Oscura: a 10 kg skipper-CCD detector to search for dark matter

Brenda Aurea Cervantes Vergara

Fermi National Accelerator Laboratory

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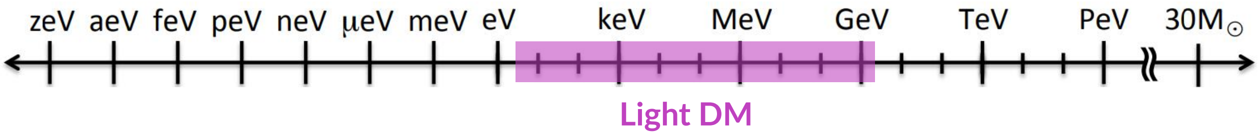
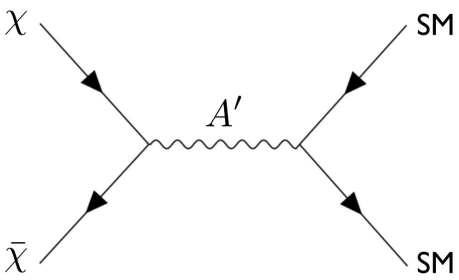
Light dark matter

DM candidates span a wide range of masses. Light DM mass lies between eV to GeV.



Popular light DM models consider DM as part of a dark sector, consistent of new particles and interactions, that communicate with the SM through portals

Dark photon (vector) portal:

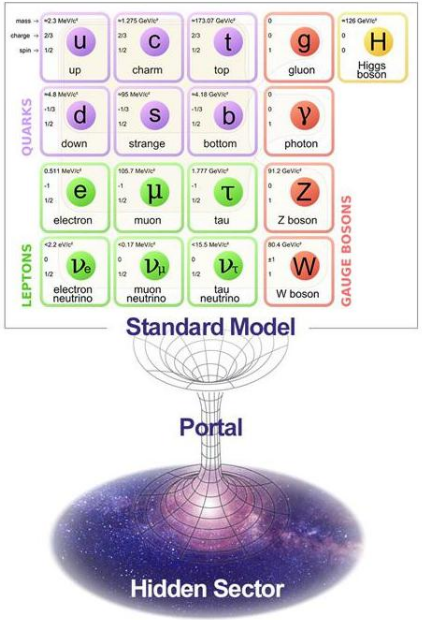


A' kinetically mixed with SM photon

"Heavy" mediator: $\mathcal{O}(\mathrm{keV}) \ll m_{A'} \leq \mathcal{O}(\mathrm{GeV})$
- DM with freeze-out abundance

"Ultra-light" mediator: $m_{A'} \ll \mathcal{O}(\mathrm{keV})$
- DM with freeze-in abundance

Massless mediator: $m_{A'} = 0$
- Millicharged DM



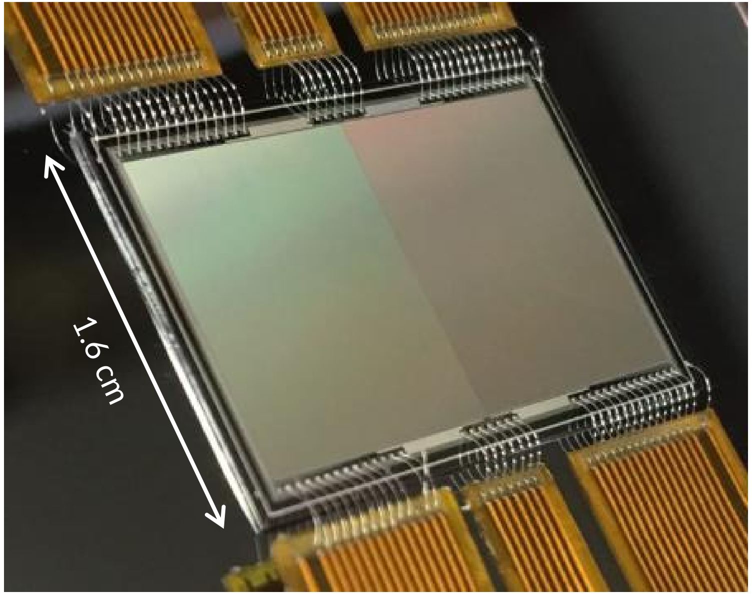
Light DM is commonly probed by low-threshold direct detection experiments

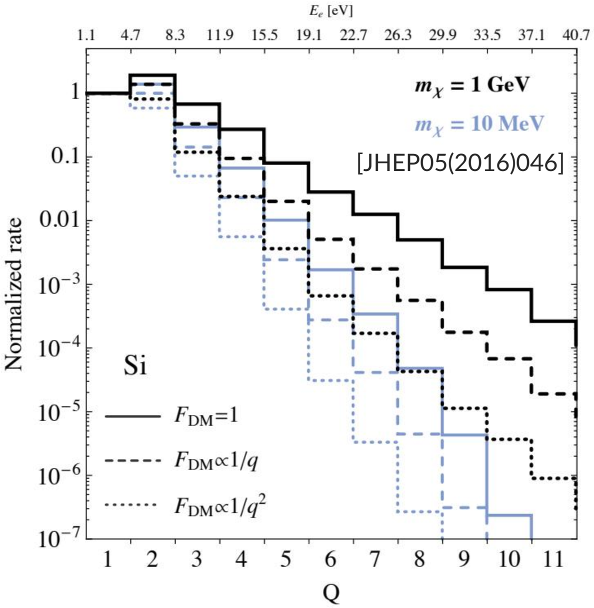
Light dark matter search with skipper-CCDs

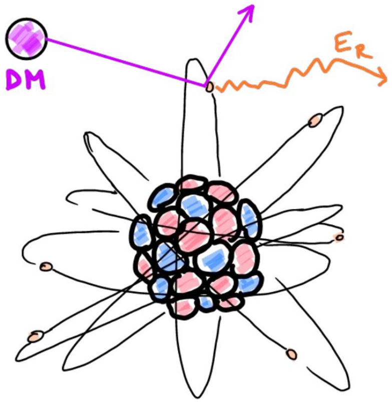
Skipper-CCDs are pixelated ionization sensors, usually made of silicon.

Multiple non-destructive measurements of the charge in each pixel makes them an **electron-counting technology**. Plus, they have **very low instrumental backgrounds.**

Light DM search through inelastic channels, e.g. DM-e- scattering, for which **1e- rate constrains sensitivity**.







G. Montefalcone (IDM24)

Light dark matter search with skipper-CCDs: ongoing program

Skipper-CCDs are constantly producing world-leading results on DM-e- interactions since 2019.

Now, we are pushing towards **more mass and less backgrounds**.

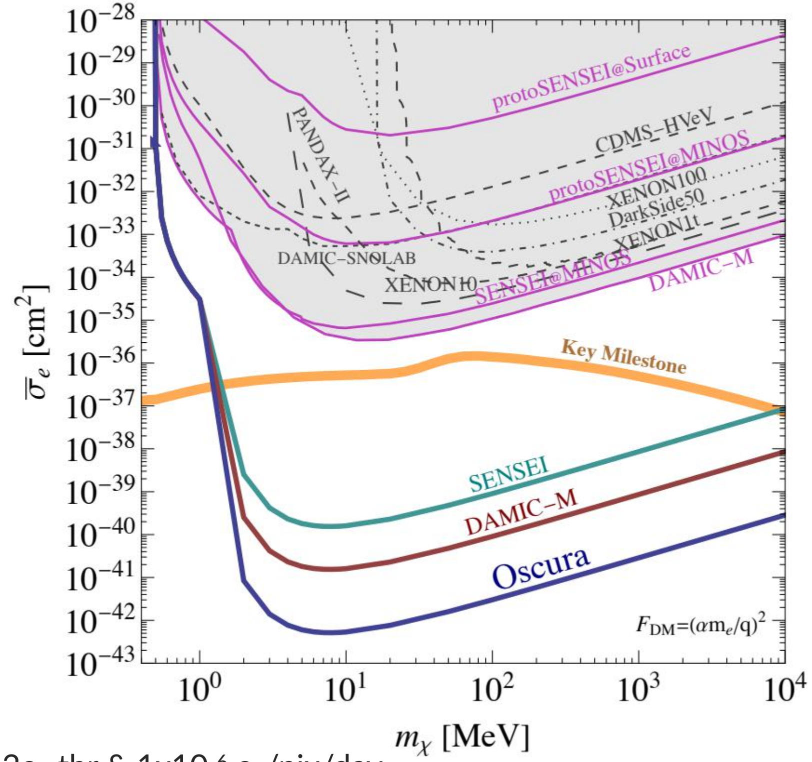
Oscura will have the ultimate DM skipper-CCD detector, joining expertise from all ongoing efforts.

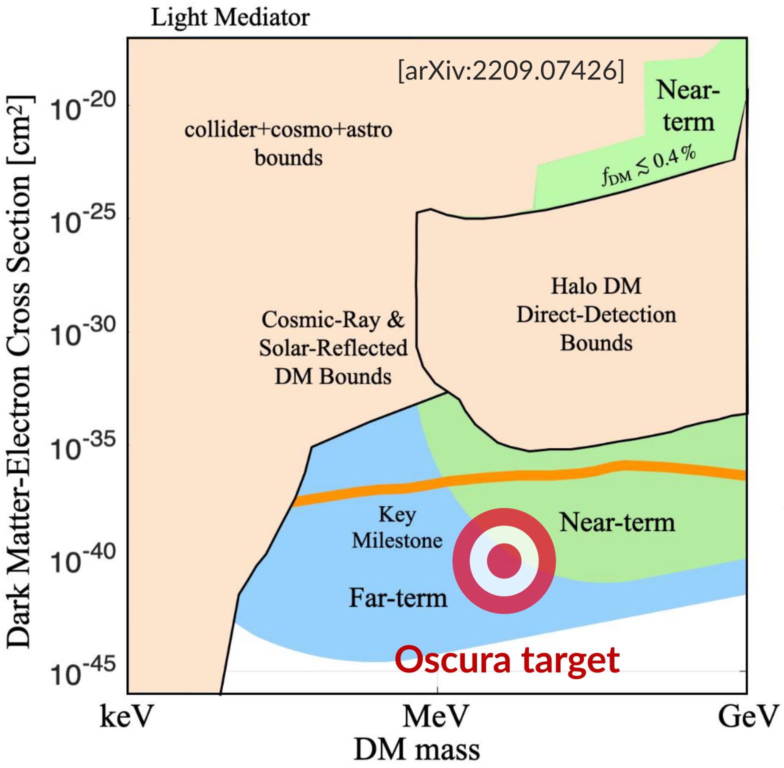
Experiment	Mass [kg]	#CCDs	Background rate <10 keV [dru]	1e- rate [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3370	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	9.7	2.4×10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	10	4.5×10^{-3}	late-2021
SENSEI @ SNOLAB	~0.04 / 0.1*	19 / 50*	~50 / 10*	1.4×10^{-5} / 1×10^{-5}*	mid-2022
DAMIC-M	~1*	~209*	0.1*		~2025
OSCURA	**~10***	**~24,000***	**0.025***	$\mathbf{1 \times 10^{-6}}$*	**~2029**

*goal

Oscura: Scientific reach

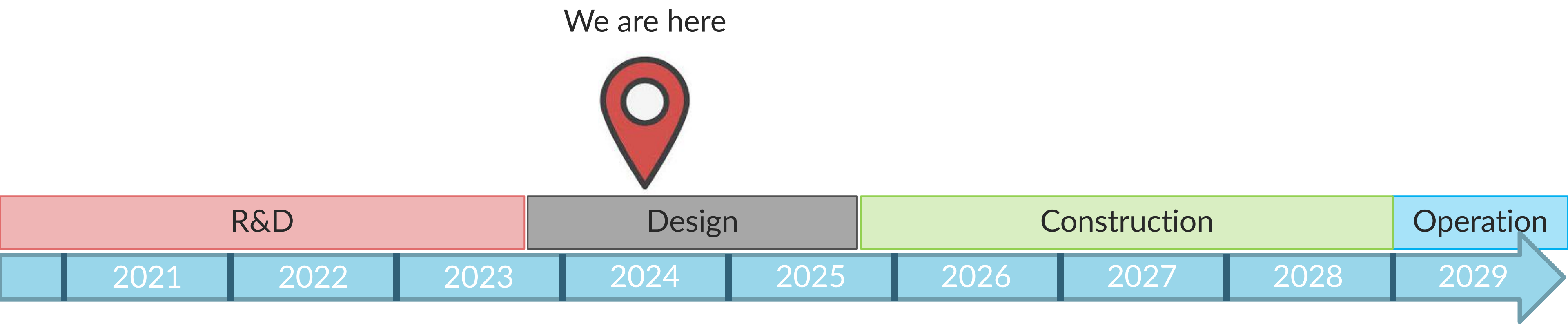
Oscura will constrain key DM models with its 30 kg-year exposure.





*2e- thr & 1x10^{-6} e-/pix/day

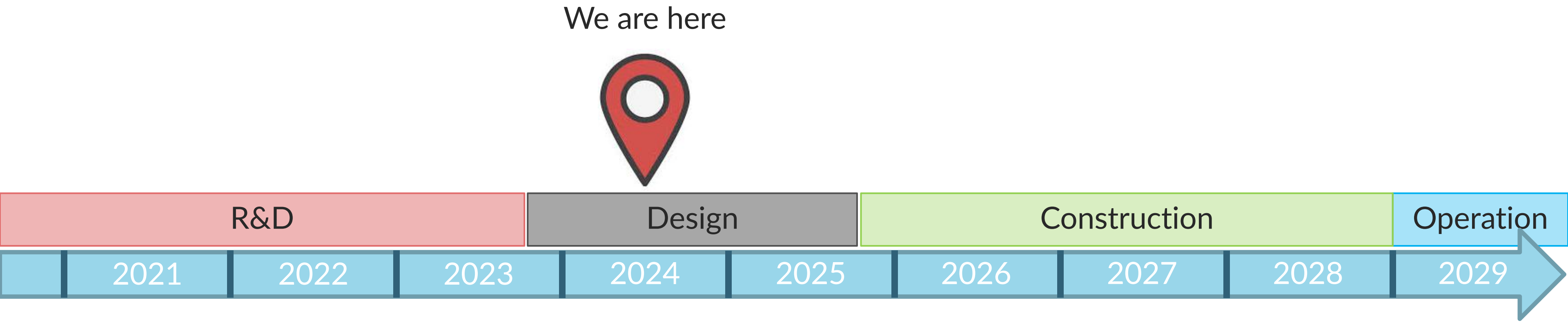
Oscura: Technically driven timeline and achieved milestones



- ✓ Design high risks addressed:
  new sensors fabrication, new electronics (cold front-end and multiplexing), new cryogenics (immerse CCDs in pressurized N_2), strict background control

- ✓ Key design decisions done and preliminary design completed

- ✓ Preliminary execution plan completed



ok... but, how does Oscura looks like?

Oscura: Design of the 10-kg skipper-CCD detector

It is a 33.1 GPix camera!

Detector payload

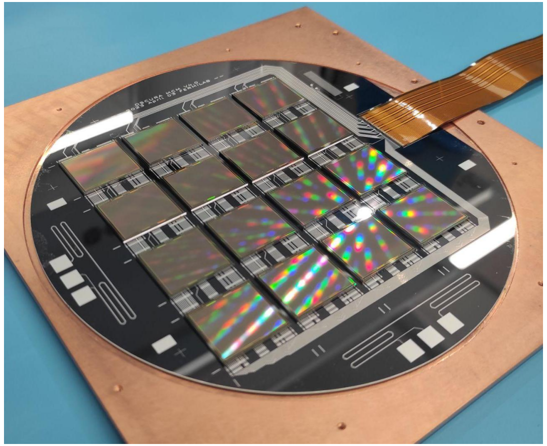
24,576 Skipper-CCDs = 1536 Multi-Chip Modules (MCMs) = **96 Super Modules** (SMs)

Skipper-CCD

p-channel sensors designed at LBNL
Fabricated at new commercial foundry
1.35 MPix each - 725 μm thick

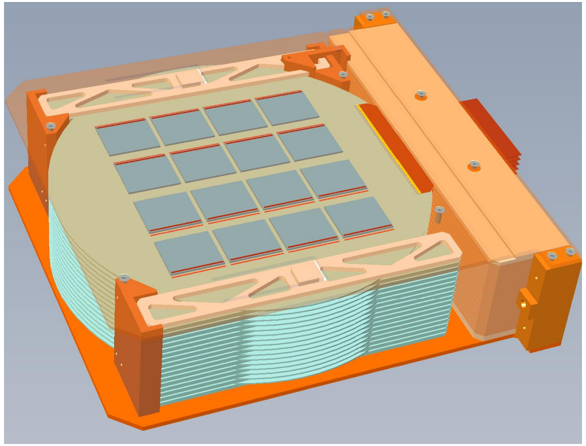
MCM

16 Skipper-CCDs
Intrinsic Si substrate with 1-layer Al traces
Low-background flex cable



SM

16 MCMs
Radiopure materials (Si, PTFE, EF-Cu)

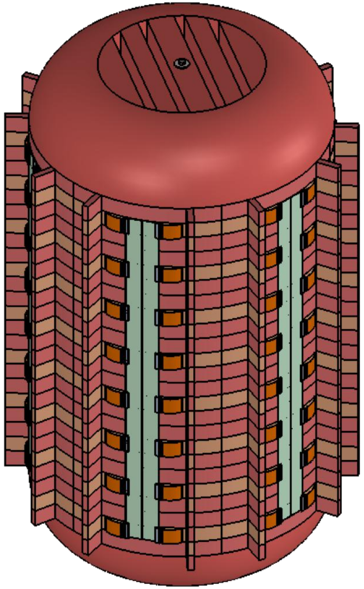


Oscura: Design of the 10-kg skipper-CCD detector

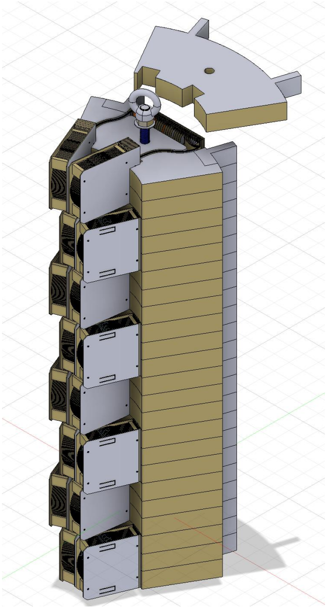
Detector payload with inner shield

96 SMs surrounded by **15-cm-thick inner shield (Pb+Cu)** to reduce backgrounds from vessel, flex cable and front-end electronics.

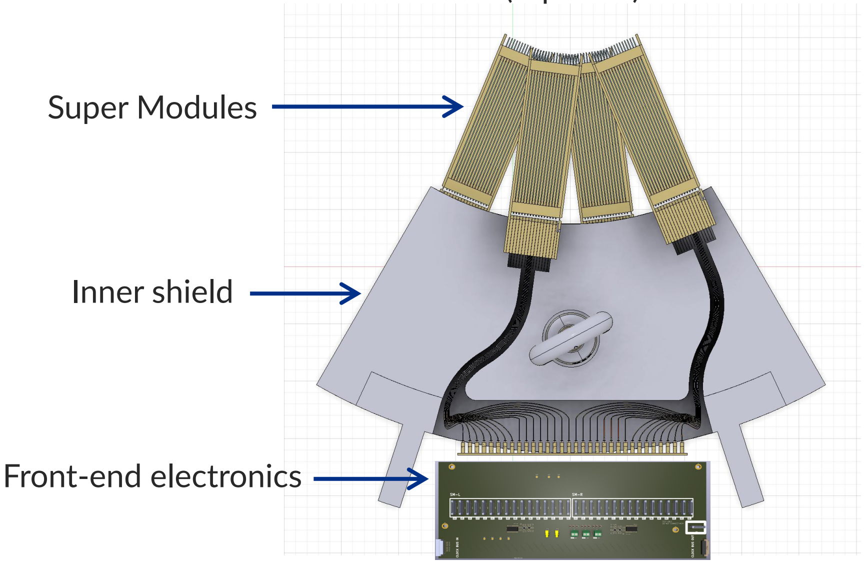
Cylinder-like array
~12.5 kg total (10 kg effective) mass



Slice of 16 SMs with inner shield



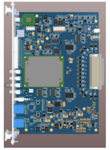
Proposed routing of flex cables
(top view)

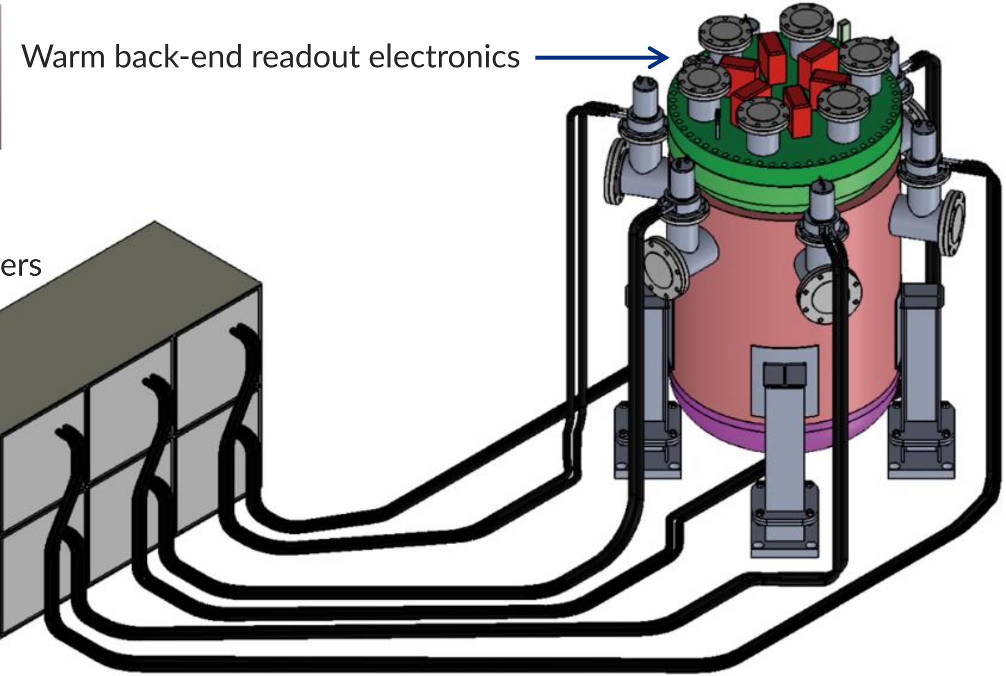


Oscura: Design of the 10-kg skipper-CCD detector

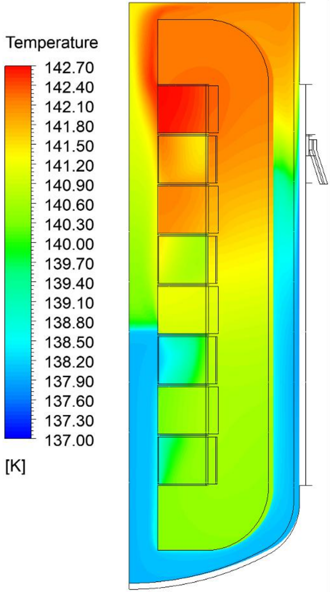
Pressure vessel

96 SMs surrounded by inner shield inside **stainless steel pressure vessel filled with N_2** at 15 PSI, externally coupled to cryocoolers for heat removal to cool down sensors to 140K





Thermal simulation with N_2 at 15 PSI



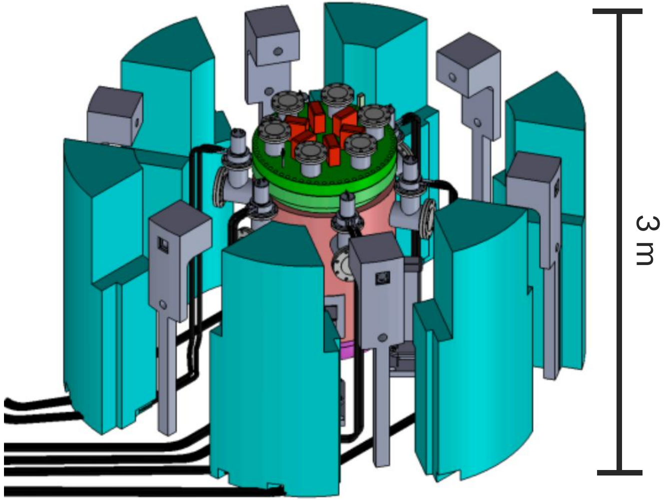
Oscura: Design of the 10-kg skipper-CCD detector

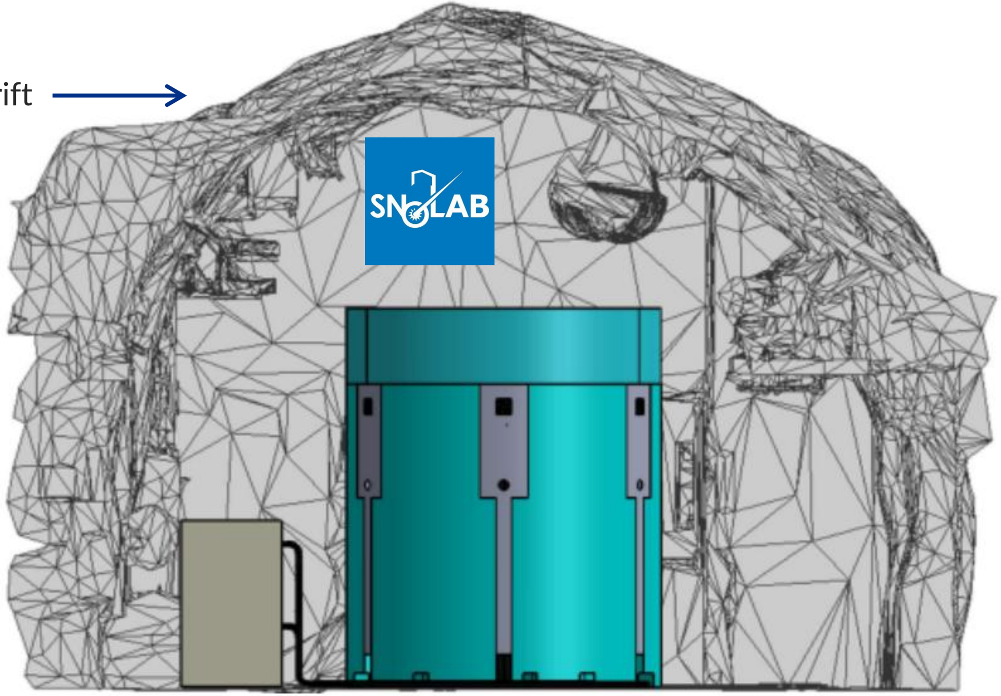
Pressure vessel with external shield at SNOLAB

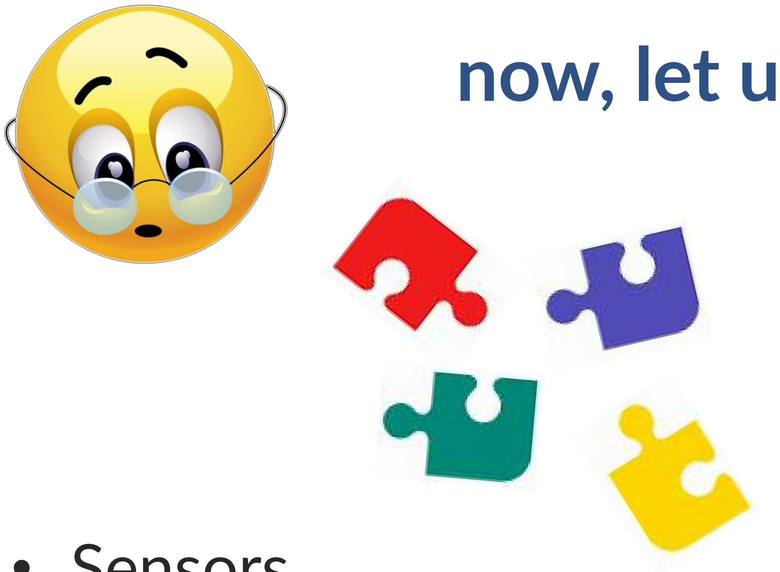
96 SMs surrounded by inner shield inside stainless steel pressure vessel surrounded by **HDPE and water outer shield at SNOLAB** (~2 km underground)

Oscura in the SNOLAB drift

Outer shield assembly

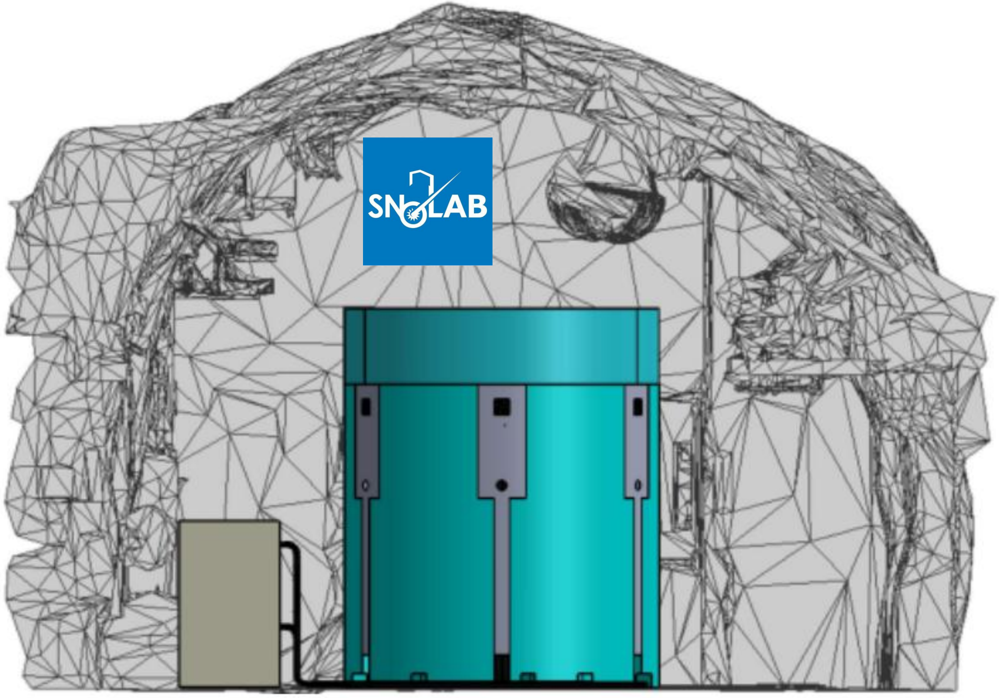






now, let us go through the main pieces!

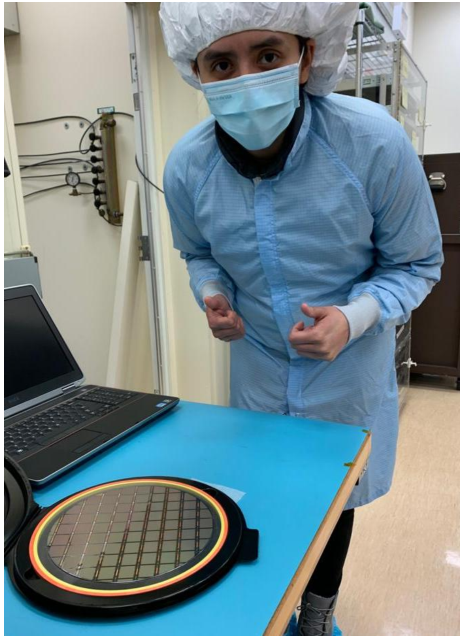
- Sensors
- Electronics
- Background control



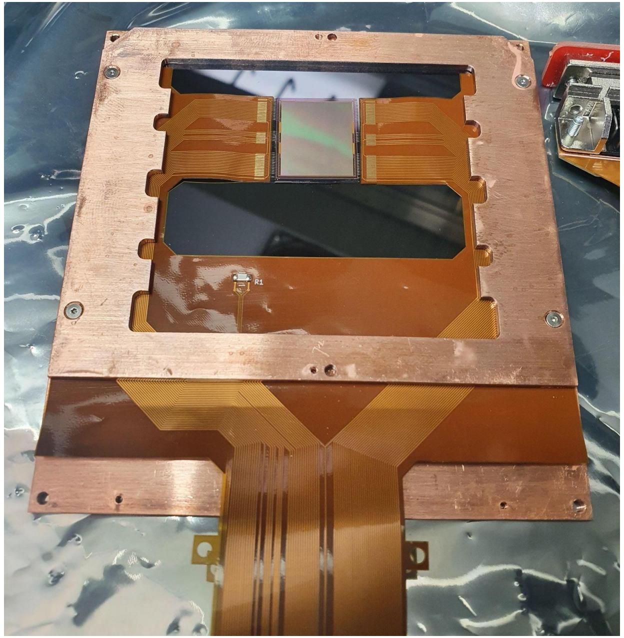
Oscura: Sensors

Sensor fabrication was done at a new foundry. Need to evaluate if their performance matches Oscura needs.
So far, we have fabricated ~50 wafers of sensors. We packaged and tested ~600 sensors!

200-mm-diameter wafer



Single sensor packaged in Cu tray

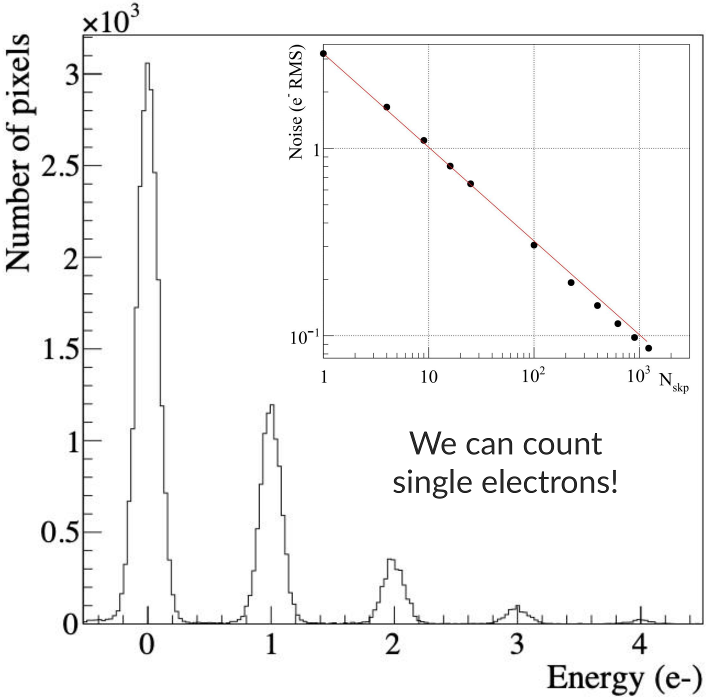


Underground testing setup

Oscura: Sensors performance

[NIMA 1046 (2023), 167681]
[JINST 18 (2023) 08, P08016]

Sensor testing demonstrated the **success of the fabrication, high yield (>85%) and uniformity.**



Parameter	3e- threshold	Performance
Pixel readout rate [pix/s]	> 76	111
Readout noise [e- RMS]	< 0.20	0.19
Exposure-dependent 1e- rate [e-/pix/day]	1.6×10^{-4}	1.8×10^{-3}
Exposure-independent 1e- rate [e-/pix/image]	$< 3.2 \times 10^{-5}$	$< 4.8 \times 10^{-4}$

Plus, **the new sensors meet most of Oscura needs!**

Oscura: Sensors performance

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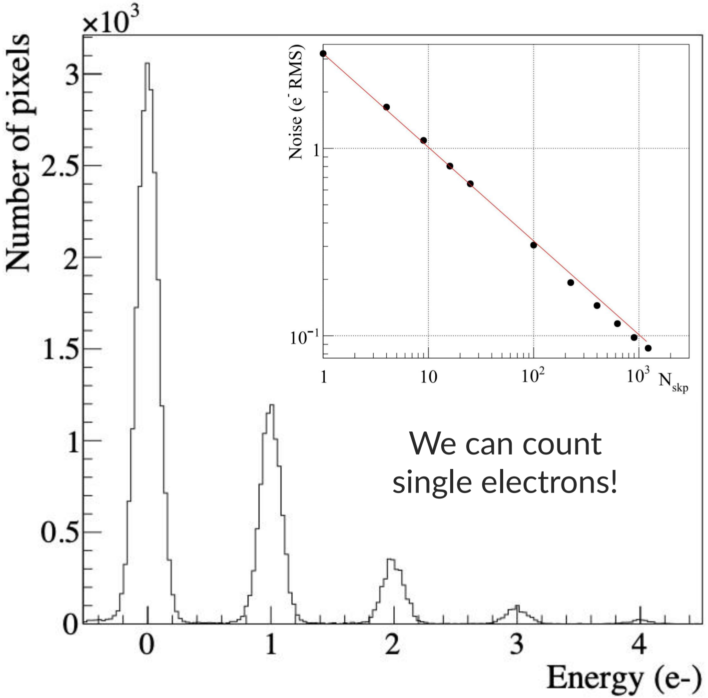

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Exposure-independent 1e- rate [e-/pix/image]	< 3.2 x 10^{-5}	< 4.8 x 10^{-4}

New results from SENSEI demonstrate lower 1e- rates are achievable!

Parameter	SENSEI new results
Exposure-dependent 1e- rate [e-/pix/day]	1.4 x 10^{-5}
Exposure-independent 1e- rate [e-/pix/image]	2.2 x 10^{-6}

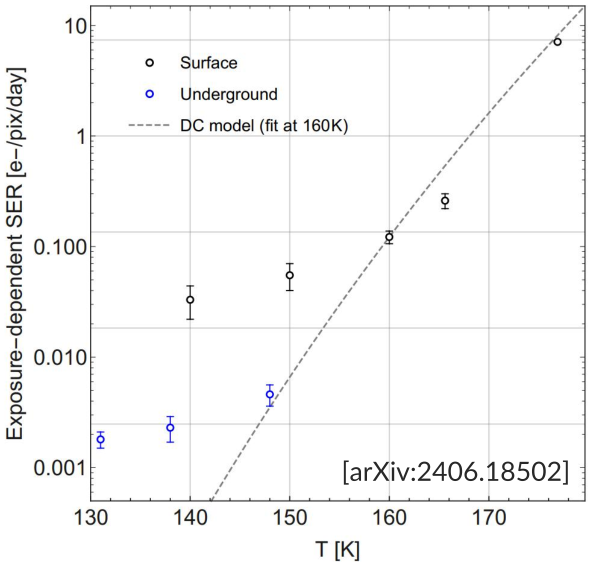
→ A. Botti talk!

Fermilab

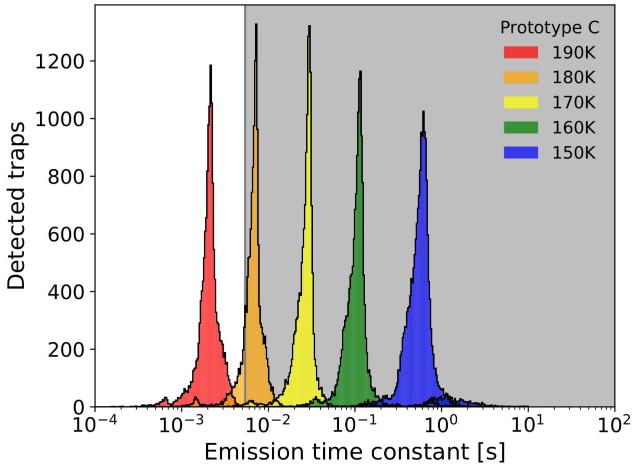
Oscura: Sensors performance

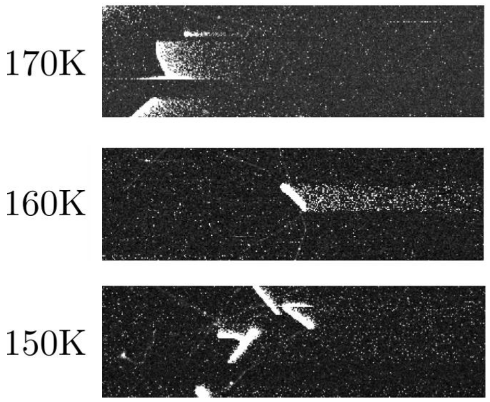
System	Parameter	3e- threshold	Sensors performance	Units
Sensors	Exposure-dependent 1e- rate	1.6 x 10^{-4}	1.8 x 10^{-3}	e-/pix/day

Measurements are likely **dominated by Cherenkov radiation** from interactions of high-energy particles. Plus, in the new sensors, there is a background of 1e- events from the emission of **single-electron traps**! Being at a lower background environment, **we expect a lower exposure-dependent 1e- rate for Oscura.**



See out-of-the-oven paper: [arXiv:2406.18502]!

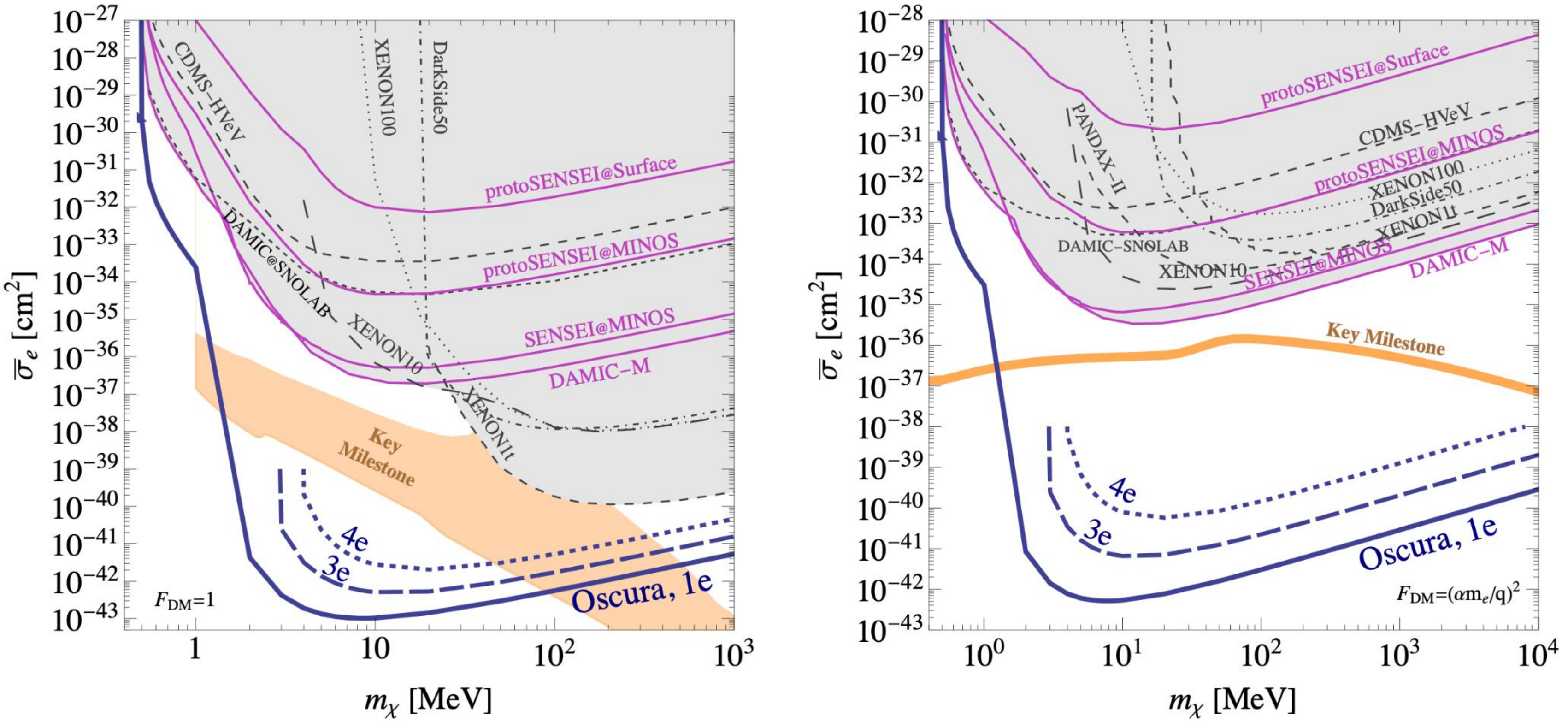




Fermilab

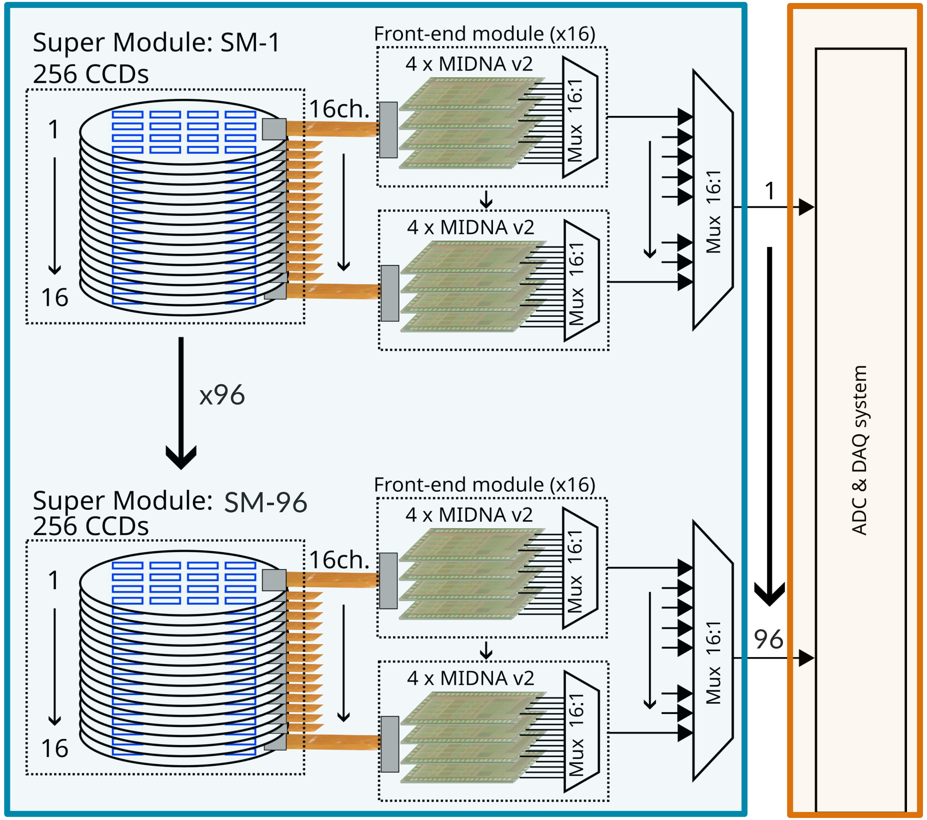
Oscura: Sensors performance to science reach

With current sensors performance, projected sensitivities lie between the 3e- and 4e- threshold curves.



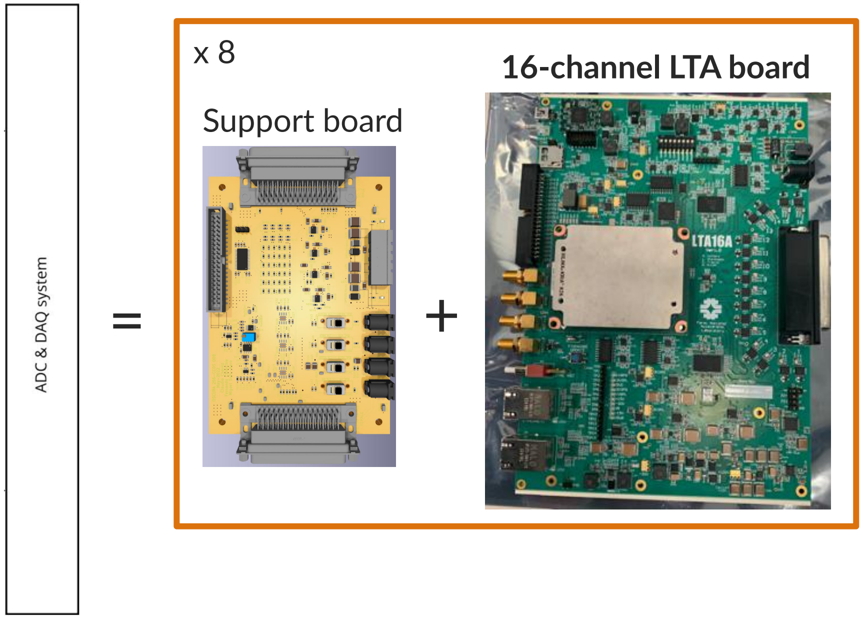
Oscura: Readout electronics

[Sensors 2022, 22(11), 4308]



Readout system for the largest CCD array ever built.
2 multiplexing stages → 256 channels = 1 signal

Warm back-end electronics:



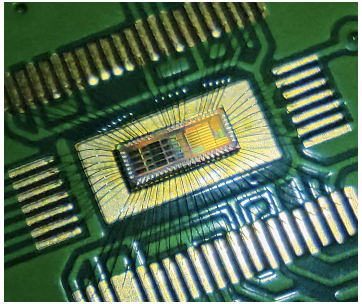
Fermilab

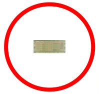
Oscura: Readout electronics

Cold front-end electronics:

MIDNA-ASIC for channel processing
Designed by F. Alcalde [10.1109/TCSI.2023.3256860]

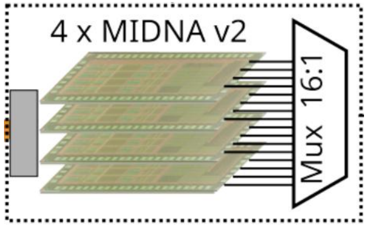
4 MIDNAS per MCM (6144 total)





actual size

1 board per MCM (1536 total)



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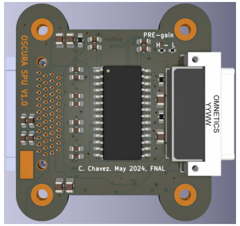

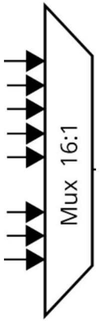

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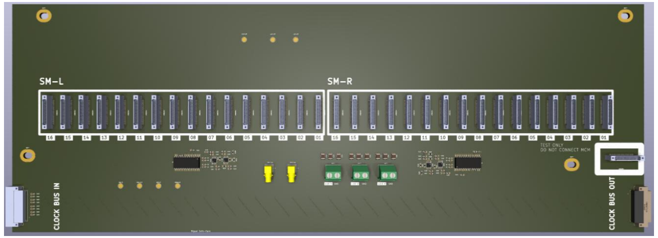
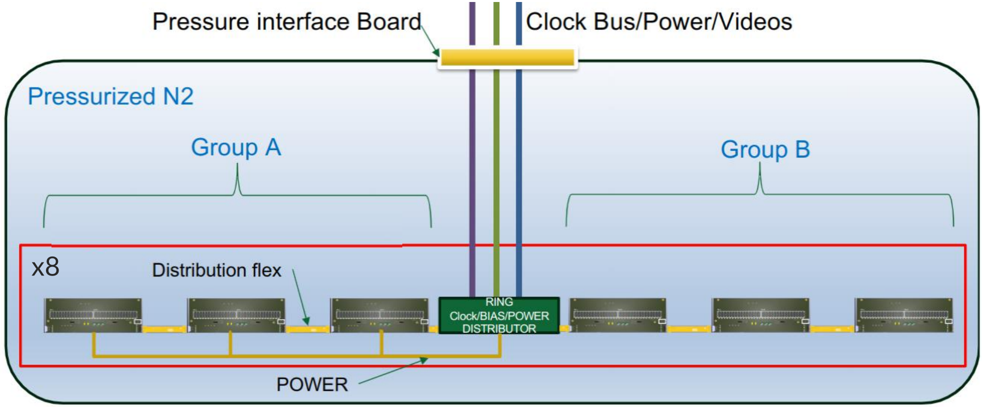
1 board per 2 SMs (48 total)



Cold electronics for whole detector array:



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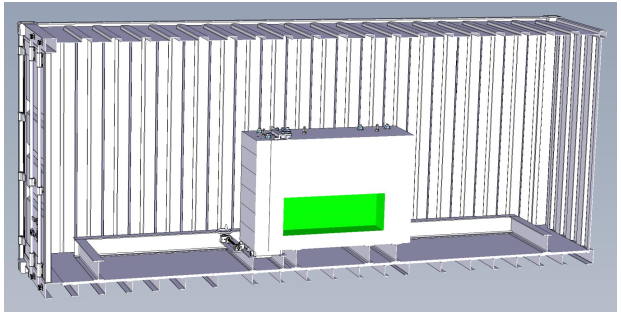
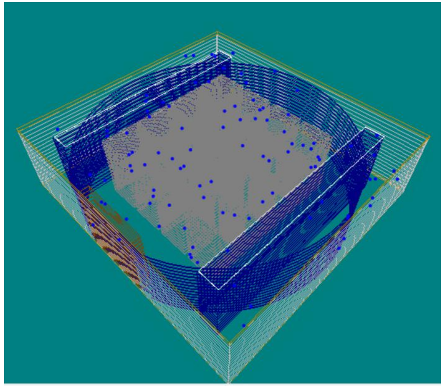
Oscura: Background control

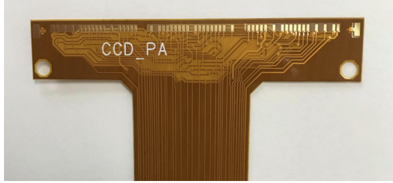
Decisions driven by simulations and by expertise from pathfinder experiments.

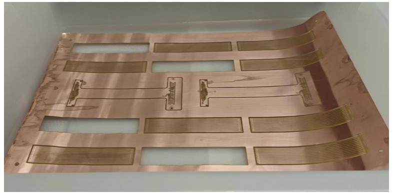
Limiting factors:



- Cosmogenic activation
  → Shielded shipping containers and transportation planning
  → Remove activation products during sensors fab [PRD 102, 102006]
  → Underground module assembly



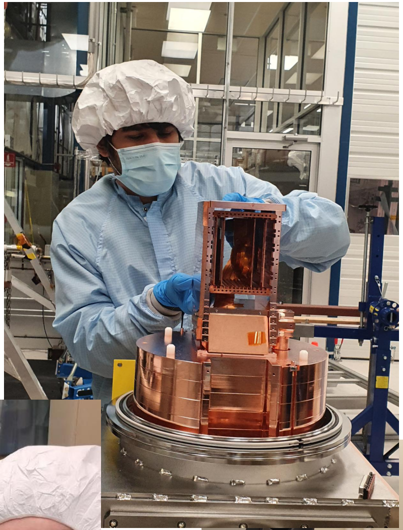


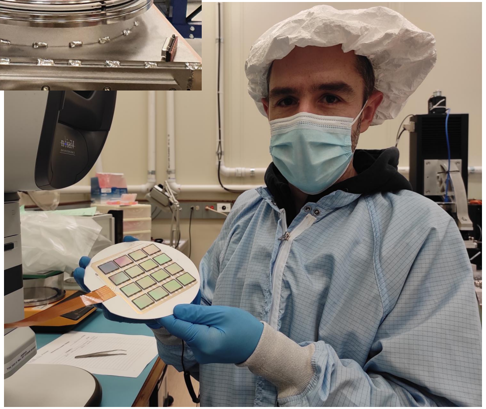


- Isotopic contamination in components near the sensors
  → Material selection for Super Modules
  → Low-background flex cable [arXiv:2303.10862]
  → Electronics behind 15-cm-thick inner shield

- External backgrounds
  Outer shield: polyethylene + water
  Inner shield: lead + copper

How is integration going?

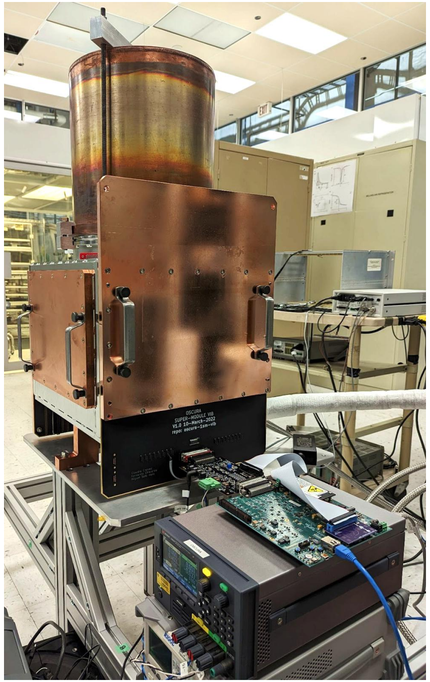


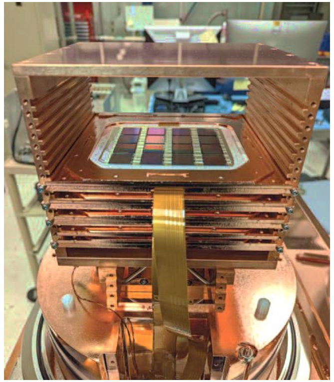


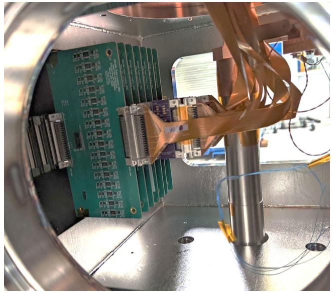
Oscura: First demonstrator (Sept 2022)

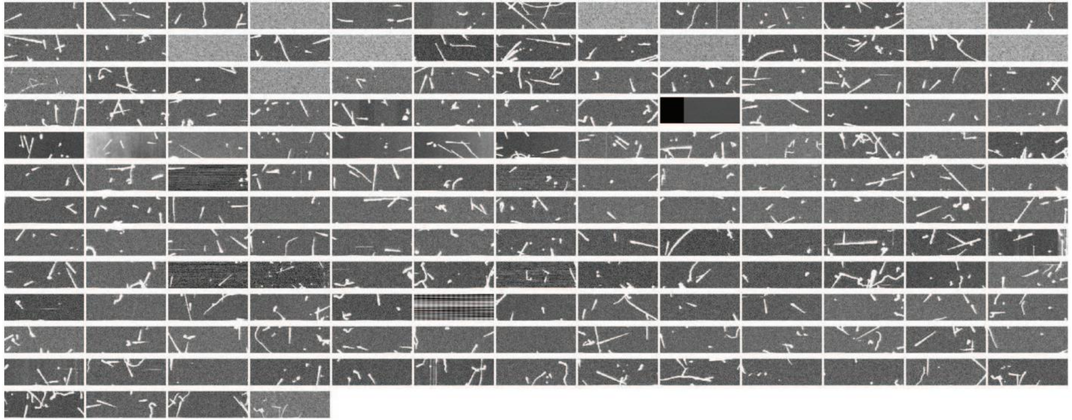
[JINST 18 P01040]

Twin of SENSEI @ SNOLAB vessel with 10 prototype ceramic MCMs and discrete electronics with multiplexing.
Largest skipper-CCD instrument ever built! (~80 g)
Demonstrated multiplexed readout, sensors yield, MCMs packaging, and sensors + electronics performance.









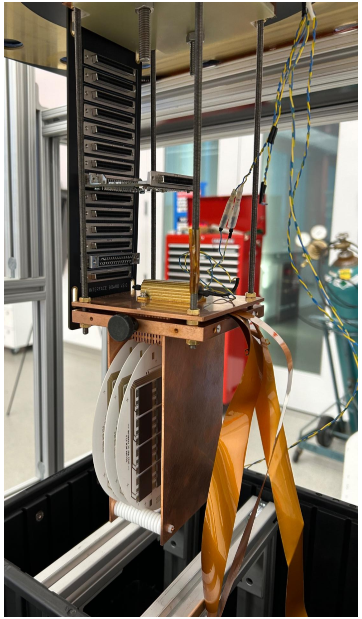
We read 160 sensors through 1 channel! and had 90% of them working without a preselection!

Setup will be commissioned soon at MINOS to perform mCPs search from NuMI beam (Dark BeaTS) → S. Perez talk!

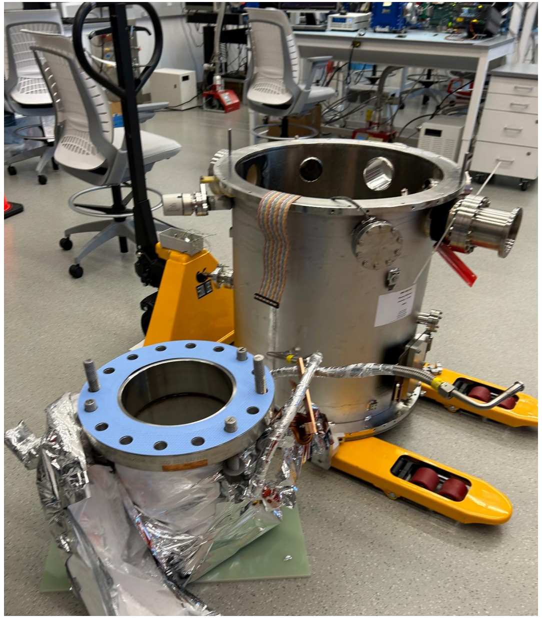
Oscura: Second demonstrator (June 2023)

10-inch pressurized vessel filled with N_2, with 3 prototype ceramic MCMs and cold front-end electronics with MIDNAs. **Demonstrated readout with ASICs, and sensors + cold front-end electronics performance and stability when cooled with N_2.**

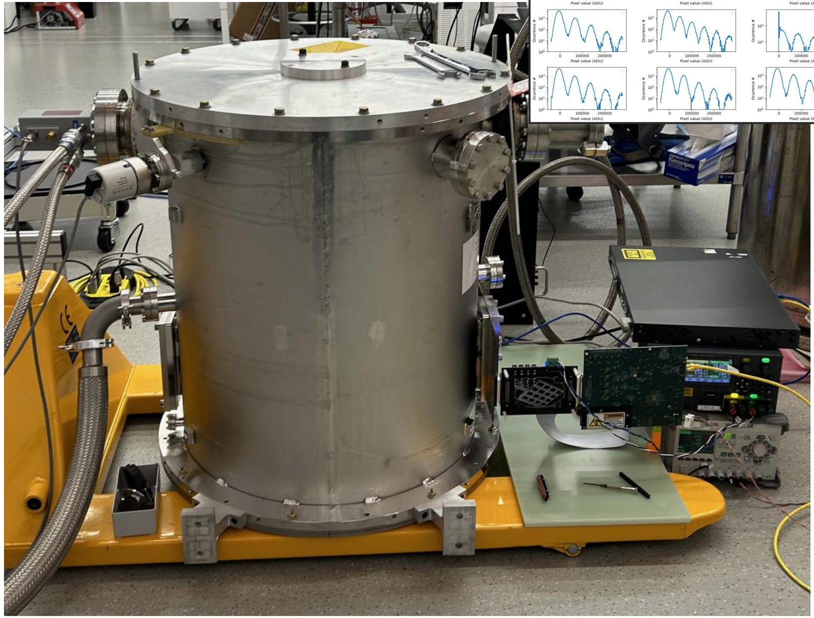
3 MCMs + board with ASICs

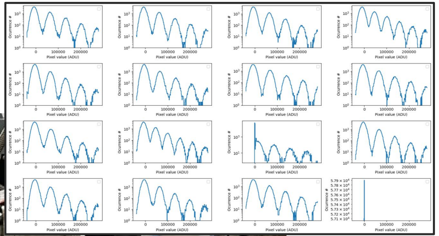


10-inch pressure vessel goes into vacuum vessel



Stable operations with N2 cryogenics

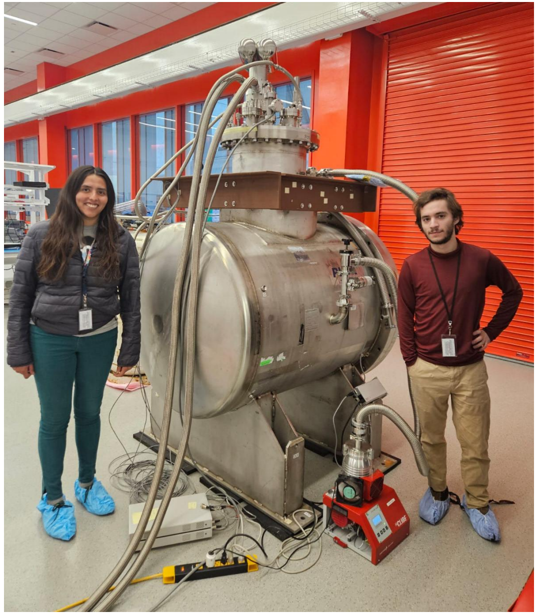


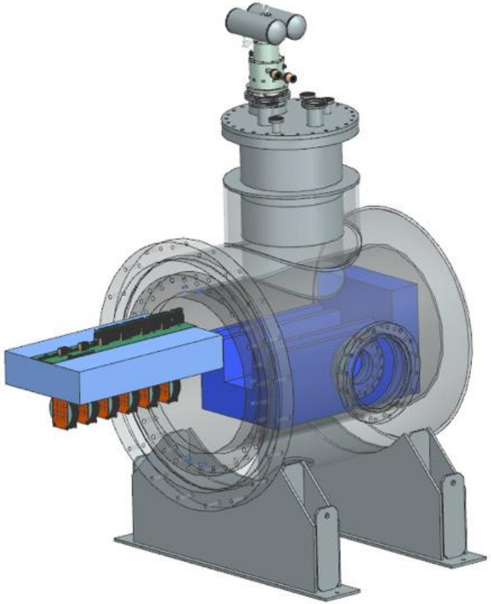


Oscura: Integration Test

Starting the integration of **vessel that can hold up to 6 SMs (780 g)**, filled with N2 at 15 PSI, with the final Oscura electronics design. Expected by end of 2024.

Short-term goals: Test systems integration and performance at large scale, high-volume assembly of MCMs, development of Oscura data processing and analysis tools.





Medium/long term goals: Use it as the underground testing vessel for final SMs pre-testing.

Parallel goals: Use it for early-science!
- Search for beam-produced mCPs

→ S. Perez talk!

Home › Journal of High Energy Physics › Article

Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab

Regular Article – Experimental Physics | Open access | Published: 13 February 2024

Volume 2024, article number 72, (2024) Cite this article

Fermilab

Take-home messages

- Oscura is the next step in skipper-CCD DM searches (~10 kg effective mass)
- It will have unprecedented sensitivity to sub-GeV DM interactions with electrons
- R&D is completed and main risks are addressed (sensors, electronics, cryogenics, background)
- Oscura preliminary design and execution plan are done
- Construction is planned for FY26, and operations at SNOLAB in FY29
- First demonstrators were successfully operated
- Integration test with 780 g is coming soon!

Stay tuned!

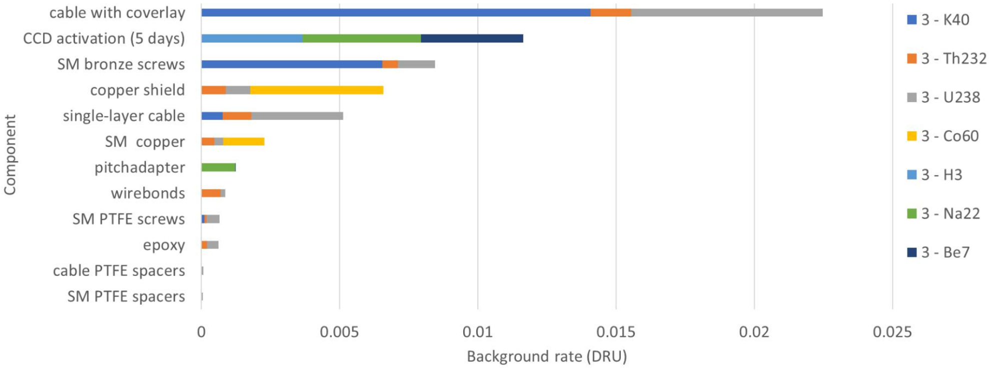
Oscura: Technical requirements

System	Parameter	Requirements	Units
Detector array	Number of pixels	33.1	GPix
Electronics	Number of channels	24,576	channels
Background	Rate (< 10 keV)	0.025	events/kg/day/keV
Pressure vessel	Operating temperature	140	K
	Operating pressure	15	PSI
Cryogenics	Capacity	1	kW
DAQ	Data handling	1	petabyte/year

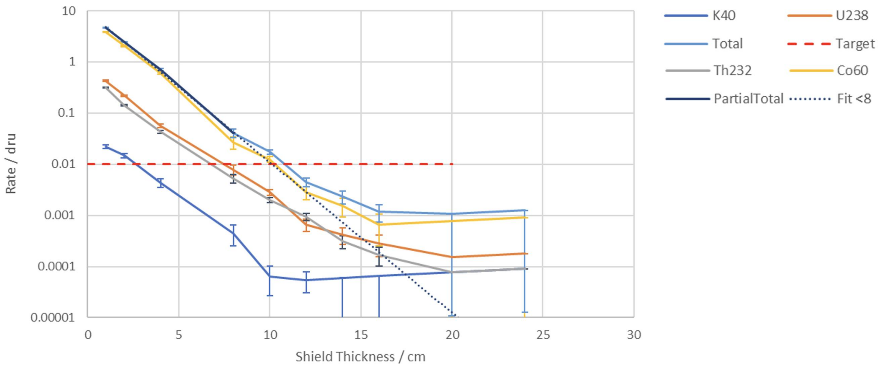
System	Parameter	2e- threshold	3e- threshold	Units
Detector array	Readout time	< 2	< 5	hours
Sensors	Readout noise	< 0.16	< 0.20	e- RMS
	Exposure-dependent 1e- rate	1×10^{-6}	1.6×10^{-4}	e-/pix/day
	Exposure-independent 1e- rate	$< 8.2 \times 10^{-8}$	$< 3.2 \times 10^{-5}$	e-/pix/exposure
Electronics	Pixel readout rate	> 188	> 76	pix/s

Oscura: Isotopic contamination control

Material selection for Super Modules

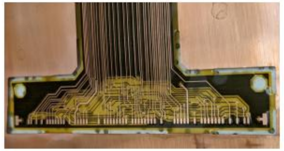


Electronics behind 15-cm-thick inner shield



Low-background flex cable [arXiv:2303.10862]

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



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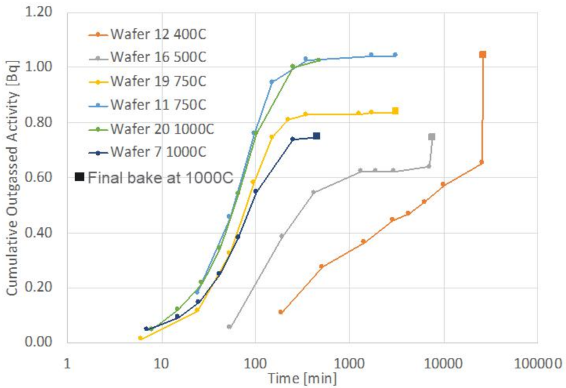
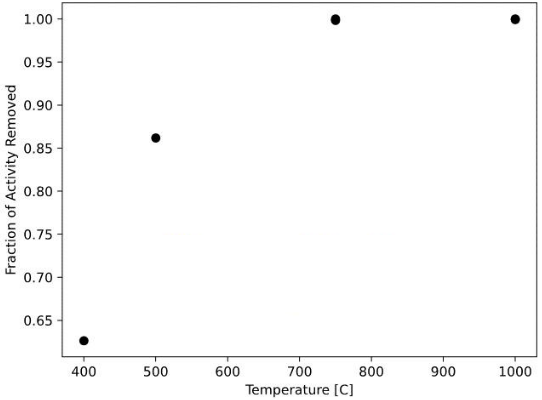
Oscura: Background cosmogenic activation control

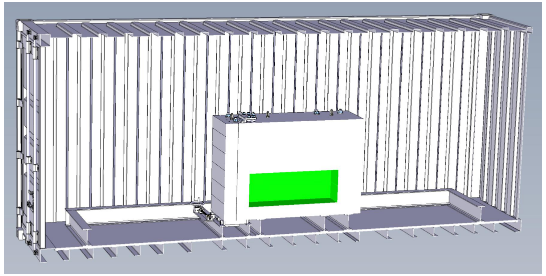
H^3 removal during sensors fabrication





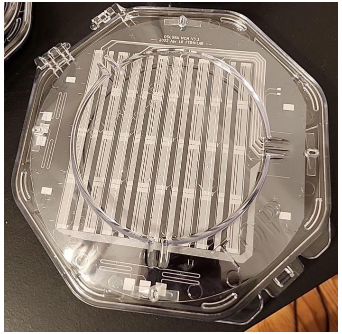
Shipping containers and transportation planning

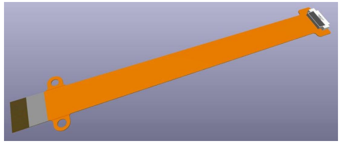
Duration [d]	Step	Location	Latitude	Longitude	Altitude [km]	Neutron Flux [n/cm2/sec]	Sea Level Factor	Shielding	Shielding Factor	Sea-level days
3	Ingot growing	TOPSIL, Frederikssund, Denmark	55.83	12.11	0.015	3.41E-03	1.16	None	1	3.48
14	Ingot storage	Hospital basement, Copenhagen, Denmark	55.68	12.56	0.045	3.51E-03	1.19	Basement	50	0.33
28	Transport to Montreal		55.68	12.56	0	3.36E-03	1.14	Shielded Container	20	1.60
3	Transport to Phoenix		45.51	-73.55	0.864	7.74E-03	2.63	Shielded Container	20	0.39
4	Wafering	SUMCO, Phoenix, AZ	33.41	-111.94	0.36	4.24E-03	1.44	Shielded Box	2.25	2.56
14	Storage	San Xavier, AZ	31.97	-111.09	1.08	7.89E-03	2.68	Shallow Underground	400	0.09
66	**PRE-FAB TOTAL**									**8.47**
32	CCD processing	Microchip, Tempe, AZ	33.41	-111.94	0.36	4.24E-03	1.44	Shielded Box	2.25	20.51
30	Storage	San Xavier, AZ	31.97	-111.09	1.08	7.89E-03	2.68	Shallow Underground	400	0.20
2	Transport to Fermilab	Fermilab, IL	31.97	-111.09	0.864	6.56E-03	2.23	Shielded Container	20	0.22
60	Packaging	MINOS tunnel	41.83	-88.26	0.216	1.50E-06	5.10E-04	None (already applied)	1	0.03
60	Testing	MINOS tunnel	41.83	-88.26	0.216	1.50E-06	5.10E-04	None (already applied)	1	0.03
1	Transport to SNOLAB		41.83	-88.26	0.216	4.16E-03	1.41	Shielded Container	20	0.07
185	**POST-FAB TOTAL**									**21.07**
251	TOTAL									29.53



Oscura: Background cosmogenic activation control

Underground module assembly





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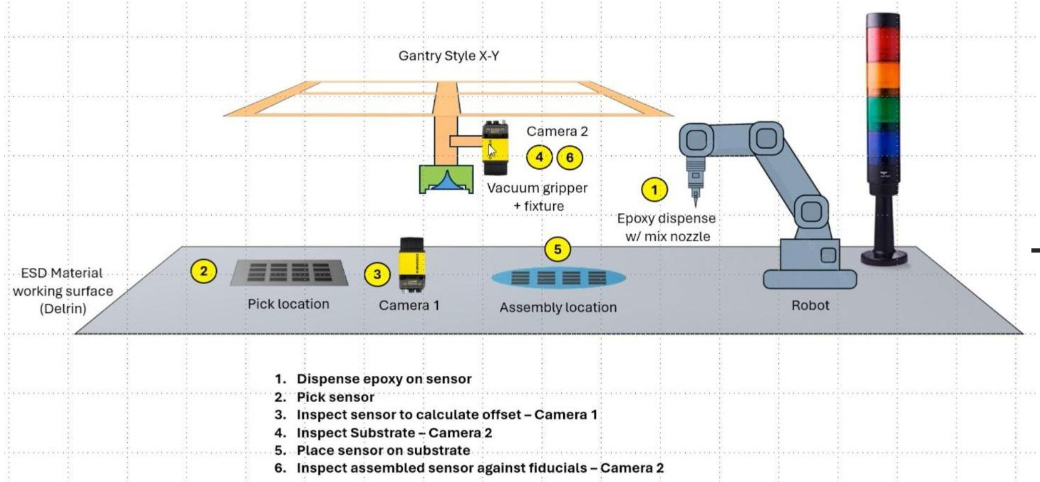

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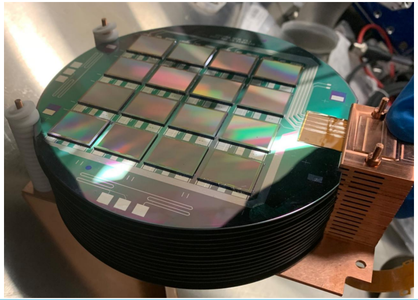
x 16 =



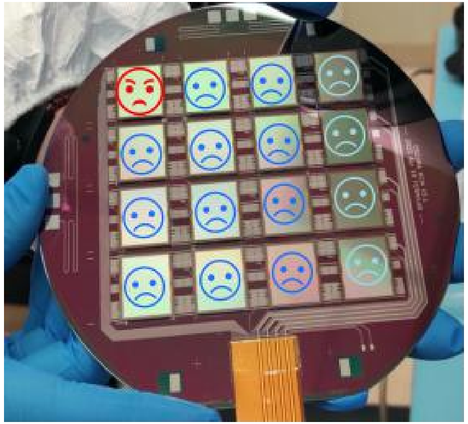
Oscura: Sensors on-assembly testing

Sensors in MCMs are tested during wire-bonding

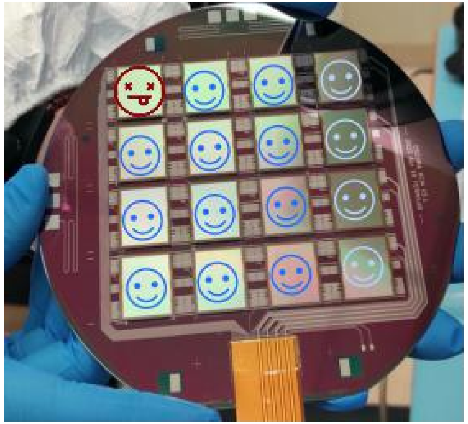
1. Wirebond one sensor
2. Use MCM tester
3. Unbond that sensor
4. Repeat this recipe for next sensor

FAILED

PASSED



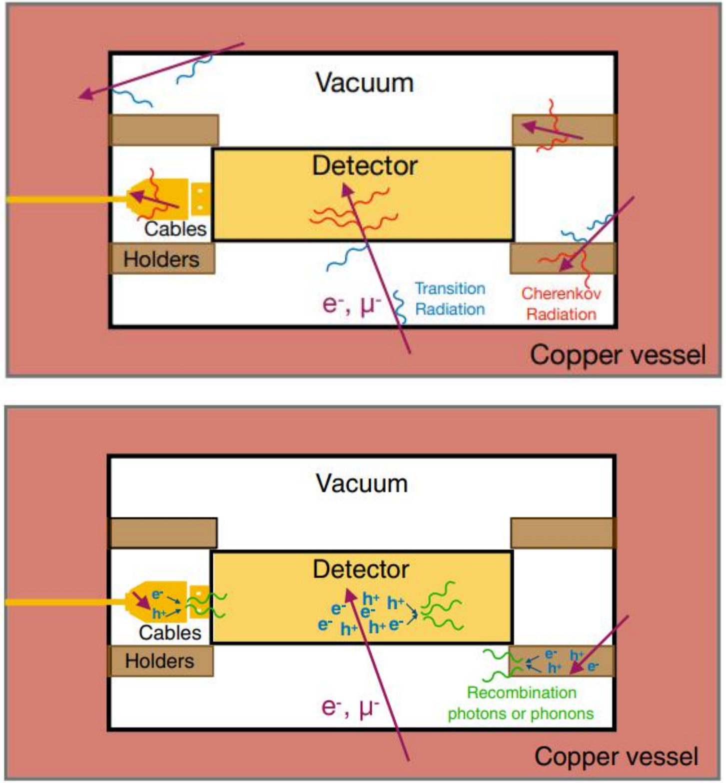
One very bad sensor can affect all neighbours



After unbonding, MCM is useful again

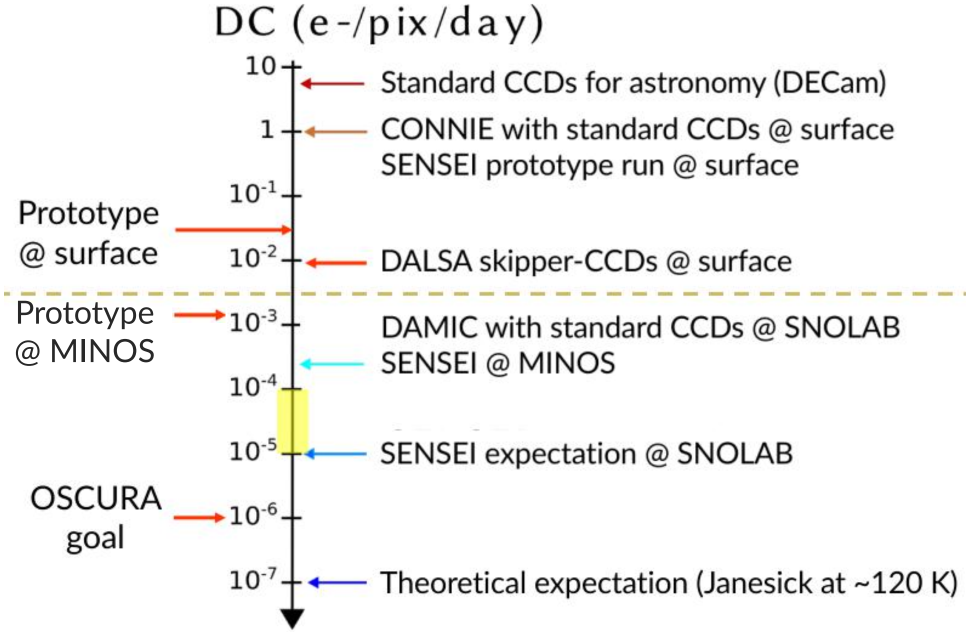
*After building ~40 MCMs, we have 1 very bad & 1 bad sensor every 16 (Yield > 85%)

Low-E background correlation with high-E events



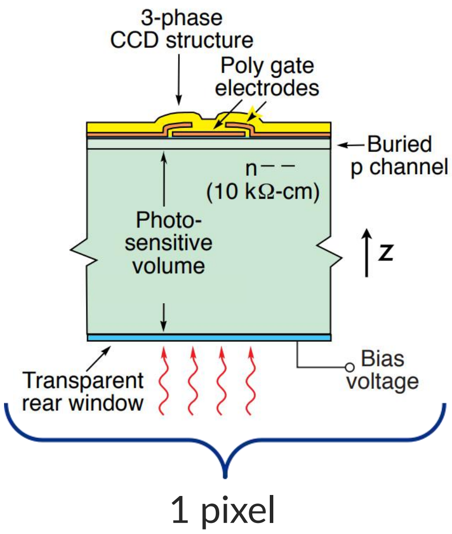
[PRX 12 (2022) 011009]

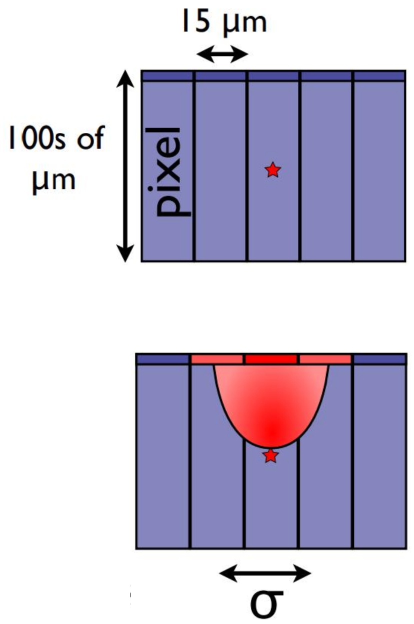
High-energy radiation interacting with setup results in low-E photons which can produce single-e- depositions that we are not efficiently extracting from our measurements

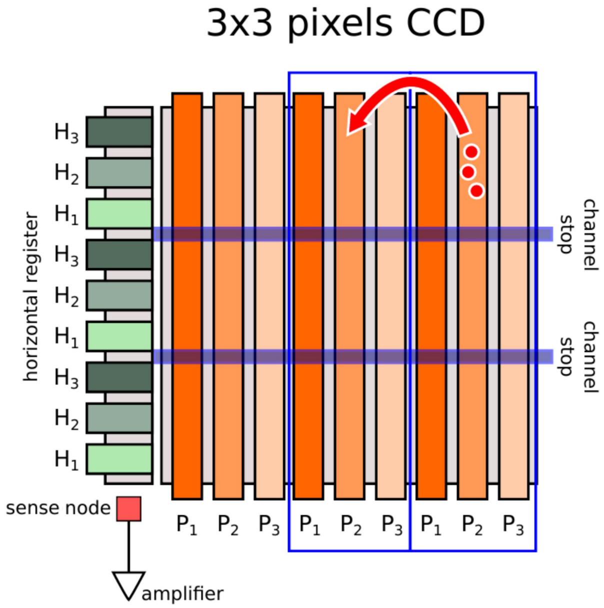


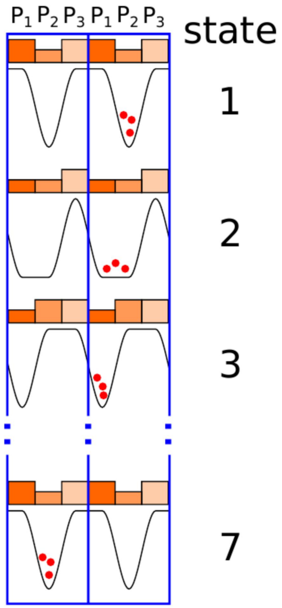
Scientific Charge-Coupled Devices: structure and operation

CCDs are essentially 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









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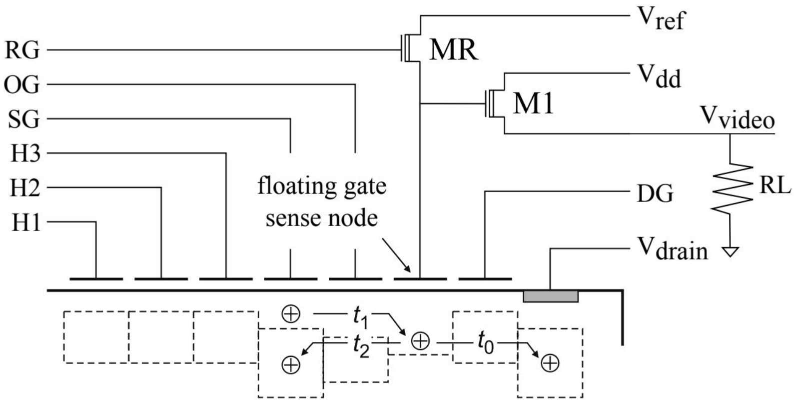
Skipper-CCDs: readout

Allows for multiple (N) measurements of same charge packet without being corrupted nor destroyed

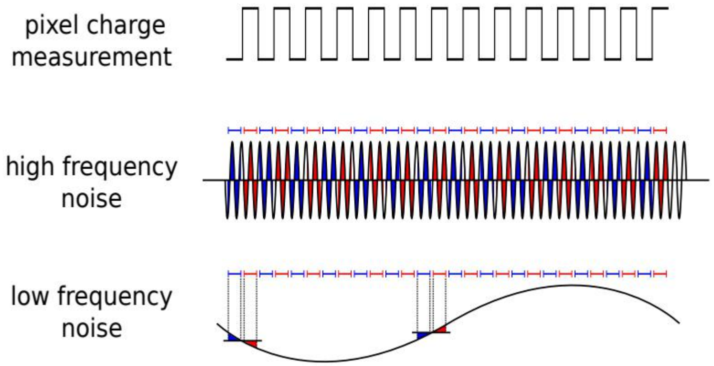
Averaging N off-chip, noise is reduced as $\sigma = \frac{\sigma_1}{\sqrt{N}}$

Readout time increases proportional to N



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:

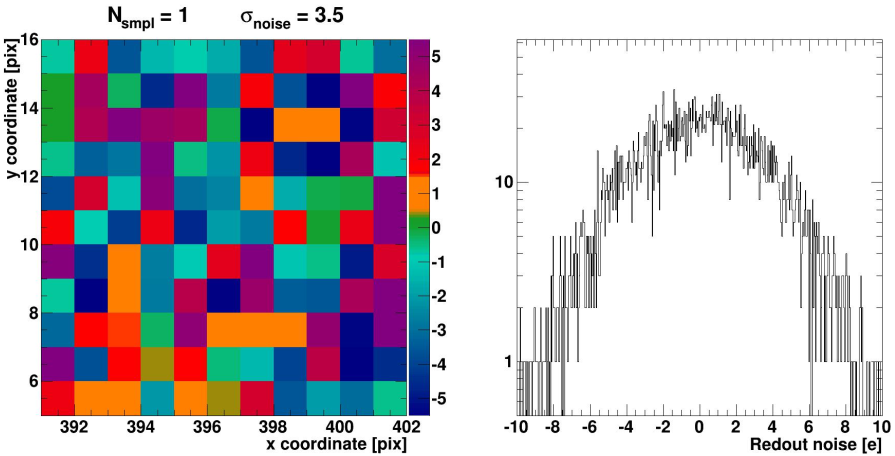


1. Pedestal integration
2. Signal integration
3. Charge = Signal - Pedestal
4. Repeat N times
5. Pixel value = average of all samples

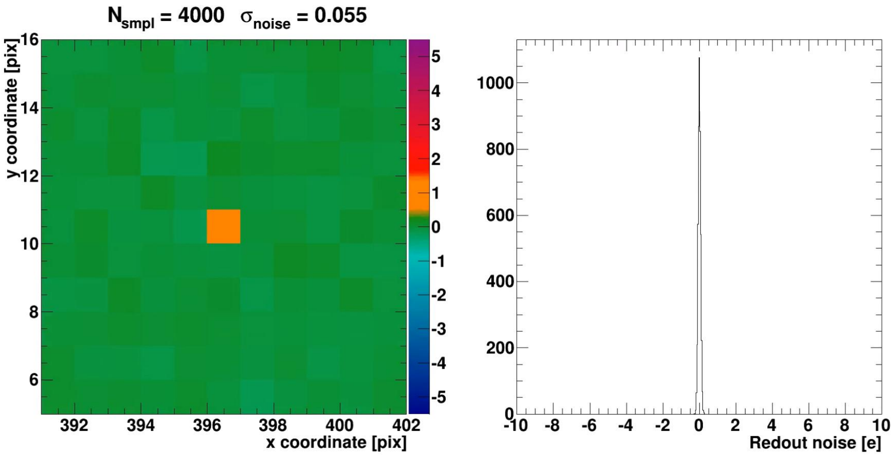
Low-frequency noise can be reduced!

Skipper-CCDs: readout noise

Standard CCD



Skipper-CCD



Taken from real data!