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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Dark sector(s)

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: $y H L N$
- Axion: $g_{a\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu}$

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.

S. Gori (Snowmass 2022)
Dark sector(s)

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.

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

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

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

Massless mediator: \( m_{A'} = 0 \)
- DM is millicharged

Phys.org
Low-threshold technologies to explore the dark sector

- Noble liquids (Xe, Ar)
- Semiconductors (Si, Ge, SiC)
- Scintillators (GaAs, NaI, CsI)
- Polar materials (GaAs, sapphire)
- Superfluid helium
- Molecular gases and liquids
- Dirac materials 3D (ZrTe5)
- Dirac materials 2D (graphene)
- Superconductors (NbN, WSi)

Skipper-CCDs!

~2.5 cm²

R. Essig - SBU; C. Cain - APS 2020
Skipper-CCDs: electron-counting silicon sensors

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

Noise ~4e-
Noise ~0.22e-
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

[10.1103/PhysRevLett.127.241101]
Fast-readout technologies with single-electron resolution

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

![Graph showing readout noise vs. readout time for a 2k x 2k pix sensor](image)

**Multi-Amplifier Sensing (MAS) CCDs**

[10.1002/asna.20230072]

**Brenda Cervantes | Dark sector searches with skipper-CCDs: current status and future ideas**

**Fast-readout technologies with single-electron resolution**

**Skipper-in-CMOS**

[B. Parpillon @ CPAD 2022]

**CCDs with n-Sisero stage**

[10.1109/TED.2022.3233288]

**G. Fernandez (FNAL)**

for a 2k x 2k pix sensor

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

**Multi-Amplifier Sensing (MAS) CCDs**

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**Brenda Cervantes | Dark sector searches with skipper-CCDs: current status and future ideas**

**Fast-readout technologies with single-electron resolution**

**Skipper-in-CMOS**

[B. Parpillon @ CPAD 2022]
Fast-readout technologies with single-electron resolution

First prototypes are currently being tested showing great results!

![Graph showing readout noise vs. readout time for different types of CCDs](image)

**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!

**CCDs with n-Sisero stage**
[arXiv:2310.13644]

See Thursday’s talk by Guillermo Fernandez for latest results on skipper-in-CMOS.

**Skipper-in-CMOS**
[B. Parpillon @ CPAD 2022]
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

- 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**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass [kg]</th>
<th>#CCDs</th>
<th>Radiation bkgd [dru]</th>
<th>Instrumental bkgd [e-/pix/day]</th>
<th>Commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSEI @ MINOS</td>
<td>~0.002</td>
<td>1</td>
<td>3400</td>
<td>1.6 x 10^-4</td>
<td>late-2019</td>
</tr>
<tr>
<td>DAMIC @ SNOLAB</td>
<td>~0.02</td>
<td>2</td>
<td>~10</td>
<td>3 x 10^-3</td>
<td>late-2021</td>
</tr>
<tr>
<td>DAMIC-M LBC</td>
<td>~0.02</td>
<td>2</td>
<td>10</td>
<td>3 x 10^-3</td>
<td>late-2021</td>
</tr>
<tr>
<td>SENSEI-100</td>
<td>~0.1</td>
<td>~50</td>
<td>10 (goal)</td>
<td></td>
<td>mid-2022</td>
</tr>
<tr>
<td>DAMIC-M</td>
<td>~1</td>
<td>~200</td>
<td>0.1 (goal)</td>
<td></td>
<td>~2023</td>
</tr>
<tr>
<td>OSCURA</td>
<td>~10</td>
<td>~25,000</td>
<td>0.01 (goal)</td>
<td>1 x 10^-6 (goal)</td>
<td>~2027</td>
</tr>
</tbody>
</table>

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**
Detector payload: ~24,000 skipper-CCDs

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.

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

\[ p \rightarrow \text{Target} \rightarrow \pi^0, \eta \rightarrow \gamma, \chi, \bar{\chi} \]

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

**mCPs search with DUNE beam**

(\sim 50 \text{ g-year})

- Combined Existing Limits:
  - MilliQ@SLAC, LHC, LEP,
  - ArgoNeuT, LSND, BEBC,
  - proto-MilliQan, SENSEI@MINOS

- S. Perez (UBA)

**mCPs search @ LHC**

(300 fb @ MilliQAN)

- Combined Existing Limits

- 0.5 g-year - 1kdru
- 1 kg-year Singlet - 50kdru
- 1 kg-year Singlet - 1kdru
- 1 kg-year Doublet

- 32-layer tracker

- S. Perez (UBA)

- 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

Standard CCD mode: charge in each pixel is measured once

New Skipper CCD: charge in each pixel is measured multiple times

Readout-noise: 3.5 e RMS

Readout-noise: 0.06 e RMS
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No events with (&gt;1\times10^{-6})</th>
<th>No events with (3\times10^{-3}) or more</th>
<th>Prototype</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark current</td>
<td>(1 \times 10^{-6})</td>
<td>(1.6 \times 10^{-4})</td>
<td>(3 \times 10^{-2})</td>
<td>(e^{-} / \text{pix/day})</td>
</tr>
<tr>
<td>Readout time for full array</td>
<td>&lt; 2</td>
<td>&lt; 5</td>
<td>3.4 (4.2)</td>
<td>hours</td>
</tr>
<tr>
<td>Pixel readout rate</td>
<td>&gt; 188</td>
<td>&gt; 76</td>
<td>111 (89)</td>
<td>pix/s</td>
</tr>
<tr>
<td>Readout noise</td>
<td>&lt; 0.16</td>
<td>&lt; 0.20</td>
<td>0.19 (0.20)</td>
<td>(e^{-}) RMS</td>
</tr>
<tr>
<td>Spurious charge</td>
<td>(&lt; 10^{-10})</td>
<td>(&lt; 10^{-8})</td>
<td>(7.2 \times 10^{-7})</td>
<td>(e^{-} / \text{pix/transfer})</td>
</tr>
<tr>
<td>Trap density with (\tau &gt; 5.3) ms</td>
<td>&lt; 0.12</td>
<td></td>
<td>(&lt; 0.015)</td>
<td>traps/pix</td>
</tr>
<tr>
<td>Charge transfer inefficiency</td>
<td>(&lt; 10^{-5})</td>
<td></td>
<td>(&lt; 5 \times 10^{-5})</td>
<td>l/transfer</td>
</tr>
<tr>
<td>VIS/NIR light blocking</td>
<td>&gt; 90%</td>
<td></td>
<td>95%</td>
<td></td>
</tr>
</tbody>
</table>

- 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.
Oscura: Radiation background control

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

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)

• External backgrounds
  Outer shield: polyethylene
  Inner shield: ancient lead and electroformed copper
Low-energy background from high-energy events

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

\[ [\text{PRX 12 (2022) 011009}] \]

\[ [\text{PRL 125 (2020) 171802}] \]
mCPs search at accelerator facilities with skipper-CCDs

Higher probability of depositing 3 to 6 e-

S. Perez (UBA)

![Graph showing detection cross-section and ionization for different numbers of electrons]

Big picture on mCPs search

![Diagram showing various energy levels and mass scales]

DarkNESS: Searching for strongly-interacting light DM

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

\[ F_{DM} = (\alpha m_e q)^2 \]

Modulation in signal rate over orbital period due to Earth shadowing

[JCAP 09 (2019) 070]
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?