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

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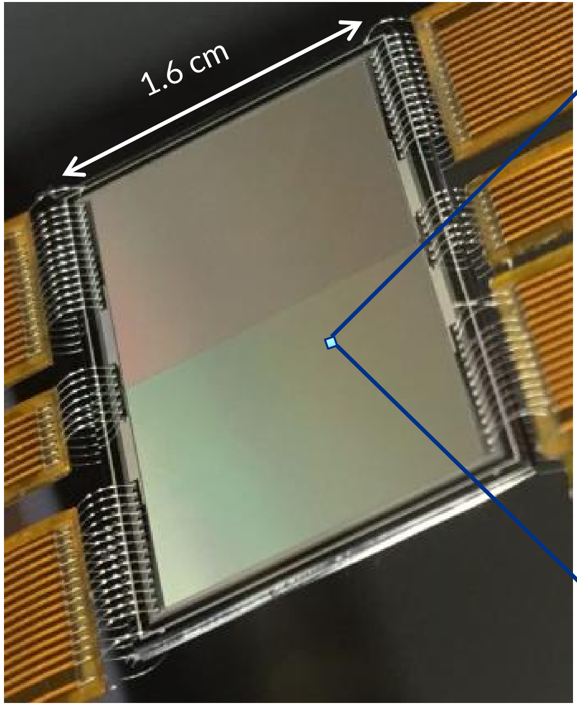
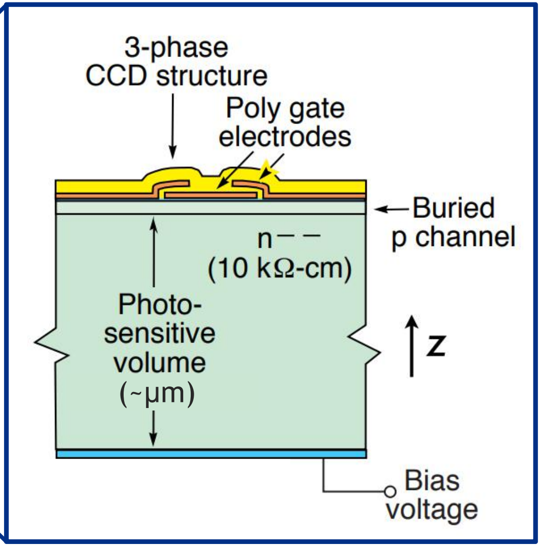
Scientific Charge-Coupled Devices

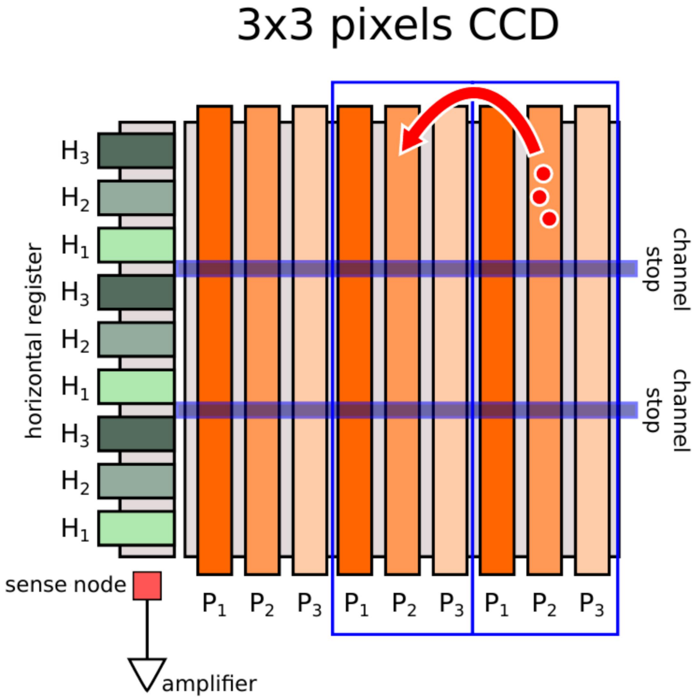
[10.1002/j.1538-7305.1970.tb01790.x]

CCDs are pixelated ionization sensors, usually made of silicon.
Ionizing radiation interacting in the substrate produces **electron-hole pairs**.
Charge is collected near the surface, transferred pixel by pixel and **read out in the sense node.**





1 pixel



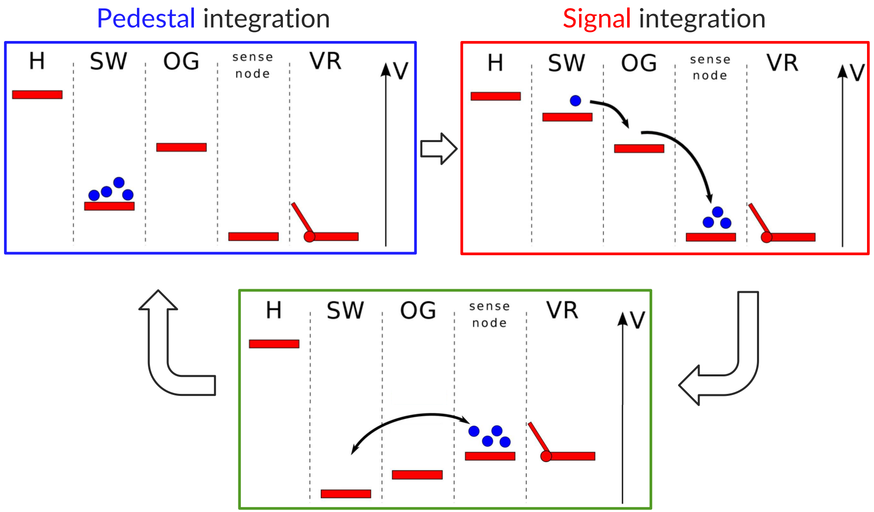
Fermilab

The skipper-CCD!

[1990ASPC....8...18J]

Floating gate sense node allows **multiple non-destructive measurements of same charge packet.**

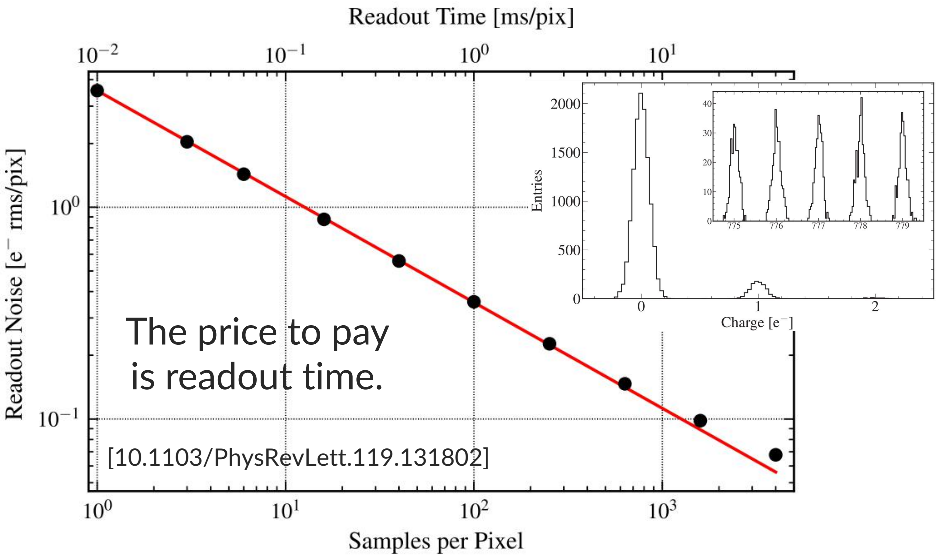
The N independent measurements are averaged off-chip and noise gets reduced as $\sigma = \frac{\sigma_1}{\sqrt{N}}$



(Charge value)$_i$ = Signal$_i$ - Pedestal$_i$

Charge value = $\frac{1}{N}\sum_{i=1}^{N}$ (Charge value)$_i$

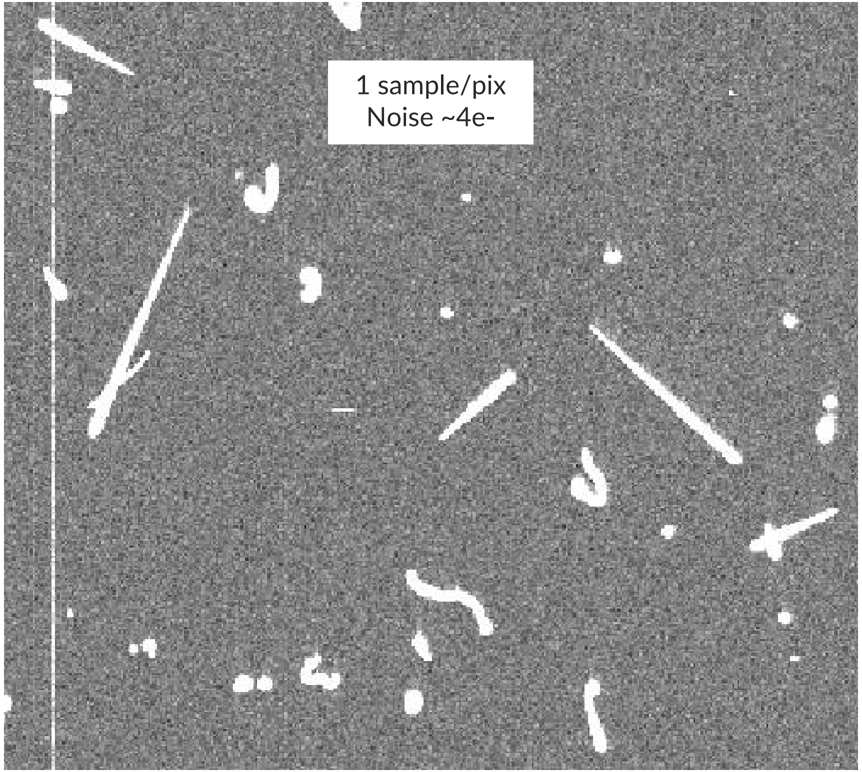
2017 → First demonstration of **discrete sub-electron noise** in a large-area detector designed by LBNL.

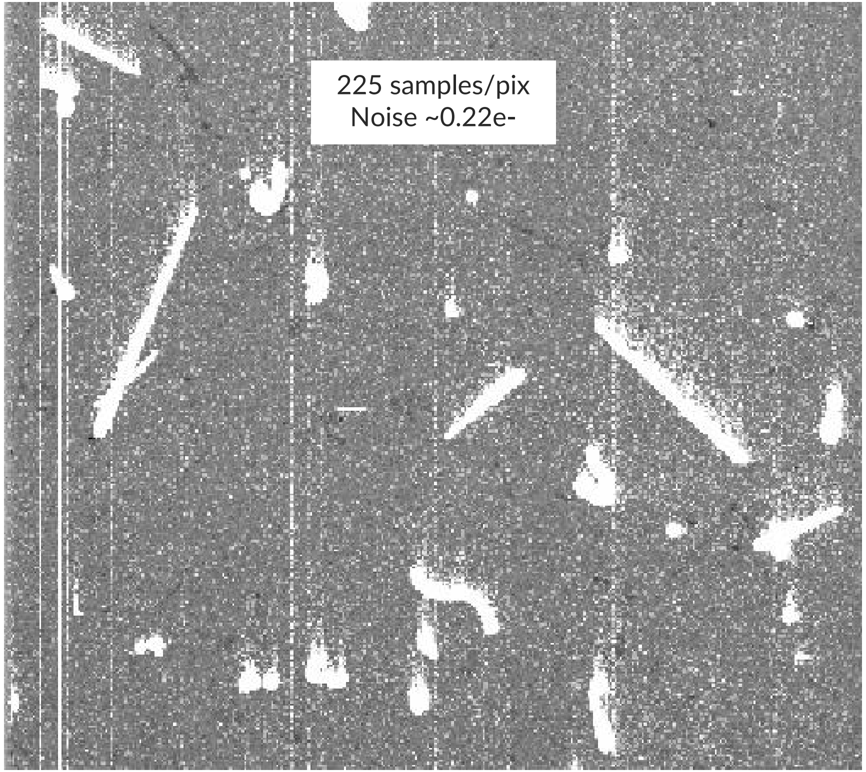


Fermilab

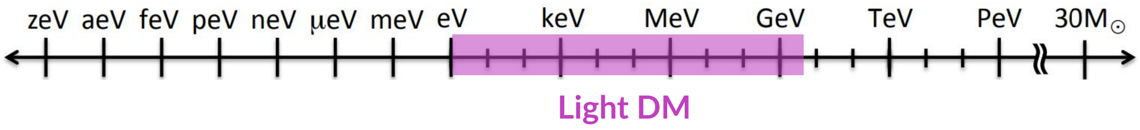
Skipper-CCDs are very powerful particle cameras!

Sub-electron noise allows to deeply explore what is invisible with standard CCDs.



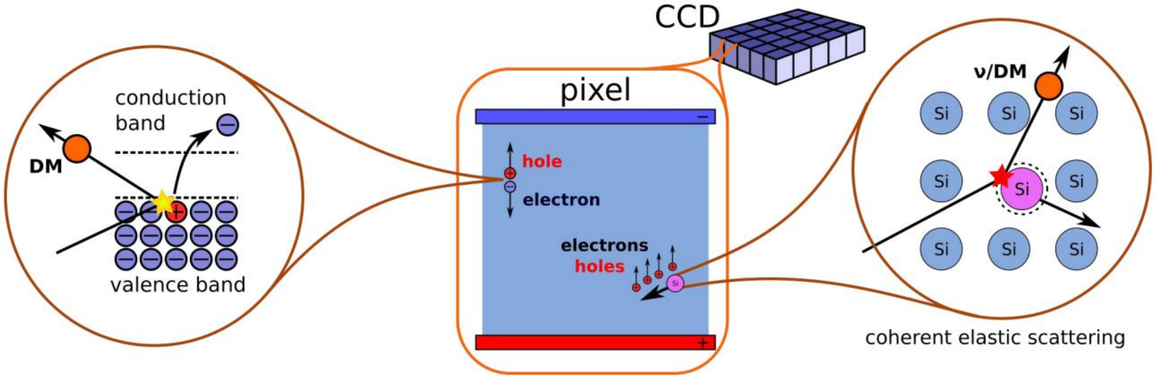


Skipper-CCDs for light dark matter direct detection

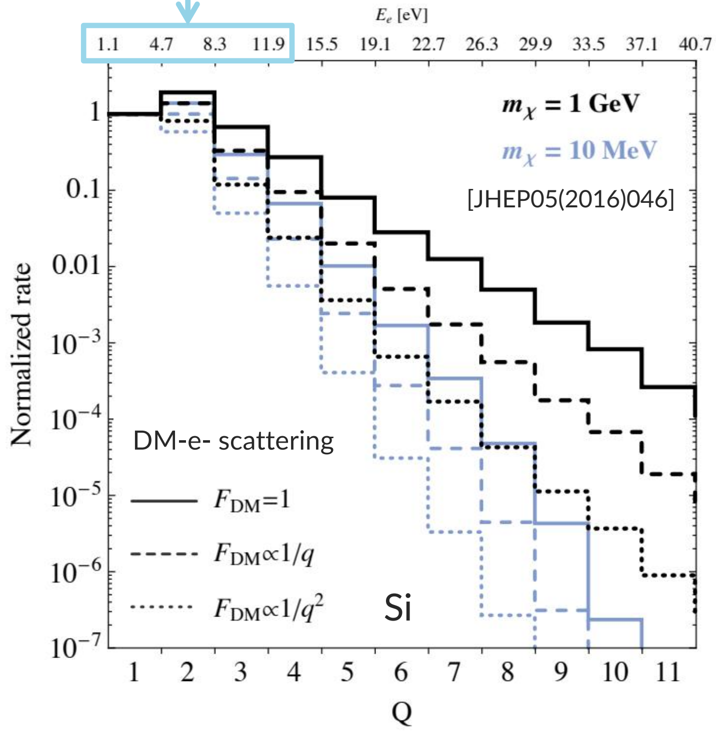


Light DM candidates are motivated by various **dark sector models**.

Light DM masses through different **detection channels**:
1-1000 MeV → DM-e- scattering
1-1000 MeV → DM-nucleus scattering through Migdal effect
1~1000 eV → DM absorption

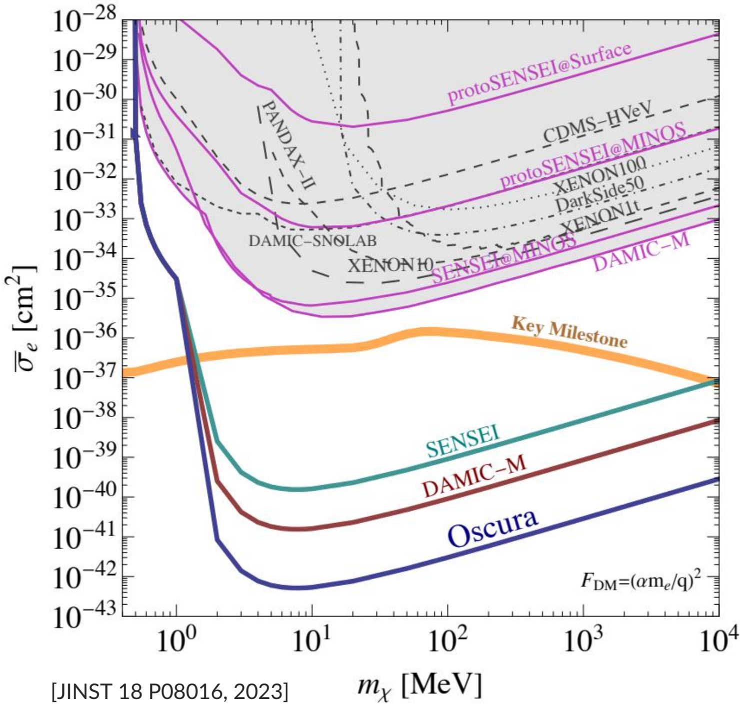


A low-threshold detector with little background is desired



Skipper-CCDs for light dark matter direct detection: ongoing program

Skipper-CCDs are constantly producing **world-leading limits on light DM candidates 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.



[JINST 18 P08016, 2023]

Experiment	Mass [kg]	#CCDs	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	~0.048 0.1*	22 50*	~50	1.4×10^{-5} 1×10^{-5}*	mid-2022
DAMIC-M	~1*	~209*	0.1*	1×10^{-5}*	~2025
OSCURA	**~10***	**~24,000***	**0.025***	**1×10^{-6}***	**~2029**

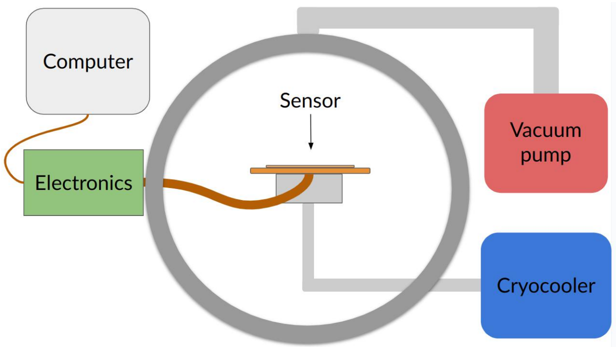
*goal

Latinos in Oscura: 

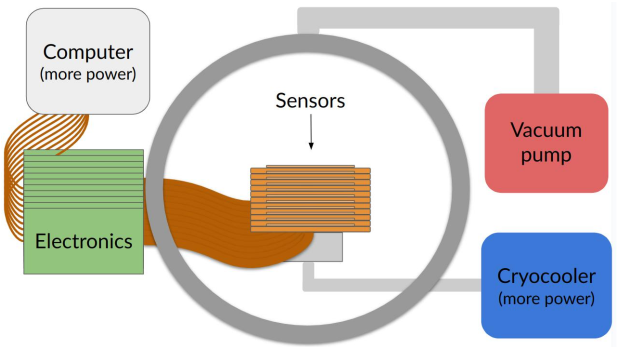
Fermilab

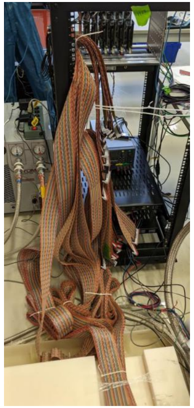
How to go bigger?

1 CCD



10s CCDs





20,000 CCDs?

Needs:
Mass-production of sensors
New sensors packaging
New cryogenics
New electronics
Strict background control

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

World largest camera (33.1 GPix)!

Detector payload

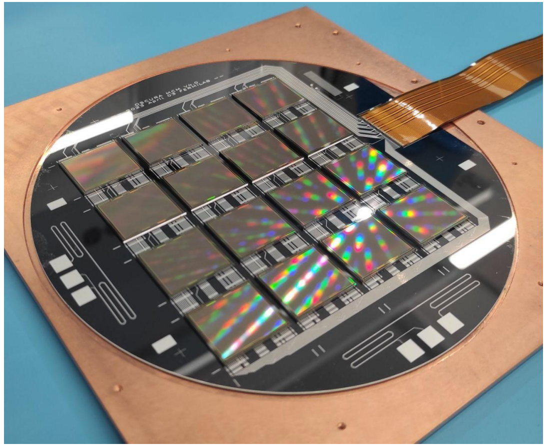
24,576 Skipper-CCDs = 1536 Multi-Chip Modules (MCMs) = **96 Super Modules** (SMs)

Skipper-CCD

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

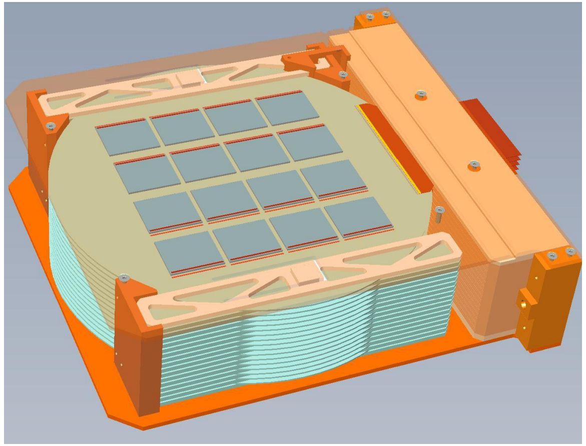
MCM

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



SM

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

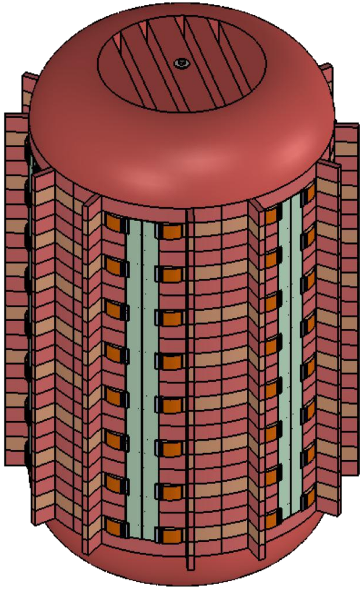


Oscura: Design of the 10-kg skipper-CCD detector

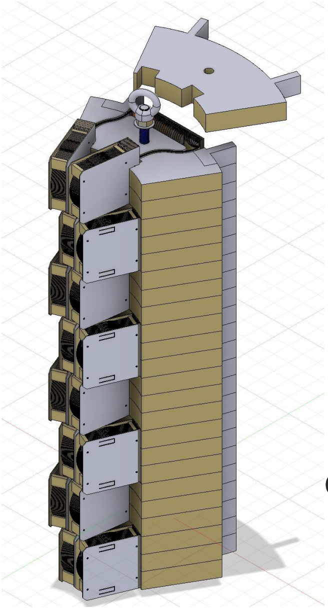
Detector payload with inner shield

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

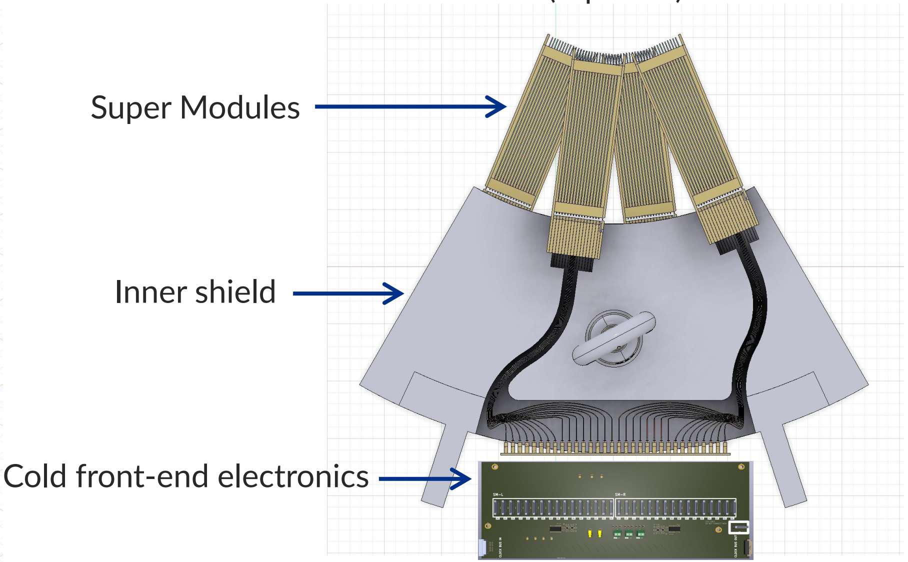
Cylinder-like array
~12.5 kg total (10 kg effective) mass



Slice of 16 SMs with inner shield



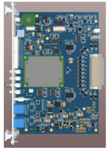
Proposed routing of flex cables
(top view)

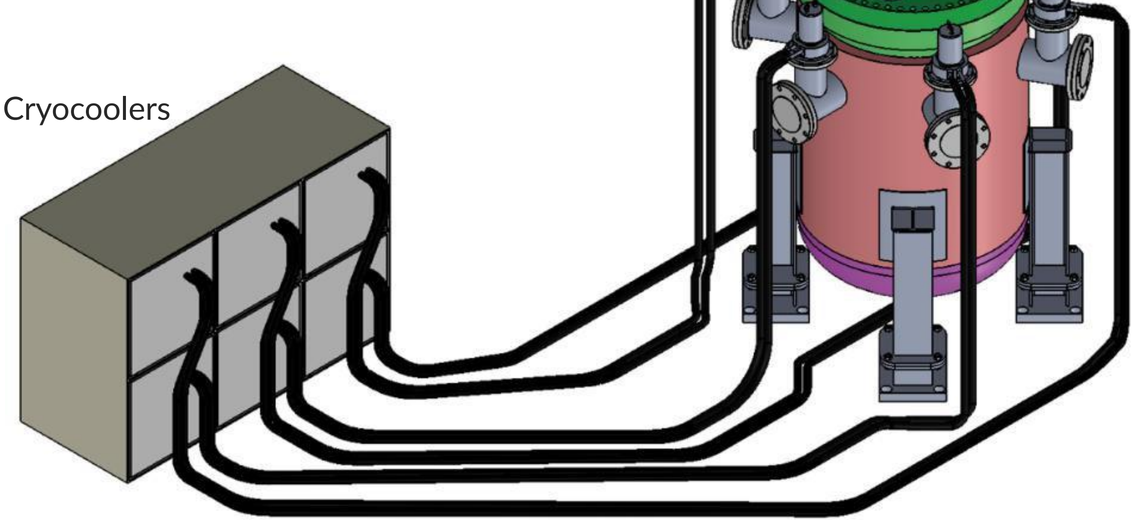


Oscura: Design of the 10-kg skipper-CCD detector

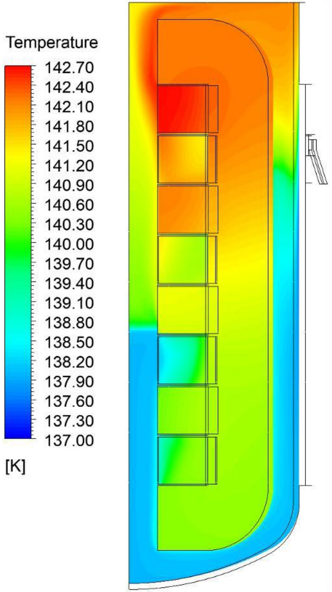
Pressure vessel

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

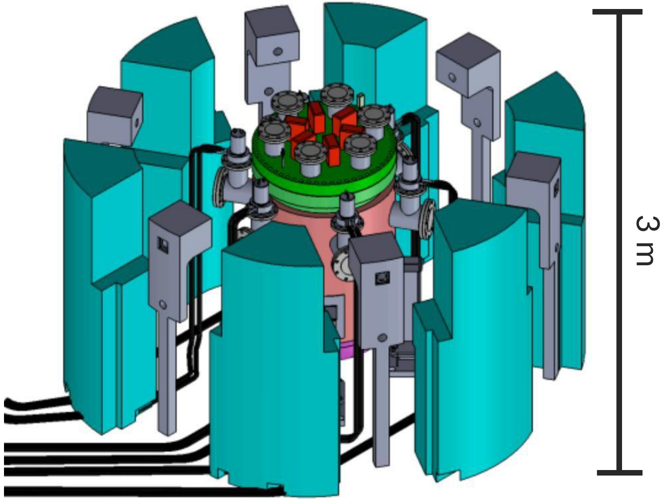


Oscura: Design of the 10-kg skipper-CCD detector

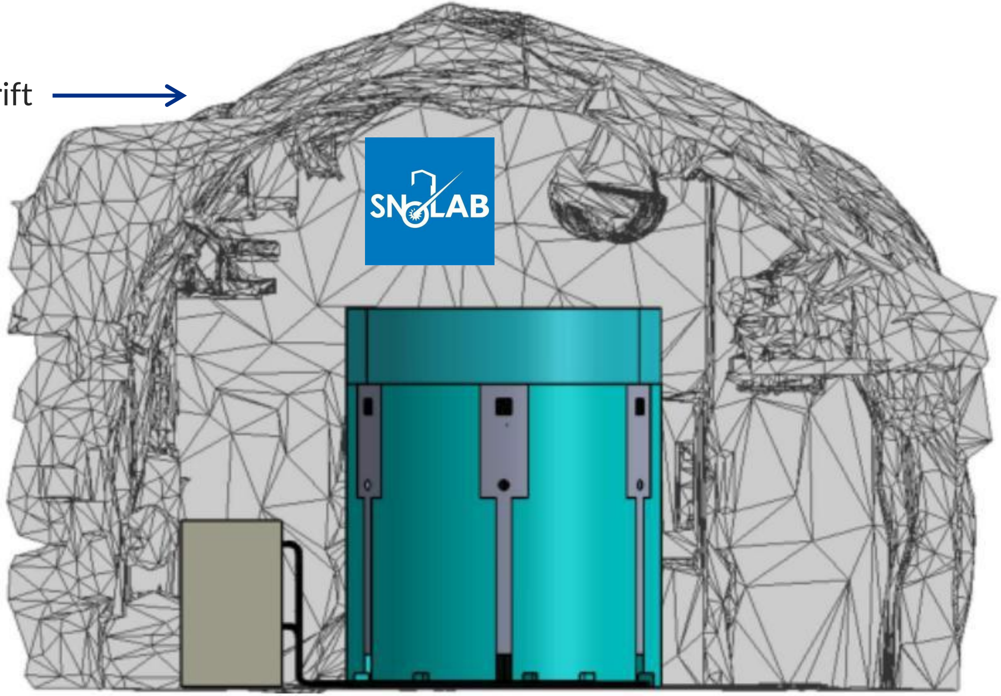
Pressure vessel with external shield at SNOLAB

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

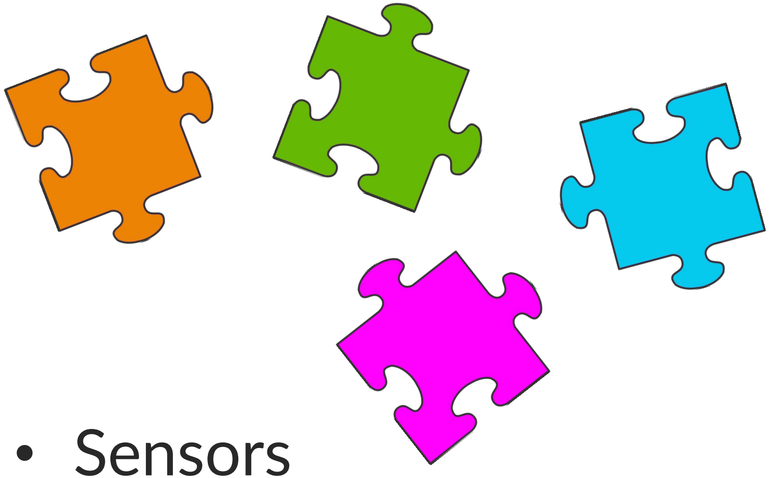
Outer shield assembly



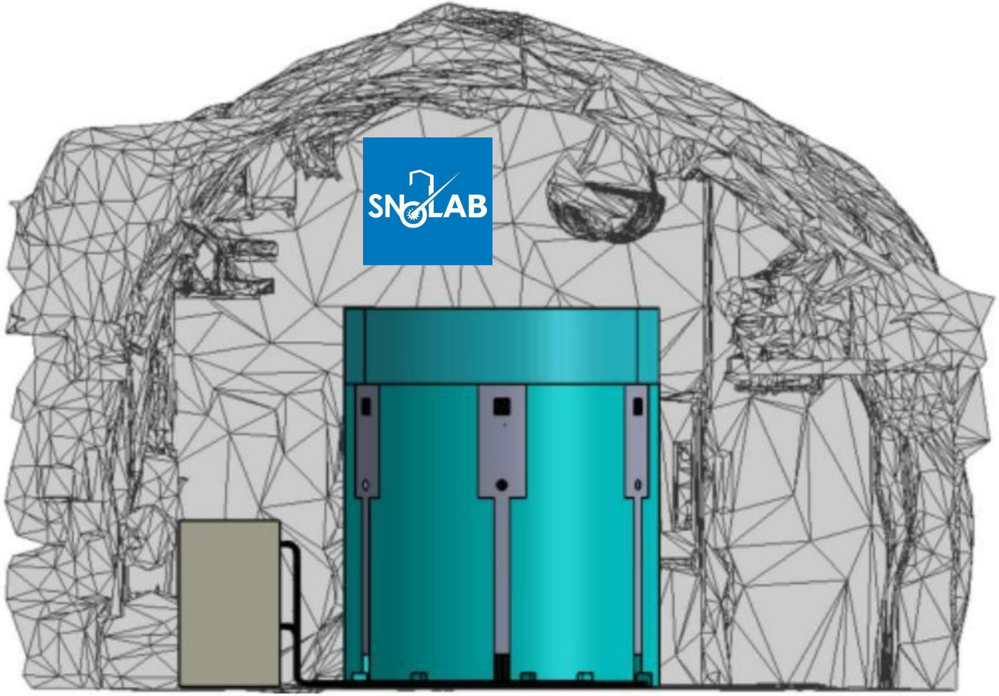
Oscura in the SNOLAB drift →



Let us go into the main pieces…



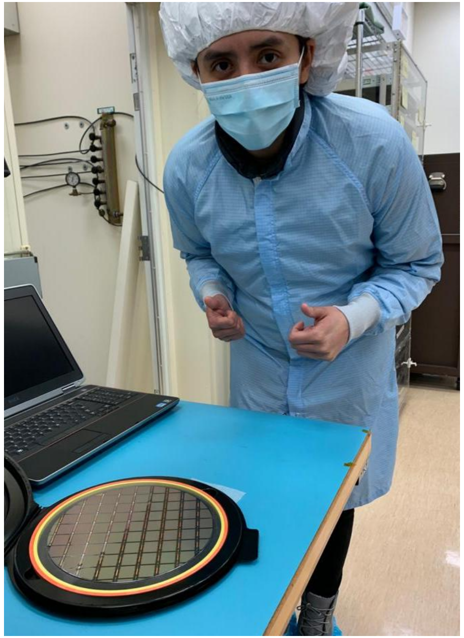
- Sensors
- Electronics
- Background control



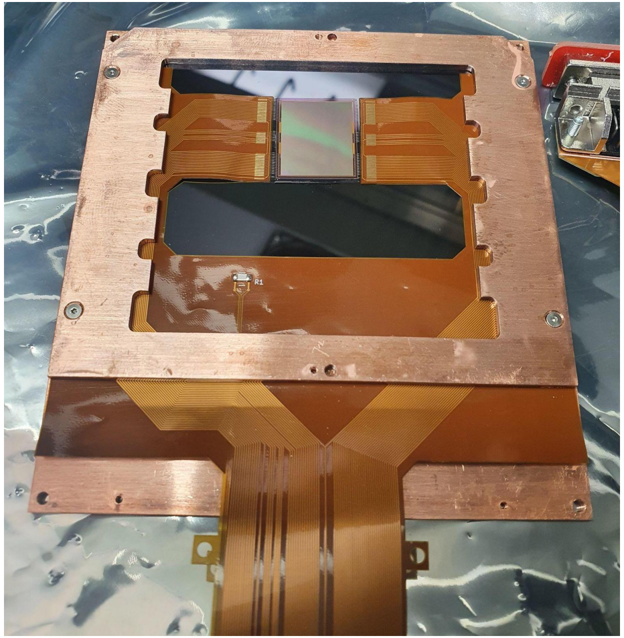
Oscura: Sensors

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



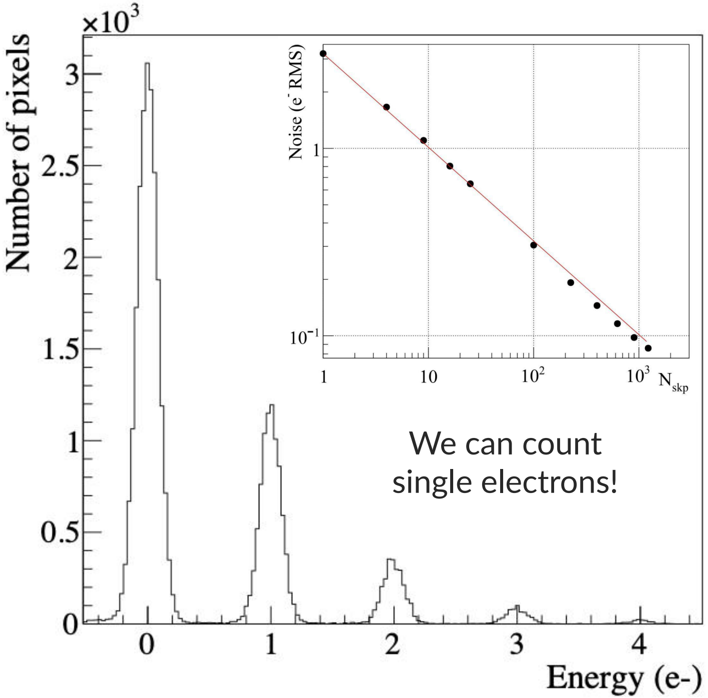
Underground testing setup

Fermilab

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.**



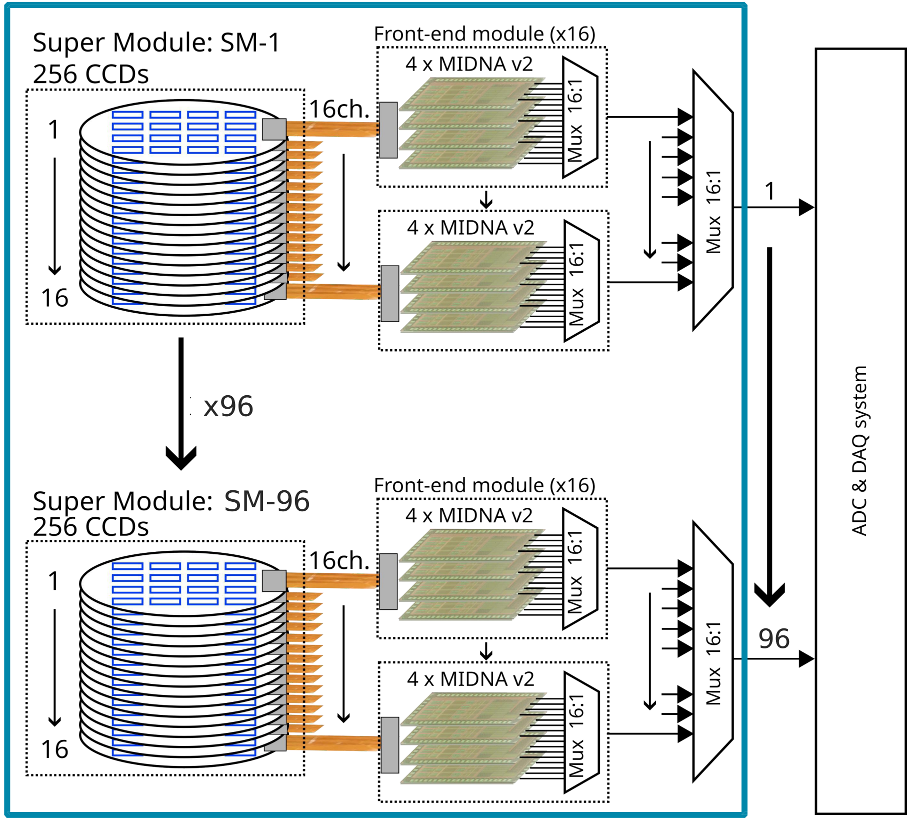
Parameter	3e- threshold	Performance
Pixel readout rate [pix/s]	> 76	111
Readout noise [e- RMS]	< 0.20	0.19
Exposure-dependent 1e- rate [e-/pix/day]	1.6×10^{-4}	1.8×10^{-3}
Exposure-independent 1e- rate [e-/pix/image]	$< 3.2 \times 10^{-5}$	$< 4.8 \times 10^{-4}$

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

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

Oscura: Readout electronics

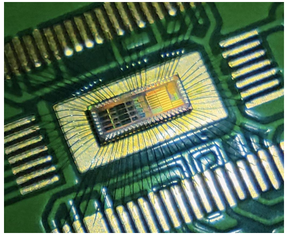
[Sensors 2022, 22(11), 4308]



Cold front-end electronics:

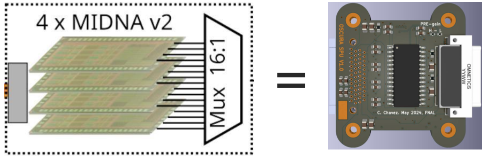
MIDNA-ASIC → Design by F. Alcalde (Inst. Balseiro)

[10.1109/TCSI.2023.3256860]

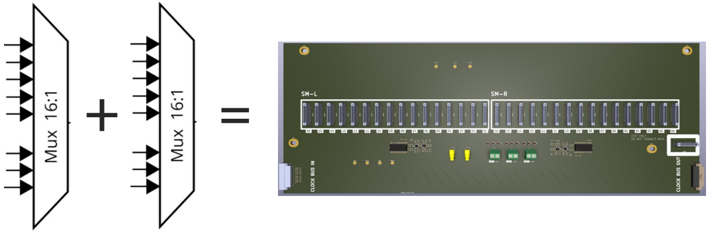


actual size

2 multiplexing stages → 256 channels = 1 signal



x1536
(1 per MCM)



x48
(1 per 2 SMs)

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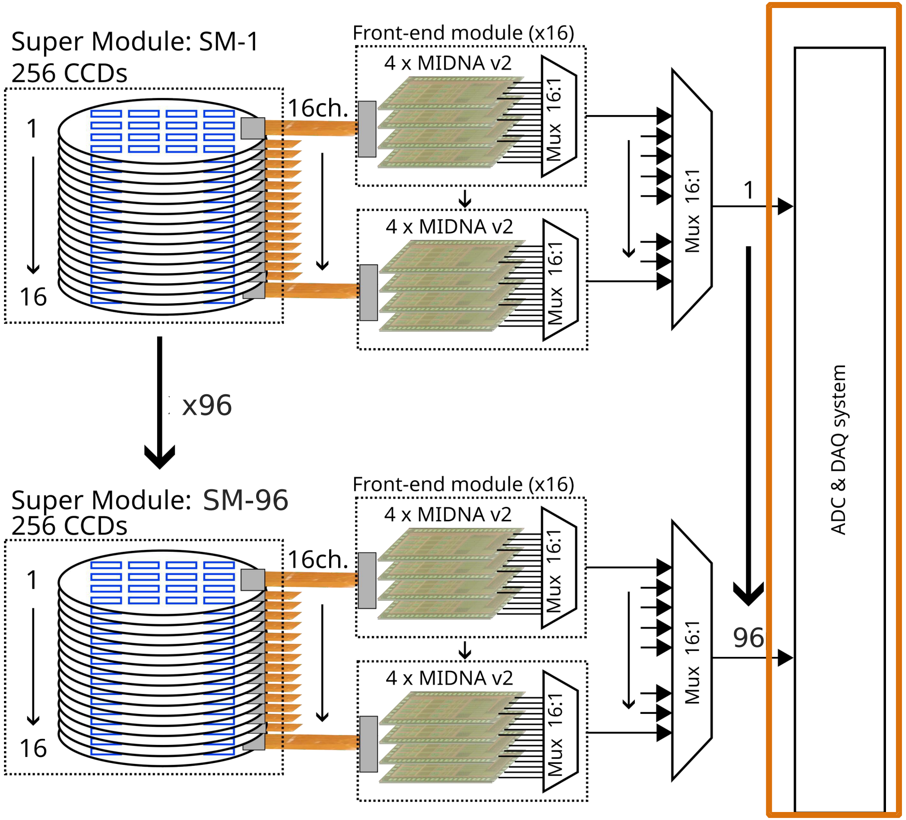
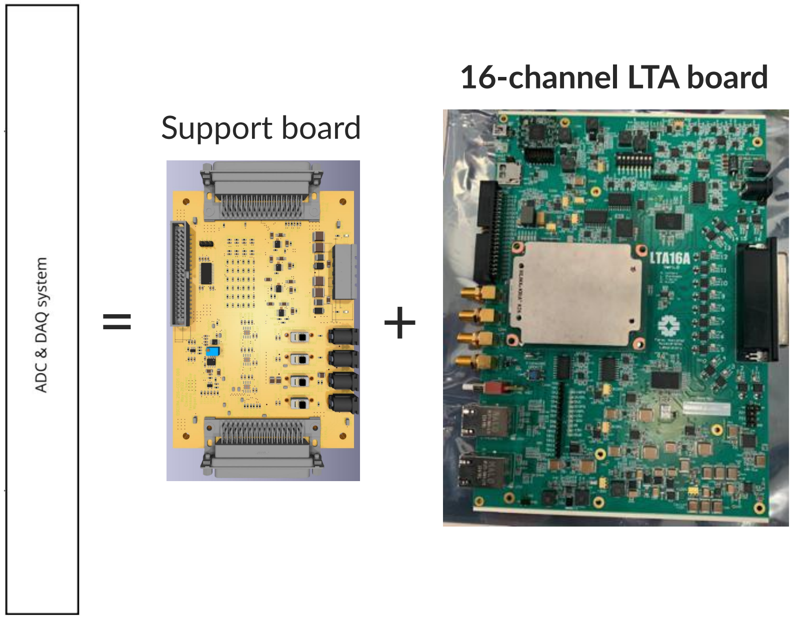
Oscura: Readout electronics

[Sensors 2022, 22(11), 4308]



Warm back-end electronics:



x6
(1 per 16 SMs)

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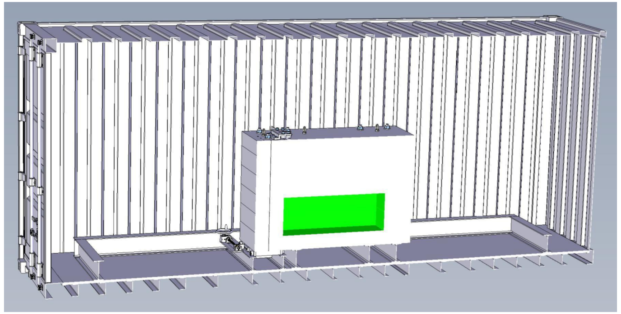
Oscura: Background control

Decisions driven by simulations and by expertise from pathfinder experiments.

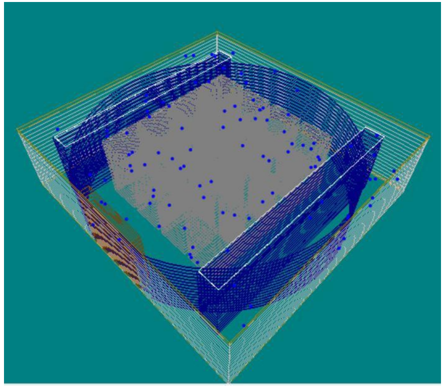


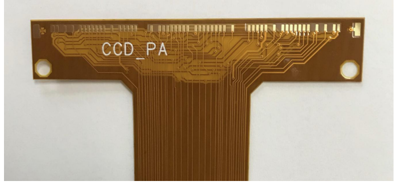
Limiting factors:

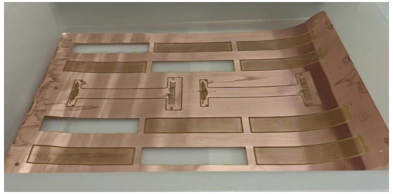
- Cosmogenic activation
  → Shielded shipping containers and transportation planning
  → Remove activation products during sensors fab [PRD 102, 102006]
  → Underground module assembly

- 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

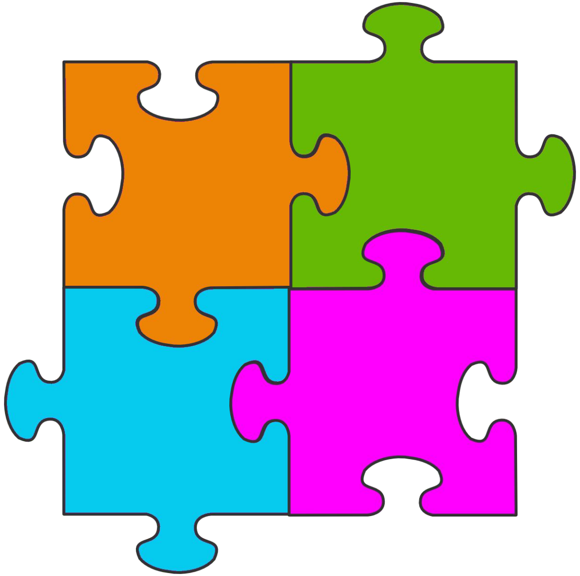






Fermilab

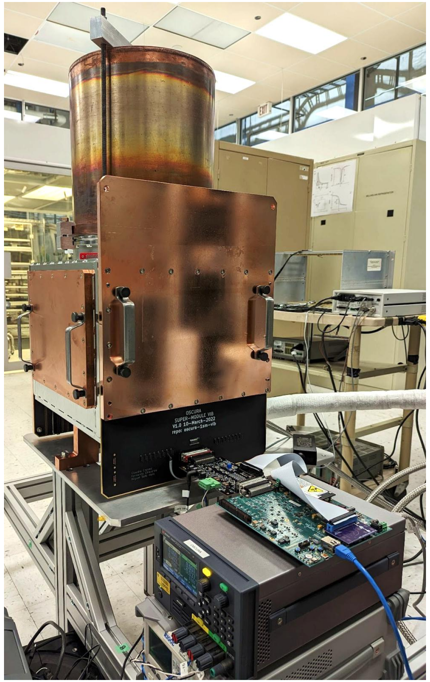
How is integration going?

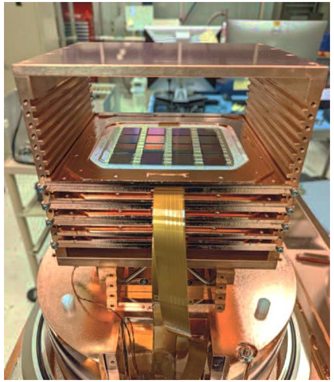


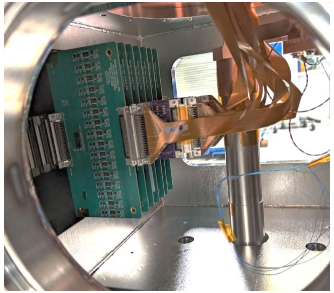
Oscura: First demonstrator (Sept 2022)

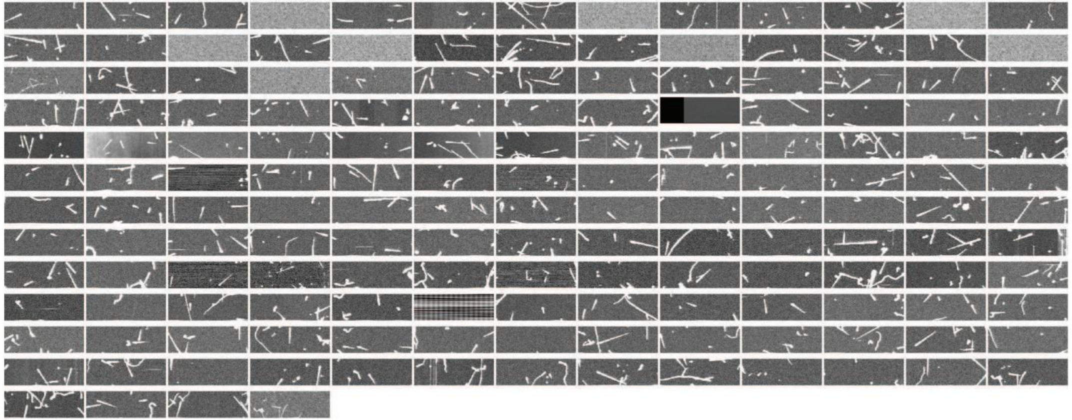
[JINST 18 P01040]

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.









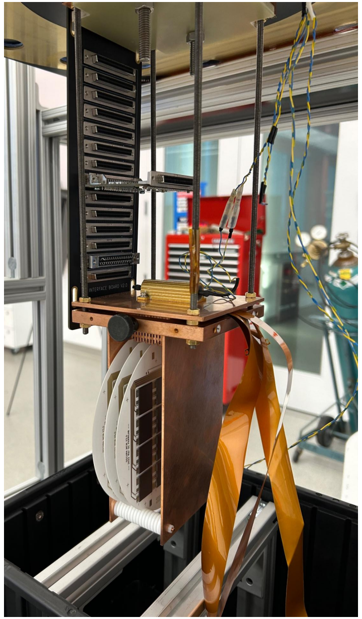
We read **160 sensors through 1 channel!** and had 90% of them working without a preselection!

Setup will be commissioned soon at MINOS with 16 MCMs to perform mCPs search from NuMI beam (Dark BeaTS)

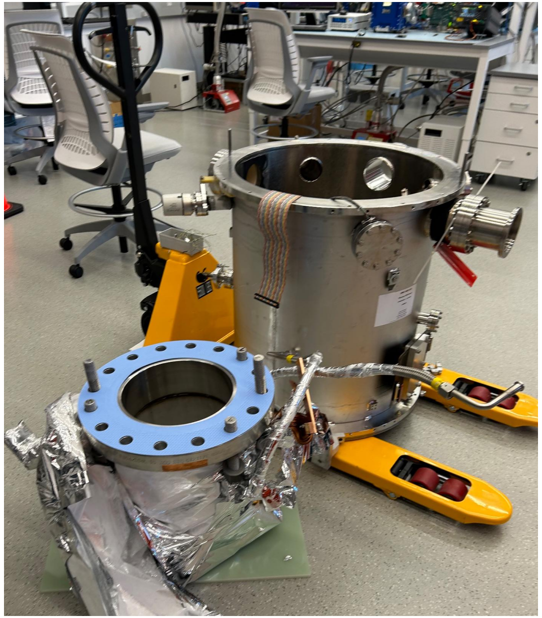
Oscura: Second demonstrator (June 2023)

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.**

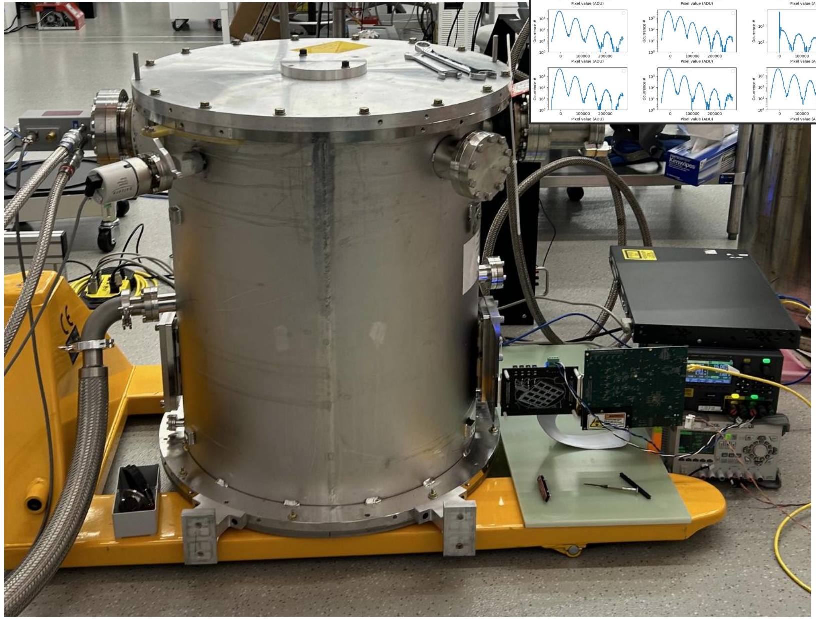
3 MCMs + board with ASICs

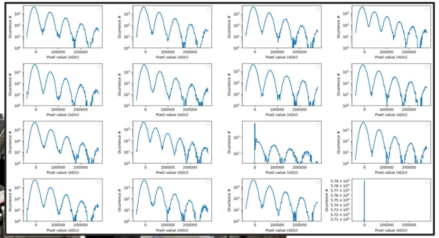


10-inch pressure vessel goes into vacuum vessel



Stable operations with N2 cryogenics

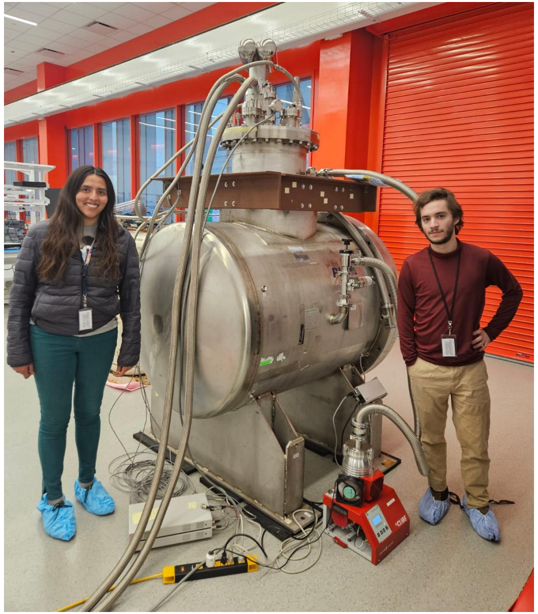


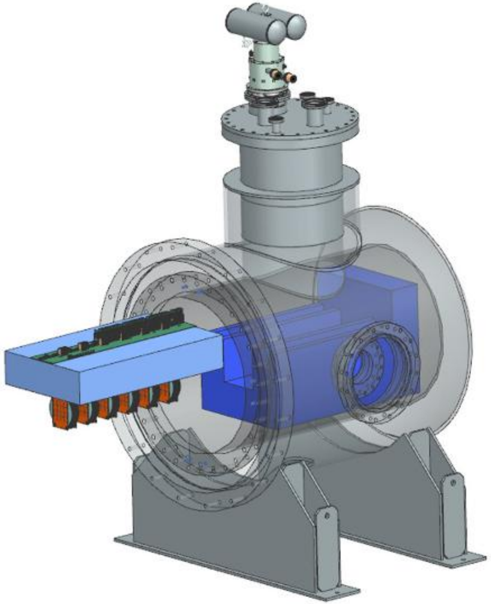


Oscura: Integration Test

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 beginning of 2025.

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


Home > Journal of High Energy Physics > Article

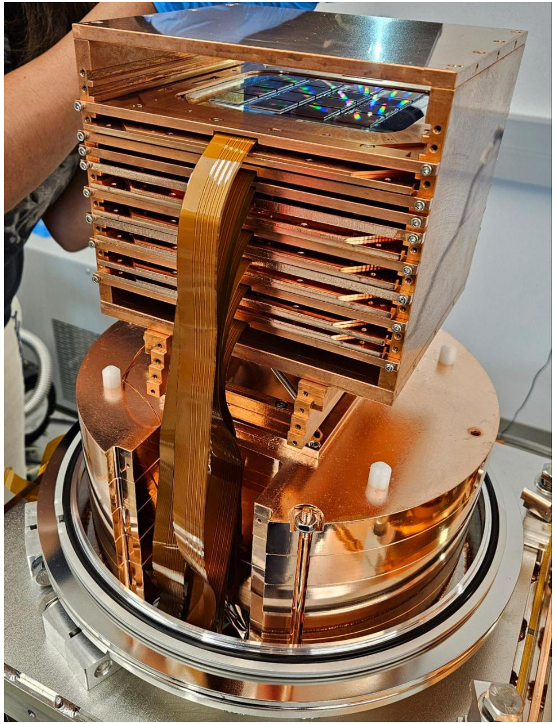
Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab

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

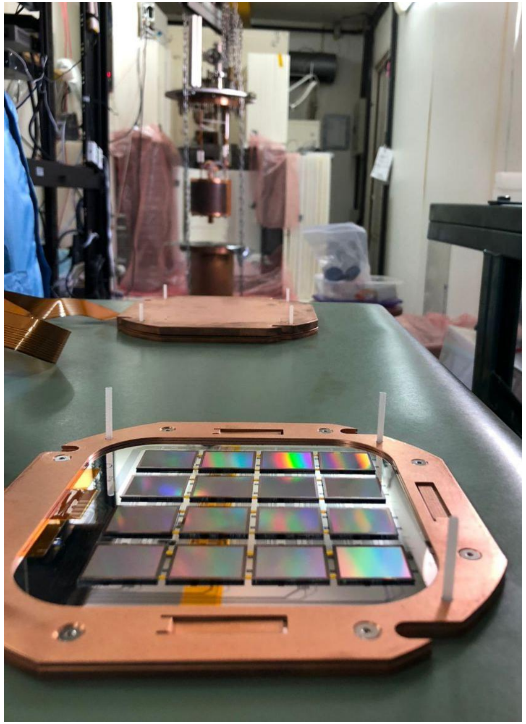
Volume 2024, article number 72, (2024) Cite this article

Interesting projects in synergy with Oscura

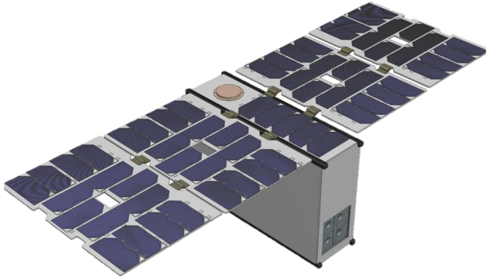
Dark BeaTS @ Fermilab
Beam-produced mCPs search

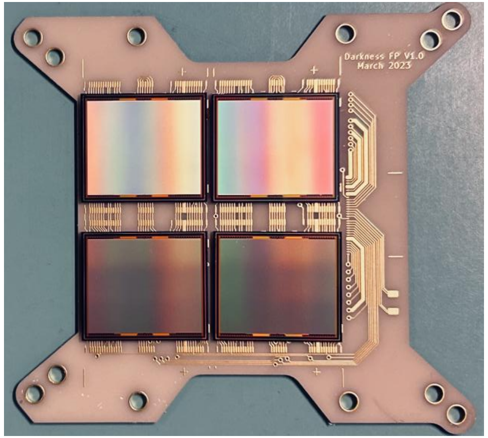


CONNIE @ Brazil
Reactor neutrino experiment



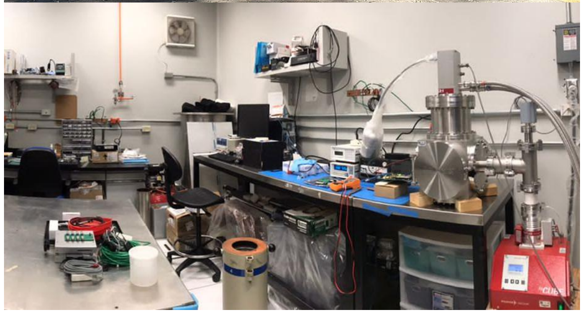
Darkness @ LEO
Milky Way diffuse X-ray emission





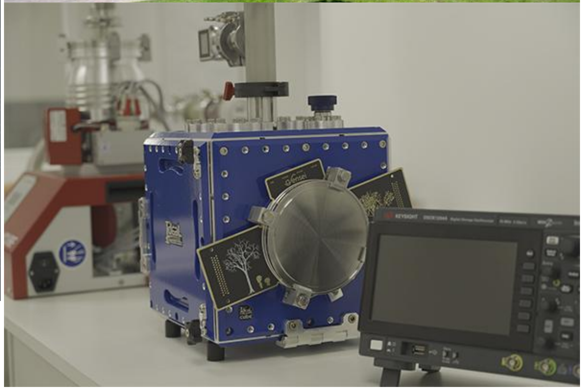
Oscura: Sensors. Latin american participation

Laboratorio de Detectores
ICN, UNAM, Mexico City
Alexis Aguilar, Juan Carlos D'Olivo



First time we saw e-peaks with
Oscura sensors (Nov 23, 2021)

LAMBDA
Pabellón 1, UBA, Buenos Aires
Dario Rodrigues



Oscura: Readout electronics. Latin american participation

UNIVERSIDAD NACIONAL DE ASUNCION · VITAM IMPENDERE VERO · REPUBLICA DEL PARAGUAY · 1889

Jorge Molina

UNIVERSIDAD NACIONAL DEL SUR · UNS · BAHÍA BLANCA

Fernando Chierchie

Instituto Balseiro

Fabricio Alcalde

UNC

Miguel Sofo

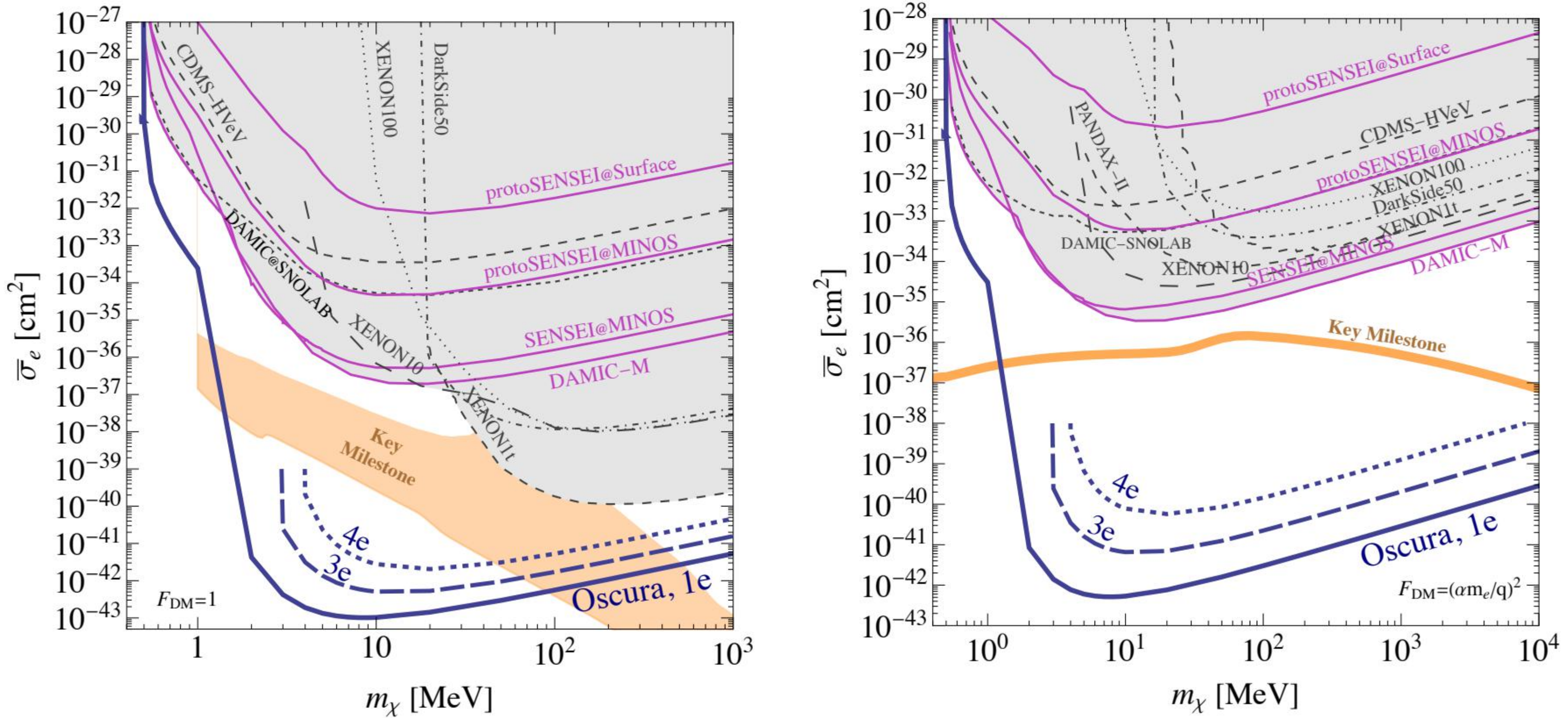
Take-home messages

- Skipper-CCDs are a powerful technology to search for light DM.
- DM search with skipper-CCDs is a strong and ongoing program aiming for more massive detectors with less background.
- Oscura, the largest of these efforts (~10 kg effective mass), has enabled the scaling of this technology to multi-kg detectors.
- Oscura is ready to, hopefully, start construction in 2025/6.
- Oscura demonstrators are being successfully operated, some will be used for early science.
- Oscura has a big working group of latinos! You are invited to join us.

Stay tuned!

Oscura: Sensors performance to science reach

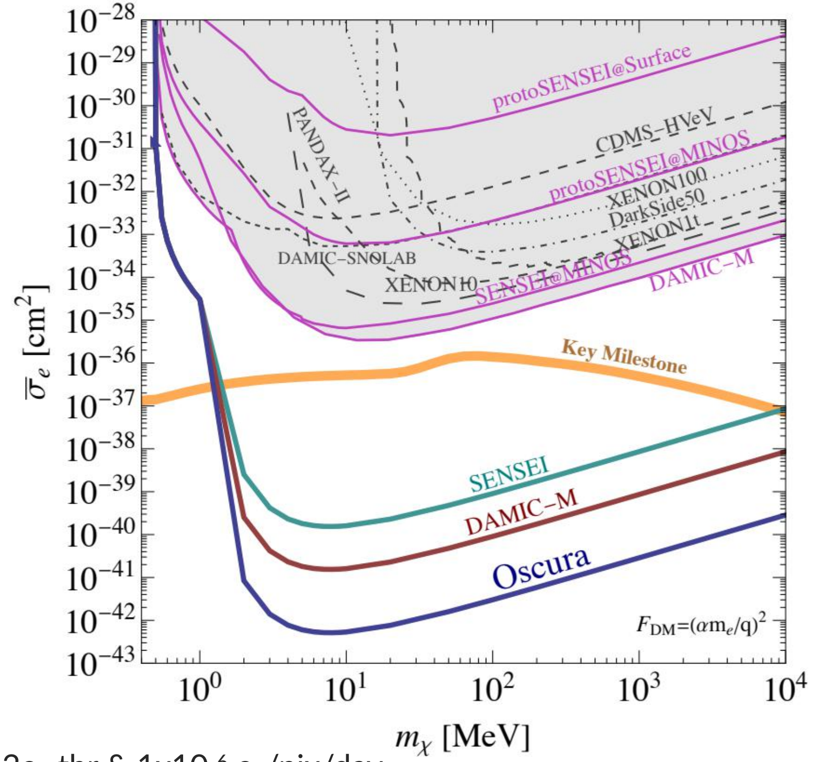
With current sensors performance, projected sensitivities lie between the 3e- and 4e- threshold curves.

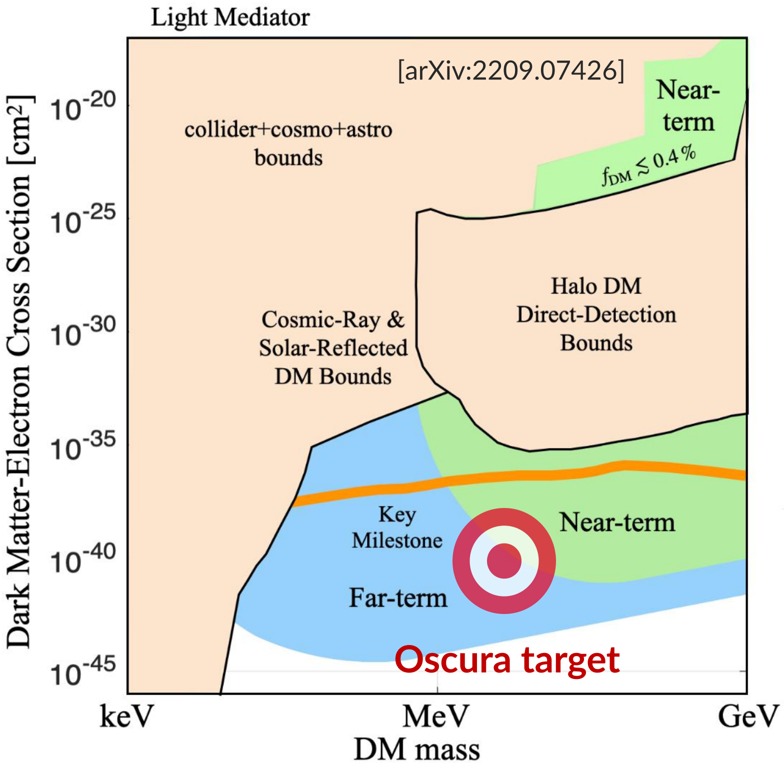


Fermilab

Oscura: Scientific reach

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



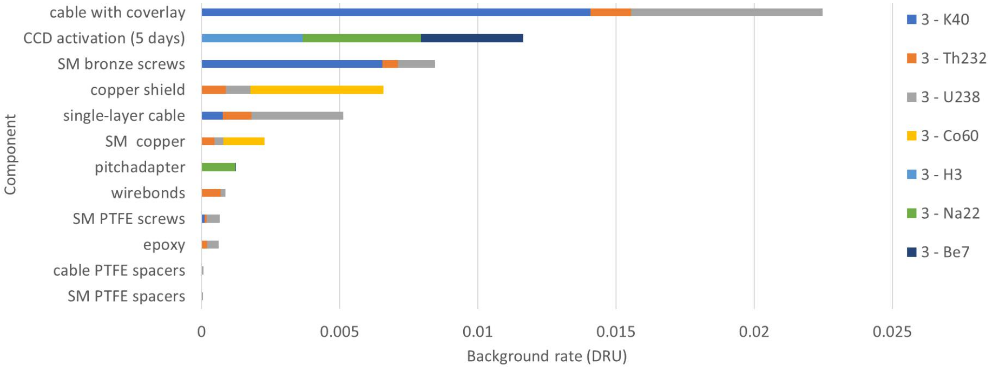


*2e- thr & 1x10^{-6} e-/pix/day

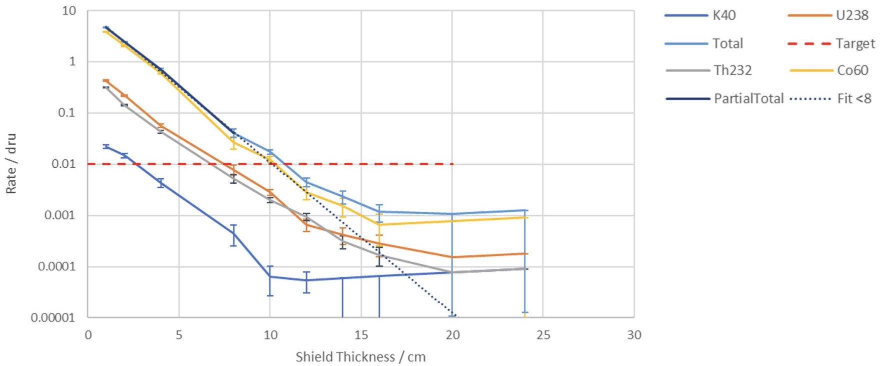
Fermilab

Oscura: Isotopic contamination control

Material selection for Super Modules

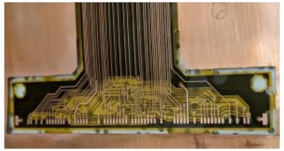


Electronics behind 15-cm-thick inner shield



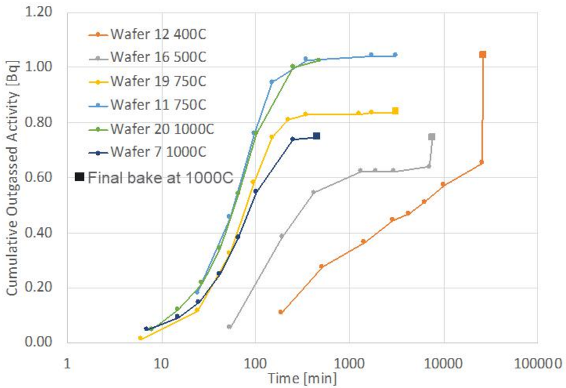
Low-background flex cable [arXiv:2303.10862]

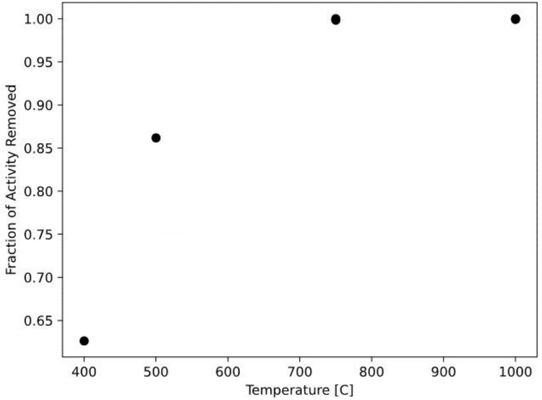
DAMIC-M cable	^{238}U [ppt]	^{232}Th [ppt]
Commercial	2600 +/- 40	261 +/- 12
Customed	**31 +/- 2**	**13 +/- 3**



Oscura: Background cosmogenic activation control

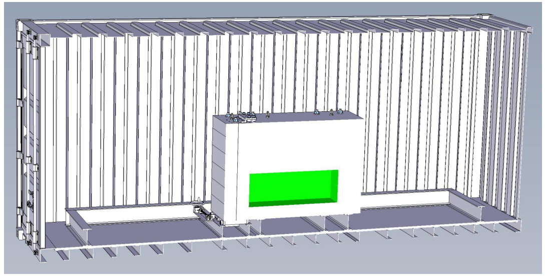
H^3 removal during sensors fabrication





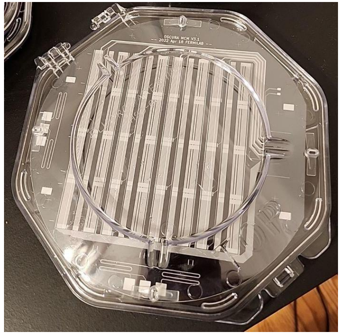
Shipping containers and transportation planning

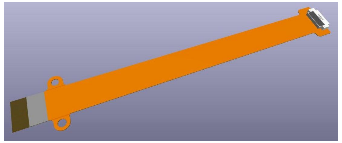
Duration [d]	Step	Location	Latitude	Longitude	Altitude [km]	Neutron Flux [n/cm2/sec]	Sea Level Factor	Shielding	Shielding Factor	Sea-level days
3	Ingot growing	TOPSIL, Frederikssund, Denmark	55.83	12.11	0.015	3.41E-03	1.16	None	1	3.48
14	Ingot storage	Hospital basement, Copenhagen, Denmark	55.68	12.56	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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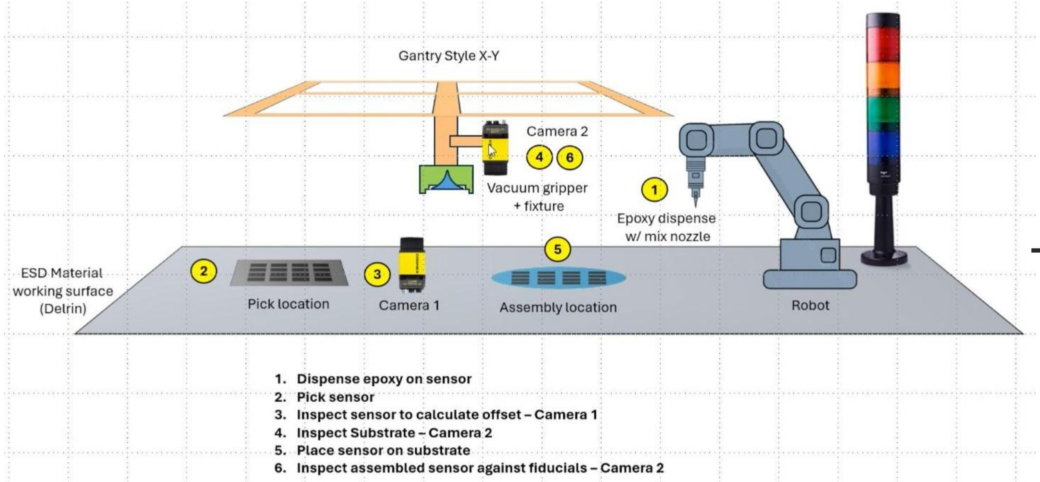
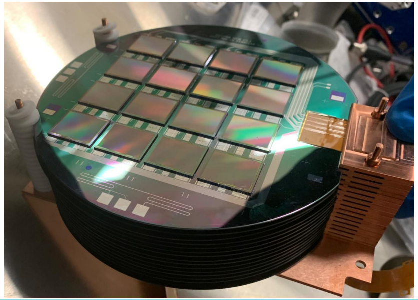


+

x 16 =



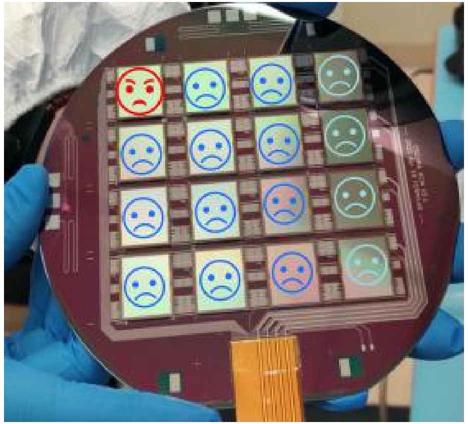
Fermilab

Oscura: Sensors on-assembly testing

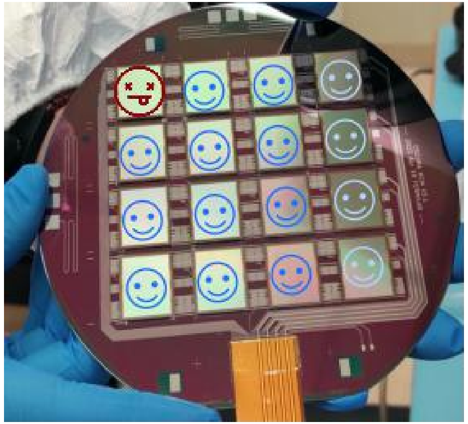
Sensors in MCMs are tested during wire-bonding

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

FAILED → 3; PASSED → 4



One very bad sensor can affect all neighbours



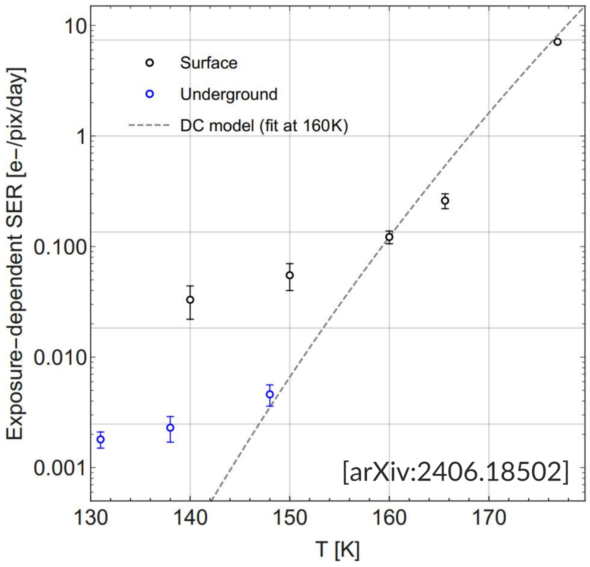
After unbonding, MCM is useful again

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

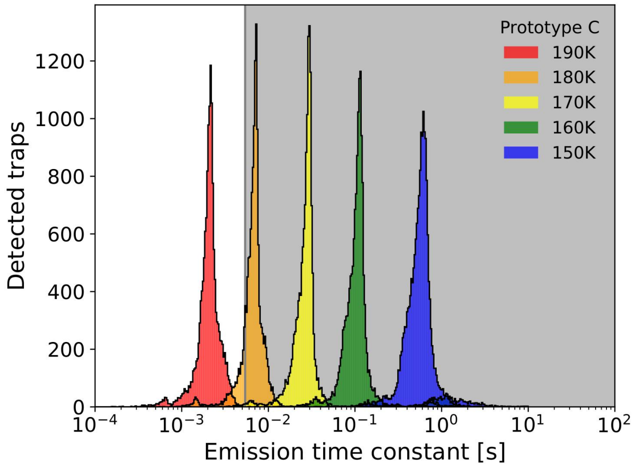
Oscura: Sensors performance

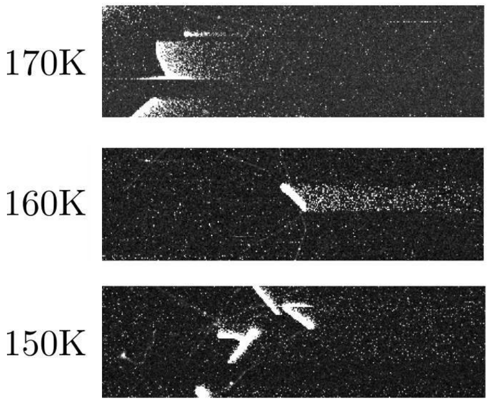
System	Parameter	3e- threshold	Sensors performance	Units
Sensors	Exposure-dependent 1e- rate	1.6×10^{-4}	1.8×10^{-3}	e-/pix/day

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.**



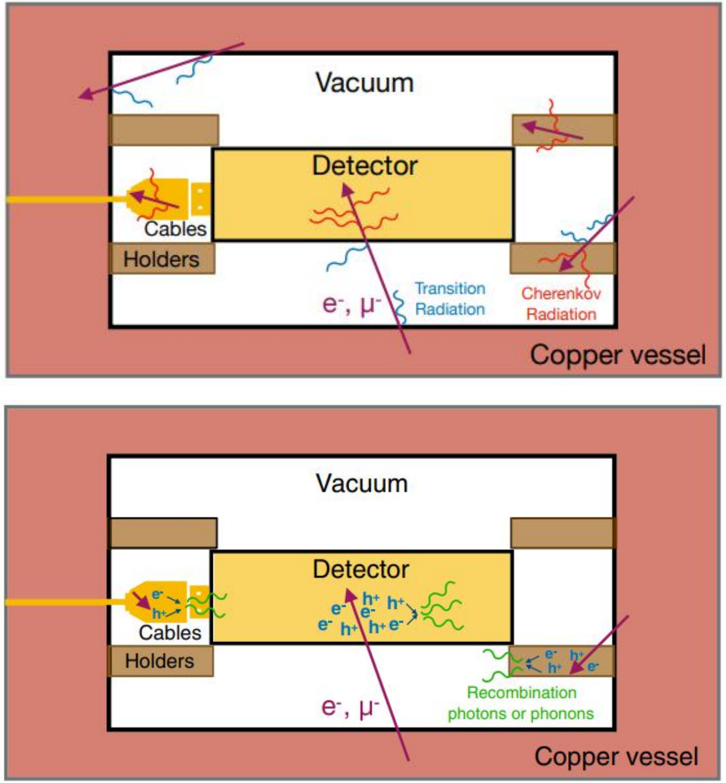
See out-of-the-oven paper: [arXiv:2406.18502]!





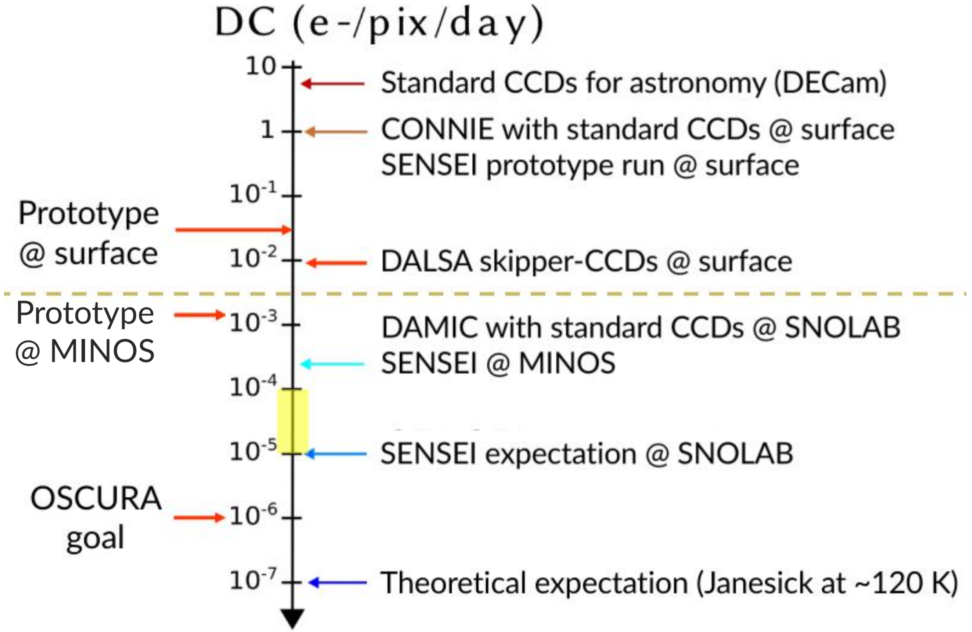
Fermilab

Low-E background correlation with high-E events



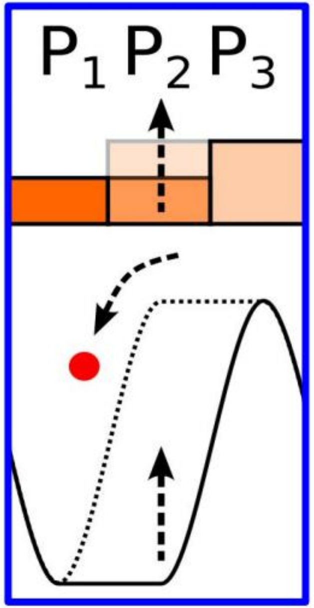
[PRX 12 (2022) 011009]

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.

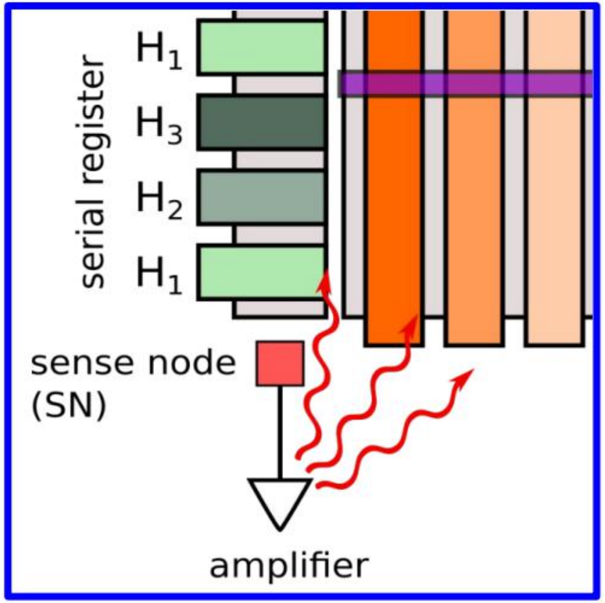


Fermilab

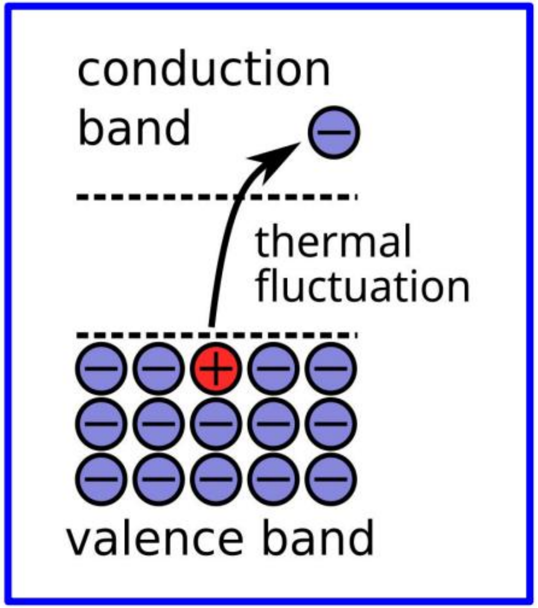
Low-E instrumental backgrounds in CCDs



Spurious charge



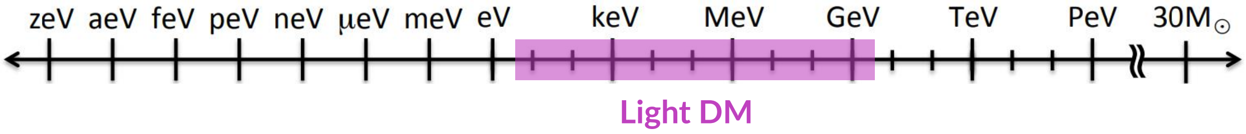
Amplifier light



Dark current (DC)

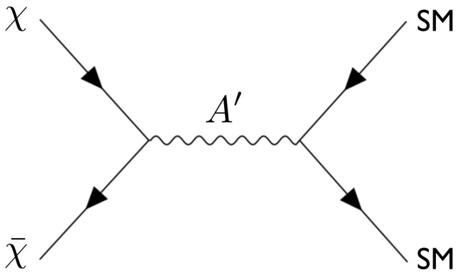
Light dark matter

Light dark matter 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.

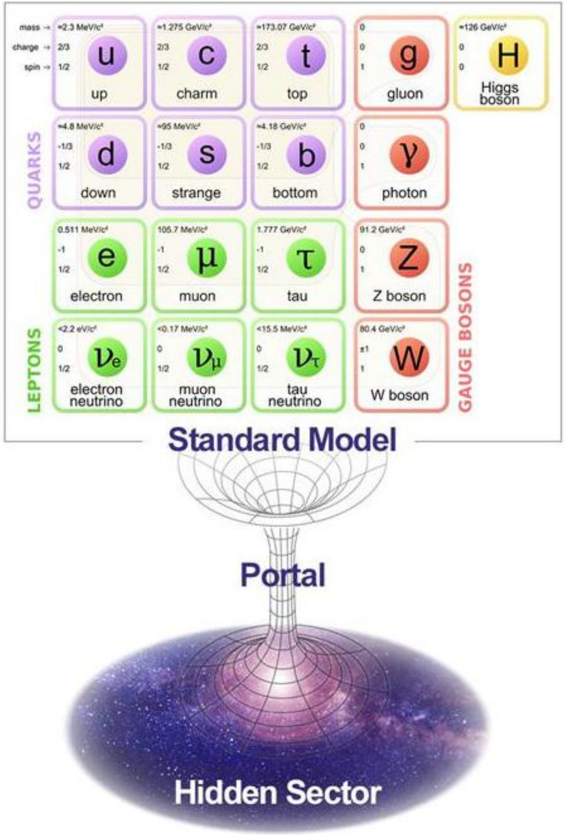
Dark photon (vector) portal: A' kinetically mixed with SM photon



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

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

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



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