The Oscura experiment

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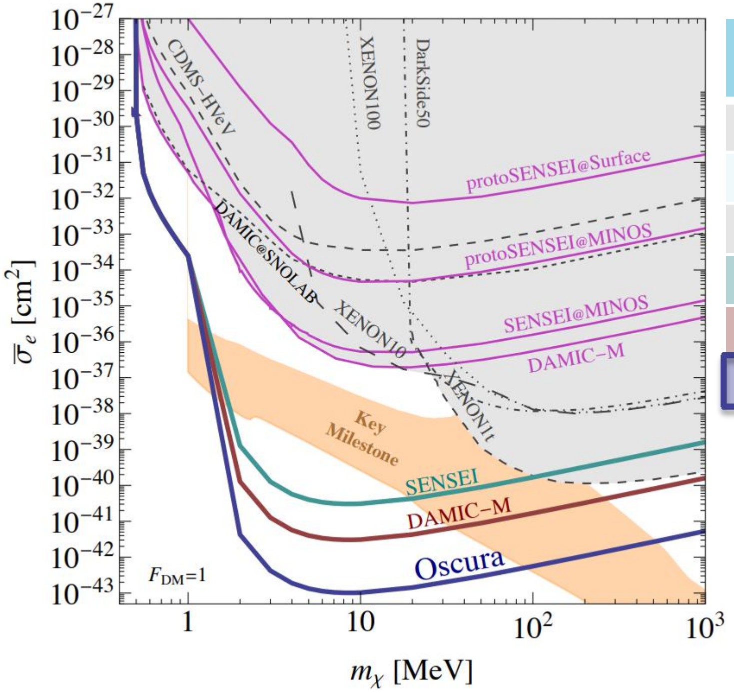
UCLA Dark Matter 2023

March 29 - April 1

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 x 10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10 (exp*)	~3 x 10^{-4} (exp*)	late-2021
DAMIC-M LBC	~0.02	2	10	3 x 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 x 10^{-6} (goal)	~2028

* expected from DAMIC with standard CCDs [PRL 123, 181802/PRL 125, 241803]

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

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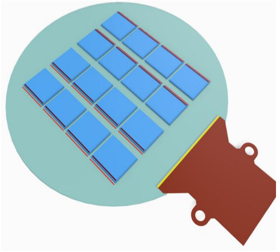
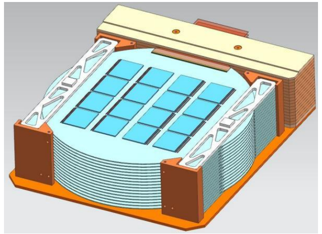
Oscura: 10-kg skipper-CCD experiment

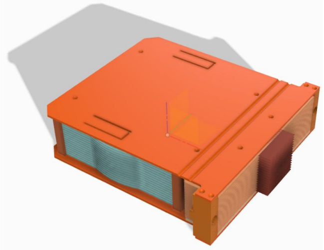
[arXiv:2202.10518]

Multi-Chip Module
(16 skipper-CCDs)

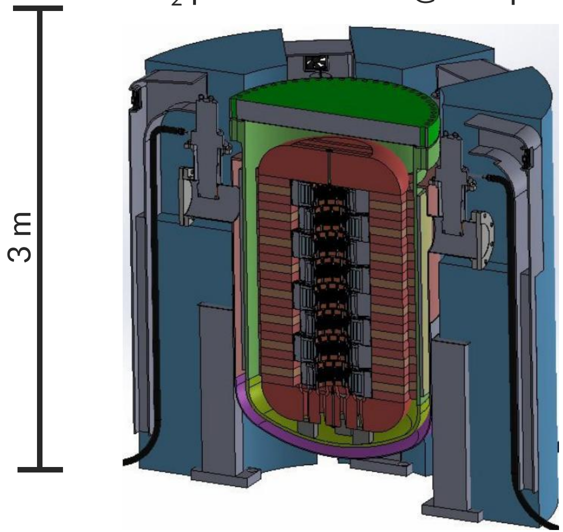




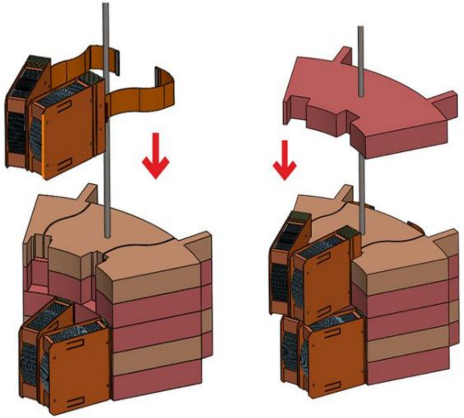
Super Module
(16 MCMs)

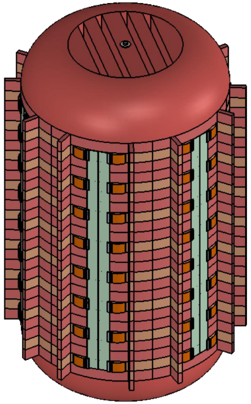


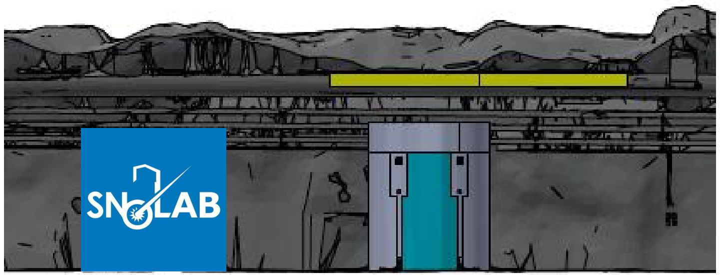
LN$_2$ pressure vessel @ 450 psi



Detector payload in 6 columnar slices (96 SMs)







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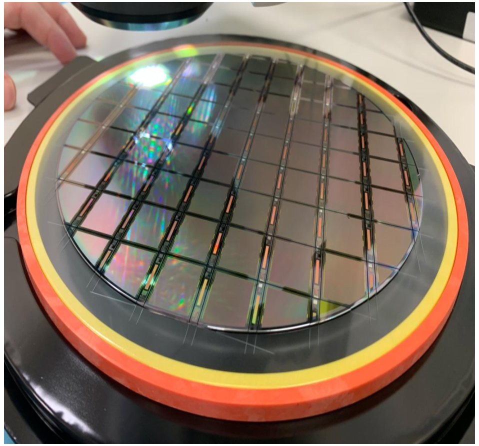
Oscura: Sensors fabrication

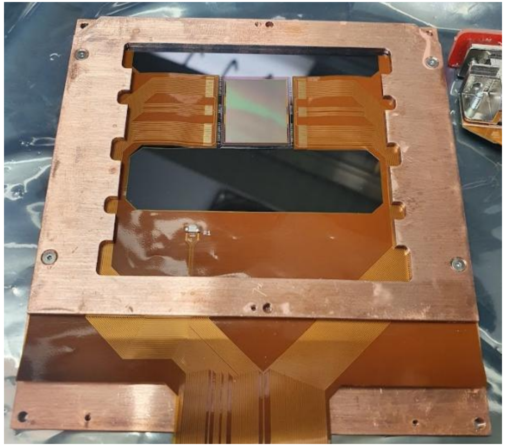
TELEDYNE DALSA
Everywhereyoulook™

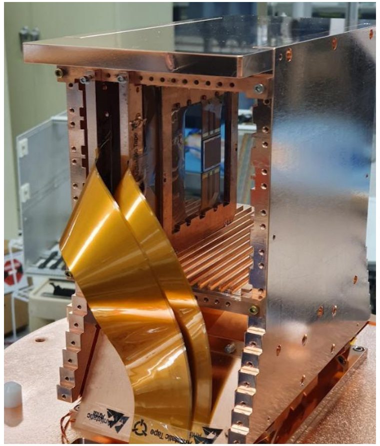
Highest risk

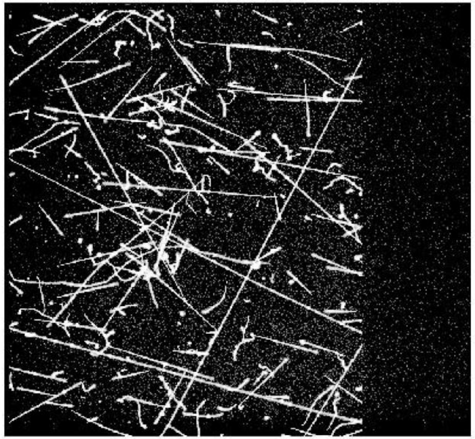
NOTIFICATION of DISCONTINUANCE of 150mm CCD process wafer fabrication. → New foundries needed!

- 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]**









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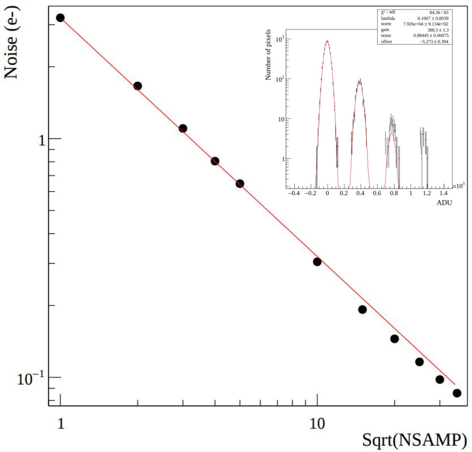
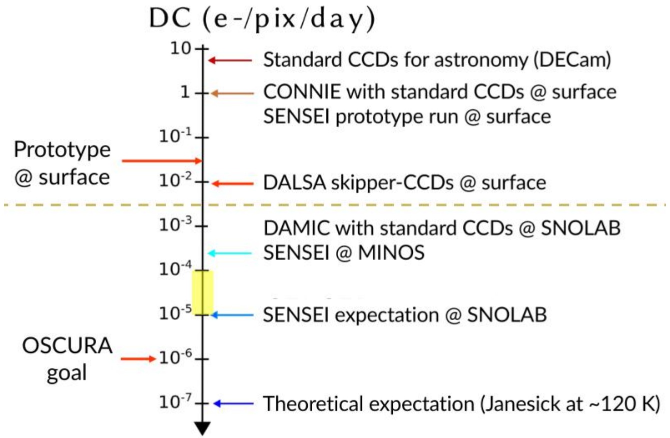
Oscura: Sensors performance

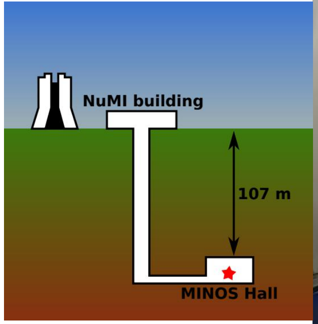
Paper coming soon!

Parameter	No events with >1e-	No events with 3e- or more	Prototype	Units
Dark current	1×10^{-6}	1.6×10^{-4} ✓	3×10^{-2}	e^-/pix/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	$< 10^{-10}$	$< 10^{-8}$	7.2×10^{-7}	e^-/pix/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







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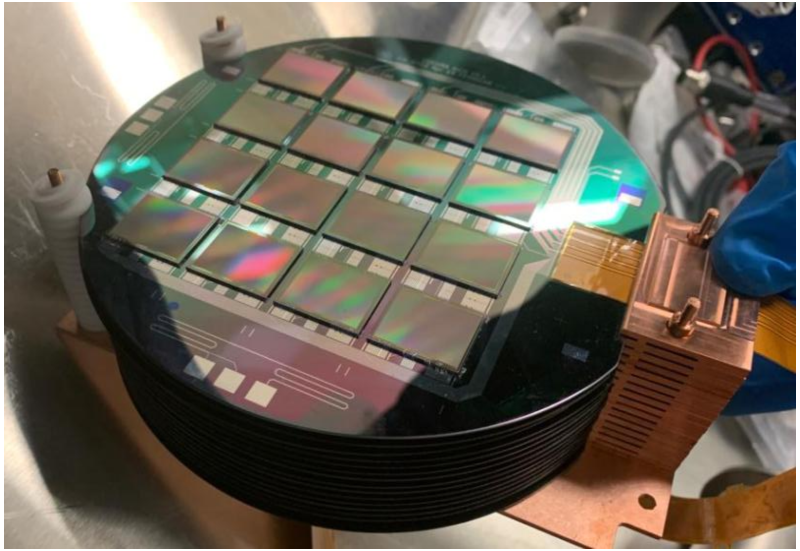
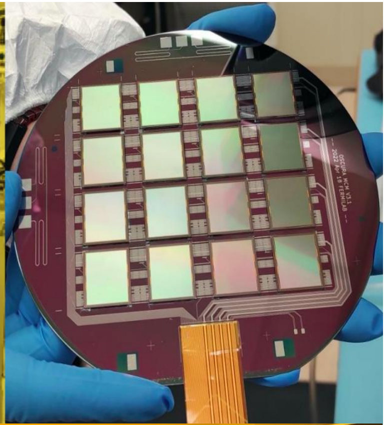
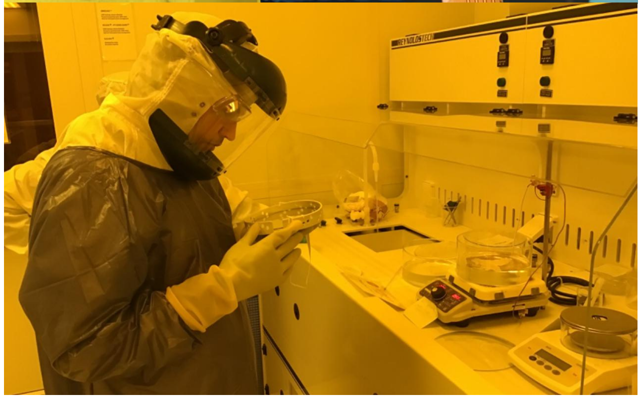
Oscura: Scaling up mass (MCMs/SMs fabrication)

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



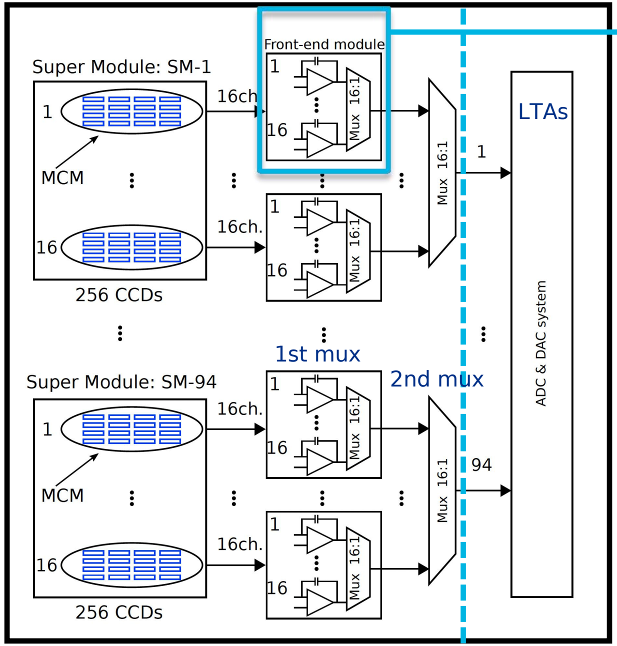




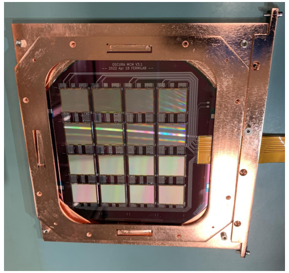
Oscura: Readout electronics

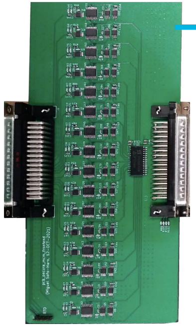
Oscura requires ~24,000 readout channels complying with noise and readout time constraints

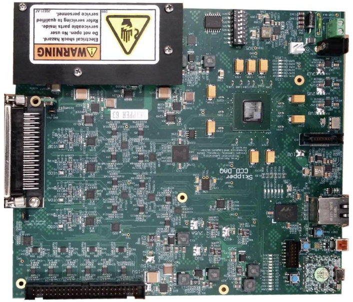
- Cold front-end electronics to reduce feedthrough complexity (only 94 cables outside vessel)
- 2 multiplexing stages → 256 channels result in 1 signal
- 1 LTA controls 4 SM (1024 sensors) → 24 LTAs needed in total

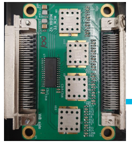


- Discrete (mux board) [Sensors 22 (2022) 11, 4308] [JINST 16 P11012]
- Integrated (MIDNA ASIC) [doi:10.2172/1841383]
  4 channels in a 2mm x 1mm chip **reducing cost, space and radioactive contamination**
  Tested and working!





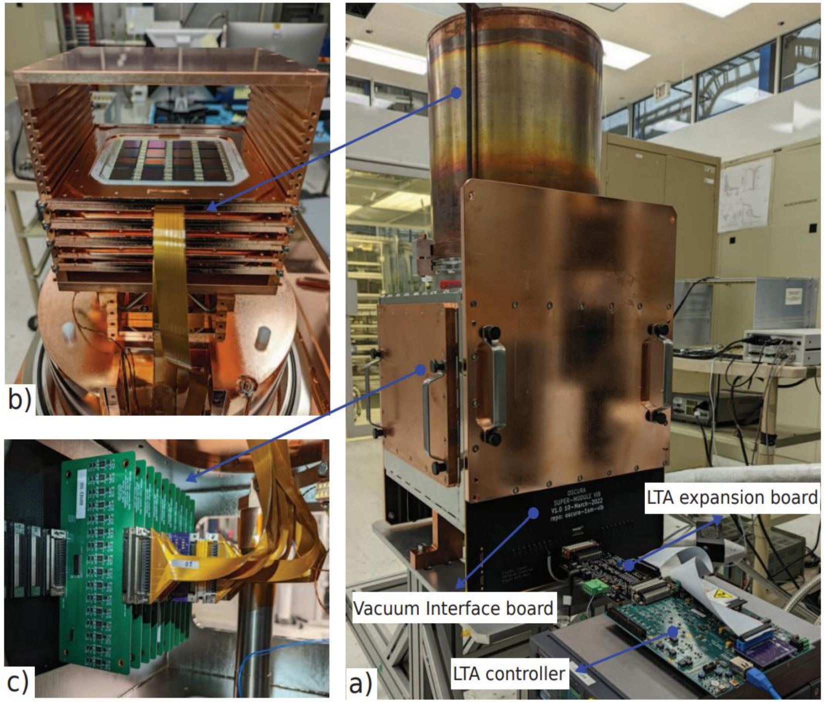


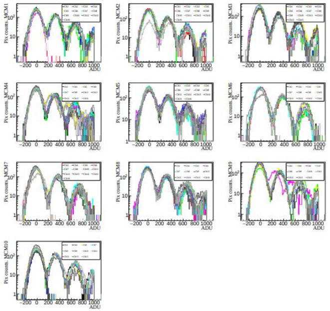


Oscura: Massive testing setup with 10 MCMs (160 sensors)

[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

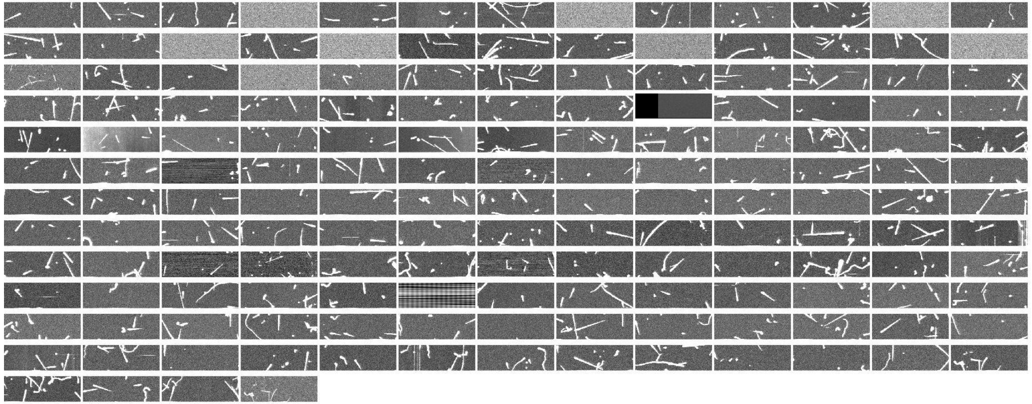




~90% of the sensors working without a preselection! This is a BIG deal!*

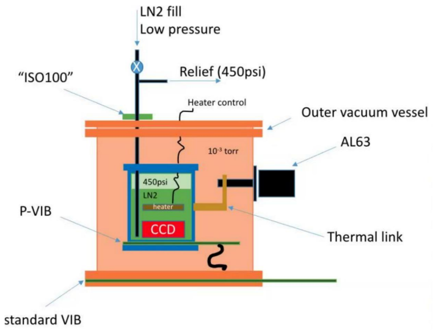
*LSST, the largest "astronomical camera" has 189 CCDs!

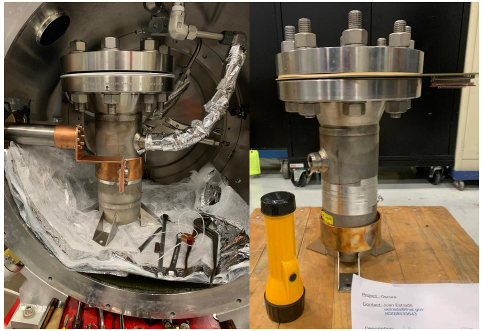
Setup is being used to develop analysis software and could be used for early science



Oscura: Operation in LN2

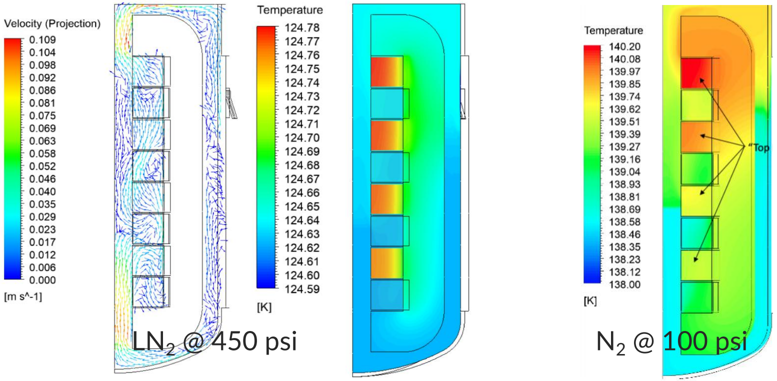
- Demonstrated stable operation of skipper-CCD in LN_2



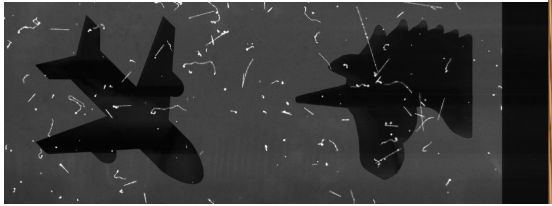


- Test of 1st SM in LN_2 coming soon!

- Simulations validate the convection flow



- Exploring new ideas to make skipper-CCDs blind to LN_2 scintillation



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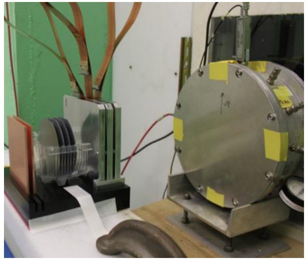
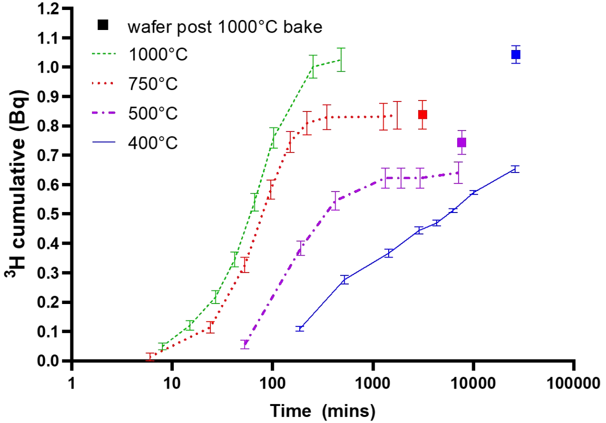
Oscura: Background control

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



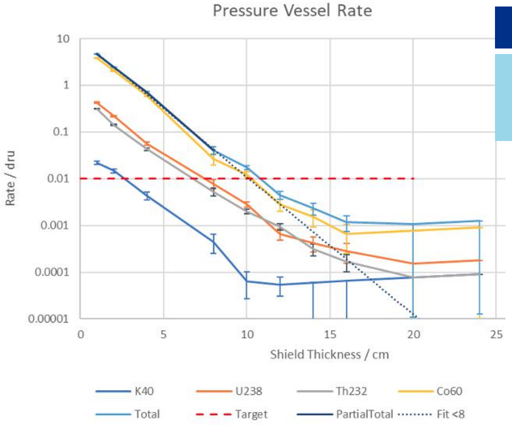
[PRD 102, 102006]



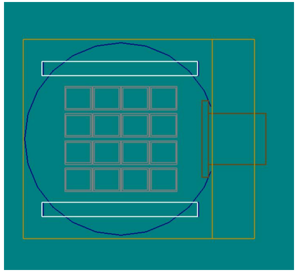
Sources:

- Cosmogenic activation of Si and Cu
  - ^{3}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)

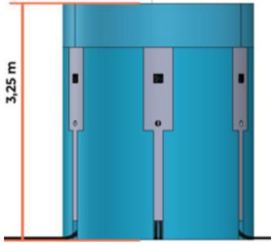
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [arXiv:2303.10862]
  - Simulations of ^{238}U, ^{232}Th and ^{40}K
  - → 4cm of cable visible to CCDs (with 15 ppt)
  - → Electronics behind inner shield (width>10cm)



DAMIC-M cable	^{238}U [ppt]	^{232}Th [ppt]
Commercial	2670 +/- 30	270 +/- 60
Customed	**31 +/- 1**	**11 +/- 1**



- External backgrounds
  - Outer shield: polyethylene
  - Inner shield: ancient lead and electroformed copper



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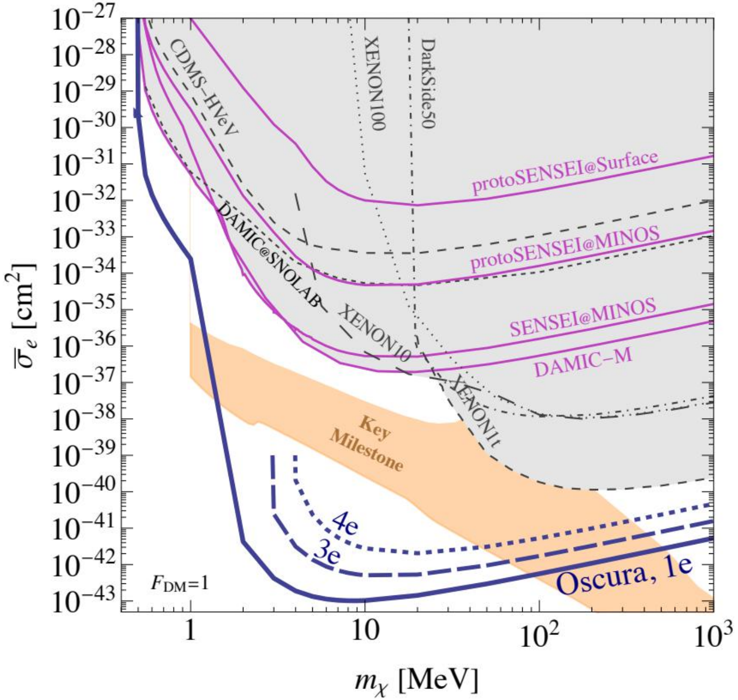
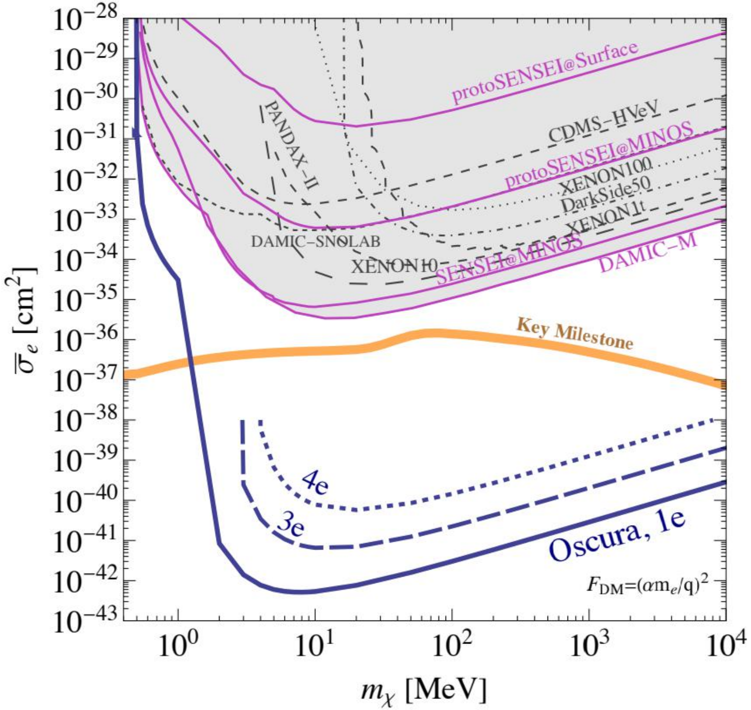
Oscura: Projected sensitivities for 30 kg-year

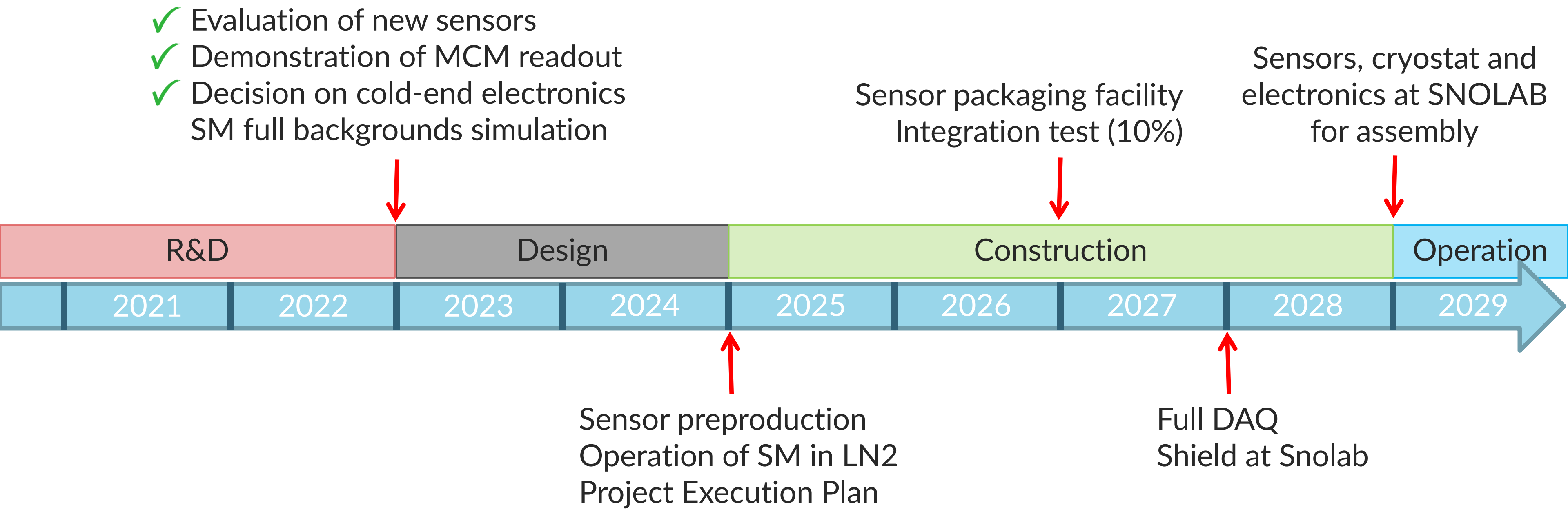
With the current sensors performance, we have zero background events with 4e⁻ or more (4e curve)





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

Oscura: Timeline and goals per period



✓ - Achieved

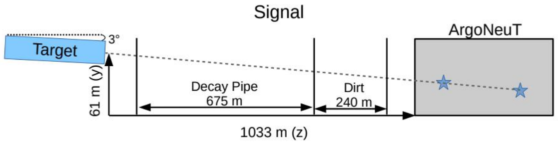
* Technically driven Oscura timeline

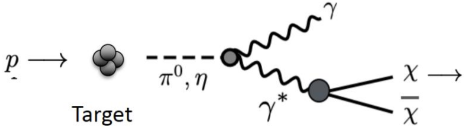
Oscura: Early science

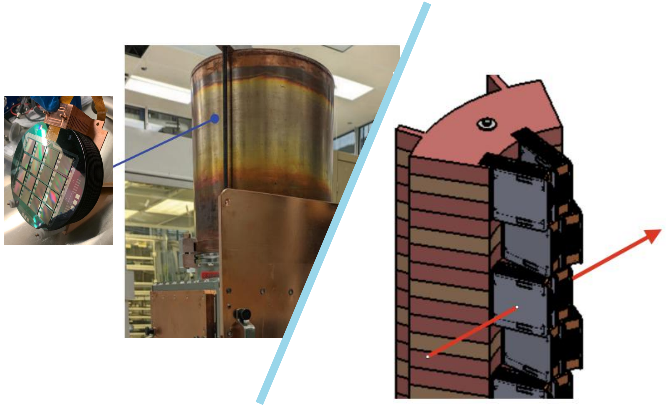
Paper coming soon!

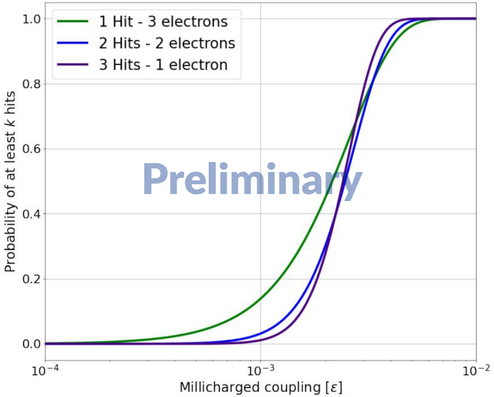
With a partial load of sensors (Massive setup/OIT) we can do early science!
Search for millicharged particles coming from the NuMI beam at Fermilab

[PRL 124, 131801 (2020)]







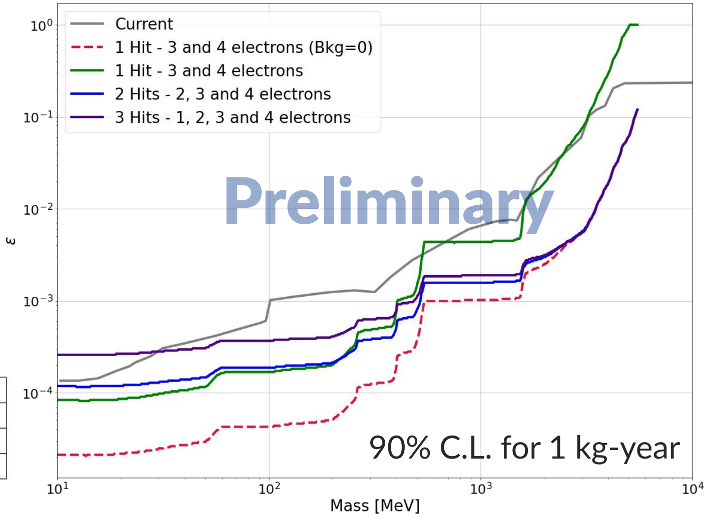


Number of fake tracks per day produced by random coincidences of uncorrelated single pixel hits

Threshold	doublets $(b=2)$	triplets$(b=3)$	p_{bkg}
$1e^-$	419	0.4	10^{-4}
$2e^-$	0.03	2.6×10^{-7}	$8.2\times10{-7}$
$3e^-$	3×10^{-4}	3×10^{-10}	8.7×10^{-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 the next step in skipper-CCD DM searches (10 kg)
- It 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 moving into design phase, with plan to begin construction in FY25 and operations at SNOLAB in FY29
- With a partial load, Oscura can do early science producing very competitive results

Stay tuned!

THANK YOU!

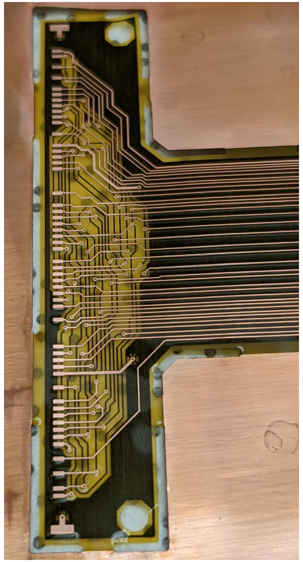
Ultra Low Background Cables
Phase II SBIR w/ Q-Flex Inc.

Q-FLEX INC.

SBIR·STTR America's Seed Fund

- Phase I: achieved 15–30× reduction in ^{238}U and ^{232}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—100× 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}U [ppt]	^{232}Th [ppt]
Commercial	2670 +/- 30	270 +/- 60
Our customed	**31 +/- 1**	**11 +/- 1**



1. Laminate Selection
2. Cut and Drill Laminate
3. Cleaning at QFlex
4. Shadow Seeding
5. Electroplating
6. Sanding
7. Cleaning at PNNL
8. Resist Coating
9. Developing
10. Etching
11. Stripping
12. Drying
13. Cleaning at PNNL
14. Coverlay Application
15. Microetching
16. ENIG Processing
17. Cleaning at PNNL

Blue: Standard Step
Orange Outline: Modified Step
Orange: New Step
Green: Step done at PNNL

*Slide from Richard Saldanha

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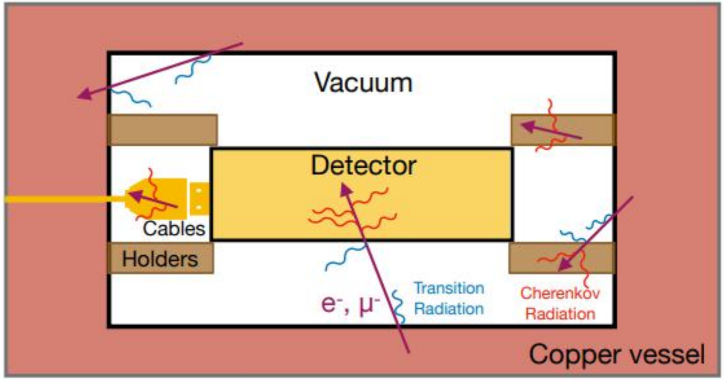
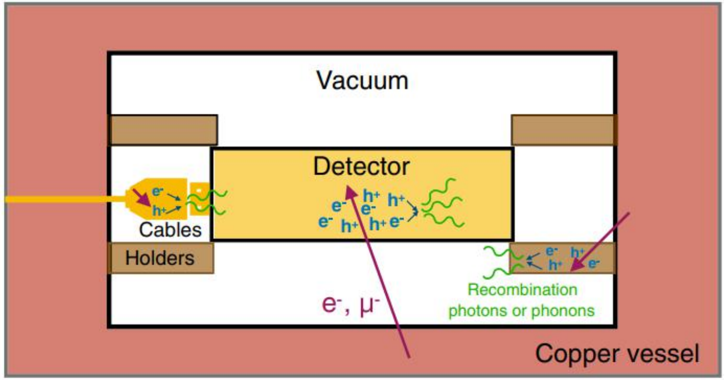
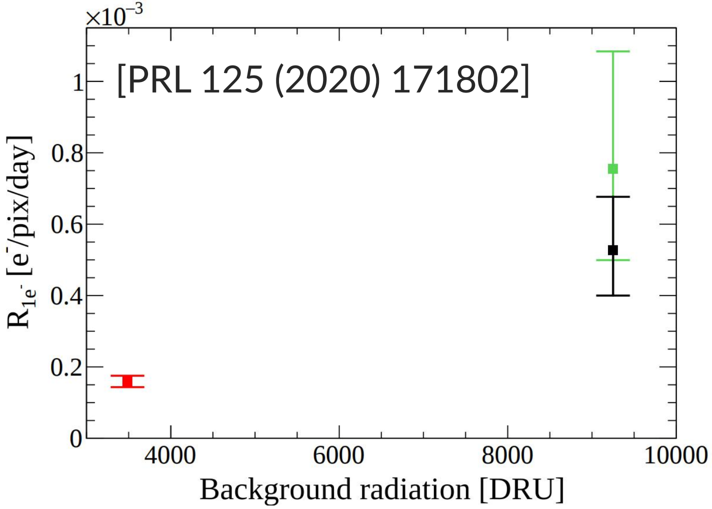
Low-E background correlation with high-E events





[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)

Oscura: Technical requirements

[arXiv:2202.10518]

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 1×10^{-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

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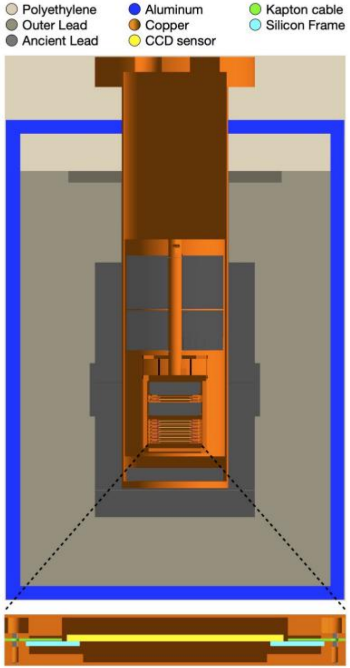
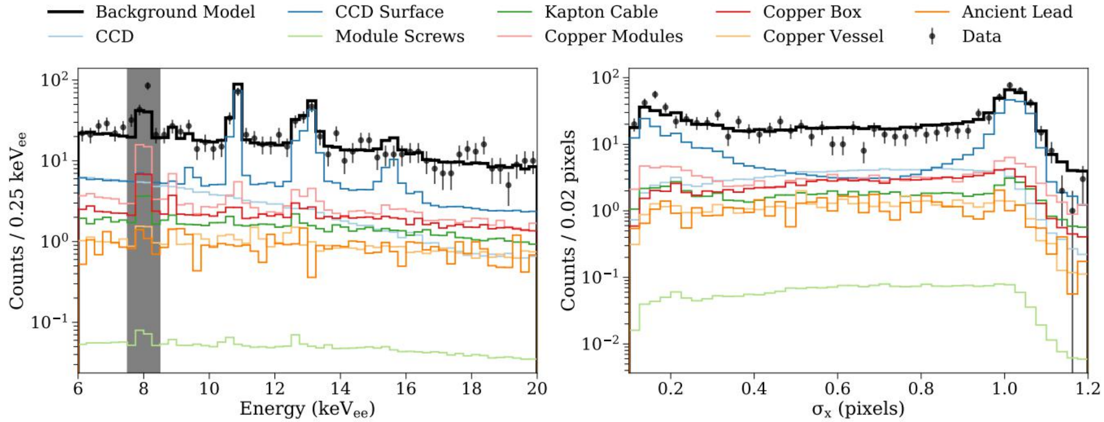
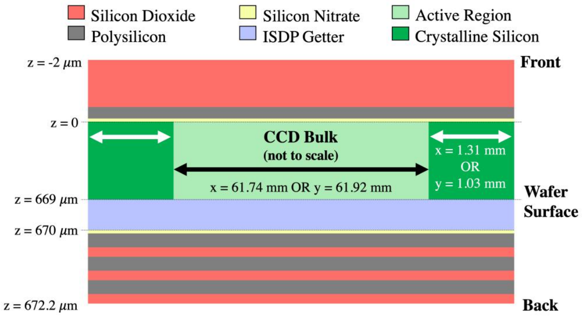
DAMIC: Background study

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

	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K	^{32}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†	2300 ± 1600 [G]	28000 ± 15000 [G]	N/A
Ancient Lead	<23 [42]	<260 [G]	33000 ± 10000‡ [42]	2.3 ± 0.1‡ [42]	<5.8 [M]	N/A
Outer Lead	<13 [26]	<200 [G]	$(19 \pm 5) \times 10^6$ [26]	<4.6 [26]	<220 [26]	N/A







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

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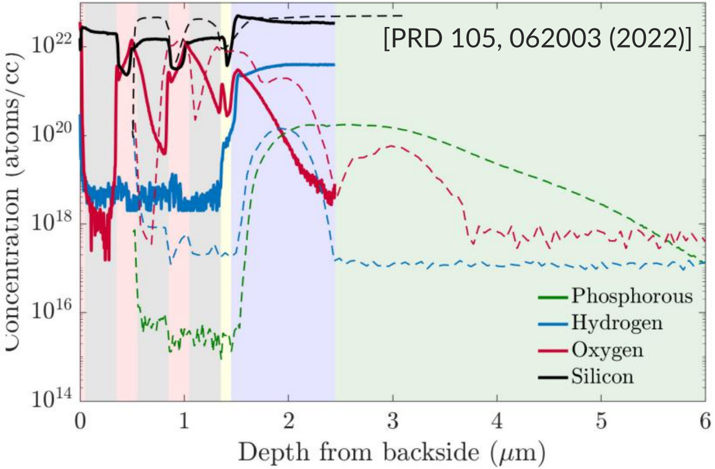
Multi e- low-E backgrounds: SR and PCC events

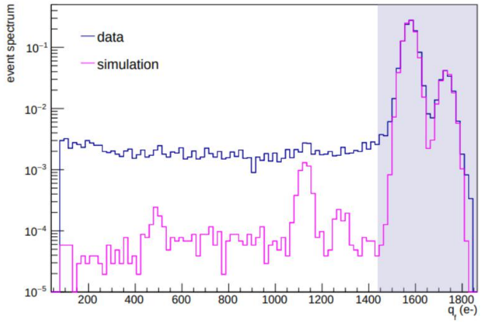
SR events

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

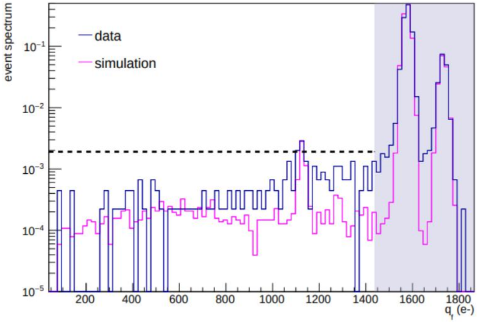
PCC events

- ~5 µm 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/cm^3)
- Backside treatment to remove this layer available





CCD without back treatment

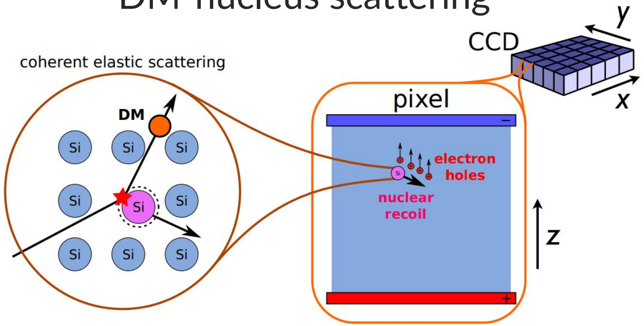


Back-treated CCD

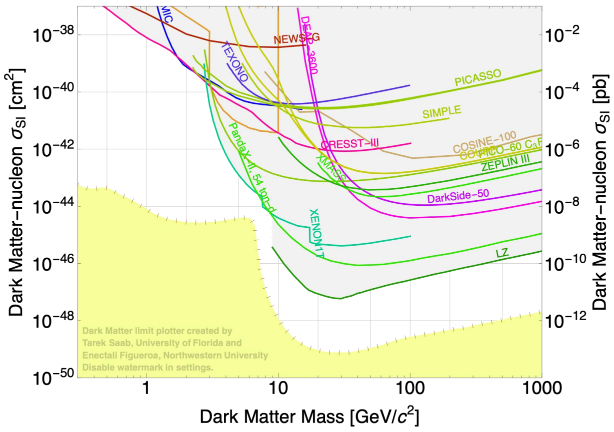
[PRA 15, 064026 (2021)]

DM direct detection with CCDs

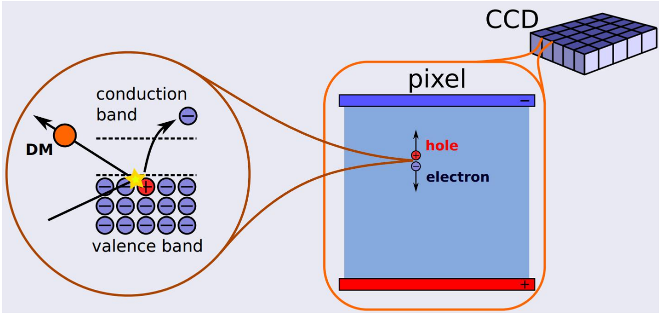
DM-nucleus scattering

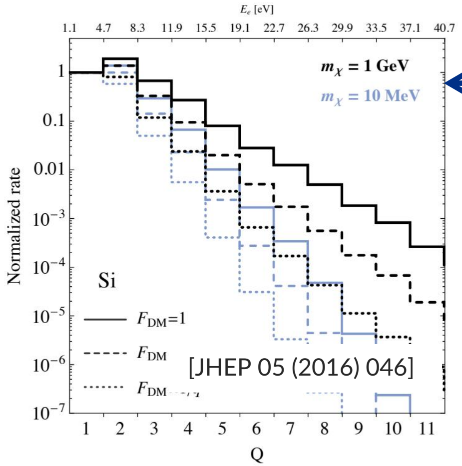


m_χ ~ GeV → energy transfer is a few keV



Sub-GeV DM needs other detection channels





[JHEP 05 (2016) 046]

DM-electron scattering
m_χ ~ MeV-GeV
→ energy transfer is a few eV

DM absorption
Bosonic DM at the eV scale
→ energy transfer equals m_χ

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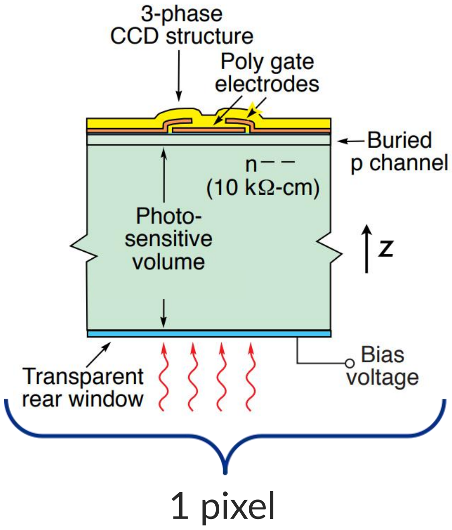
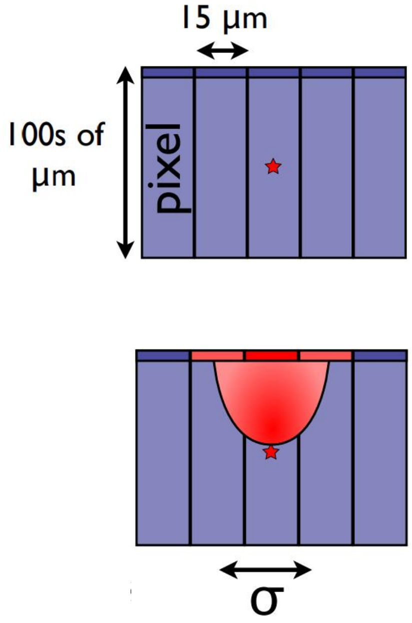
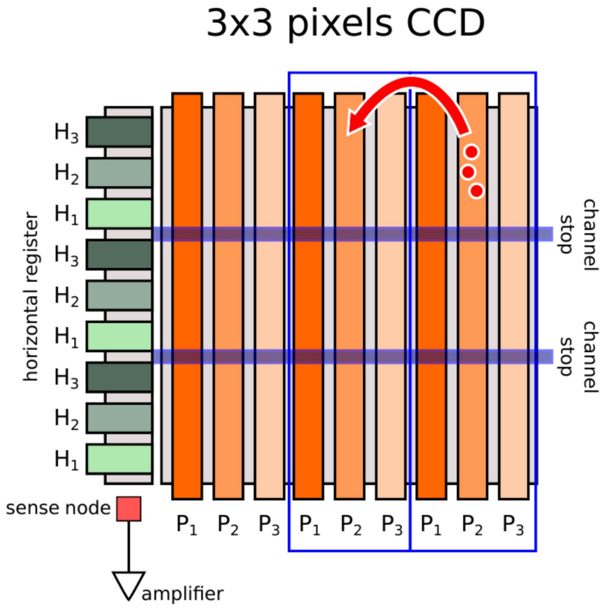
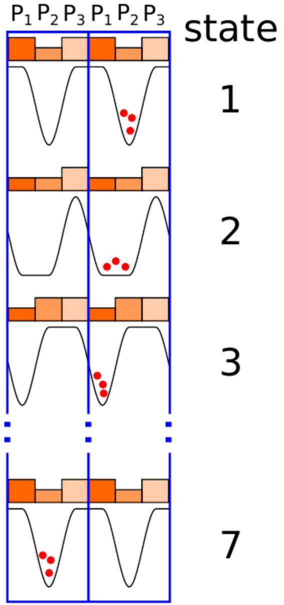
Scientific Charge-Coupled Devices: structure and operation

- 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 ~3.8 eV)
- Charge is collected near the surface, transferred varying the potential wells until reaching the readout stage



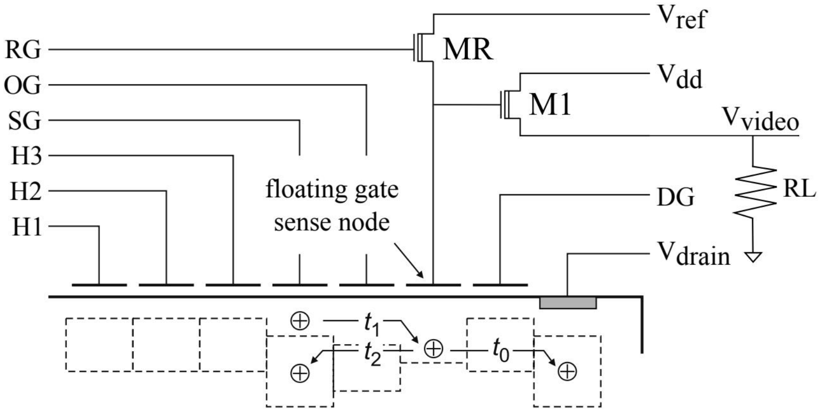






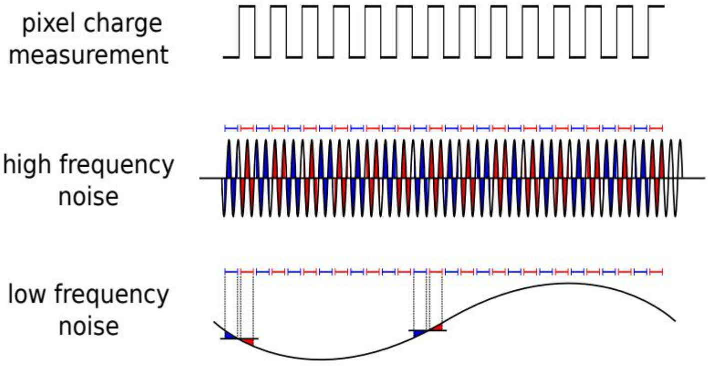
Skipper-CCDs: readout

- 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!

Skipper-CCDs: readout noise

Taken from real data!