Novel multi-channel skipper-CCD packages for the OSCURA† experiment

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CPAD Workshop 2022

Nov 29 - Dec 2, 2022

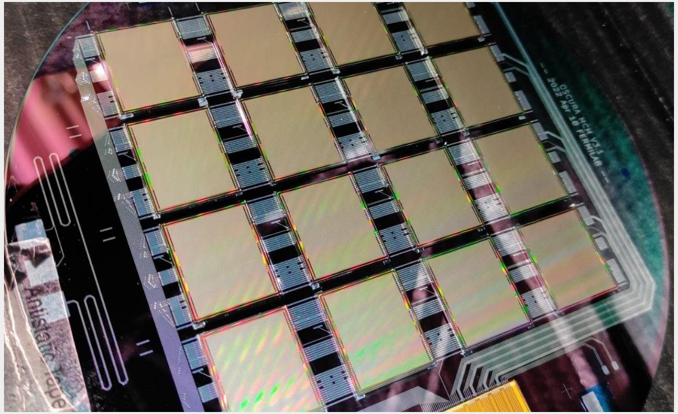

Image: OSCURA multi-chip module

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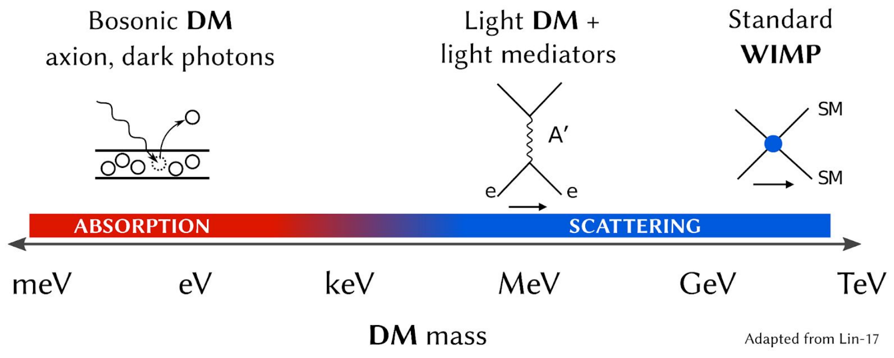
† Observatory of Skipper CCDs Unveiling Recoiling Atoms · https://astro.fnal.gov/science/dark-matter/oscura/

Dark-matter direct detection



Field like **Particle like**

Weakly interacting massive particles:
- ➔ Favoured by ΛCDM
- ➔ experimentally accessible

Light dark matter:
- ➔ New theoretical models
- ➔ New enabling technologies (semiconductors, cryogenics, noble gasses, etc)

Search for sub-GeV dark matter in Silicon:
- ➔ e- recoils
- ➔ Nuclear recoils
- ➔ Absorption

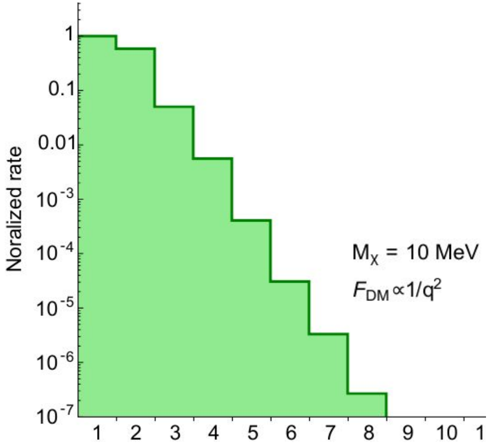
Light dark matter in Silicon

Light-**DM** mass range:

- 1-1000 MeV for **e⁻** recoil
- 1~1000 eV for **absorption**
- 0.5~1000 MeV **Nucleus** recoil (Migdal effect)

Sensitivity to **1,2,3 e⁻** signals needed: **Skippers-CCD** can do this!

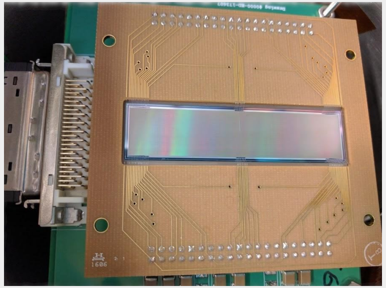
Expected spectrum from benchmark models (e⁻ recoil)



R. Essig et al, JHEP 05 (2016), 046

First Skipper-CCD prototypes

- New generation Charge Coupled Devices **(CCD)**
- Readout noise **~ 0.1 e$^-$**
- Energy threshold ~1.1 eV (Si bandgap)
- Designed at **LBNL MSL**
- Parasitic run, optic coating and Si resistivity ~10kΩ



Instrument:

· System integration done at **Fermilab**

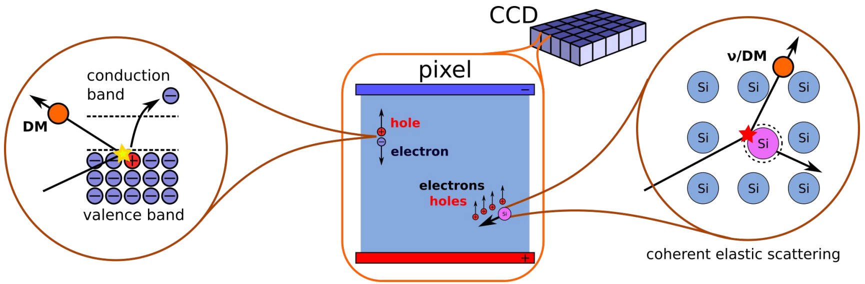
· Custom cold electronics

· Firmware and image processing software

· Optimization of operation parameters

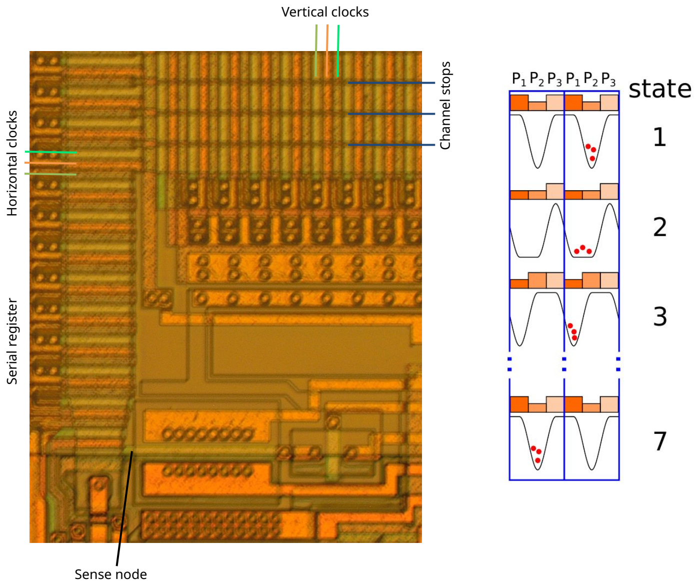
Tiffenberg, Javier, et al. Physical Review Letters 119.13 (2017): 131802.

Charge-coupled devices (CCD)



DM-electron scattering

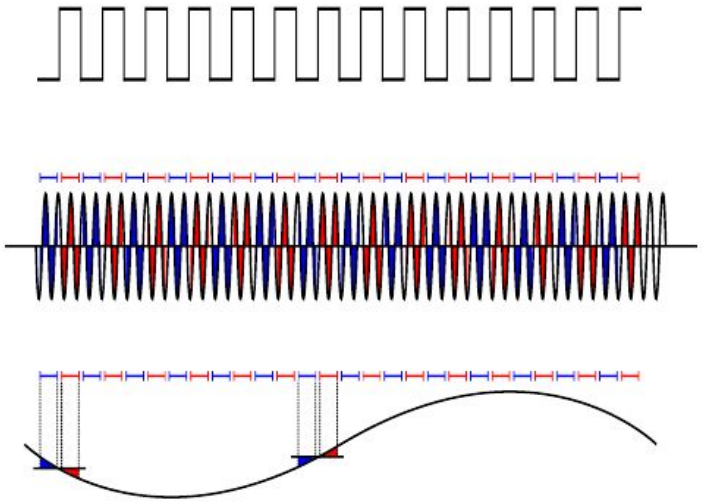
DM-Nucleus scattering



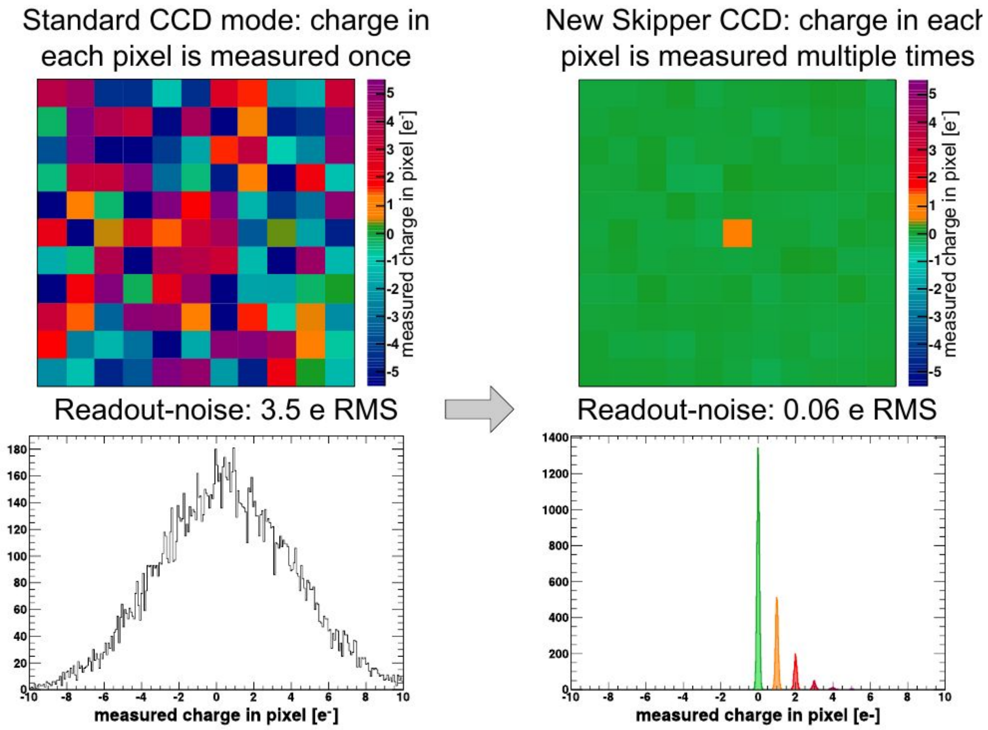
Skipper CCD read-out

1. **pedestal** integration.
2. **signal** integration.
3. **charge** = **signal** – **pedestal**.
4. **Repeat** N times.
5. **Average** all samples.

Then, both high- and low-frequency noise is reduced



Skipper-CCD read-out noise

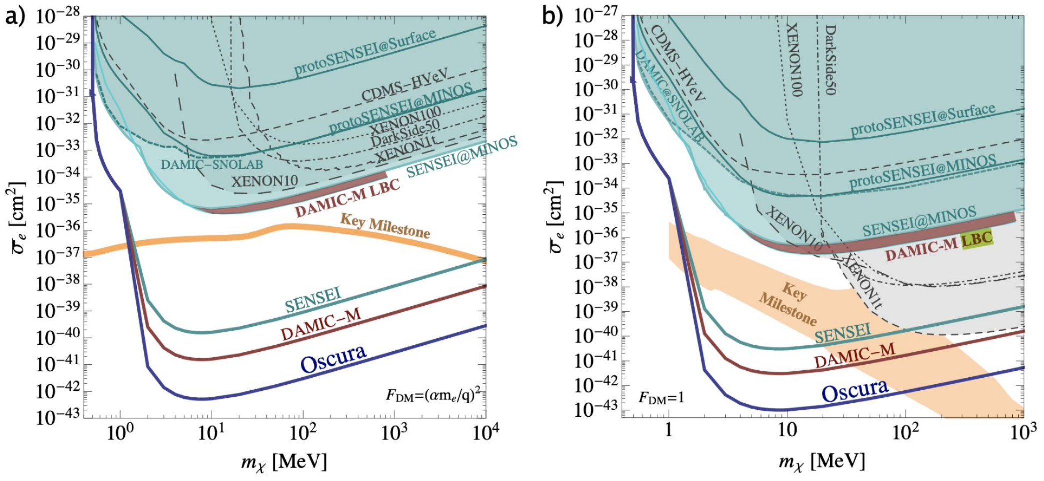


Perspectives: skipper CCDs and Dark Matter

SENSEI 100g (5 dru) — 2021

DAMIC-M 1kg (0.1 dru) — 2024

OSCURA 10kg (0.01 dru) — 2027



Many challenges to scale the mass and reduce the background in two order of magnitude!

The Oscura Experiment
arXiv: 2202.10518

Chavarria (arXiv:2210.05661)

OSCURA Collaborators

BERKELEY LAB
Bringing Science Solutions to the World

Fermilab

Pacific Northwest
NATIONAL LABORATORY

Stony Brook University

UNIVERSITY of WASHINGTON

THE UNIVERSITY OF CHICAGO

UNIVERSITY OF OREGON

Comisión Nacional de Energía Atómica

universidad de buenos aires - exactas
departamento de Física
Juan José Giambiagi

ICAS

IFCA
Instituto de Física de Cantabria

Instituto de Ciencias Nucleares UNAM

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TEL AVIV UNIVERSITY אוניברסיטת תל אביב

SNOLAB

OSCURA package

10 kg skipper-CCDs:

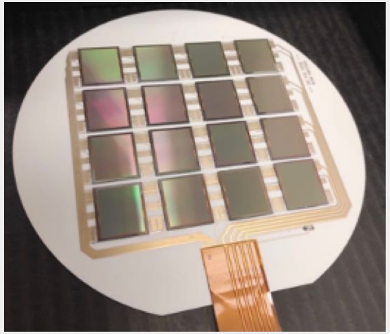
- ➔ 24000 channels/devices (28 GPix)
- ➔ 1500 multi-chip modules (MCM) with 16 CCDs each
- ➔ 94 super modules with 16 MCMs each

Read-out:

- ➔ High-density package **(This talk)**
- ➔ Multiplexer + SENSEI electronics **(see C. Chavez's talk)**
- ➔ ASICs **(see T. England talk)**

Background goal (0.01 dru):

- ➔ Silicon based pitch adapter **(This talk)**
- ➔ Aluminum shielding **(This talk)**
- ➔ Low-background materials



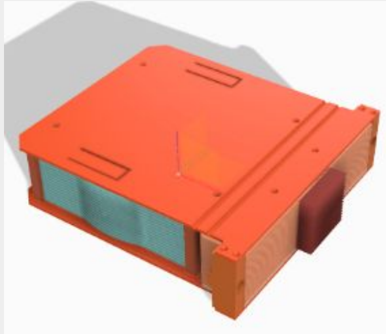


Image: ceramic multi-chip module and super module

C. Chavez et al. Sensors 22 (2022) 11, 4308
F. Chierchie et al. arXiv:2210.16418

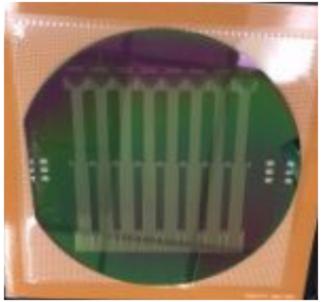
1st silicon prototypes

User proposal approved at Argonne National Laboratory

Based on SENSEI pitch adapters (at PNF/Chicago):

- ➔ 675 um hires 6 in Si substrate
- ➔ 500 nm SiOx insulation
- ➔ 500 nm Al circuit
- ➔ 500 nm SiO2 passivation

Image: SENSEI detector and pitch adapters produced at PNF



The SENSEI Collaboration. Phys. Rev. Lett. 125, 171802 (2020)

Silicon fabrication at ANL

Insulation layer:

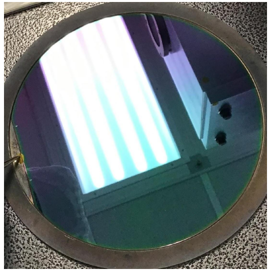
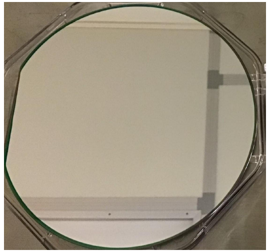
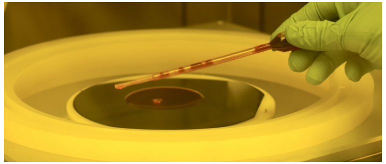
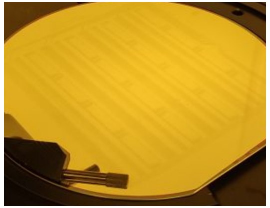
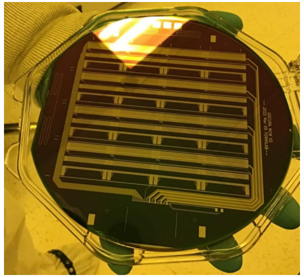
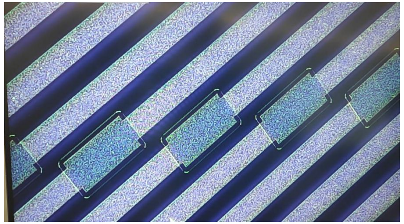
- ➔ AJA dielectric sputtering system at 400°C
- ➔ 390 nm SiO_2

Aluminum layer:

- ➔ AJA Metal sputtering system
- ➔ 480 um Al on SiO_2
- ➔ 1um SPR-955 + Heidelberg MLA 150
- ➔ CD-26 developer + Al Type-A wet etcher

Passivation layer:

- ➔ AJA dielectric sputtering system at 275°C
- ➔ 390 nm SiO_2
- ➔ Oxford Plasmalab 100 dry etching
- ➔ e3511 ESI Plasma Asher (EOP)

Assembly and first tests

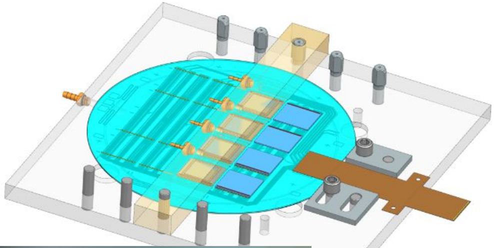
Tools developed for assembly and testing at FNAL

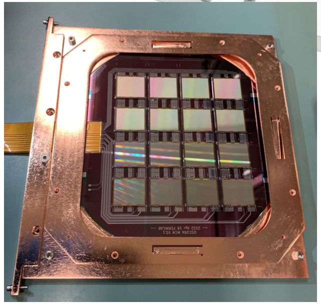
Assembly Process:

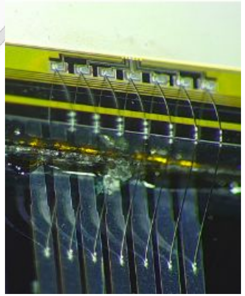
- ➔ Glue flex cable with laminate
- ➔ Glue CCDs with EPoxy
- ➔ Wire bonds

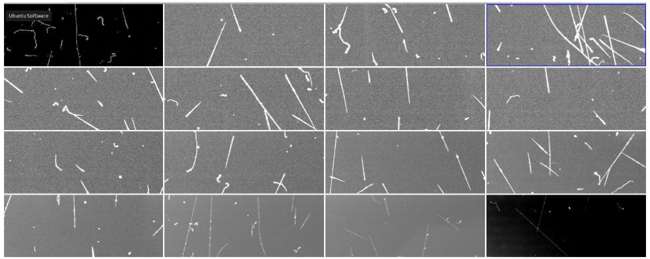
Testing:

- ➔ Electrical (shorts and impedance)
- ➔ Reverse bias
- ➔ Cold (with multiplexed read-out electronics)









Issues and outlook

Clock coupling in video out

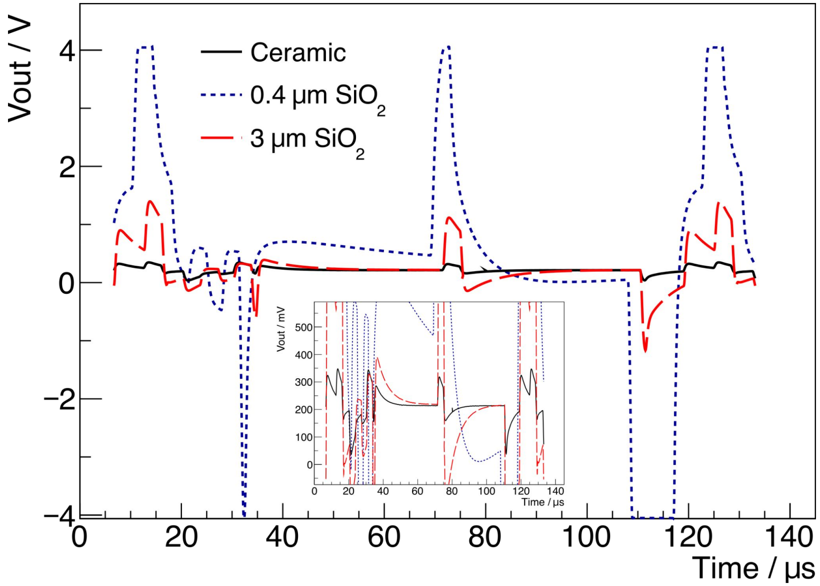
- ➔ Thicker insulation seems to help

Long recovery time

- ➔ Reduce resistivity
- ➔ Reduce capacitance

Next steps

- ➔ Thicker SiO2
- ➔ Thicker metal (Al/Au)
- ➔ Intrinsic Si
- ➔ Change design rules



CCD aluminum shielding

Cooling down

- ➔ CCDs in LN2
- ➔ LN2 scintillates
- ➔ Cherenkov

Imagine throwing the CCD in a Cherenkov tank!

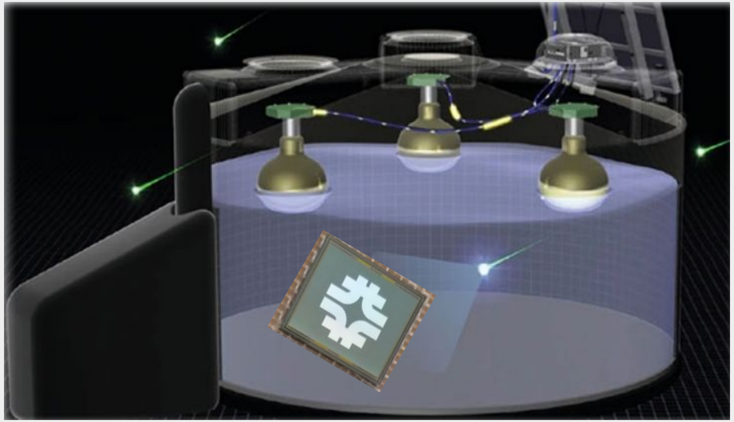


Image: CERN courier (The Pierre Auger Observatory)

CCD aluminum shielding

Lift-off process at ANL:

- ➔ 1um SPR-955 + Heidelberg MLA 150
- ➔ Temescal FC2000 E-Beam Evaporator
- ➔ 50 nm Al + 1165 remover

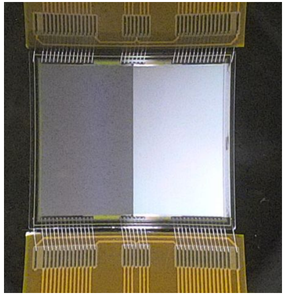
Testing:

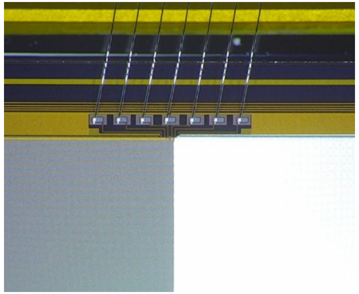
- ➔ Expose to LED
- ➔ Expose to environmental radiation
- ➔ Some things to understand (but success in 1st try!)

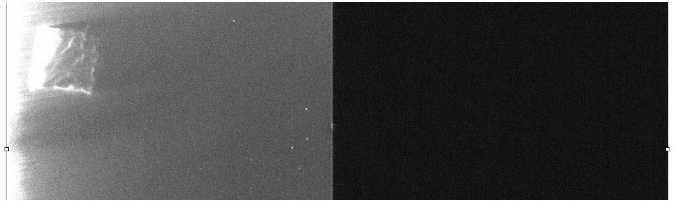
Next steps:

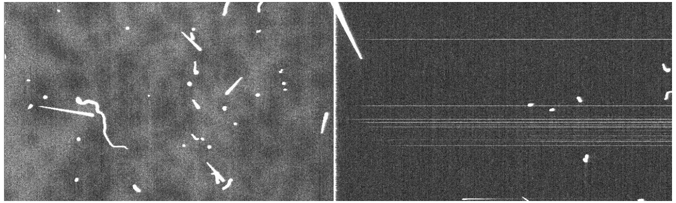
- ➔ Extra cleaning
- ➔ Try different thickness
- ➔ Test with different wavelengths

Very important step for X-ray detection with skipper-CCDs!







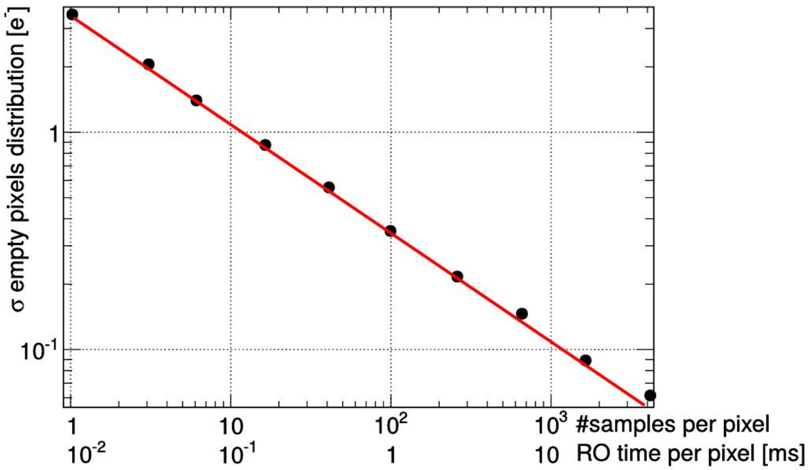


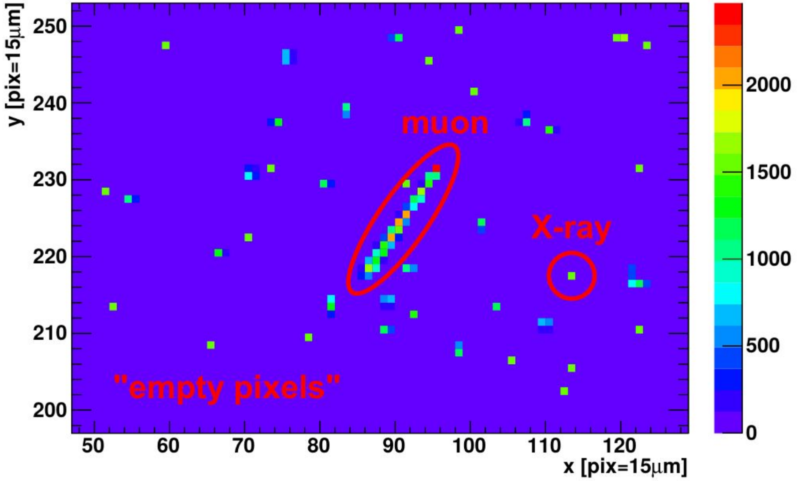
Summary

- **OSCURA** 10 kg skipper-CCD for light dark matter detection; major effort from most institutions working with **skipper-CCDs**
- Background goal of **0.01 dru** is the main challenge
- **24000** read-out channels/devices
- First high-density package achieved (working ceramic version). First **Silicon** prototypes produced at **ANL**
- Great improvement in first two versions
- Signal coupling and recovery time needs to be improved (**clear plans on how to**)
- Further prototypes at **ANL** (and probably **PNF**)
- Preliminary engagement with **production facility** to process **1500** wafers
- First production of CCDs with **Aluminum shielding** at ANL. First tests were **successful** (more are coming)
- Al shielding opens a door for **X-ray detection** with skipper CCDs (beyond OSCURA)

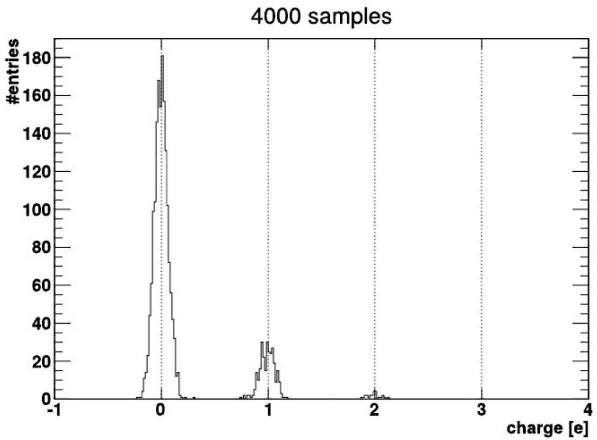
Backup slides

Skipper-CCD read-out noise

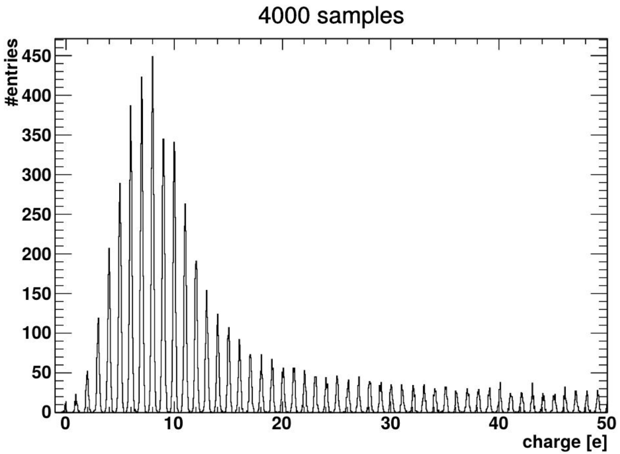




Skipper-CCD resolution



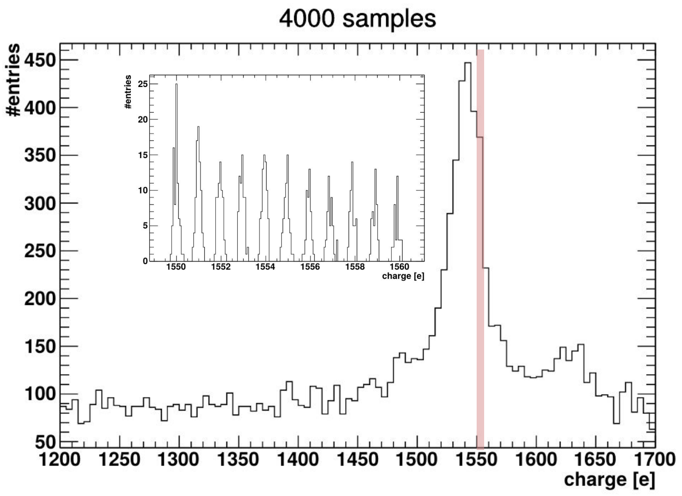
(Almost) Empty CCD



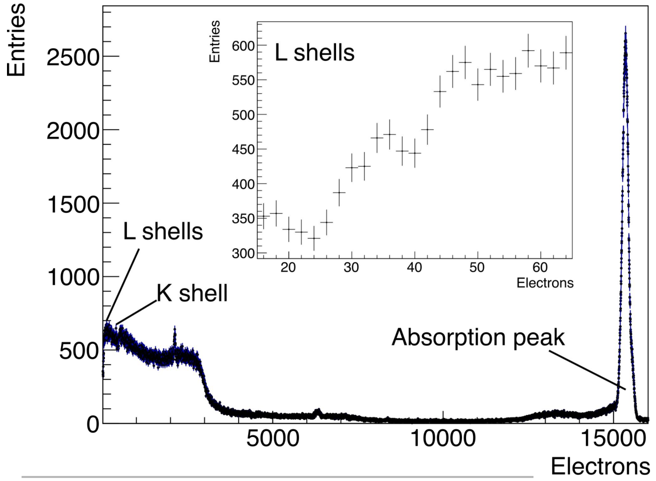
Front-illuminated CCD

Skipper-CCD for photo detection

D. Rodrigues et al., NIMA A 1010 165511



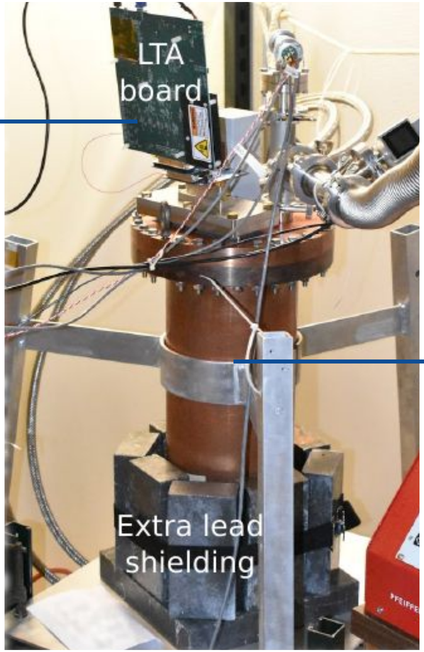
Charge per event for 55Fe x-ray source

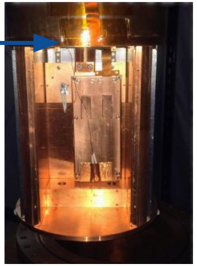


Compton scattering spectrum in Silicon with 241Am γ-ray source

Setup @ MINOS

- 230 m.w.e.
- Previous vessel + extra shielding
- T ~ 135 K + vacuum
- LTA board



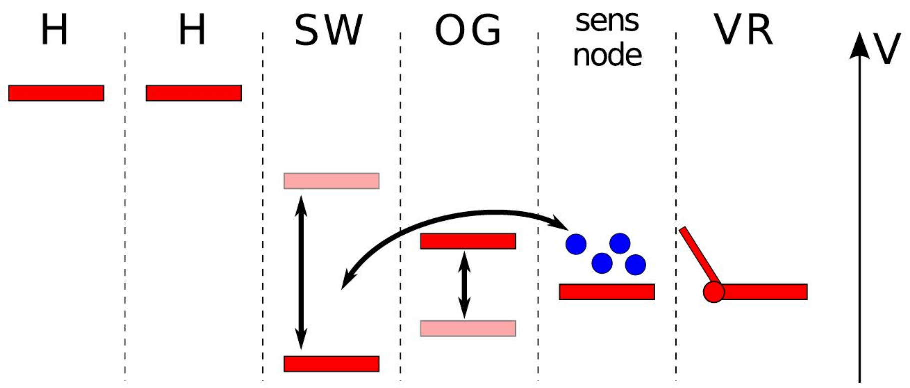


Skipper CCD read-out

Multiple sampling of same pixel without corrupting the **charge** packet.

Pixel value = **average** of all samples

Suggested in **1990** by Janesick et al. (doi:10.1117/12.19452)

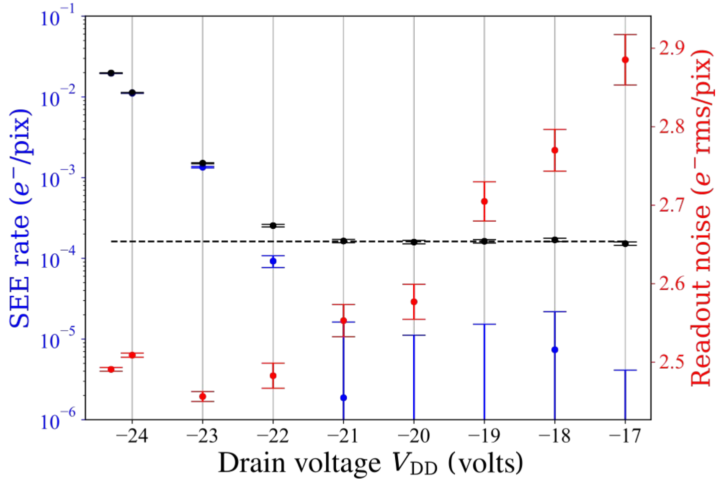


Background sources: detector

Exposure dependent
- Dark current (10^{-5} e^-/pix/day at 135 K)
- Amplifier light (10^{-1} to 10^{-5} e^-/pix/day)

Exposure independent
- Spurious charge (10^{-2} to 10^{-5} e^-/pix/image)

Single electron rate reduced by optimizing operation parameters
- Read-out mode: continuous vs expose
- Voltage configuration
- Amplifier off while exposure



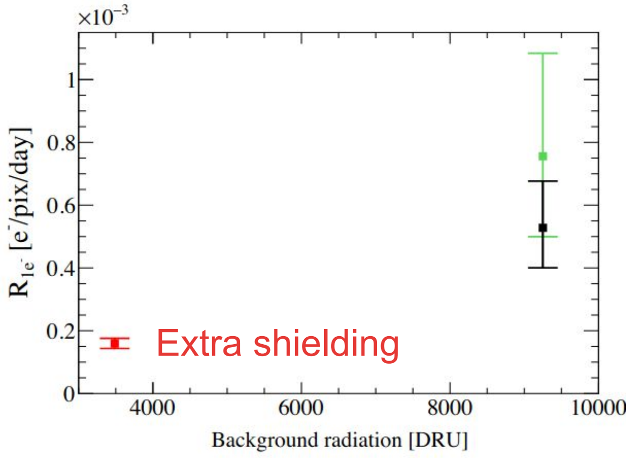
The SENSEI Collaboration. Phys. Rev. Applied 17, 014022 (2022)

Background sources: environment

High-energy:
- Air shower muons
- Nuclear decays
- x/ɣ-rays

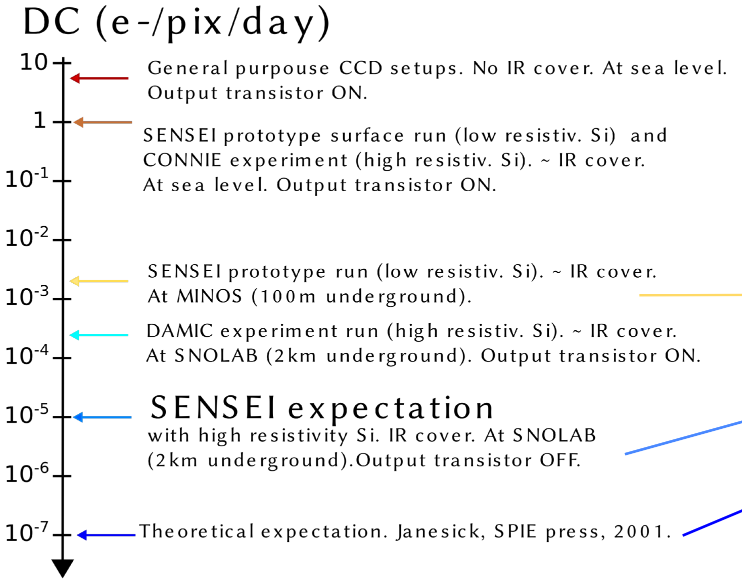
Low-energy:
- IR photons
- Halo and transfer inefficiency
- Compton scattering
- Charge collection inefficiency

Environmental background is reduced with shielding, and removed from data with quality cuts



The SENSEI Collaboration - Phys. Rev. Lett. 125, 171802 (2020)

Background goal



Dark Current $[e^- pix^{-1} day^{-1}]$	$\geq 1e^-$ [pix]	$\geq 2e^-$ [pix]	$\geq 3e^-$ [pix]
10^{-3}	1×10^{8}	3×10^{3}	7×10^{-2}
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}
10^{-7}	1×10^{4}	3×10^{-5}	7×10^{-14}

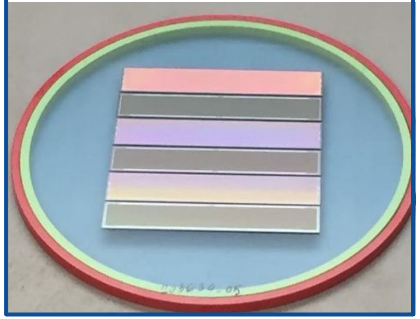
Background estimations for 1 year and 100 g.

Blue: discovery channel (background free)
Red: modulation or limits

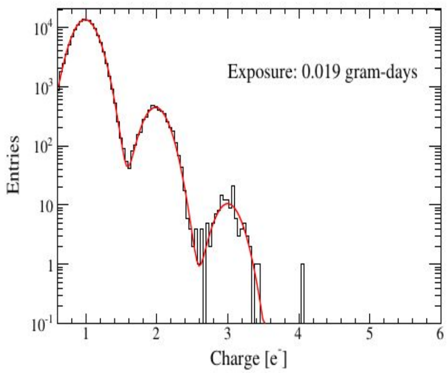
Latest SENSEI published result: **1.6×10^{-4} e-/pix/day**

The SENSEI Experiment

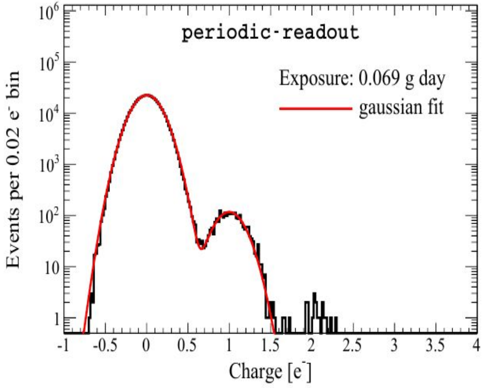
2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)



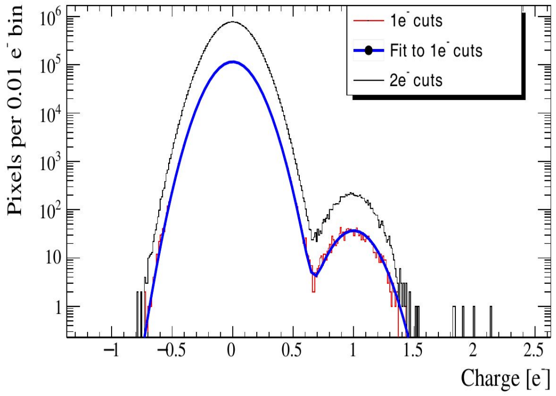
Summary: from prototype to science grade



Active mass ~ **0.1 g**
0.019 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **1.14 e-/pixel/day**



Active mass ~ **0.1 g**
0.069 gram-day exposure
0.14 e- RO noise
(**800** samples)
SEE ~ **0.005 e-/pix/day**



Active mass ~ **2 g**
19.926 gram-day exposure
0.14 e- RO noise
(**300** samples)
SEE ~ **1.6x10^{-4} e-/pix/day**

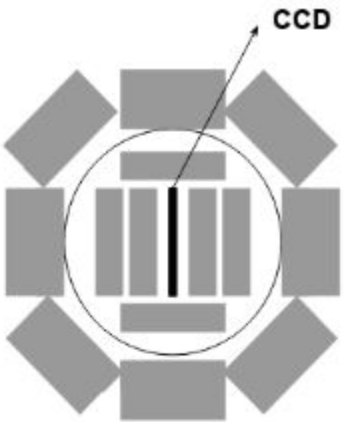
SENSEI @ SNOLAB

- Science-grade skipper-CCDs achieved
- Packaging and electronics also achieved
- Phase 1 system @ SNOLAB
- Vessel deployed at SNOLAB (during the pandemic!!!)
- First 10 CCDs deployed

Towards a **100 g** skipper-CCD detector:

- Produce ~ **50** devices
- **Packaging** at Fermilab
- **Testing**
- Deliver and deploy at **SNOLAB**

➔ **10000** dru (MINOS standard shield): proto-SENSEI
➔ **3000** dru (MINOS extra shield): first science grade skipper
➔ **5 (ultimate goal)** dru (SNOLAB): SENSEI 100 g


CCD