The Oscura Experiment – Searching for low-mass dark matter with a very-large array of skipper-CCDs

7/18/22

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The search for sub-GeV dark matter

- ❑ Direct detection experiments have historically focused on WIMP DM with masses down to *O*(GeV)
  - Well motivated ("WIMP miracle"), experimentally accessible (nuclear recoils)
- ❑ New complementary searches for lower masses
  - Theoretical interest in dark sectors
  - New technologies with lower thresholds

- ❑ One promising direction: Skipper-CCDs for electron recoil, with thresholds near the silicon bandgap

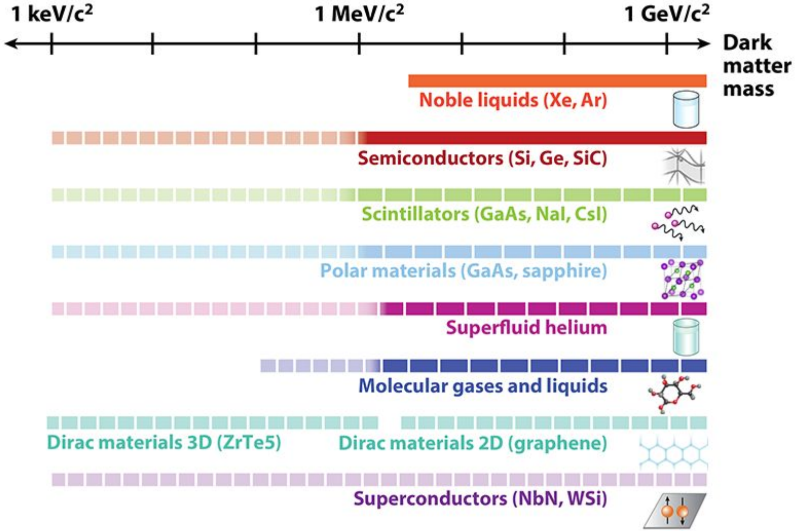
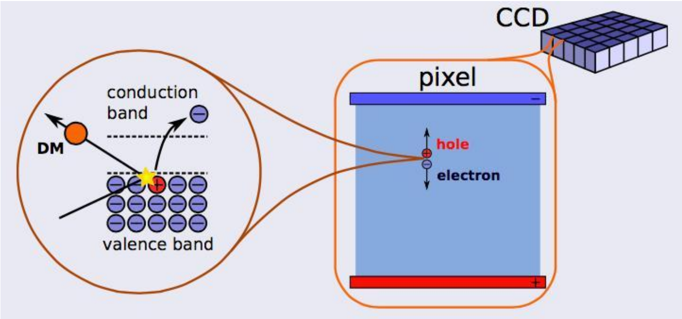
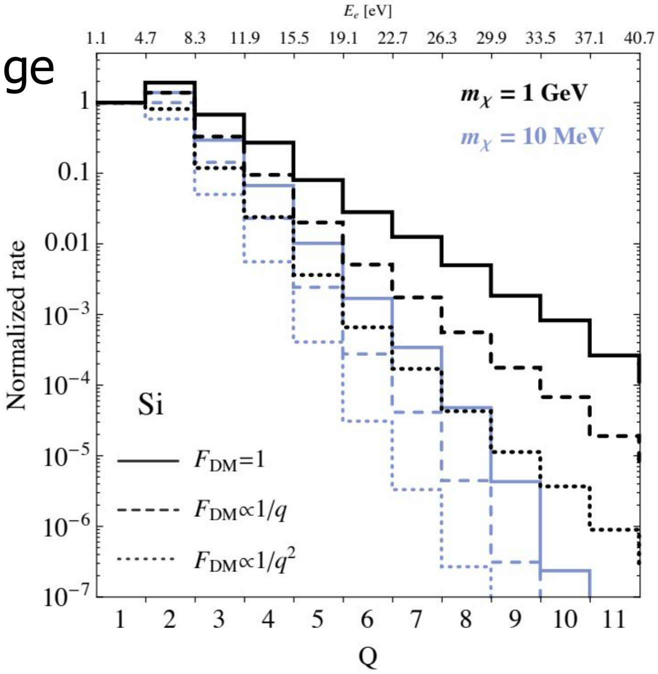


Image Credit: R. Essig, SBU; C. Cain, APS

Electron recoils in silicon

- ❑ We look for DM interactions with electrons in silicon
  - DM-electron scattering: m_χ in the MeV-GeV range
    - Energy transfer is a few eV, good match to semiconductor band gap
  - DM absorption
    - Energy transfer equals m_χ
  - Energy transfer creates ionization, and we measure the number of electron-hole pairs

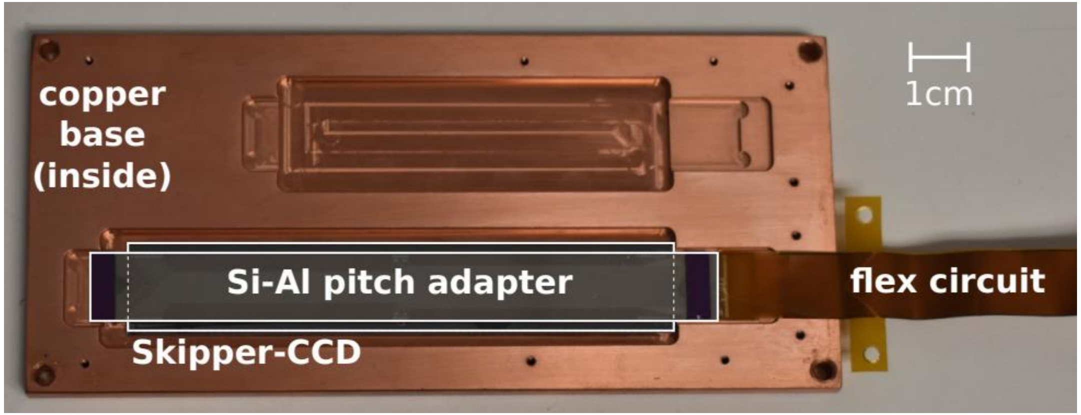




(Essig+, arXiv:1509.01598)

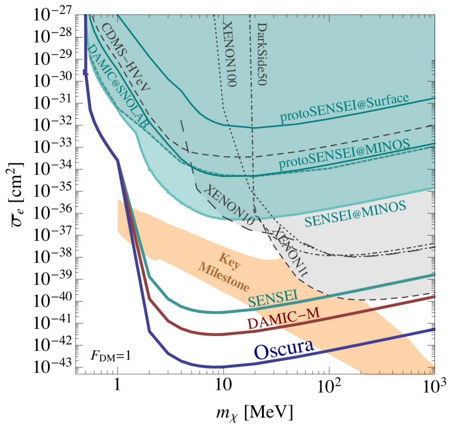
Strategy

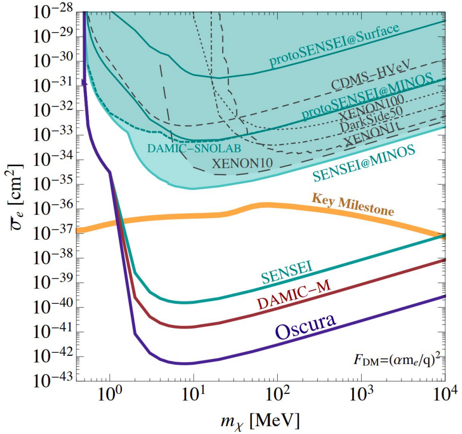
- ❑ Challenges:
  1. Unambiguously identify $1e^-$, $2e^-$ events
  2. Minimize background sources of charge
  3. Minimize coincidence background
- ❑ We use CCDs to search for DM
  - Mature technology, used for DM in DAMIC
  - Achieves #3 using spatial resolution / pixel segmentation



CCD searches for dark matter

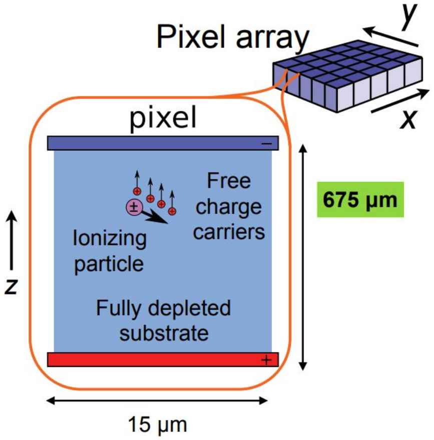
- DAMIC (40 g, ongoing): first CCD DM experiment
- SENSEI (*O*(100) g started in 2021): first DM experiment using skipper-CCDs
  - Several physics results (most recent 2020) from prototypes and test runs; full scale experiment being commissioned at SNOLAB
  - Active mass and radiopurity similar to DAMIC
- DAMIC-M (*O*(1) kg starting ~2024): next-generation Skipper experiment
  - Scaling up in mass, with corresponding improvement in radiopurity
- Oscura (*O*(10) kg, in development): next-generation Skipper experiment

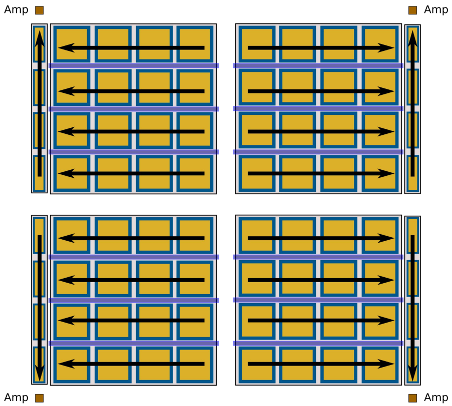




CCDs

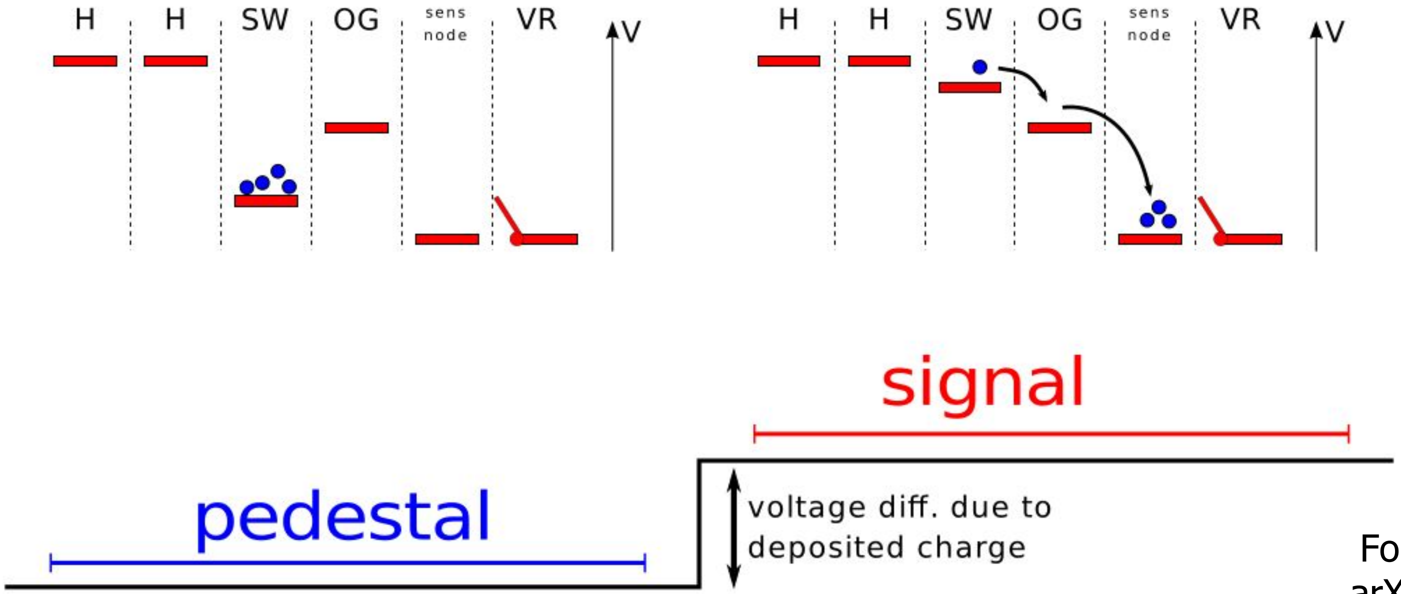
- ☐ Charge coupled devices (CCDs) are integrated circuits that produce images of the energy depositions in a pixelated Si substrate
- ☐ Holes drift through substrate and collect in pixels near the surface
- ☐ Charge packets are shifted to a shared amplifier (1 per quadrant) for readout
- ☐ CCDs for DM are designed by LBNL MSL, based on fully-depleted CCD designs proven in astronomy
  - ▪ High-efficiency charge collection and transport, low dark current
  - ▪ Thickness limited only by capabilities of commercial foundries
- ☐ Conventional CCDs are limited to noise of ~2e$^-$





Skipper readout

- ❑ In a conventional CCD, charge moved to the sense node must be drained
    - ▪ You can integrate longer, but you cannot beat the 1/f noise
- ❑ The Skipper amplifier lets you make multiple non-destructive measurements!

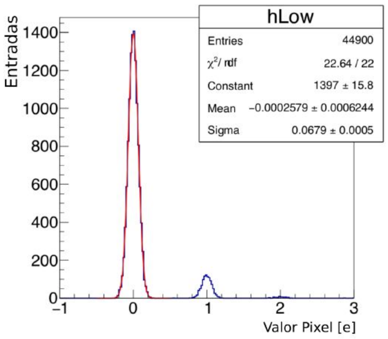


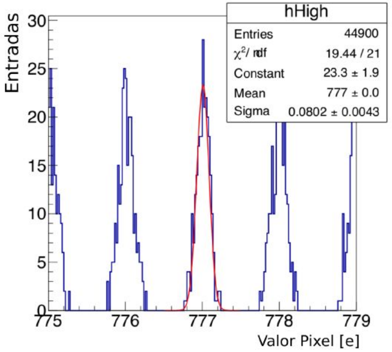
For review see: arXiV:1106.1839

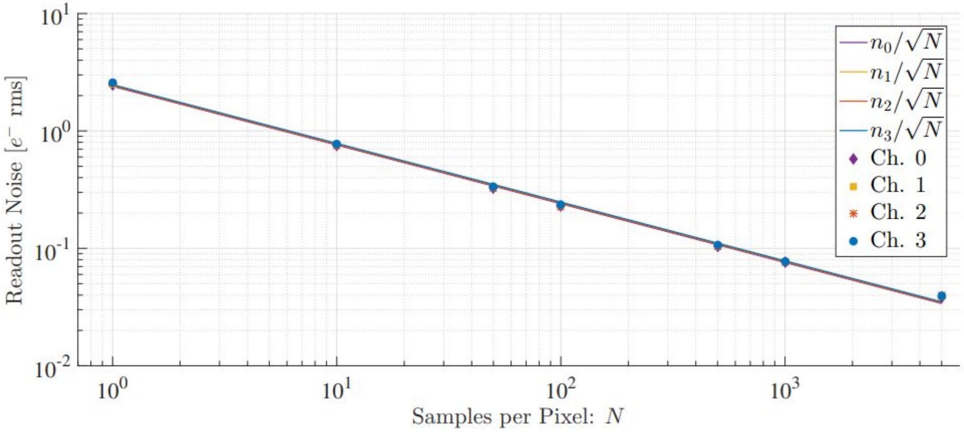
Sub-electron readout noise

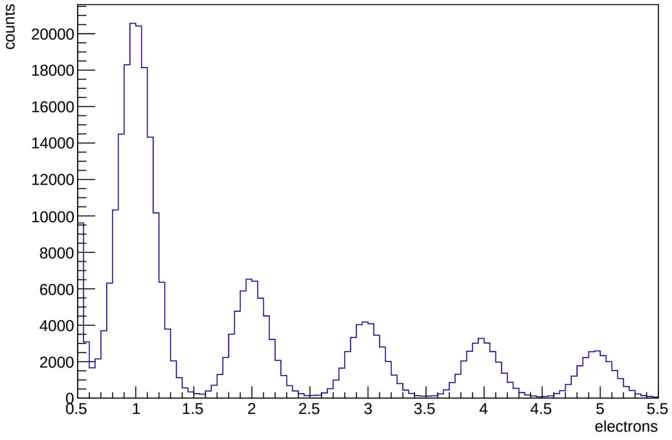
- ❑ Skipper noise scales as $1/\sqrt{N}$:
  - trade charge resolution for speed

- ❑ We can count single electrons: self-calibrating charge measurement





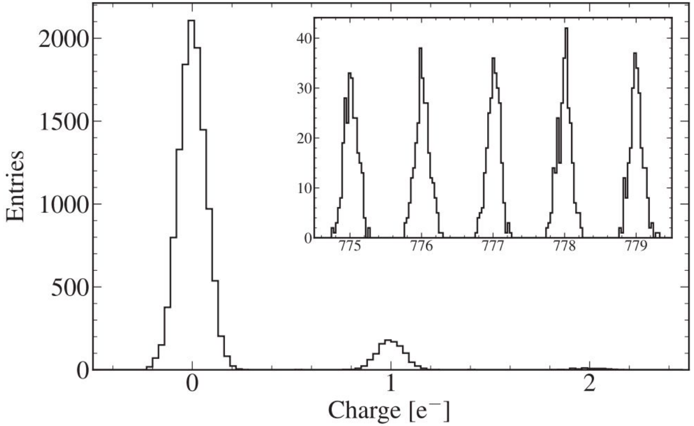




The SENSEI Experiment

Timeline

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	DM search with 100 g of science-grade CCDs at SNOLAB (6000 m.w.e)



J. Tiffenberg+, PRL 119, 131802 (2017)

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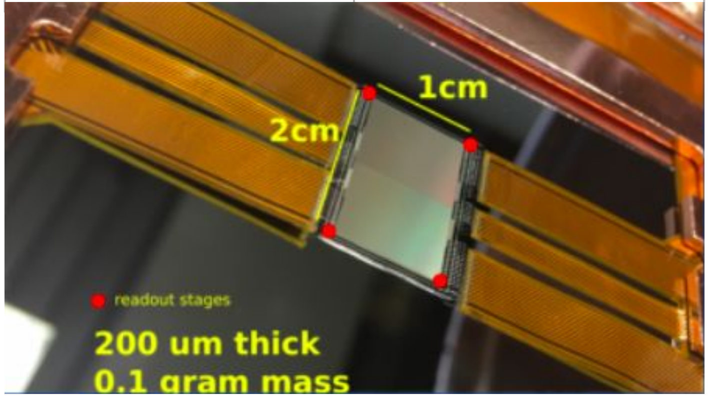
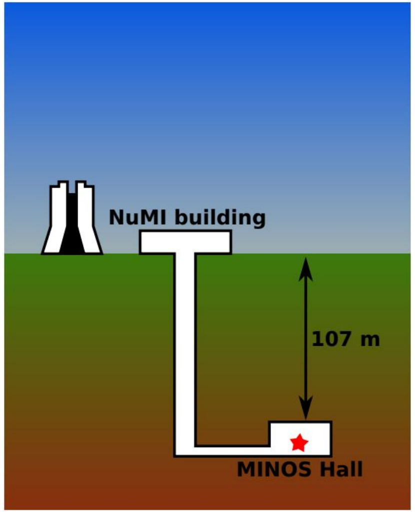


The SENSEI Collaboration, PRL 121.6 (2018): 061803.
The SENSEI Collaboration, PRL 122.16 (2019): 161801.



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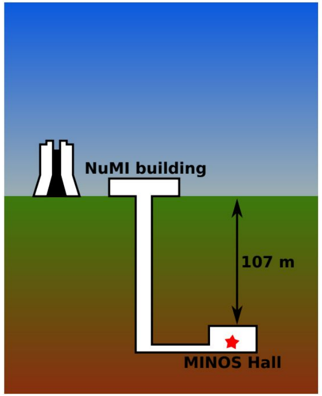
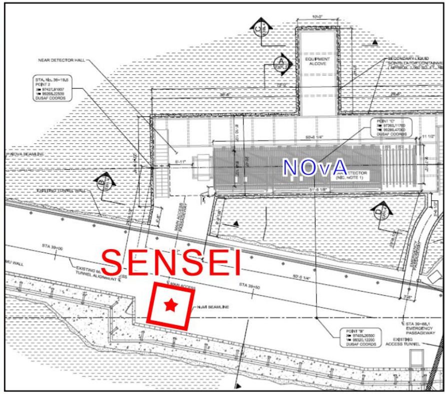
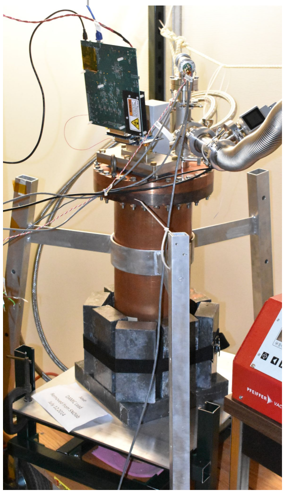




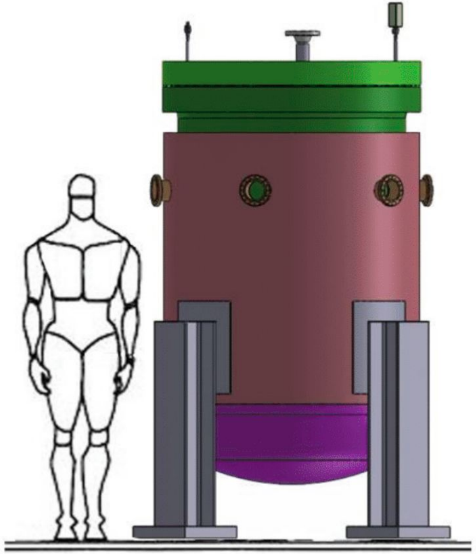


The SENSEI Collaboration, PRL 125 (2020): 171802.

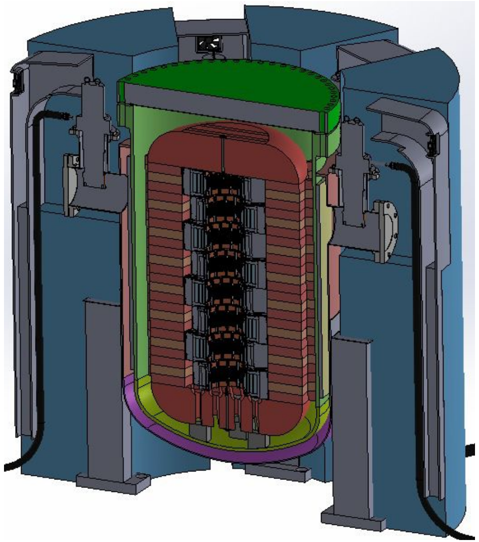
The Oscura Experiment

Oscura: 10-kg skipper-CCD experiment

- ❑ Science goal: electron recoil direct DM search (1 MeV-1 GeV), 30 kg-yr exposure
- ❑ Technology: skipper-CCD array at underground lab (planning for SNOLAB)
- ❑ R&D: scale the existing technology towards a 10 kg experiment
- ❑ Recent Oscura review paper: arXiv:2202.10518



10 kg vessel



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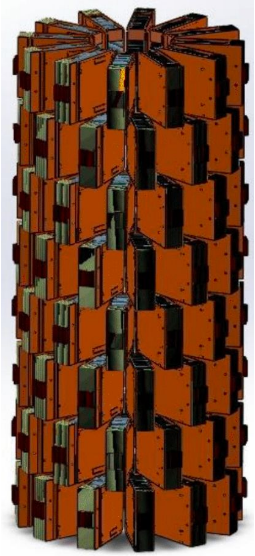
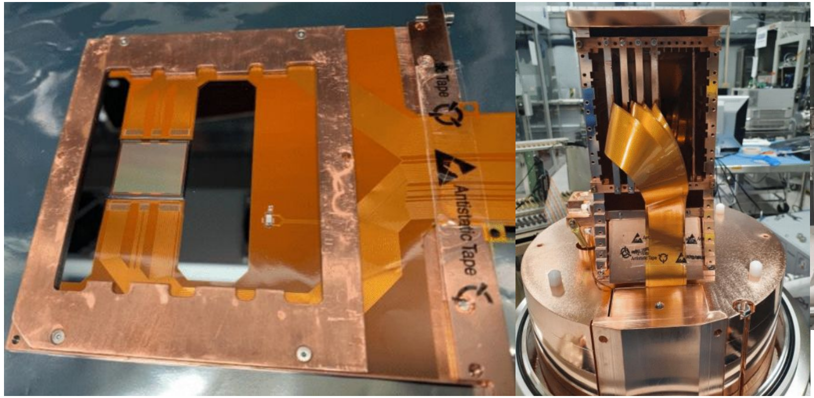
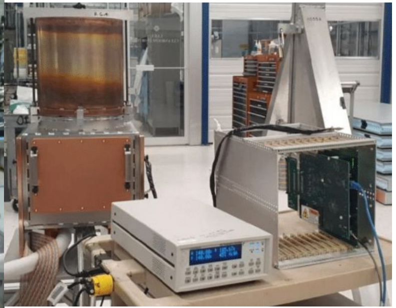


detector payload

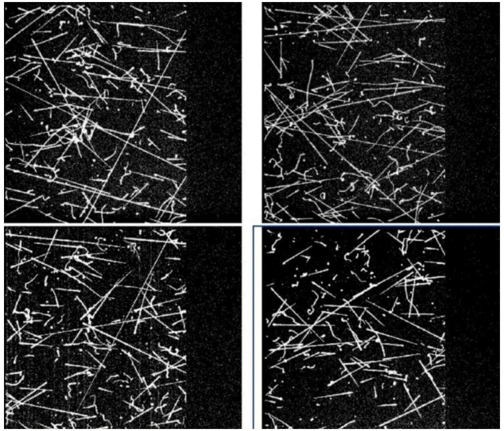
CCD Fabrication

- CCD manufacturer is retiring production line of CCDs that have been used for 17+ years.
    - Engaging new foundries in CCD fabrication, commissioning ongoing
    - Promising results from Microchip CCD surface runs, planning for low-background test at MINOS



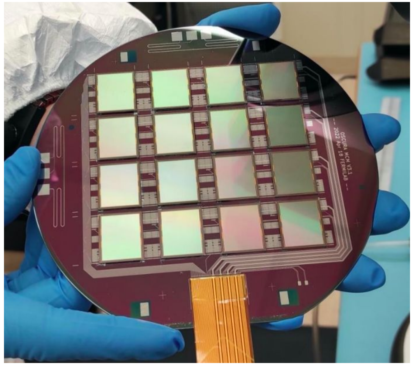


Microchip CCD packaged and installed in CCD test station



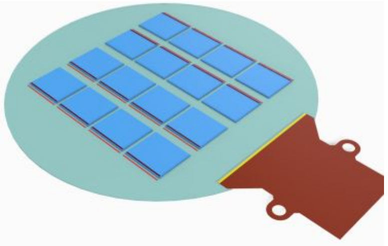
Operated by Brenda Cervantez (PhD student) at Fermilab using a copy of the SENSEI vessel

Scaling up the detector mass

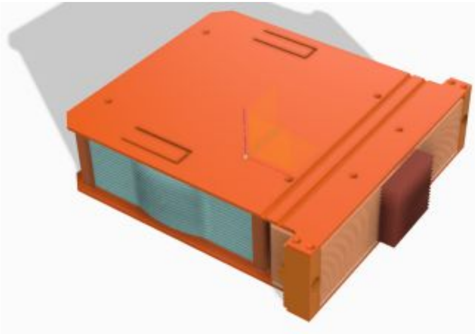


- Lots of progress on the MCM design!
- Plan to have fully-instrumented supermodule by October 2022
- Technology development can also be leveraged by other rare-event searches (e.g. CONNIE)

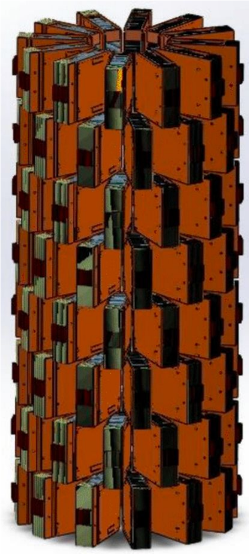
28 gigapixels in full Oscura instrument!
Compare to LSST camera's 3.2 gigapixels



Multi Chip Module (MCM):
16 CCDs mounted on one silicon wafer



Super Module (SM):
16 MCMs housed in electroformed copper

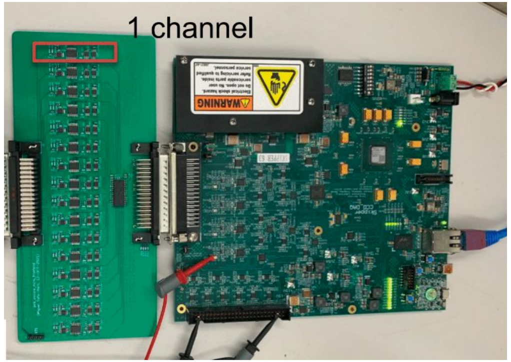


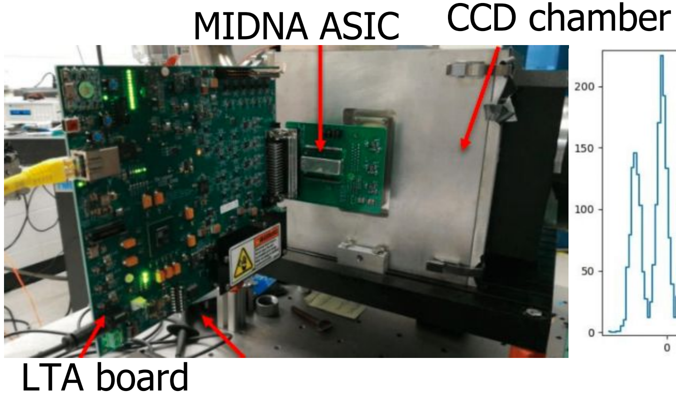
Oscura Experiment:
100 SMs → 10 kg!

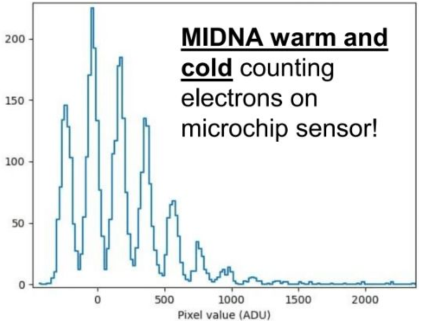
Readout Electronics

- Oscura will require ~24,000 readout channels and a readout time of ~2 hours for the full instrument
  - Use small format CCDs (1278x1058 pixels) to reduce readout time
  - Cold front end electronics required for multiplexing and signal processing in vessel to reduce feedthrough complexity and data rate
- Exploring discrete (Sofo Haro+ 2021, arXiv:2108.09389) and ASIC (England+ 2021, doi:10.2172/1841383) solutions

Discrete component solution for MCM multiplexing



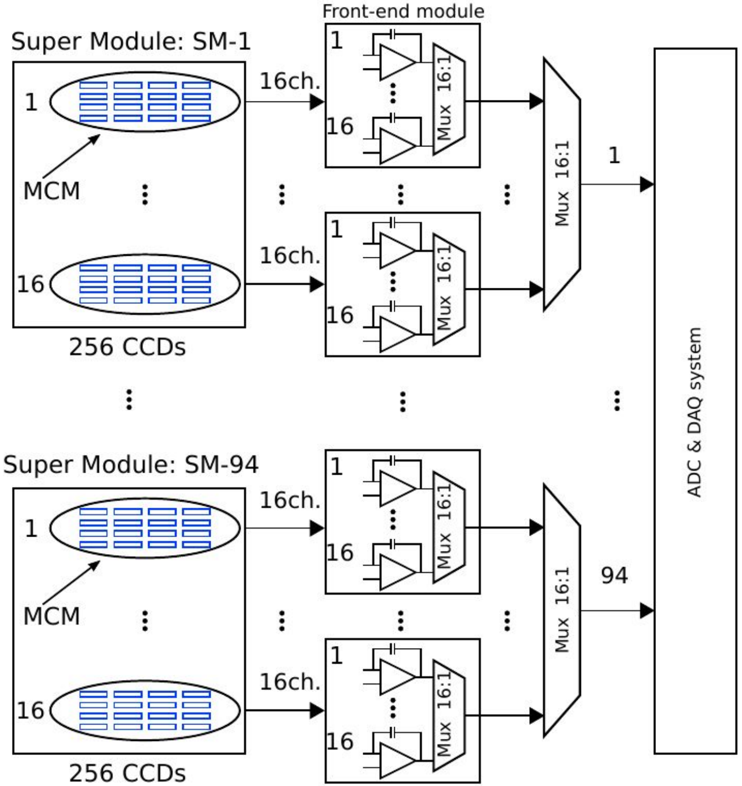




MIDNA warm and cold counting electrons on microchip sensor!

Readout Electronics

- ❑ Analog pile-up circuit averages samples from pixels without recording each value to disk (Sofo Haro+ 2021, arXiv:2108.09389)
  - ▪ Reduces data rate and data storage requirements by factor of ~400
- ❑ Two-stage multiplexing combines 256 SM channels to one output
  - ▪ parallel multiplexing capabilities – can multiplex and send previous pixel values while collecting pixel samples!
- ❑ Recent progress presented in Chavez+ 2022, Sensors, 22(11), 4308 (doi:10.3390/s22114308)



Schematic of Oscura readout system with two-stage multiplexing

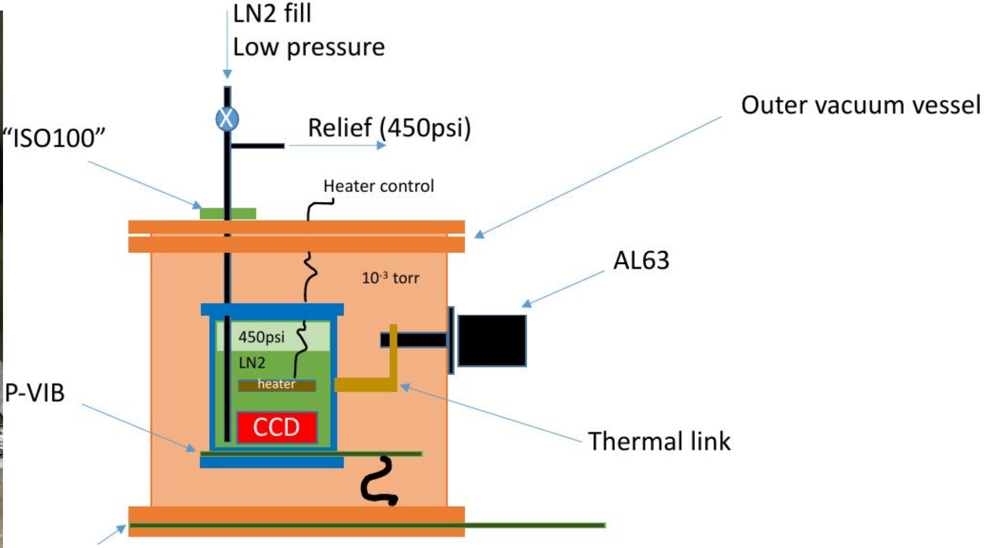
Immersion Cooling

Goal: Cool skipper CCDs to operational temperatures in pressurized LN2 bath

Status: Have demonstrated stable operation of skipper-CCDs in LN2 at 120K and performed initial measurements of scintillation in LN2

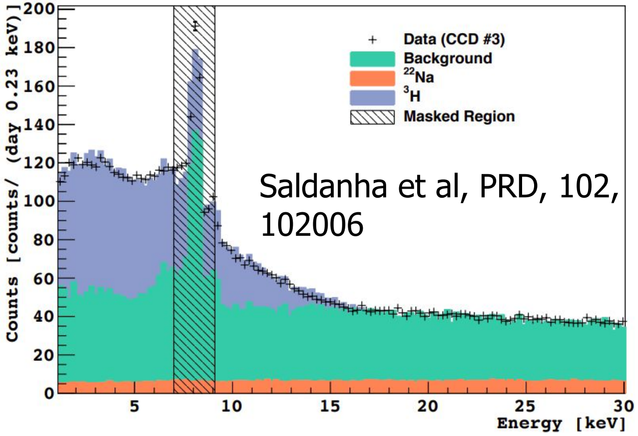
Nitrogen gas is known to scintillate!

No known measurements of scintillation of LN2, work ongoing at PNNL



Background control

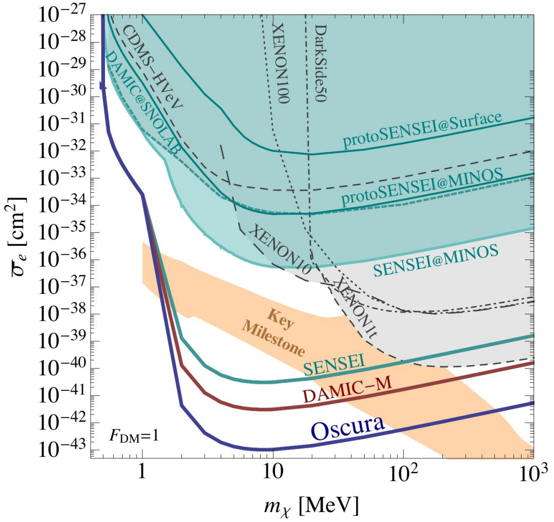
- ☐ **Goal:** achieve a radiation background rate of 0.01 counts/kg/keV/day
- ☐ **Strategy:** Focus on reducing risk of background from components in the core of the detector:
  - Tritium (^{3}H) impurities cosmogenically activated in Si
    - $t_{1/2}$=12.3 yr, undergoes beta decay with Q-value of 18.6 keV
    - can be baked out of Si substrate!
    - Require <5 days at sea level exposure equivalent after tritium removal
  - Low radioactivity flexible cable fabrication
  - Shielding informed by full-detector simulation, use 'ancient' lead for innermost layers of shield
  - Majority of detector module mass consisting of silicon and electroformed copper
- ☐ DAMIC-M paving the way in background control techniques

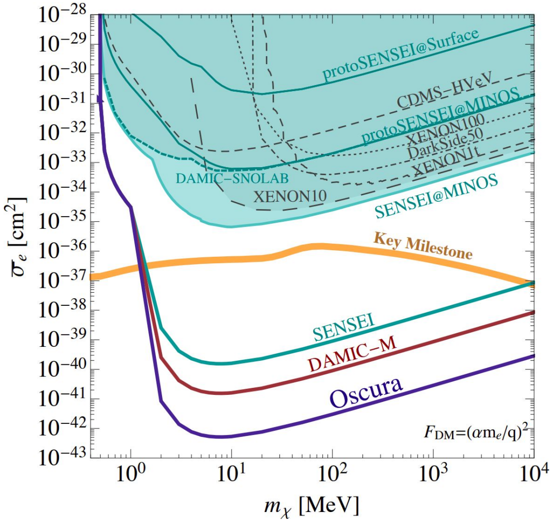


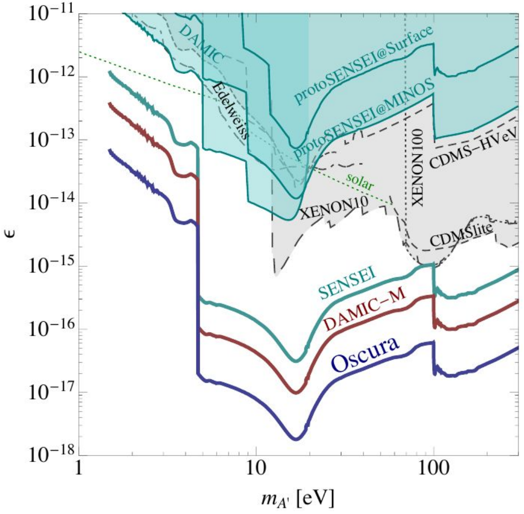
Saldanha et al, PRD, 102, 102006

Projected Sensitivity

- Projected sensitivity to DM-electron scattering mediated by a heavy (left) or light (center) mediator, and absorption of dark photon DM on electrons (right)
  - Assume 30 kg-yr exposure for Oscura (see arXiv:2202.10518)







Summary

❑ The Oscura experiment will deploy a very-large array of skipper-CCDs to conduct a direct DM search

❑ R&D work is ongoing and we are beginning to move into design phase, with plan to begin construction in FY24

❑ Deploy at SNOLAB in 2028

❑ Oscura will provide unprecedented sensitivity to sub-GeV DM that interacts with electrons

Oscura Timeline

2020-2022	2023	2024	2025-2028	2029…
Research & Development	Design Phase	Final design complete, commission 10% prototype system	Fabrication of full system, installation at SNOLAB	30 kg-yr science exposure

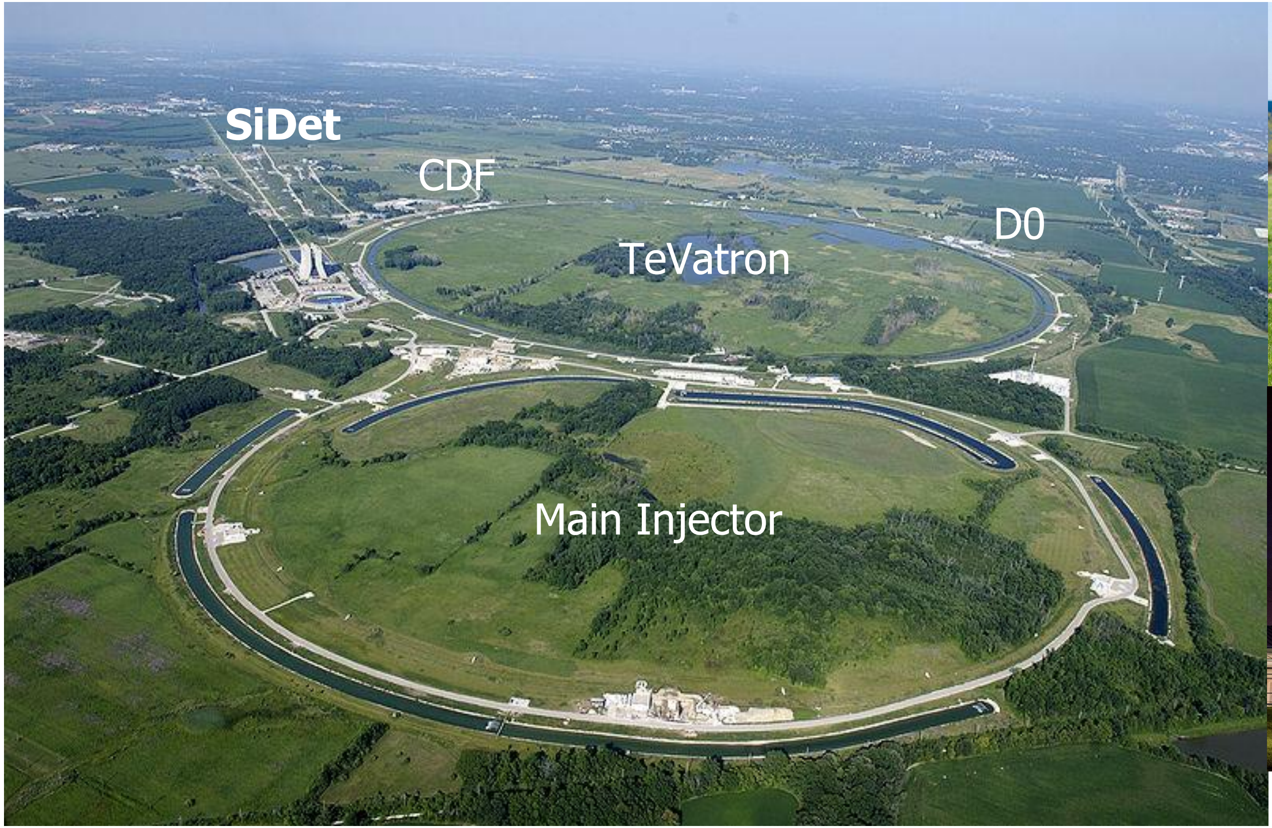
Oscura Collaboration*

1) Universidad Nacional Autonoma de México
2) Centro Atomico Bariloche
3) ECyT-UNSAM
4) Fermilab National Accelerator Laboratory
5) Universidad de Buenos Aires
6) Instituto de Física de Cantabria (IFCA)
7) University of Washington
8) Universidad Nacional del Sur, Argentina
9) Universidad Nacional de Asuncion
10) Stony Brook University
11) Tel Aviv University
12) Lawrence Berkeley National Laboratory
13) Pacific Northwest National Laboratory
14) University of Chicago

Alexis Aguilar-Arevalo[1], Fabricio Alcalde Bessia[2], Nicolas Avalos[2], Daniel Baxter[4], Xavier Bertou[2], Carla Bonifazi[3], Ana Botti[4], Mariano Cababie[5], Gustavo Cancelo[4], Brenda Aurea Cervantes-Vergara[1], Nuria Castello-Mor[6], Alvaro Chavarria[7], Claudio R. Chavez[4,8], Fernando Chierchie[8], Juan Manuel De Egea[9], Juan Carlos D'Olivo[1], Cyrus E. Dreyer[10,15], Alex Drlica-Wagner[4,14], Rouven Essig[10], Juan Estrada[4], Ezequiel Estrada[2], Erez Etzion[11], Guillermo Fernandez-Moroni[4], Marivi Fernández-Serra[10], Steve Holland[12], Agustin Lantero Barreda[6], Andrew Lathrop[4], José Lipovetzky[2], Ben Loer[13], Edgar Marrufo Villalpando[14,4], Jorge Molina[9], Sravan Munagavalasa[14], Danielle Norcini[14], Santiago Perez[5], Paolo Privitera[14], Dario Rodrigues[5], Richard Saldanha[13], Diego Santa Cruz[9], Aman Singal[10], Nathan Saffold[4], Leandro Stefanazzi[4], Miguel Sofo-Haro[2], Javier Tiffenberg[4], Christian Torres[9], Sho Uemura[4], and Rocio Vilar[6]

*As of 2022 Oscura review paper (arXiv:2202.10518)

Thank you!



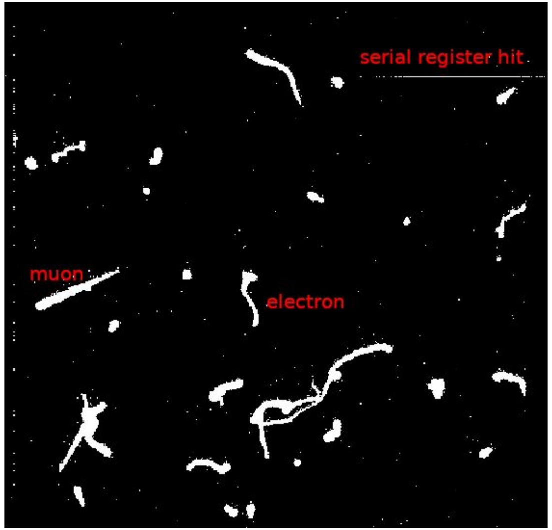
15-foot bubble chamber at SiDet

Backup

Data Analysis

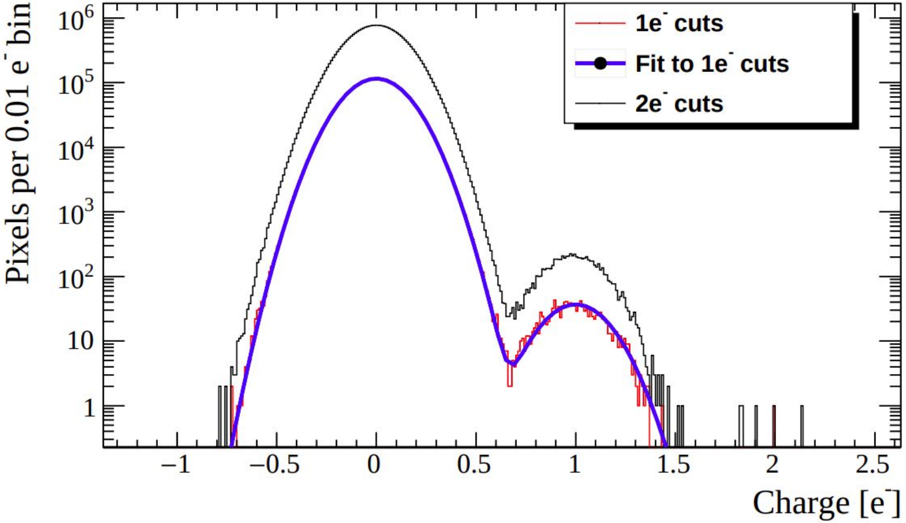
- Images are taken and processed to produce a charge spectrum
- Selection criteria are applied to mask regions near high-energy tracks and known instrumental pathologies

Images



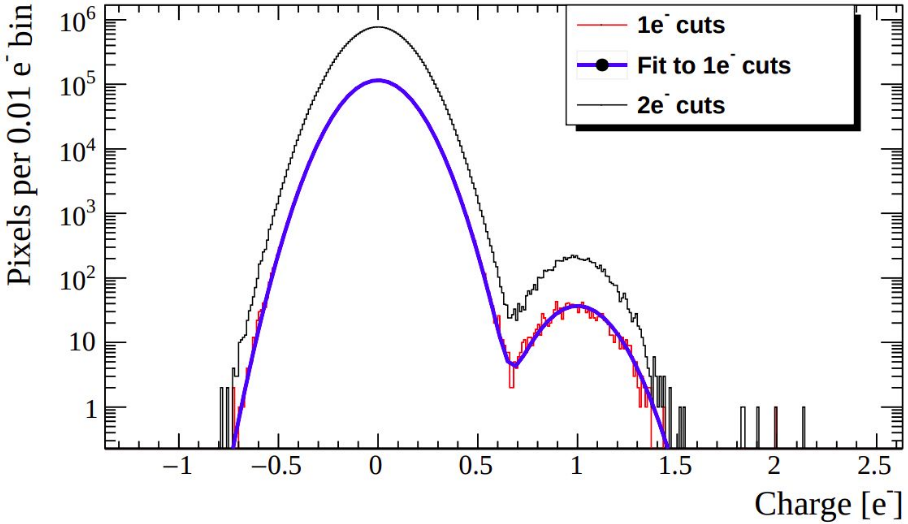
Calibration
Clustering
Masking/Cuts

Spectra



Searches and backgrounds

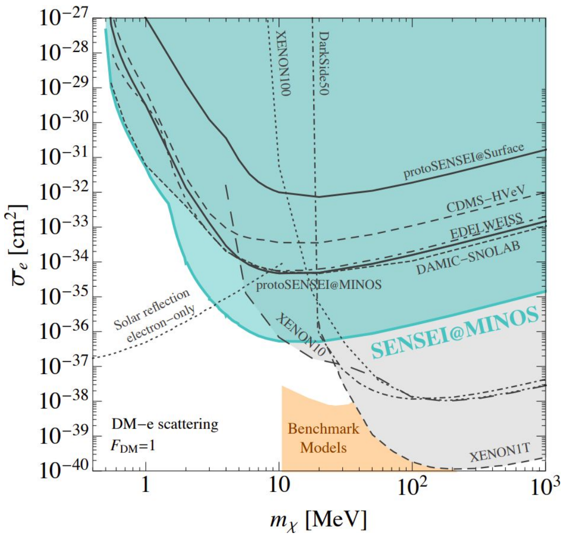
- ❑ Single-electron: background-dominated
- ❑ Multiple electrons (single-pixel or cluster): low-background
  - Coincidence of 1*e*⁻ processes
  - True multi-*e*⁻ processes

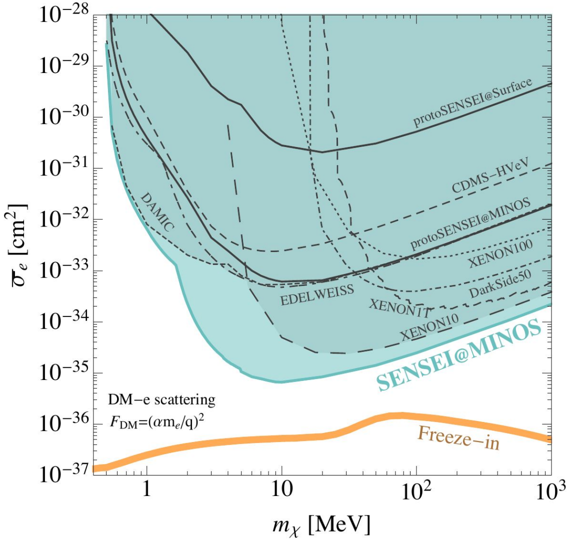


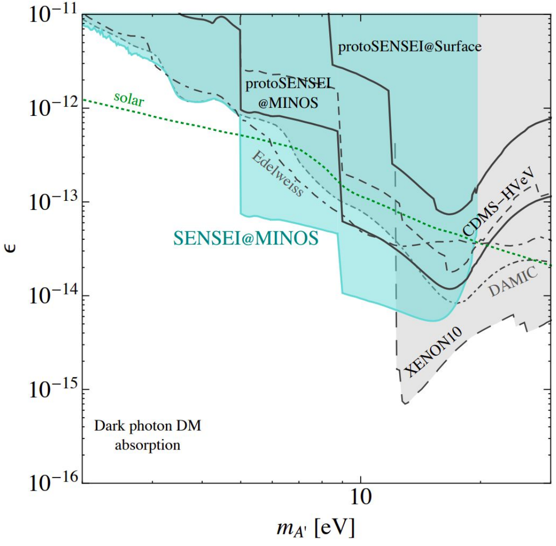
- ❑ 1*e*⁻ processes
  - Local sources of charge: ionizing radiation, amplifier luminescence, CCD defects
  - Spatially uniform sources of charge:
    - Spurious charge: charge generated during readout
    - Intrinsic dark current: charge generated during exposure by thermal excitation
- ❑ Multi-*e*⁻ processes: rare but irreducible:
  - Compton scattering
  - Partial charge collection

Limits from SENSEI@MINOS

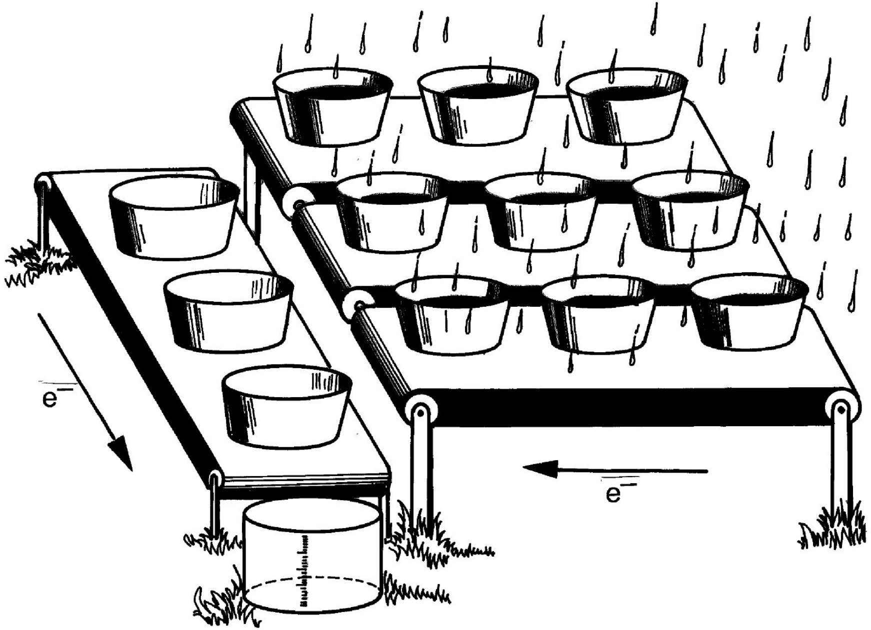
- ❑ Record lows for semiconductor detectors and DM searches at these thresholds
- ❑ Derived DM constraints are summarized in arXiv:2004.11378
  - Left to right: $F_{DM}=1$ scattering (heavy mediator), $F_{DM}=(\alpha/m_e q)^2$ scattering (light mediator), absorption



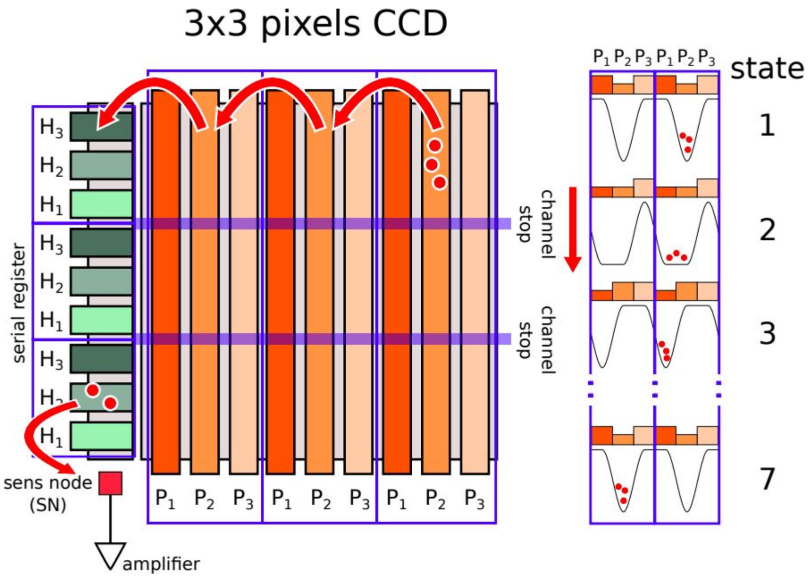




CCDs



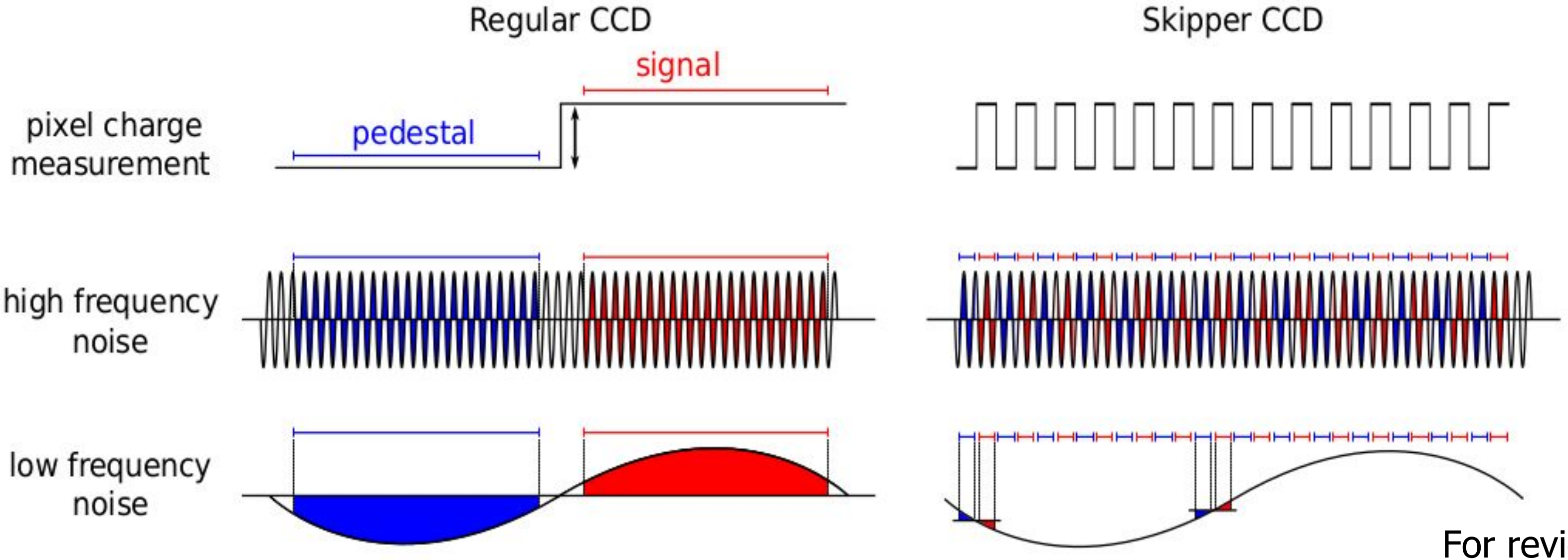
"Bucket brigade" analogy for CCD readout



Schematic of charge transfer in 3x3 pixelated CCD

Skipper readout

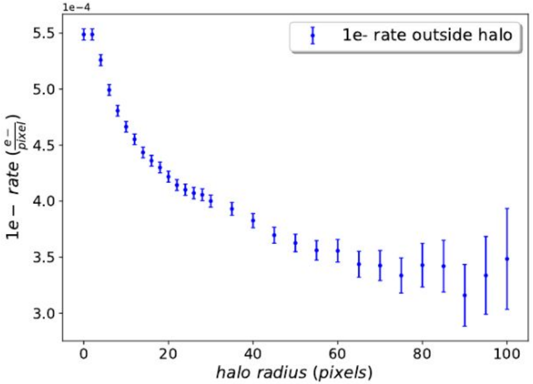
- ❑ In a conventional CCD, charge moved to the sense node must be drained
  - ▪ You can integrate longer, but you cannot beat the 1/f noise
- ❑ The Skipper amplifier lets you make multiple non-destructive measurements!

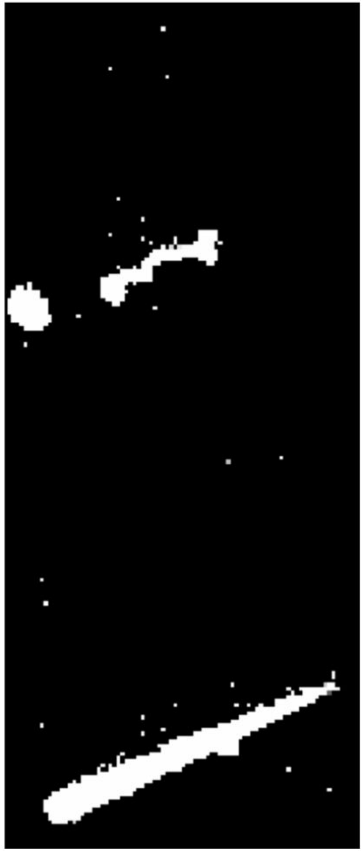


For review see:
arXiV:1106.1839

Localized charge from high-energy events

- Bleeding: charge “left behind” by charge transfer
- Halo: excess of charge near high-charge pixels
  - Probably near-bandgap photons from Cherenkov radiation and electron-hole recombination (see arXiV:2011.13939)
- Loose clusters: regions with high charge density
  - May be Cherenkov photons (reflected, or generated outside of CCD)
- After cuts, charge density of $3.188(90) \times 10^{-4}\ e^{-}$/pixel

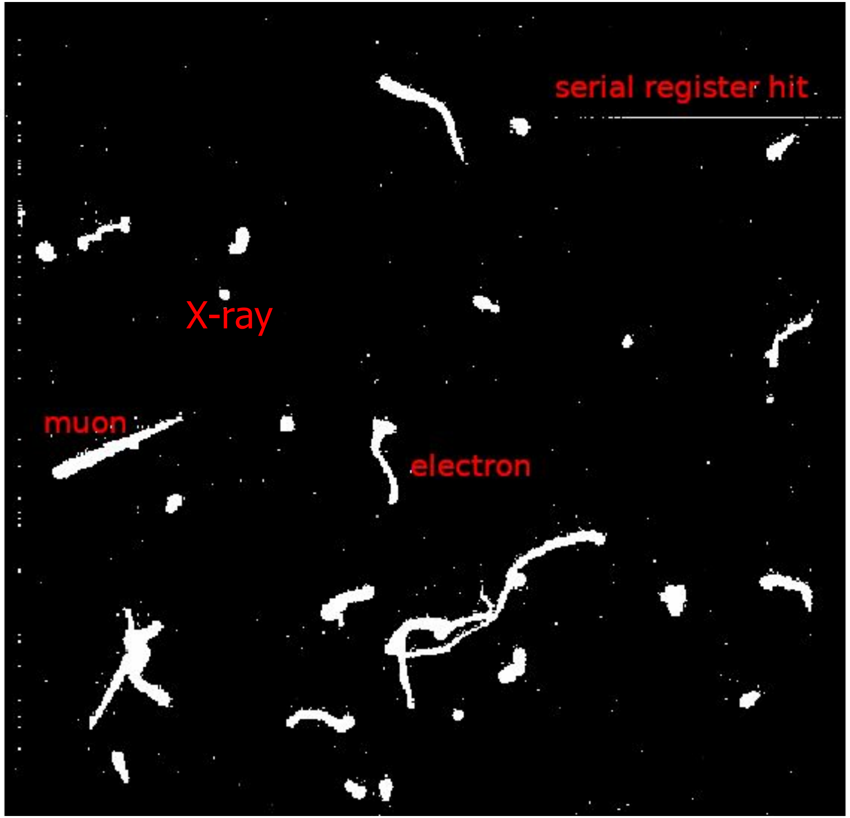




Images!

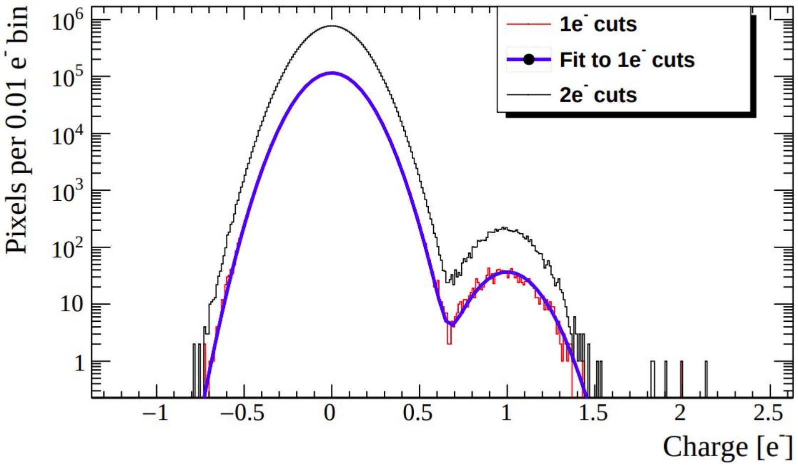
- ☐ This is 1/6th of one quadrant
- ☐ 20 hr exposure, 5.15 hr readout time
    - During readout, the image continues to accumulate hits and charge
- ☐ 22 images in the blinded dataset

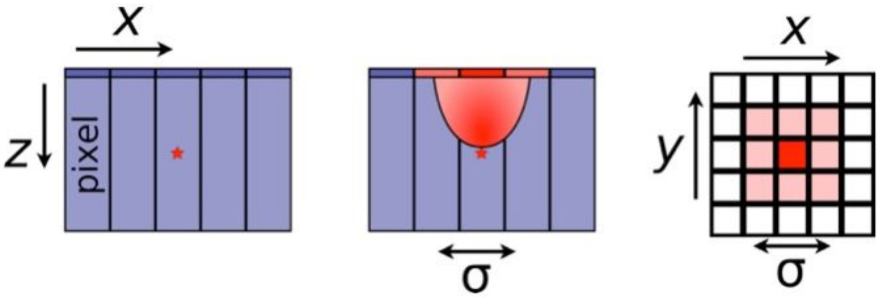
Search	Exposure post-cuts
$1e^-$	1.38 gram-days
$2e^-$	9.17 gram-days
$3e^-$	11.87 gram-days
$4e^-$	11.70 gram-days



Multi-*e*⁻ searches

- We observe 5 2*e*⁻ pixels and no 3, 4*e*⁻ clusters
- Some multi-*e*⁻ events will be lost when they diffuse
    - We calibrate diffusion width using muon tracks and simulate the geometric efficiencies: 22.8% for 2*e*⁻ to stay in one pixel, 76.1%, 77.8% for 3, 4*e*⁻ to form a contiguous cluster
- Now we can put limits on the rate of events

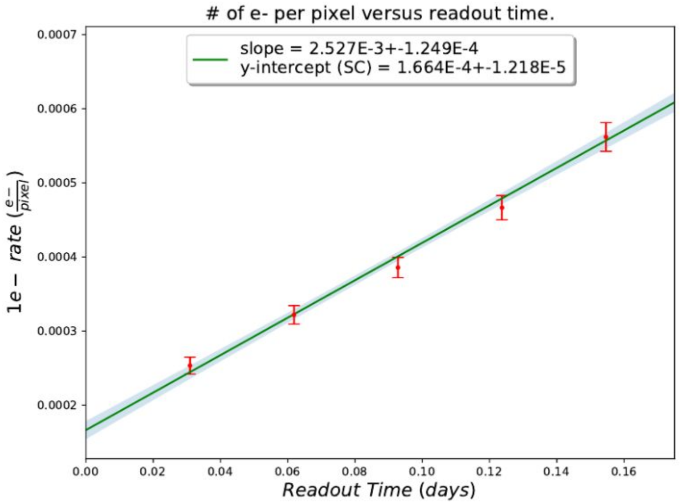


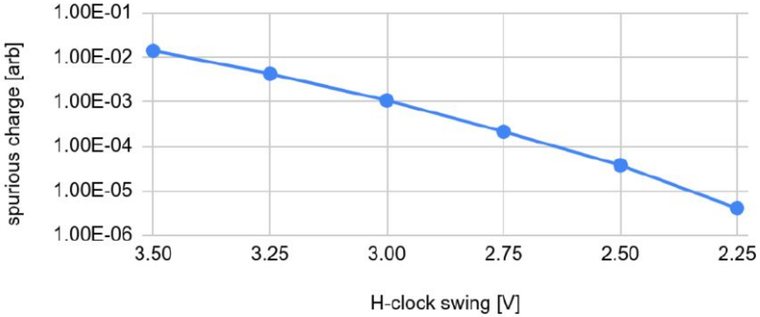


	90% CL
$1e^-$	525.2 events/g-day
$2e^-$	4.449 events/g-day
$3e^-$	0.255 events/g-day
$4e^-$	0.253 events/g-day

Spurious Charge

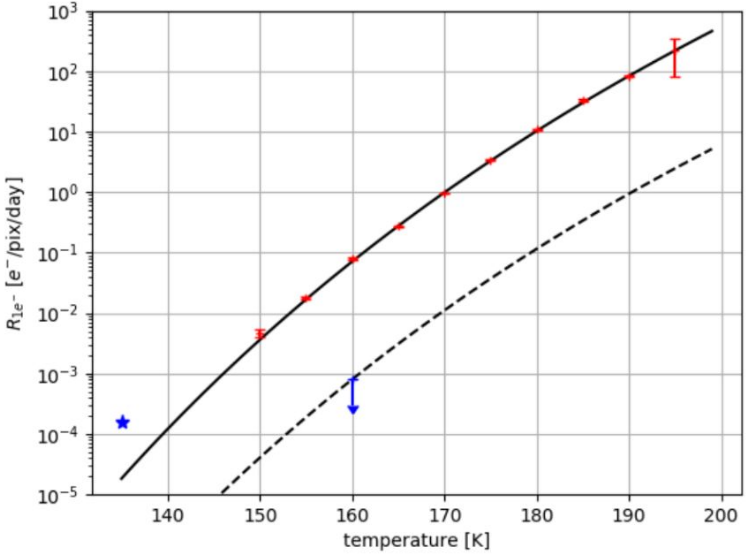
- Measurements with shorter exposures show a limiting value for the CCD charge: $1.66(12) \times 10^{-4}\ e^{-}$/pixel
  - Half of the $1e^{-}$ events we see are due to spurious charge!
  - Optimization of the CCD voltage waveforms will reduce this background in future runs
- Subtracting the exposure-independent charge, our 1e- rate is $1.59(16) \times 10^{-4}$ e^{-}/pixel/day





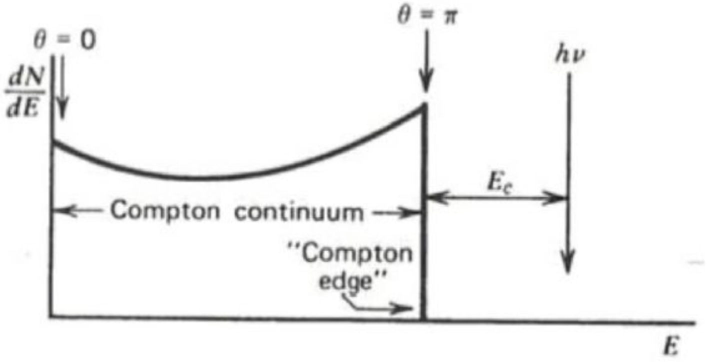
Intrinsic Dark Current

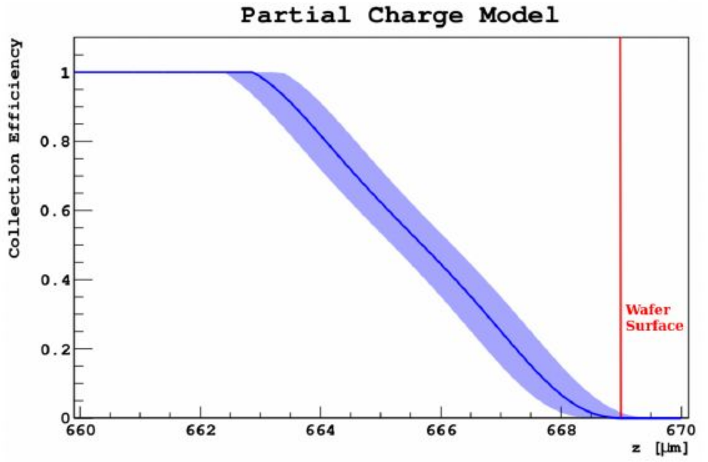
- Subtracting the exposure-independent charge, our 1e- rate is $1.59(16) \times 10^{-4}$ e^{-}/pixel/day
- Intrinsic dark current is the usual suspect
  - Thermal generation of electron-hole pairs, mediated by lattice defects
- However:
  - Extrapolation from higher temperatures (dashed black line) predicts $\ll 1 \times 10^{-5}$ e^{-}/pixel/day at our operating temperature of 135 K
    - ★ Suppressing surface dark current gets us from red data points to blue
- High-quality silicon has made this a subdominant background



Multi-e^- backgrounds

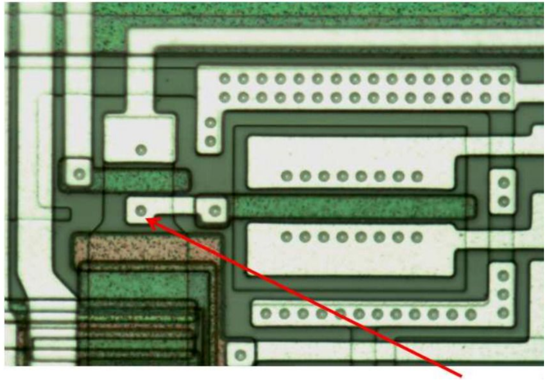
- At the low-energy end of the Compton spectrum, a gamma ray can create arbitrarily small-energy electron recoils
  - DAMIC and SENSEI efforts to measure this spectrum and compare to theory
- Depending on details of processing, some CCDs have a highly-doped backside layer with partial charge collection: this can create low-charge events
  - DAMIC and SENSEI are affected, but future CCDs will not have this layer

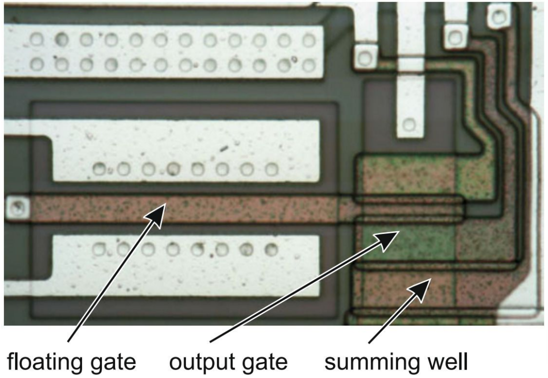


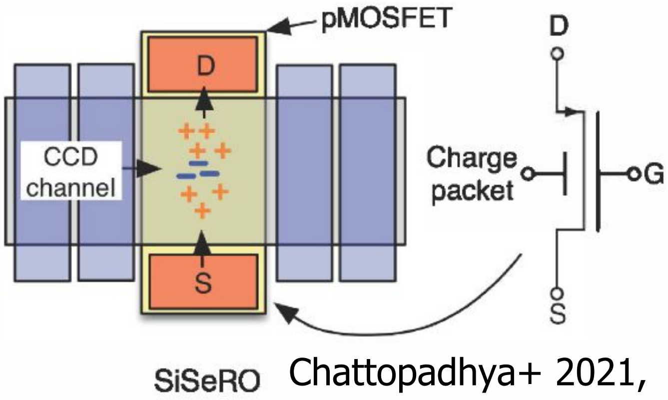


CCD Amplifiers

- Floating diffusion: standard CCD amplifier
- Floating gate: used in our Skippers
  - Enables non-destructive readout at the cost of S/N
- SiSERO: under development by MIT-LL:
  - Best of both worlds: nondestructve and excellent S/N
  - Possible option for Oscura







Chattopadhya+ 2021, arXiv:2112.05033

Buried channel CCDs

- Buried-channel potential well provides better charge transfer efficiency compared to surface-channel CCDs