The SENSEI[†] project

things you can do with less than one electron

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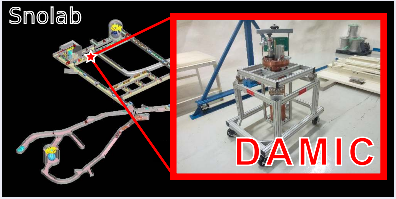
† **S**ub-**E**lectron-**N**oise **S**kipperCCD **E**xperimental **I**nstrument

Talk summary

- Motivation for low-energy-threshold/low-noise detectors
- SENSEI project: status and prospects
- Applications: DM searches, ν-physics, astronomical instruments

Motivation

DAMIC



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

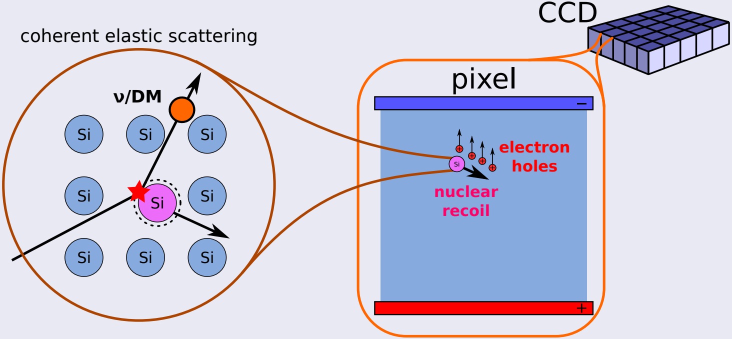
CONNIE

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

Goal: lower the energy threshold in Si detectors

Detect coherent DM/ν-nucleus interactions by measuring the ionization produced by the nuclear recoils

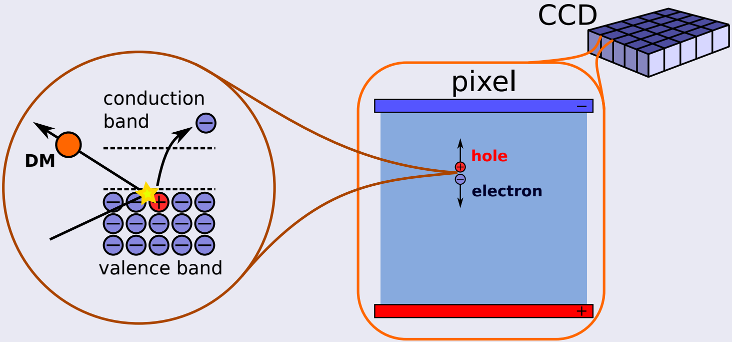
Idea: use CCDs as target and record the ionization produced



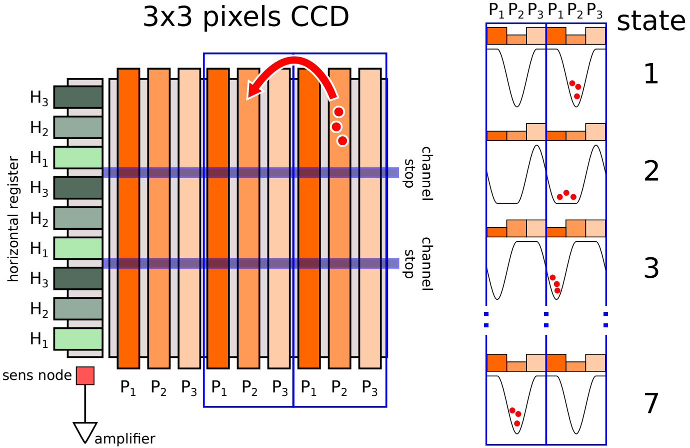
Goal: lower the energy threshold in Si detectors

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

Idea: use CCDs as target and record the ionization produced

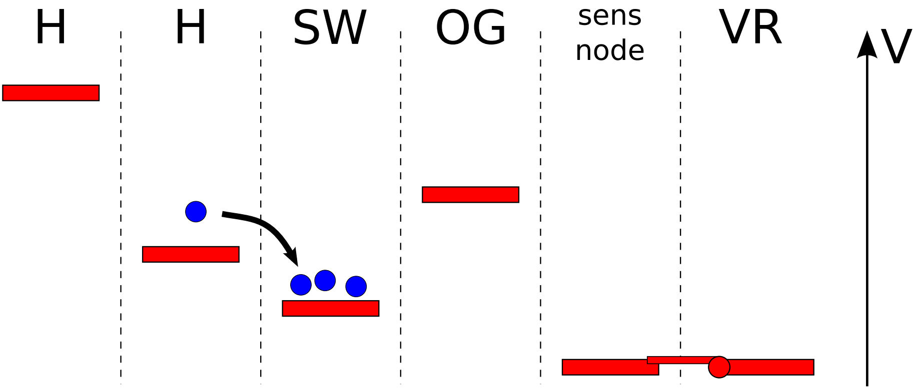


CCD: readout



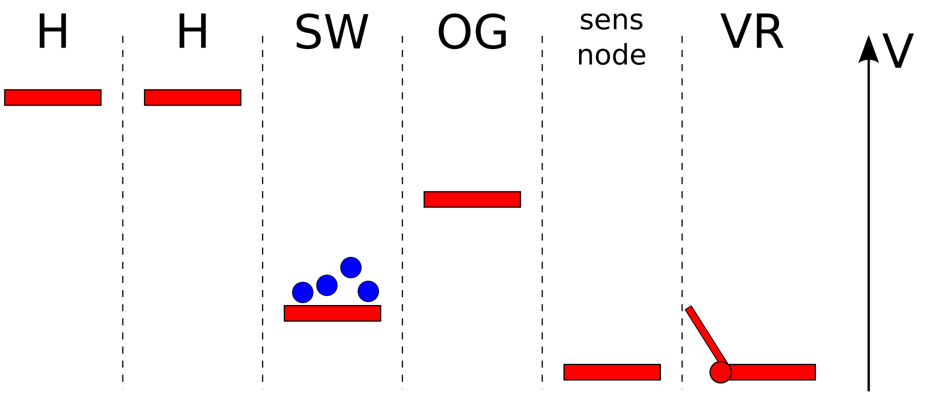
capacitance of the system is set by the SN: $C=0.05pF \rightarrow 3\mu V/e$

CCD: readout



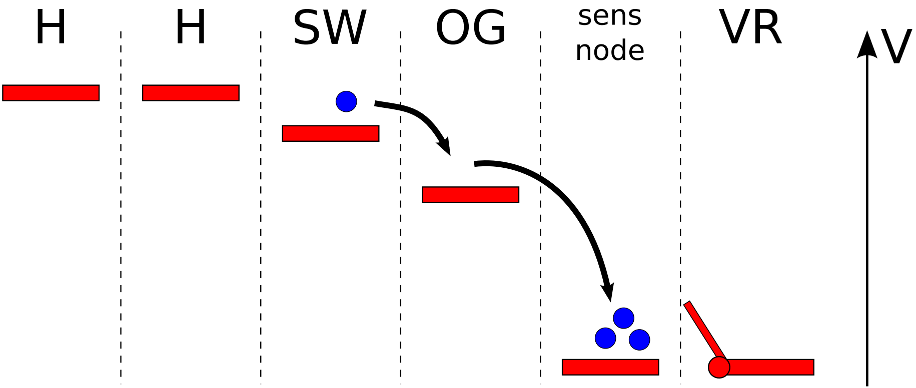
Accumulate the charge in the SW and reset the SN voltage

CCD: readout



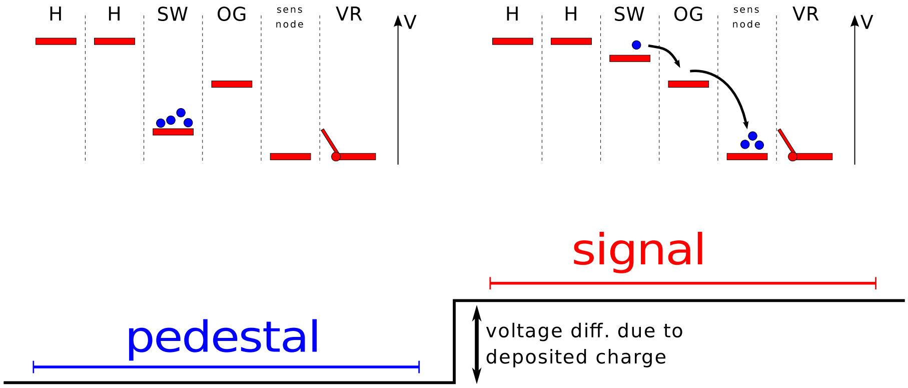
Disconnect the SN so it's floating. Measure the baseline voltage in the SN.

CCD: readout

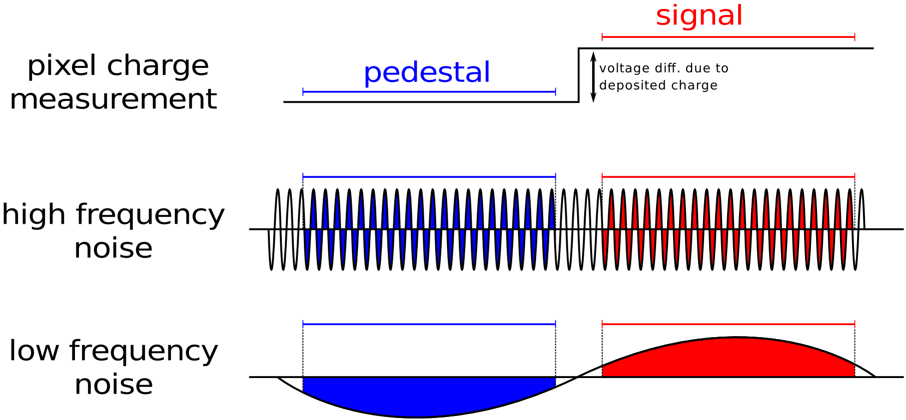


Move the change to the SN and measure the shift in the voltage

CCD: readout

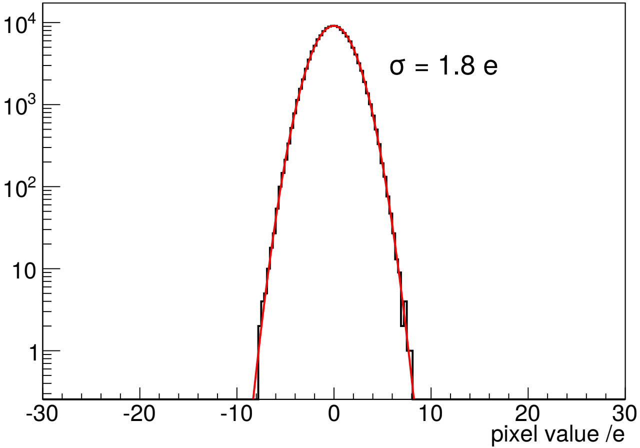

H
H
SW
OG
sens node
VR
V
signal
pedestal
voltage diff. due to
deposited charge

CCD: readout



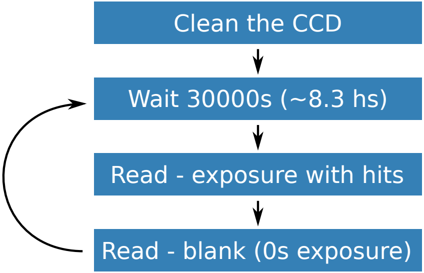
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution



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

CCD: readout - typical operation for rare events searches



We take long exposures to minimize the number of readouts. The exposure is eventually limited by the dark current.

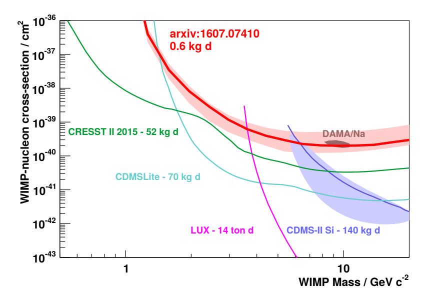
The blank images provide an excelent measurement of the background produced by readout

- The number of **real** events (produced by particles) scales with the total exposure time.
- The number of **fake** events (product of readout noise) scale with the number of readings (images taken).

It is better to read as few times as possible.

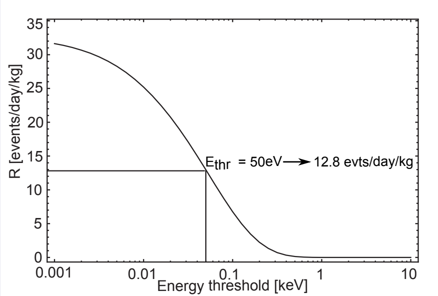
Status of the experiments

DAMIC



- Eng WIMP search: 1607.07410
- Fully commissioned Jan-17

CONNIE



- Eng run: 1604.01343
- Fully commissioned Aug-16

Both searches are limited by the readout noise of the sensors

Very limited electron-recoil sensitivity: threshold $\sim$10e$^-$

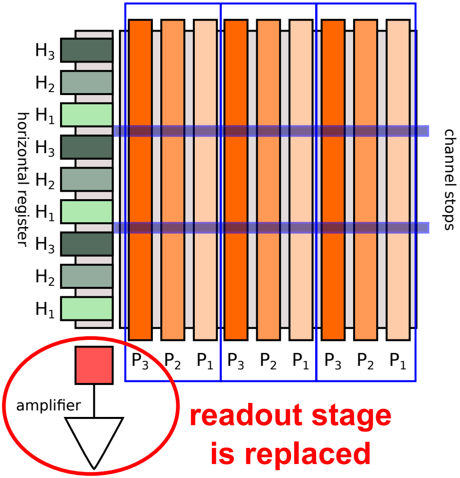
Awarded proposal: Fermilab LDRD 2016

Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) and a readout noise of 0.1 electrons using a new generation skipper CCD developed by the LBNL MicroSystems Lab

Plan

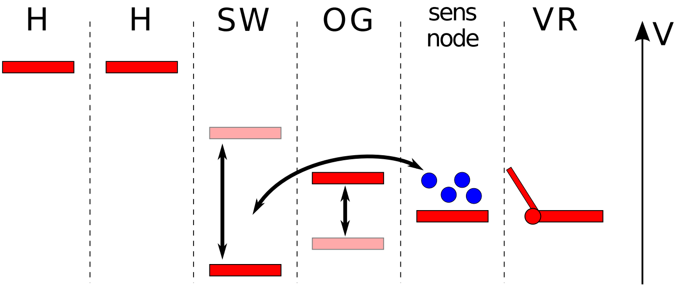
- Build the first working detector using Skipper-CCDs.
- Optimize the operation parameters and running conditions.
- Produce a low radiation package for the Skipper-CCDs.
- Install the detector in a low radiation environment (MINOS).
- Validate the technology for DM and ν experiments.

Lowering the noise: Skipper CCD



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
  $\mathbf{Pixel\,value = \frac{1}{N}\Sigma_i^N\,(pixel\,sample)_i}$



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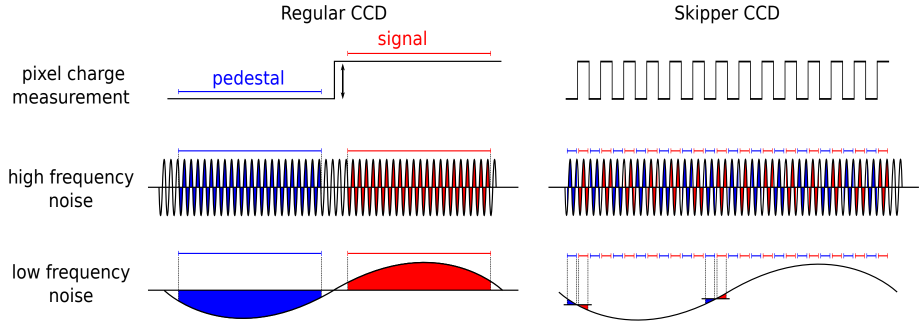
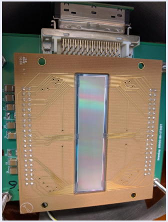


SENSEI: First working instrument using SkipperCCD tech

Sensors

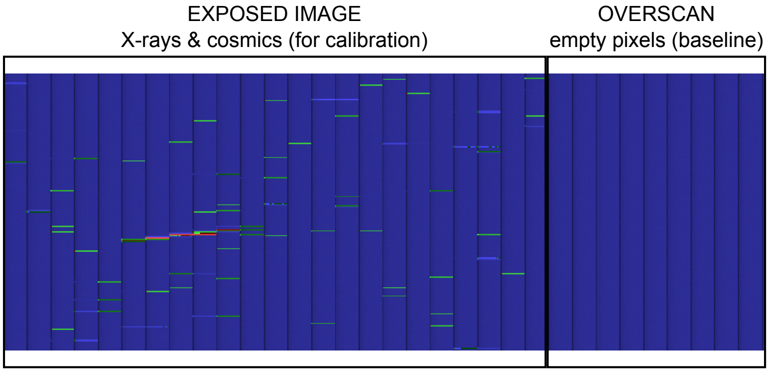


- Skipper-CCD prototype designed by LBL MSL
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k$\times$1k & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

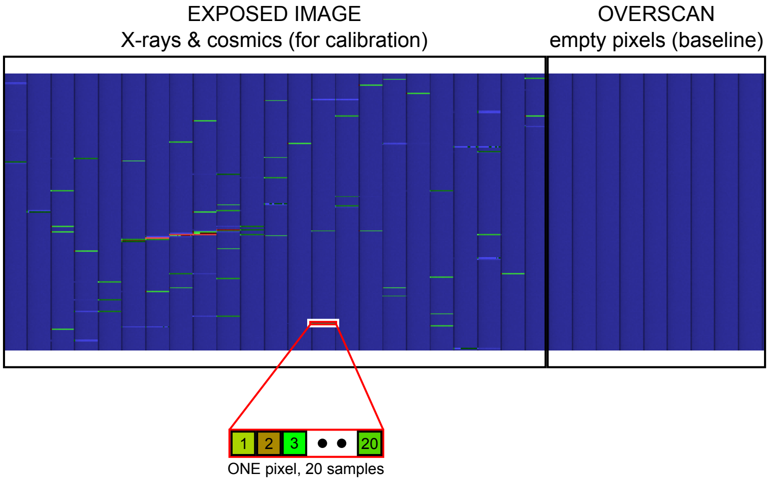
Instrument

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

Raw image taken with SENSEI: 20 samples per pixel



Raw image taken with SENSEI: 20 samples per pixel



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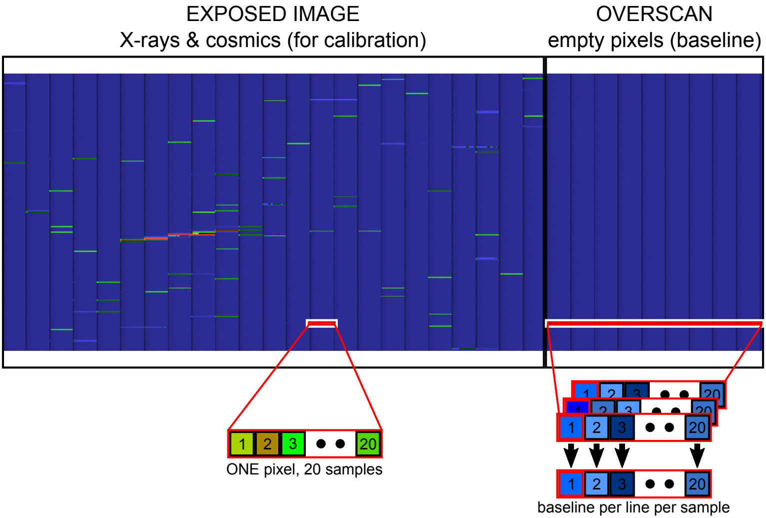
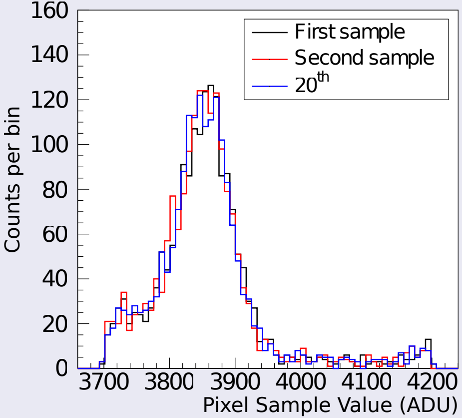


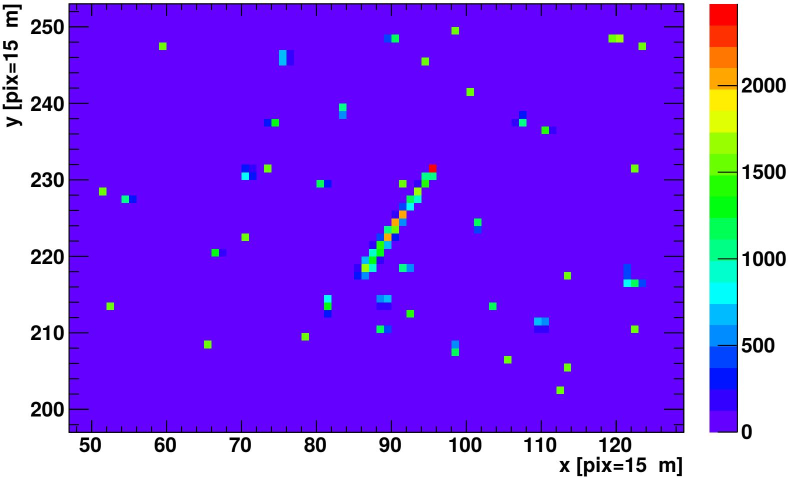
Image taken with SENSEI: 20 samples per pixel

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



The gain is the same for all the samples

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



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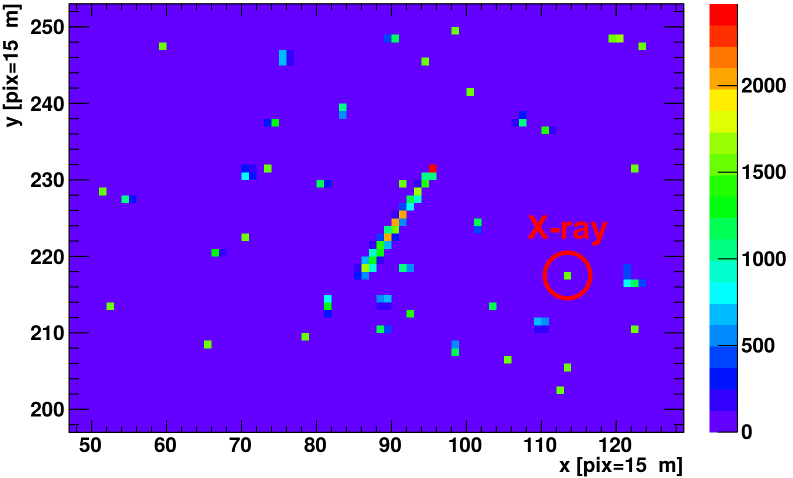

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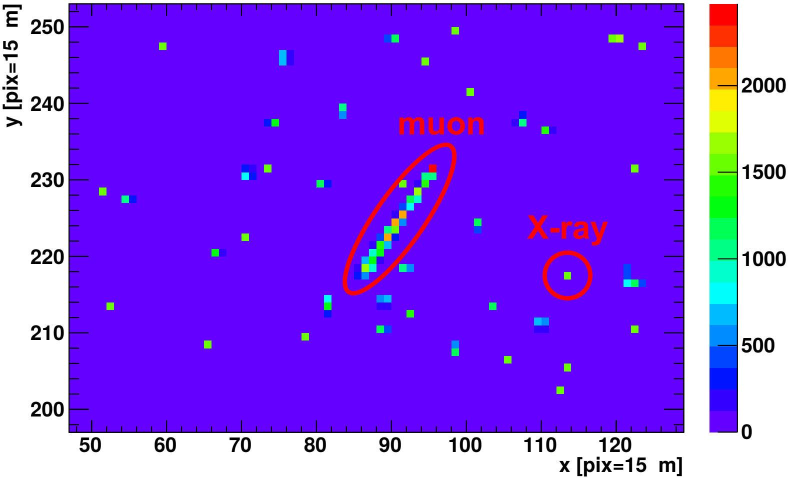

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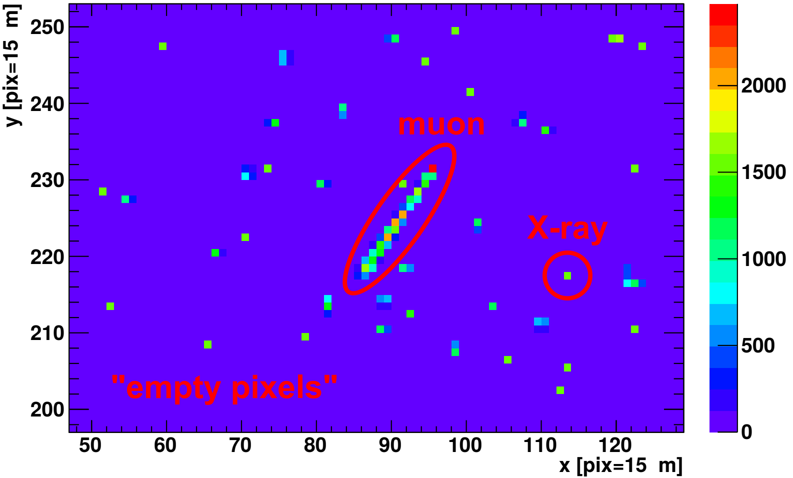
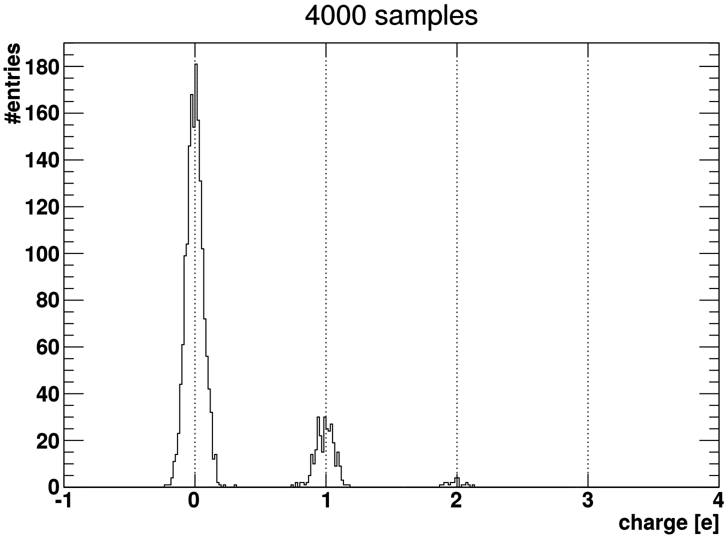


Charge in pixel distribution. Counting electrons: 0, 1, 2..



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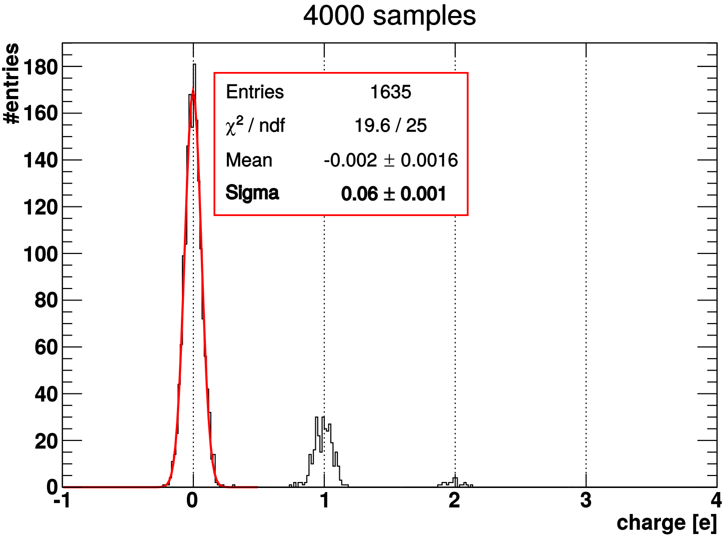
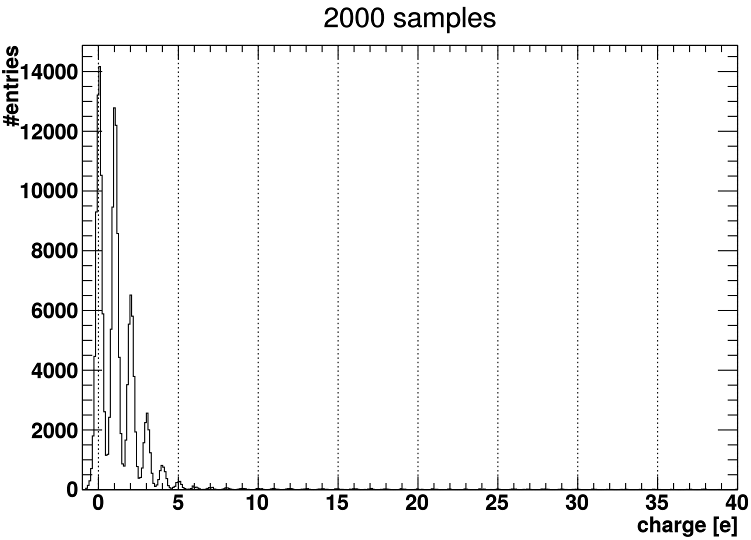


Counting electrons: ..38, 39, 40..



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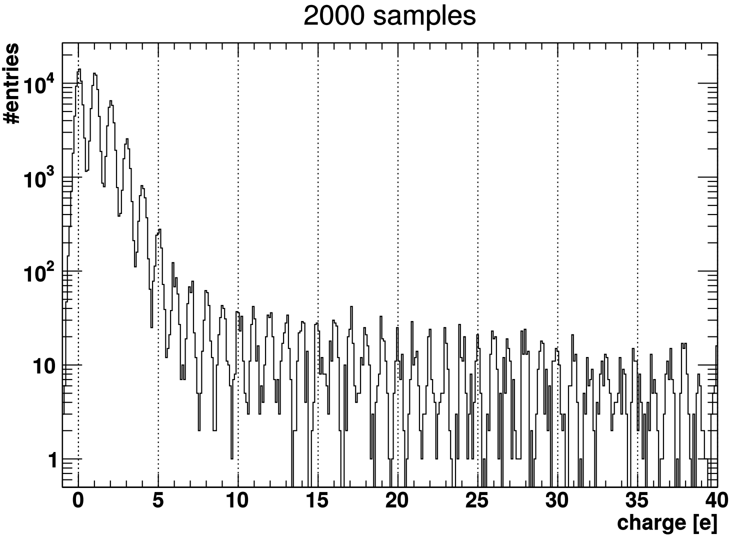
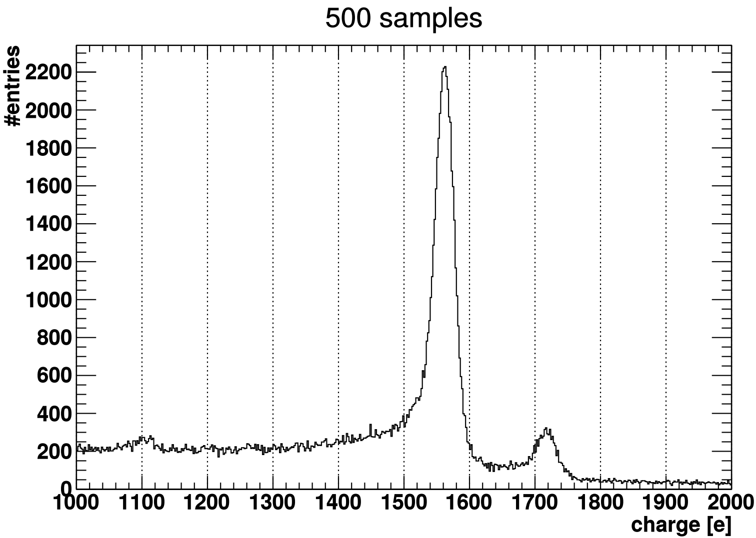


^{55}Fe X-ray source



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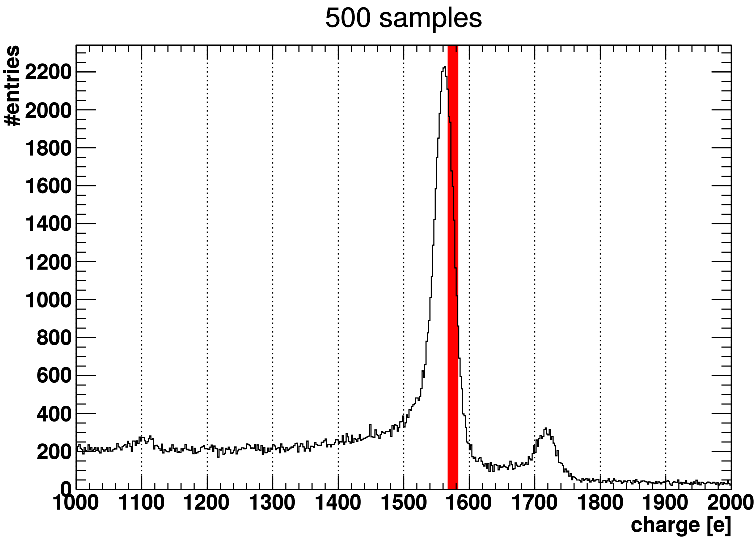
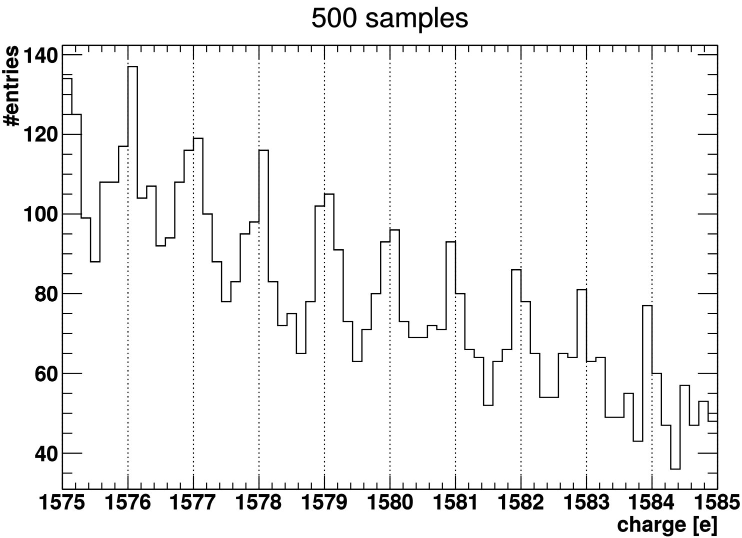
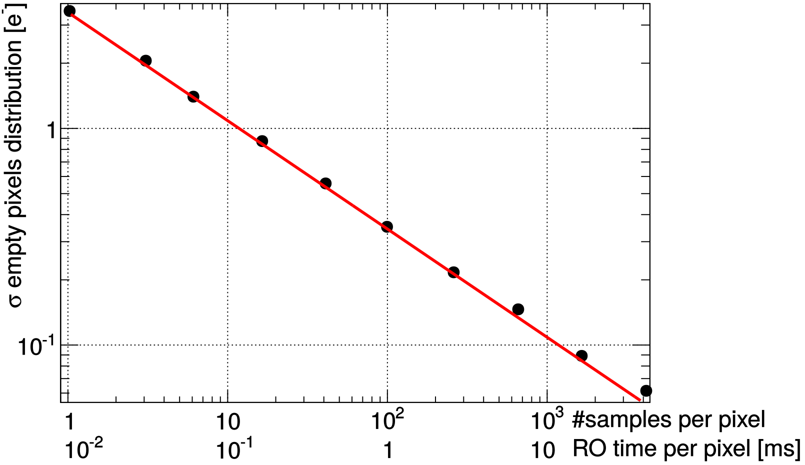


keep counting: ..1575, 1576, 1577..

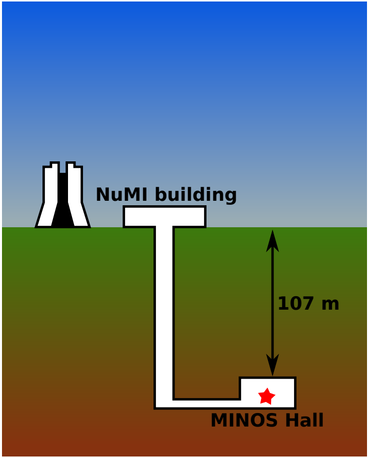


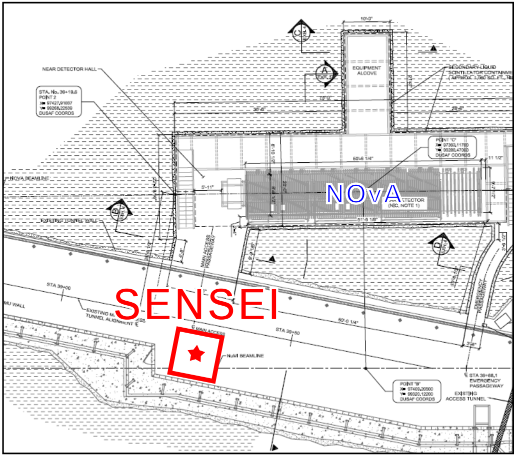
Noise vs. #samples - $1/\sqrt{N}$



Whats next: Installation @MINOS & low radiation package

Technology demonstration: installation at shallow underground site





Whats next: Installation @MINOS & low radiation package

Filtered air tent installed, low radioactivity package being tested

SENSEI: DM search operation mode

- Counting electrons ⇒ **noise has zero impact**
- It can take about 1h to readout a 4kx4k sensor
- **Dark Current is the limiting factor**

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

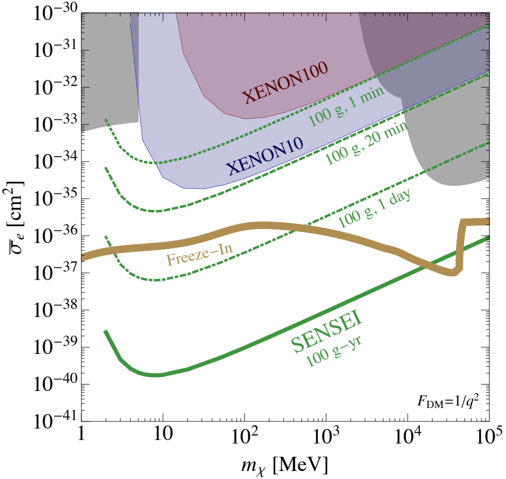
	Number of DC events (100 g y)	
Thr /e	$\mathbf{DC = 1 \times 10^{-3}}$ **e pix**$^{-1}$**day**$^{-1}$	$\mathbf{DC = 10^{-7}}$ **e pix**$^{-1}$**day**$^{-1}$
1	1×10^{8}	1×10^{4}
2	2×10^{4}	2×10^{-5}
3	3×10^{-2}	3×10^{-14}

Measured upper limit for the DC in CCDs is $\mathbf{1 \times 10^{-3}}$ **e pix**$^{-1}$**day**$^{-1}$. Could be orders of magnitude lower. Theoretical prediction is $\mathbf{O(10^{-7})}$.

Fermilab

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

Light Dark Photon



Rouven Essig, Tomer Volansky & Tien-Tien Yu.

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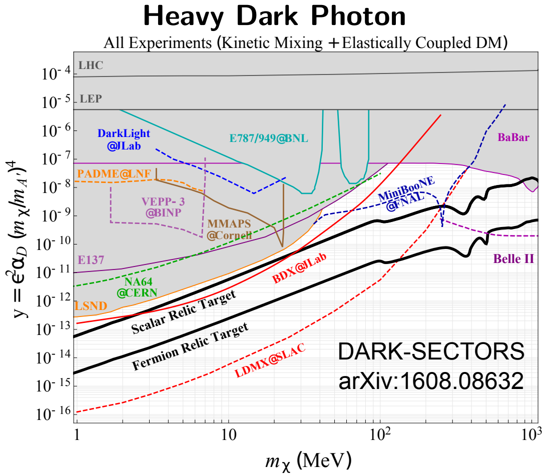
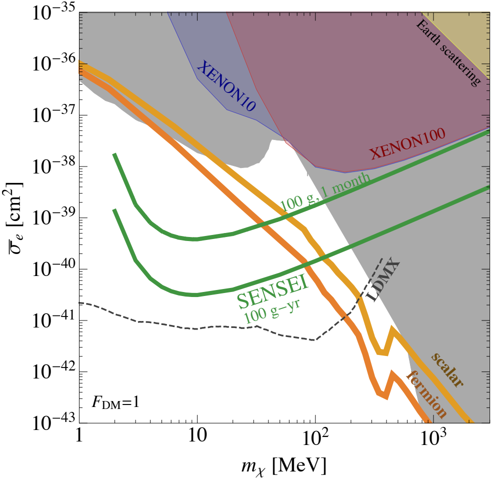


$$\overline{\sigma}_e \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D\epsilon^2}{m_{A'}^4}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D\epsilon^2}{(\alpha m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases}, \text{and} \quad F_{DM}(q) \simeq \begin{cases} 1\,, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}\,, & m_{A'} \ll \alpha m_e \end{cases}$$

Fermilab

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

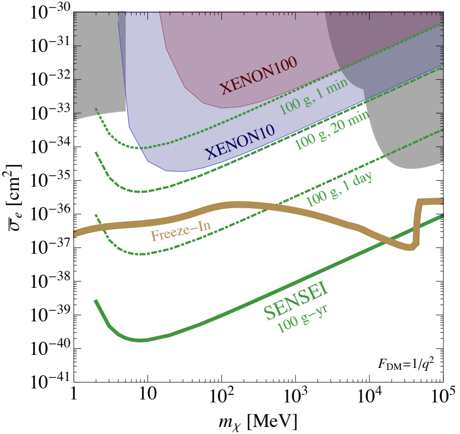
Heavy Dark Photon

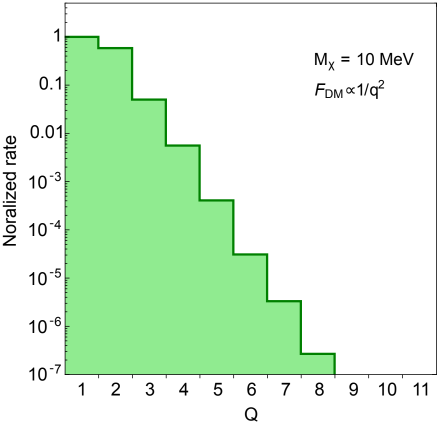


Rouven Essig, Tomer Volansky & Tien-Tien Yu.

SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin





Rouven Essig, Tomer Volansky & Tien-Tien Yu.

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

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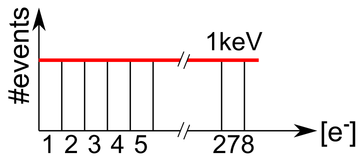


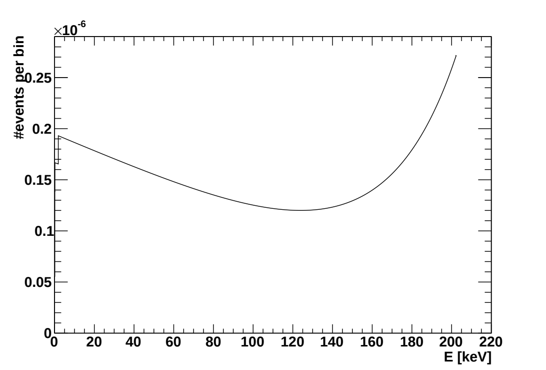
182.5 events over the 278 charge bins in the 0-1keV range

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

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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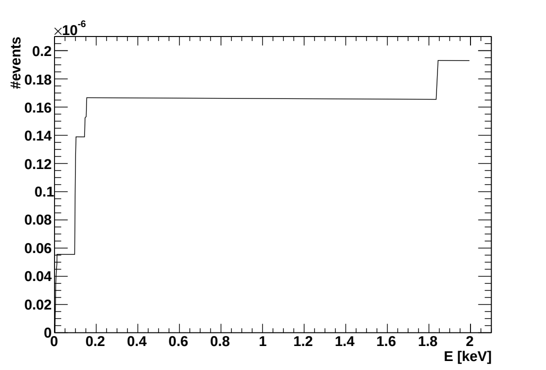

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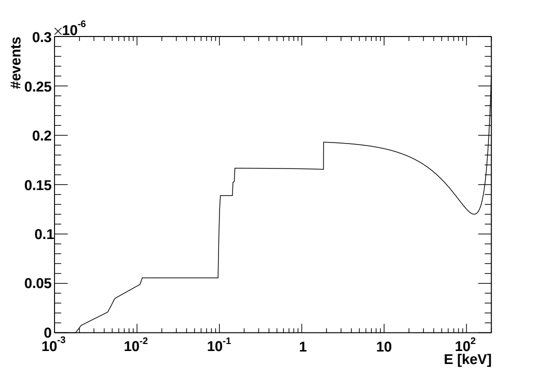

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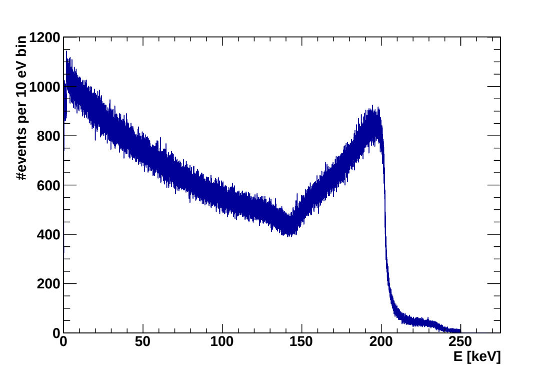

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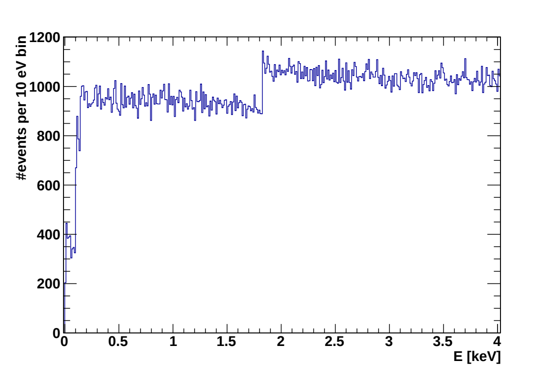

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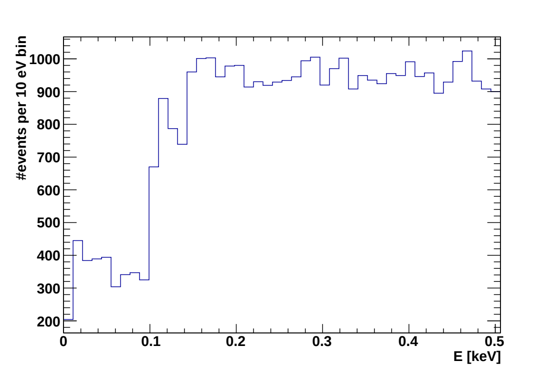

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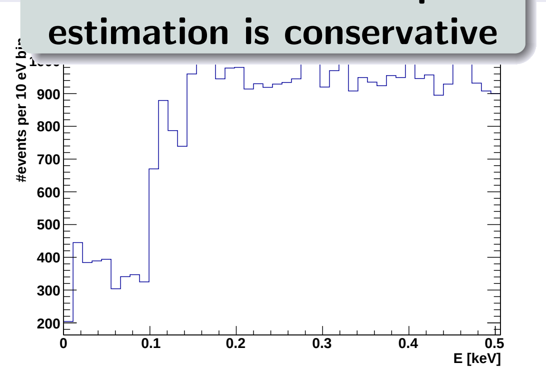
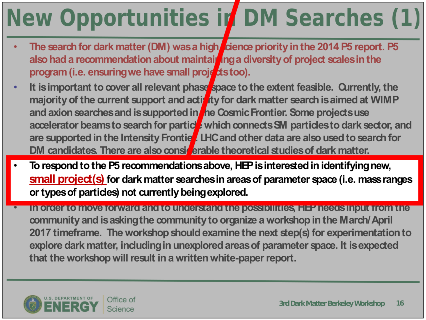
Back of the envelope estimation is conservative



From DOE Agency-Perspective talks

[..] HEP is interested in identifying new, small project(s), for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being explored.

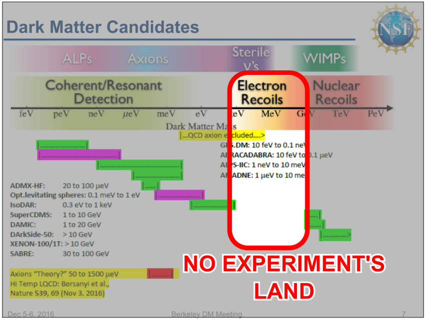


New Opportunities in DM Searches (1)

- The search for dark matter (DM) was a high science priority in the 2014 P5 report. P5 also had a recommendation about maintaining a diversity of project scales in the program (i.e. ensuring we have small projects too).
- It is important to cover all relevant phase space to the extent feasible. Currently, the majority of the current support and activity for dark matter search is aimed at WIMP and axion searches and is supported in the Cosmic Frontier. Some projects use accelerator beams to search for particle which connects SM particles to dark sector, and are supported in the Intensity Frontier. LHC and other data are also used to search for DM candidates. There are also considerable theoretical studies of dark matter.
- To respond to the P5 recommendations above, HEP is interested in identifying new, small project(s) for dark matter searches in areas of parameter space (i.e. mass ranges or types of particles) not currently being explored.
- In order to move forward and to understand the possibilities, HEP needs input from the community and is asking the community to organize a workshop in the March/April 2017 timeframe. The workshop should examine the next step(s) for experimentation to explore dark matter, including in unexplored areas of parameter space. It is expected that the workshop will result in a written white-paper report.

U.S. DEPARTMENT OF ENERGY | Office of Science

3rd Dark Matter Berkeley Workshop 16



SENSEI is the ultimate silicon ionization detector
Dream sensor for electron recoil channel

Fermilab

SENSEI path

Advantages

- Complementary to LDMX.
- Minimal R&D required for the sensors and readout electronics.
- Can be build quickly.
- Radioactive backgrounds not so challenging.
- We'll probably have science results from the MINOS run.
- Developing this technology can produce spin-offs.

Next steps

- DOE Cosmic Visions Workshop.
- White paper and detailed budget and schedule (drafts are ready).

SENSEI and Skipper-CCD detectors prospects

SENSEI is the ultimate silicon ionization detector
Unmatched performance for electron recoil channels

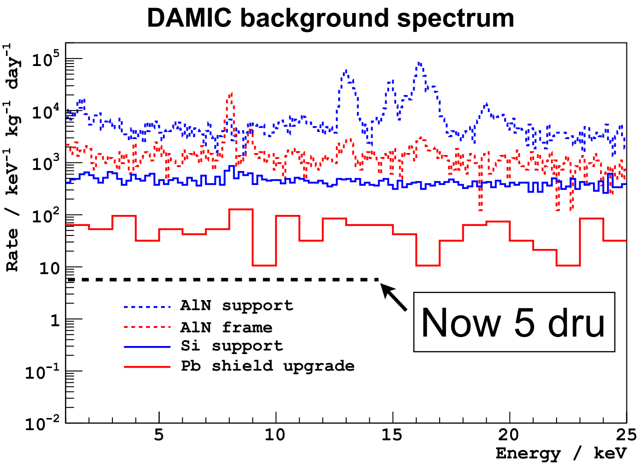
- Probe DM masses at the MeV scale through electron recoil.
- Probe axion and hidden-photon DM with masses down to 1 eV.
- Probe DM masses as low as 0.1 GeV through nuclear recoil.
- Push boundaries of coherent ν-nucleus interaction experiments.
- Improve high resolution spectroscopic instruments.

Participants

- **Fermilab:** Javier Tiffenberg, Yann Guardincerri, Miguel Sofo Haro
- **LBNL:** Steve Holland, Christopher Bebek
- **Stony Brook:** Rouven Essig
- **Tel Aviv University:** Tomer Volansky
- **CERN:** Tien-Tien Yu
- **Stanford University*:** Jeremy Mardon

BACK UP SLIDES

DAMIC background

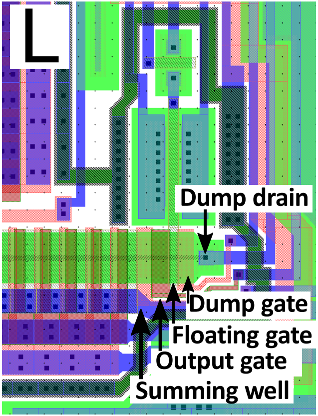


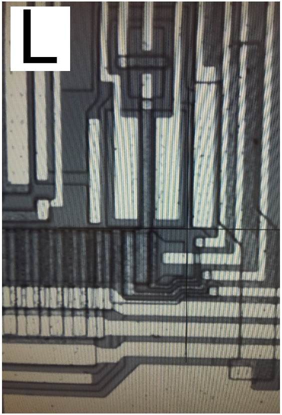
SuperCDMS SNOLAB projected background

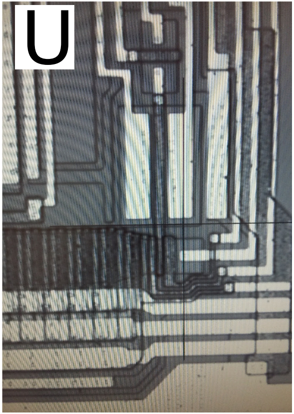
"Singles" Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.

From arXiv:1610.00006

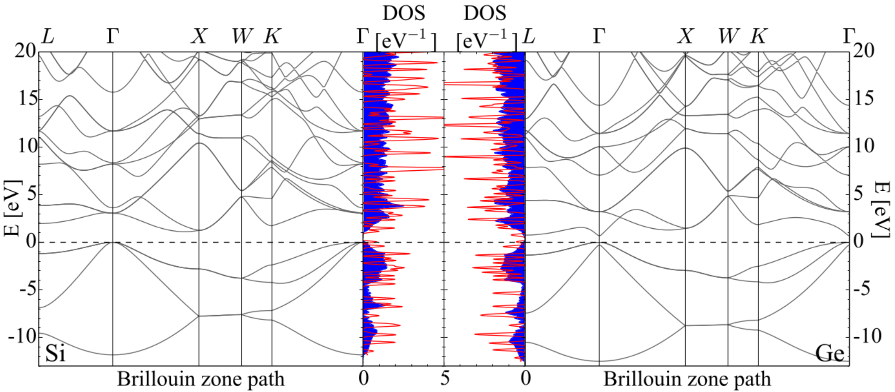
Readout stage design







Electron density-of-states (1509.1598)



SENSEI budget draft

	M&S	Effort	Total
1. Sensors & package	350 k$	100 k$	450 k$
2. Readout electronics	200 k$	0 k$	200 k$
3. Vessel & support systems	115 k$	100 k$	215 k$
4. Installation	0 k$	50 k$	50 k$
5. Contingency	150 k$	50 k$	200 k$
Total	815 k$	300 k$	**1.15 M$**