The SENSEI† project

how to look for DM-electron scattering events

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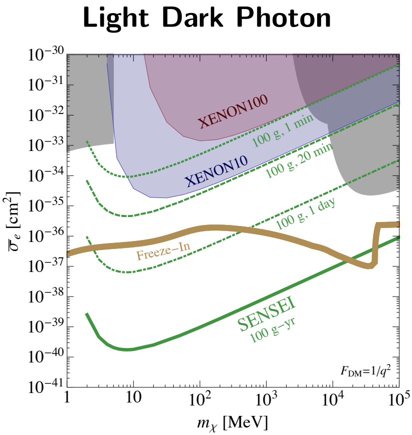
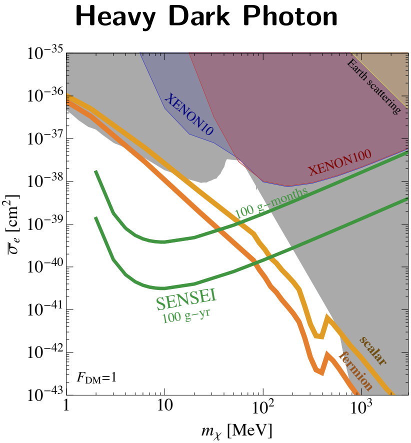
March 25, 2017

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

Motivation for SENSEI: a detector that can do this NOW

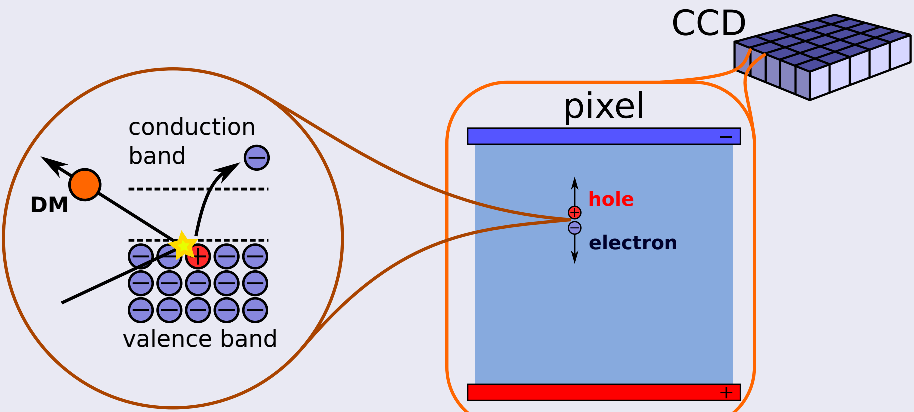




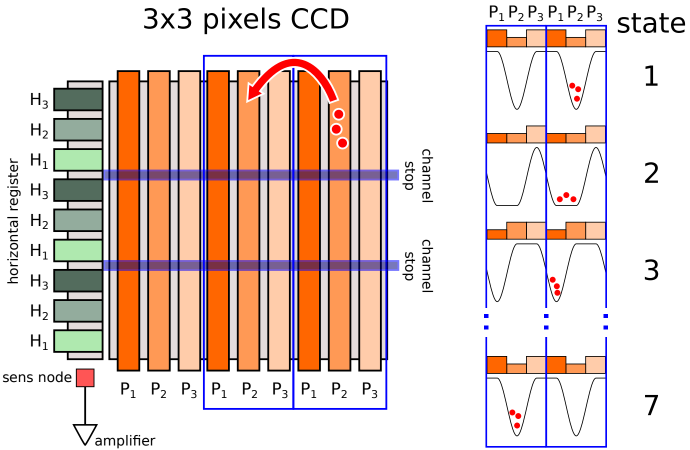
Plots from: Rouven Essig, Tomer Volansky & Tien-Tien Yu.

How?

use CCDs as target to record the ionization produced by DM



CCD: readout



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

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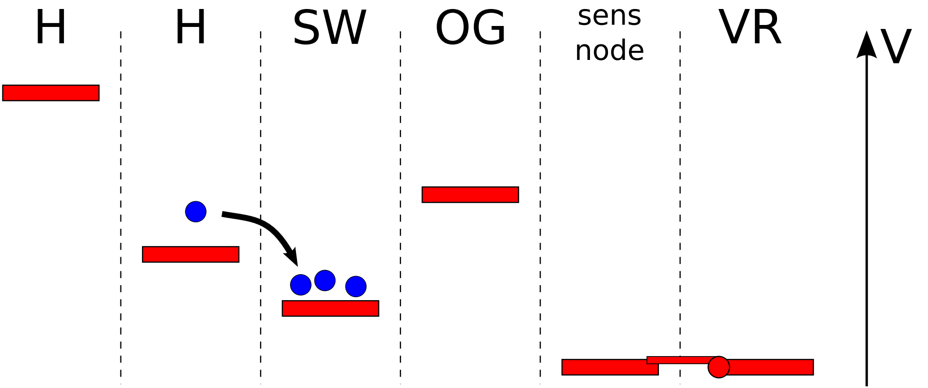
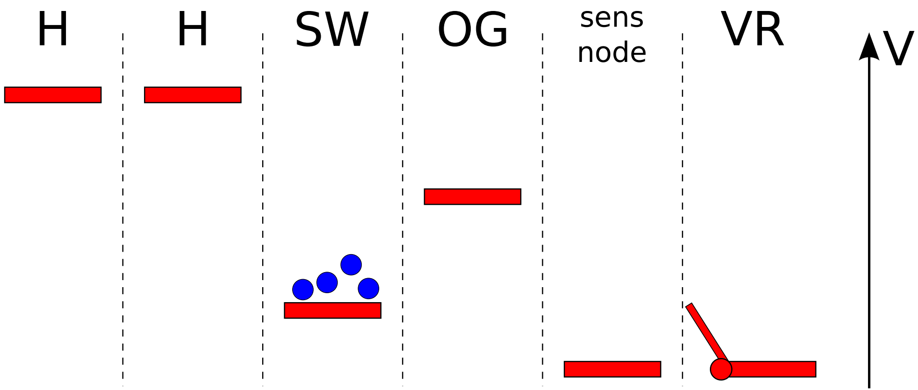


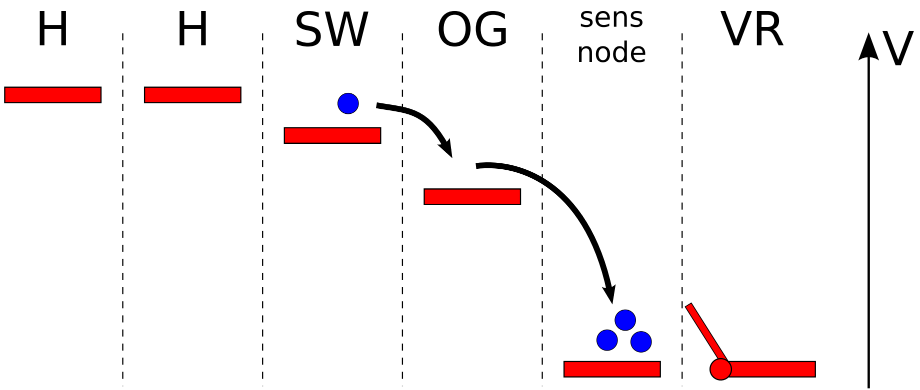
Accumulate the charge in the SW and reset the SN voltage

CCD: readout



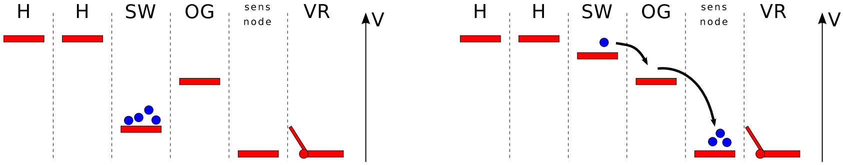
Disconnect the SN so it's floating. Measure the baseline voltage in the SN.

CCD: readout

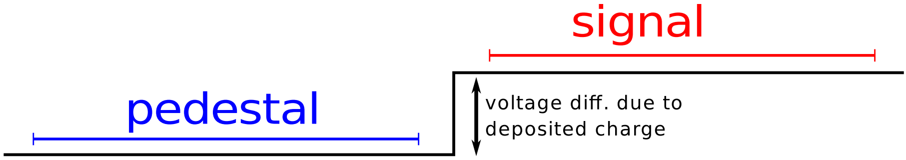


Move the change to the SN and measure the shift in the voltage

CCD: readout

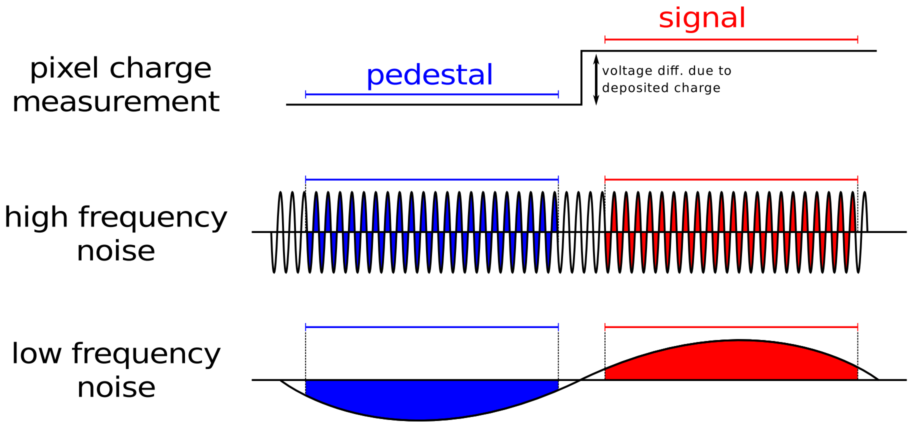


H
H
SW
OG
sens node
VR
V
H
H
SW
OG
sens node
VR
V



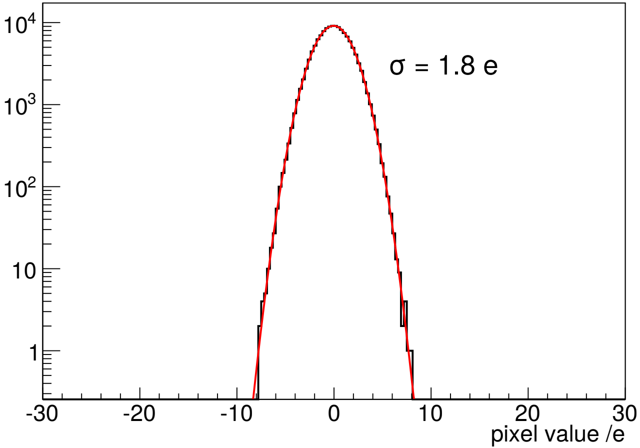
signal
pedestal
voltage diff. due to deposited charge

CCD: readout



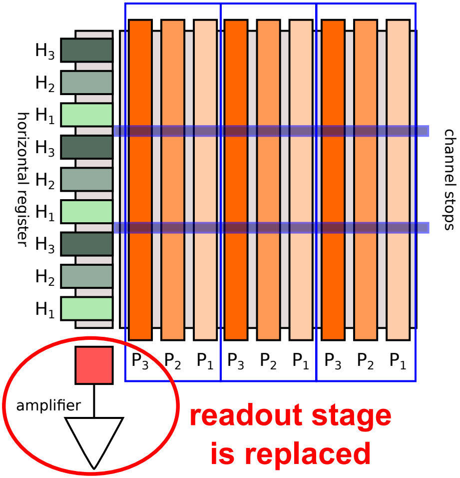
excellent for removing high frequency noise but sensitive to low frequencies

Readout noise: empty pixels distribution



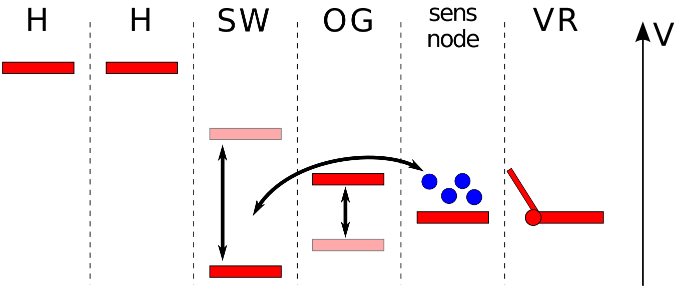
2 e⁻ readout noise roughly corresponds to 50 eV energy threshold

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



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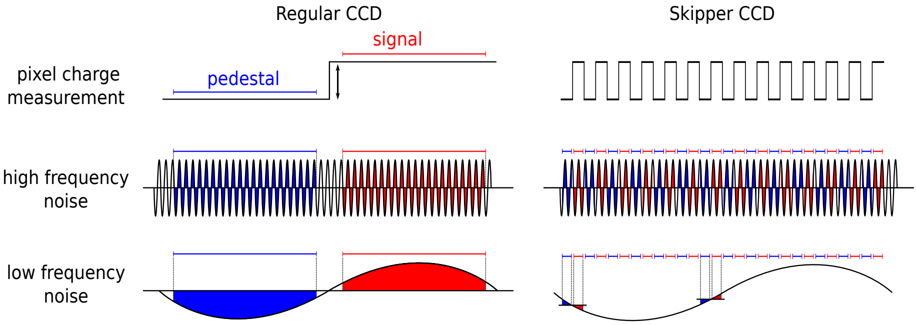


Awarded proposal: **Fermilab LDRD 2016** - PI Javier Tiffenberg

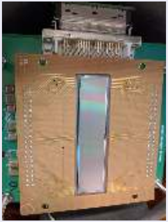
Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) and a readout noise of 0.1 electrons using a new generation skipper CCD developed by the **LBNL MicroSystems Lab**

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.

SENSEI: First working instrument using SkipperCCD tech

Sensors

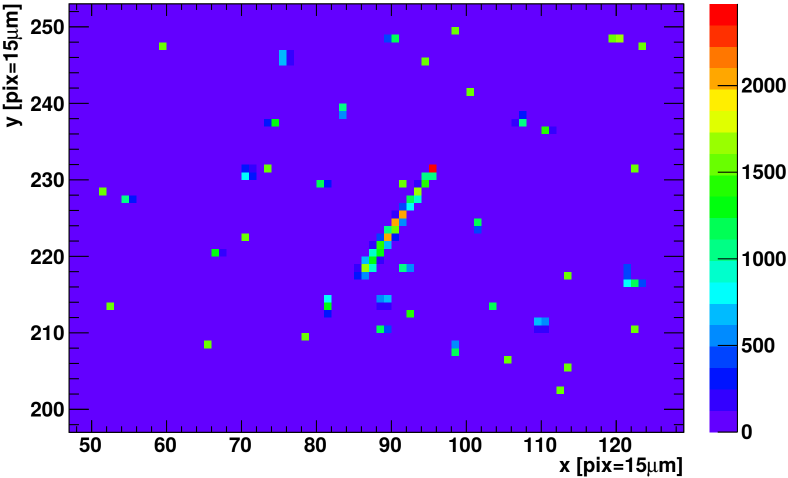


- Skipper-CCD prototype designed by **LBL MSL**
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k$\times$1k (0.5gr) & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

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)



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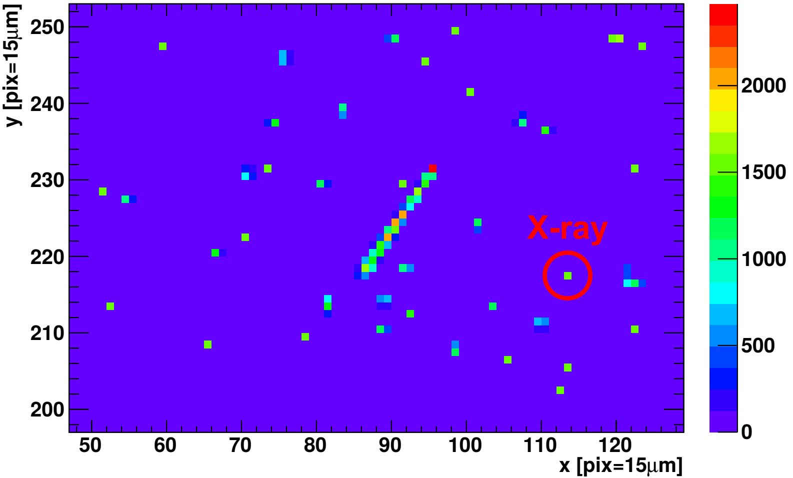

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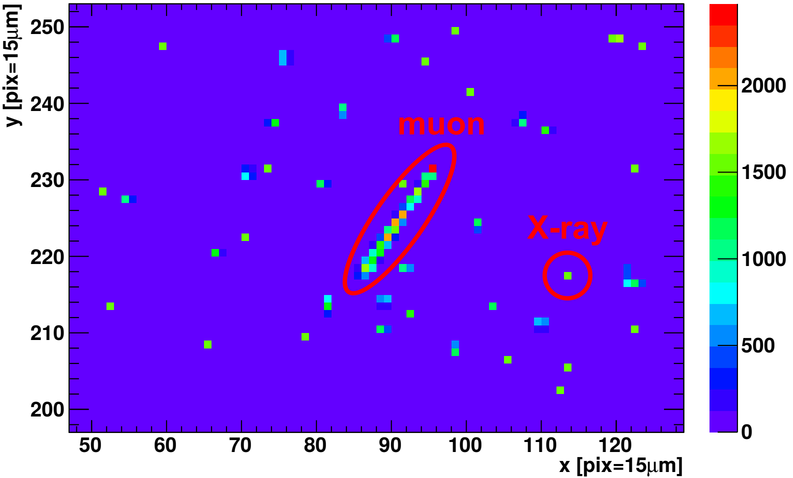

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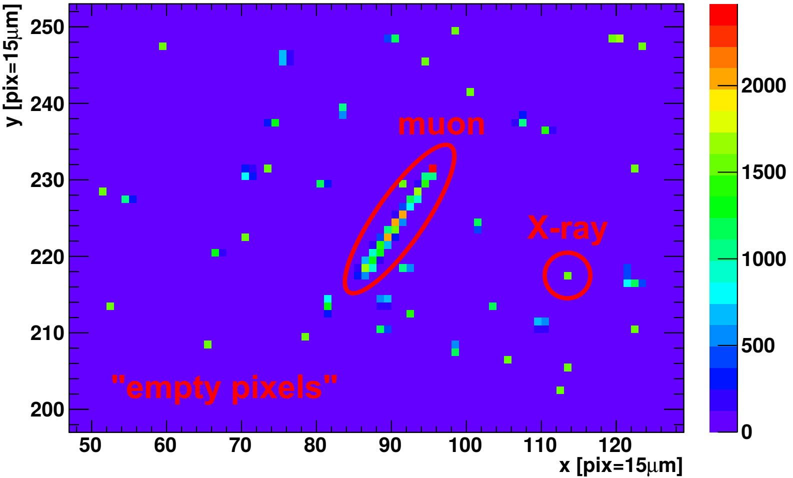
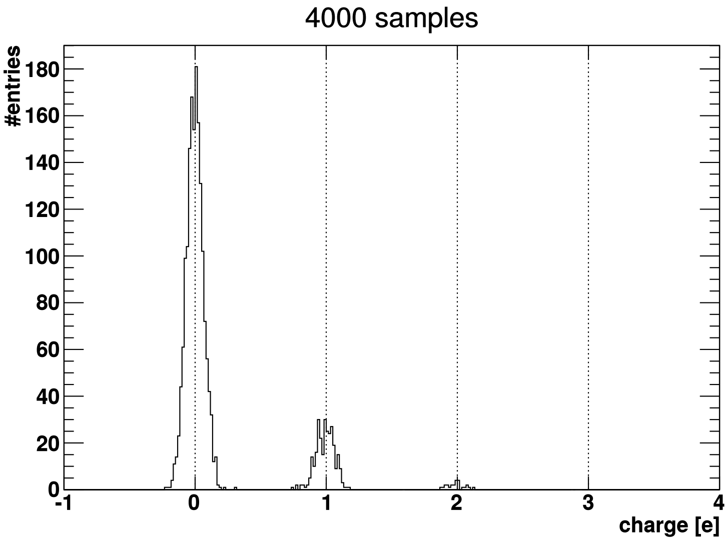


Charge in pixel distribution. Counting electrons: 0, 1, 2..



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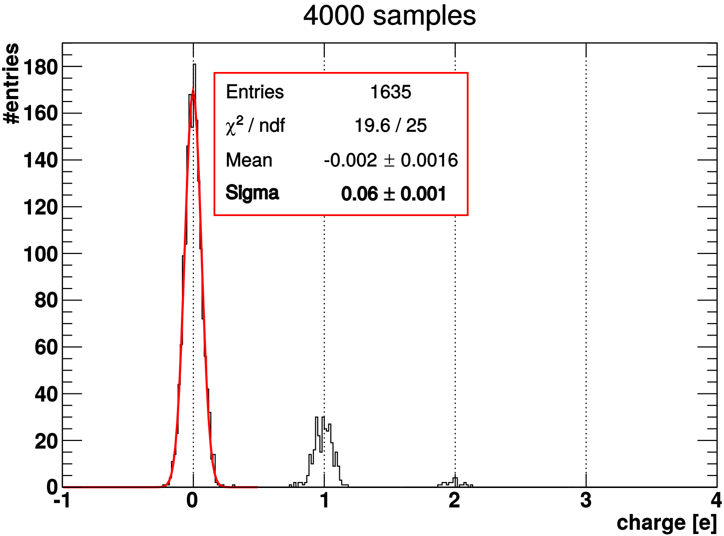
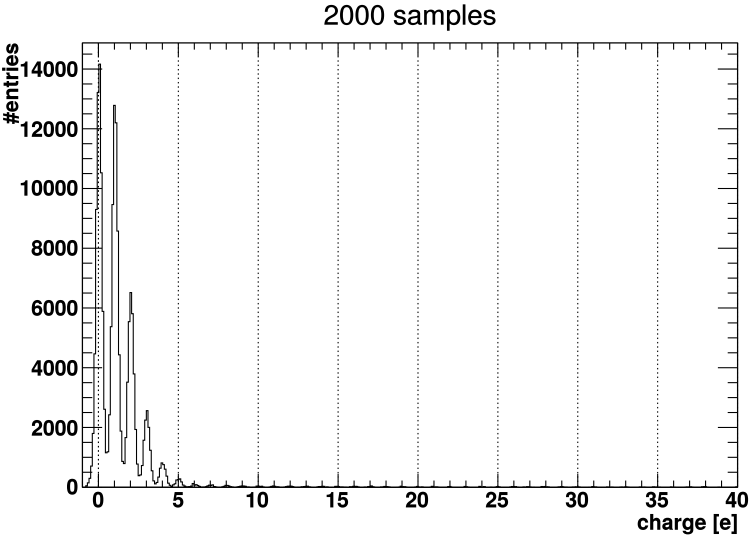


Counting electrons: ..38, 39, 40..



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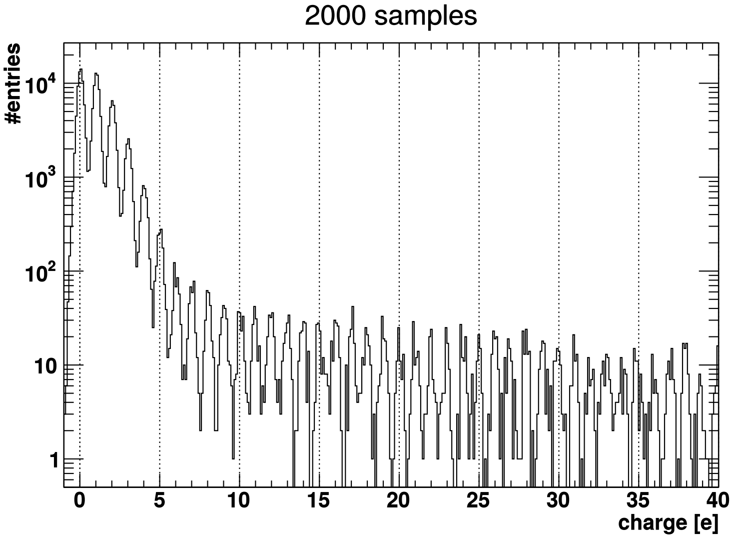
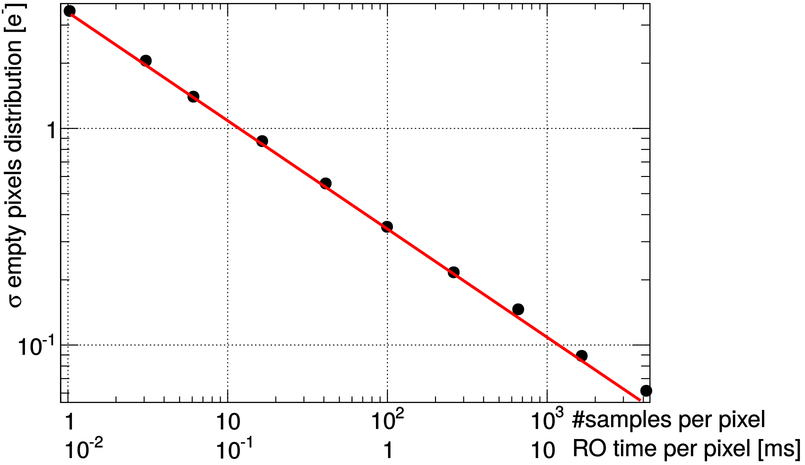
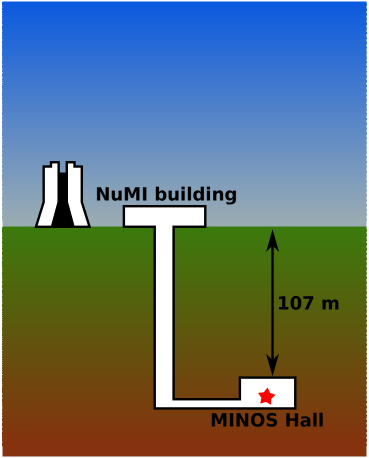


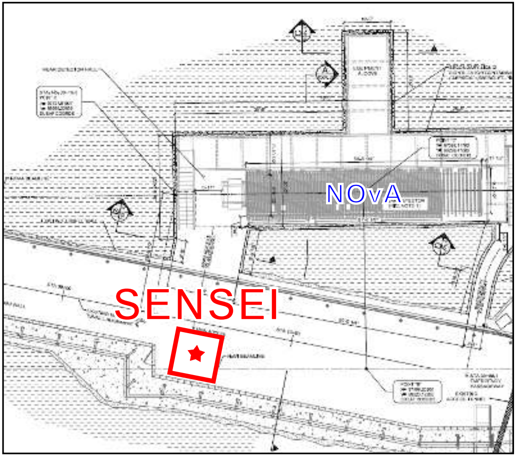
Noise vs. #samples - $1/\sqrt{N}$



Whats next: Installation @MINOS & low radiation package

Technology demonstration: installation at shallow underground site





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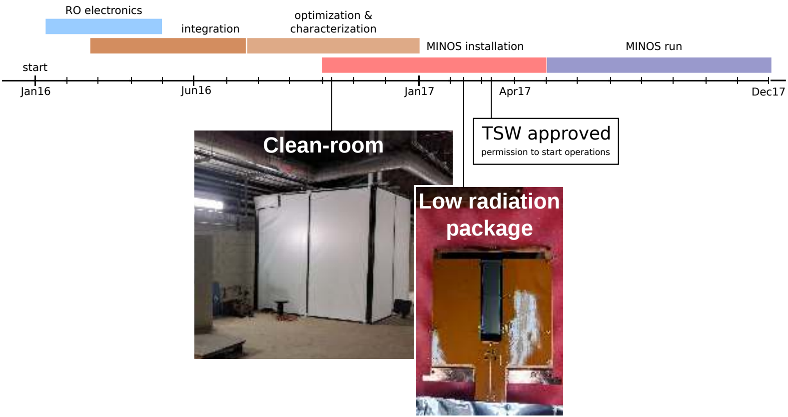


Commissioning of 1gr at MINOS by the end of April 2017

SENSEI: DM search operation mode

- Counting electrons $\Rightarrow$ **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

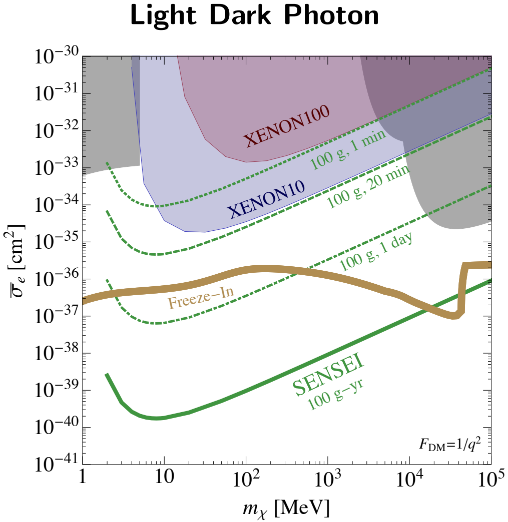
	Number of DC events (100 g y)	
Thr /e	$\mathbf{DC = 1 \times 10^{-3}}$ **e pix^{-1}day^{-1}**	$\mathbf{DC = 10^{-5}}$ **e pix^{-1}day^{-1}**
1	1×10^{8}	7×10^{5}
2	2×10^{4}	0.2
3	3×10^{-2}	3×10^{-8}

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 $\mathbf{O(10^{-7})}$**

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



Rouven Essig, Tomer Volansky & Tien-Tien Yu.

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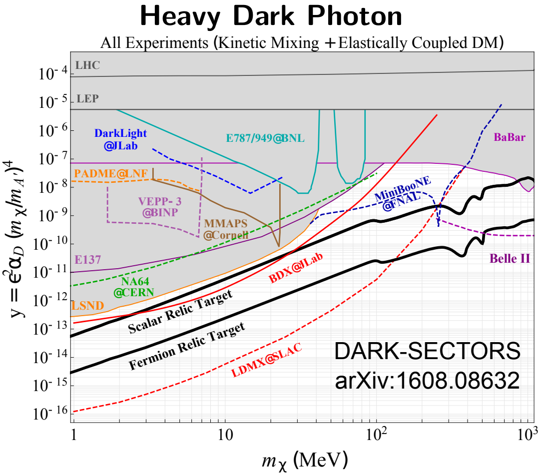
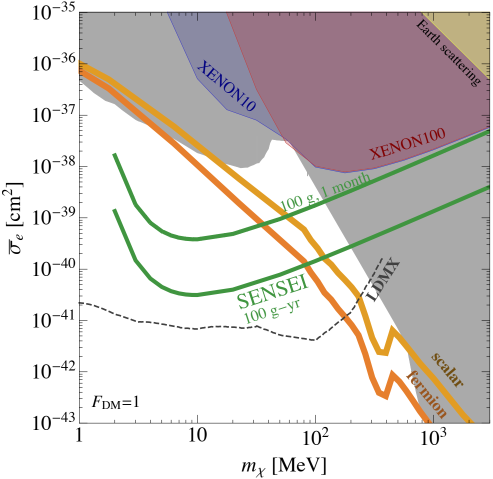


$$\overline{\sigma}_e \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D \epsilon^2}{m_{A'}^4}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2 \alpha\alpha_D \epsilon^2}{(\alpha m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases}, \text{ and } \quad F_{DM}(q) \simeq \begin{cases} 1, & m_{A'}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

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

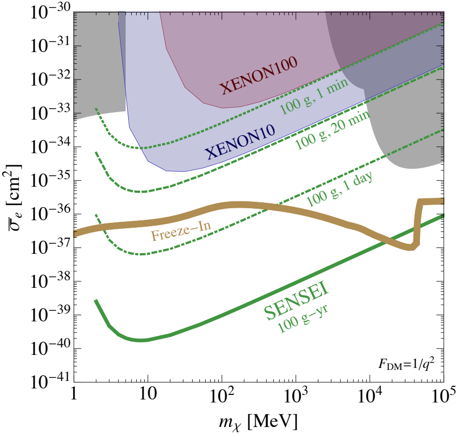
Heavy Dark Photon: complemetary to LDMX

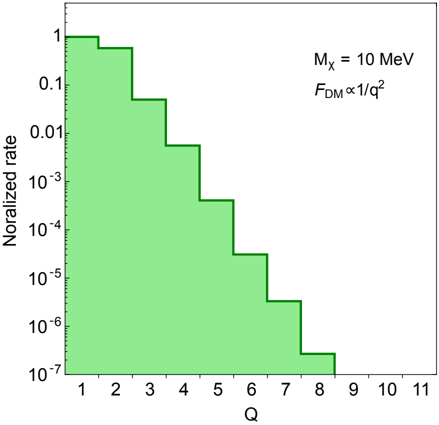


Rouven Essig, Tomer Volansky & Tien-Tien Yu.

SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin





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

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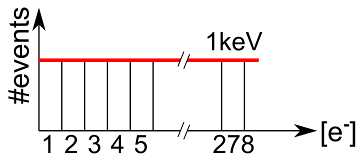


182.5 events over the 278 charge bins in the 0-1keV range

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

SENSEI path

Summary

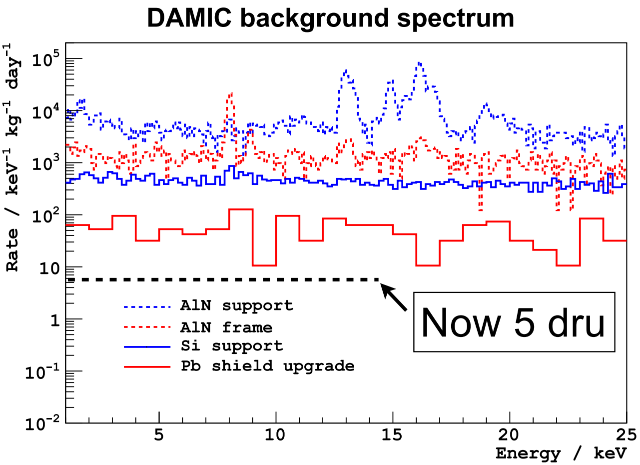
- Demonstrated technology: working detector
- Demonstrated bkg: no R&D needed.
  - this level already reached by running experiments
- Minimal R&D required for the packaging of the sensors.
- 100 g construction could start on FY18.
  - 1.2 M$ in 2 yrs (scaled from DAMIC experience)
- Complementary to LDMX and DAMIC-1K
- Small scale demonstration at the MINOS. Results by the end of 2017.
- MINOS site is good up to a 10g experiment. SURF/Snolab for 100g.

BACK UP SLIDES

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$**

DAMIC background



SuperCDMS SNOLAB projected background

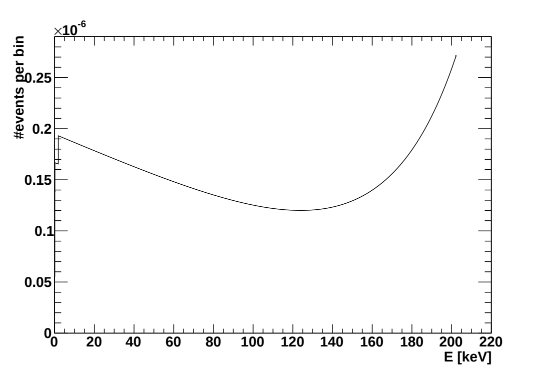
"Singles" Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	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

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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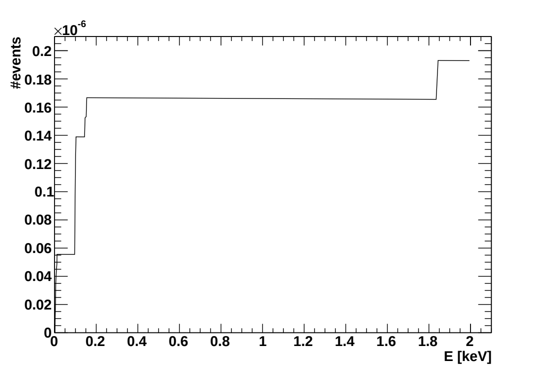

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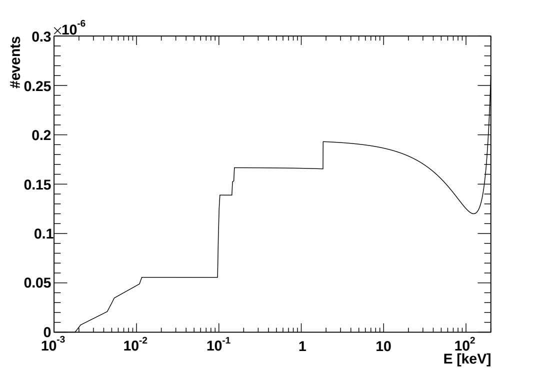

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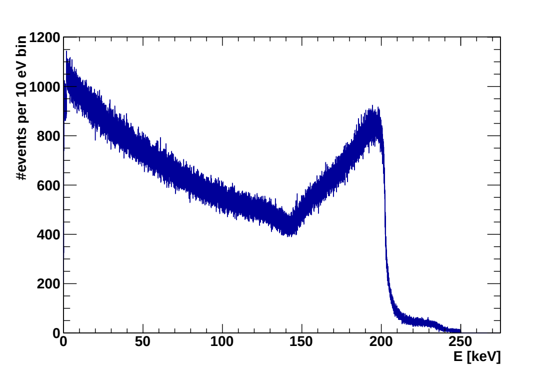

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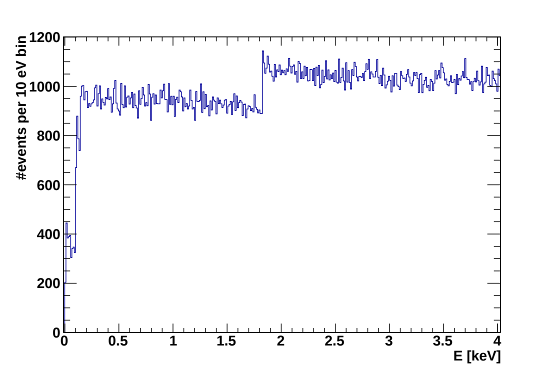

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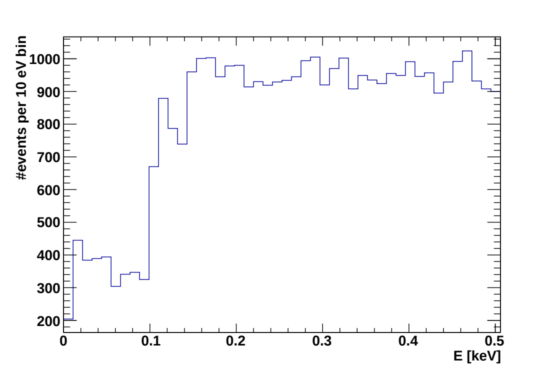

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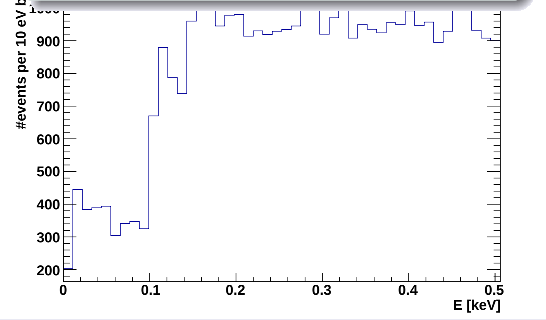
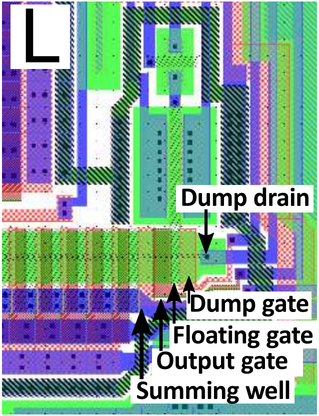
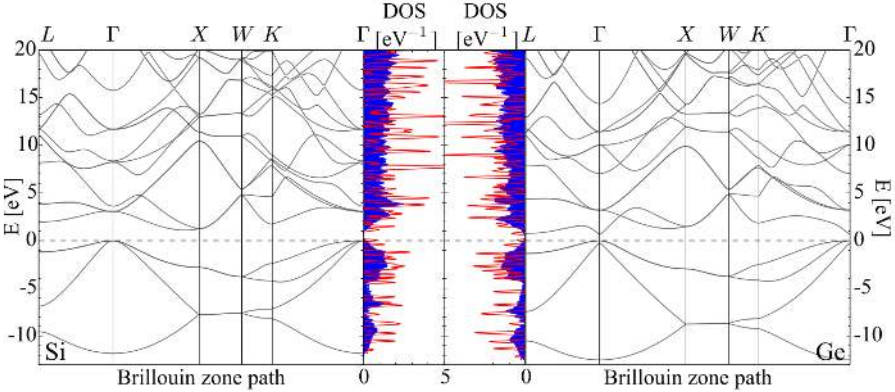
Back of the envelope estimation is conservative



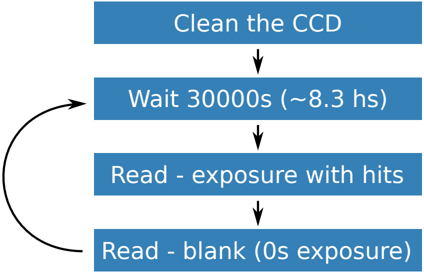
Readout stage design



Electron density-of-states (1509.1598)



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.

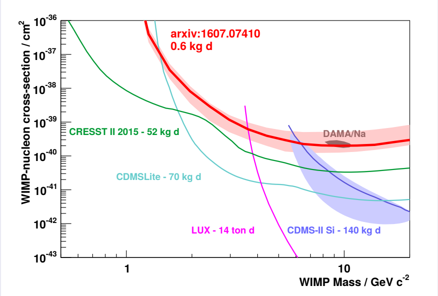
The blank images provide an excelent measurement of the background produced by readout

- 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.

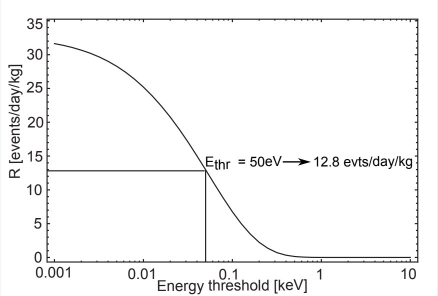
Status of the experiments

DAMIC



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

CONNIE



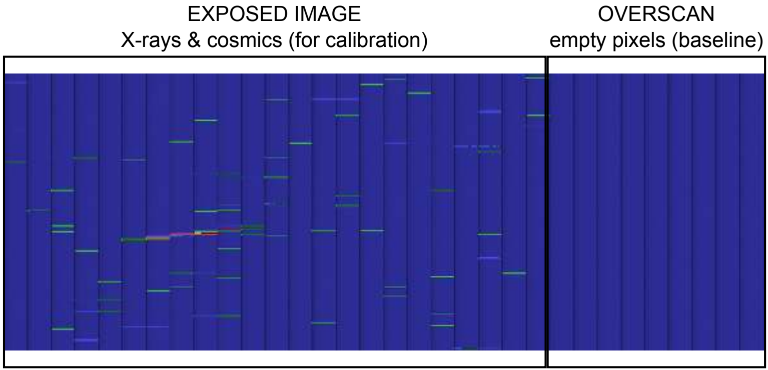
- Eng run: 1604.01343
- Fully commissioned Aug-16

Both searches are limited by the readout noise of the sensors

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

Fermilab

Raw image taken with SENSEI: 20 samples per pixel



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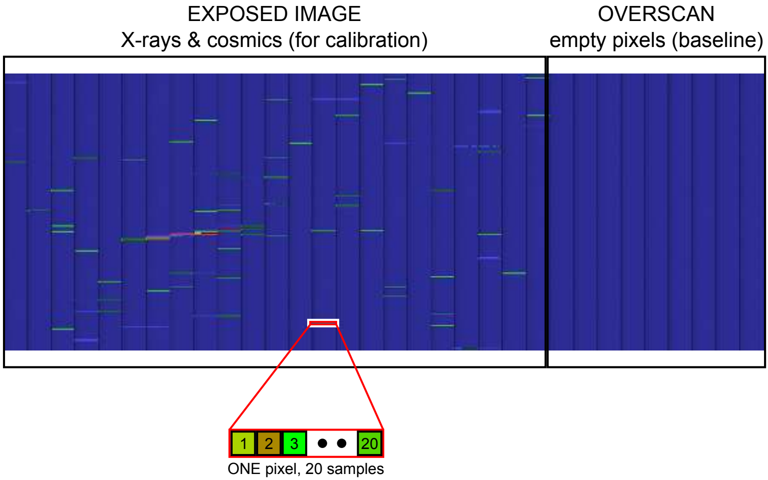


Raw image taken with SENSEI: 20 samples per pixel

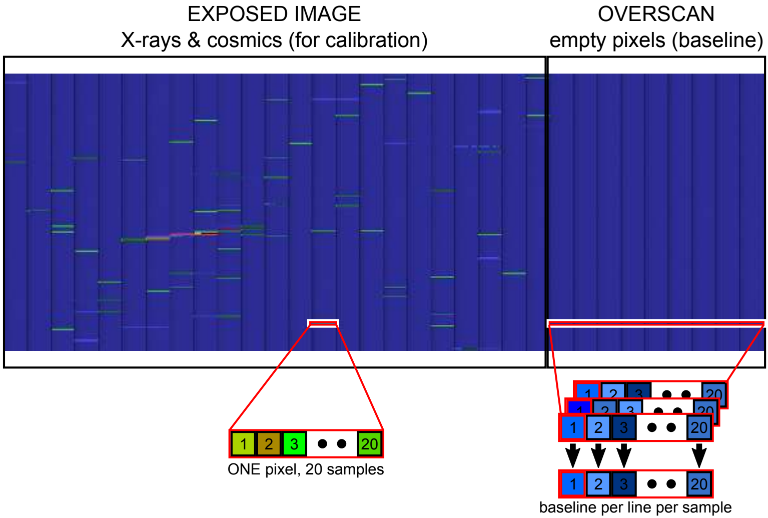
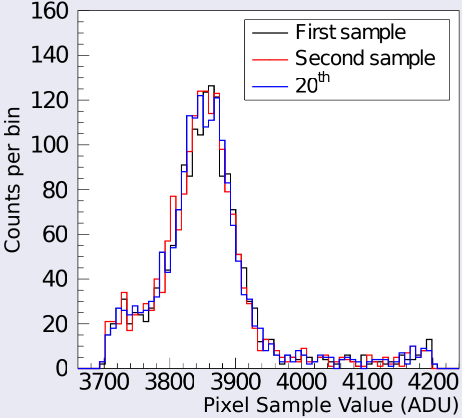


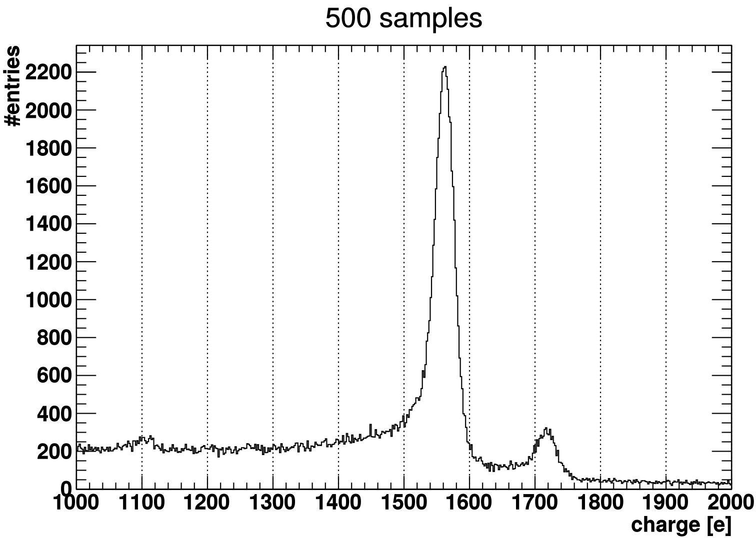
Image taken with SENSEI: 20 samples per pixel

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

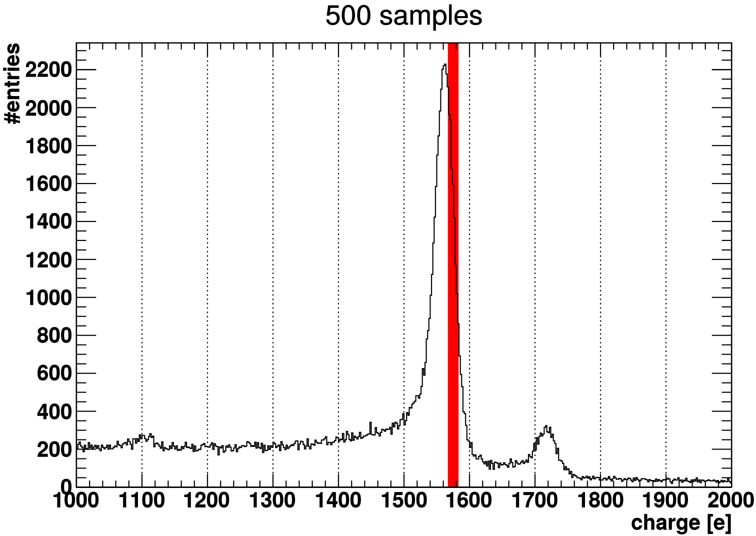


The gain is the same for all the samples

^{55}Fe X-ray source



^{55}Fe X-ray source



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