Nuclear Recoil in CCDs

CIPANP - 2025
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for the DAMIC-M collaboration

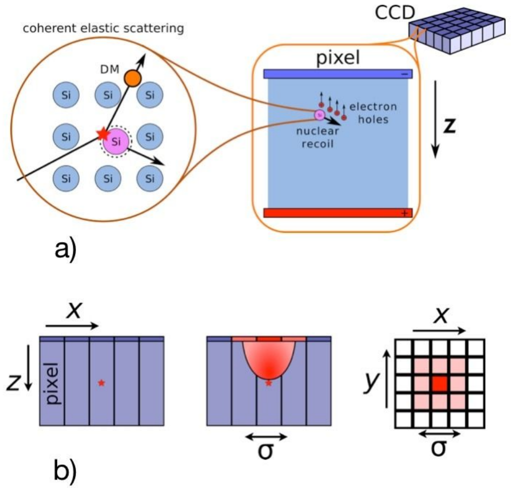
The National Science Foundation

Overview

- Introduction to CCDs
- Nuclear recoil ionization efficiency measurement
- Nuclear recoil identification experiment
- Exploration

Scientific Charge-Coupled Devices (CCDs)

- A CCD is a silicon substrate detector that can detect charge excitations in the substrate due to a energy deposition.
- Skipper CCDs implements multiple Non-Destructive Charge Measurements (NDCMs or skips) leading to single electron resolution
- The pixel readout noise decreases by the square root of the number of NDCMs



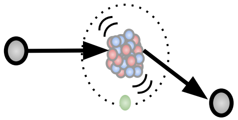
See plenary talk by P.Privitera

Nuclear Recoils in CCDs

Neutral Particle

Silicon CCDs

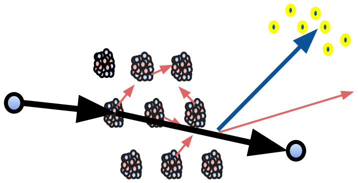
Ionization Efficiency



Phys. Rev. D 94, 082007 (2016)

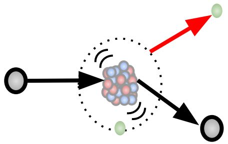
[J. Cuevas-Zepeda et. al., 2025, In preparation]

Defects

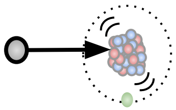


Phys. Rev. D **110**, 043008 (2024)

Migdal Effect

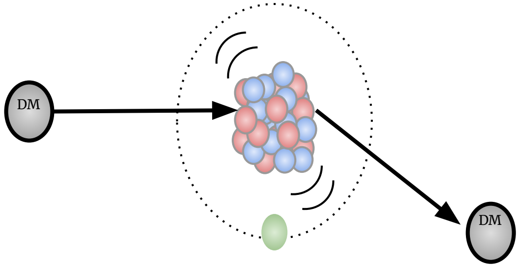


Neutron Capture



etc

Nuclear Recoil Ionization Efficiency

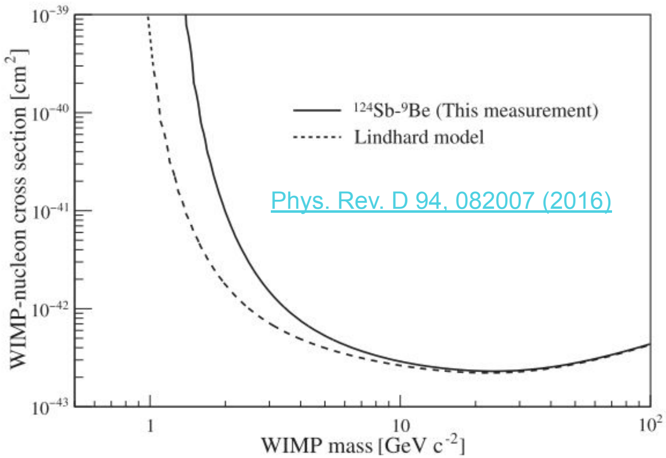


- ➔ Elastic scattering of neutral particles from silicon nuclei, after a certain threshold energy, produces ionization electrons.

- ➔ Relationship between nuclear recoil energy and energy of ionization is referred to as **ionization efficiency**

- ➔ Theoretical models (Lindhard etc.,) fail at energies < 20 keV_{nr}

- ➔ Previous measurement with a conventional CCD was performed by Chavarria et al.(2016), with a threshold of 60 eV_{ee}



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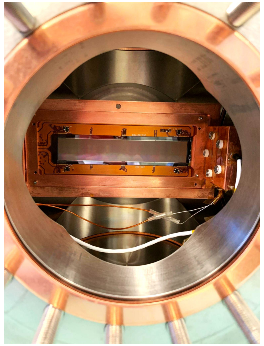
Nuclear Recoil Ionization Efficiency Measurement

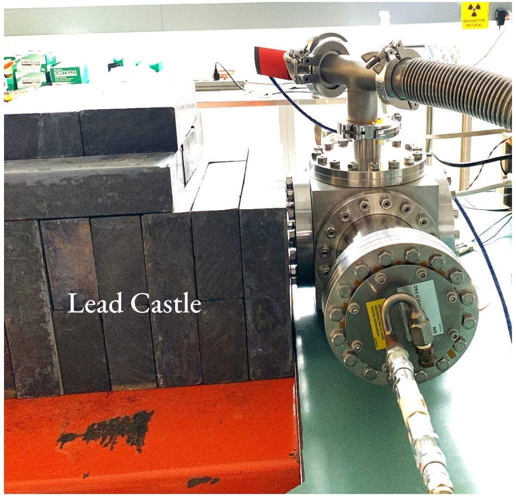


- 1k x 6k skipper CCD

Beryllium Oxide holder

Activated ^{124}Sb Pellets

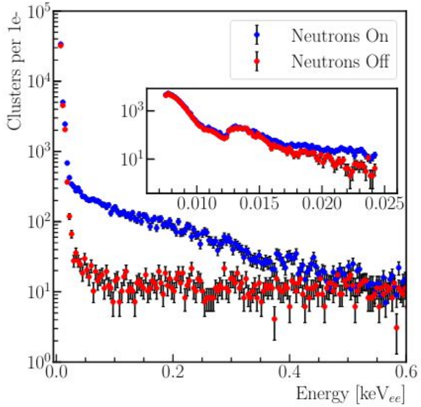
- ❖ A ^{124}Sb-^{9}Be photoneutron source was used to produce mono-energetic neutrons (~23 keV)
- ❖ Antimony (^{124}Sb) pellets were activated (~5.4 mCi) to produce 1.69MeV gammas (47%)
- ❖ The ^{124}Sb source was placed inside a BeO holder that will emit neutrons
- ❖ $^{9}Be + \gamma \rightarrow {}^{8}Be + n$ (~23 keV)

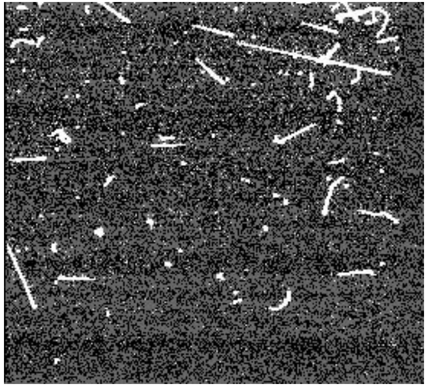


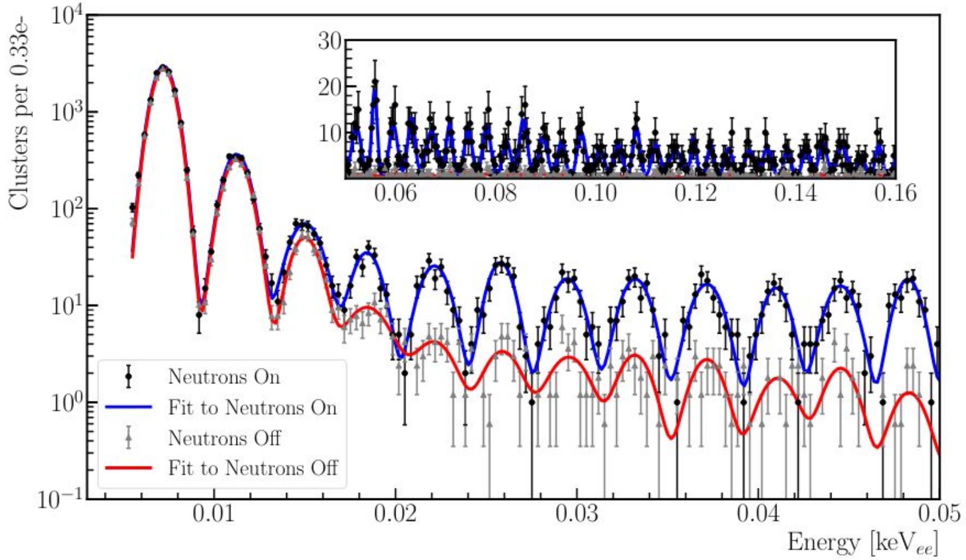
- ★ The source was placed inside a lead castle to shield the CCD from gammas.
- ★ The BeO holder was interchanged with an Aluminum holder to collect the gamma background data without neutrons
- ★ Neutron flux around the setup was measured using a ^{3}He counter.

Data

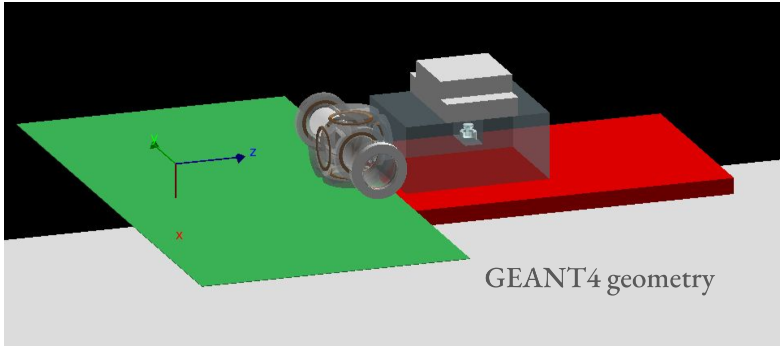
- 1600 NDCMs
- 4x4 Binning
- Image size : 250 rows, 275 columns
- Resolution : ~0.15 e-
- ^{124}Sb in BeO (neutrons + gammas) : exposure = 35.84 days
- ^{124}Sb in Al (only gammas) : exposure = 13.10 days
- Ambient background with no ^{124}Sb source was also collected



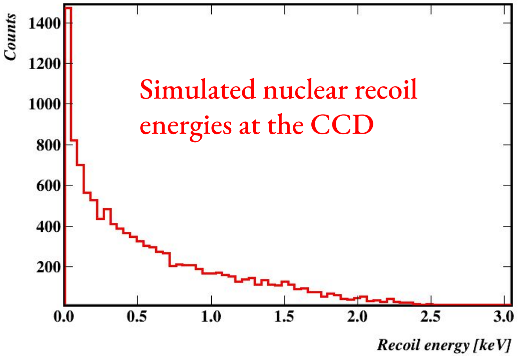


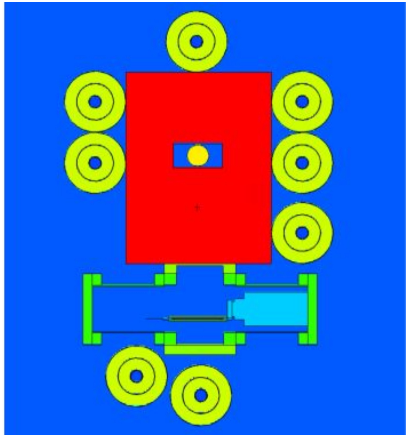


Simulations

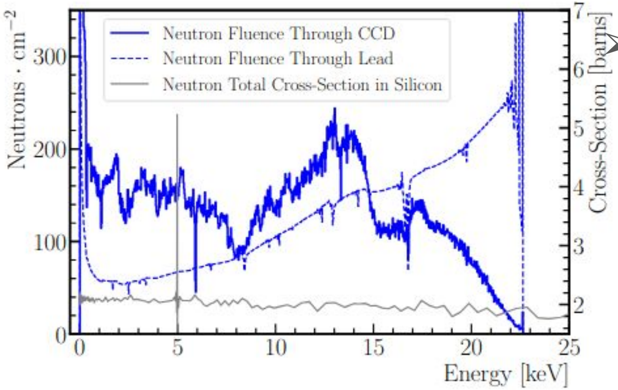


GEANT4 geometry





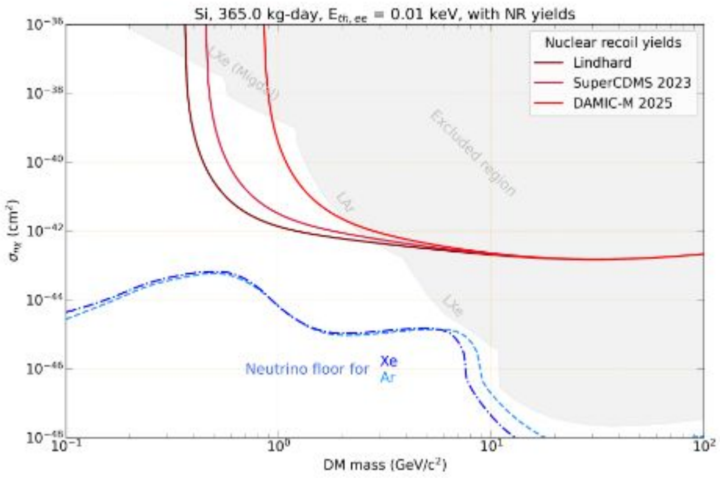
MCNP geometry

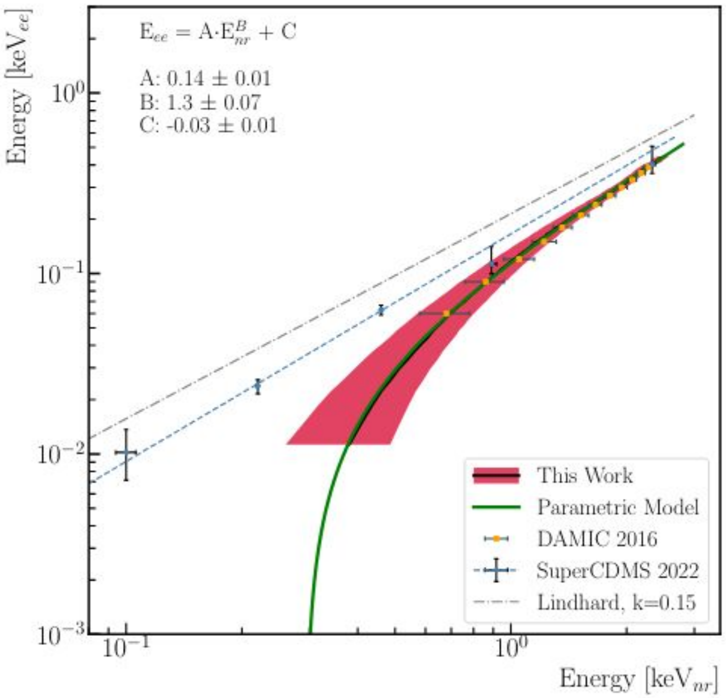


- Nuclear recoil energies at the CCD are simulated with the complete geometry using MCNP and GEANT4 independently
- Neutron flux around the setup was measured using a ^{3}He counter and verified by MCNP simulations

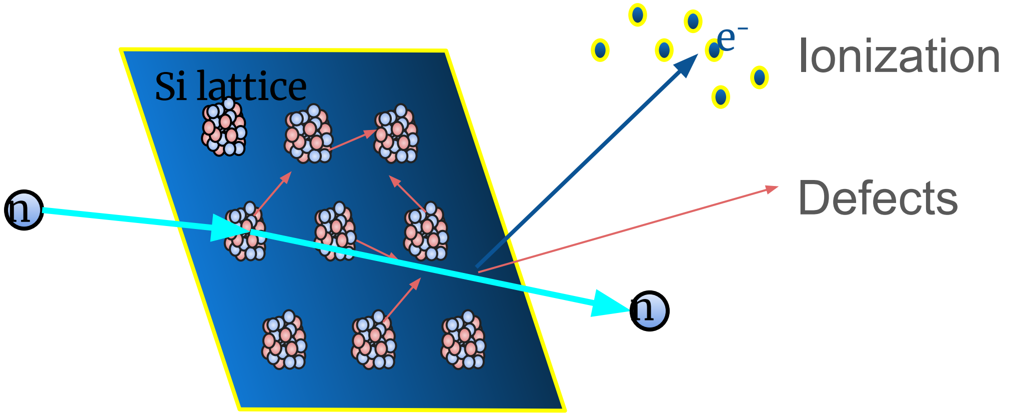
Results

- We use a data-driven iterative procedure to map the subtracted ionization spectrum to the simulated recoil energies.
- Model Independent MCMC was used to independently verify the ionization efficiency.





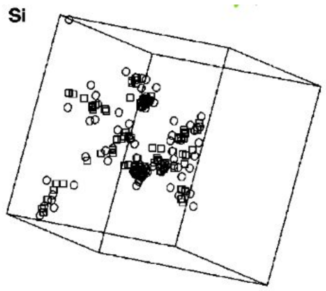
Nuclear Recoil Identification



➔ Sometimes nuclear recoils result in **defects** in the crystal lattice.

➔ These defects generate a leakage current when the CCD is at high temperatures

➔ Identification of defects in correlation with location of nuclear recoil events can help uniquely identify nuclear recoils events.



Defects from 10 keV NR

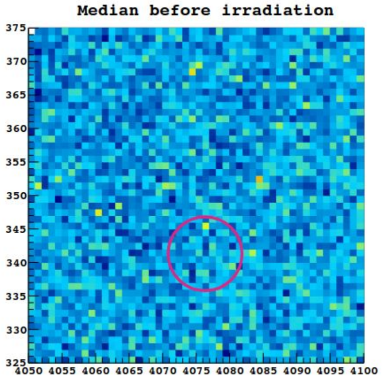
Measurement

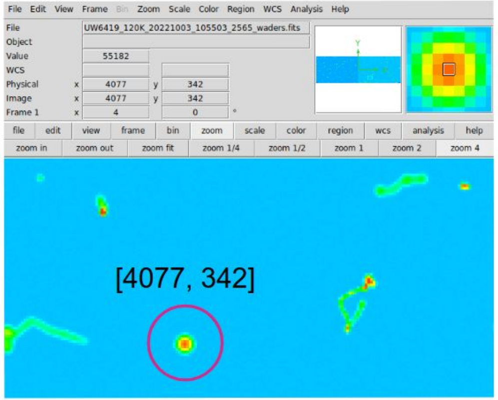
Experiment at UW:

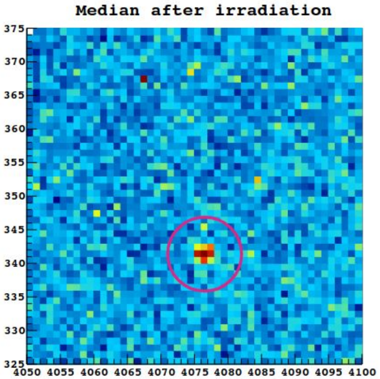
Series of warm images (223 K) to identify existing defects

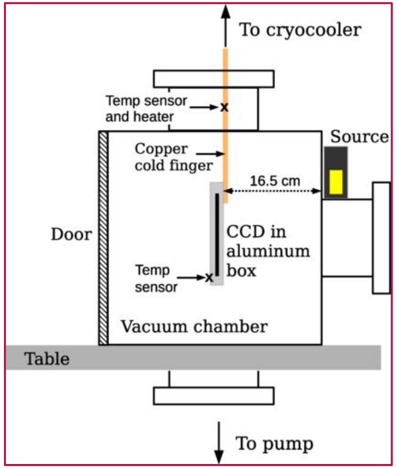
Cold images (147 K) during irradiation with a neutron source to identify primary ionization events

Series of warm images (223 K) to identify new defects

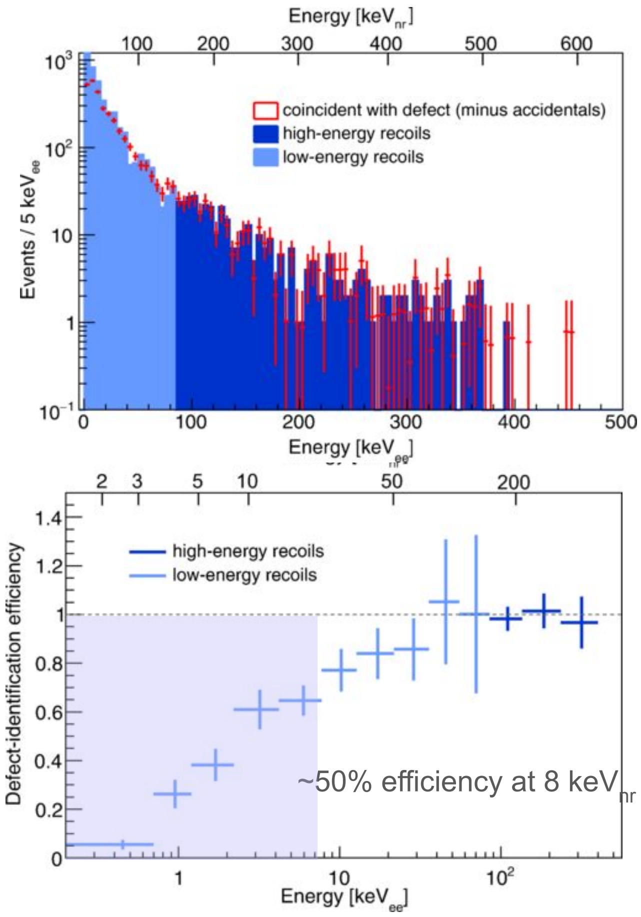








Setup diagram



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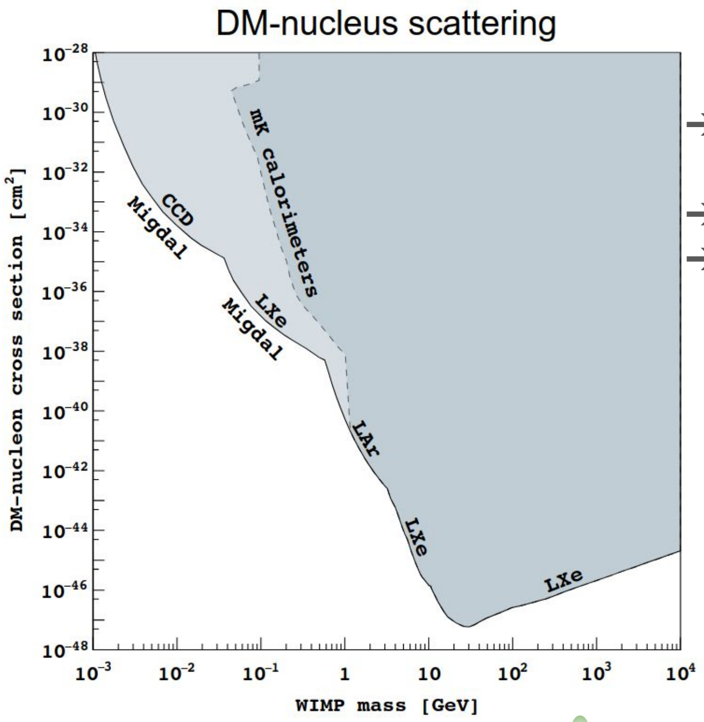
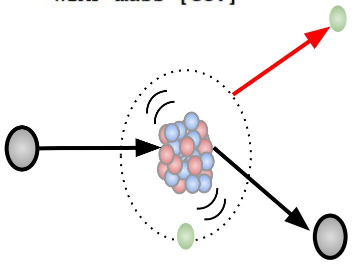
Results

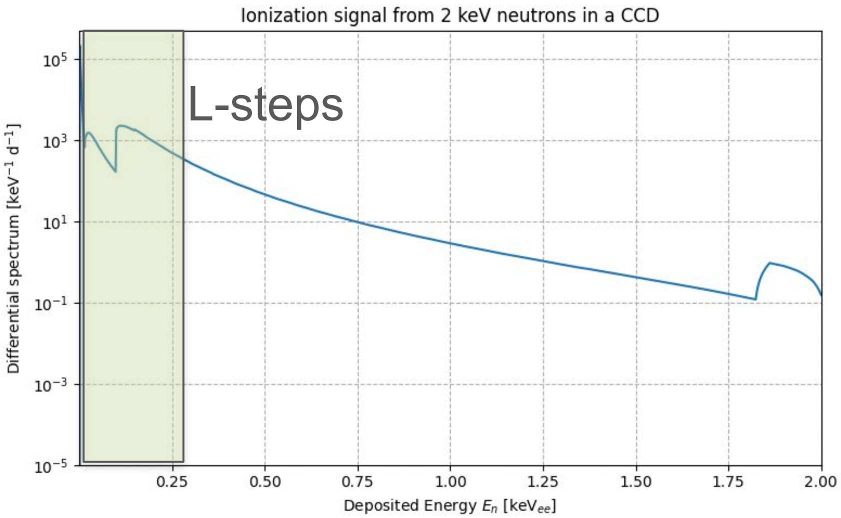
- We demonstrated that CCDs can distinguish between interactions with nuclei and electrons.
- We are exploring to extend sensitivity to sub-keV energies by optical stimulation
- This will allow DAMIC-M to perform ER and NR dark-matter searches independently, for significantly increased sensitivity and discovery potential.

Migdal Effect



- ➔ Potential to measure migdal effect in CCDs, probing recoil energies < 0.3 keV_{nr} where the ionization efficiency goes to 0.
- ➔ Can look for L-step occurrence from migdal electrons
- ➔ Observation of the Migdal effect will allow us to re-interpret DAMIC-M results as the most stringent exclusion limits for DM-nucleus interactions for DM particles below 10s to 100 MeV





Status

- Nuclear recoil ionization efficiency of silicon CCD was measured down to 3 e^- ionization.
- Nuclear recoil events can be distinguished from electron recoil events via the observation of defects–with ~100% efficiency down to a few keV_{nr}.

Outlook

- Defect measurement can be made more efficient at lower energies by exploring IR irradiation as opposed to thermal cycling
- Potential to probe Migdal effect below 0.3 keV_{nr}.
- Potential to perform fano factor modelling using a neutron capture measurement setup.

Thank You

Questions?