Dual-sided Skipper-CCDs for sub-GeV dark matter searches
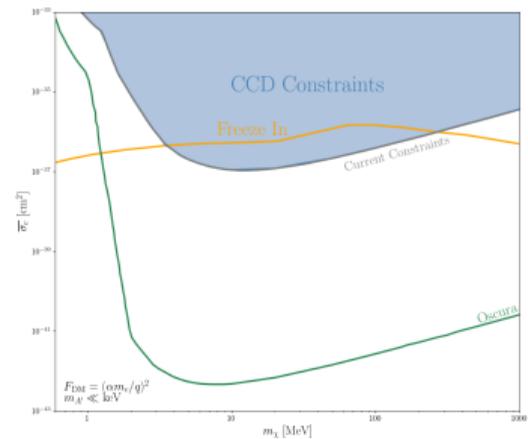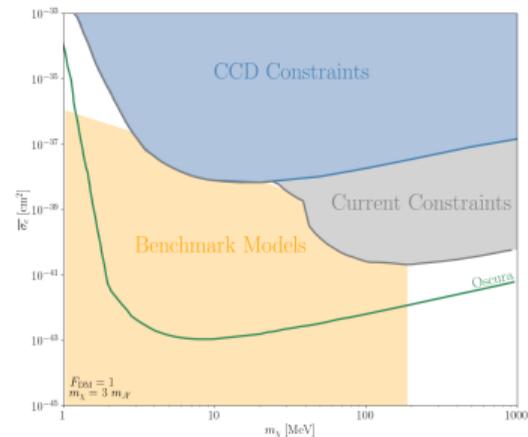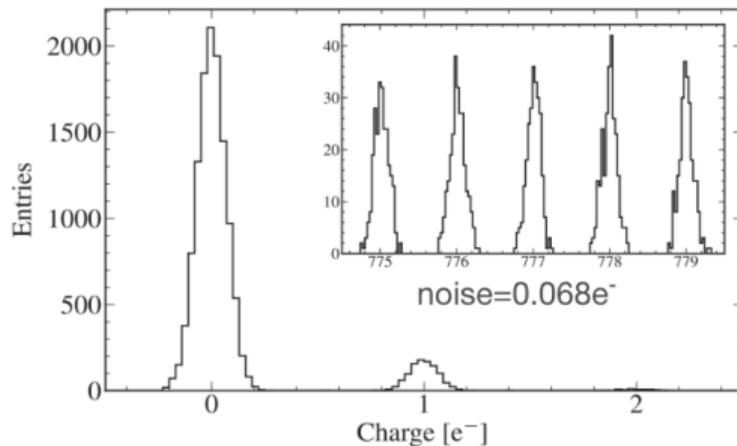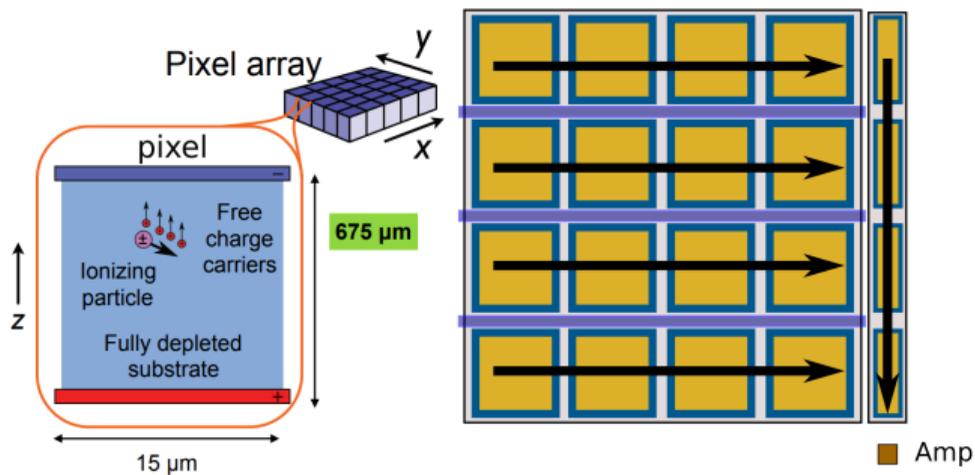
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Fermilab

Introduction

- Skipper-CCDs hold a lead in searches for sub-GeV DM — the DAMIC-M LBC has started to reach freeze-out/freeze-in targets for DM-e scattering

- Skippers also hold promise for millicharged particle searches, CEνNS

- Perfect charge measurement and record-low charge backgrounds $\rightarrow$ an excellent detector for few-eV phenomena
  - (Also useful as photodetectors — see Nora Hoch in RDC 2)

- Today: a concept (2307.13723) to improve background rejection using double-sided readout
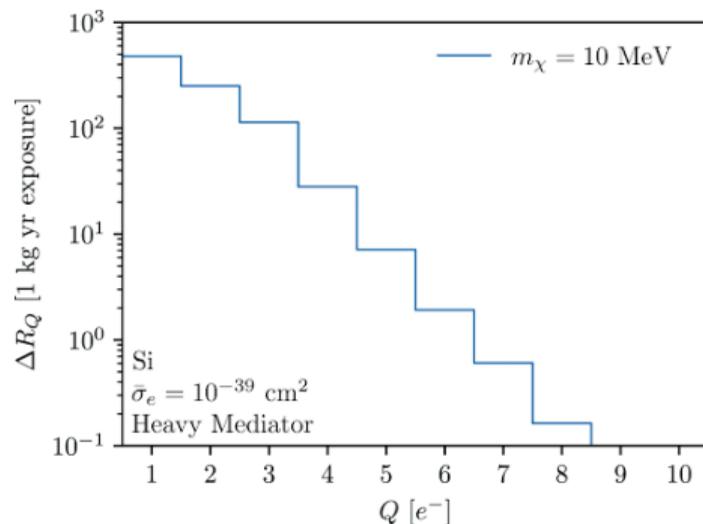
Basics of Skipper-CCDs

- Ionization creates electron-hole pairs; holes are drifted to the frontside and collected in pixels
- Charge packets are shifted, row to row and pixel to pixel, to a readout amplifier
- "Skipper" amplifier uses repeated measurements of each charge packet, for charge resolution $\sigma \propto 1/\sqrt{N}$
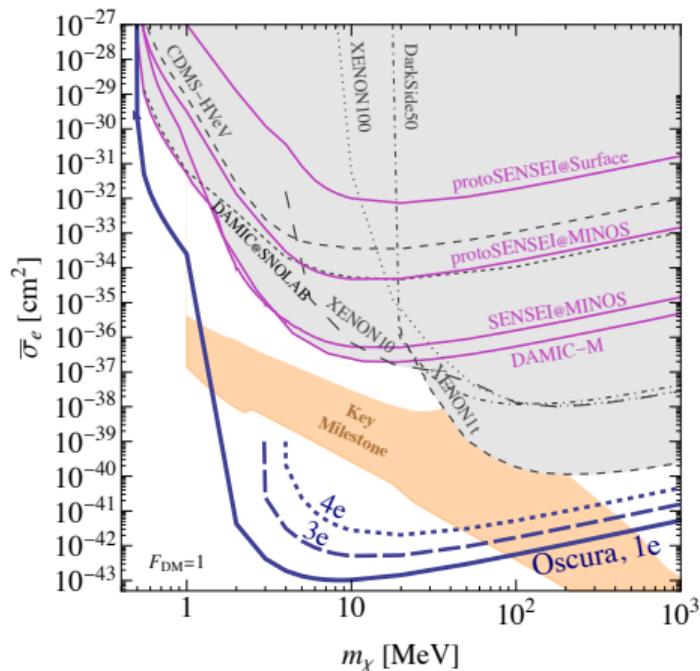
Signals and backgrounds

- Because the charge measurement is so good, our sensitivity is limited by backgrounds
  - No known backgrounds with a natural scale of a few $e^- h^+$
  - High-energy backgrounds are flat-ish (either naturally, or through secondary processes e.g. Compton) in our energy range $\rightarrow$ a floor
  - Single-charge backgrounds pile up to a Poisson spectrum $\rightarrow$ a threshold
- Let's focus on the single-charge backgrounds, where SENSEI has measured record lows and is making further progress — see Yikai Wu next session

2306.14944

Physics applications: dark matter

- Current experiments (SENSEI, DAMIC-M) are free of pileup backgrounds down to 3 $e^- h^+$, with exposures (so far) of $O(1)$ kg-day
- For Oscura (30 kg-year goal), control of charge backgrounds is critical
  - The commercially fabricated Oscura CCDs have new challenges, in particular a high level of "spurious charge" generated during readout
  - (Not the only challenge! DAMIC-M has been working on scaleup and radiogenic backgrounds, see Richard Saldanha next session)

2304.04401

Physics applications: CEνNS, mCPs

- Skipper-CCD experiments under development for reactor-based CEνNS (CONNIE, Atucha) and accelerator-based millicharge searches (MOSKITA, DarkBeaTS)
  - ▶ Signal spectra are either steeply falling or peaked at a few $e^- h^+$, similar to DM-e scattering
  - ▶ Compact Skipper-CCD systems can get close to the source
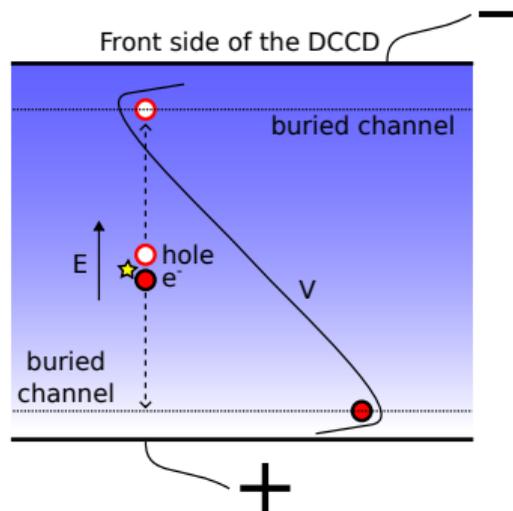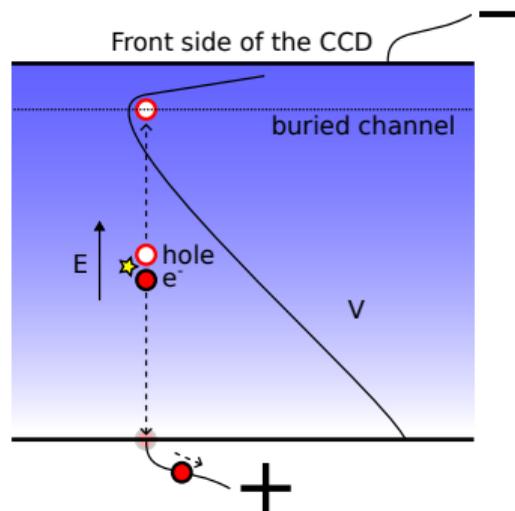- Cherenkov photons from cosmic-ray muons are a significant source of single-charge background
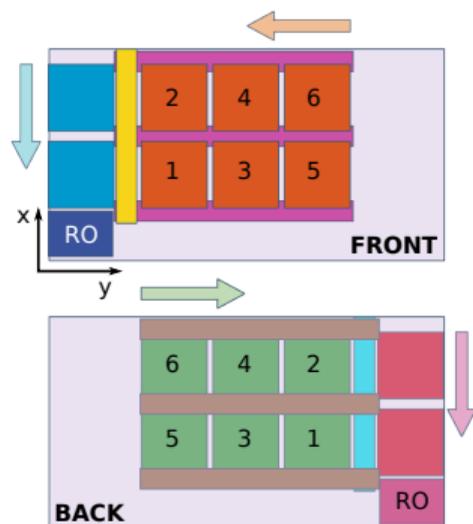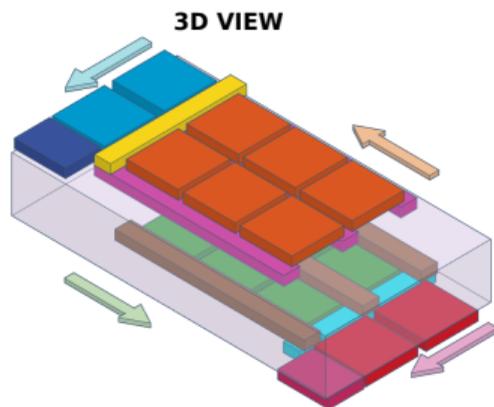
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Dual-sided charge collection

- A single-sided p-channel CCD collects holes, discards electrons
- A dual-sided CCD (DCCD) would collect both, with a p-channel frontside and an n-channel backside
  - Charge backgrounds generated at either surface will only be collected on that surface
  - Charge generated in the bulk will be collected on both sides; since we can shift the collected charge independently on the two sides, we can discriminate between pileup and true multi-charge events

Front side of the CCD   buried channel   E   hole   e⁻   V

Front side of the DCCD   buried channel   E   hole   e⁻   V   buried channel

Reading the DCCD

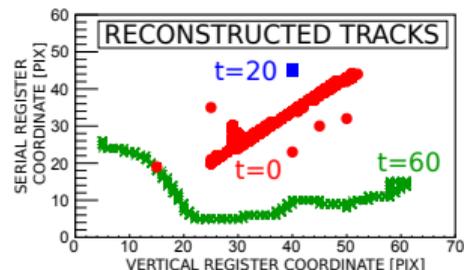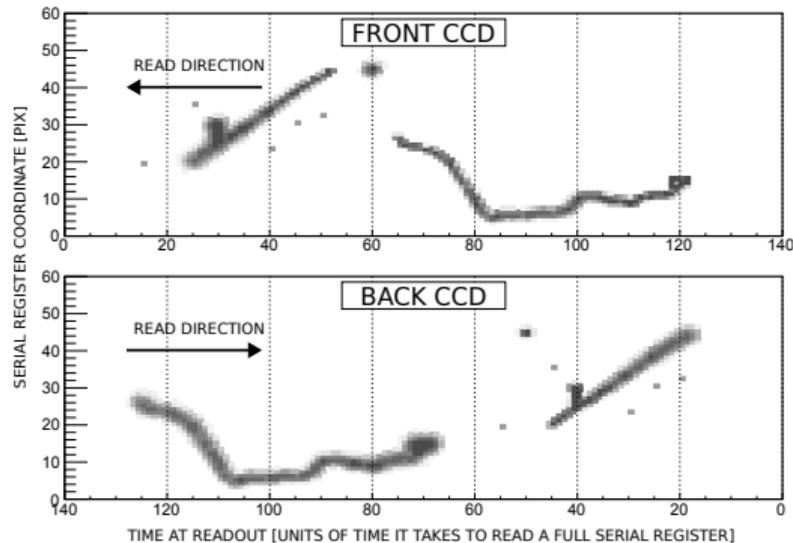- Both sides have identical (modulo polarity) pixels and readout amplifiers
- When reading, we shift charge in opposite directions on the two sides

- In timed-exposure mode (expose, then read), bulk events from exposure will appear in the same place on both sides; we can reject everything else
  - Useful if we have a lot of spurious charge (which gets rejected) but not much bulk background (which doesn't)

Continuous readout

- If we have a lot of bulk background, we're better off reading out continuously
- Real ionization events get read out on each side at (time of event) + (time to shift charge from event position to readout)
  - By matching frontside and backside events, we can reconstruct both position and time — this can be used to reject Cherenkov photons
- Background charges appear at random positions and times, so pileup events are uncorrelated between the two sides
  - Given a pileup event on the frontside, we can reject it unless it coincides with a similar event on the backside
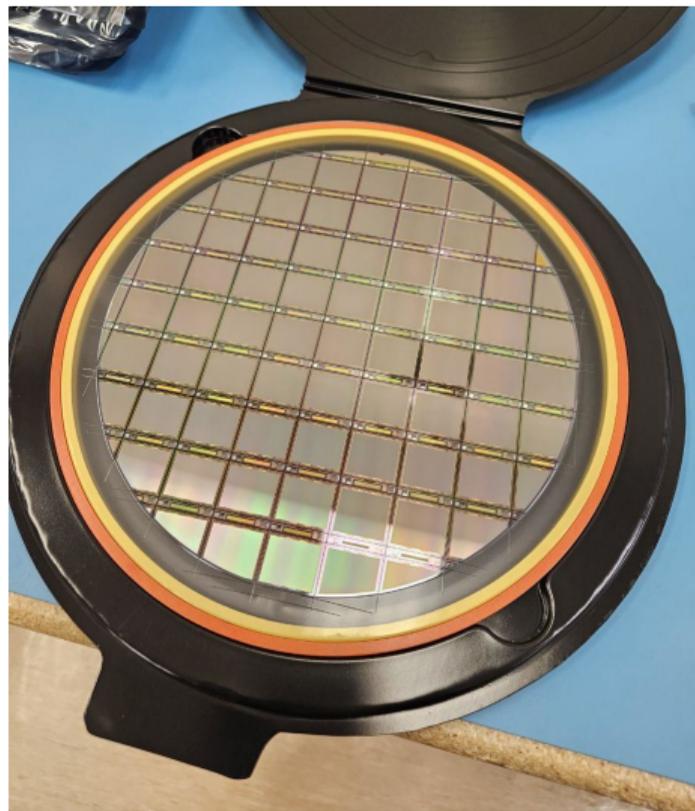

FRONT CCD

READ DIRECTION

BACK CCD

READ DIRECTION

TIME AT READOUT [UNITS OF TIME IT TAKES TO READ A FULL SERIAL REGISTER]

RECONSTRUCTED TRACKS

t=20

t=0

t=60

VERTICAL REGISTER COORDINATE [PIX]

Performance

- Use the Oscura design as a starting point:
  - 1278 rows, 1058 columns, 0.5 gram
  - Full-frame readout time $\sim$ 4 hours
- Assume that both sides of the DCCD perform similarly to the Oscura CCDs
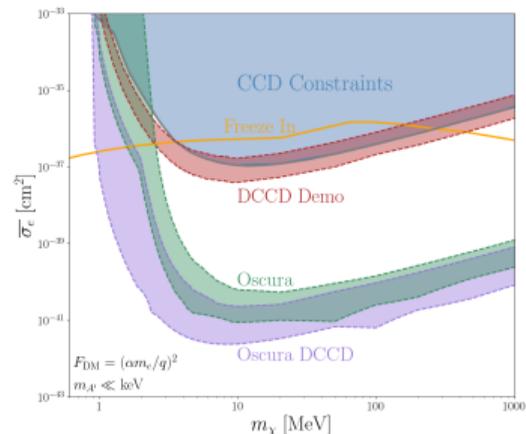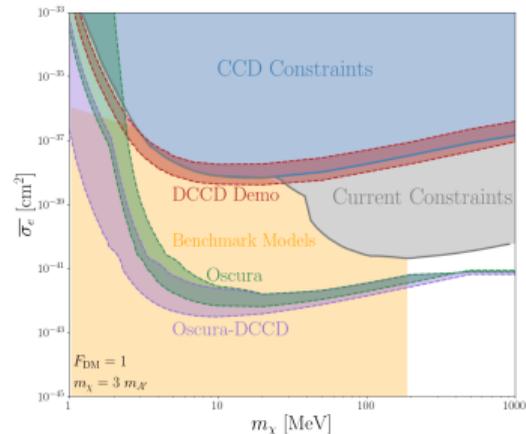 - For the frontside and bulk this is plausible (though not a given); for the backside this is a benchmark

Performance

- How does the DCCD help with $2e^- h^+$ pileup backgrounds? Two scenarios:
  - Spurious charge $O(5 \times 10^{-4})$ e/pix/image (current Oscura level) $\rightarrow O(1)$ 2e event per full-frame readout, a single-sided CCD will need to do physics with a 3e or 4e threshold
    - ★ For a DCCD in timed-exposure mode, the spurious charge is totally uncorrelated and we'll reject a frontside event unless a backside event happens to be in the same place (modulo PSF): a "rejection factor" of $O(10^{-5})$
  - Cherenkov background $O(1 \times 10^{-3})$ e/pix/day (typical at sea level)
    - ★ For a DCCD in continuous-readout mode, the charges that pile up on the frontside will be in random rows on the backside: a rejection factor of $O(10^{-3})$
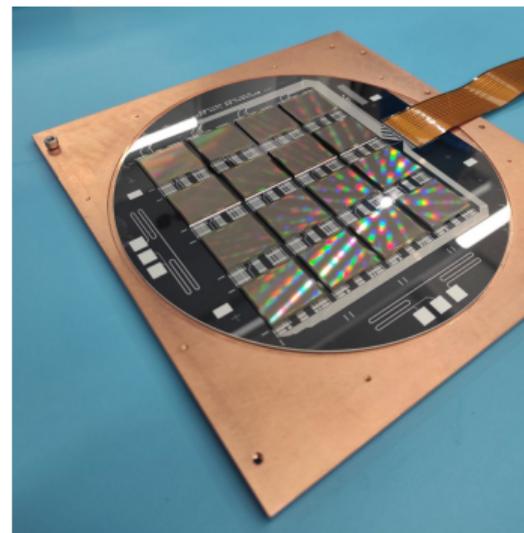
Physics impact

- Consider two scenarios for the charge backgrounds:
  - Pessimistic: similar to current Oscura CCDs
  - Optimistic: spurious charge similar to current SENSEI/DAMIC-M CCDs
- A small-scale (~ 1 kg-day) "demonstrator" experiment, comparable to the DAMIC-M LBC or a compact mCP/CEνNS experiment:
  - The $2e^- h^+$ channel has $O(2)$ events in the pessimistic case, background-free in the optimistic case
- A large-scale (30 kg-year) experiment, comparable to Oscura:
  - Lowers the background-free threshold from 4 to $3e^- h^+$ in the pessimistic case, from 3 to 2 in the optimistic case $\rightarrow$ big sensitivity improvements at lower masses

Development plan

- Fabricate and characterize DCCDs based on the Oscura design, and build a small demonstrator system
- Goals/challenges:
  - Understand the charge backgrounds for a DCCD
    - ★ How does DCCD fabrication affect the frontside performance? Can the backside perform as well as the frontside?
  - Develop the packaging and the readout electronics for a DCCD
    - ★ Wirebonds on both sides; frontside and backside readout electronics running at a relative voltage of up to 100 V
  - Validate the end-to-end performance of the DCCD idea in a setup of similar scale to an mCP or CEνNS experiment, and prepare a path to scaling up for DM experiments

Current status, conclusion

- Pursuing funding opportunities
- Oscura foundries believe the DCCD is compatible with their processes; working with them to refine the plan
  - Making sure the backside fabrication doesn't damage the frontside or its doping profiles, or interfere with the gettering process (for reducing charge traps and dark current)
  - Evaluating the possibility of fabricating a simpler "feasibility test" device elsewhere as a first step
- The DCCD has the potential to greatly enhance the sensitivity of many planned Skipper-CCD experiments