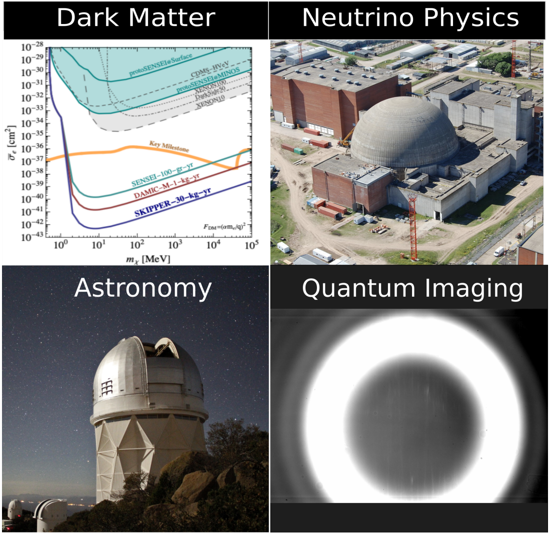
Counting electrons with the Skipper-CCD

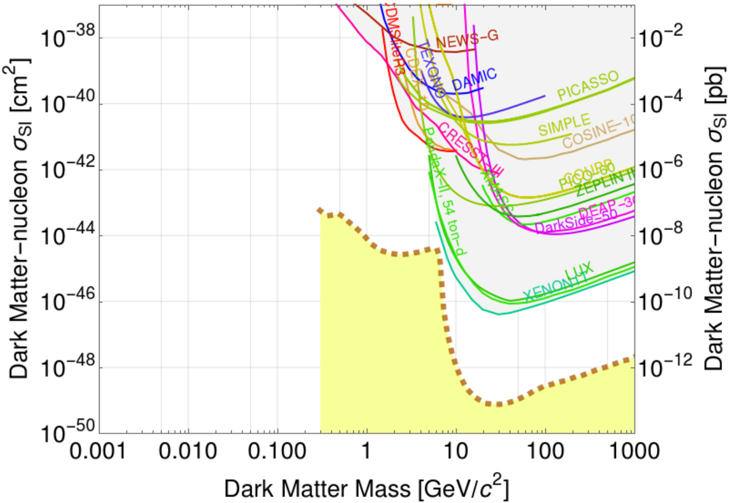
Javier Tiffenberg
Fermi National Laboratory

Aug 12, 2020

Skipper-CCD applications



Context & Motivation: Direct detection history

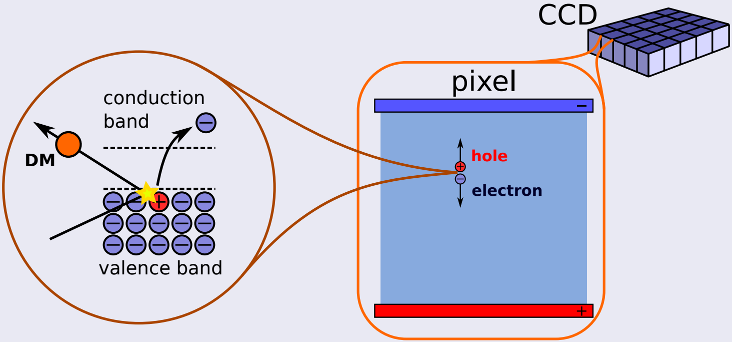


Dark Matter Limit Plotter v5.00, updated Feb 14, 2019.

Goal: 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 of a CCD as targets



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
- **CERN:** Tien-Tien Yu
- **Stanford University*:** Jeremy Mardon

Main goals

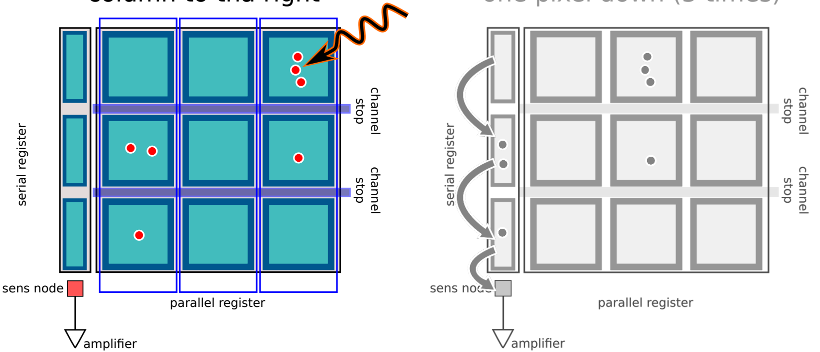
- Build the first working detector using Skipper-CCDs.
- Validate the technology for DM and ν experiments.
- Probe DM masses at the MeV scale through electron recoil.
- Probe axion and hidden-photon DM with masses down to 1 eV.
- Single photon imaging with low dark counts.

CCD: readout

3x3 pixels CCD

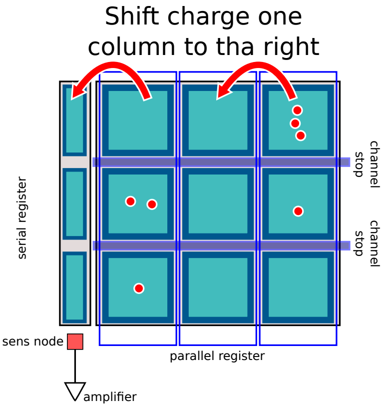
Shift charge one column to tha right

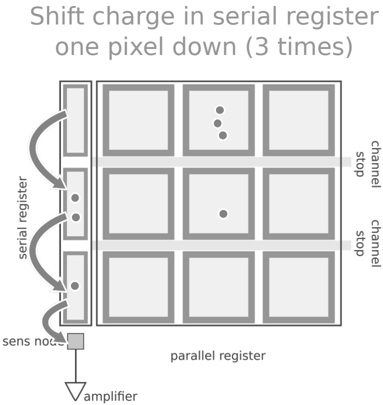
Shift charge in serial register one pixel down (3 times)



CCD: readout

3x3 pixels CCD





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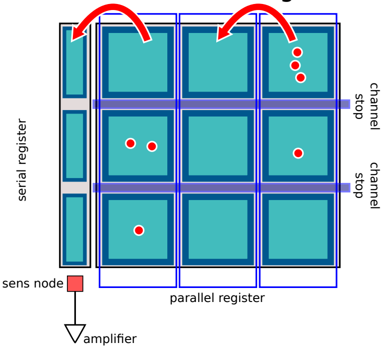
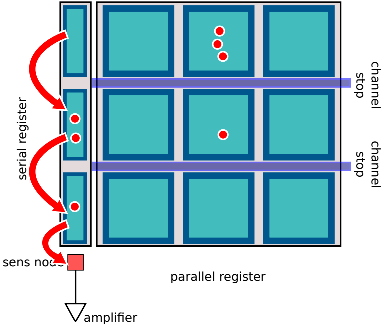
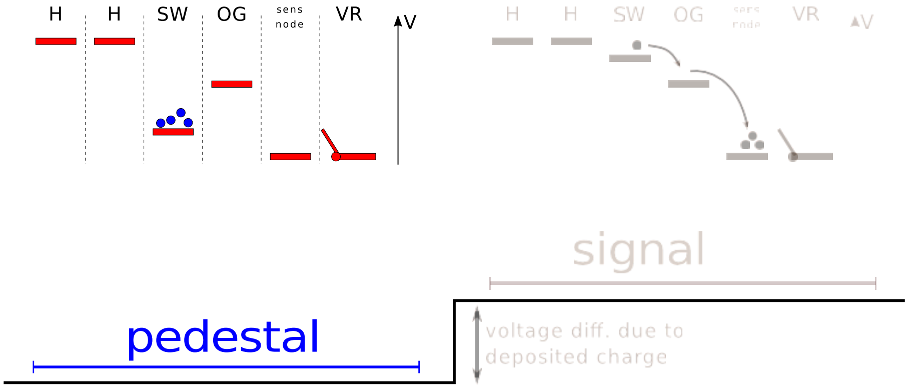


Shift charge in serial register one pixel down (3 times)



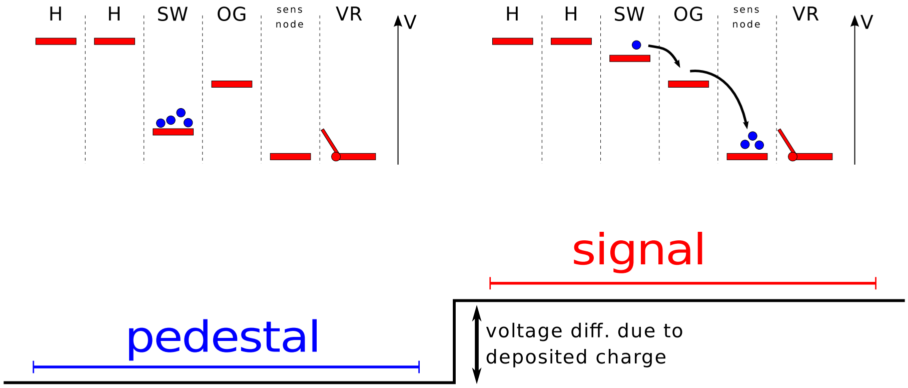
capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

CCD: readout



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

CCD: readout


H
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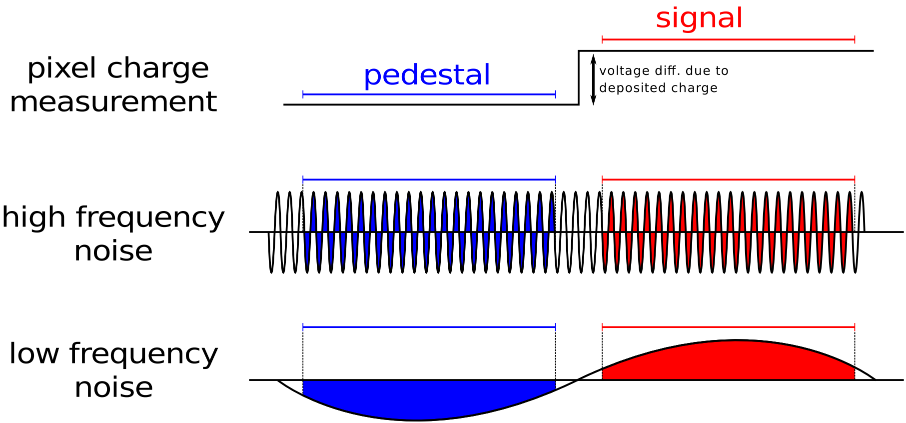
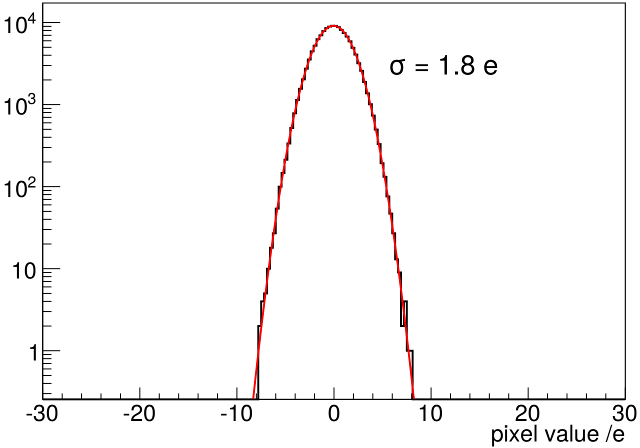
CCD: readout



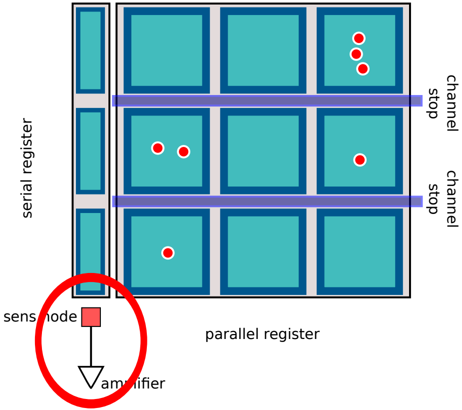
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution, regular scientific CCD



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

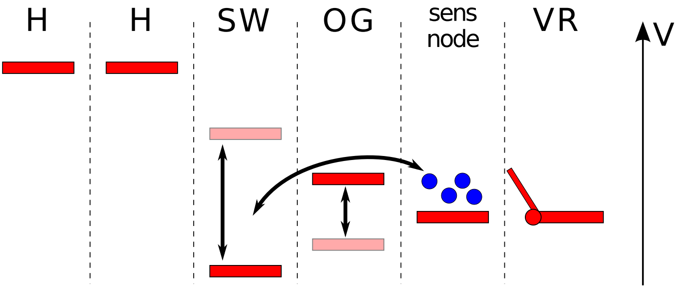
Lowering the noise: Skipper CCD



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



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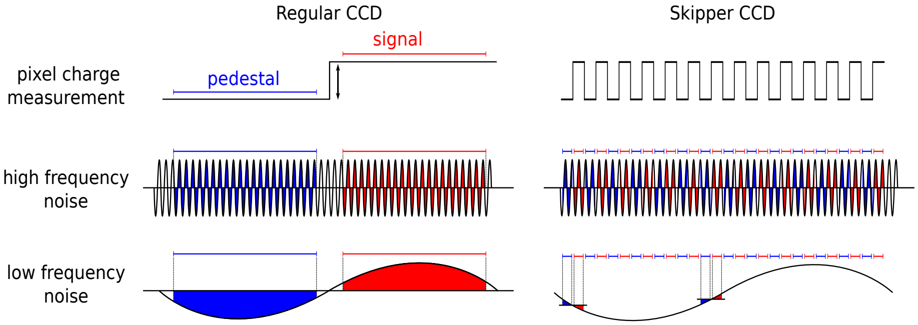
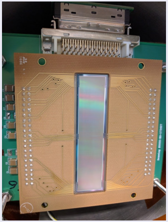


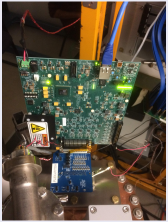
SENSEI: First working instrument using SkipperCCD tech

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
- Low Threshold Acquisition electronics: 2004.07599
- Firmware and image processing software
- Optimization of operation parameters

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

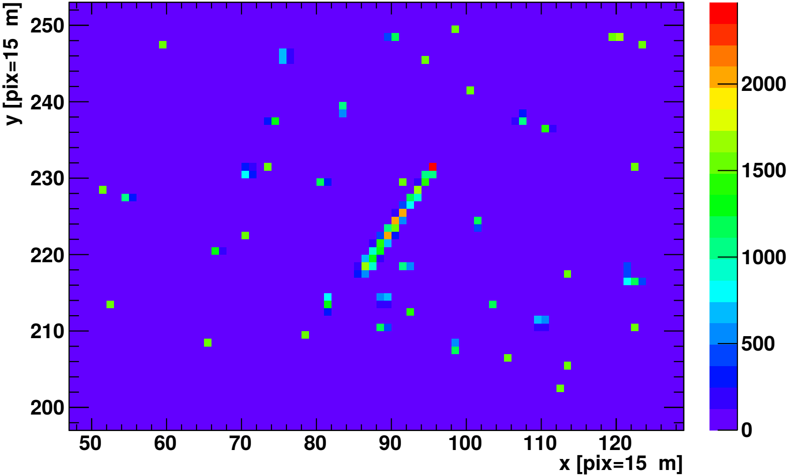
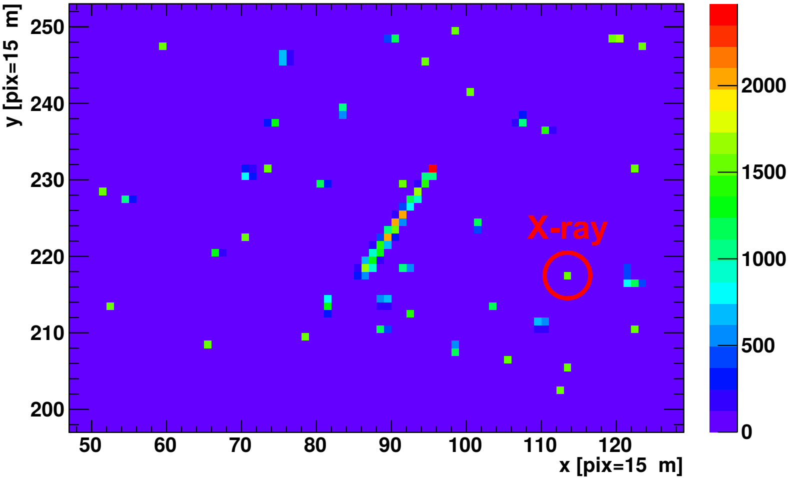


Image taken with SENSEI: 4000 samples per pixel (processed)



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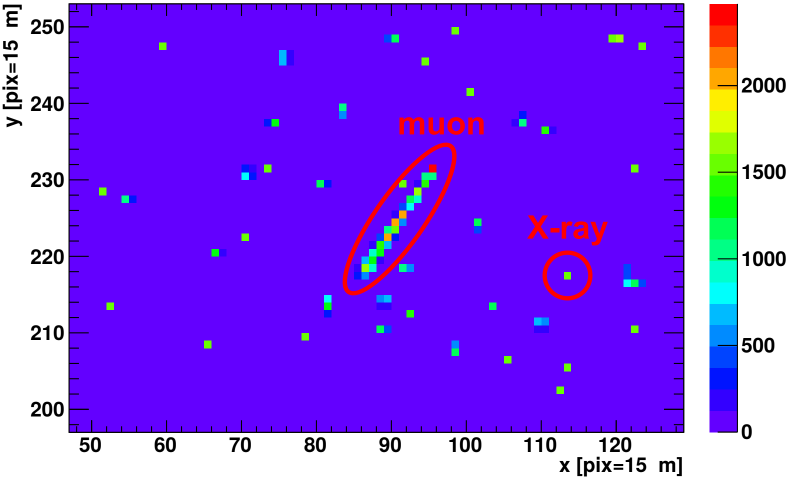
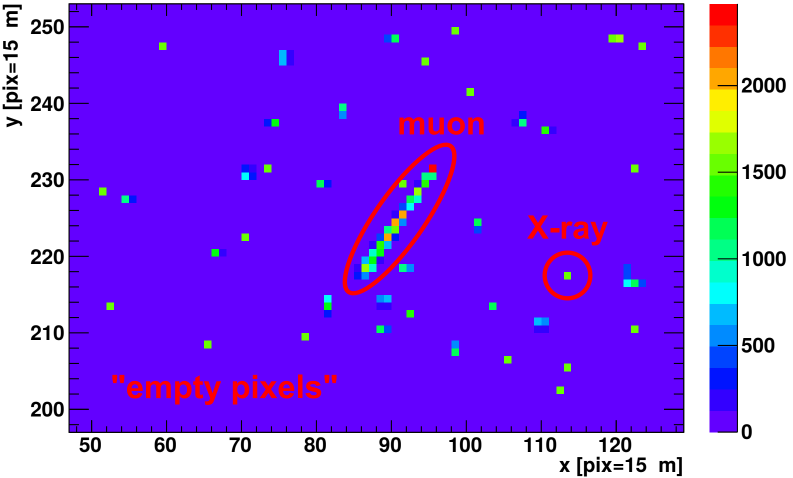
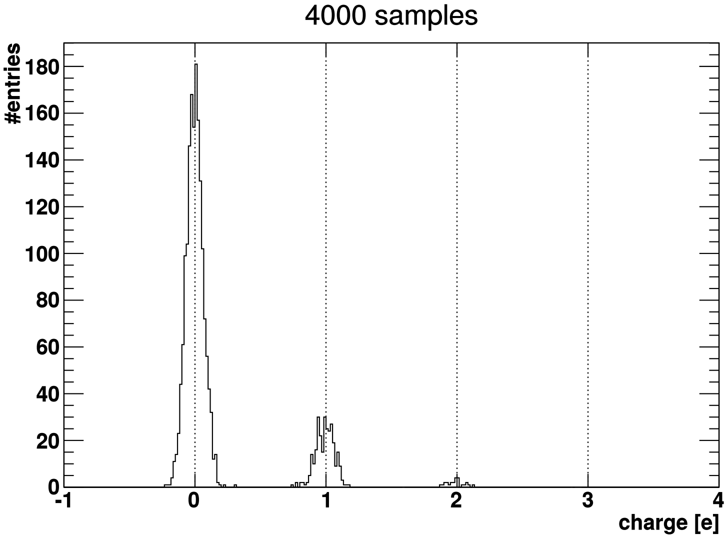


Image taken with SENSEI: 4000 samples per pixel (processed)



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



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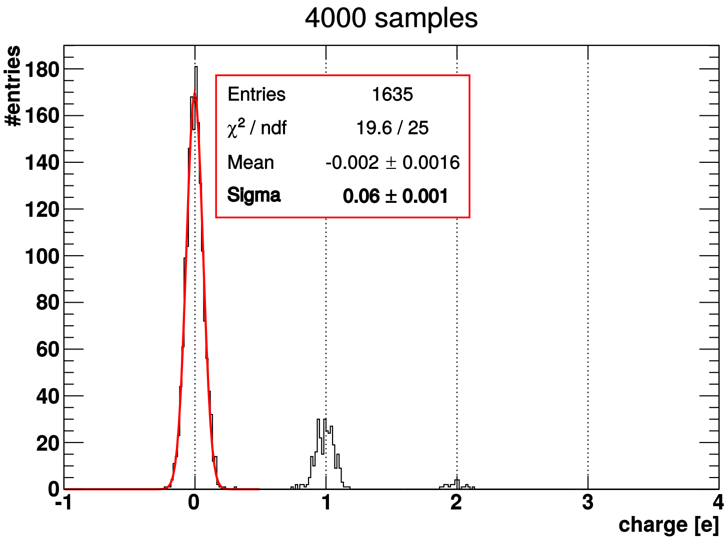
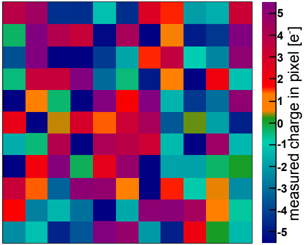
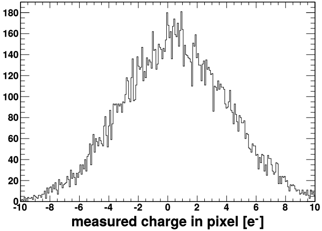


Counting electrons: 0, 1, 2..

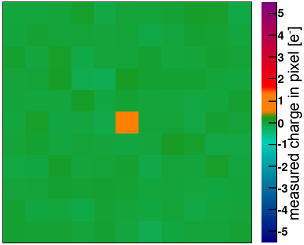
Standard CCD mode: charge in each pixel is measured once



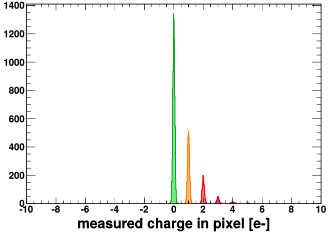
Readout-noise: 3.5 e RMS



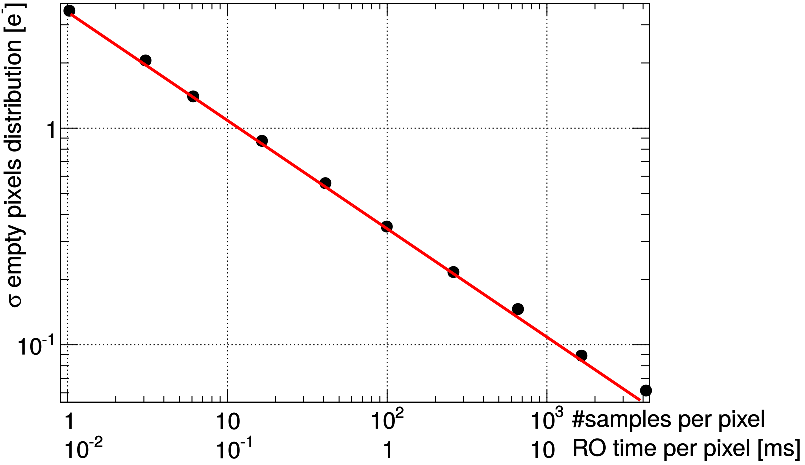
New Skipper CCD: charge in each pixel is measured multiple times



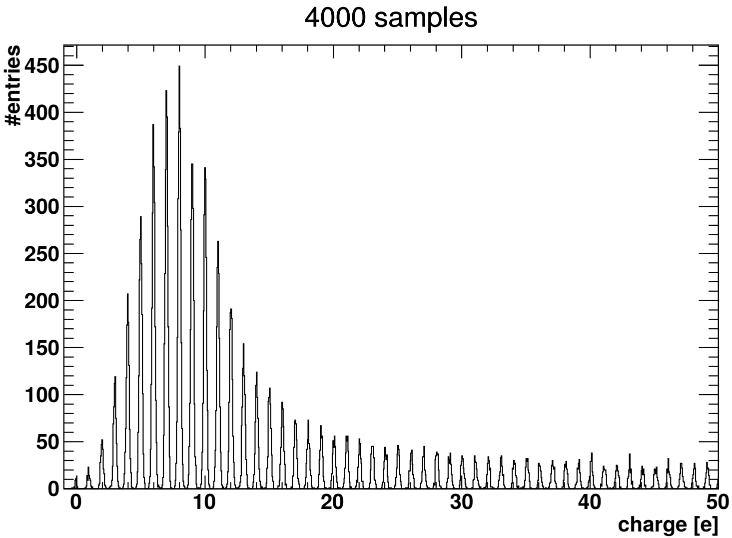
Readout-noise: 0.06 e RMS



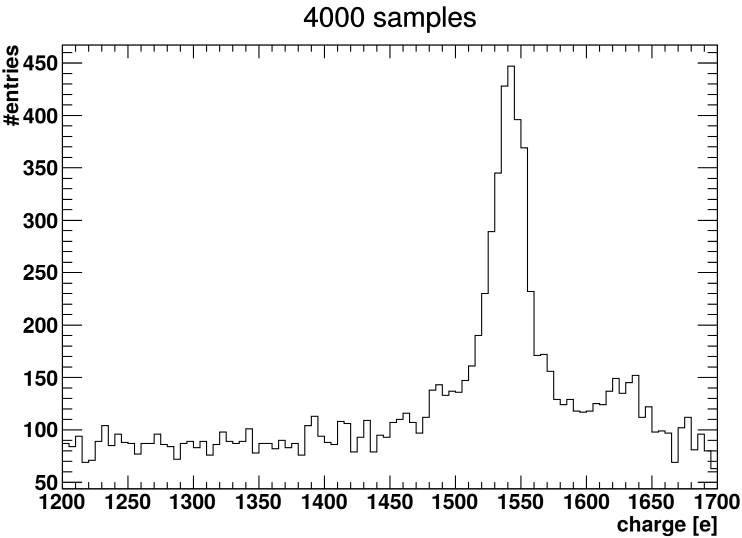
Noise vs. #samples - $1/\sqrt{N}$



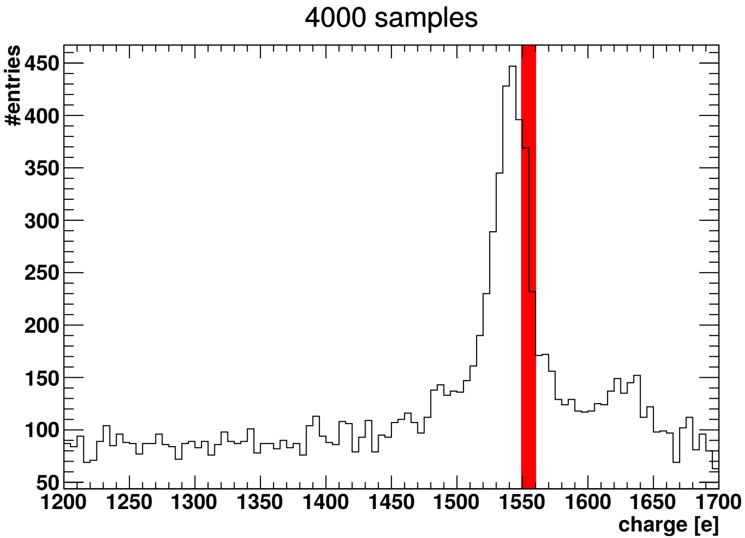
Counting electrons: ..48, 49, 50..



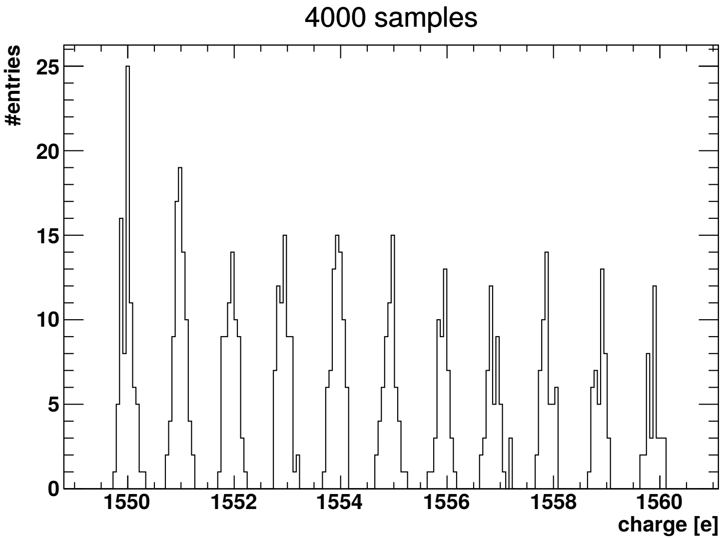
^{55}Fe X-ray source



^{55}Fe X-ray source

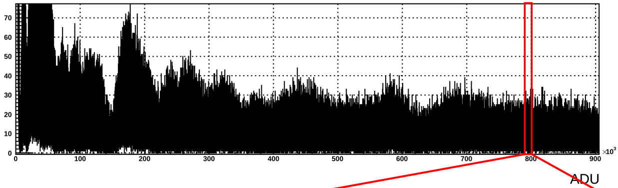


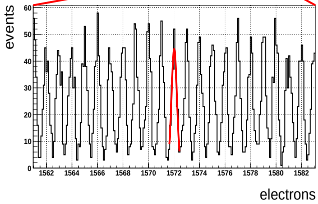
keep counting: ..1550, 1551, 1552..



Absolute self-calibration!

The signal that corresponds to each electron peak can be counted from 0 to 2000 to produce an absolute calibration without an external reference!





We used this technique to produce the most precise measurement of the Fano factor in silicon (see: arXiv:2004.11499)

The SENSEI Collaboration

Fermilab:

- F. Chierchie, M. Cababie, G. Cancelo, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez-Moroni, D. Rodrigues, M. Sofo-Haro, L. Stefanazzi, J. Tiffenberg

Stony Brook:

- L. Chaplinsky, Dawa, R. Essig, D. Gift, S. Munagavalasa, A. Singal

Tel-Aviv:

- L. Barak, I. Bloch, E. Etzion, A. Orly, S. Uemura, T. Volansky

U. Oregon:

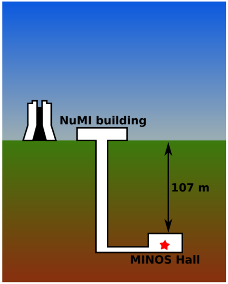
- T.-T. Yu

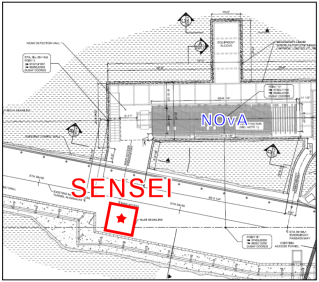
Fully funded by Heising-Simons Foundation

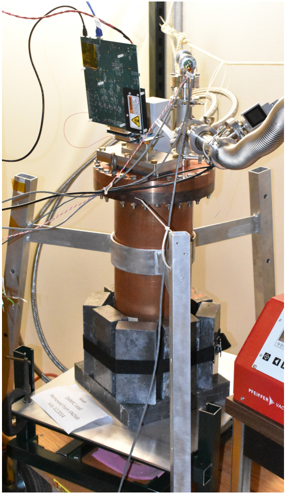
& leveraging R&D support from Fermilab

protoSENSEI: MINOS setup

- Shallow underground site reduces muon rate from cosmic rays; lead shielding reduces gamma rate from ambient radioactivity
- Cryocooler and insulating vacuum keep the CCD cold to minimize dark current

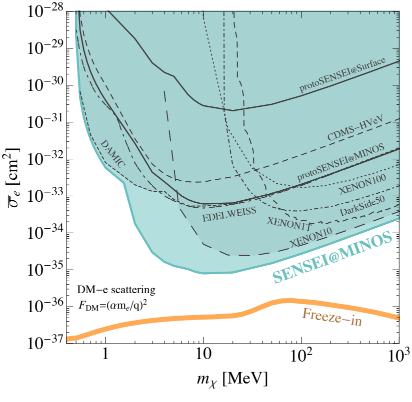


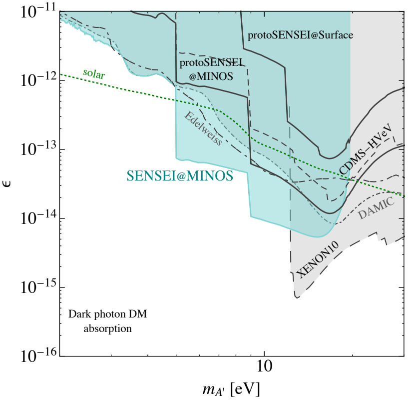




Limits on dark matter

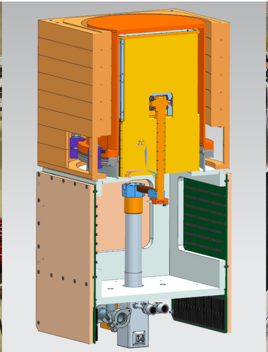
- World best limits for light dark matter candidates
  - Left to right: $F_{DM} = (\alpha m_e/q)^2$ scattering (light mediator), absorption
- Paper arXiv:2004.11378





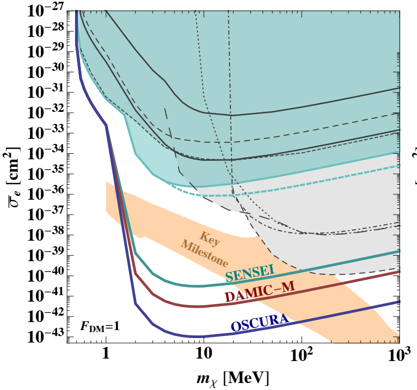
SENSEI@SNOLAB

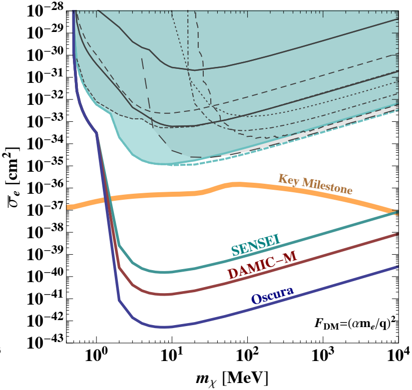
- We are building the full-scale SENSEI experiment, deep underground at SNOLAB with a low-background shield
- "Phase 1" system is operating at SNOLAB
- Vessel build and undergoing testing at Fermilab



The future of Skippers

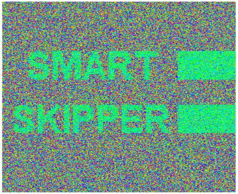
- SENSEI@MINOS demonstrated that Skipper CCDs have the performance we need to reach theory targets
  - SENSEI@SNOLAB: 100 grams
  - DAMIC-M: 1 kg
  - Oscura: 10 kg



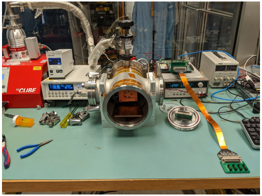


Many spin-offs at Fermilab

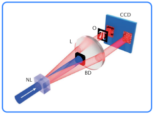

Neutrino physics at nuclear reactors



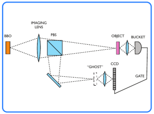
SMART-Skipper for faster readout

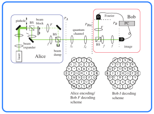

Fundamental physics of low energy interactions

Quantum imaging

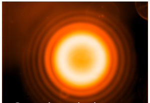


Quantum ghost imaging

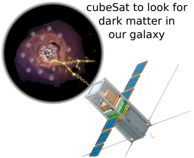




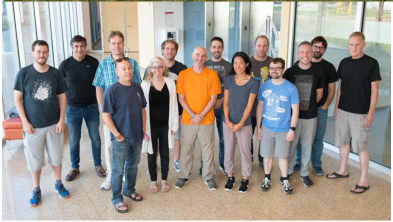
Quantum cryptography


Correlated photons measured at Fermilab


Astronomical instruments


cubeSat to look for dark matter in our galaxy

Thanks!

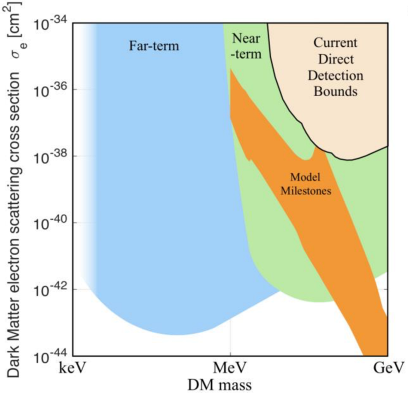


and within the wonderful SENSEI collaboration

BACK UP SLIDES

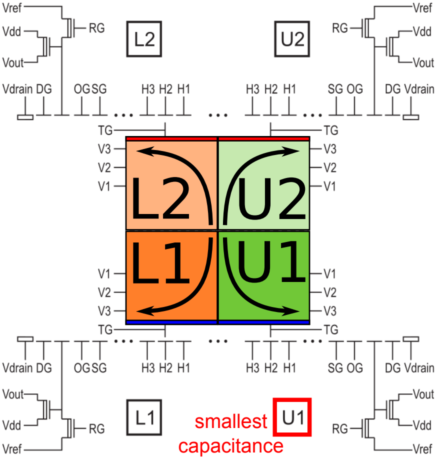
Context & Motivation: community interest - new candidates

Single electron sensitivity opens several order of magnitude in mass and cross section for small projects.



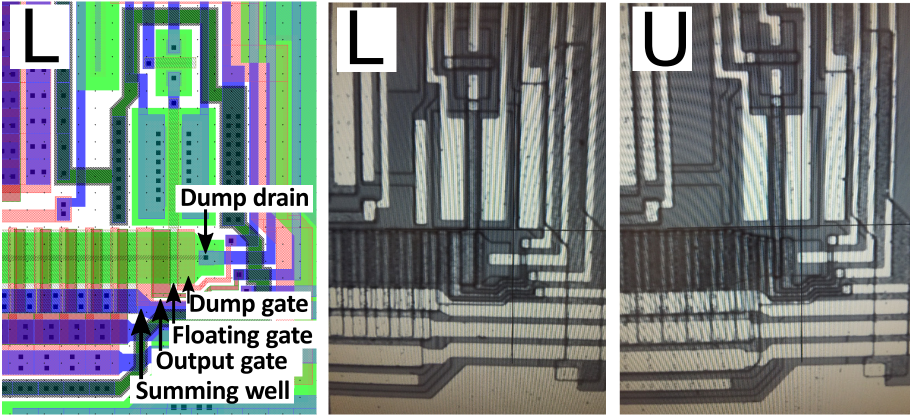
DOE report for basic research needs for Dark Matter Science.
https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

CCD: readout

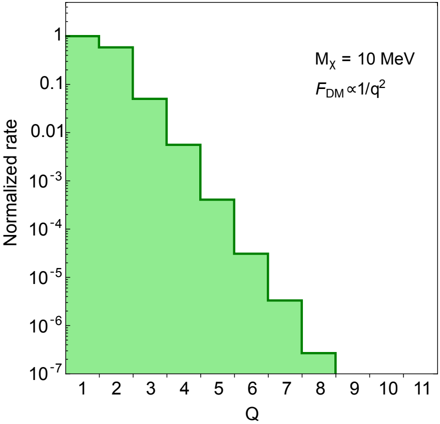


4 amplifiers per CCD, three different RO stage designs. The design with the smallest capacitance (U1) is the one that performs better.

Readout stage design



Typical e^--recoil spectrum for benchmark models



- the sensitivity is limited by the lowest charge bin.
- background impact is reduced due to the small energy window.
- main background for semiconductors detectors is the **dark current.**