Developments on Skipper-CCD detectors for dark matter searches

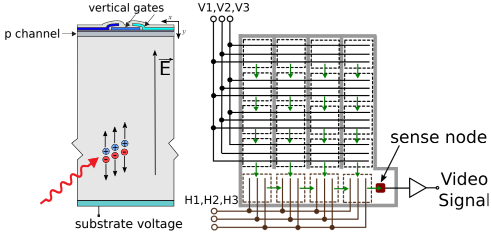
Miguel Sofo Haro
for the SENSEI Collaboration

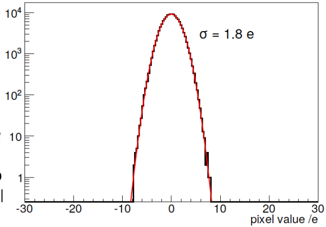
July 18, 2019

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

Fermilab

Fully-Depleted Charge Coupled Devices (CCDs)

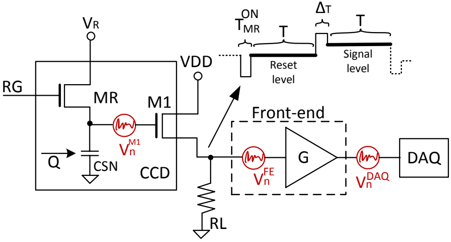


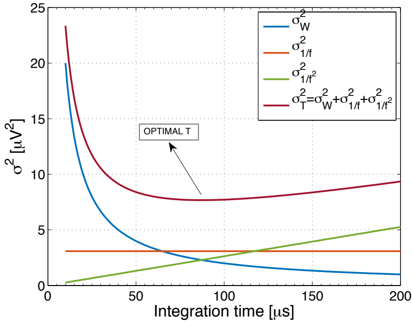


- $C_{SN} < 0.05\mathrm{pf} \rightarrow S_{V/e^-} > 3\mu V/e^-$ $\rightarrow$ low readout noise $\rightarrow \sim 50\,\mathrm{eV}$ energy threshold.
- 675 μm, $6{\times}6\,\mathrm{cm}^2$ detector have a mass of 5.2 g

Has motivated their application in **low energy threshold particle experiments**. Two examples are CONNIE (Coherent Neutrino Nucleous Interaction Experiment) and DAMIC (Dark Matter in CCDs).

CCDs readout noise





- CDS is excellent for removing high frequency noise but sensitive to low frequencies
- 1/f impose a minimum noise.

SENSEI: Sub-Electron-Noise SkipperCCD Experimental Instrument

SENSEI LDRD Collaboration (2015)

- **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

Objetive:

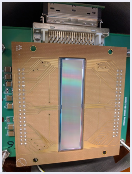
Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) using SkipperCCDs.

Skipper-CCD:

Idea proposed in 1990 by Janesick et al. (doi:10.1117/12.19452)

SENSEI: First working instrument using SkipperCCD tech

Sensors



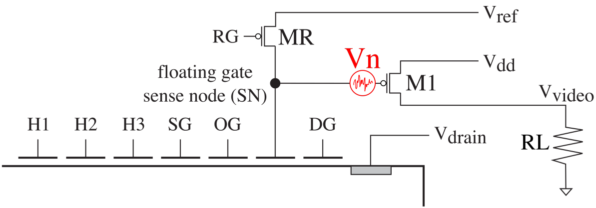
- Skipper-CCD prototype designed at LBNL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

Instrument

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

Skipper-CCD

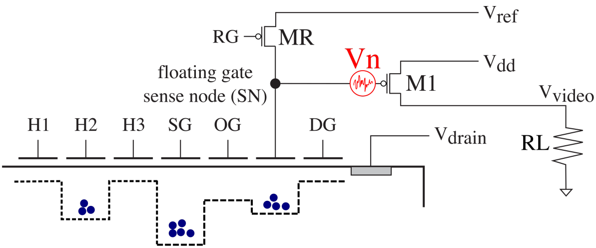
Output stage with non-destructive charge readout.



The final pixel value is the average of the samples $\frac{1}{N}\Sigma_i^N\,(\textit{pixel sample})_i$

Skipper-CCD

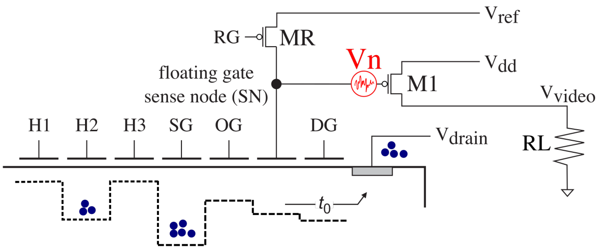
Output stage with non-destructive charge readout.



The final pixel value is the average of the samples $\frac{1}{N}\Sigma_i^N\,(\textit{pixel sample})_i$

Skipper-CCD

Output stage with non-destructive charge readout.

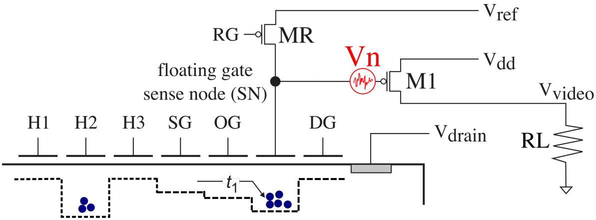


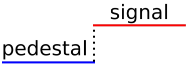
pedestal

The final pixel value is the average of the samples $\frac{1}{N}\Sigma_i^N\,(pixel\ sample)_i$

Skipper-CCD

Output stage with non-destructive charge readout.

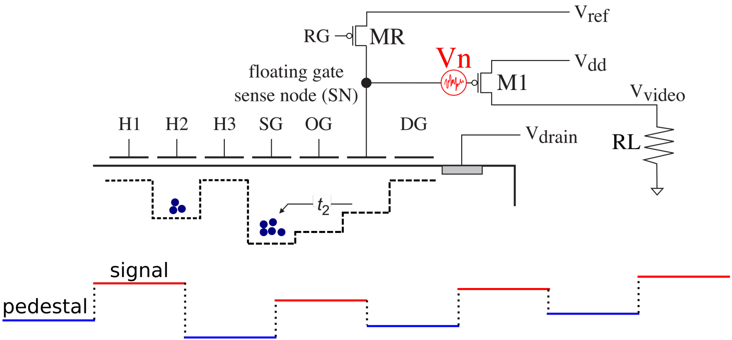




The final pixel value is the average of the samples $\frac{1}{N}\Sigma_i^N\,(pixel\ sample)_i$

Skipper-CCD

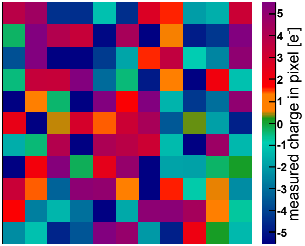
Output stage with non-destructive charge readout.



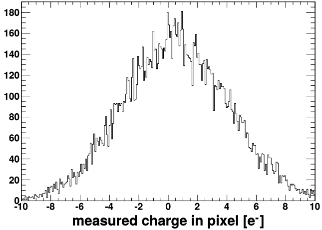
The final pixel value is the average of the samples $\frac{1}{N}\boldsymbol{\Sigma}_i^N\,\boldsymbol{(}\textit{pixel sample}\boldsymbol{)}_i$

Counting electrons: 0, 1, 2..

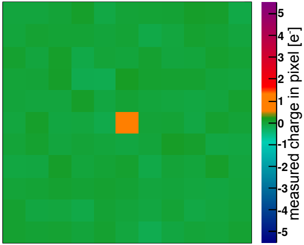
Standard CCD mode: charge in each pixel is measured once



Readout-noise: 3.5 e RMS



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



Readout-noise: 0.06 e RMS

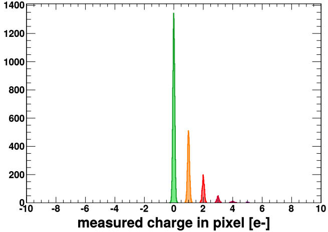
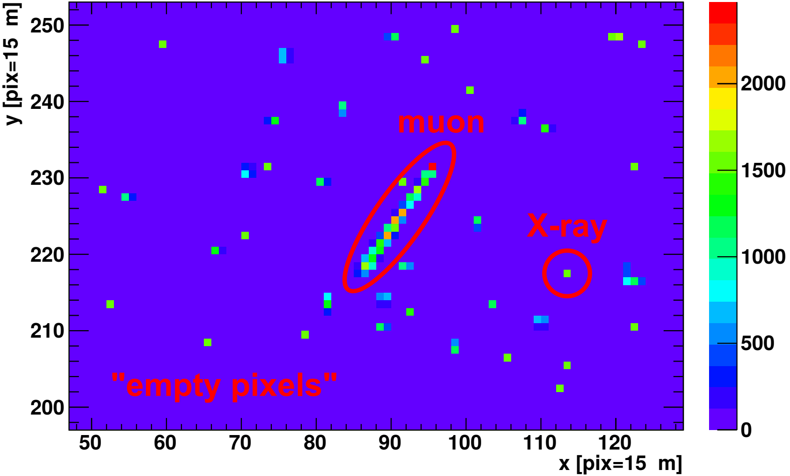
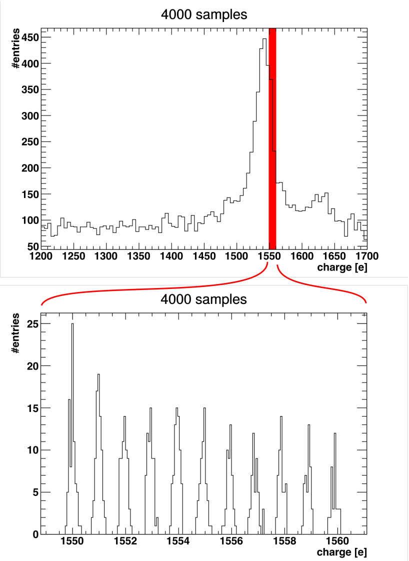


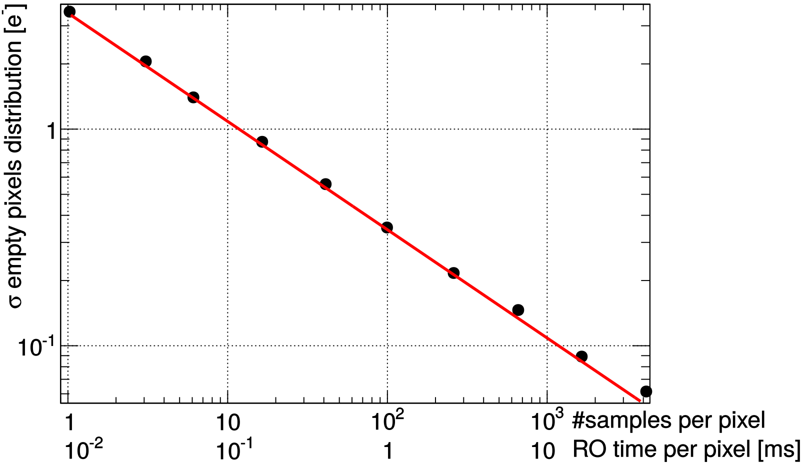
Image taken with SENSEI: 4000 samples per pixel (processed)



^{55}Fe X-ray source: keep counting: ..1550, 1551, 1552..



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



SENSEI Collaboration

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

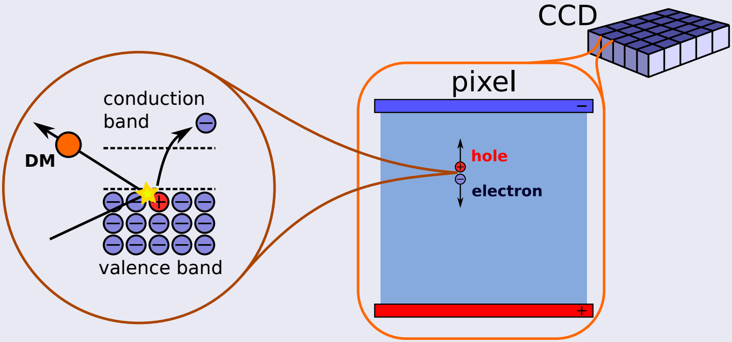
- **Fermilab:** Michael Crisler, Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg
- **Oregon University:** Tien-Tien Yu
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Liron Barack, Erez Ezion, Tomer Volansky
- **+ several additional students + more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

Fully funded by Heising-Simons Foundation & Fermilab

SENSEI: lower the energy threshold to look for light DM candidates

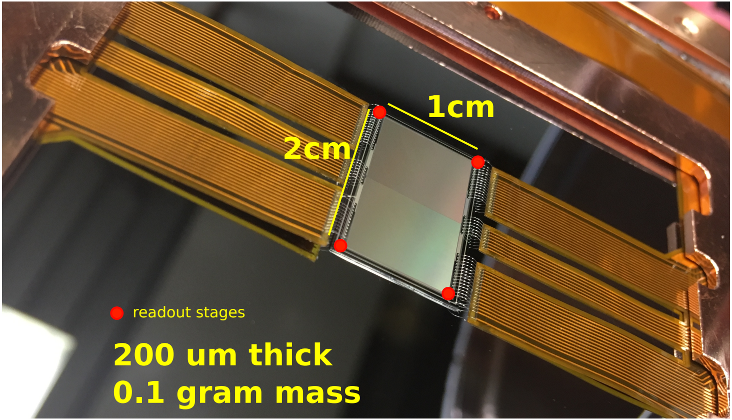
Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

Idea: use electrons in the bulk silicon from a CCD as target



This requires very low noise!

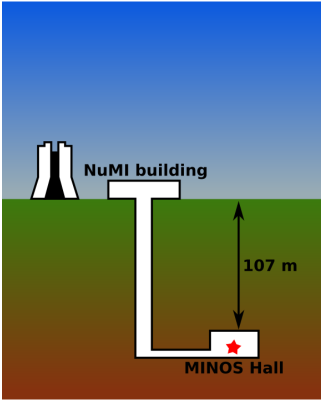
protoSENSEI: technology demonstrator

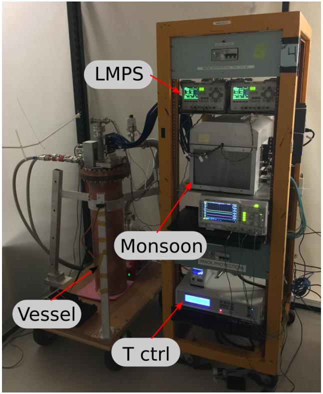


We used the parasitically-fabricated R&D sensors to learn how to optimize operations and produce early-science results

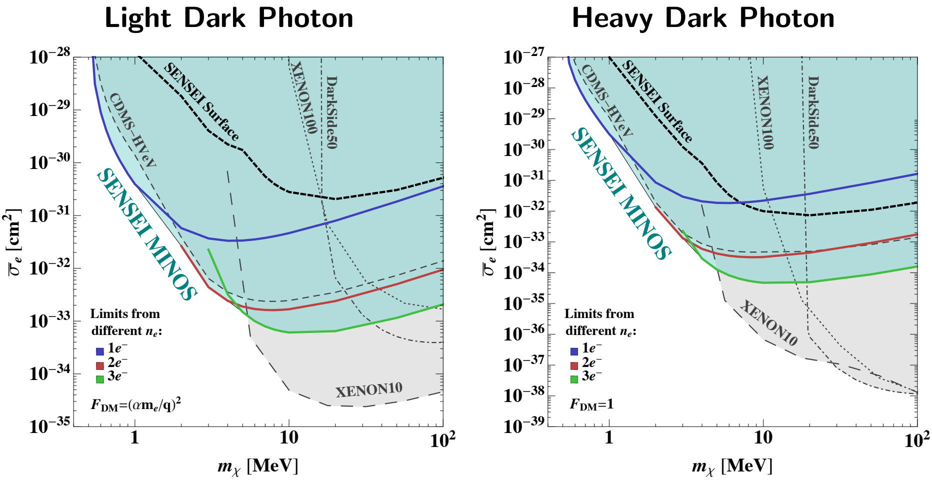
ProtoSENSEI @MINOS

Technology demonstration: installation at shallow underground site





protoSENSEI @MINOS: results



World best limit below 5 MeV!!

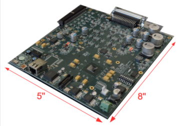
What are the next steps for SENSEI?

Build an experiment with more mass
Reduce dark current

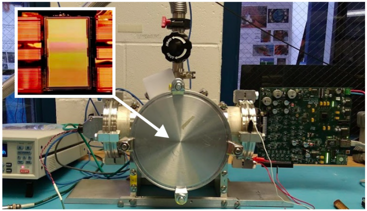
- 10 gram Skipper-CCD system in 2019 → MINOS.
- 100-gram Skipper-CCD system in 2020 → SNOLAB, 2000 mts.

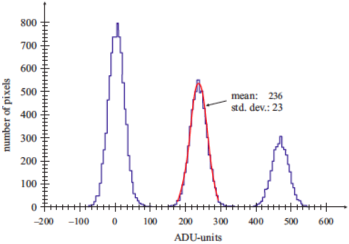
- New detectors
- New RO electronics.

LTA: Low Treshold Adquisition



- Single board → four quadrants Skipper-CCD
- Clock voltages range and shape suitable for Skipper-CCDs
- Fully digital: ADC → FPGA → DCDS.
- Smart readout and DSP techniques for noise reduction.
- Easy scalable to houndred of detectors.

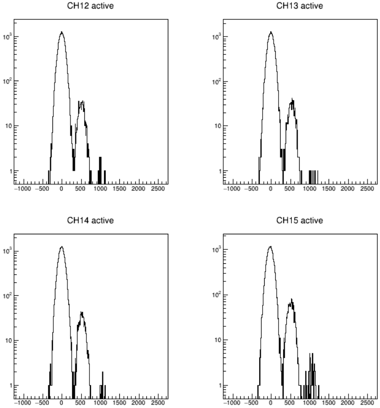




New Skipper-CCDs

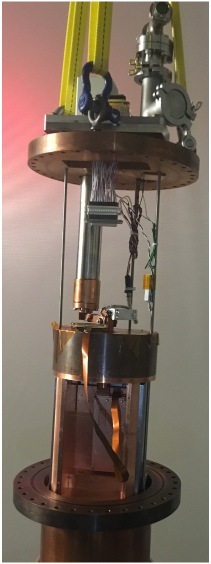
- New silicon with higher resistivity and IR cover to reduce DC.
- Thicker detectors of 675 μm, 6144×886 pixels of 15×15 μm^2
  - 10 grams → 5 skp-CCDs
  - 100 grams → 50 skp-CCDs
- Detector packaging
  - low radiation background
  - good thermal conductivity
- Output stage with high single-electron sensitivity.

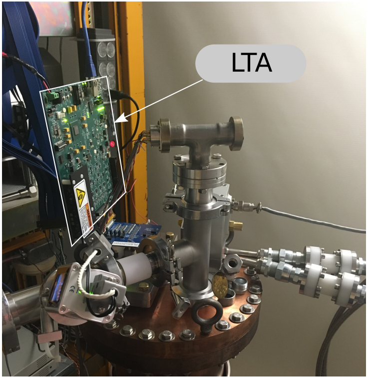
New Skipper-CCDs, surface test



$0.14\,e^-_{\rm rms}/{\rm pix}$ (300 samples and IW=30 μs)

Current Step: single-device at MINOS





Currently taking data:

- optimization
- DC measurement

SENSEI path

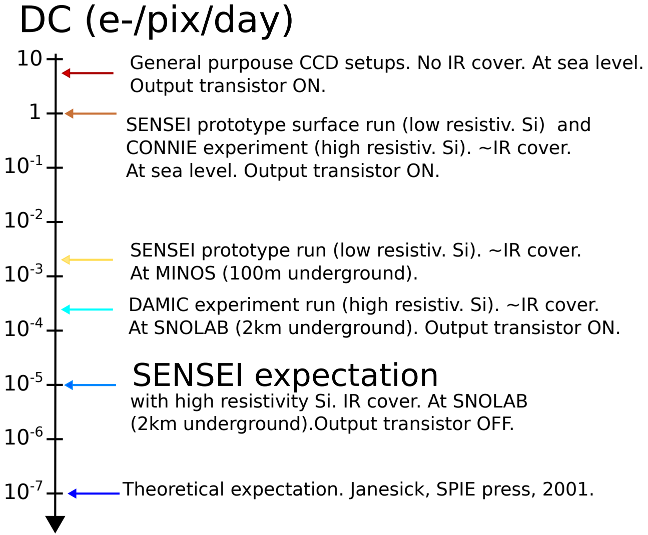
Summary

- SENSEI is the first dedicated experiment searching for electron-DM interactions
- protoSENSEI:
  - surface $\rightarrow$ probed 0.5-4 MeV masses for the first time, and larger xsec than existing direct-detection constraints.
  - MINOS $\rightarrow$ produced best limit for light DM with masses bellow 5 MeV
- 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 done, construction started.
  - Grant from Heising-Simons Foundation
  - Full technical support from Fermilab

THANK YOU!

BACK UP SLIDES

Dark current measurements and expectation



SENSEI threshold vs dark current

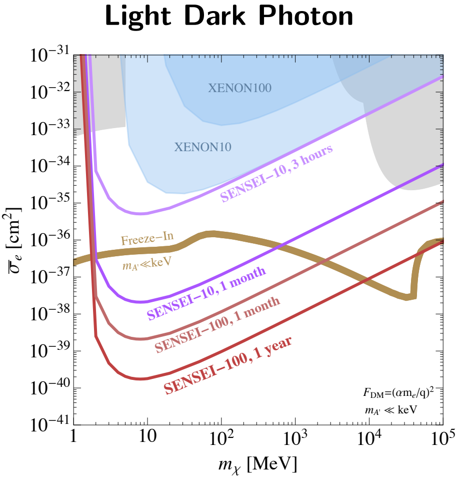
- Counting electrons ⇒ **noise has zero impact**
- It can take about 1h to read the sensors
- **Dark Current is the limiting factor**

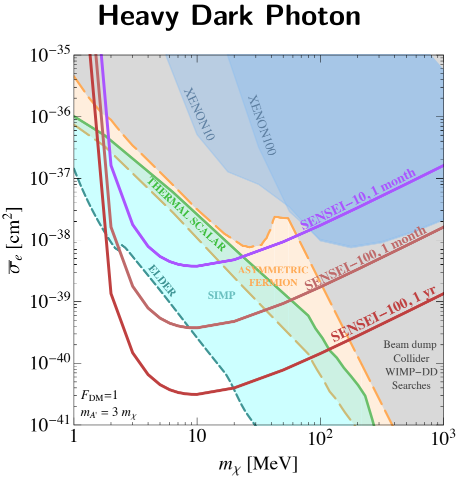
It's better to readout continuously to minimize the impact of the DC

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}

Operation mode (continuous-RO or long-exposures) will depend on the measured DC and spurious charge of the Science sensors

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

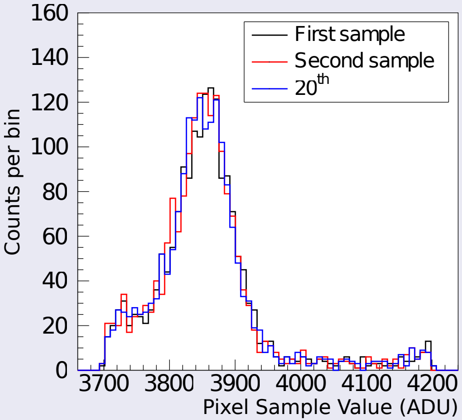




Fermilab

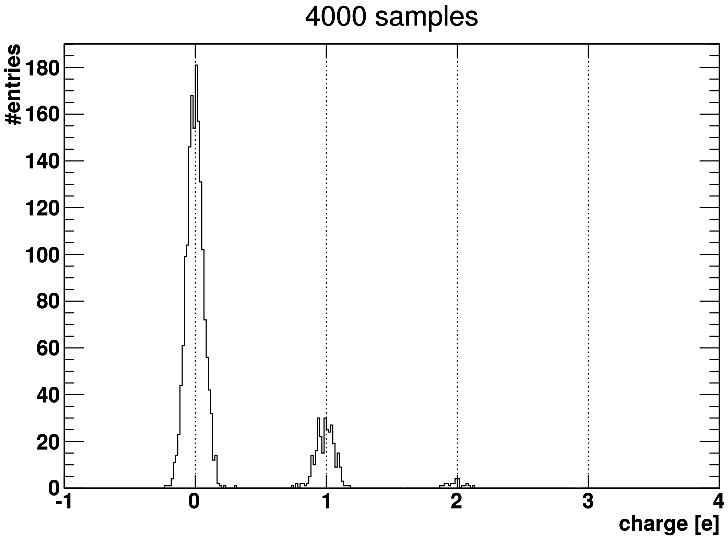
Image taken with SENSEI: 20 samples per pixel

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

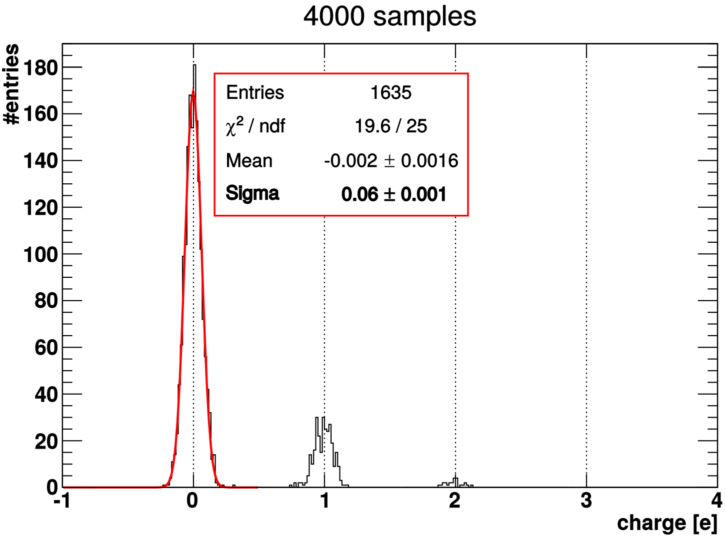


The gain is the same for all the samples

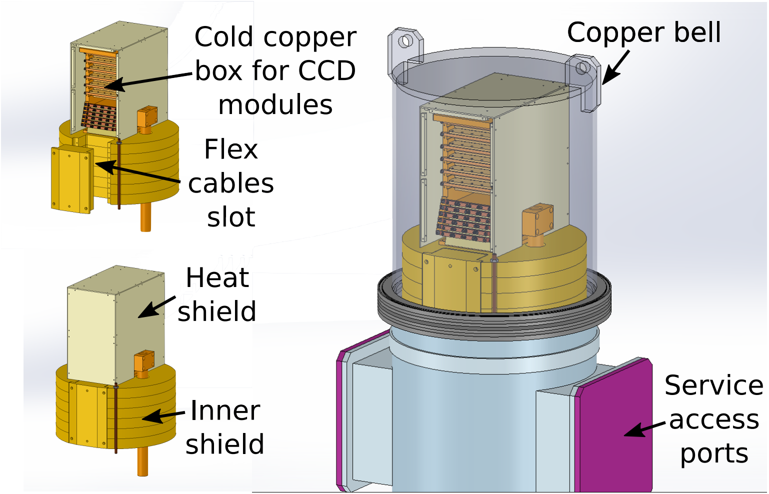
Charge in pixel distribution. Counting electrons: 0, 1, 2..



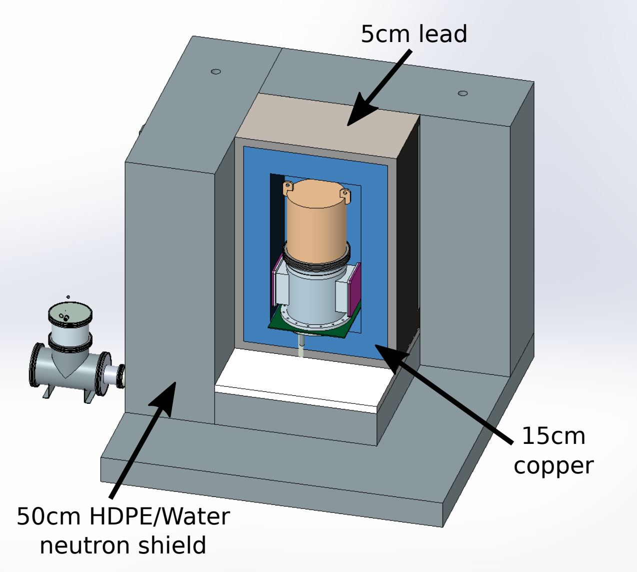
Charge in pixel distribution. Counting electrons: 0, 1, 2..



Snolab vacuum vessel design

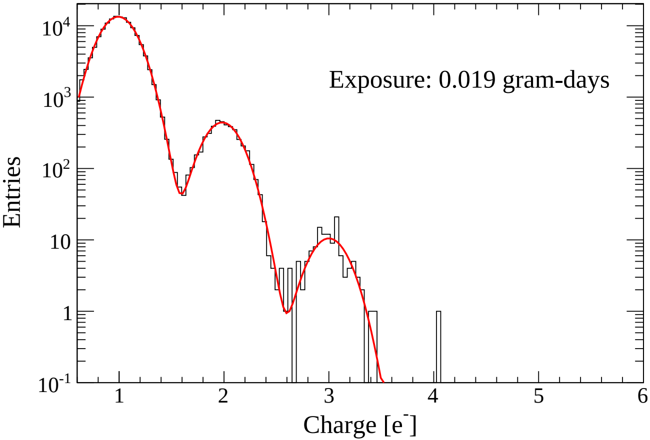


Snolab shield design



protoSENSEI: commissioning run at surface: arXiv:1804.00088

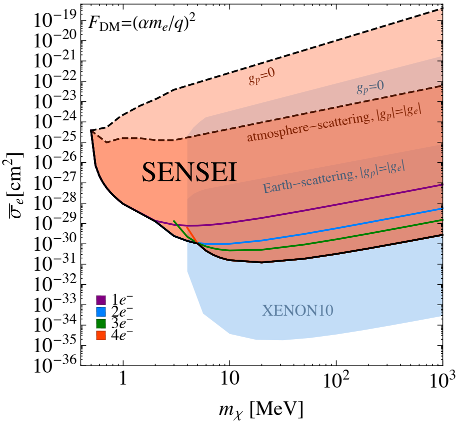
Observed spectrum using 800 samples per pixel



dark current: ~1.1 e^{-} /pix/day; no events with 5-100 electrons

protoSENSEI: commissioning run at surface: arXiv:1804.00088

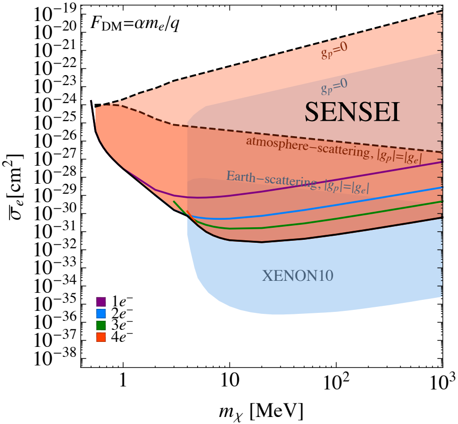
First direct-detection constraints between ∼500 keV to 4 MeV!



Terrestrial effects: Emken, Essig, Kouvaris, Sholapurkar (to appear)

SENSEI commissioning run at surface: arXiv:1804.00088

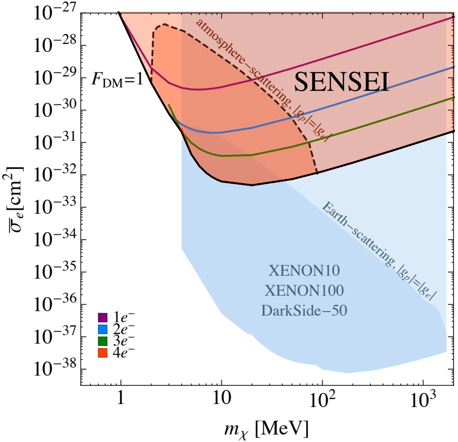
First direct-detection constraints between ∼500 keV to 4 MeV!



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

SENSEI commissioning run at surface: arXiv:1804.00088

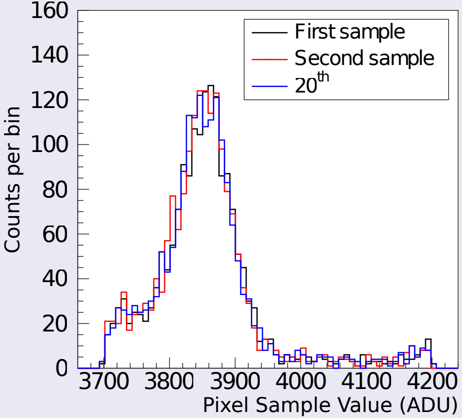
First direct-detection constraints between ∼500 keV to 4 MeV!



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

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