Dark sector searches with skipper-CCDs: current status and future ideas

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Coordinating Panel for Advanced Detectors (CPAD) Workshop
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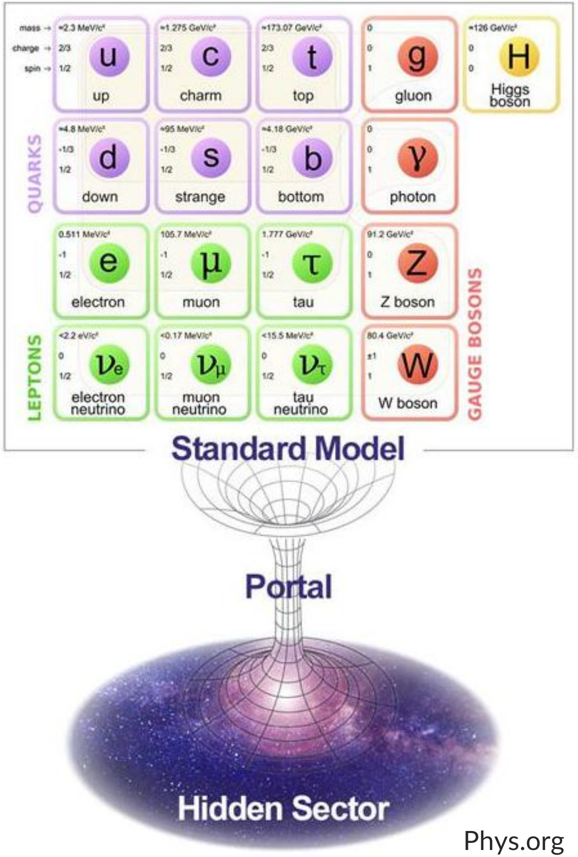
Fermilab

Dark sector(s)



Phys.org

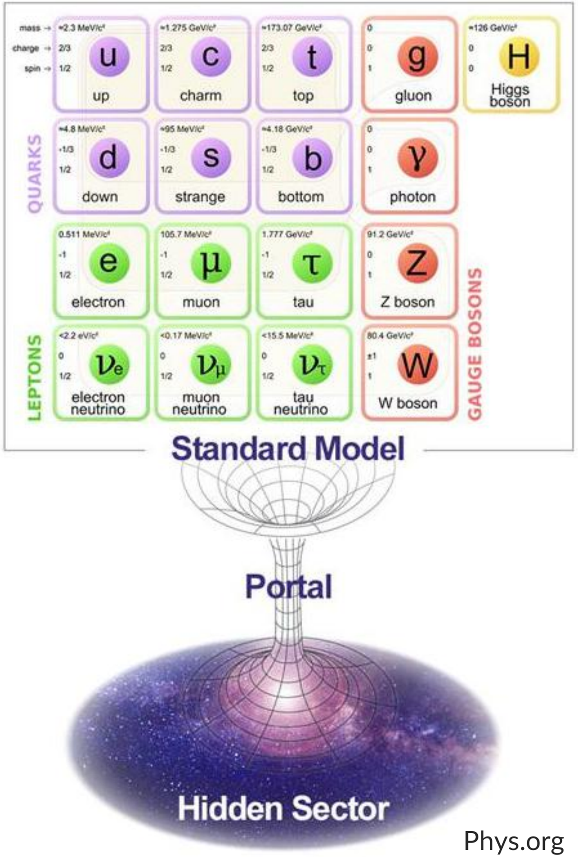
New particle(s) and field(s), along with new interactions and interaction strengths, that do not couple directly to the SM but communicate to it through portals.

Vector	$\epsilon B^{\mu\nu}\tilde{Z}'_{\mu\nu}$
Scalar	$\kappa\|H\|^2\|S\|^2$
Neutrino	$yHLN$
Axion	$g_{a\gamma}a\tilde{F}_{\mu\nu}F^{\mu\nu}$

S. Gori (Snowmass 2022)

DS particles naturally arise in several new physics models addressing, for example, the hierarchy problem, the strong CP problem, the generation of neutrino masses, the matter-antimatter asymmetry, light dark matter, etc.

Dark sector(s)



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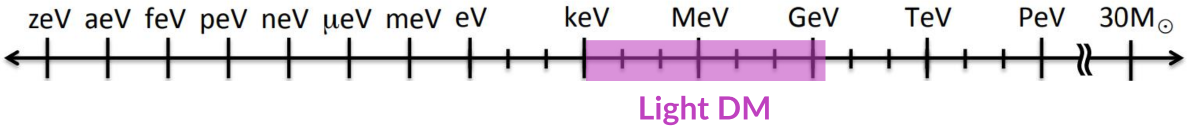
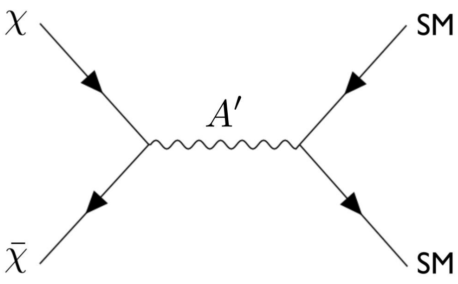


Dark photon (vector) portal: A' kinetically mixed with SM photon

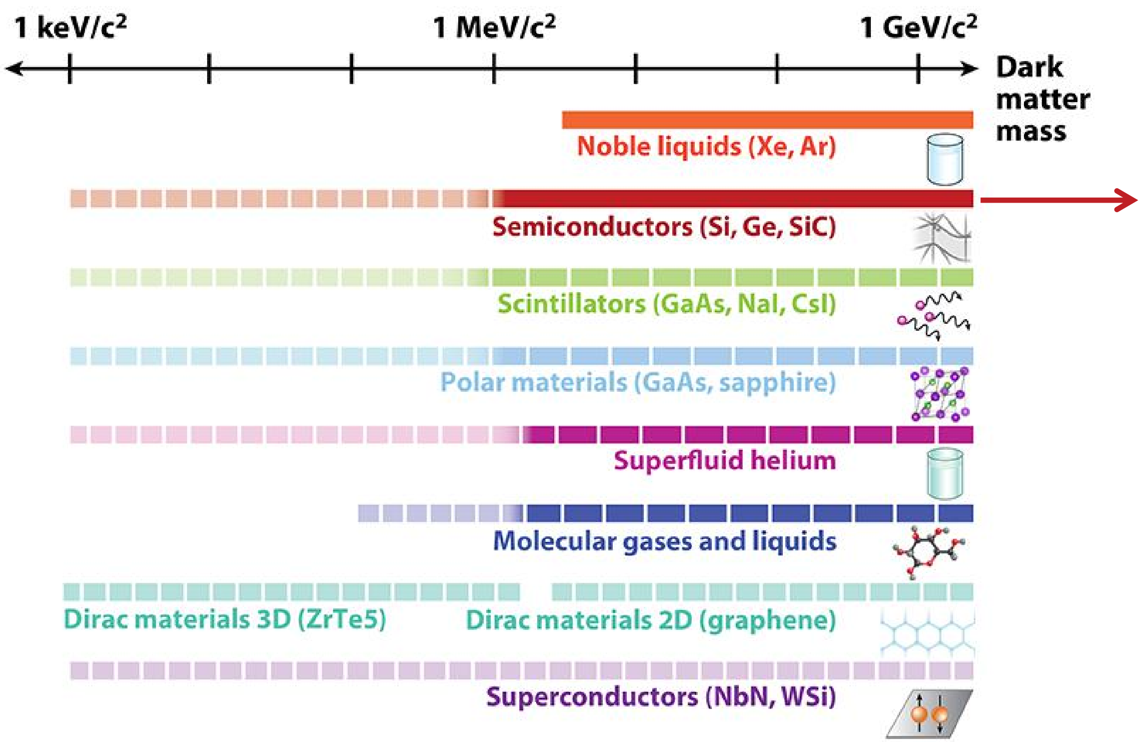


"Heavy" mediator: $\mathcal{O}(\mathrm{keV}) \ll m_{A'} \leq \mathcal{O}(\mathrm{GeV})$
- **LDM** with freeze-out abundance

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

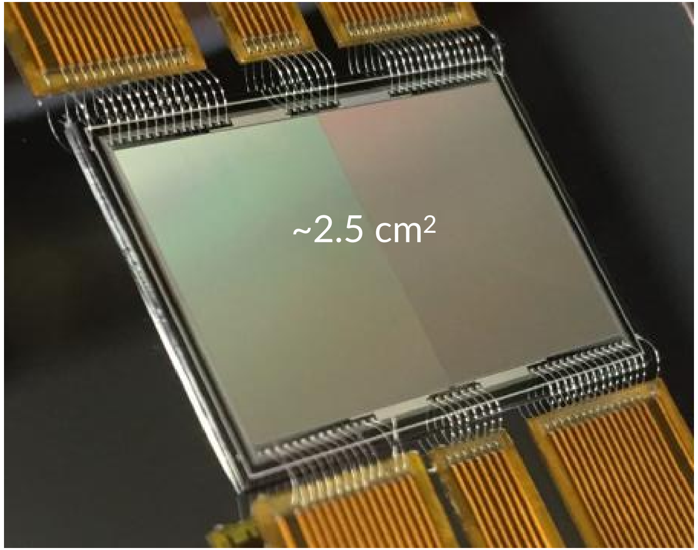
Massless mediator: $m_{A'} = 0$
- DM is **millicharged**

Low-threshold technologies to explore the dark sector



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

Skipper-CCDs!



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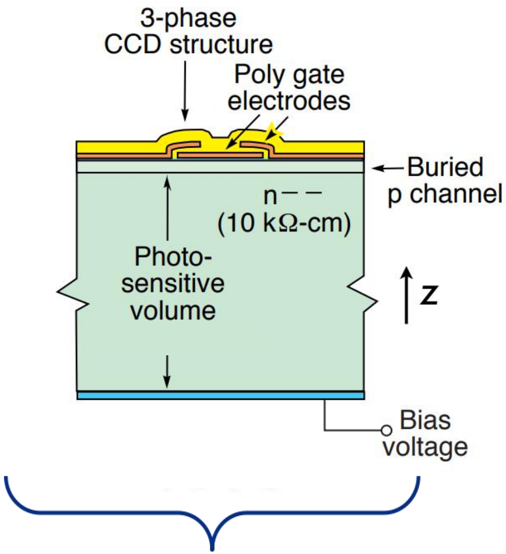
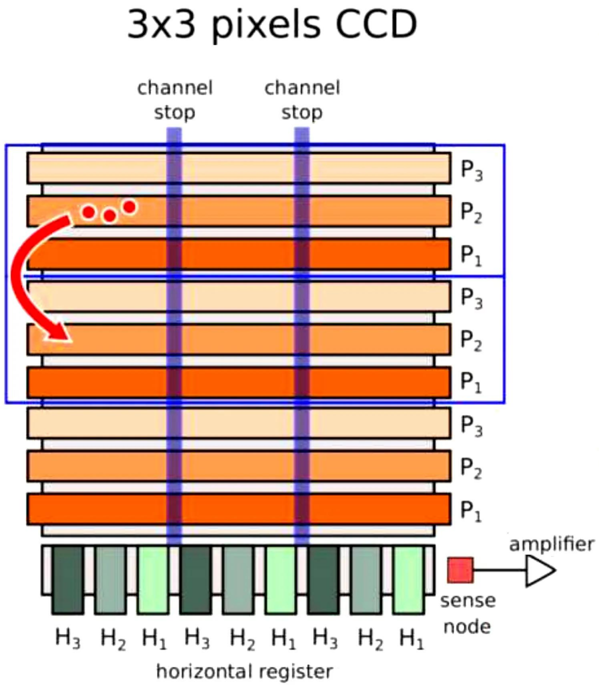
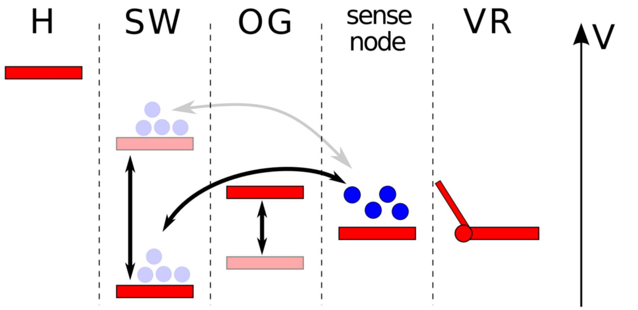
Skipper-CCDs: electron-counting silicon sensors

Steve Holland

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







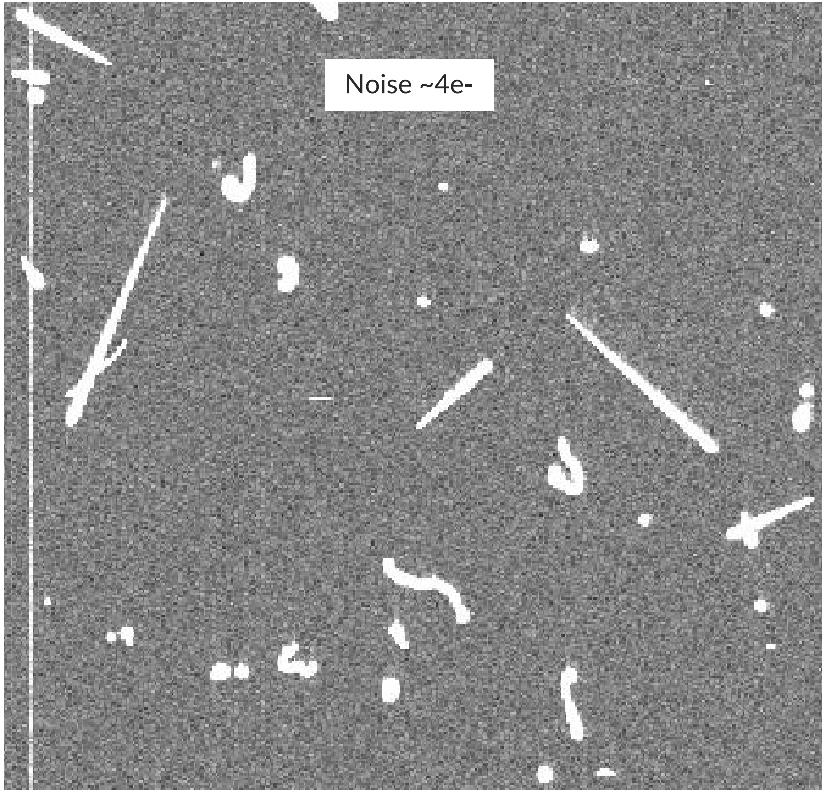
Skipper output stage allows to perform multiple non-destructive measurements

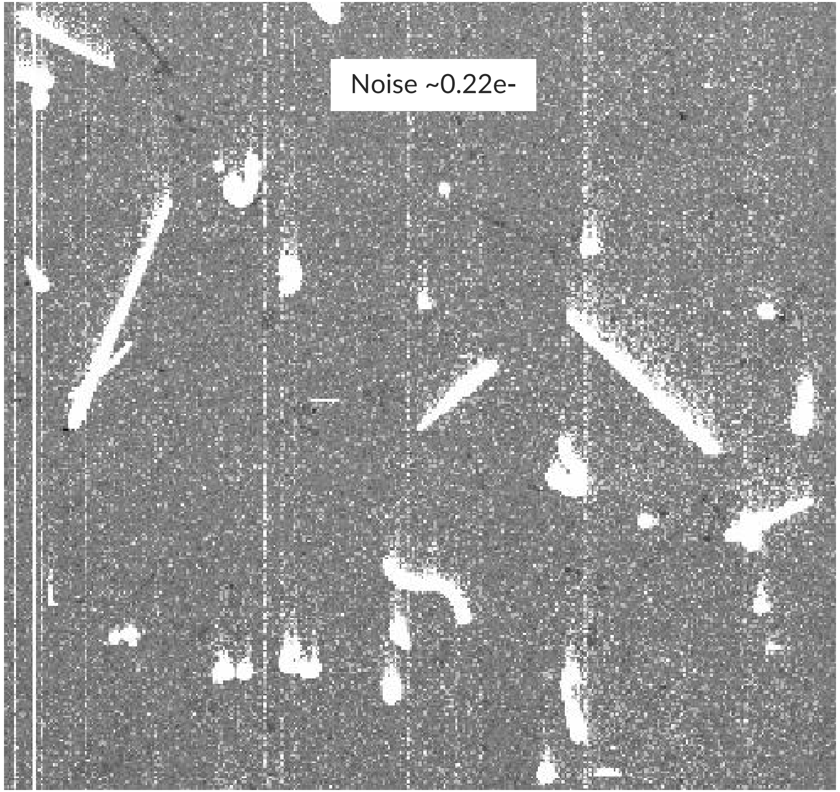
Sub-electron noise can be achieved as

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

Skipper-CCDs: electron-counting silicon sensors

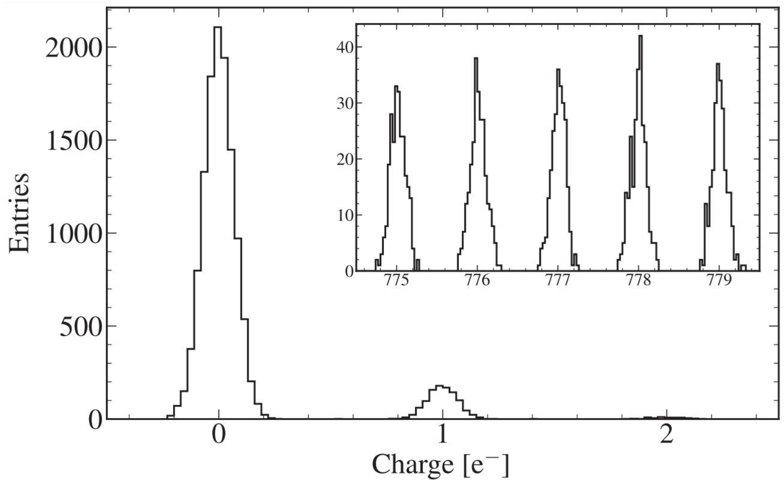
Achieving sub-electron noise allows to deeply explore what is invisible with standard CCDs

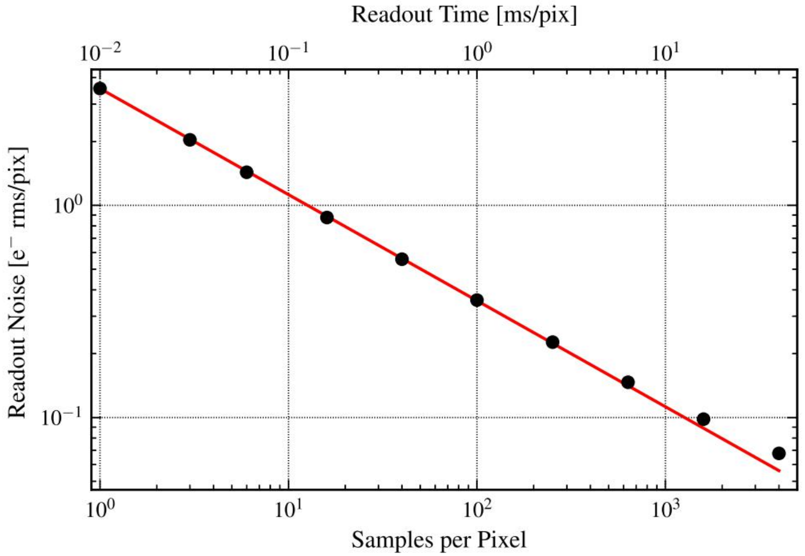




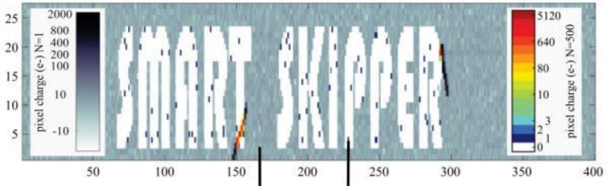
Skipper-CCDs: electron-counting silicon sensors

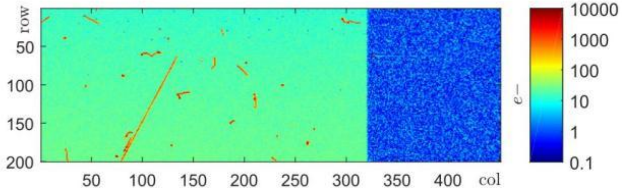
We can count single electrons in a wide dynamic range: self-calibrating charge measurement
Trade-off between charge resolution and readout time





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





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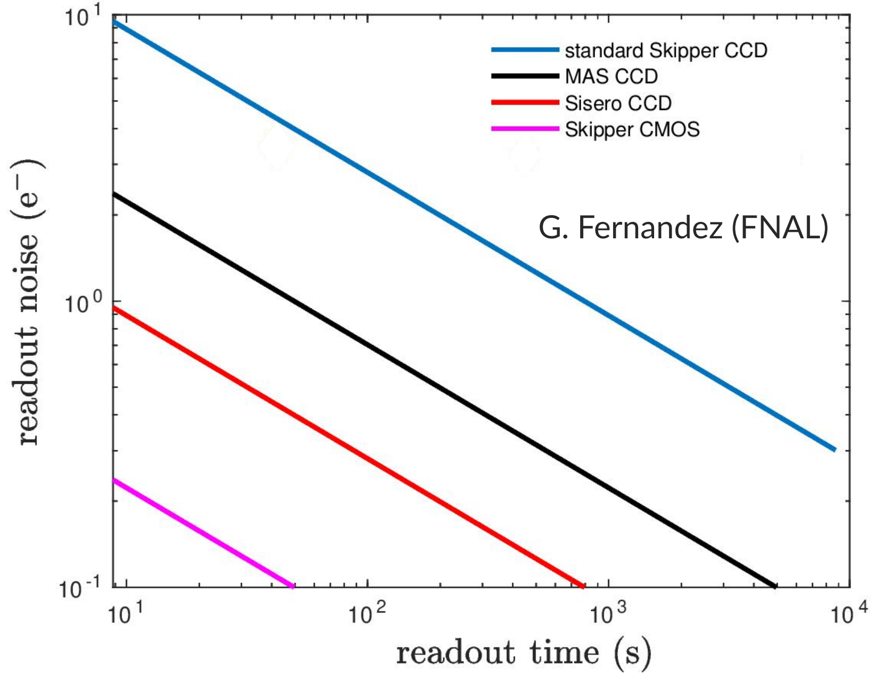
Fast-readout technologies with single-electron resolution

Pop-up Ad

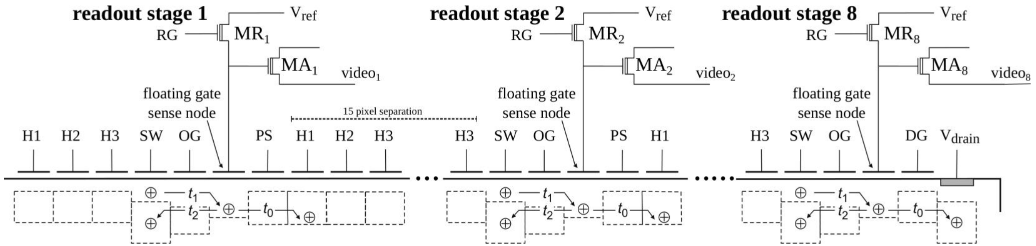
Non-destructive readout silicon sensors achieving lower readout times are being developed



for a 2k x 2k pix sensor

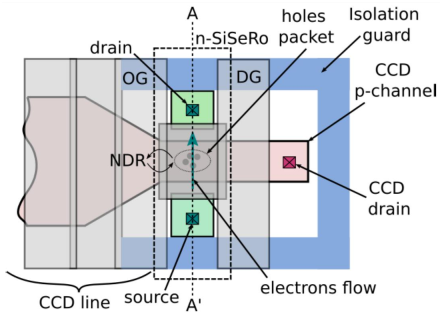
Multi-Amplifier Sensing (MAS) CCDs

[10.1002/asna.20230072]



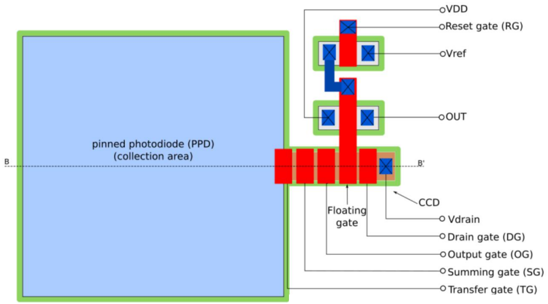
CCDs with n-Sisero stage

[10.1109/TED.2022.3233288]



Skipper-in-CMOS

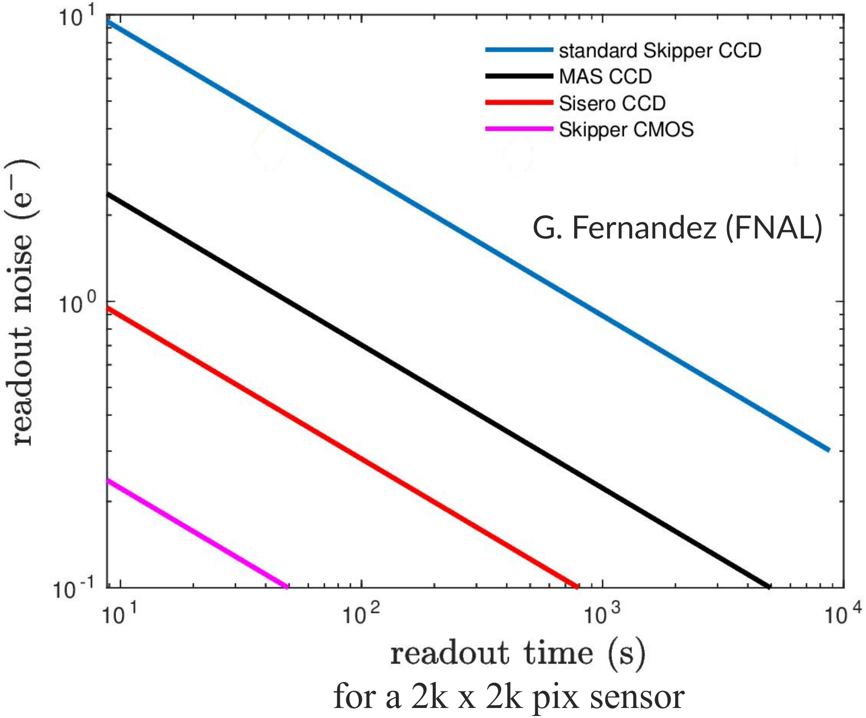
[B. Parpillon @ CPAD 2022]



Fast-readout technologies with single-electron resolution

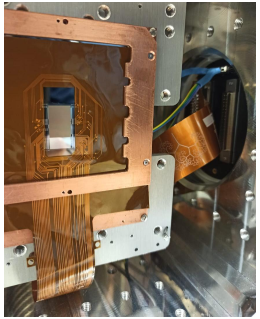
Pop-up Ad

First prototypes are currently being tested showing great results!



Multi-Amplifier Sensing (MAS) CCDs

[arXiv:2308.09822]

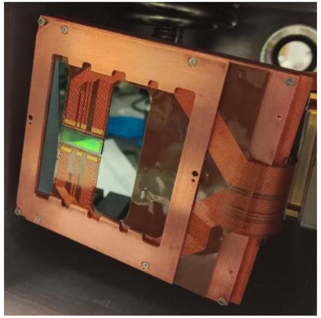


See Wednesday's talk by Kenneth Lin and Thursday's talk by Blas Irigoyen for latest results on MAS!

and Thursday's talk by Guillermo Fernandez for latest results on skipper-in-CMOS

CCDs with n-Sisero stage

[arXiv:2310.13644]



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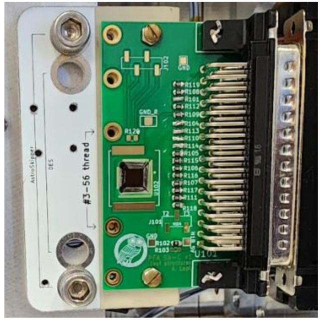
[B. Parpillon @ CPAD 2022]



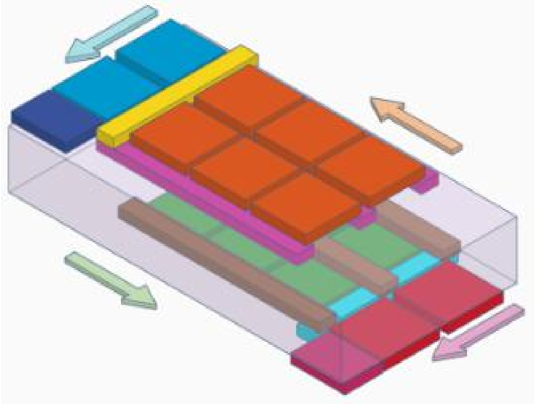
CCDs with timing resolution: Dual-side CCD

Pop-up Ad

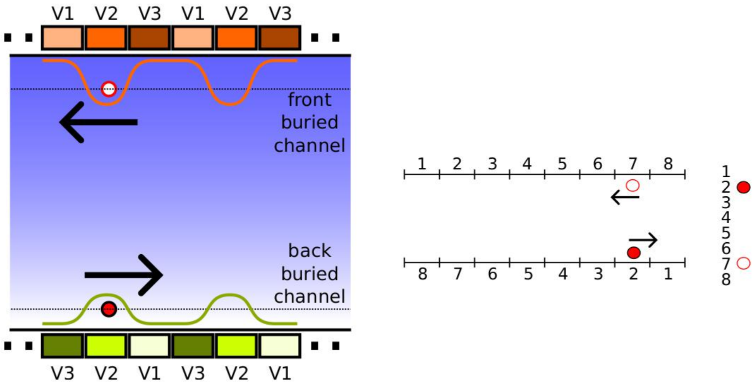
Device with gate structures and buried-channels of opposite polarity in both (front and back) sides to **collect BOTH electrons and holes**

Charge carriers are moved in opposite directions towards different serial registers

Novel idea from
Javier Tiffenberg (FNAL)
[arXiv:2307.13723]



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

coming back to current and future applications of the skipper-CCD technology...

DM search at underground facilities with skipper-CCDs

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

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)	~2027

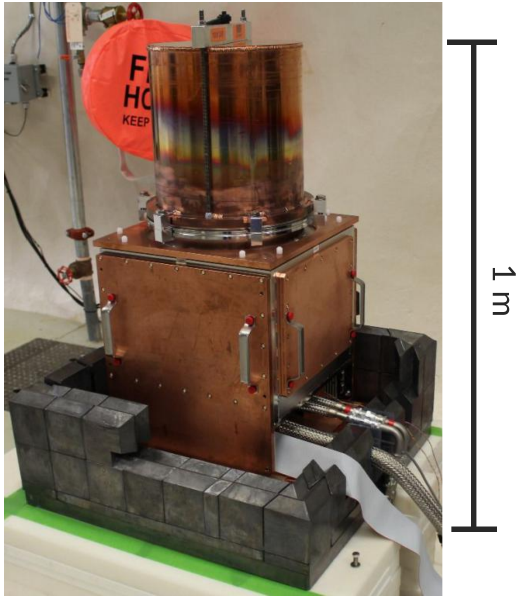
Lowest 1e- rate achieved in silicon

See next talk by Miguel Daal for SENSEI's latest results

DM search at underground facilities with skipper-CCDs

SENSEI @ SNOLAB

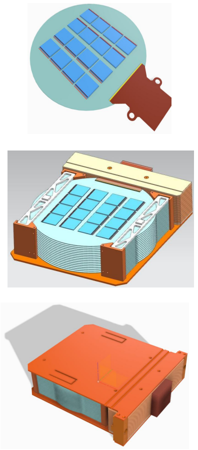
Detector payload: 6 skipper-CCDs

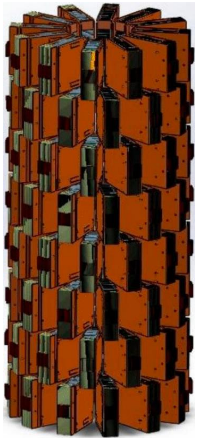


OSCURA @ SNOLAB

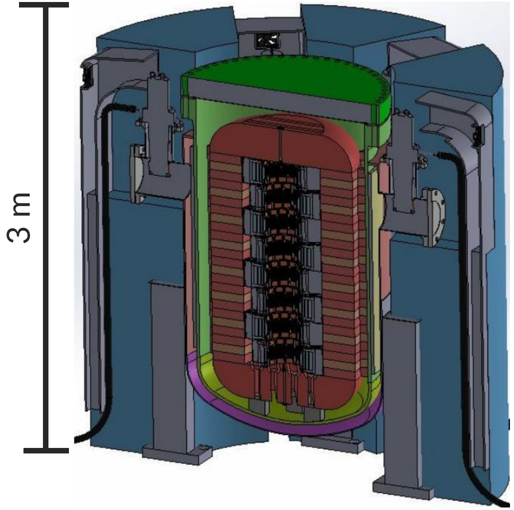
[arXiv:2202.10518]

Detector payload:
~24,000 skipper-CCDs





LN$_2$ pressure vessel

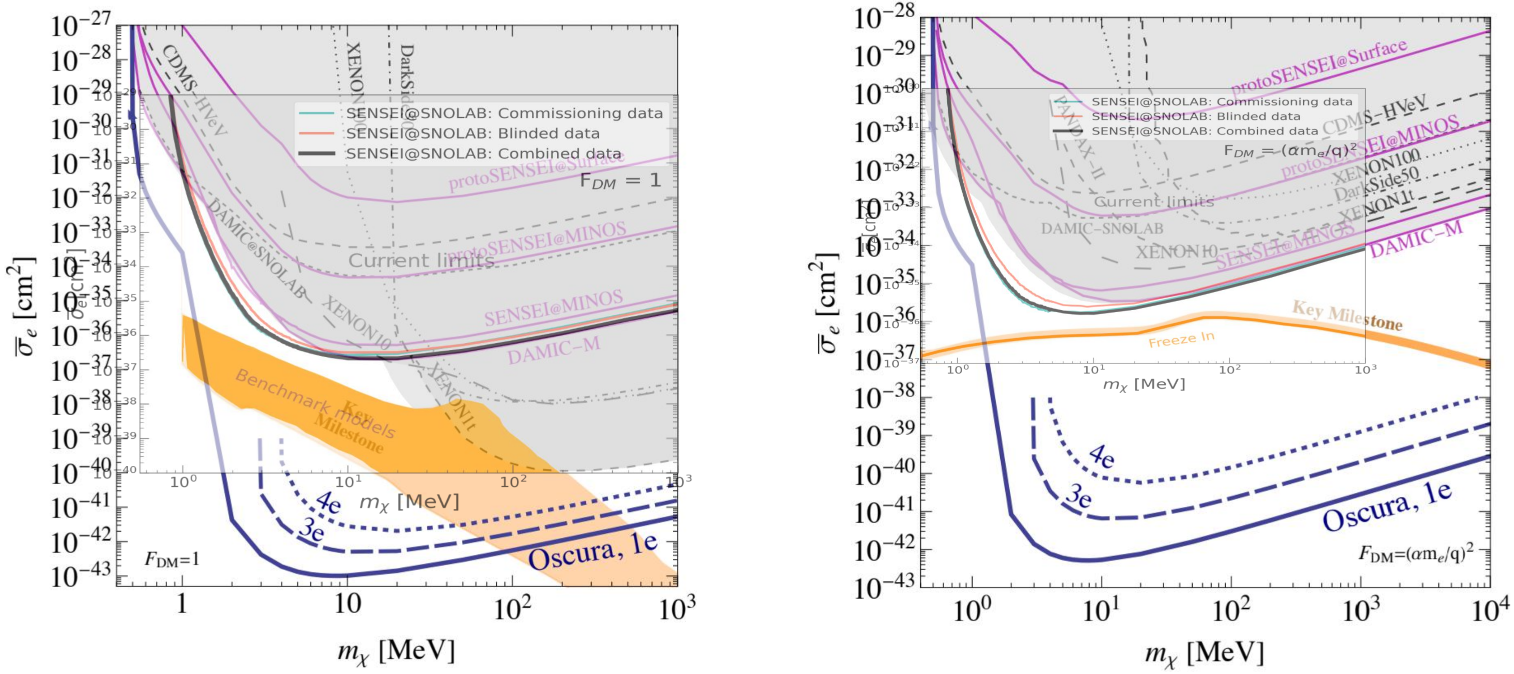


Major R&D:
- Mass skipper-CCD production
- New packaging and cryogenics
- Cold electronics and multiplexing
- Low radiation background design

See Friday's talk by Claudio Chavez for latest progress

DM search at underground facilities with skipper-CCDs

World-best limits for light DM candidates (< 30 MeV) due to low backgrounds.
Oscura will probe benchmark models with its unprecedented sensitivity.

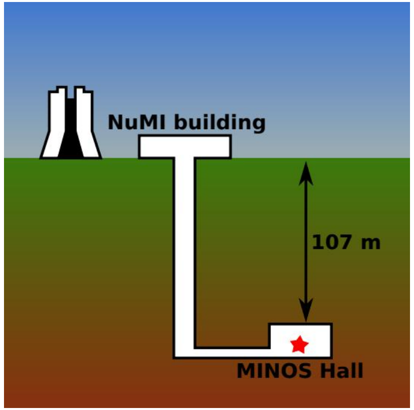


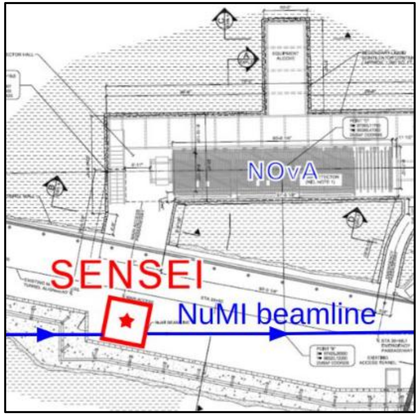
DM-electron scattering mediated by a heavy (left) or ultra light (right) vector mediator
4e- curve corresponds to the Oscura prototype skipper-CCDs performance

mCPs search at accelerator facilities with skipper-CCDs

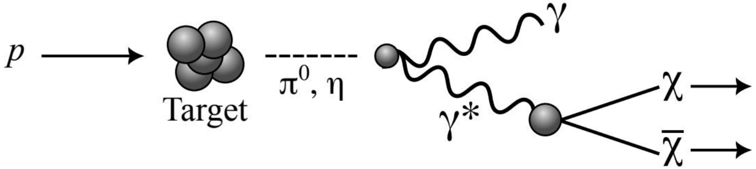
Due to low backgrounds, skipper-CCD experiments have sensitivity to unexplored regions of mCPs.

SENSEI @ MINOS



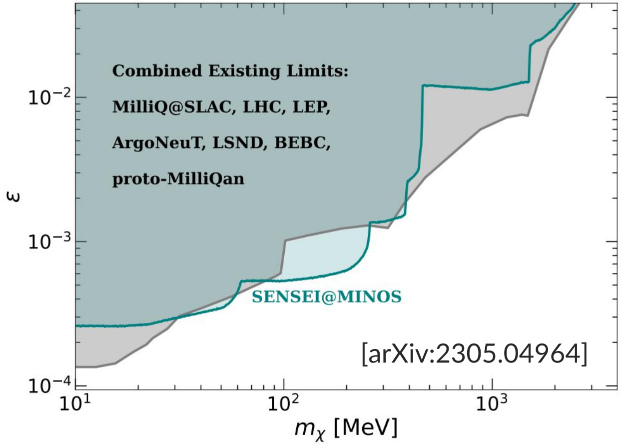


Proton collisions with fixed target can produce mCPs collinear with NuMI beamline



Proof-of-concept demonstrating skipper-CCDs potential for future mCPs searches at accelerators

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Eff. 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



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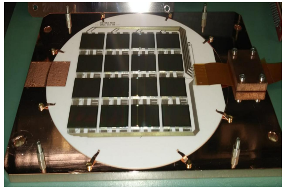
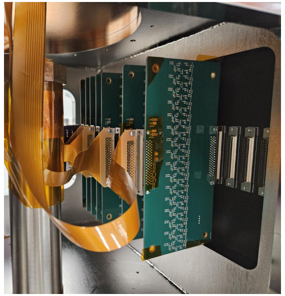
mCPs search at accelerator facilities with skipper-CCDs

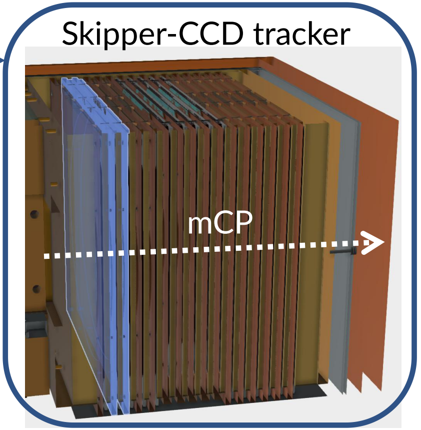
To further reduce backgrounds and enhance sensitivity we are aiming to build a **skipper-CCD tracker**!

Dark BeaTS (Dark sector searches at Beams using a Tracker with Skipper-CCDs)

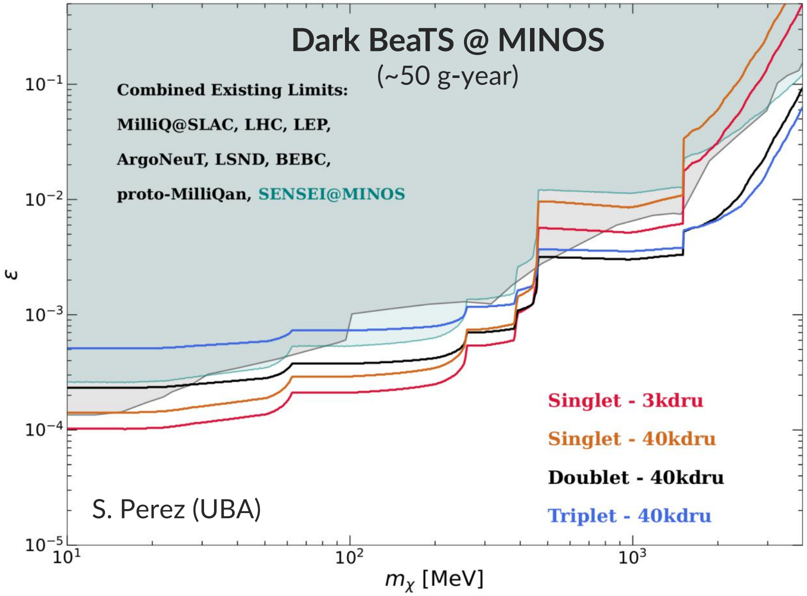
Repurpose/redesign SENSEI and Oscura hardware
Develop tracking software for multi-hit search







Tracking enhances sensitivity at ~GeV masses



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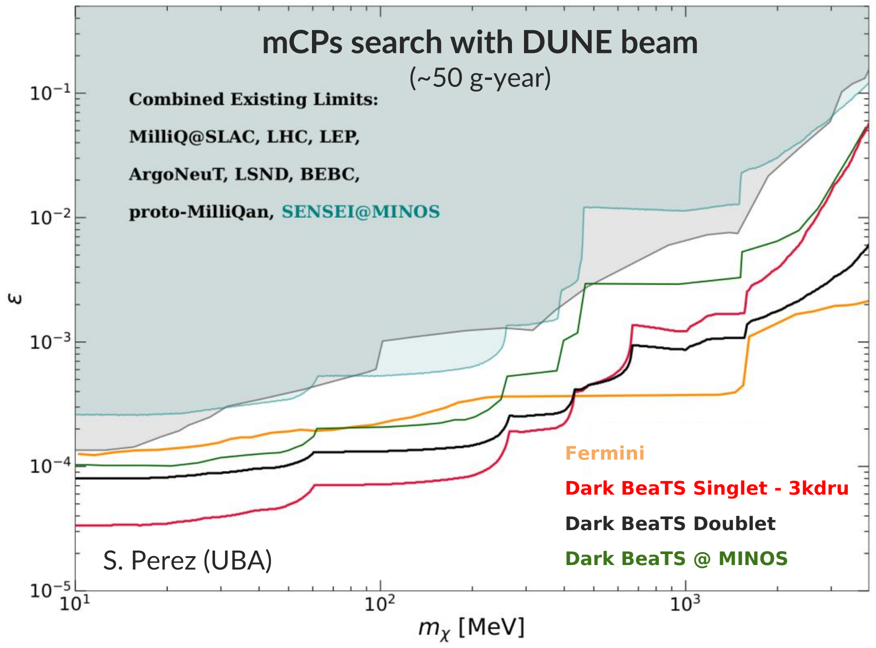
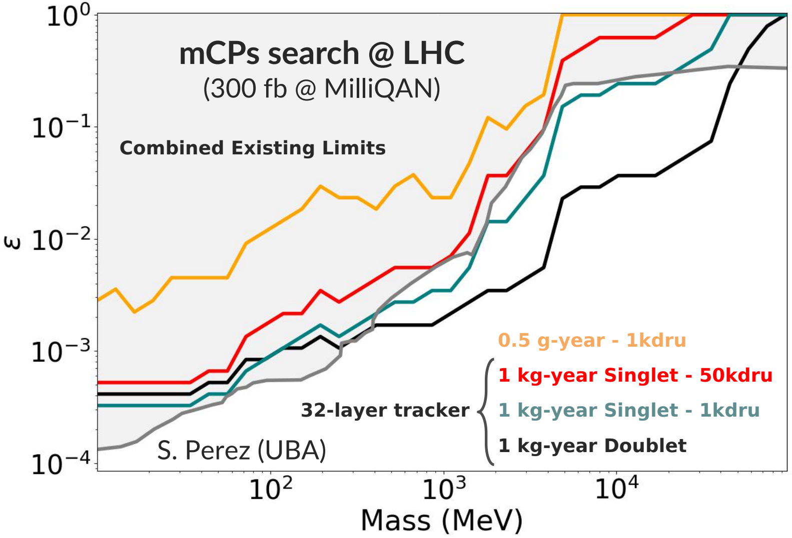
mCPs search at accelerator facilities with skipper-CCDs

Dark BeaTS will be the pathfinder for future dark sector searches with skipper-CCDs at accelerators

Complementary searches at different facilities allow probing wide range of mCPs masses and couplings



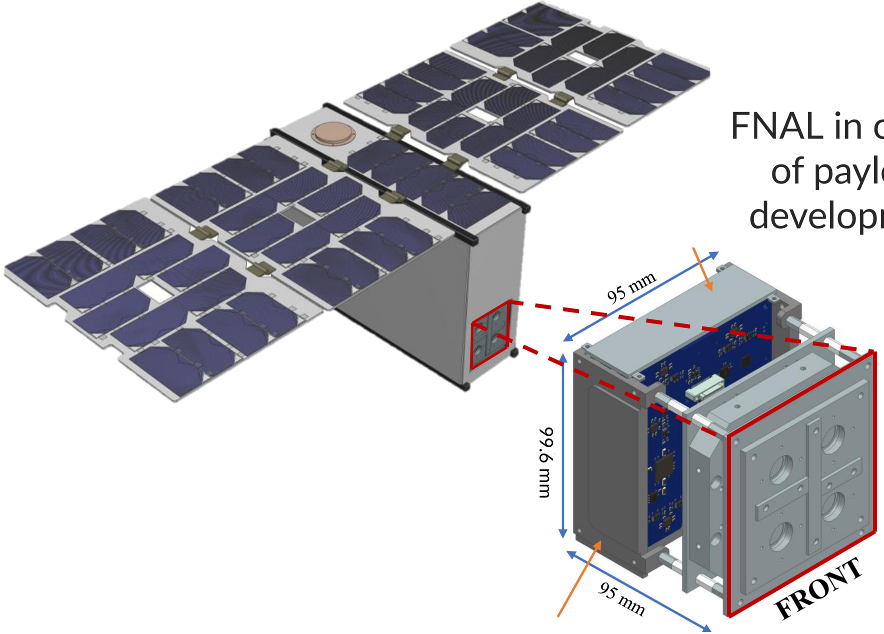


Ongoing: Send a skipper-CCD to LHC to estimate backgrounds

DM search at space with skipper-CCDs

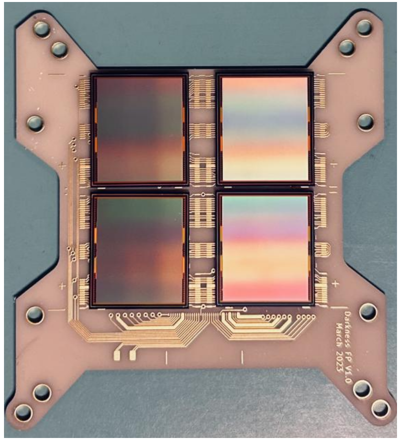
DarkNESS (Dark matter Nanosatellite Equipped with Skipper Sensors)

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



FNAL in charge of payload development

5.4 MPix skipper-CCD array



New optimized readout electronics

Take-home messages

- Electron-counting skipper-CCD technology allows exploring the dark sector

- Searching for LDM at underground laboratories with skipper-CCDs is a robust experimental program (Oscura is the ultimate goal)

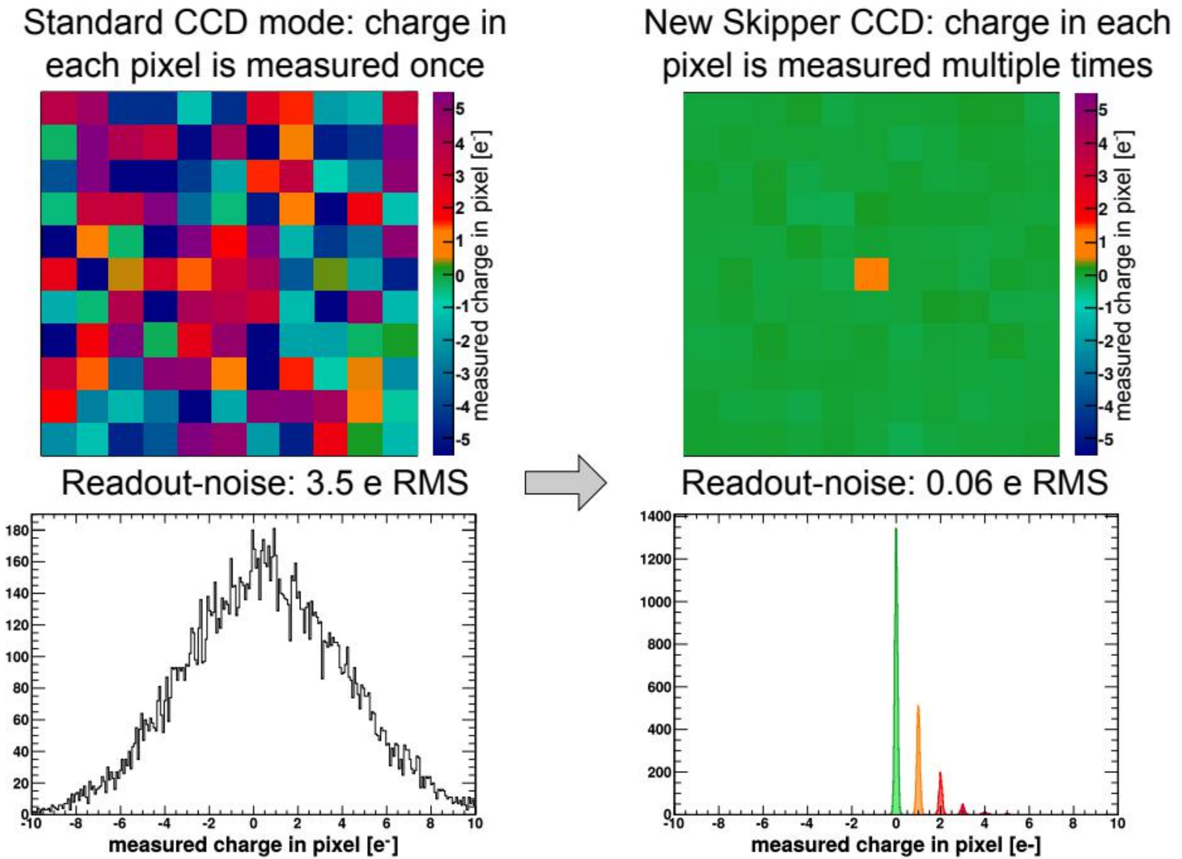
- mCPs search with skipper-CCDs at accelerators seems promising (Dark BeaTS will be the pathfinder for future dedicated experiments)

- 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!

Skipper-CCDs: readout noise



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Skipper-CCDs: smart readout

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

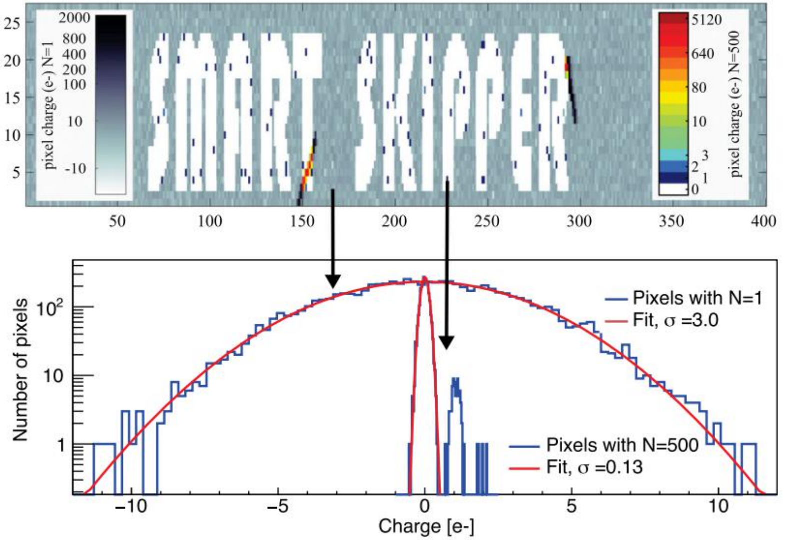


FIG. 3. Measurement using ROI technique. Pixels in the words have $N = 500$ (right scale); pixels outside the words have $N = 1$ (left scale). s_f was zero in most pixels, with some pixels having $s_f = 1, 2, 3$ or very large values for the two muon tracks that are observed.

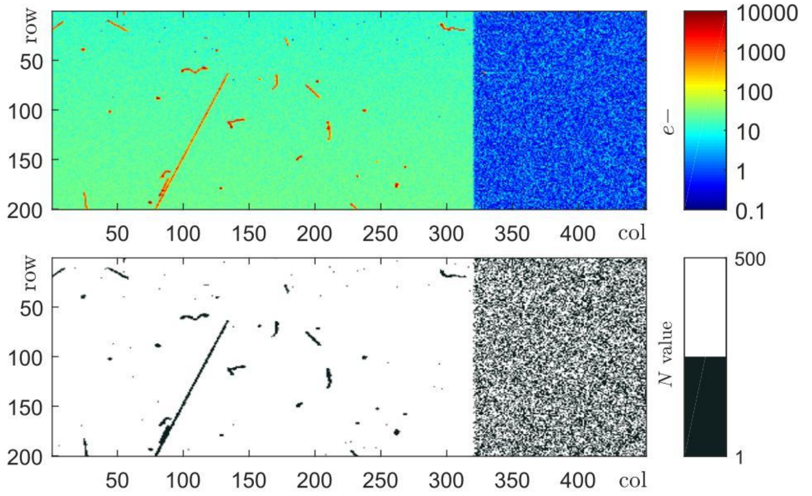


FIG. 4. (Top) Image using EOI technique. (Bottom) N for each pixel.

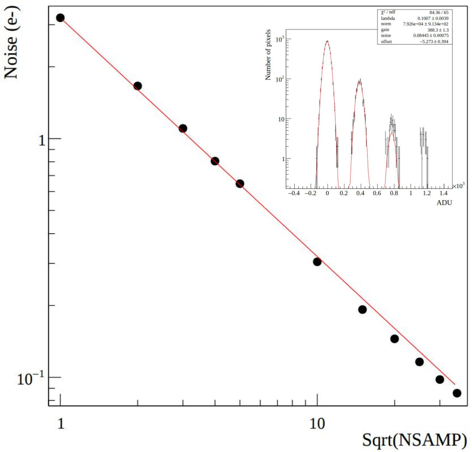
[10.1103/PhysRevLett.127.241101]

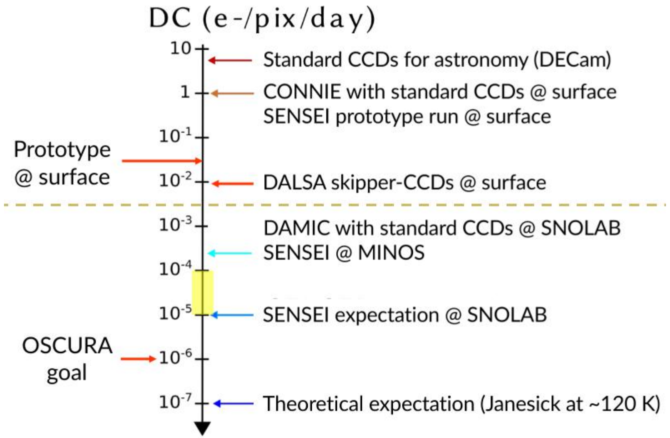
Oscura: Prototype sensors performance

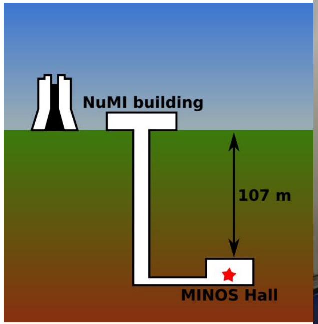
My work → [arXiv:2304.04401]

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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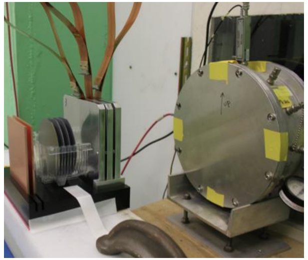
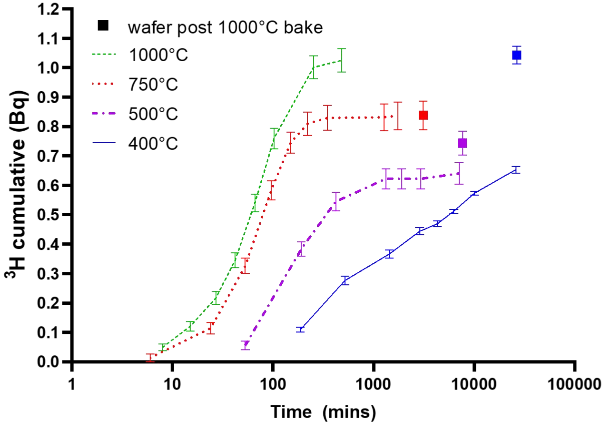
Oscura: Radiation background control

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



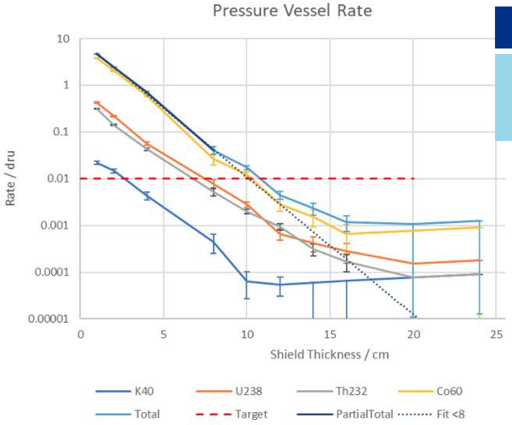
[PRD 102, 102006]



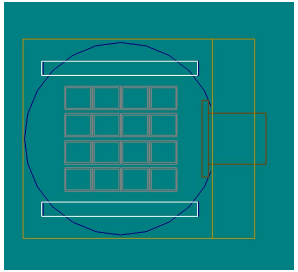
Sources:

- 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)

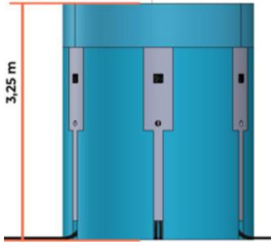
- Isotopic contamination on front-end electronics, cables and components near the sensors
  - Low radioactive flex cable [arXiv:2303.10862]
  - Simulations of ^{238}U, ^{232}Th and ^{40}K
  - → 4cm of cable visible to CCDs (with 15 ppt)
  - → Electronics behind inner shield (width>10cm)



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

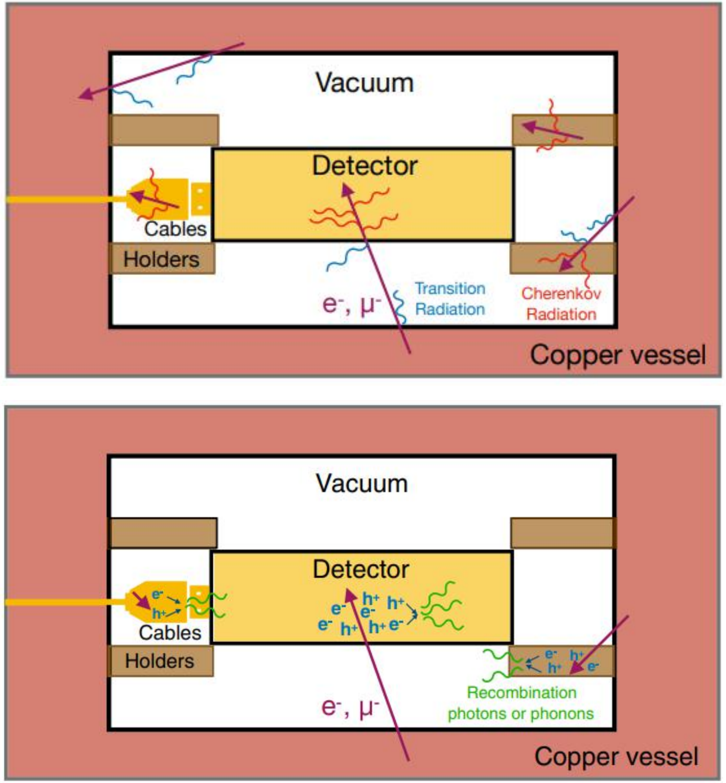


- External backgrounds
  - Outer shield: polyethylene
  - Inner shield: ancient lead and electroformed copper



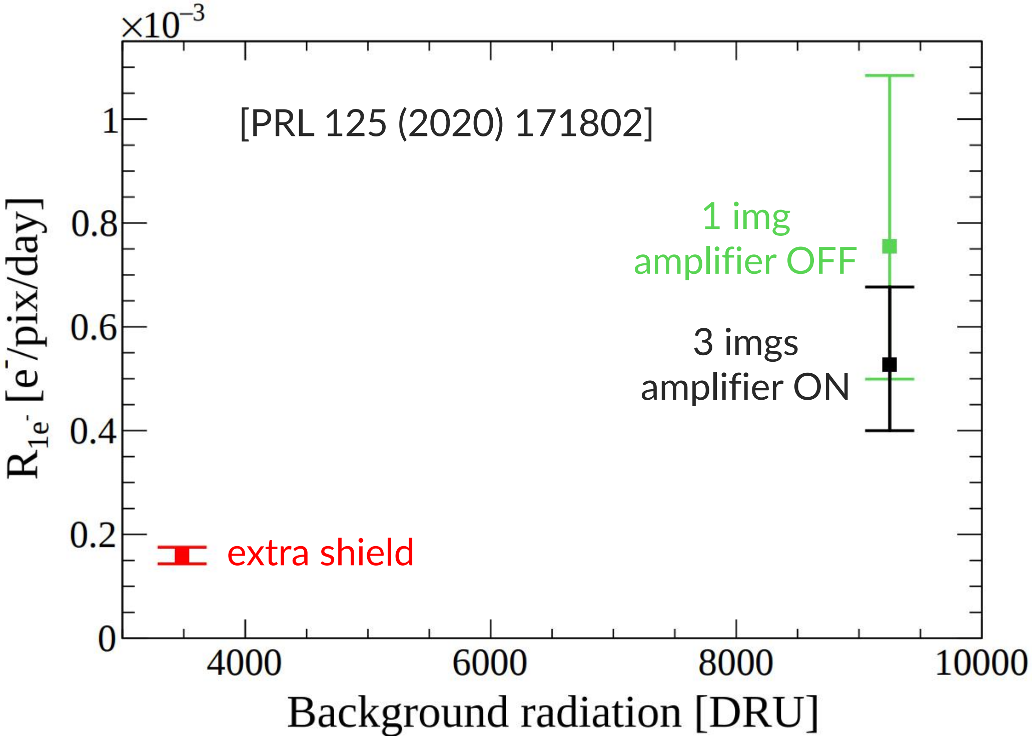
Fermilab

Low-energy background from high-energy events



[PRX 12 (2022) 011009]

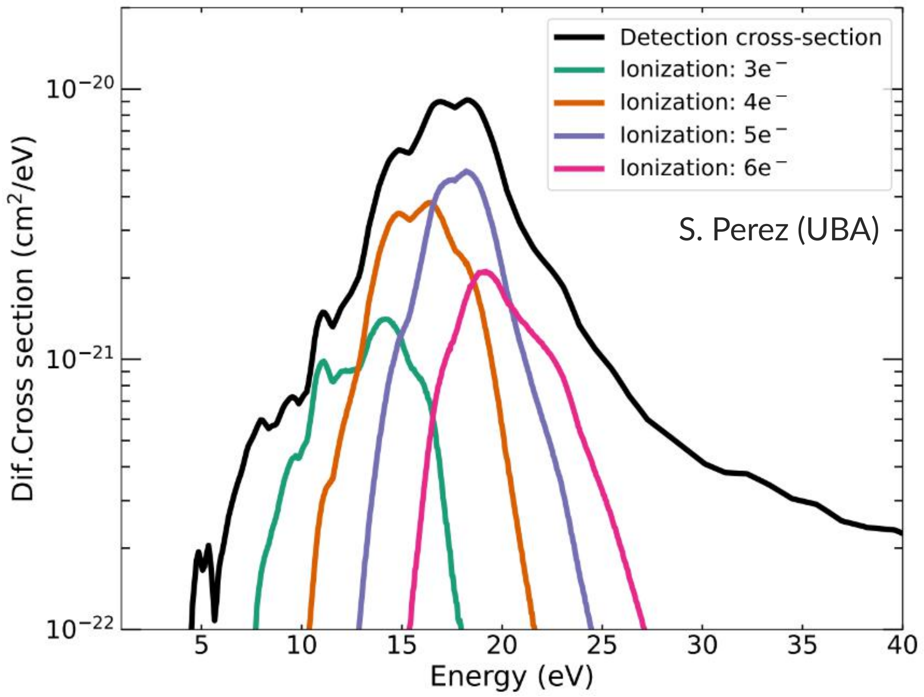
High-energy radiation interacting with setup results in low-E photons which can produce single-e- depositions



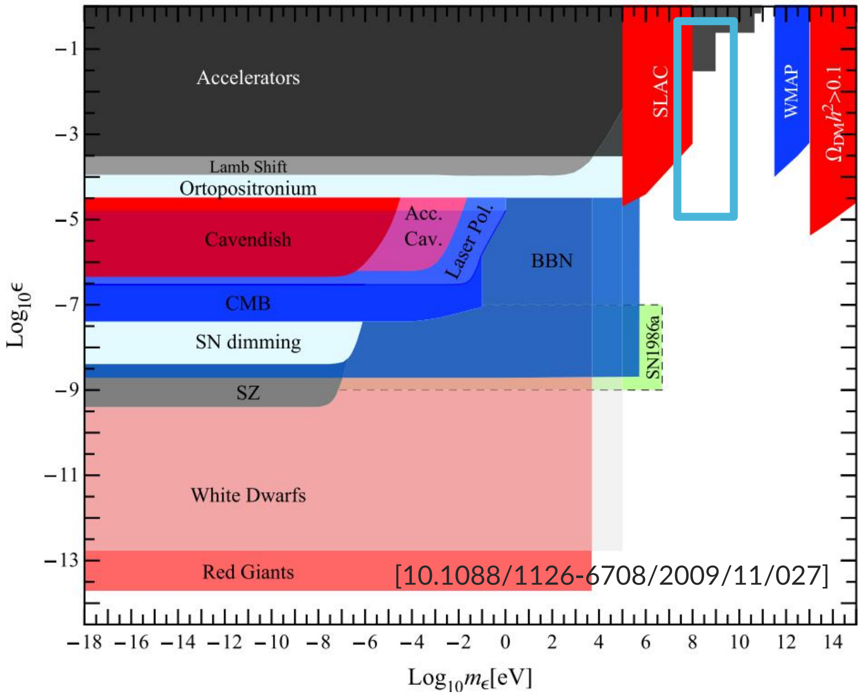
Fermilab

mCPs search at accelerator facilities with skipper-CCDs

Higher probability of depositing 3 to 6 e-

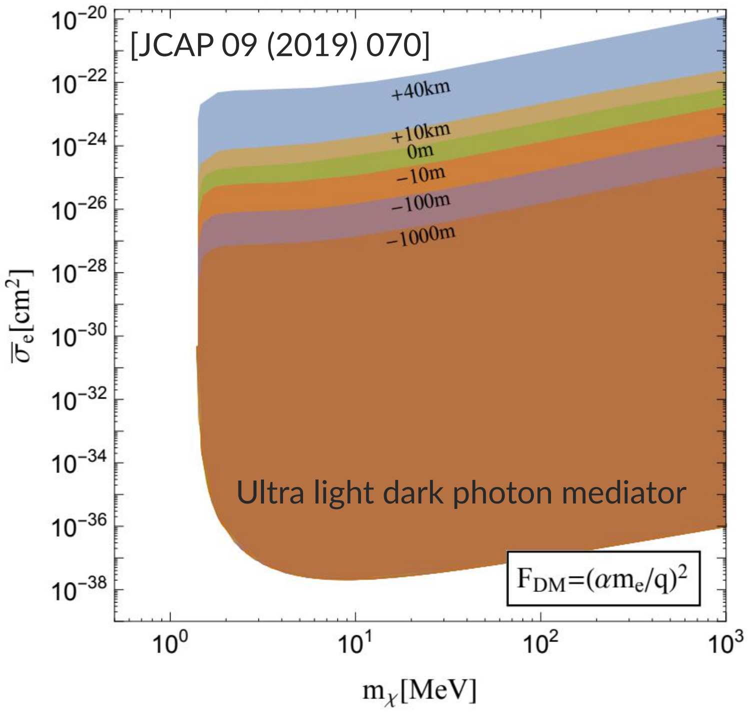


Big picture on mCPs search

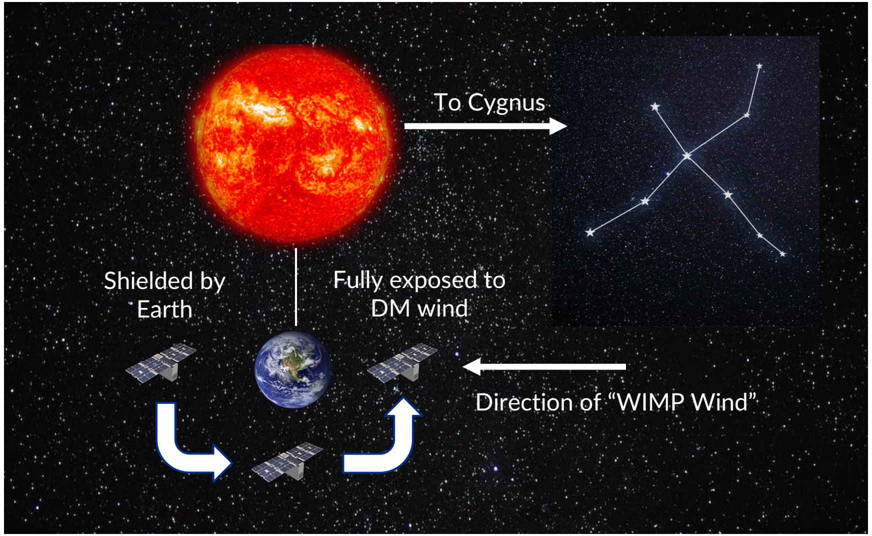


DarkNESS: Searching for strongly-interacting light DM

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



Modulation in signal rate over orbital period due to Earth shadowing



Fermilab

[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