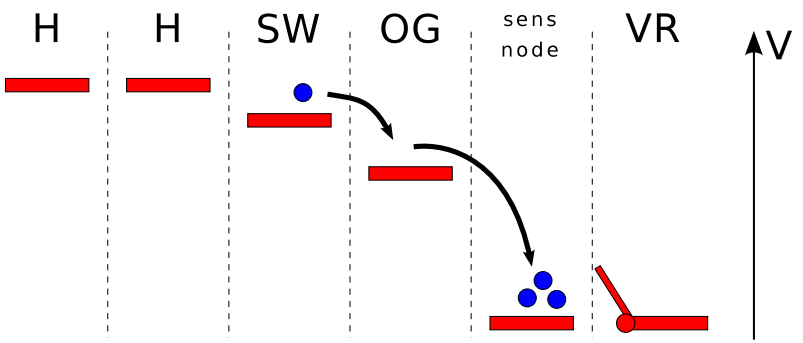
H
H
SW
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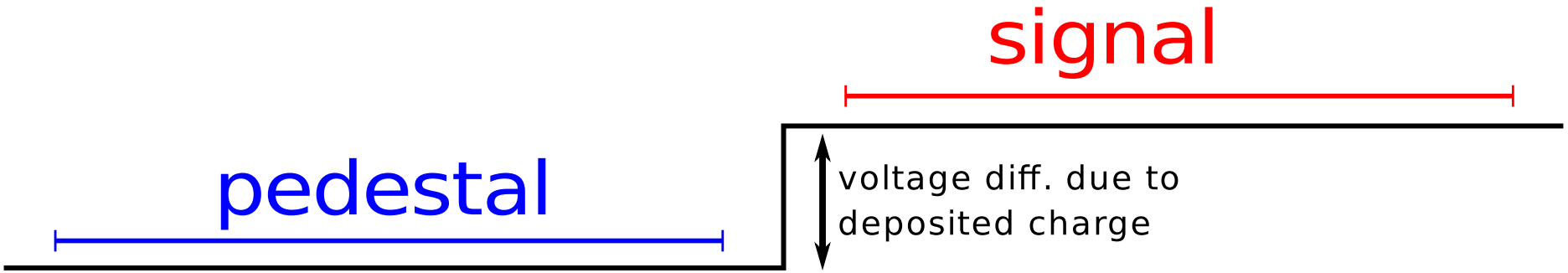
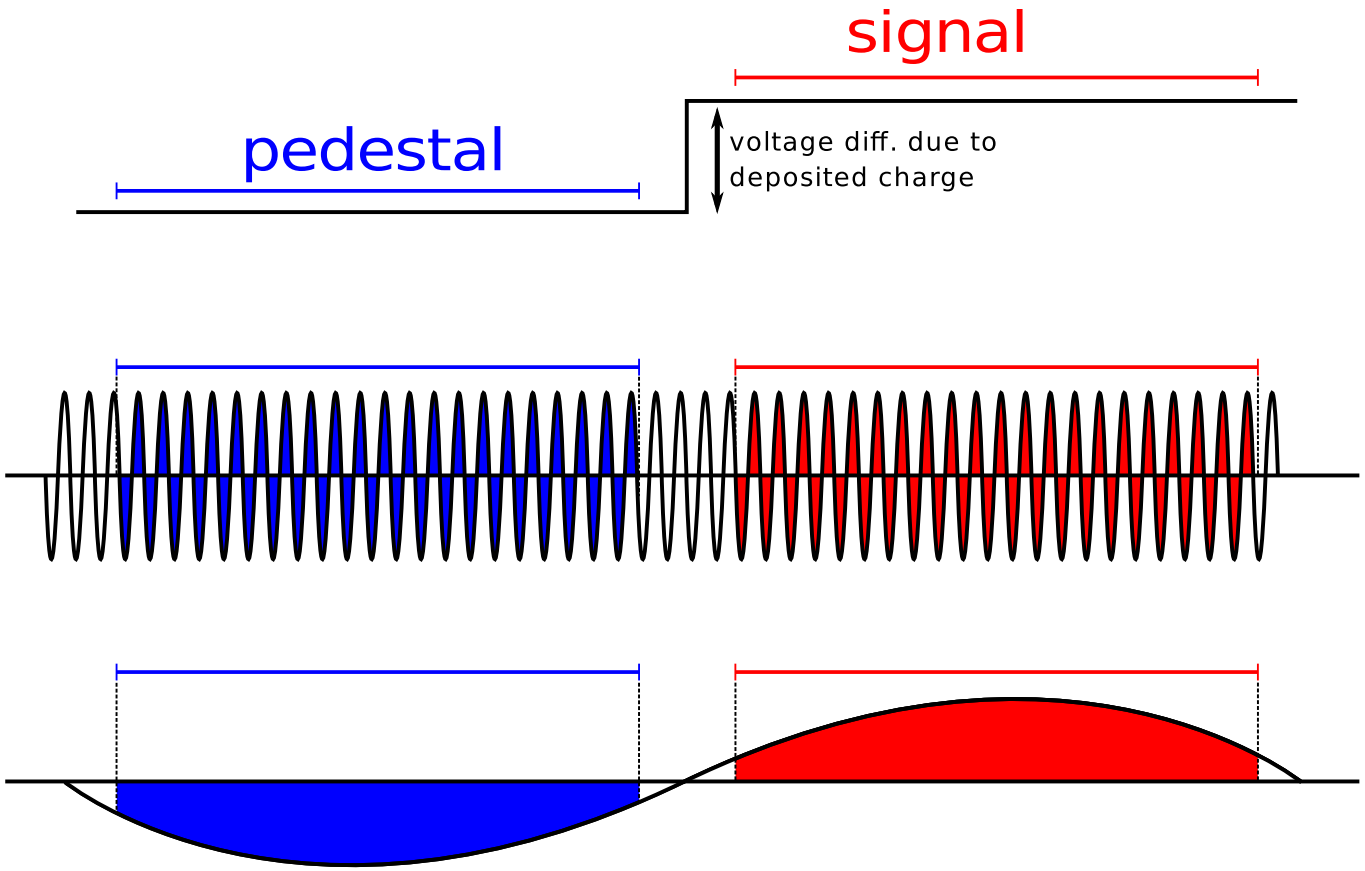

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout

pixel charge measurement

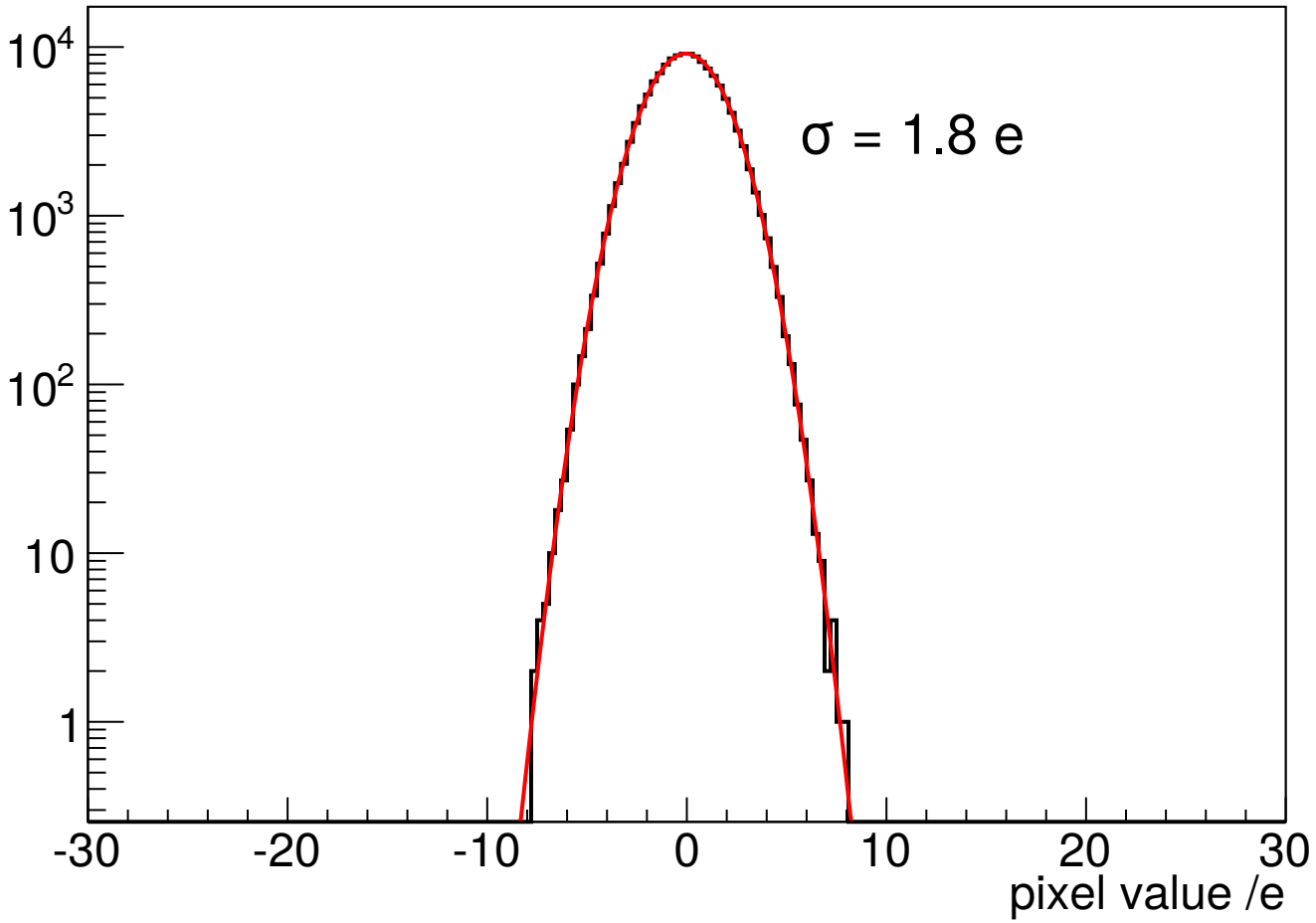
high frequency noise

low frequency noise



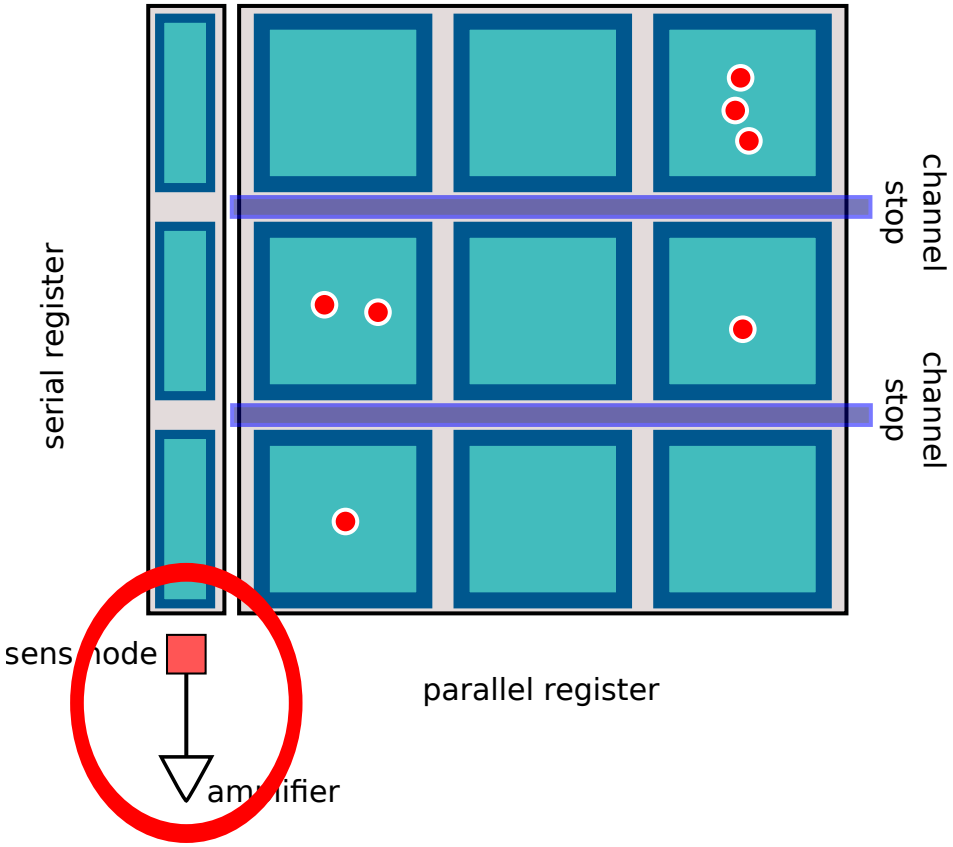
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution, regular scientific CCD



2 e^- readout noise roughly corresponds to 50 eV energy threshold

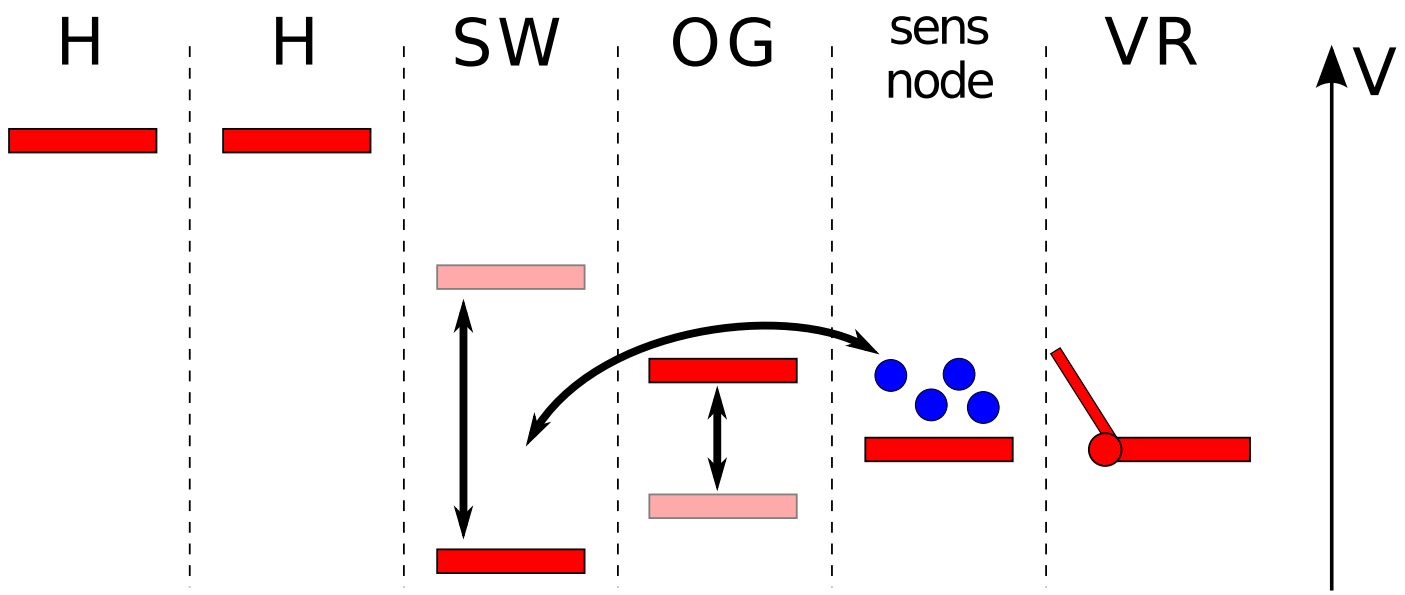
Lowering the noise: Skipper CCD



Only the readout stage is modified

Lowering the noise: 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
  $\boldsymbol{Pixel\ value = \frac{1}{N}\Sigma_i^N\,(pixel\ sample)_i}$
- Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)



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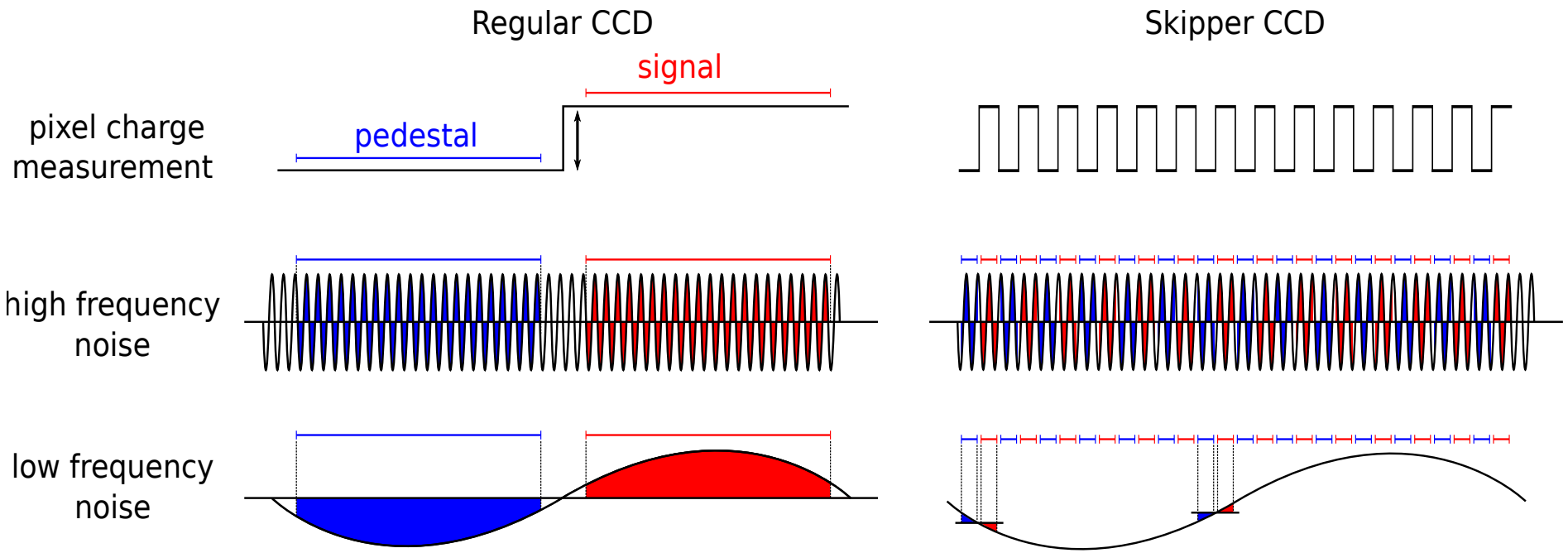
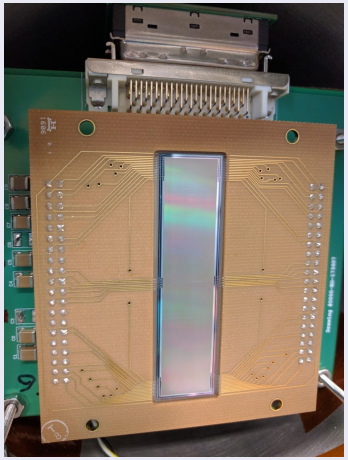


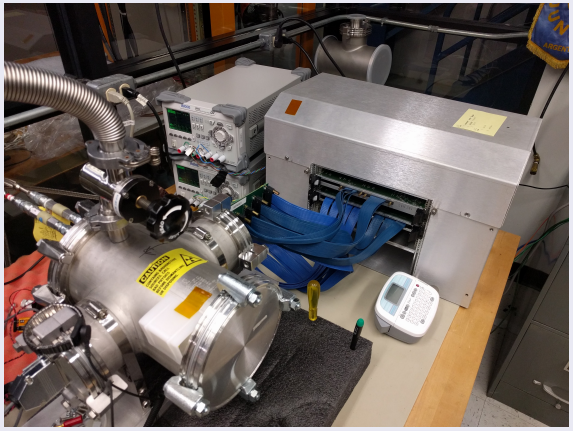
SENSEI: First working instrument using SkipperCCD tech

Sensors



- Skipper-CCD prototype designed at LBL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k$\times$1k (0.5gr) & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

Instrument



- System integration done at Fermilab
- Custom cold electronics
- Modified DES electronics for read out
- Firmware and image processing software
- Optimization of operation parameters

Image taken with SENSEI: 4000 samples per pixel (processed)

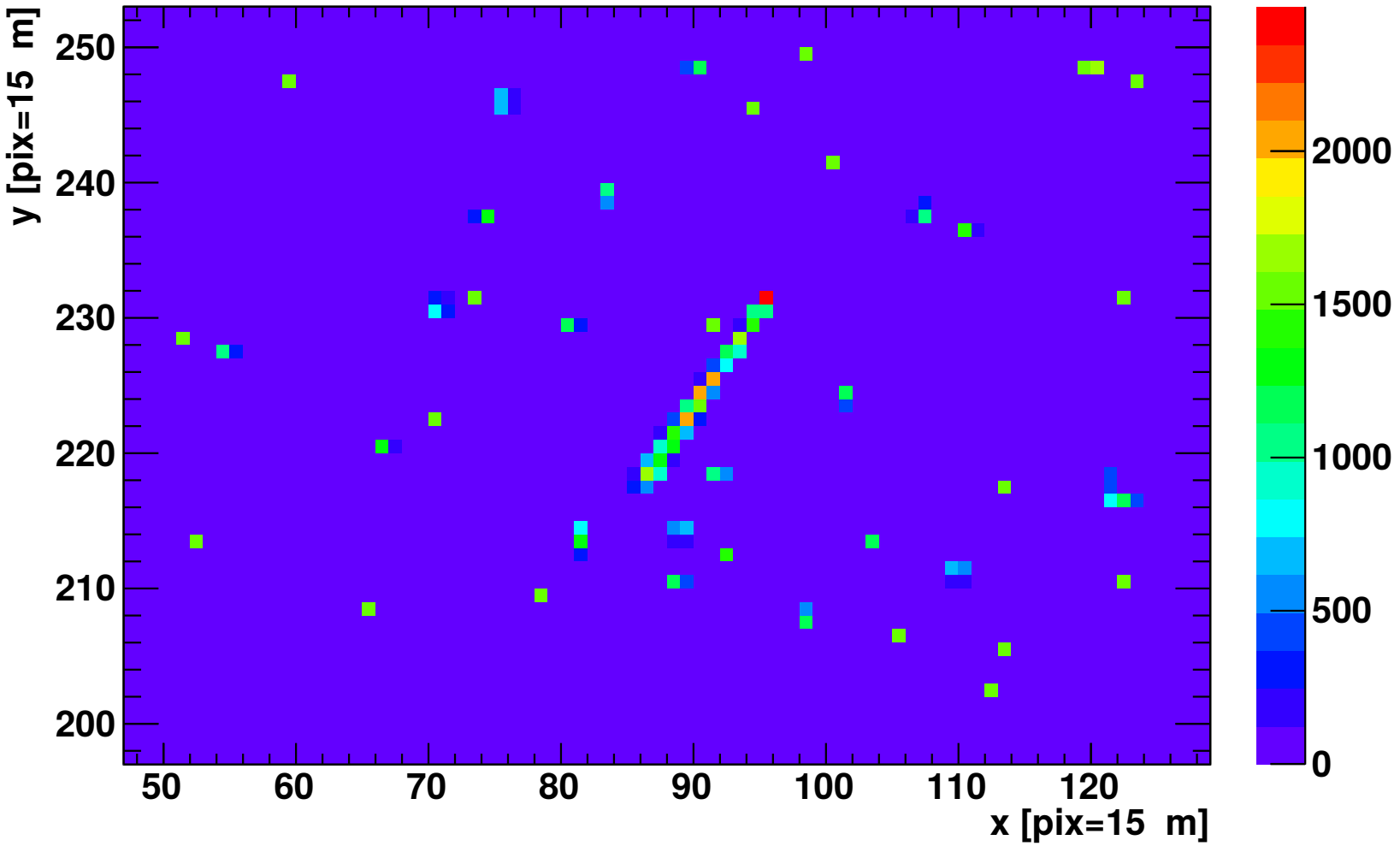
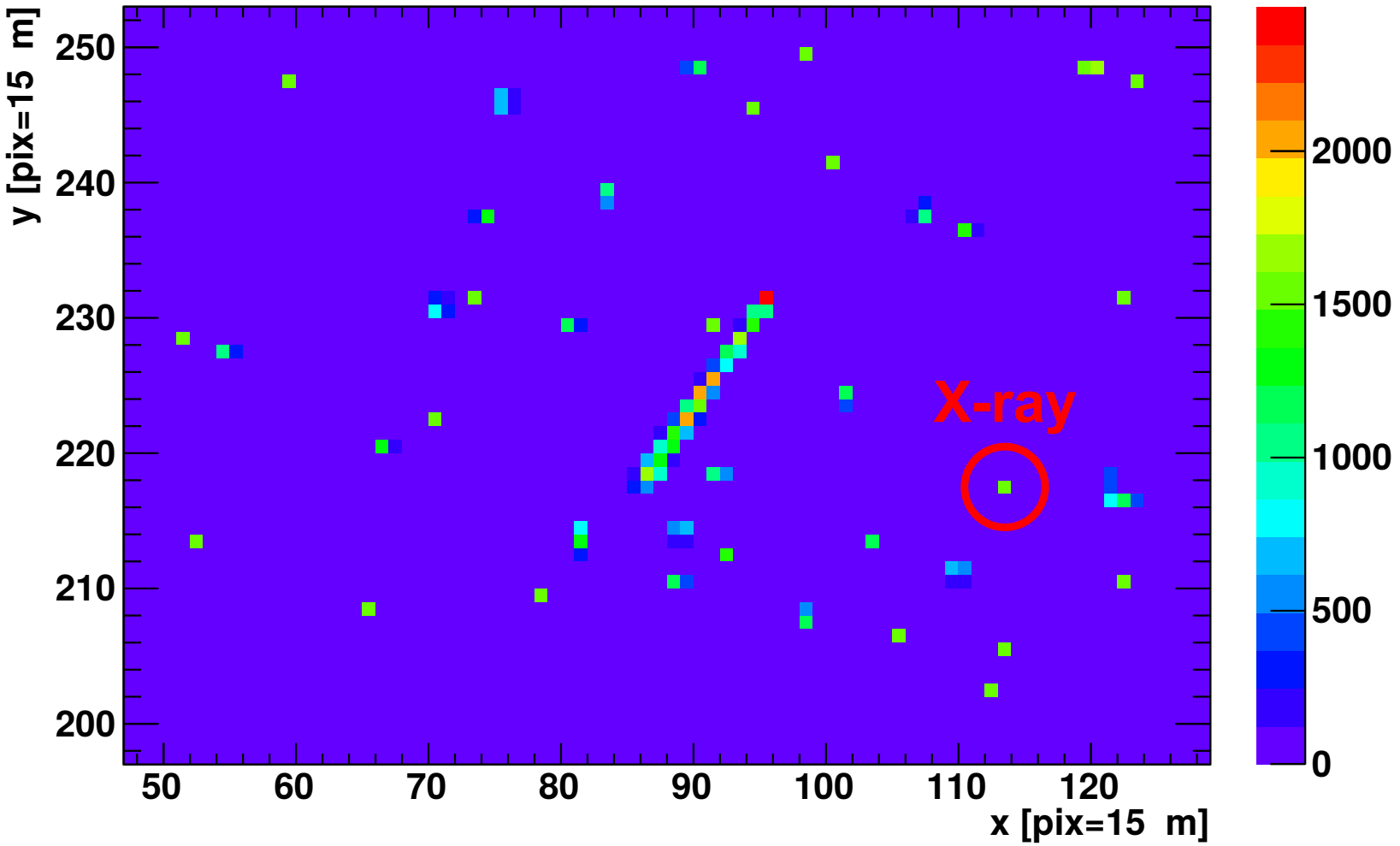


Image taken with SENSEI: 4000 samples per pixel (processed)



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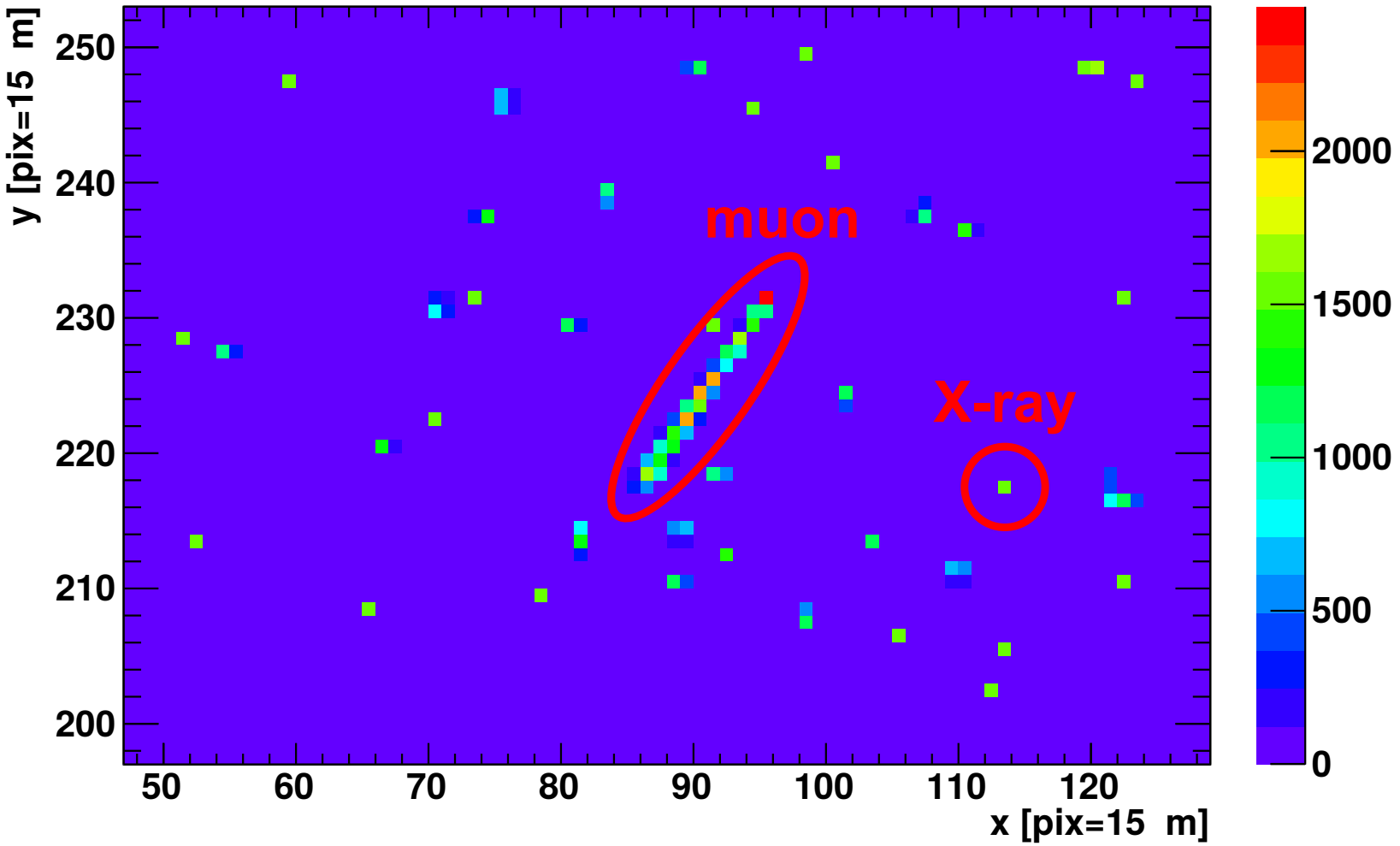

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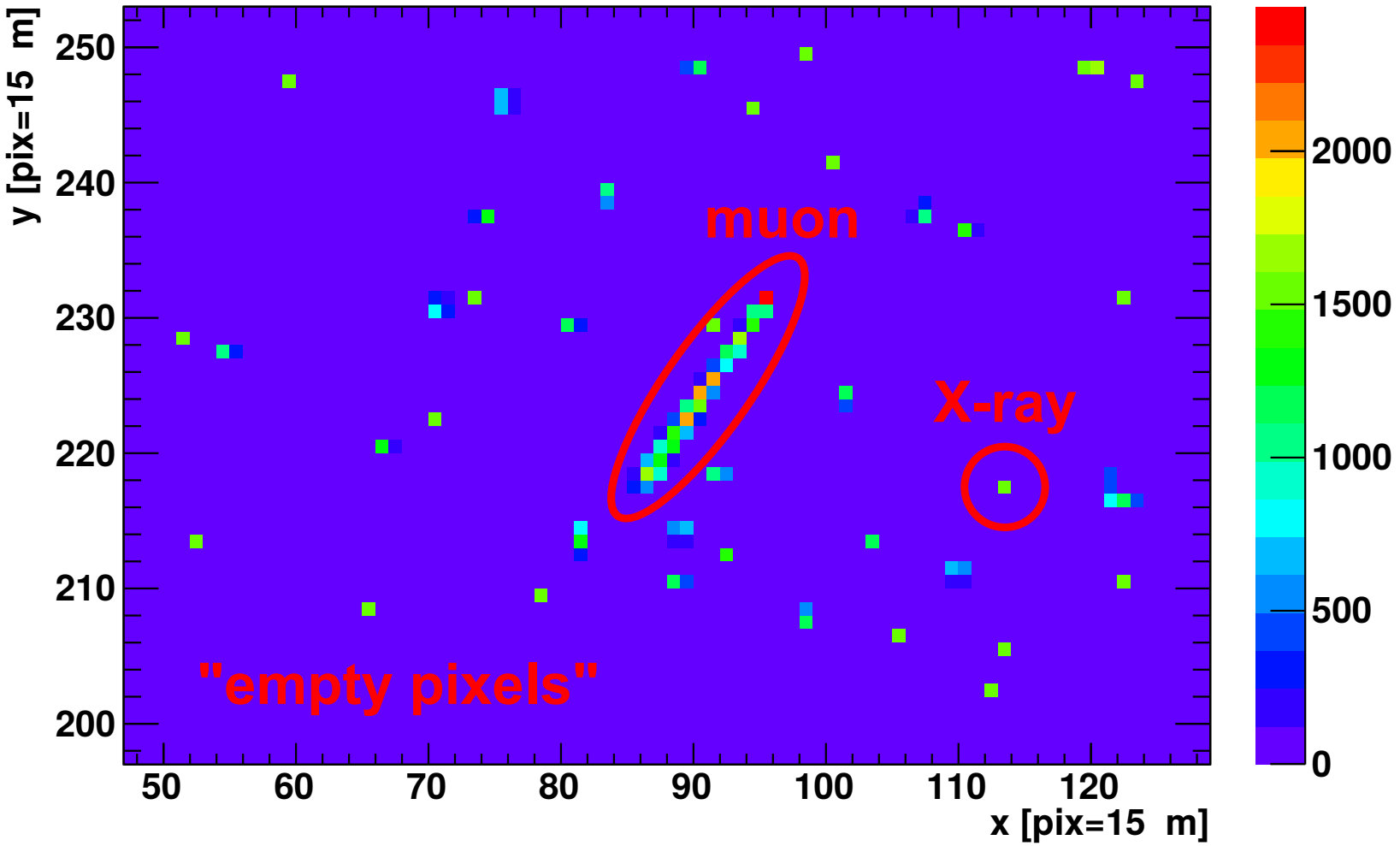
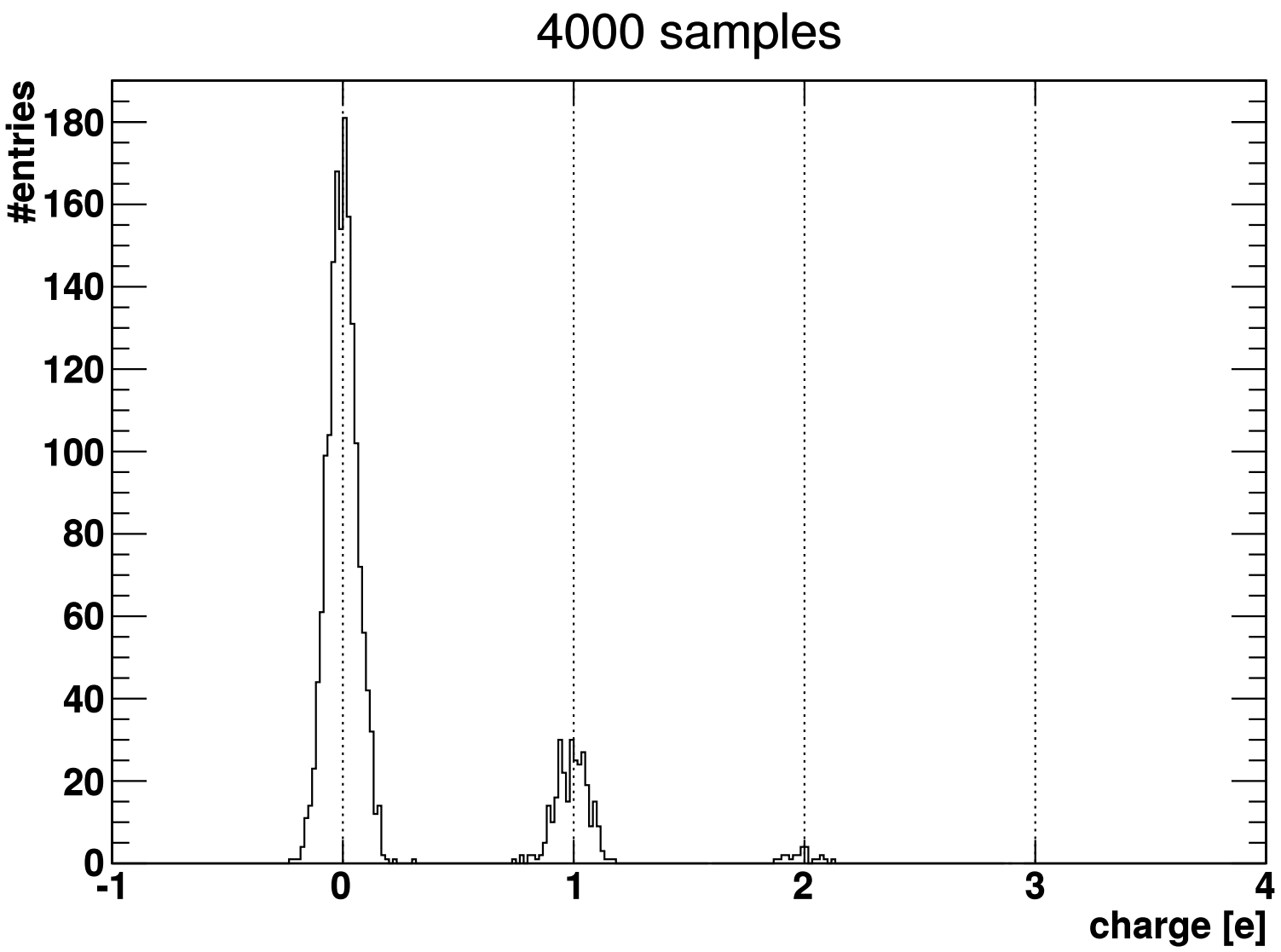
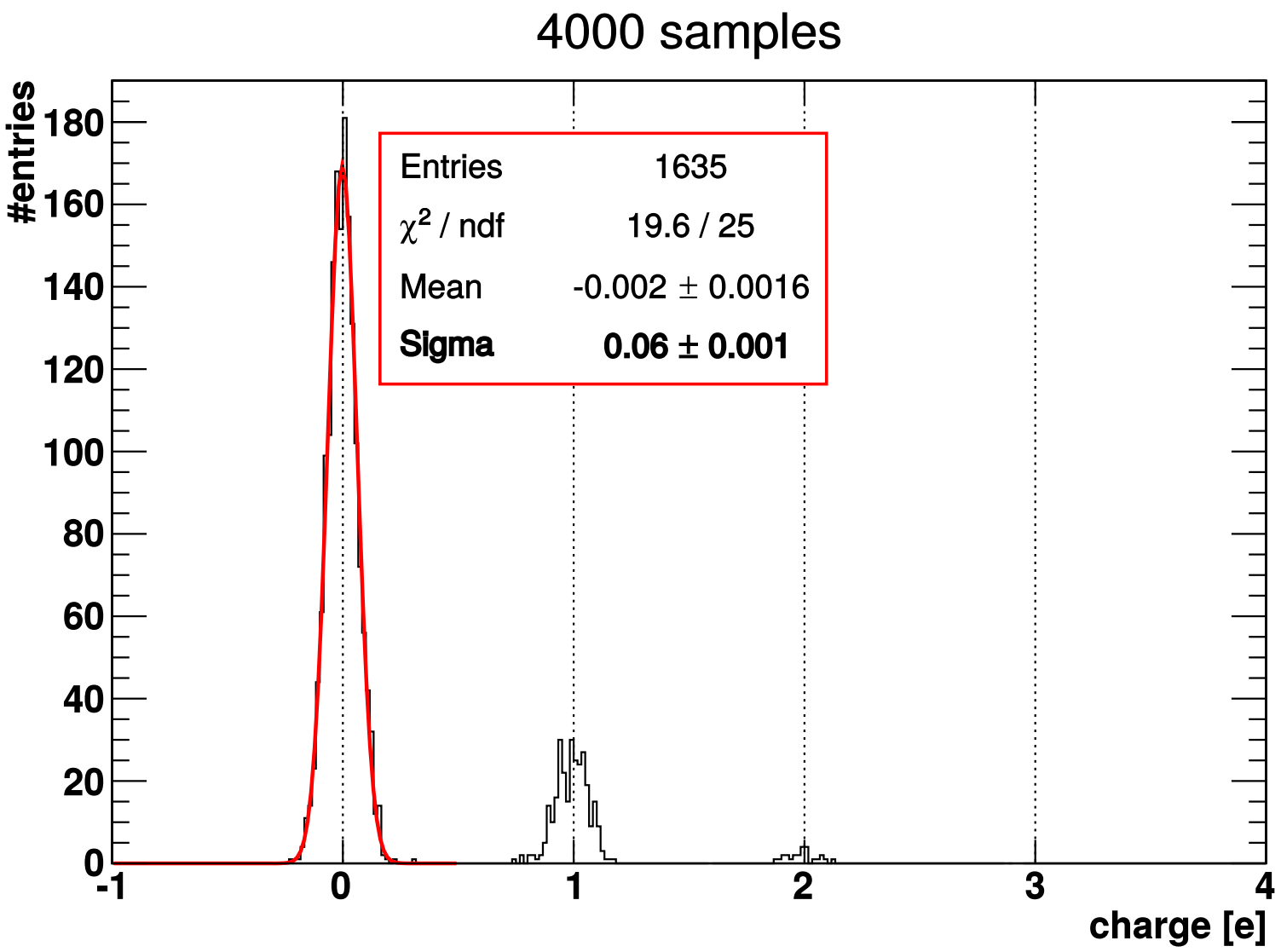


Charge in pixel distribution. Counting electrons: 0, 1, 2..

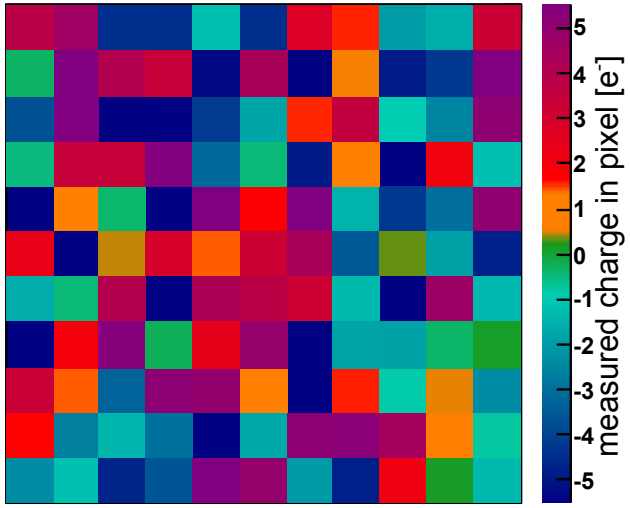


Charge in pixel distribution. Counting electrons: 0, 1, 2..

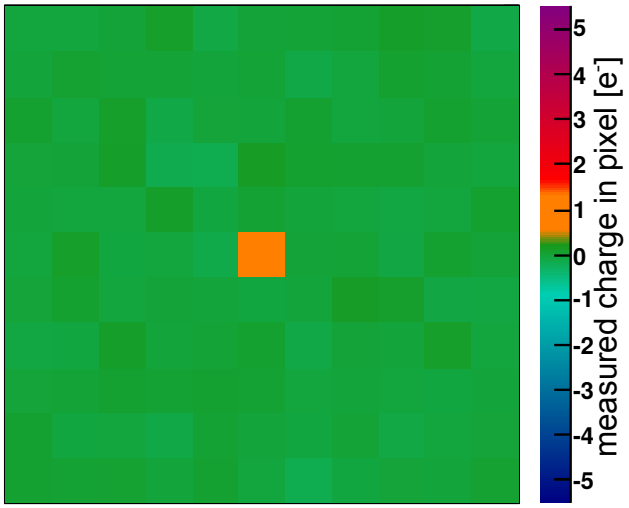


Counting electrons: 0, 1, 2..

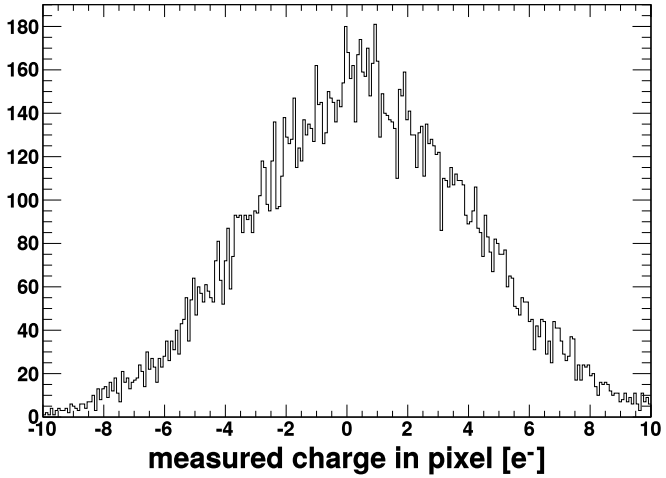
Standard CCD mode: charge in each pixel is measured once



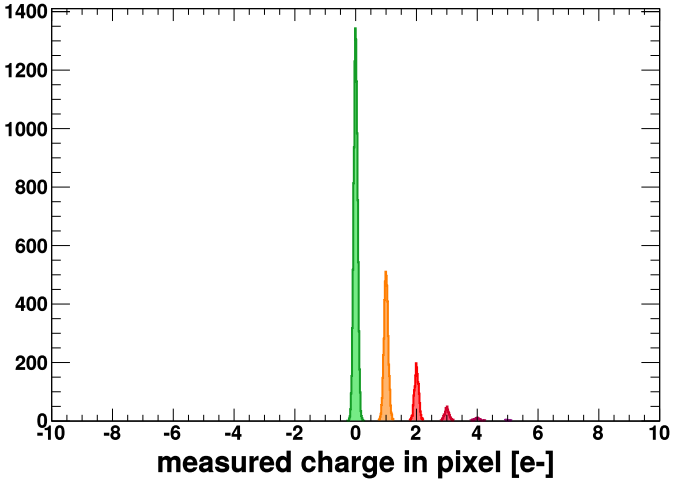
New Skipper CCD: charge in each pixel is measured multiple times



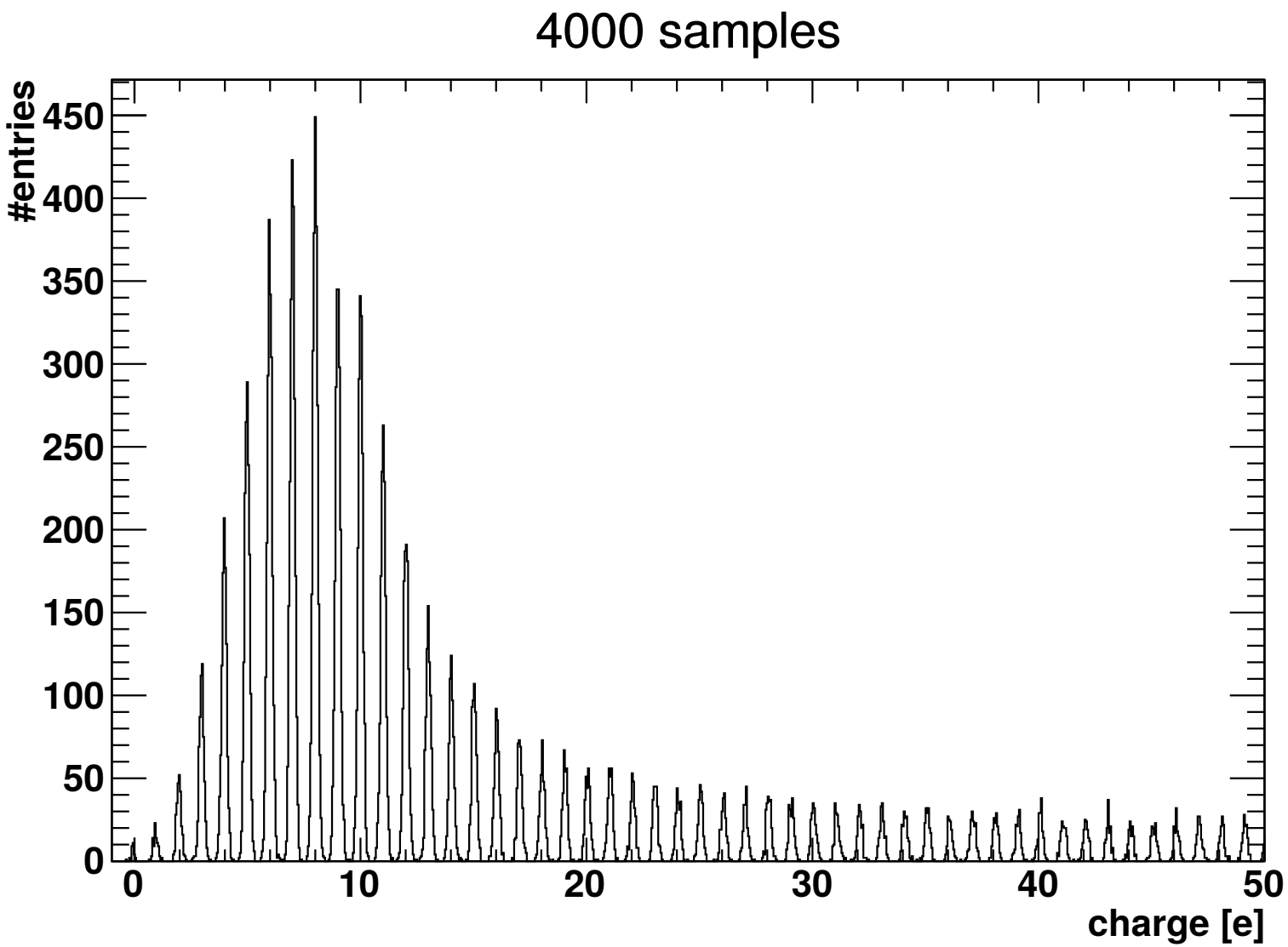
Readout-noise: 3.5 e RMS



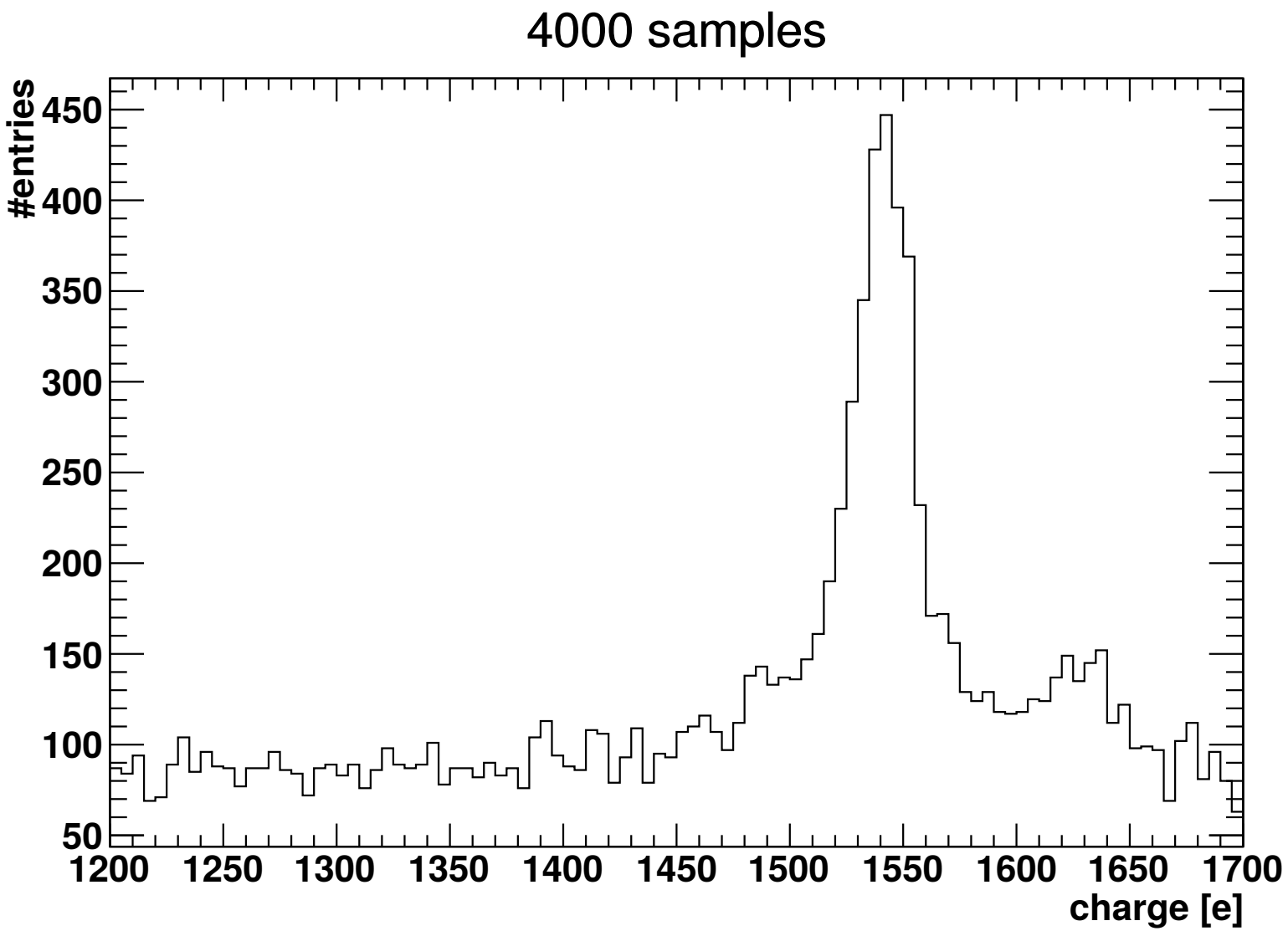
Readout-noise: 0.06 e RMS



Counting electrons: ..48, 49, 50..



^{55}Fe X-ray source



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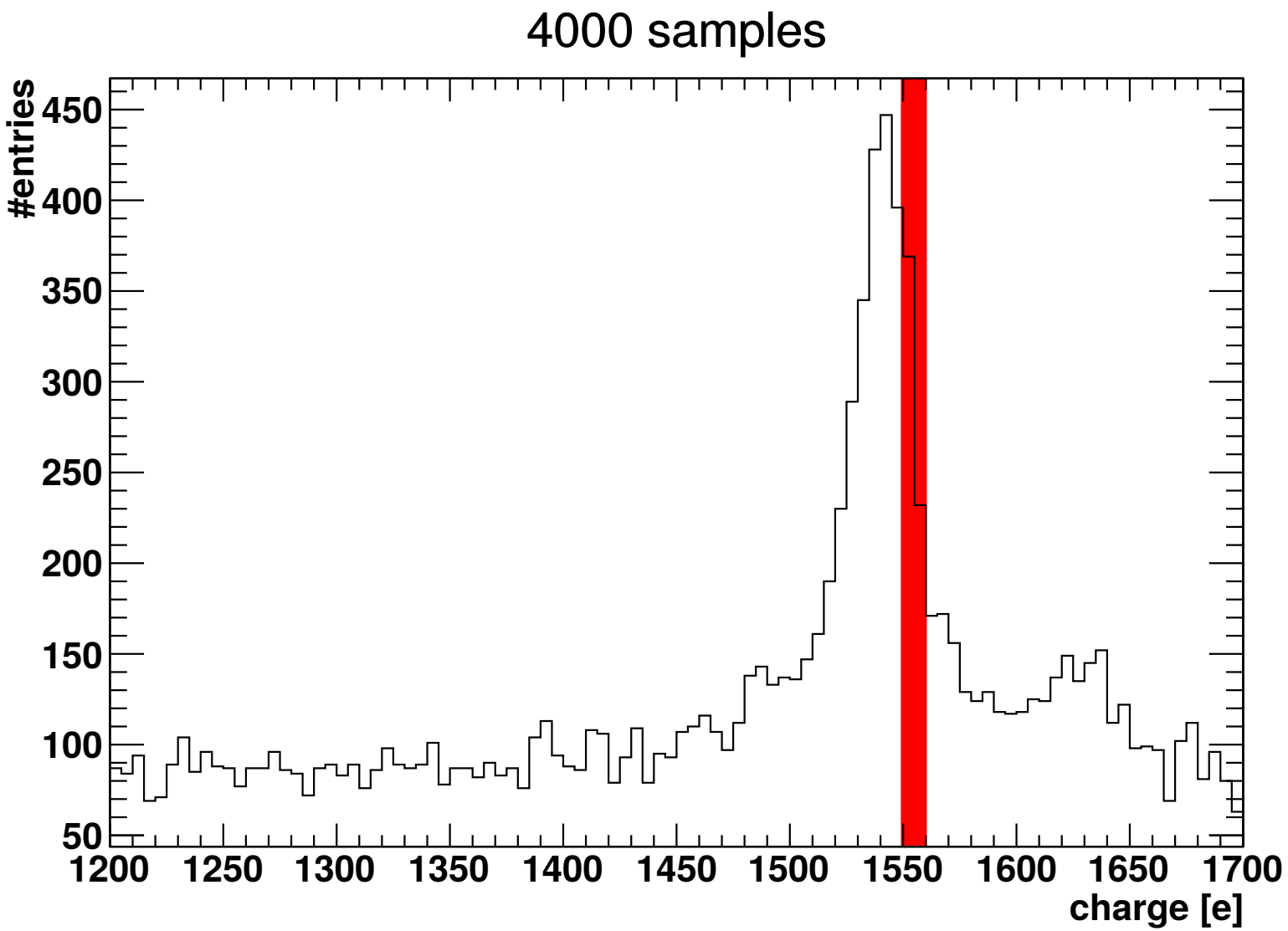


keep counting: ..1550, 1551, 1552..

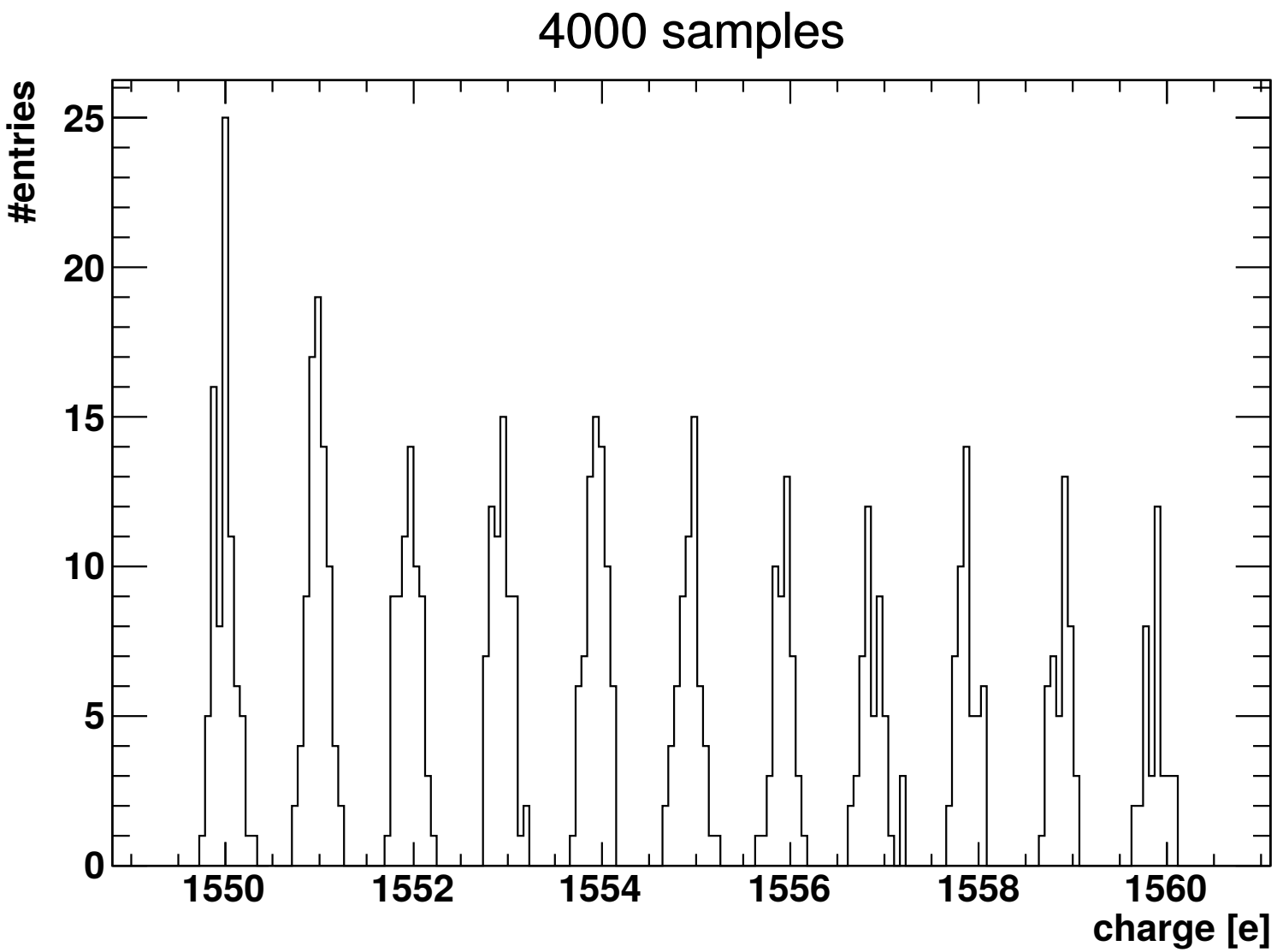
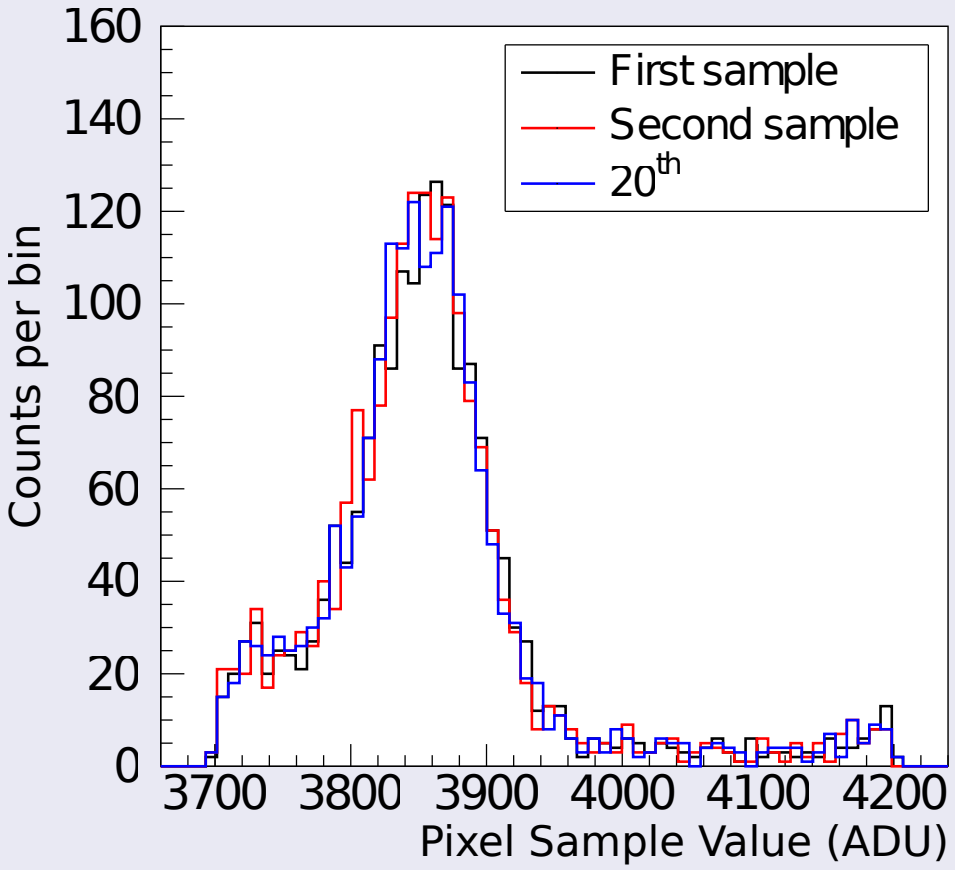


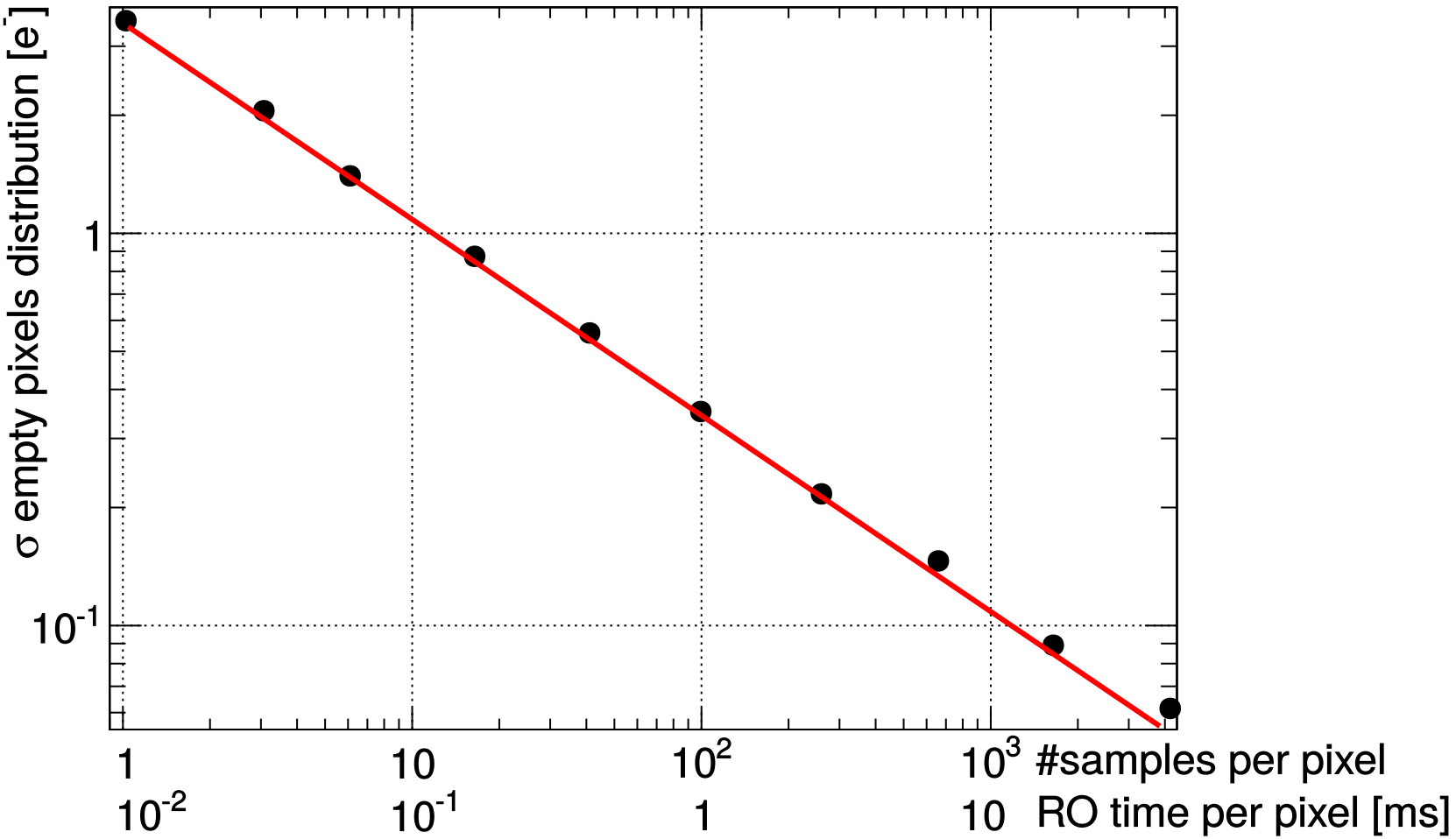
Image taken with SENSEI: 20 samples per pixel

Single pixel distribution: X-rays from ^{55}Fe



The gain is the same for all the samples

Noise vs. #samples - $1/\sqrt{N}$



Summary

Ongoing applications using SkipperCCD sensors

- SENSEI experiment for light-DM searches
  - Fully funded by Heising-Simons Foundation and Fermilab's support.
  - Already produced world leading results using prototype R&D sensors.
  - Currently commissioning new generation of science grade SkipperCCDs!
- DAMIC-M experiment
  - Will deploy a 1kg scale experiment using SkipperCCDs.
- SkipperCCD cameras for astronomical applications are being build.
- SkipperCCDs are being used for quantum imaging efforts.
- Plans to incorporate SkipperCCDs on reactor-neutrino experiments.

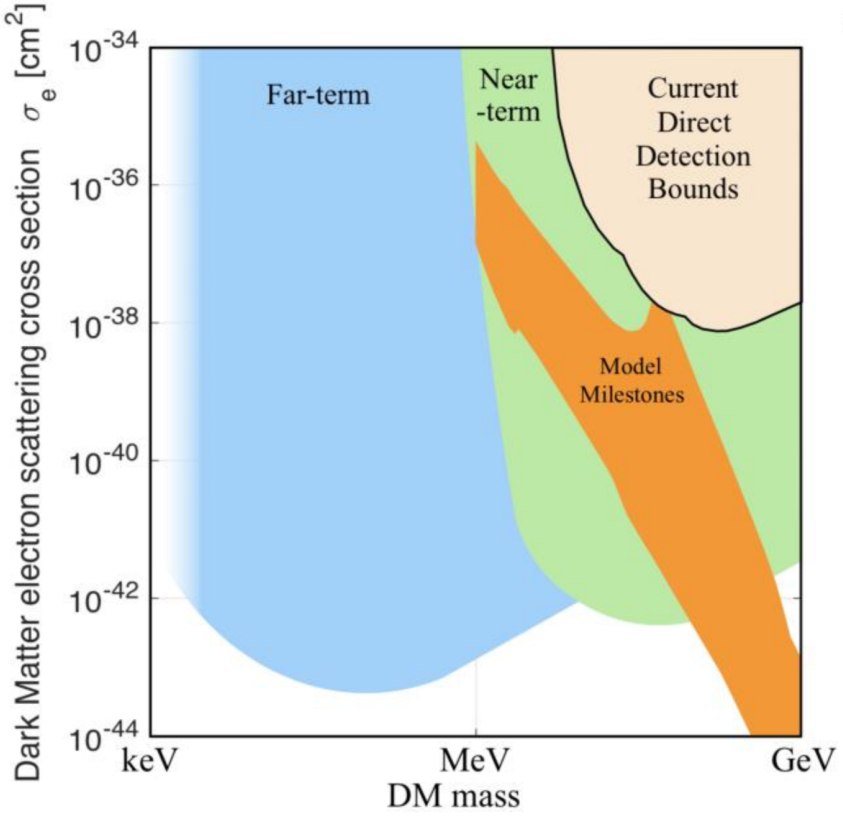
Continuing the R&D effort

- DOE ECA: scale up the number of sensors for ν instruments.
- Quantum Imaging: faster readout for imaging applications

BACK UP SLIDES

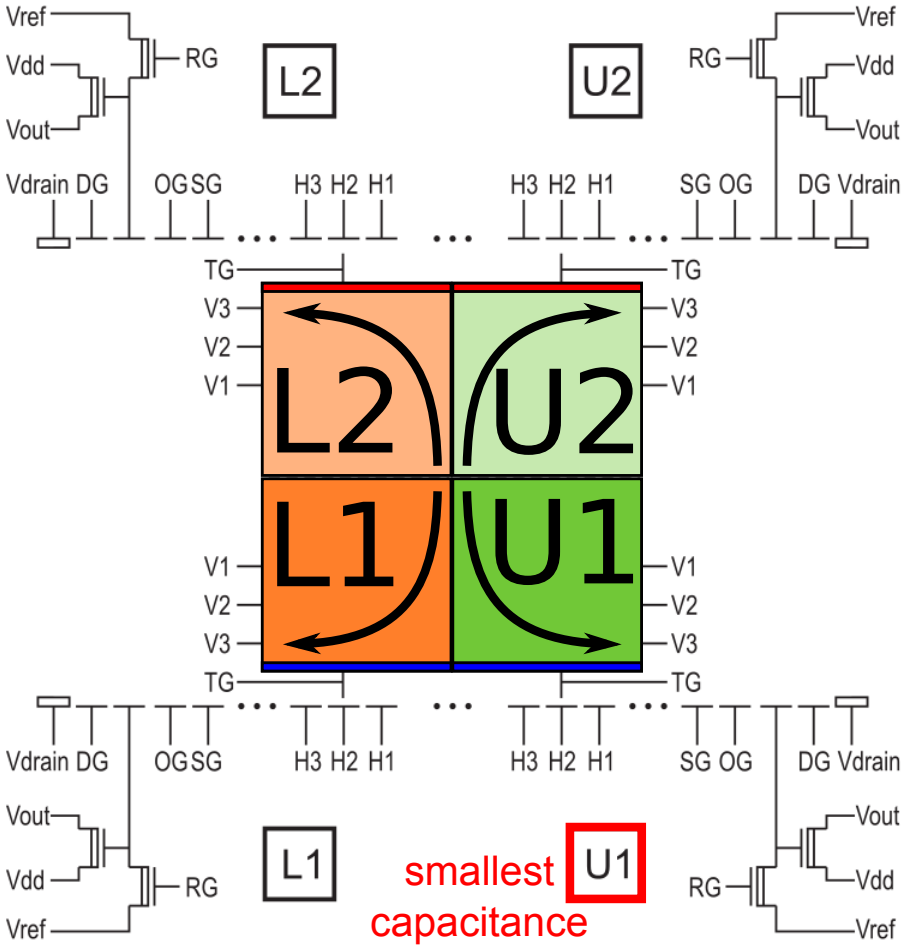
Context & Motivation: community interest - new candidates

Single electron sensitivity opens several order of magnitude in mass and cross section for small projects.



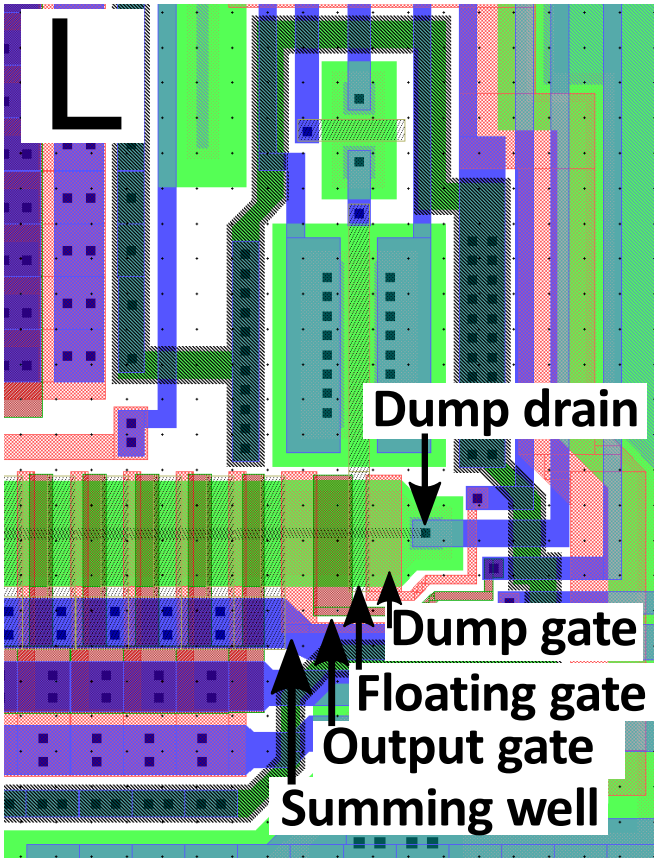
DOE report for basic research needs for Dark Matter Science.
https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

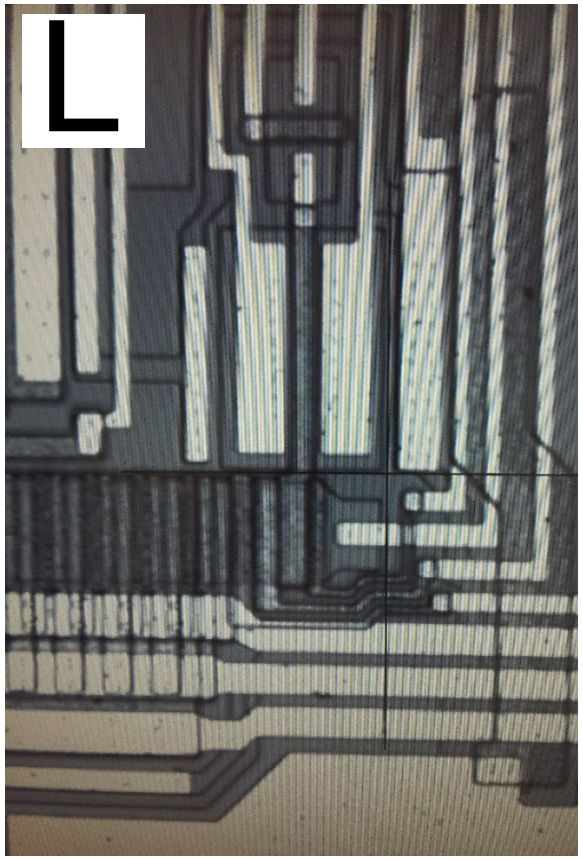
CCD: readout

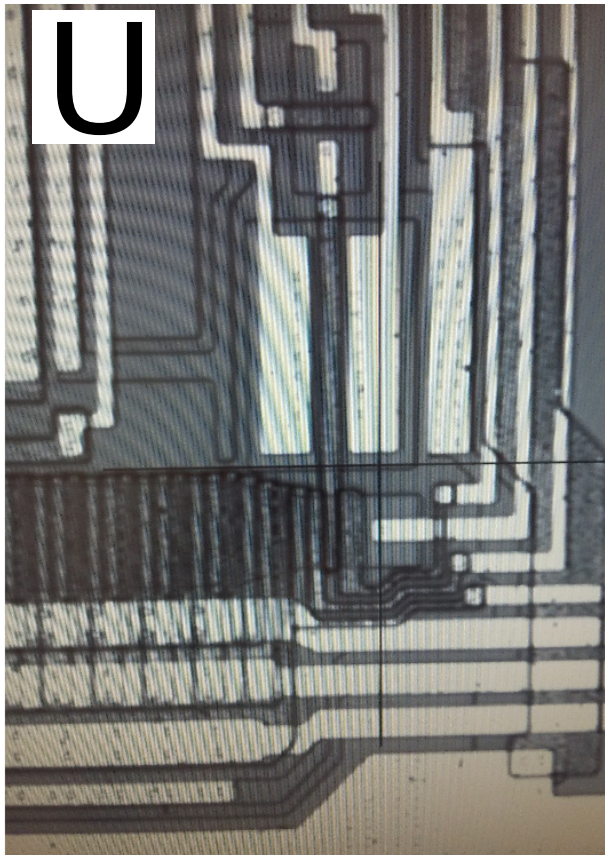


4 amplifiers per CCD, three different RO stage designs. The design with the smallest capacitance (U1) is the one that performs better.

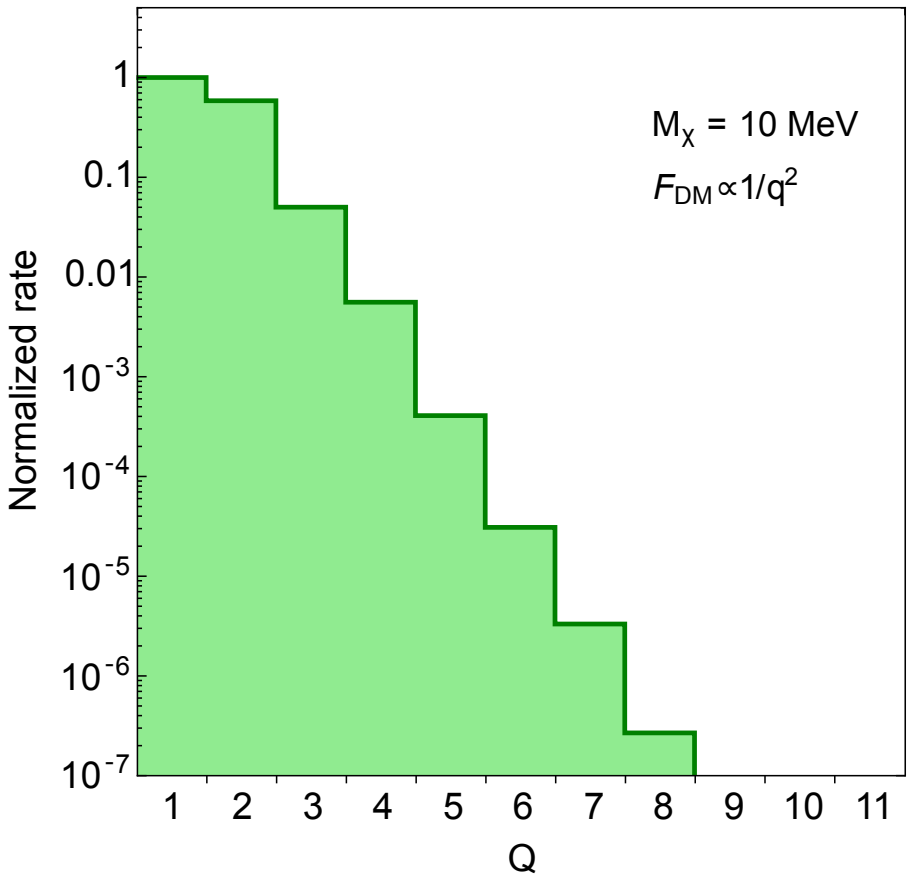
Readout stage design







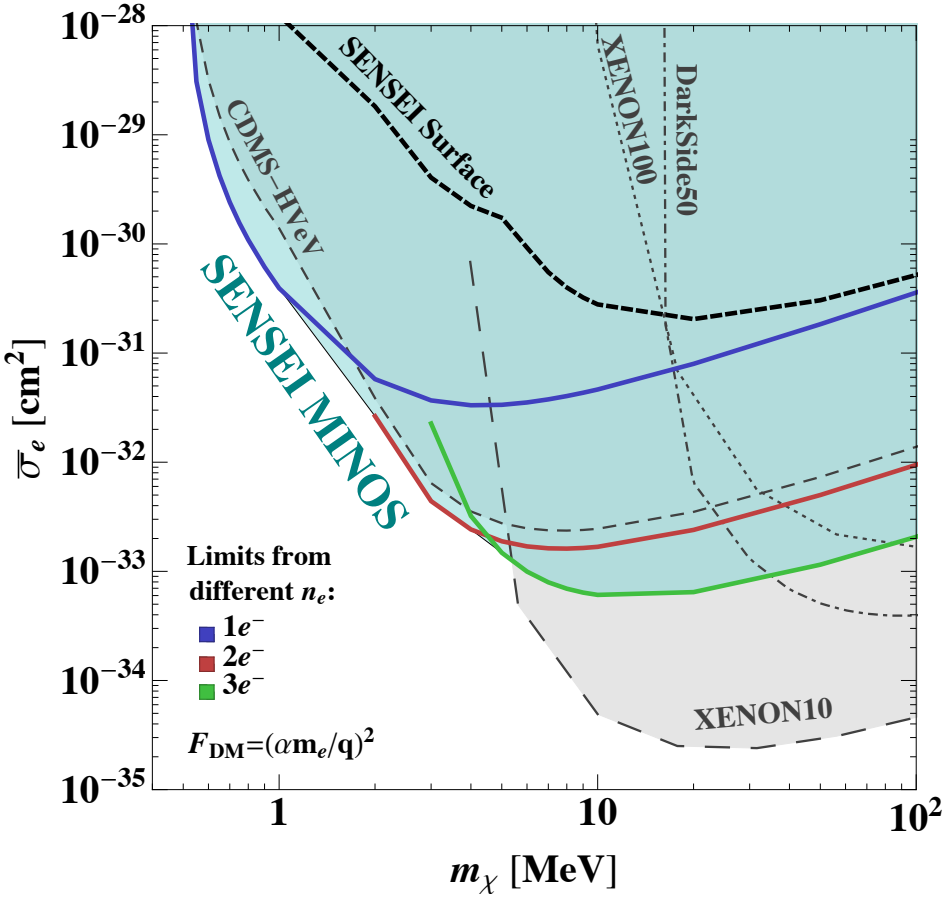
Typical e⁻-recoil spectrum for benchmark models



- the sensitivity is limited by the lowest charge bin.
- background impact is reduced due to the small energy window.
- main background for semiconductors detectors is the **dark current.**

protoSENSEI @MINOS: results

Light Dark Photon



Heavy Dark Photon