# SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

## Fermilab LDRD-2016-004

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) and a readout noise of 0.1 electrons using a new generation skipper CCD developed by the LBNL MicroSystems Lab

## Plan

- Build the first working detector using Skipper-CCDs
- Optimize the operation parameters and running conditions
- Produce a low radiation package for the Skipper-CCDs
- Install the detector in a low radiation environment (MINOS)
- **Dvlp and validate a new technology for DM and $\nu$ experiments**

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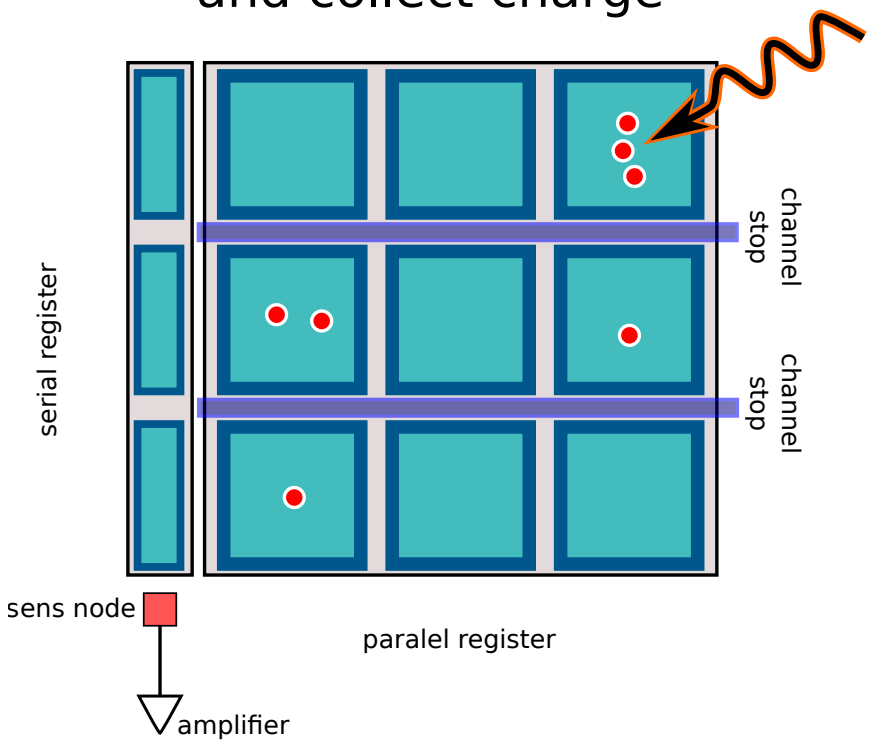
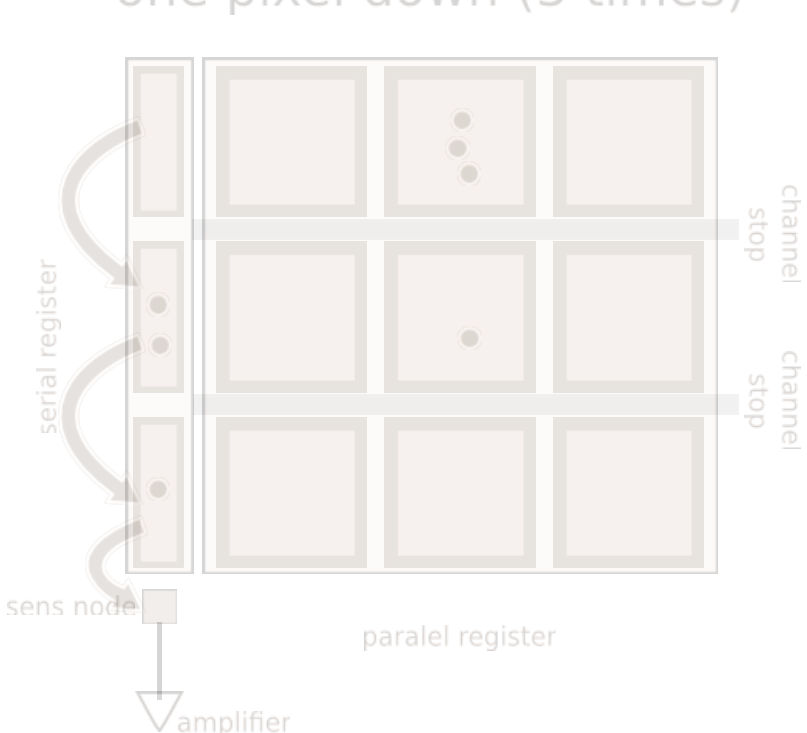
# CCD: readout

3x3 pixels CCD

Expose the CCD to particles and collect charge

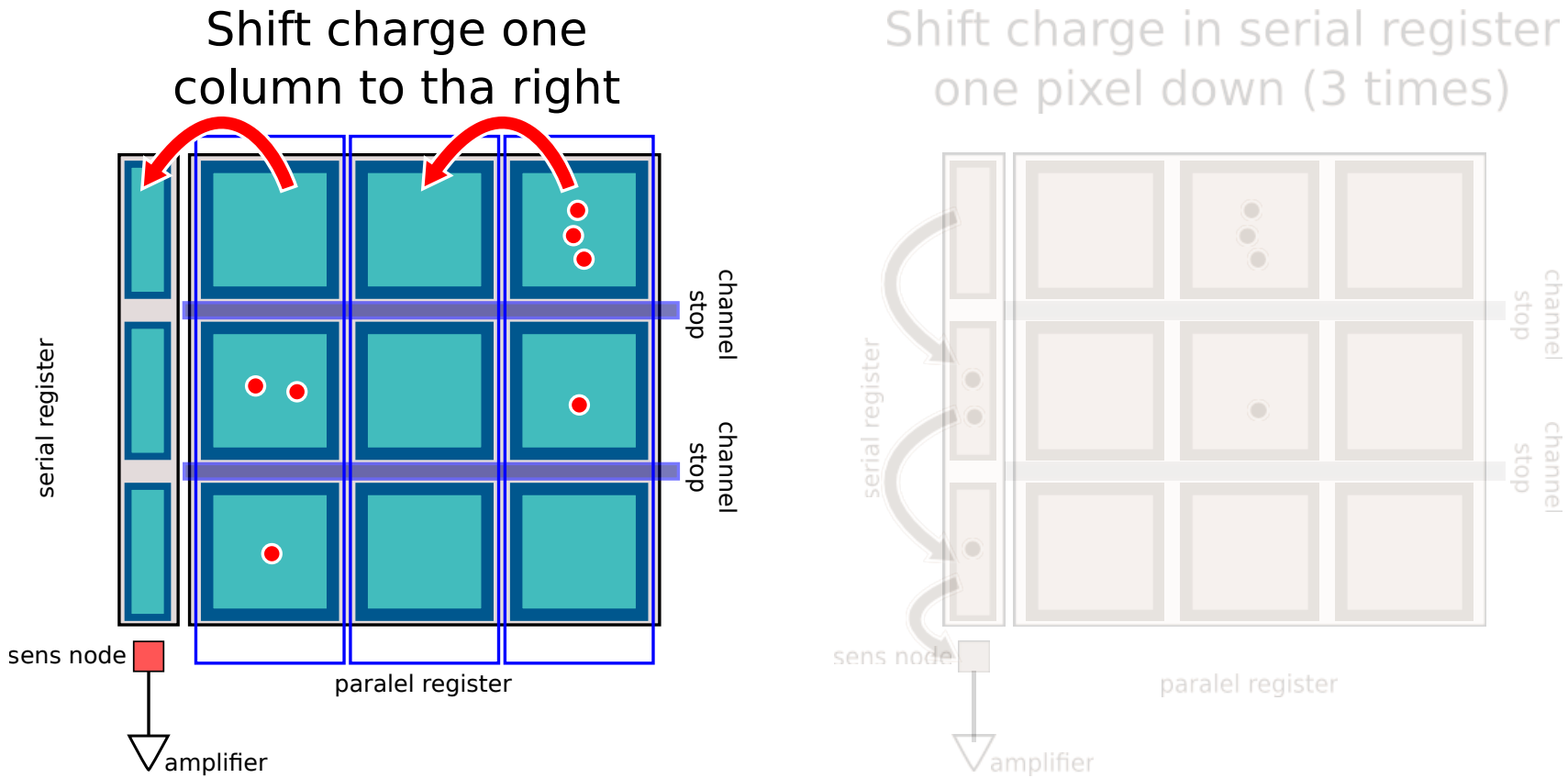



Shift charge in serial register one pixel down (3 times)



# CCD: readout

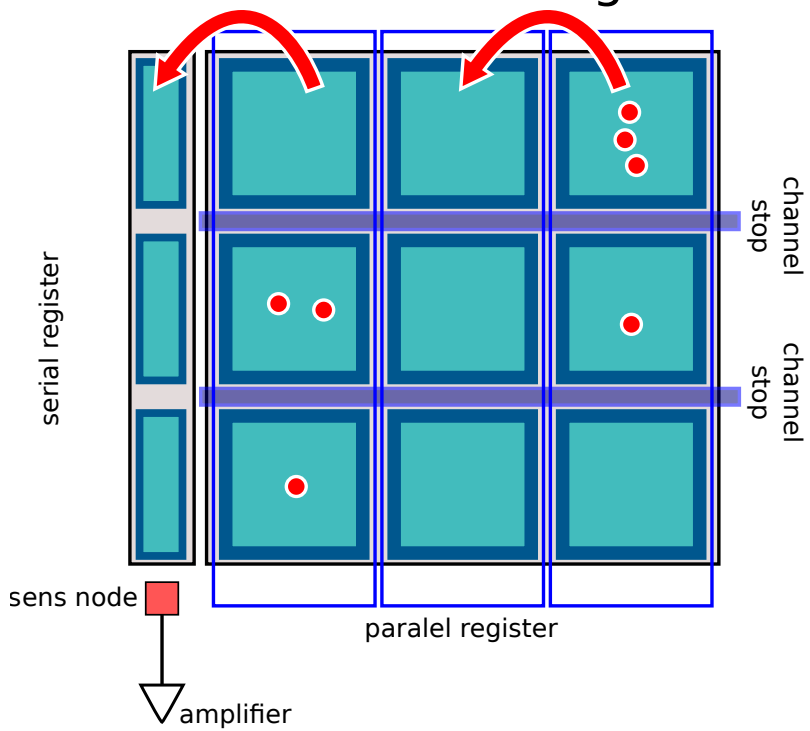
3x3 pixels CCD



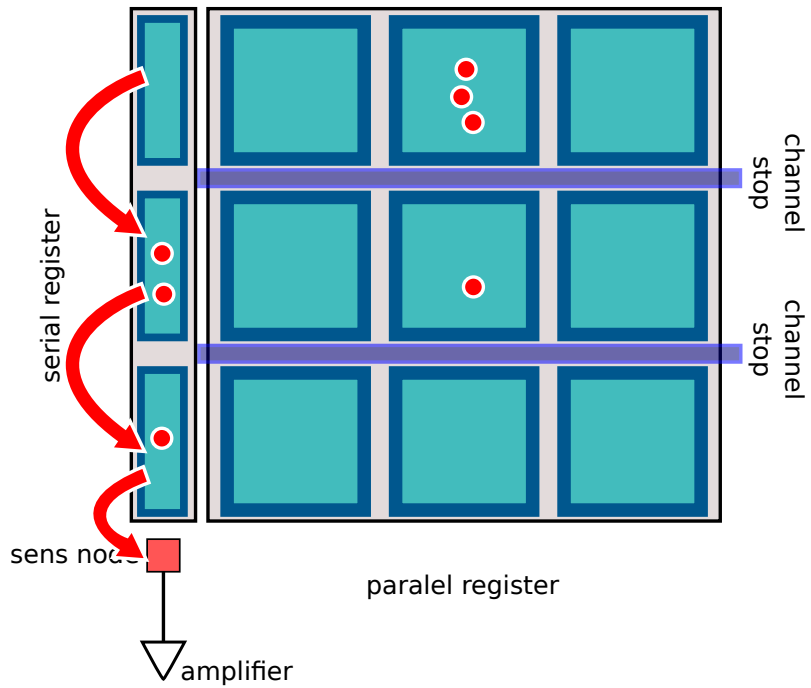
# CCD: readout

3x3 pixels CCD

Shift charge one column to tha right

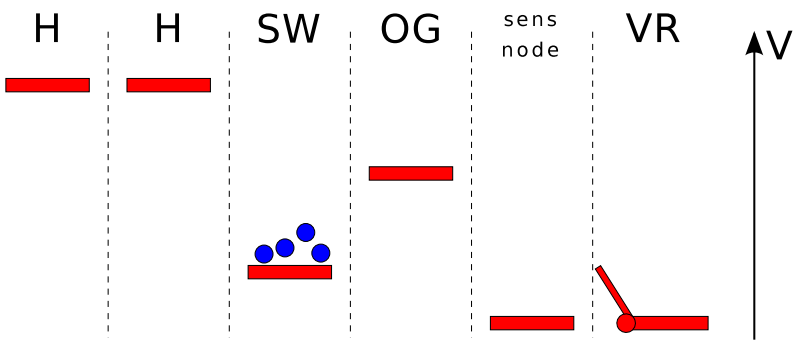


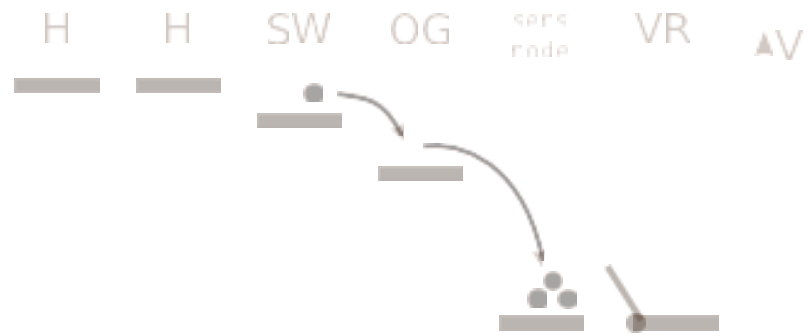

Shift charge in serial register one pixel down (3 times)




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

# CCD: readout


H
H
SW
OG
sens
node
VR
V


H
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SW
OG
VR
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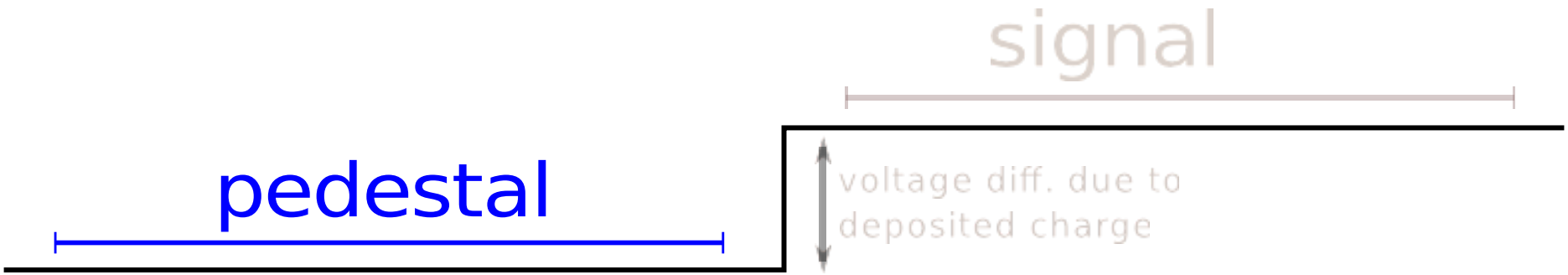
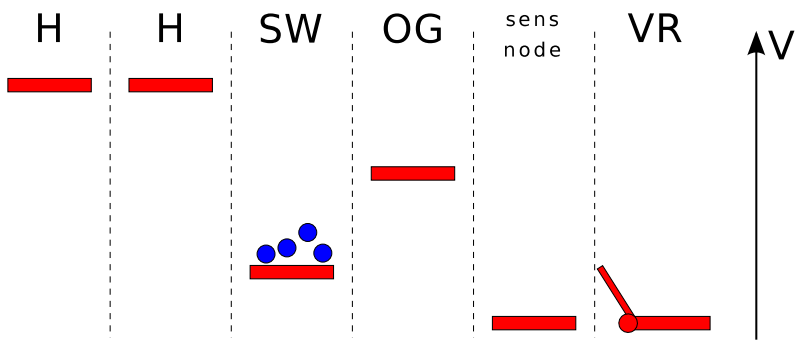

signal
pedestal
voltage diff. due to
deposited charge

# CCD: readout


H
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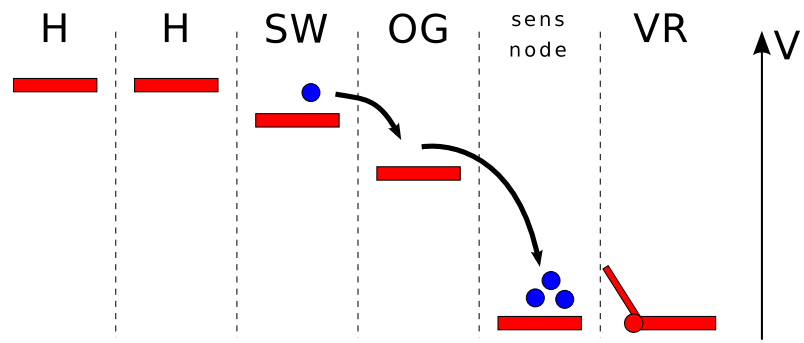
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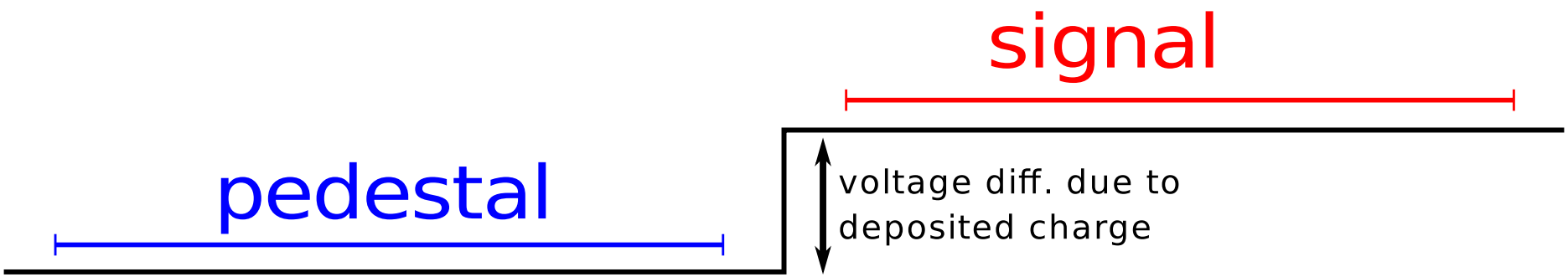
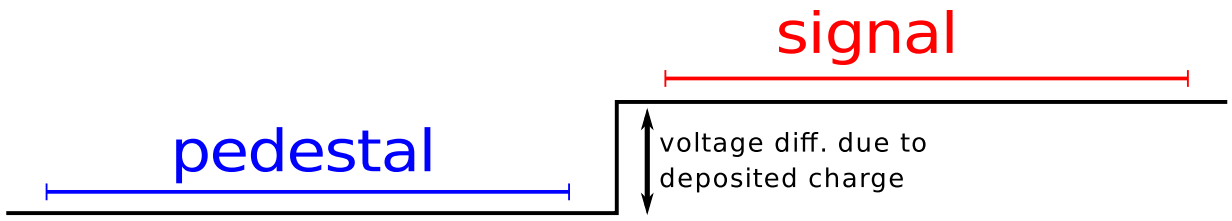
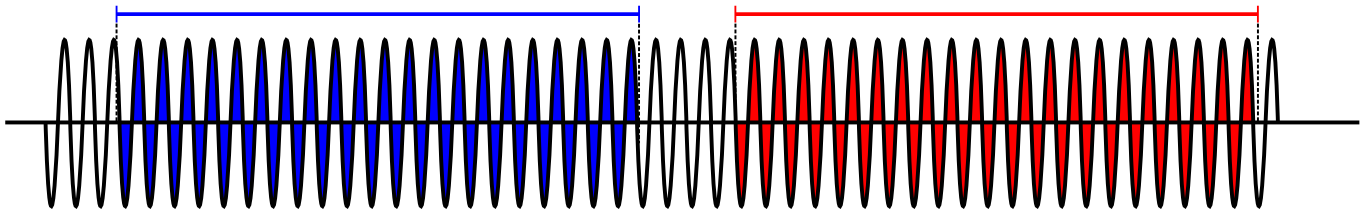

signal
pedestal
voltage diff. due to
deposited charge

# CCD: readout

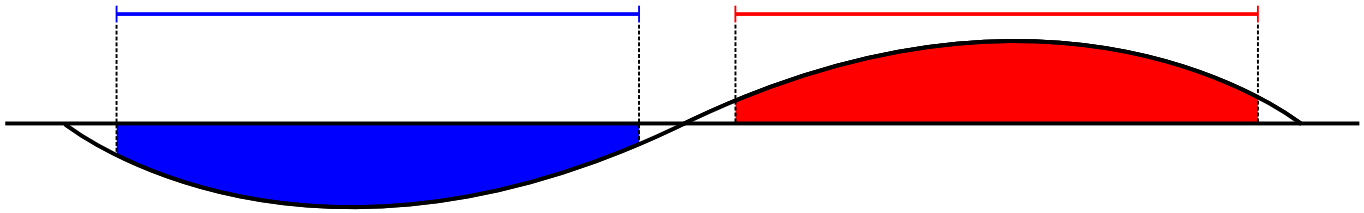
pixel charge measurement




high frequency noise

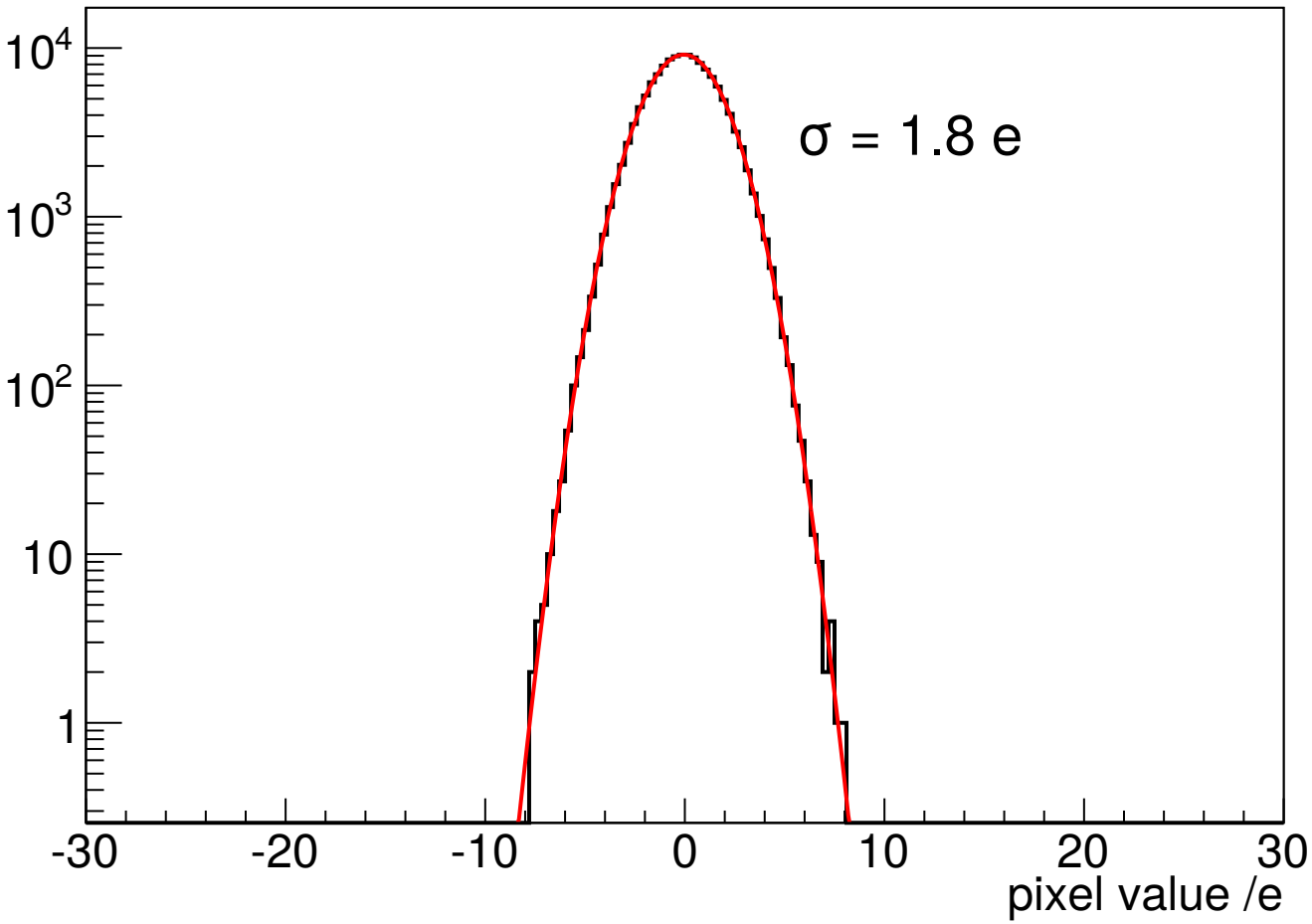


low frequency noise



excellent for removing high frequency noise but sensitive to low frequencies

# Readout noise: empty pixels distribution




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

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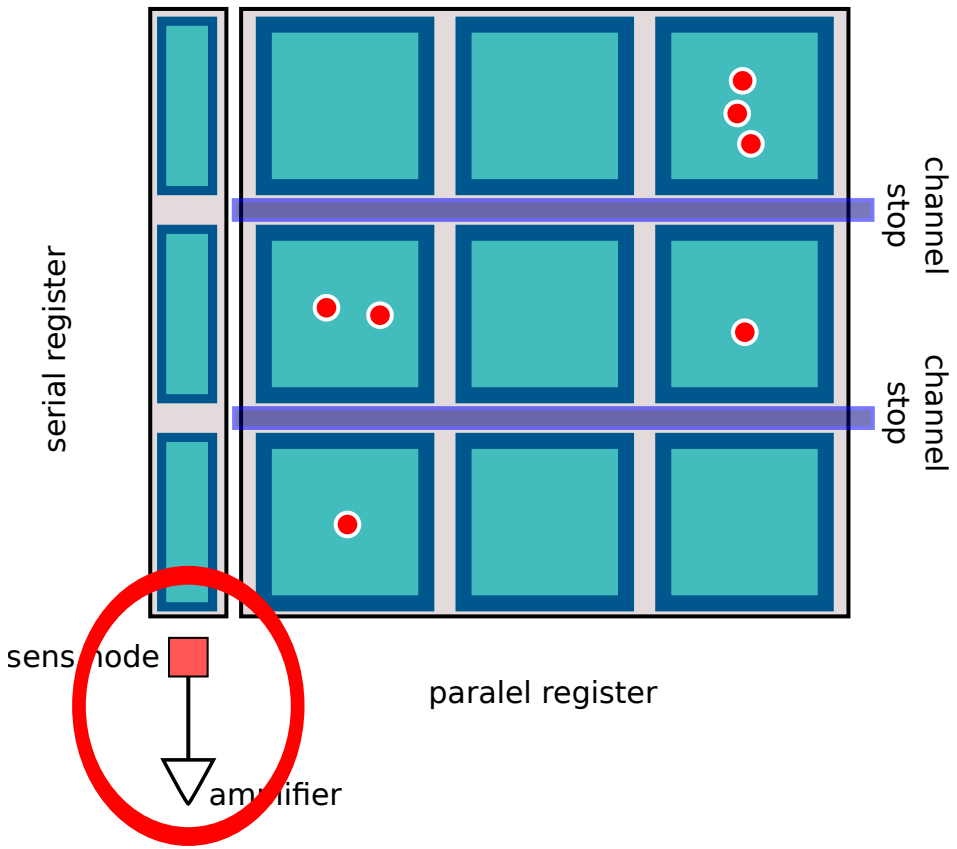
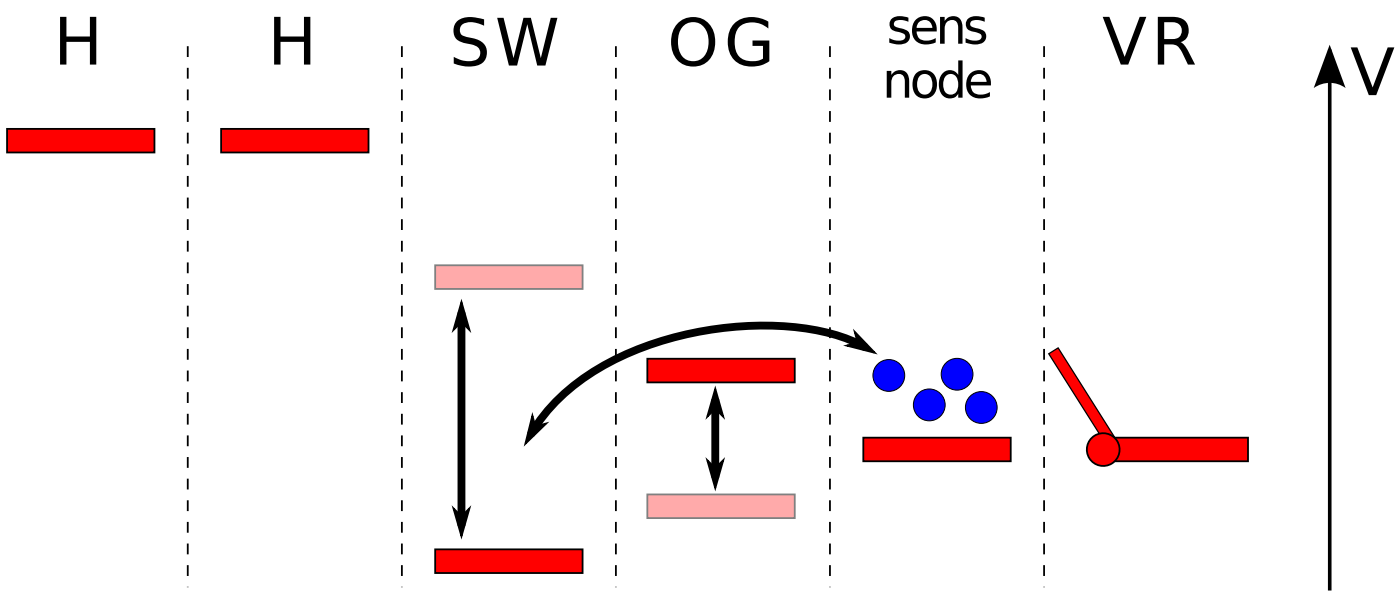
# Lowering the noise: Skipper CCD




**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
  **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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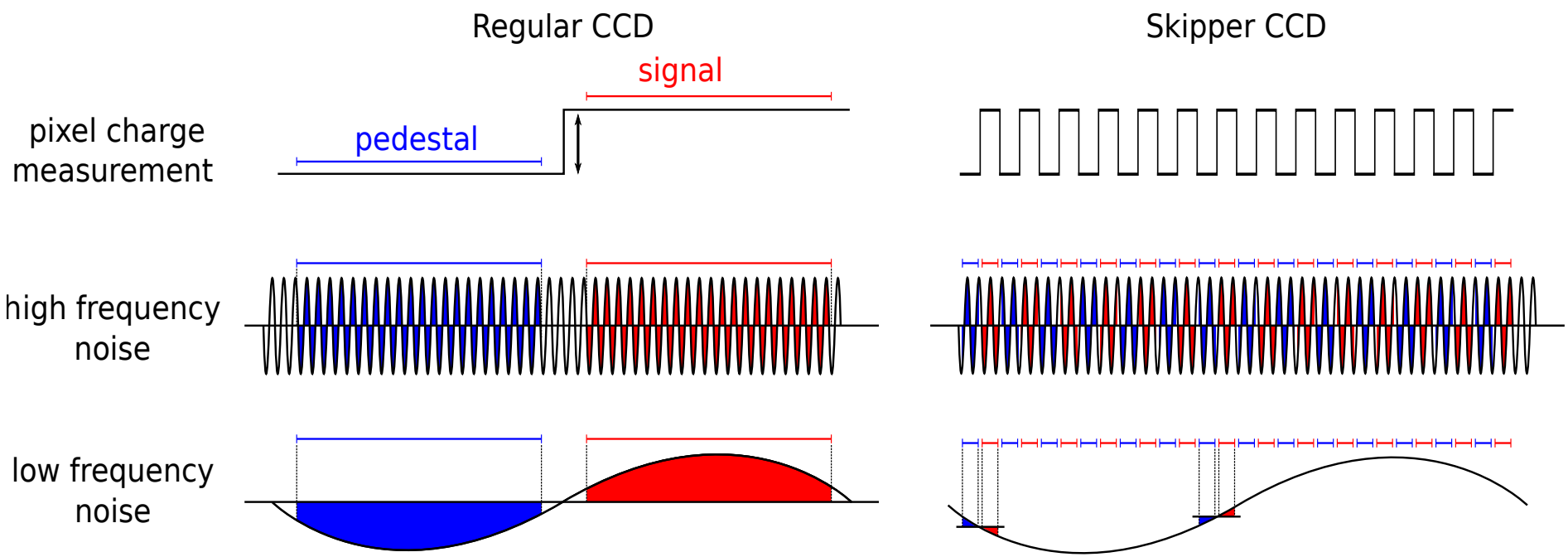
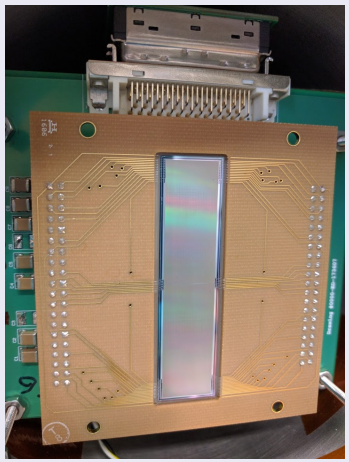


# SENSEI: First working instrument using SkipperCCD tech

## Sensors



- Skipper-CCD prototype designed by LBL MSL
- 200 & 250 $\mu$m thick, 15 $\mu$m pixel size
- Two form factors 4k$\times$1k & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10k$\Omega$
- 4 amplifiers per CCD, three different RO stage designs

## Instrument

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

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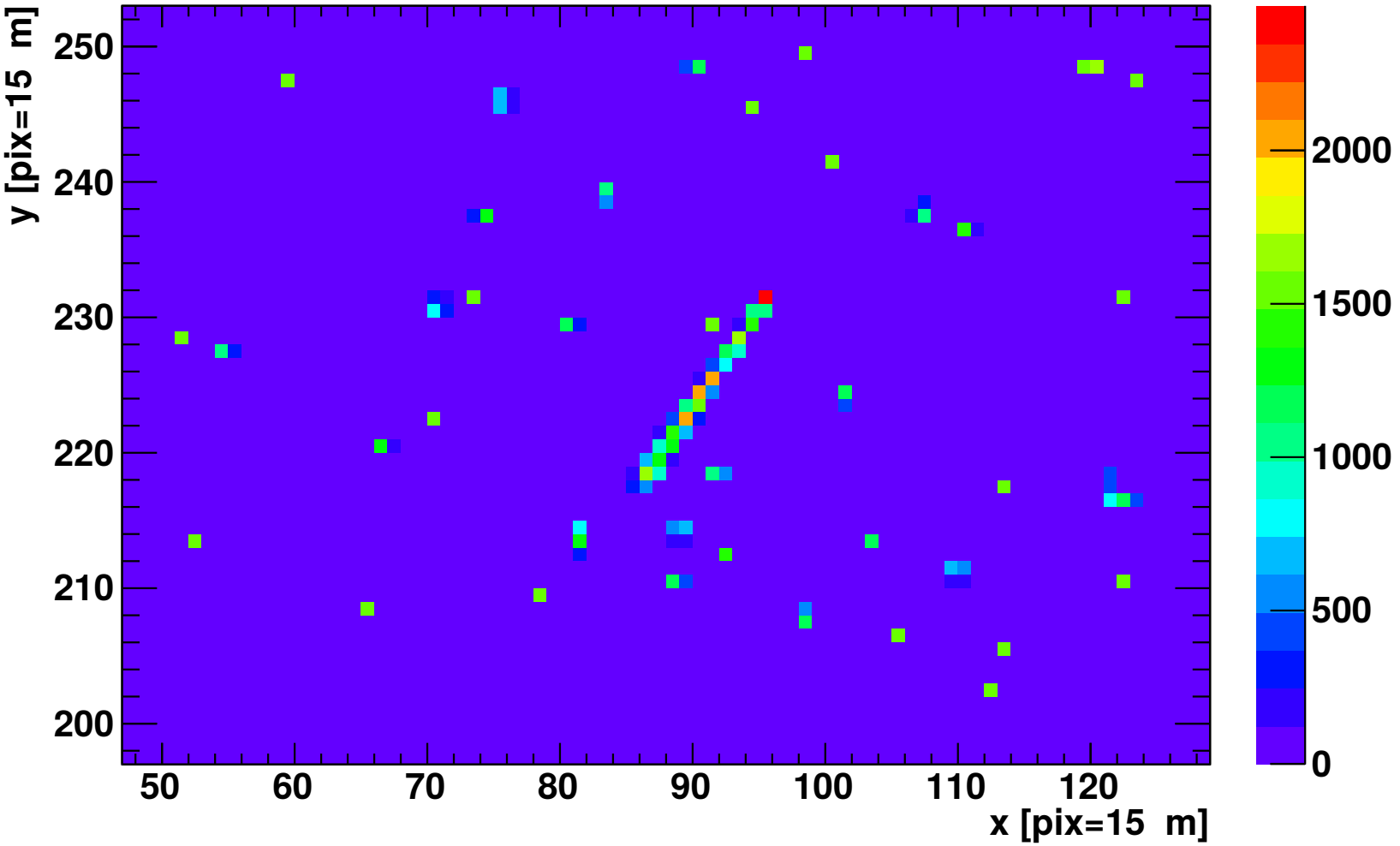
# Image taken with SENSEI: 4000 samples per pixel (processed)

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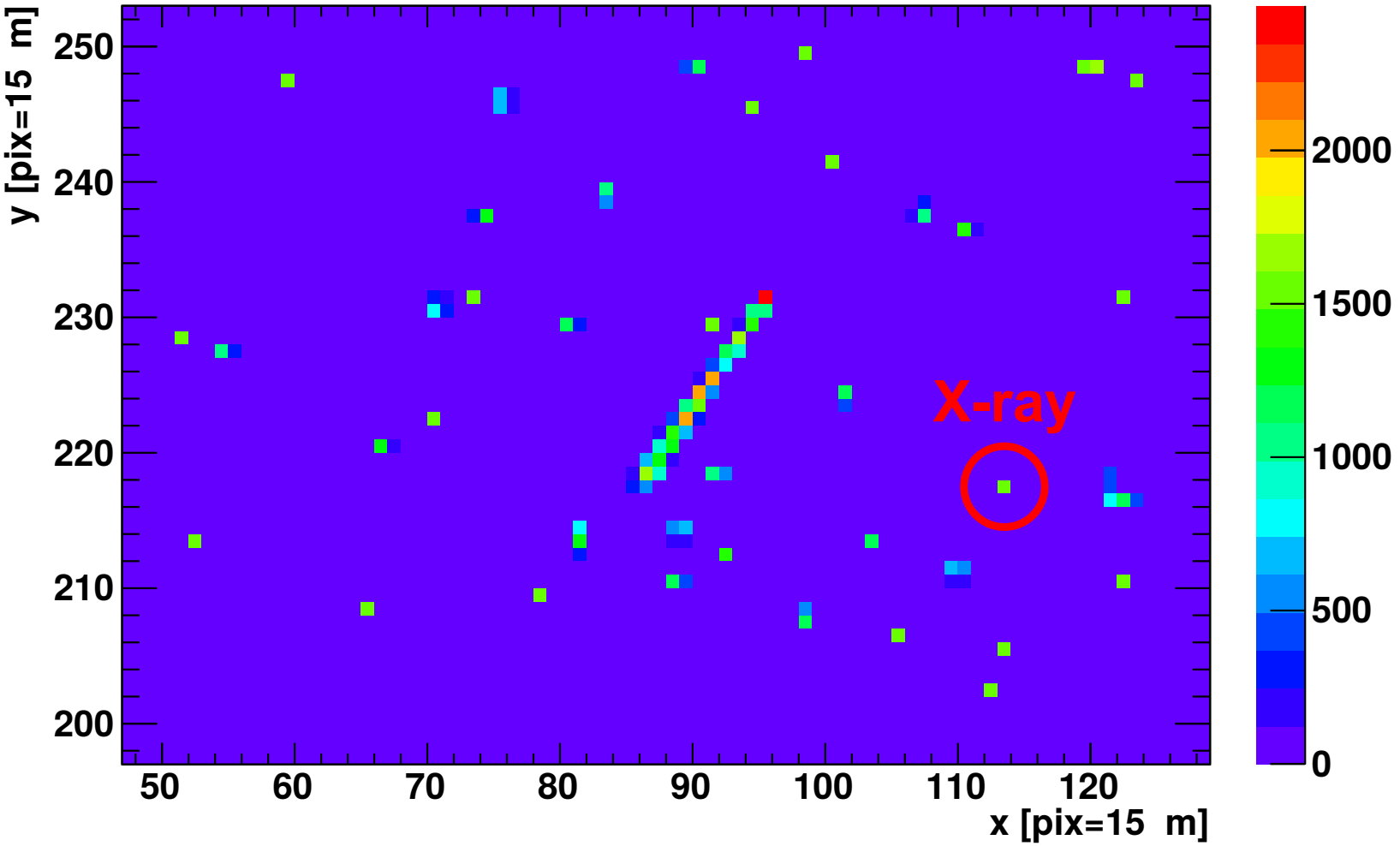
# Image taken with SENSEI: 4000 samples per pixel (processed)



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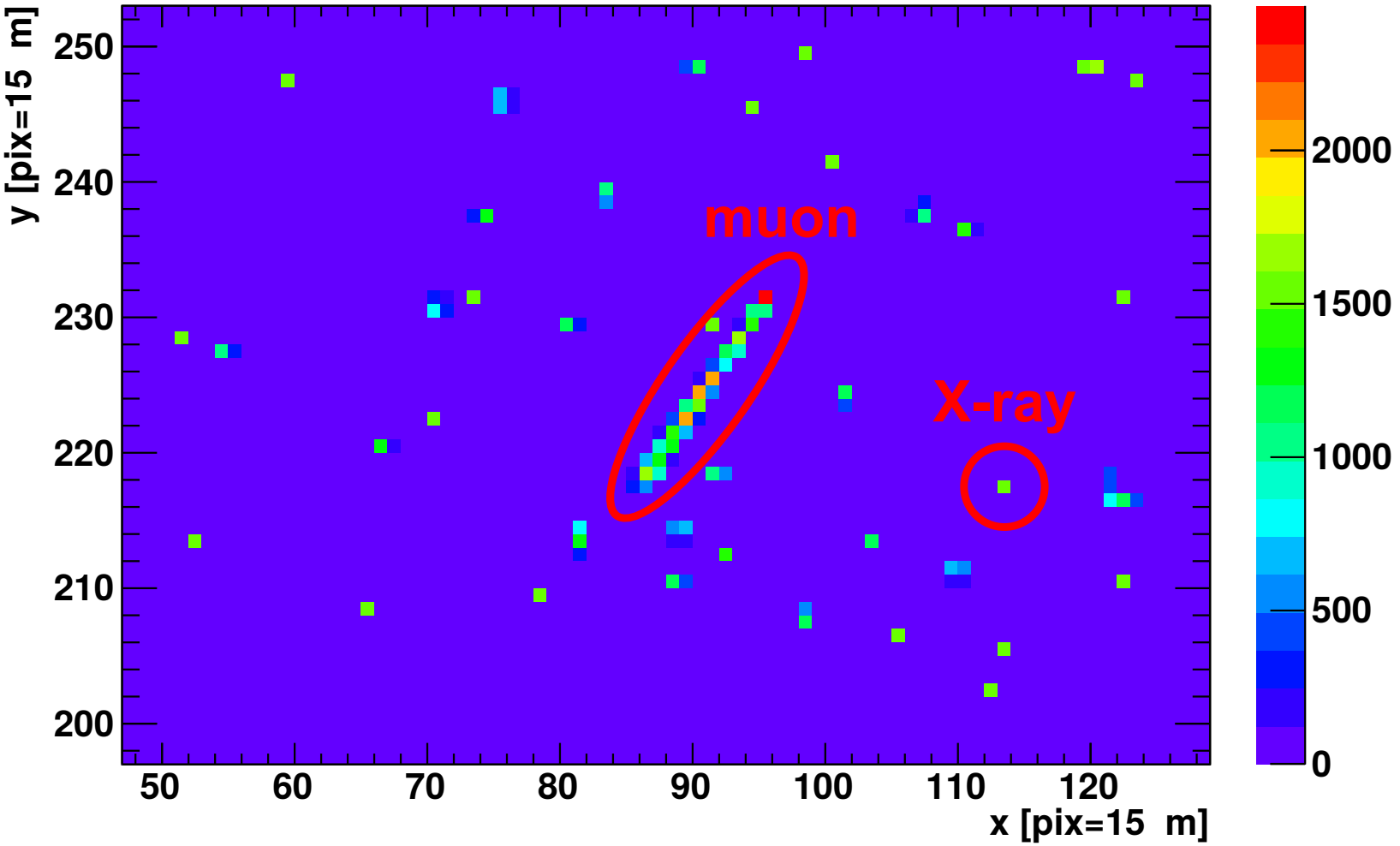

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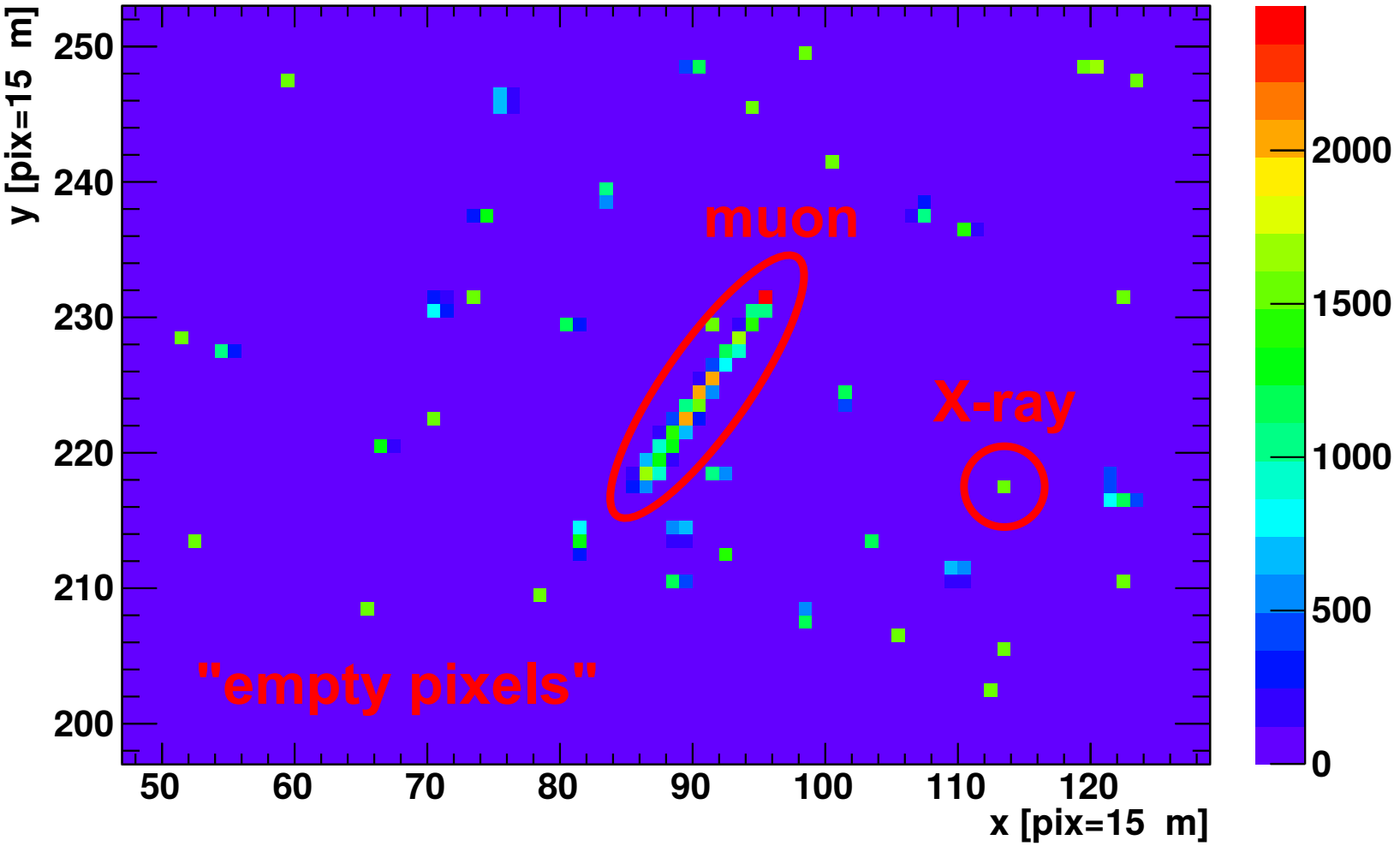
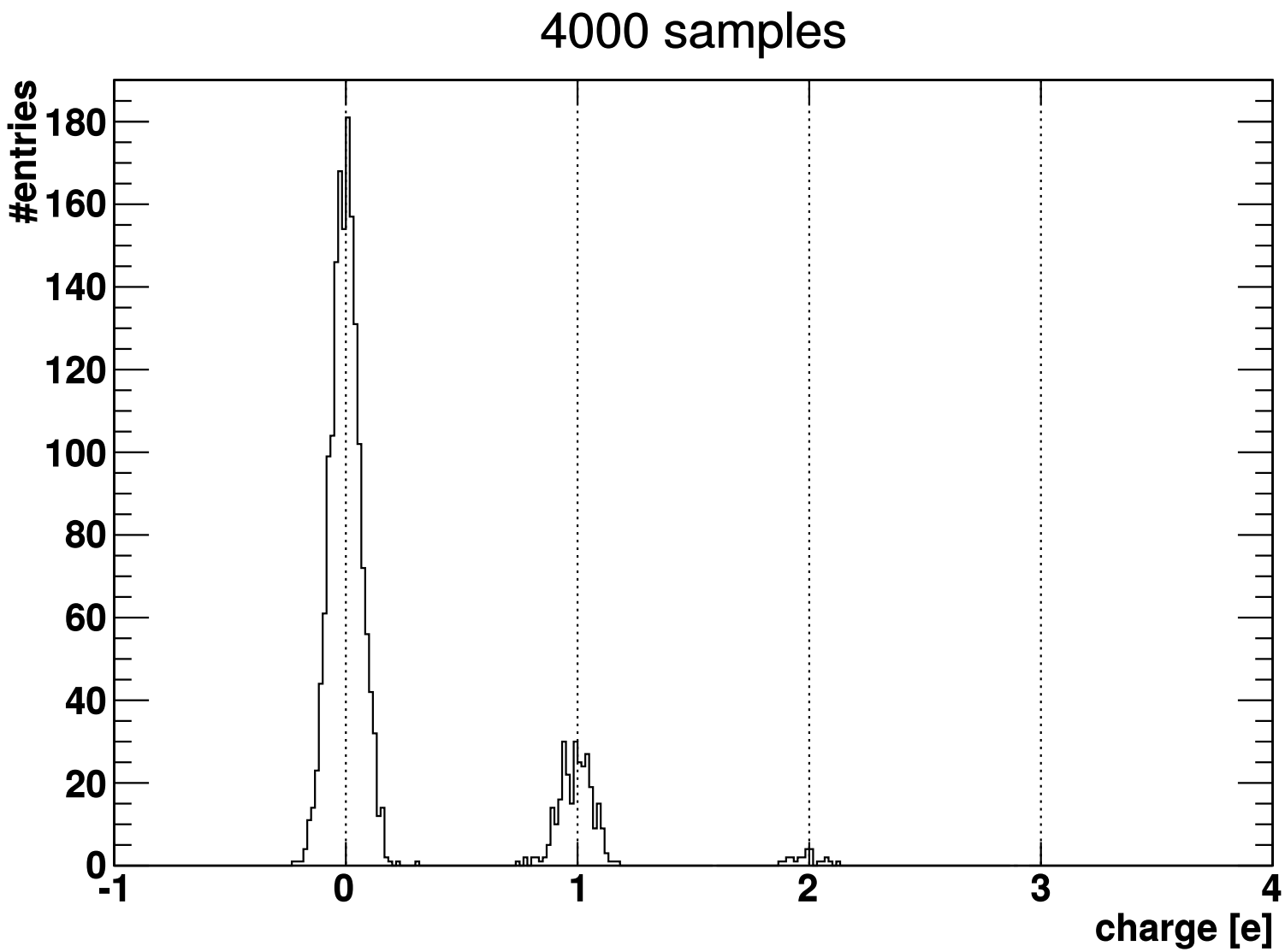
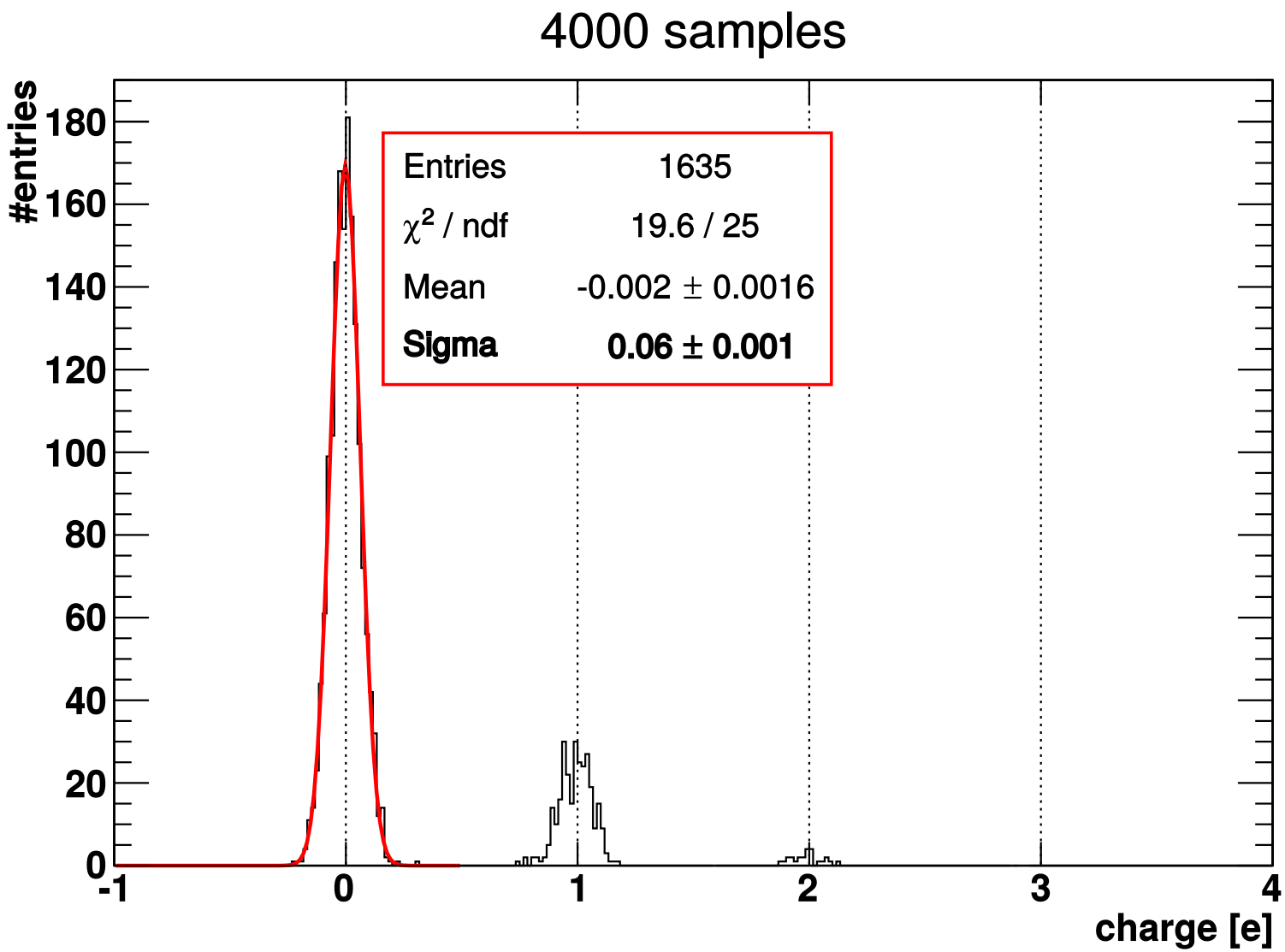


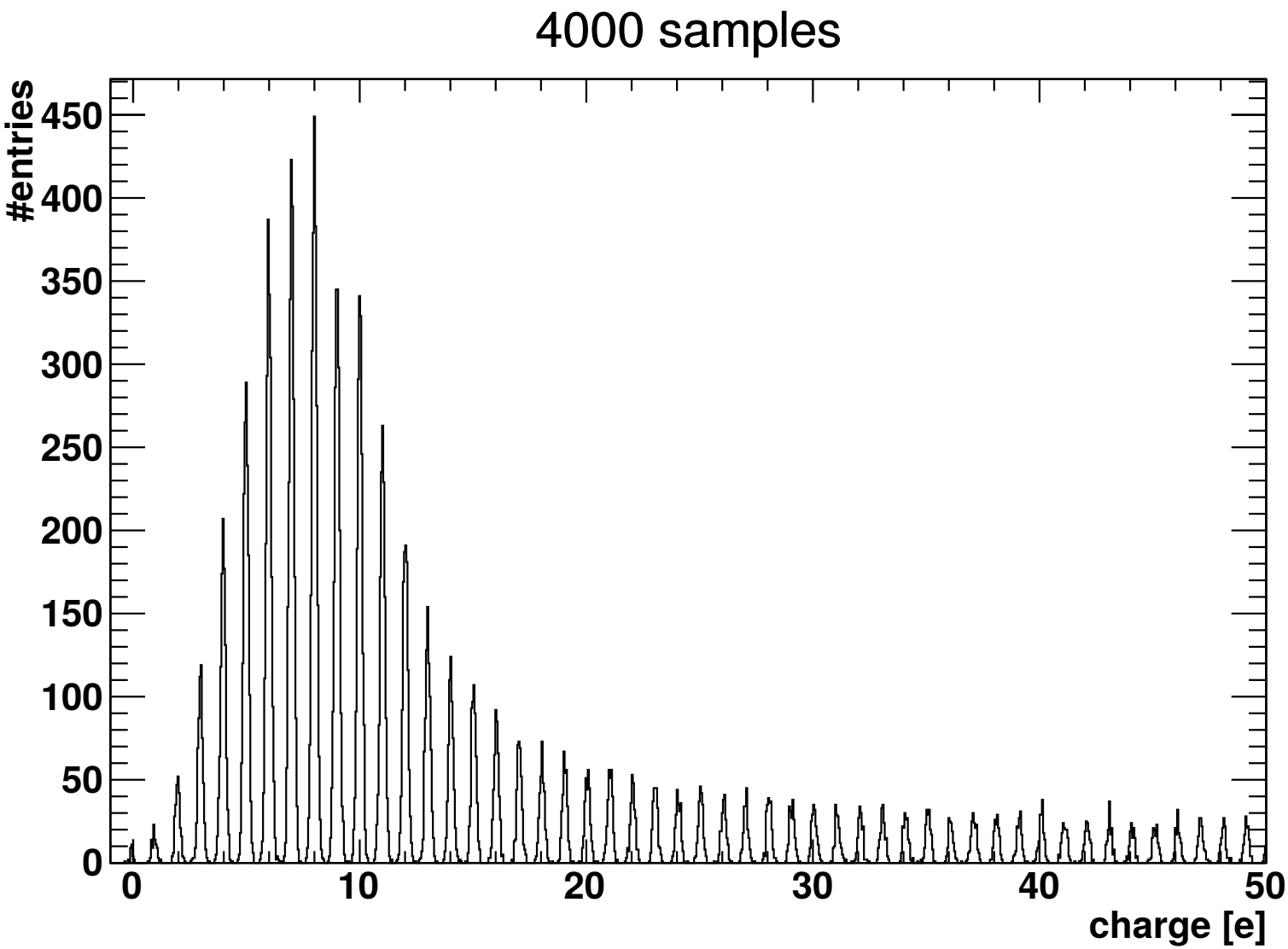
# Charge in pixel distribution. Counting electrons: 0, 1, 2..



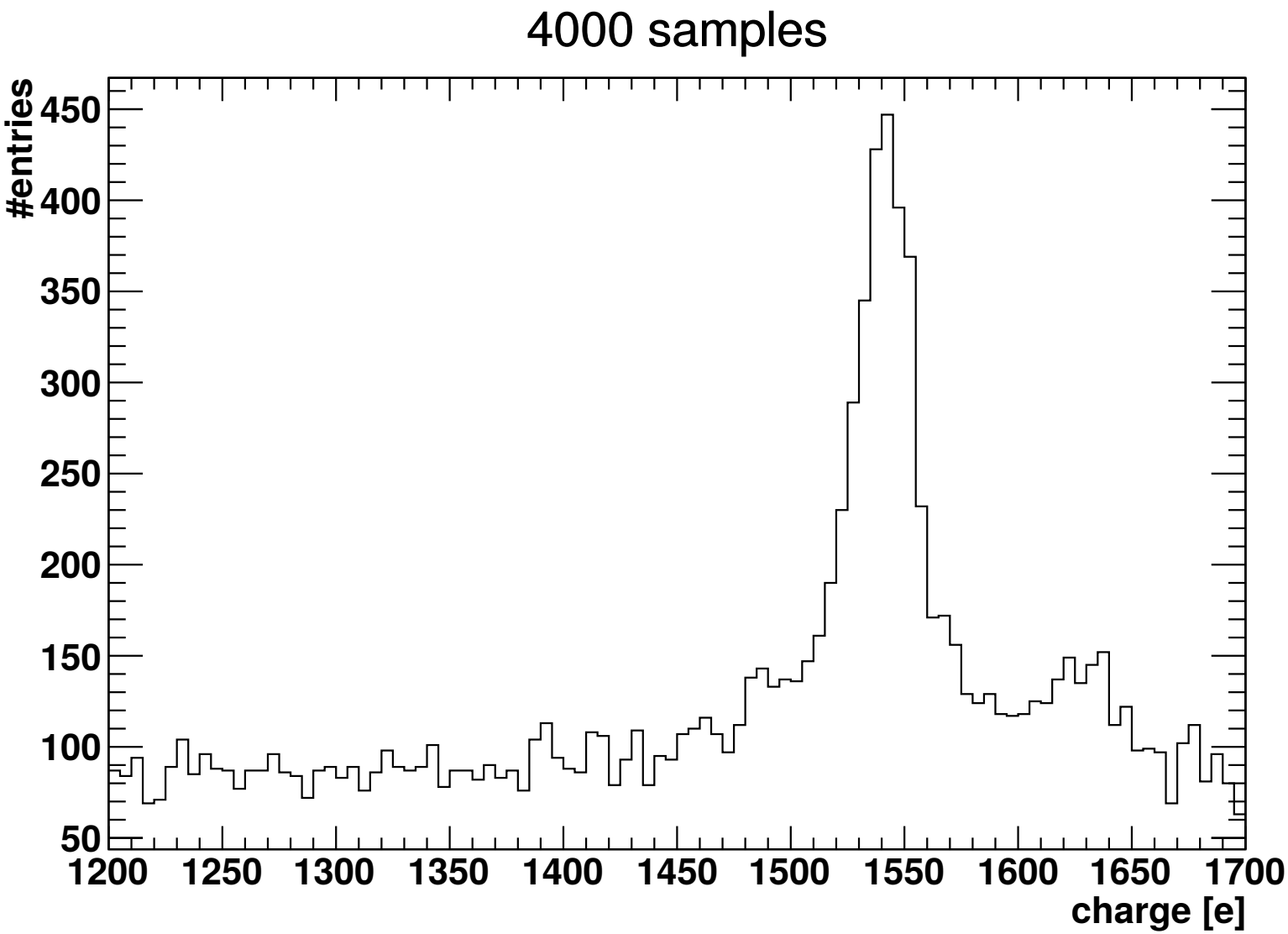
# Charge in pixel distribution. Counting electrons: 0, 1, 2..



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



# $^{55}$Fe X-ray source



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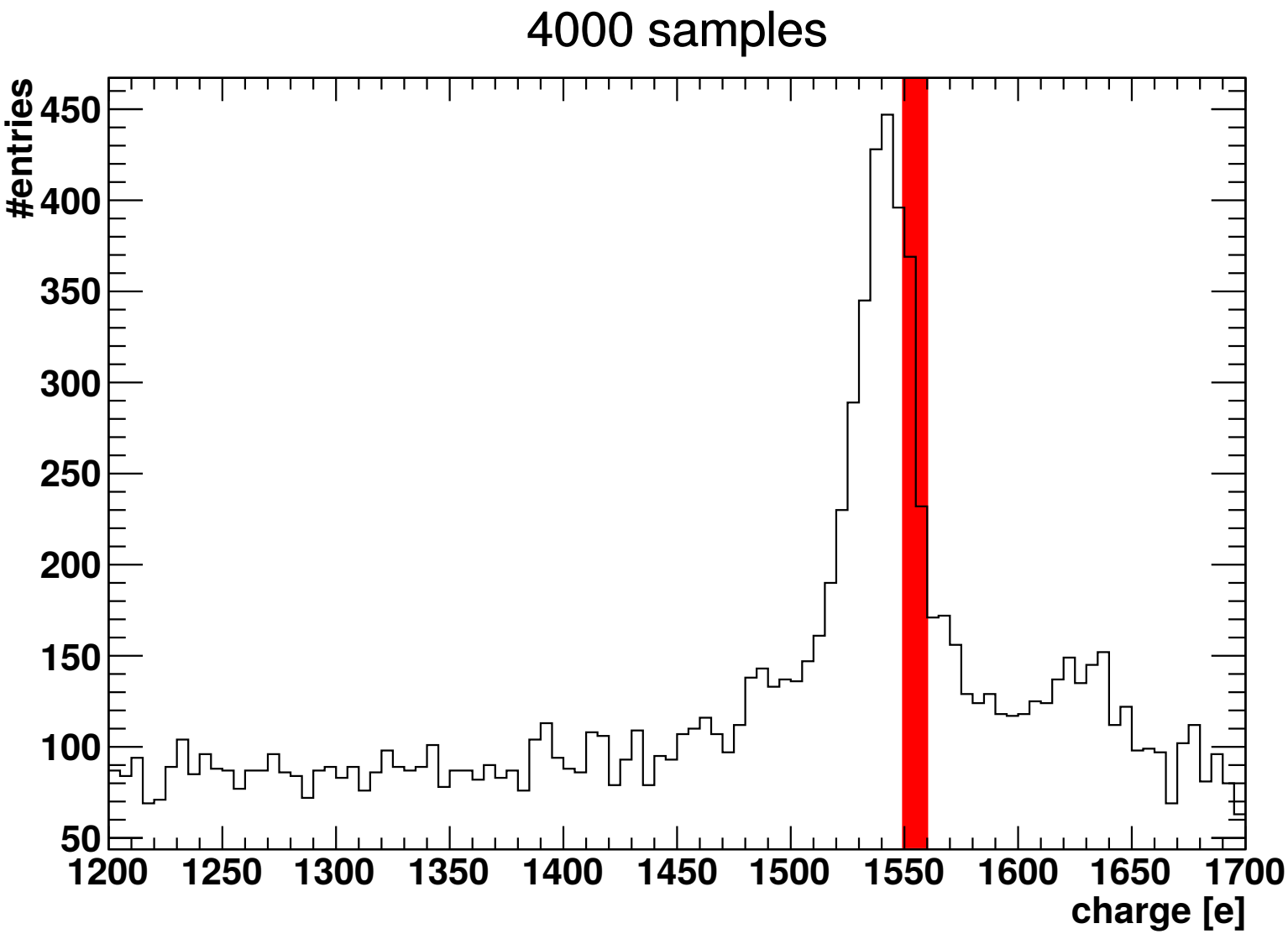
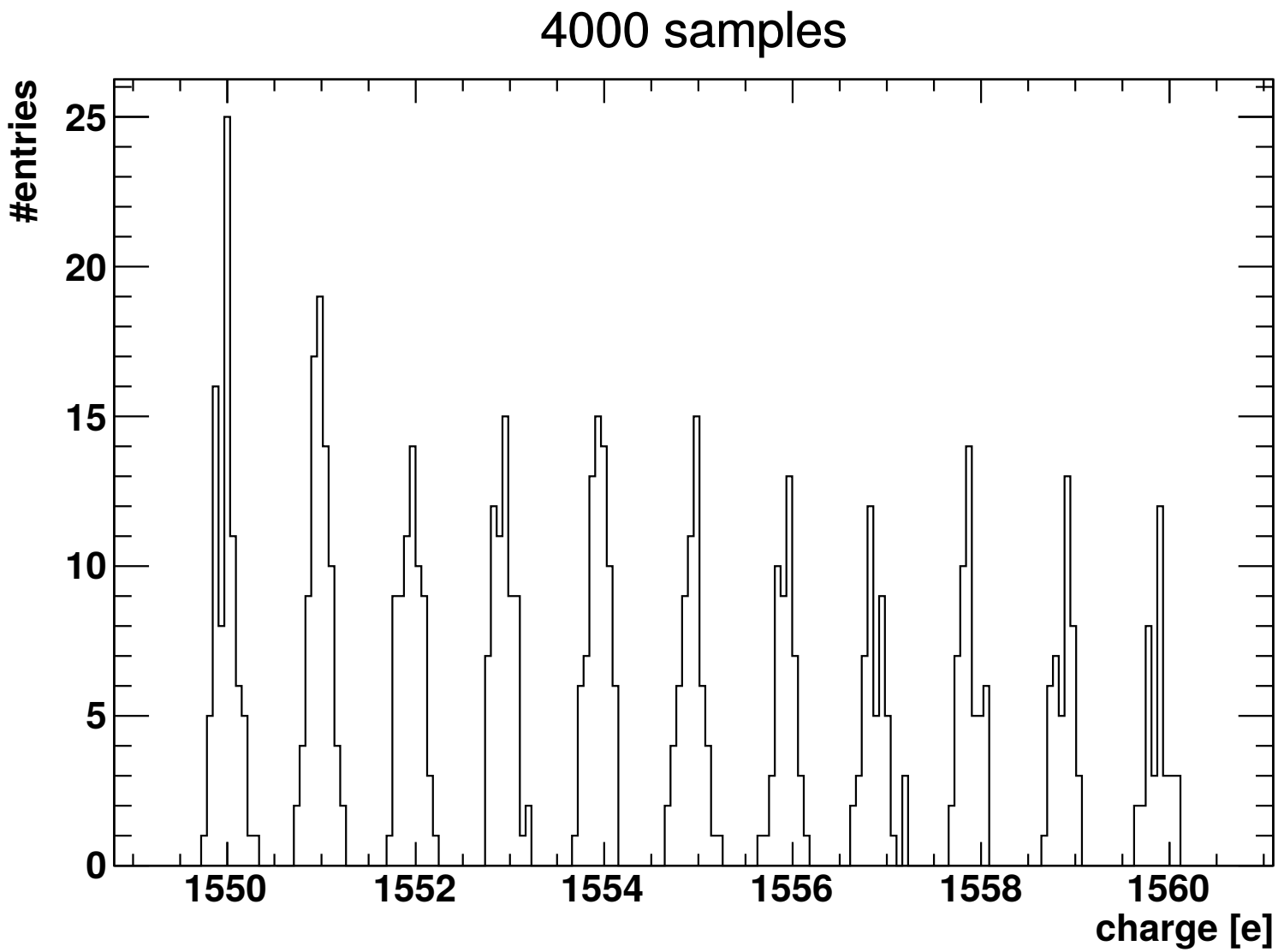
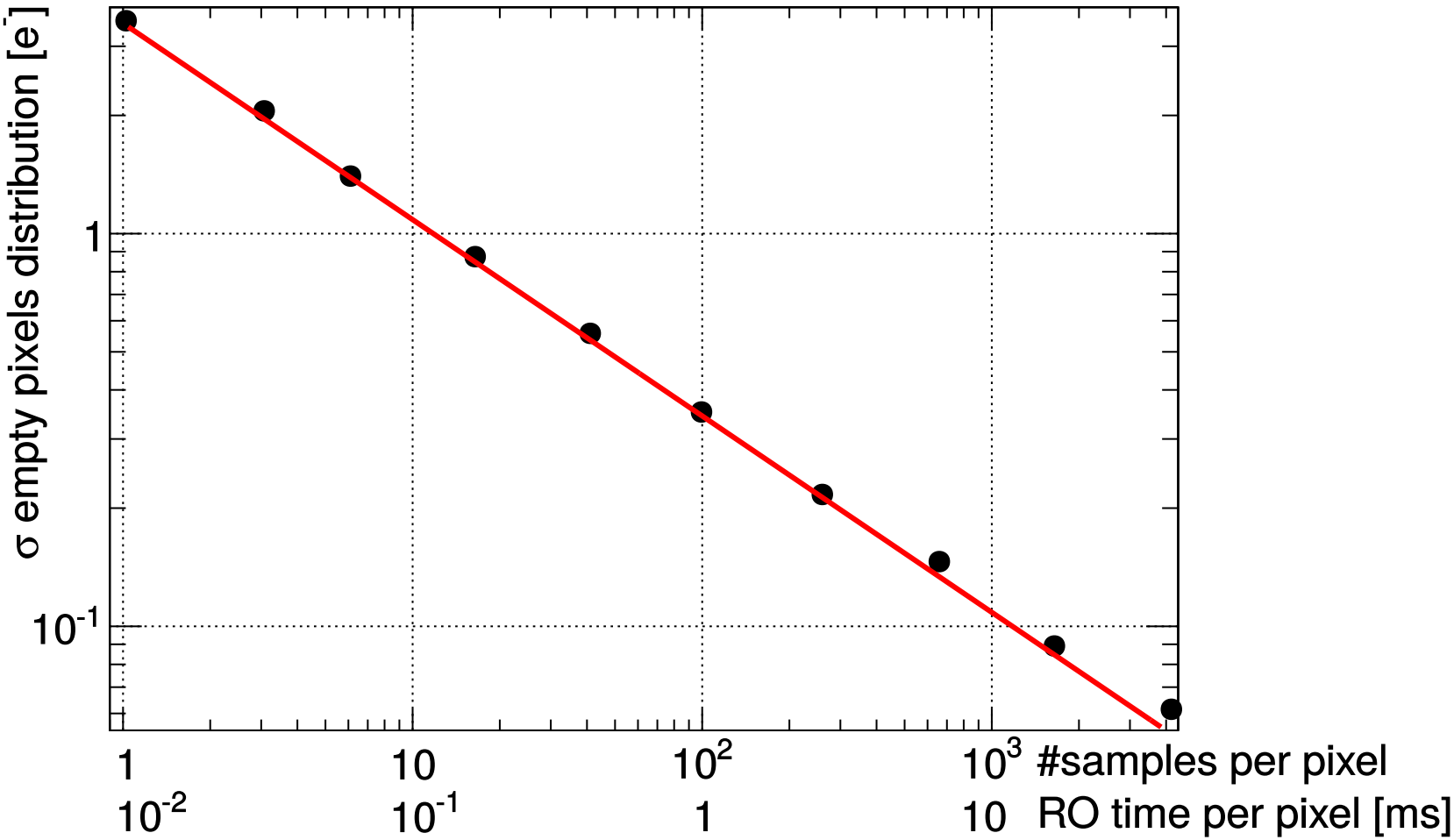


# keep counting: ..1550, 1551, 1552..

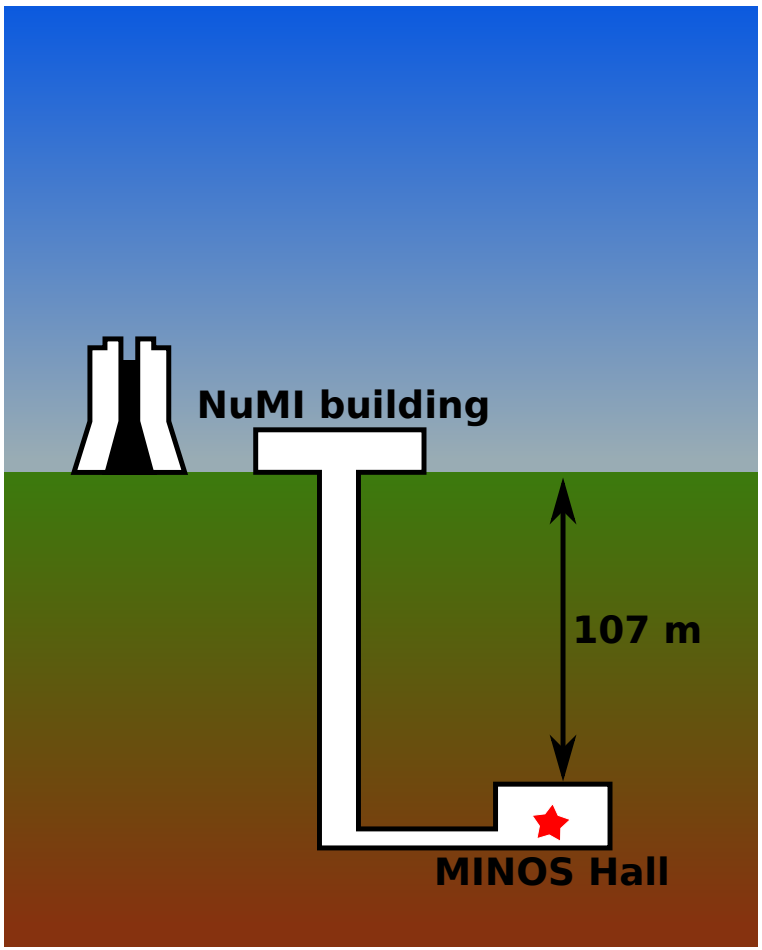


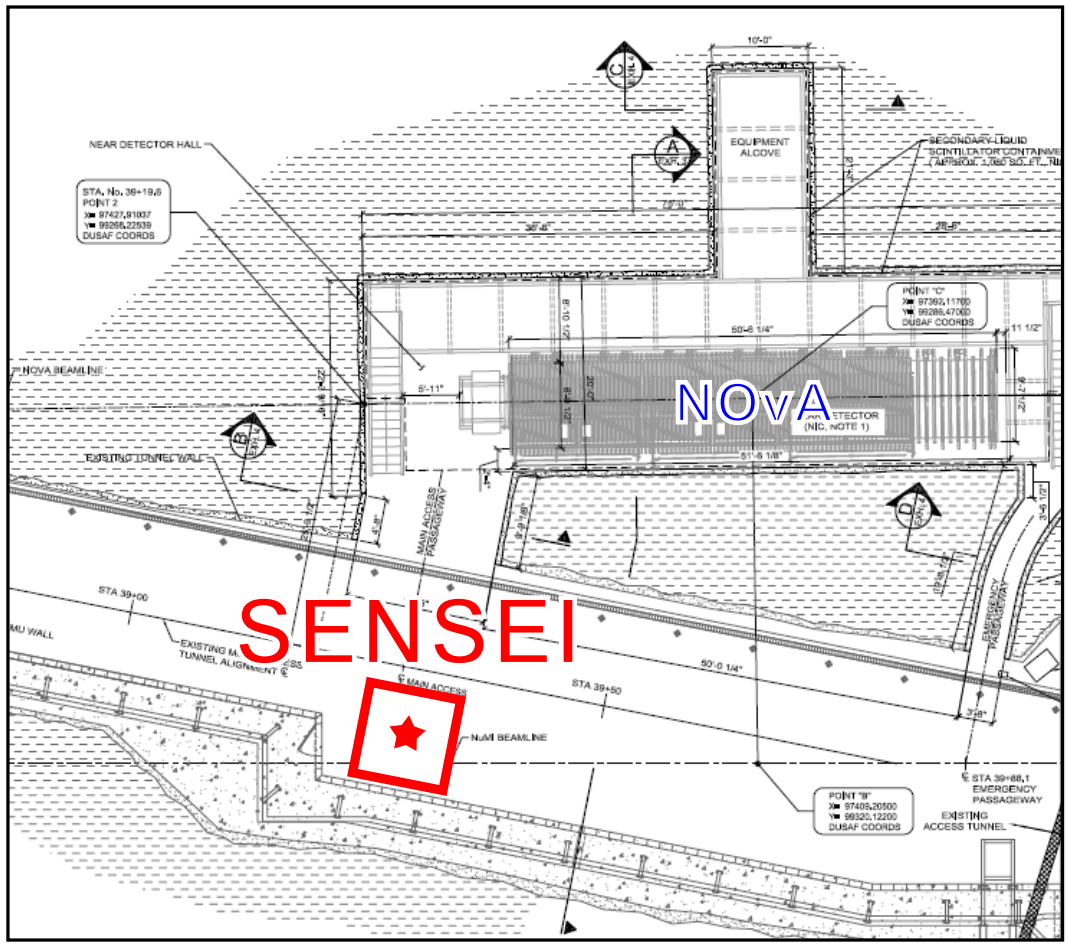
# Noise vs. #samples - $1/\sqrt{N}$



# Whats next: Installation @MINOS & low radiation package

Technology demonstration: installation at shallow underground site



# Whats next: Installation @MINOS & low radiation package

Filtered air tent installed, low radioactivity package being tested



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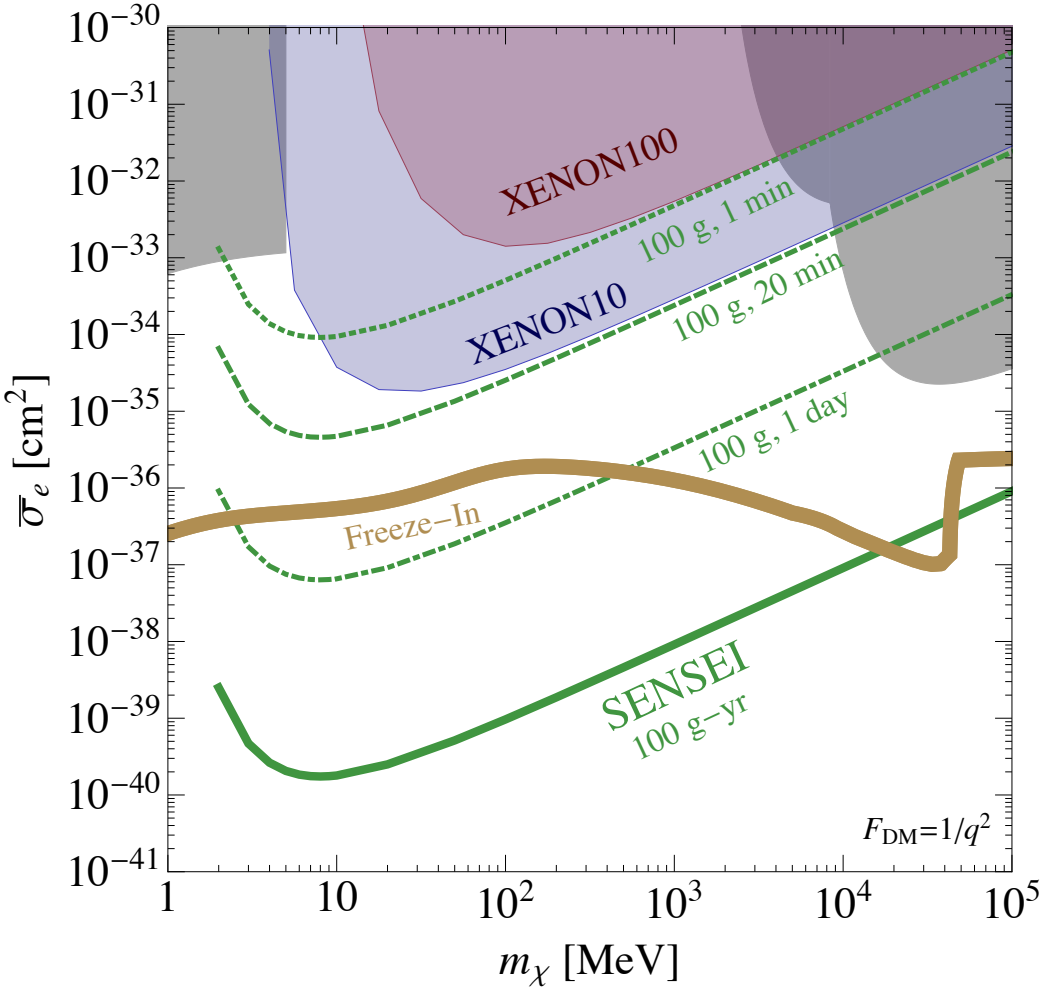
# SENSEI: reach of a 100g, *zeroish-background* experiment

## Light Dark Photon




Rouven Essig, Tomer Volansky & Tien-Tien Yu.

# SENSEI and Skipper-CCD detectors prospects

**SENSEI is the ultimate silicon ionization detector**
**Unmatched performance for electron recoil channels**

- Probe DM masses at the MeV scale through electron recoil.
- Probe axion and hidden-photon DM with masses down to 1 eV.
- Probe DM masses as low as 0.1 GeV through nuclear recoil.
- Push boundaries of coherent $\nu$-nucleus interaction experiments.
- Improve high resolution spectroscopic instruments.

## Participants

- **Fermilab:** Javier Tiffenberg, Miguel Sofo Haro
- **LBNL:** Steve Holland
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Tomer Volansky
- **CERN:** Tien-Tien Yu

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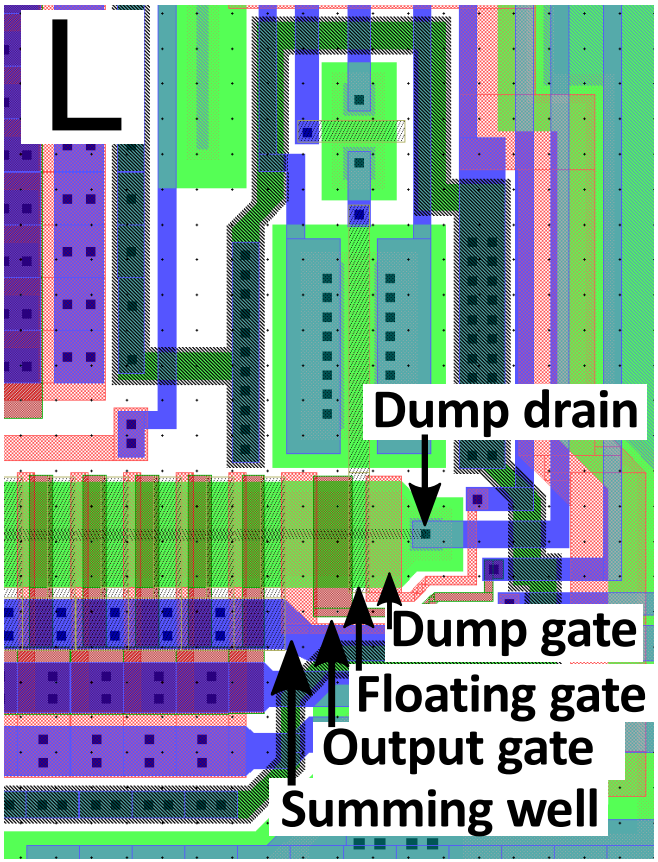
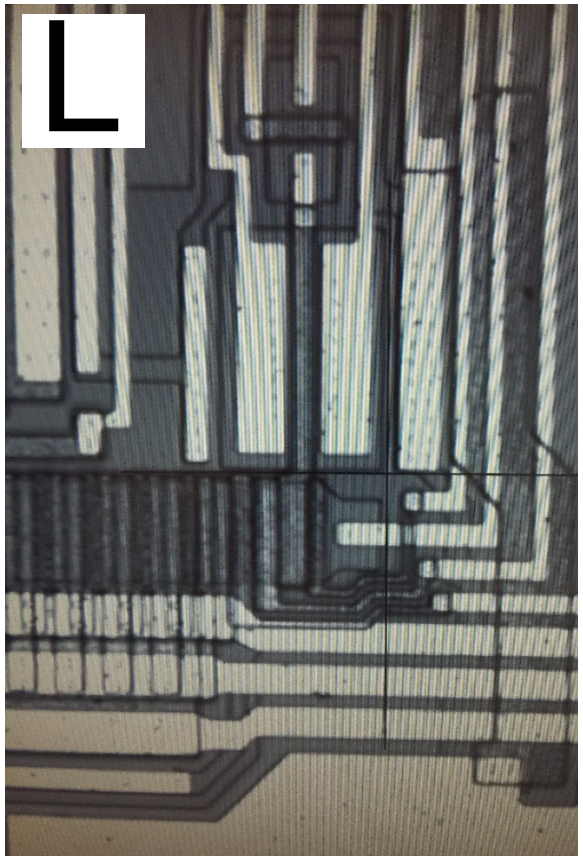
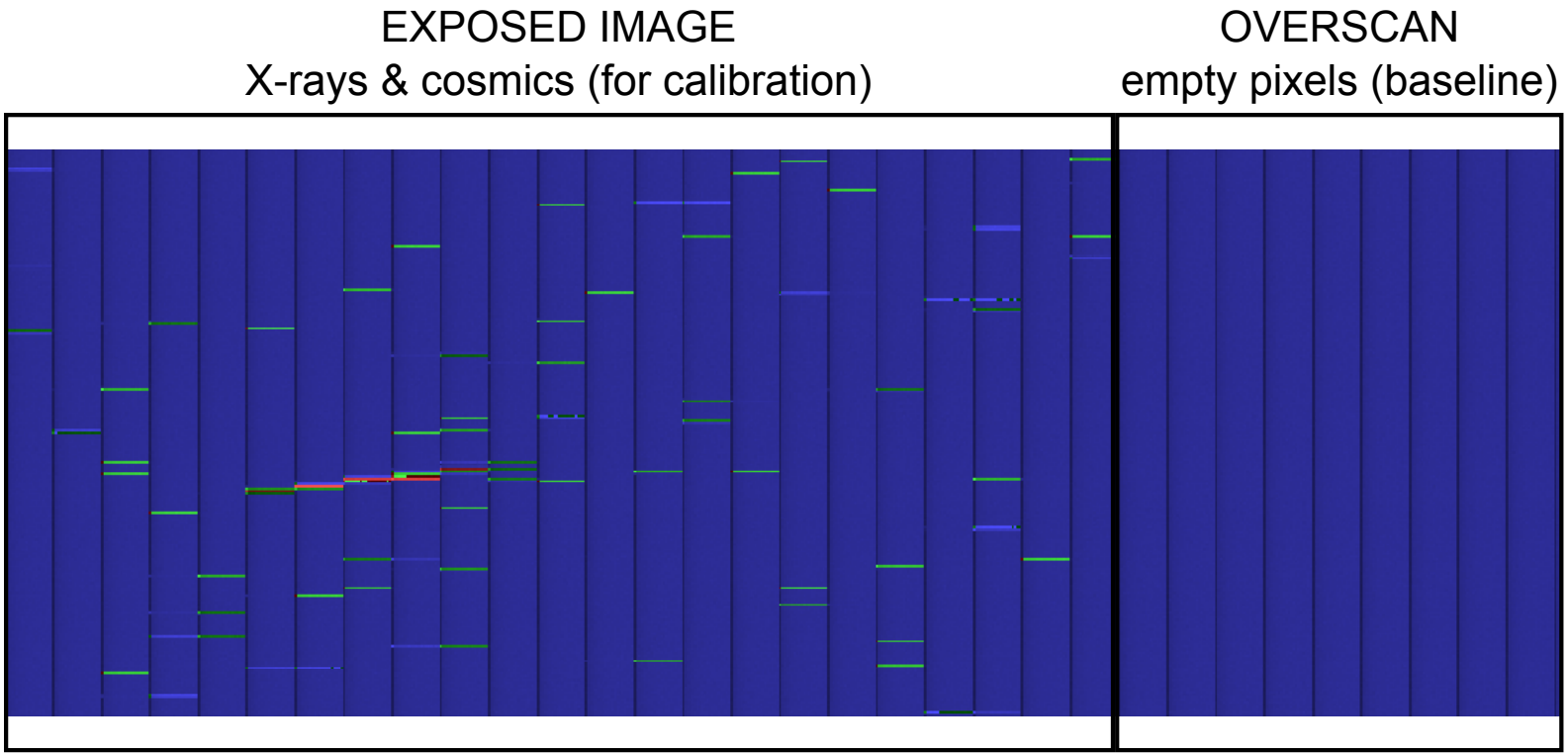
# BACK UP SLIDES

# Readout stage design




# Raw image taken with SENSEI: 20 samples per pixel



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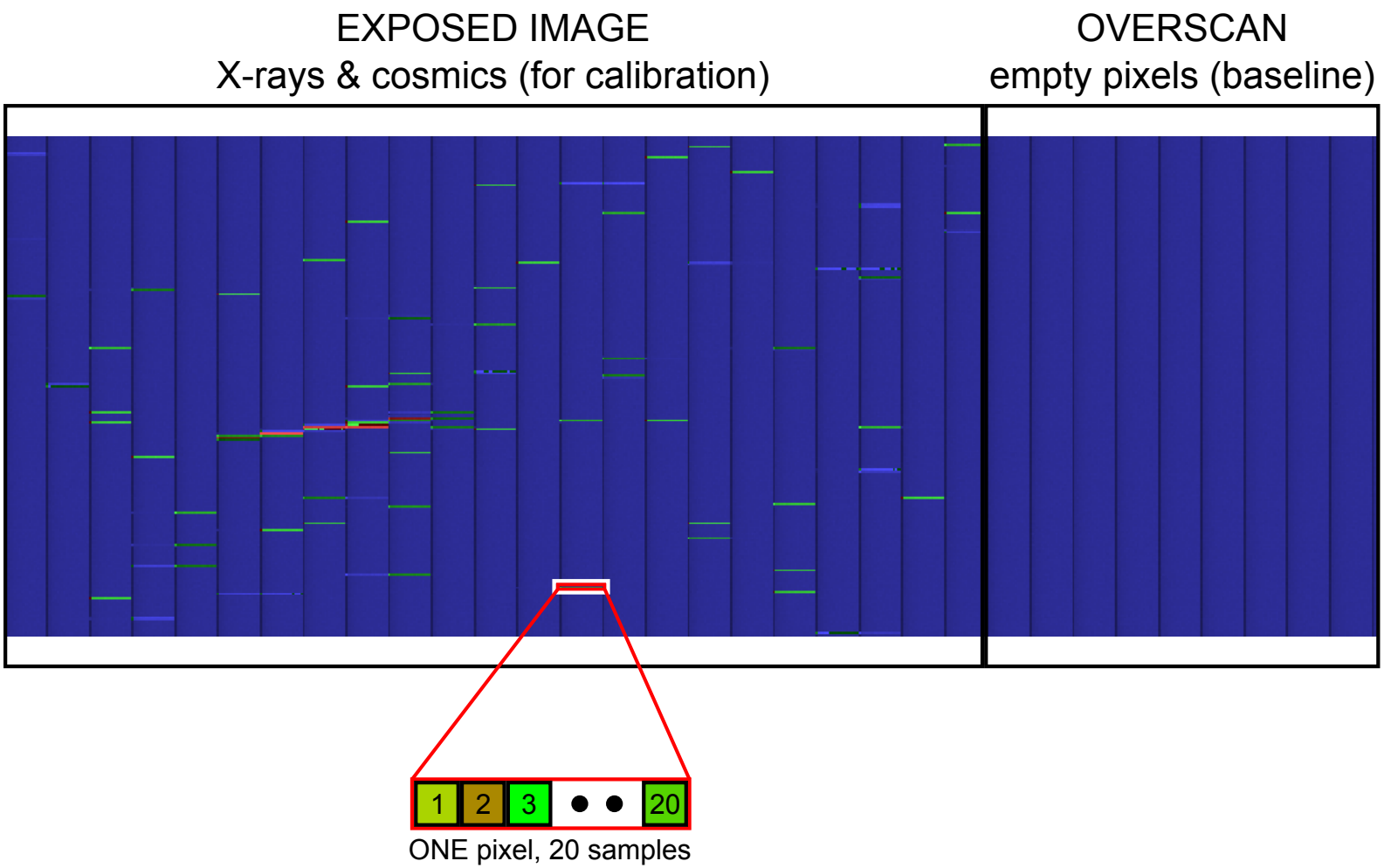

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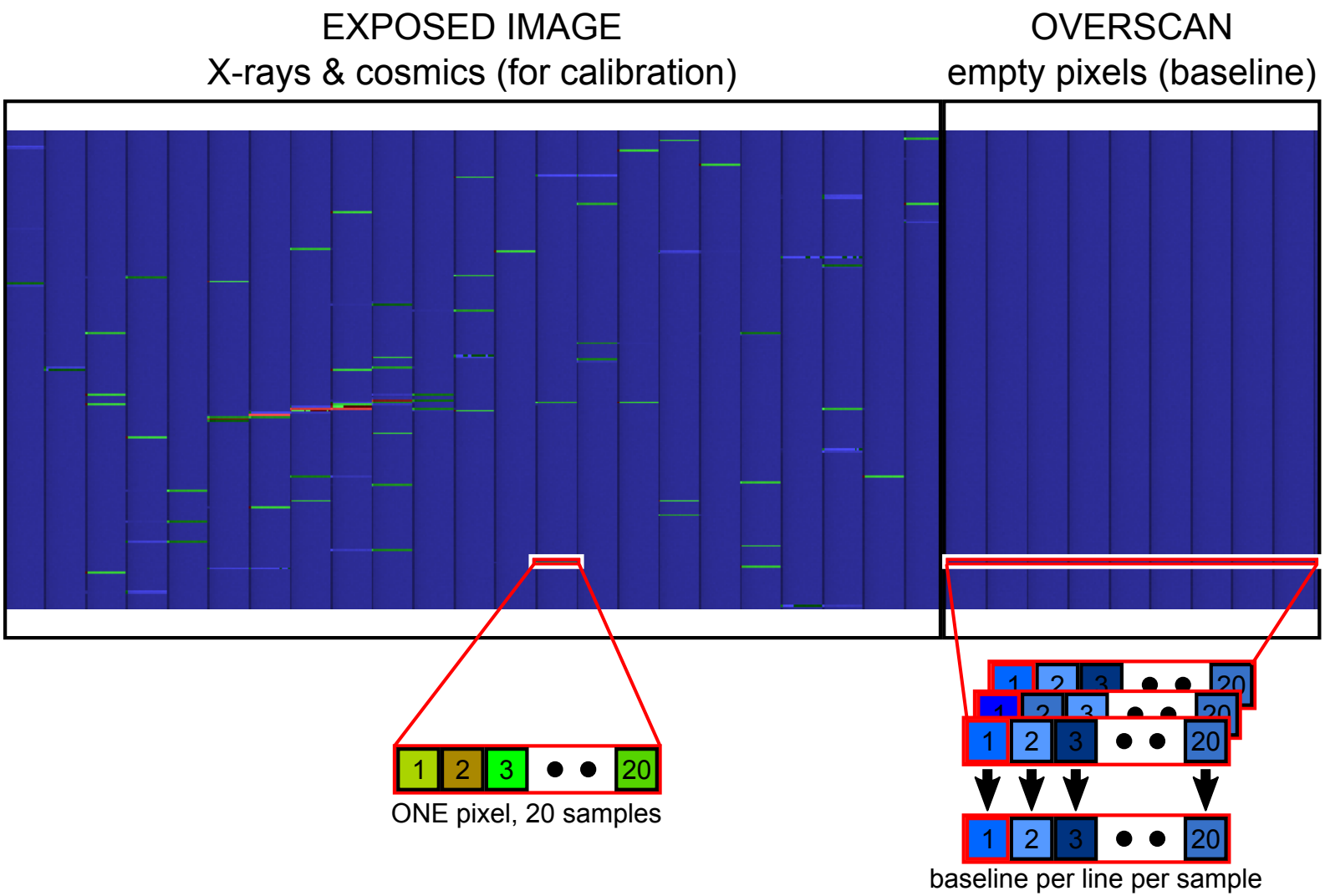
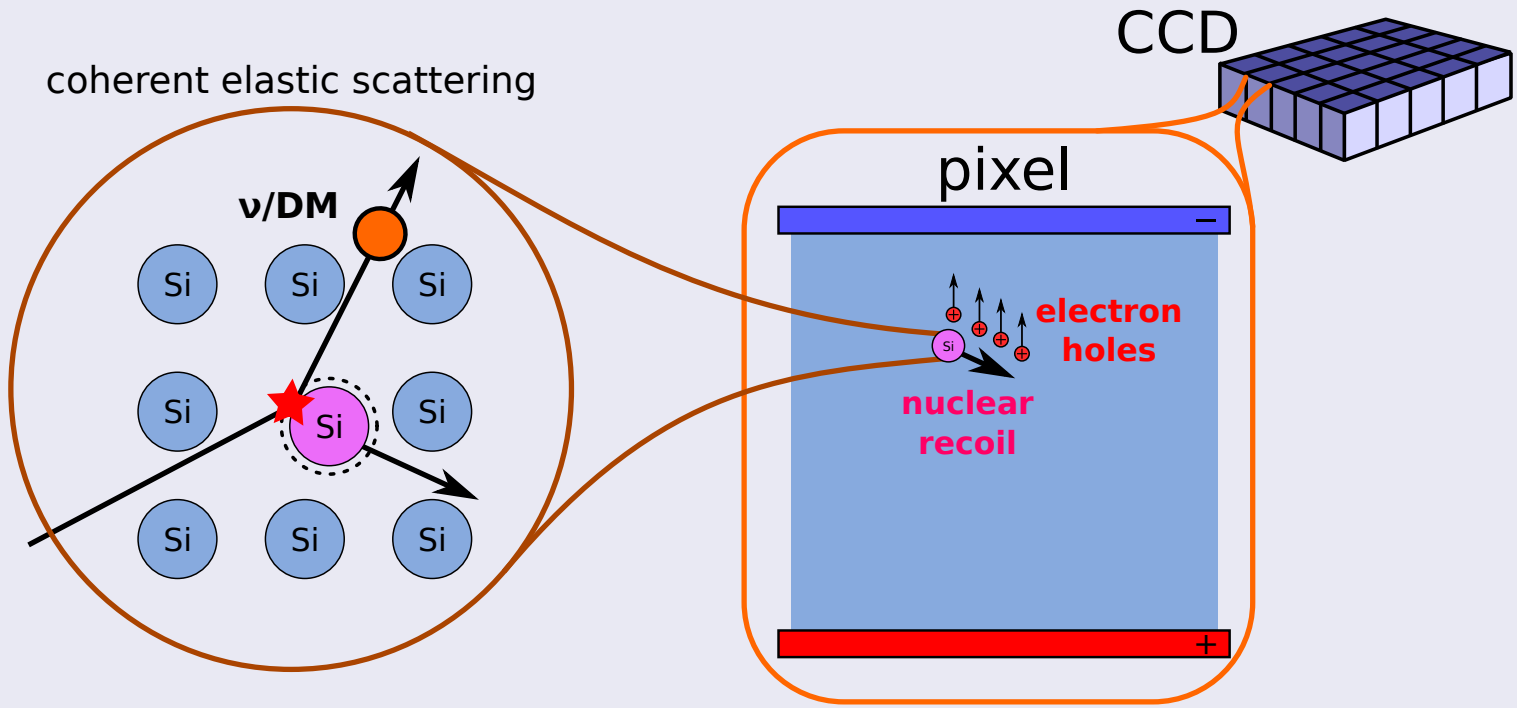


## Goal: lower the energy threshold in Si detectors

**Detect coherent DM/$\nu$-nucleus interactions by measuring the ionization produced by the nuclear recoils**

## Idea: use CCDs as target and record the ionization produced



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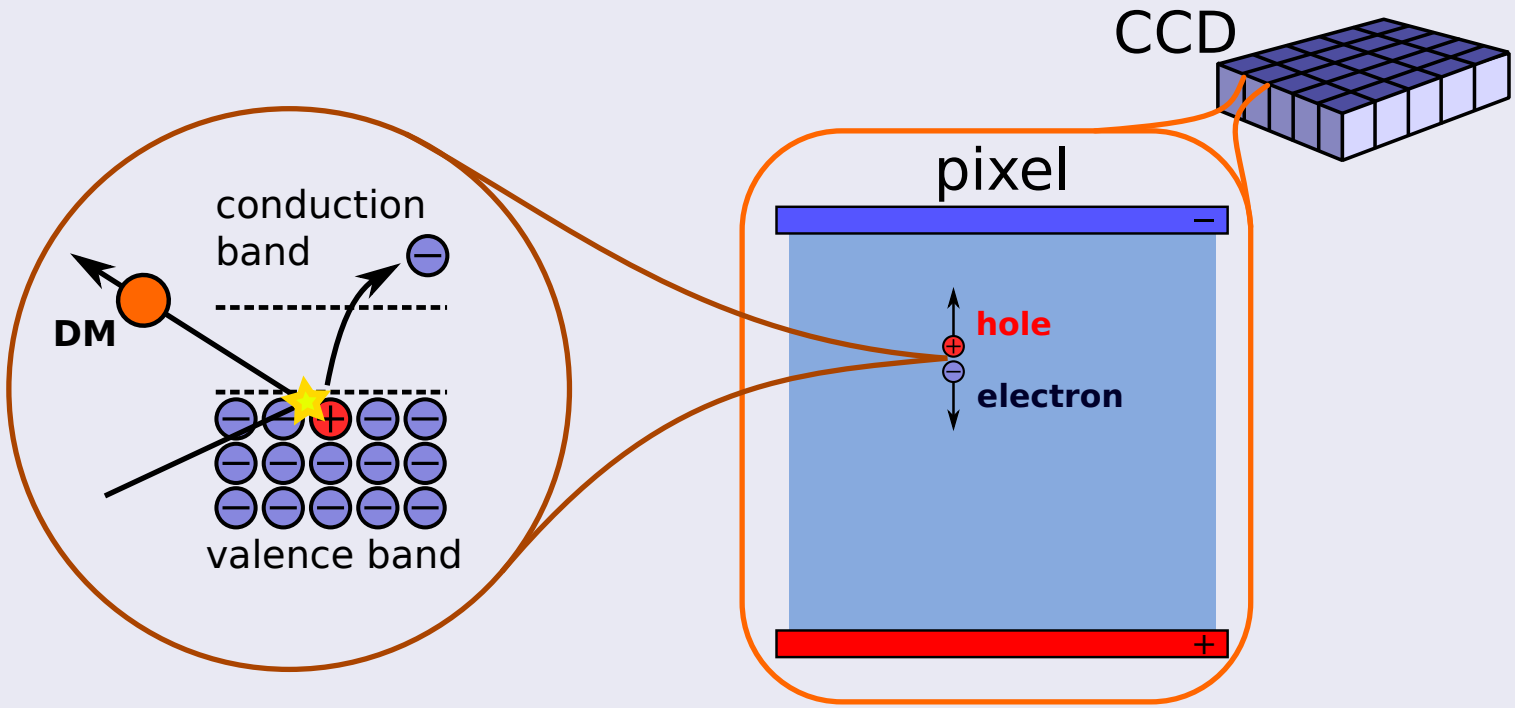
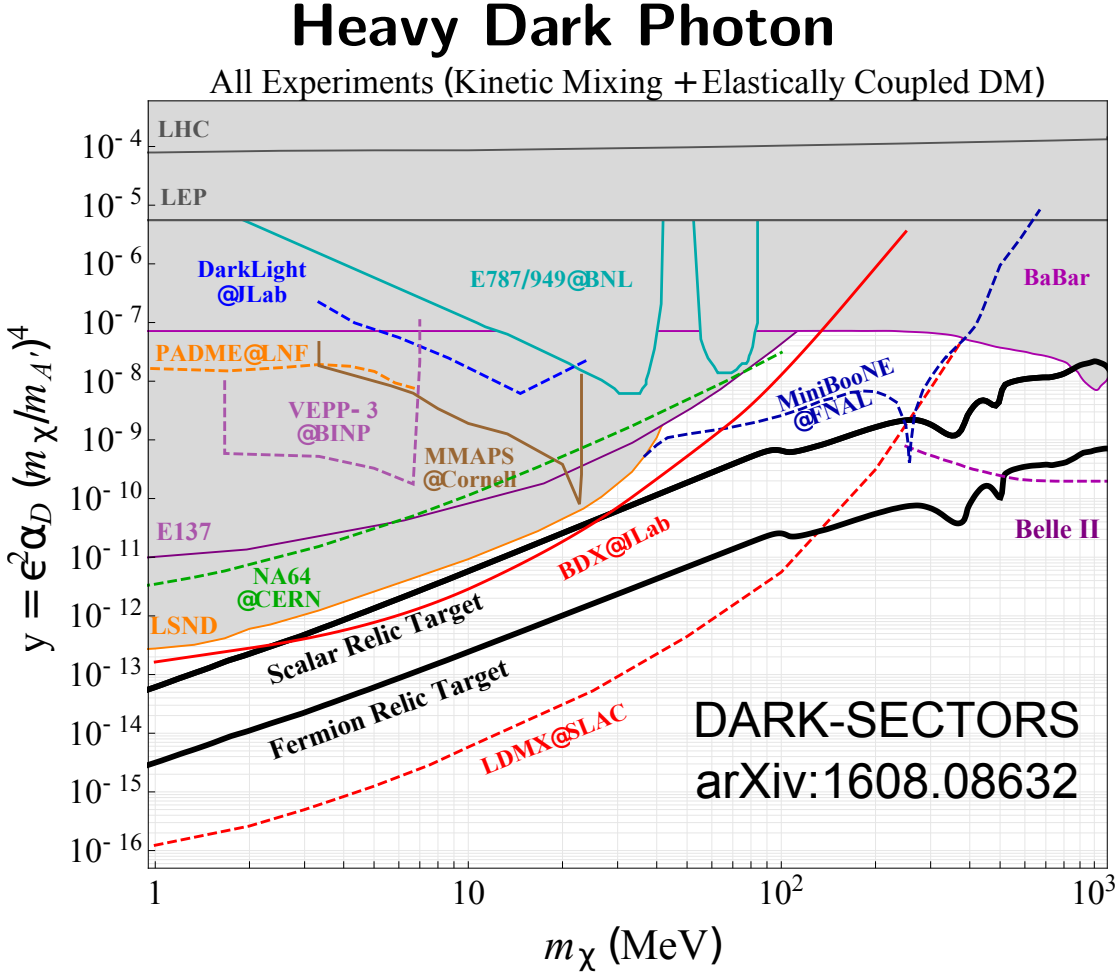


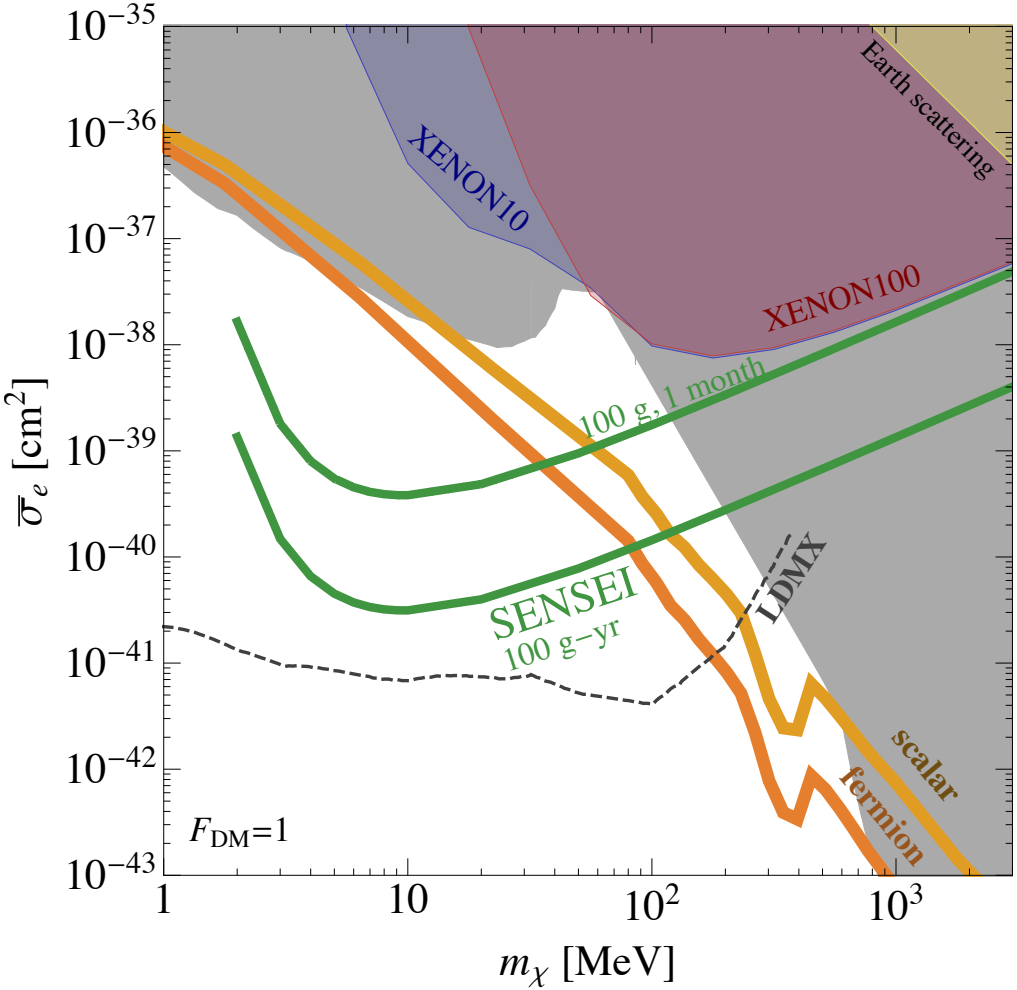
# SENSEI: reach of a 100g, *zeroish-background* experiment




$$\overline{\sigma}_e \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{m_{A'}^4}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2 \alpha \alpha_D \epsilon^2}{(\alpha m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases}, \text{and} \quad F_{DM}(q) \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}, & m_{A'} \ll \alpha m_e \end{cases}$$

# SENSEI: reach of a 100g, *zeroish-background* experiment

## Heavy Dark Photon

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