The SENSEI† project

LDRD-2016-004

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Fermi National Laboratory

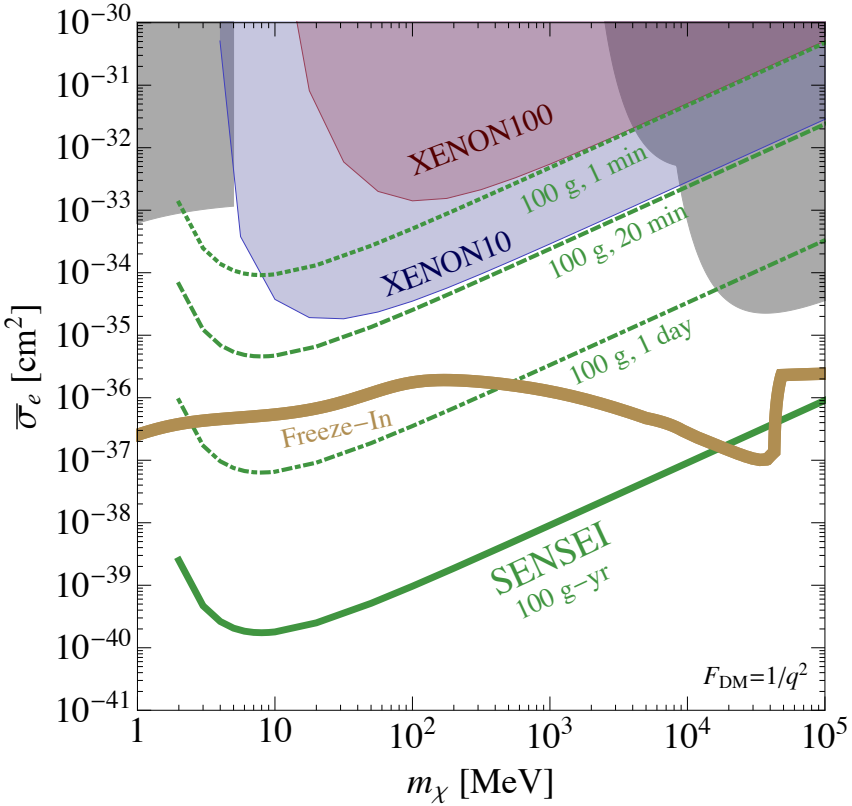
July 31, 2017

† **S**ub-**E**lectron-**N**oise **S**kipperCCD **E**xperimental **I**nstrument

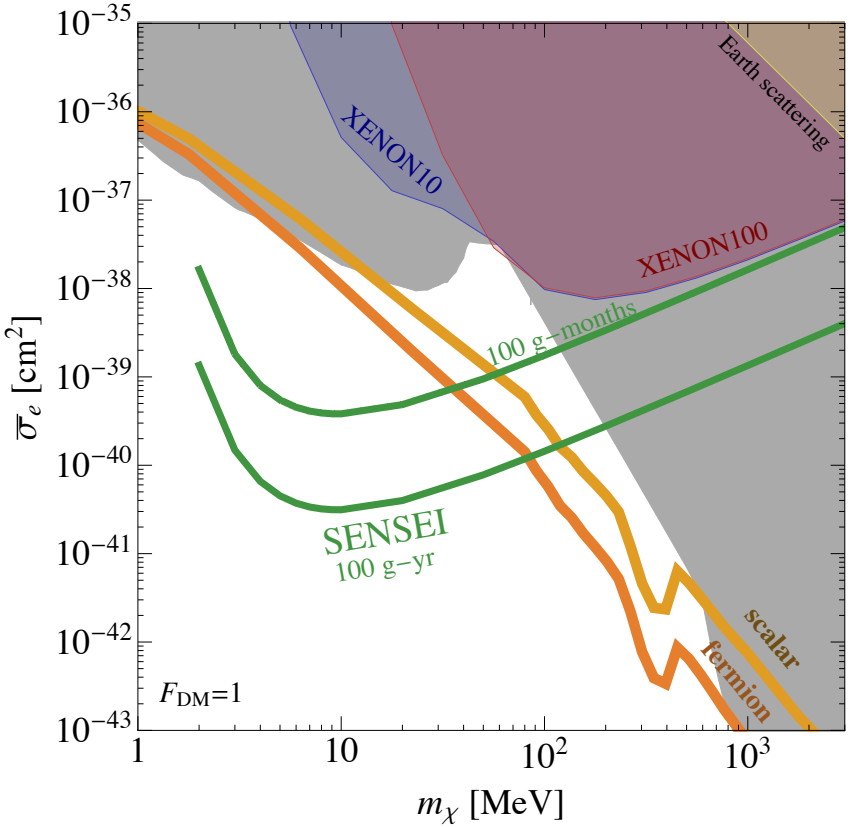
Fermilab

Motivation for SENSEI: a detector that can do this NOW

Light Dark Photon



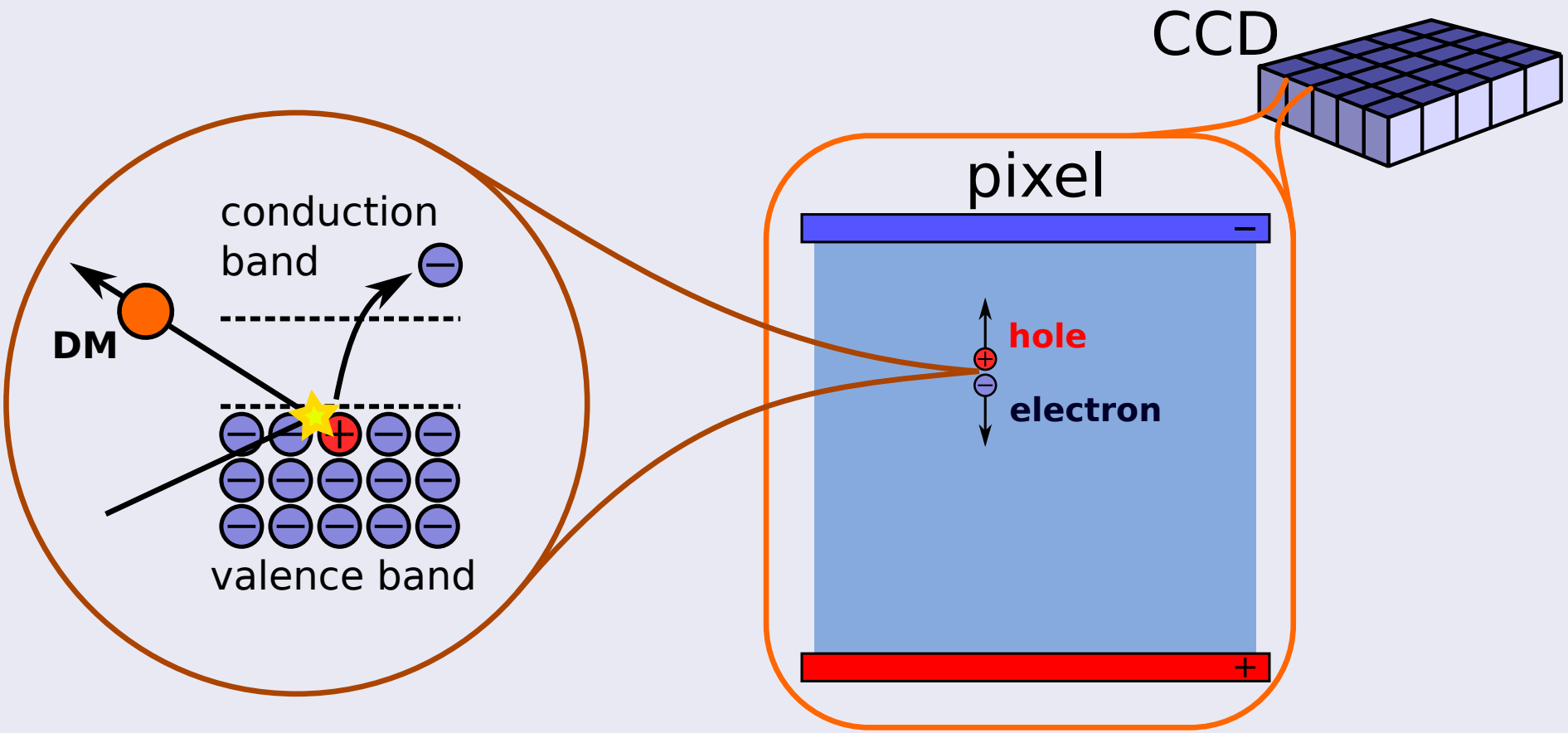
Heavy Dark Photon



Plots from: Rouven Essig, Tomer Volansky & Tien-Tien Yu.

How?

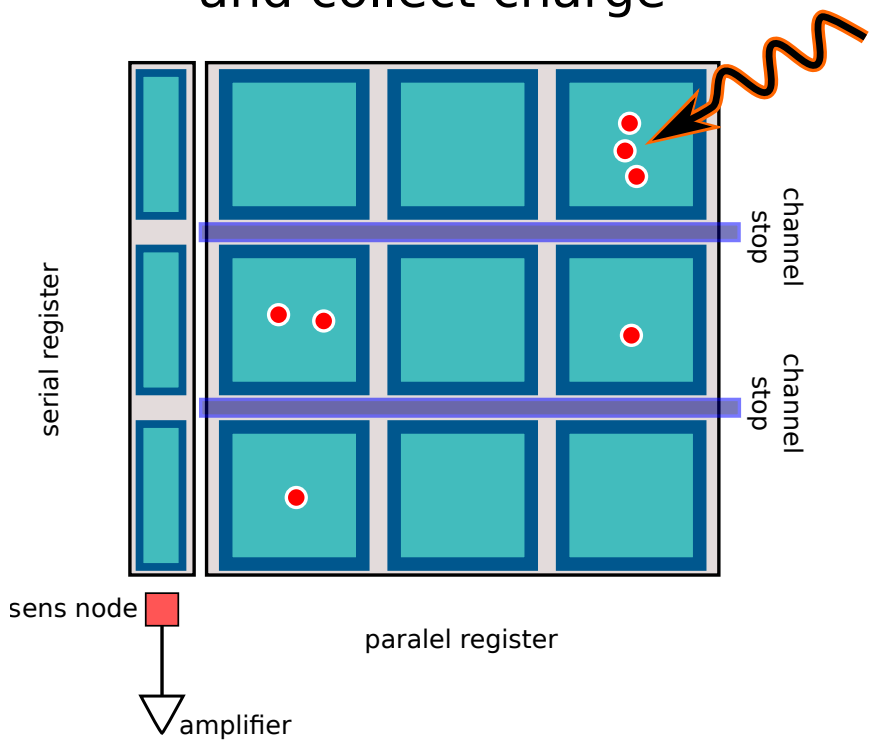
use CCDs as target to record the ionization produced by DM



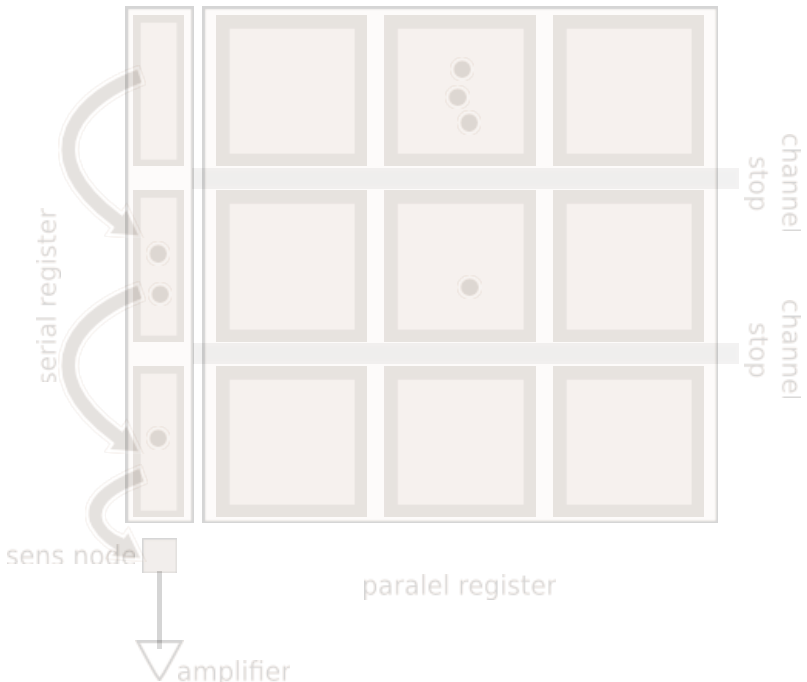
CCD: readout

3x3 pixels CCD

Expose the CCD to particles and collect charge



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



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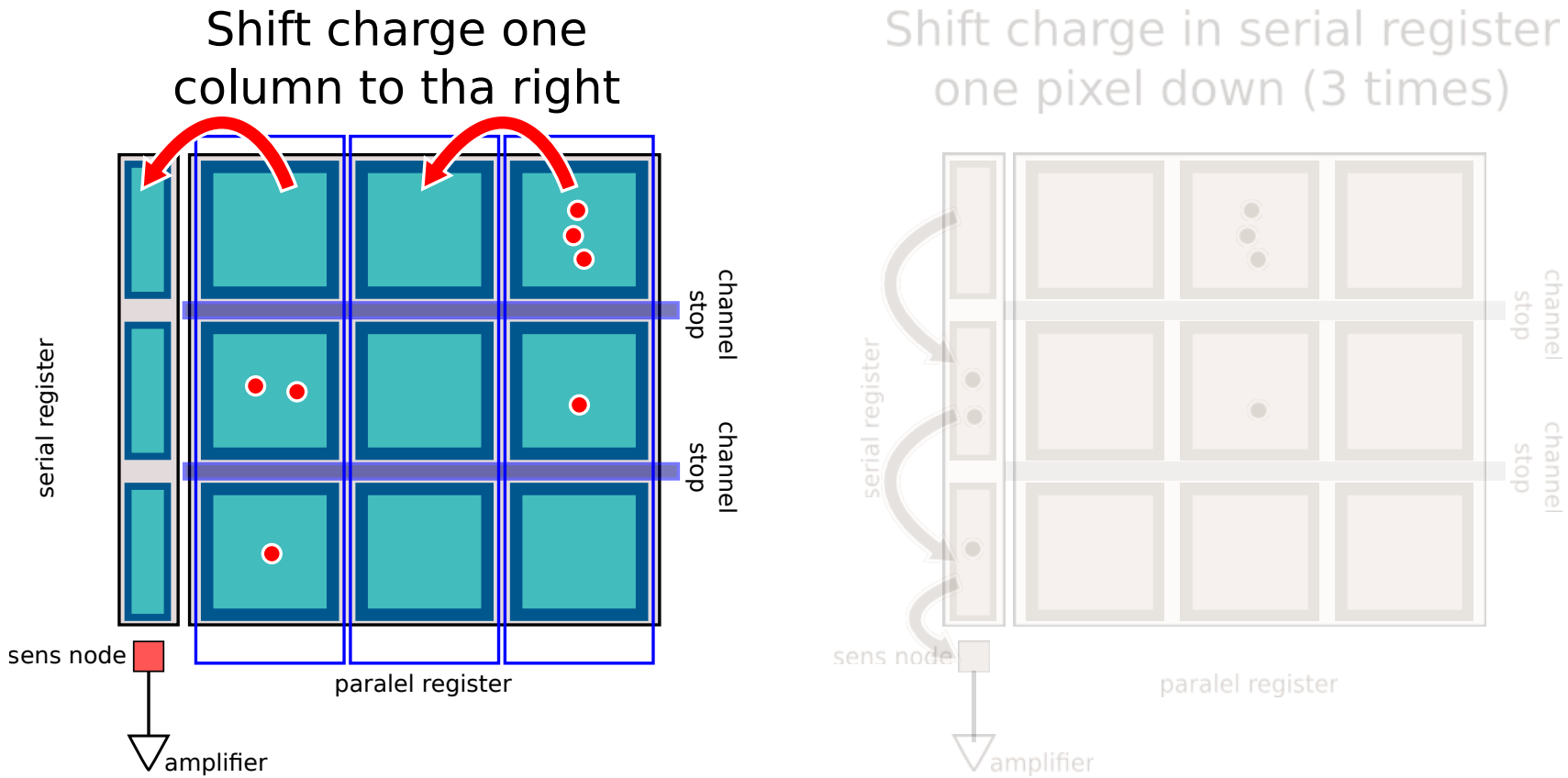
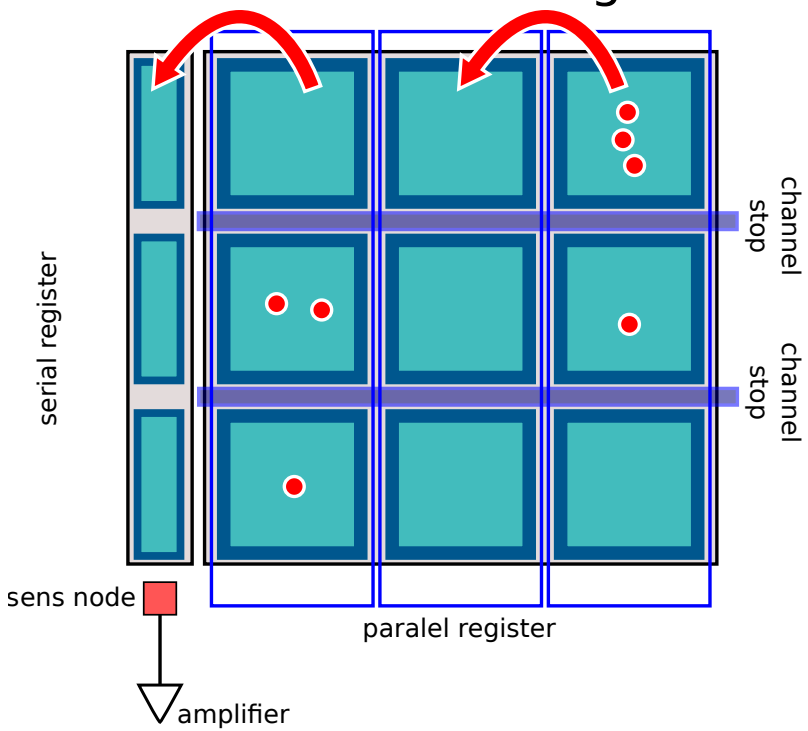


CCD: readout

3x3 pixels CCD

Shift charge one column to tha right



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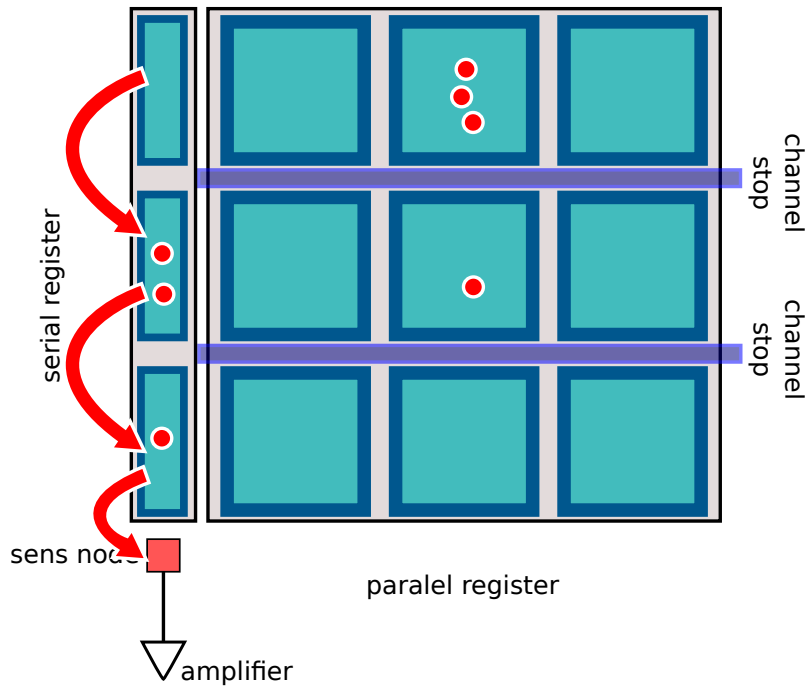
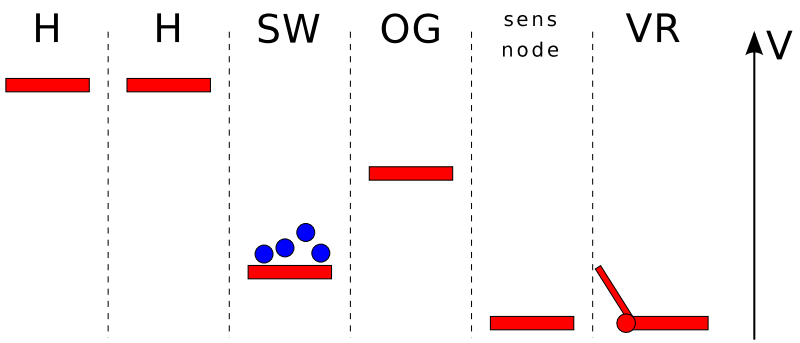
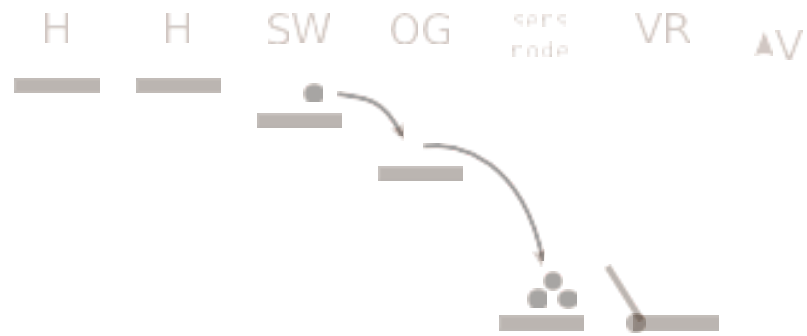


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

CCD: readout


H
H
SW
OG
sens
node
VR
V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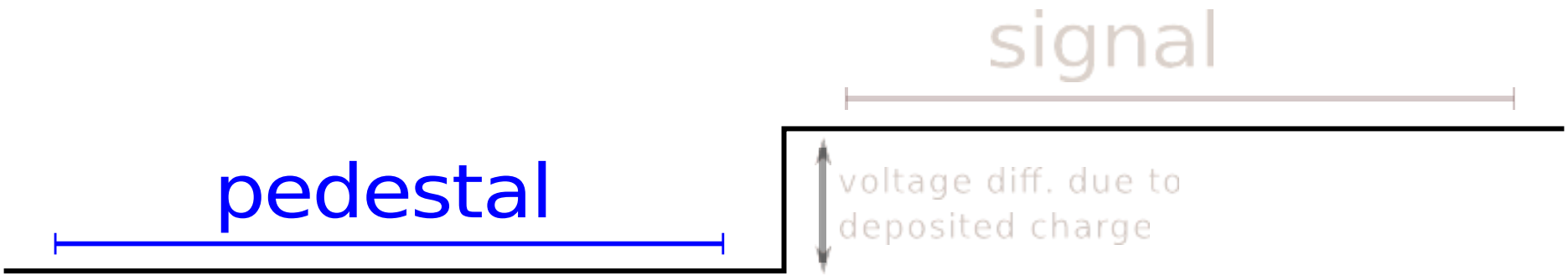
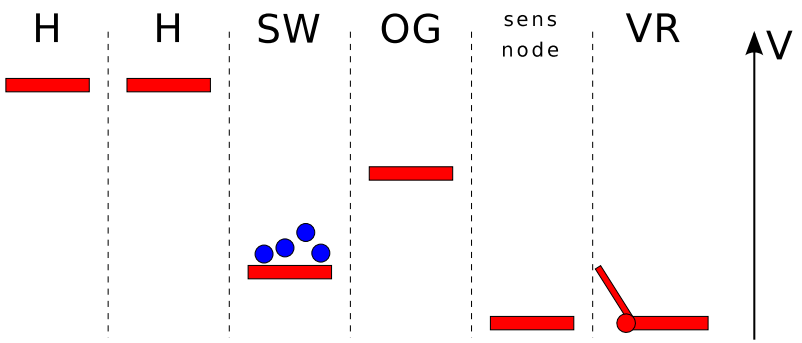

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout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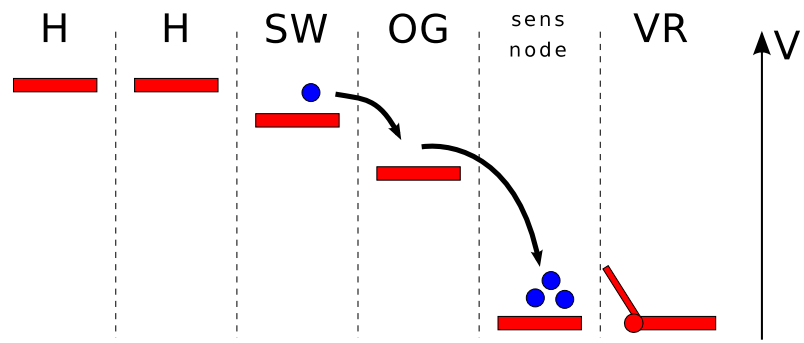
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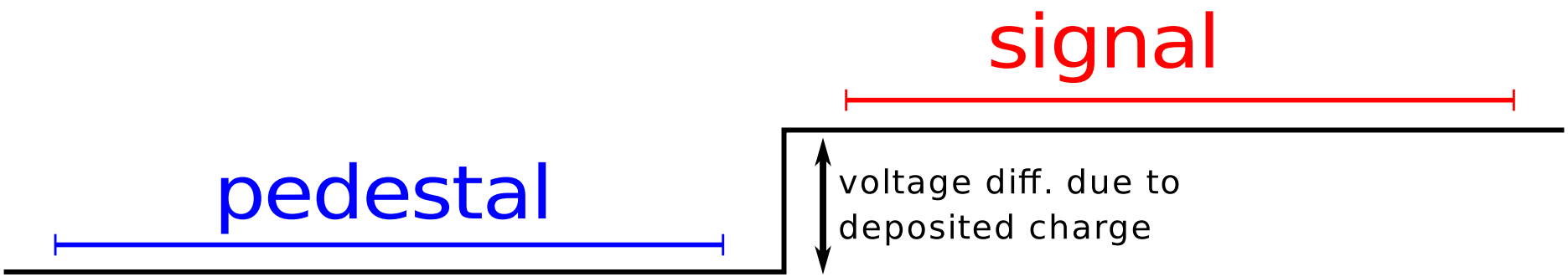
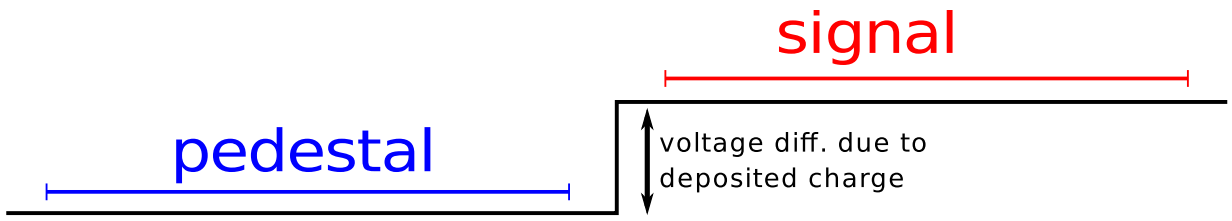
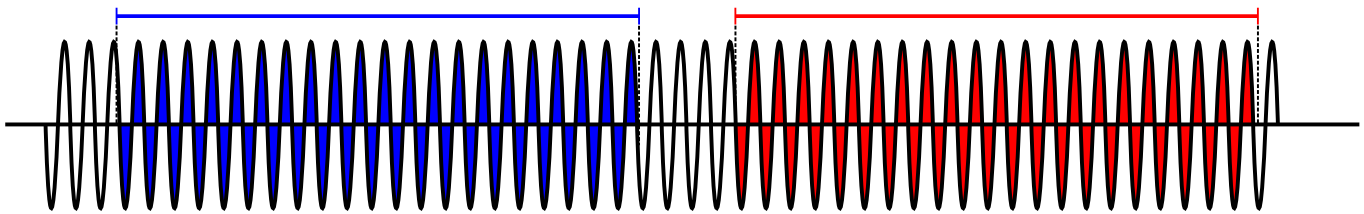

signal
pedestal
voltage diff. due to
deposited charge

CCD: readout

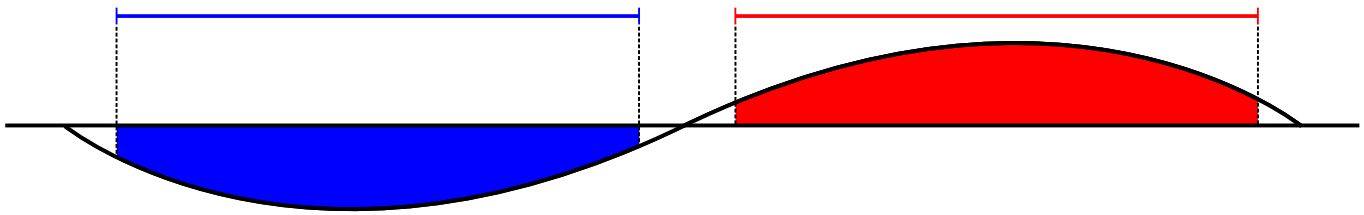
pixel charge measurement



high frequency noise

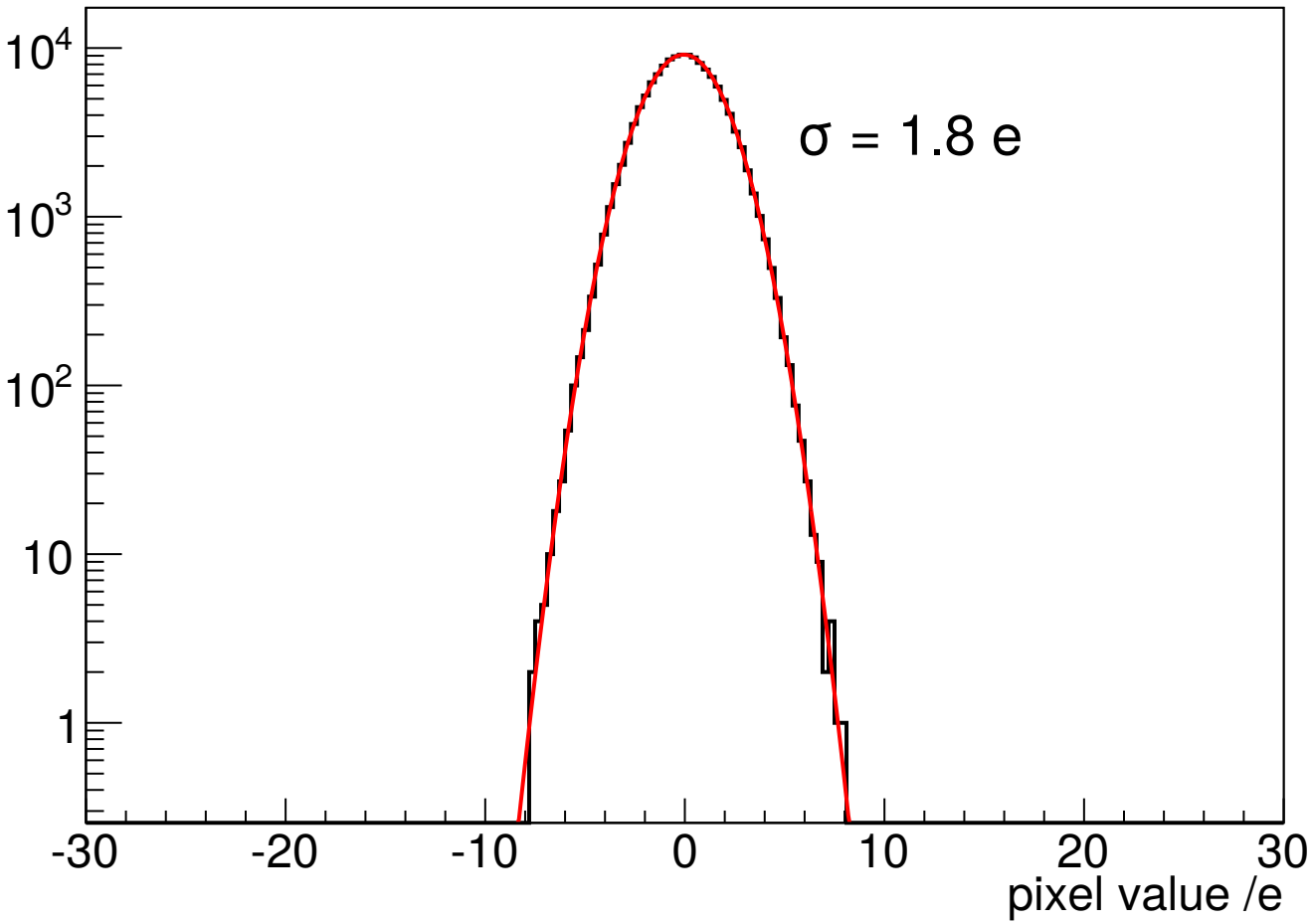


low frequency noise



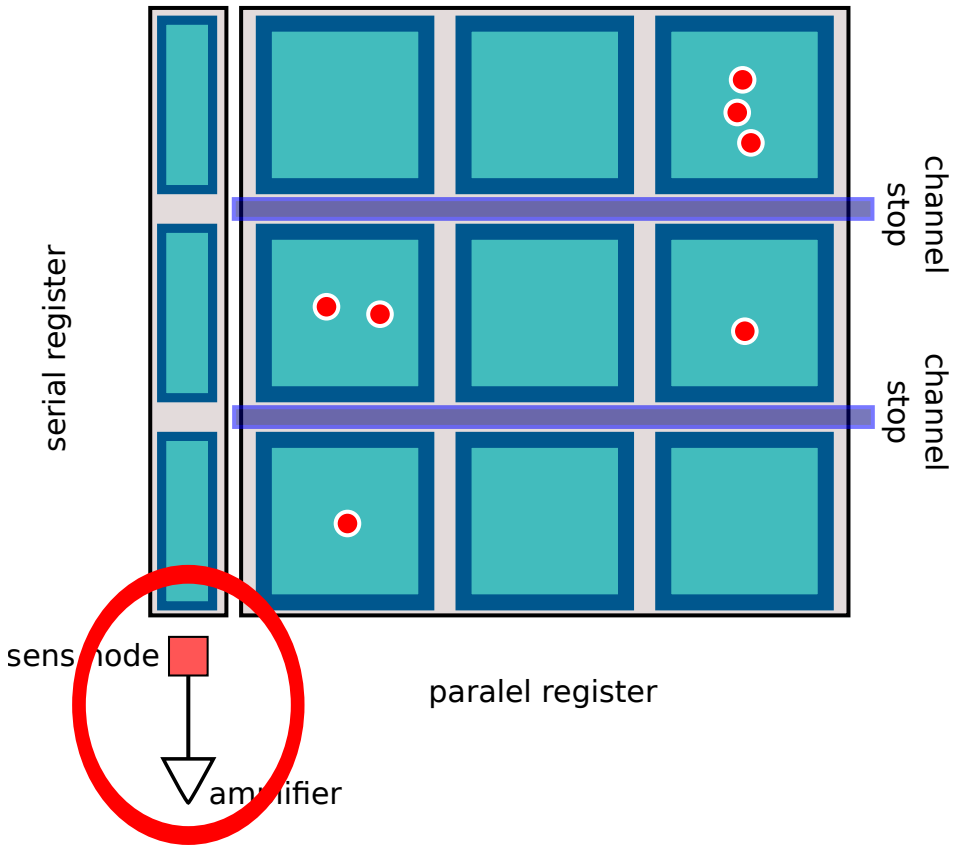
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution



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

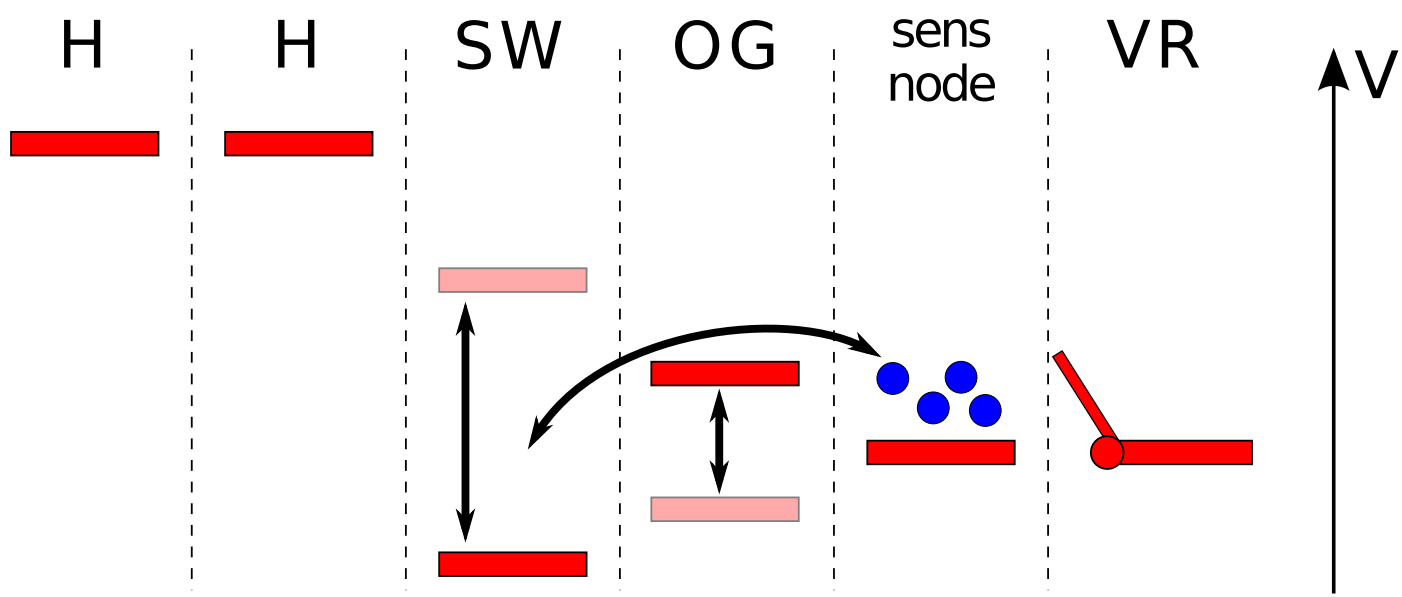
Lowering the noise: Skipper CCD



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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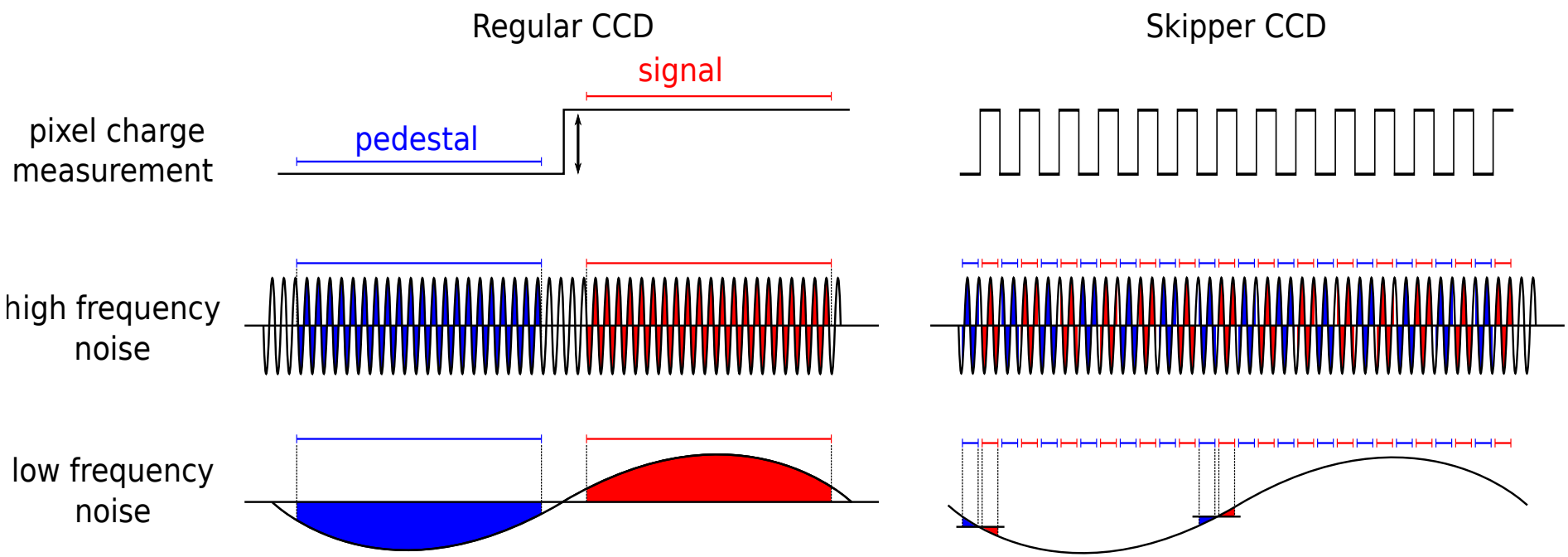


SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

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**

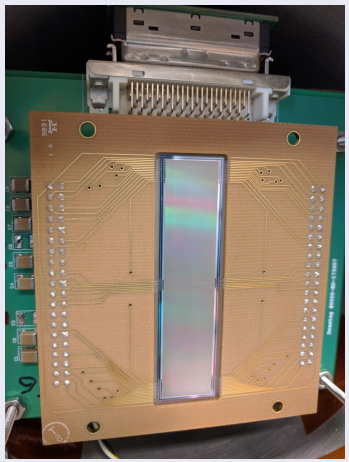
Plan

- 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).
- Validate the technology for DM and ν experiments.

Fermilab

SENSEI: First working instrument using SkipperCCD tech

Sensors



- Skipper-CCD prototype designed by **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

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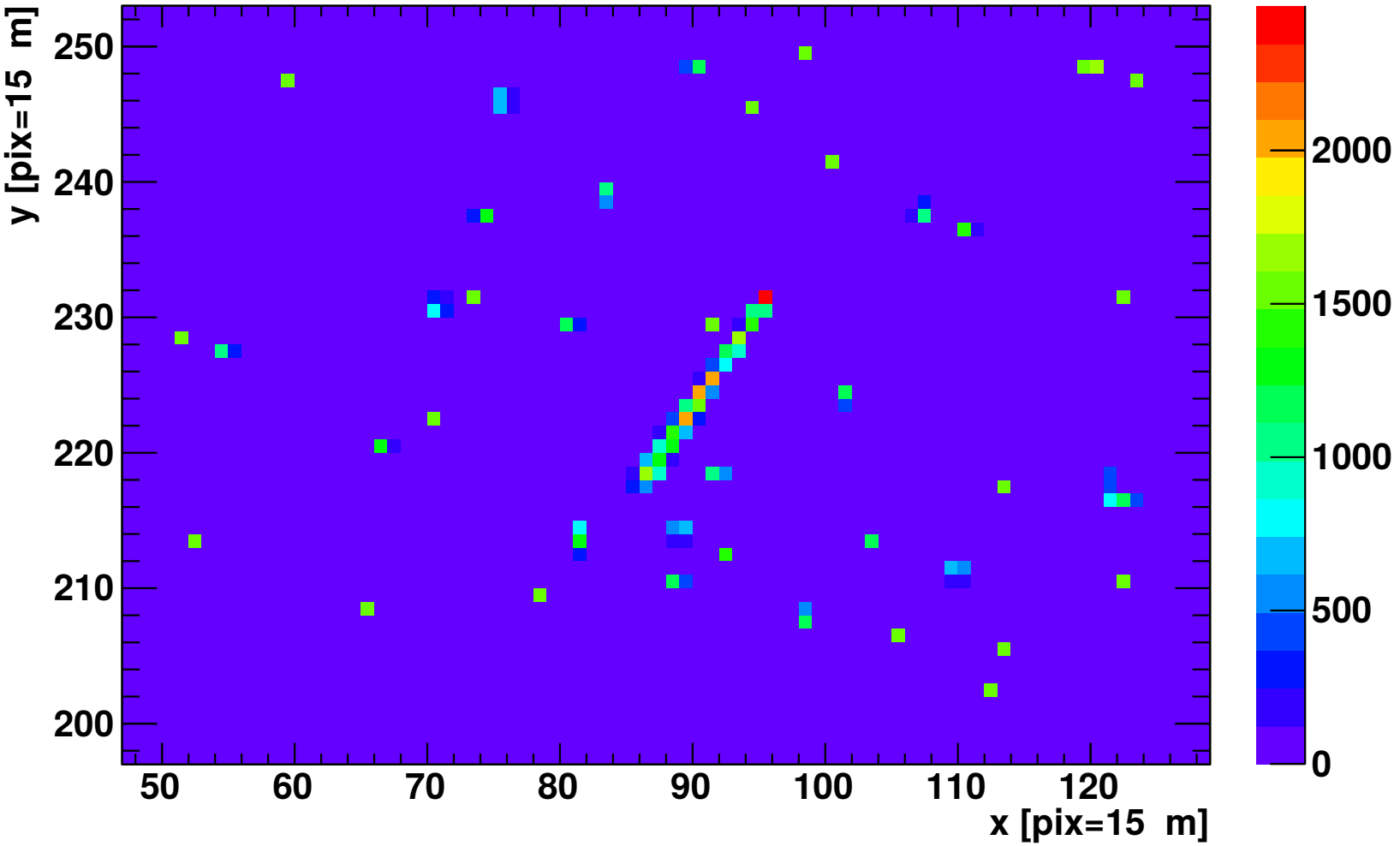
Image taken with SENSEI: 4000 samples per pixel (processed)



Fermilab

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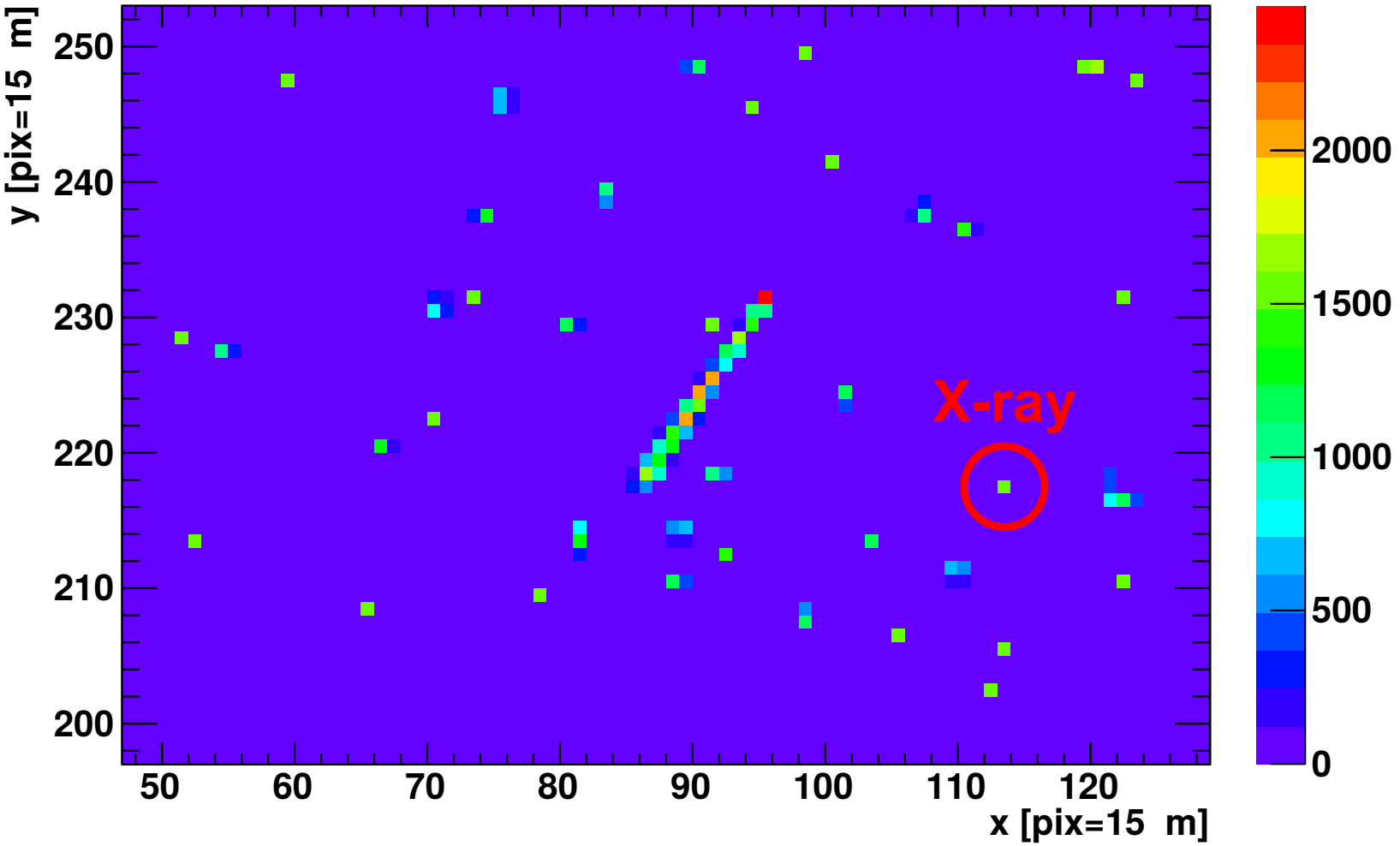

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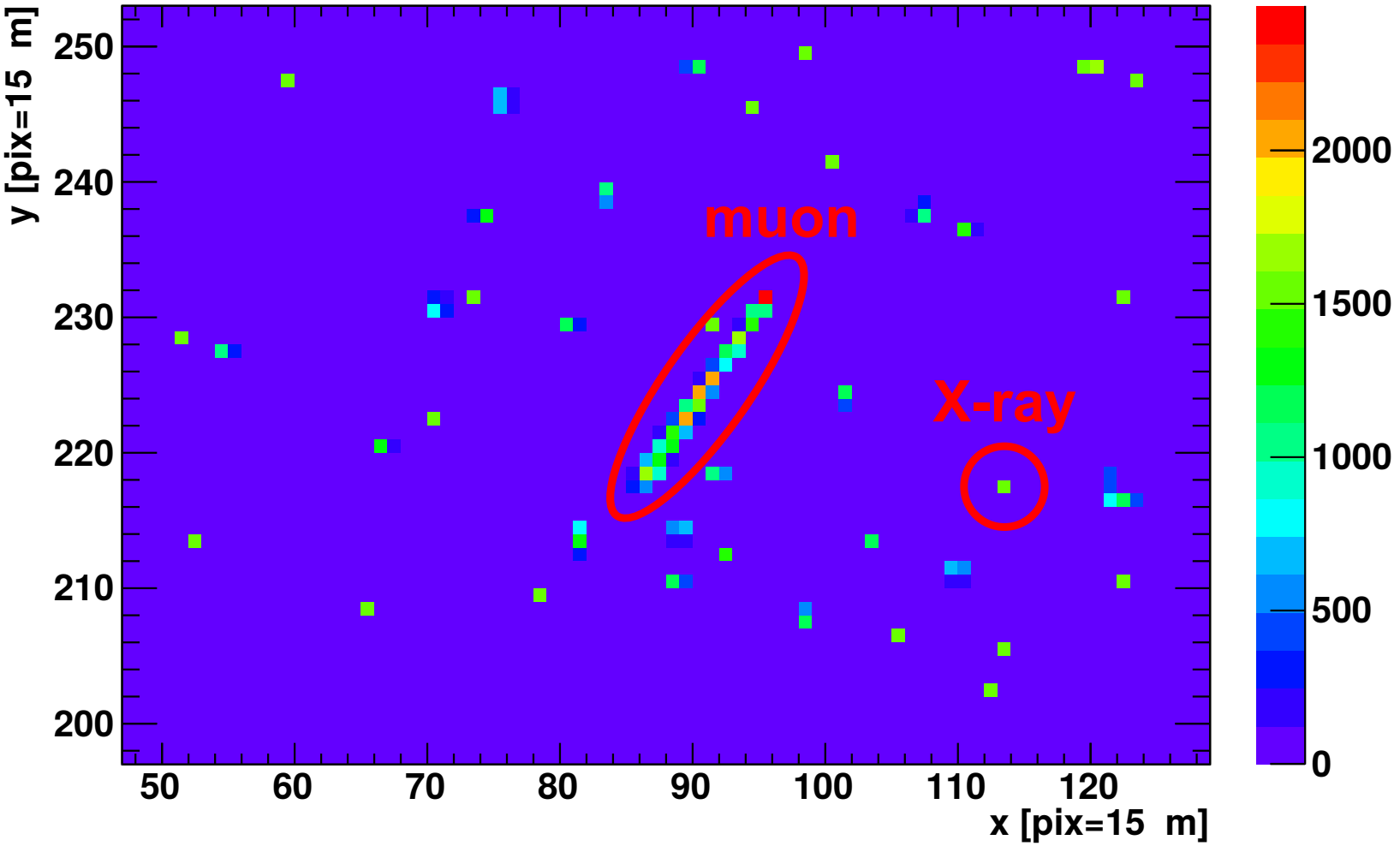

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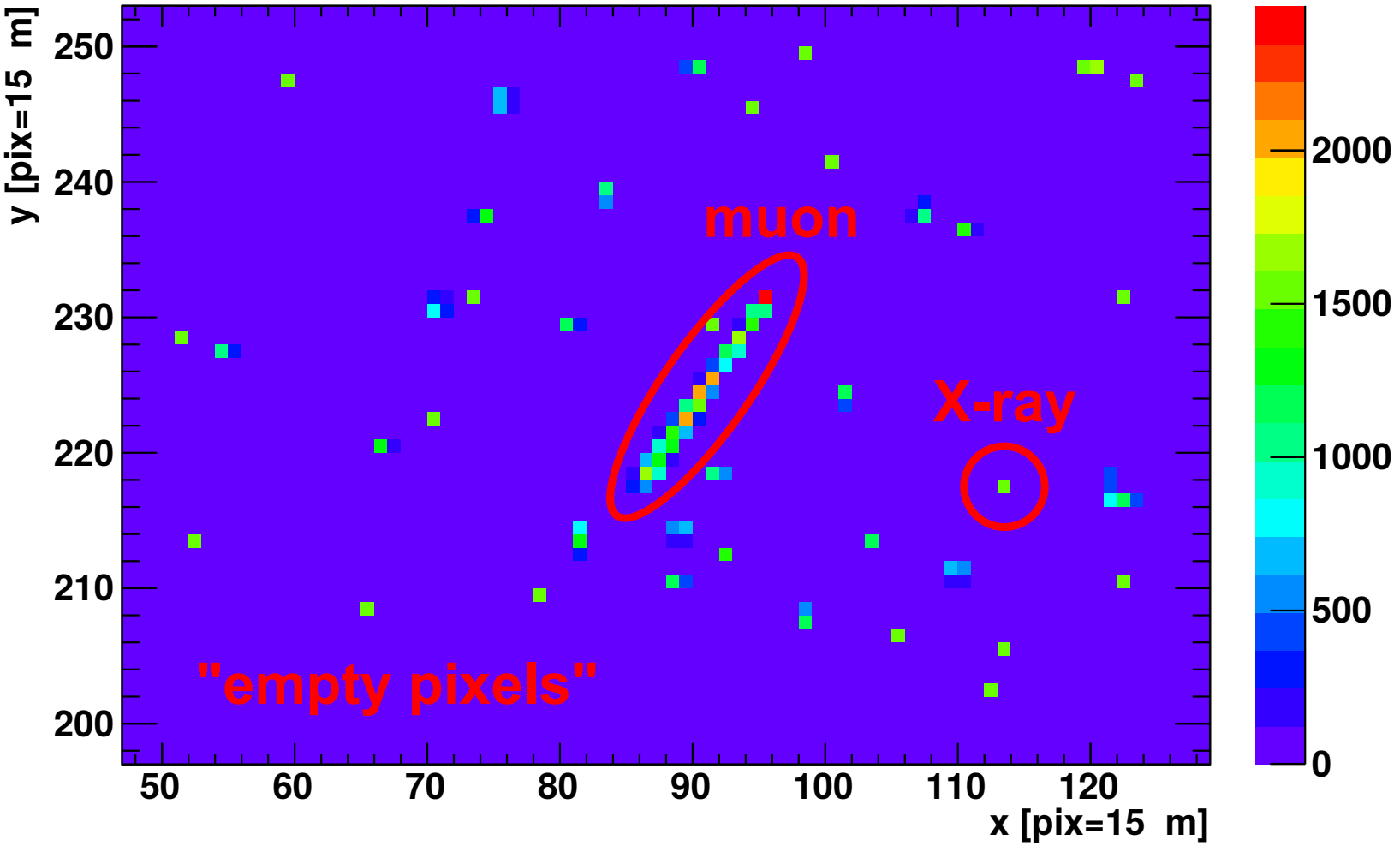
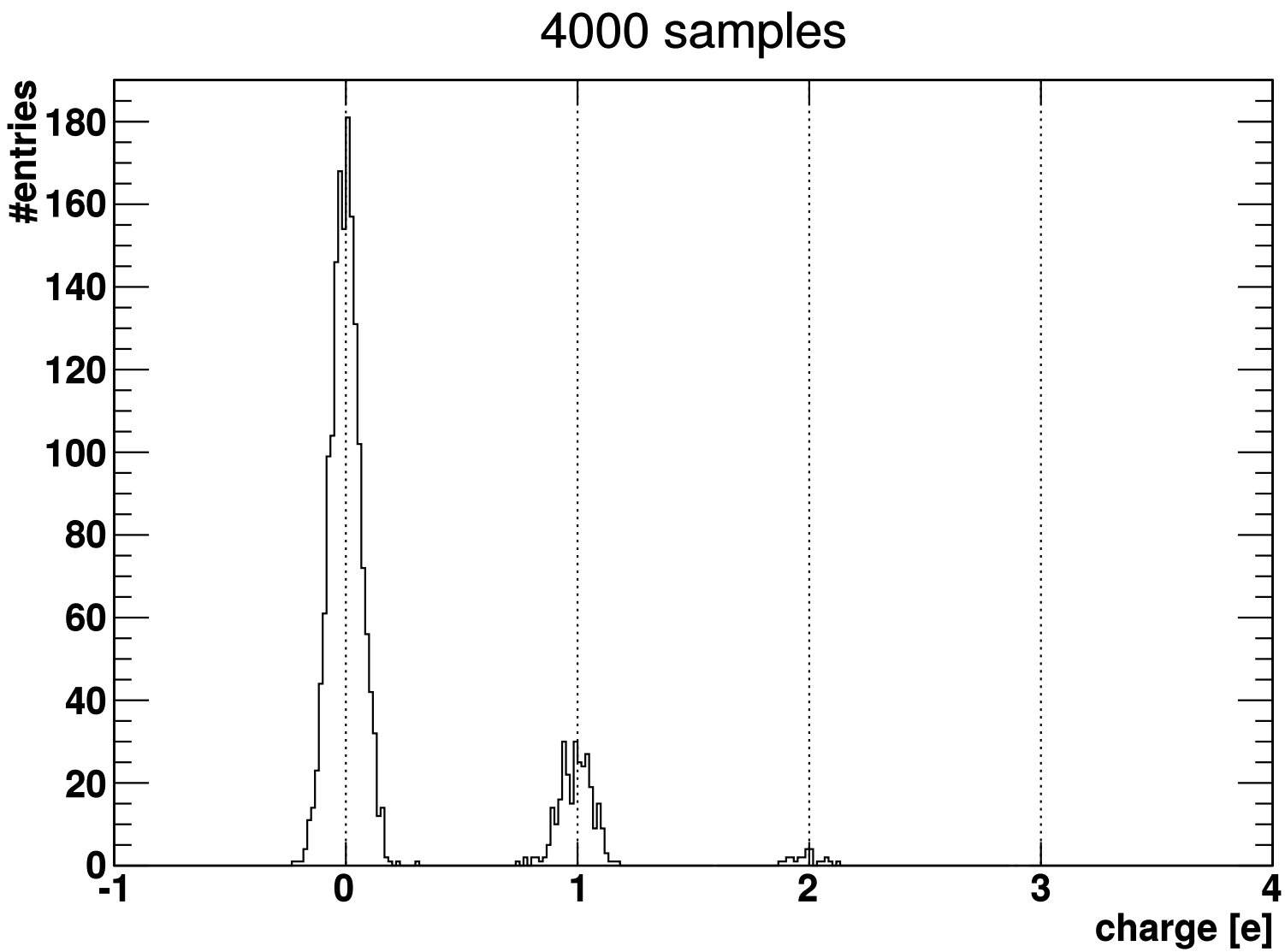


Charge in pixel distribution. Counting electrons: 0, 1, 2..



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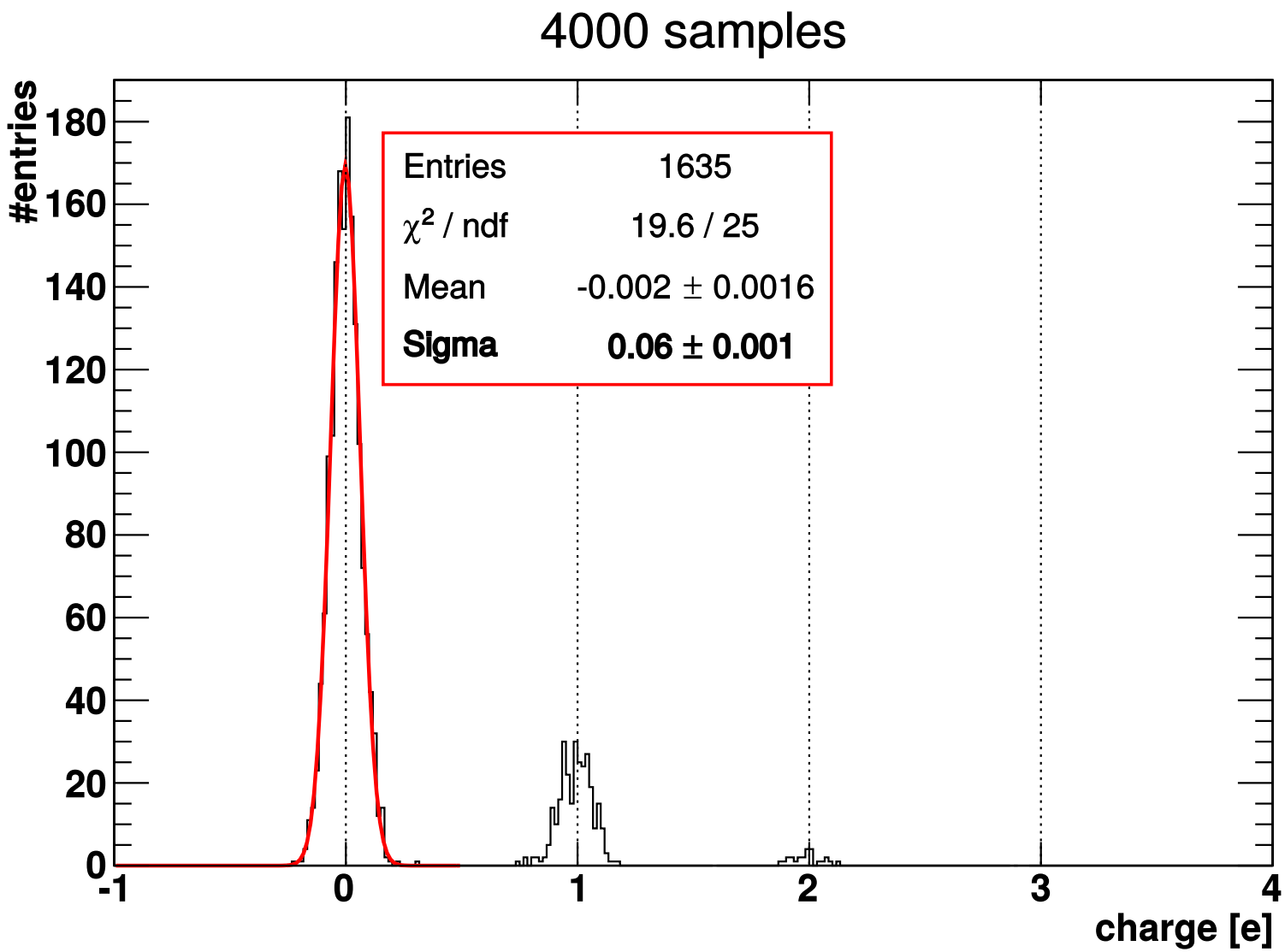
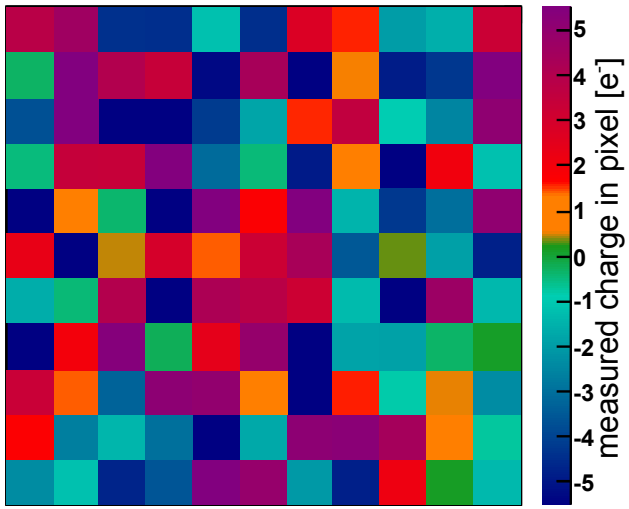
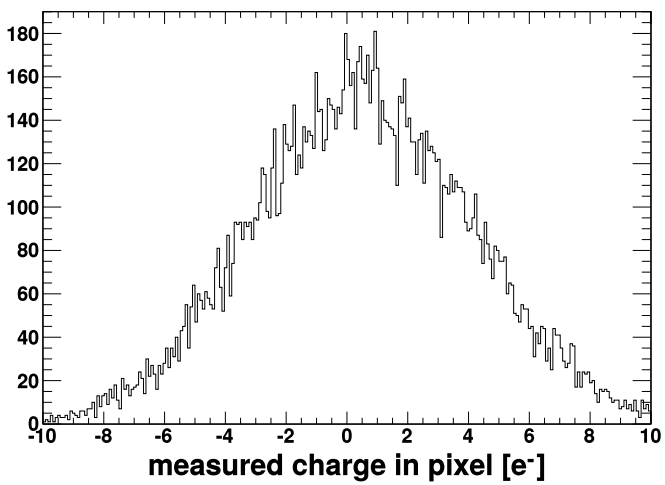


Counting electrons: 0, 1, 2..

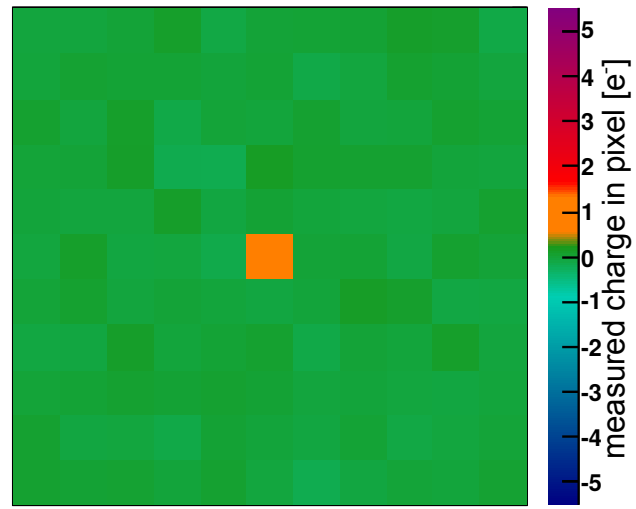
Standard CCD mode: charge in each pixel is measured once



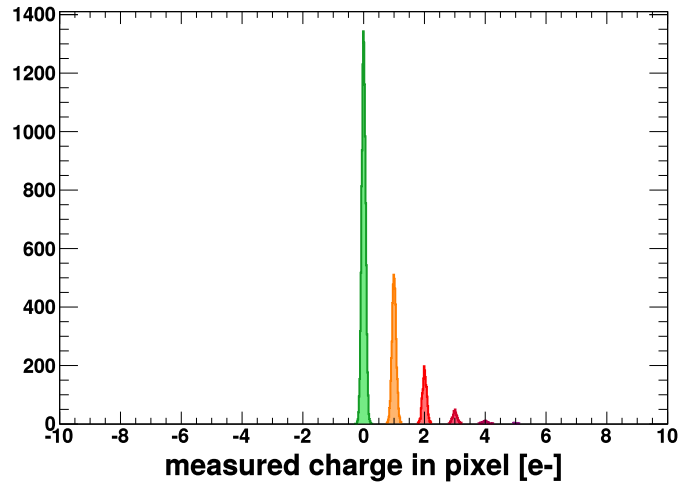
Readout-noise: 3.5 e RMS



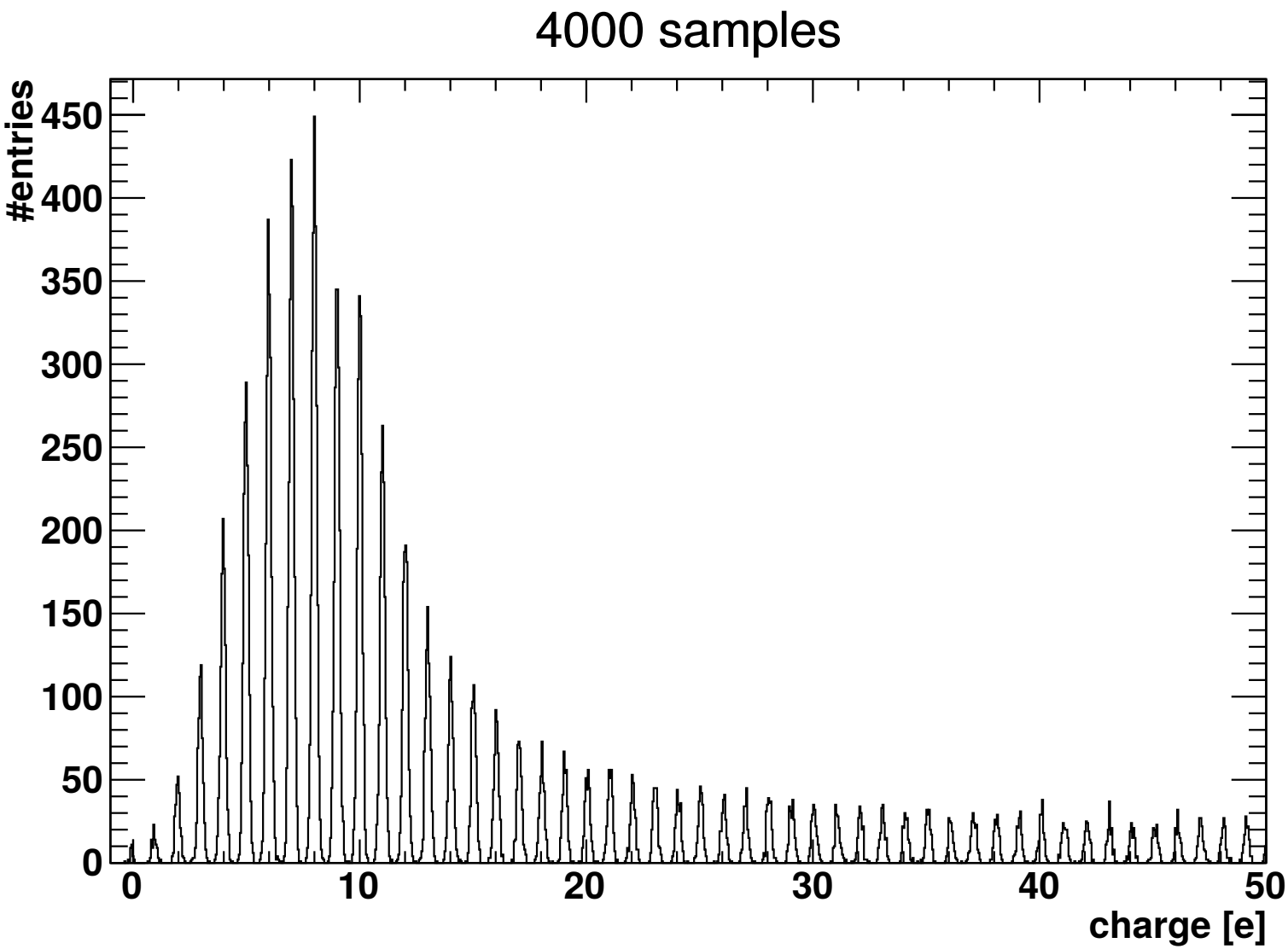
New Skipper CCD: charge in each pixel is measured multiple times



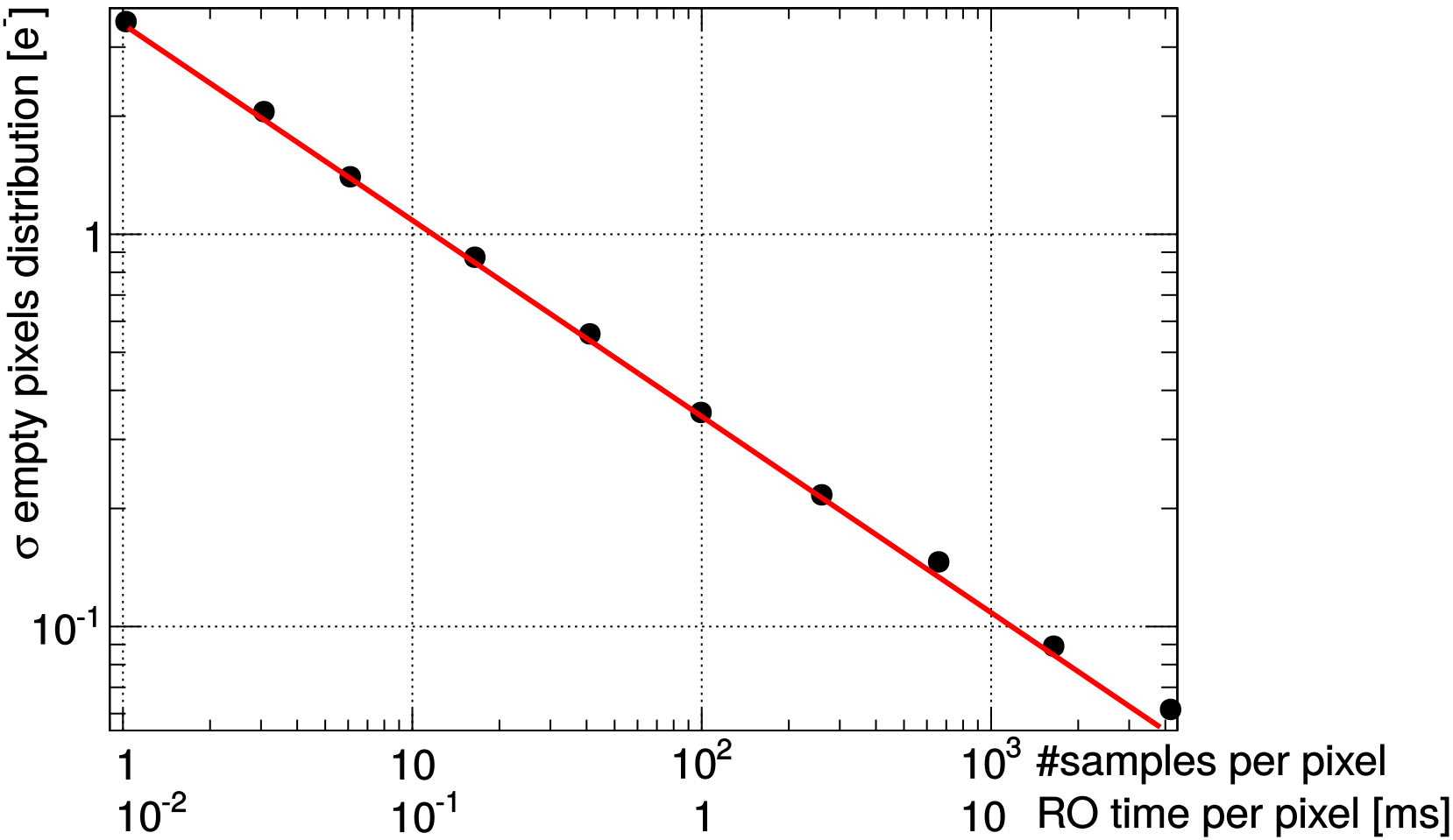
Readout-noise: 0.06 e RMS



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



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



SENSEI: DM search operation mode

- Counting electrons $\Rightarrow$ **noise has zero impact**
- It can take about 1h to read the sensors
- **Dark Current is the limiting factor**

It's better to readout continuously to minimize the impact of the DC

Dark Current $[e^- pix^{-1} day^{-1}]$	$\geq$ **1e$^-$** **[pix]**	$\geq$ **2e$^-$** **[pix]**	$\geq$ **3e$^-$** **[pix]**
10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

Measured upper limit for the DC in CCDs is:

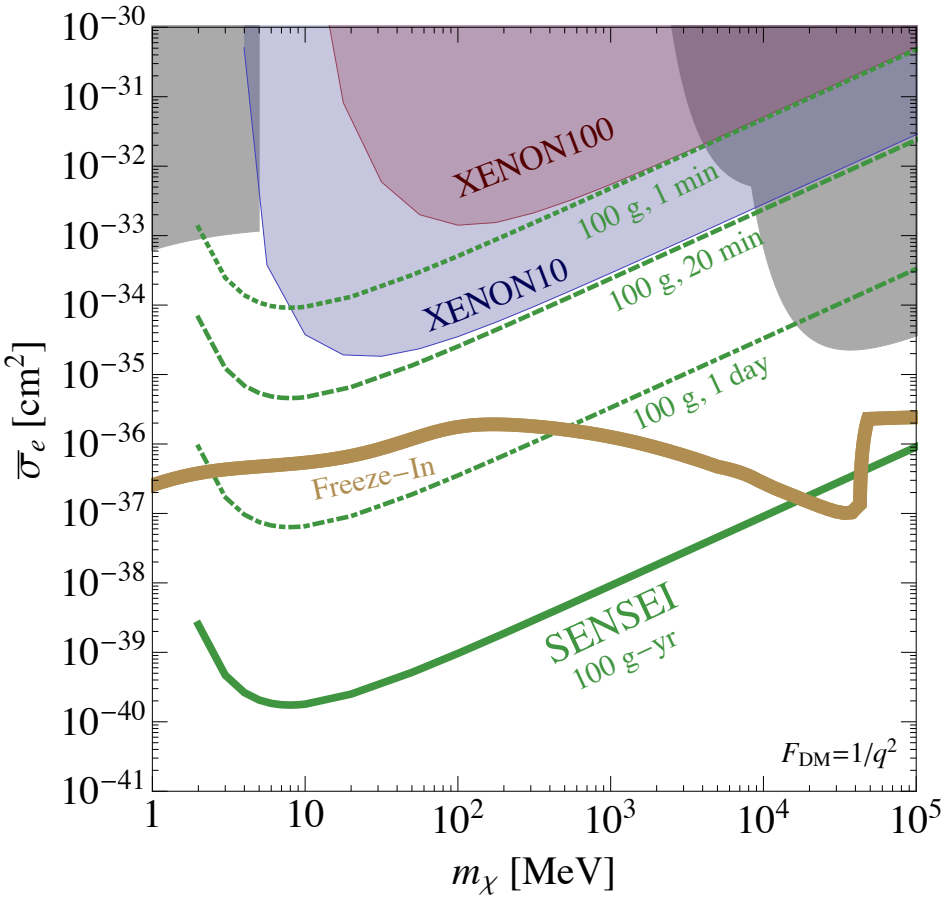
$$1 \times 10^{-3} \text{ e pix}^{-1}\text{day}^{-1}$$ arXiv:1611.03066

Could be orders of magnitude lower. **Theoretical prediction is O(10^{-7})**

Fermilab

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

Light Dark Photon



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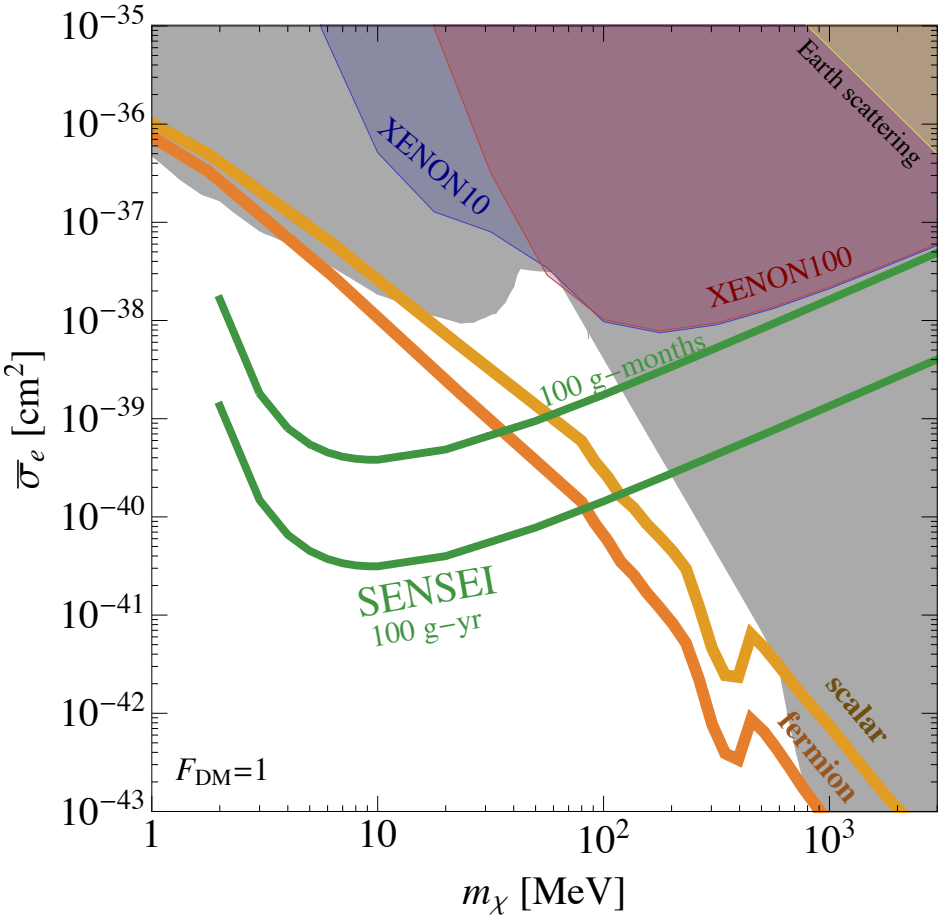
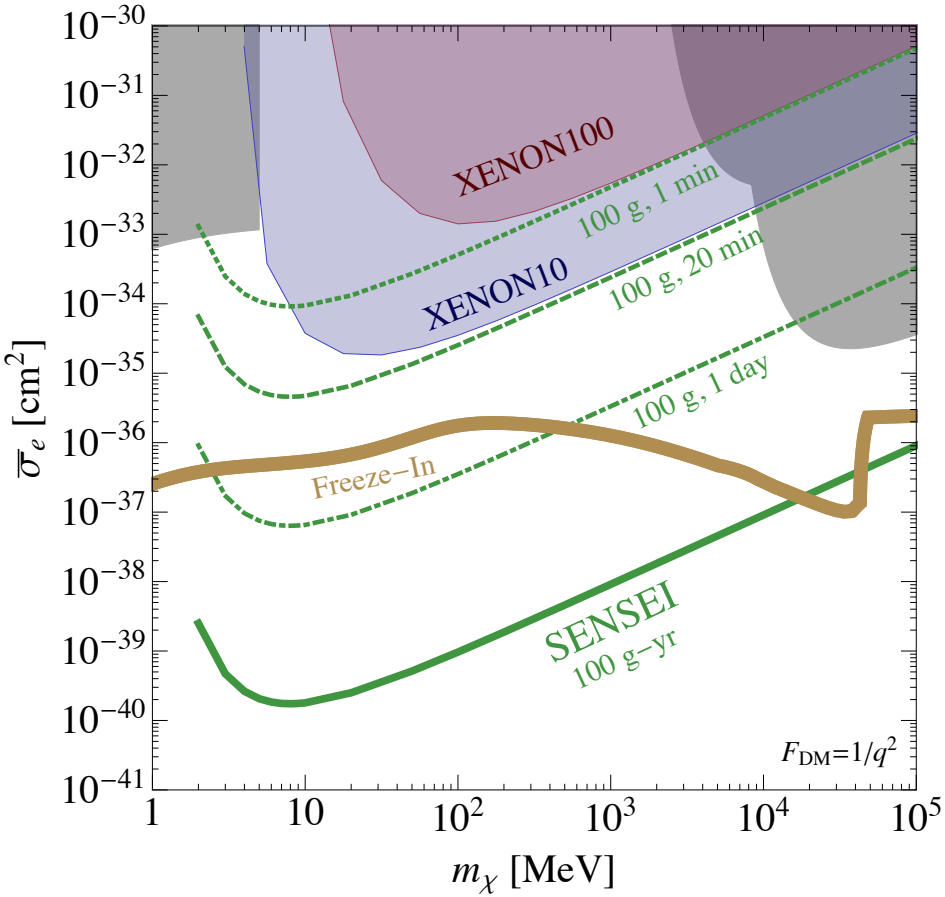
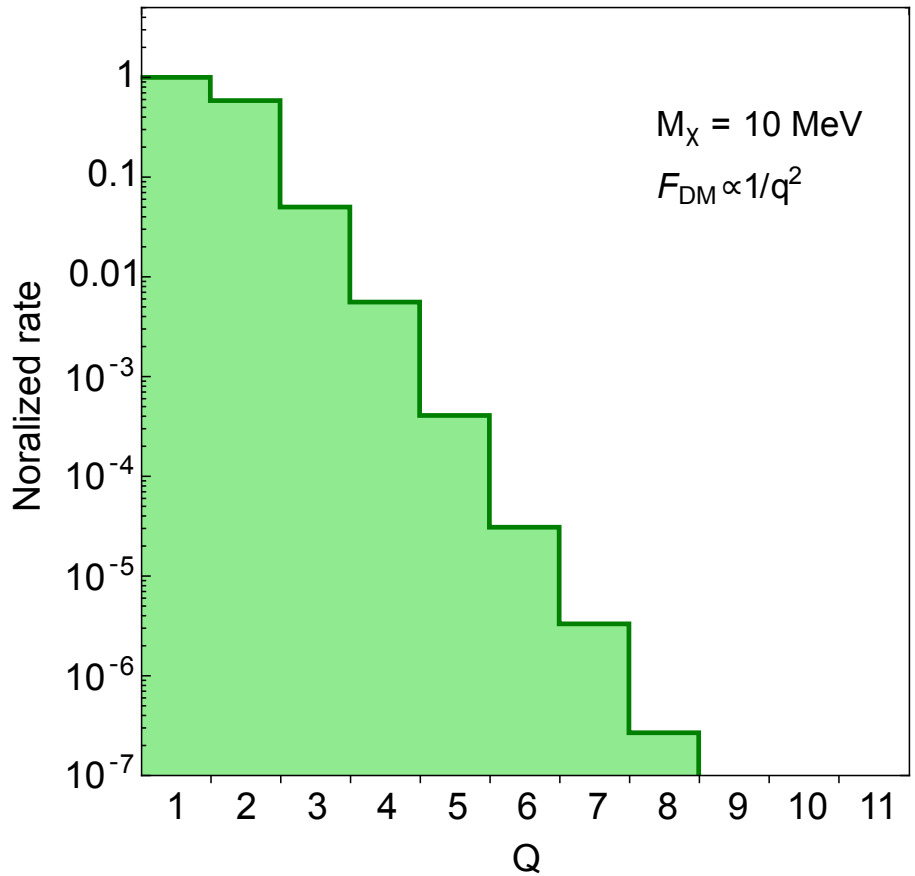


SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin





Rouven Essig, Tomer Volansky & Tien-Tien Yu.

SENSEI: electron recoil background requirements

Back of the envelope calculation

A 100g detector that takes data for one year $\rightarrow$ **Expo = 36.5kg · day**

Assuming same background as in DAMIC:

- **5 DRU** (events·kg^{-1}·day^{-1}·keV^{-1}) in the 0-1keV range
  $\rightarrow$ $\mathbf{N_{bkg}}$ **= 36.5** kg · day $\times$ **5** DRU **= 182.5** events
- Dominated by external gammas $\rightarrow$ **flat Compton spectrum**

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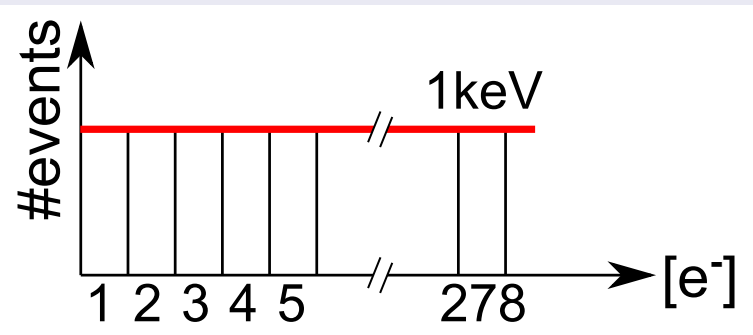
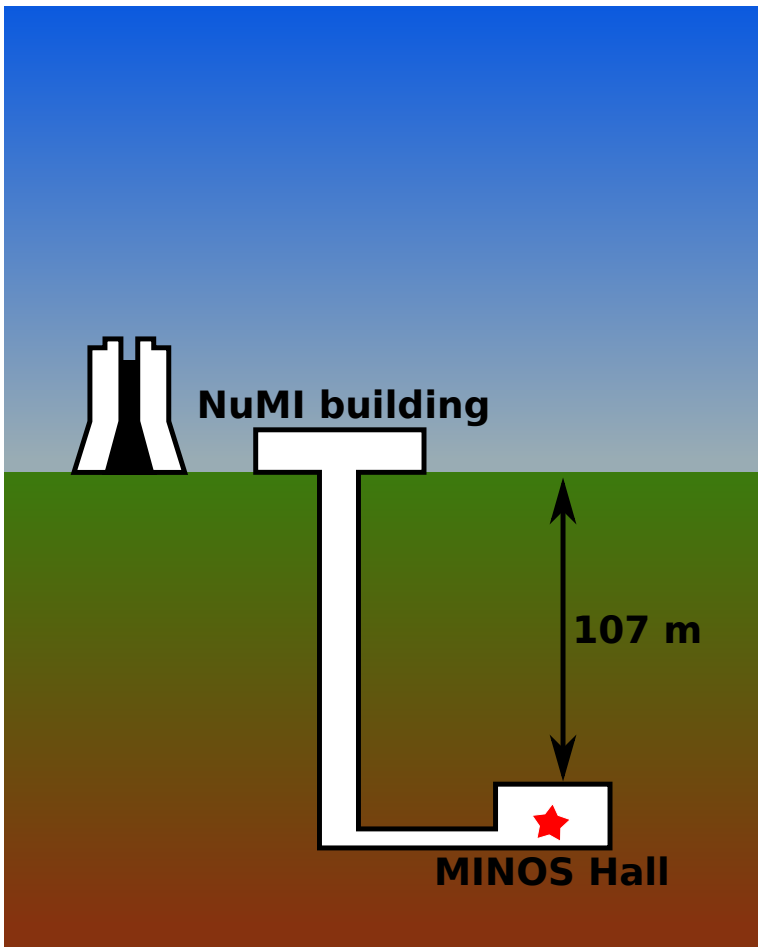


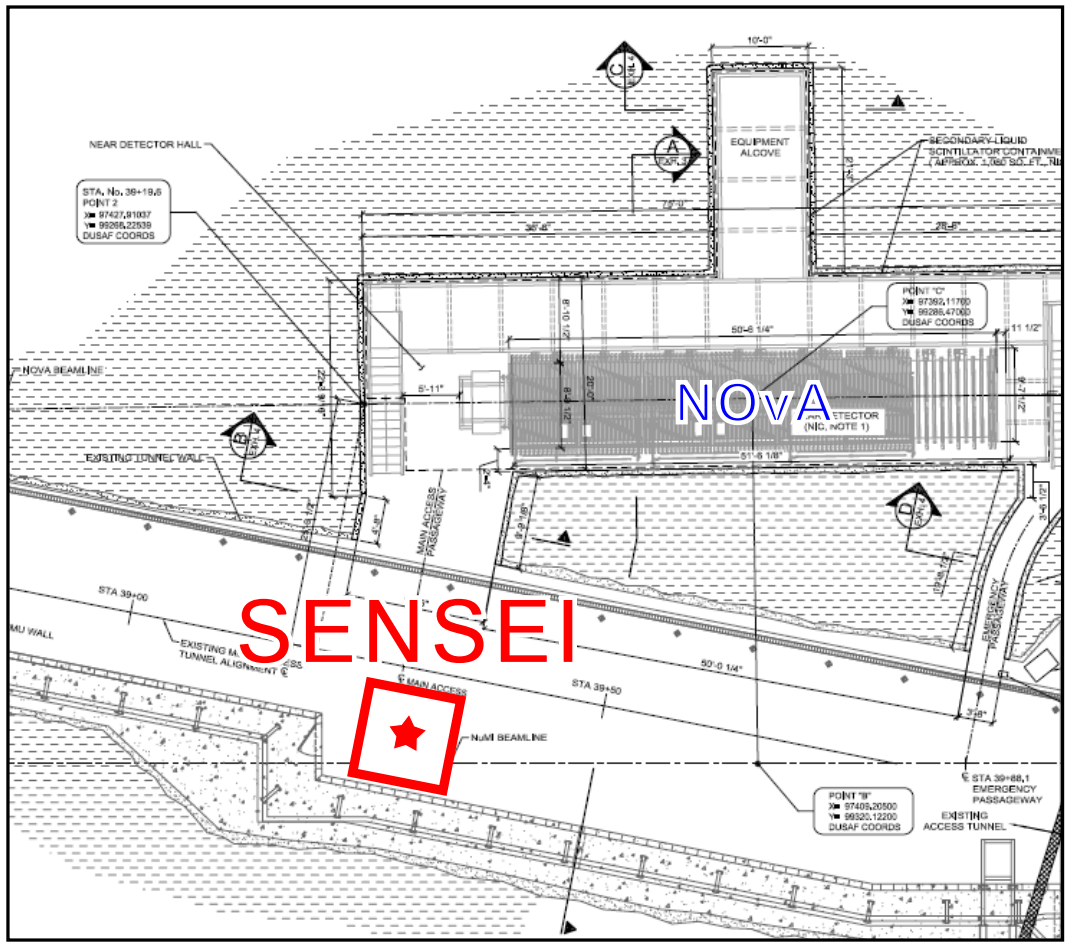
182.5 events over the 278 charge bins in the 0-1keV range

Expect 0.65 bkd events in the lowest (2 e$^-$) charge-bin

Whats going on now: Installation @MINOS

Technology demonstration: installation at shallow underground site





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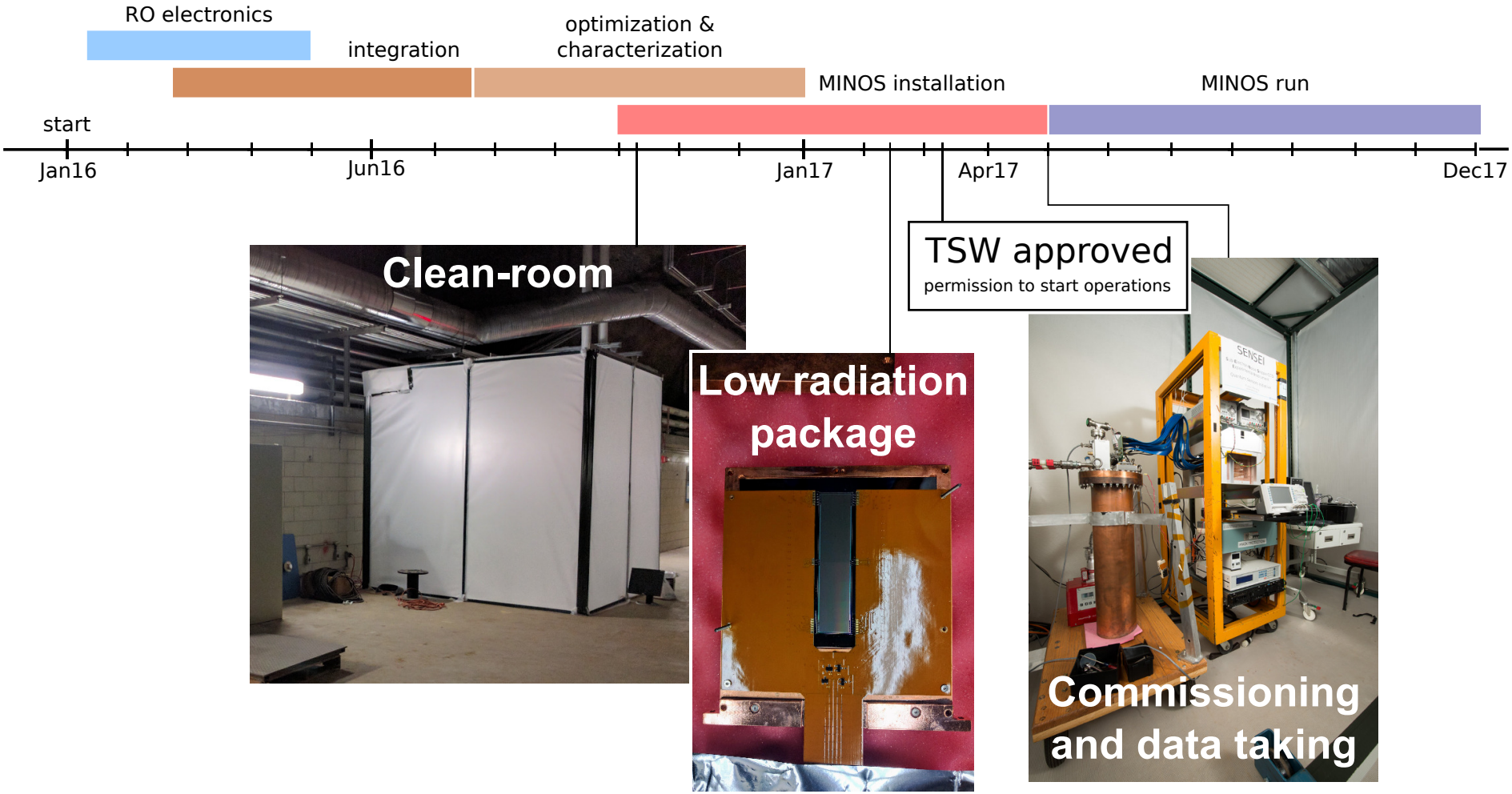


Taking data to understand if current (parasitically–fabricated) detectors are good enough to produce a science result

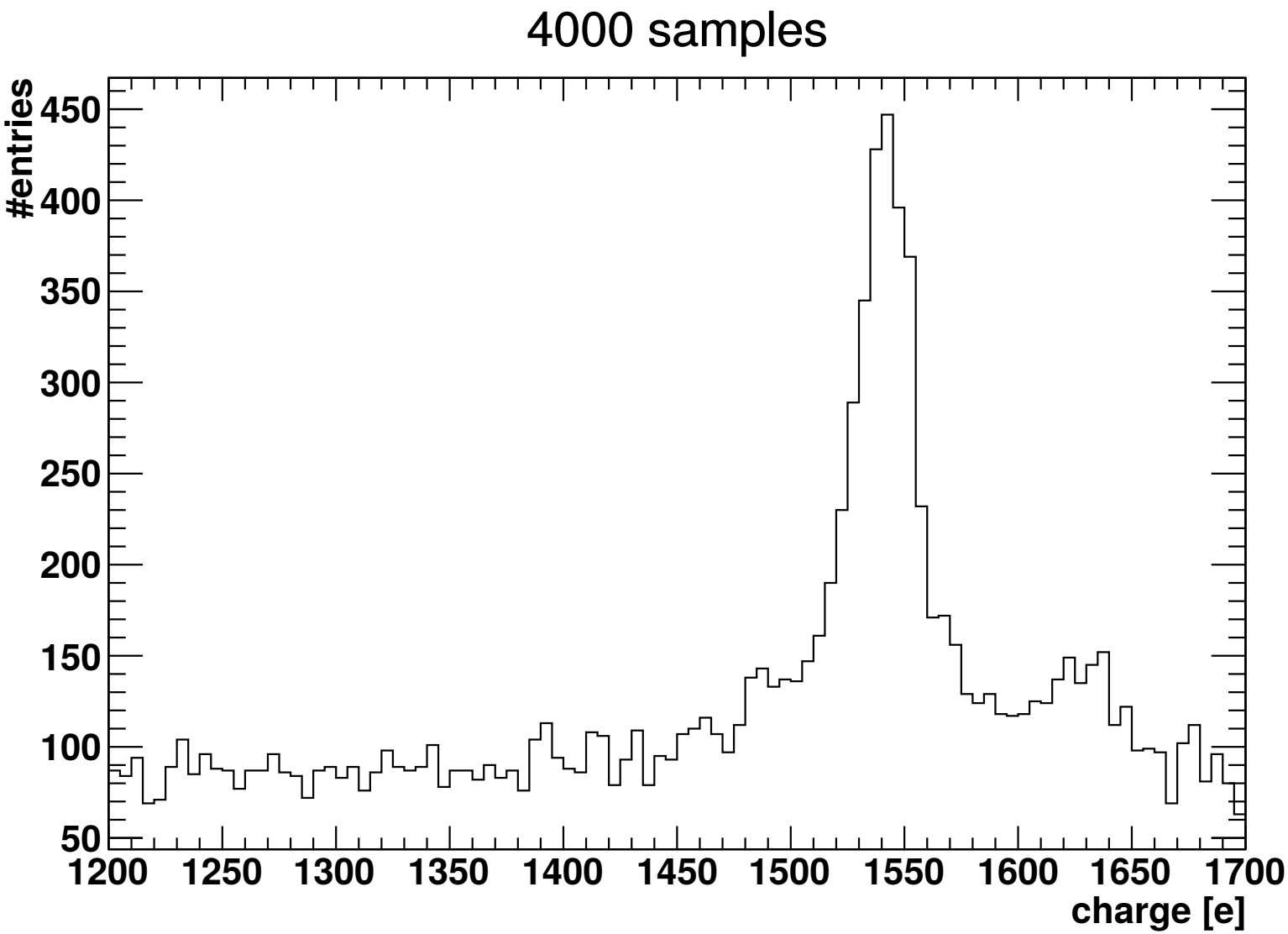
SENSEI path

Summary

- Demonstrated technology: working detector.
- Demonstrated bkg: no R&D needed.
  - required bkg level already reached by running experiments.
- Minimal R&D required for the packaging of the sensors.
- 100 g construction could start on FY18.
  - 1.2 M$ in 2 yrs (scaled from DAMIC experience).
- Complementary to LDMX and DAMIC-1K.
- Small scale demonstration already running at MINOS. Results by the end of 2017.
- MINOS site is good up to a 10g experiment. Deeper location (Snolab/SURF) is required for 100g.

BACK UP SLIDES

^{55}Fe X-ray source



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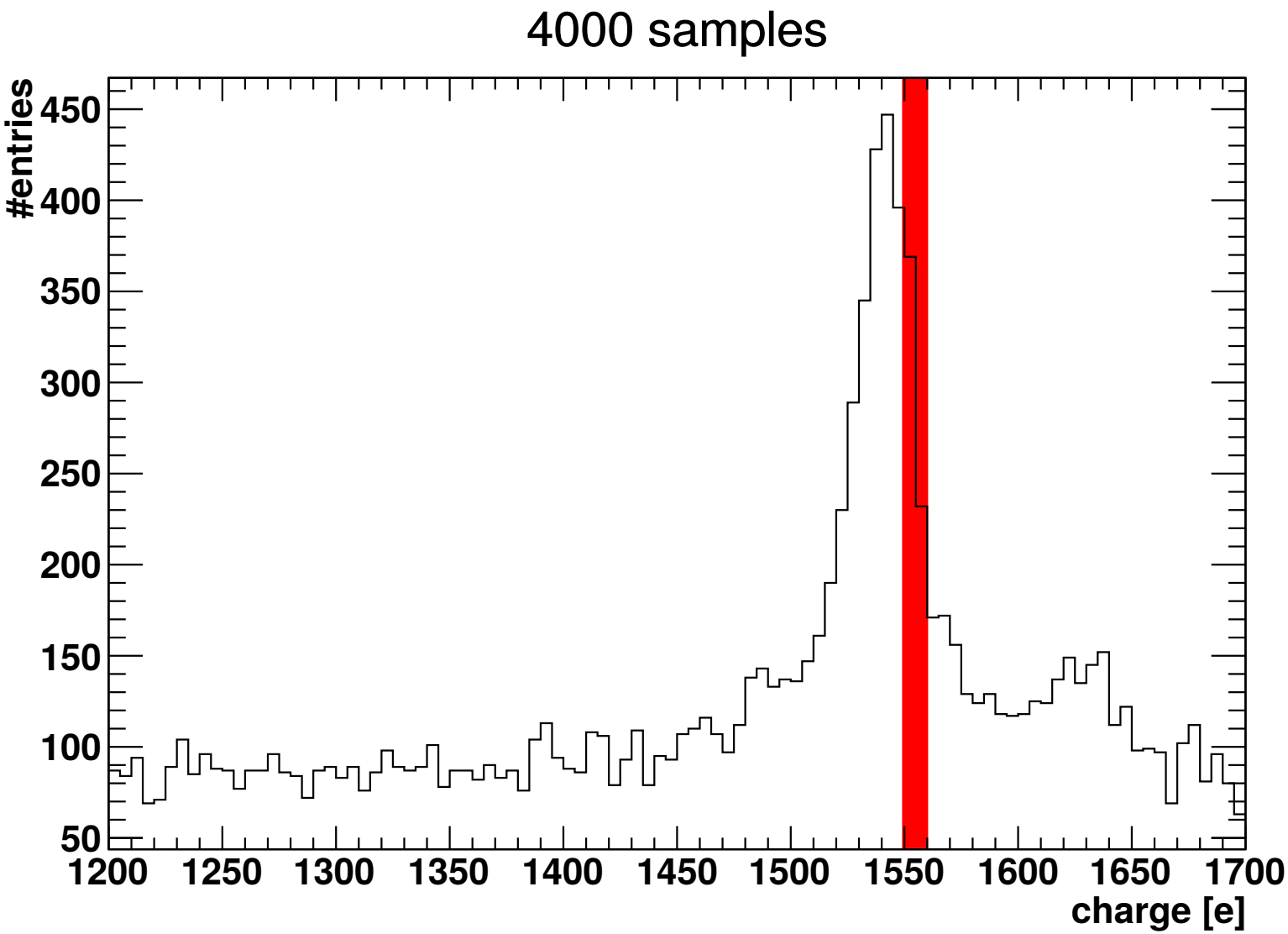
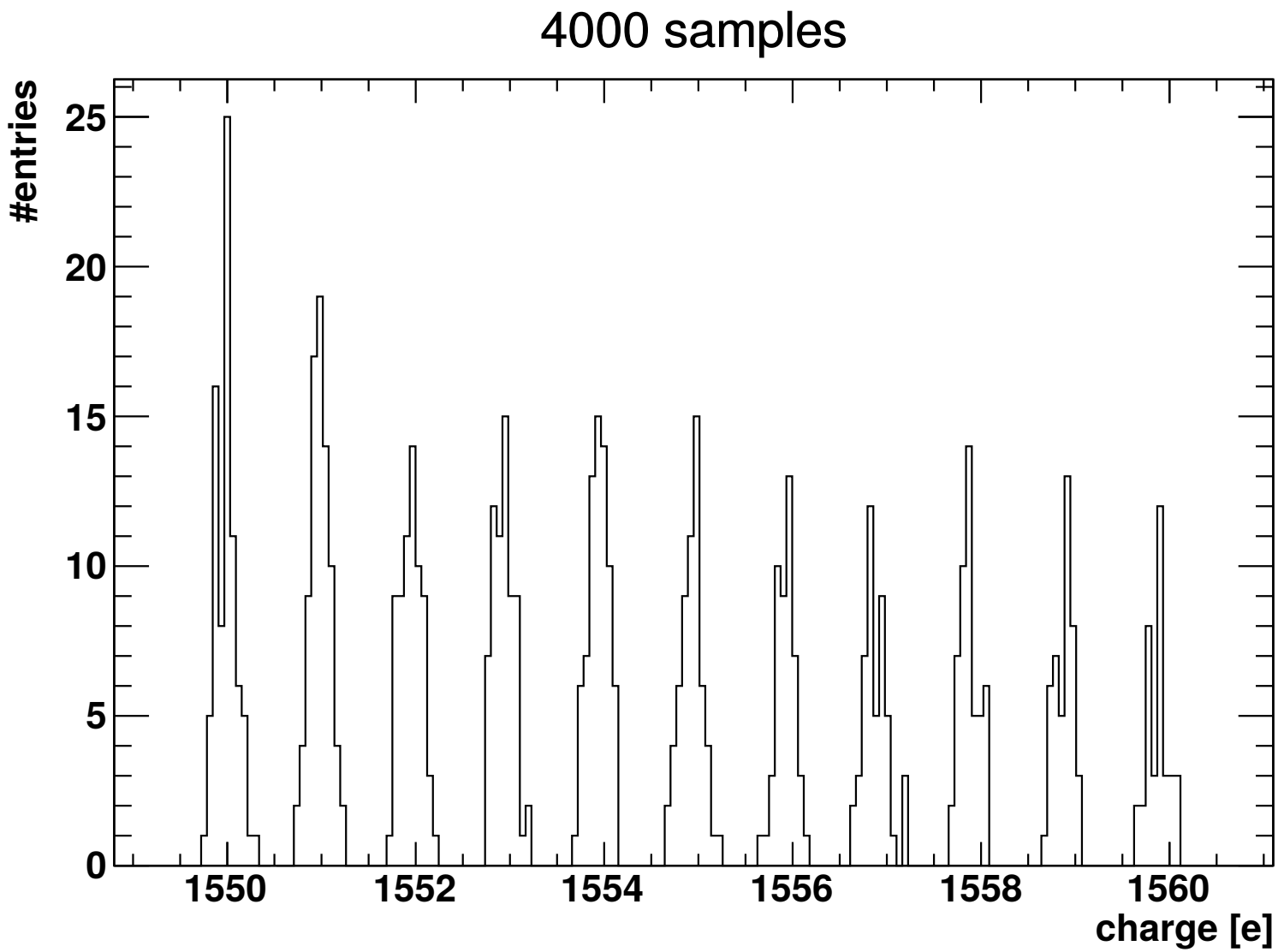
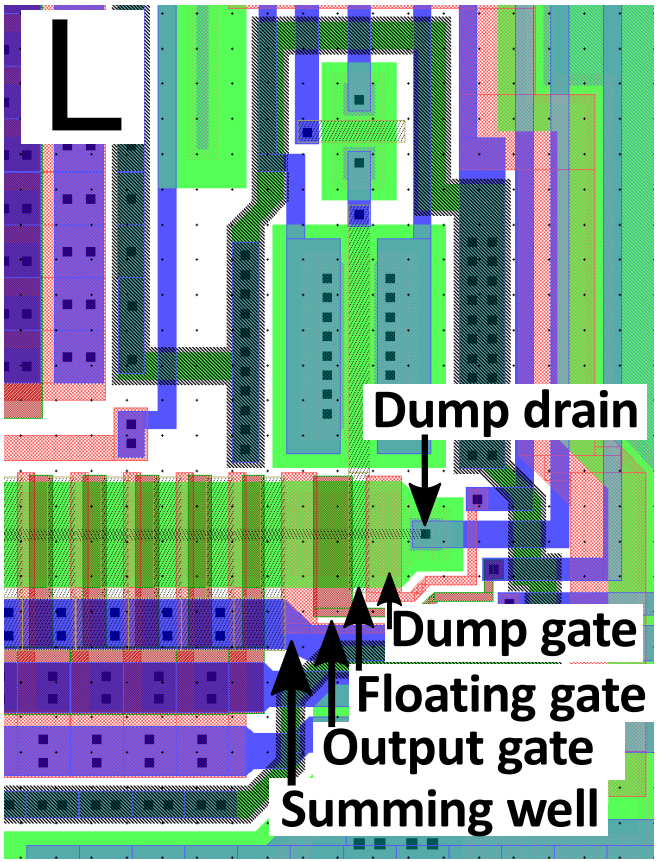
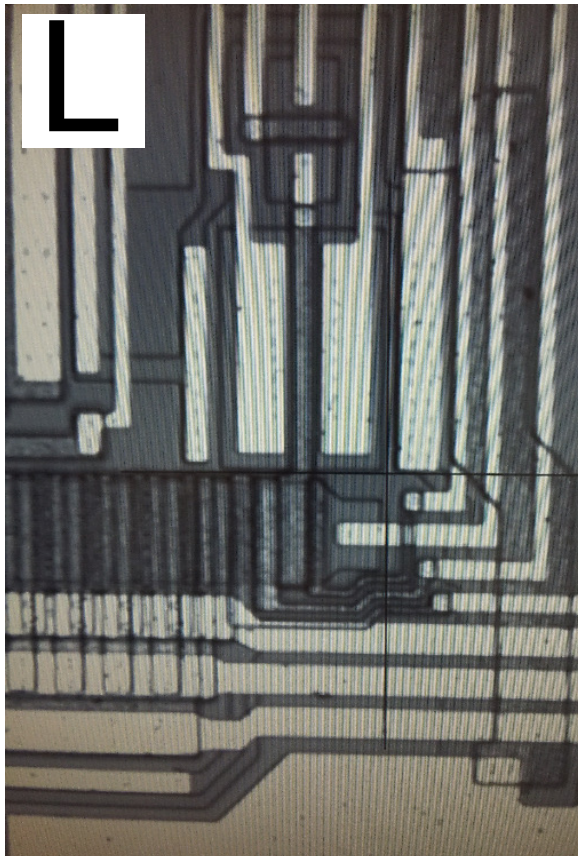


keep counting: ..1550, 1551, 1552..



Readout stage design

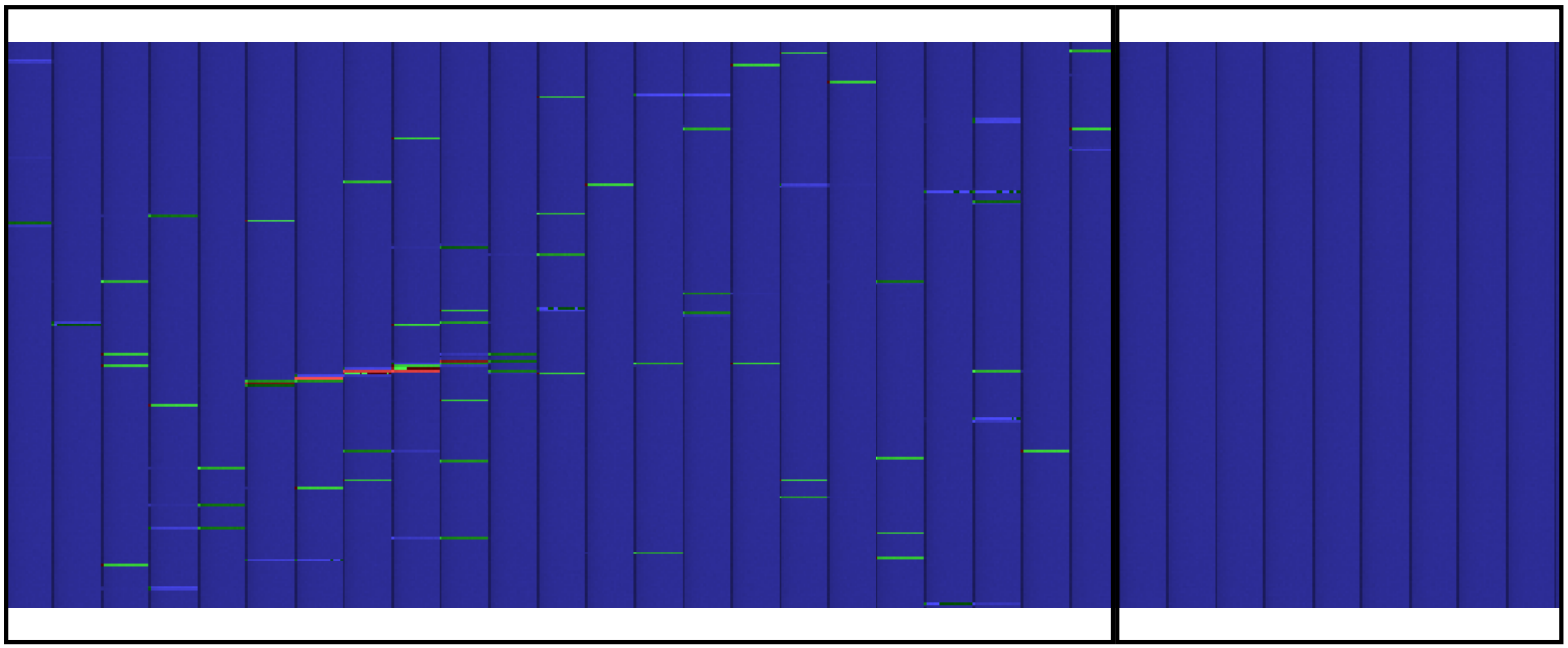




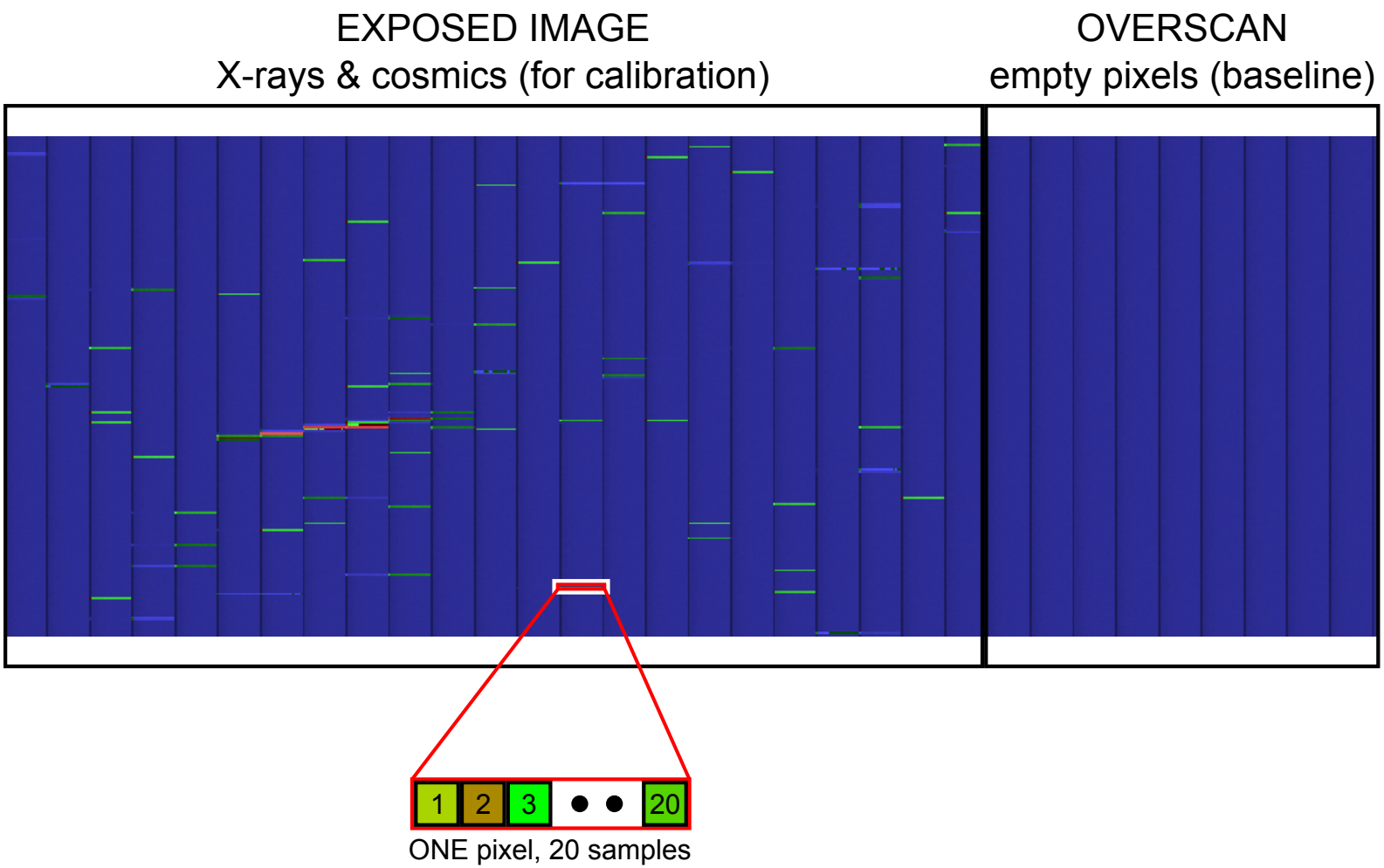
Raw image taken with SENSEI: 20 samples per pixel

EXPOSED IMAGE
X-rays & cosmics (for calibration)

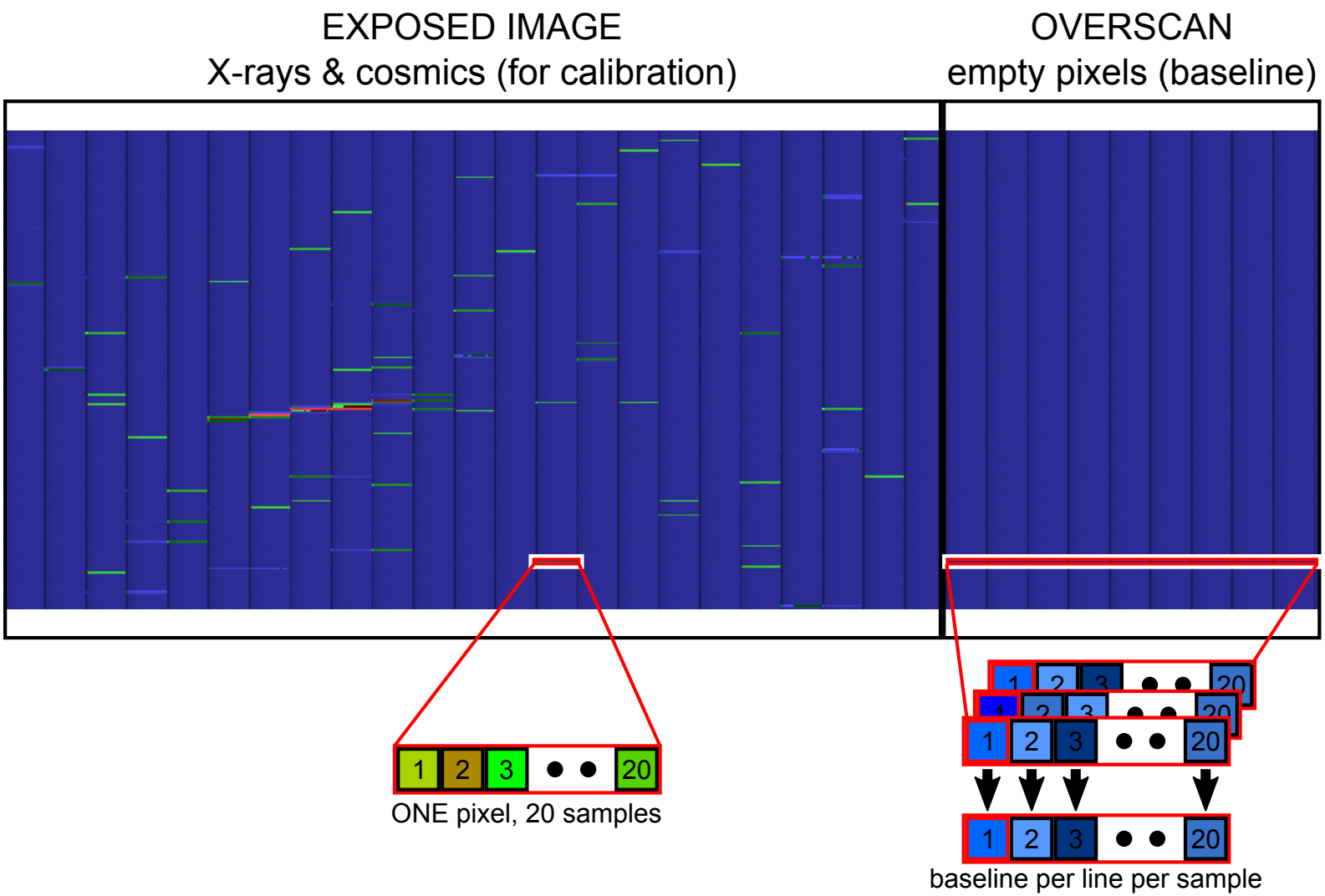
OVERSCAN
empty pixels (baseline)



Raw image taken with SENSEI: 20 samples per pixel



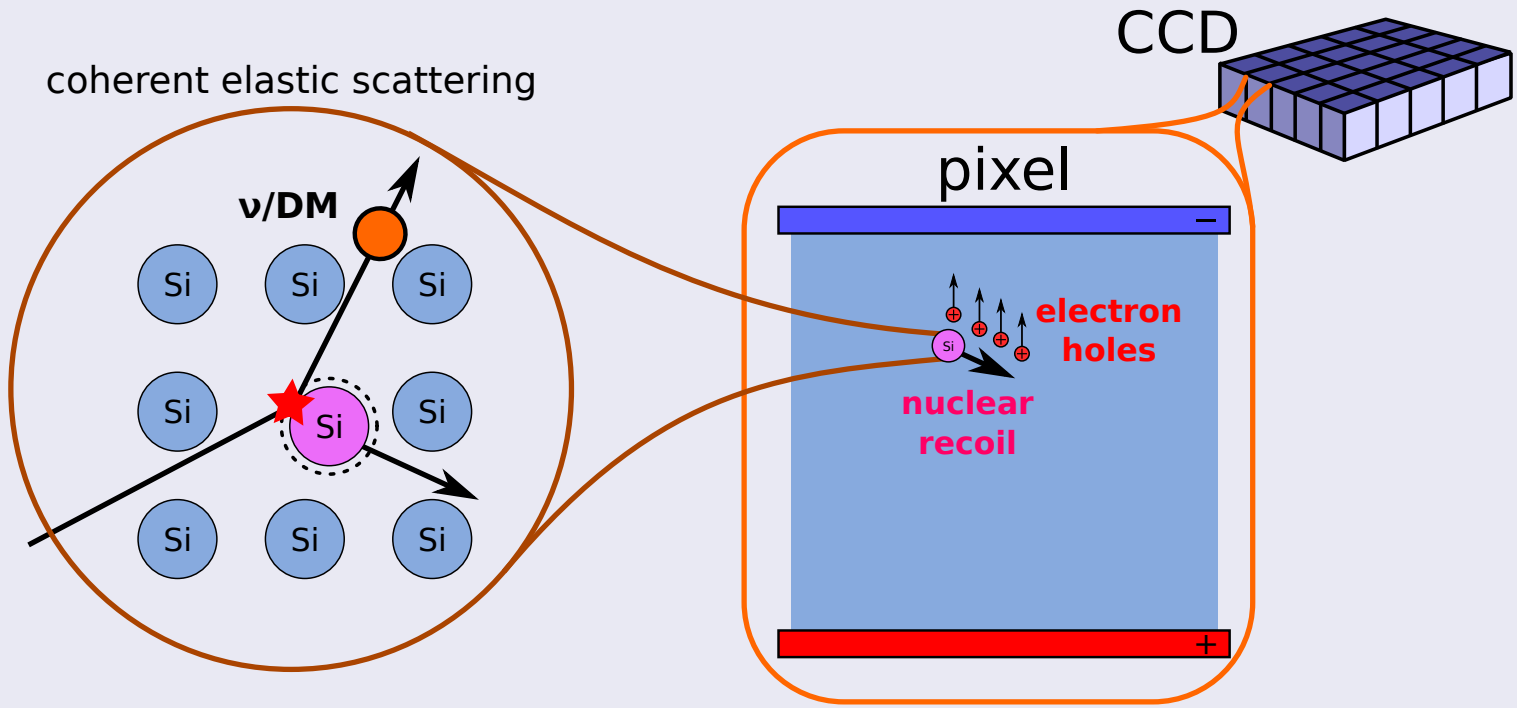
Raw image taken with SENSEI: 20 samples per pixel



Goal: lower the energy threshold in Si detectors

Detect coherent DM/ν-nucleus interactions by measuring the ionization produced by the nuclear recoils

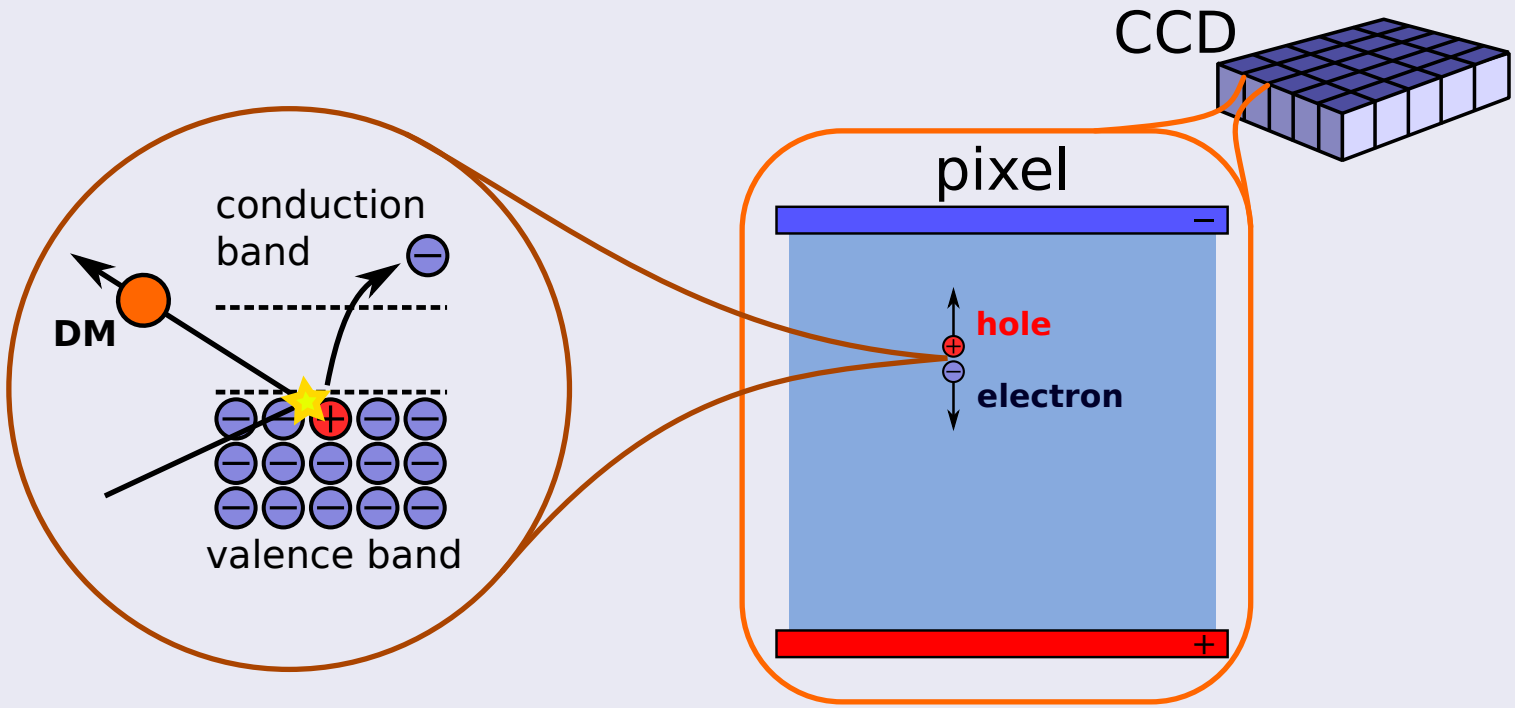
Idea: use CCDs as target and record the ionization produced



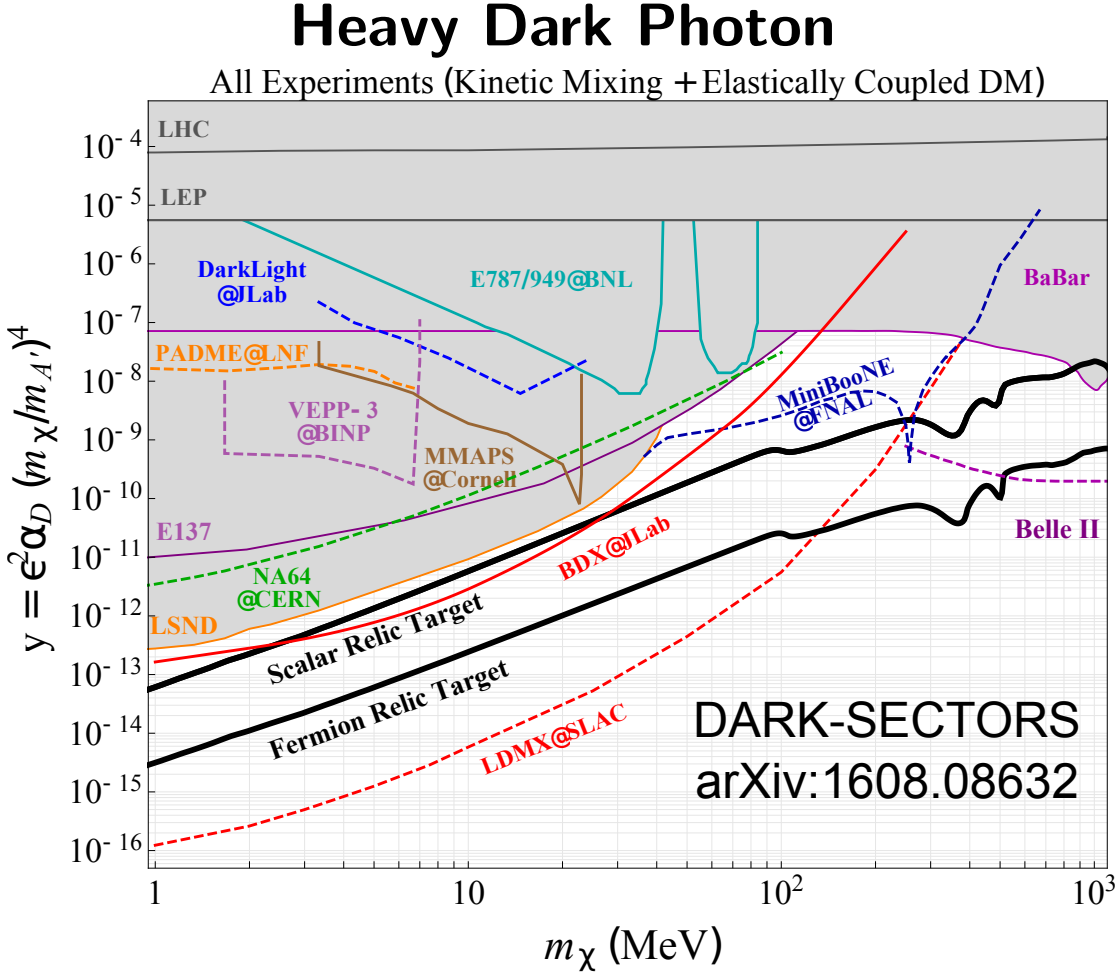
Goal: lower the energy threshold in Si detectors

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

Idea: use CCDs as target and record the ionization produced



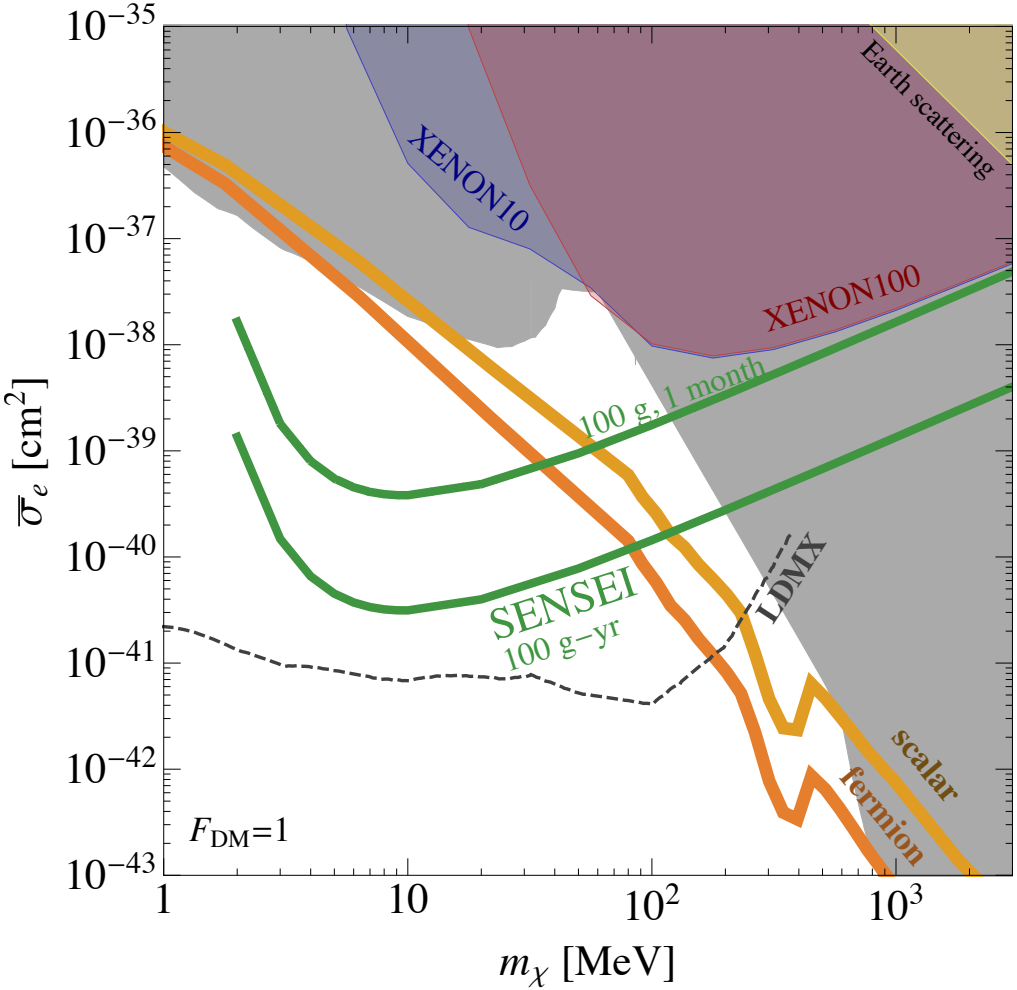
SENSEI: reach of a 100g, *zeroish-background* experiment



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

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

Heavy Dark Photon



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