The SENSEI† project

a zero noise detector for DM searches

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Fermi National Laboratory

February 18, 2018

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

Fermilab

Origin of the Collaboration

SnowPAC 2013 | SnowDARK 2013 | SnowCluster 2013

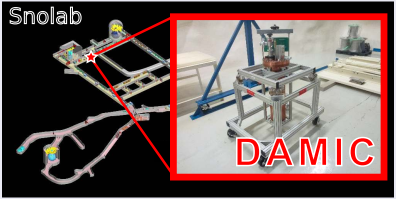
March 22 - 25, 2013

Talk summary

- Scientific CCDs as low-energy-threshold/low-noise particle detectors
- SENSEI project: status and prospects
- Application to light DM searches

Current experiments using Scientific CCDs

DAMIC

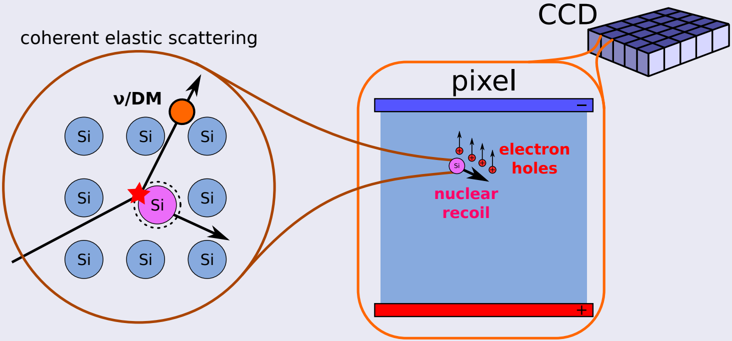


- Low mass Dark Matter search (WIMP/NR-optimized)
- Installed at Snolab on Dec-2012
- Currently taking data

CONNIE

- Coherent ν-nucleous interaction
- Installed next to Angra nuclear power plant on Dec-2014
- technique could be used for SBν-Ex
- Currently taking data

DAMIC & CONNIE use CCDs as targets to detect coherent DM/ν-nucleus interactions by measuring the ionization produced by the nuclear recoils

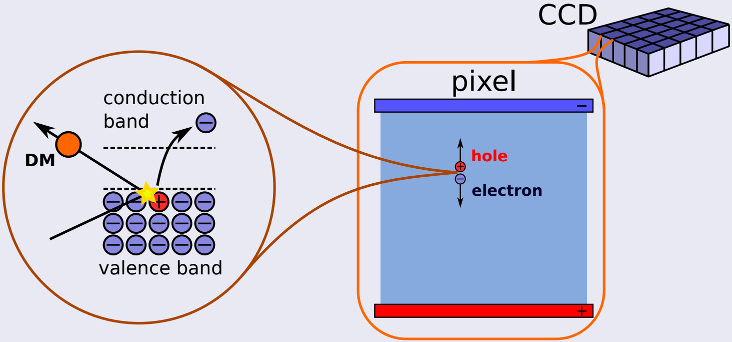


Sensitivity is limited by readout noise and NR-ionization yield

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 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

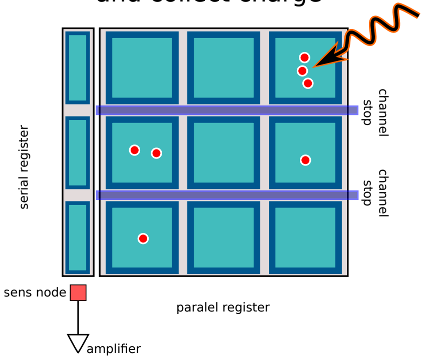
Main goals

- 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.

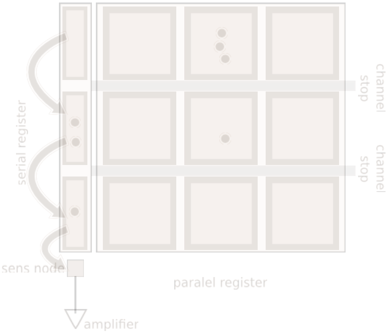
CCD: readout

3x3 pixels CCD

Expose the CCD to particles
and collect charge



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



CCD: readout

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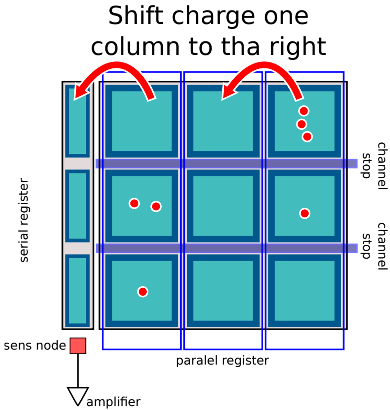

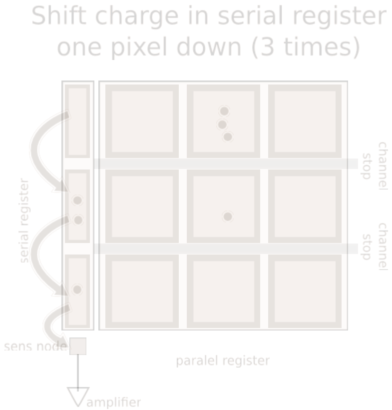

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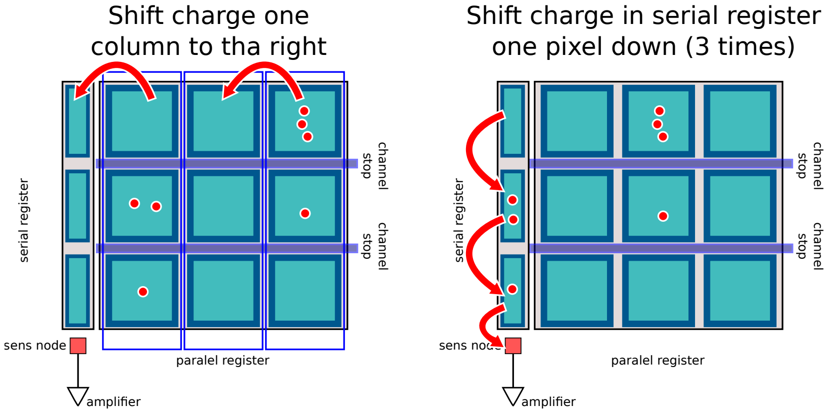
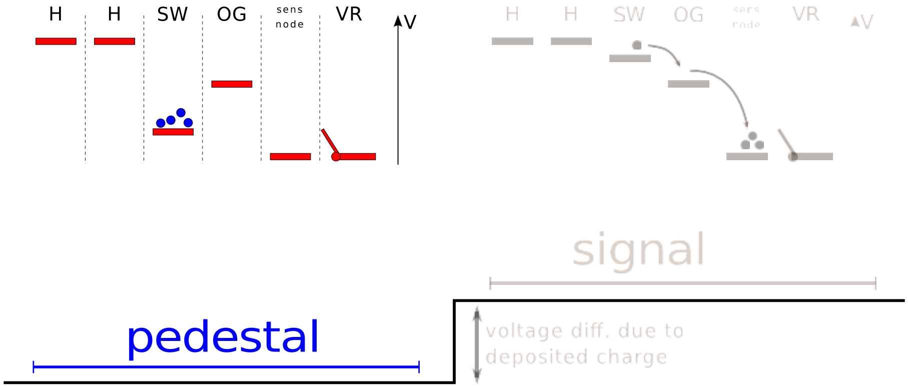
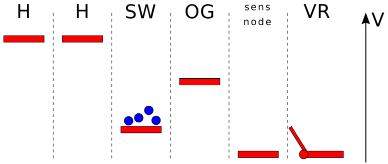


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

CCD: readout


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

CCD: readout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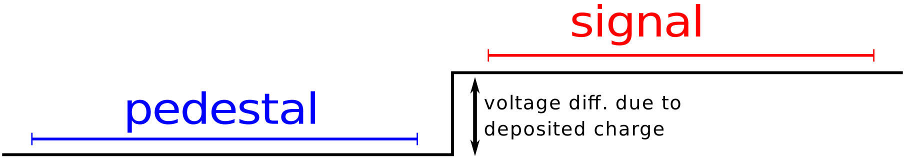
signal
pedestal
voltage diff. due to
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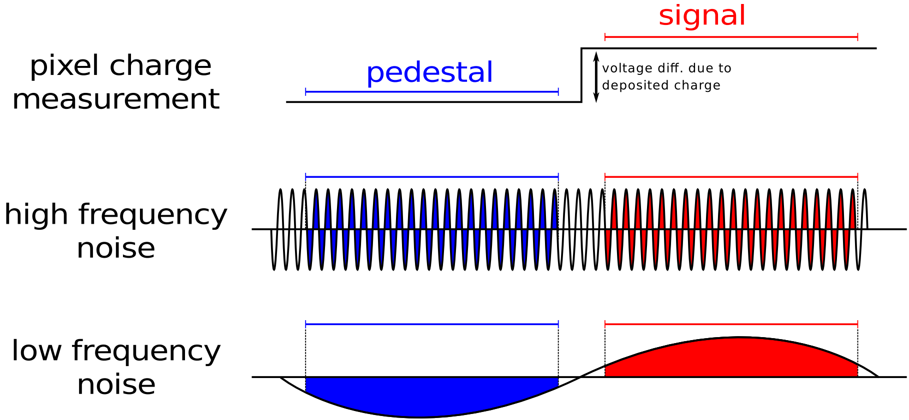
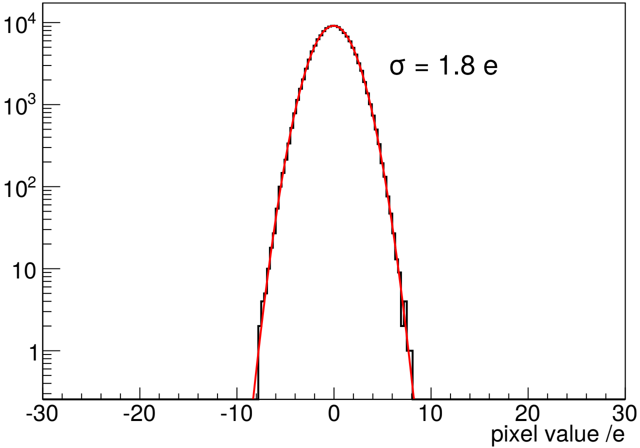


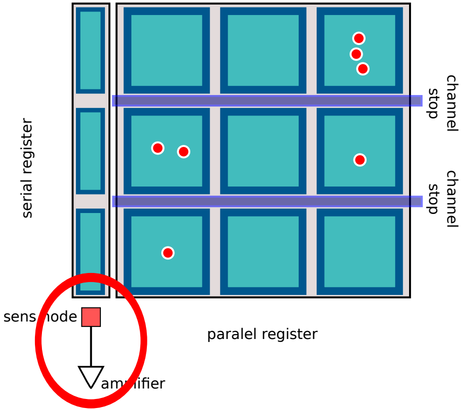
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution, regular scientific CCD



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

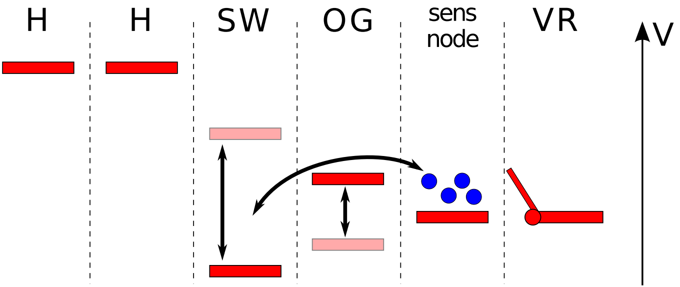
Lowering the noise: Skipper CCD



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



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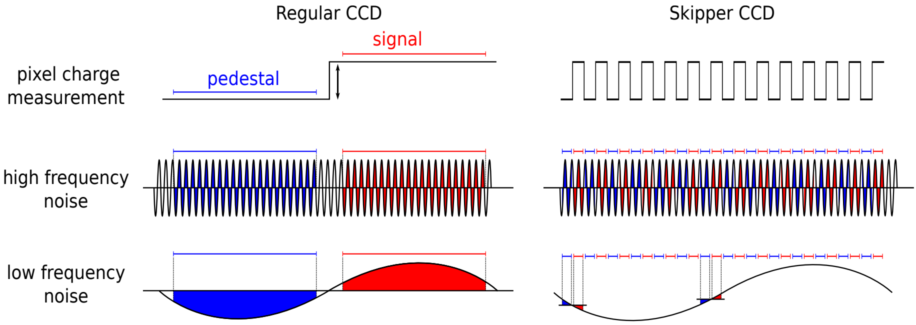

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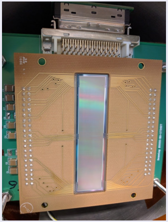
SENSEI: First working instrument using SkipperCCD tech

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)

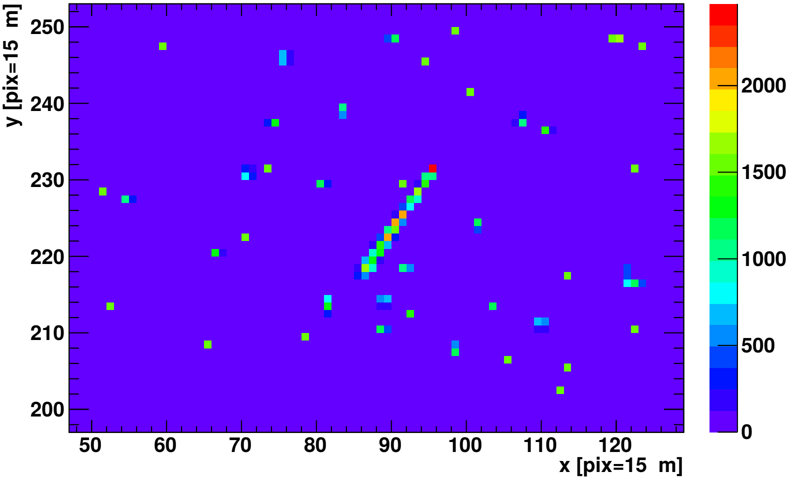
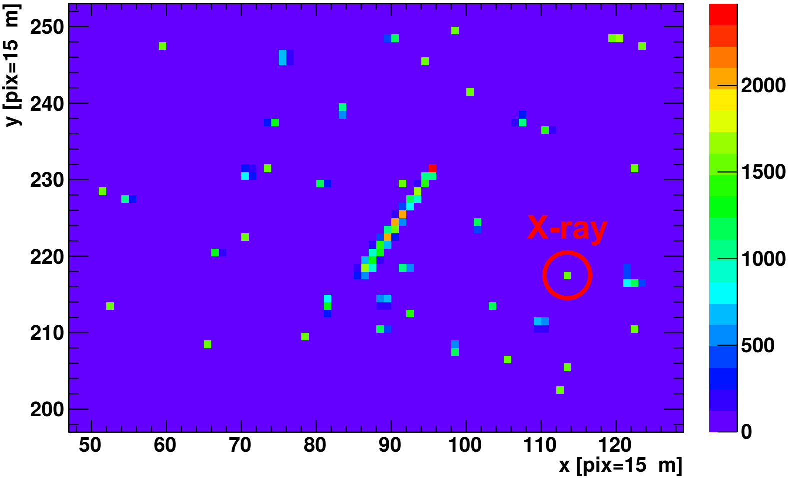


Image taken with SENSEI: 4000 samples per pixel (processed)



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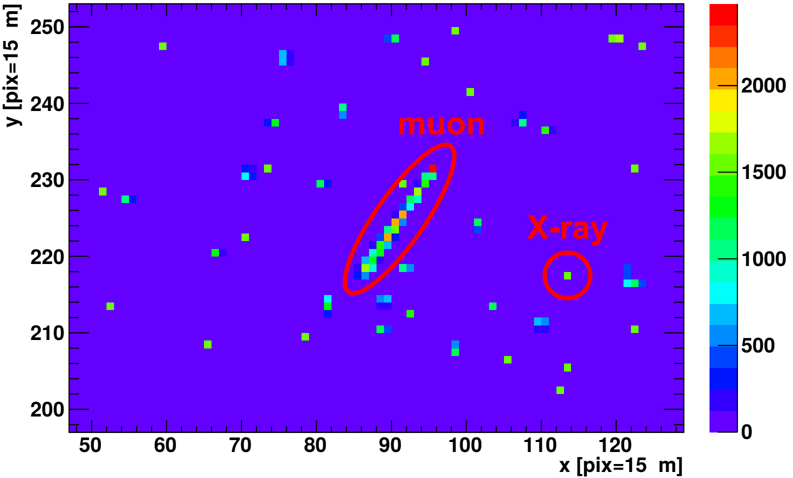

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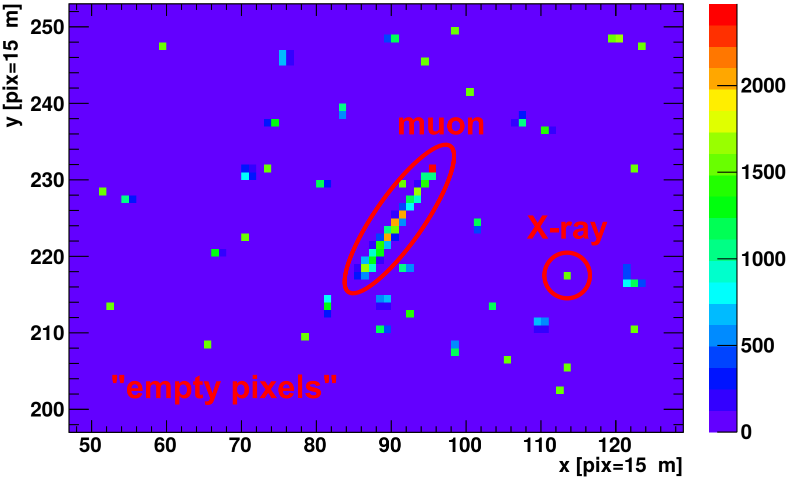
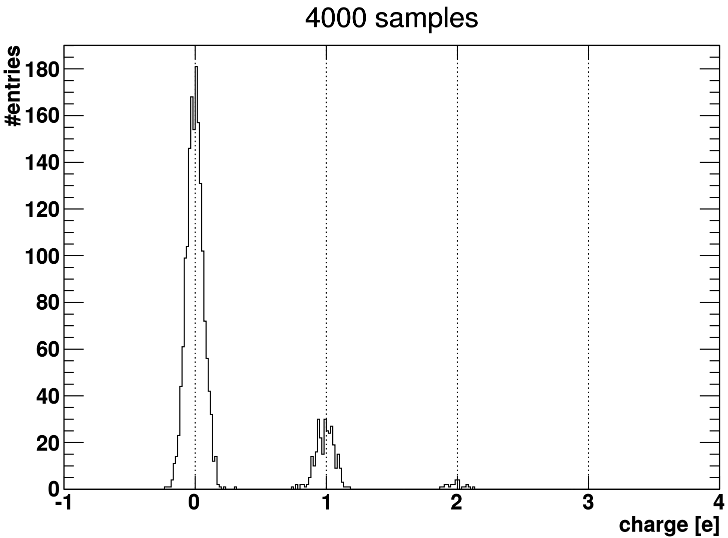


Charge in pixel distribution. Counting electrons: 0, 1, 2..



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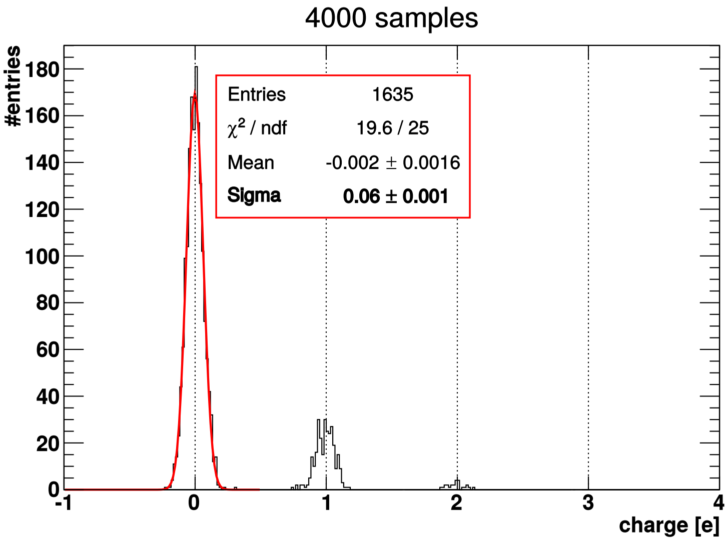
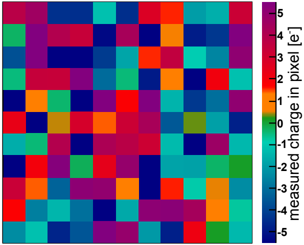
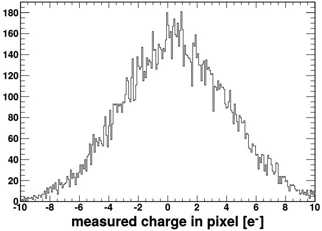


Counting electrons: 0, 1, 2..

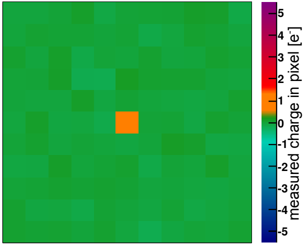
Standard CCD mode: charge in each pixel is measured once



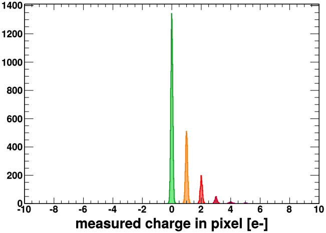
Readout-noise: 3.5 e RMS



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



Readout-noise: 0.06 e RMS



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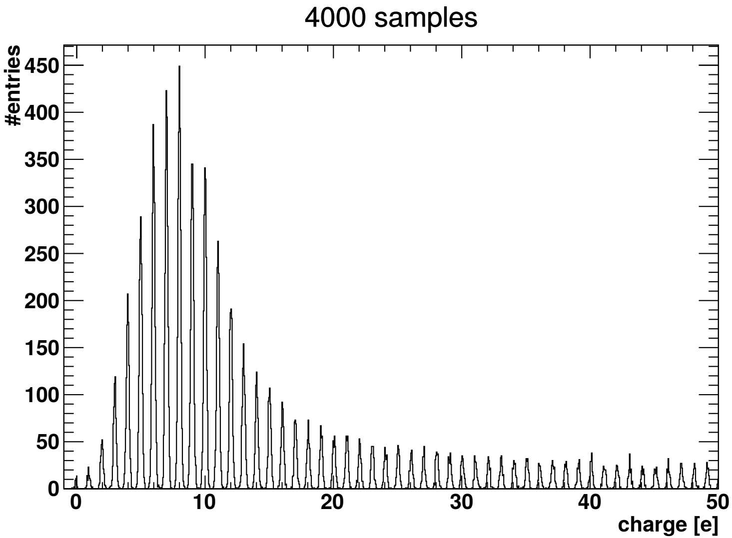
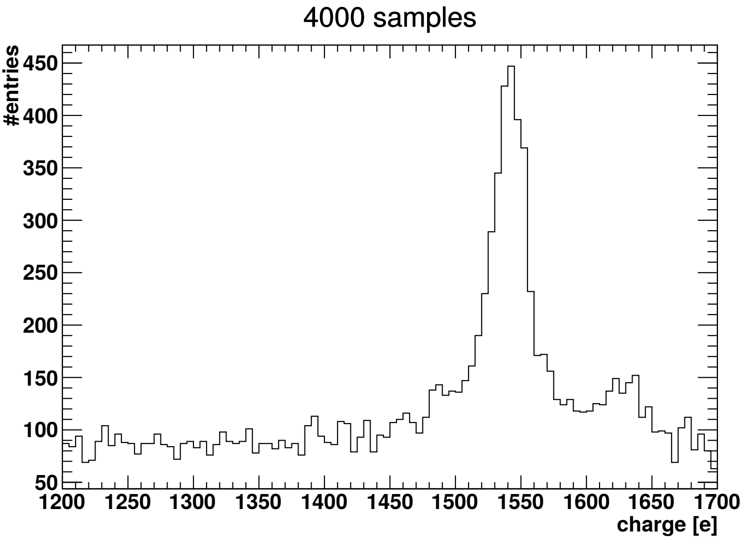
Counting electrons: ..48, 49, 50..



^{55}Fe X-ray source



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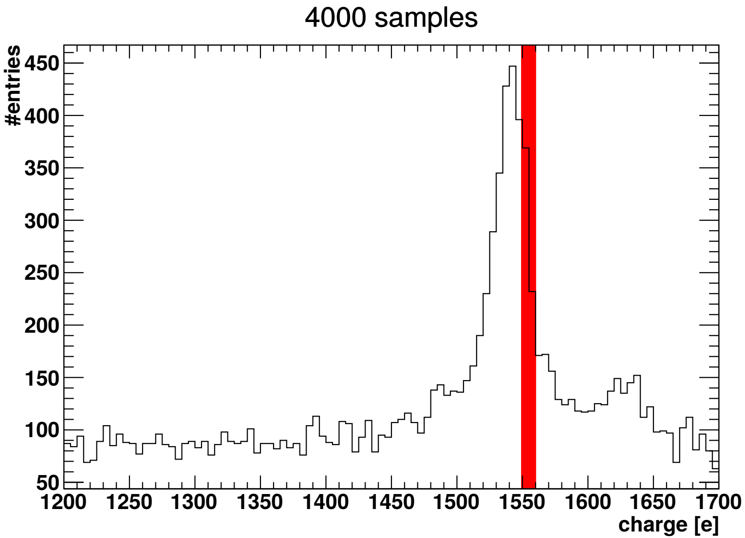


keep counting: ..1550, 1551, 1552..

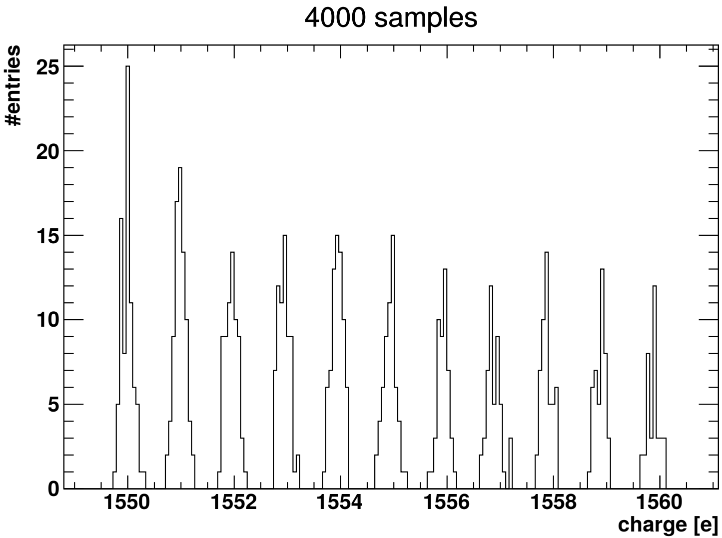
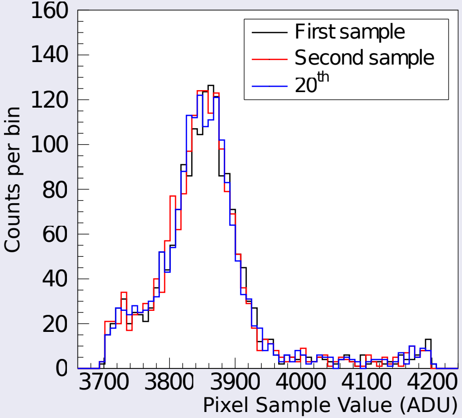


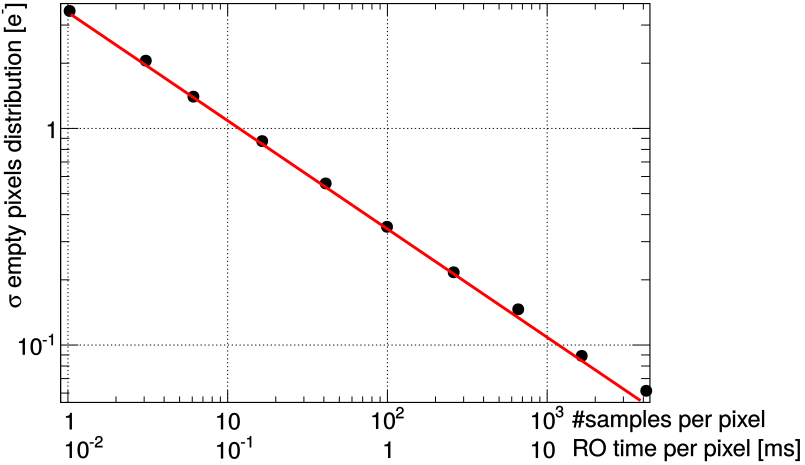
Image taken with SENSEI: 20 samples per pixel

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



The gain is the same for all the samples

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



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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}

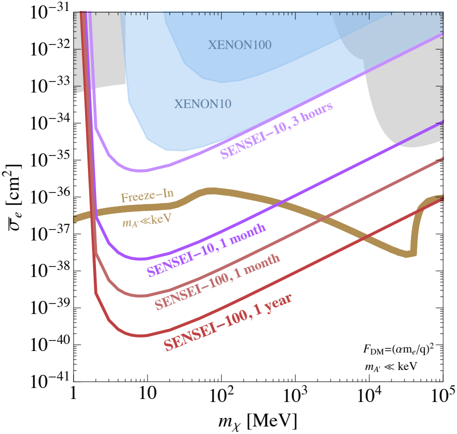
Measured upper limit for the DC in CCDs is:

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

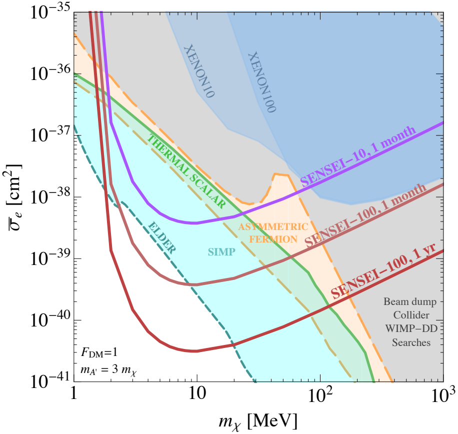
Could be orders of magnitude lower. **Theoretical prediction is O(10^{-7})**

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

Light Dark Photon



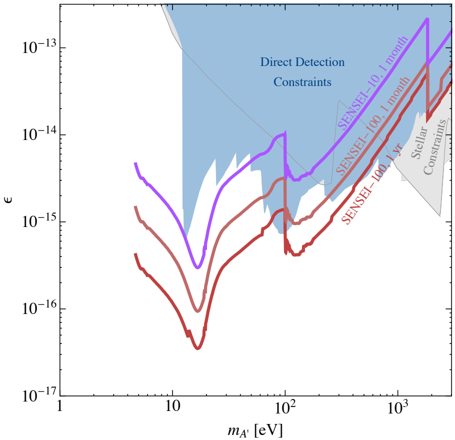
Heavy Dark Photon



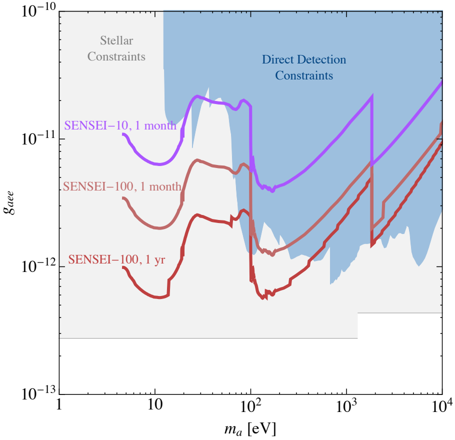
Rouven Essig, Tomer Volansky & Tien-Tien Yu.

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

Dark photon (A')



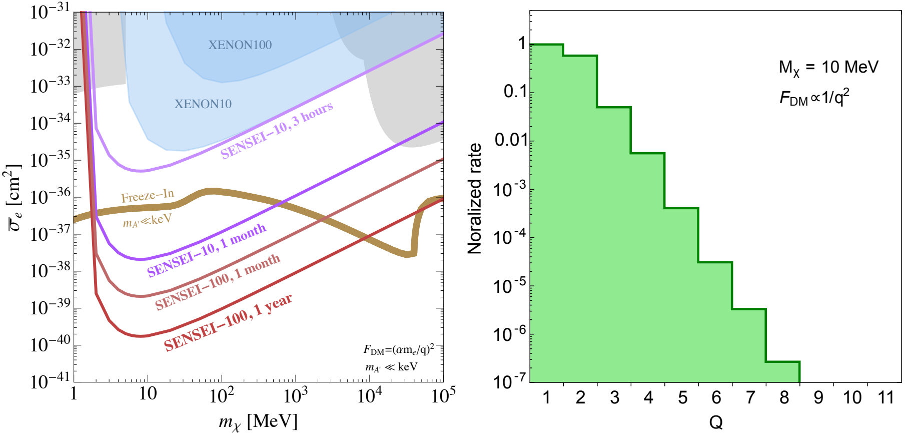
Axion-like-particle (ALP)



Rouven Essig, Tomer Volansky & Tien-Tien Yu.

SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin



Rouven Essig, Tomer Volansky & Tien-Tien Yu.

SENSEI: electron recoil background requirements

Back of the envelope calculation

A 100g detector that takes data for one year $\rightarrow$ $\mathbf{Expo = 36.5kg \cdot day}$

Assuming same background as in DAMIC:

- **5 DRU** (events$\cdot$kg$^{-1}\cdot$day$^{-1}\cdot$keV^{-1}) in the 0-1keV range
  $\rightarrow \mathbf{N_{bkg} = 36.5}$ kg $\cdot$ day $\times$ **5** DRU $=$ **182.5** events
- Dominated by external gammas $\rightarrow$ **flat Compton spectrum**

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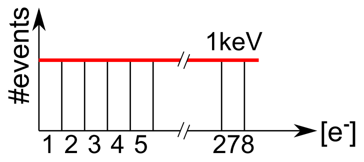


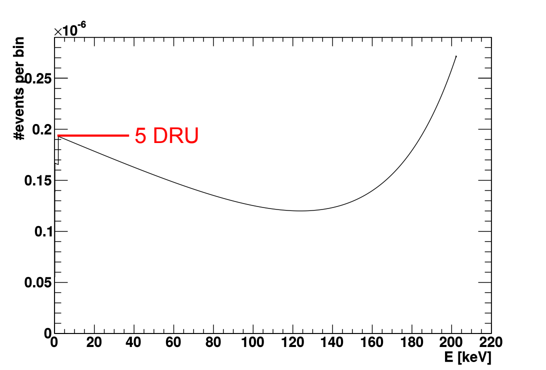
182.5 events over the 278 charge bins in the 0-1keV range

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

Skipper CCD - 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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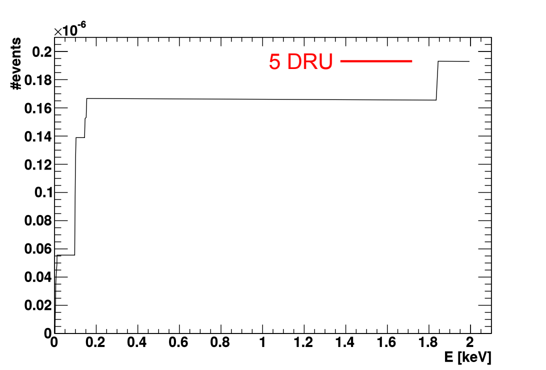

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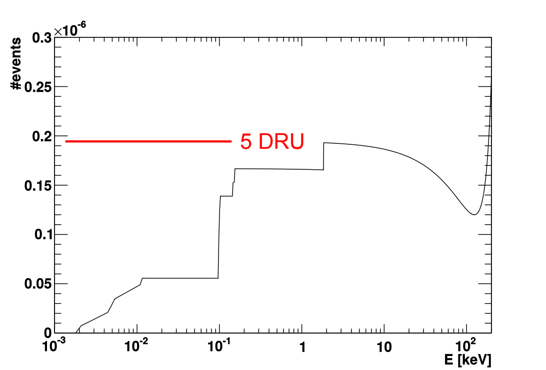

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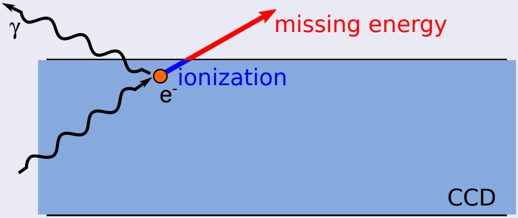

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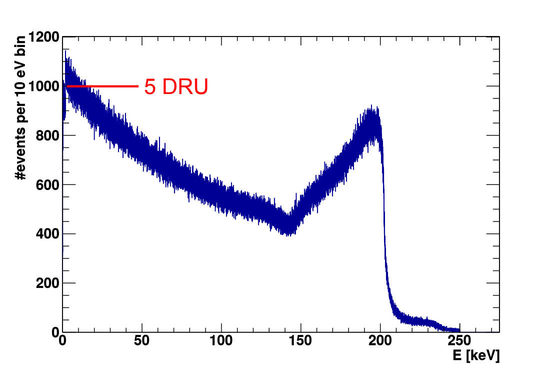

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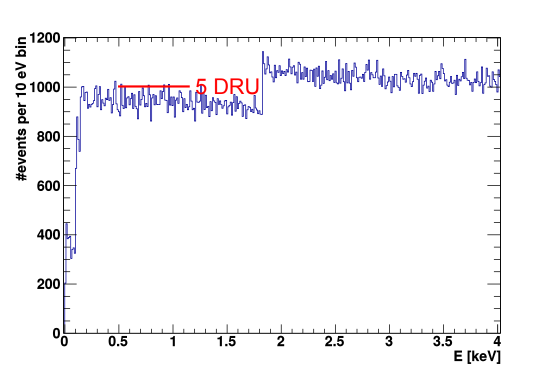

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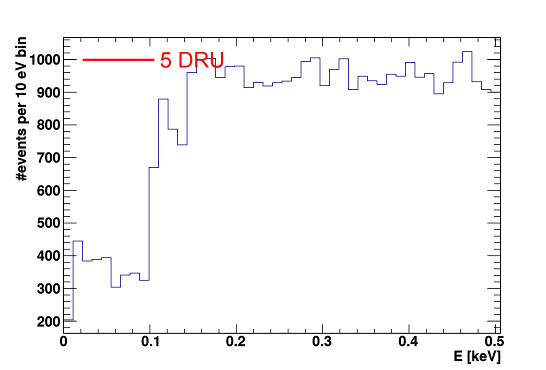

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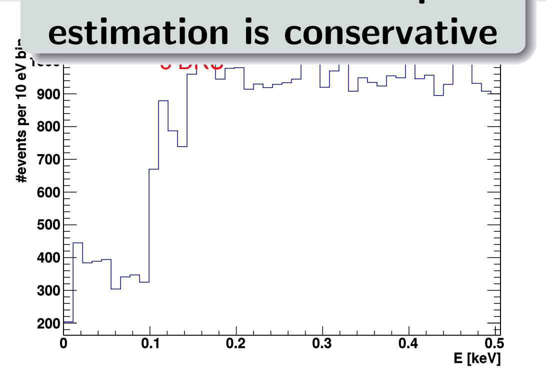
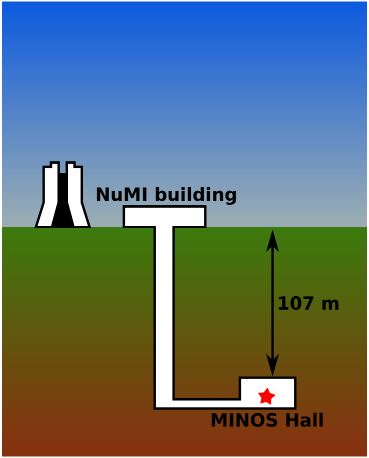
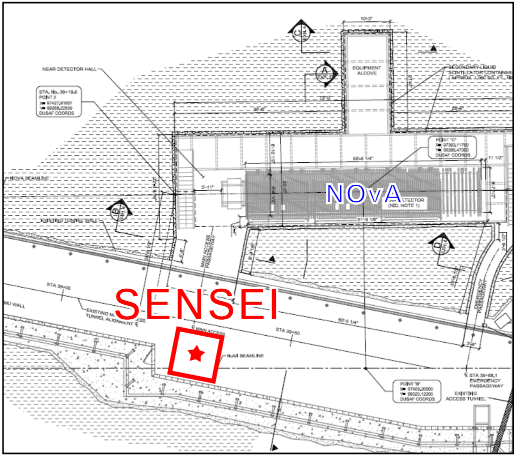
Back of the envelope estimation is conservative



Whats going on now: Installation @MINOS

Technology demonstration: installation at shallow underground site





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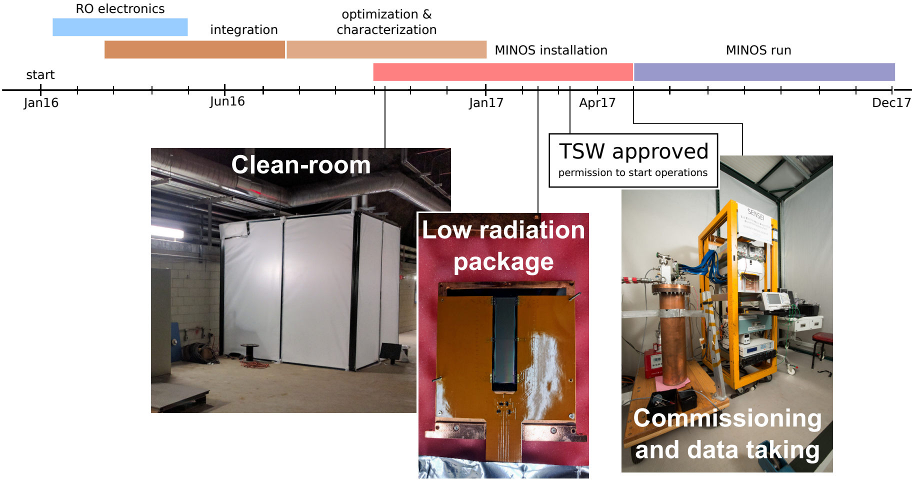

Taking data to understand if current (parasitically–fabricated) detectors are good enough to produce a science result

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

- Demonstrated technology: working detector.
- Demonstrated bkg: no R&D needed.
  - required bkg level already reached by running experiments.
- Minimal R&D required for the packaging of the sensors.
- 10g & 100g desing/construction started.
  - Grant from Heising-Simons Foundation
  - Full technical support from Fermilab
- Complementary to LDMX.
- 10g Scientific Skipper-CCDs will start taking data at MINOS by the end of 2018.
- MINOS site is good up to a 10g experiment. Deeper location (Snolab/SURF) is required for 100g.