Oscura/SENSEI and more

Juan Estrada

CFC Meeting

10/30/2023

People

- Scientists:

  Juan Estrada (Oscura)

  Guillermo Fernandez Moroni (Spec-5 R&D, MAS, skipper-CMOS)

  Javier Tiffenberg (SENSEI)

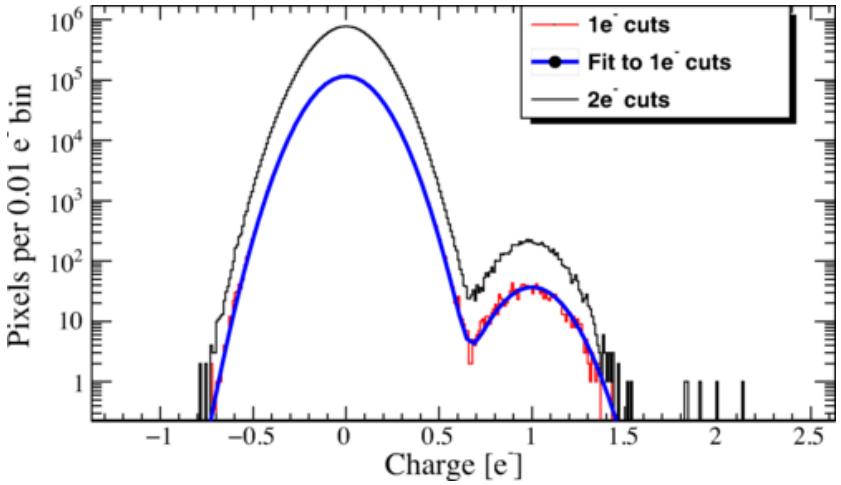
- Postdocs:
  - Ana Botti R.A. (SENSEI, Oscura, quantum imager)
  - Brenda Cervantez - Schramm Fellow (Oscura, SENSEI, DarkBeats)
  - Nate Saffold - Lederman Fellow (SENSEI, Oscura, DarkNESS)
  - Claudio Chavez - Engineering Physicist (Oscura, IERC CCD lab manager, $\pm$)

SENSEI

2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with **proto-SENSEI** (0.1 g) at **surface**	DM search with **proto-SENSEI** at **MINOS** (230 m.w.e.)	DM search with **science grade** (~2 g) at **MINOS**	**Production** (100g) + commissioning at **SNOLAB** (6000 m.w.e.)

The SENSEI Collaboration Phys. Rev. Lett. 125, 171802 (2020)

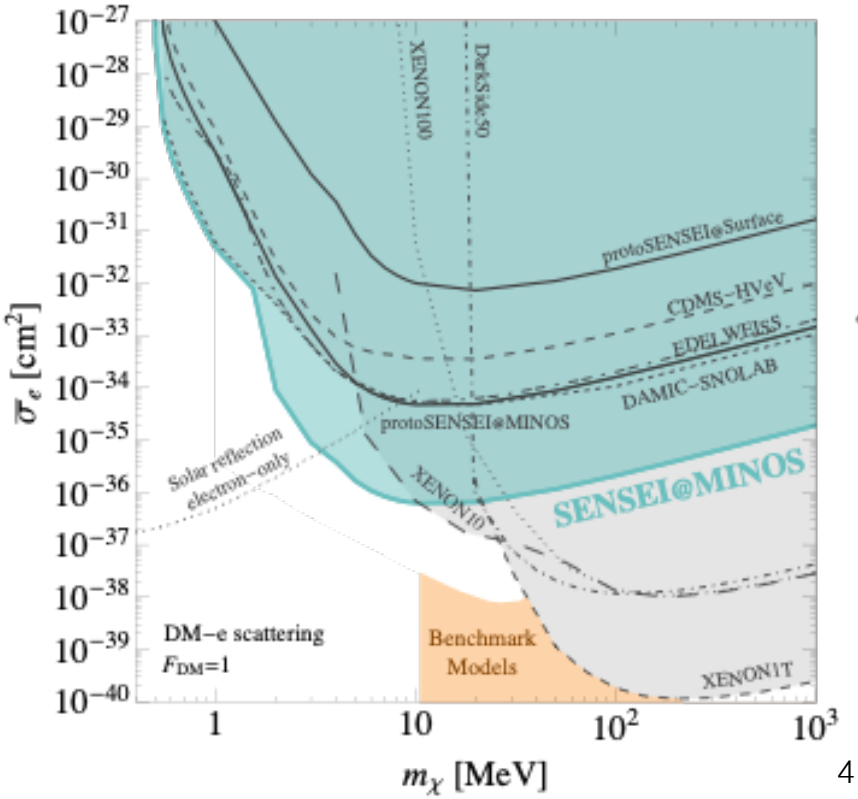
New Horizons Award

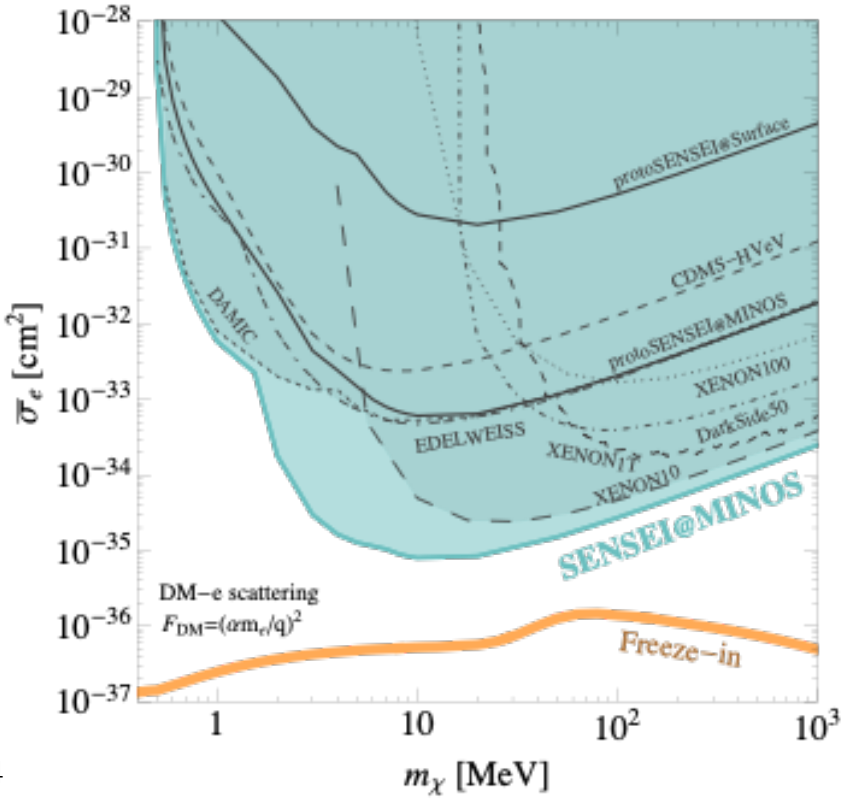


Rates:

- **1e- = 450 ev/g-day (1.6 10^{-4} e/pix/day)**
- 2e- = 2.4 ev/g-day

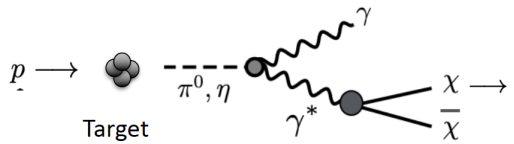
Phys. Rev. Lett. **125**, 171802 – Published 20 October 2020



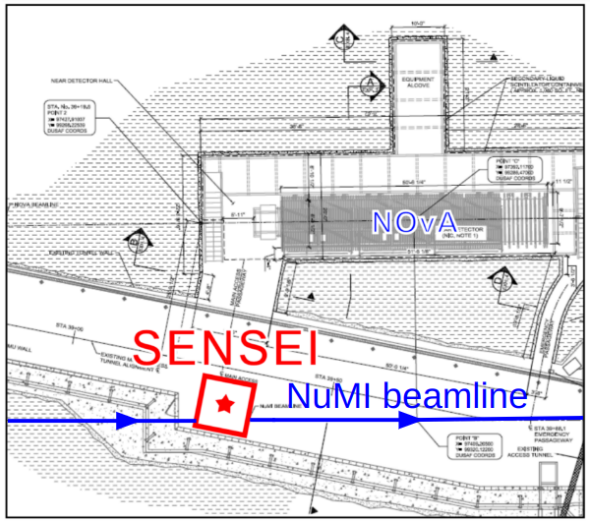


2023: Milli-charged particles @ MINOS

Proton collisions w/ fixed target -> mCPs collinear w/ NuMI beamline:

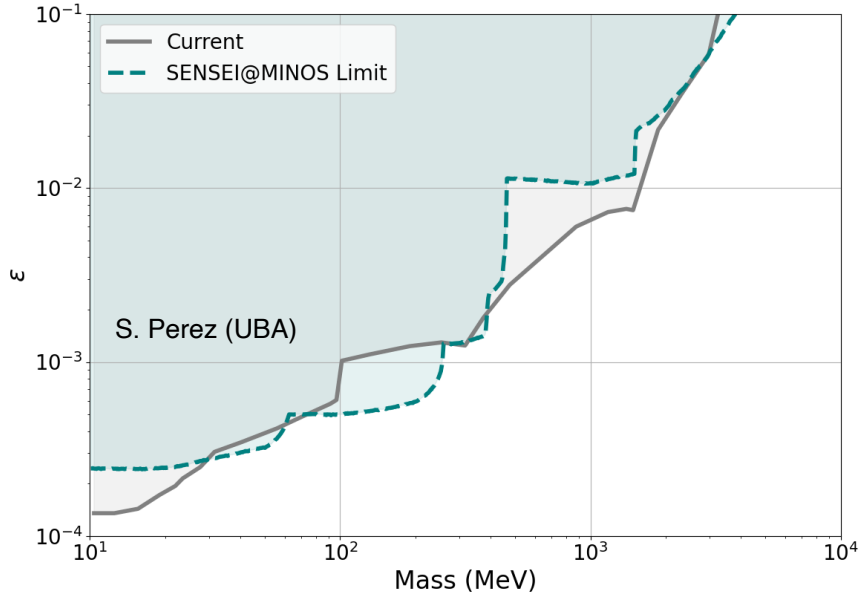


arXiV:1902.03246



Extension of previous analysis to 6e-

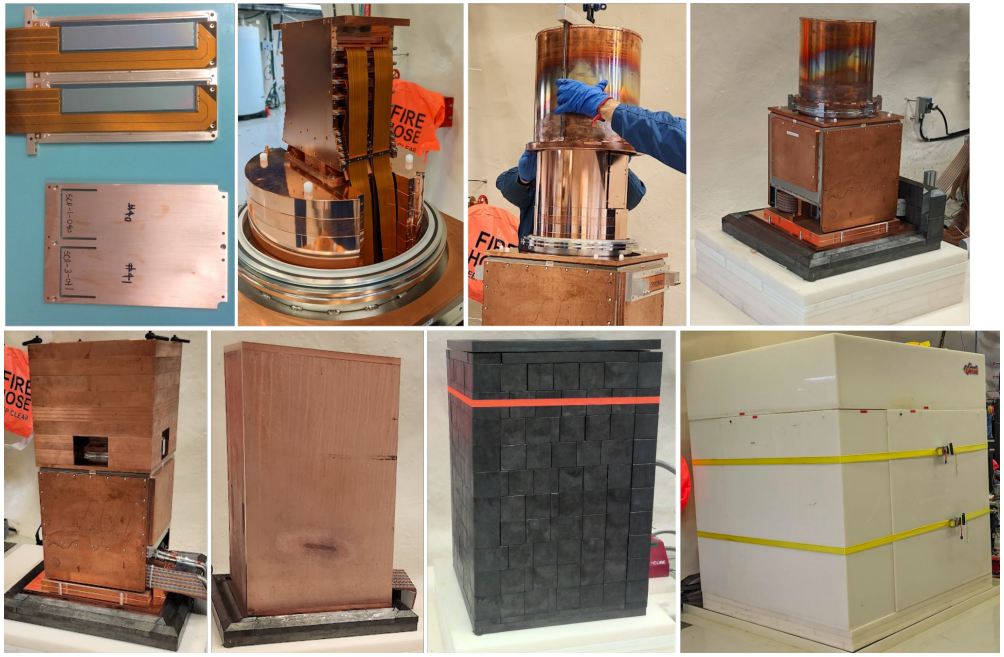
	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exp. [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Obs. Events	1311.7	5	0	0	0	0



arXiv:2305.04964

Using same analysis as PRL 125.171802, but extending up to 6e-

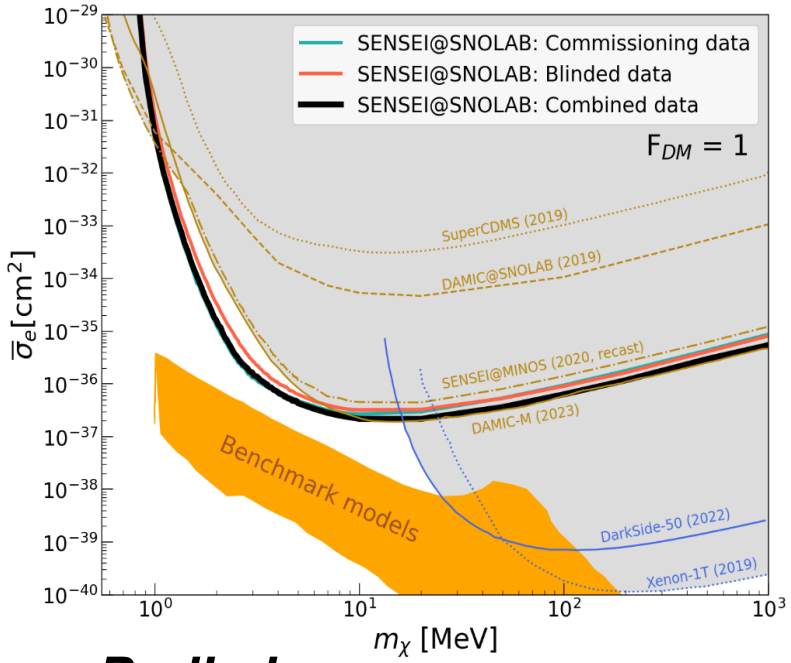
SENSEI @ SNOLAB: The current results!



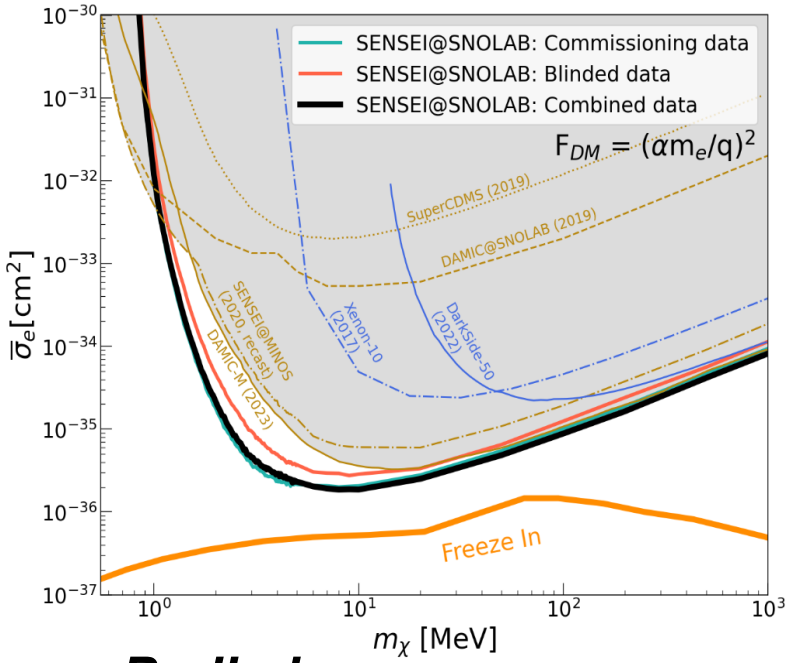
Setup:

- Copper box for 12 copper tray
- Each tray for 2 (4) ~2g CCDs.
- Cold copper box
- 6-in copper bricks and hat inner shield
- Vacuum pump (< 2x10^-4 mbar)
- Cryocooler + heater (~140 K)
- 2 layer of copper outer shield
- 3-in lead
- 42-inch polyethylene and water shield

SENSEI @ SNOLAB: First results



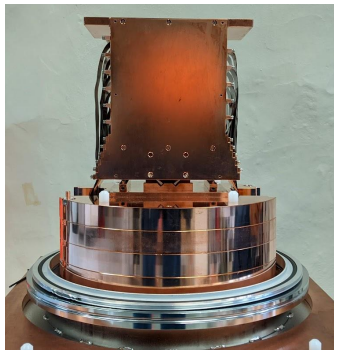
Preliminary

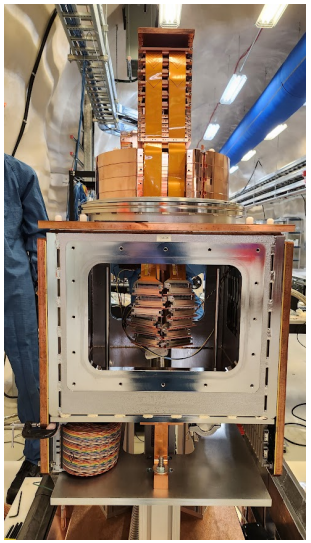


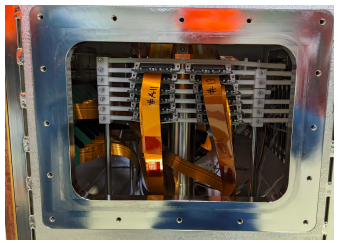
Preliminary

Paper almost out… with very nice results!

SENSEI @ SNOLAB: Second science run







- **19 CCDs (~ 40 g)**
- Improved support
- Shield fully deployed
- Data acquisition starting soon

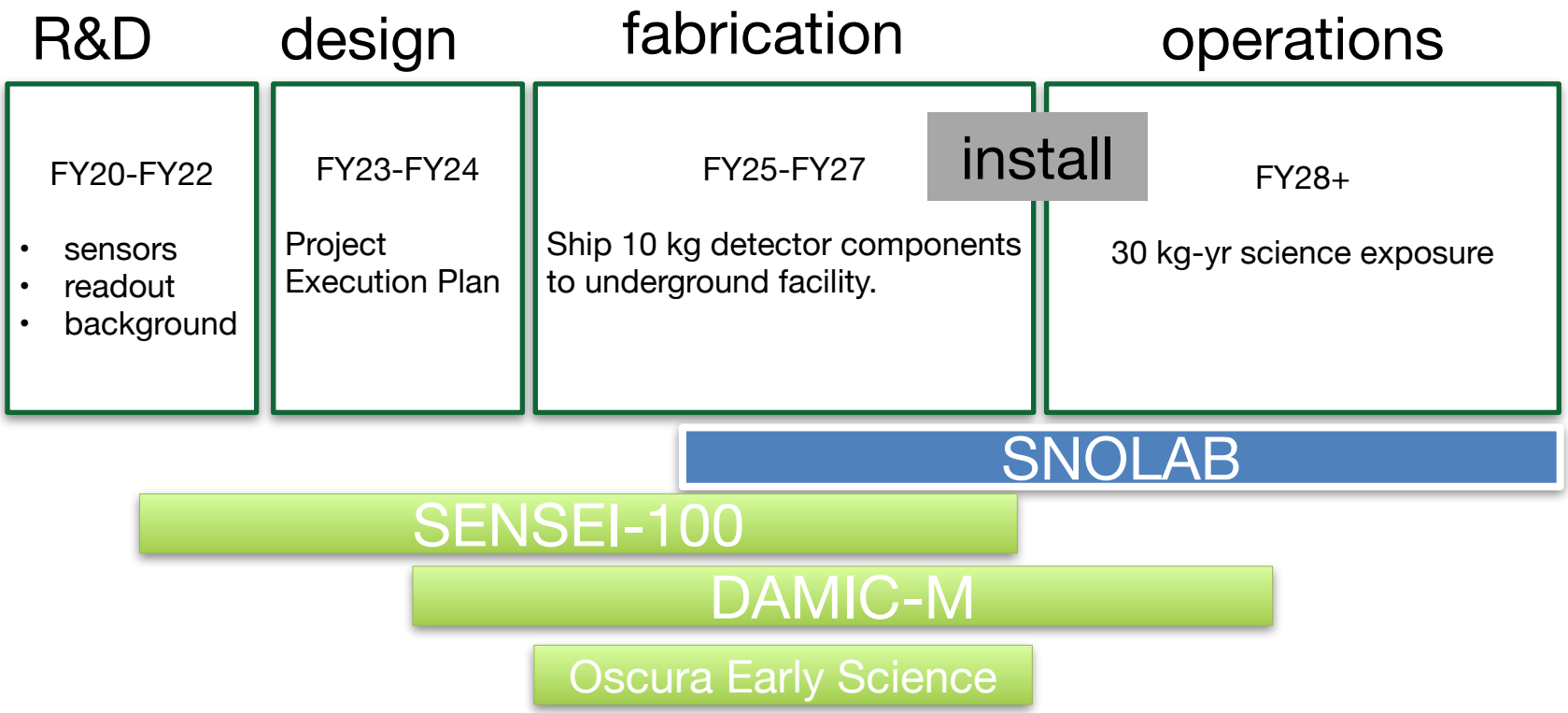
No details yet… but we are happy on how this is looking.

Skipper-CCD DM program : technology roadmap

Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10	3×10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	10	3×10^{-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)	1×10^{-6} (goal)	~2028

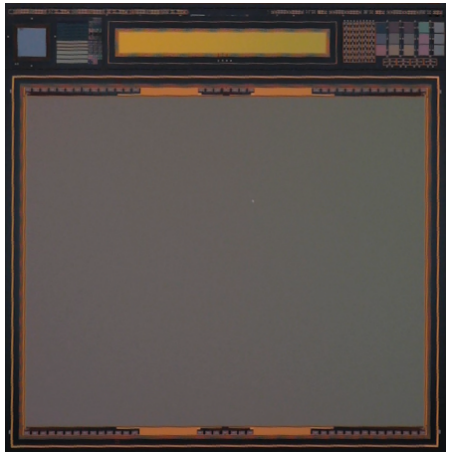
Oscura is an ambitious program that brings together the DAMIC, SENSEI and DAMIC-M teams for the development of ultimate DM experiment with skipper-CCDs.

Oscura stages and deliverables

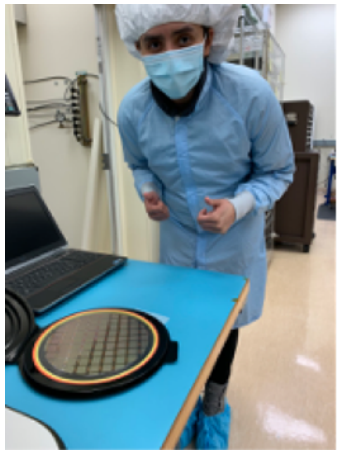


Completed R&D : sensors

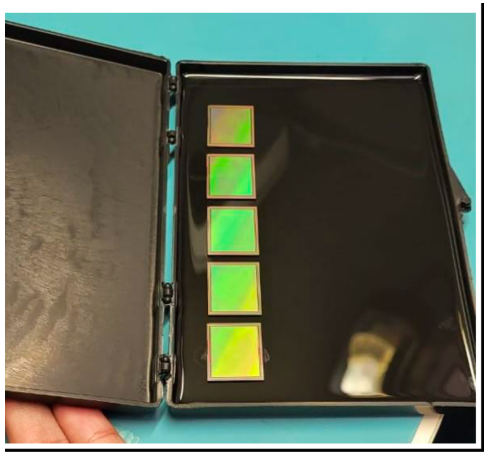
Brenda



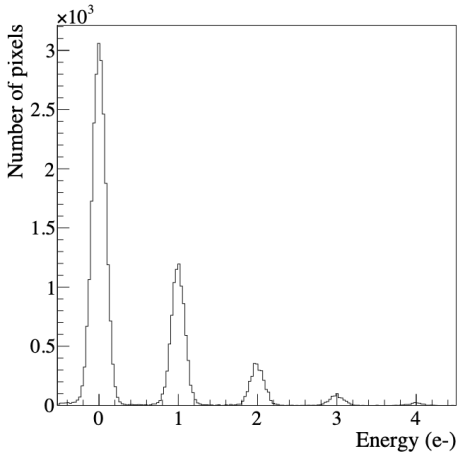
Designed new sensor(LBNL).



Microchip fabrication received 2021.



MIT-LL fabrication received 2022.



New skipper-CCD work!

MICROCHIP

MIT LINCOLN LABORATORY

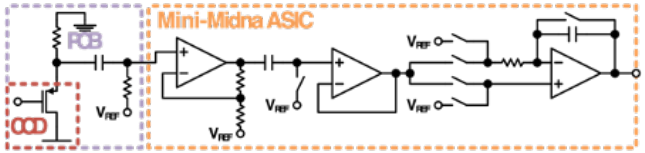
BERKELEY LAB
Lawrence Berkeley National Laboratory

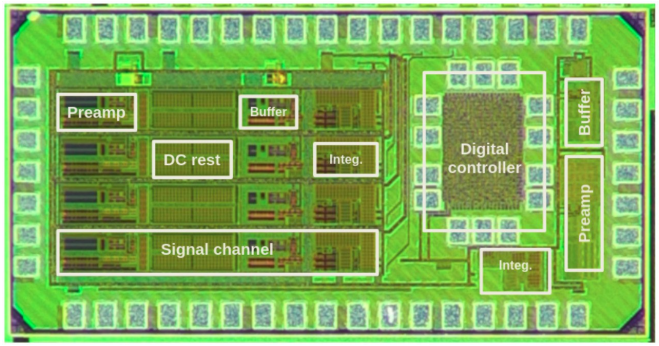
This addressed the issue of the sensors. The optimization for the Oscura detector payload will depend a bit on cost and schedule decisions. <u>It is good to have the two options!</u>

S.Holland LBNL leading the tech transfer to new foundries.

Completed R&D : electronics

Cold front end:



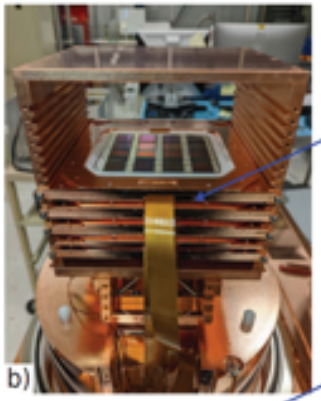


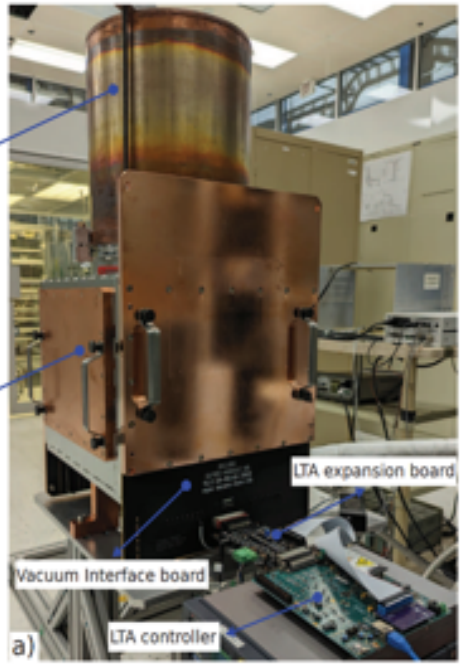
Designed, Fabricated and Tested the MIDNA ASIC. Cold front end electronics for skipper-CCD. 4-channel **(Fabricio Alcalde).**

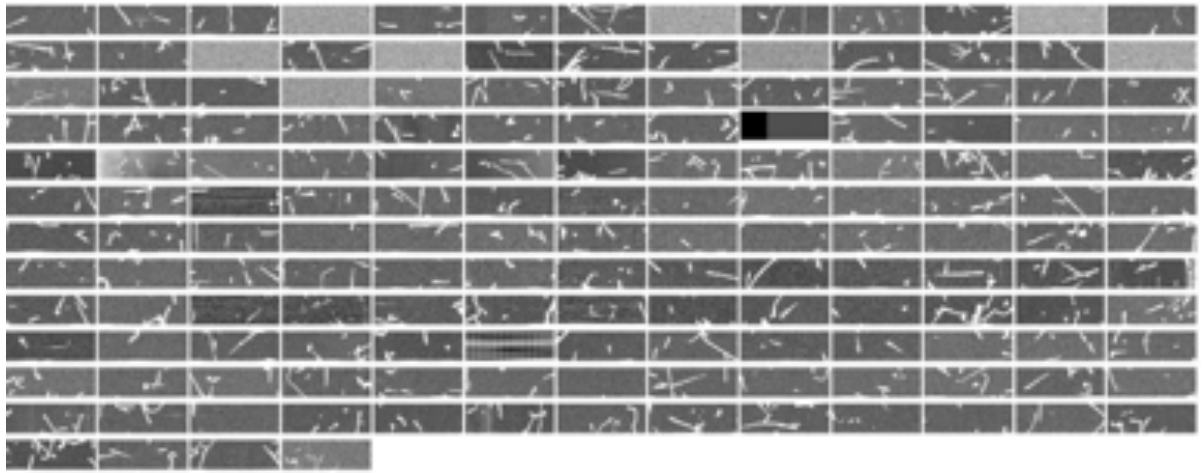
https://arxiv.org/abs/2304.13088

Back end : Designed and tested a multiplexer solution for the back end. Operated 160 CCDs with single readout channel.

Sensors 2022, 22(11), 4308



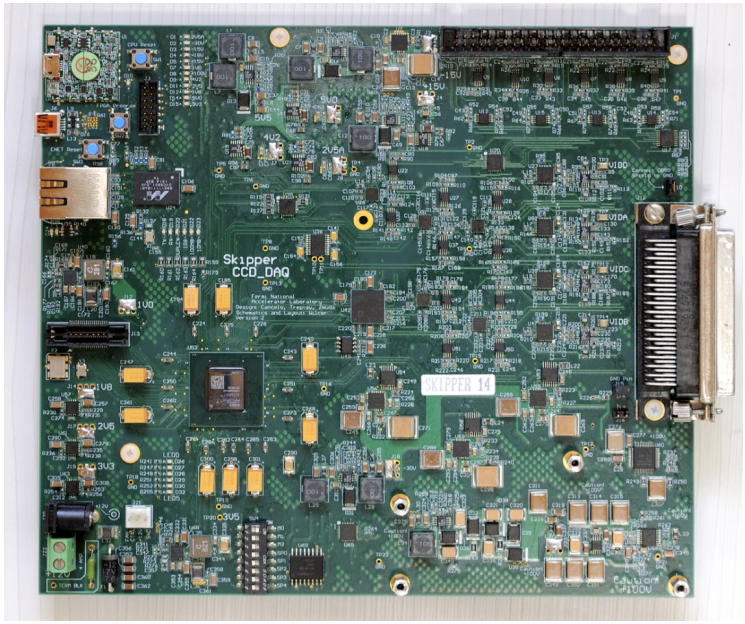




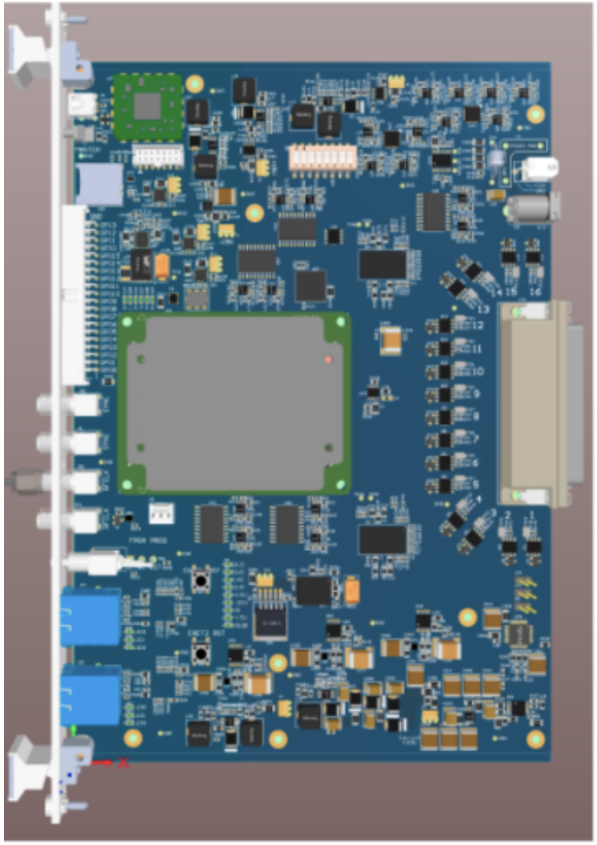
Claudio Chavez et al...

Completed R&D : electronics

Board we have been using until now for skipper-CCD. LTA with 4 channels.

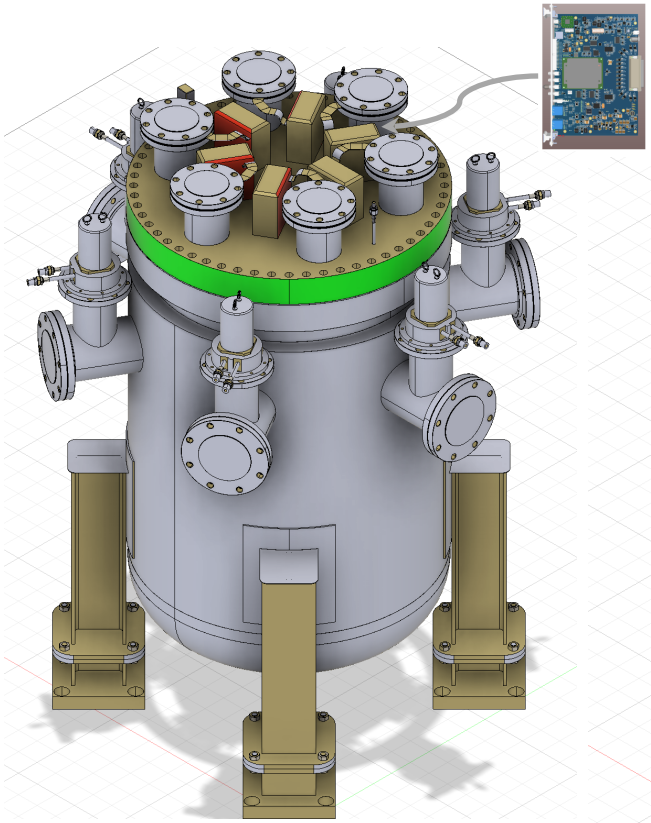


New design with 16 channels that we plan to use in Oscura - LTA16. (We need 6 of this)

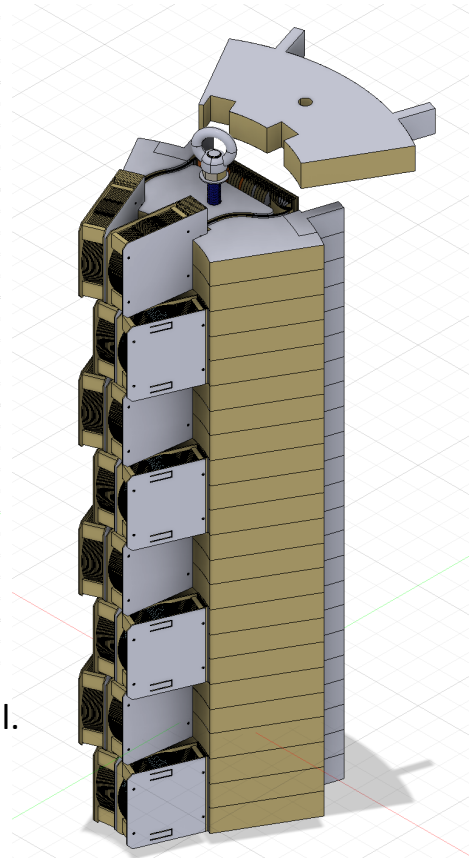


Extremely important to have the supper of Gustavo, Leo, Sho from the “Quantum and Astrophysics Systems” in “Real Time Processing Systems Division”.

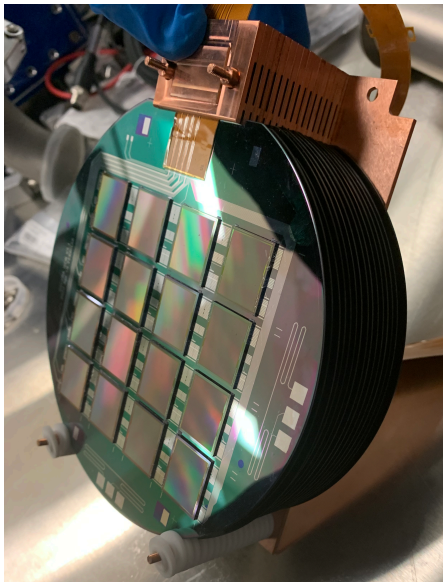
Some more details of the design

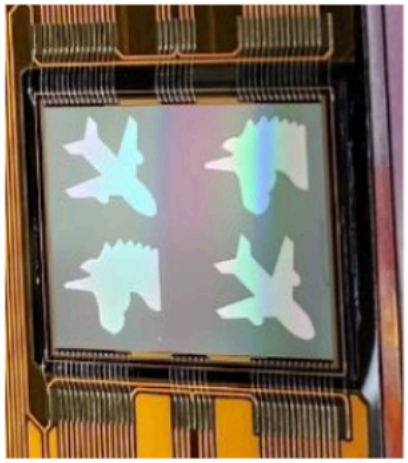


Vessel with mods to fit into cage and rail.



Slide of 16 SM with inner shield





GW0 - APPROVAL

To: Juan Estrada (estrada@fnal.gov)
Fermilab, Batavia IL 60510 USA

5-May-2021

RE: GW-0 APPROVAL FOR PROJECT 054 OSCURA

Dear Juan;

I am pleased to receive your Expression of Interest (EoI) for the proposed OSCURA project to develop and deploy a 10kg active mass scale-up of the skipper-CCD technology already prototyped in the DAMIC and SENSEI projects. We have now completed a facility impact assessment, and the proposal has been reviewed by the SNOLAB Programme Oversight Group and the Experiments Advisory Committee. The recommendation is that the project aligns with the scientific strategy and objectives of SNOLAB, and has good feasibility with the space and resources at SNOLAB within the expected time frame. I am therefore pleased to allocate Gateway-0, *Initiation Approval*, to the Project. OSCURA will be integrated as SNOLAB Project 054 and entered into the SNOLAB Project Life Cycle process to manage the development and deployment within the SNOLAB facility. At this phase of the lifecycle, space has not yet been allocated for OSCURA, and continuation as a SNOLAB Project is contingent upon:

- Favourable progress of the Project through the SNOLAB Project Life Cycle process and other external reviews, including any required funding agency reviews;
- Continued relevance of the scientific programme as determined, at a minimum, by on-going biannual reports and reviews by the SNOLAB Experiment Advisory Committee; and
- The project and collaboration staff complying with the general requirements at SNOLAB including those related to health and safety and SNOLAB policies and procedures.

As described in the SNOLAB Project Life Cycle, OSCURA is now in *Phase 1: Definition*, which allows the project to request SNOLAB resources, such as design engineering support, while the project develops a conceptual design.

We look forward to working with OSCURA towards the successful development of this project at SNOLAB.

Sincerely yours,

Clarence J. Virtue
Interim Executive Director, SNOLAB

CC: Richard Ford - Director of Projects
Jeter Hall - Director of Research
Allan Barr - Director of Operations
Mitch Seguin – Manager PMO

- GW0 Approval Letter dated May 5, 2021
- Following SNOLAB staff assigned to assist with OSCURA
  - Ian Lawson – Research Scientist
  - Paul Grylls – Project Manager
  - Graham Berardi – Engineering Lead for Conceptual Design Phase
- WBS 10 Facilities Infrastructure added
- Biweekly meeting established

GW1 - APPROVAL

To: Juan Estrada (estrada@fnal.gov)
Fermilab, Batavia IL 60510 USA

11-Jan-2023

RE: GW-1 APPROVAL FOR PROJECT 054 OSCURA

Dear Juan;

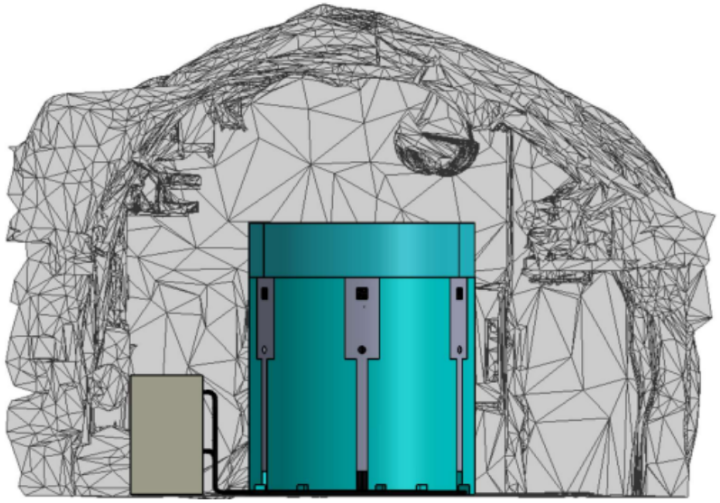
Following the conceptual design review (CDR) held at SNOLAB on 8-Dec-2022, the review committee finds the project meets the appropriate design maturity and project development for a conceptual design, and as such recommends that project 054-OSCURA passes the GW-1. Having reviewed the committee report, I am pleased to authorize GW-1 with a contingent space allocation and SNOLAB support for the technical design phase. SNOLAB support for projects past GW-1 are contingent on:

- Continued development of the project technical design, and demonstrated and communicated on-going intention to deploy the Project at SNOLAB;
- Those issues or caveats identified during the CDR and detailed in the committee report being addressed at the appropriate stages in the Project Lifecycle;
- Continued favourable progress on the Project through the SNOLAB Project Lifecycle Process and other external reviews, including any required funding agency reviews;
- Continued provision of adequate resources and funding to the Project;
- Continued relevance of the scientific programme as determined, at a minimum, by on-going biannual reports and reviews by the SNOLAB Experiment Advisory Committee; and
- The project and collaboration staff complying with the general requirements at SNOLAB, including those related to health and safety and SNOLAB policies and procedures.

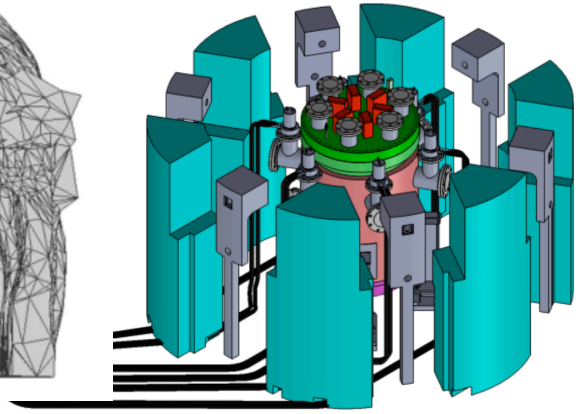
This support approval may be withdrawn if these conditions are not met, at the discretion of the Executive Director, which will be communicated in writing after appropriate dialogue with the project leadership. As described in the Project Life Cycle, OSCURA is now in *Phase 2: Development*, and working toward *GW-2: Deployment Approval*. During phase 2, materials or equipment should not be delivered to or deployed at SNOLAB without explicit SNOLAB management approval. A project manager will be assigned to the Project, who will support the project, be the point of contact, and will maintain the *issue tracker*.

- GW1 Approval Letter dated Jan 11, 2023
  - **<u>Contingent space allocation</u>**

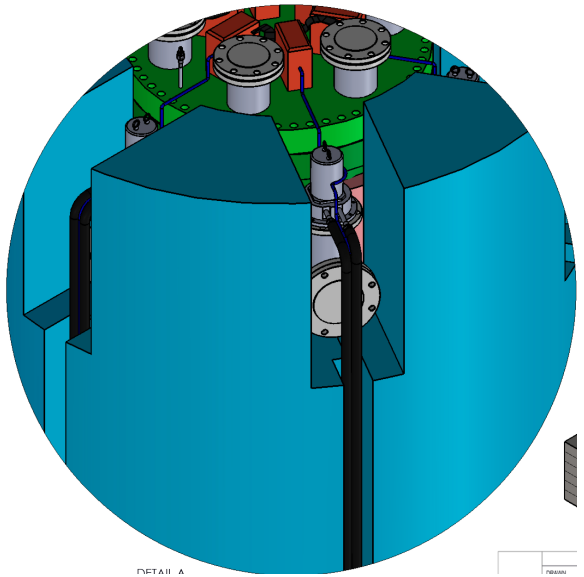
Design: outer shield and installation inside SNOLAB



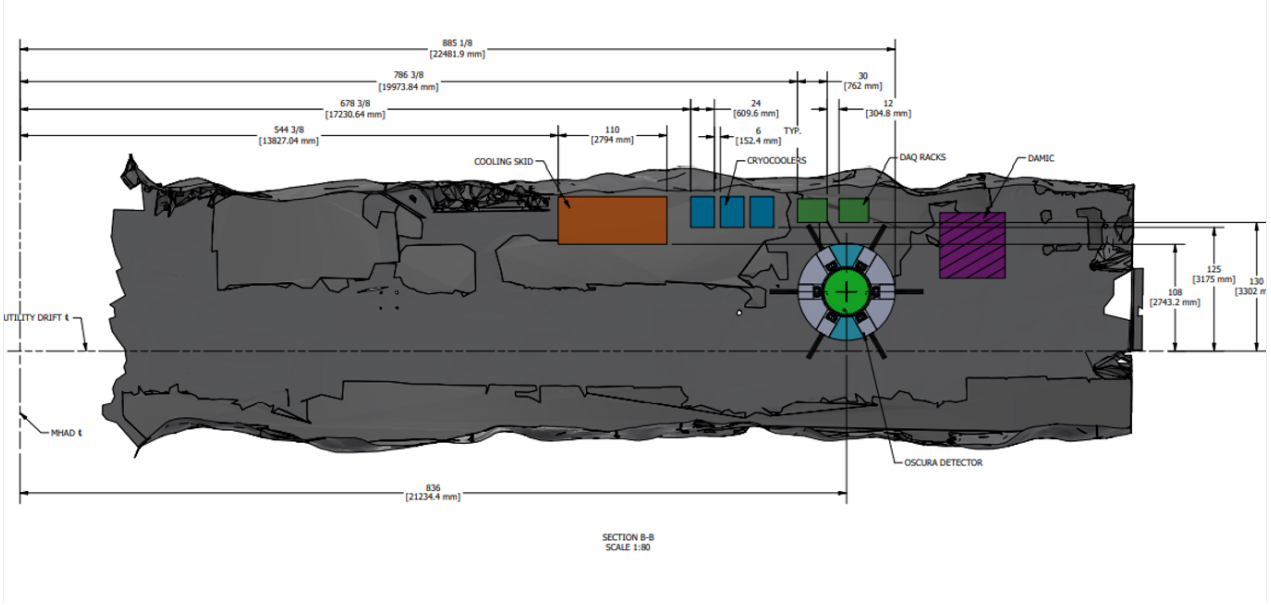
Outer shield assembly



Detail of helium lines

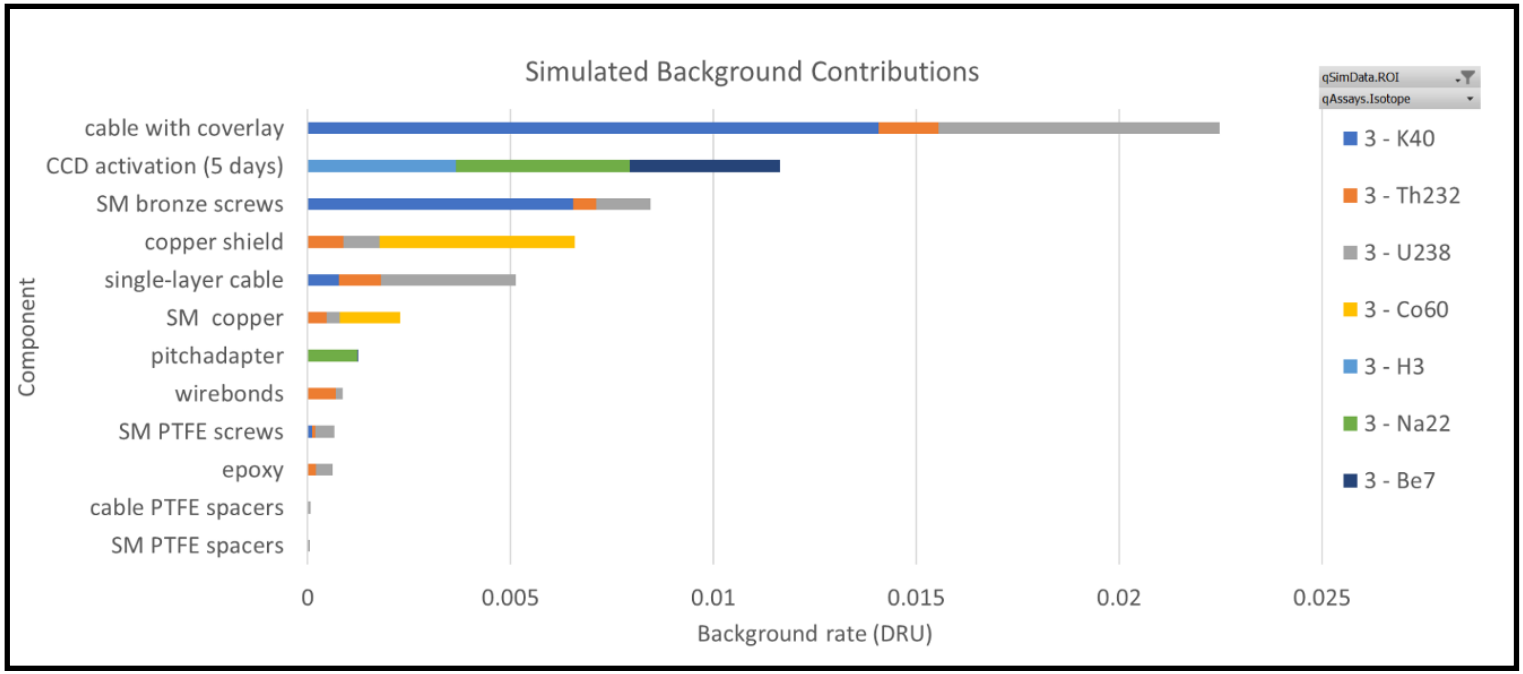


In the SNOLAB drift



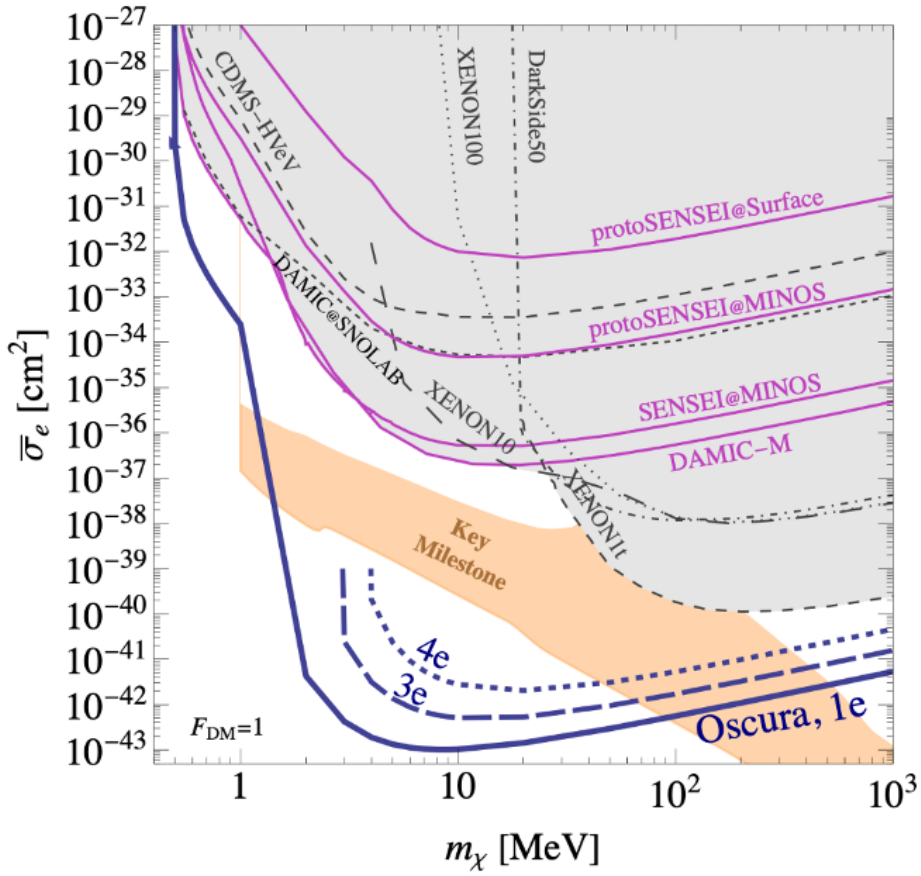
PRELIMINARY Projected Internal Backgrounds

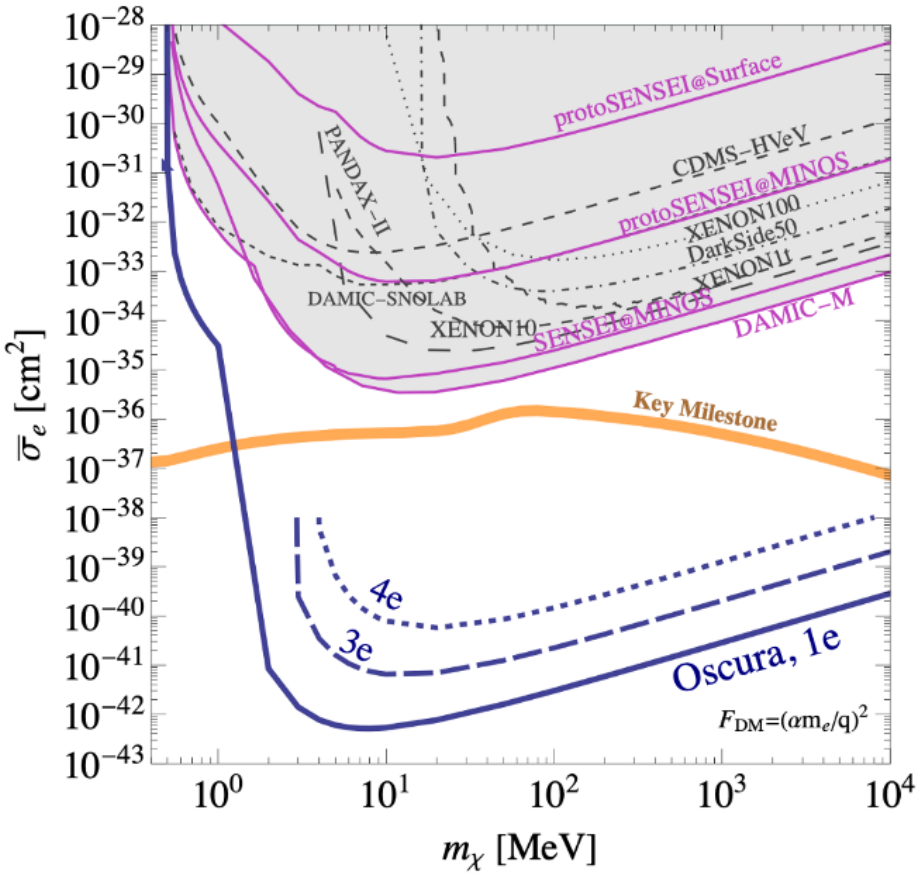
(PNNL, B.Loer and R.Saldanha)



Background from cosmogenic activation and materials is the next big challenge. Effort is focused on how to control this in an affordable way for the project.

Oscura forecast





- **Threshold considerations :**
  - **1e- : goal**
  - **3e- : requirement**
  - **4e- : current sensor performance**

Quantum imager (A. Botti, R&D seed grant)

Infrared photon-number-resolving imager using a Skipper-CCD

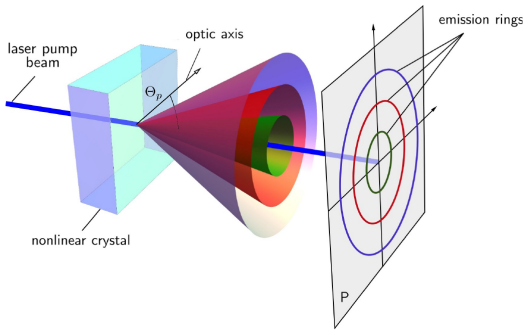
Q. Pears Stefano, A. G. Magnoni, J. Estrada, C. Iemmi, D. Rodrigues, J. Tiffenberg

PRApplied. Reviewer A replied: **"A natural question for a searcher in optics like me is: do exist some plans to commercialize such a camera at a reasonable price, and what could be the delay and the price?"**

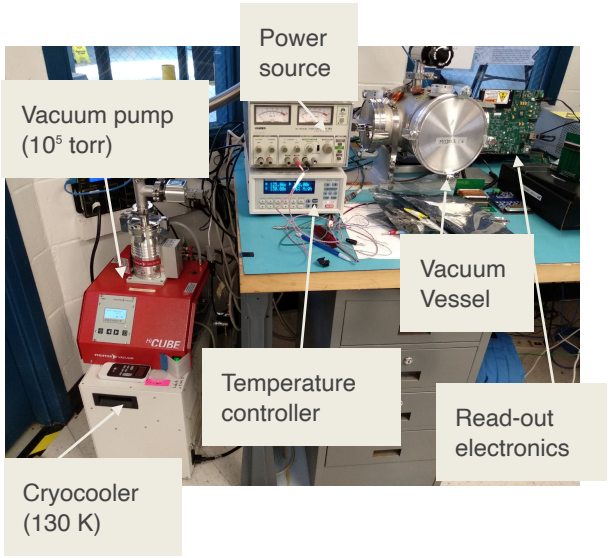
But, if we want to have skippers at:

Kwiat Quantum Information Group

in the Department of Physics in Engineering & LAS at Illinois



We need to go from:



To:

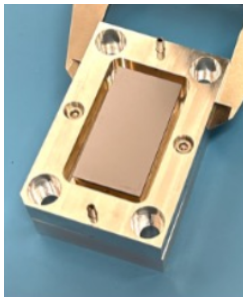
iXon Life 897
EMCCD
(19 x 16 x 14) cm

Quantum imager (A. Botti, R&D seed grant)

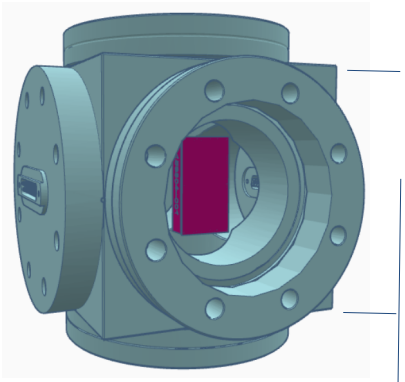
Not such a crazy idea:

Compact read-out

Micro-cooler

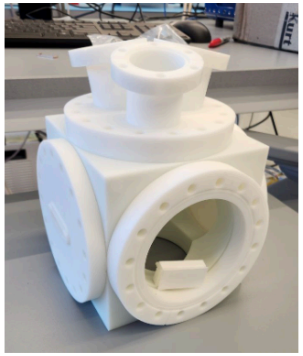


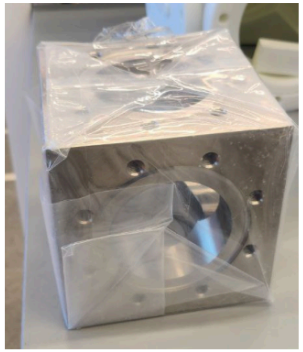
QIS detector

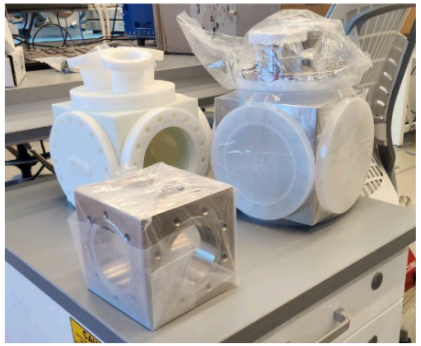


New design with UHV components

Vessel parts already arriving at IERC. Working on inner components.

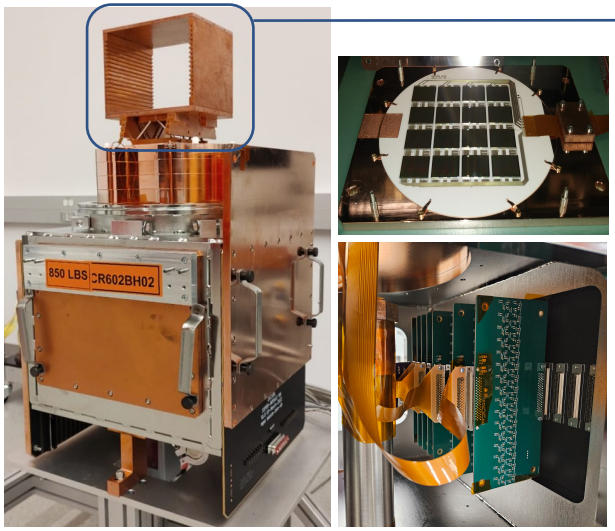




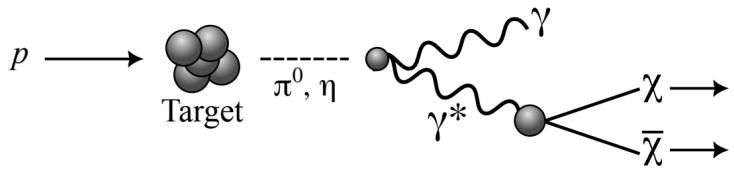


Dark BeaTS: Dark sector searches at Beams using a Tracker with Skipper-CCDs (B.Cervantes)

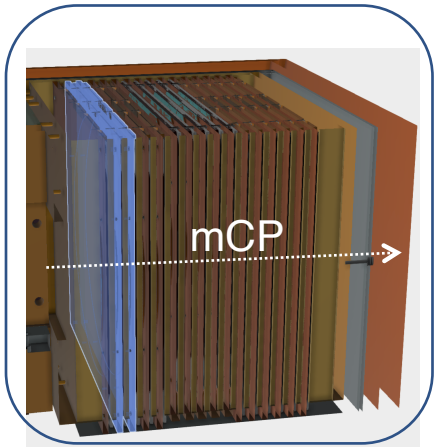
Repurpose/redesign SENSEI and Oscura hardware



mCPs search using NuMI beam with Dark BeaTS

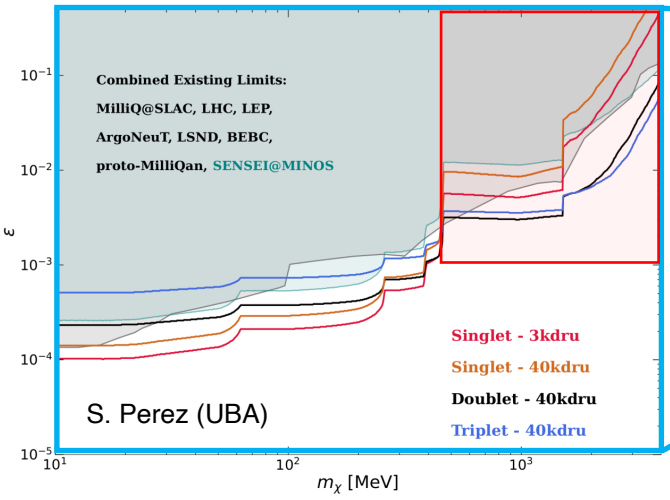


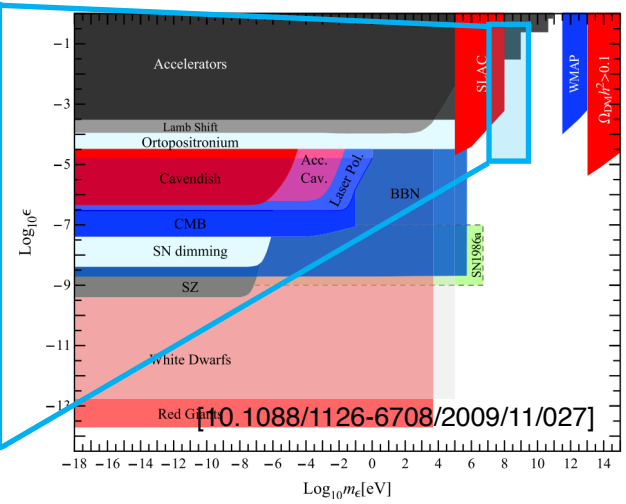
Skipper-CCD tracker



Pathfinder for future dark sector searches at accelerators (PIP-II, DUNE) with skipper-CCDs

Tracking enhances sensitivity to high m_χ





[10.1088/1126-6708/2009/11/027]

Ongoing: Skipper-CCD to LHC!

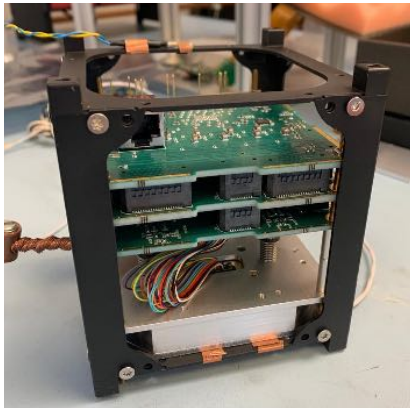
The DarkNESS Mission (N.Saffold)

DarkNESS: Dark matter **N**anosatellite **E**quipped with **S**kipper **S**ensors

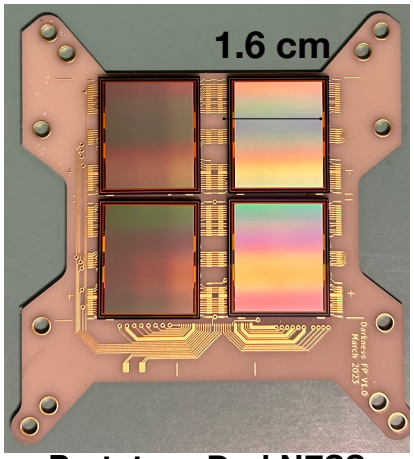
- Since their invention, skipper-CCDs have been used for:
  - Direct dark matter searches (DAMIC, SENSEI)
  - Neutrino experiments (CevNS)
  - Ground-based astronomy
- There is interest in using skipper-CCDs as single-photon counting and X-ray detectors for space-based imaging, but skipper-CCD operation in **space** has not been demonstrated

DarkNESS is a 6U CubeSat housing four 1.3 Mpix skipper-CCDs that will search for dark matter (DM)

Collaboration between Fermilab and UIUC Laboratory for Advanced Space Systems at Illinois (LASSI)



Space LTA

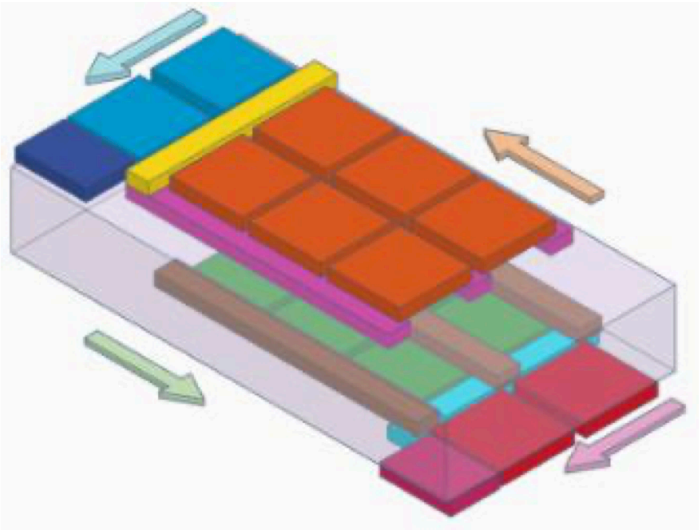


Prototype DarkNESS detector module

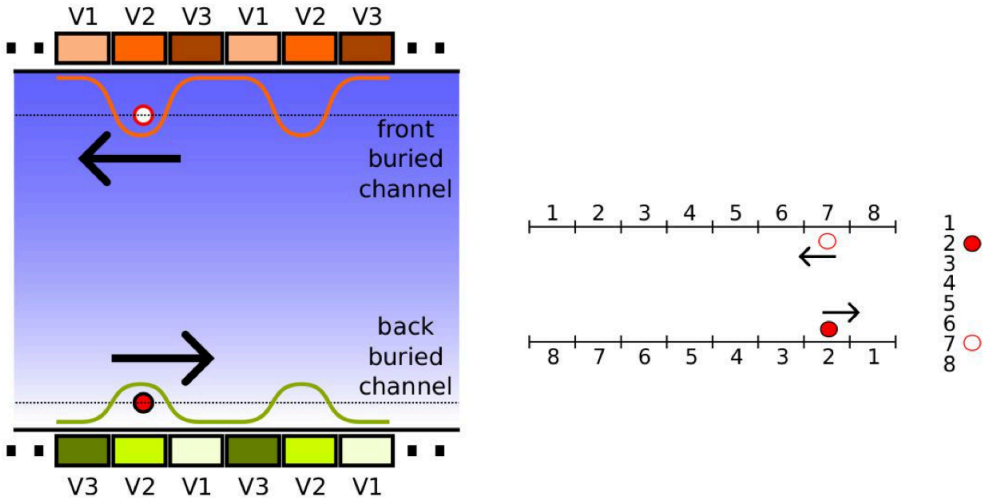
CCDs with timing resolution: Dual-side CCD

Device with gate structures and buried-channels of opposite polarity in both (front and back) sides to **collect BOTH electrons and holes**

Charge carriers are moved in opposite directions towards different serial registers



3D diagram of 3 x 2 pix DS-CCD



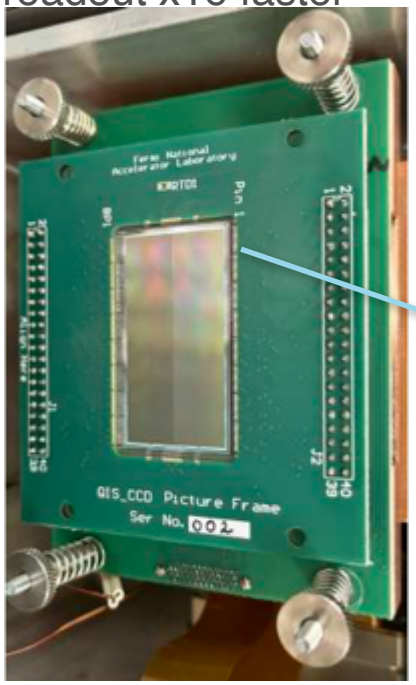
Readout mode and space-time reconstruction

- Continuous mode readout: Timestamp for each recorded interaction
- Still-exposure readout: Rejection of events happening during readout

New idea from Javier…

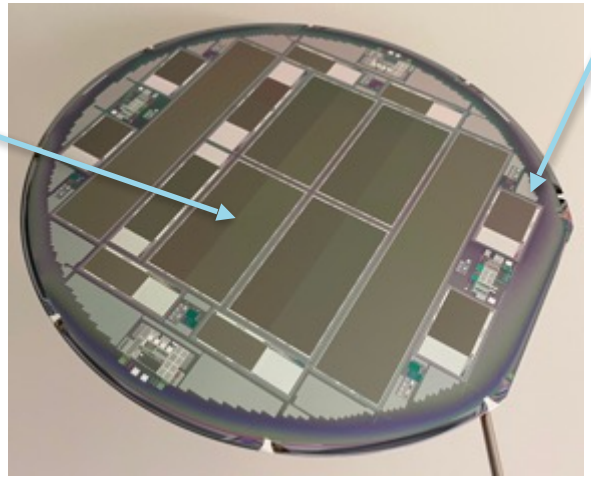
Skipper-CCD : going faster (QIS/ECA synergy)

16 channel CCD to readout x16 faster

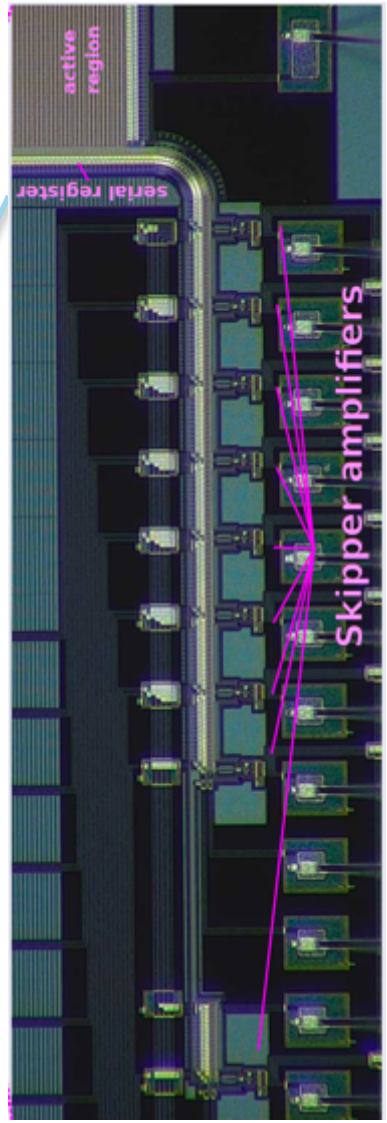


Low risk approach

Together with LBNL we have been working towards faster skippers. Trying two strategies:

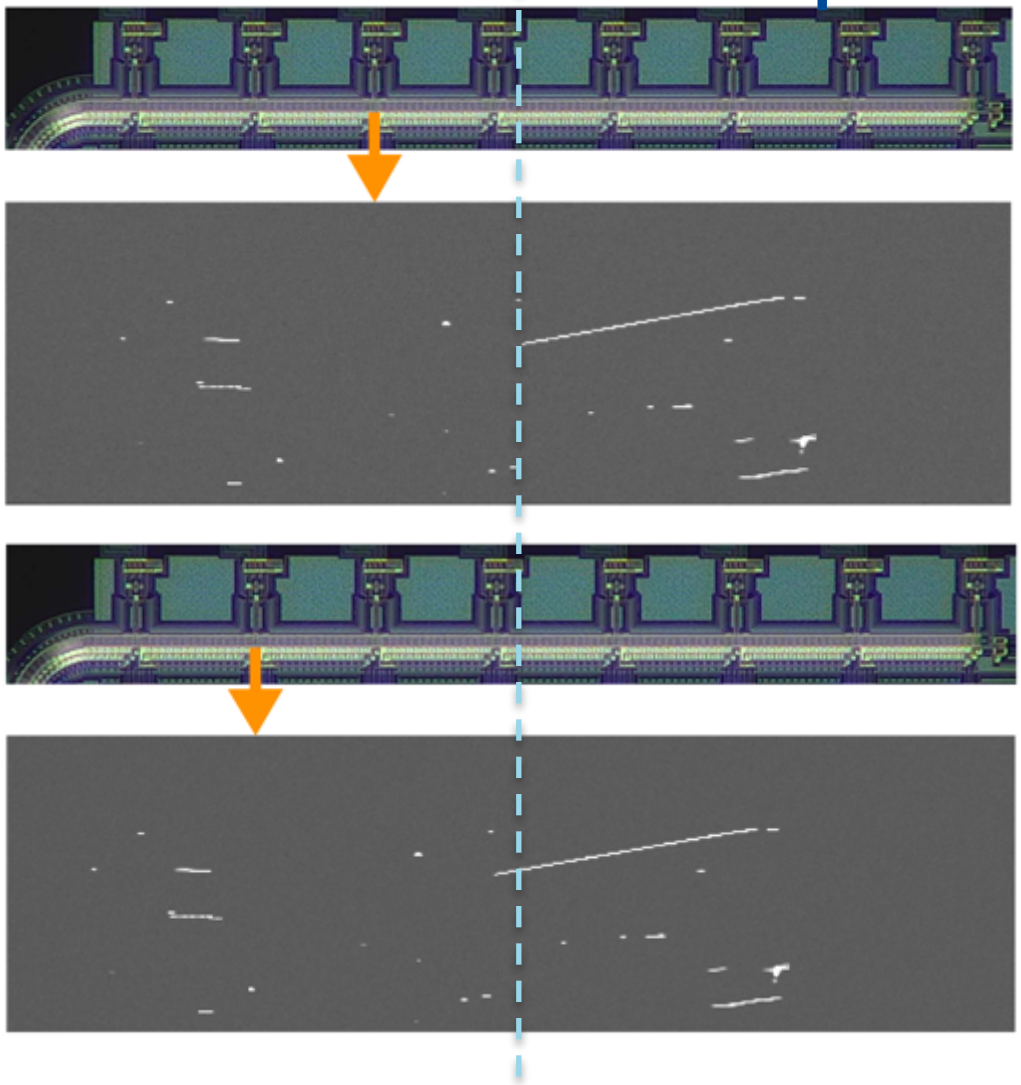


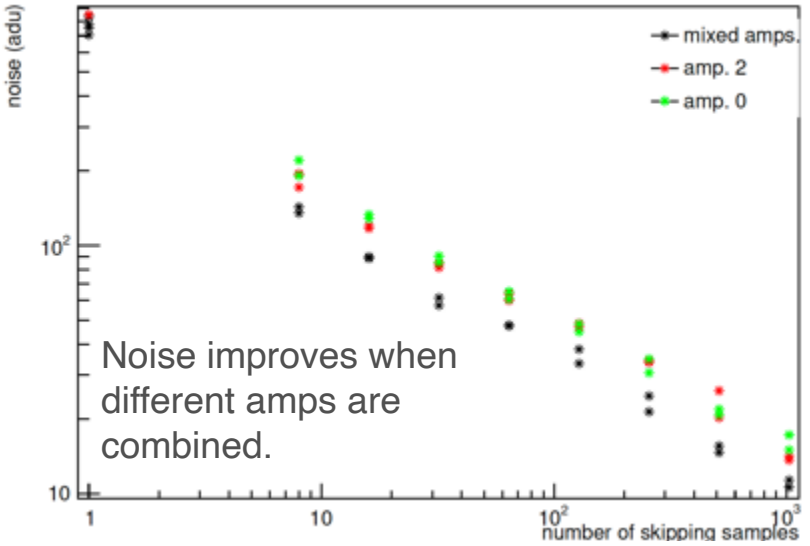
MAS CCD



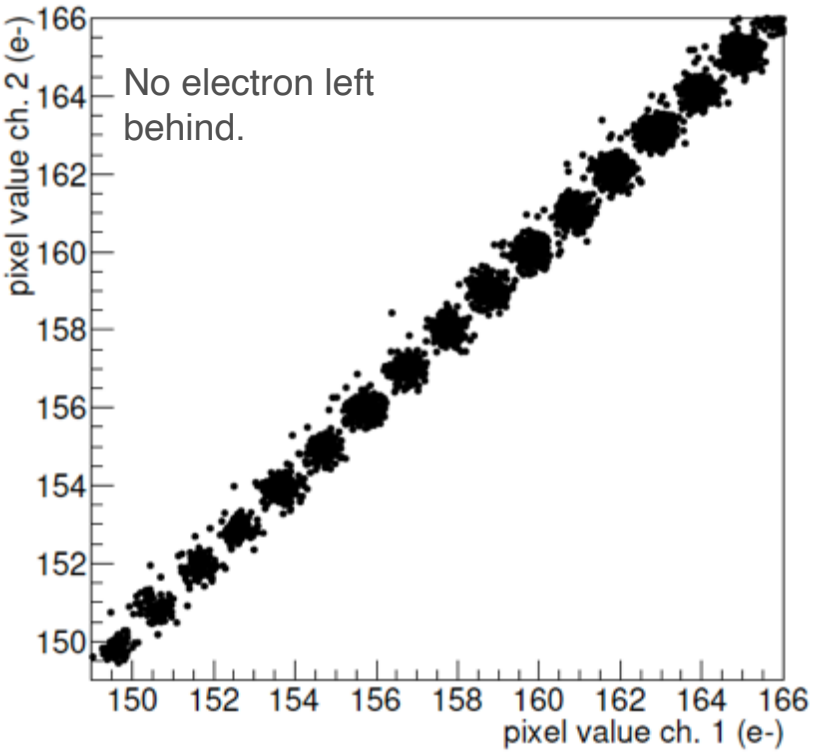
Huge interest in new photon counting technologies for many HEP areas (Snowmass arXiv:2203.12542 , SDW 2022 workshop).

MAS : works ! (R&D seed)
Joint FNAL/LBNL development





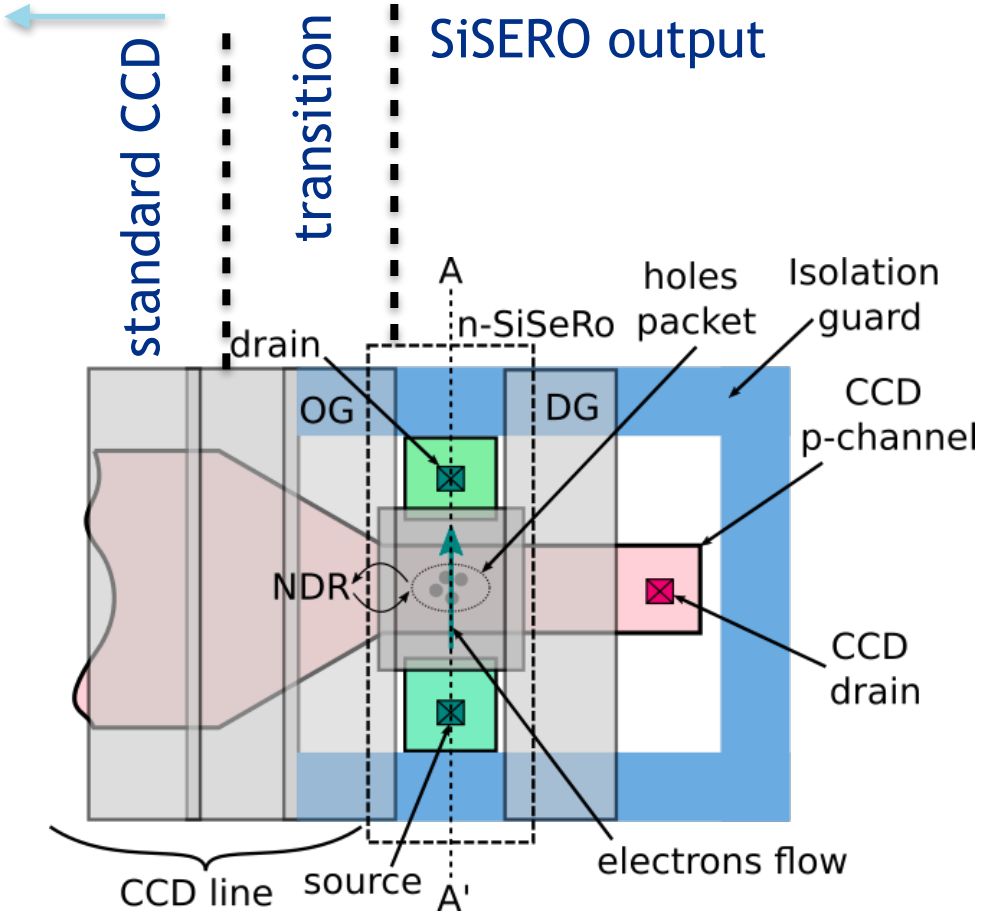
Noise improves when different amps are combined.

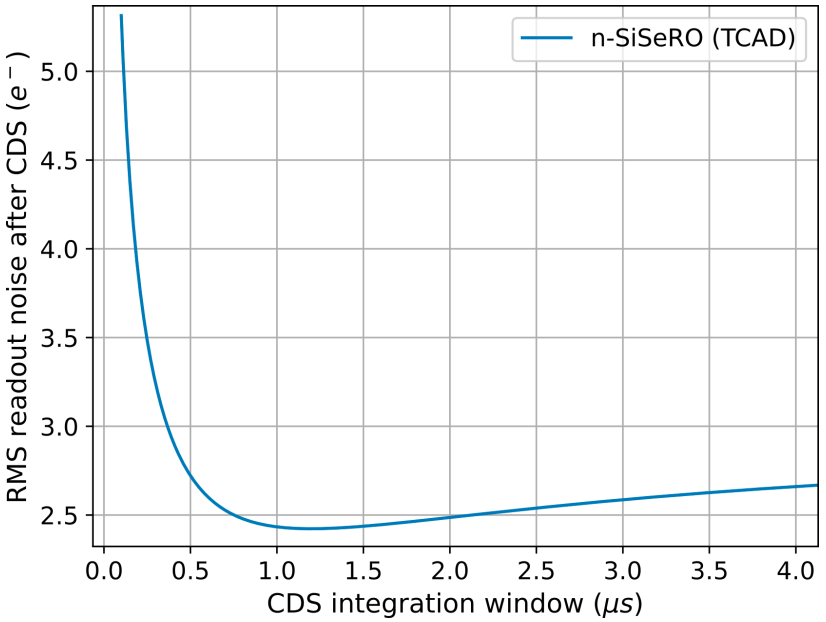


No electron left behind.

choice for DESI-2 and maybe also Spec5.

SiSERO (2023!!!) — see RTS by Miguel yesterday

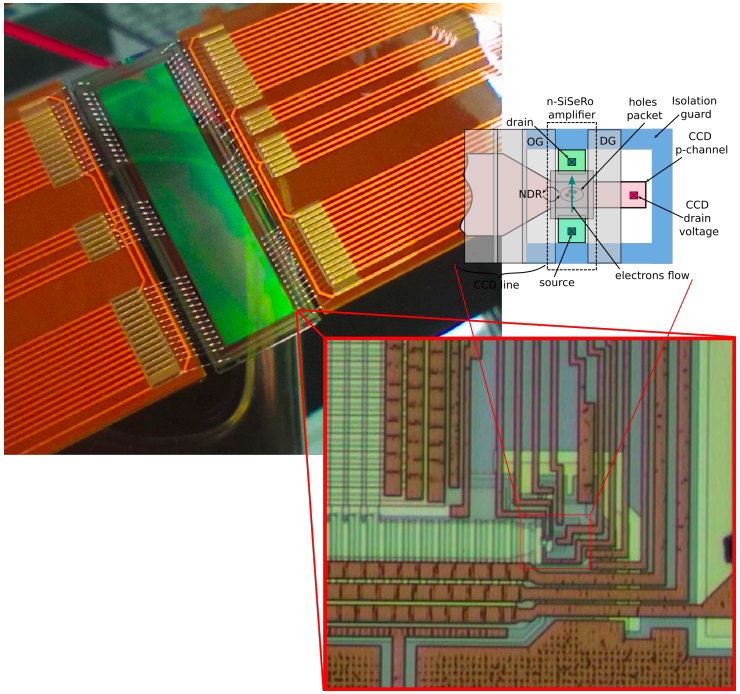


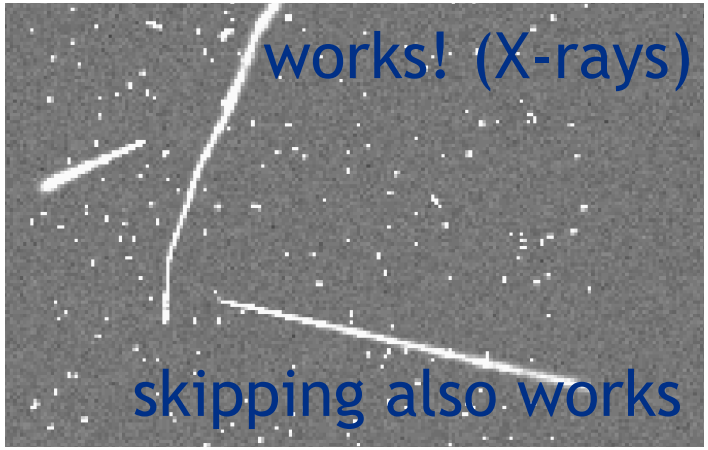


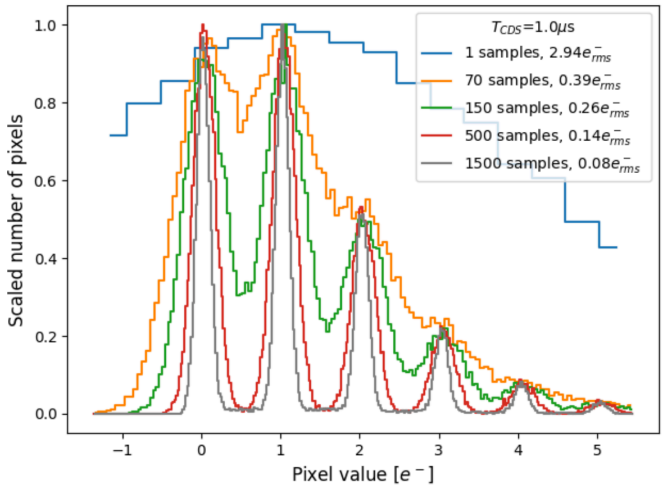
simulation predicts faster readout

FNAL, LBNL , MIT-LL, Universidad Nacional de Cordoba (Miguel Sofo-Haro).

SiSERO (2023!!!)







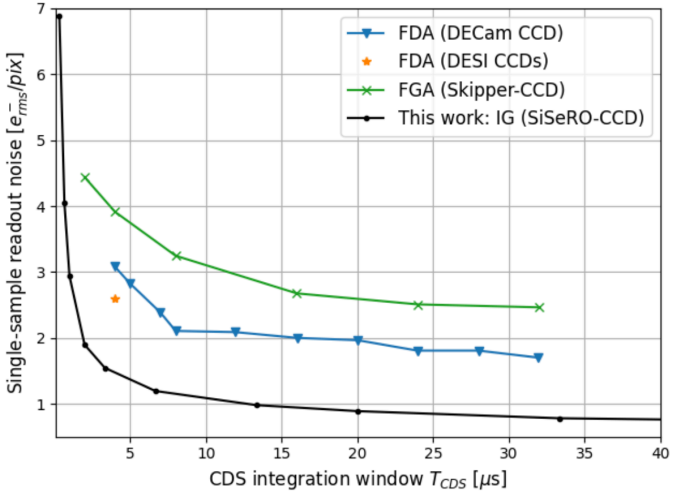
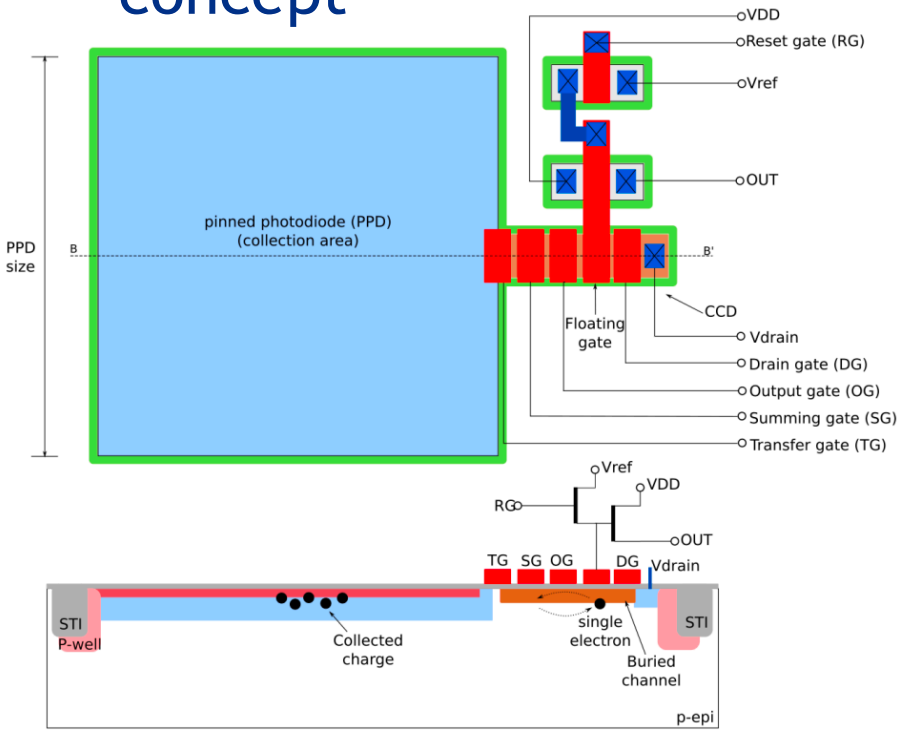


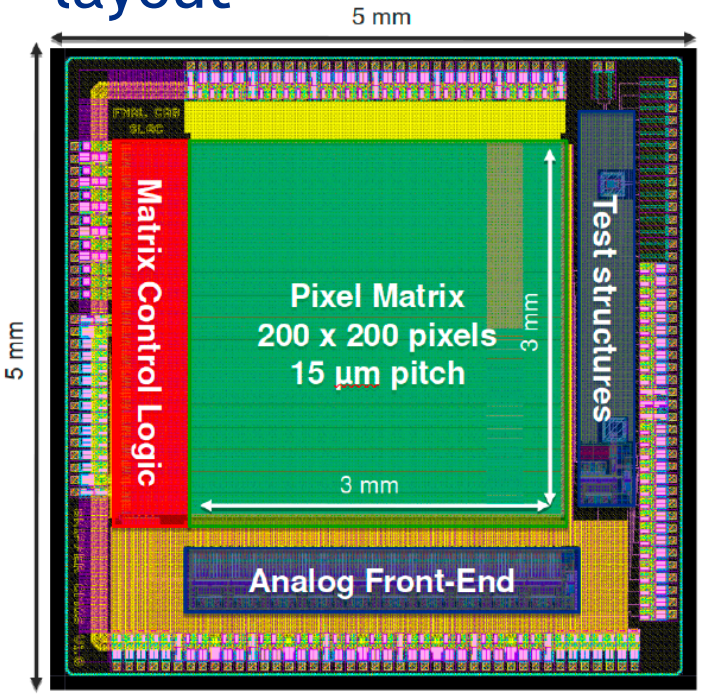
FIG. 3. Single-sample readout noise versus the correlated-double sampling (CDS) integration time T_{CDS}. As observed, the SiSeRO-CCD consistently achieves lower readout noise throughout the entire integration time range, highlighting the advantage of its internal gate (IG) sensing structure over fully-depleted thick CCDs with FDA [3, 6] or FGA [44] output structures.

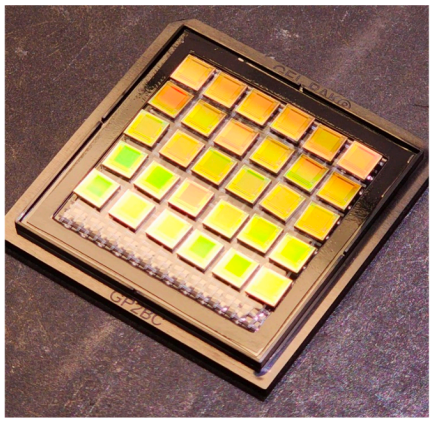
Skipper-CMOS (FNAL+SLAC+Tower+Universidad Nacional de Cordoba+UNS+Instituto Balseiro)

concept



layout





in hand (Tower)

Also works!

Conclusion

- SENSEI producing world class science…
- Oscura to start construction soon (FY25). We know what to do, we are working on the optimization of cost/schedule.
- Very active in other applications of this technology.