The SENSEI† experiment

For direct detection of light dark matter

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for the SENSEI Collaboration

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

SENSEI Collaboration

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

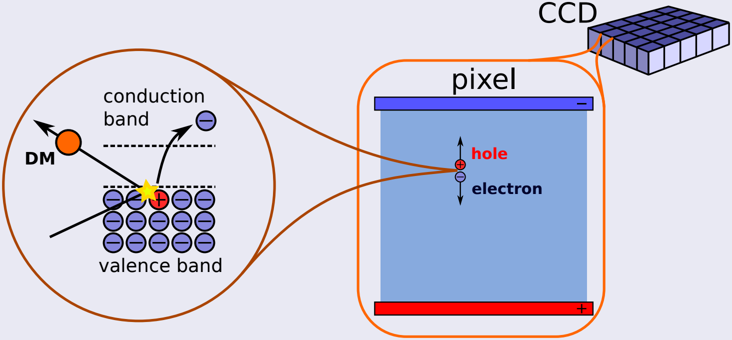
- **Fermilab:** Michael Crisler, Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Liron Barack, Erez Ezion, Tomer Volansky
- **Oregon University:** Tien-Tien Yu
- **+ several additional students + more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

Fully funded by Heising-Simons Foundation & Fermilab

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

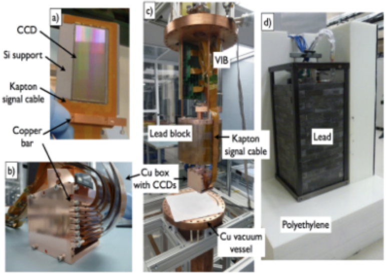
Idea: use electrons in the CCDs as target



Signal of only 1, 2 or 3 e-h pairs. This requires very low noise!

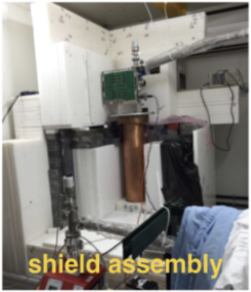
before SENSEI...we were looking for nuclear recoils

DArk Matter In CCDs



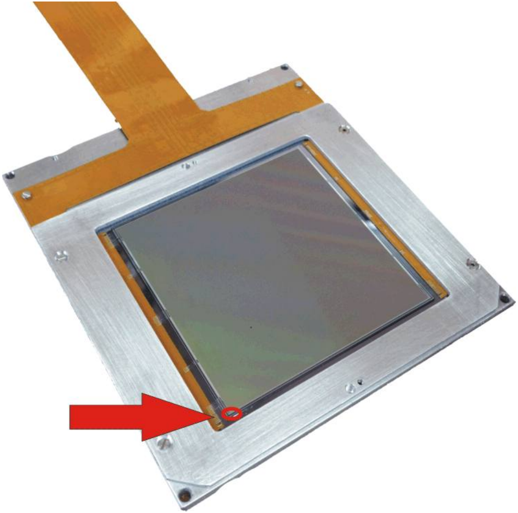
running at SNOLAB ~2 km underground

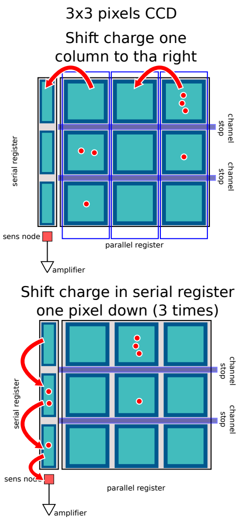
COherent Neutrino-Nucleus Interaction Experiment



running at Nuclear Plant in Brazil, by the beach

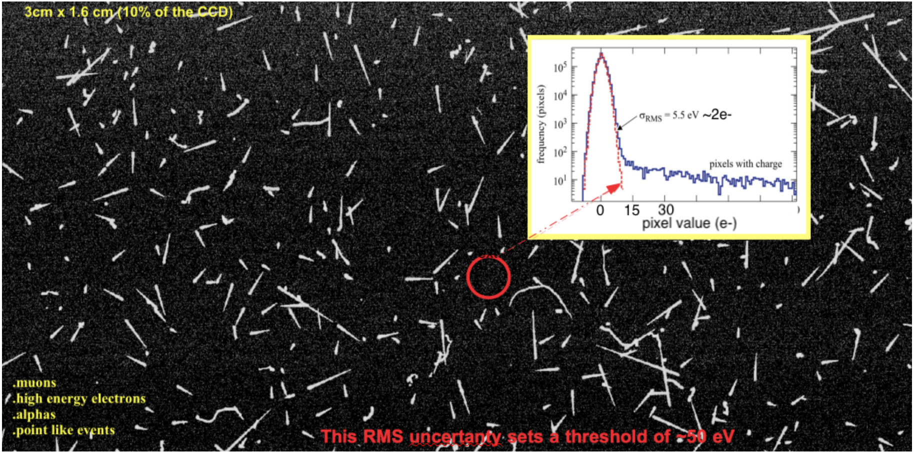
CCD: readout





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

before SENSEI...we couldn't see single electron recoils

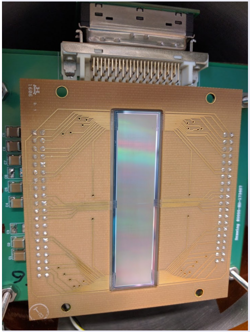


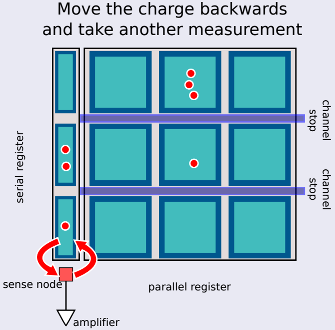
Now, new experiments based on Skipper CCD

- 2011: Achieving sub-electron readout noise in Skipper CCDs (arXiv:1106.1839v2)
- 2017: Single-electron and single-photon sensitivity with a silicon Skipper CCD (arXiv:1706.00028)

- approx. 8 years on the R&D of the Skipper CCD
- designed at LBNL: 200 & 250 μm thick, 15 μm pixel size

Sensors

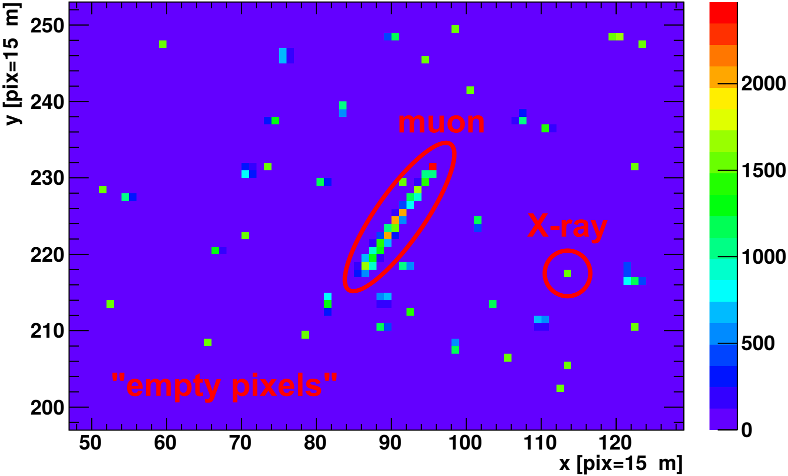




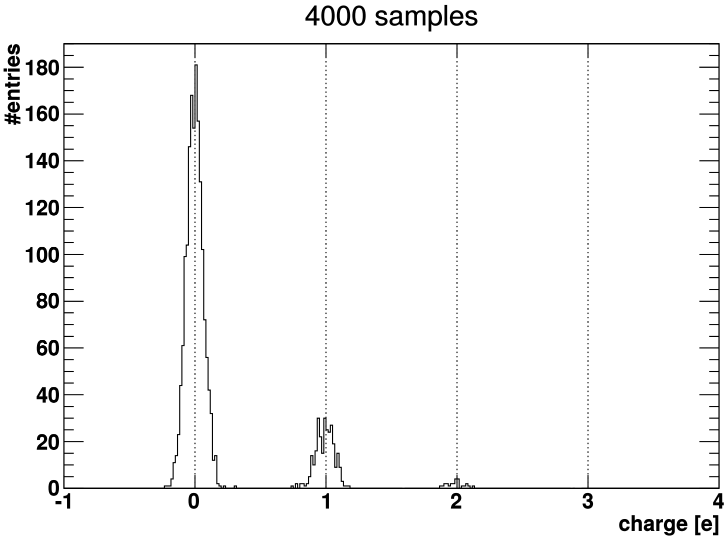
- ***Final pixel value =***

$$\frac{1}{N}\Sigma_i^N \,(\textit{pixel sample})_i$$

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



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



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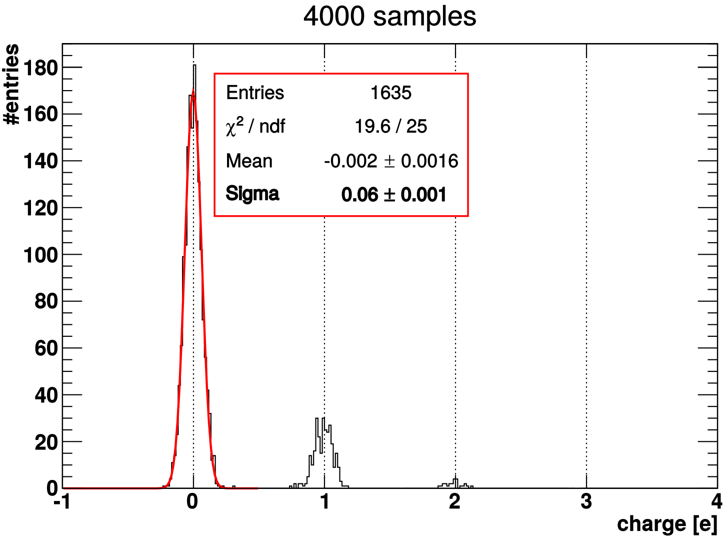
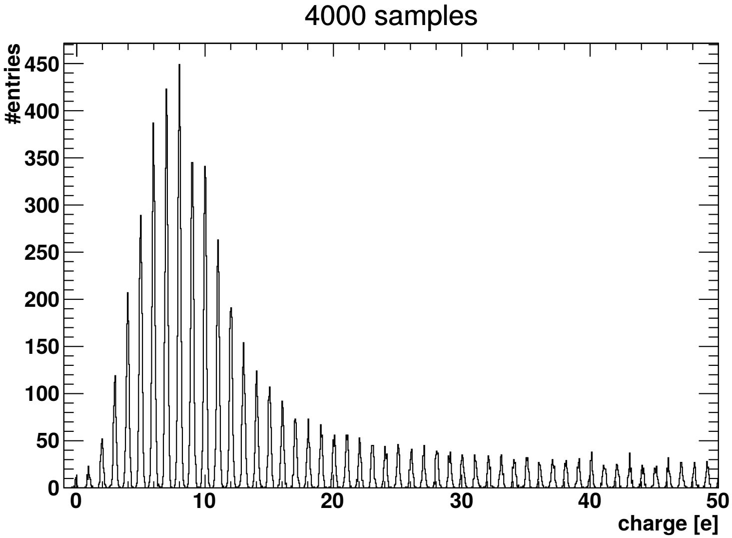
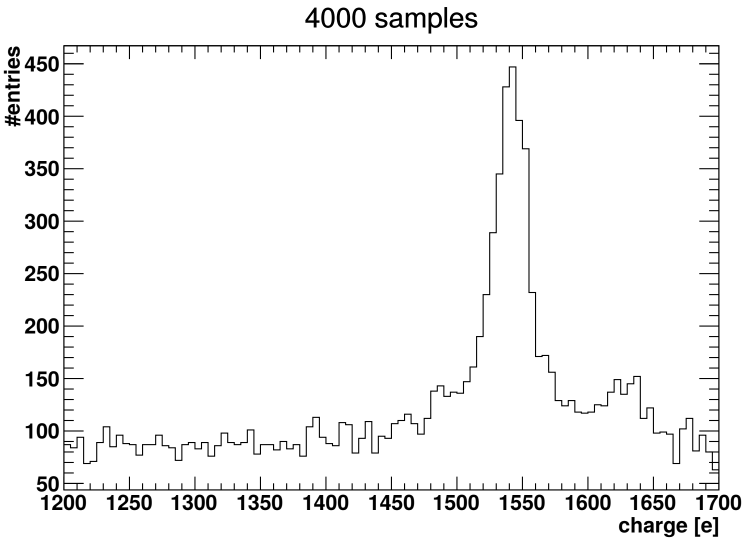


Counting electrons: ..48, 49, 50..



^{55}Fe X-ray source



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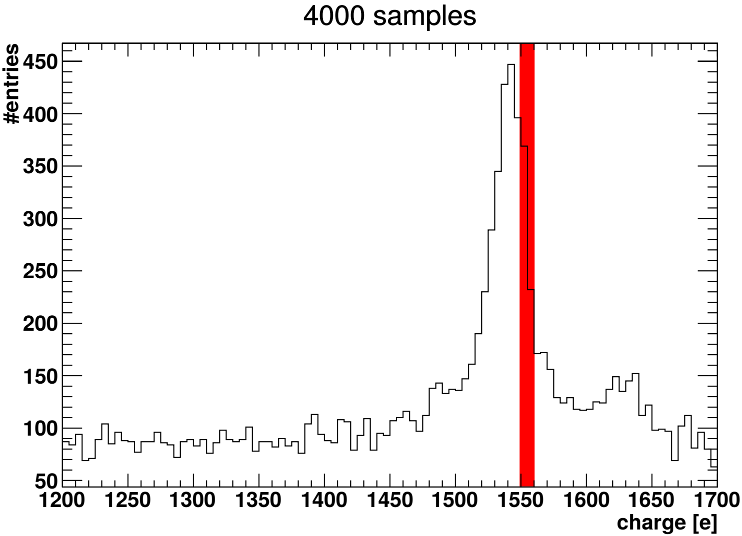
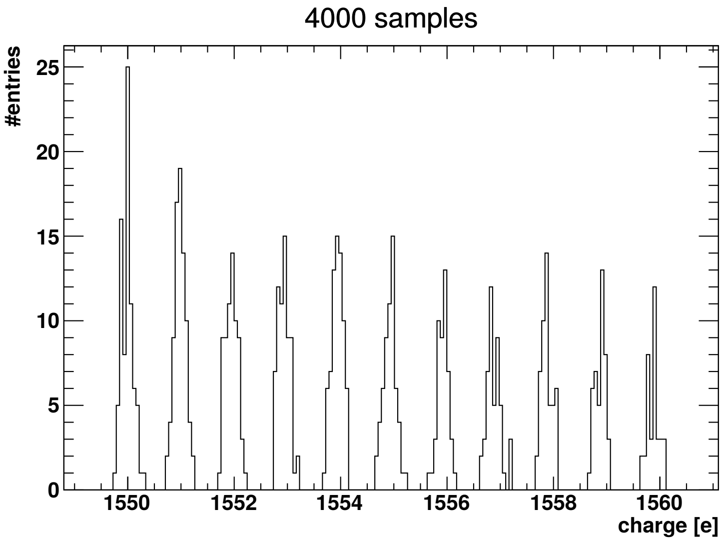
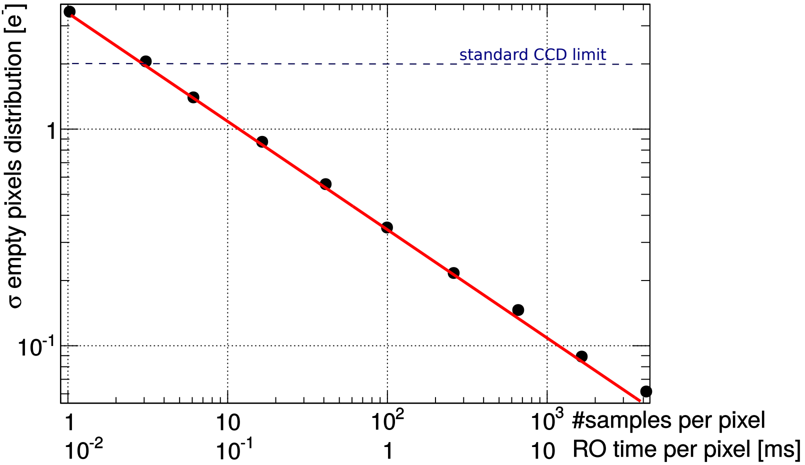


keep counting: ..1550, 1551, 1552..



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



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

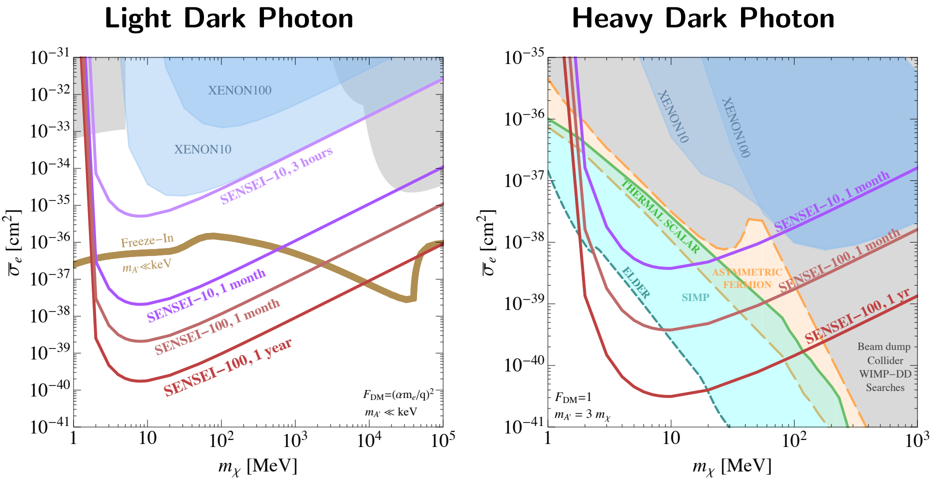
Dark Current $[e^{-}pix^{-1}day^{-1}]$	$\geq 1e^{-}$ [pix]	$\geq 2e^{-}$ [pix]	$\geq 3e^{-}$ [pix]
$\mathbf{10^{-3}}$	1×10^{8}	3×10^{3}	7×10^{-2}
$\mathbf{10^{-5}}$	1×10^{6}	3×10^{-1}	7×10^{-8}
$\mathbf{10^{-7}}$	1×10^{4}	3×10^{-5}	7×10^{-14}

Measured upper limit for the DC in CCDs is:

$\mathbf{1\times10^{-3}}$ **e pix^{-1}day^{-1}** arXiv:1611.03066

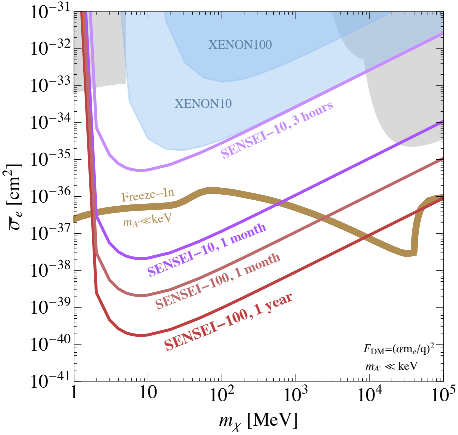
Could be orders of magnitude lower. **Theoretical prediction is $O(10^{-7})$**

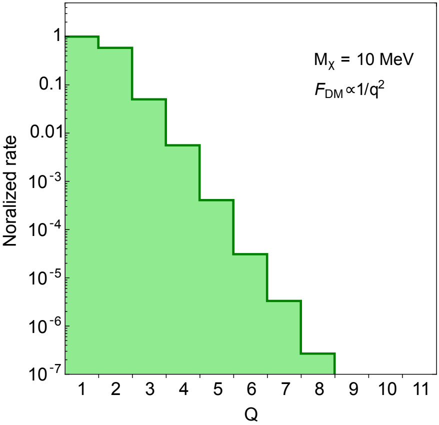
SENSEI: reach of a 100g, *zeroish-background* experiment



SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin





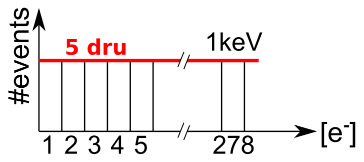
SENSEI: electron recoil background requirements

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

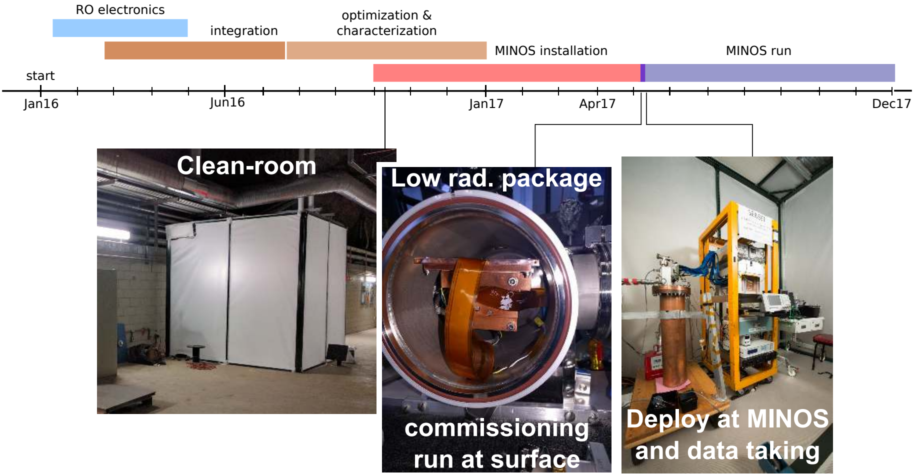


182.5 events over the 278 charge bins in the 0-1keV range

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

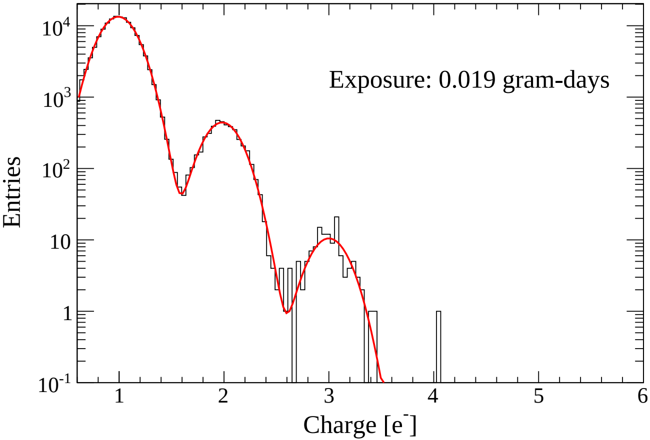
Whats going on now: Installation @MINOS (FNAL), 100m underground

Technology demonstration: installation at shallow underground site



SENSEI commissioning run at surface: arXiv:1804.00088

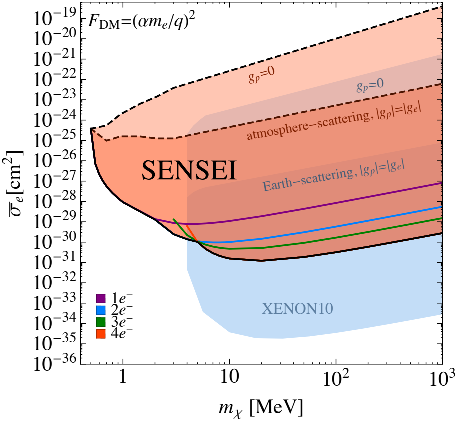
Observed spectrum using 800 samples per pixel



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: arXiv:1702.07750

SENSEI path

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

BACK UP SLIDES

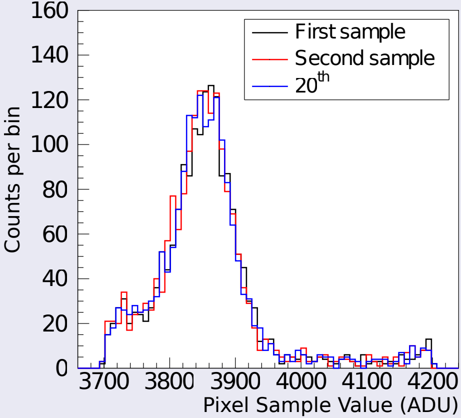
SENSEI path

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

Image taken with SENSEI: 20 samples per pixel

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

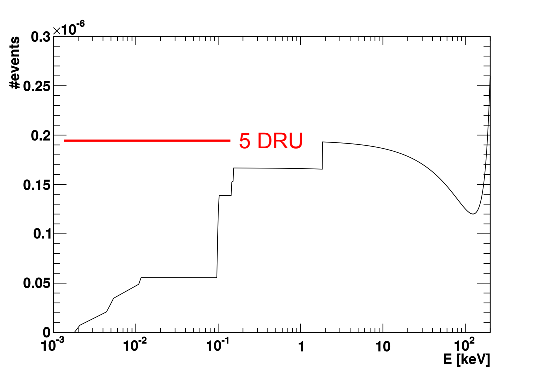


The gain is the same for all the samples

Skipper CCD - electron recoil background requirements

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

- **at lower energies atomic binding energies are relevant**



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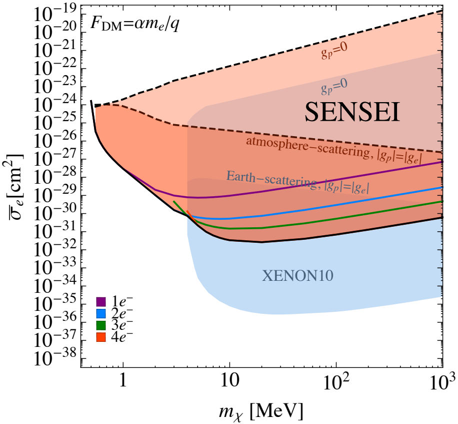

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)

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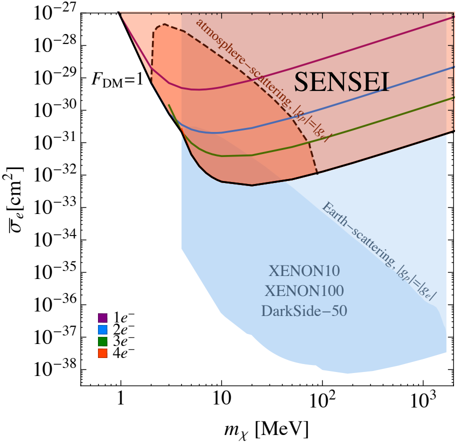

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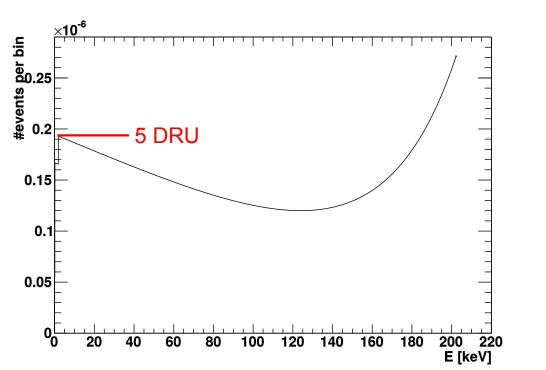

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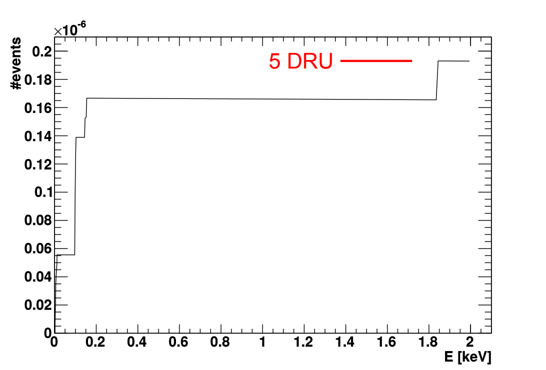

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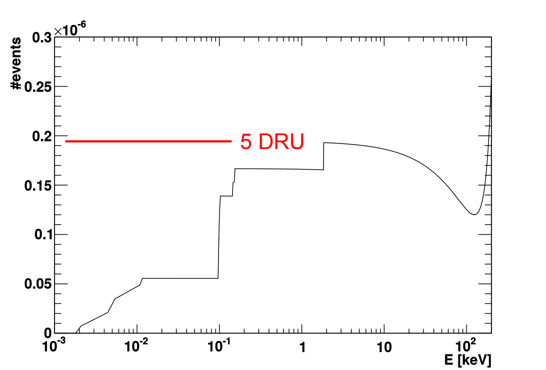

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A more detailed analysis: MC simulation, G4 3D Monash model

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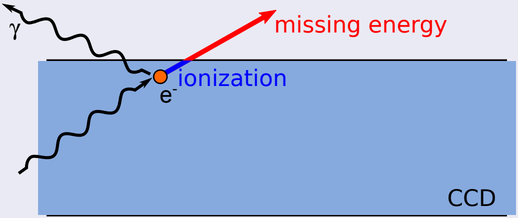

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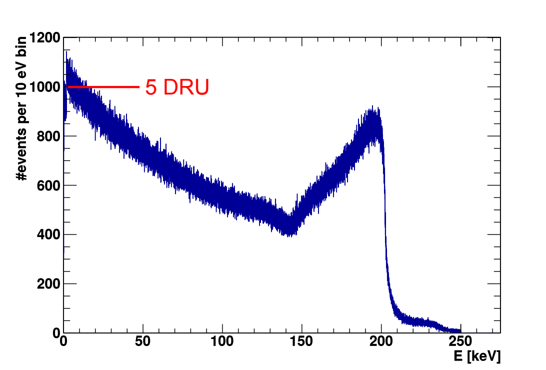

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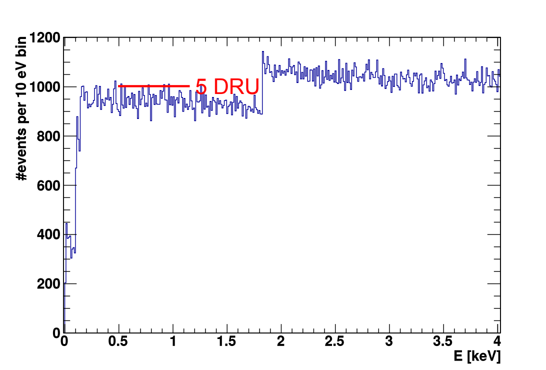

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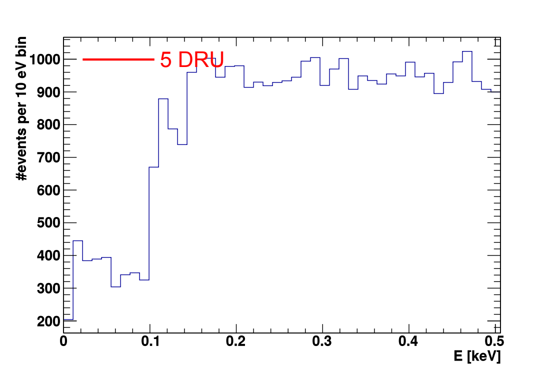

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Back of the envelope estimation is conservative