The SENSEI† experiment

A zero noise detector for DM searches

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for the SENSEI Collaboration

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† Sub-Electron-Noise SkipperCCD Experimental Instrument
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: 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 $\nu$ 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 candidates

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

Fully funded by Heising-Simons Foundation & Fermilab
CCD: readout

3x3 pixels CCD

state

1
2
3
7

channel stop

serial register

sens node
(SN)

amplifier

The capacitance of the system is set by the SN: $C = 0.05 \text{pF} \rightarrow 3 \mu\text{V/e}$
CCD: readout

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Capacitance of the system is set by the SN: $C = 0.05 \text{pF} \rightarrow 3 \mu \text{V/e}$
CCD: readout

signal

pedestal

voltage diff. due to deposited charge
CCD: readout

signal

pedestal

voltage diff. due to deposited charge
CCD: readout

- Pixel charge measurement
  - pedestal
  - Voltage diff. due to deposited charge

- Signal

- High frequency noise

- Low frequency noise

Excellent for removing high frequency noise but sensitive to low frequencies.
2 e⁻ readout noise roughly corresponds to 50 eV energy threshold
Lowering the noise: Skipper CCD

Only the readout stage is modified

Readout stage is replaced
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
  \[
  \text{Pixel value} = \frac{1}{N} \sum_{i=1}^{N} (\text{pixel sample})_i
  \]
- 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 \( \mu \text{m} \) thick, 15 \( \mu \text{m} \) pixel size
- Two form factors 4k\( \times \)1k (0.5gr) & 1.2k\( \times \)0.7k pixels
- Parasitic run, optic coating and Si resistivity \( \sim 10k\Omega \)
- 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)
Charge in pixel distribution. Counting electrons: 0, 1, 2..
Charge in pixel distribution. Counting electrons: 0, 1, 2..

4000 samples

Entries: 1635
$\chi^2$/ndf: 19.6/25
Mean: $-0.002 \pm 0.0016$
Sigma: $0.06 \pm 0.001$
Counting electrons: 0, 1, 2..

Standard CCD mode: charge in each pixel is measured once

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

Readout-noise: 3.5 e RMS

Readout-noise: 0.06 e RMS
Counting electrons: ..48, 49, 50..
55 Fe X-ray source

4000 samples

charge [e]

#entries

1200 1250 1300 1350 1400 1450 1500 1550 1600 1650 1700

#entries

50 100 150 200 250 300 350 400 450

pix/4.1781 + 300.2 \{ohdu==2 && x<300 && x>35 && abs(pix/4.17817-1254.7)<500.48\}
55 Fe X-ray source

4000 samples

#entries

charge [e]

pix/4.1781 + 300.2 \{(ohdu==2 && x<300 && x>35 && abs(pix/4.17817-1254.7)<500.48)\}
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 - $1/\sqrt{N}$
SENSEI: DM search operation mode

- Counting electrons ⇒ 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

<table>
<thead>
<tr>
<th>Dark Current [e⁻ pix⁻¹ day⁻¹]</th>
<th>≥ 1e⁻ [pix]</th>
<th>≥ 2e⁻ [pix]</th>
<th>≥ 3e⁻ [pix]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻³</td>
<td>1 × 10⁸</td>
<td>3 × 10³</td>
<td>7 × 10⁻²</td>
</tr>
<tr>
<td>10⁻⁵</td>
<td>1 × 10⁶</td>
<td>3 × 10⁻¹</td>
<td>7 × 10⁻⁸</td>
</tr>
<tr>
<td>10⁻⁷</td>
<td>1 × 10⁴</td>
<td>3 × 10⁻⁵</td>
<td>7 × 10⁻¹⁴</td>
</tr>
</tbody>
</table>

Measured upper limit for the DC in CCDs is:

\[ 1 \times 10^{-3} \, \text{e pix}^{-1} \text{day}^{-1} \]

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**

![Graph showing the reach of a 100g zeroish-background experiment for light dark photons.](image)

**Heavy Dark Photon**

![Graph showing the reach of a 100g zeroish-background experiment for heavy dark photons.](image)
SENSEI: reach of a 100g, *zeroish-background* experiment

**Dark photon ($A'$)**

**Axion-like-particle (ALP)**
SENSEI: electron recoil background requirements

The sensitivity is dominated by the lowest energy/charge bin

\[ \sigma_e \ll \sigma \]

\[ M_\chi = 10 \text{ MeV} \]

\[ F_{DM} \propto 1/q^2 \]
SENSEI: electron recoil background requirements

Back of the envelope calculation

A 100g detector that takes data for one year → Expo = 36.5kg · day

Assuming same background as in DAMIC:

- 5 DRU (events·kg⁻¹·day⁻¹·keV⁻¹) in the 0-1keV range
  → \(N_{\text{bkg}} = 36.5 \text{ kg} \cdot \text{day} \times 5 \text{ DRU} = 182.5 \text{ events}\)

- Dominated by external gammas → flat Compton spectrum
SENSEI: electron recoil background requirements

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

Expect 0.65 bkd events in the lowest (2 e\(^{-}\)) charge-bin
Whats going on now: Installation @MINOS

Technology demonstration: installation at shallow underground site

[Diagram showing the location of NuMI building, MINOS Hall, SENSEI, and NOvA at a depth of 107 meters]
What's going on now: Installation @MINOS

- RO electronics integration
- Optimization & characterization
- MINOS installation
- MINOS run
- Clean-room Deploy at MINOS
- Low rad. package run at surface
- Data taking

Jan16 Jun16 Jan17 Dec17

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SENSEI commissioning run at surface: arXiv:1804.00088

Observed spectrum using 800 samples per pixel

Exposure: 0.019 gram-days

dark current: \( \sim 1.1 \, \text{e}^- /\text{pix/day} \); no events with 5-100 electrons
SENSEI commissioning run at surface: arXiv:1804.00088

First direct-detection constraints between $\sim 500$ keV to 4 MeV!

Terrestrial effects: Emken, Essig, Kouvaris, Sholapurkar (to appear)
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
CDMS recent results - arXiv:1804.10697

Differential Event Rate (Hz/neh)

Data
MC
Signal Model

Electron-Hole Pairs

Efficiency

Efficiency Model
Good Noise Cut
Pulse Time Cut
2 Cut

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SENSEI path

Summary

- SENSEI is the first dedicated experiment searching for electron recoils

- SENSEI’s first results, using a prototype detector on the surface, probes 0.5-4 MeV masses for the first time, and larger cross sections than existing sub-GeV direct-detection constraints

- SENSEI experiment will use better sensors & collect almost 2 million times the exposure of this surface run in next ~2-3 years, probing large regions of uncharted territory populated by popular models

- Fully funded: 10g & 100g design/construction started.
  - Grant from Heising-Simons Foundation
  - Full technical support from Fermilab
BACK UP SLIDES
Diffusion
The optimal effective pixel size can be chosen by using hw binning

\[
\mu_{\text{single}} = R_{\text{DC}} \times \left( T_{\text{pix}} \times n_{\text{pix}} \right) = \mu_{\text{binning}} = \left( n_{\text{bin}} \times R_{\text{DC}} \right) \times \frac{T_{\text{pix}} \times n_{\text{pix}}}{n_{\text{bin}}} \]

Eff DC \quad T_{\text{expo}}
SENSEI commissioning run at surface: arXiv:1804.00088

First direct-detection constraints between $\sim 500$ keV to 4 MeV!

Digital signal processing for SENSEI event reconstruction: arXiv:1804.00099

Terrestrial effects: Timon Emken, RE, Kouvaris, Mukul Sholapurkar (to appear)
First direct-detection constraints between $\sim 500$ keV to 4 MeV!

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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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![Graph showing electron recoil background requirements with 5 DRU marked at 0.2 events per 10^-6.]
A more detailed analysis: MC simulation, G4 3D Monash model

- at lower energies atomic binding energies are relevant
- partial energy depositions populate low E region (thin det)

Diagram showing a gamma ray interacting with material, resulting in ionization within a CCD, with missing energy indicated.
A more detailed analysis: MC simulation, G4 3D Monash model

- at lower energies atomic binding energies are relevant
- **partial energy depositions populate low E region (thin det)**
A more detailed analysis: MC simulation, G4 3D Monash model

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![Graph showing energy deposition distribution](image)
A more detailed analysis: MC simulation, G4 3D Monash model

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Back of the envelope estimation is conservative