Skipper-CCD technology

A zero noise detector for DM searches and neutrino experiments

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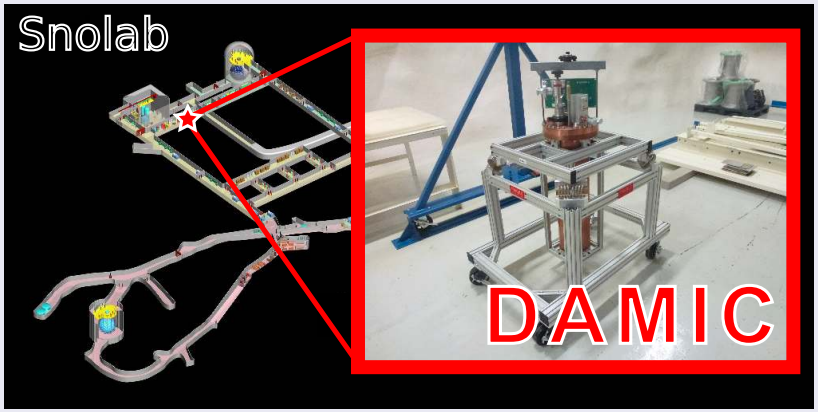
Ricardo Piegaia (UBA)

April 26, 2018

Origin of the project: experiments using scientific CCDs

DAMIC



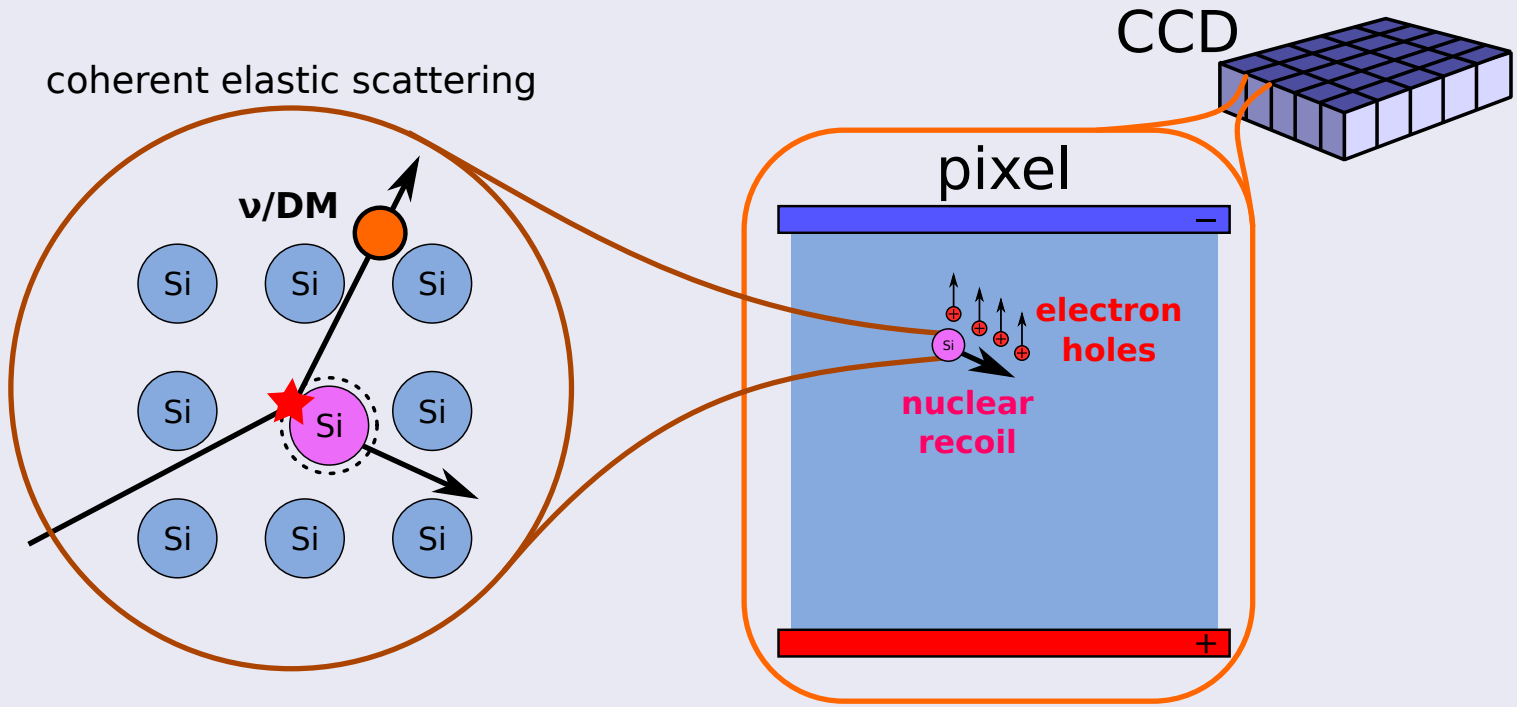
- Low mass Dark Matter search
- Installed at Snolab on Dec-2012
- Currently taking data

CONNIE

- Coherent ν-nucleous interaction
- Installed next to Angra nuclear power plant on Dec-2014
- technique could be used for SBν-Ex
- Currently taking data

Origin of the project: experiments using scientific CCDs

DAMIC & CONNIE use CCDs as targets to detect coherent DM/ν-nucleus interactions by measuring the ionization produced by the nuclear recoils



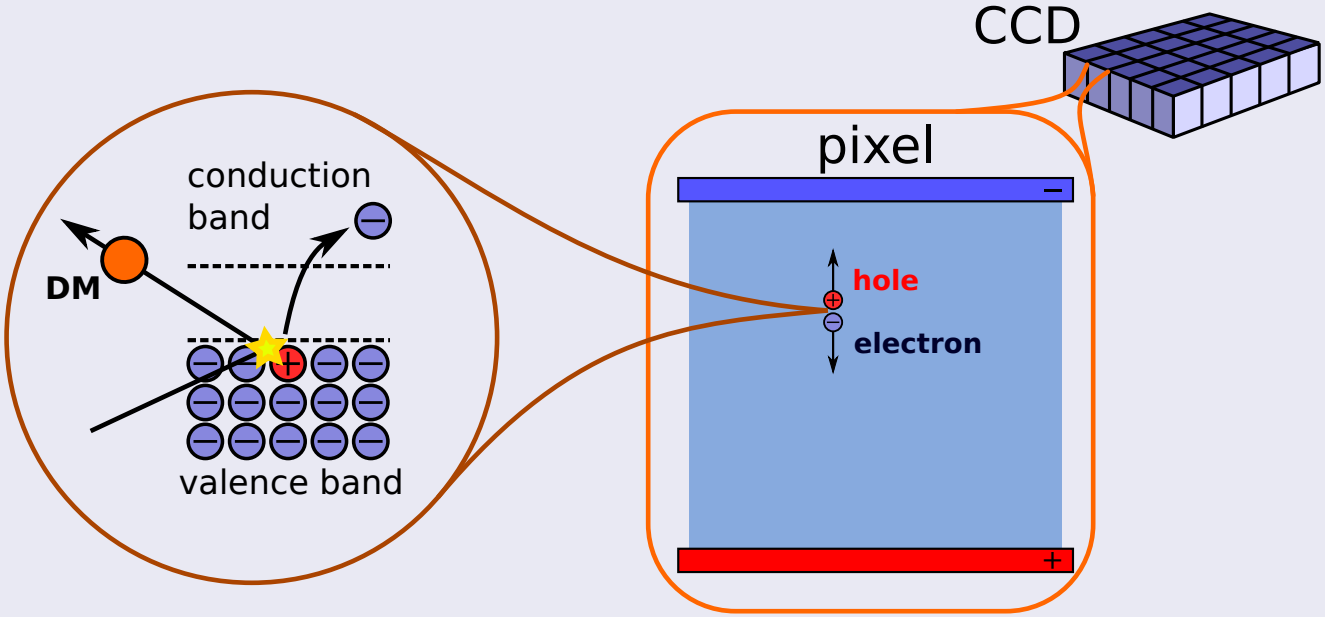
Sensitivity is limited by readout noise and NR-ionization yield

Origin of the project: motivation

Lower the energy threshold to look for light DM candidates

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

Idea: use electrons in the CCDs as target



This requires very low noise!

SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

SENSEI LDRD* Collaboration (2015)

Develop a sub-electron resolution detector with an energy threshold close to the silicon band gap (1.1 eV) using SkipperCCDs from LBNL MSL

Group at Fermilab:

Tiffenberg, Guardincerri, F Moroni, Sofo Haro, Estrada, Cancelo

* The Laboratory Directed Research and Development (LDRD) program enables high risk R&D at the US National Laboratories in areas of potential national value.

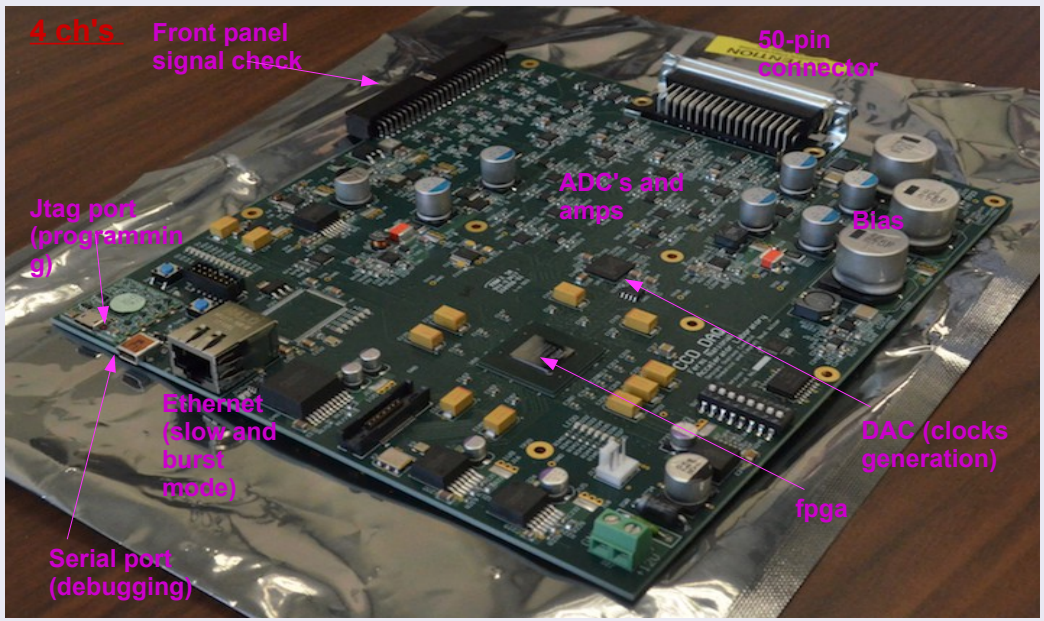
Successful completion of LDRD objectives

- Built the first working detector using Skipper-CCDs.
- First single-electron/single-photon detector with millions of pixels
- Validated 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

Groups in Argentina working on the Skipper-CCD effort

Instituto de Investigaciones en Ingeniería Eléctrica, CONICET-UNS

- Development at IIIE of new readout electronics system specially designed for low threshold experiments using CCDs & Skipper-CCDs.
  - Under PICT-2016-4825 grant. Prototypes to be fabricated in Tecnopolis del Sur (public-private consortium in Bahia Blanca).
  - Technology transfer to ArsUltra company.
- Soto, Stefanazzi, Paolini, Chierchie, Mandolesi, Schlenker, F Moroni



Groups in Argentina working on the Skipper-CCD effort

Departamento de Física, FCEyN-UBA and IFIBA

- Detector comissioning, event reconstruction and MC simulation.
- Tiffenberg to return to IFIBA in mid-2019 as Investigador Adjunto:
  - build a "*Laboratorio de Detectores de Ultra Bajo Umbral*".
  - continue R&D on SENSEI experiment.
  - study potential Skipper-CCD applications.
- Donadón, Rodrigues, Cababié, Piegaia

Centro Atómico Bariloche

- Generic detector R&D on Skipper-CCDs.
- Investigating possibilities to build a Skipper-CCD based DM detector to be installed on the Southern Hemisphere.
- Bertou, Sofo Haro

Skipper-CCD performance

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

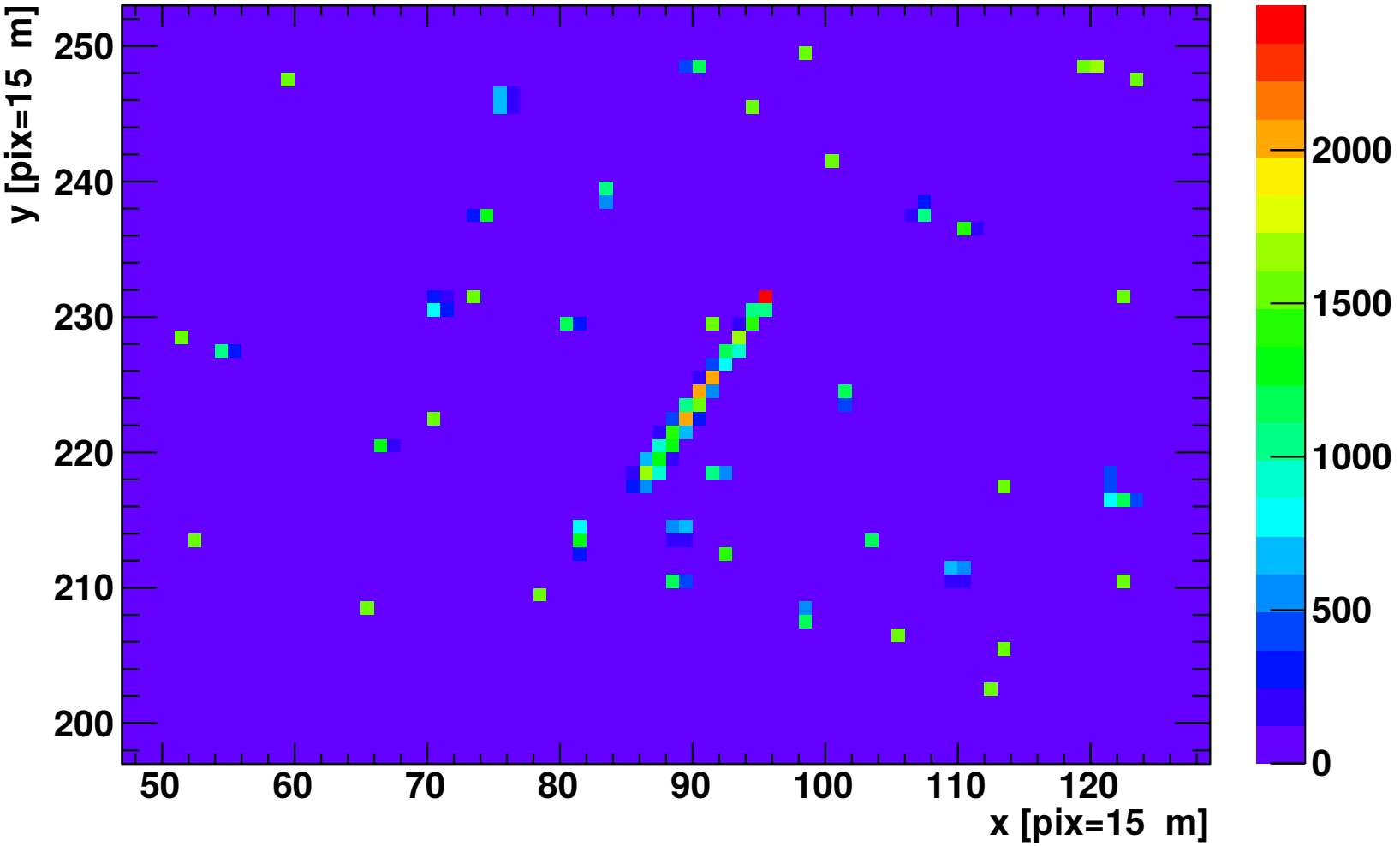


Image taken with SENSEI: 4000 samples per pixel (processed)

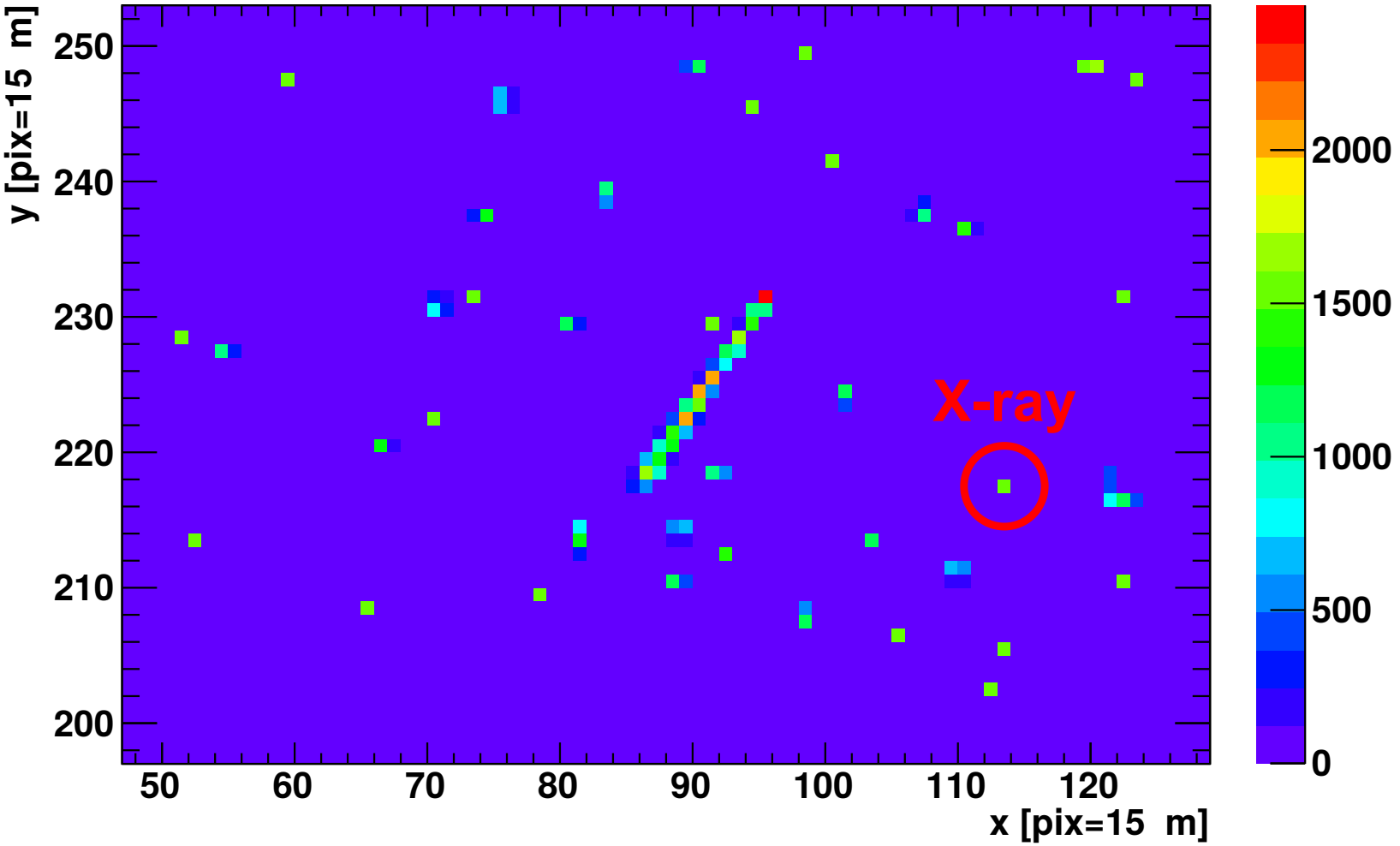


Image taken with SENSEI: 4000 samples per pixel (processed)

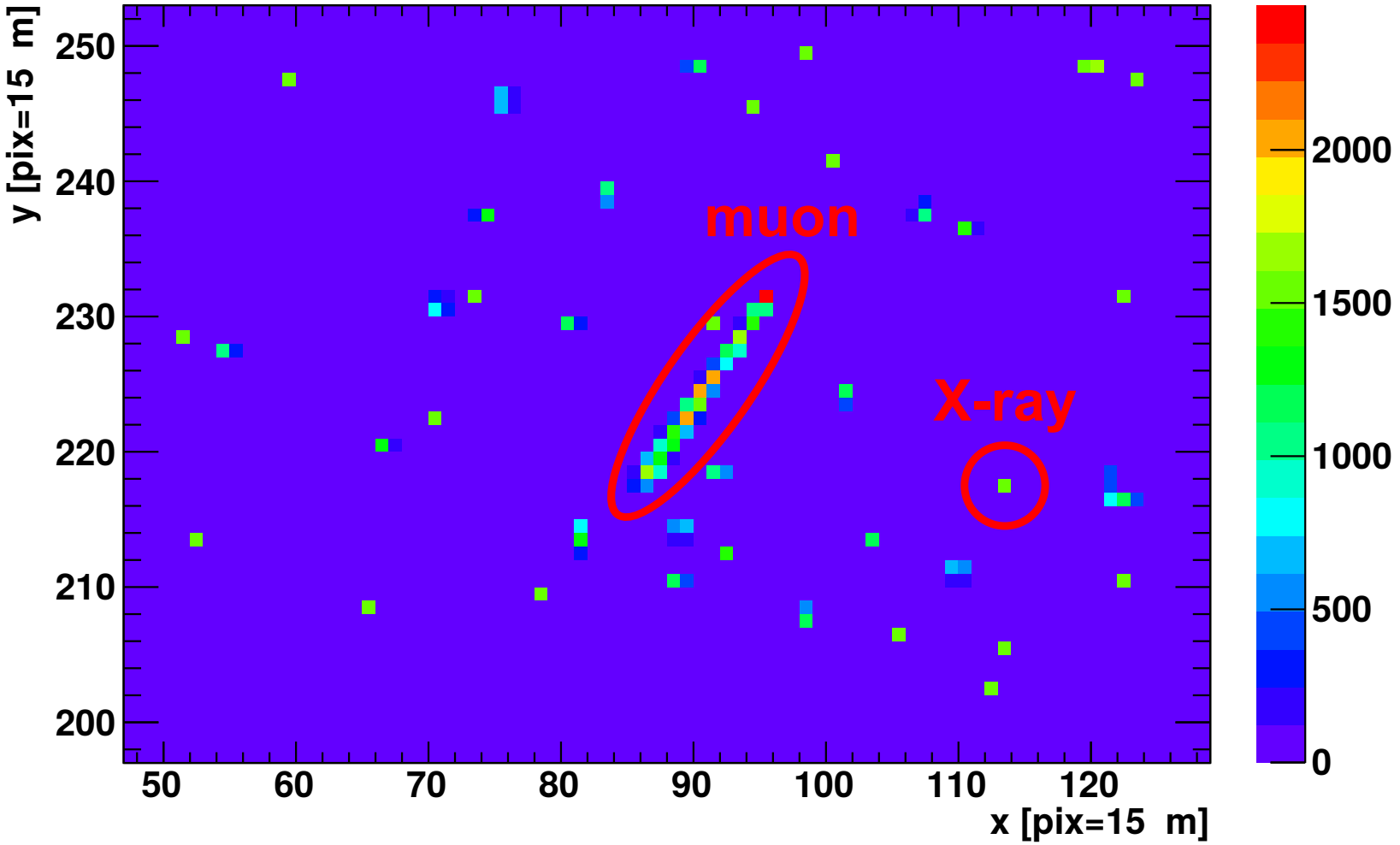
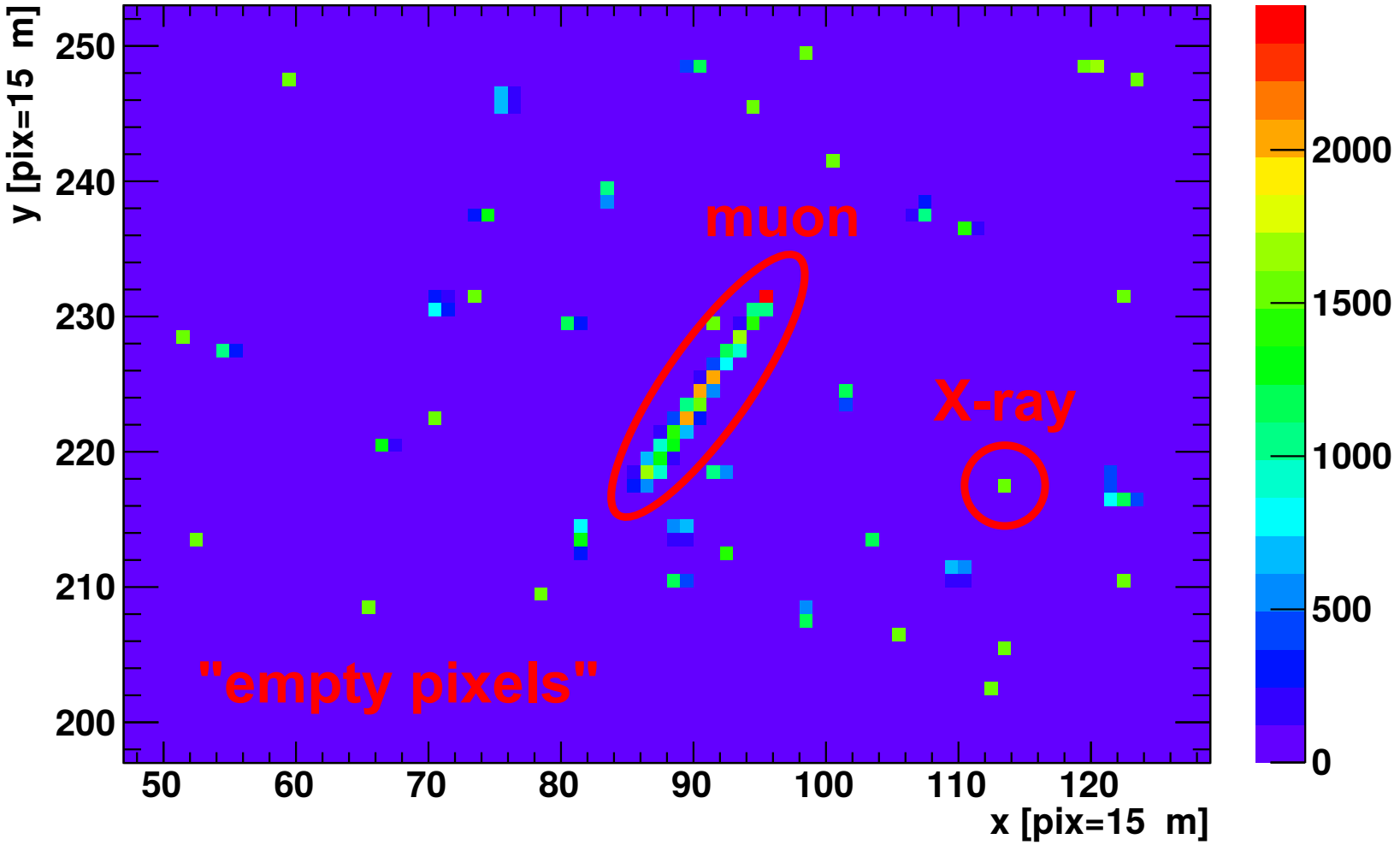
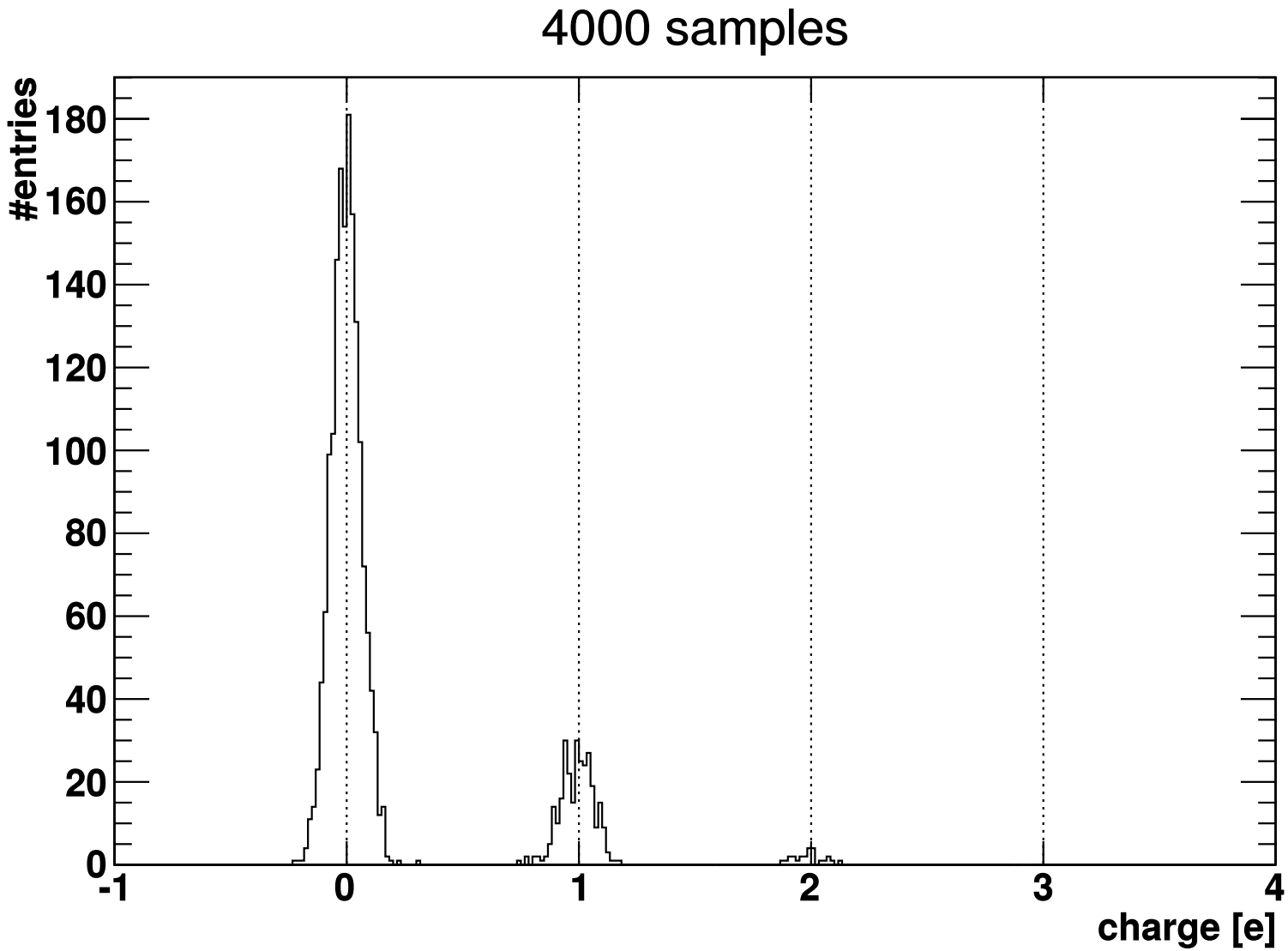


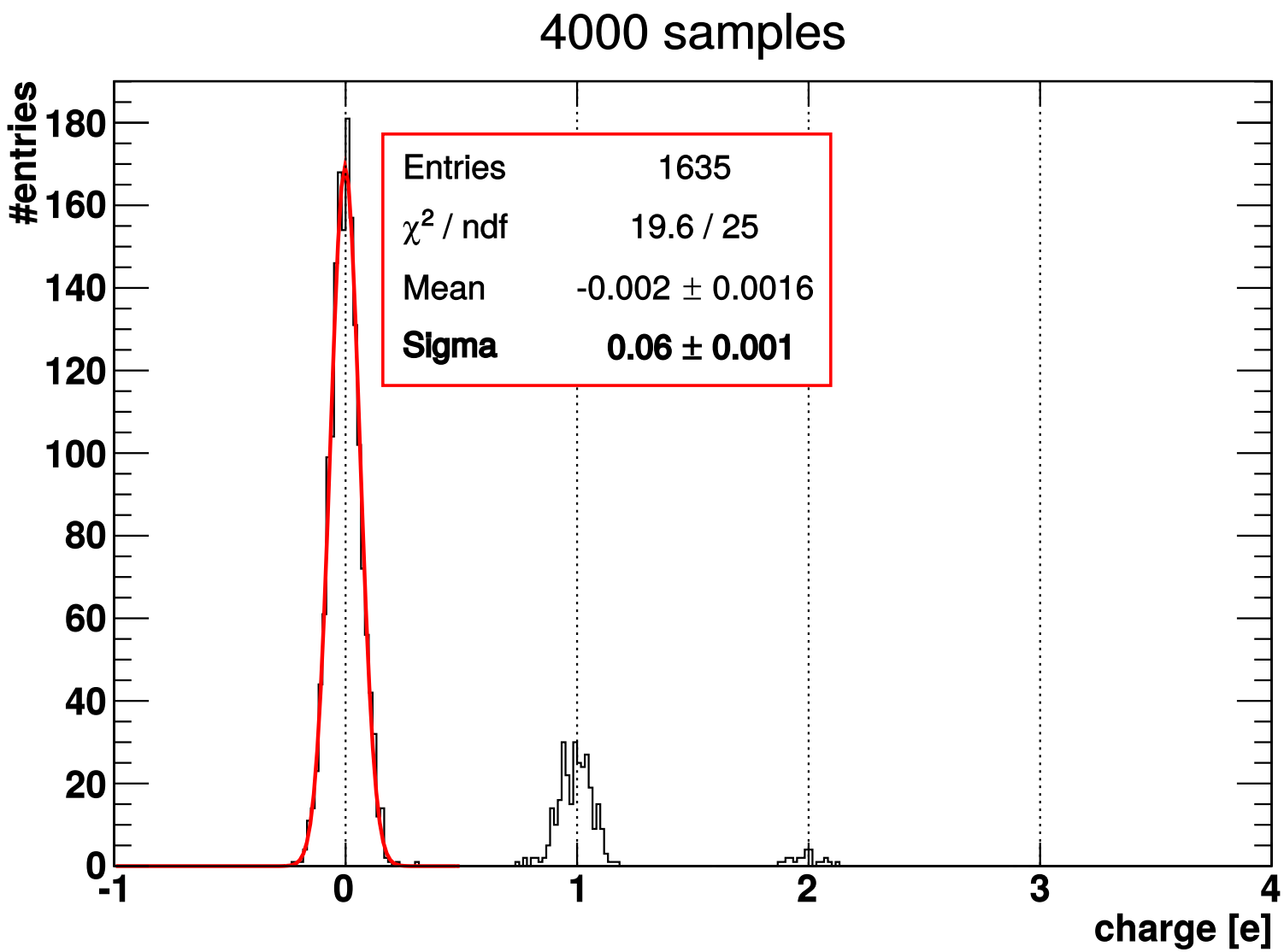
Image taken with SENSEI: 4000 samples per pixel (processed)



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

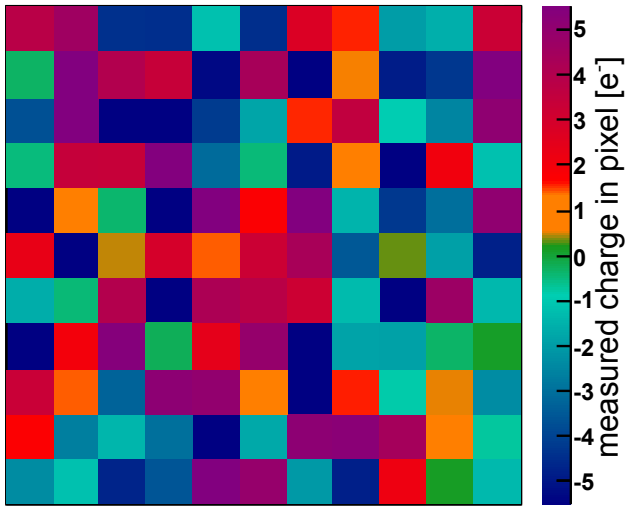


Charge in pixel distribution. Counting electrons: 0, 1, 2..

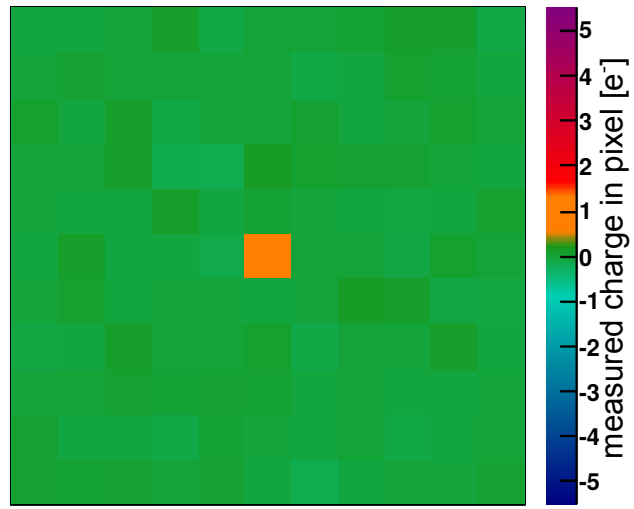


Counting electrons: 0, 1, 2..

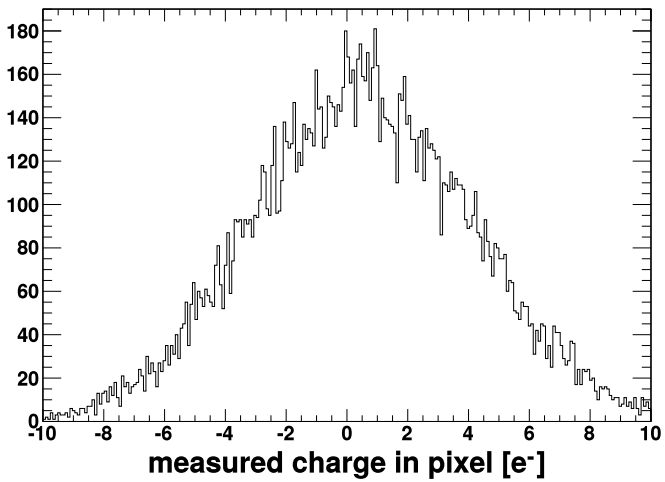
Standard CCD mode: charge in each pixel is measured once



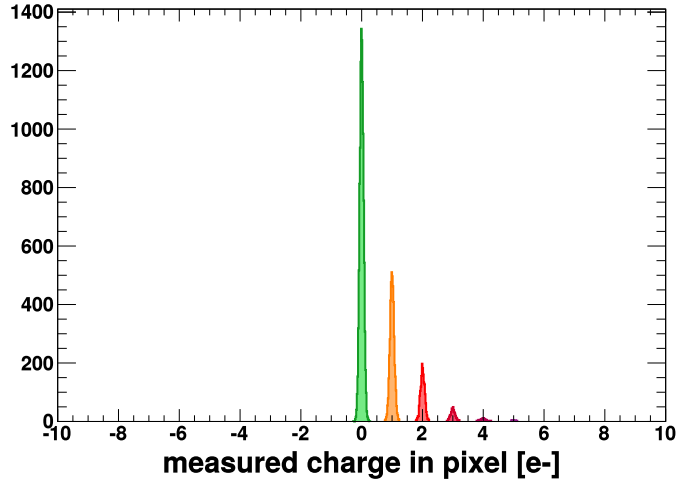
New Skipper CCD: charge in each pixel is measured multiple times



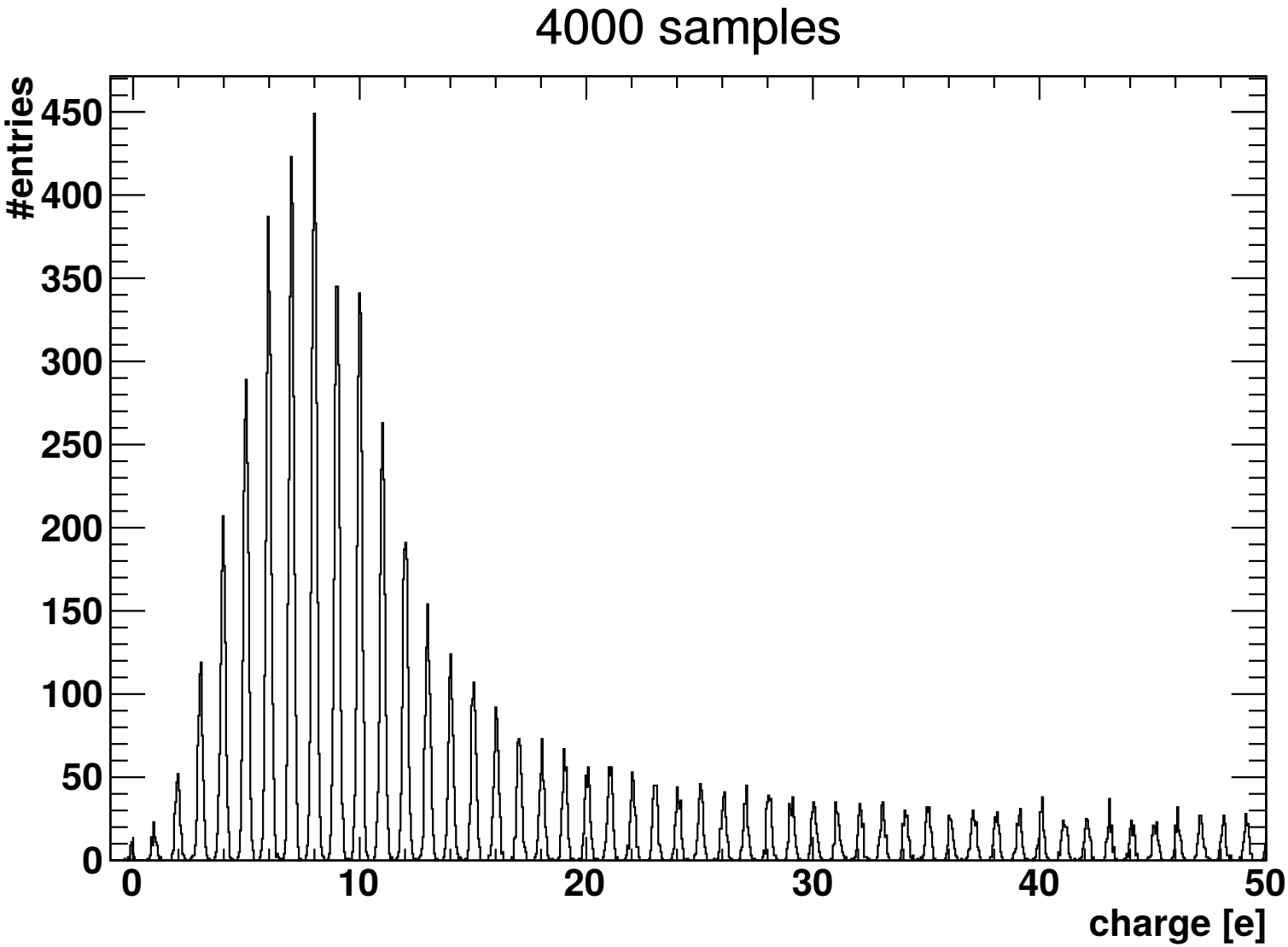
Readout-noise: 3.5 e RMS



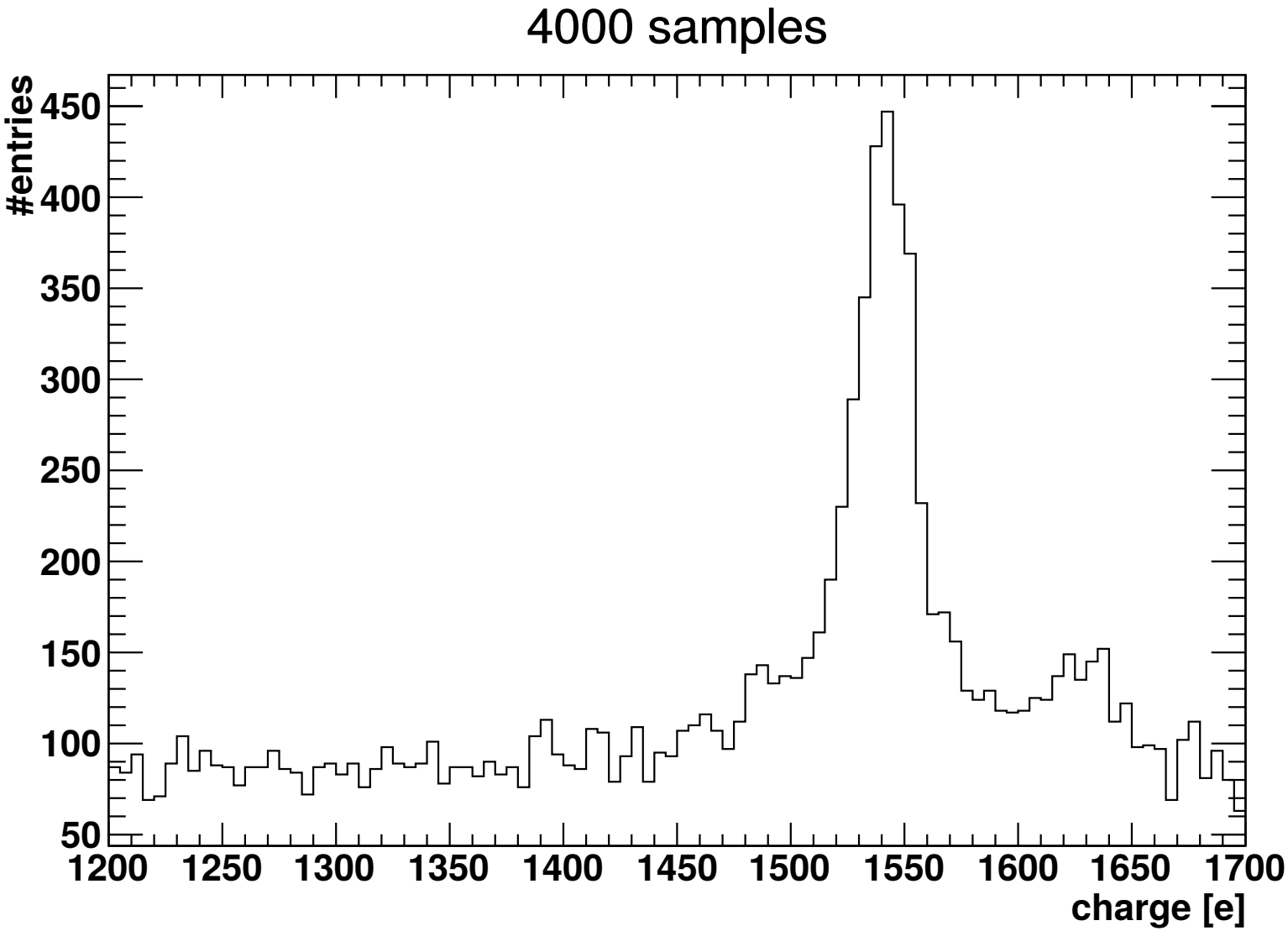
Readout-noise: 0.06 e RMS



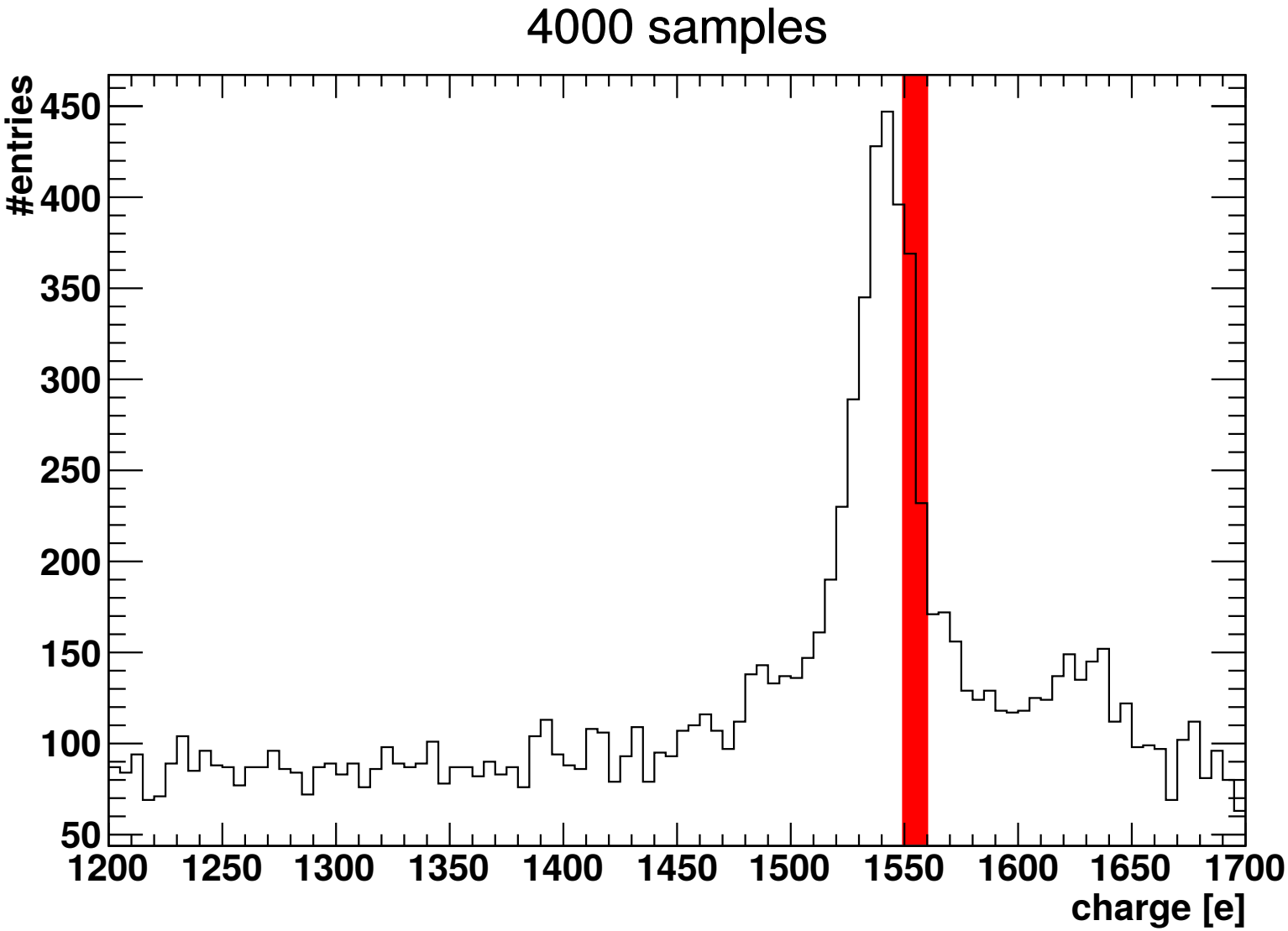
Counting electrons: ..48, 49, 50..



^{55}Fe X-ray source



^{55}Fe X-ray source



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

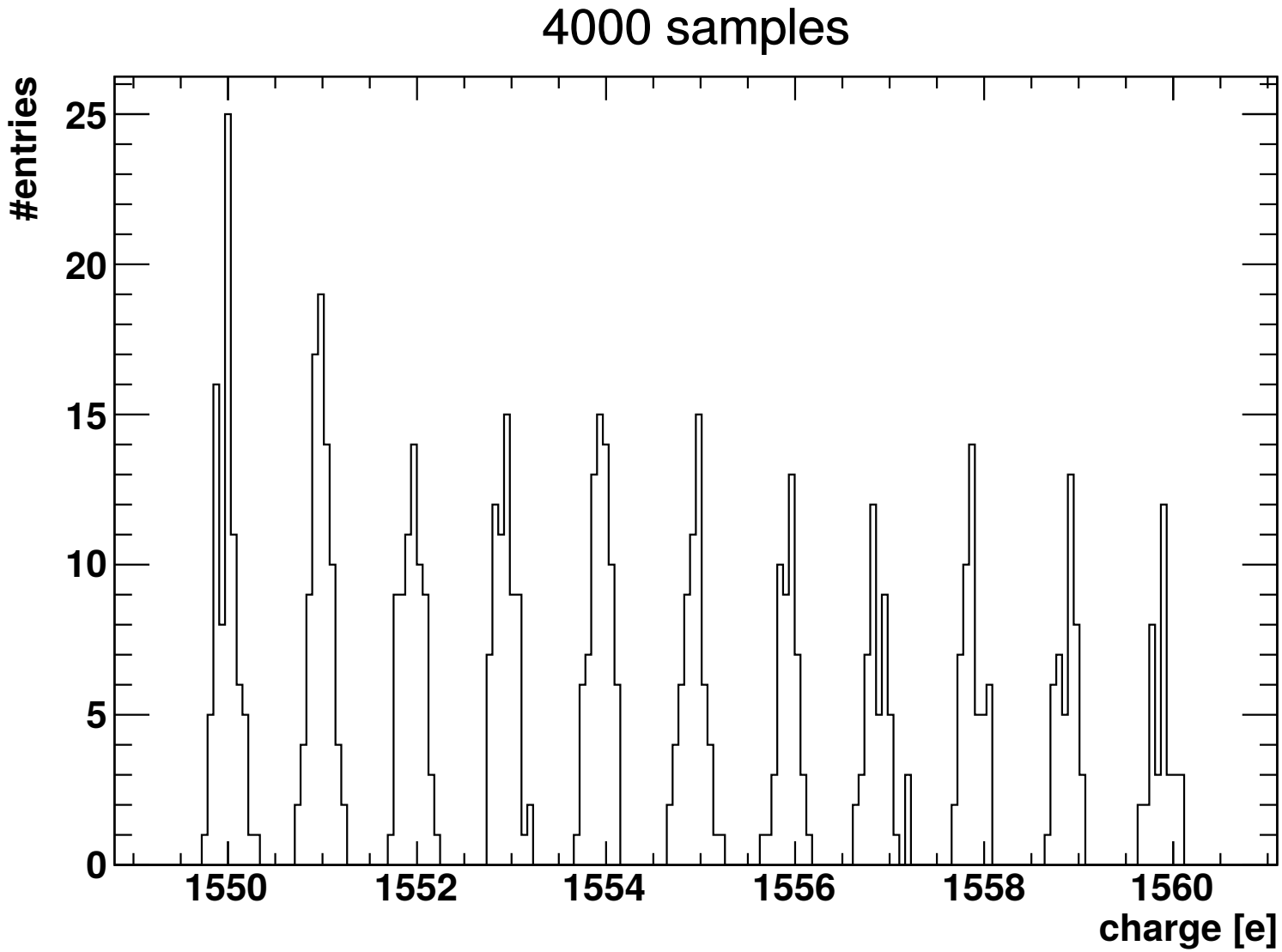
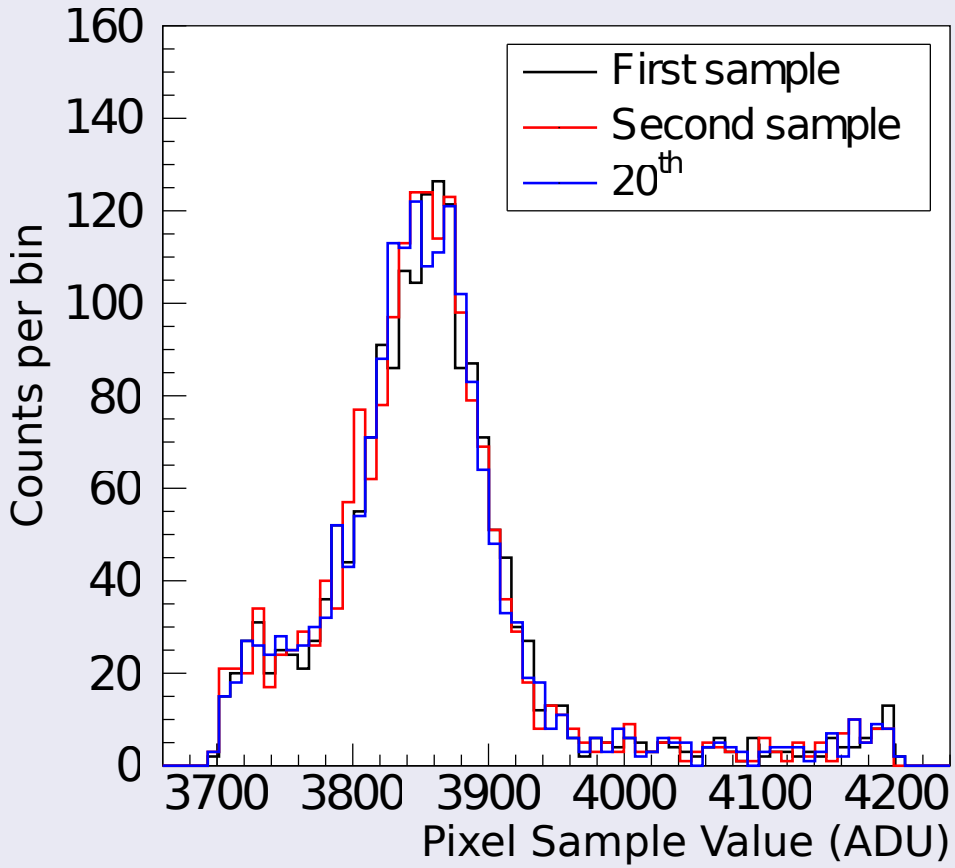


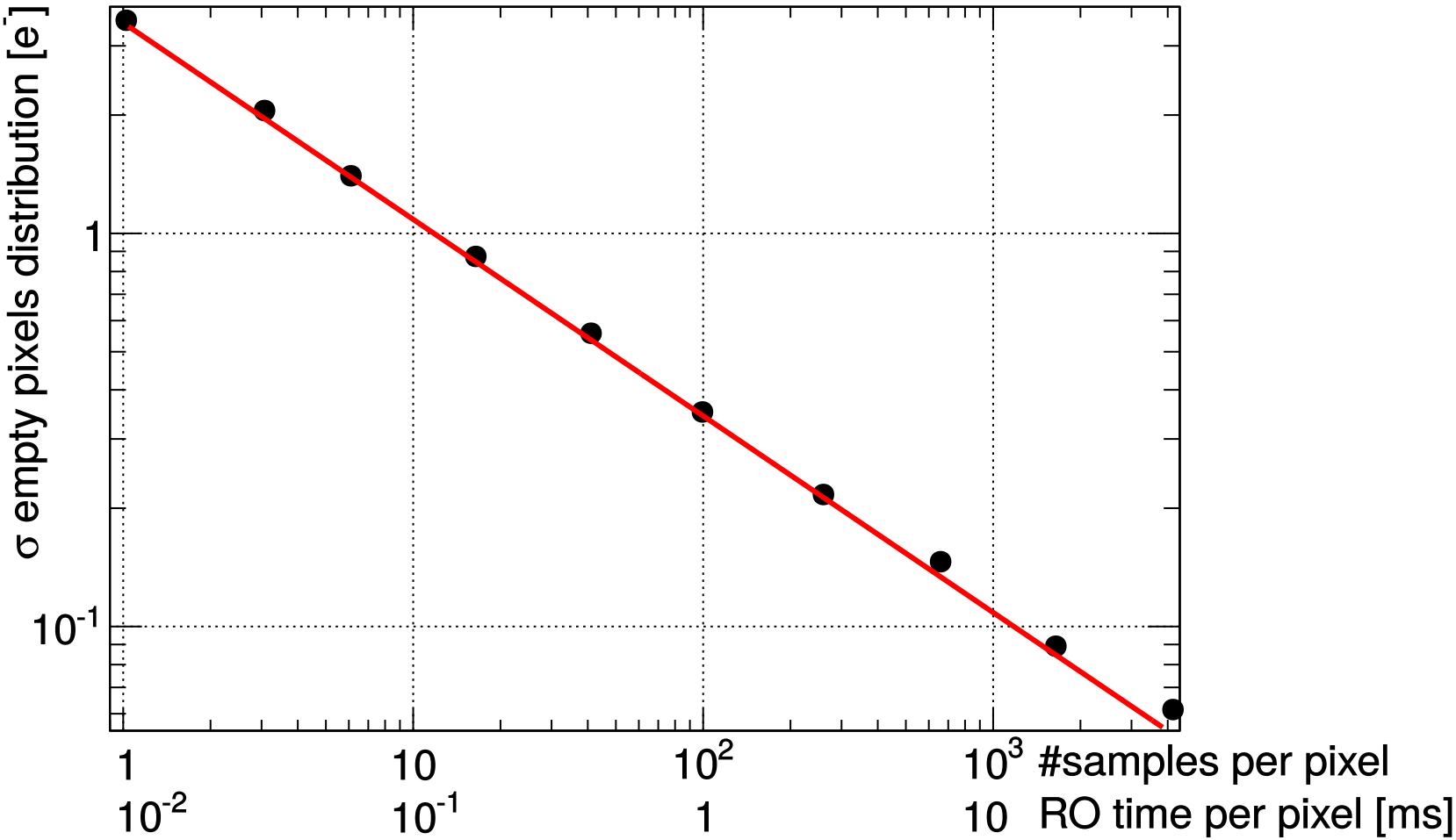
Image taken with SENSEI: 20 samples per pixel

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



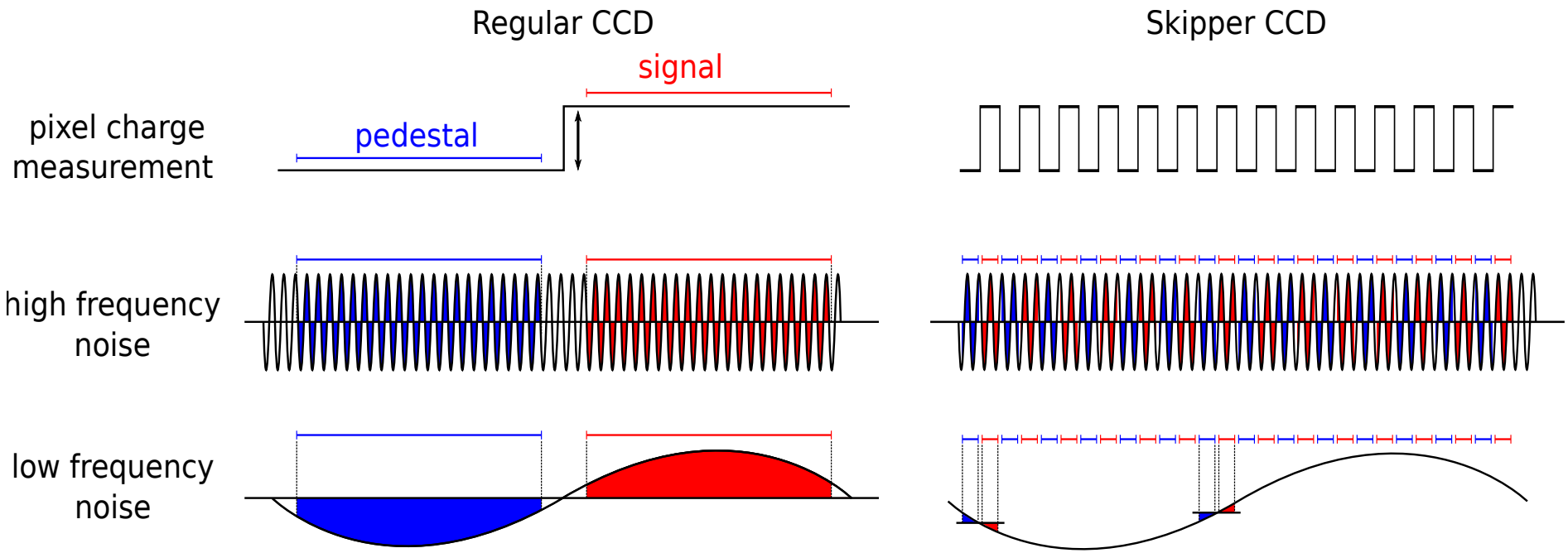
The gain is the same for all the samples

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



Lowering the noise: Skipper CCD

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

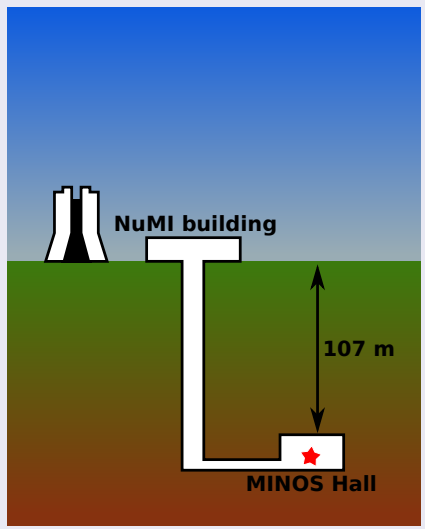


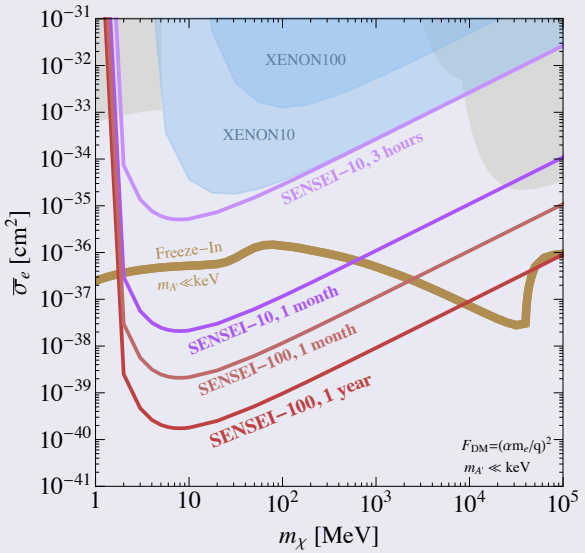
Ongoing Fermilab projects based on Skipper-CCD technology

First detector using Skipper-CCDs. SENSEI: light DM searches

- S-10, a 10g detector, to be assembled and tested at MINOS hall.
- Engineering run in a low radiation environment.
- Ongoing construction, project started on Dec-2017.
- To be followed by SENSEI S-100 at a deep mine location.
- Looking at options to install a detector on the Southern Hemisphere.

Project fully funded:
Heising-Simons Foundation
& Fermilab





Ongoing Fermilab projects based on Skipper-CCD technology

CubeSat

- Science: look for DM annihilation signals
- Space certification of Skipper-CCD sensors
- Fully funded by Fermilab LDRD grant to start on Sep-18

R&D for large scale reactor-neutrino detector

- R&D needed to integrate a large scale Skipper-CCD instrument
- Cold electronics to digitize signal on detector package
- Applications to short-base line ν oscillations and reactor monitoring
- Awarded Fermilab LDRD grant to start on Sep-18

Collaboration opportunities

SENSEI & DM

- Small scale DM detector can make significant scientific contributions
- (CAB) project to install a detector on the Southern Hemisphere

CubeSat

- Only conceptual design done so far. Timescale $\sim$3-4 yrs
- Need help with electronics, comms, thermal design, ...

R&D for large scale reactor-neutrino detector

- Cold electronics to digitize signal on detector package
- System design: data bus, analog bus. Develop a custom ASIC?

Imaging applications

- Explore high-resolution imaging applications for astronomical instruments and bio-medical research.

Summary

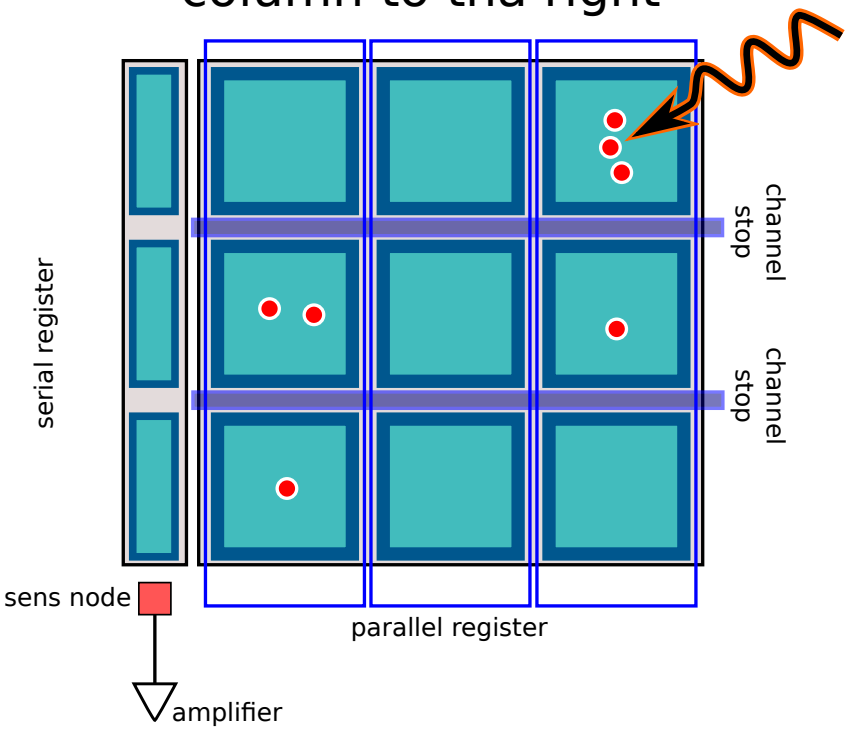
- Skipper-CCD is a technological leap: many immediate applications
  - Dark Matter searches
  - Detection of neutrinos from nuclear reactors
  - Imaging: stable photon counting over millions of pixels
- Several funded projects with collaboration opportunities
  - SENSEI experiments S-10 and S-100 for light DM searches.
  - CubeSat R&D
  - Large scale neutrino detector R&D
- *Laboratorio de Detectores de Ultra Bajo Umbral* at FCEyN, UBA
  - R&D on Skipper-CCD technologies
- Collaboration with IIIE and CAB to build experiments in Argentina
  - Small scale DM detector can make significant scientific contributions
  - Argentina has nuclear reactors that are perfect for neutrino experiments
  - Andes Laboratory could also host future versions of the DM detector

BACK UP SLIDES

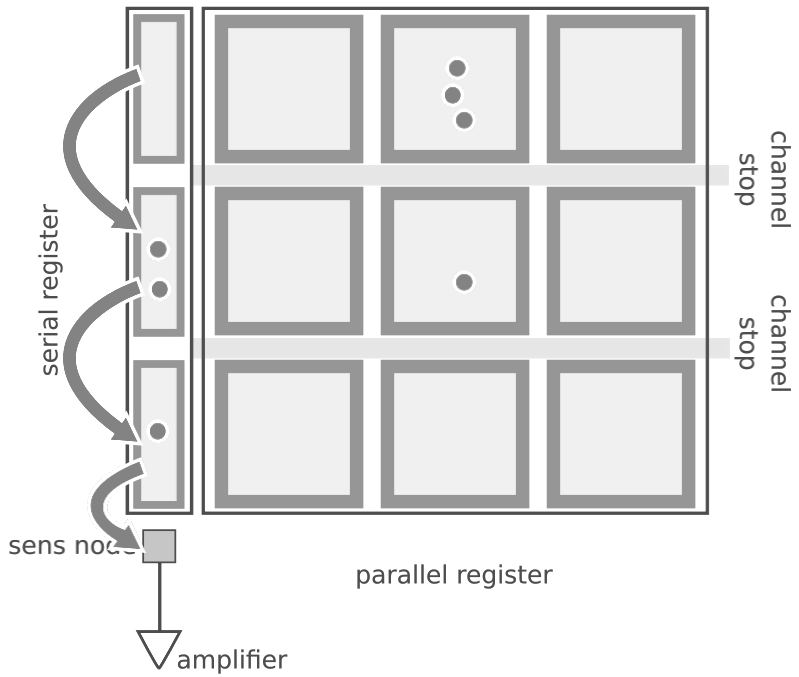
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



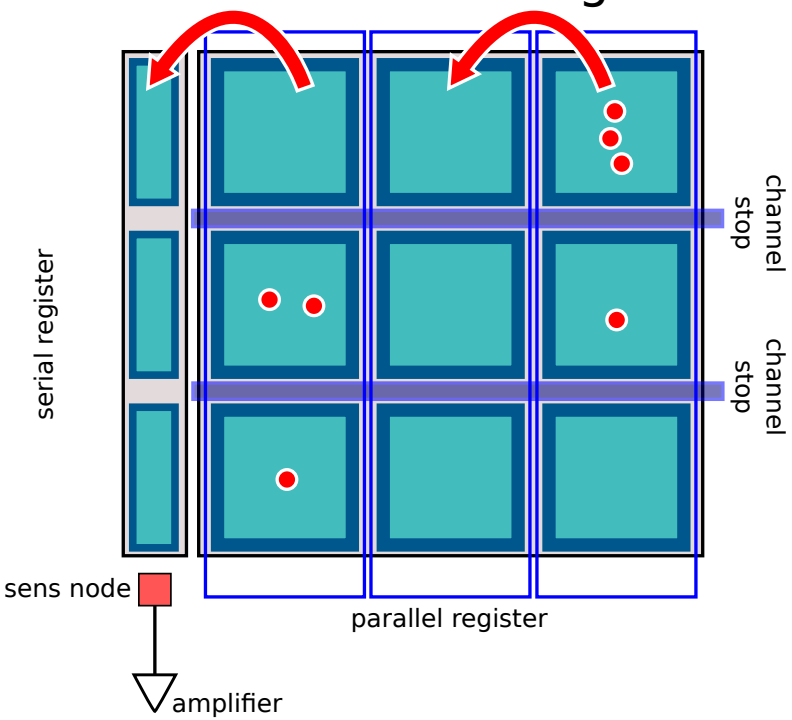
Shift charge in serial register one pixel down (3 times)



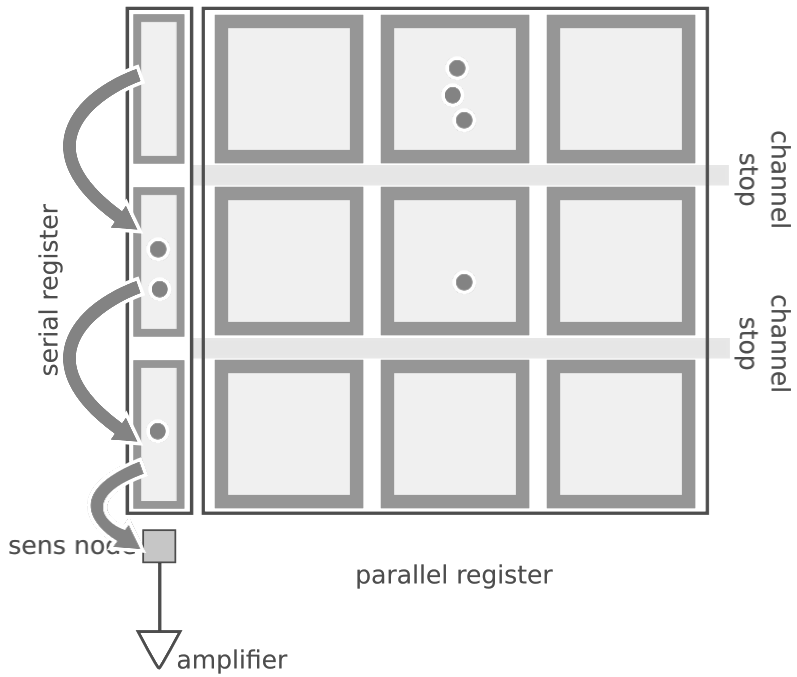
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



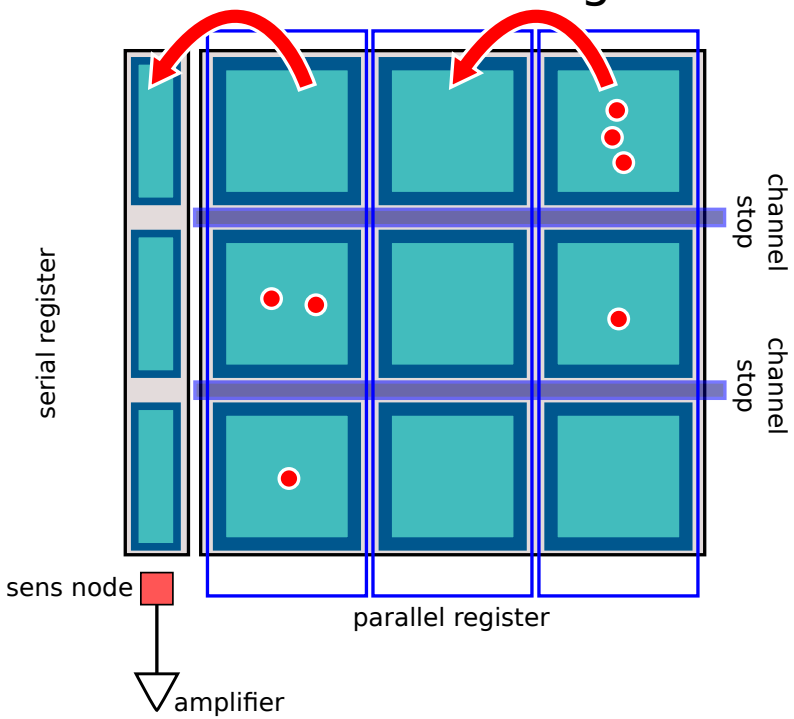
Shift charge in serial register one pixel down (3 times)



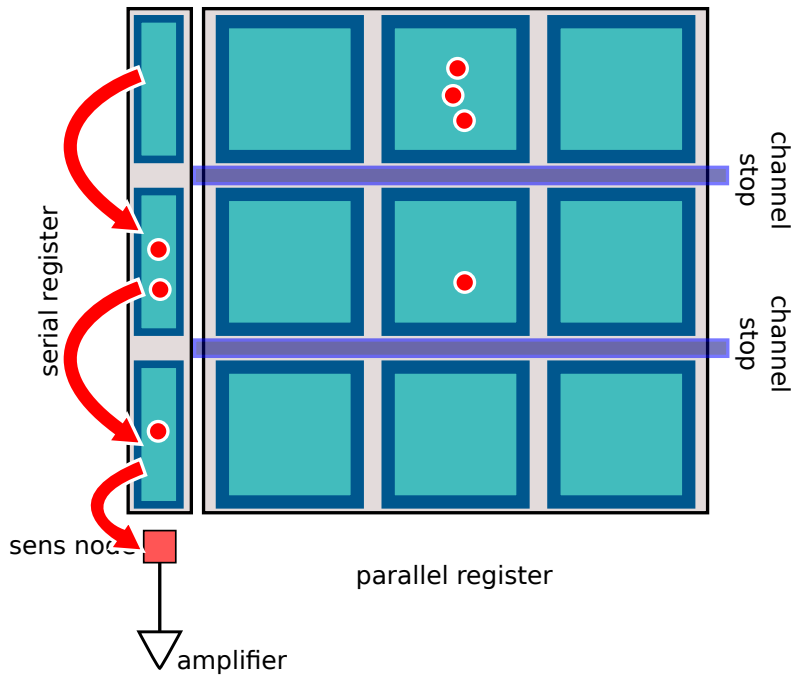
CCD: readout

3x3 pixels CCD

Shift charge one column to tha right

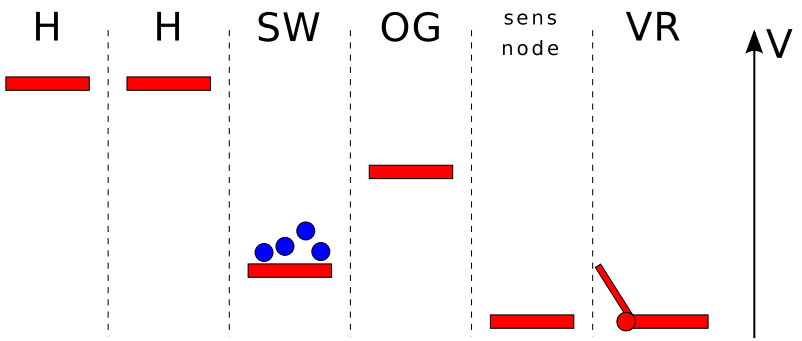


Shift charge in serial register one pixel down (3 times)



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

CCD: readout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SW
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sens
node
VR
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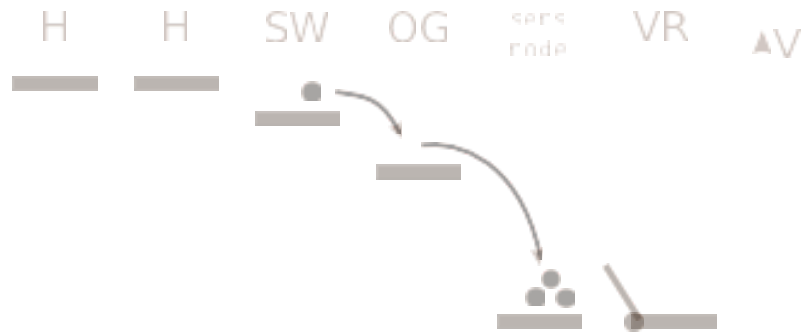
H
H
SW
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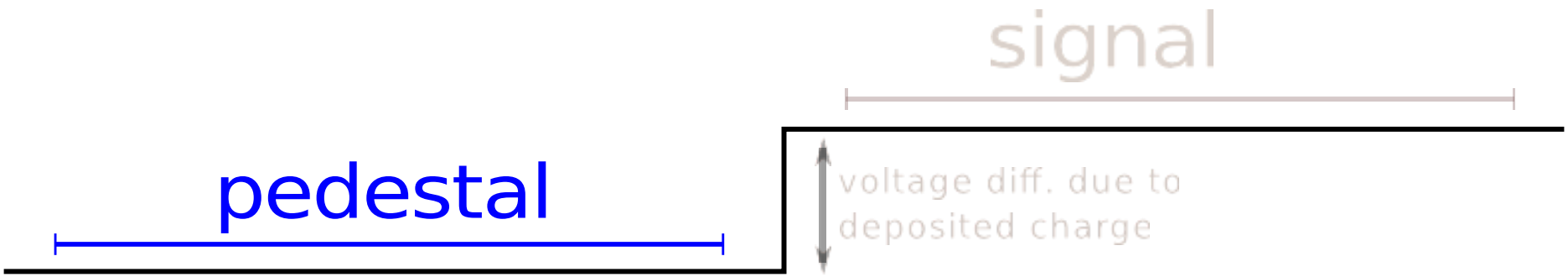
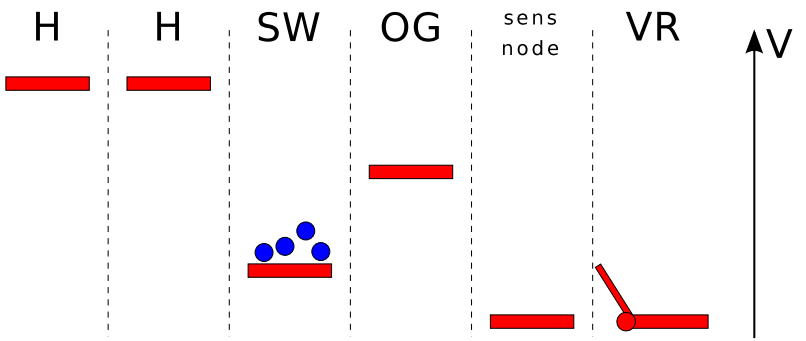

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout


H
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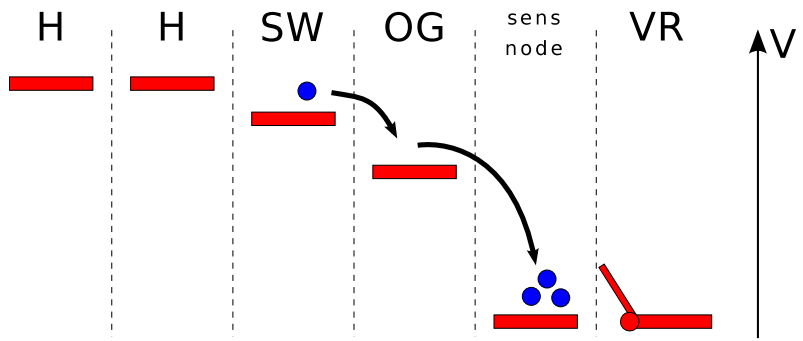
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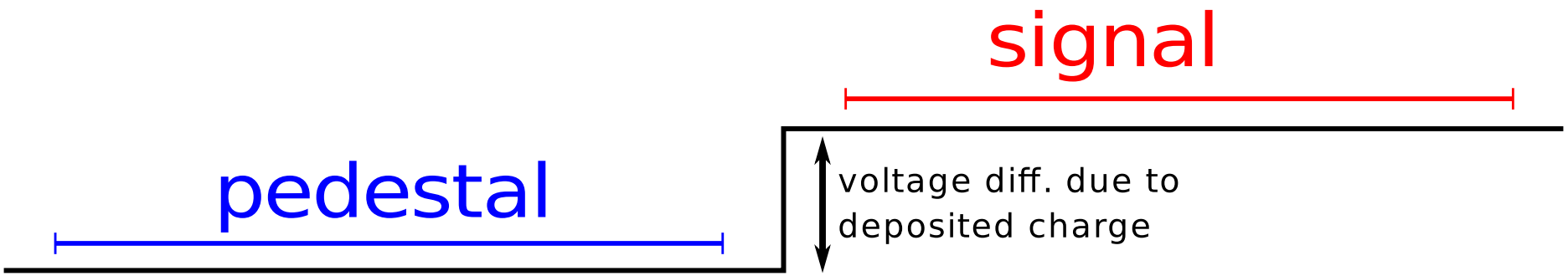
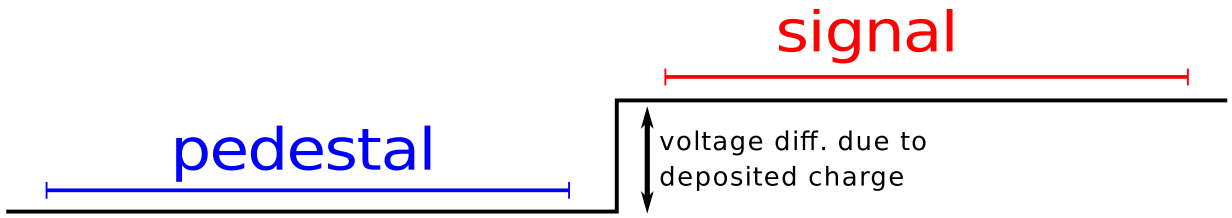
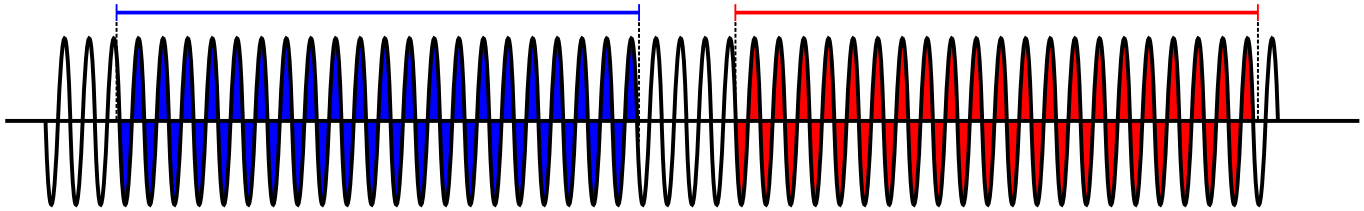

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout

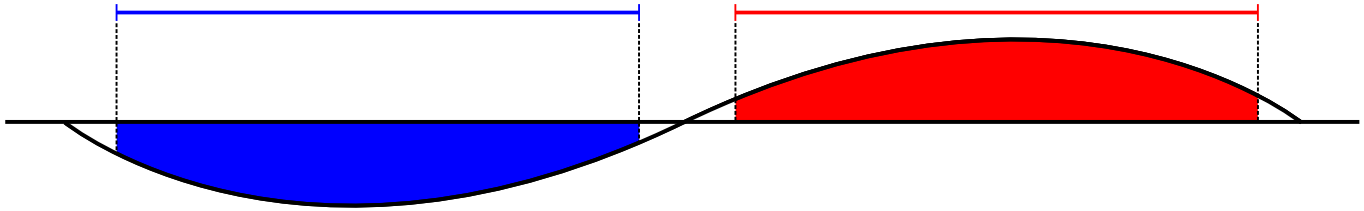
pixel charge measurement



high frequency noise

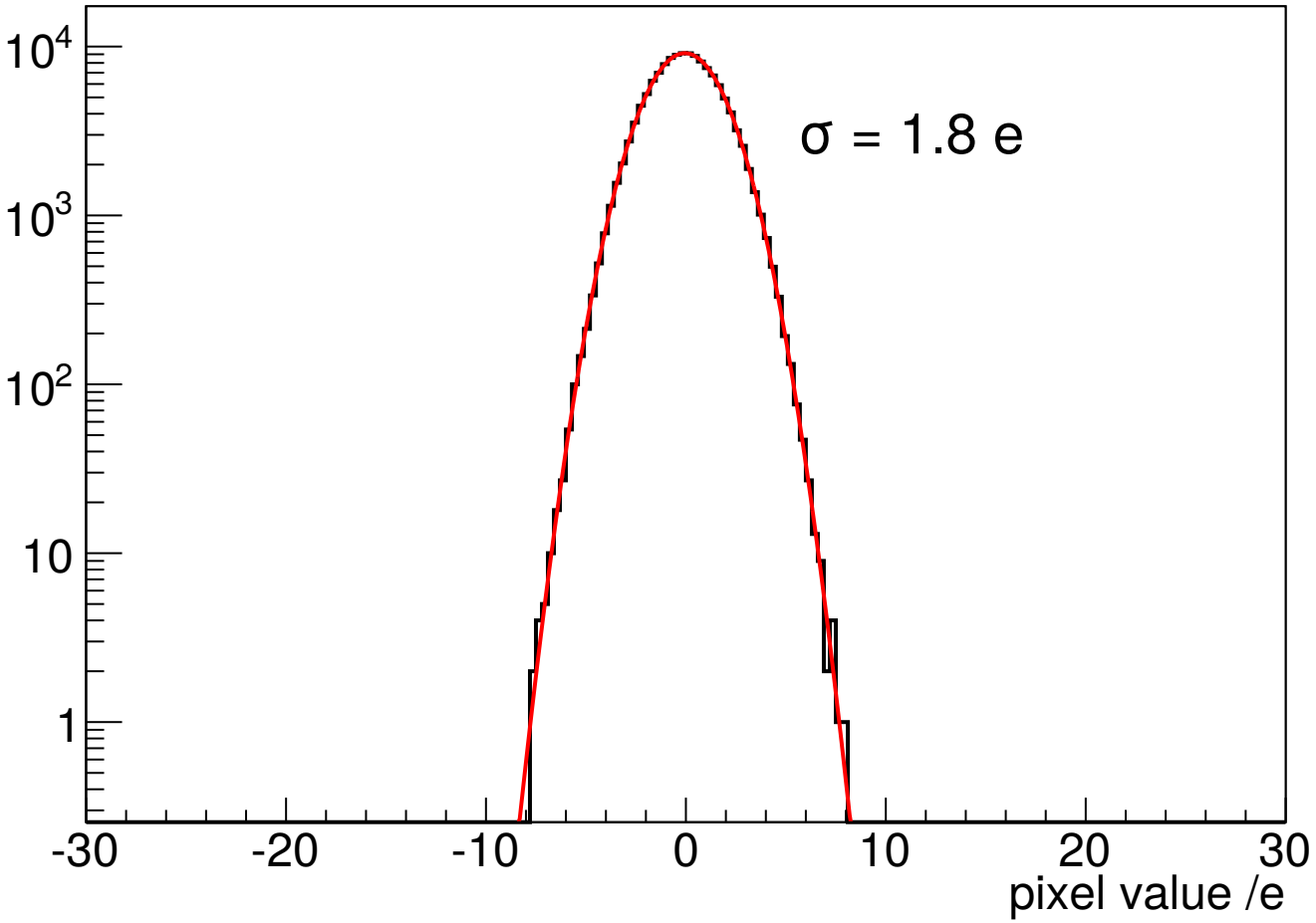


low frequency noise



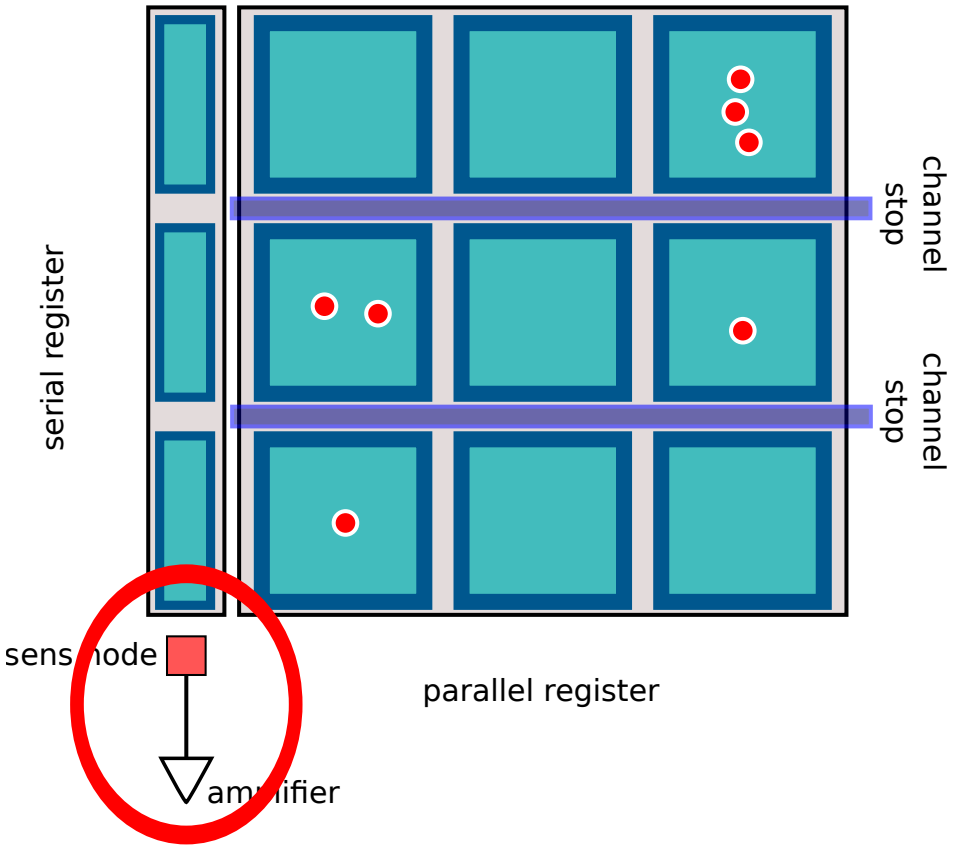
excellent for removing high frequency noise but sensitive to low frequencies

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

SENSEI Collaboration

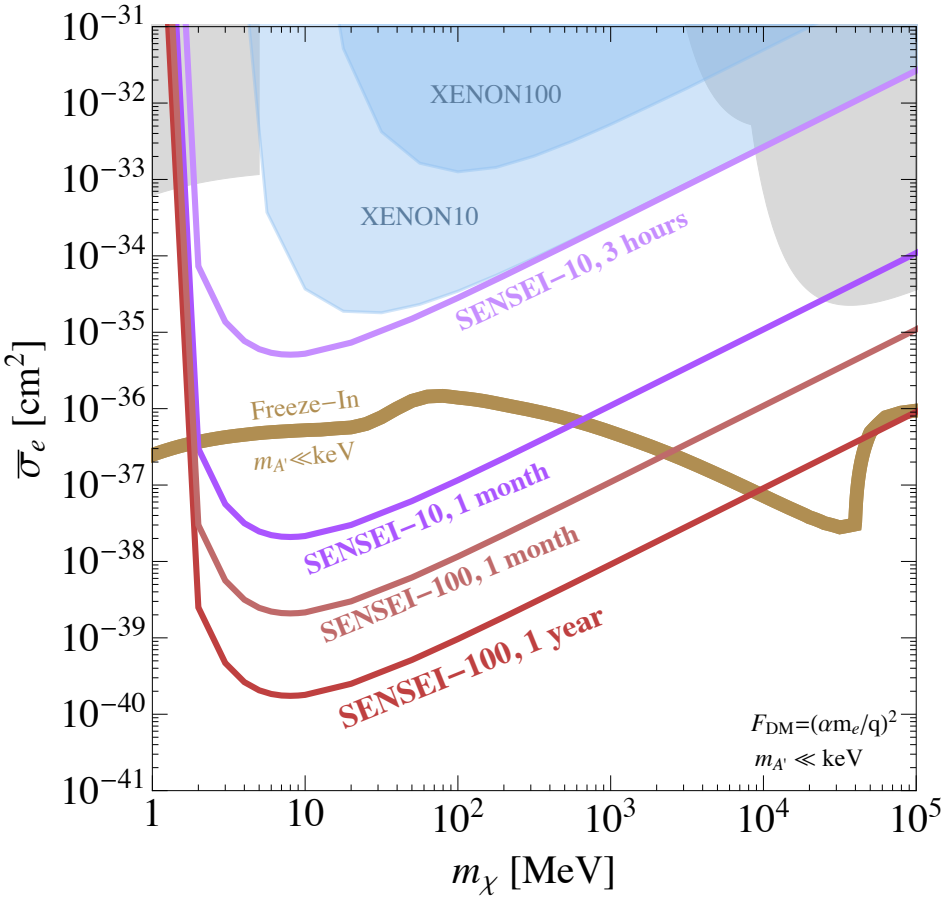
Build a detector using Skipper-CCDs to search for light DM canditates

- **Fermilab:** Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro **(CAB)** , Javier Tiffenberg **(UBA)**
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Liron Barack, Erez Ezion, Tomer Volansky
- **Oregon University:** Tien-Tien Yu
- **+ several additional students**

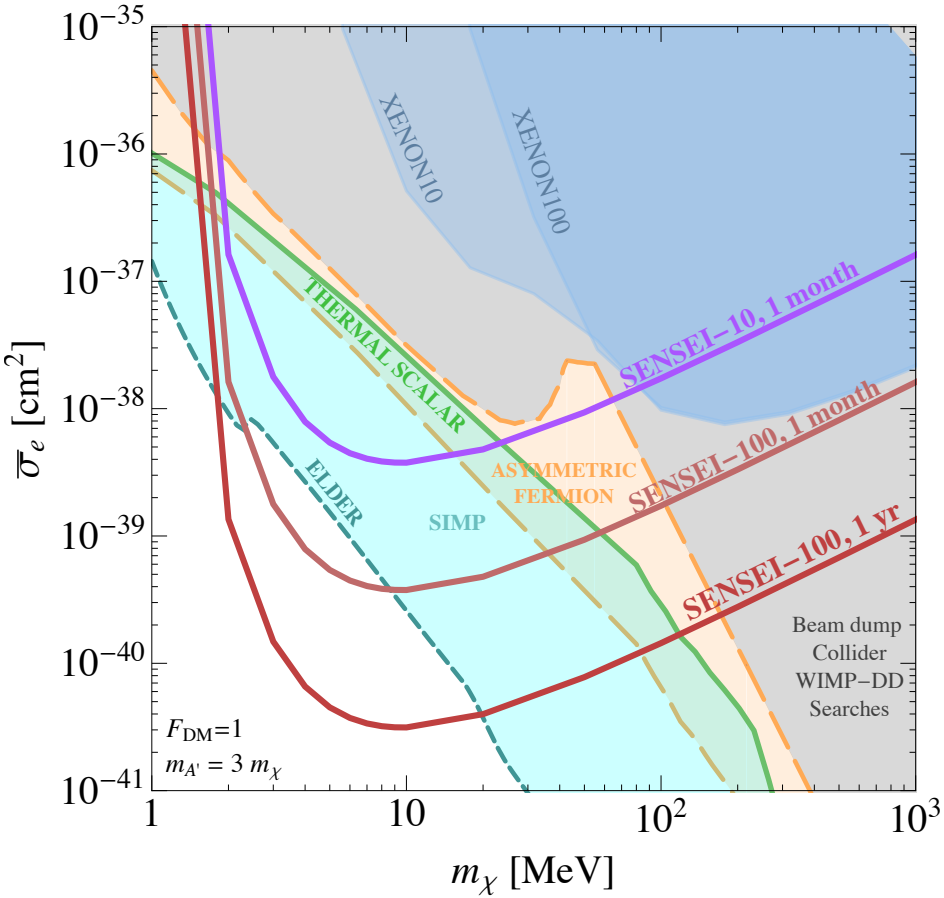
Fully funded by Heising-Simons Foundation & Fermilab

SENSEI: reach of a 100g, experiment

Light Dark Photon

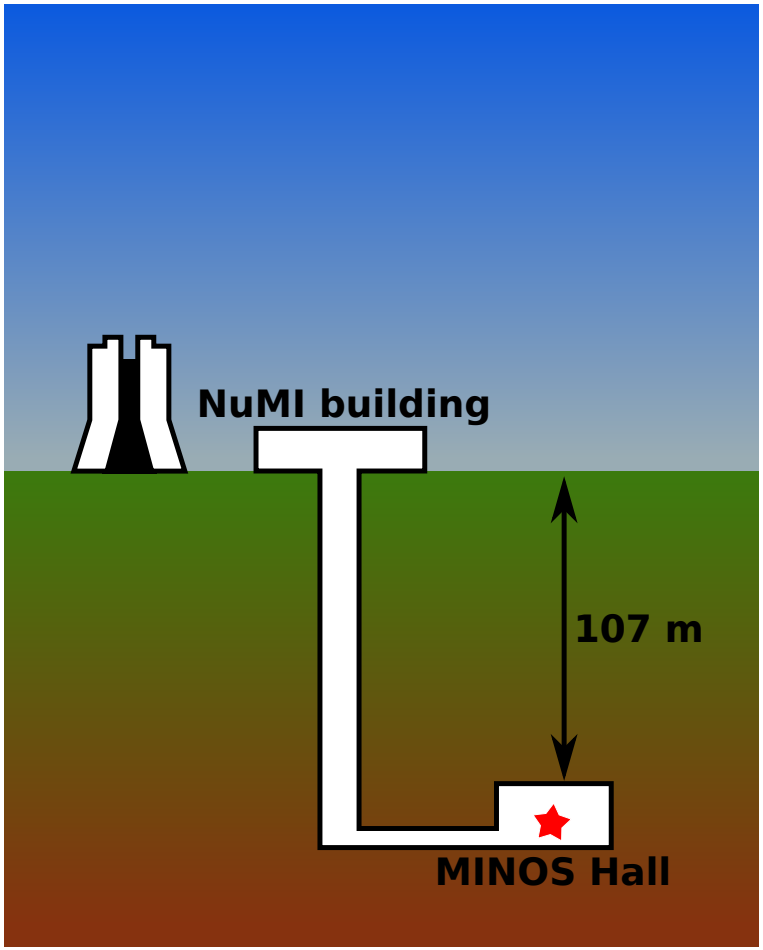


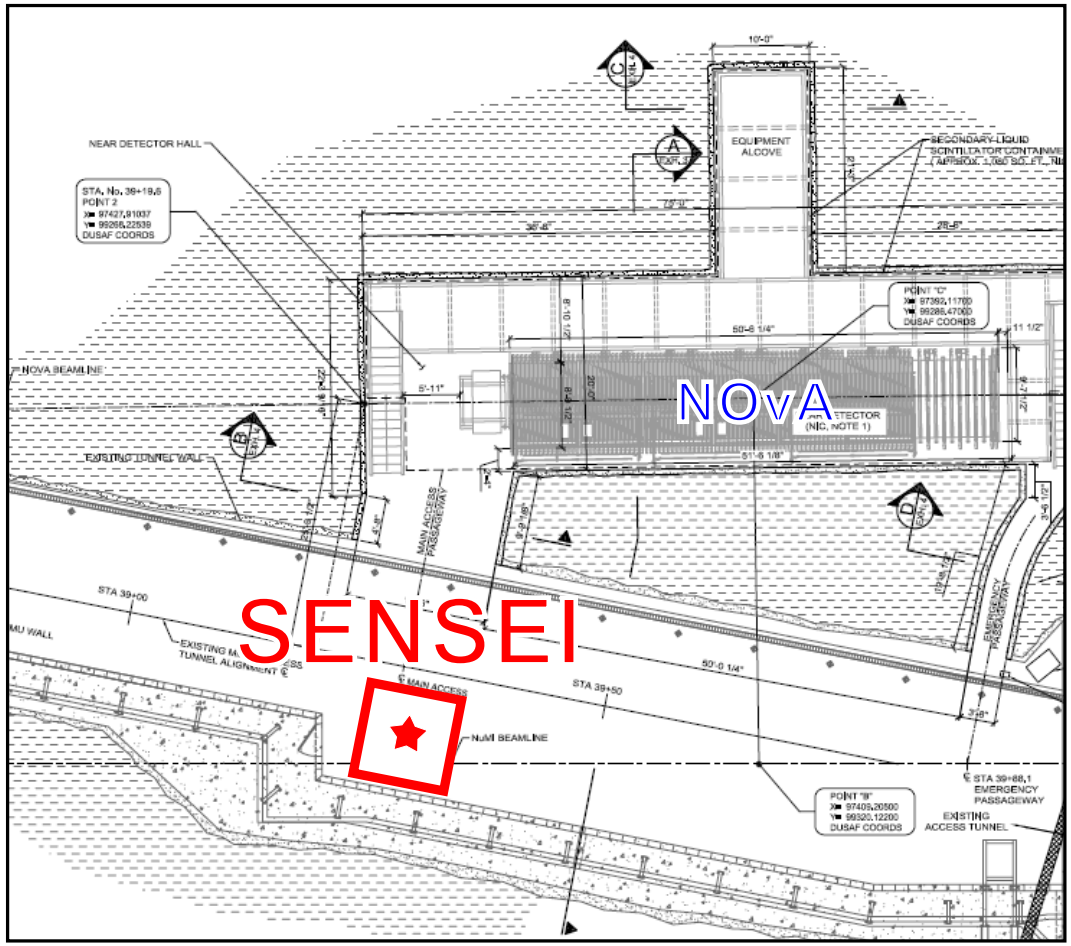
Heavy Dark Photon



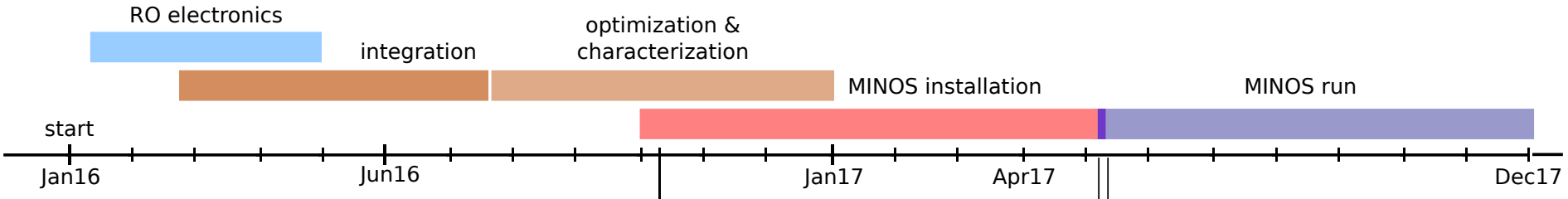
Whats going on now: Installation @MINOS

Technology demonstration: installation at shallow underground site





Whats going on now: Installation @MINOS



SENSEI Timeline