New Ideas in Cosmic Frontier

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UNAM / FNAL

FNAL Users Meeting 2023
June 30, 2023

New Ideas in Cosmic Frontier

explored with electron-counting silicon detectors!

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Dark matter exists!

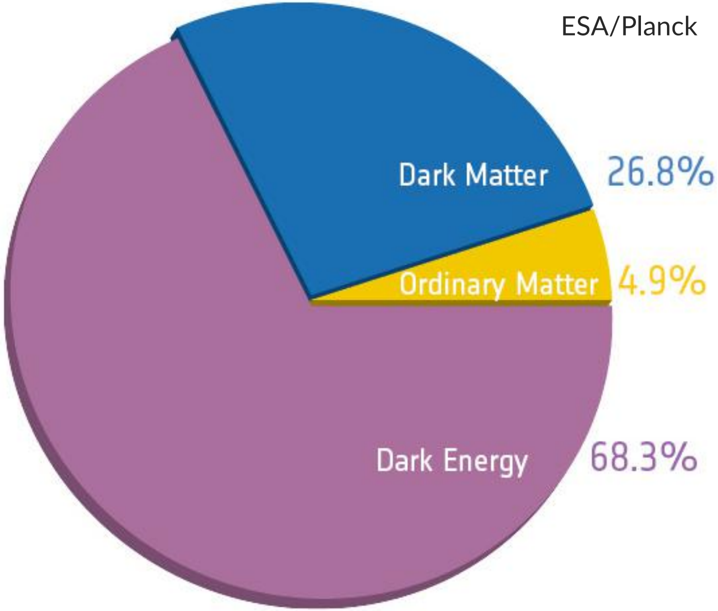
Observational evidence spans a wide range of space and time scales

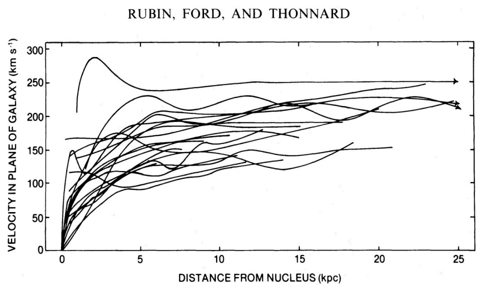
Astrophysical probes

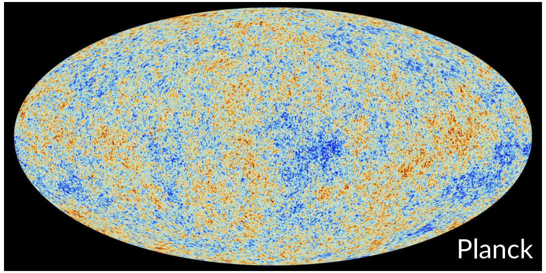
Dynamics (rotation curves, cluster collisions)
Gravitational lensing

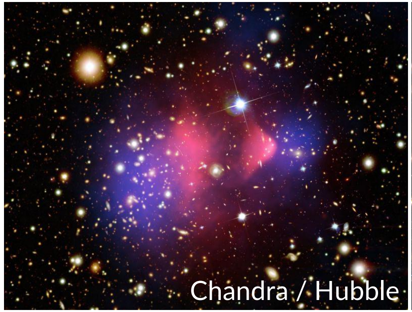
Cosmological probes

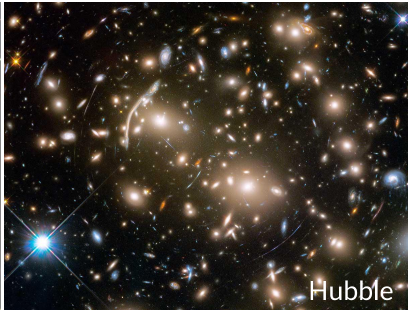
CMB anisotropies
Structure formation

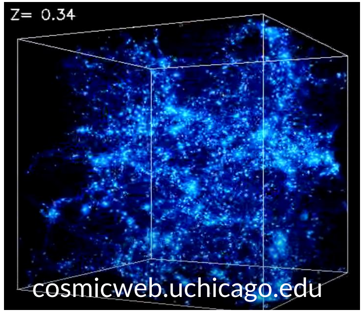












Universe content today
5x more DM than baryonic matter

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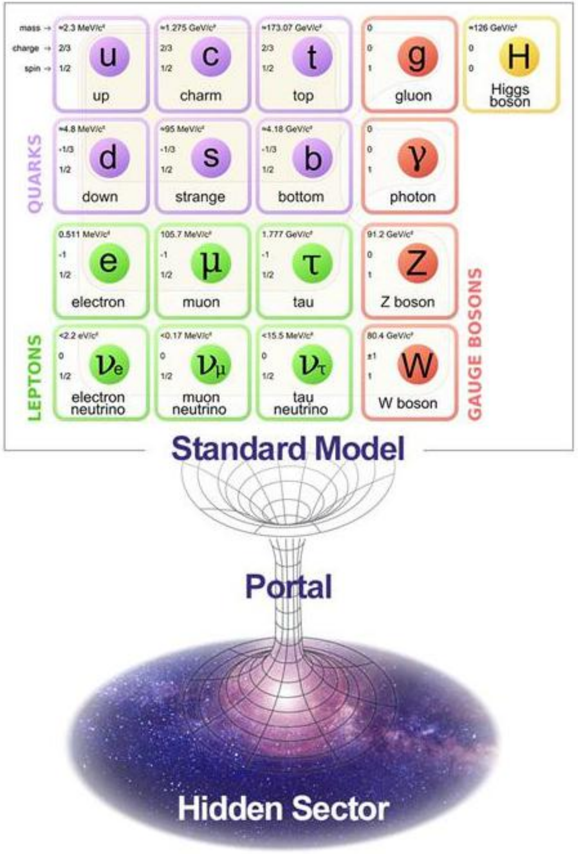
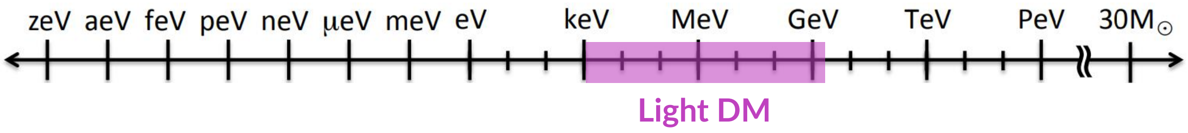
Dark matter as part of a dark sector

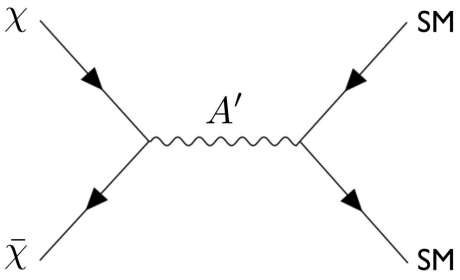


Consistent of new particles and fields, along with new interactions and interaction strengths, communicating with the SM through portals



Some models with light DM are consistent with the dark sector idea

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



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

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

Massless mediator: $m_{A'} = 0$
- DM is **millicharged**

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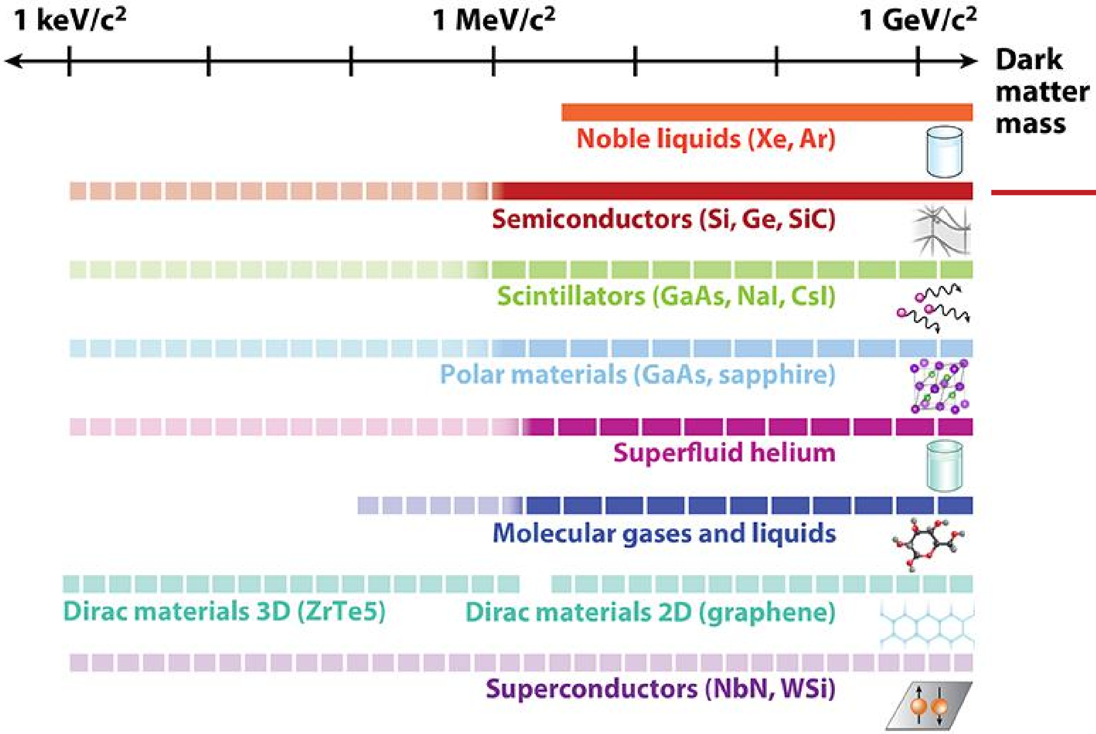
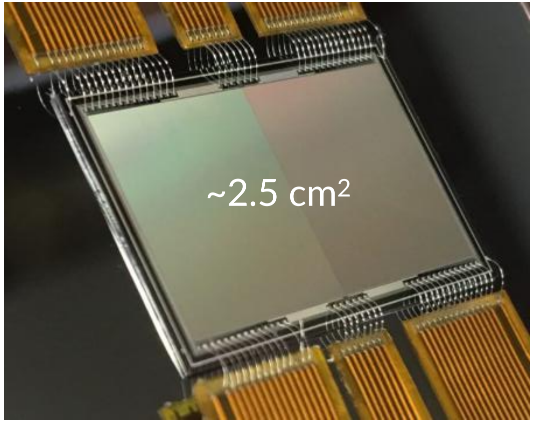
Exploring sub-GeV DM with low-threshold technologies

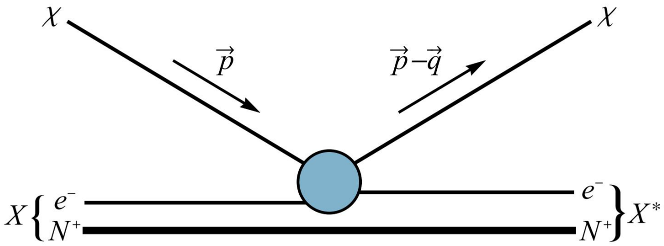


R. Essig - SBU; C. Cain - APS 2020

Skipper-CCDs!



Inelastic detection channels, for example DM-e^- scattering



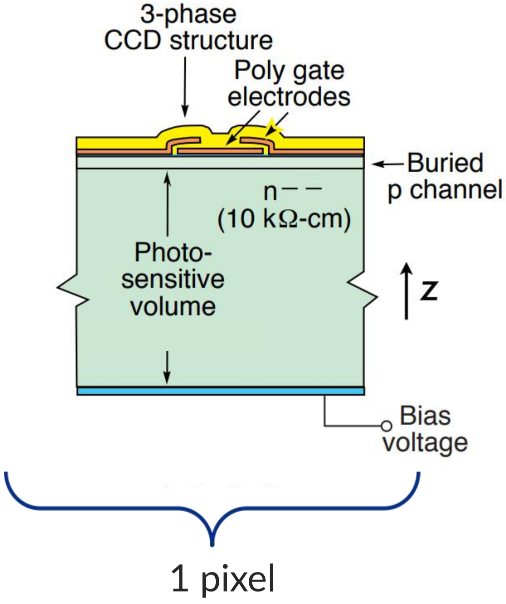
Skipper-CCDs: electron-counting silicon sensors

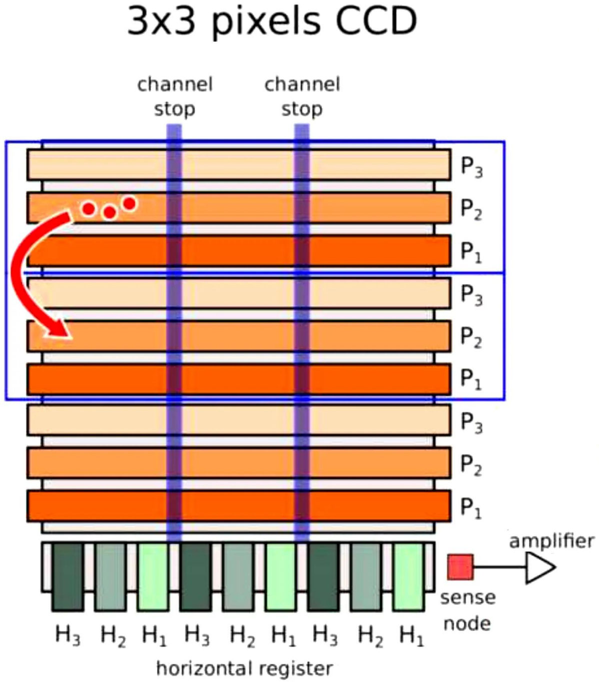
Steve Holland, Engineer/Extraterrestrial Rock Star

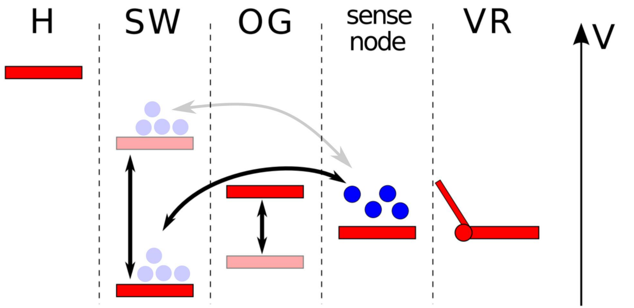
***Asteroid #40981** (1999 TL284)
Presented to: Stephen Holland, *CCD Developer Extraordinaire*

BERKELEY LAB

CCDs are an array of Metal-Oxide-Semiconductor capacitors
Ionizing radiation produces e-h pairs (In silicon, 1 e-h pair ~ 3.75 eV)
Charge is collected near the surface, transferred along the device until the readout stage







Skipper output stage allows to perform multiple non-destructive measurements

Sub-electron noise can be achieved as

$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

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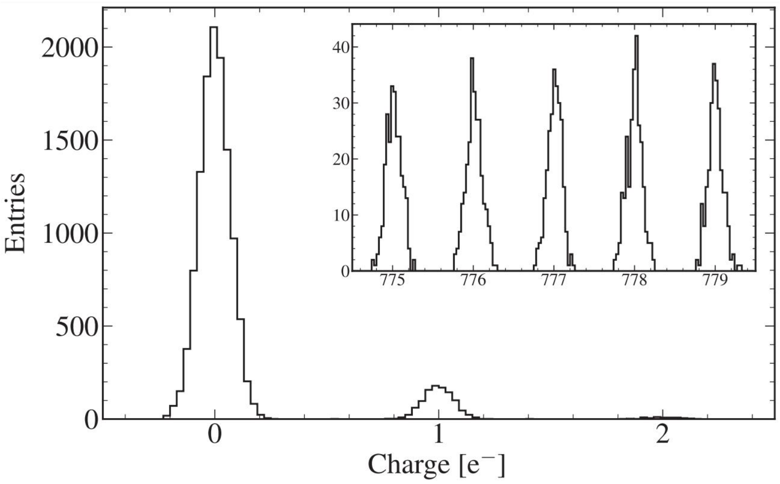
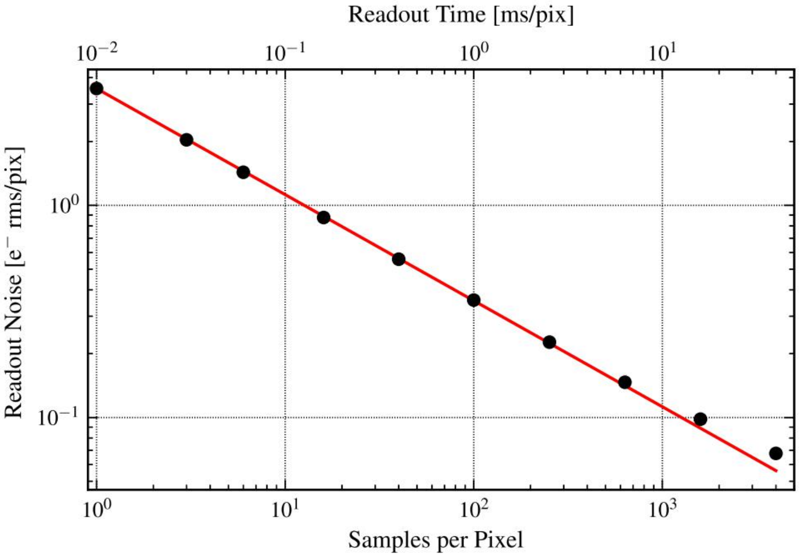
Skipper-CCDs: electron-counting silicon sensors

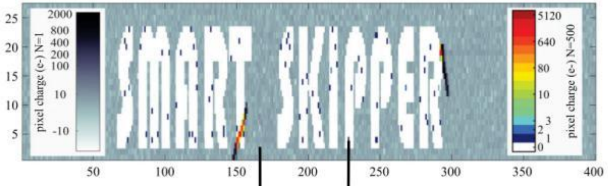
We can count single electrons in a wide dynamic range: self-calibrating charge measurement

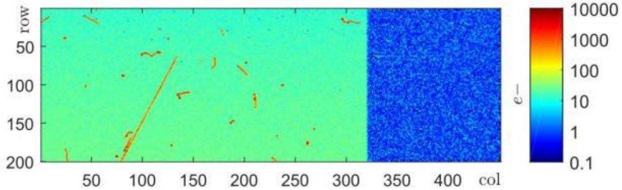
Trade-off between charge resolution and readout time





Fast-readout DAQ approach: Smart readout [10.1103/PhysRevLett.127.241101]



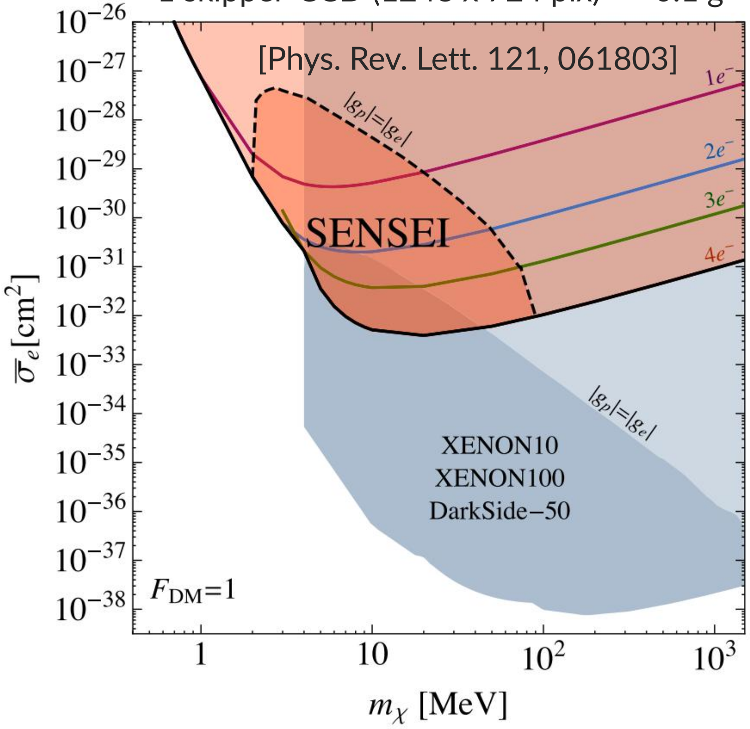


Skipper-CCDs: world best limits for sub-GeV DM candidates

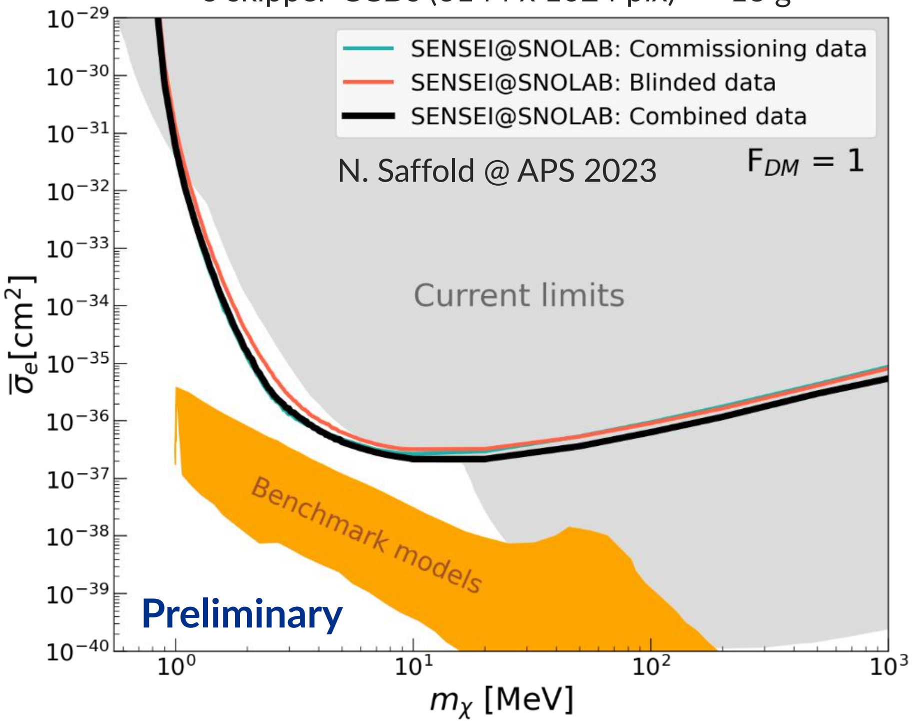
With a g-size detector!

SENSEI @ MINOS: [Phys. Rev. Lett. 125, 171802 (2020)]

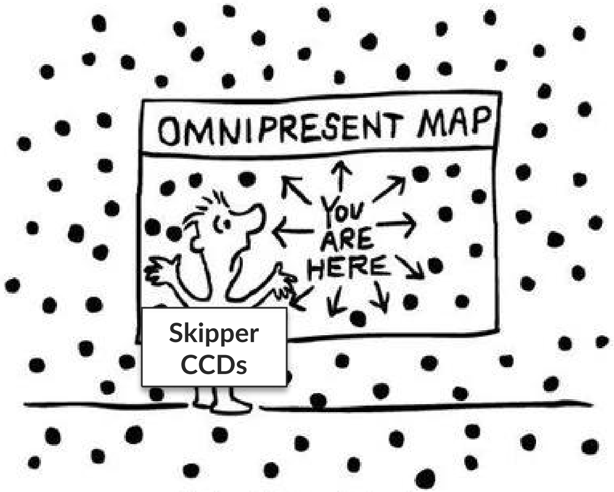
2018 - SENSEI surface run
1 skipper-CCD (1248 x 724 pix) = ~0.1 g



2023 - SENSEI @ SNOLAB
6 skipper-CCDs (6144 x 1024 pix) = ~13 g



R&D and new science ideas with skipper-CCDs



This is the new stuff.

DM (direct detection) at underground facilities with skipper-CCDs

Ongoing program to **increase detector mass** and to **reduce backgrounds**

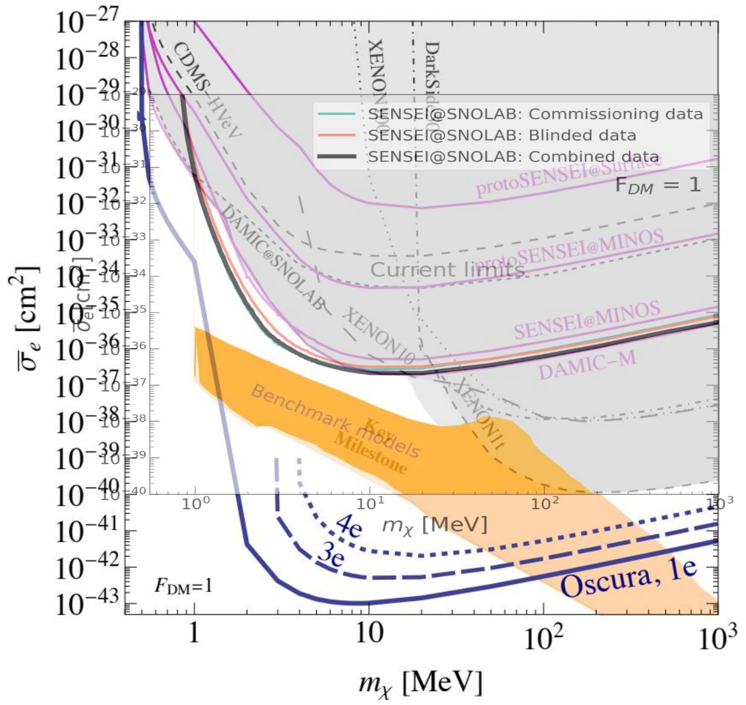
The Oscura experiment is the ultimate goal aiming to build a ~30 GPix low-background detector

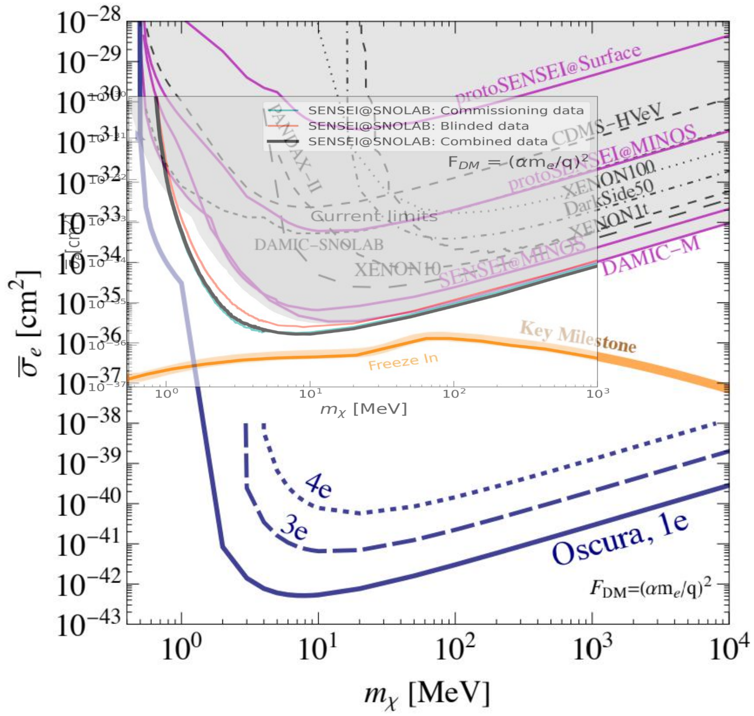
Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10	3×10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	10	3×10^{-3}	late-2021
SENSEI-100	~0.1	~50	10 (goal)		mid-2022
DAMIC-M	~1	~200	0.1 (goal)		~2023
OSCURA	~10	~25,000	0.01 (goal)	1×10^{-6} (goal)	~2028

Oscura: Science reach

[arXiv:2304.04401]

Goal: Direct search for sub-GeV DM looking at DM-electron interactions; it will probe benchmark models





DM-electron scattering mediated by a heavy (left) or ultra light (right) vector mediator
4e- curve corresponds to the Oscura prototype skipper-CCDs performance

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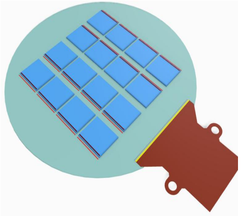
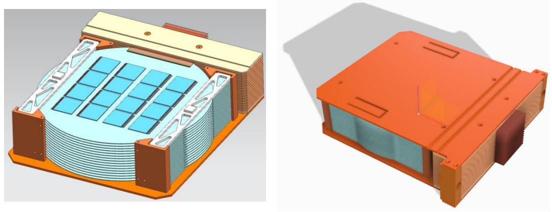
Oscura: First multi-kg (10-kg) skipper-CCD detector

[arXiv:2202.10518]

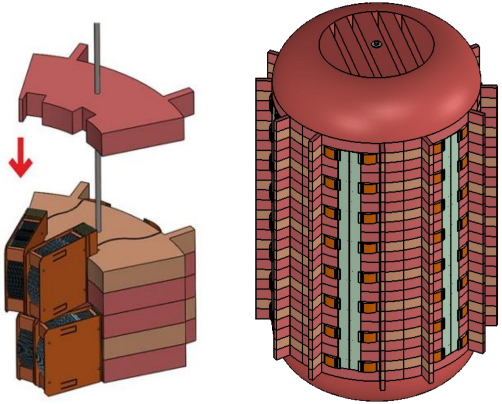
Multi-Chip Module (16 skipper-CCDs)



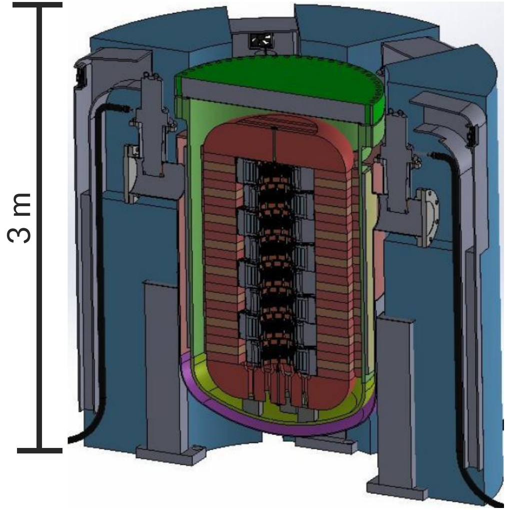
Super Module (16 MCMs)



Detector payload in 6 columnar slices
(96 Super Modules)



LN_2 pressure vessel (450 psi) @ SNOLAB



DM New Initiatives

Oscura conducted a major R&D:

- Mass production of science-grade skipper-CCDs
- New sensors packaging and cryogenics for multi-kg detectors
- Cold front-end electronics for thousands of readout channels
- Low radiation background design

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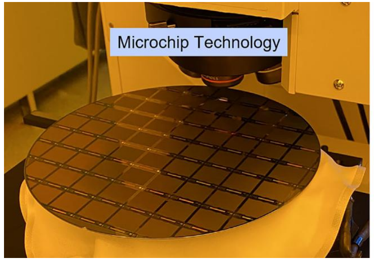
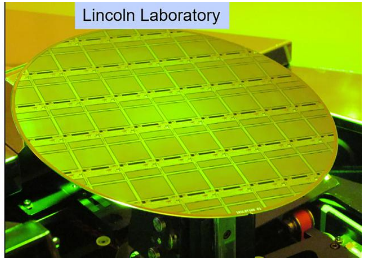
Oscura: Sensors and MCMs fabrication

Success!

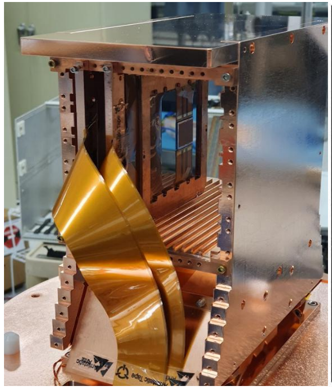
Fabrication of sensors at two NEW foundries: Microchip Technology Inc. and MIT Lincoln Lab



[10.1002/asna.20230072]



[NIMA 1046 (2023), 167681]



Skipper-CCD mounted in cryostat

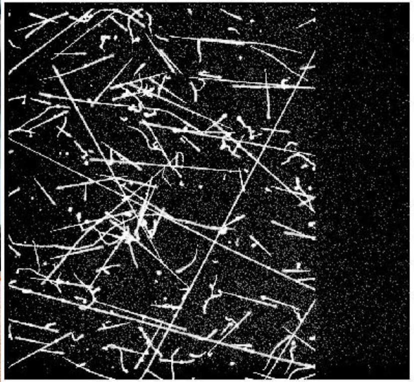
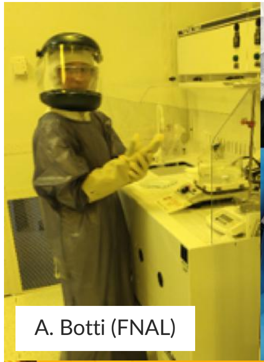
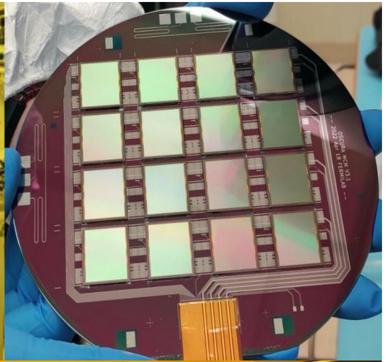


Image from prototype CCD

My work → [arXiv:2304.04401]

Fabrication of silicon MCMs at Argonne National Lab in collaboration with FNAL





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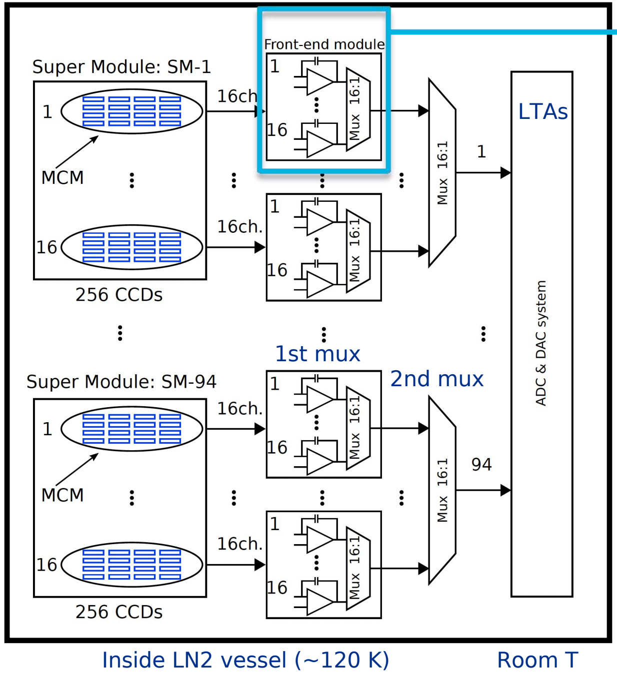
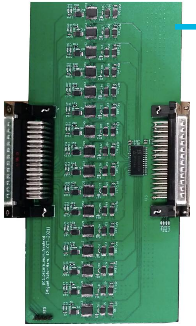
Oscura: Readout electronics

Oscura requires ~24,000 readout channels complying with noise and readout time constraints
- Cold front-end electronics to reduce feedthrough complexity (only 96 cables outside vessel)
- 2 multiplexing stages → 256 channels result in 1 signal
- 1 LTA controls 4 SM (1024 sensors) → 24 LTAs needed in total

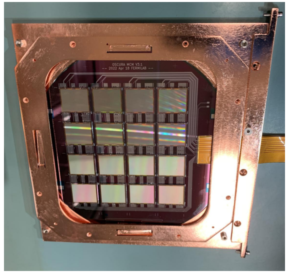


- Discrete (mux board) [Sensors 22 (2022) 11, 4308] [JINST 16 P11012]
- Integrated (MIDNA ASIC) [10.2172/1841383]
  4 channels in 2 mm² chip **reducing cost, space and radioactive contamination**
  Tested and working!

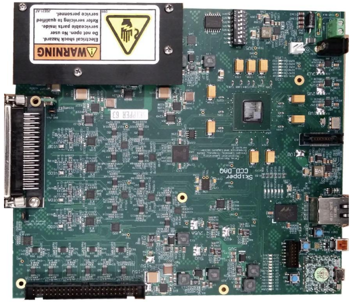
Mux board

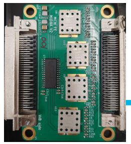


MCM



LTA [1.JATIS.7.1.015001]





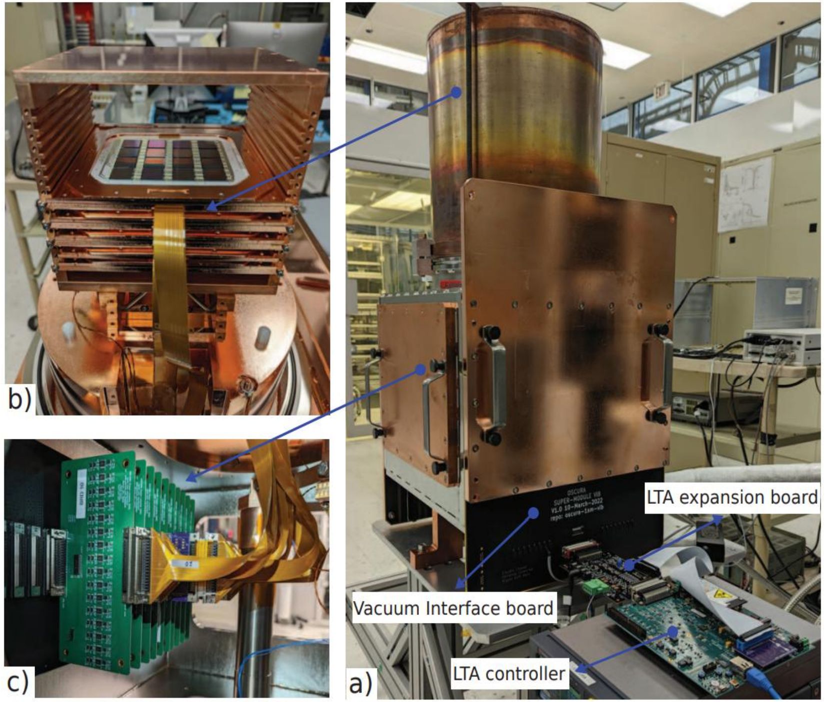
Board with 4 MIDNAs

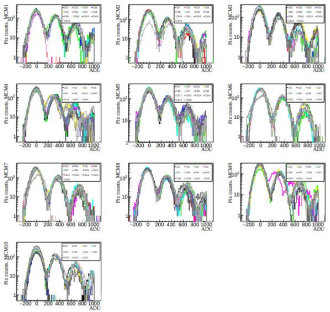
Oscura: Massive testing setup with 160 skipper-CCDs

[JINST 18 P01040]

Copy of SENSEI-100 vessel with 10 prototype ceramic MCMs and the discrete readout electronics

Largest ever built instrument with skipper-CCDs controlled by 1 LTA → Demonstrates electronics solution

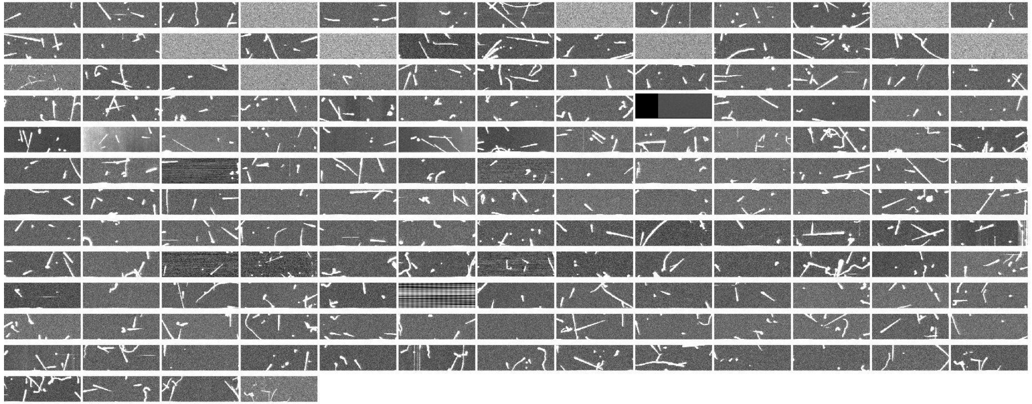




~90% of the sensors working without a preselection! This is a BIG deal!*

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

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



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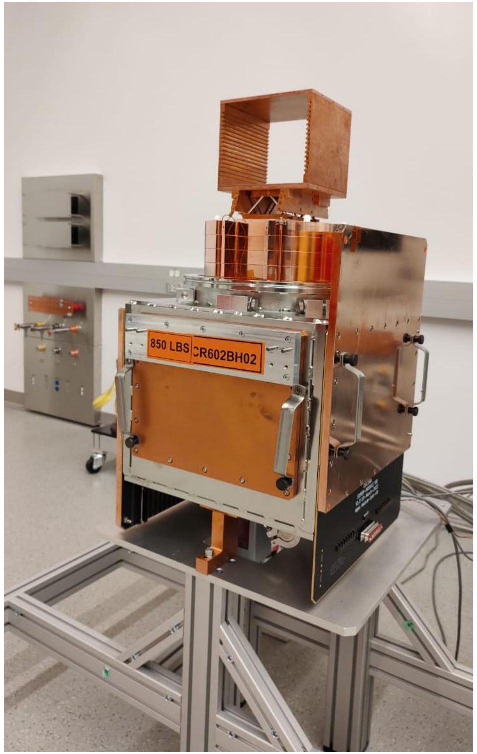
Oscura: Massive testing setup now at IERC!

Come meet our new lab!

Image credit: F. Chierchie



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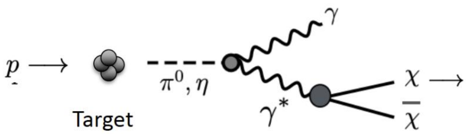
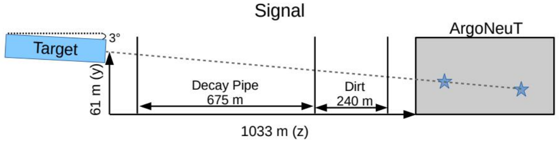
Oscura: Early science (DM production)

[arXiv:2304.08625]

With a 10% mass load (32-layer tracker), **search for millicharged particles** produced at the NuMI beam at FNAL

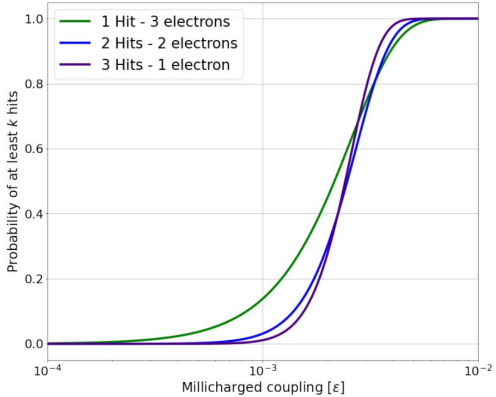


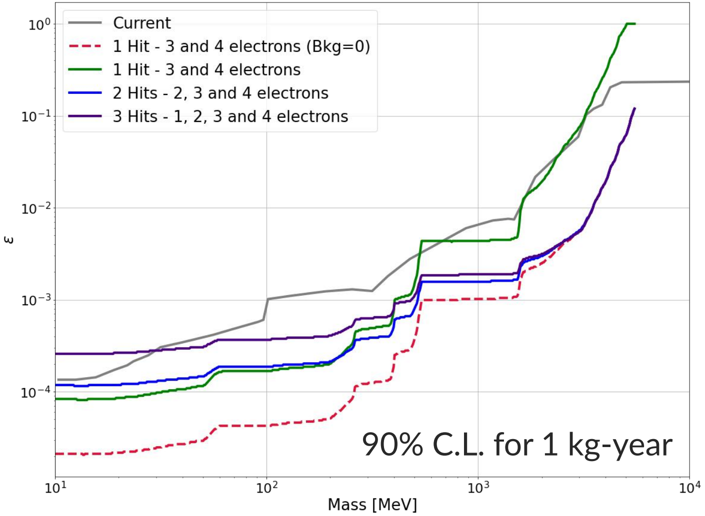
[PRL 124, 131801 (2020)]

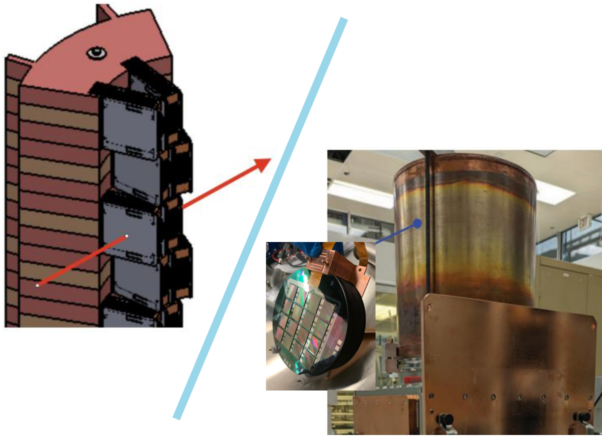


Multiple-hit search could reduce bkgds
Exclusion limits are promising!

mCPs skipper-CCD detector:
- Large-mass setup (tracker?)
- Location @ accelerator facilities





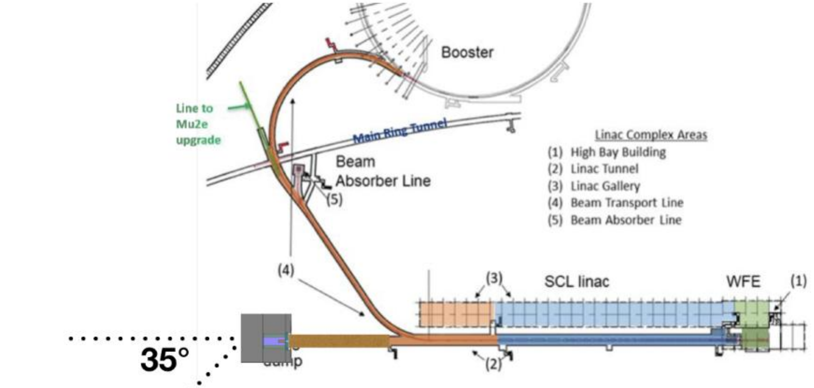


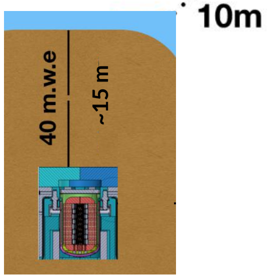
Number of fake tracks per day produced by random coincidences of uncorrelated single pixel hits

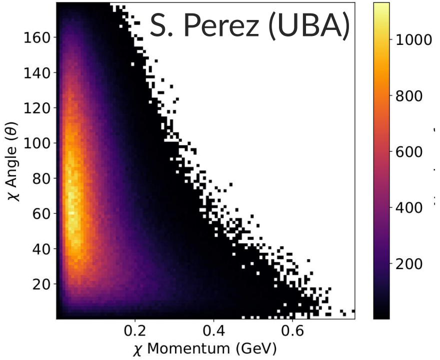
Threshold	doublets $(b=2)$	triplets$(b=3)$	p_{bkg}
$1e^-$	3822	11.4	3×10^{-4}
$2e^-$	0.031	2.72×10^{-7}	$8.6\times10{-}7$
$3e^-$	9.06×10^{-5}	4.17×10^{-11}	4.6×10^{-8}

mCPs search with skipper-CCDs at accelerator facilities: PIP II

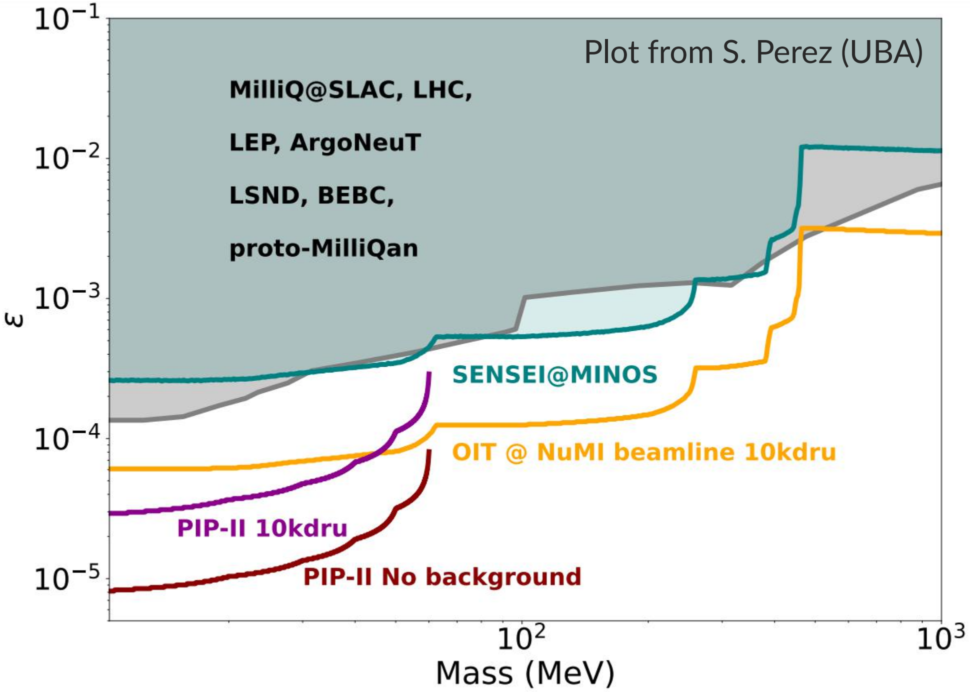
Opportunity at future Fermilab accelerator complex, as discussed in May 2023 at the “Physics Opportunities at Beam Dump Facility in PIP-II and Beyond” workshop (White paper in progress)







Different facilities allow to explore a wide mass range



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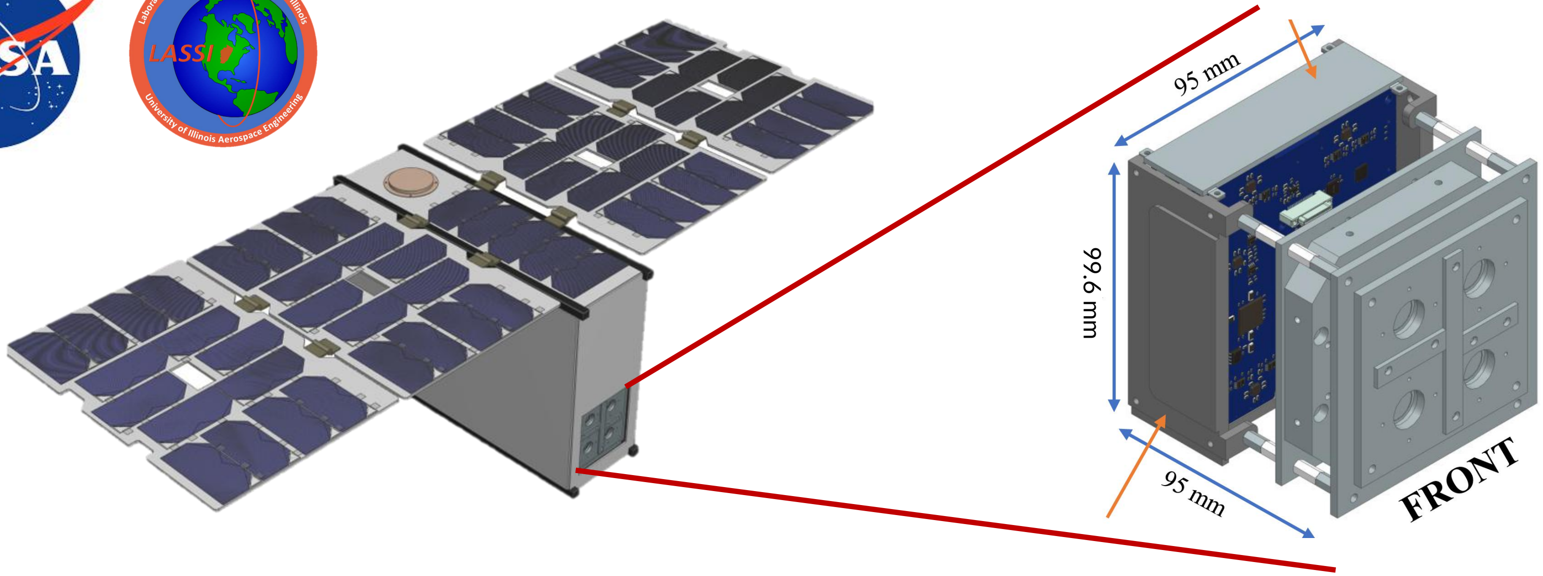
DM search with skipper-CCDs in space!

DarkNESS (Dark matter Nanosatellite Equipped with Skipper Sensors): 6U CubeSat housing 4 skippers-CCDs
Science goal: Map the diffuse X-ray background in the Milky Way and search for DM
First demonstration of skipper-CCDs in space and for X-ray astronomy

Collaboration with NASA and UIUC-LASSI

FNAL in charge of payload development



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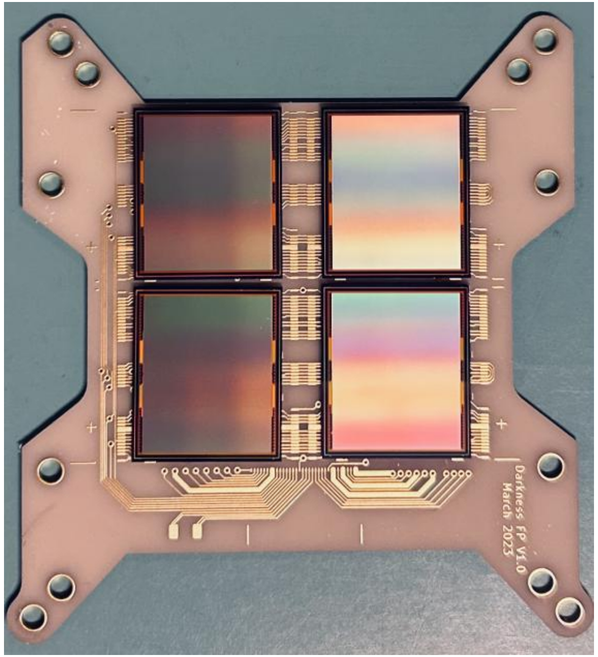
DarkNESS: Developing skipper-CCDs for space missions

Mechanical prototype of the 5.4 MPix skipper-CCD array



Aluminum shield to blind visible and IR photons*

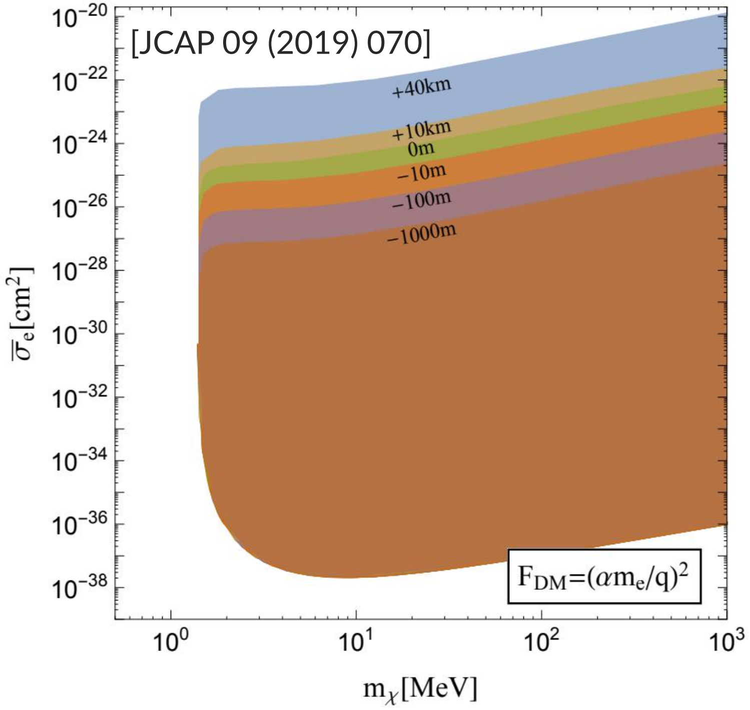
New optimized space-LTA readout electronics

* Part of Oscura R&D to avoid LN2 scintillation light

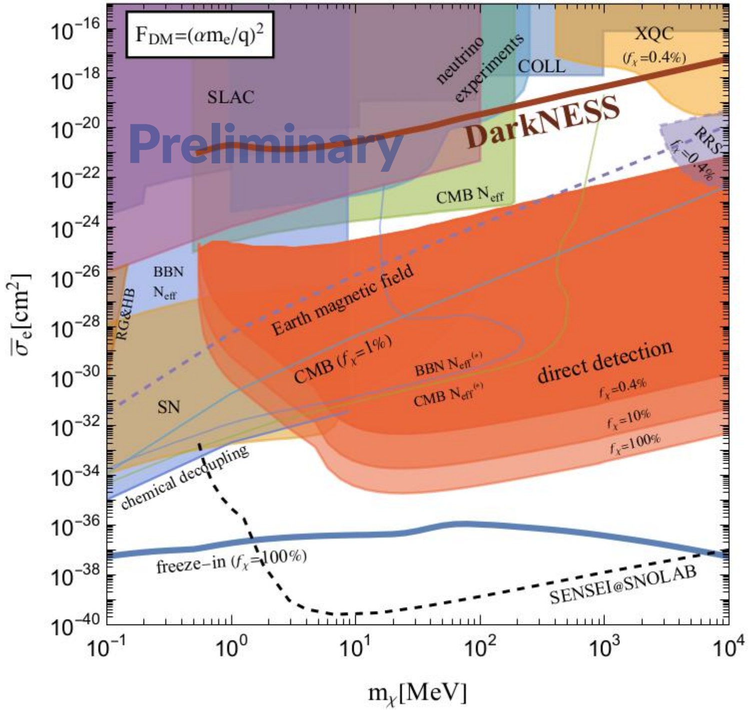
DarkNESS: Searching for strongly-interacting light DM (direct detection)

Upper DM cross section boundary depends on depth (Earth's atmosphere and crust attenuate LDM flux)

Ultra light dark photon mediator



0.1 g-month exposure and 10^9 background events



Plot from N. Saffold (FNAL)

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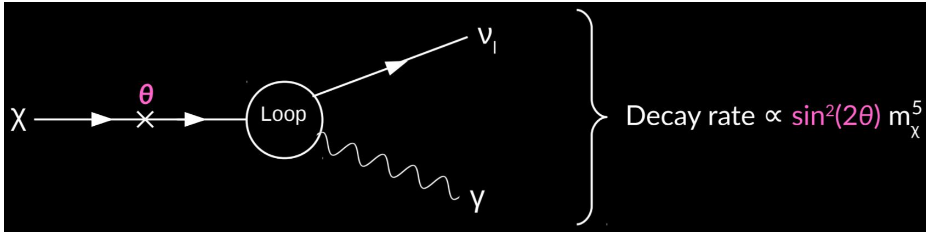
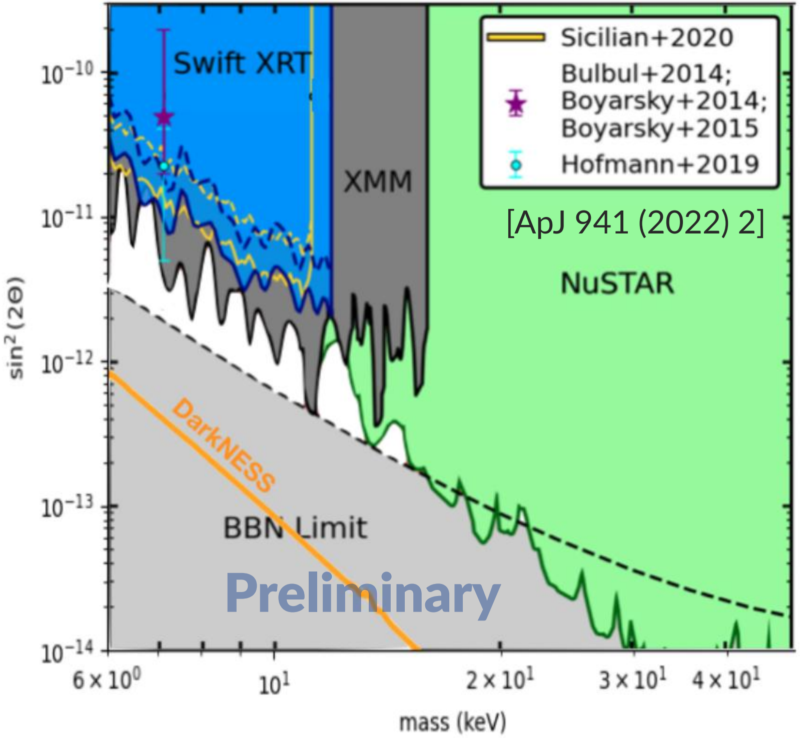
DarkNESS: Searching for sterile neutrino DM (DM decay)

keV-scale sterile neutrinos are DM candidates that could decay to photons with $E = m_{\nu_s}/2$



From B. Roach slides @ FNAL CPC seminar (April 2022)

1 Msec exposure on the Galactic center



Plot from N. Saffold (FNAL)

Consistent with unidentified X-ray emmision (~3.5 keV) in DM-dominated objects [ApJ 789 (2014) 13]

It is very likely that this signal is not DM as recent results have significantly excluded it

DarkNESS will be sensitive to that parameter space

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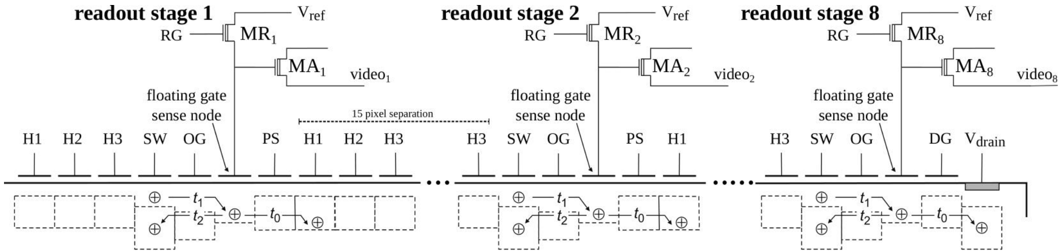
Emerging technologies

Fast-readout technologies with single-electron resolution

New Initiatives Grant

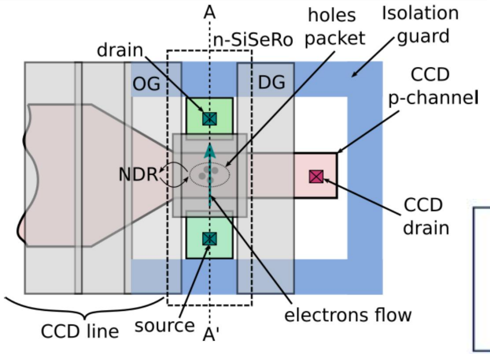
Multi-Amplifier Sensing (MAS) CCDs

[10.1002/asna.20230072]



CCDs with n-Sisero stages

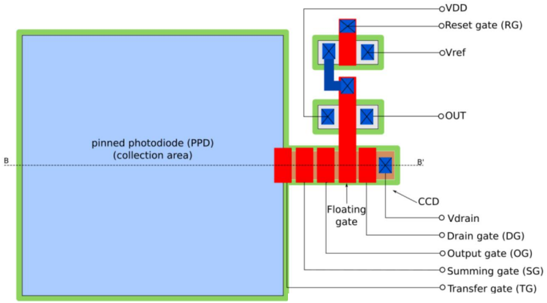
[10.1109/TED.2022.3233288]



[indico.fnal.gov/event/58707]

Skipper-in-CMOS

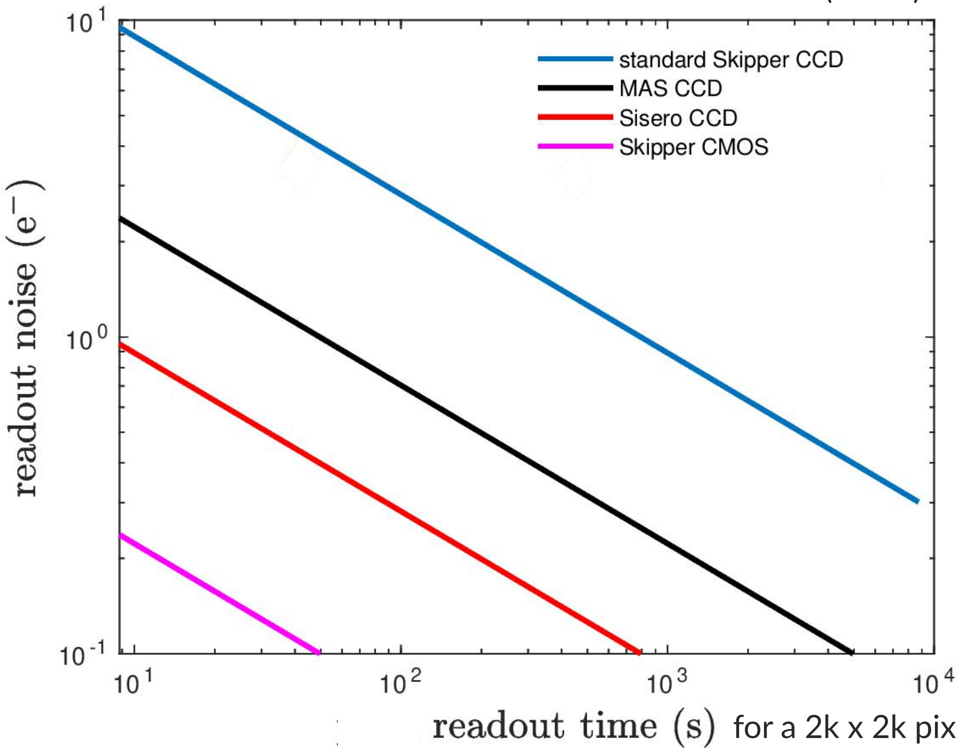
[B. Parpillon @ CPAD 2022]



Fast-readout technologies with single-electron resolution

Improve readout time, compared to skipper-CCDs, without losing electron-counting capability

Plot from G. Fernandez Moroni (FNAL)



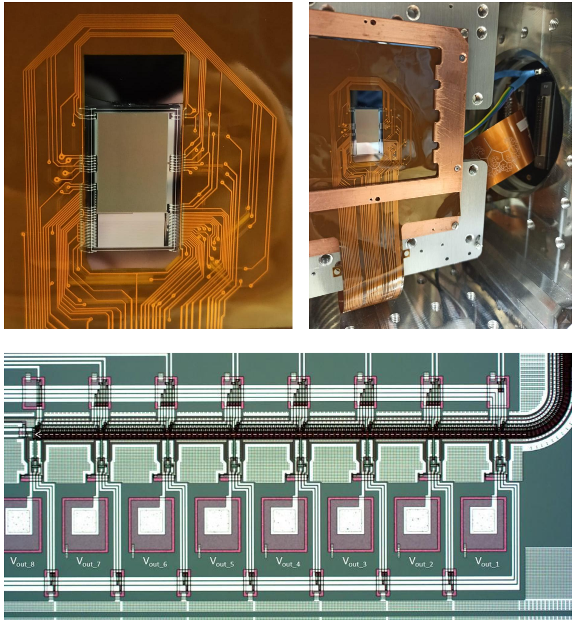
for a 2k x 2k pix sensor

Fast-readout technologies with single-electron resolution

First prototypes are being tested at SiDet!

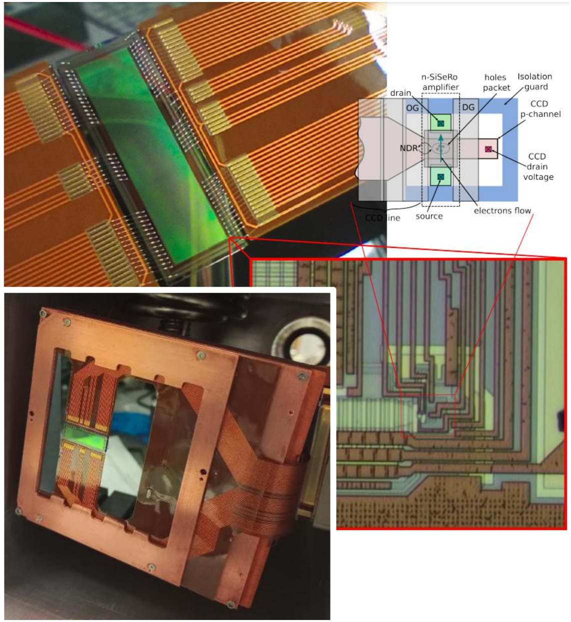
Multi-Amplifier Sensing (MAS) CCDs

[10.1002/asna.20230072]



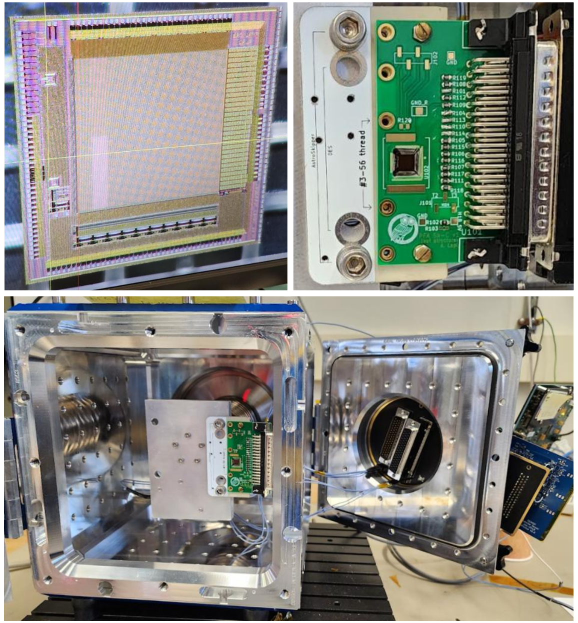
CCDs with n-Sisero stages

[10.1109/TED.2022.3233288]
[indico.fnal.gov/event/58707]



Skipper-in-CMOS

[B. Parpillon @ CPAD 2022]



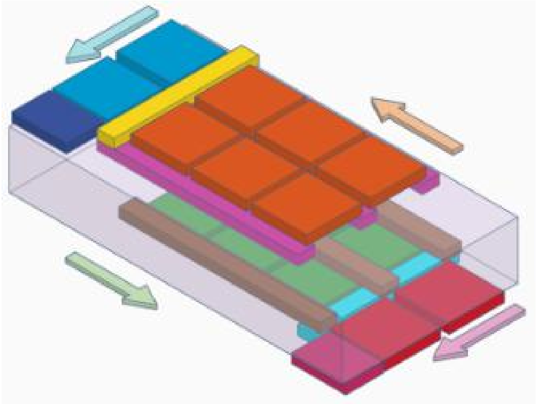
Stay tuned for results!

CCDs with timing resolution: Dual-side CCD

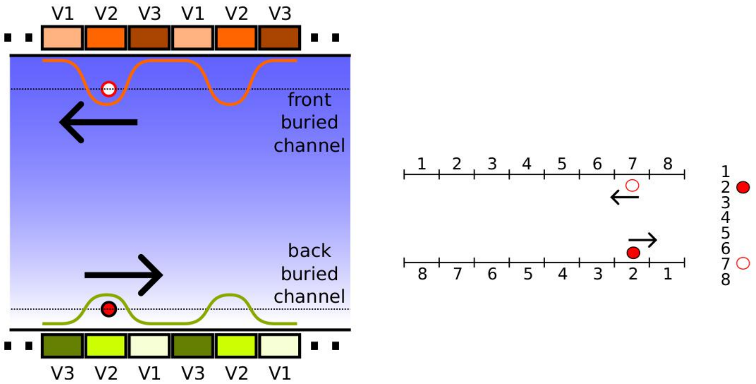
Device with gate structures and buried-channels of opposite polarity in both (front and back) sides to **collect BOTH electrons and holes**

Charge carriers are moved in opposite directions towards different serial registers

Novel idea from
Javier Tiffenberg (FNAL)



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

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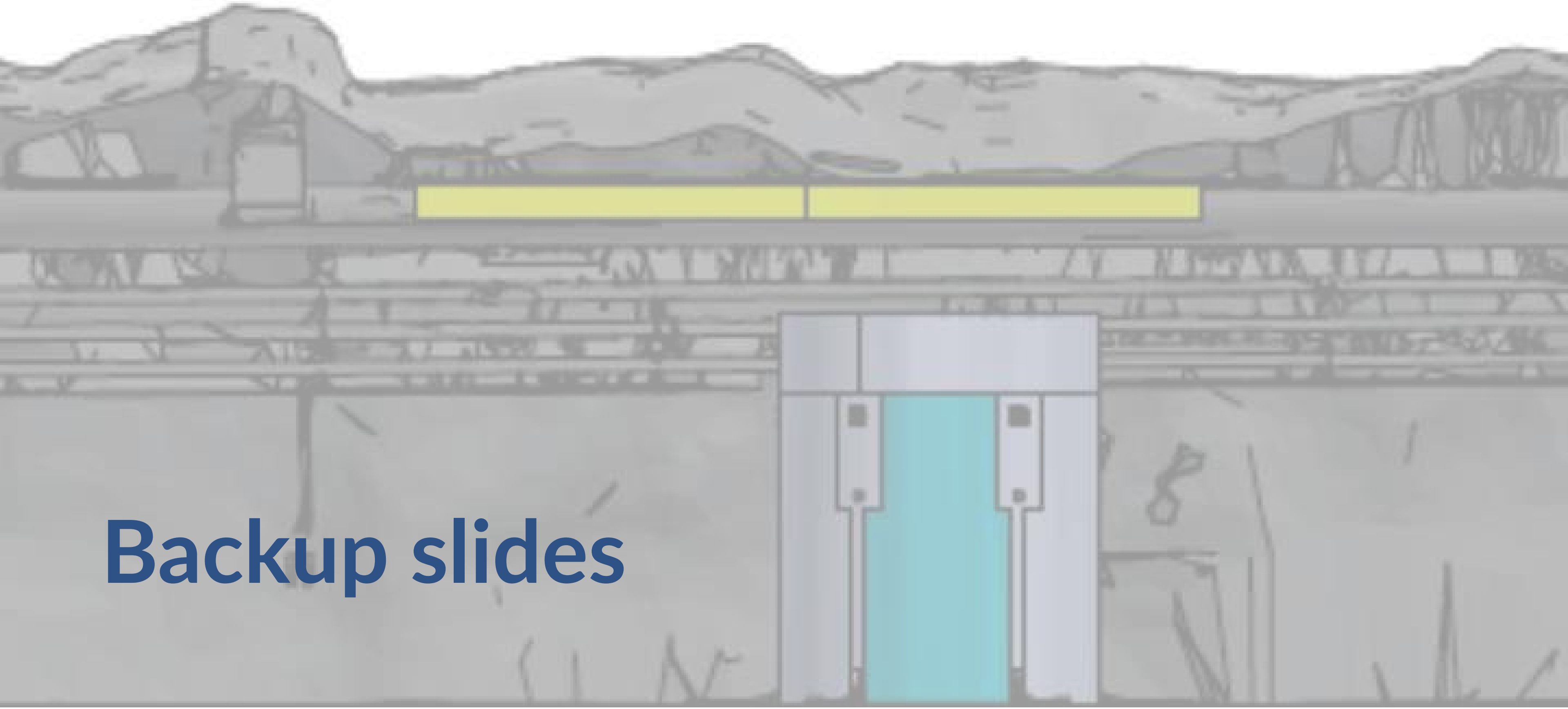
Take-home messages

- Electron-counting skipper-CCD technology allows exploring the dark sector
- Development of multi-kg low-background skipper-CCD detectors is ongoing
- Searching for LDM at underground laboratories with skipper-CCDs is a robust experimental program (Oscura being the ultimate goal)
- Millicharged particles search with skipper-CCDs at accelerators seems promising
- Enabling skipper-CCD technology for space-based applications is a new research area (DarkNESS is the pioneer experiment)
- Emerging fast-readout semiconductor technologies with single-electron resolution are being developed (useful to reject backgrounds)

Thank you!



Backup slides

Skipper-CCDs: smart readout

Two approaches during DAQ: Region-of-interest (ROI) and Energy-of-interest (EOI)
Decreases overall sensor readout time

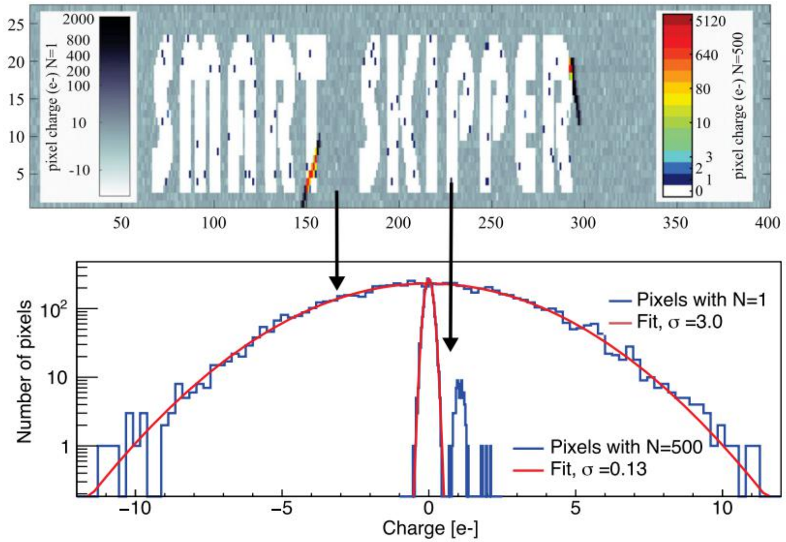


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

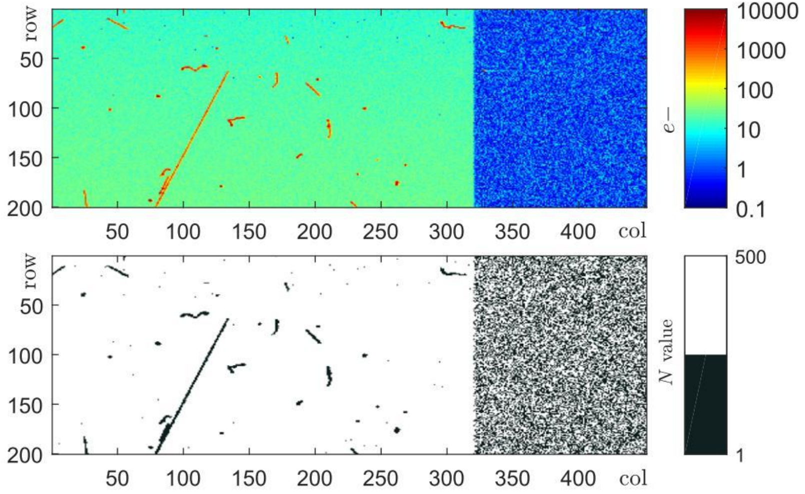


FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

[10.1103/PhysRevLett.127.241101]

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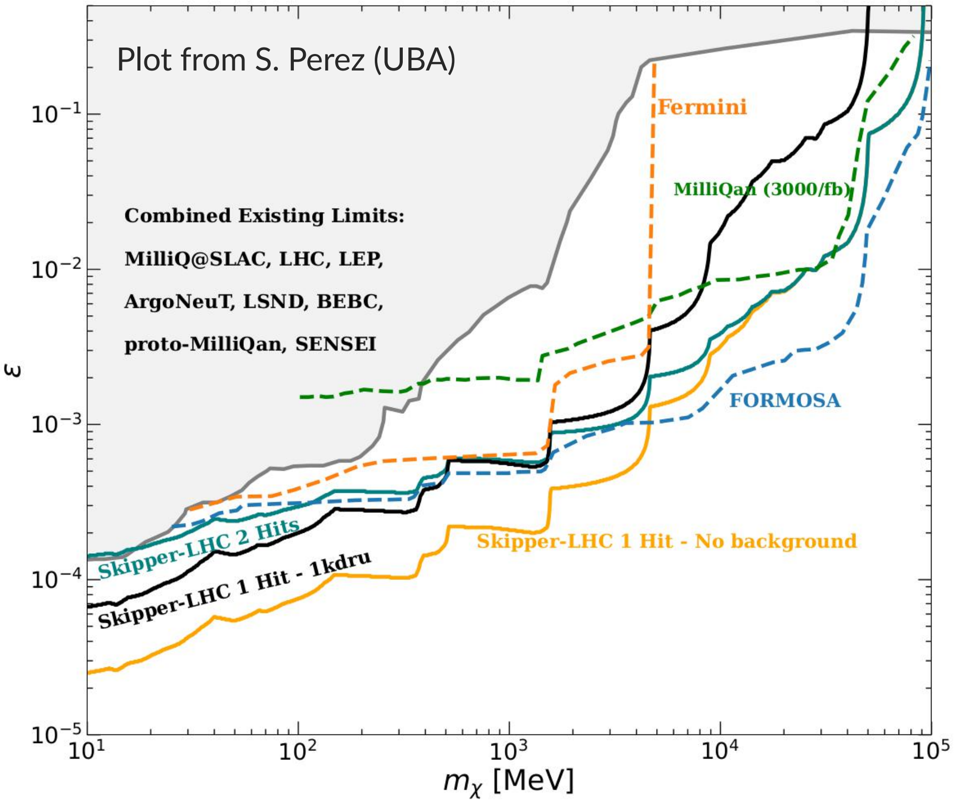
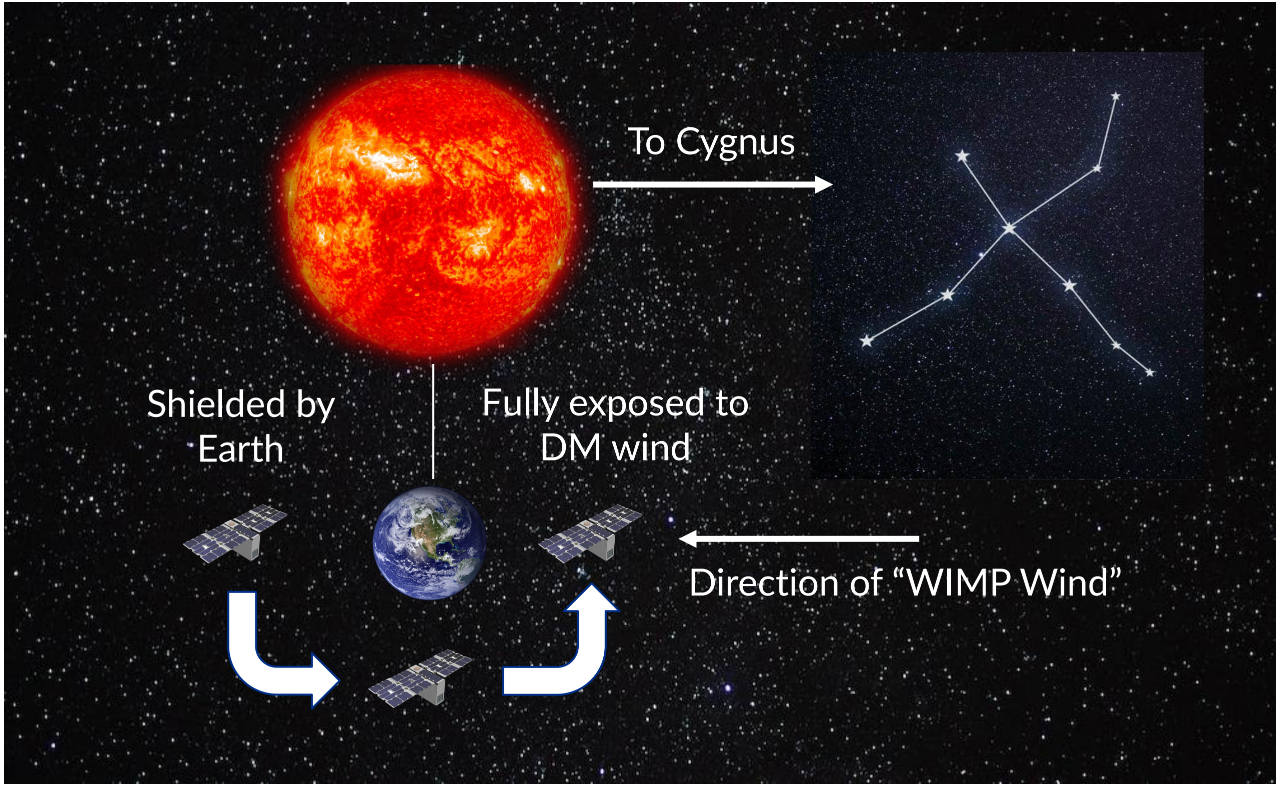
mCPs search with skipper-CCDs at accelerator facilities: LHC

At HL-LHC there are O(TeV) proton-proton interactions



DarkNESS: Searching for strongly-interacting light DM

Modulation in signal rate over orbital period due to Earth shadowing



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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 1×10^{-6} e-/pix/day

Front-end electronics

- Develop a low-cost, scalable, cold readout system and multiplexing

Radiation background

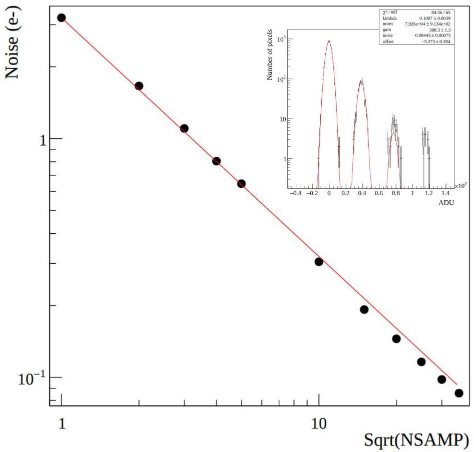
- Ensure use of low-background materials and cosmogenic activation control
- Oscura experiment design all driven by simulations to reach 0.01 dru

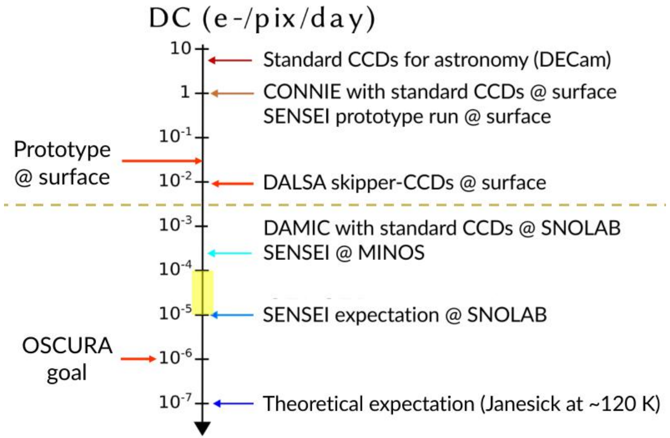
Oscura: Prototype sensors performance

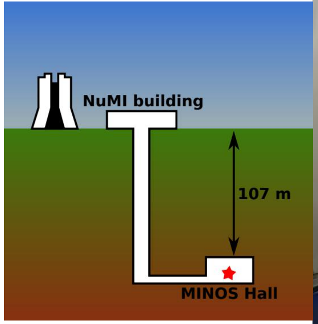
My work → [arXiv:2304.04401]

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%	

- 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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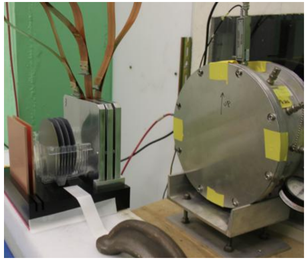
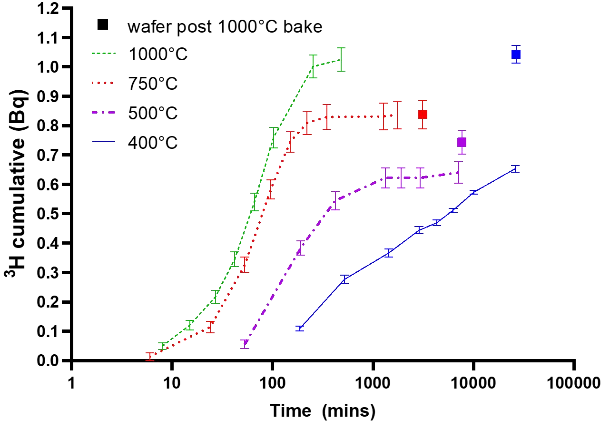
Oscura: Radiation background control

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



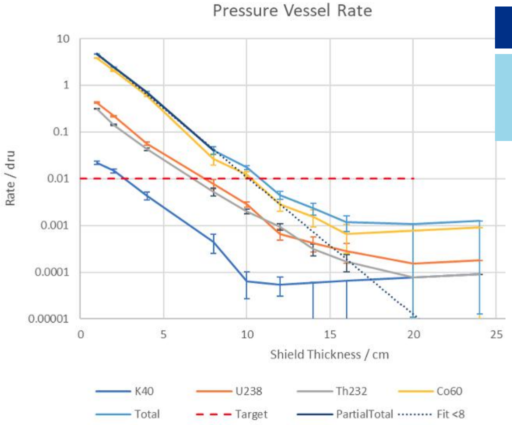
[PRD 102, 102006]



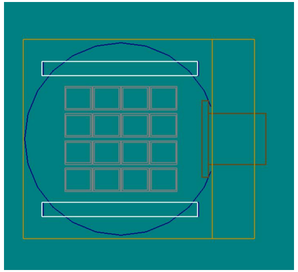
Sources:

- 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)

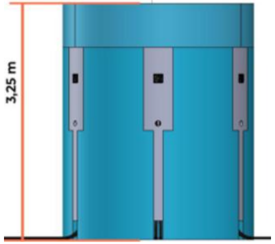
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [arXiv:2303.10862]
  - Simulations of ^{238}U, ^{232}Th and ^{40}K
  - → 4cm of cable visible to CCDs (with 15 ppt)
  - → Electronics behind inner shield (width>10cm)



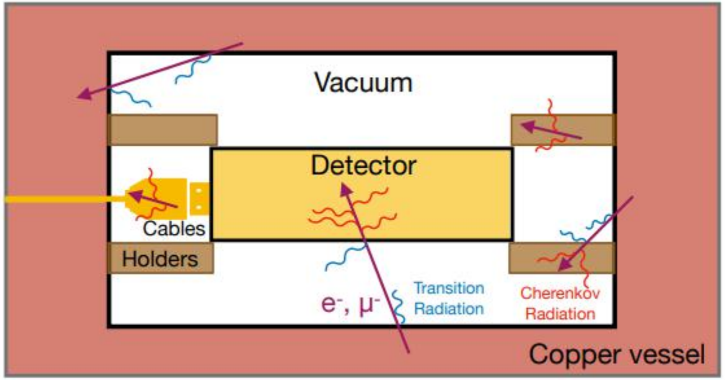
DAMIC-M cable	^{238}U [ppt]	^{232}Th [ppt]
Commercial	2670 +/- 30	270 +/- 60
Customed	**31 +/- 1**	**11 +/- 1**

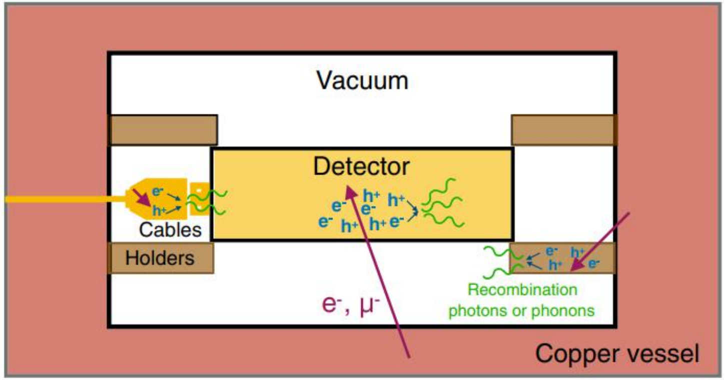


- External backgrounds
  - Outer shield: polyethylene
  - Inner shield: ancient lead and electroformed copper



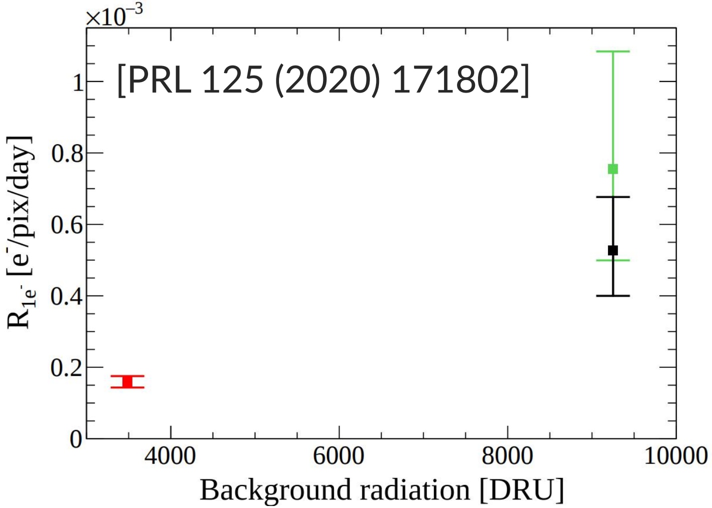
Low-energy background from high-energy events





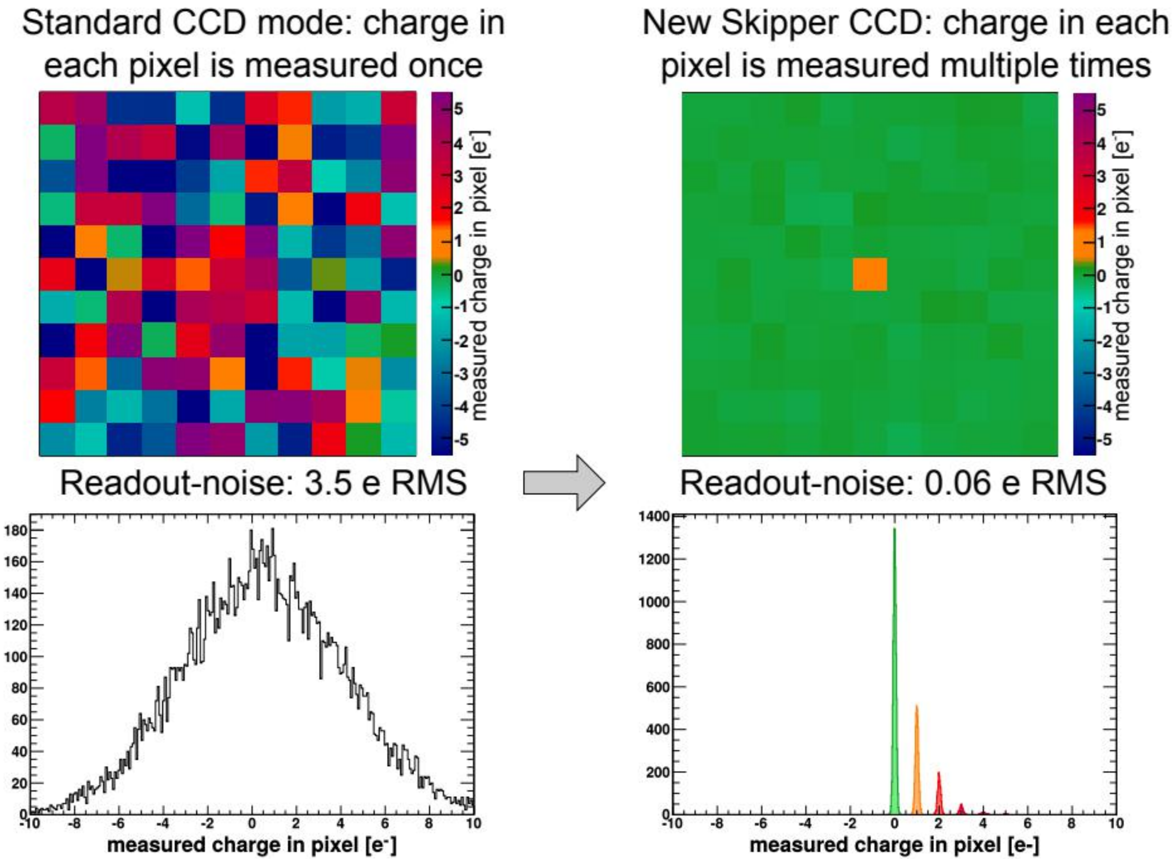
[PRX 12 (2022) 011009]

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 (2 in Pb shield) @ MINOS (100 m underground)

Skipper-CCDs: readout noise



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[https://www.astronomy.ohio-state.edu/weinberg.21/Rap/index.html]

The Dark Matter Rap: A Cosmological History

by David Weinberg, ©1992
Lyrics updated 2023

...

WIMPy, fuzzy, warm, dark atomic, superlight,
so hard to find it feels like they are hiding out of spite.
So we huddle deep in mines with the world's supply of xenon
seeking scintillating flashes of the insight we are keen on.
Mic silicon-germanium to listen in for phonons.
Build hyper-volume radios, tuning in for axions.
We search the skies for gamma-rays from WIMP annihilation,
those tiny sparks that light the dark in EM radiation.
We smash together protons, search for tracks in the debris,
to prove we made our own DM within the LHC.
The search is ever-popular, as many realize
that the detector of dark matter may well win the Nobel Prize.

So now you've heard my lecture, and it's time to end this session
with the standard closing line: Thank you, any questions?

Symmetry

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