The SENSEI† experiment

A zero noise detector for DM searches

Javier Tiffenberg
for the SENSEI Collaboration

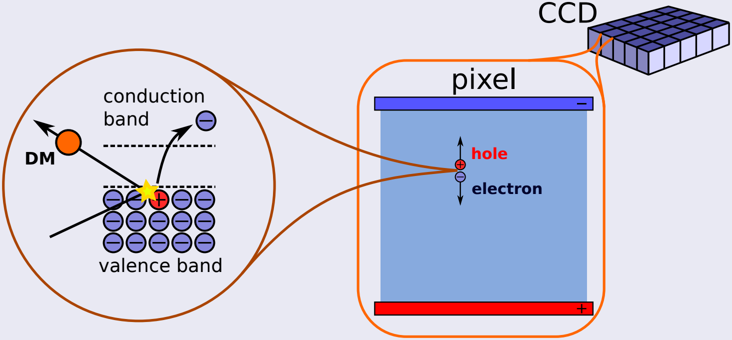
May 7, 2018

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

SENSEI: 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 CCDs as target



This requires very low noise!

SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

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
- **University of Oregon:** Tien-Tien Yu
- **Stanford University*:** Jeremy Mardon

Successful completion of LDRD objectives (2017)

- 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.

SENSEI Collaboration

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

Fermilab 50 Years of Discovery · Stony Brook University · TEL AVIV UNIVERSITY · UNIVERSITY OF OREGON

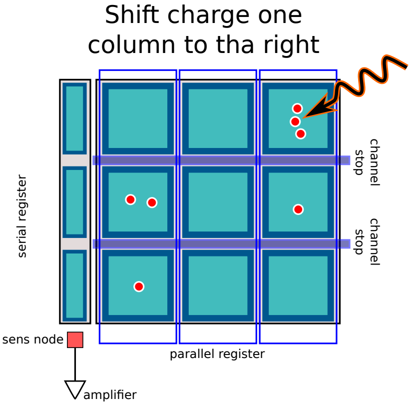
- **Fermilab:** Michael Crisler, Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Liron Barack, Erez Ezion, Tomer Volansky
- **Oregon University:** Tien-Tien Yu
- **+ several additional students + more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

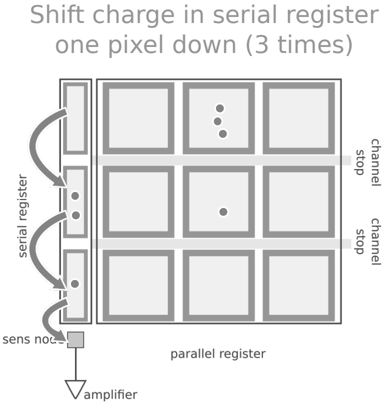
Fully funded by Heising-Simons Foundation & Fermilab

HEISING-SIMONS FOUNDATION

CCD: readout

3x3 pixels CCD





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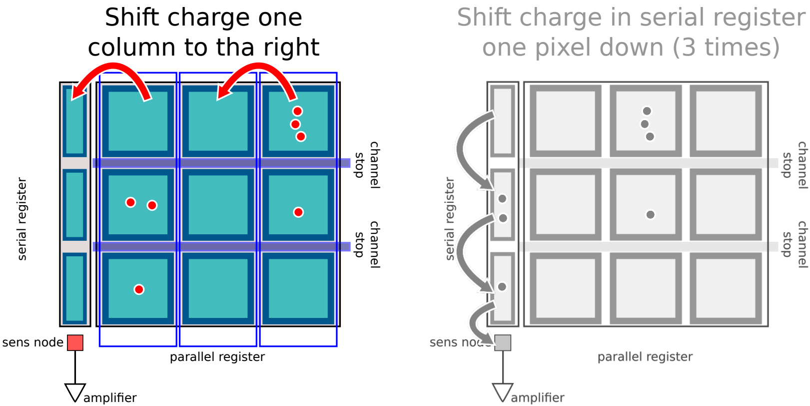

Fermilab

CCD: readout

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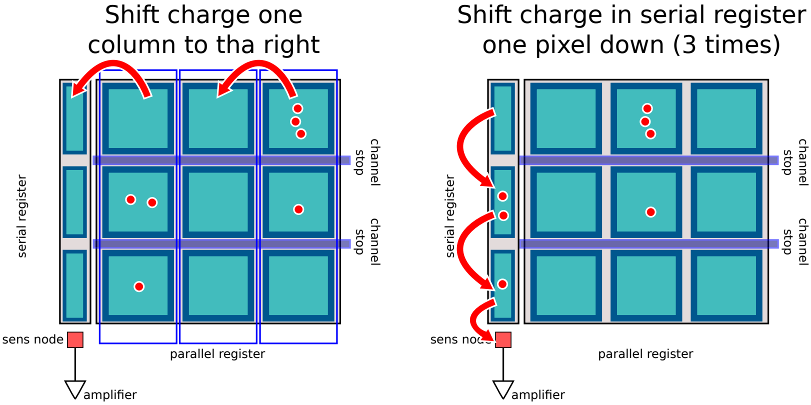
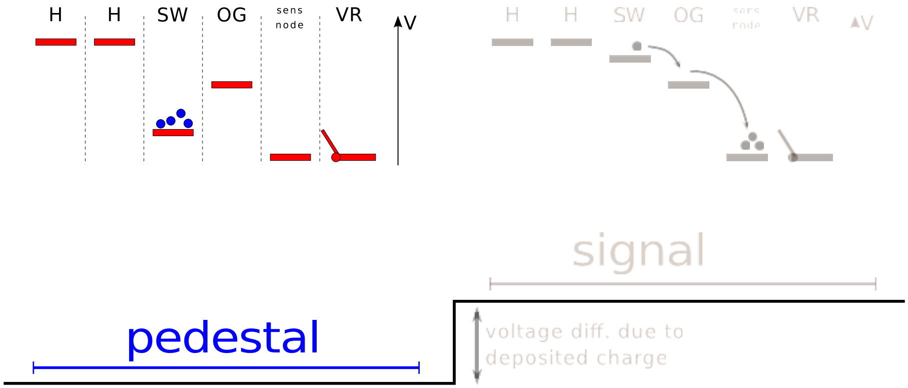


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

CCD: readout


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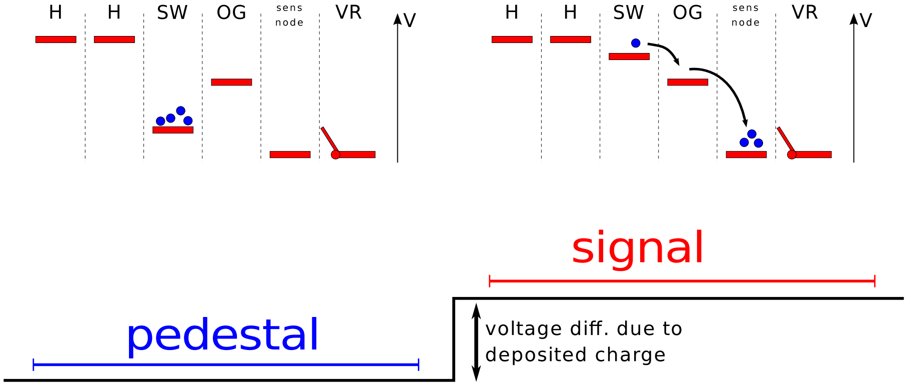
signal
pedestal
voltage diff. due to deposited charge

CCD: readout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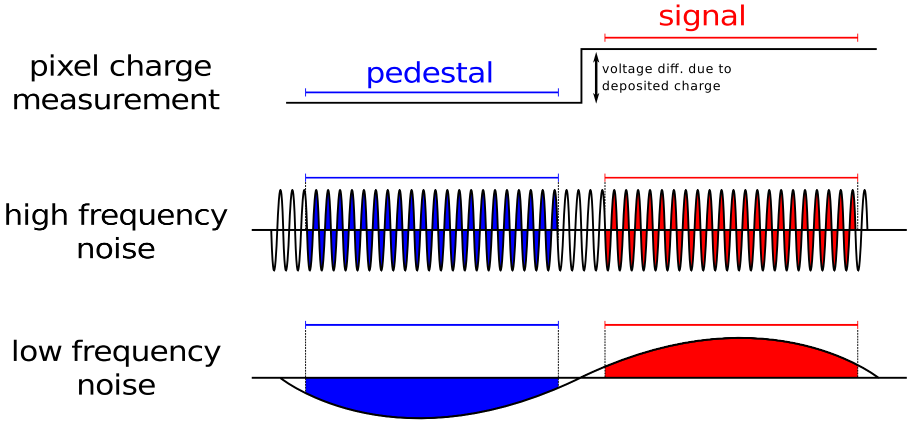
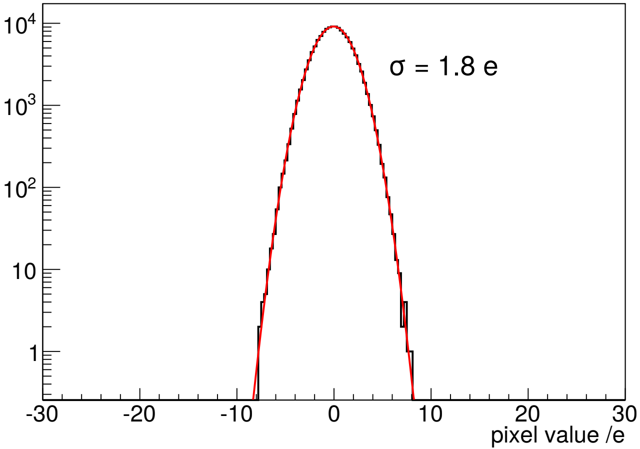


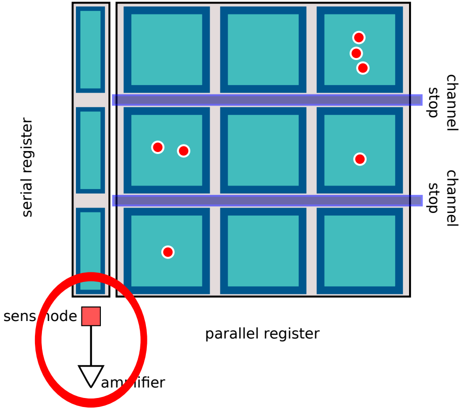
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution, regular scientific CCD



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

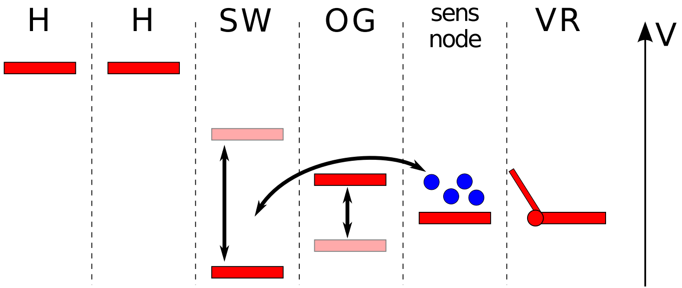
Lowering the noise: Skipper CCD



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



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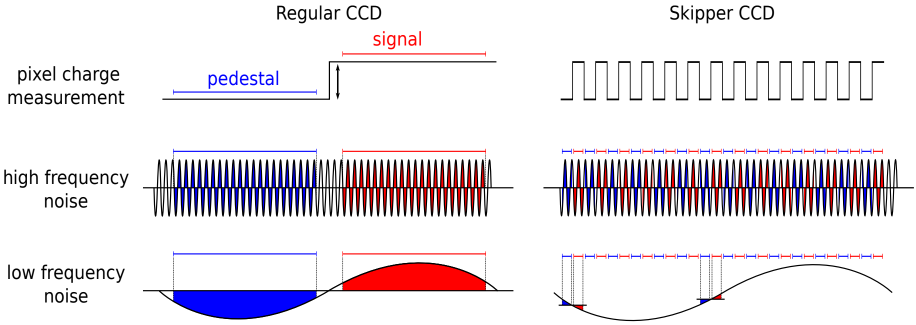
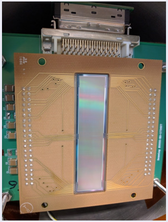


SENSEI: First working instrument using SkipperCCD tech

Sensors

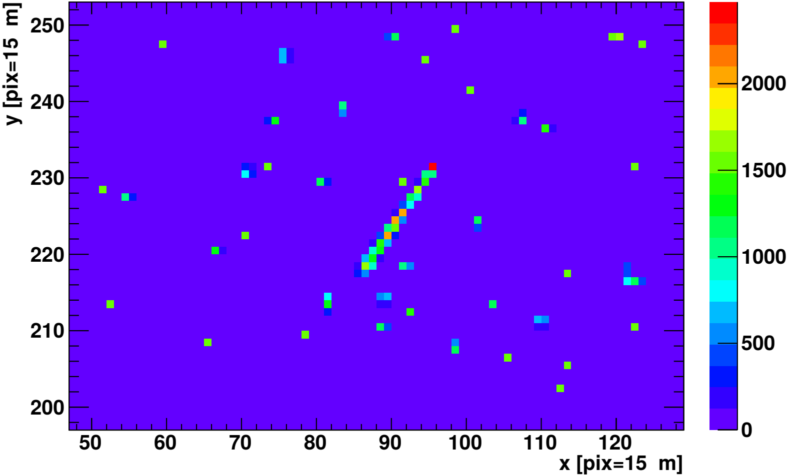


- Skipper-CCD prototype designed at LBL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k$\times$1k (0.5gr) & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

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)



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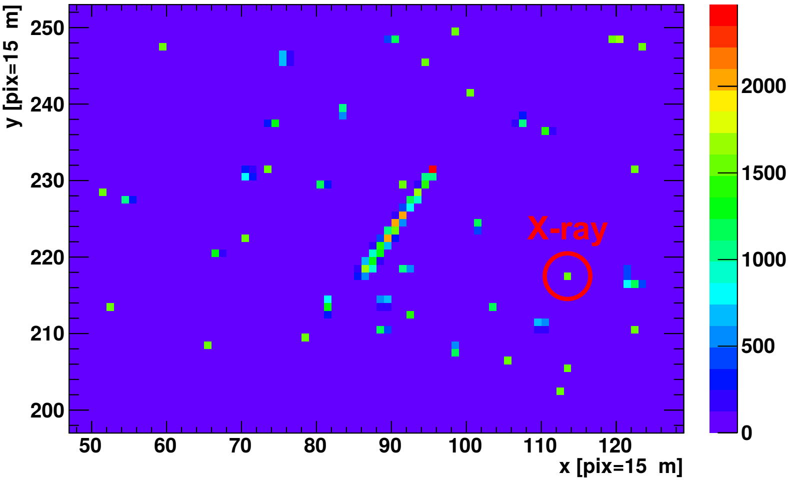

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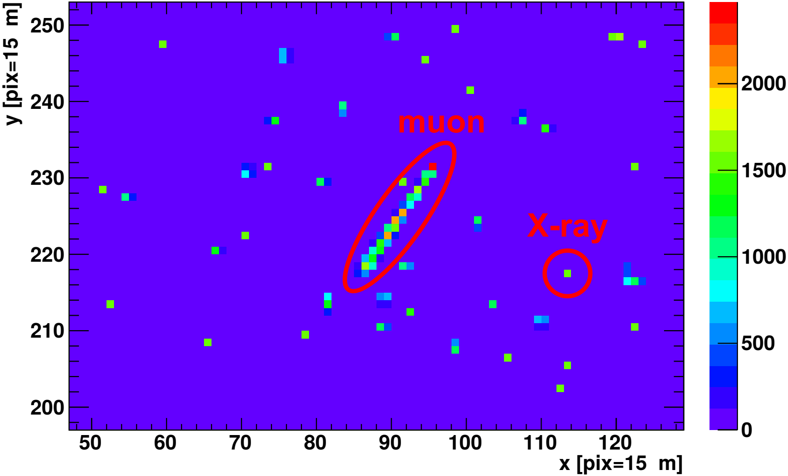

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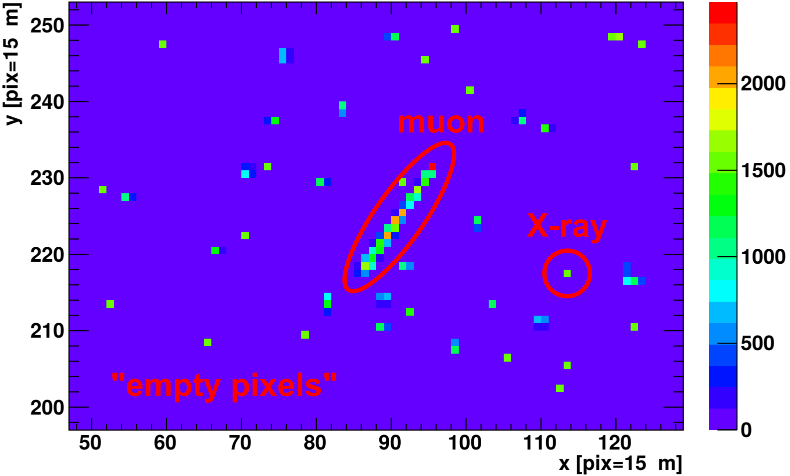
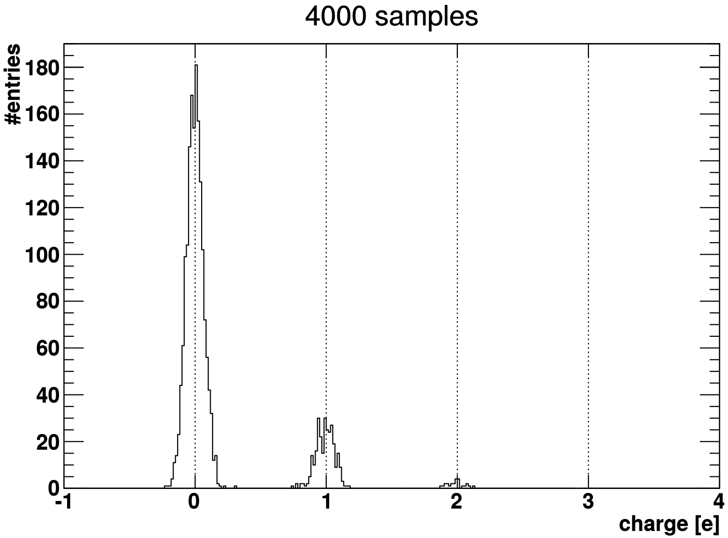


Charge in pixel distribution. Counting electrons: 0, 1, 2..



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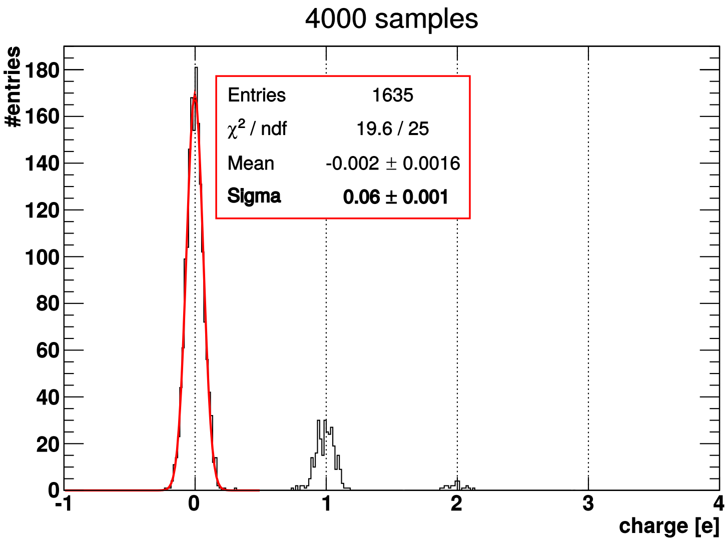
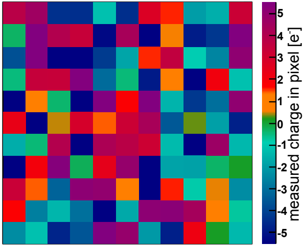
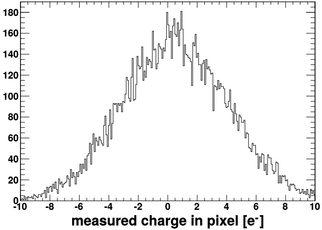


Counting electrons: 0, 1, 2..

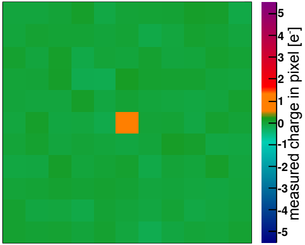
Standard CCD mode: charge in each pixel is measured once



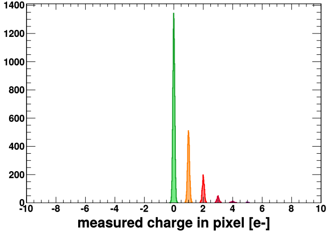
Readout-noise: 3.5 e RMS



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

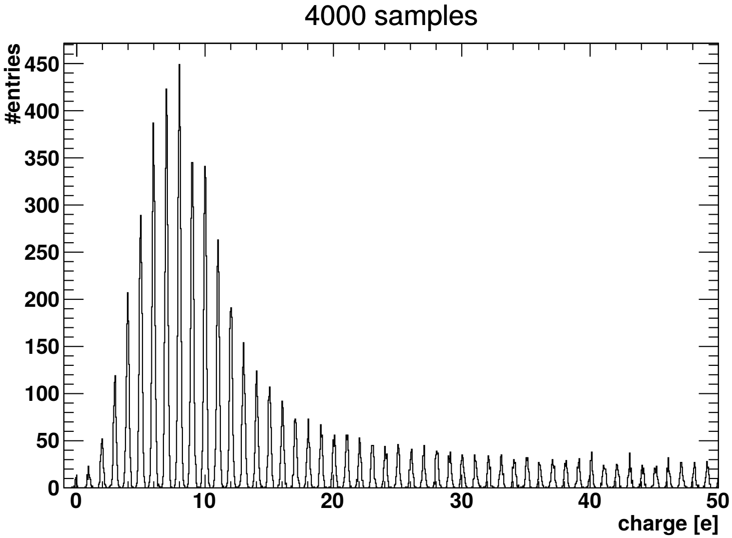


Readout-noise: 0.06 e RMS

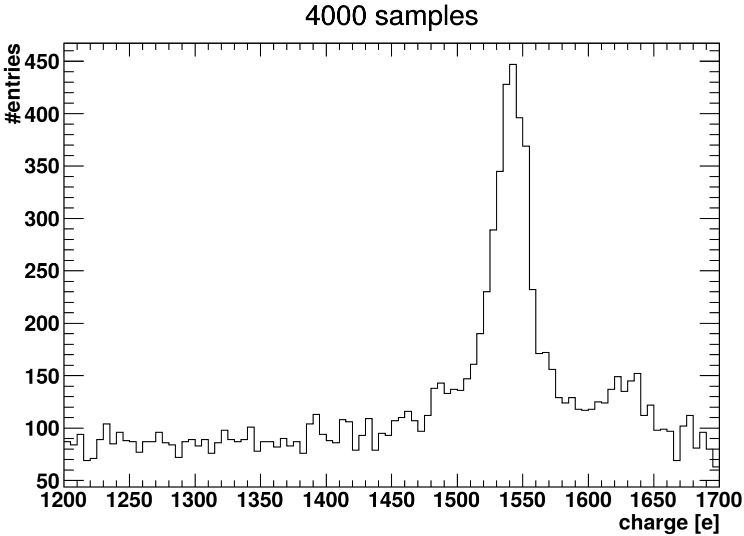


Fermilab

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



^{55}Fe X-ray source



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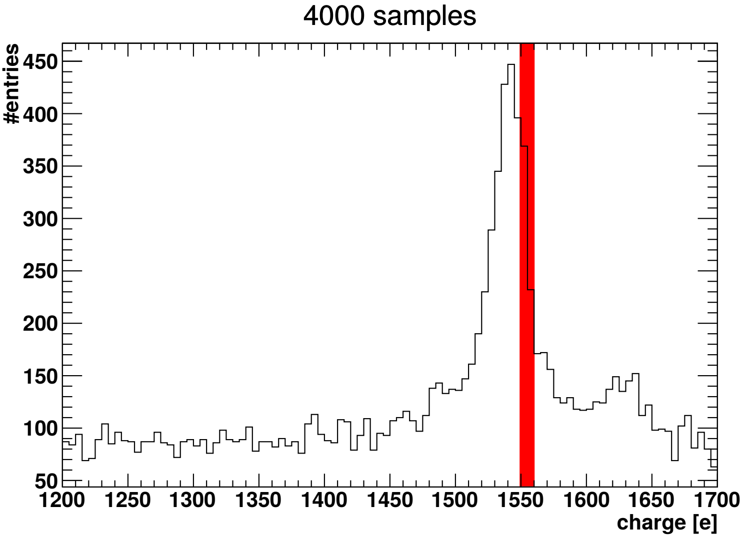


keep counting: ..1550, 1551, 1552..

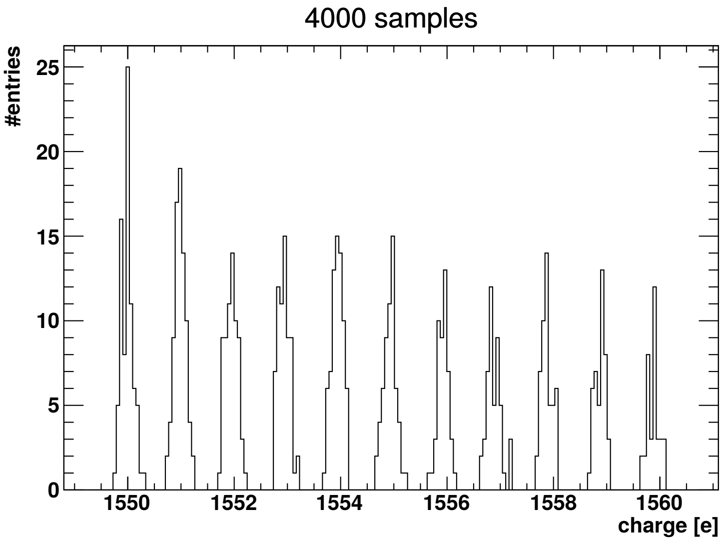
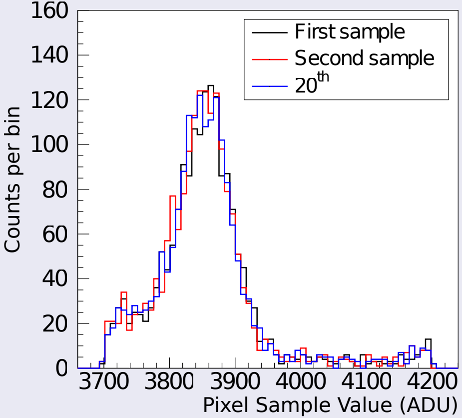


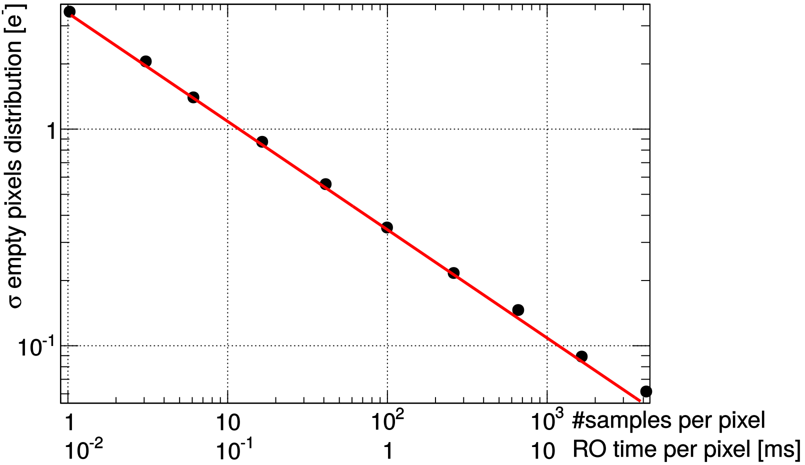
Image taken with SENSEI: 20 samples per pixel

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



The gain is the same for all the samples

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



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

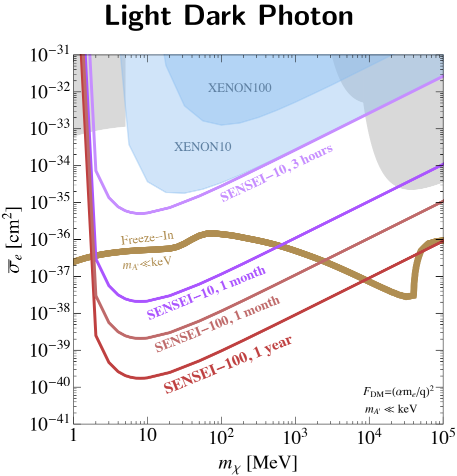
Dark Current **[e^-pix^{-1}day^{-1}]**	$\geq$ **1e$^-$** **[pix]**	$\geq$ **2e$^-$** **[pix]**	$\geq$ **3e$^-$** **[pix]**
$\mathbf{10^{-3}}$	1×10^8	3×10^3	7×10^{-2}
$\mathbf{10^{-5}}$	1×10^6	3×10^{-1}	7×10^{-8}
$\mathbf{10^{-7}}$	1×10^4	3×10^{-5}	7×10^{-14}

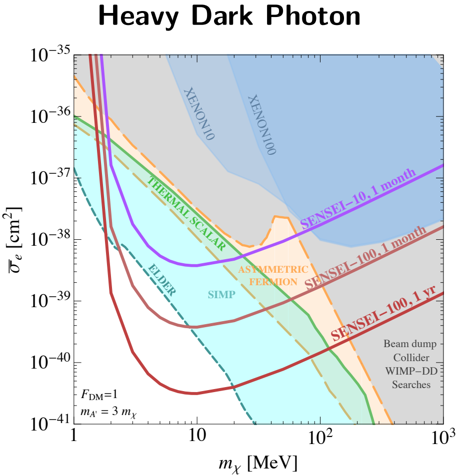
Measured upper limit for the DC in CCDs is:

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

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

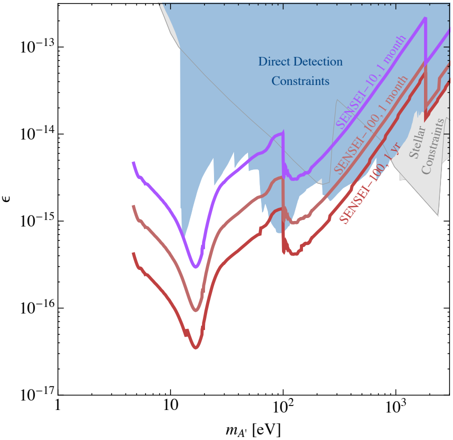
SENSEI: reach of a 100g, *zeroish-background* experiment



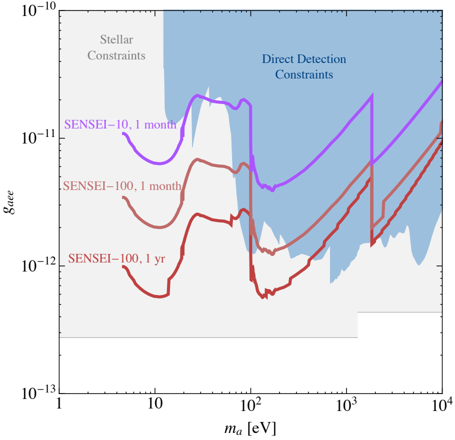


SENSEI: reach of a 100g, *zeroish-background* experiment

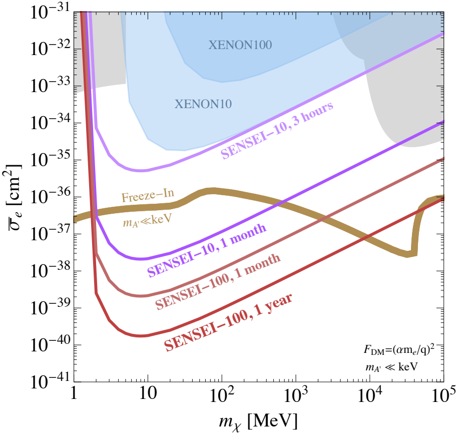
Dark photon (A')

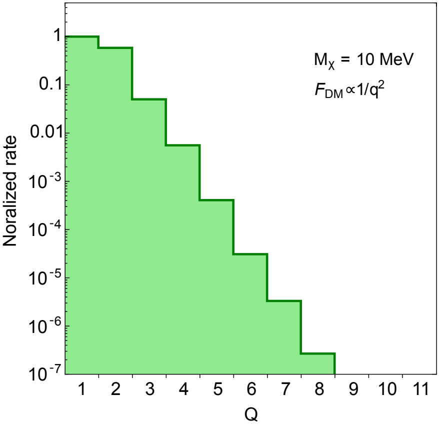


Axion-like-particle (ALP)



The sensitivity is dominated by the lowest energy/charge bin





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
  $\rightarrow$ $\mathbf{N_{bkg}} = \mathbf{36.5}$ kg · day $\times$ **5** DRU = **182.5** events
- Dominated by external gammas $\rightarrow$ **flat Compton spectrum**

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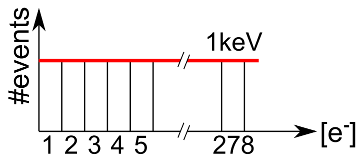
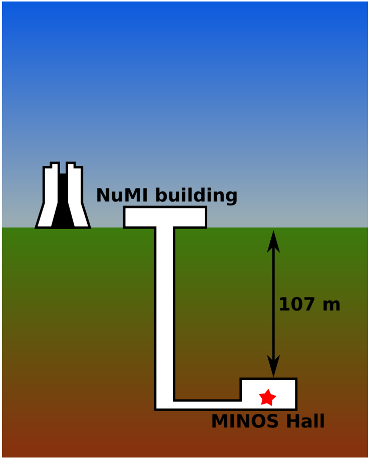


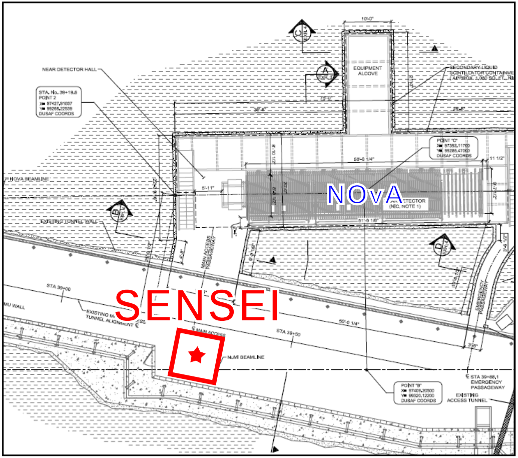
182.5 events over the 278 charge bins in the 0-1keV range

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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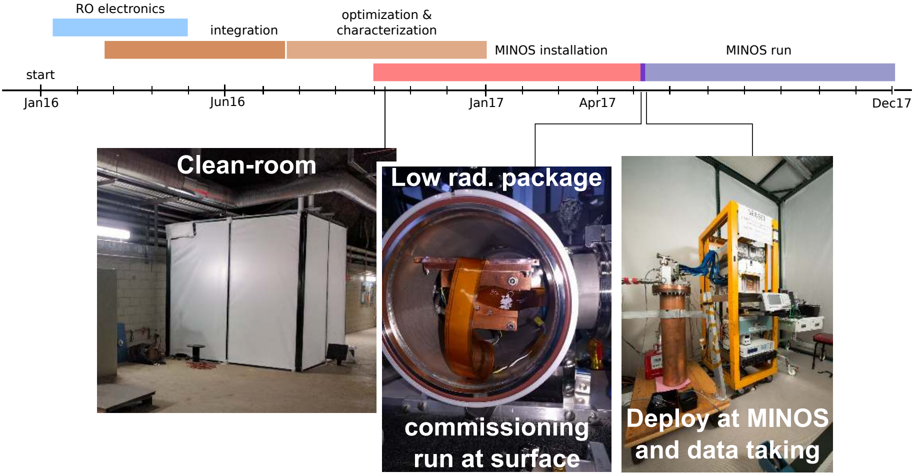
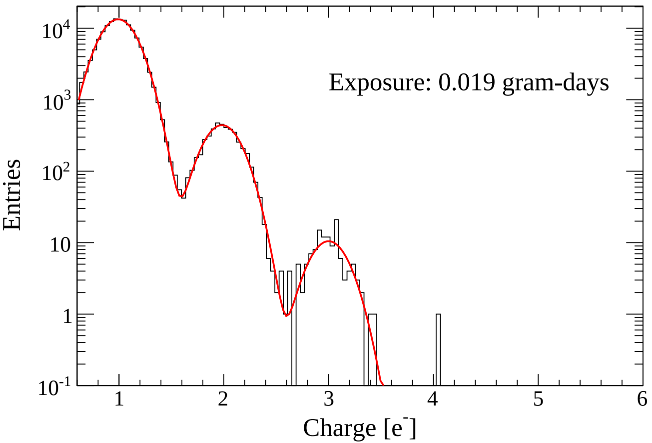


SENSEI commissioning run at surface: arXiv:1804.00088

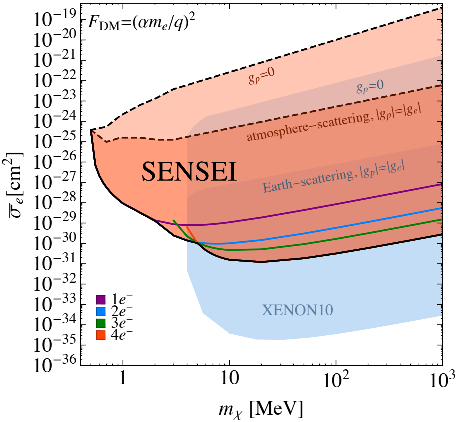
Observed spectrum using 800 samples per pixel



dark current: ∼1.1 e⁻ /pix/day; no events with 5-100 electrons

SENSEI commissioning run at surface: arXiv:1804.00088

First direct-detection constraints between ∼500 keV to 4 MeV!



Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)

Timeline

2016

LDRD funded,
fabrication of SkipperCCD
prototype

2017

testing of prototype,
received funding from HSF
for S-10 and S-100

2018

assembly and testing of S-10,
take data

2019

take more data with S-10, begin analysis
assembly and testing of S-100

2020

continue S-10 analysis,
take data with S-100

2021

S-100 analysis

SENSEI path

Summary

- SENSEI is the first dedicated experiment searching for electron recoils
- SENSEI's first results, using a prototype detector on the surface, probes 0.5-4 MeV masses for the first time, and larger cross sections than existing sub-GeV direct-detection constraints
- SENSEI experiment will use better sensors & collect almost 2 million times the exposure of this surface run in next $\sim$2-3 years, probing large regions of uncharted territory populated by popular models
- Fully funded: 10g & 100g design/construction started.
  - Grant from Heising-Simons Foundation
  - Full technical support from Fermilab

Fermilab

BACK UP SLIDES

SENSEI commissioning run at surface: arXiv:1804.00088

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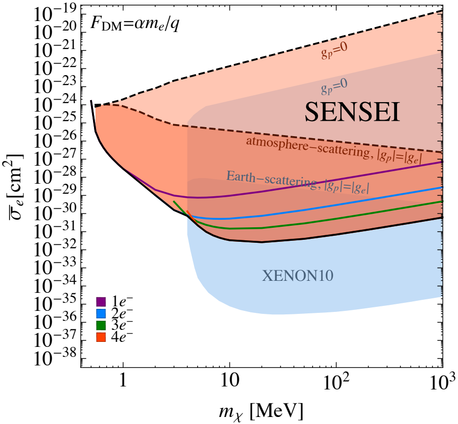

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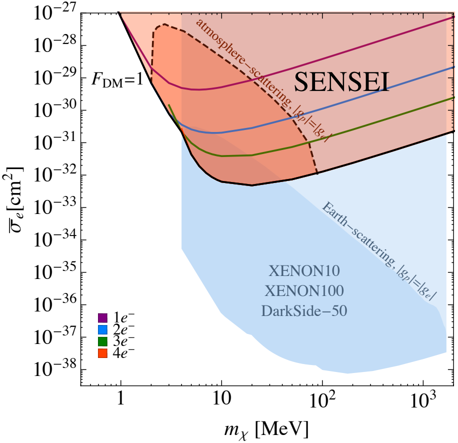

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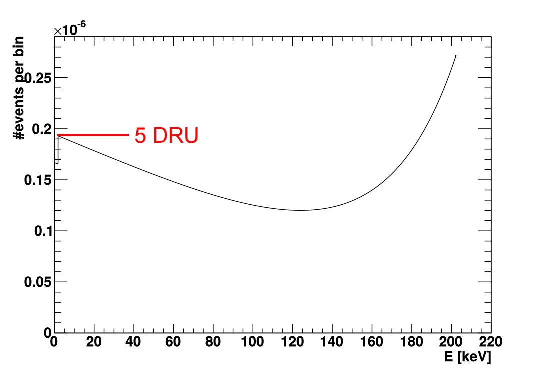
A more detailed analysis: Klein-Nishina + binding energy correction

- **at lower energies atomic binding energies are relevant**
- partial energy depositions populate low E region (thin det)



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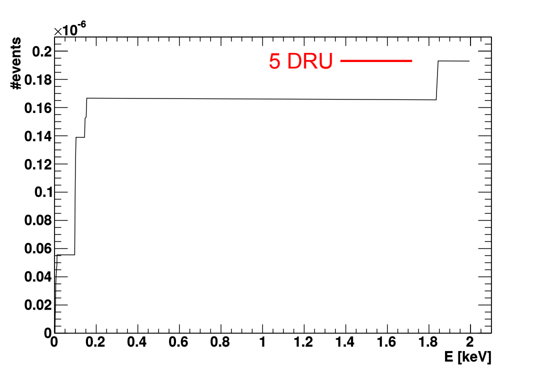

Skipper CCD - electron recoil background requirements

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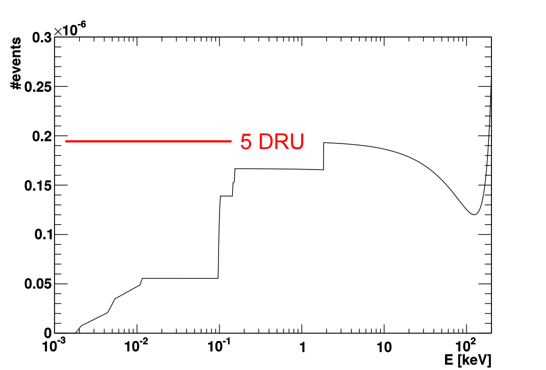

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A more detailed analysis: MC simulation, G4 3D Monash model

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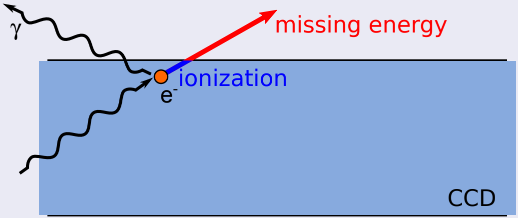

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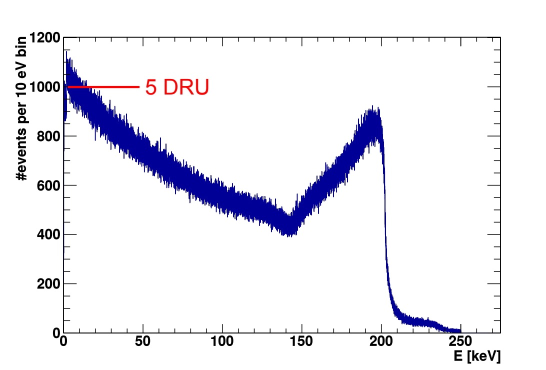

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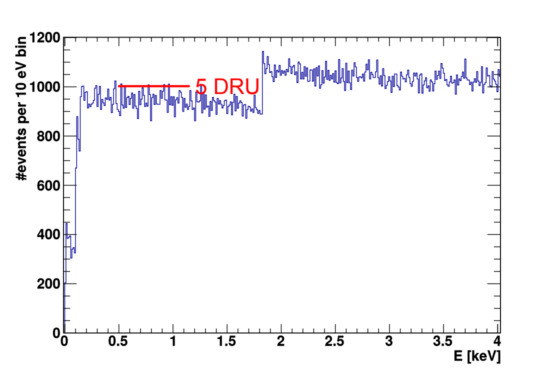

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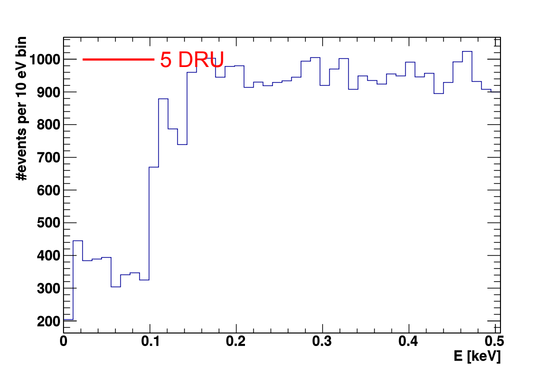

Skipper CCD - electron recoil background requirements

A more detailed analysis: MC simulation, G4 3D Monash model

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Back of the envelope estimation is conservative