SENSEI† first results, status and plans

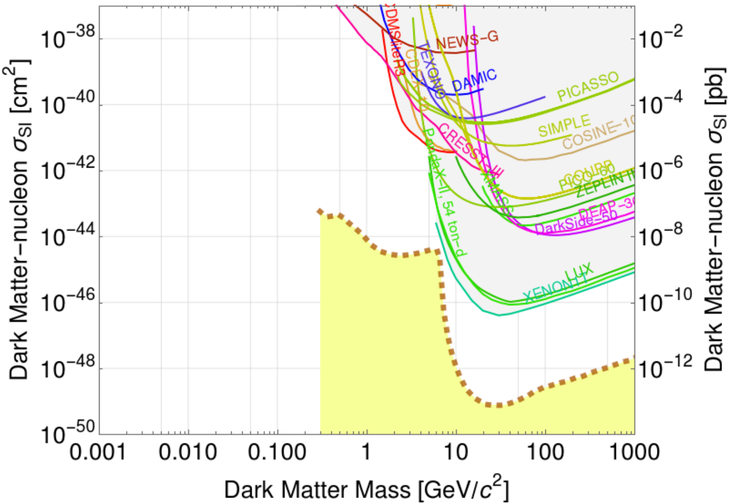
Javier Tiffenberg
for the SENSEI Collaboration

May 9, 2019

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

Fermilab

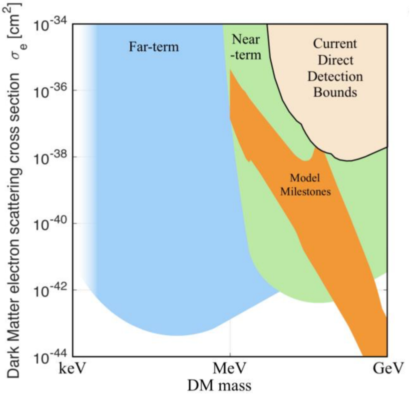
Context & Motivation: Direct detection history



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

Context & Motivation: community interest - new candidates

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



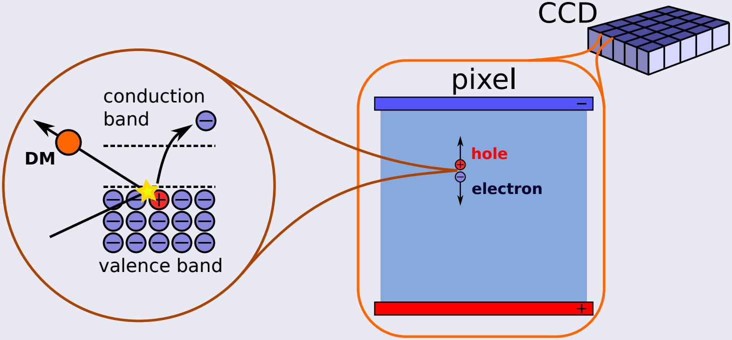
DOE report for basic research needs for Dark Matter Science.

https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

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

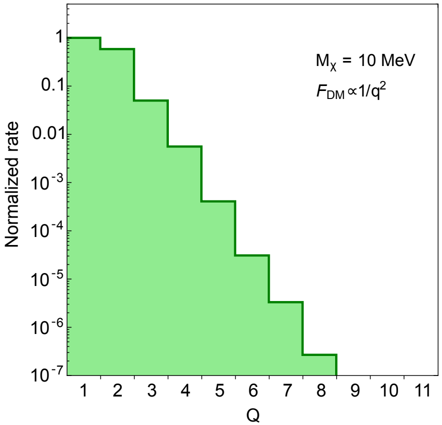
Detect DM-e interactions by measuring the ionization produced by the electron recoils. See arXiv:1509.01598

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



This requires very low noise!

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.**

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.

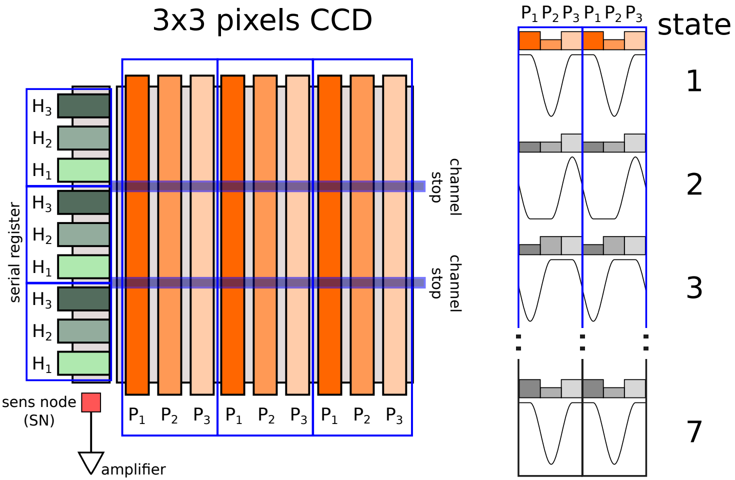
SENSEI Collaboration

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

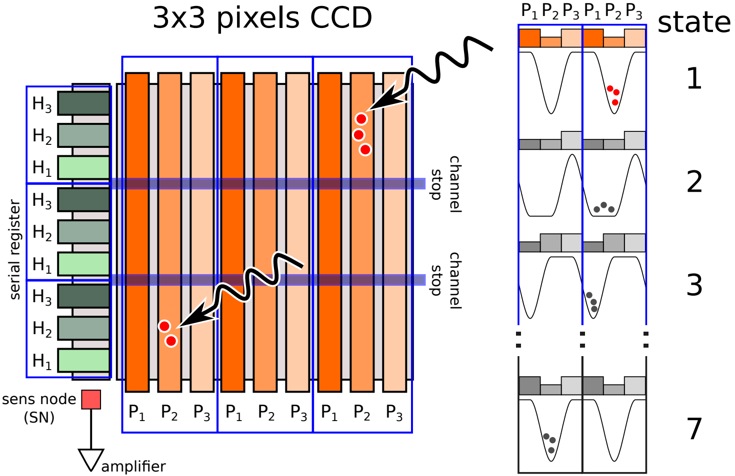
- **Fermilab:** Michael Crisler, Alex Drlica-Wagner, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg
- **Oregon University:** Tien-Tien Yu
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Liron Barack, Erez Ezion, Tomer Volansky
- **+ several additional students + more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

Fully funded by Heising-Simons Foundation & Fermilab

CCD: readout


3x3 pixels CCD
H3
H2
H1
serial register
channel stop
channel stop
sens node (SN)
amplifier
P1 P2 P3 P1 P2 P3 P1 P2 P3
P1 P2 P3 P1 P2 P3
state
1
2
3
7

CCD: readout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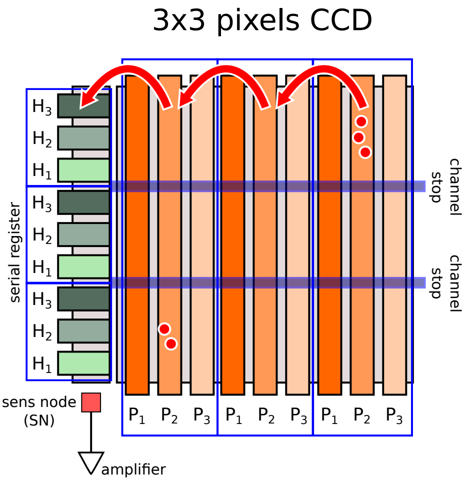
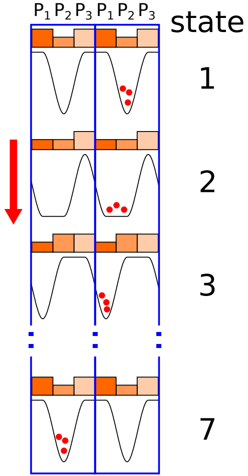
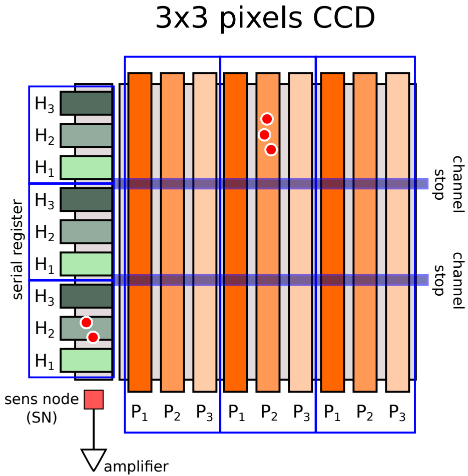

3x3 pixels CCD
H$_3$
H$_2$
H$_1$
H$_3$
H$_2$
H$_1$
H$_3$
H$_2$
H$_1$
serial register
channel stop
channel stop
sens node (SN)
amplifier
P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$


P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$
state
1
2
3
7

CCD: readout



3x3 pixels CCD
H$_3$
H$_2$
H$_1$
H$_3$
H$_2$
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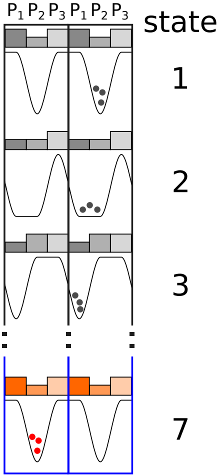
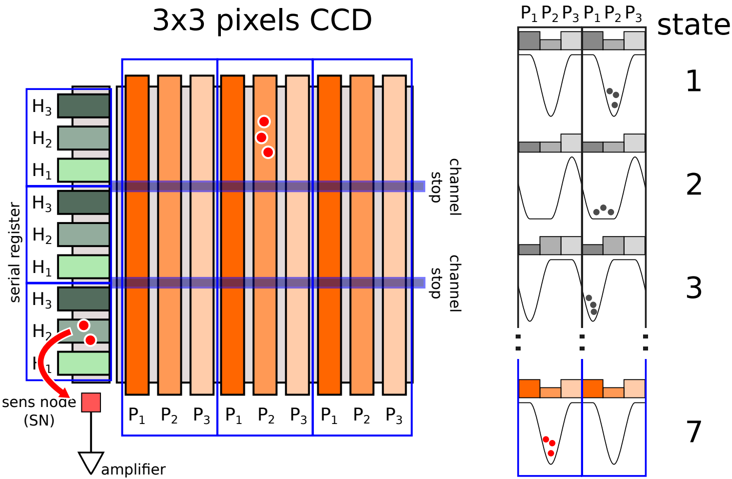
amplifier
P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$



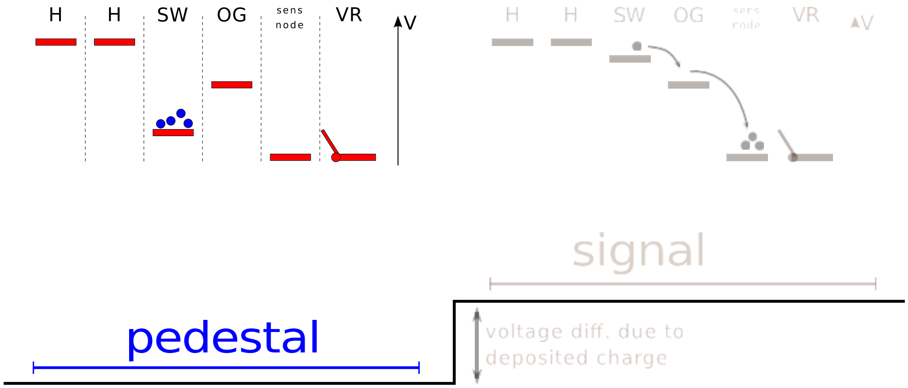
P$_1$ P$_2$ P$_3$ P$_1$ P$_2$ P$_3$
state
1
2
3
7

CCD: readout

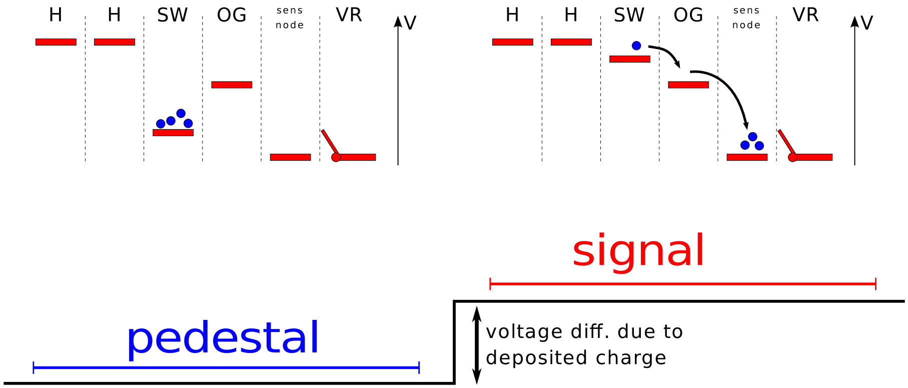


capacitance of the system is set by the SN: C=0.05pF→ 3μV/e

CCD: readout


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

CCD: readout


H
H
SW
OG
sens node
VR
V
H
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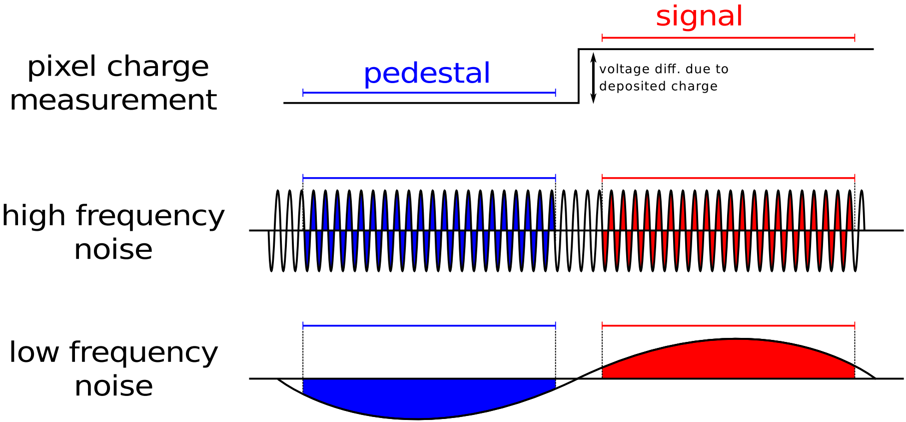
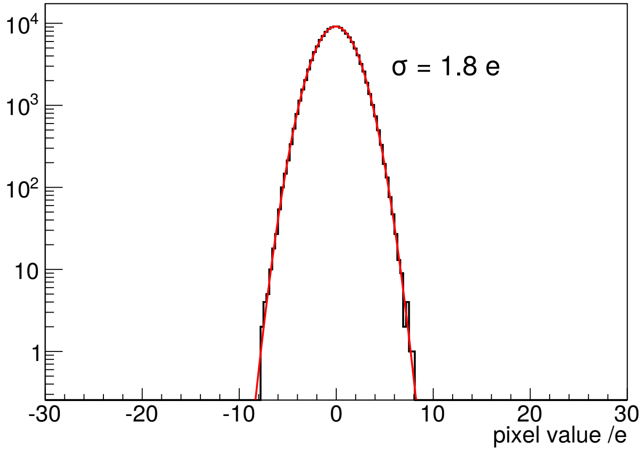
CCD: readout



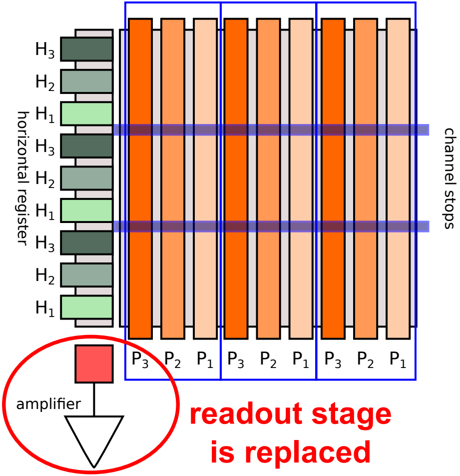
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution, regular scientific CCD



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

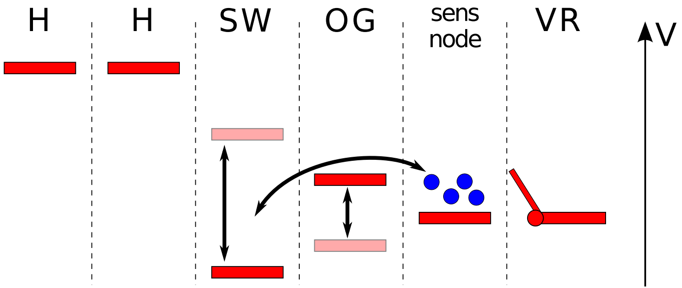
Lowering the noise: Skipper CCD



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



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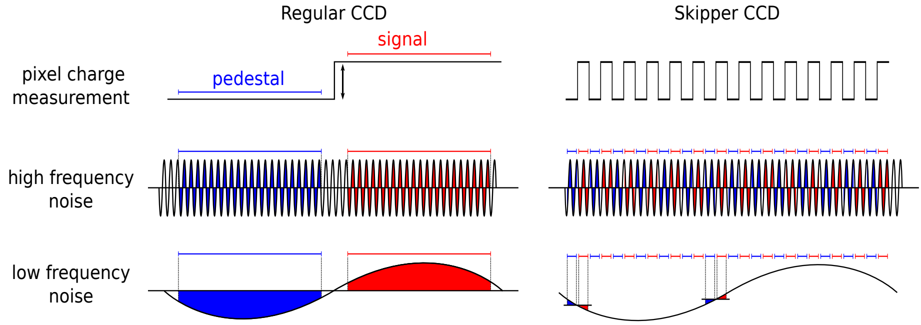
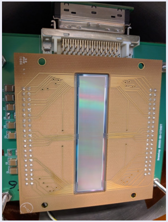


SENSEI: First working instrument using SkipperCCD tech

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)

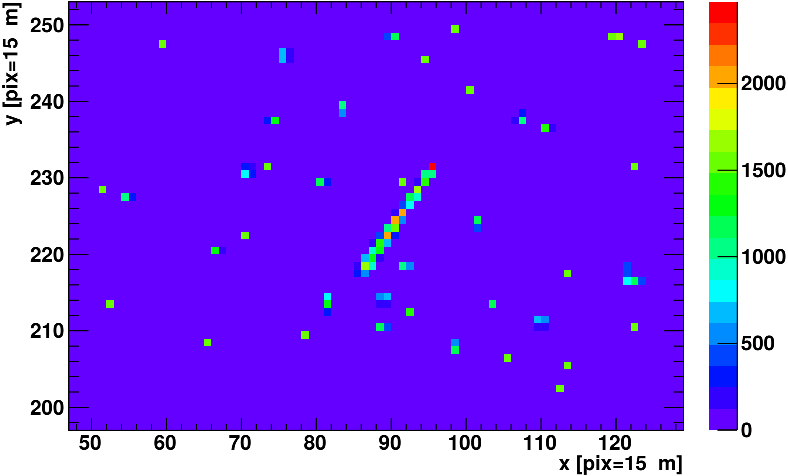


Image taken with SENSEI: 4000 samples per pixel (processed)

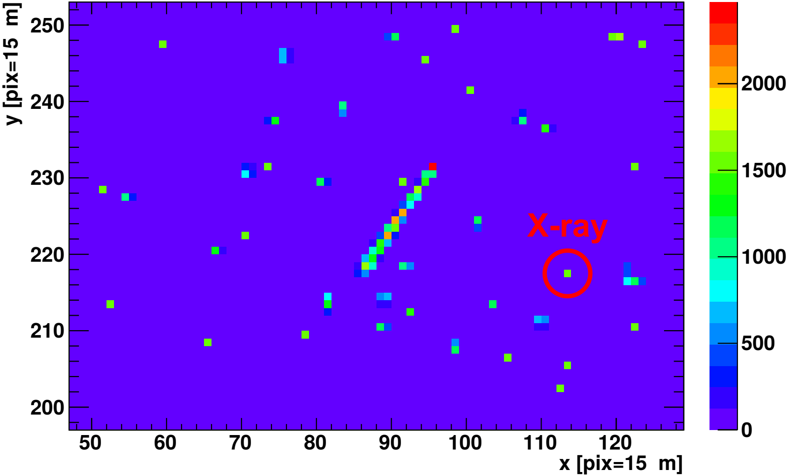


Image taken with SENSEI: 4000 samples per pixel (processed)

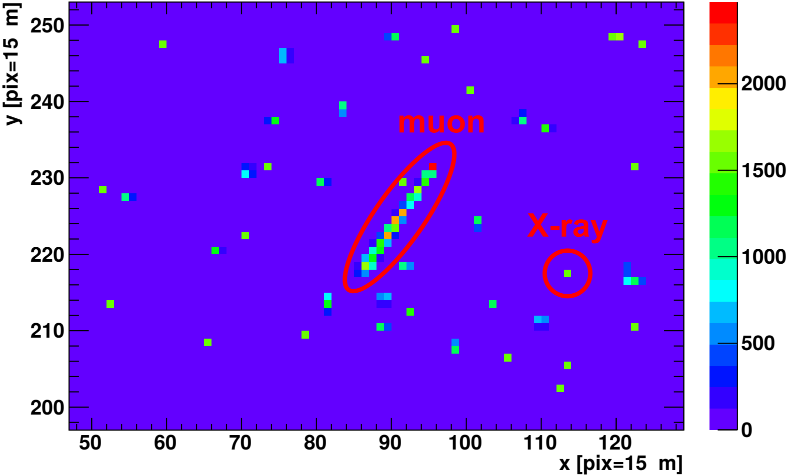
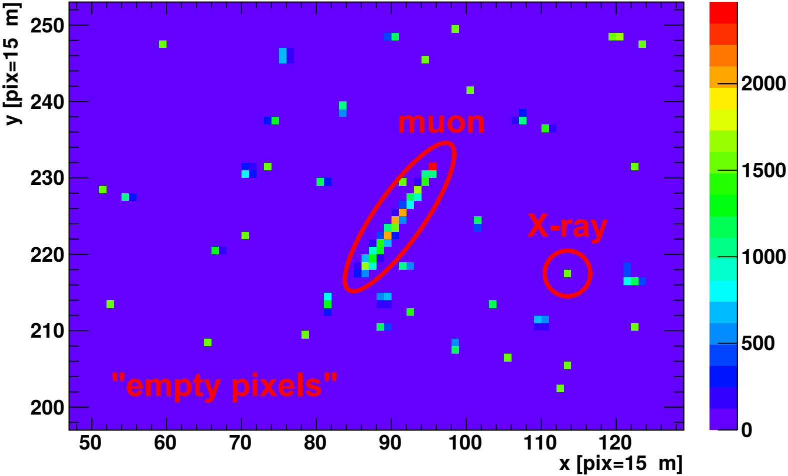
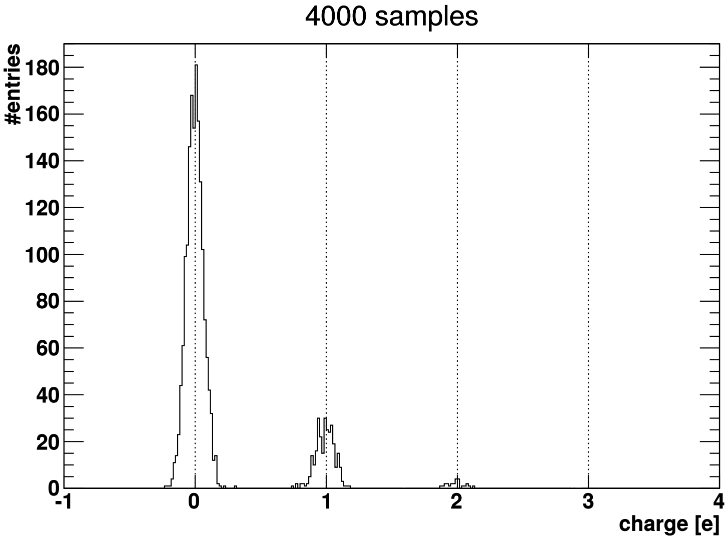


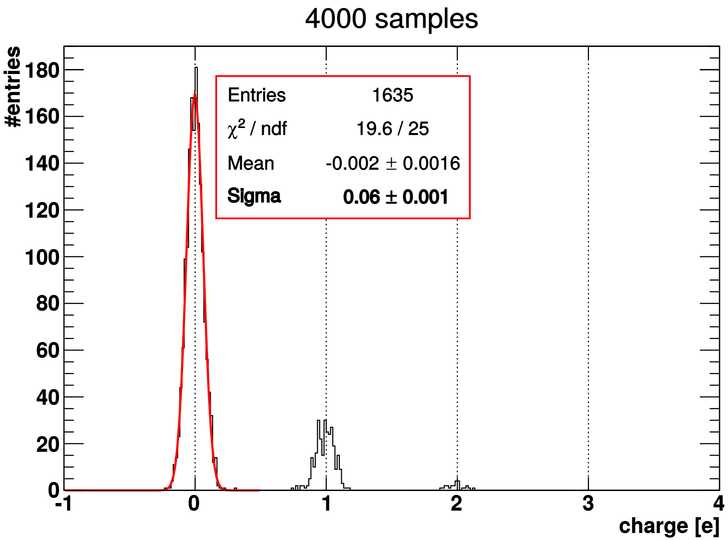
Image taken with SENSEI: 4000 samples per pixel (processed)



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

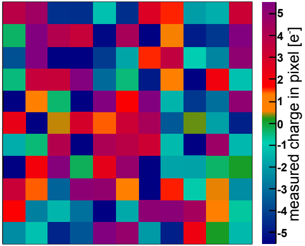


Charge in pixel distribution. Counting electrons: 0, 1, 2..

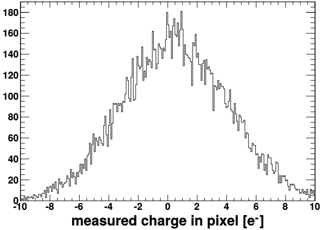


Counting electrons: 0, 1, 2..

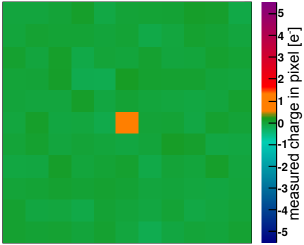
Standard CCD mode: charge in each pixel is measured once



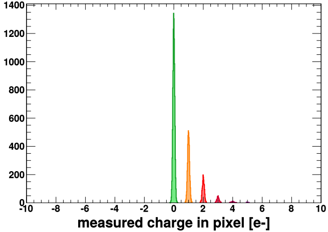
Readout-noise: 3.5 e RMS



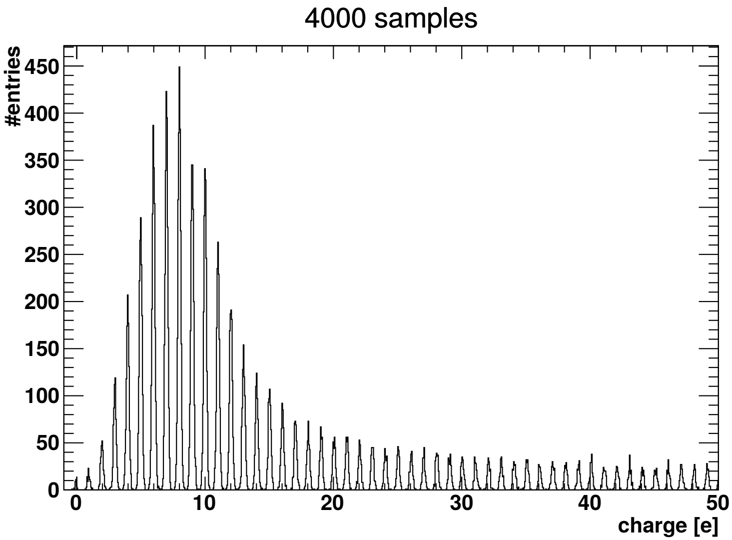
New Skipper CCD: charge in each pixel is measured multiple times



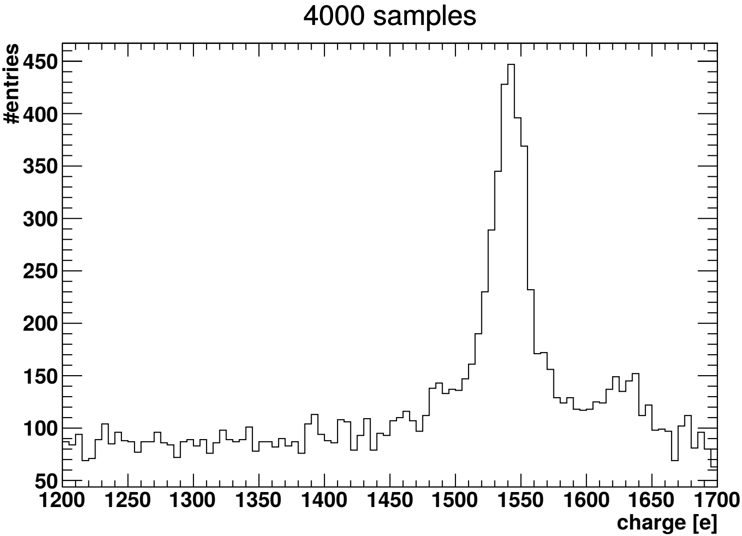
Readout-noise: 0.06 e RMS



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



^{55}Fe X-ray source



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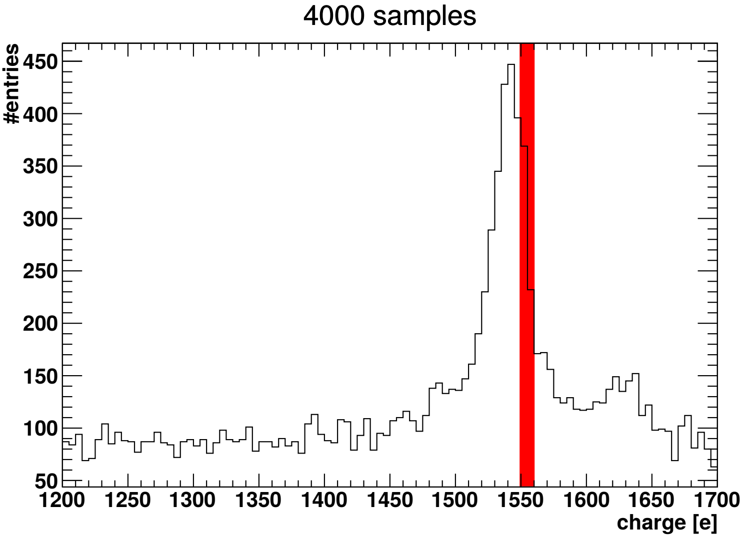
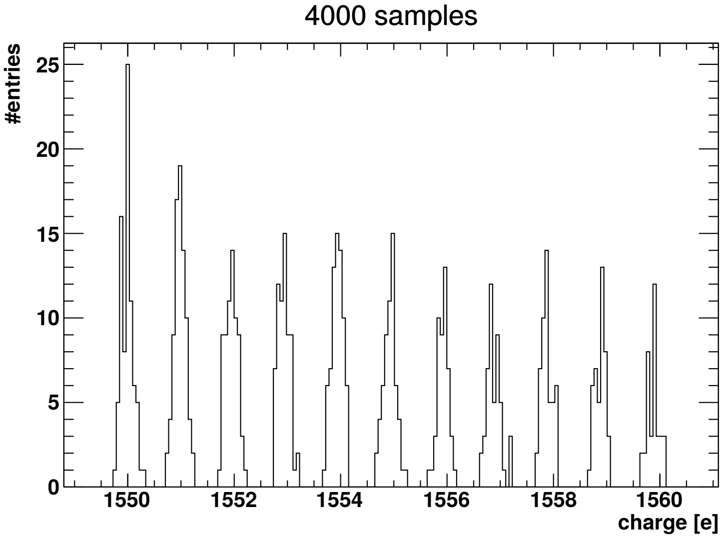
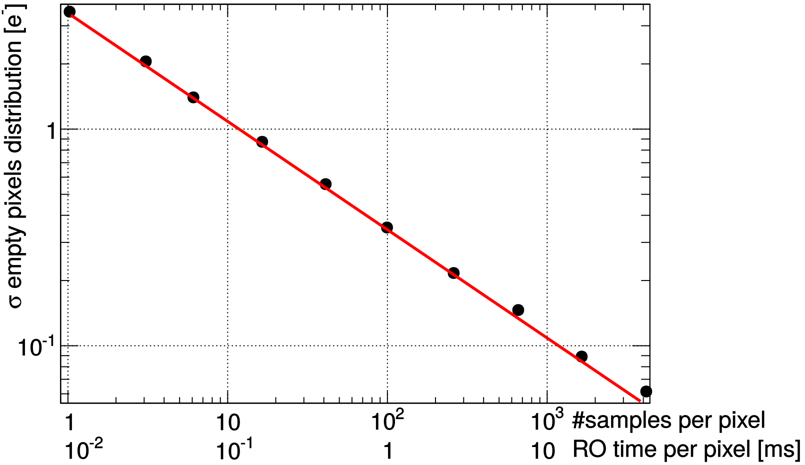


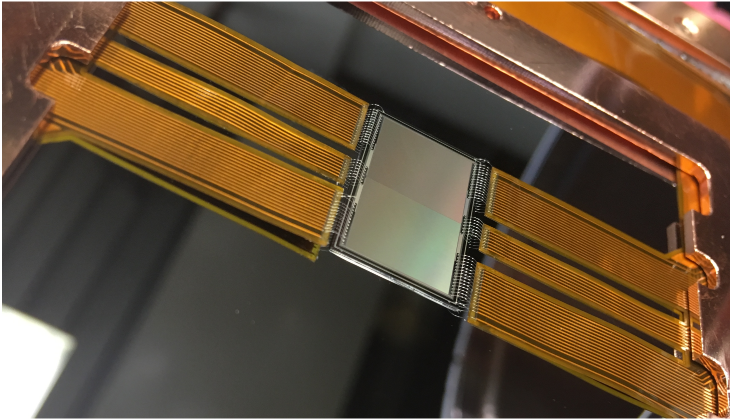
keep counting: ..1550, 1551, 1552..



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



protoSENSEI: technology demonstrator



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

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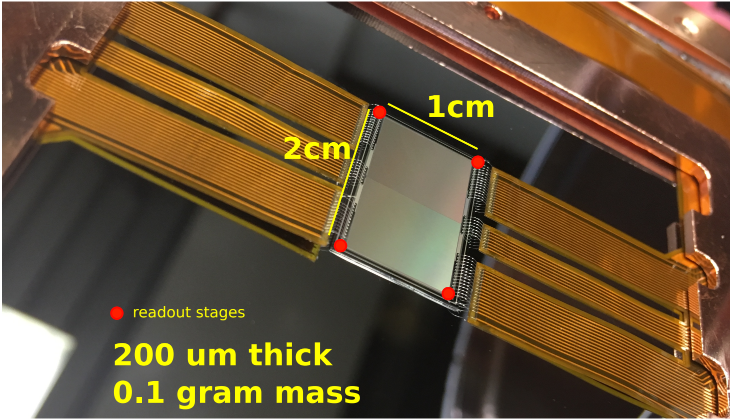
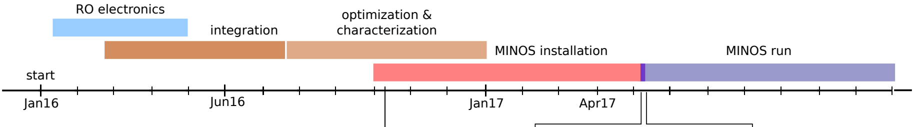


We used the parasitically-fabricated R&D sensors to learn how to optimize operations and produce early-science results

protoSENSEI: project timeline



explore high xsec

arXiv:1804.00088

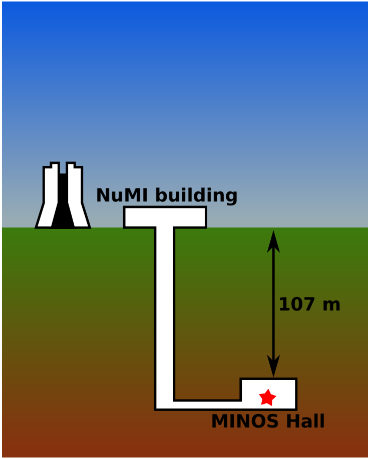
explore small xsec

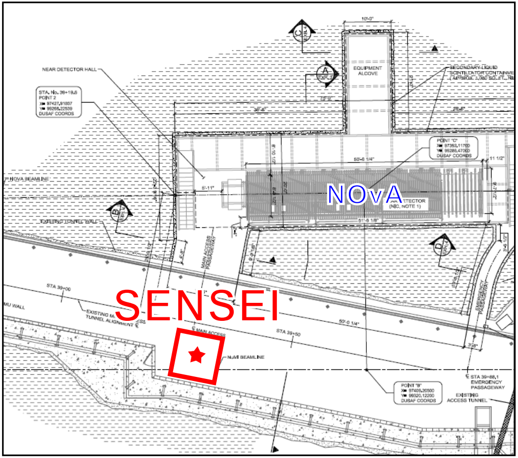
arXiv:1901.10478

Fermilab

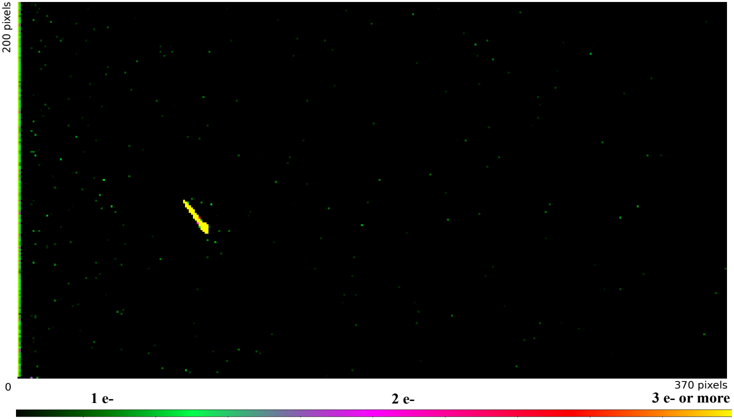
Current step: Prototype running @MINOS

Technology demonstration: installation at shallow underground site



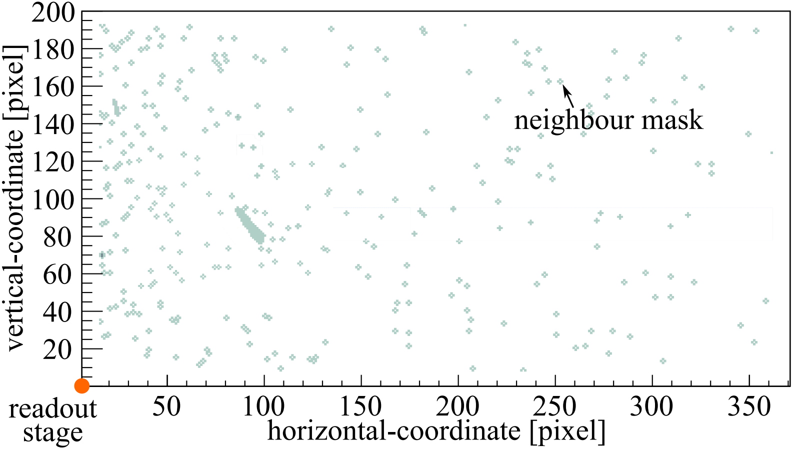


protoSENSEI @MINOS: raw image/data (70 min exposure)



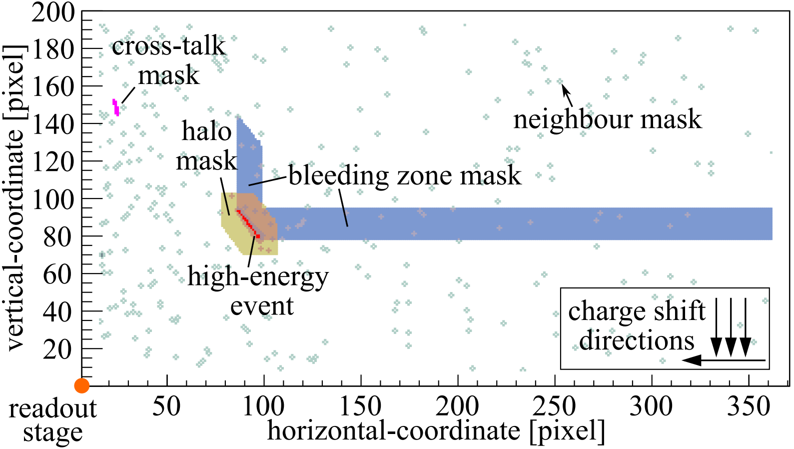
adjacent pixels with one or more electrons are grouped together

protoSENSEI @MINOS: clustering and event reconstruction

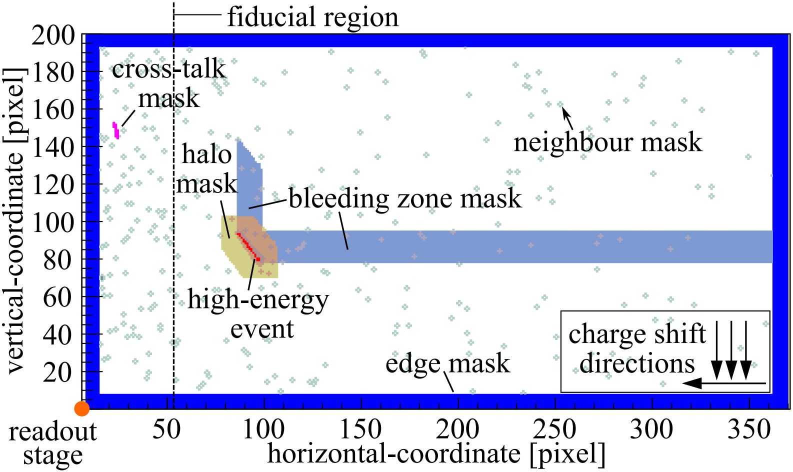


adjacent pixels with one or more electrons are grouped together

protoSENSEI @MINOS: selection cuts

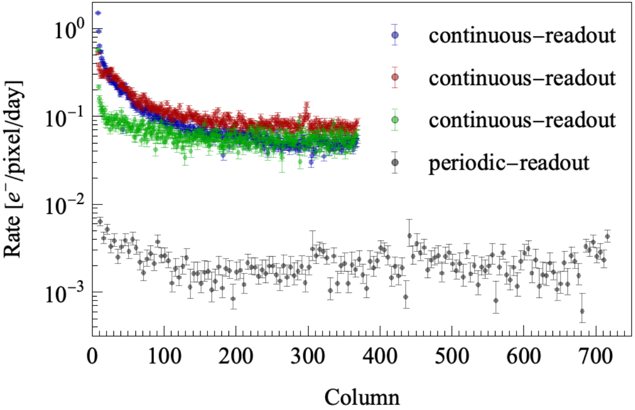


Cross talk, Bleeding and Halo



Edges and column dependence.

Column dependence may point to different readout scheme



protoSENSEI @MINOS: efficiency and exposure

Cuts \ N_e	periodic			continuous		
	1	2	3	3	4	5
1. DM in single pixel	1	0.62	0.48	0.48	0.41	0.36
2. Nearest Neighbour	0.92			0.96		
3. Electronic Noise	1			$\sim$1		
4. Edge	0.92			0.88		
5. Bleeding	0.71			0.98		
6. Halo	0.80			0.99		
7. Cross-talk	0.99			$\sim$1		
8. Bad columns	0.80			0.94		
Total Efficiency	0.38	0.24	0.18	0.37	0.31	0.28
Eff. Expo. [g day]	0.069	0.043	0.033	0.085	0.073	0.064
Number of events	2353	21	0	0	0	0

protoSENSEI @MINOS: all the information, pick your model

N_e / Cuts	periodic			continuous		
	1	2	3	3	4	5
1. DM in single pixel	1	0.62	0.48	0.48	0.41	0.36
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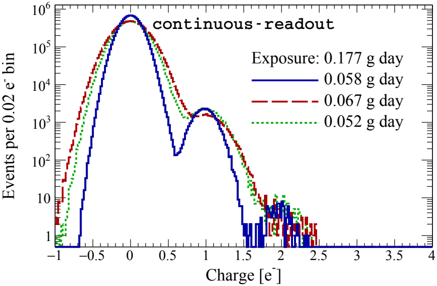
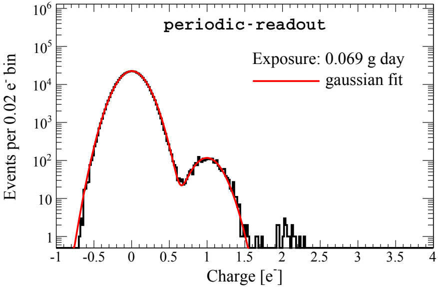
protoSENSEI @MINOS: event spectra

Continuous readout

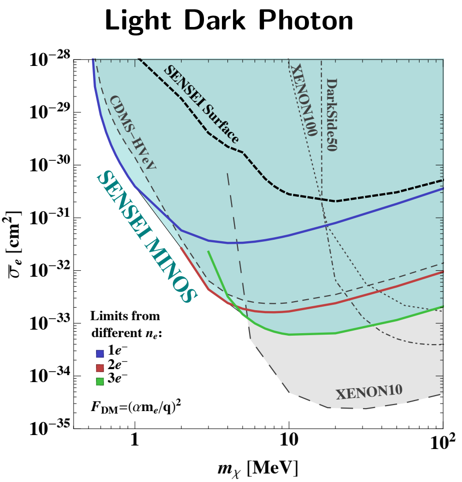


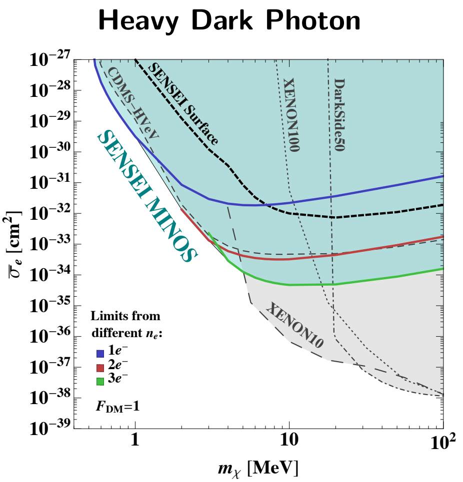
Periodic readout



- **No events with $3e^-$ or more**
- **Seems to follow a Poisson distribution. Still under studies.**

protoSENSEI @MINOS: results





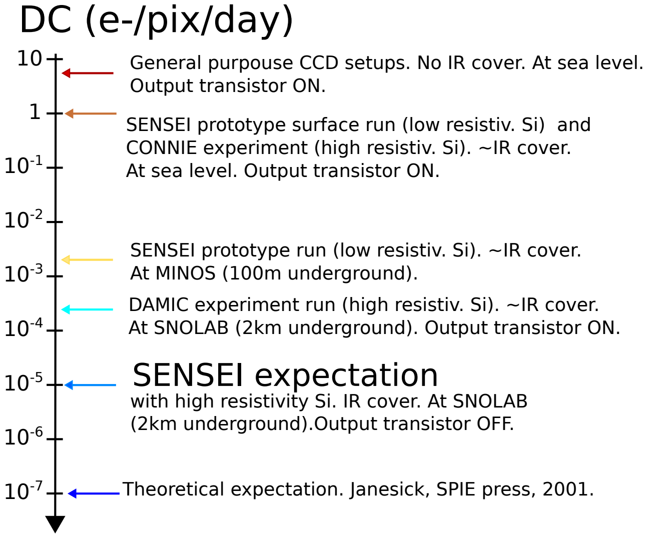
World best limit below 5 MeV!!

What are the next steps for SENSEI?

- 10 gram Skipper CCD system in 2019.
- 100-gram Skipper CCD system in 2020.

we know how to build hundred-grams CCD systems (DAMIC, CONNIE).

Dark current measurements and expectation



SENSEI threshold vs dark current

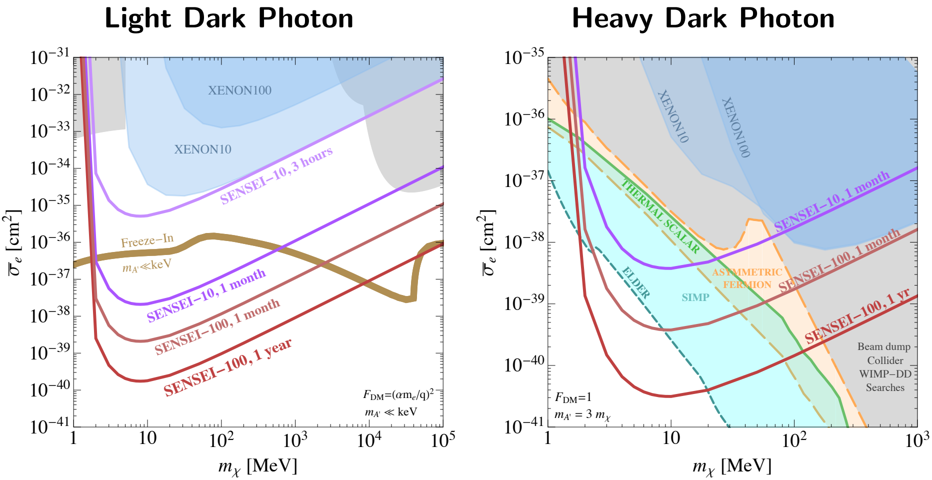
- Counting electrons $\Rightarrow$ **noise has zero impact**
- It can take about 1h to read the sensors
- **Dark Current is the limiting factor**

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}

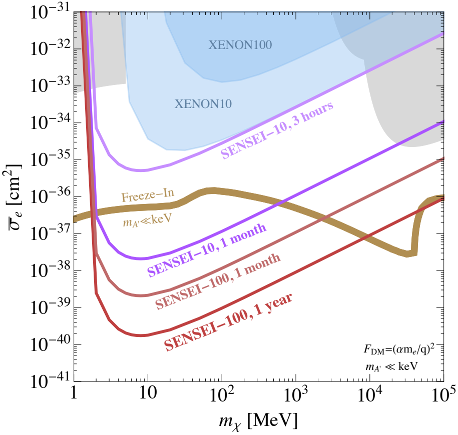
Operation mode (continuous-RO or long-exposures) will depend on the measured DC and spurious charge of the Science sensors

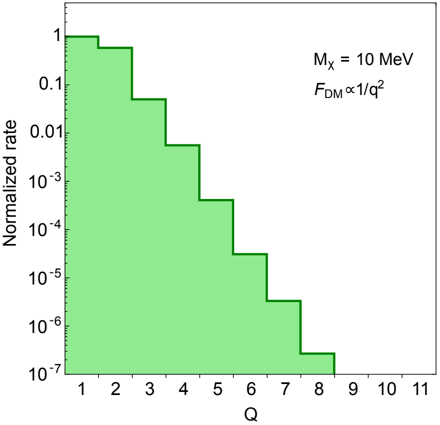
SENSEI: reach of a 100g, *zeroish-background* experiment



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

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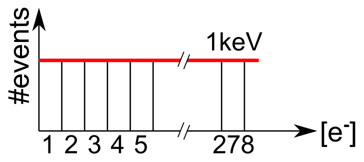
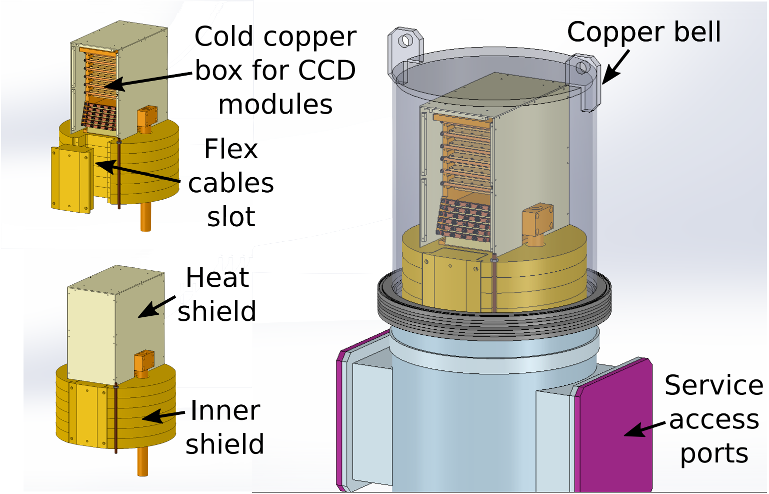


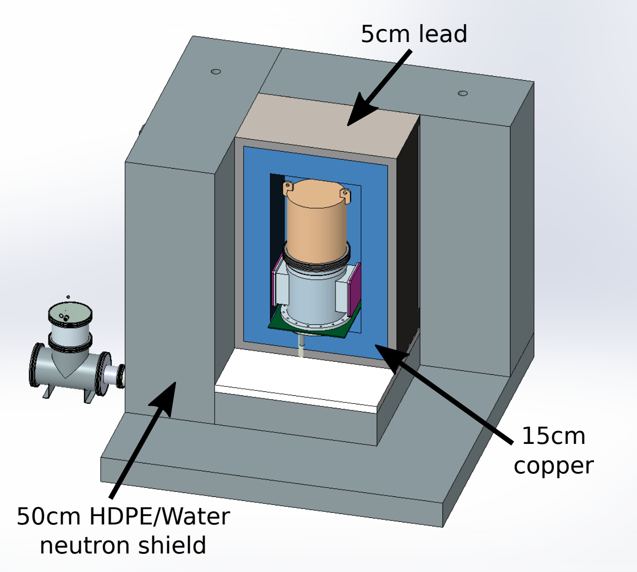
182.5 events over the 278 charge bins in the 0-1keV range

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

Snolab vacuum vessel design



Snolab shield design



Timeline

2016

LDRD funded,
fabrication of SkipperCCD prototype

2017

testing of prototype,
received funding from HSF for SENSEI experiment

2018

early science from prototypes and design and fabrication of SENSEI experiment

2019

SENSEI at MINOS (∼10 gr)
commissioning at Snolab (∼100 gr)

2020

analisis of SENSEI at Minos and take data at Snolab

2021

analisis of Snolab data

SENSEI path

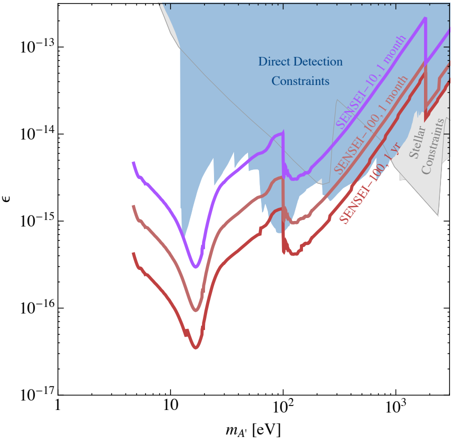
Summary

- SENSEI is the first dedicated experiment searching for electron-DM interactions
- protoSENSEI at the surface probed 0.5-4 MeV masses for the first time, and larger xsec than existing direct-detection constraints
- protoSENSEI at MINOS 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

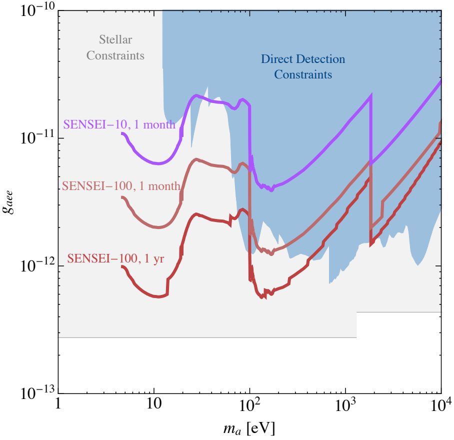
BACK UP SLIDES

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

Dark photon (A')



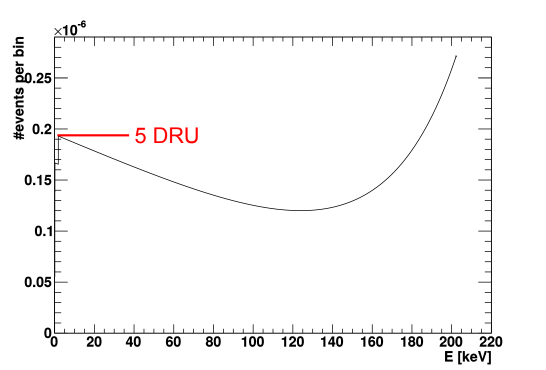
Axion-like-particle (ALP)



SENSEI: electron recoil background requirements

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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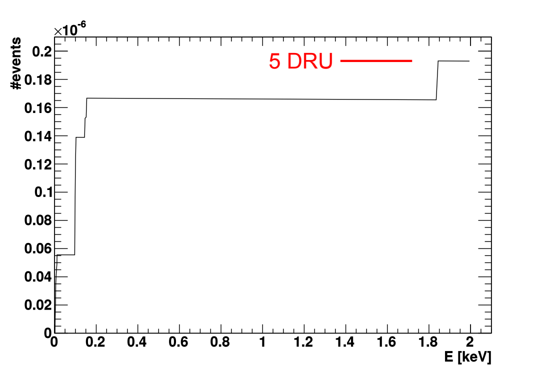

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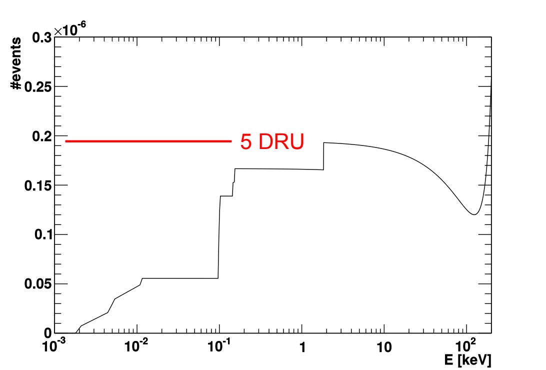

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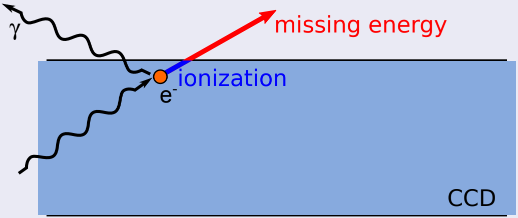

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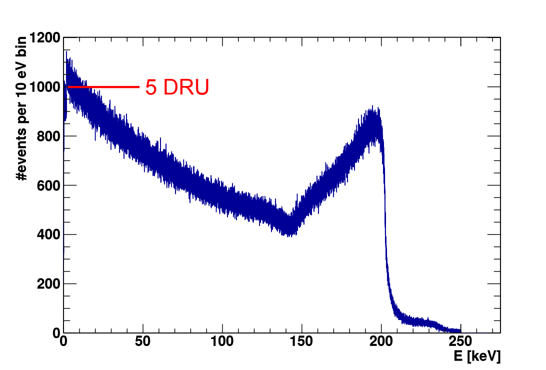

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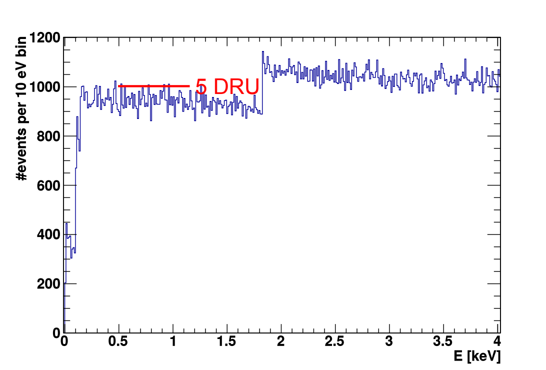

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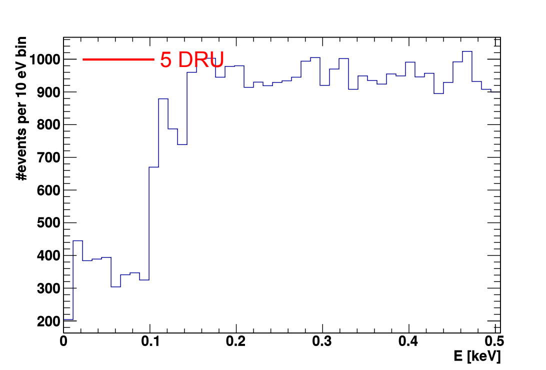

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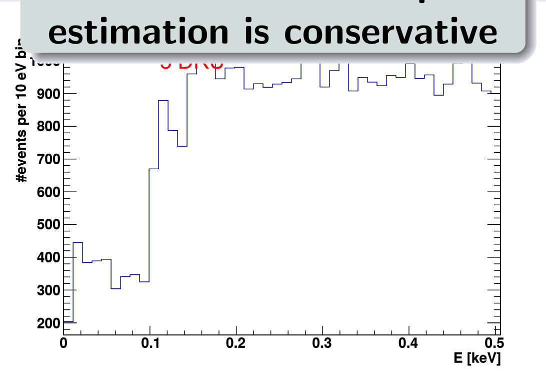
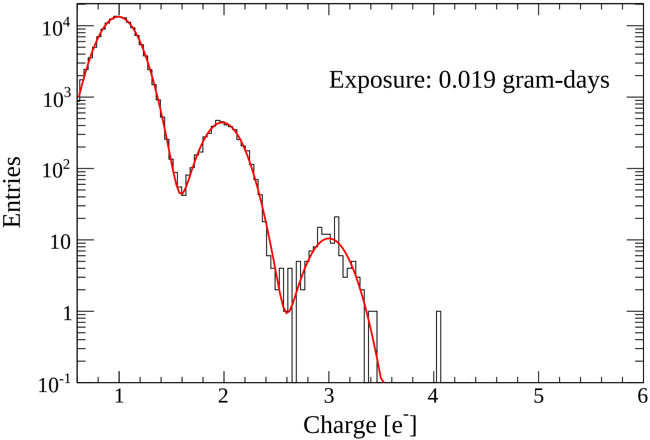


Back of the envelope estimation is conservative

protoSENSEI: commissioning run at surface: arXiv:1804.00088

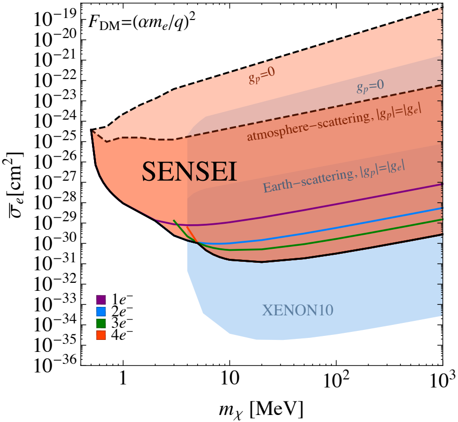
Observed spectrum using 800 samples per pixel



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!

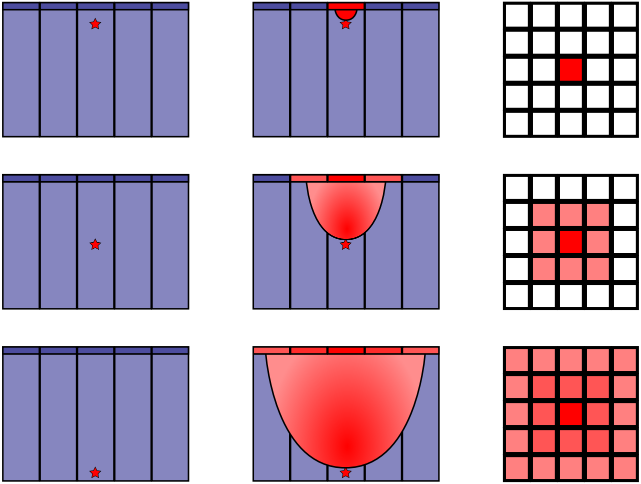


Terrestrial effects: Emken, Essig, Kouvaris, Sholapurkar (to appear)

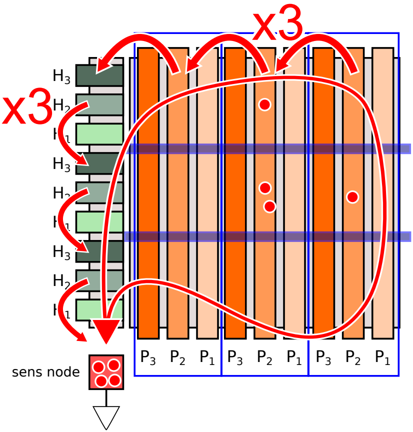
Selection efficiency

Cuts \ $N_{e,\mathrm{min}}$	1	2	3	4	5
1. Single pixel	1	0.62	0.48	0.41	0.37
2. Nearest Neighbor	0.8	0.8	0.8	0.8	0.8
3. Noise	0.88	0.88	0.88	0.88	0.88
4. Bleeding	0.95	0.95	0.95	0.95	0.95
Total	0.67	0.41	0.32	0.27	0.24
Number of events	140,302	4,676	131	1	0

Diffusion



Hardware binning



The optimal effective pixel size can be chosen by using hw binning

$$\mu_{\text{sigle}} = R_{\text{DC}} \times \underbrace{(T_{\text{pix}} \times n_{\text{pix}})}_{T_{\text{expo}}} = \mu_{\text{binning}} = \underbrace{(n_{\text{bin}} \times R_{\text{DC}})}_{\text{Eff DC}} \times \underbrace{T_{\text{pix}} \times n_{\text{pix}}/n_{\text{bin}}}_{T_{\text{expo}}}$$

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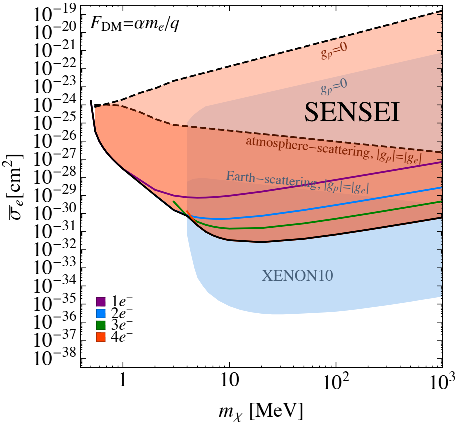

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)

SENSEI commissioning run at surface: arXiv:1804.00088

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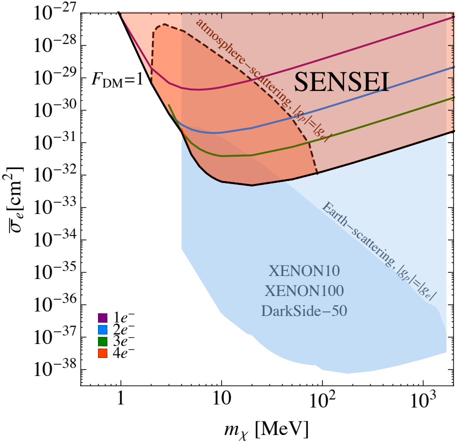
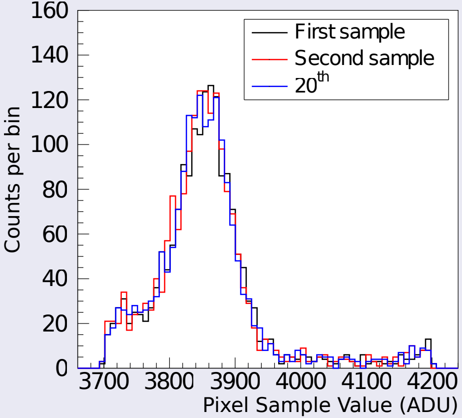


Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)

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