Charge-Coupled Devices

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UNAM / Fermilab

Physics Opportunities at Beam Dump Facility in PIP-II and Beyond

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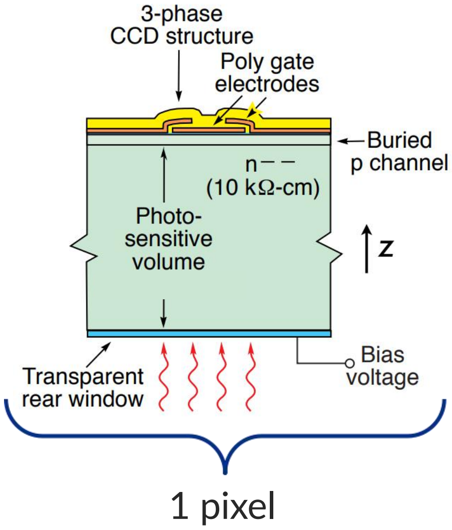
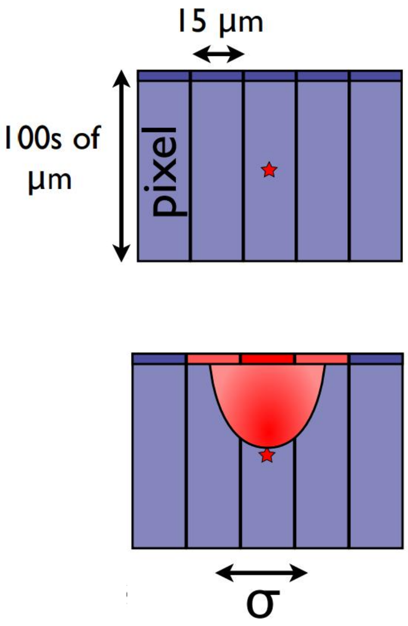
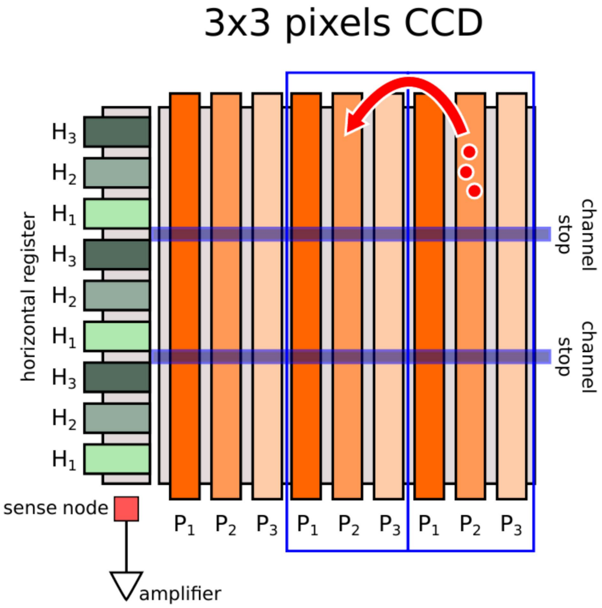
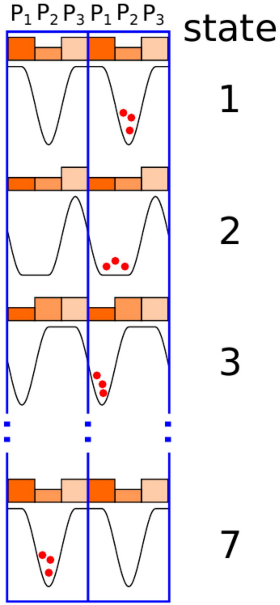
Charge-Coupled Devices: structure and operation

- CCDs are essentially an array of Metal-Oxide-Semiconductor capacitors (pixelated sensors)
- 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









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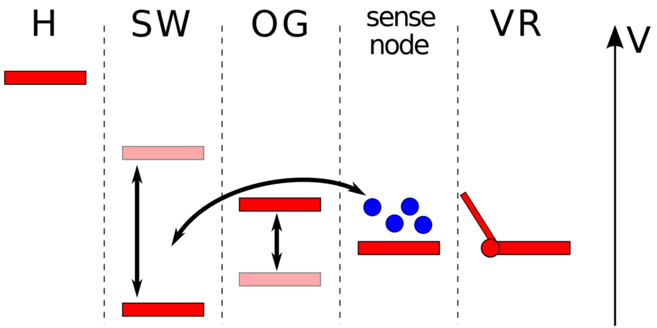
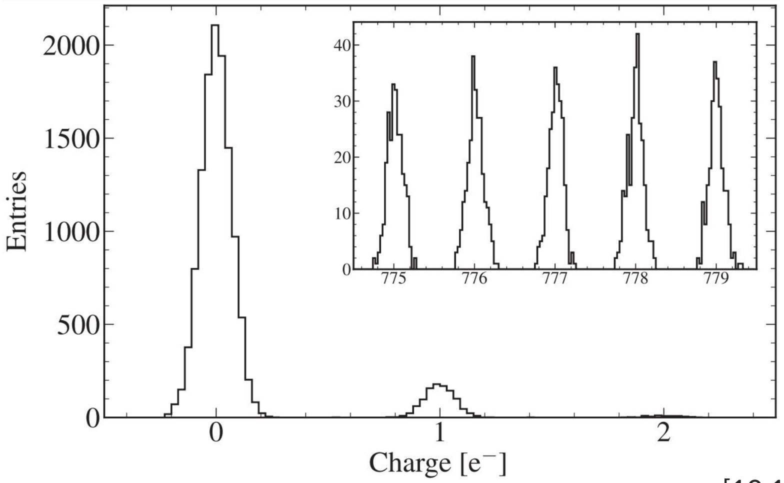
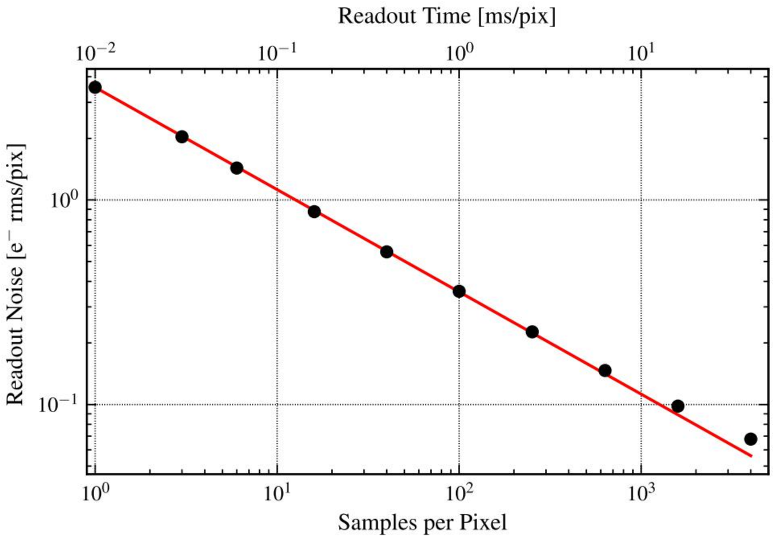
Skipper-CCDs: electron-counting sensors



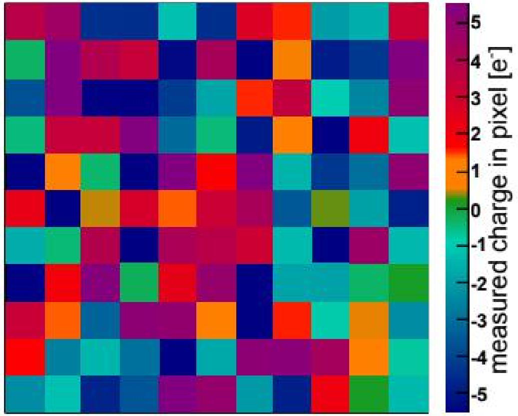
- Multiple (N) measurements of same charge packet without being corrupted nor destroyed
- Averaging N off-chip, noise is reduced as $\sigma = \frac{\sigma_1}{\sqrt{N}}$
- **Count electrons in a wide dynamic range!**
- Readout time increases proportional to N (can be optimized*)



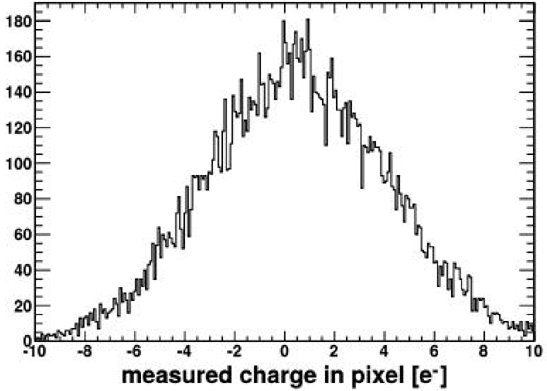


[10.1103/PhysRevLett.119.131802]

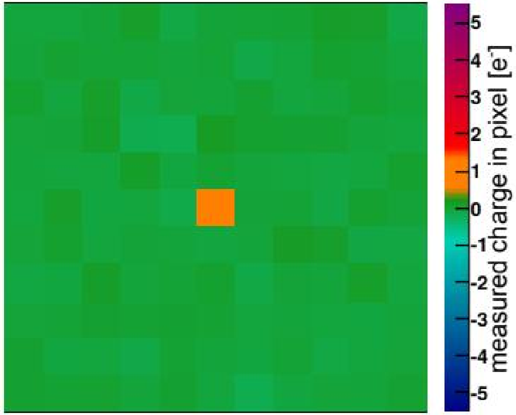
Standard CCD mode: charge in each pixel is measured once



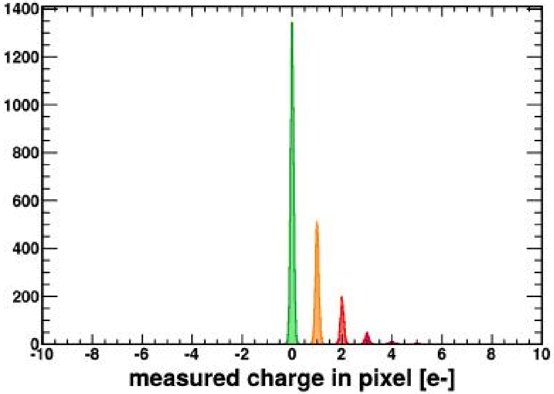
Readout-noise: 3.5 e RMS



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

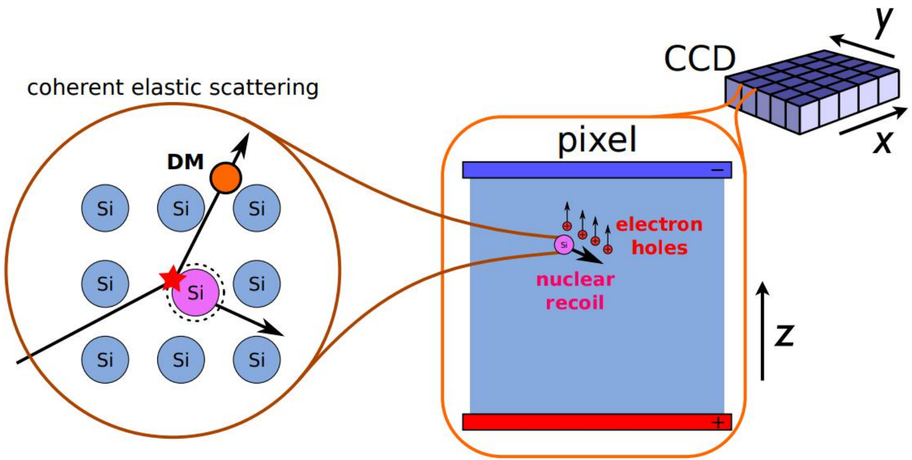


Readout-noise: 0.06 e RMS



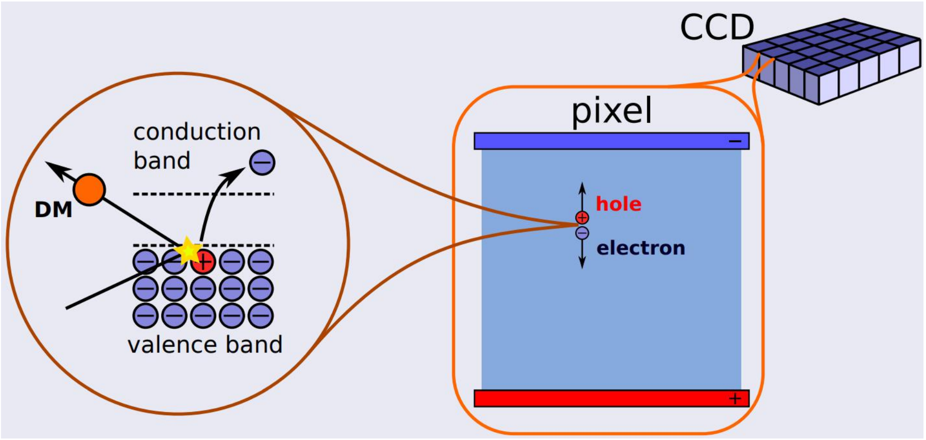
Skipper CCDs: low-energy interactions

X-nucleus scattering



DM
ν

X-electron scattering



DM
ν
mCPs

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Image from skipper-CCD at surface with N=300 samples/pix

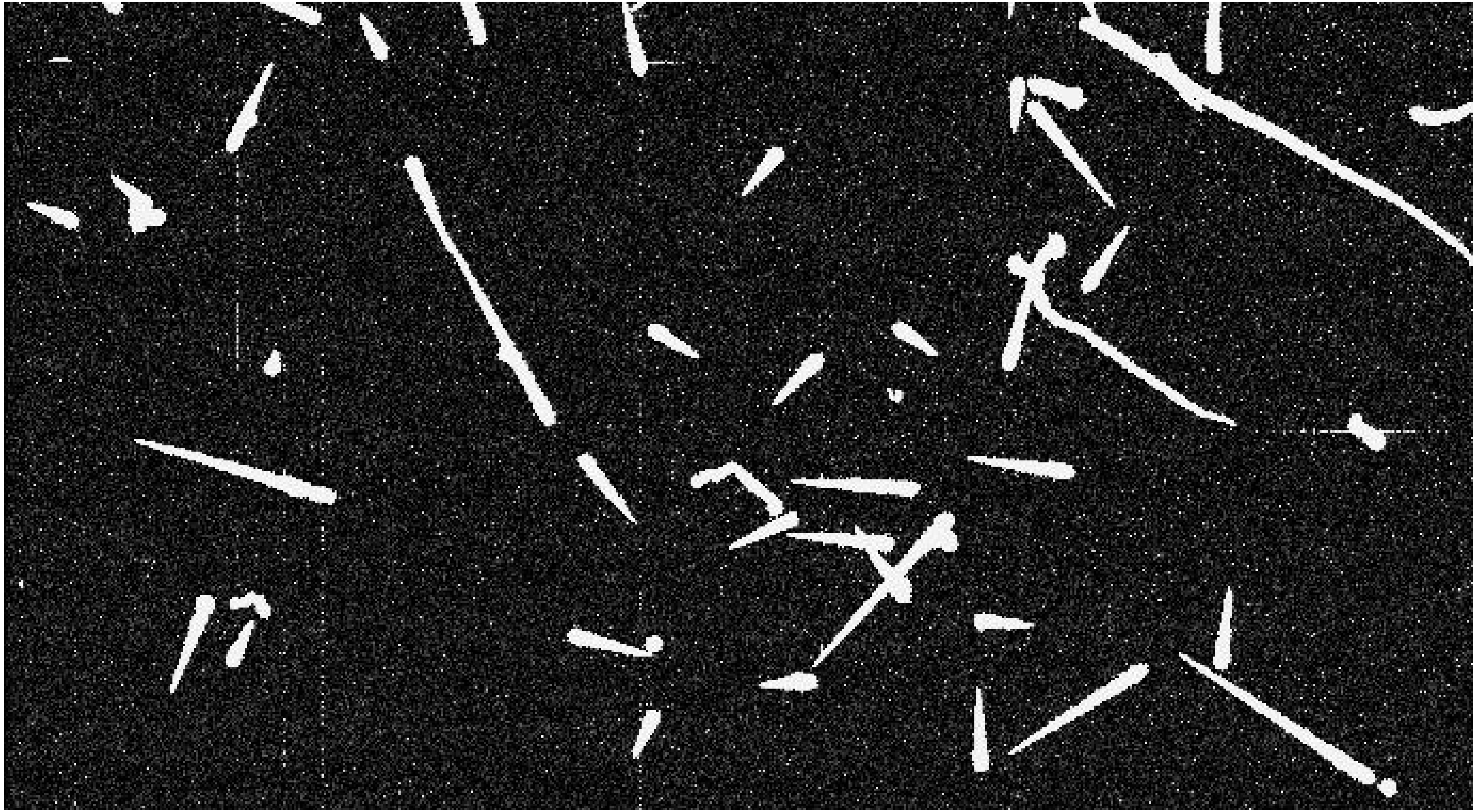
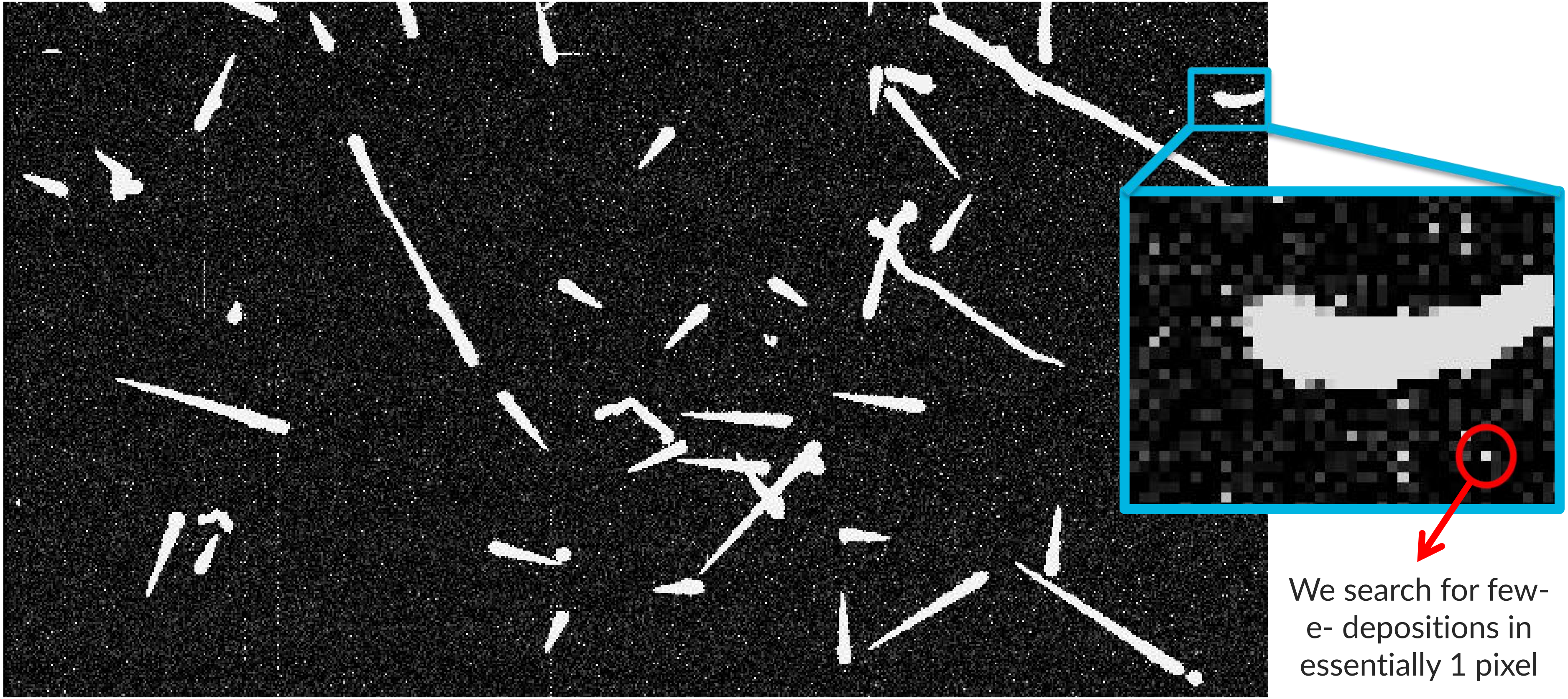


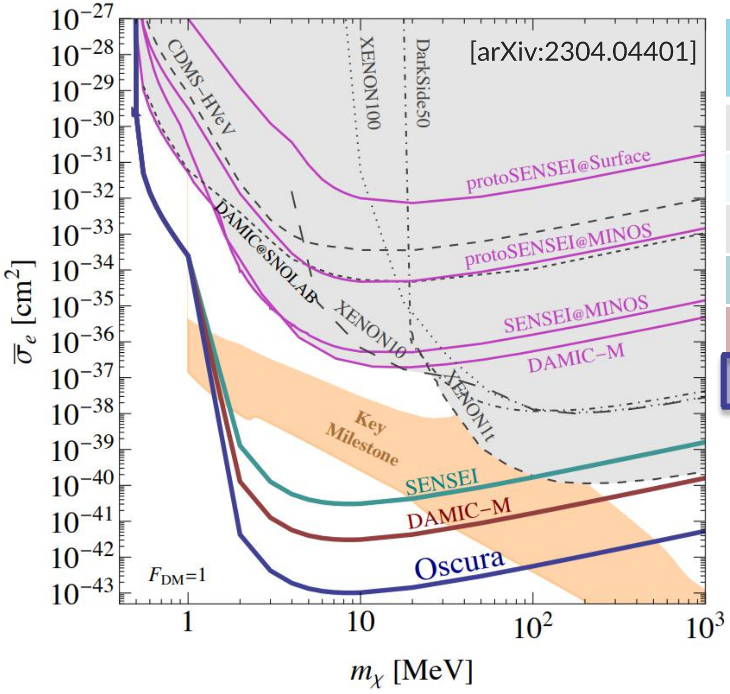
Image from skipper-CCD at surface with N=300 samples/pix



We search for few-e- depositions in essentially 1 pixel

Skipper-CCDs lead the search for sub-GeV DM

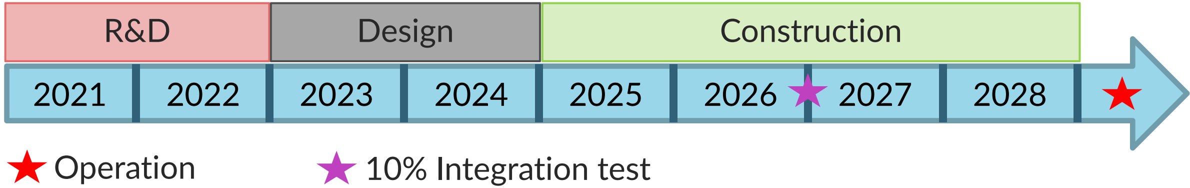
- **World best limits on DM-e- interactions** with this technology because of its **low backgrounds!**



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]

Major R&D to increase mass and reduce backgrounds



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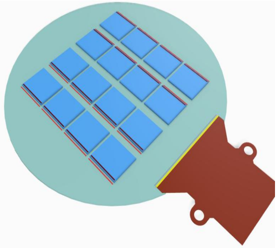
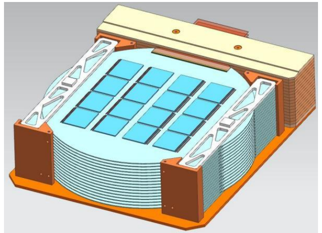
Oscura: 10-kg skipper-CCD experiment

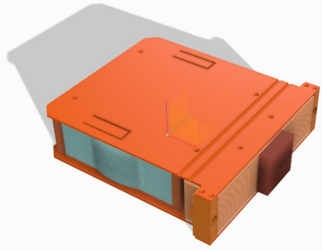
[arXiv:2202.10518]

Multi-Chip Module
(16 skipper-CCDs)

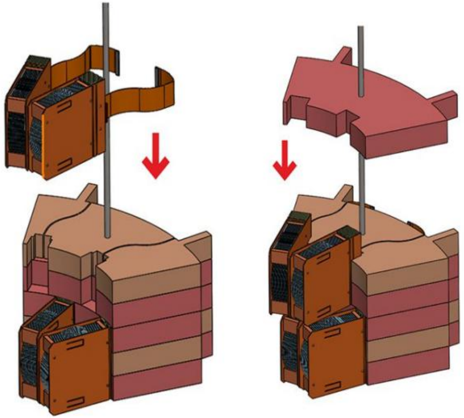


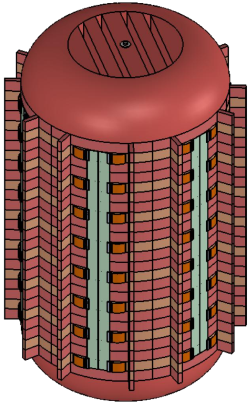


Super Module
(16 MCMs)

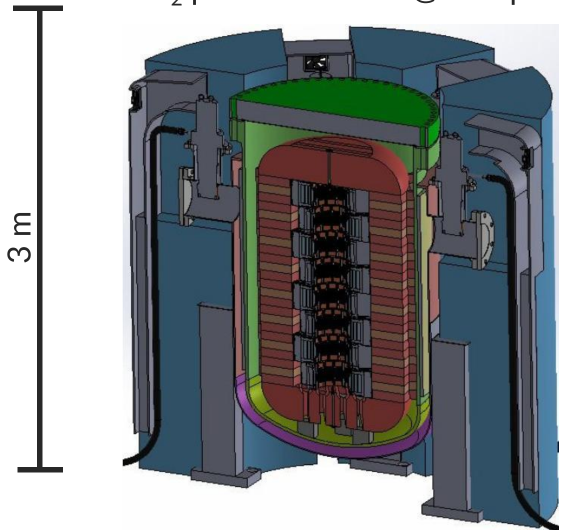


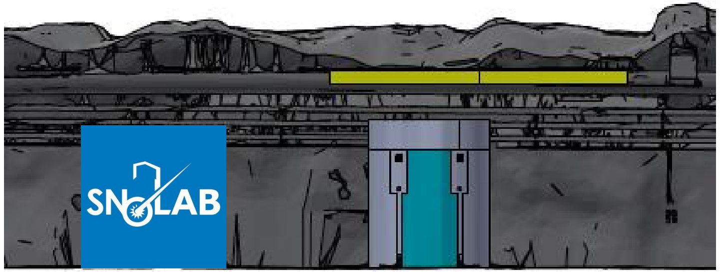
Detector payload in 6 columnar slices (96 SMs)





LN_2 pressure vessel @ 450 psi



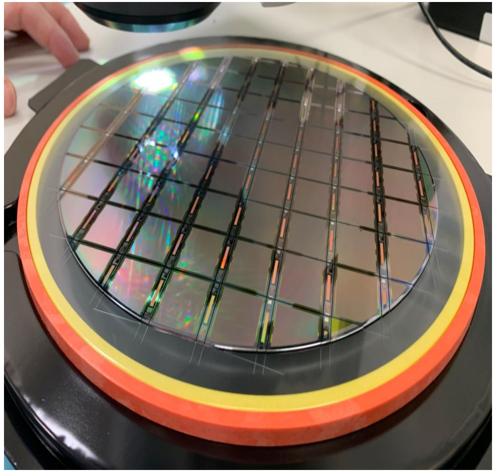


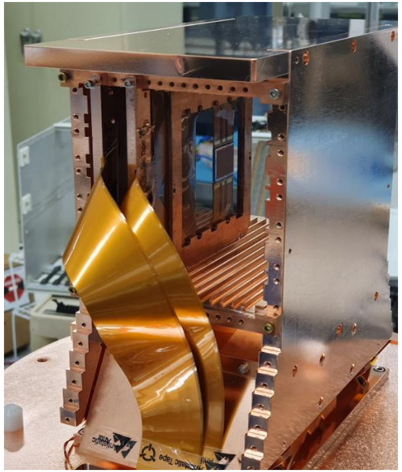
Oscura: R&D results

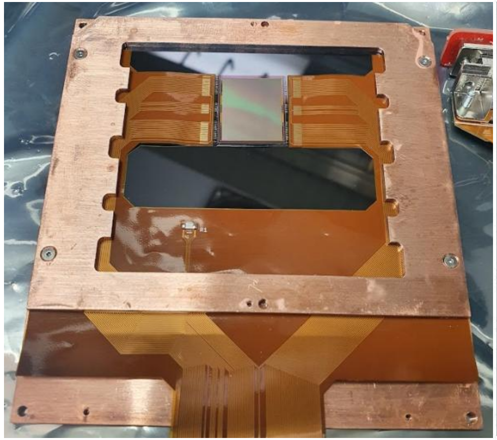
- Partnered with new skipper-CCD foundries to ensure sensor mass-production
- **Demonstrated the success of the fabrication [NIMA 1046 (2023), 167681] [arXiv:2304.04401]**

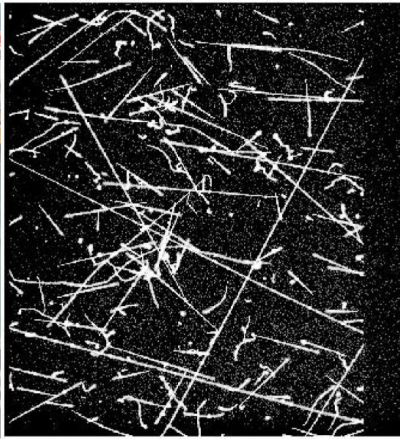
Parameter	No events with >1e-	No events with 3e- or more	Prototype	Units
Dark current	1×10^{-6}	1.6×10^{-4} ✓	3×10^{-2}	e^-/pix/day
Readout time for full array	< 2	< 5 ✓	3.4 (4.2)	hours
Pixel readout rate	> 188	> 76 ✓	111 (89)	pix/s
Readout noise	< 0.16	< 0.20 ✓	0.19 (0.20)	e^- RMS
Spurious charge	$< 10^{-10}$	$< 10^{-8}$	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%	

With the Oscura prototype performance we expect no events with 4e- or more from instrumental background in 30 kg-year





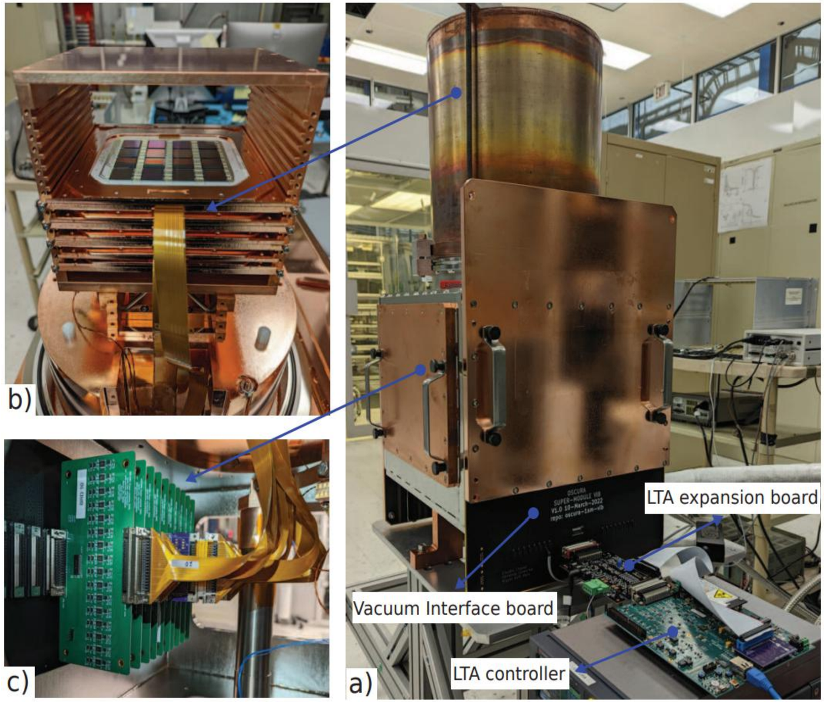


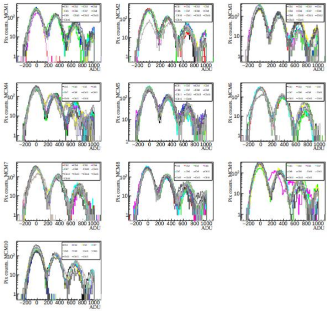


Oscura: R&D results

[JINST 18 P01040]

- **Largest ever built instrument with skipper-CCDs and single-electron resolution (160 sensors!)**
- Copy of SENSEI-100 vessel with 10 prototype ceramic MCMs and the discrete readout electronics solution

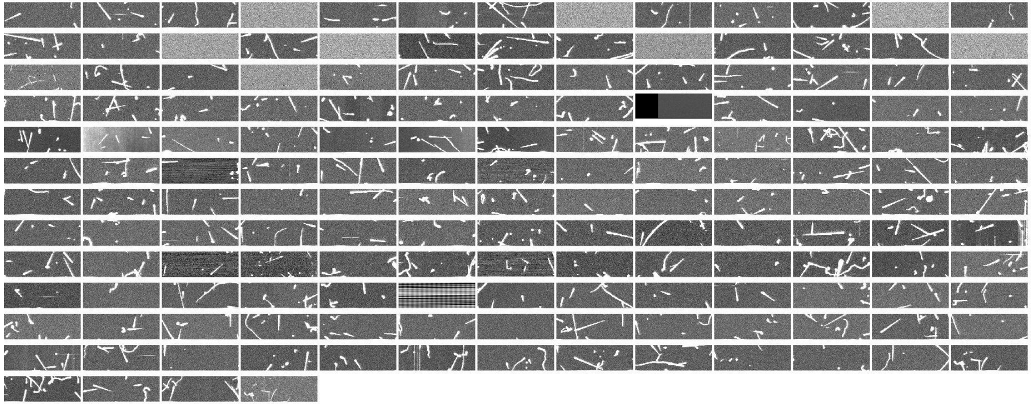




~90% of the sensors working without a preselection! This is a BIG deal!*

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

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



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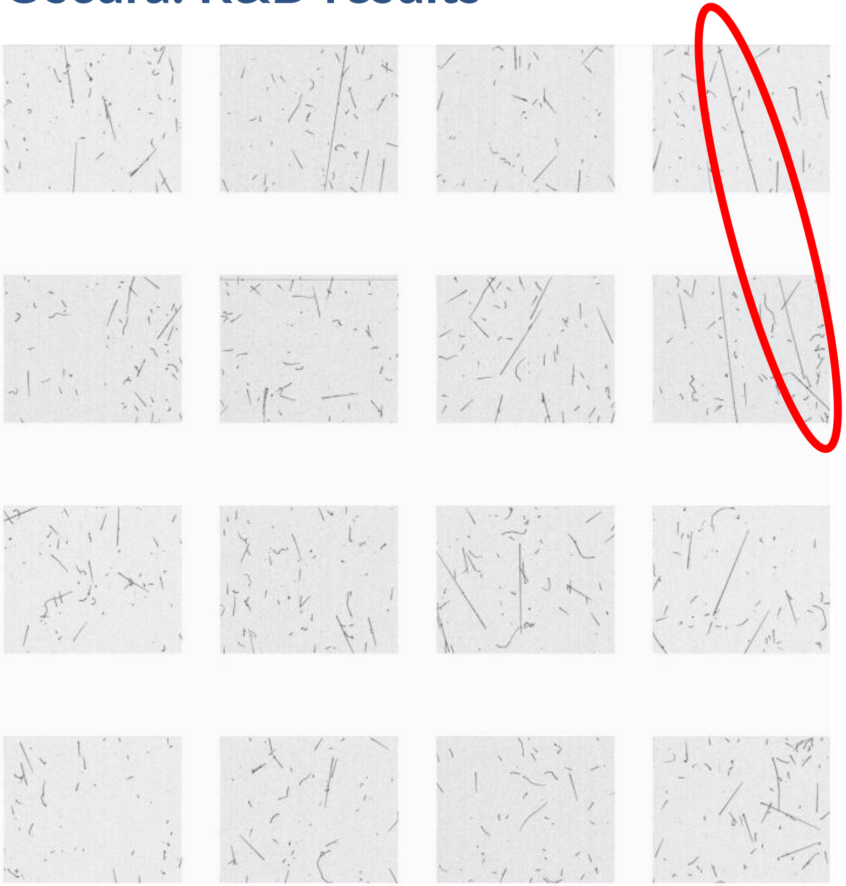
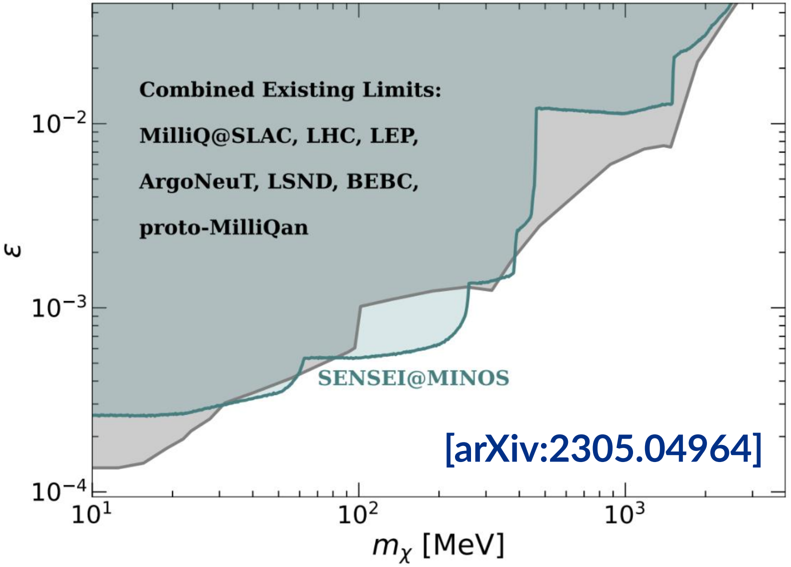
Oscura: R&D results

[JINST 18 P01040]



- With an array of sensors **particle tracking is possible**!

Skipper CCD technology capability to search for mCPs from proton beams using single hits



what happens if we account for tracking?

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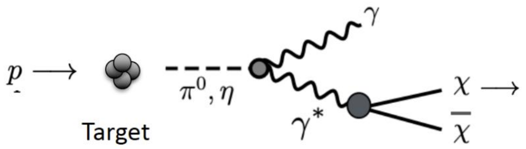
Oscura: Early science

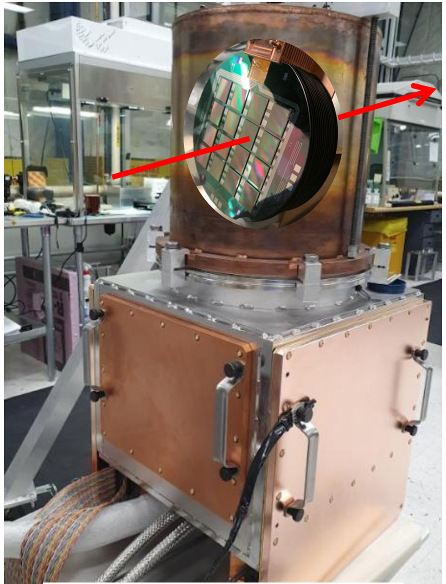
[arXiv:2304.08625]



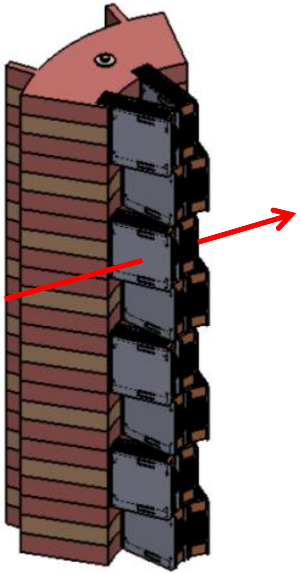
- **Search for millicharged particles** from a proton beam
- Tracking reduce our backgrounds

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

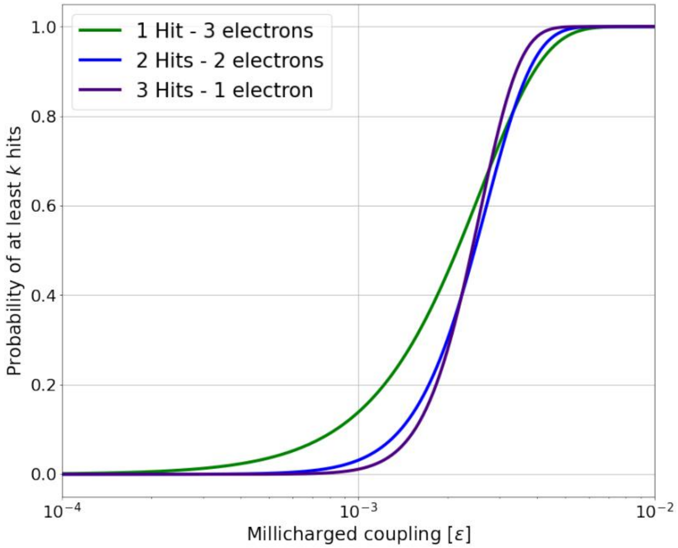
Threshold	doublets $(b = 2)$	triplets$(b = 3)$	p_{bkg}
$1e^-$	3822	11.4	3×10^{-4}
$2e^-$	0.031	2.72×10^{-7}	$8.6 \times 10-7$
$3e^-$	9.06×10^{-5}	4.17×10^{-11}	4.6×10^{-8}



10(16)-layer tracker



32-layer tracker



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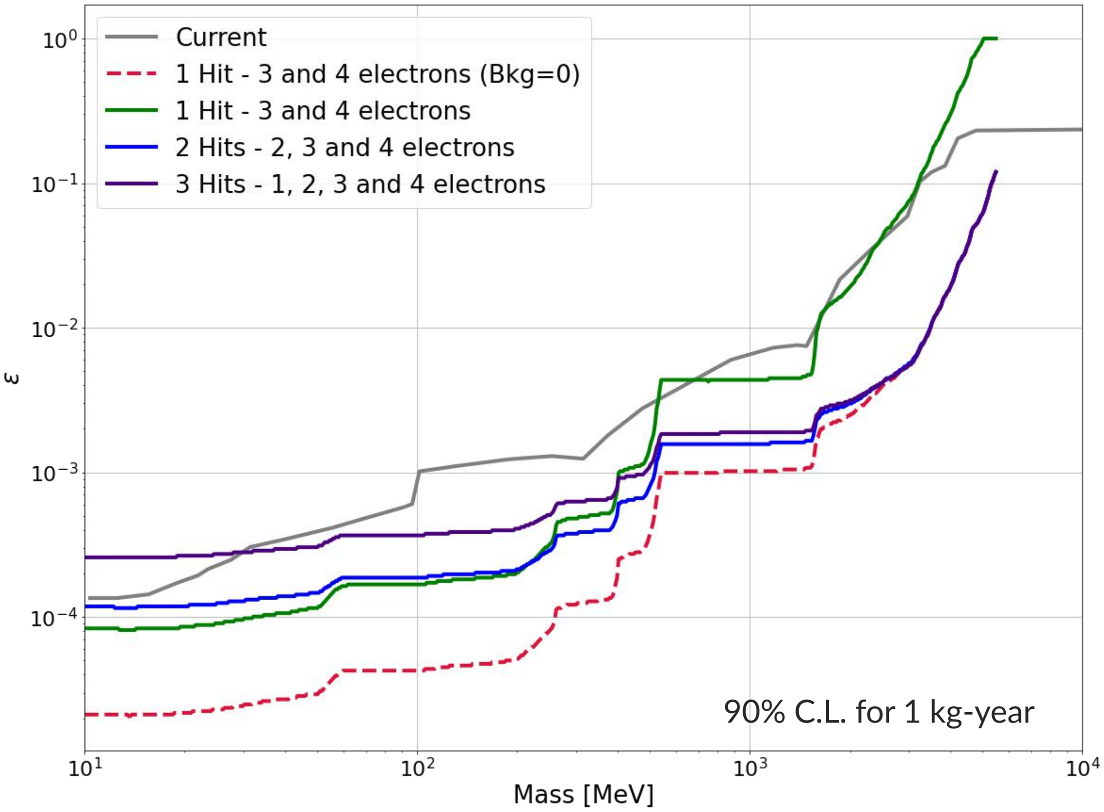
Oscura: Early science

[arXiv:2304.08625]

- Assuming a 1 kg detector with 32 layers for tracking, ~10^{18} POT from the NuMI beam (120 GeV protons) and a flat background of 1000 evts/kg/day/keV

- For higher ε the mean free path of the mCPs is smaller than the width of the tracker, increasing the probability of multiple hits

$$\lambda \propto \frac{E_{recoil}}{\varepsilon^2}$$



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Take-home messages

- Skipper-CCDs and their e- counting capability are promising for exploring the dark sector
- Multi-kg skipper-CCD experiments are being built; Oscura is the ultimate goal (10 kg)
- We have a ~80 g skipper-CCD detector working at FNAL with low instrumental background
- A massive skipper-CCD detector to search for mCPs from proton beams can produce very competitive limits

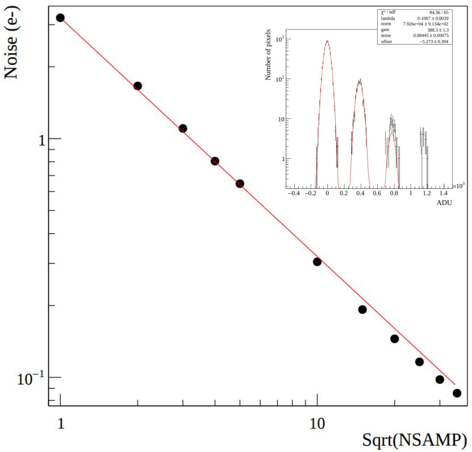
Thank you!

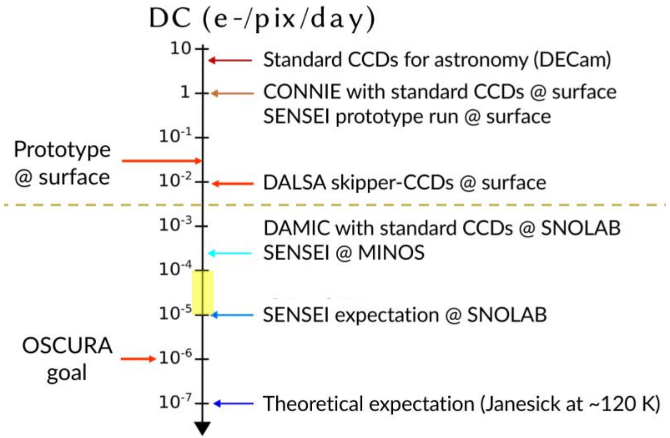
Oscura: Sensors performance

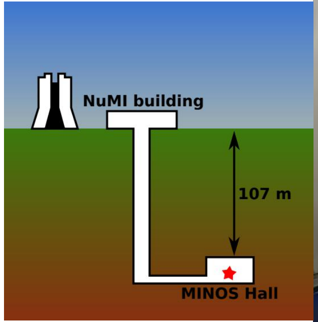
Paper coming soon!

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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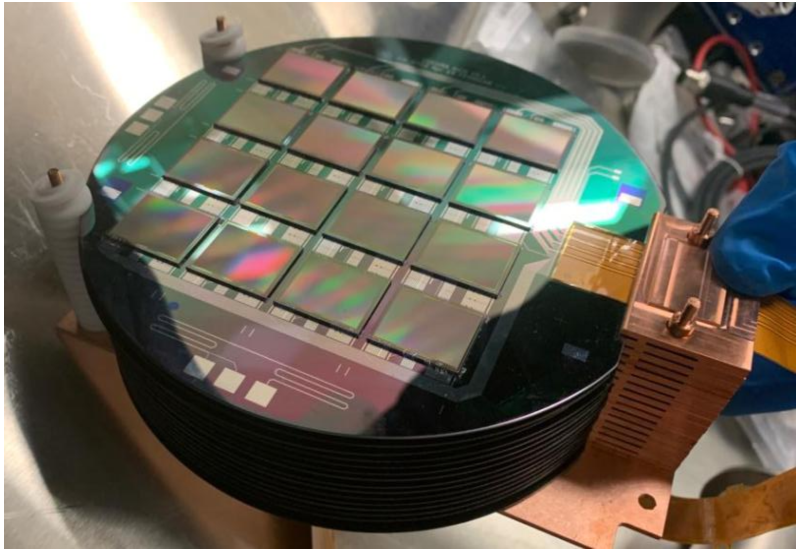
Oscura: Scaling up mass (MCMs/SMs fabrication)

- 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



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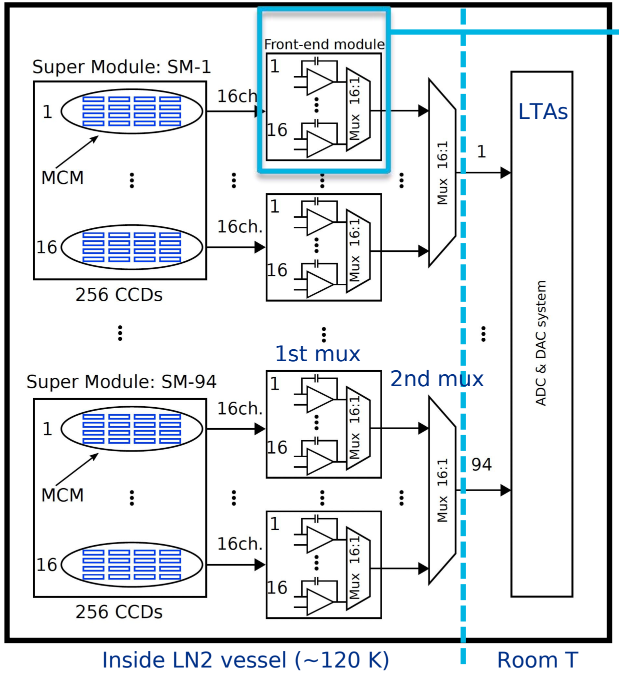
Oscura: Readout electronics

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

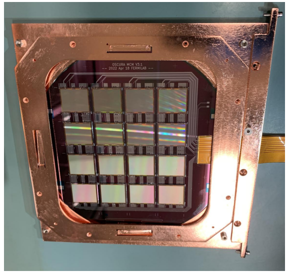


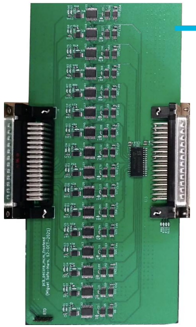
- Discrete (mux board) **[Sensors 22 (2022) 11, 4308] [JINST 16 P11012]**
- Integrated (MIDNA ASIC) **[doi:10.2172/1841383]**

  4 channels in a 2mm x 1mm chip **reducing cost, space and radioactive contamination**

  Tested and working!

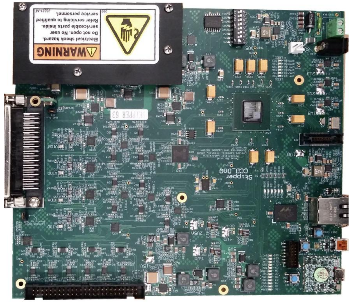
MCM

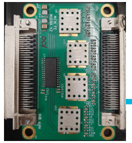




Mux board

LTA **[1.JATIS.7.1.015001]**





Board with 4 MIDNAs

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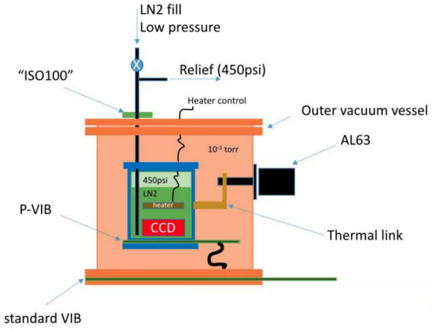
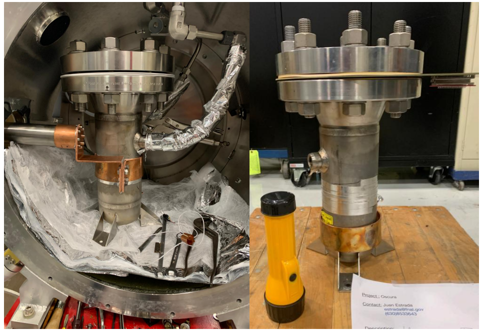
Oscura: Operation in LN2

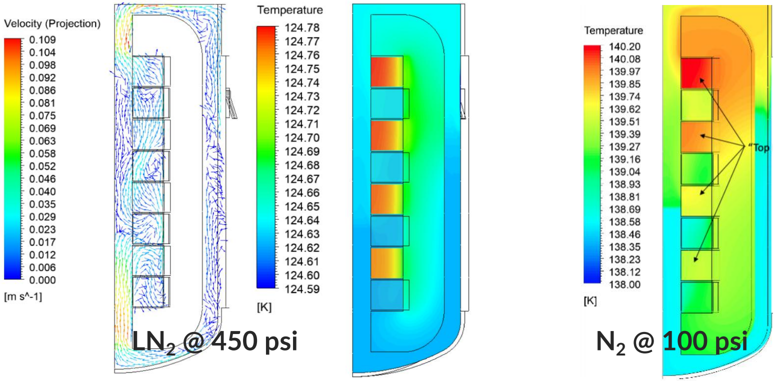
- Demonstrated stable operation of skipper-CCD in LN_2



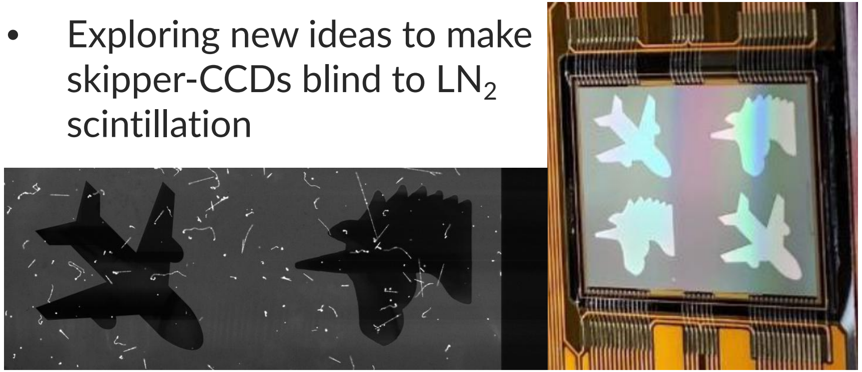


- Test of 1st SM in LN_2 coming soon!

- Simulations validate the convection flow



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



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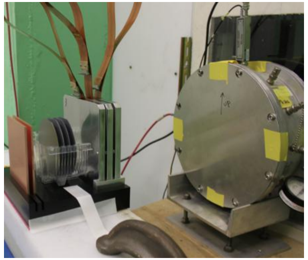
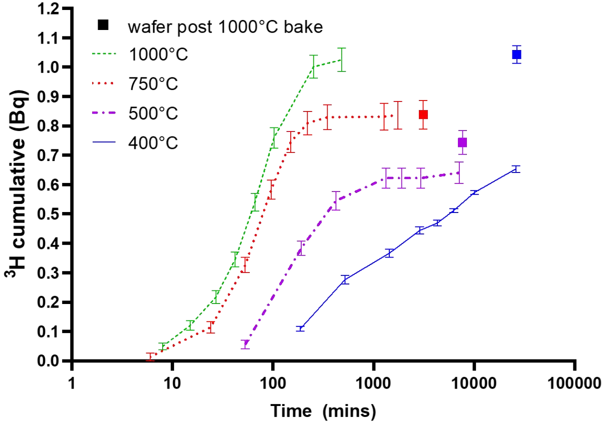
Oscura: Background control

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



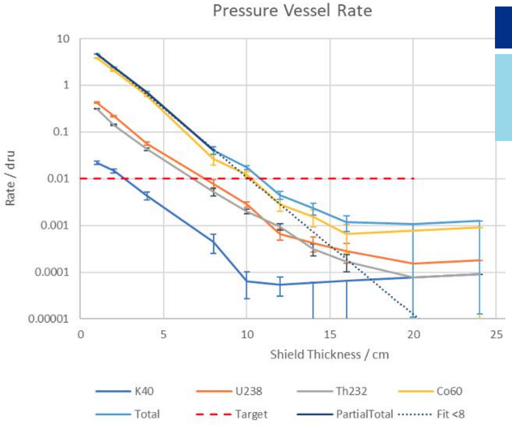
[PRD 102, 102006]



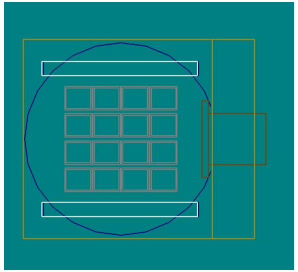
Sources:

- 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)

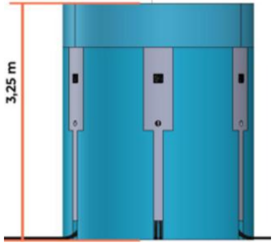
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [arXiv:2303.10862]
  - Simulations of ^{238}U, ^{232}Th and ^{40}K
  - → 4cm of cable visible to CCDs (with 15 ppt)
  - → Electronics behind inner shield (width>10cm)



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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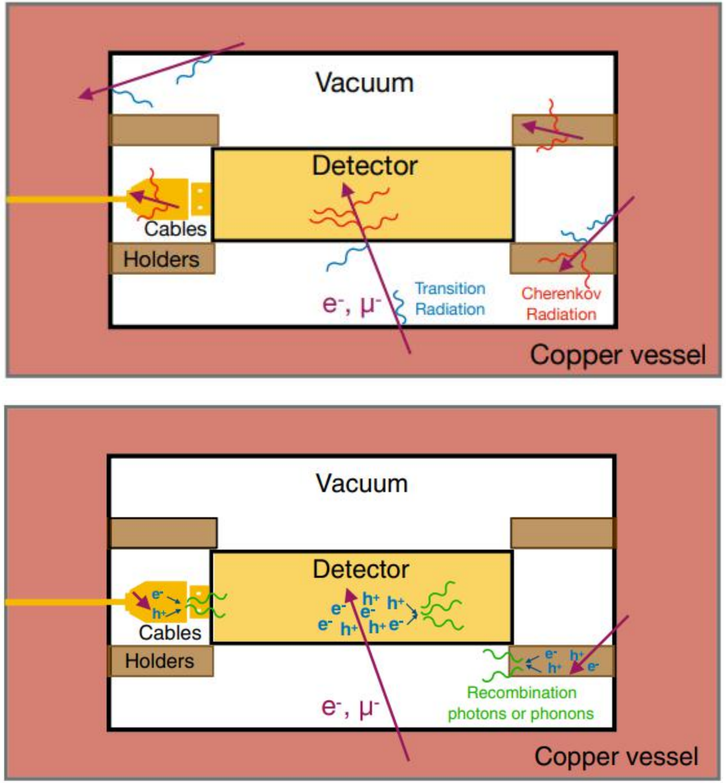
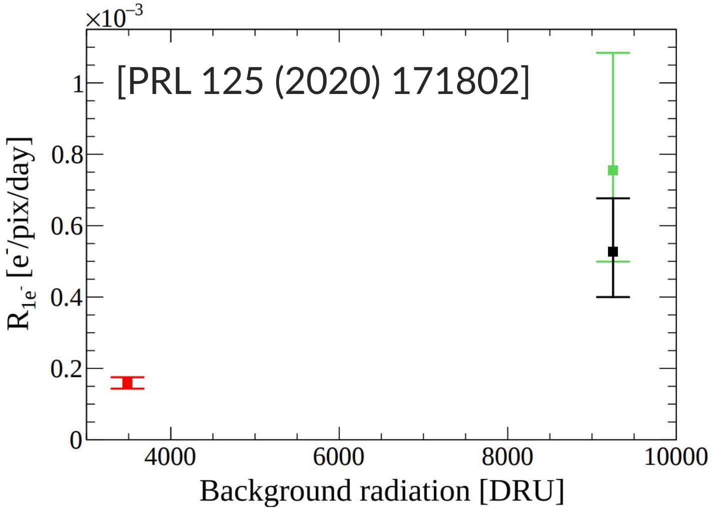
Low-E background correlation with high-E events



[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

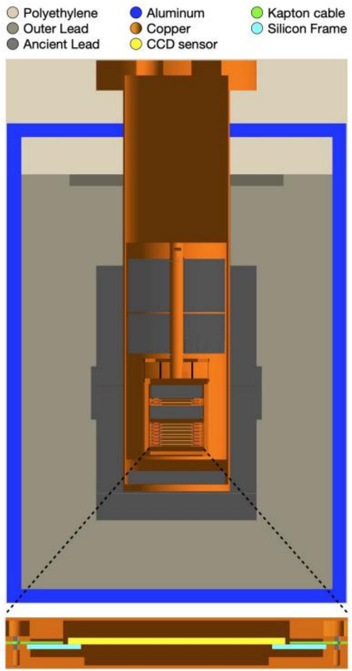


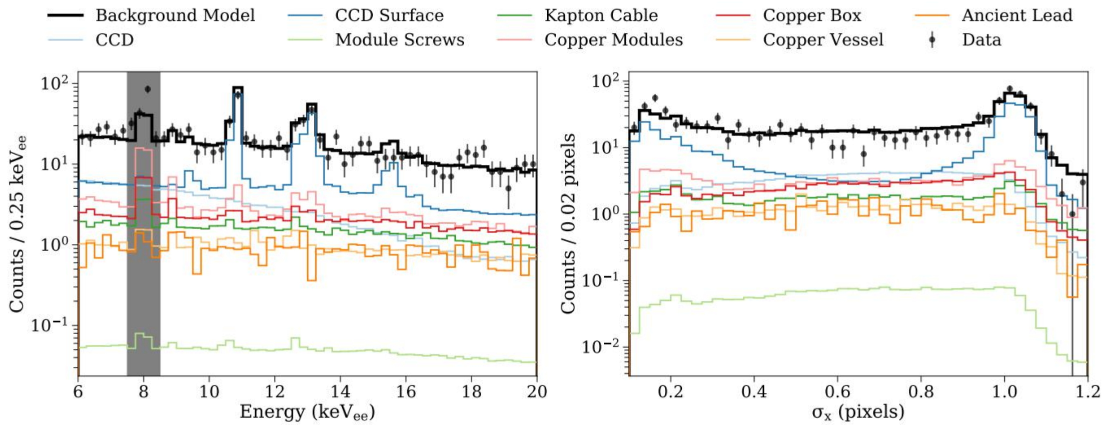
For Oscura, to determine the ultimate instrumental background, tests in a low-background environment are desired: MOSKITA (2in Pb shield) @ MINOS (100 m underground)

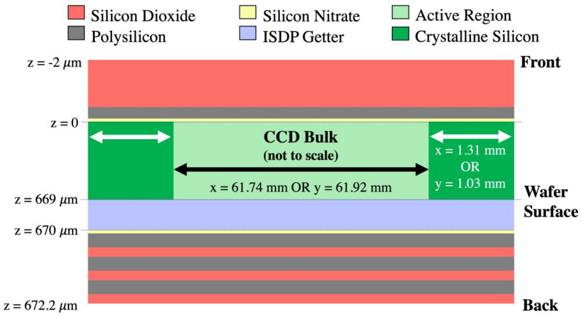
DAMIC: Background study

[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 ± 5)×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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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 1x10^{-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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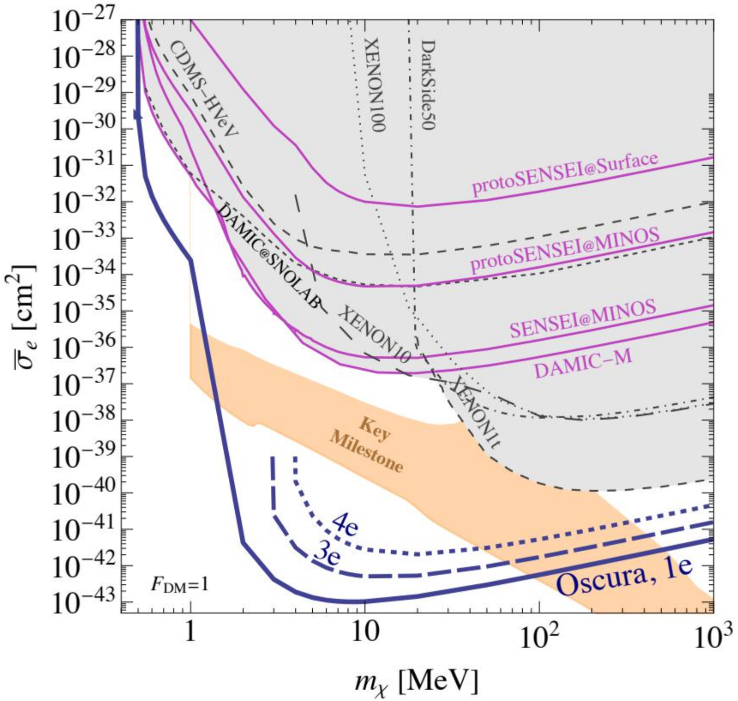
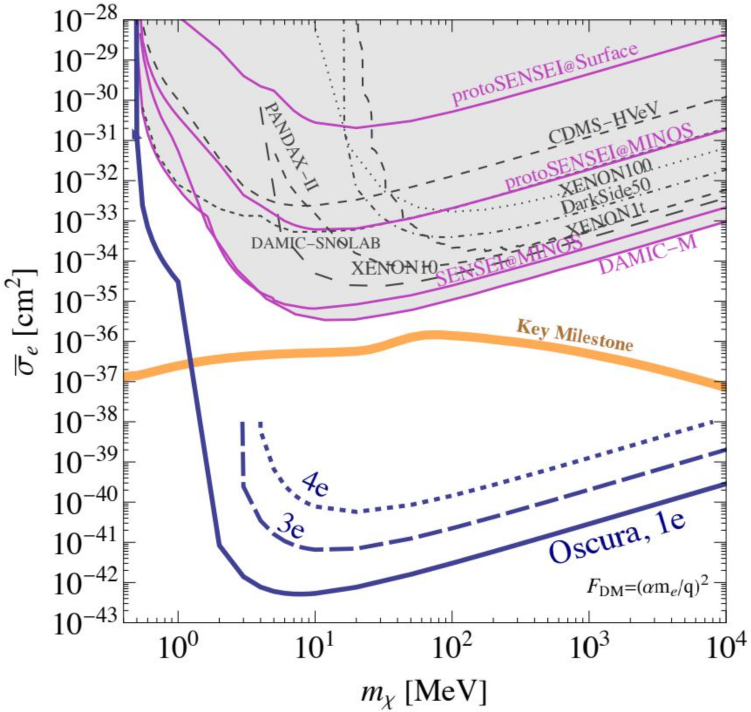
Oscura: Projected sensitivities for 30 kg-year

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





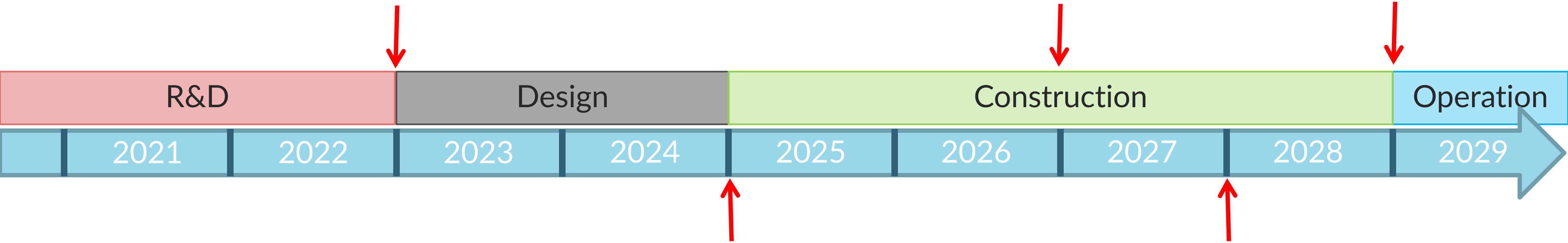
DM-electron scattering mediated by a heavy (left) or light (right) mediator

Oscura: Timeline and goals per period

- ✓ Evaluation of new sensors
- ✓ Demonstration of MCM readout
- ✓ Decision on cold-end electronics
- SM full backgrounds simulation

Sensor packaging facility
Integration test (10%)

Sensors, cryostat and electronics at SNOLAB for assembly



Sensor preproduction
Operation of SM in LN2
Project Execution Plan

Full DAQ
Shield at Snolab

✓ - Achieved

* Technically driven Oscura timeline

Skipper-CCDs: smart readout

[PRL.127.241101]

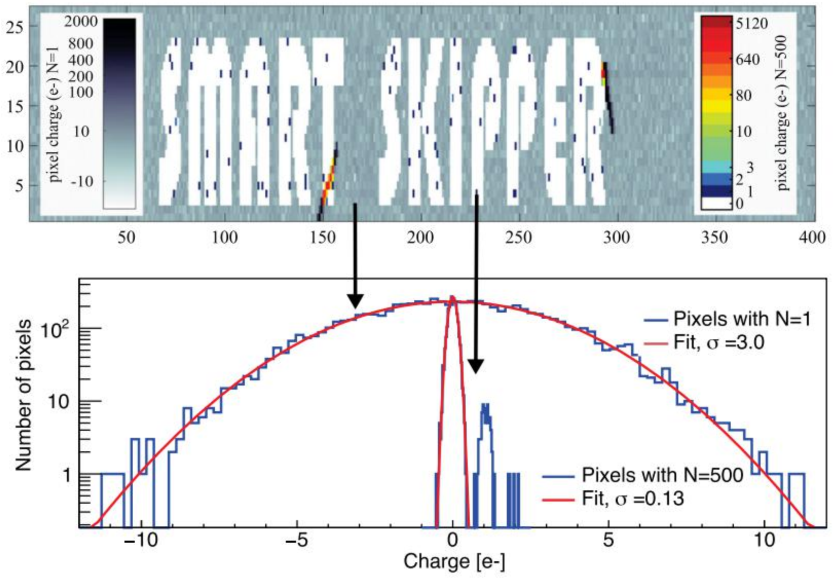


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

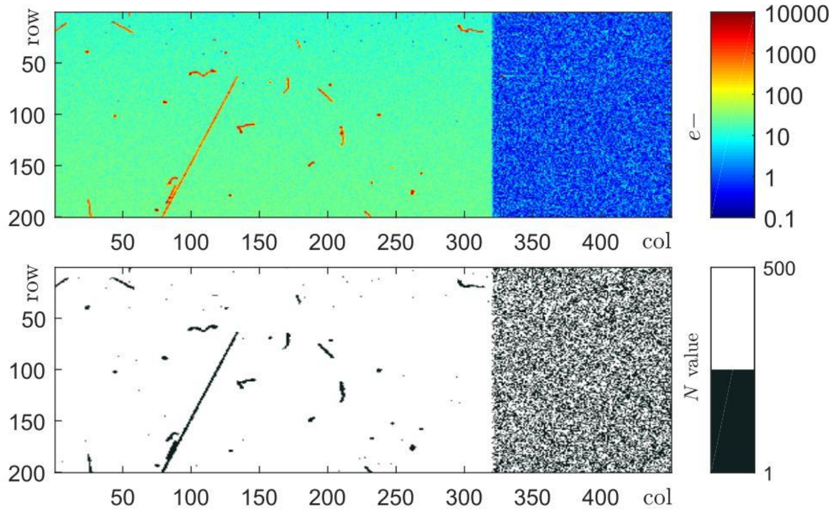


FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

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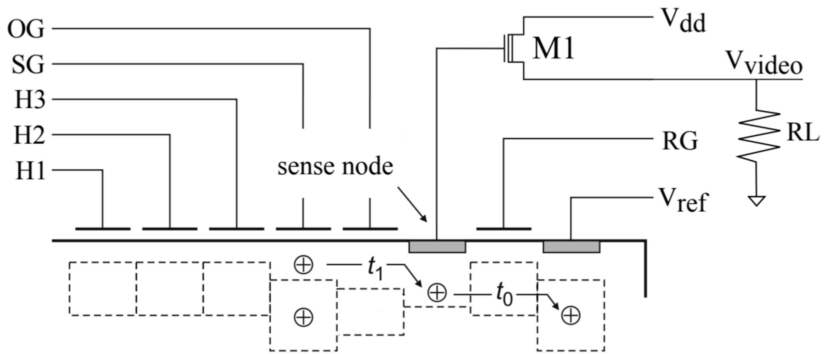
Output stage: standard vs skipper

Standard CCD



Skipper CCD