Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Review on Excess Signals Observed in CCD Detectors

Daniel Baxter

EXCESS @ IDM

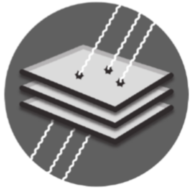
16 July 2022

IDM Session Advertisement

July 18: Parallel 1A – Direct Detection I (Room E17)

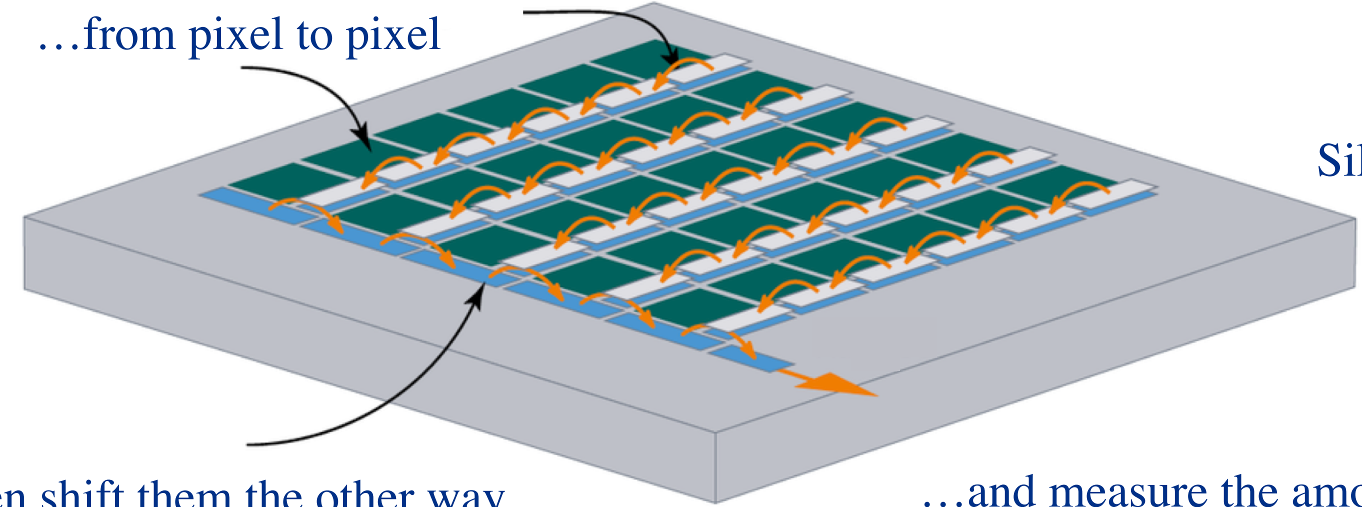
14:00	**The DAMIC-M Experiment: Status and First Results** *EI7*	*Danielle Norcini* 14:00 - 14:20
	The low-energy spectrum in DAMIC at SNOLAB *EI7*	*Alvaro Chavarria* 14:20 - 14:40
	SENSEI: Sub-GeV Dark Matter Search with Skipper CCDs *EI7*	*Mariano Cababie* 14:40 - 15:00
15:00	**The Oscura experiment – searching for low-mass dark matter with a very-large array of skipper-CCDs** *EI7*	*Nathan Saffold* 15:00 - 15:20
	First 100 eV nuclear recoil ionization yield measurement in silicon *EI7*	*Dr Valentina Novati* 15:20 - 15:40
	Measurement of low-energy Compton and neutron scattering in Si CCDs for dark matter searches *EI7*	*R Smida* 15:40 - 16:00

Charge Coupled Devices



Shift charges in one direction…

…from pixel to pixel



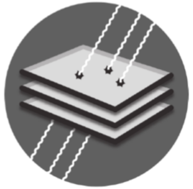
Silicon

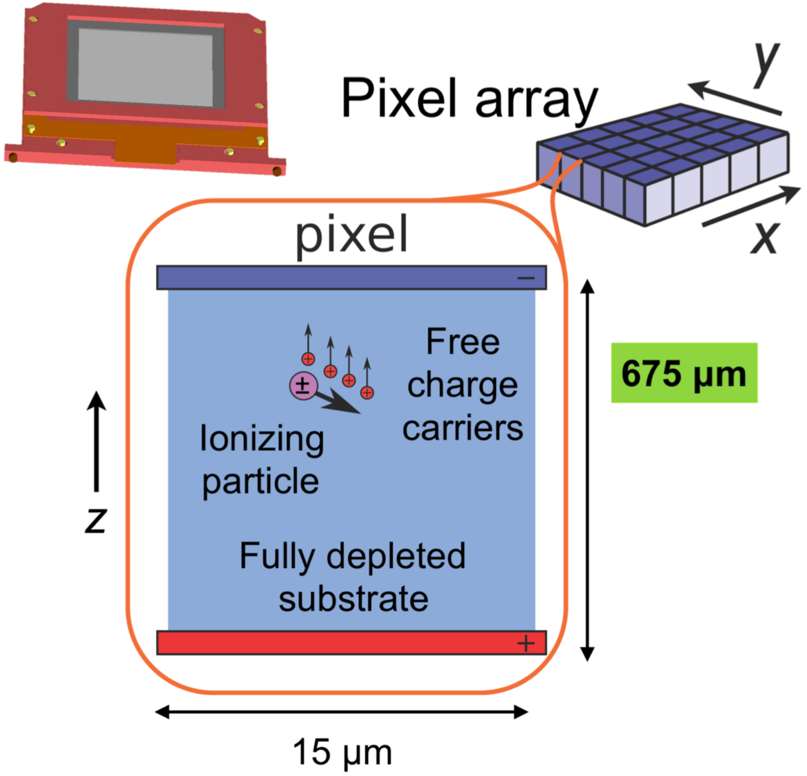
Then shift them the other way…
(“Serial Register”)

…and measure the amount of charge in each pixel!

Graphic by Stemmer Imaging

Charge Coupled Devices





Interaction with silicon produces free charge carriers…

- …which are drifted across fully-depleted region…
  - *no loss of charge*
- …and collected in 15 micron square pixels…
  - *exceptional position resolution*
- …to be stored until a user-defined readout time after many hours.
  - *large exposures*

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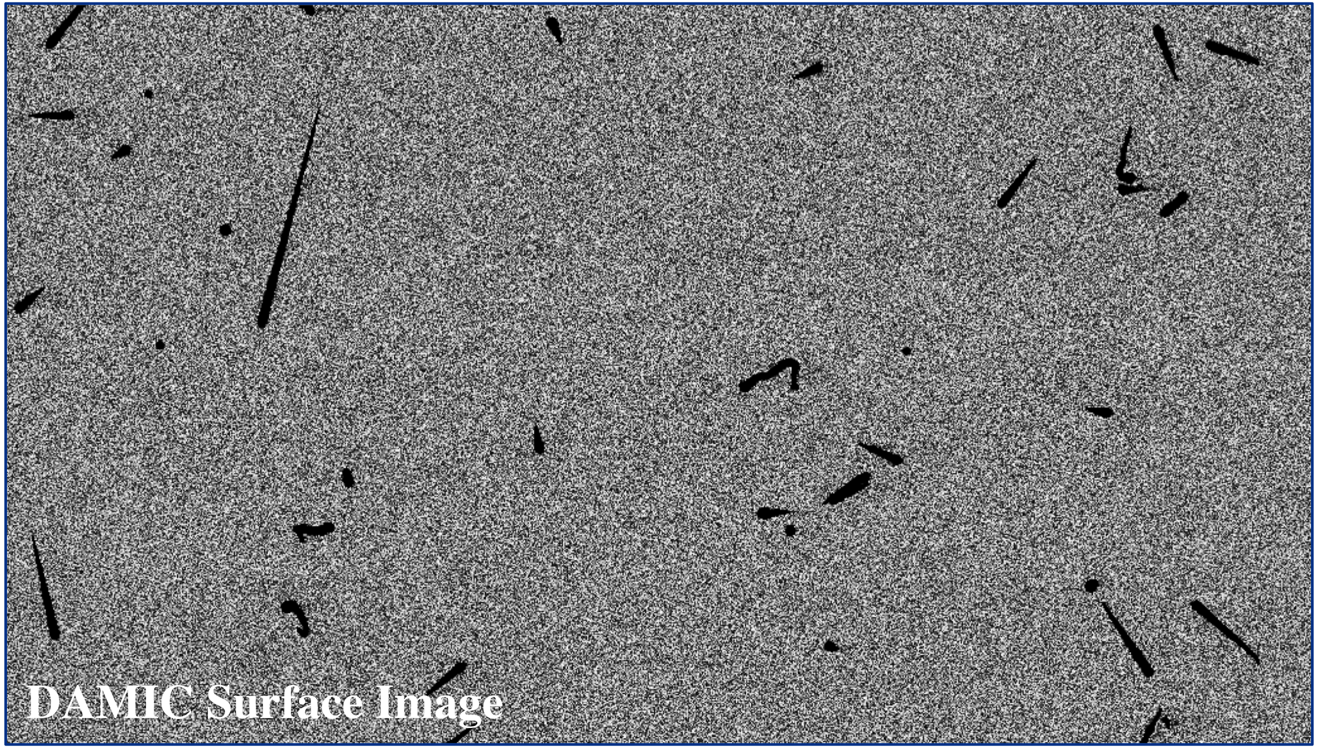
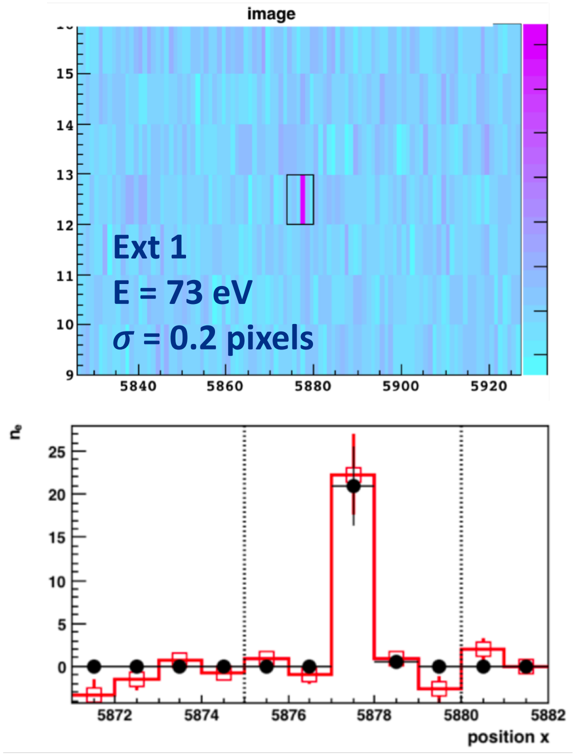
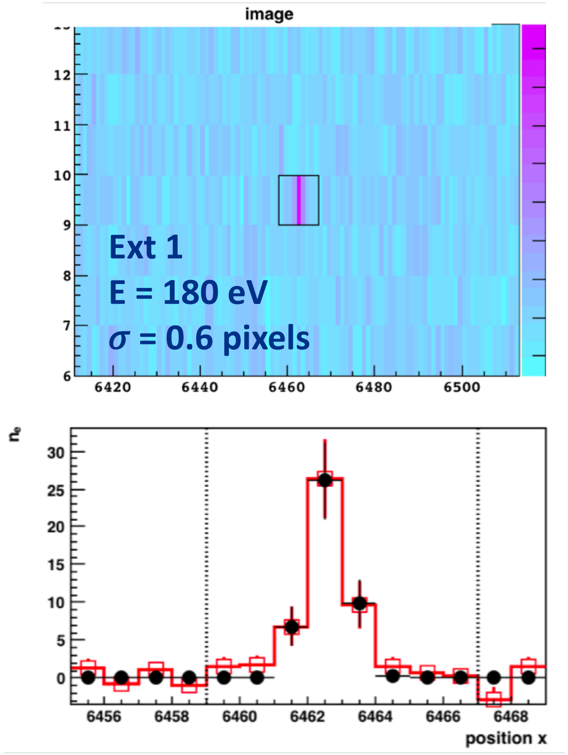
Charge Coupled Devices

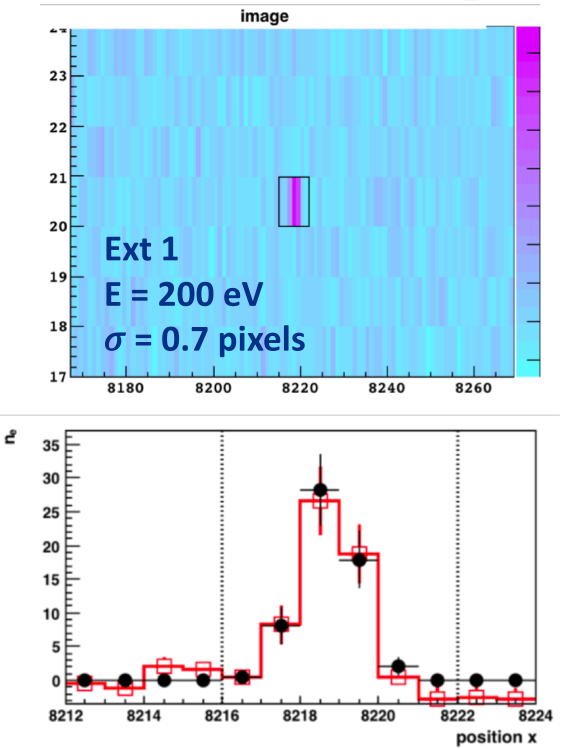


Charge Coupled Devices

DAMIC at SNOLAB







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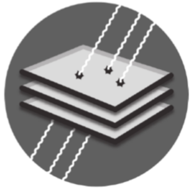
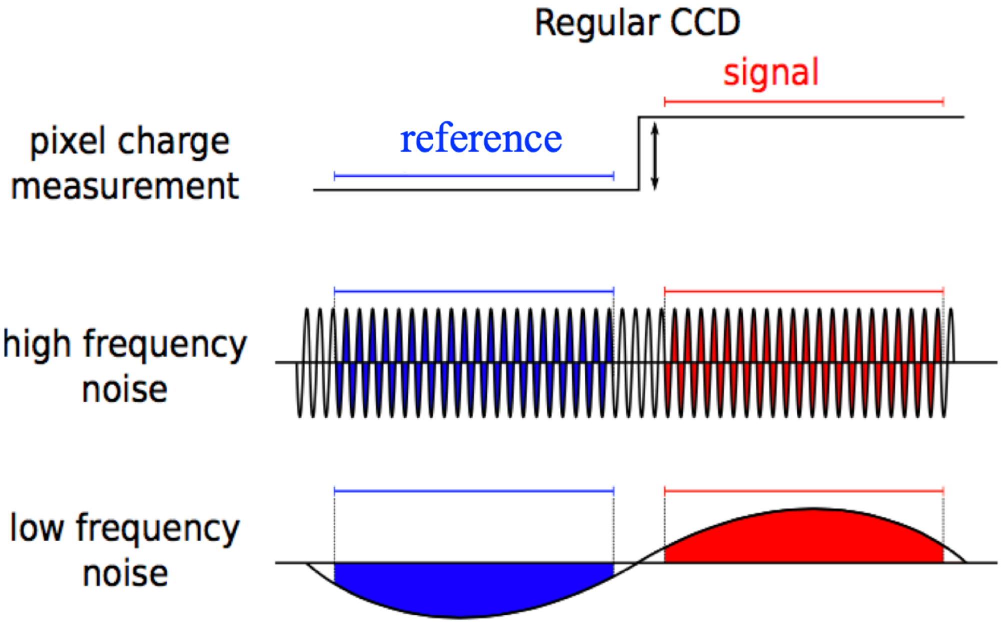
Charge Coupled Devices



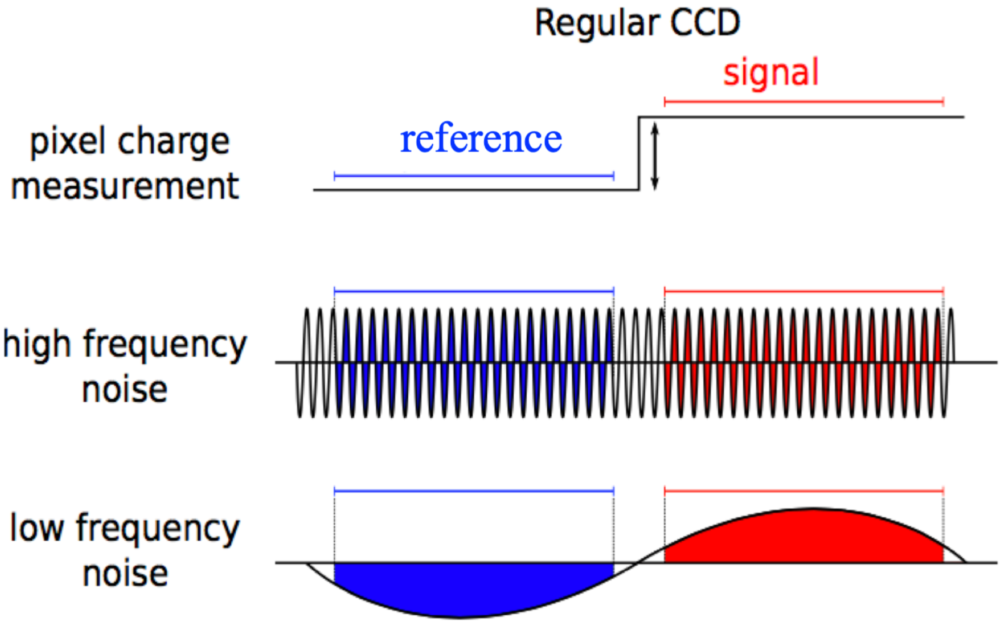
Correlated double-sampling (CDS)

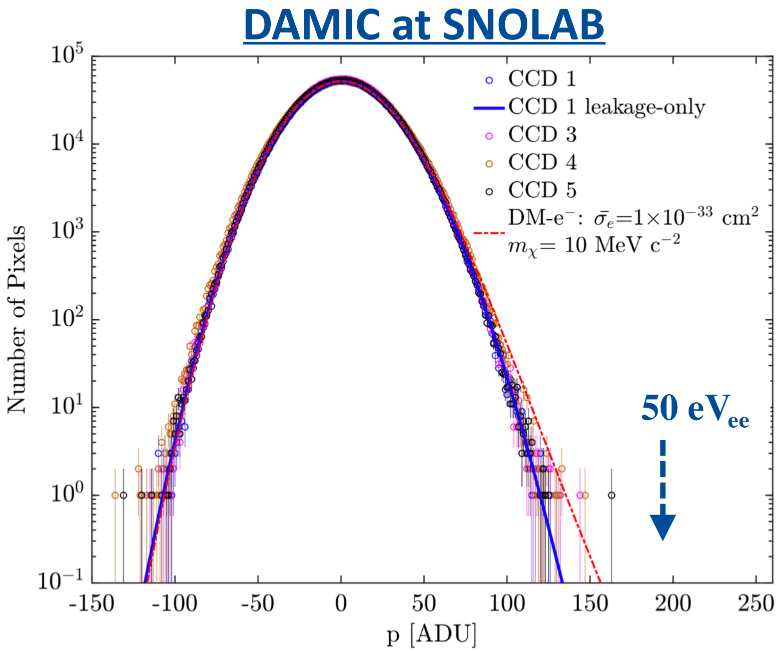


1. Integrate over the summing well when empty (reference)
2. Repeat this integration after transferring pixel charge in (signal)
3. Subtract the reference from the signal

Charge Coupled Devices

Correlated double-sampling (CDS)

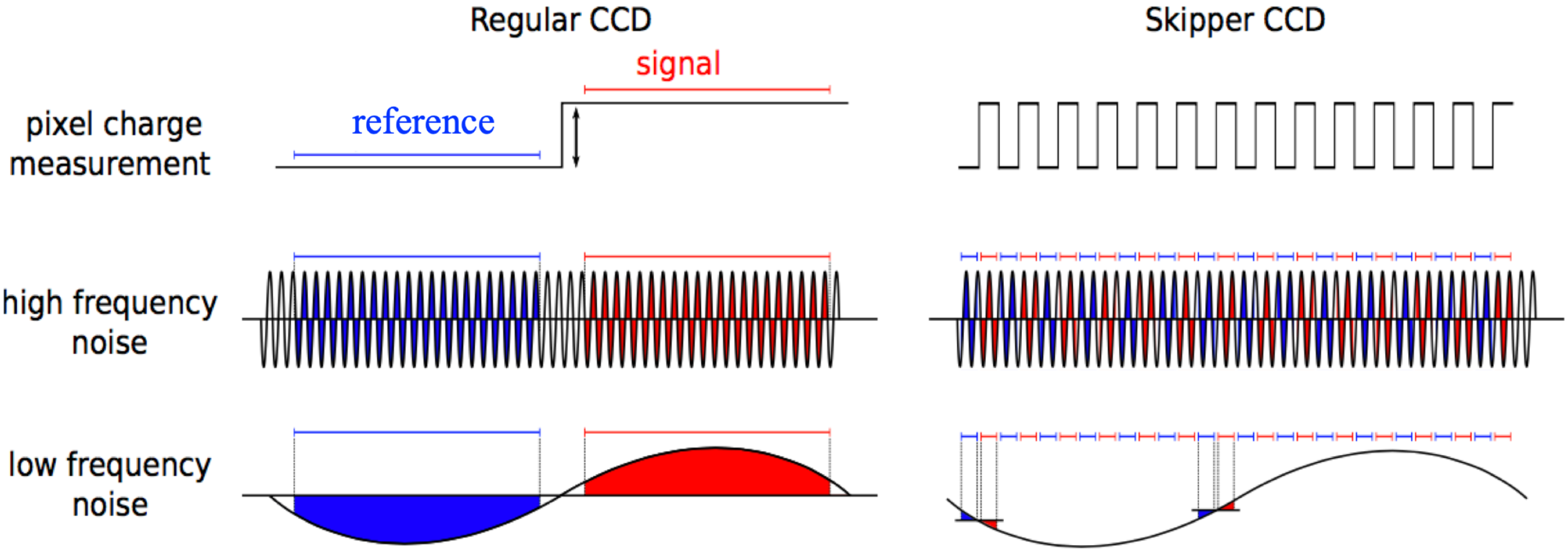




A. Aguilar-Arevalo et al. PRL 123, 181802 (2019) [arXiv:1907.12628]

Charge Coupled Devices

Skipper Amplifiers: allow repeated, non-destructive CDS



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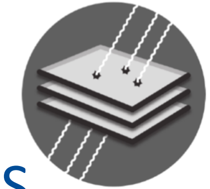
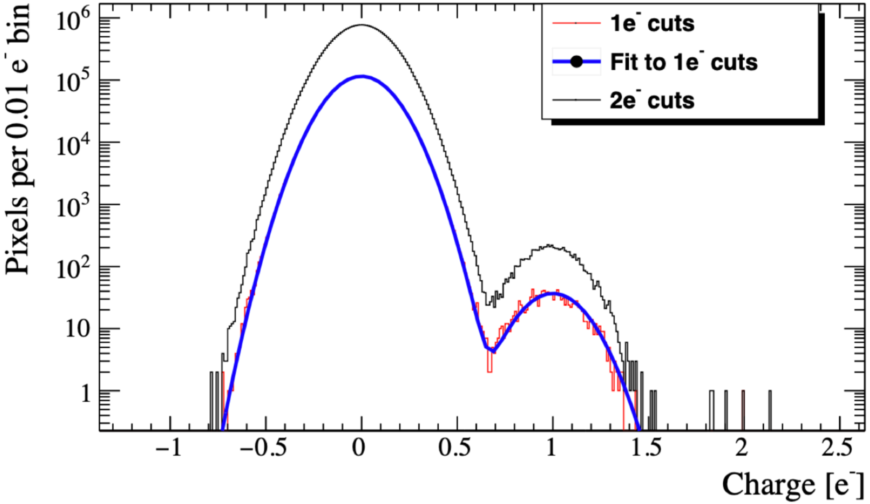
Charge Coupled Devices



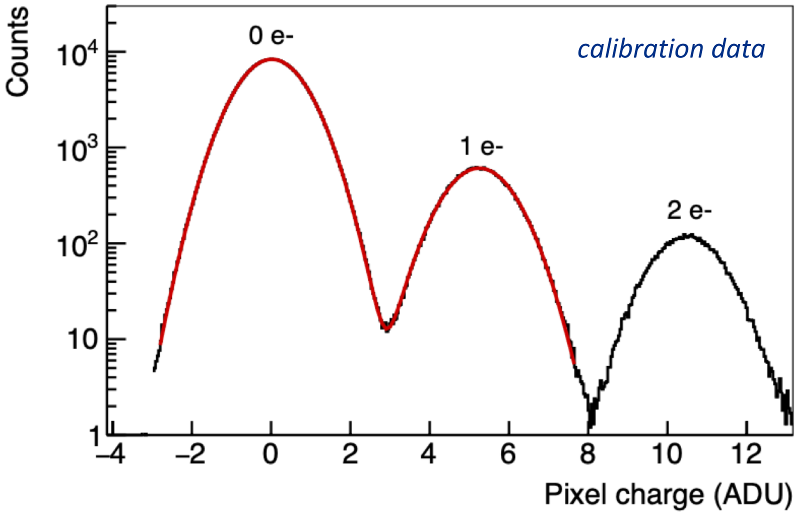
Skipper Amplifiers: allow repeated, non-destructive CDS

SENSEI



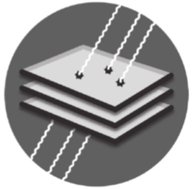
L. Barak et al. PRL 125, 171802 (2020) [arXiv:2004.11378]

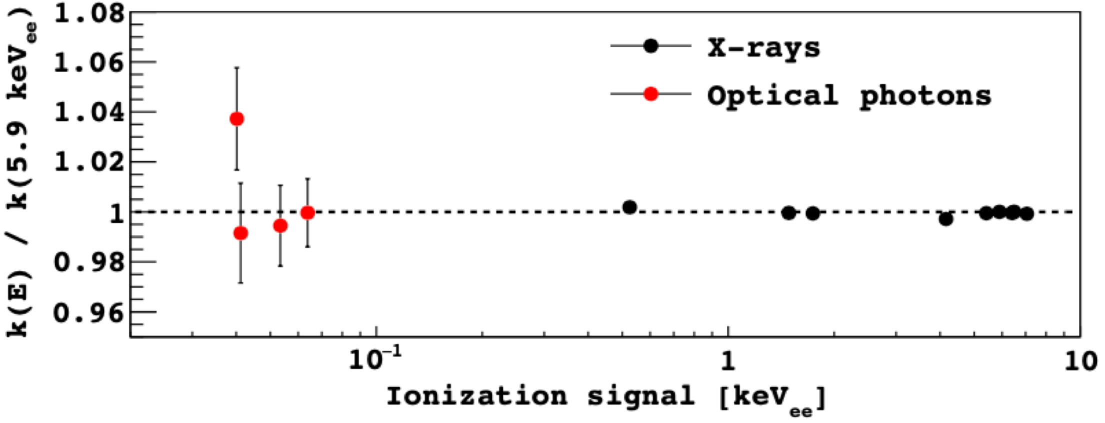
DAMIC-M



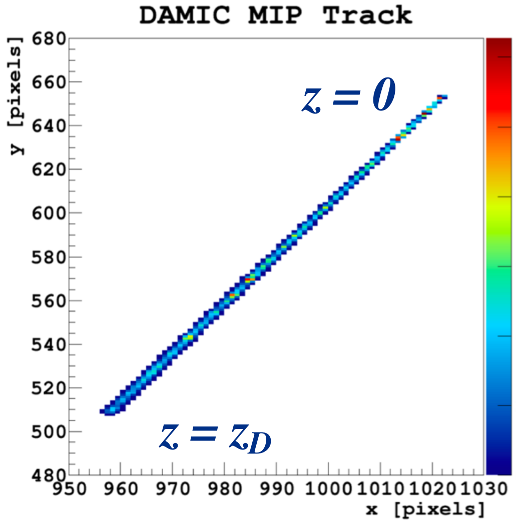
D. Norcini et al. (2022) [arXiv:2207.00809]

Charge Coupled Devices





- Muons give an excellent calibration for the depth-dependence of sigma



- CCDs have exceptionally **linear** energy response up to high (keV-scale) energies, allowing relatively straightforward energy calibration

A. Aguilar-Arevalo et al. PRD 94, 082006 (2016) [arXiv:1607.07410]

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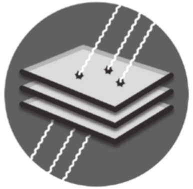
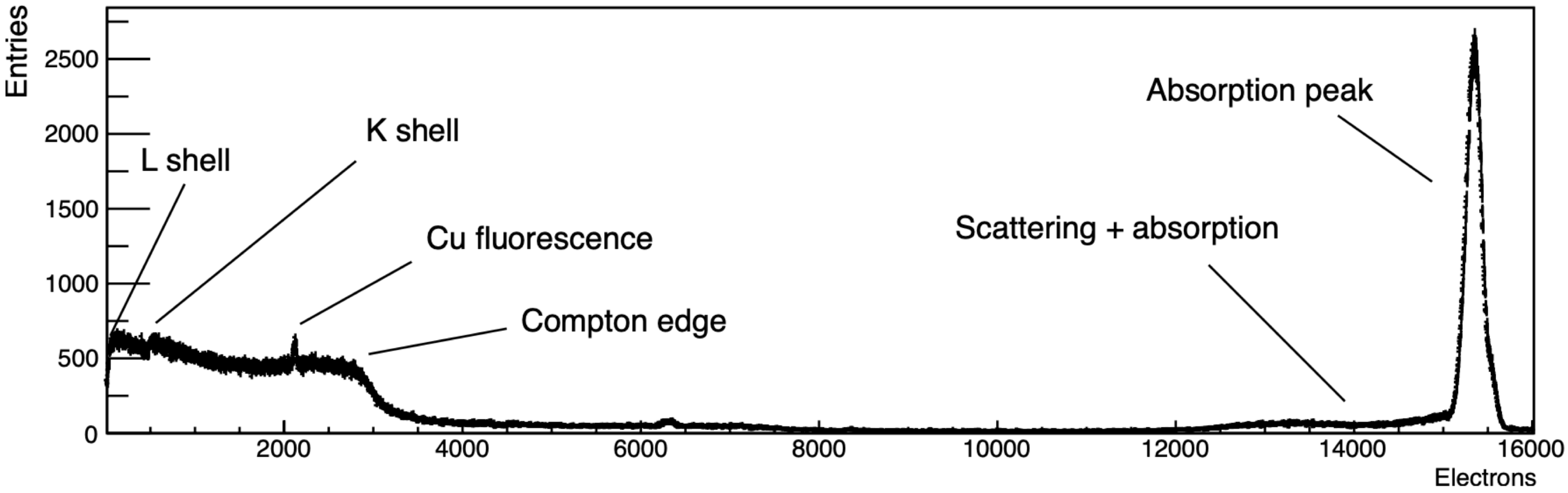
Charge Coupled Devices

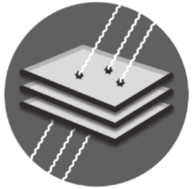


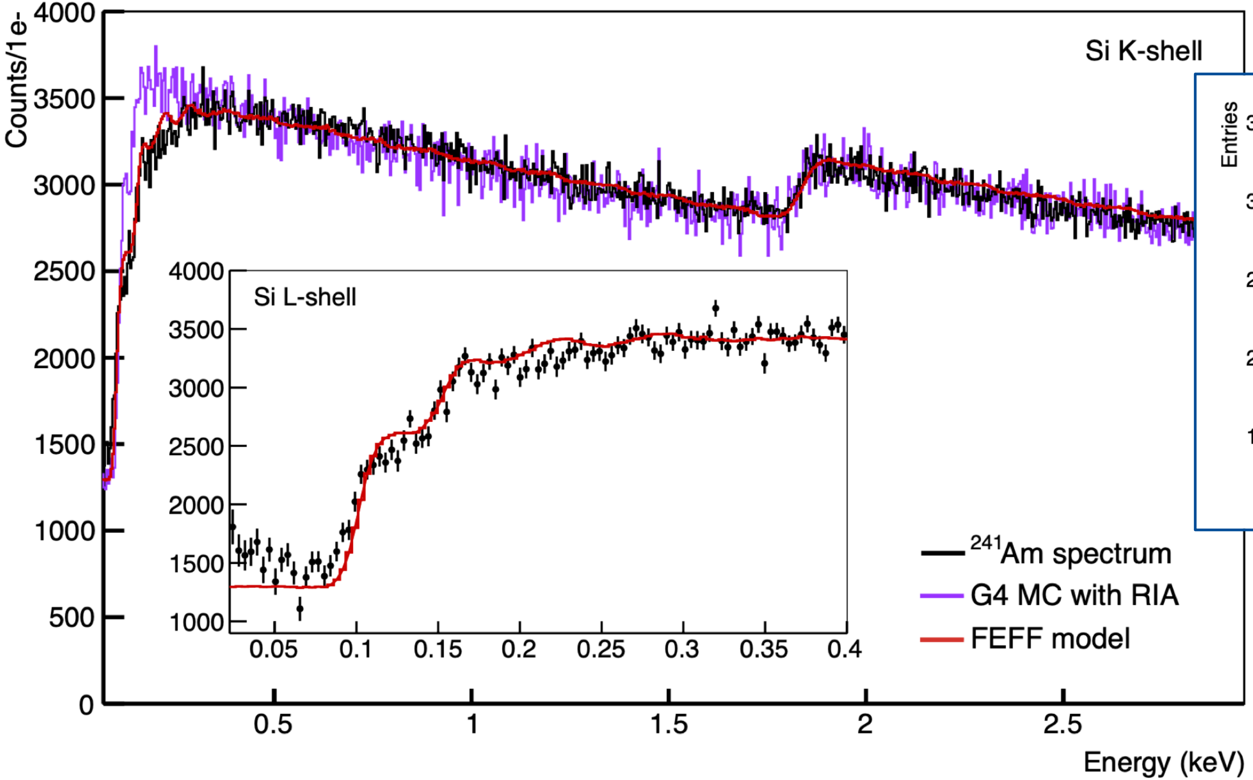
59.54 keV γ-rays from ^{241}Am

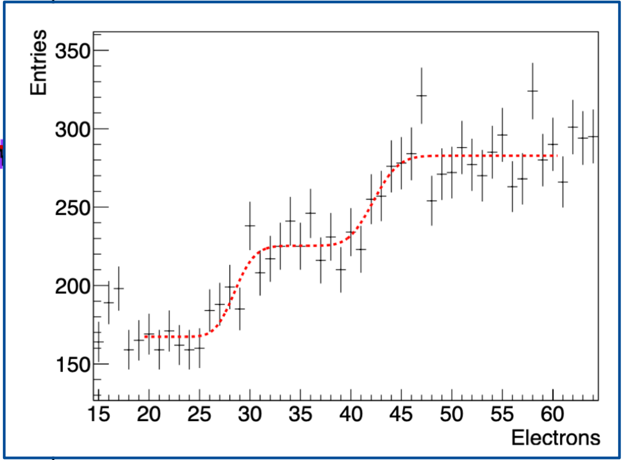


A. M. Botti et al. (2022) [arXiv:2202.03924]

Charge Coupled Devices







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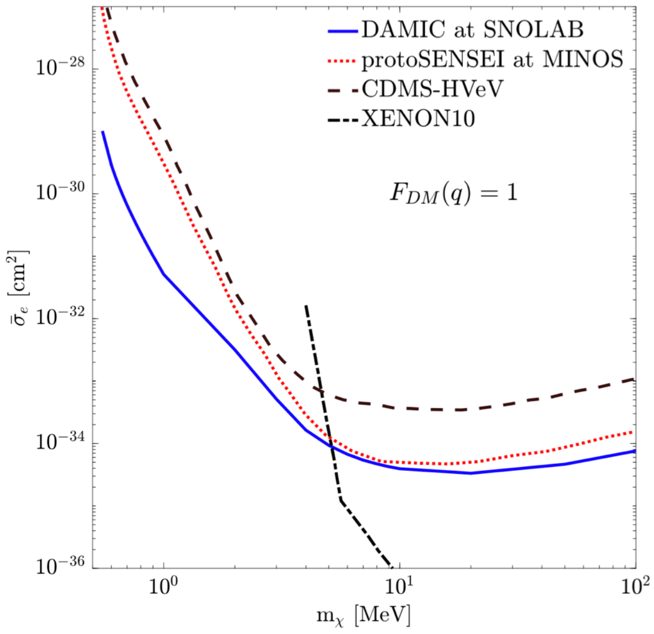
Dark Matter Electron Scattering

DAMIC at SNOLAB



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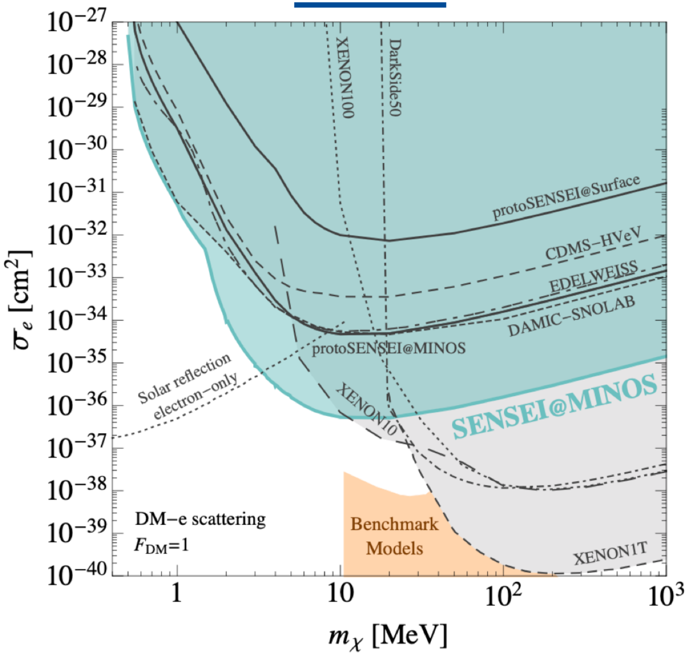
SENSEI



L. Barak et al. PRL 125, 171802 (2020) [arXiv:2004.11378]

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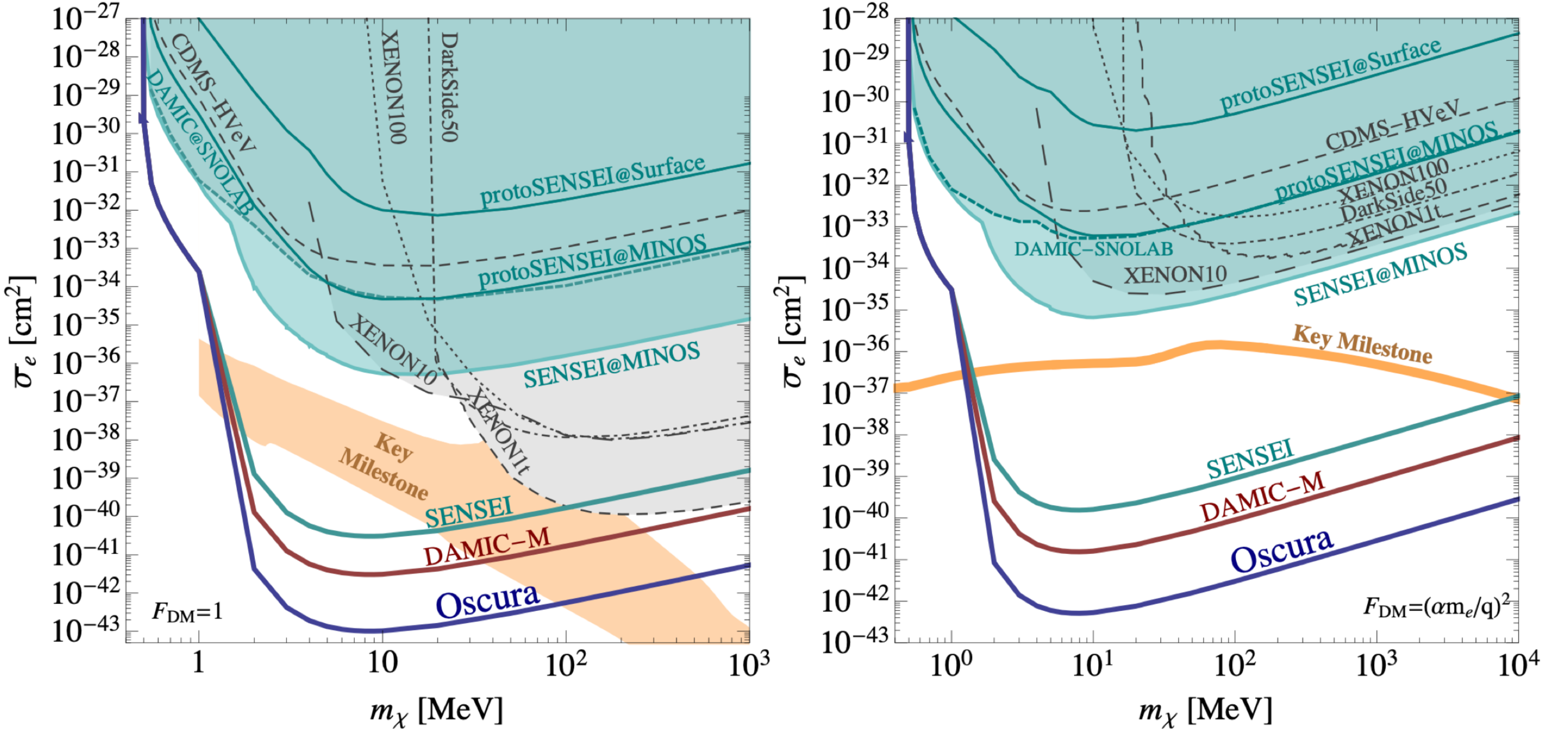
Dark Matter Electron Scattering

Projected Sensitivity



A. Aguilar-Arevalo et al. (2022) [arXiv:2202.10518]

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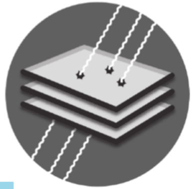
Dark Rates

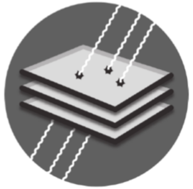


Detector	Temperature (Kelvin)	Resolution (e^-)	Background Level (dru)	Dark Rate (e^- /pix /day) [Hz/kg]
DAMIC at SNOLAB	140	1.6	12	2.3 x 10^{-4} [7]
DAMIC at SNOLAB (skipper upgrade)	~110 *	0.16	12	24 x 10^{-4} [73] *
SENSEI at MINOS	135	0.14	9700	5 x 10^{-4} [16]
SENSEI at MINOS (with shielding)	135	0.14	3370	1.6 x 10^{-4} [5]
SENSEI at SNOLAB				
DAMIC-M LBC at Modane	130 *	~0.2 *	~10 *	30 x 10^{-4} [91] *
SuperCDMS HVeV	0.05	0.03	>1000	[1,700]

works in progress

* = …further improvement expected in coming months!

Dark Rates – What can we say so far



- The substantially lower dark rates in CCDs relative to SuperCDMS HVeV (and EDELWEISS HV) likely indicates different origins. (*see arXiv:2011.13939*)
- *Preliminary* data indicates that lowering temperature does not improve this dark rate, indicating a non-thermal origin.
- The SENSEI shield-off to shield-on comparison suggests at least some component of dark rate still scales with radiation level.
    - **Serial register events**: radiation events during readout can avoid cuts (*see arXiv:2107.00168*)
    - **Charge transfer inefficiency**: individual charges left behind during transfer (masked)
- <u>DAMIC at SNOLAB and SENSEI at MINOS observe statistically comparable rates despite 10^3 difference in background rate.</u>
- The comparison of skippers run in DAMIC at SNOLAB, SENSEI at SNOLAB, and DAMIC-M LBC at Modane will tell us a lot about the origins of the remaining ~1 $e^-/mm^2/day$ surface OR ~5 Hz/kg bulk rates

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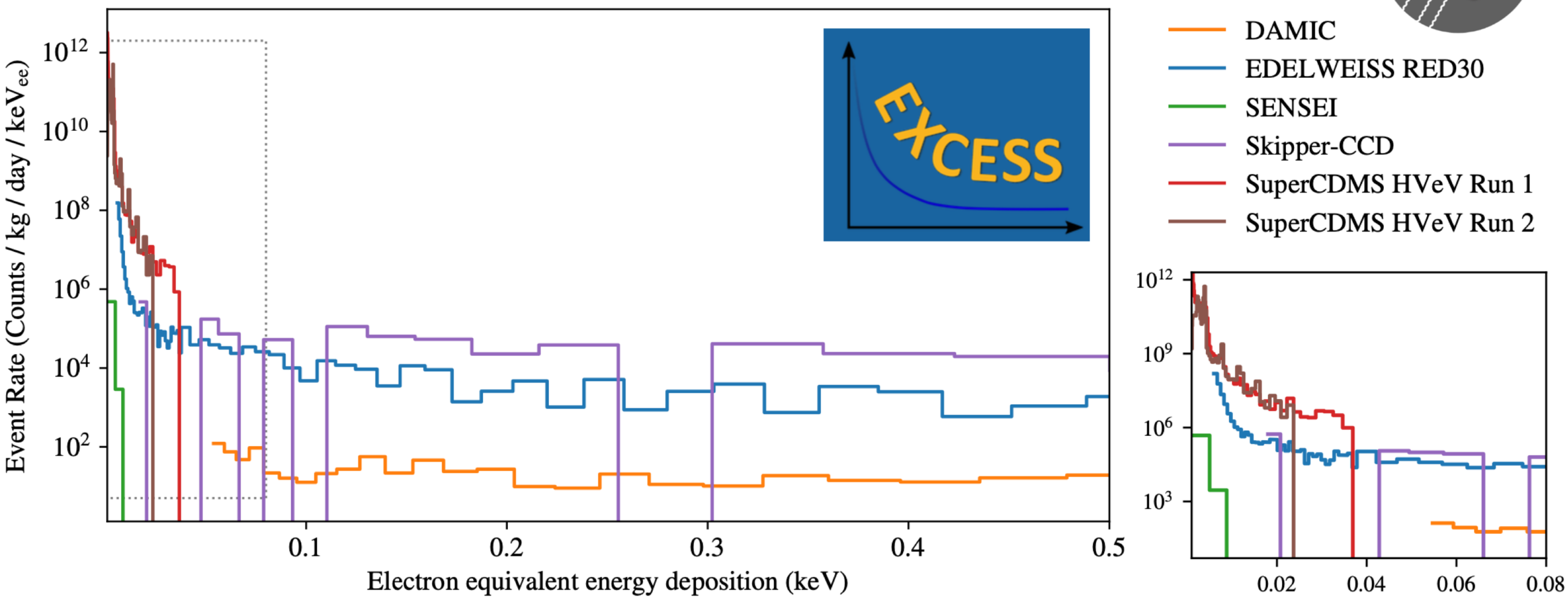
Dark Rates



P. Adari et al. (2022) [arXiv:2202.05097]

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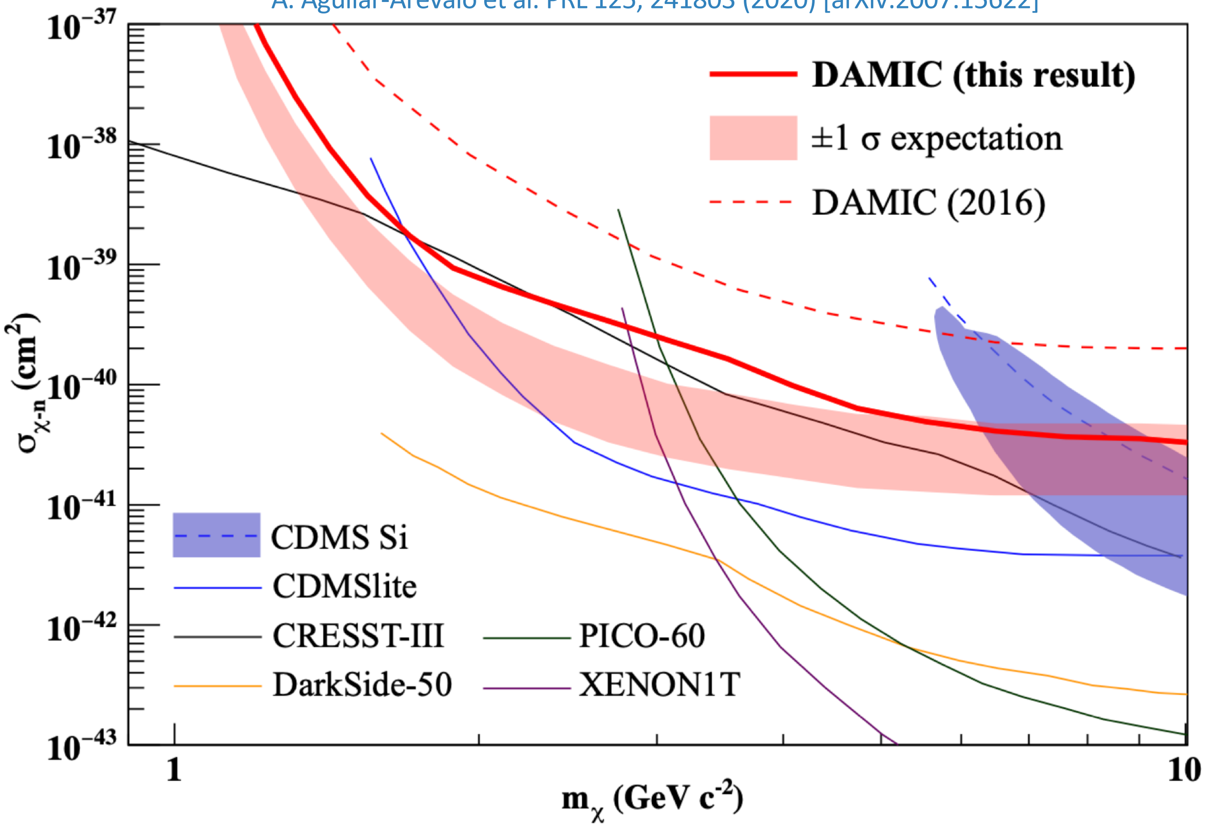
Dark Matter Nucleon Scattering

A. Aguilar-Arevalo et al. PRL 125, 241803 (2020) [arXiv:2007.15622]



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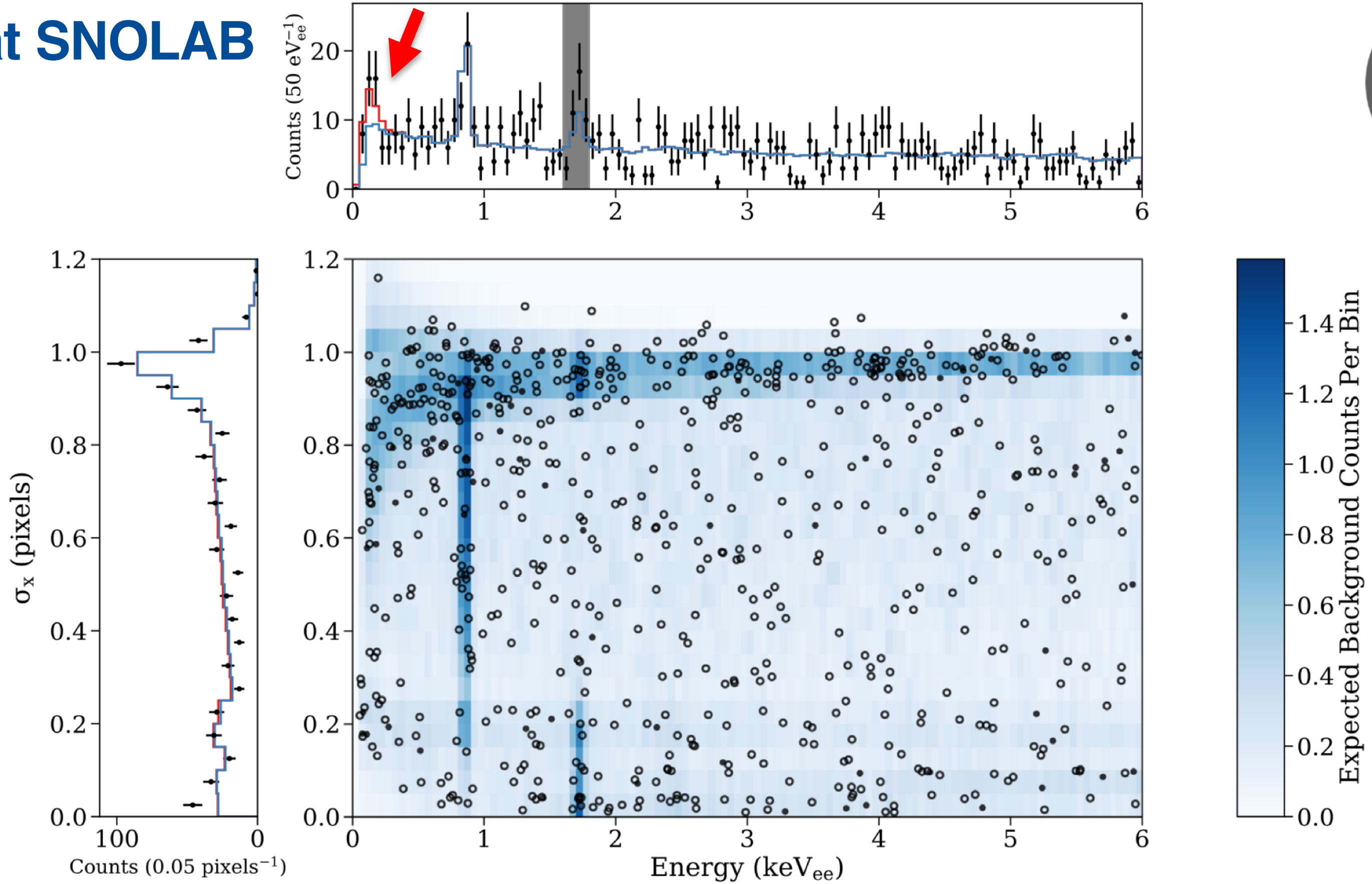
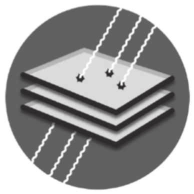
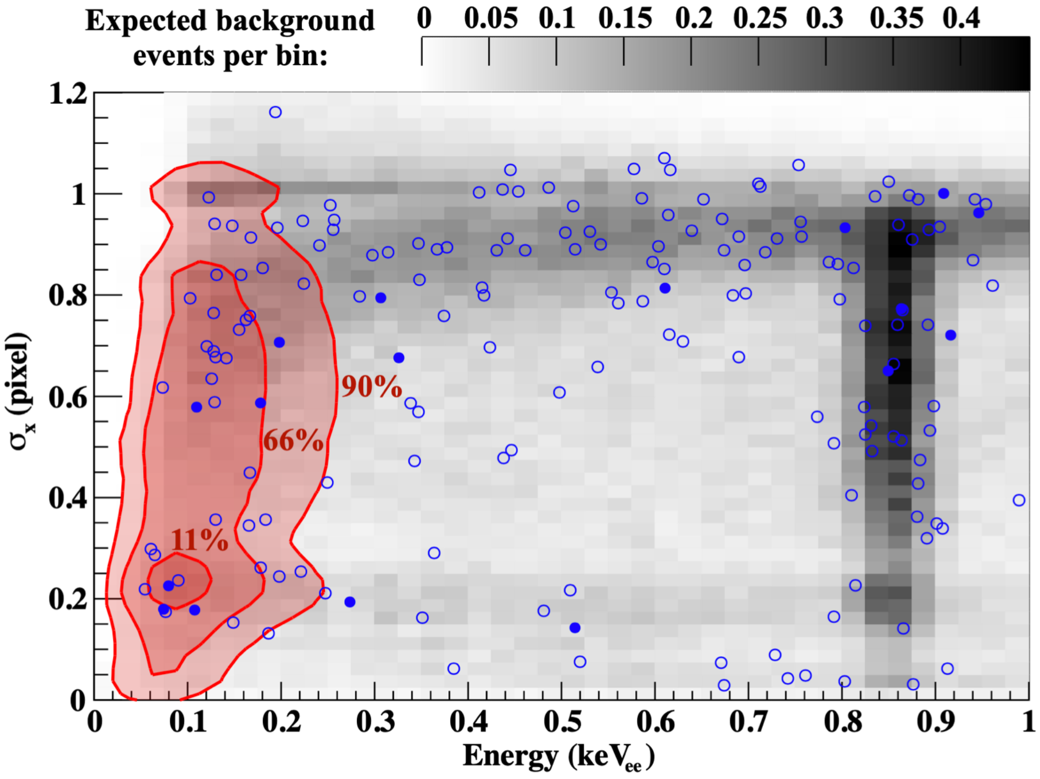
DAMIC at SNOLAB





A. Aguilar-Arevalo et al. PRD 105, 062003 (2022) [arXiv:2110.13133]

DAMIC at SNOLAB



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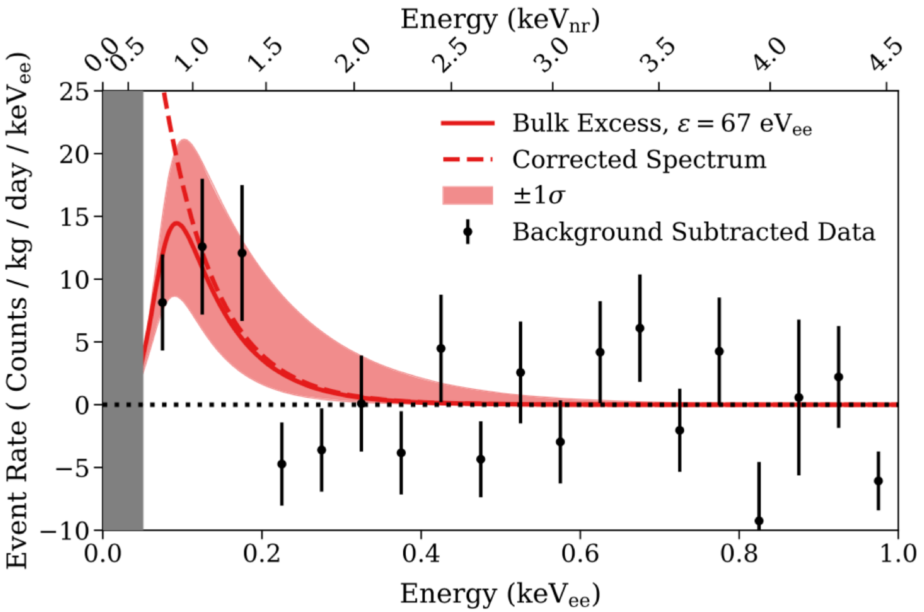
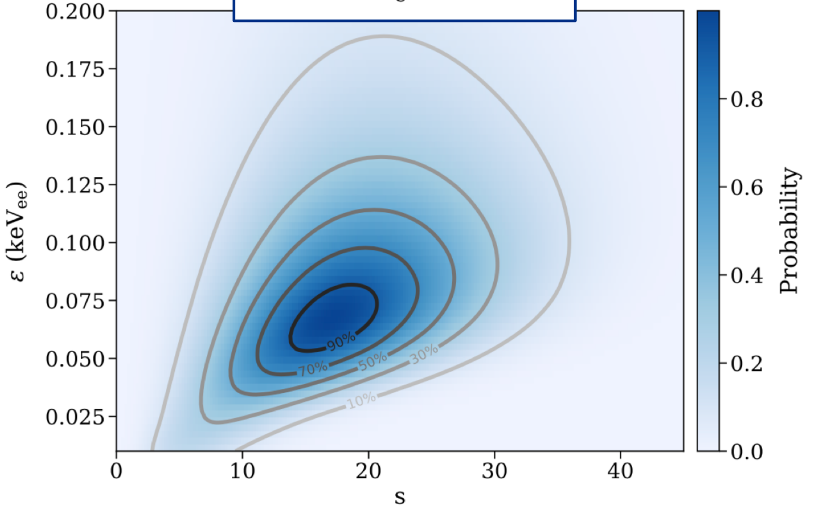


$$f_s(E|\epsilon) = \frac{1}{\epsilon}\exp(-E/\epsilon)$$



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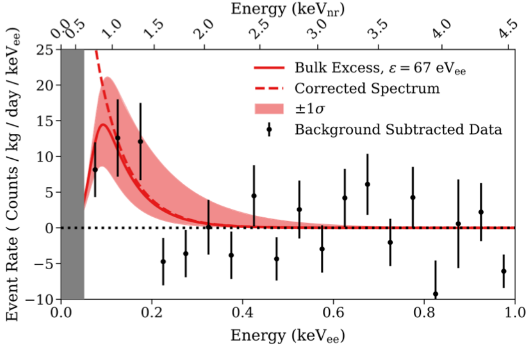

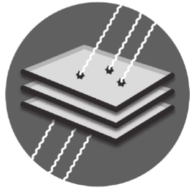

Possibilities:

1. We are missing a bulk component in our background model
2. We are missing a front component in our background model
3. We are incorrectly modeling detector threshold effects
4. We are missing a front detector effect
5. **We are observing interesting new silicon physics**
6. **We are observing some type of dark matter interaction**

Items 1–4: **Background Model**

Items 5–6: **New Physics**

A. Aguilar-Arevalo et al. PRD 105, 062003 (2022) [arXiv:2110.13133]

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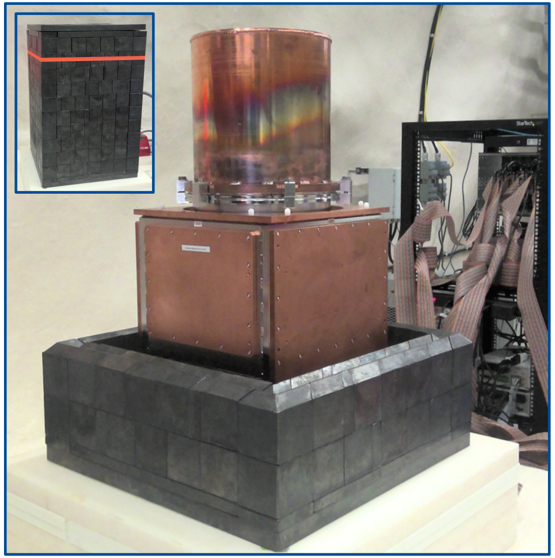
CCD EXCESS

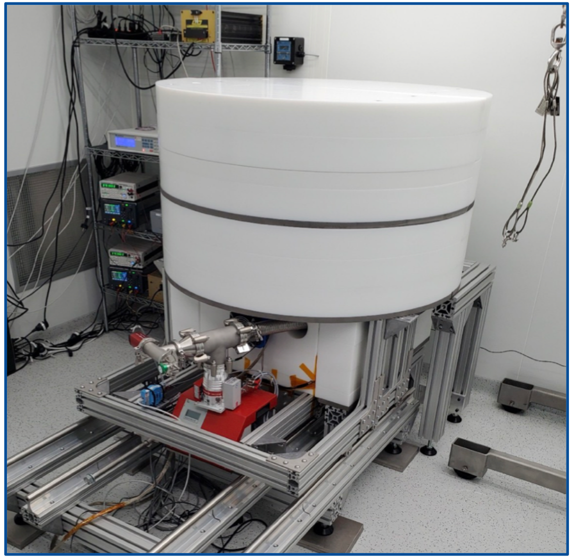
Three simultaneous verification efforts with Skippers

DAMIC at SNOLAB

SENSEI at SNOLAB



DAMIC-M LBC

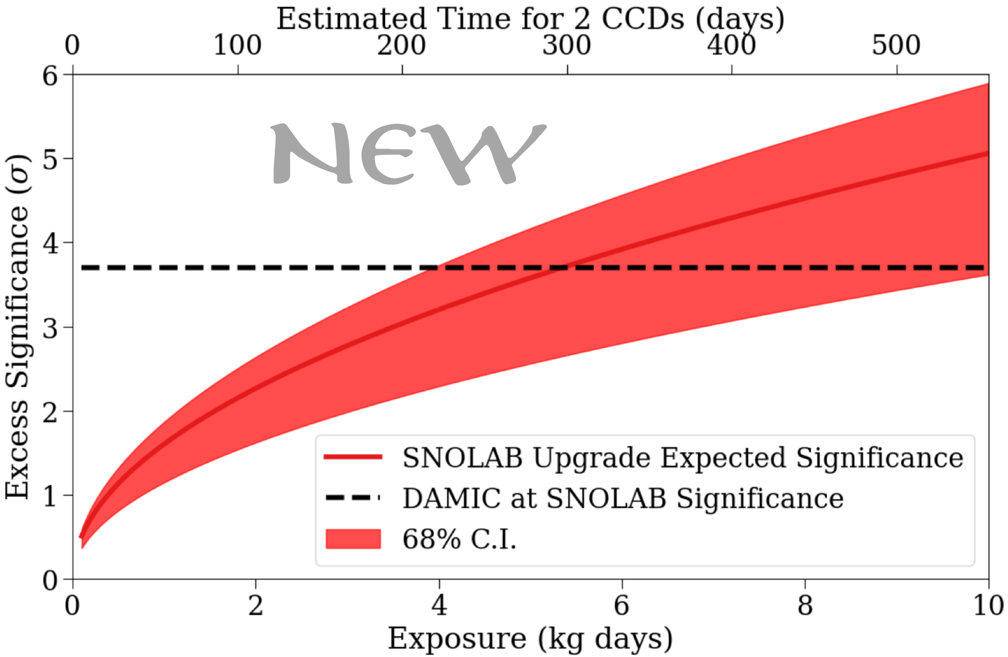


…expect results soon!

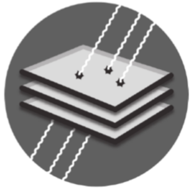
CCD EXCESS

Monte Carlo expectation for 18g of Skippers

DAMIC at SNOLAB



CCD EXCESS



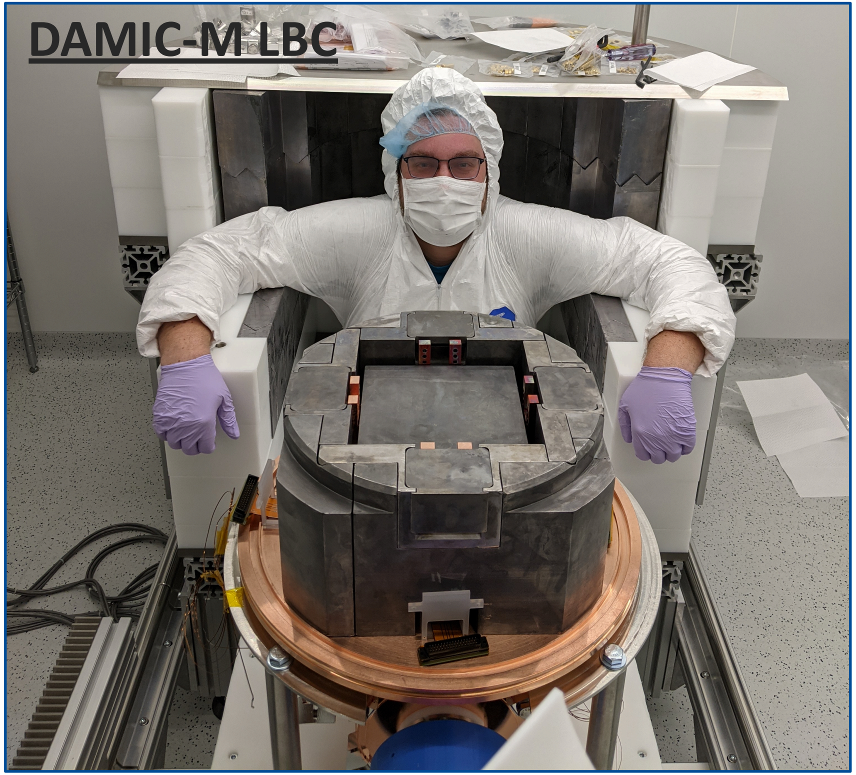
Statistical significance of excess at 3.7σ…

	Parameter	Null hypothesis	All events	CCD 1 only	CCDs 2–7 only	>200 eV_{ee}	$n_{pix} > 1$
(signal)	s [events]	0	17.1 ± 7.6	6.4 ± 3.0	8.9 ± 7.2	0	13.9 ± 6.8
(decay constant)	ϵ [eV_{ee}]	-	67 ± 37	89 ± 50	51 ± 39	-	78 ± 33
(CCD 1 background)	b_1 [events]	56.2	57.6 ± 3.3	56.0 ± 3.1	-	54.8 ± 3.0	43.6 ± 2.5
(CCD2-7 background)	b_{2-7} [events]	625	609 ± 21	-	613 ± 21	591 ± 21	535 ± 19
(CCD1 backside)	c_1 [events]	5.4	0.9 ± 1.1	0 ± 0.9	-	0.40 ± 0.87	1 ± 1.1
(CCD2-7 backside)	c_{2-7} [events]	41.6	6.6 ± 8.9	-	5.0 ± 7.0	3.0 ± 6.5	8 ± 8.7
	exposure [kg-day]	-	10.9	1.6	9.3	10.9	10.3
	no-signal p-value	-	2.2×10^{-4}	5.8×10^{-4}	0.039	1	5.1×10^{-3}
	g.o.f. p-value	-	0.10	0.94	0.21	0.32	0.69

- Bulk excess is present with significance in CCD 1 and CCDs 2-7 taken together and separately, only below 200 eV_{ee}, and even when event clusters containing a single pixel are excluded.
- Serial register events cannot account for excess due to long exposure time relative to read-out combined with low background rate (3 dru).

A. Aguilar-Arevalo et al. PRD 105, 062003 (2022) [arXiv:2110.13133]

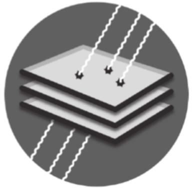
Conclusions



- CCDs continue to demonstrate the lowest dark rates of any solid-state dark matter detector, …
- …but this rate is still orders of magnitude above thermal predictions
- The DAMIC at SNOLAB 50-200 eV EXCESS remains a mystery at 3.7σ

- **Three parallel experiments are about to shed light on these mysteries in the coming months, with many more results in the next few years.**

Questions?



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	Measurement of low-energy Compton and neutron scattering in Si CCDs for dark matter searches	*EI7*	*R Smida*	15:40 - 16:00

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