



## Oscura: Dark Matter search with 10 kg of skipper-CCDs

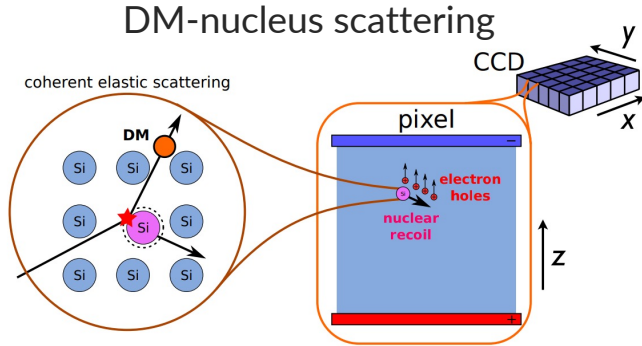
Nate Saffold on behalf of the Oscura collaboration

Fermilab

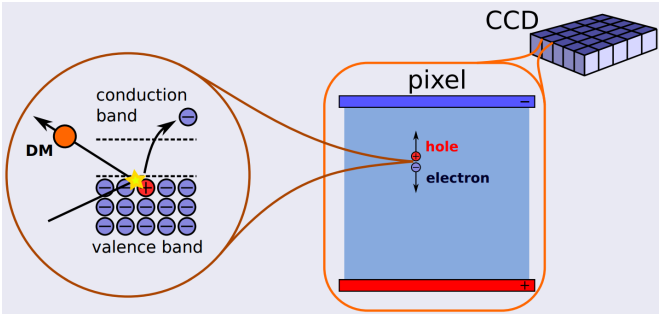
TAUP 2023

August 28, 2023

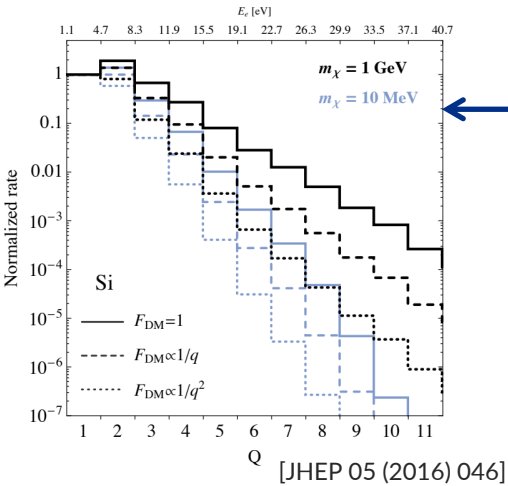
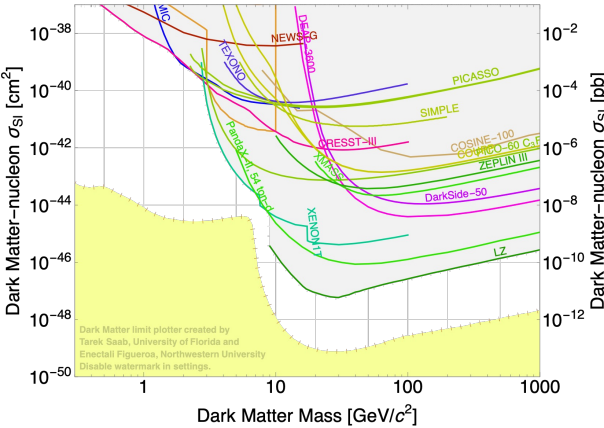
# DM direct detection with CCDs



Searching for sub-GeV DM motivates other detection channels



$m_\chi \sim \text{GeV} \rightarrow$  energy transfer is a few keV

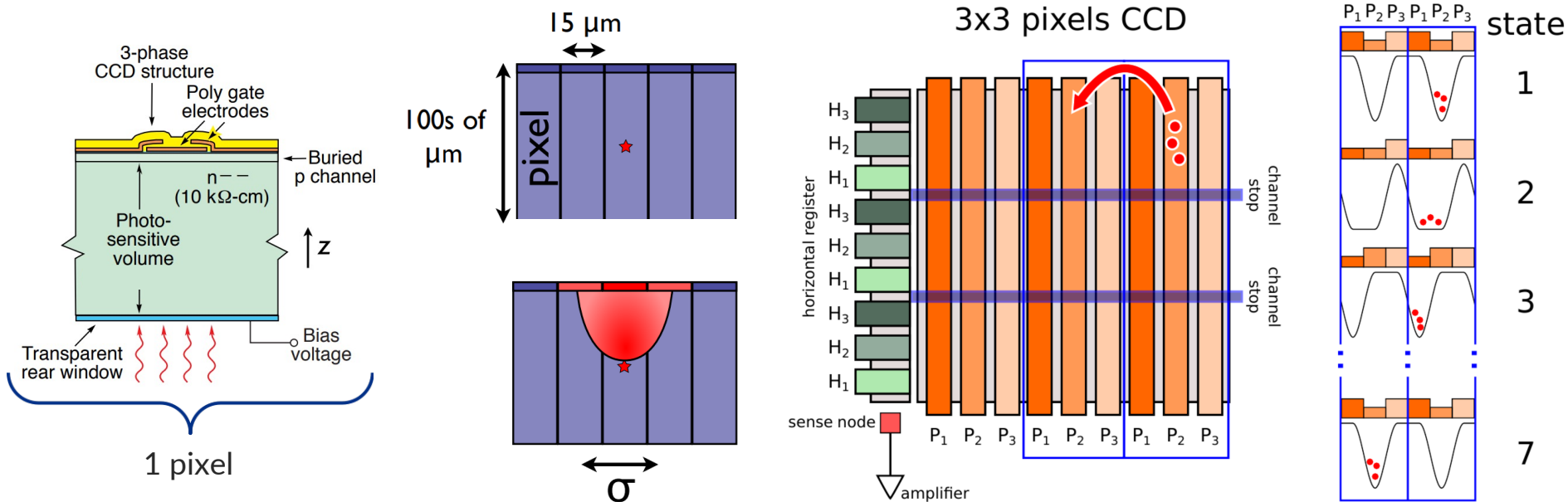


DM-electron scattering  
 $m_\chi \sim \text{MeV-GeV}$   
 $\rightarrow$  energy transfer is a few eV

DM absorption  
Bosonic DM at the eV scale  
 $\rightarrow$  energy transfer equals  $m_\chi$

# Scientific Charge-Coupled Devices (CCDs): structure and operation

- CCDs are an array of Metal-Oxide-Semiconductor capacitors
- Ionizing radiation interacting in the substrate produces e-h pairs (in Si, 1 e-h pair corresponds to  $\sim 3.8$  eV)
- Charge is collected near the surface, transferred varying the potential wells until reaching the readout stage
- Conventional CCDs are limited to noise of  $\sim 2e^-$

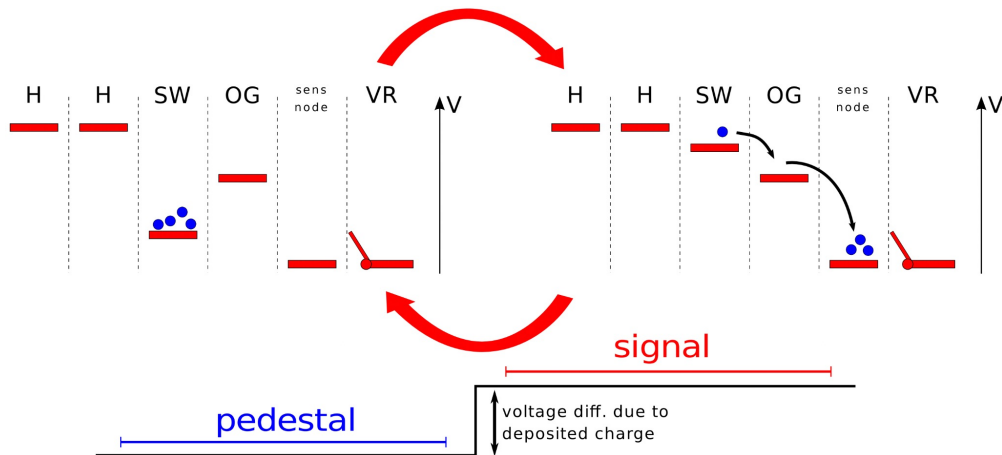


[\[IEEE Trans. Electron Devices 50 \(2003\) 1\]](#)

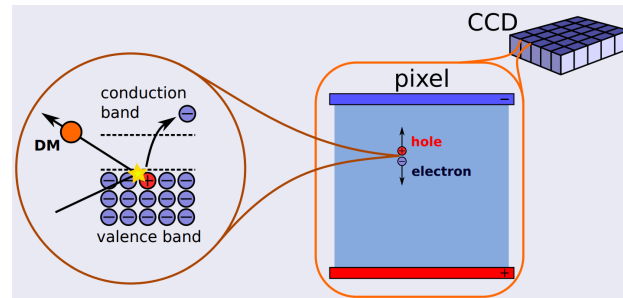
# Skipper-CCDs for direct DM search

## Silicon charge-coupled devices (CCDs) w/ Skipper amplification (designed by LBNL):

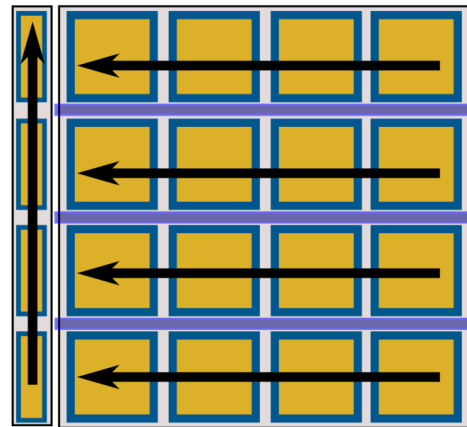
- Energy threshold of Si bandgap ( $\sim 1.1$  eV)
- Low dark current ( $\sim 10^{-4}$   $e^-$ /pix/day)
- Sub-electron ( $\sim 0.1e^-$ ) readout noise



Skipper amplifier makes repetitive, non-destructive measurement of the pixel charge, reducing noise to sub-electron levels



Amp ■





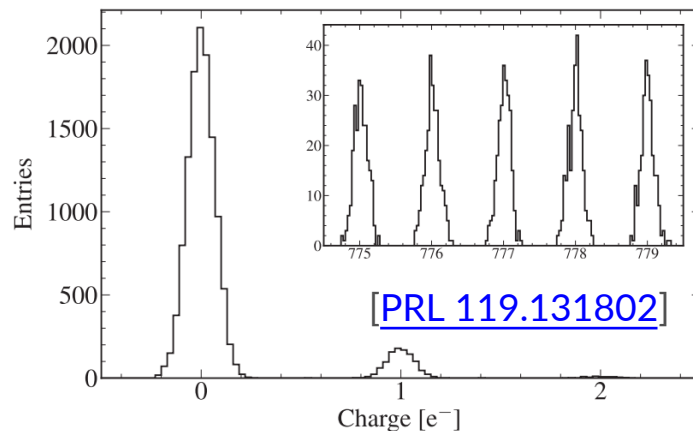
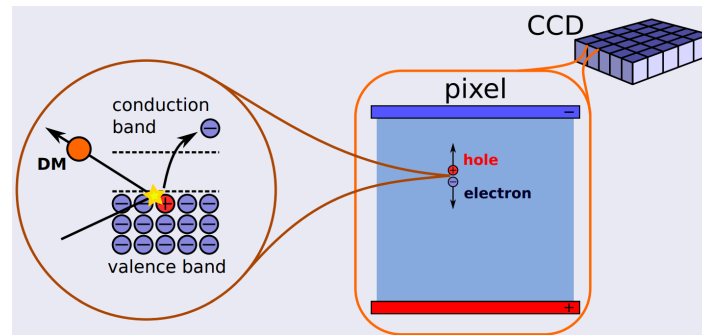
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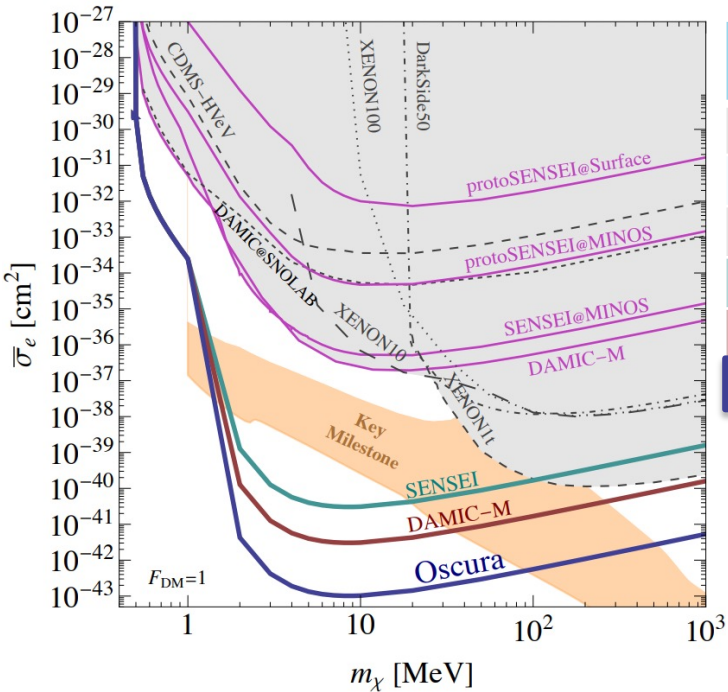
## Low threshold enables low-mass searches:

- Electron scattering of 1-1000 MeV DM
- Nuclear scattering of 1-1000 MeV DM via Migdal effect
- Absorption of 1-1000 eV DM
- Scattering of milli-charged particles
- Etc...



# Skipper-CCDs for direct DM search

World best limits for sub-GeV DM candidates with this technology → Ongoing program



Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	$1.6 \times 10^{-4}$	late-2019
DAMIC @ SNOLAB	~0.02	2	5	$\sim 3 \times 10^{-3}$	late-2021
DAMIC-M LBC	~0.02	2	~10	$3 \times 10^{-3}$	late-2021
SENSEI-100	~0.1	50	10 (goal)		mid-2022
DAMIC-M	~1	200	0.1 (goal)		~2023
OSCURA	~10	20,000	0.01 (goal)	$1 \times 10^{-6}$ (goal)	~2028

Oscura builds on existing efforts

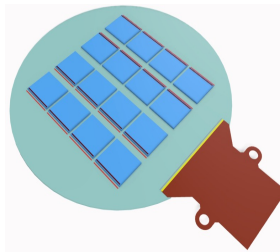
The challenges are to increase mass (from 10s to 10,000s CCDs)  
and to reduce the backgrounds (2 orders of magnitude)

Major R&D ←

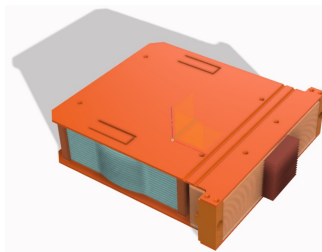
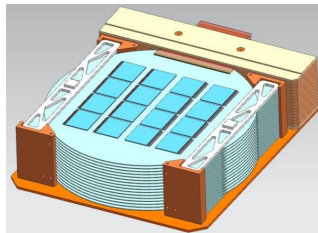
# Oscura: 10-kg skipper-CCD experiment

[arXiv:2202.10518]

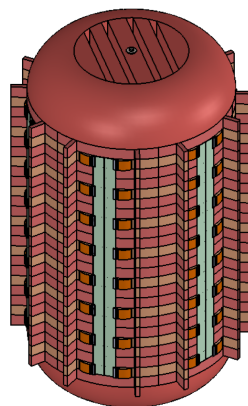
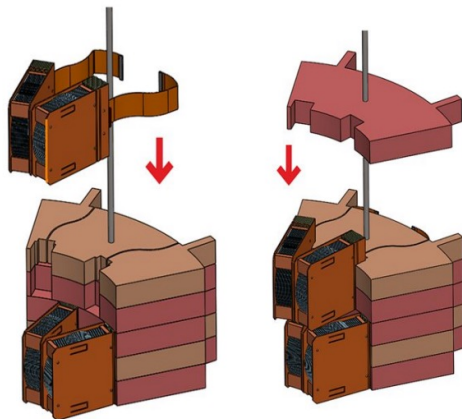
Multi-Chip Module  
(16 skipper-CCDs)



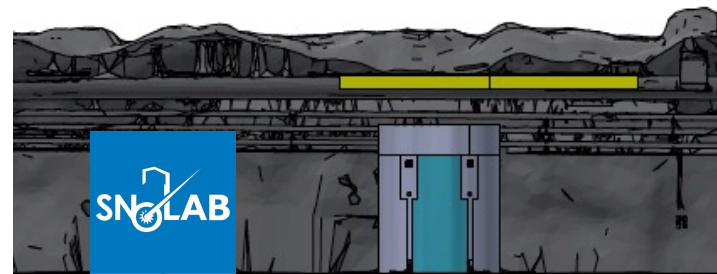
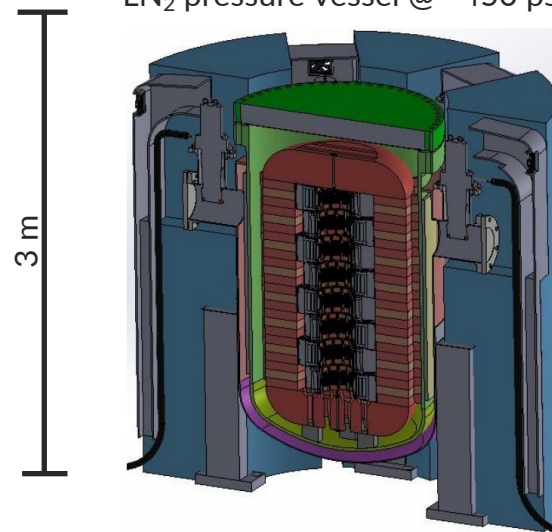
Super Module  
(16 MCMs)



Detector payload in 6 columnar slices (96 SMs)



LN<sub>2</sub> pressure vessel @ ~450 psi

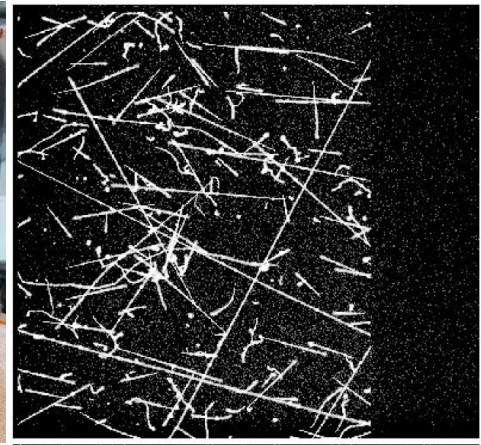
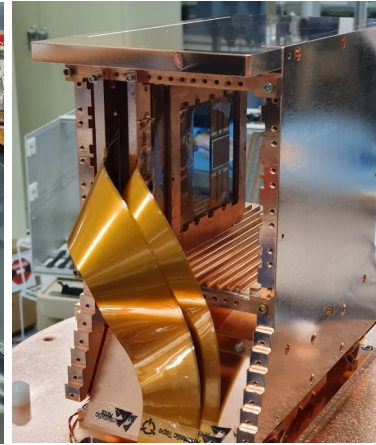
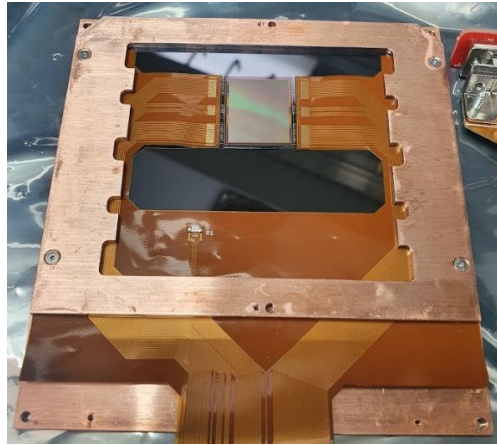
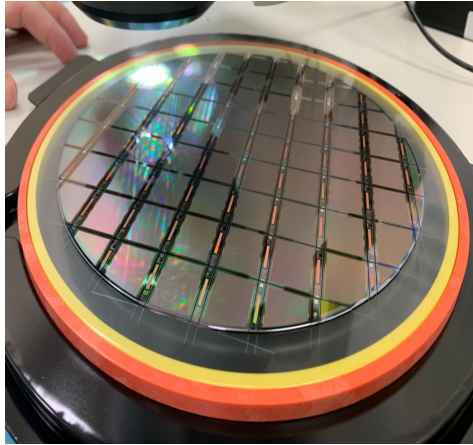


# Oscura: Sensors fabrication



**NOTIFICATION of DISCONTINUANCE of 150mm CCD process wafer fabrication.** —————> **New foundries needed!**

- Partnered with 2 foundries: Microchip Technology Inc. and MIT Lincoln Laboratory
- Stephen Holland (LBNL) adapted the design to the 200 mm diameter wafer processes
- In summer 2021 we received first batch of Oscura prototype skipper-CCDs (1278 x 1058 pix) and, after testing, we **demonstrated the success of the fabrication** [[NIMA 1046 \(2023\)](#), [167681](#)]



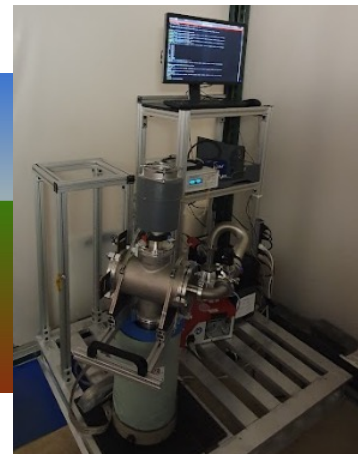
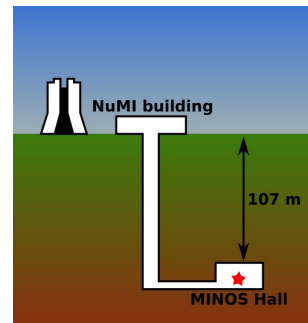
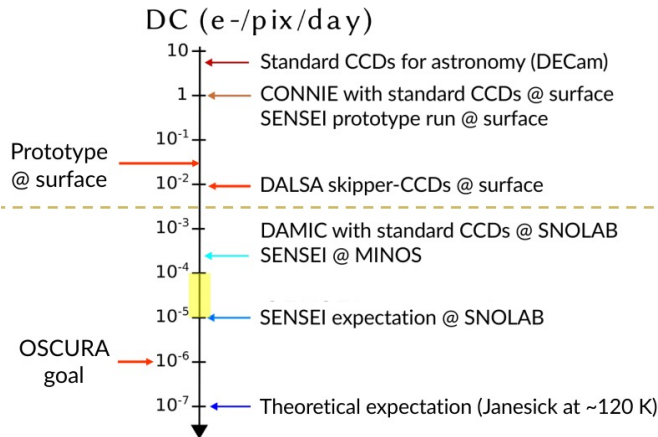
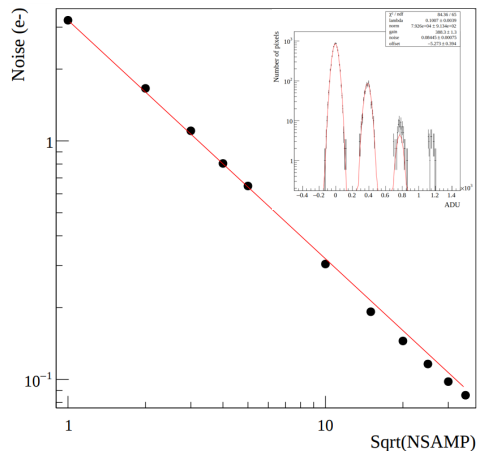


# Oscura: Sensors performance

JINST 18 (2023), P08016

Parameter	No events with >1e-	No events with 3e- or more	Prototype	Units
Dark current	$1 \times 10^{-6}$	$1.6 \times 10^{-4}$ ✓	$3 \times 10^{-2}$	$e^-/\text{pix}/\text{day}$
Readout time for full array	< 2	< 5 ✓	3.4 (4.2)	hours
Pixel readout rate	> 188	> 76 ✓	111 (89)	pix/s
Readout noise	< 0.16	< 0.20 ✓	0.19 (0.20)	$e^-$ RMS
Spurious charge	< $10^{-10}$	< $10^{-8}$	$7.2 \times 10^{-7}$	$e^-/\text{pix}/\text{transfer}$
Trap density with $\tau > 5.3$ ms	< 0.12	✓	< 0.015	traps/pix
Charge transfer inefficiency	< $10^{-5}$	✓	< $5 \times 10^{-5}$	1/transfer
VIS/NIR light blocking	> 90%	✓	95%	

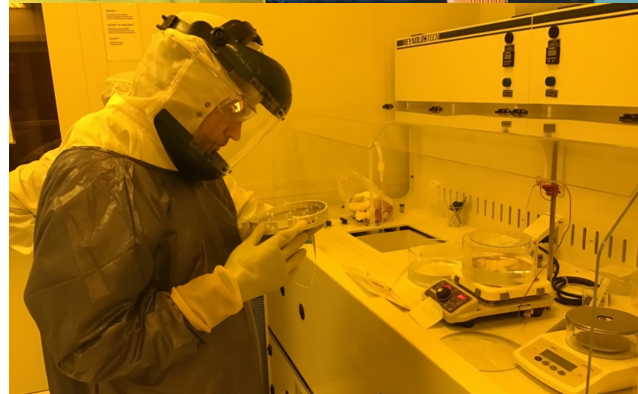
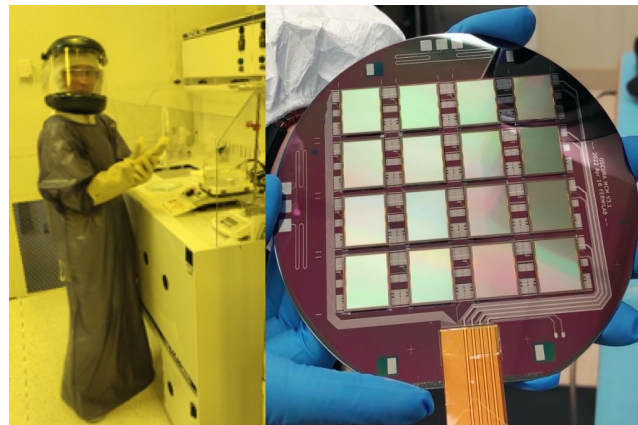
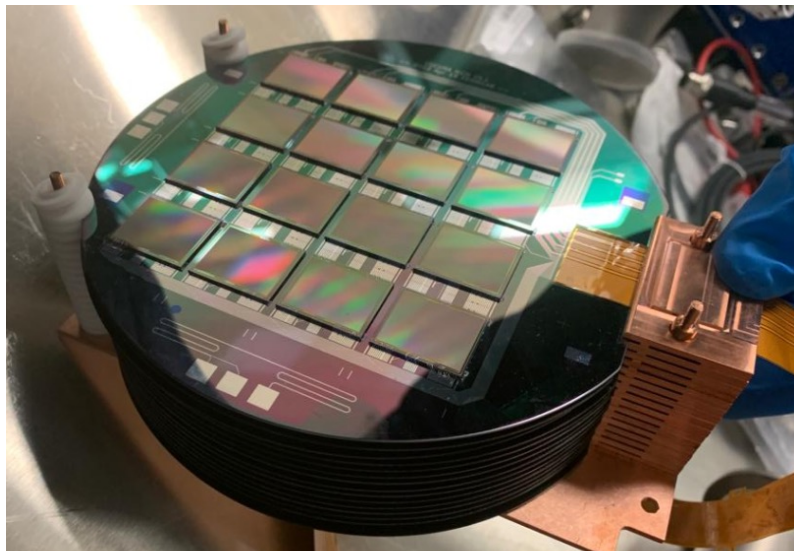
- Sensors reach sub-electron noise and meet almost all constraints to reach desired instrumental background
- Spurious charge is under study and new approaches are being implemented
- Installed underground setup at MINOS (MOSKITA) to measure the ultimate DC





# Oscura: Scaling up mass (MCMs/SMs fabrication)

- Fabrication of prototype Si MCMs at Argonne National Laboratory (Oscura needs ~1500 MCMs)
- Epoxying and wirebonding of sensors is done by hand → Plans to automate this process
- Si MCMs production will start soon to build the first Oscura SM

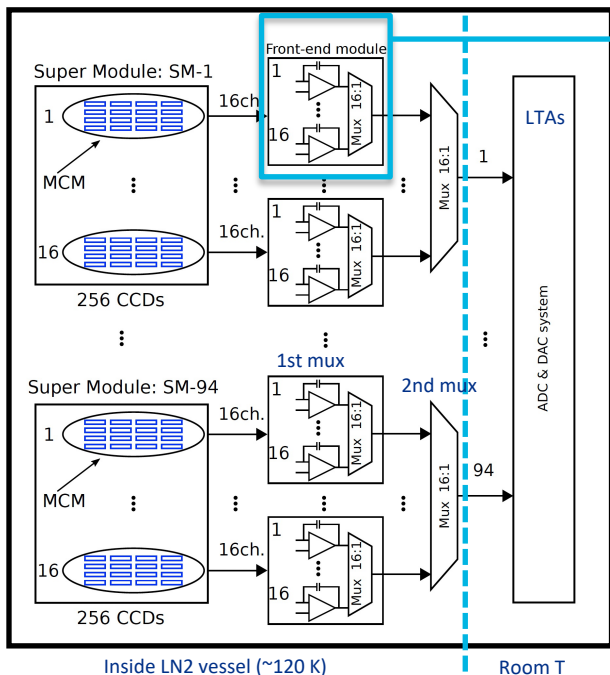


# Oscura: Readout electronics

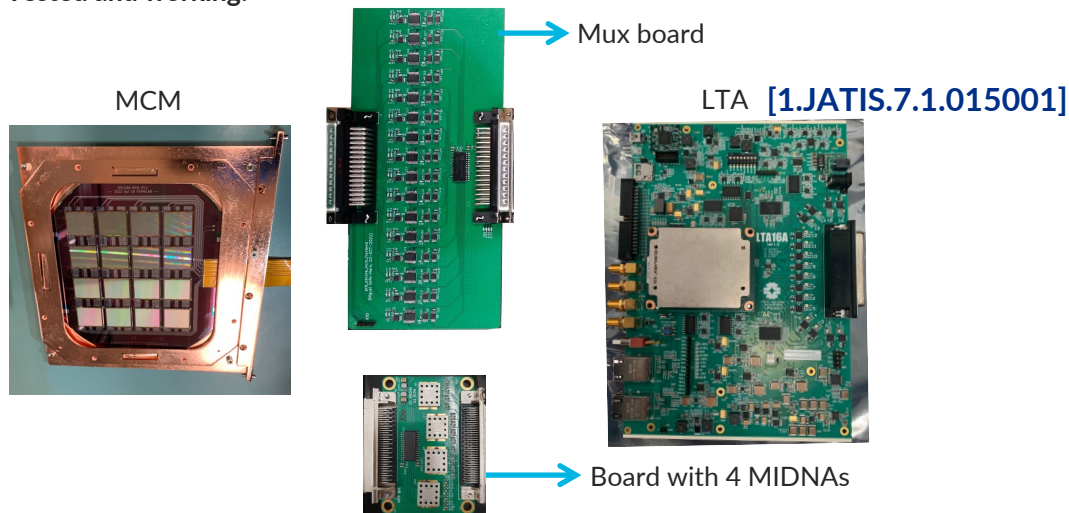
Check out Ana Botti's poster tonight!

Oscura requires ~24,000 readout channels complying with noise and readout time constraints

- Cold front-end electronics to reduce feedthrough complexity (only 94 cables outside vessel)
- 2 multiplexing stages → 256 channels result in 1 signal
- 1 LTA controls up to 16 SMs (4096 sensors) → 6 LTAs needed in total



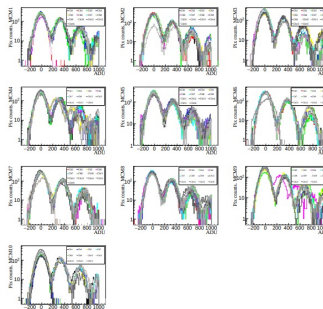
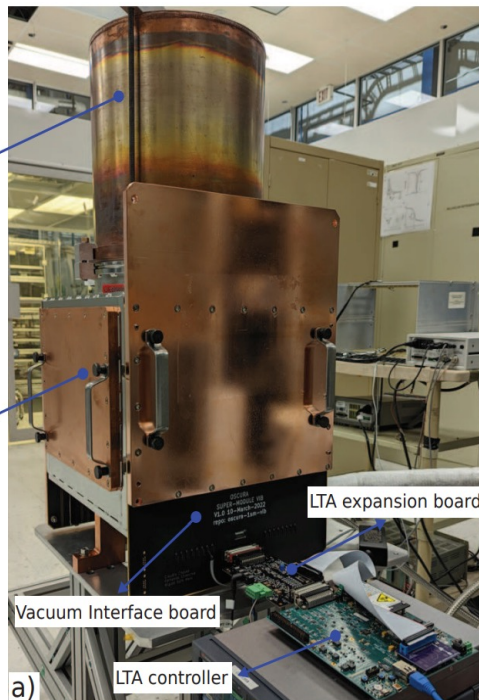
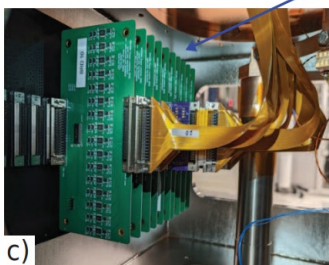
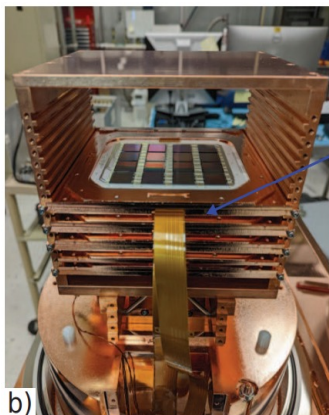
- Discrete (mux board) [[Sensors 22 \(2022\) 11, 4308](#)] [[JINST 16 P11012](#)]
- Integrated (MIDNA ASIC) [[doi:10.2172/1841383](#)]  
4 channels in a 2mm x 1mm chip reducing cost, space, and radioactive contamination  
Tested and working!



# Oscura: Massive testing setup with 10 MCMs (160 sensors)

[JINST 18 P01040]

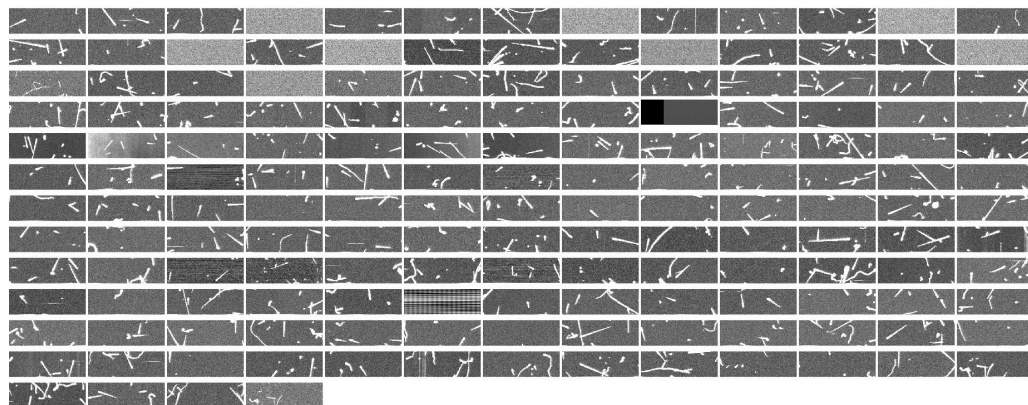
- Copy of SENSEI-100 vessel with 10 prototype ceramic MCMs and the discrete readout electronics
- **Largest ever built instrument with skipper-CCDs controlled by 1 LTA** → Demonstrates electronics solution



**~90% of the sensors working without a preselection! This is a BIG deal!\***

\*LSST, the largest “astronomical camera” has 189 CCDs!

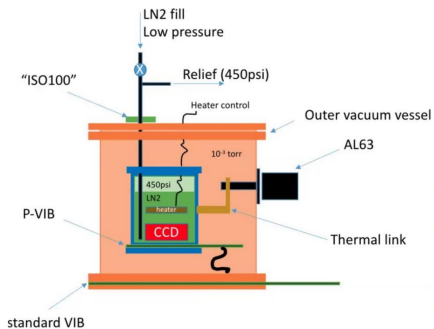
Setup is being used to develop analysis software and could be used for early science





# Oscura: Operation in LN2

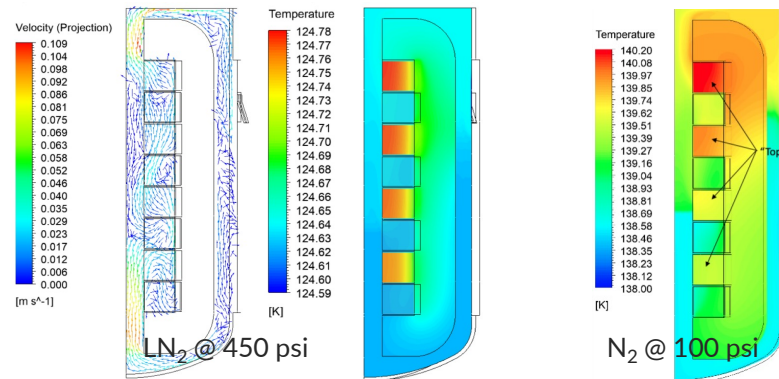
- Demonstrated stable operation of skipper-CCD in LN<sub>2</sub>



- Test of 1st SM in LN<sub>2</sub> coming soon!



- Simulations validate the convective flow



- Exploring new ideas to make skipper-CCDs blind to LN<sub>2</sub> light emission

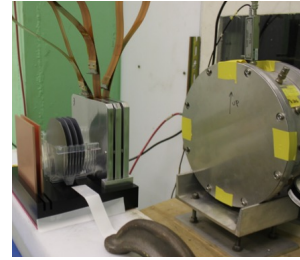


# Oscura: Background control

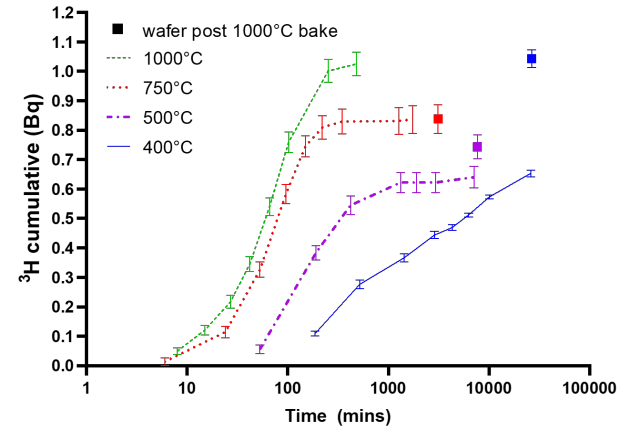
Goal: 0.01 dru → Pathfinder experiments paving the way  
Decisions driven by simulations

Sources:

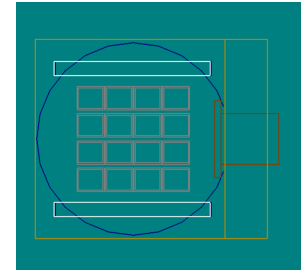
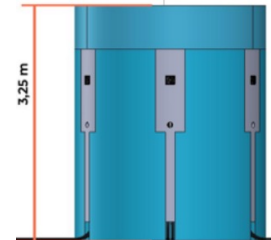
- Cosmogenic activation of Si and Cu
  - $^3\text{H}$  in Si: Main bkgd (2 mdru/day at sea level)
    - <5 days on surface
    - Can be baked out during fab! (“total” removal at 1000°C)
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [[arXiv:2303.10862](https://arxiv.org/abs/2303.10862)]
  - Simulations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ 
    - 4cm of cable visible to CCDs
    - Electronics behind inner shield (width>10cm)
- External backgrounds
  - Outer shield: polyethylene
  - Inner shield: ancient lead and electroformed copper



[PRD 102, 102006]



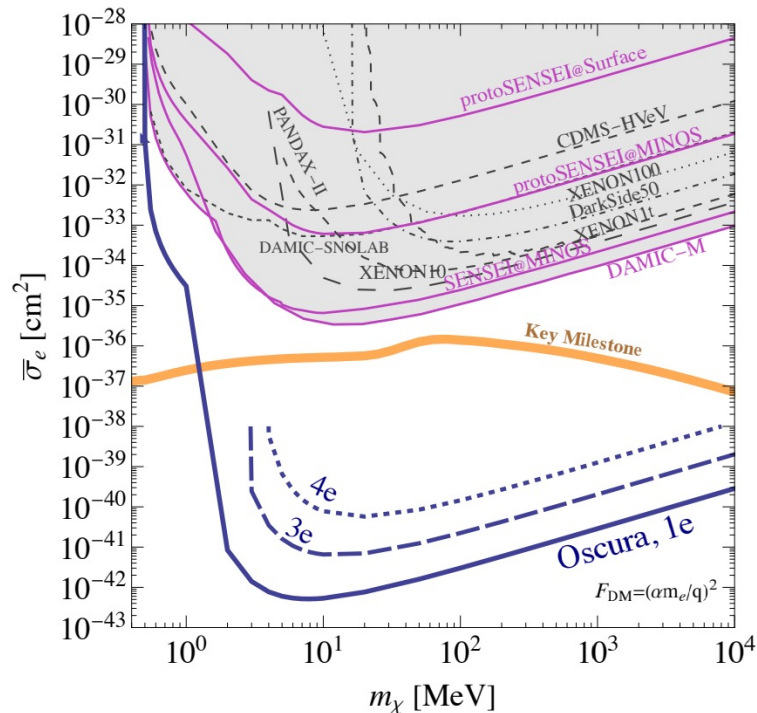
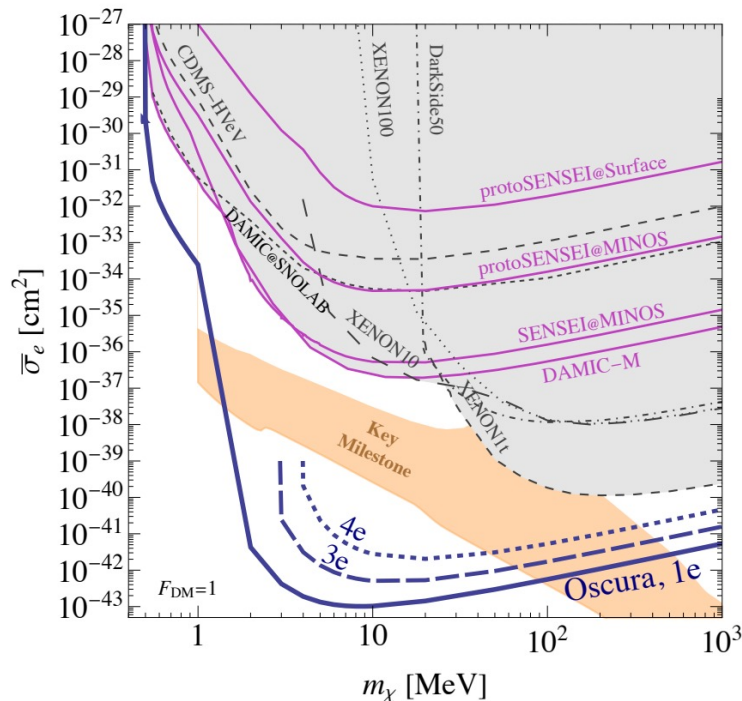
DAMIC-M cable	$^{238}\text{U}$ [ppt]	$^{232}\text{Th}$ [ppt]
Commercial	2600 +/- 40	261 +/- 12
Customed	31 +/- 2	13 +/- 3





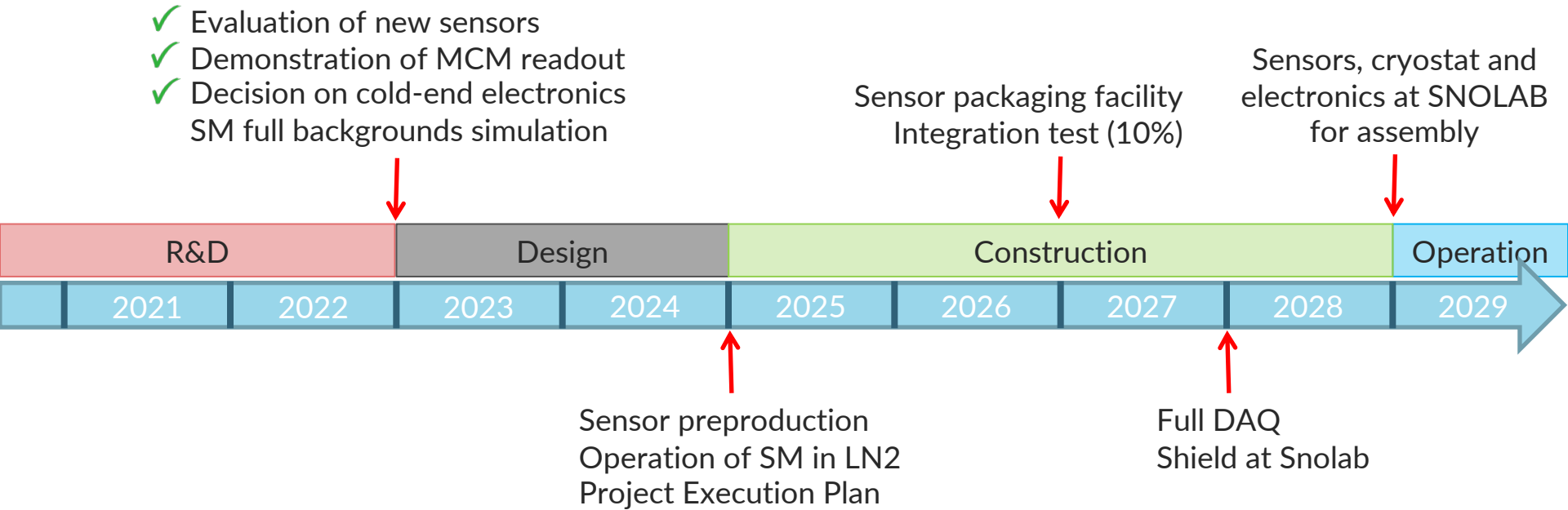
# Oscura: Projected sensitivities for 30 kg-year

With the current sensor performance, we have zero background events with 4e<sup>-</sup> or more (4e curve)



DM-electron scattering mediated by a heavy (left) or light (right) mediator

# Oscura: Timeline and goals per period



✓ - Achieved

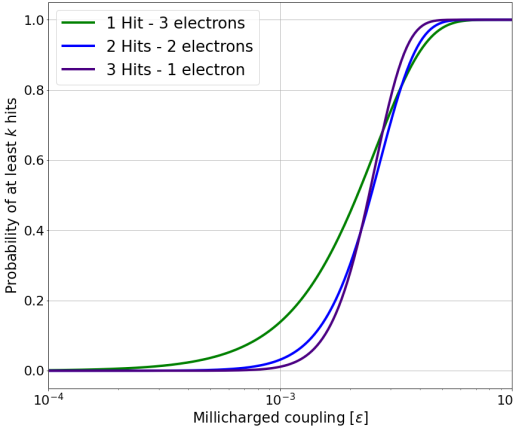
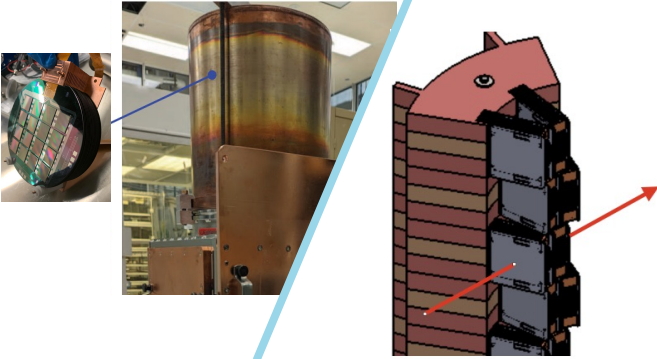
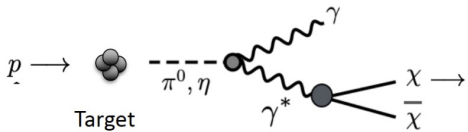
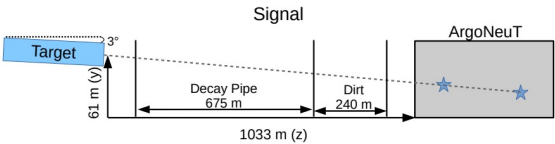
\* Technically driven Oscura timeline

# Oscura: Early science

With a partial load of sensors (Massive setup/OIT) we can do early science!  
**Search for millicharged particles coming from the NuMI beam at Fermilab**

arXiv:2304.08625

[PRL 124, 131801 (2020)]



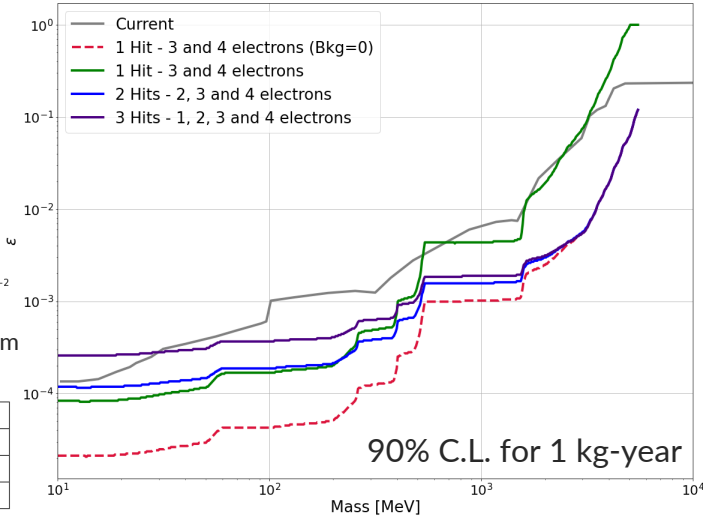
Number of fake tracks per day produced by random coincidences of uncorrelated single pixel hits

Threshold	doublets ( $b = 2$ )	triplets ( $b = 3$ )	$p_{bkg}$
$1e^-$	3822	11.4	$3 \times 10^{-4}$
$2e^-$	0.031	$2.72 \times 10^{-7}$	$8.6 \times 10^{-7}$
$3e^-$	$9.06 \times 10^{-5}$	$4.17 \times 10^{-11}$	$4.6 \times 10^{-8}$

If doing tracking, we are essentially background-free!

Essential items:

- Large-mass setup → Massive setup / SM
- Location @ MINOS → MOSKITA



Exclusion limits are promising!

## Take-home messages

- Oscura is a next-generation skipper-CCD DM search (10 kg active mass)
- Oscura will provide unprecedented sensitivity to sub-GeV DM interacting with electrons
- R&D work has been successfully completed and main risks have been addressed
- Oscura is in the design phase, with plan to begin construction in FY25 and operations at SNOLAB in FY29
- With a partial detector payload, Oscura can perform early science producing very competitive results

**Stay tuned!**



# THANK YOU!



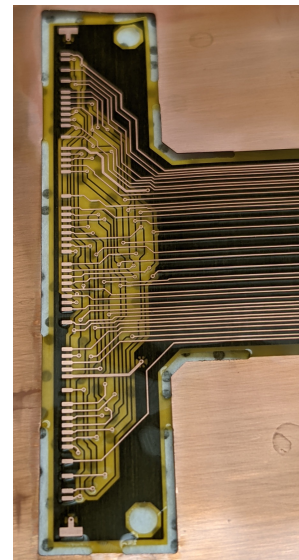
# Ultra Low Background Cables

## Phase II SBIR w/ Q-Flex Inc.



- Phase I: achieved 15–30x reduction in  $^{238}\text{U}$  and  $^{232}\text{Th}$  content.
- Phase II: Developed new low-background fabrication procedure.
  - Identified new radiopure raw materials
  - Developed custom cleaning method at PNNL
  - Changed process for key steps
- Phase II: Produced fully-functional cables with **10-30 ppt U and Th (25–100x reduction)**
  - Presented at Low Radioactivity Techniques 2022
  - Paper on arXiv last week. To be submitted to journal <https://doi.org/10.48550/arXiv.2303.10862>

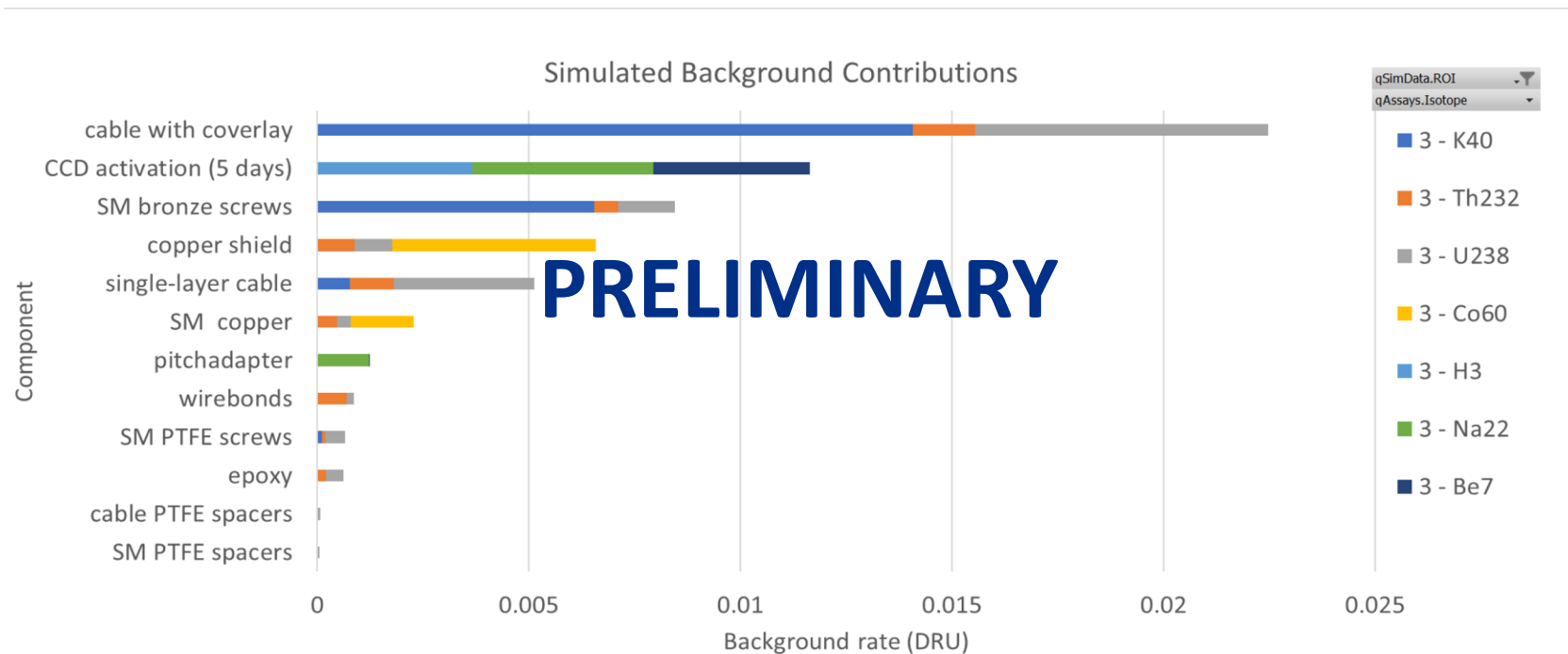
DAMIC-M CCD cable	$^{238}\text{U}$ [ppt]	$^{232}\text{Th}$ [ppt]
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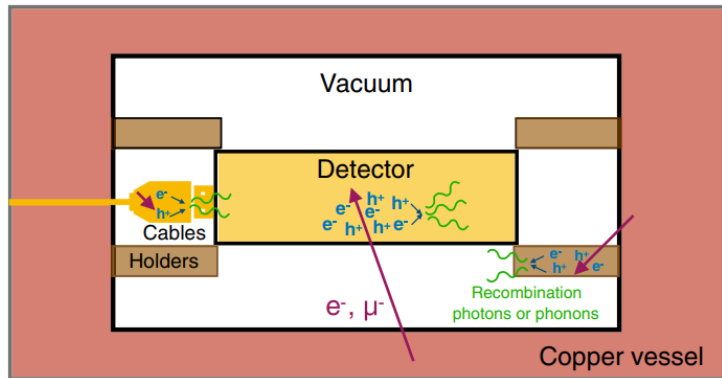
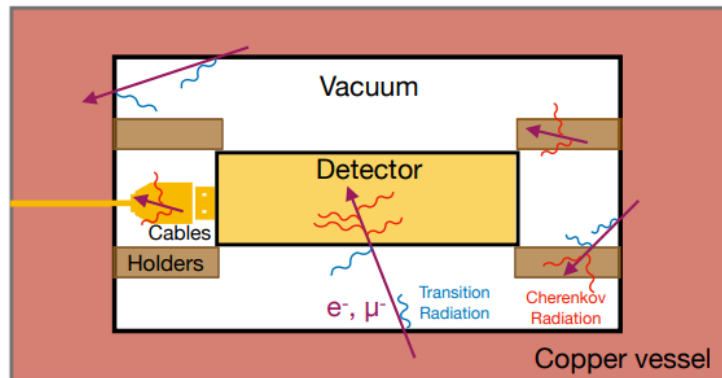
\*Slide from Richard Saldanha

# Projected Internal Backgrounds

- Simulations that indicate background requirement is within reach

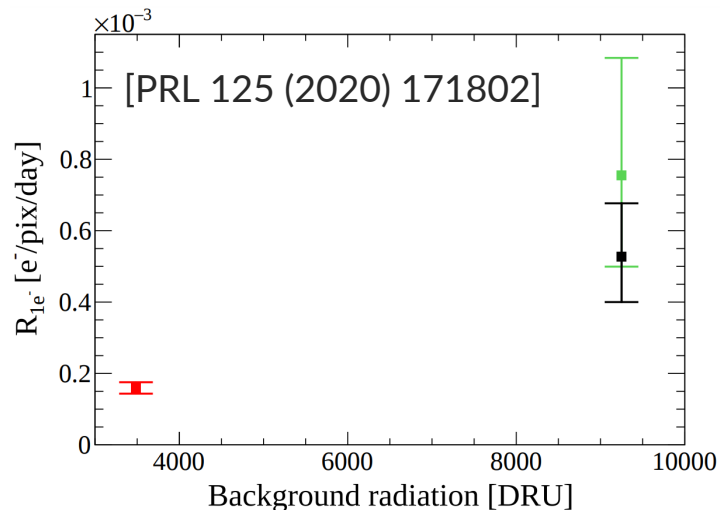


# Low-E background correlation with high-E events



[PRX 12 (2022) 011009]

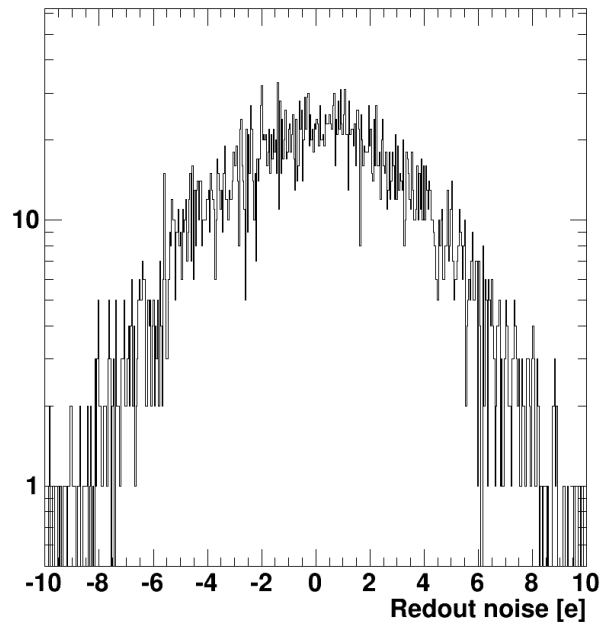
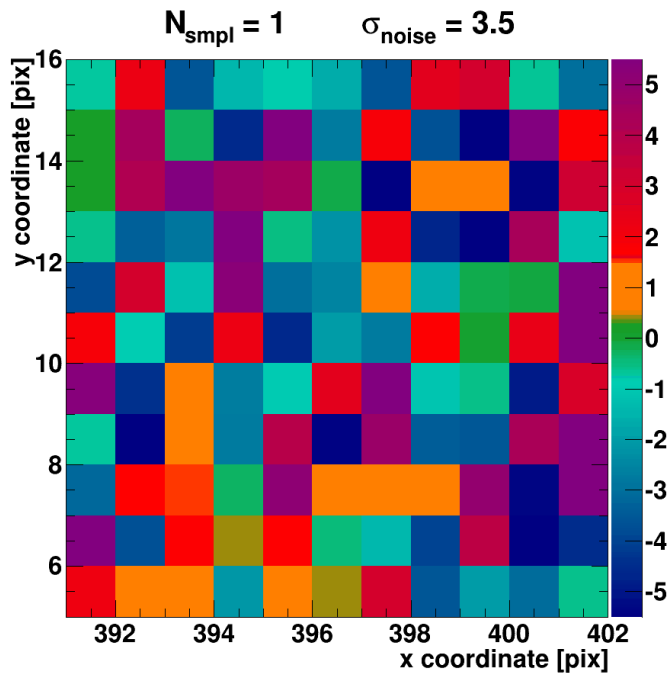
- High-energy radiation interacting with setup results in low-E photons which can produce single-e- depositions that we are not efficiently extracting from our measurements



For Oscura, to determine the ultimate instrumental background, tests in a low-background environment are desired: MOSKITA (2in Pb shield) @ MINOS (100 m underground)

# Skipper-CCDs: readout noise

Taken from real data!



system	description	goal
sensor	readout noise	0.15 e- RMS
sensor	dark current	$10^{-6}$ e/pix/day
readout	speed	166 pix/sec
readout	channel count	24,000
detector array	total mass	10 kg
detector array	number of pixels	28 Gpix
background	rate	0.01 dru
LN2 vessel	operating pressure	450 psi
cooling	capacity	1 kW
DAQ	data handling	1 petabyte/year

## Sensors

- Find new foundries for mass-production of scientific-grade skipper-CCDs
- Reduce instrumental background below  $1 \times 10^{-6}$  e-/pix/day

## Front-end electronics

- Develop a low-cost, scalable, cold readout system and multiplexing

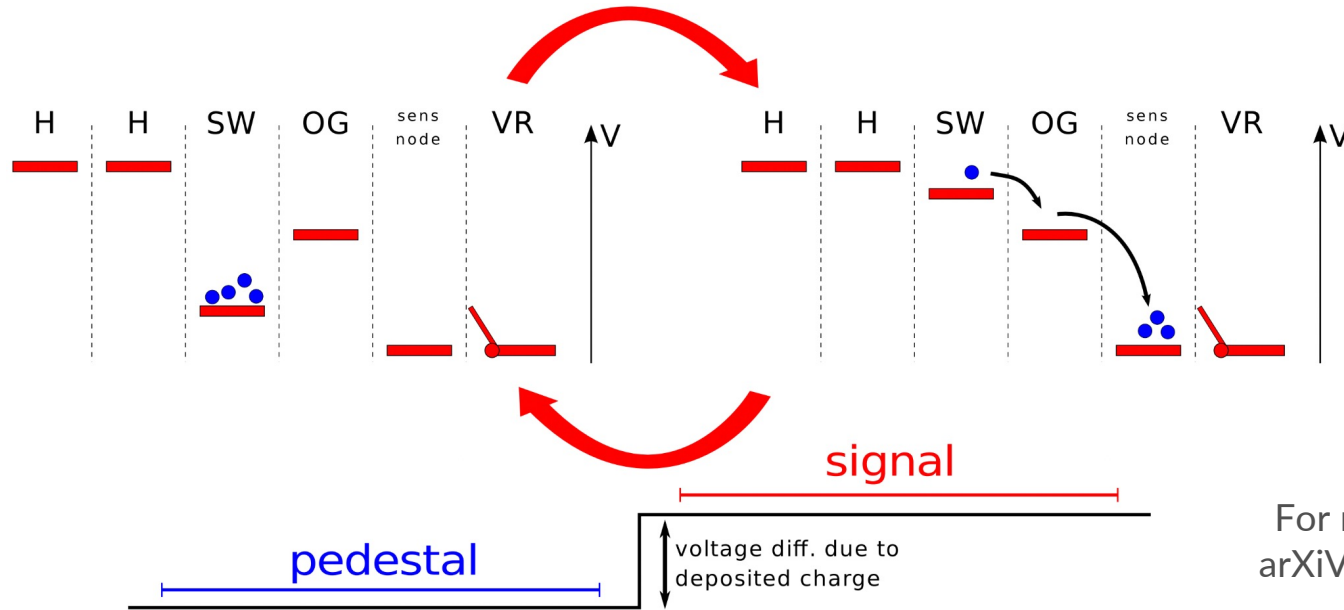
## Radiation background

- Ensure use of low-background materials and cosmogenic activation control
- Oscura experiment design all driven by simulations to reach 0.01 dru



# 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!

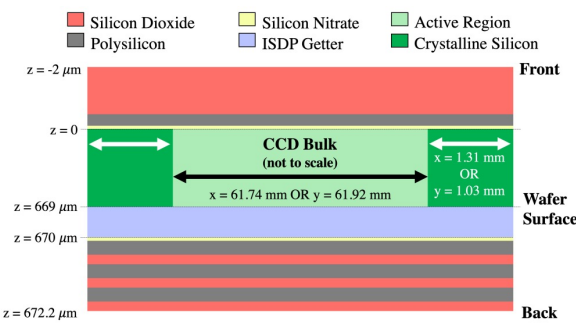
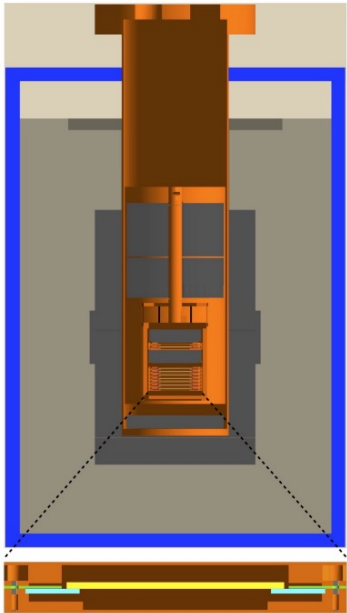


For review see:  
arXiv:1106.1839

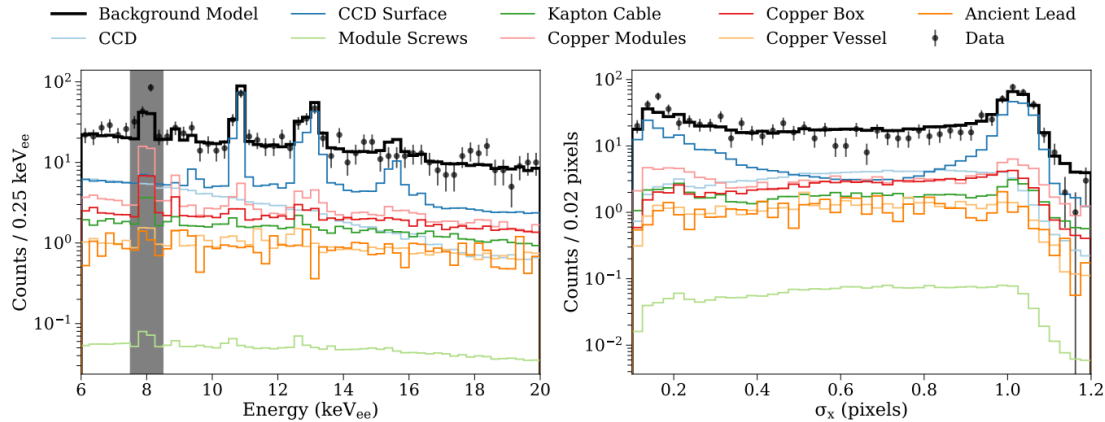
# DAMIC: Background study

[PRD 105, 062003]  
[JINST 16 P06019]  
[PRL 125, 241803]

- Polyethylene
- Aluminum
- Kapton cable
- Outer Lead
- Copper
- Silicon Frame
- Ancient Lead
- CCD sensor



	<sup>238</sup> U	<sup>226</sup> Ra	<sup>210</sup> Pb	<sup>232</sup> Th	<sup>40</sup> K	<sup>32</sup> Si
CCD / Si frame	<11 [37]	<5.3 [37]	<160* [37]	<7.3 [37]	<0.5 [M]	140 ± 30 [37]
Kapton Cable	58000 ± 5000 [M]	4900 ± 5700 [G]	not measured	3200 ± 500 [M]	29000 ± 2000 [M]	N/A
OFHC Copper	<120 [M]	<130 [G]	27000 ± 8000 [41]	<41 [M]	<31 [M]	N/A
Module Screws	16000 ± 44000 [G]	<138 [G]	27000 ± 8000 <sup>†</sup>	2300 ± 1600 [G]	28000 ± 15000 [G]	N/A
Ancient Lead	<23 [42]	<260 [G]	33000 ± 10000 <sup>‡</sup> [42]	2.3 ± 0.1 <sup>‡</sup> [42]	<5.8 [M]	N/A
Outer Lead	<13 [26]	<200 [G]	(19 ± 5) × 10 <sup>6</sup> [26]	<4.6 [26]	<220 [26]	N/A



Detector Part	Chain	$C_l$	Best-Fit Activity	Rate (dru): CCDs 2–7	
				1–6 keV <sub>ee</sub>	6–20 keV <sub>ee</sub>
1 CCD	<sup>238</sup> U	0.897	< 9.86 $\mu$ Bq/kg	0.01	0.01
2 CCD	<sup>226</sup> Ra	0.900	< 4.79 $\mu$ Bq/kg	0.01	0.01
3 CCD	<sup>232</sup> Th	0.900	< 6.56 $\mu$ Bq/kg	0.01	0.03
4 CCD	<sup>40</sup> K	0.910	< 0.42 $\mu$ Bq/kg	< 0.01	< 0.01
5 CCD	<sup>22</sup> Na	1.066	340 ± 60 $\mu$ Bq/kg	0.17	0.16
6 CCD	<sup>32</sup> Si	1.042	150 ± 30 $\mu$ Bq/kg	0.19	0.17
7 CCD	<sup>3</sup> H	1.131	330 ± 90 $\mu$ Bq/kg	2.86	0.78
8 CCD (front surf.)	<sup>210</sup> Pb	1.658	69 ± 12 nBq/cm <sup>2</sup>	1.45	1.67
9 CCD (back surf.)	<sup>210</sup> Pb	< 10 <sup>-4</sup>	< 0.1 nBq/cm <sup>2</sup>	< 0.01	< 0.01
10 CCD (wafer surf.)	<sup>210</sup> Pb	1.343	56 ± 8 nBq/cm <sup>2</sup>	2.43	1.84



# Multi e- low-E backgrounds: SR and PCC events

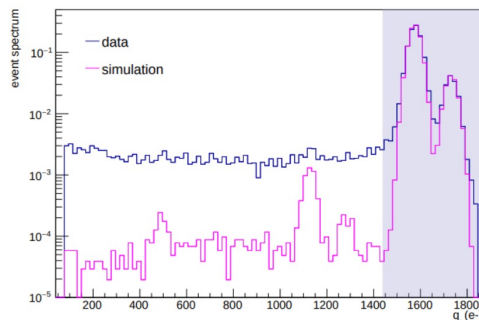
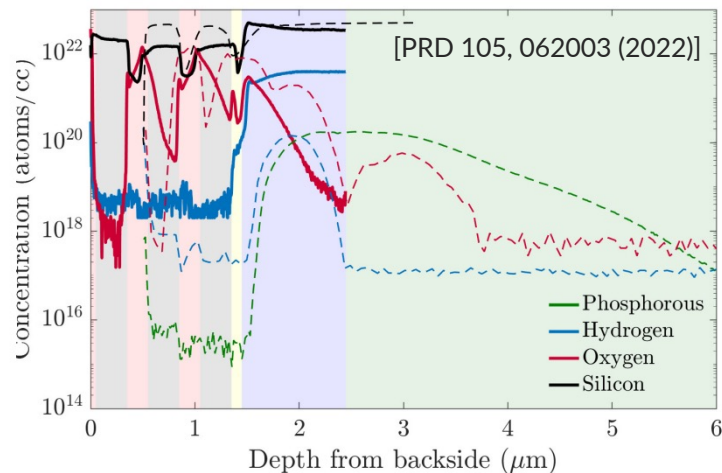
## SR events

- Charge deposition in the inactive volume of the sensor
- Can be identified by their shape and masked

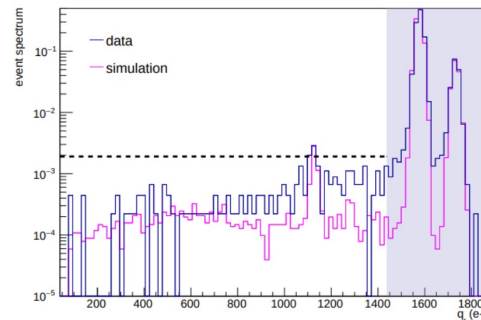


## PCC events

- $\sim 5 \mu\text{m}$  layer in the back of the sensors where charge partially recombines because of a gradient in the P concentration ( $10^{20} \rightarrow 10^{11}$  P atoms/ $\text{cm}^3$ )
- Backside treatment to remove this layer available



CCD without back treatment

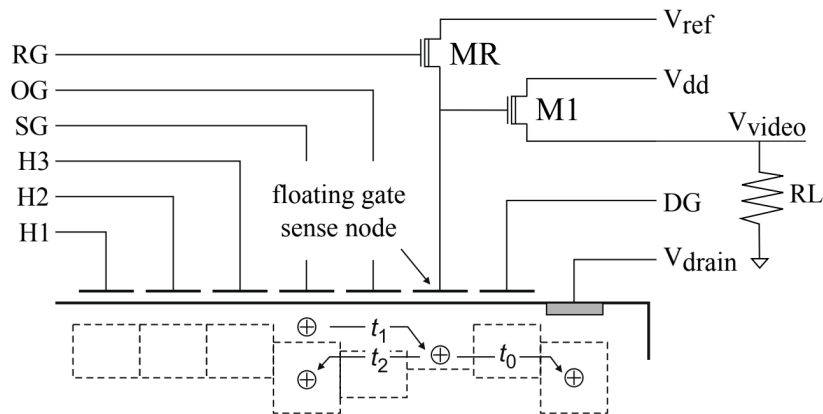


Back-treated CCD

[PRA 15, 064026 (2021)]

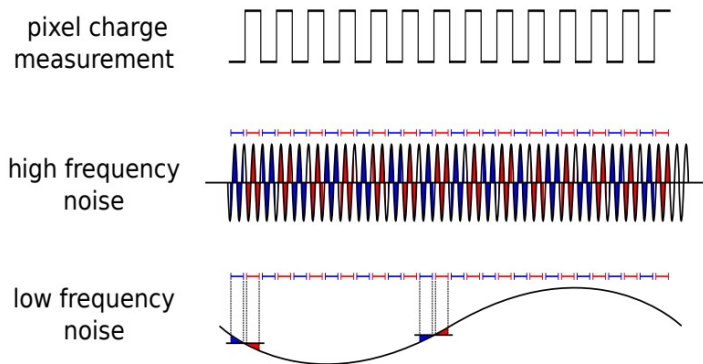
# Skipper-CCDs: readout

- Multiple (N) measurements of same charge packet without being corrupted nor destroyed
- Averaging N off-chip, noise is reduced as  $\sigma = \frac{\sigma_1}{\sqrt{N}}$
- Readout time increases proportional to N (can be optimized depending on your interests)



First performance demonstration with a detector designed by Stephen Holland (LBNL) allowing to count electrons in a wide dynamic range! [PRL 119, 131802 (2017)]

Correlated Double Sampling to measure charge:



1. Pedestal integration
2. Signal integration
3. Charge = Signal - Pedestal
4. Repeat N times
5. Pixel value = average of all samples

Low-frequency noise can be reduced!