SUPER CDMS
Cryogenic Dark Matter Search

IMPACT

TUNL
Triangle Universities Nuclear Laboratory

First 100 eV nuclear recoil ionization yield measurement in silicon

Valentina Novati on behalf of the SuperCDMS collaboration

IDM 2022
14th International Conference on Identification of Dark Matter
18-22 July 2022
Vienna, Austria

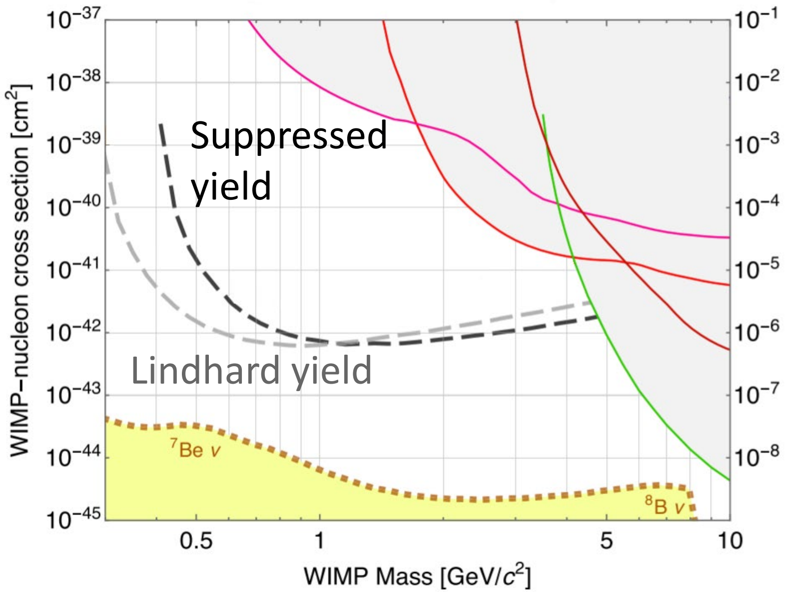
Northwestern

Nuclear recoil ionization

SuperCDMS Cryogenic Dark Matter Search

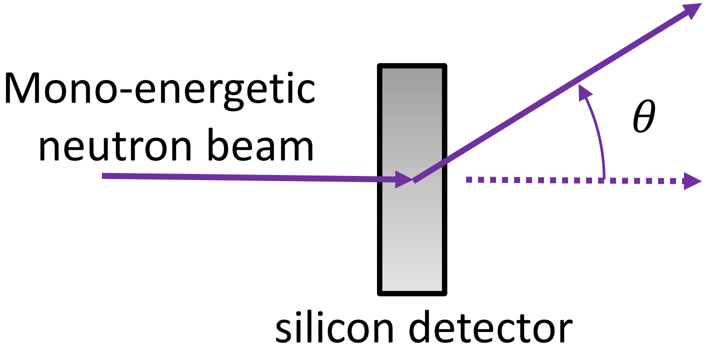
Detector response for ionization sensitive detectors is fundamental to assess sensitivity to nuclear recoils:

- weakly interacting massive particle (WIMP) scattering
- coherent elastic neutrino-nucleus scattering (CEvNS) interactions



R. Agnese et al., Phys. Rev. D 95, 082002 (2017)

Scattering measurement



The kinematics establishes neutron recoil energy (E_{rec}) as a function of the scattering angle (θ):

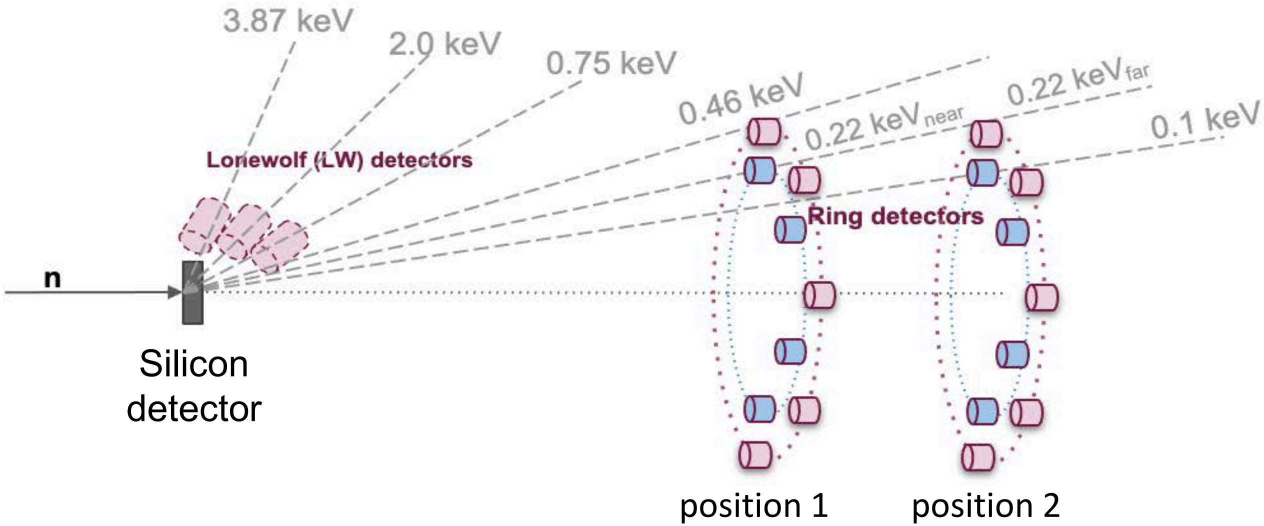
$$E_{rec} = 2E_n \frac{M_n^2}{(M_n + M_T)^2}\left(\frac{M_T}{M_n} + \sin^2\theta - \cos\theta\sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta}\right)$$

- E_n, neutron energy
- M_T and M_n, mass of the target and the neutron
- θ, scattering angle

Neutron tagging

Neutron tagging performed with EJ301/EJ309 liquid scintillators readout by PMTs
6 scattering angles measured:

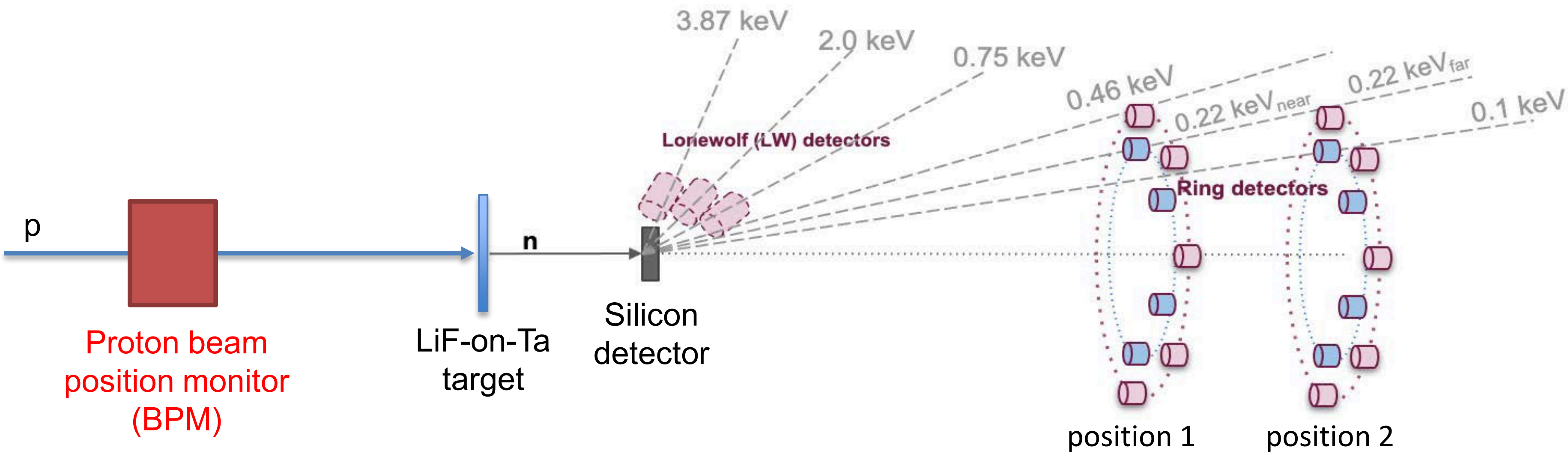
- 3 "Lonewolf" detectors testing previously measured energies: 0.75 keV, 2 keV, 3.87 keV
- a backing array, composed of two concentric rings, is set up at two different distances to test a total of 3 energies: 100 eV, 220 eV, 460 eV



Neutron production

Mono-energetic neutron beam from Triangle Universities Nuclear Laboratory - TUNL (North Carolina, US)

- 1.889 MeV Proton production with a pulsed Tandem beam (2.5 MHz)
- 100-nm thick LiF-on-Ta target → ~56 keV low energy neutron beam
- Aim for ^{28}Si elastic scattering resonance at 55.7 keV



Silicon detector

R. Ren *et al.* Phys. Rev. D 104, 032010, 2021

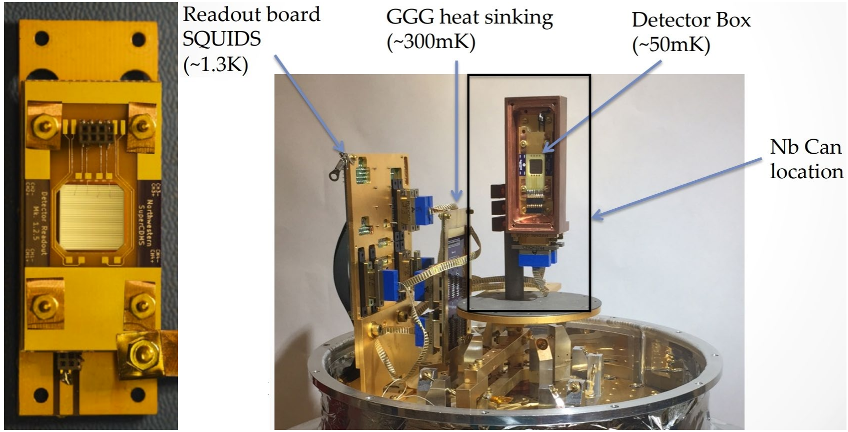
charge signals are amplified by the Neganov-Trofimov-Luke (NTL) effect

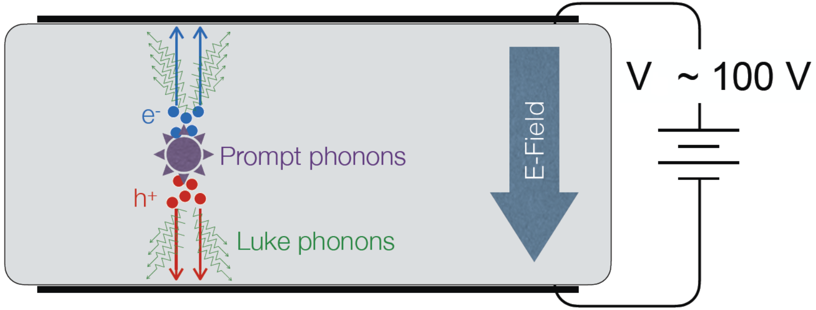
SuperCDMS HVeV detector:
- operated at 52 mK in an Adiabatic Demagnetization Refrigerator (ADR)
- $(1 \times 1 \times 0.4)\ \mathrm{cm}^3$ 0.93 g silicon crystal
- Transition-Edge Sensor (TES) readout

$$E_{ph} = E_{rec}\left(1 + \frac{\mathbf{Y} \cdot e \cdot V}{\varepsilon}\right)$$

Energy to produce a charge

Ionization yield





0V mode V = 0:
Total phonon energy = Recoil energy
HV mode V ≠ 0:
Total phonon energy = Recoil energy + NTL energy

B. S. Neganov and V. N. Trofimov, Otkryt. Izobret., 146, 215 (1985)
P. N. Luke, J. Applied Phys. 64,6858 (1988)

Silicon detector

R. Ren *et al.* Phys. Rev. D 104, 032010, 2021

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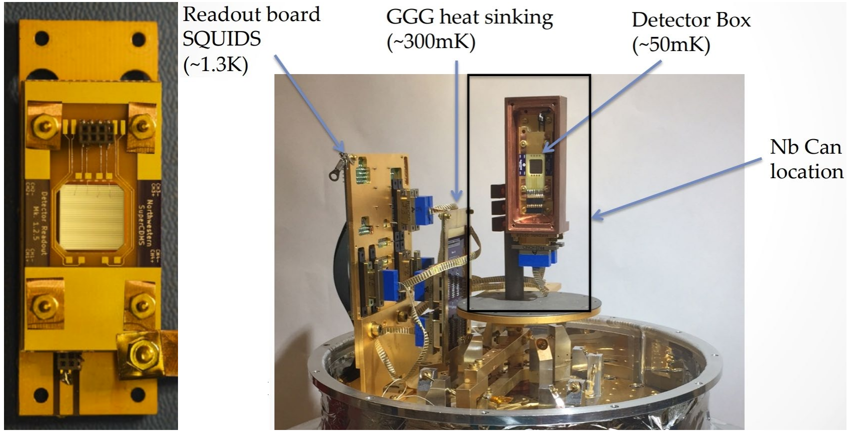
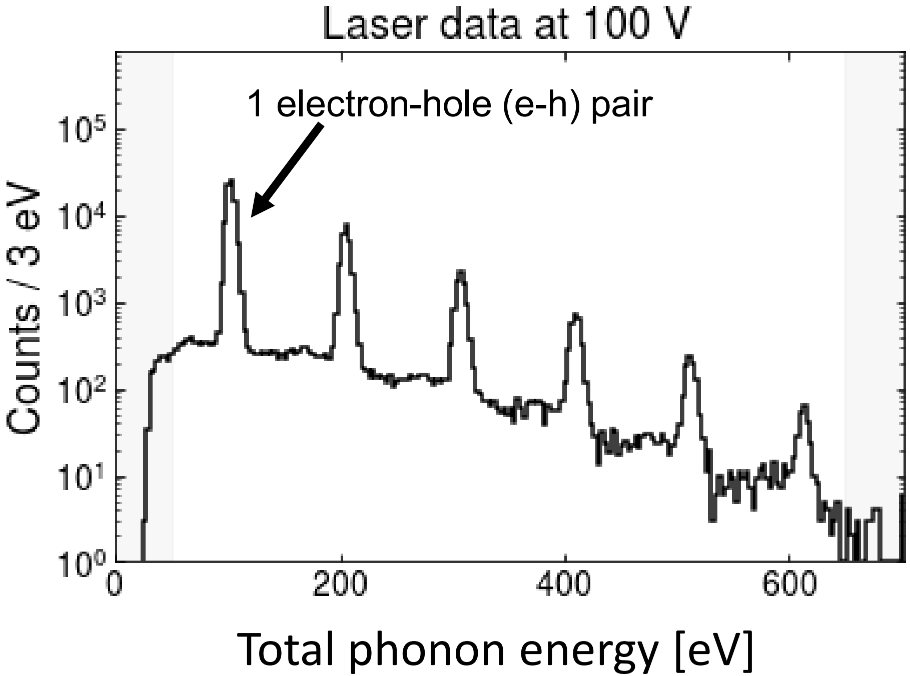


Single electron-hole-pair sensitivity



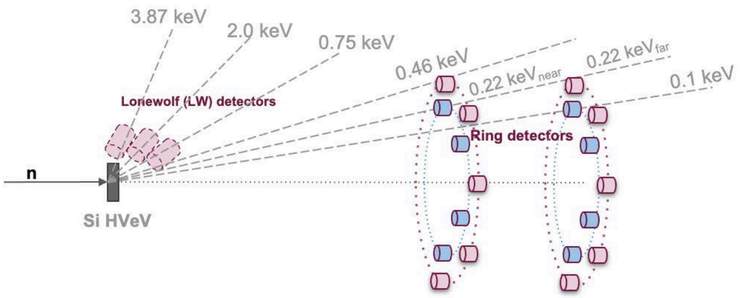
D. W. Amaral *et al.* Phys. Rev. D 102, 091101(R), 2020

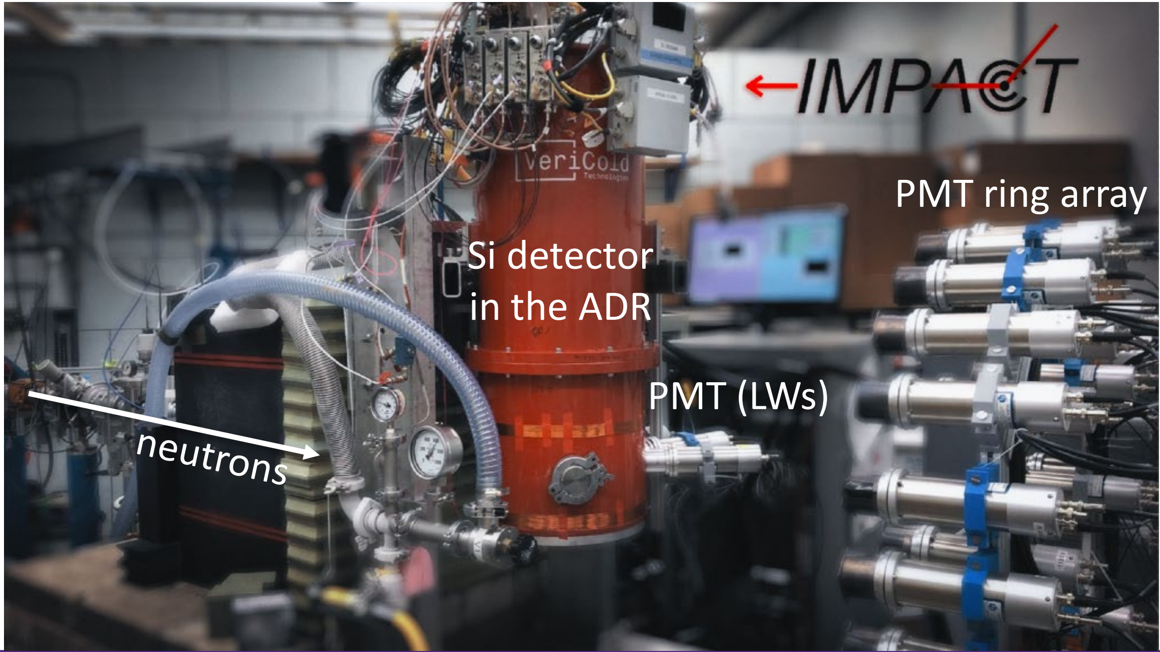
Acquired data

Data taking 2019:

- 3 weeks of beam data
- 50% duty cycle (ADR cycle)
- Two days at 0 V (Validation data)
- Calibration with 635-nm laser, ^{55}Fe and ^{57}Co source
- Beam data taken at 20, 100, and 180 V for exploring yield dependence on the electric field

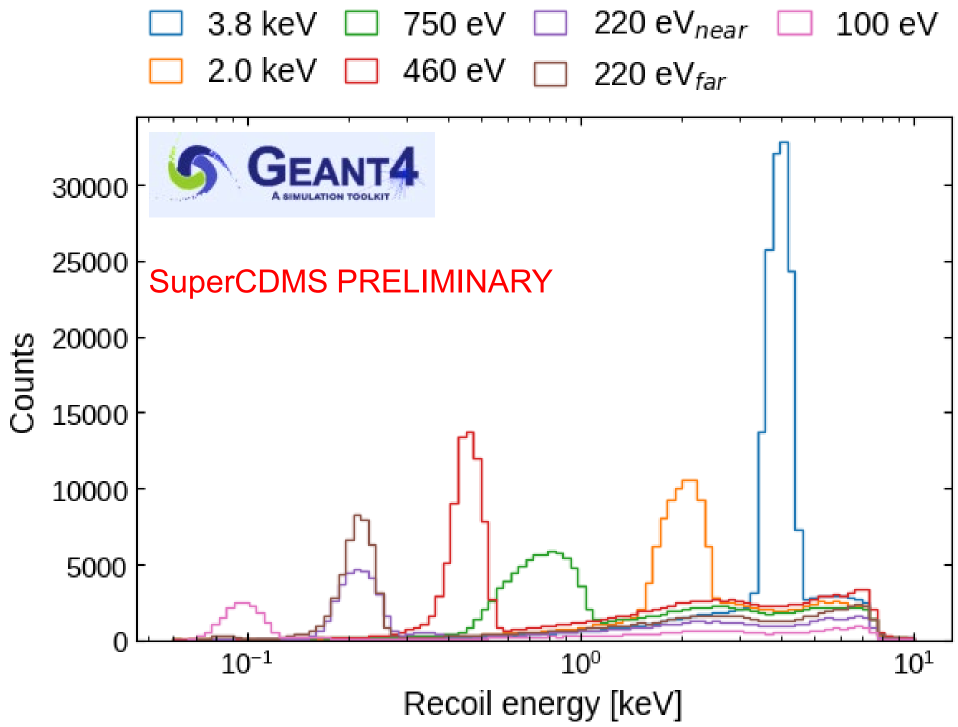
Here: Present 0 V cross-check & 100 V nuclear recoil yield measurement



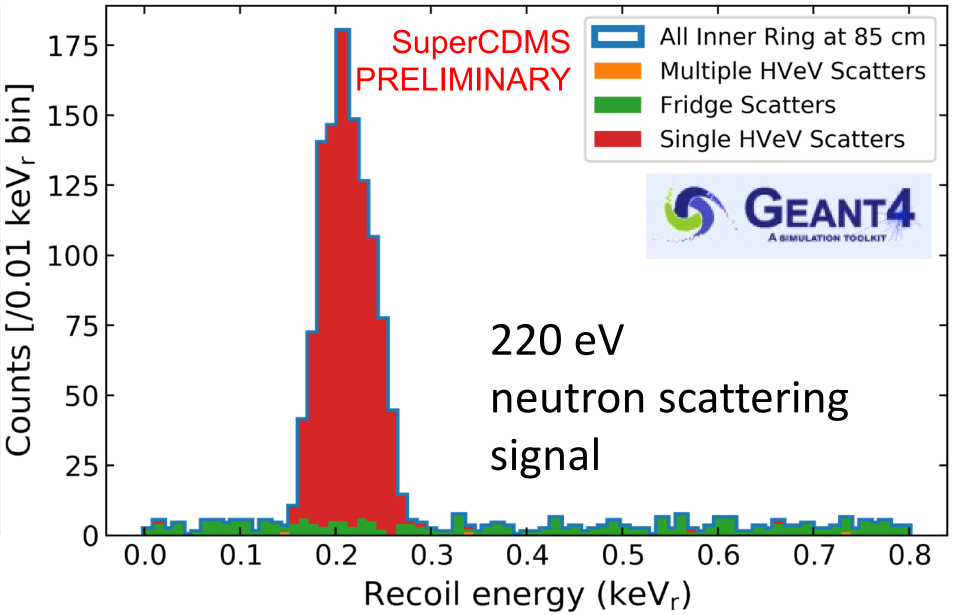


Geant4 signal simulations

Kinematic neutron-scattering energy

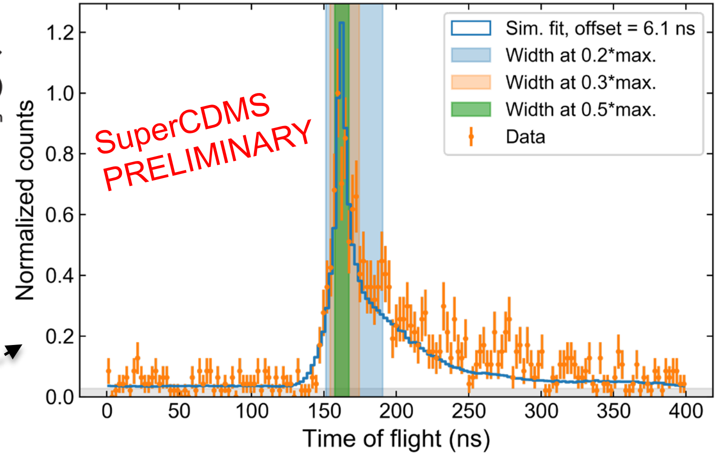


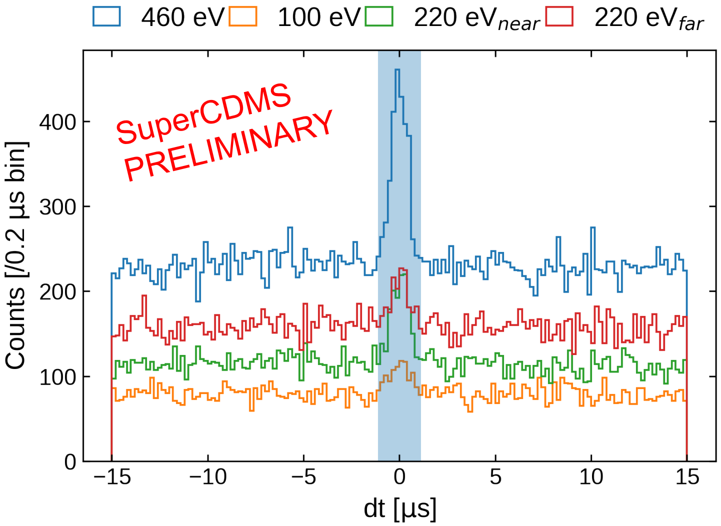
Small silicon-detectors size suppresses multiple scatters



Data selection

silicon detector + liquid scintillator with PMT
data quality cuts
+
Time of flight between TUNL Beam Position Monitor and EJ301/EJ309 liquid scintillator with PMT
+
Time difference between Si HVeV detector and EJ301/EJ309 liquid scintillator with PMT





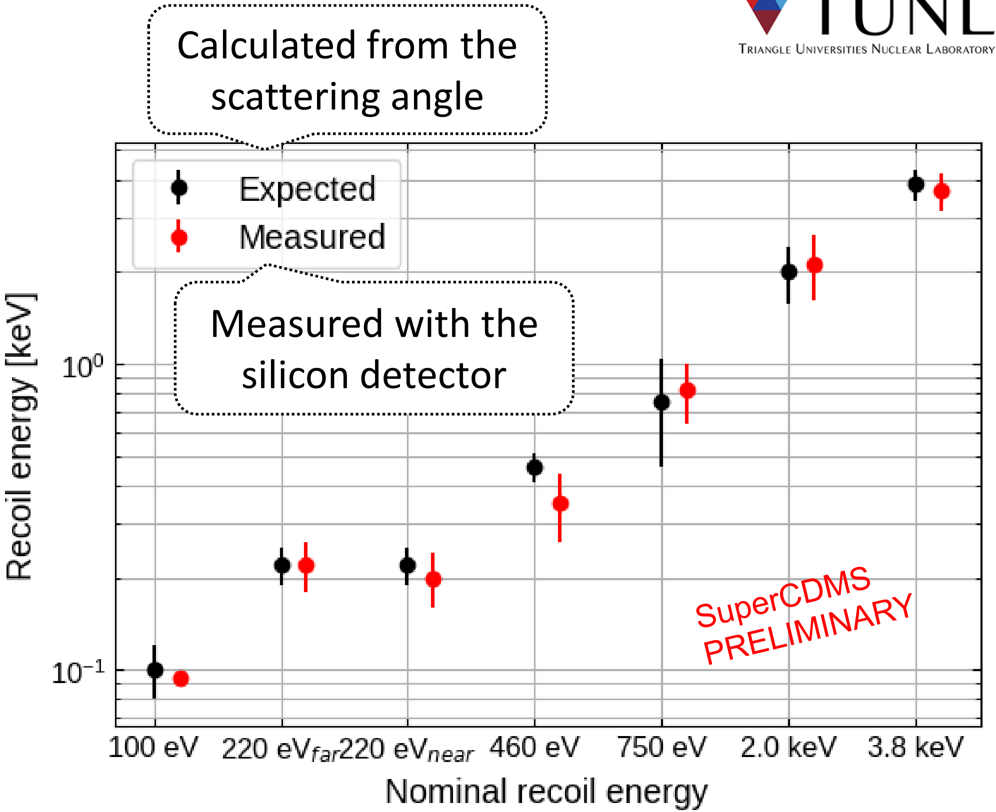
Strong background suppression
Expect a very clean signal

0V data cross check

Before measuring the ionization yield with the HV data, two days of 0V data were used to check:

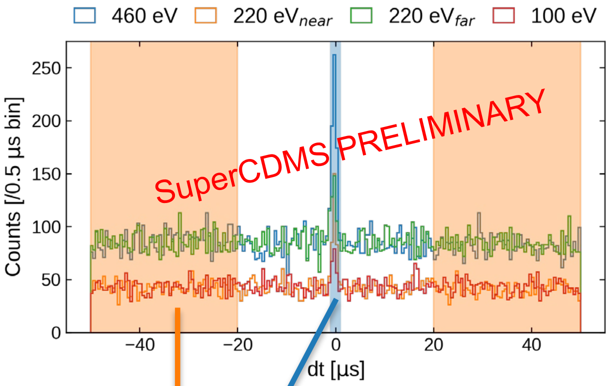
- the beam conditions
- the detector calibration
- the geometry reconstruction

The 0 V coincidence analysis does not provide new information on the ionization yield.

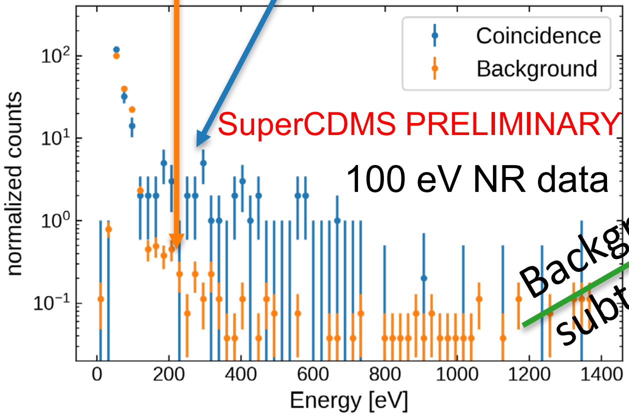


Background subtraction

Time difference between
Si HVeV detector and
PMT backing array

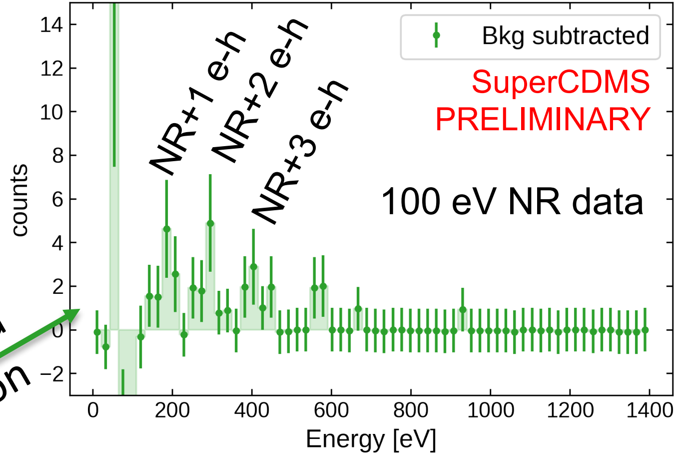


neutron-scatter signal
off-beam Bkg
(estimated from dt sidebands)



Background subtraction

100 V Data
Observe quantization!

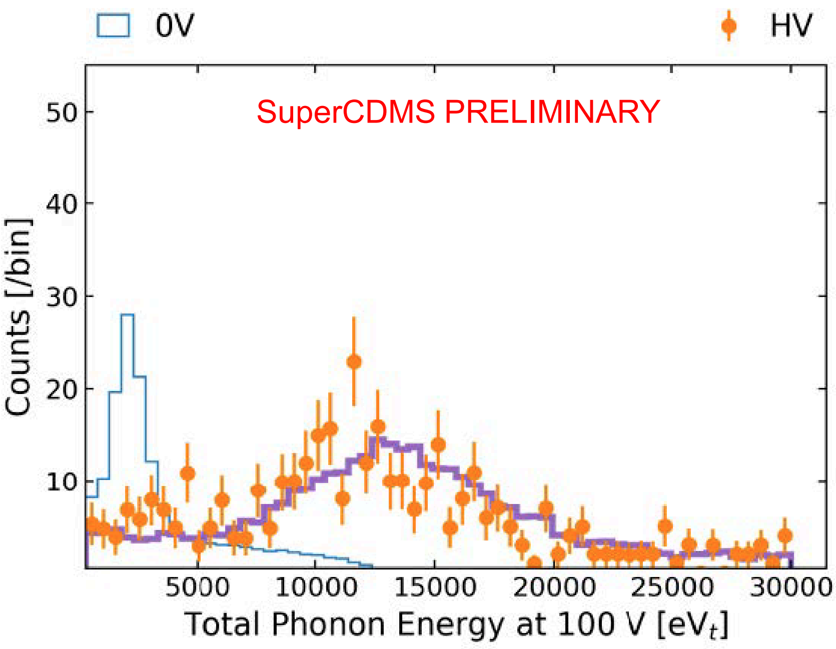


Analysis scheme - Yield measurement

1 - Measurement: Total phonon energy spectrum for events coincident between HVeV and PMT

$$E_{ph} = E_{rec}\left(1 + \frac{\mathbf{Y} \cdot e \cdot V}{\varepsilon}\right)$$

2 - Simulation:
Geant4 simulation of recoil energy spectrum for events coincident between HVeV and PMT



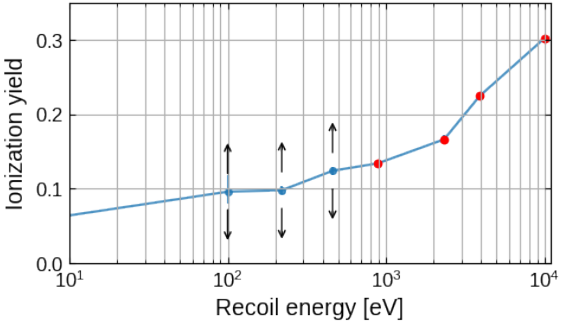
3 - Fit:
Determine Y by fitting the E_{rec} simulation to the HV measurement of E_{ph}

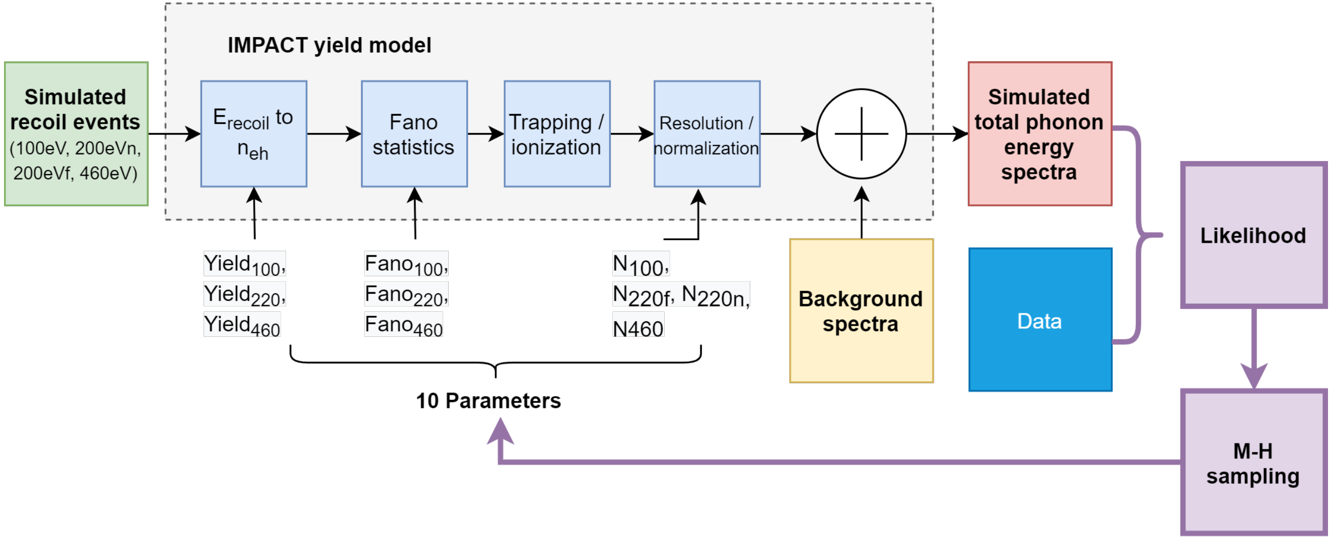
Bayesian Analysis Toolkit

4 - Systematic Uncertainty:
- Coincidence timing window
- Time of flight window
- Neutron beam energy
- Detector energy calibration
- Impact ionization and charge trapping
- Fano factor

Nuclear recoil ionization – 1st iteration

Ionization yield analysis for ring detector with the following assumptions:
- yield @ 0 eV = 0
- yield @ 10 keV and LWs = $Y_{Chavarria}$

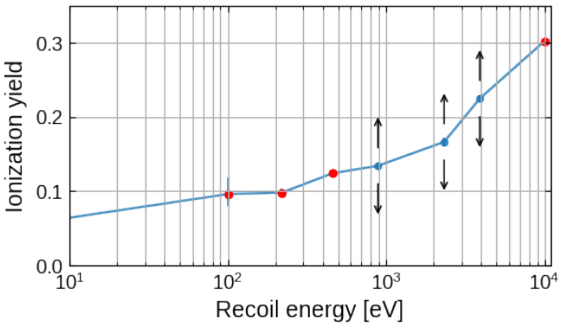


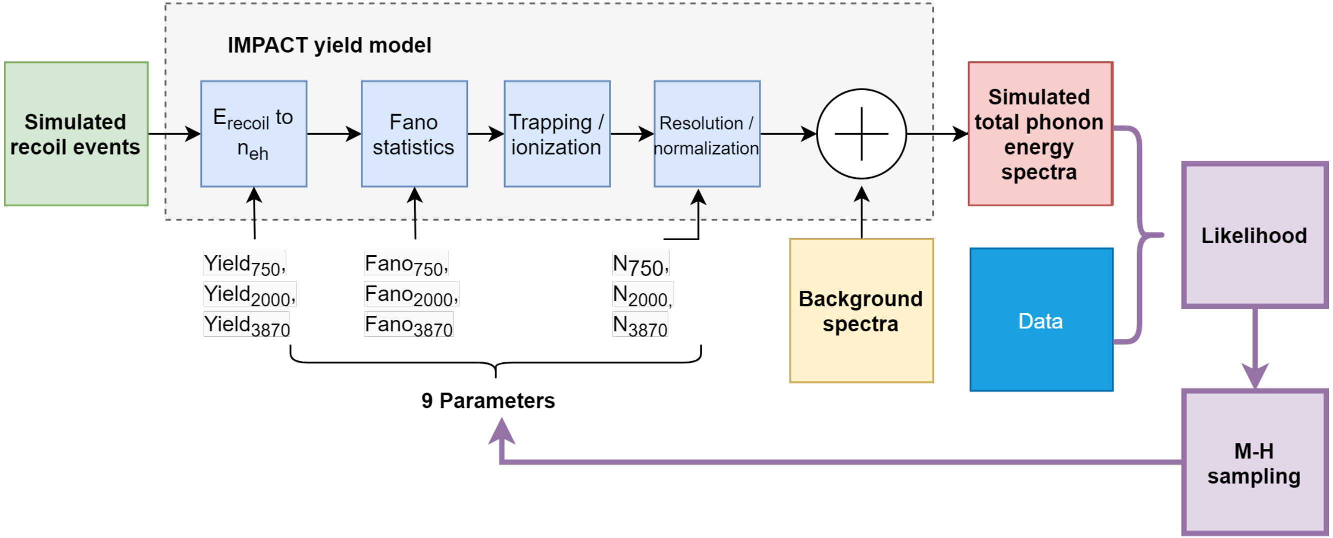


Nuclear recoil ionization – 2nd iteration

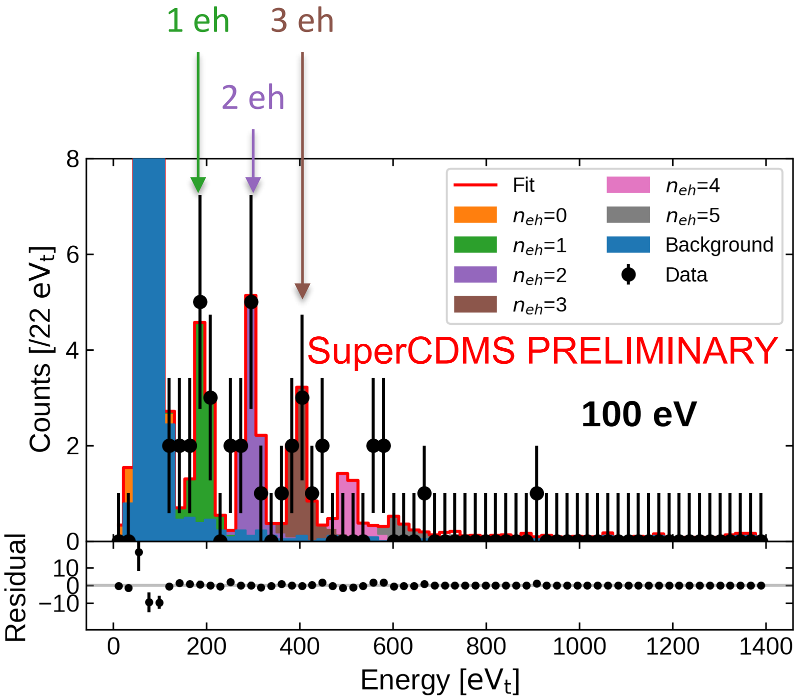
Ionization yield analysis for ring array with the following assumptions:

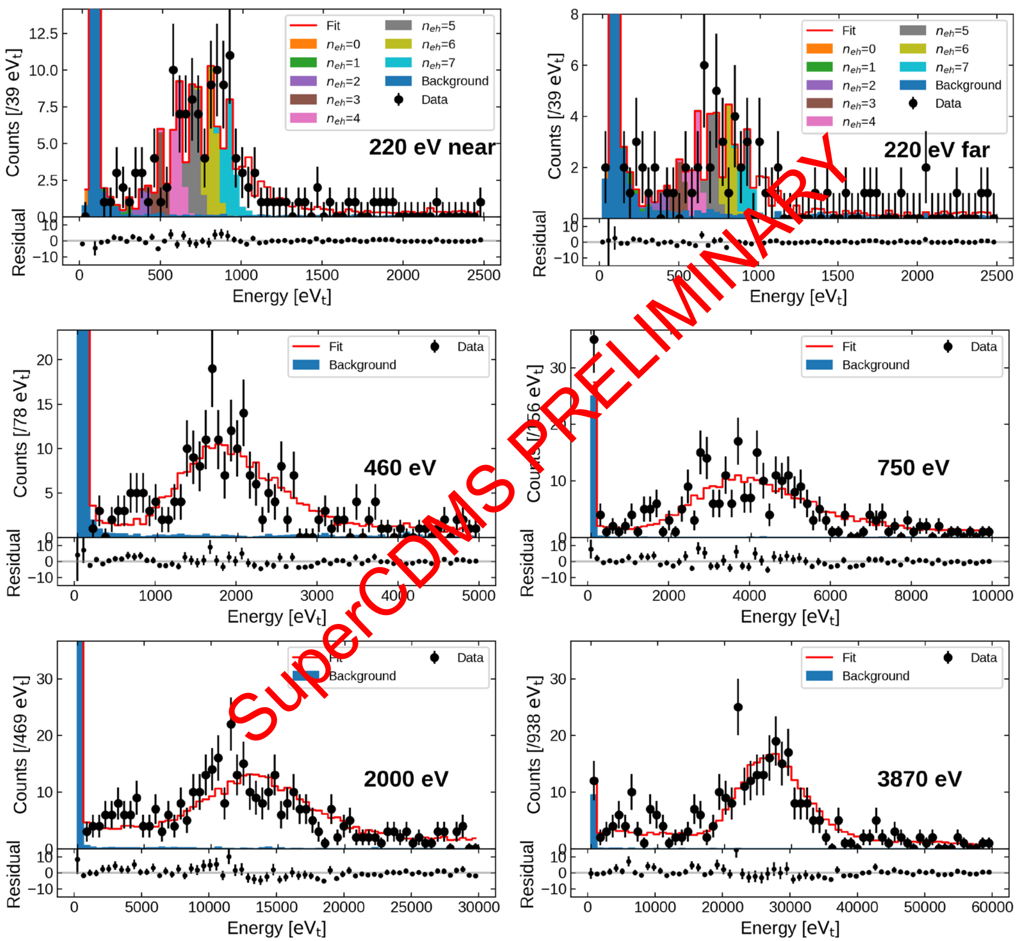
- yield @ 0 eV = 0
- yield @ (100, 220, 460) eV as fit in the 1st iteration
- yield @ 10 keV = $Y_{Chavarria}$





Result: 3rd fit iteration

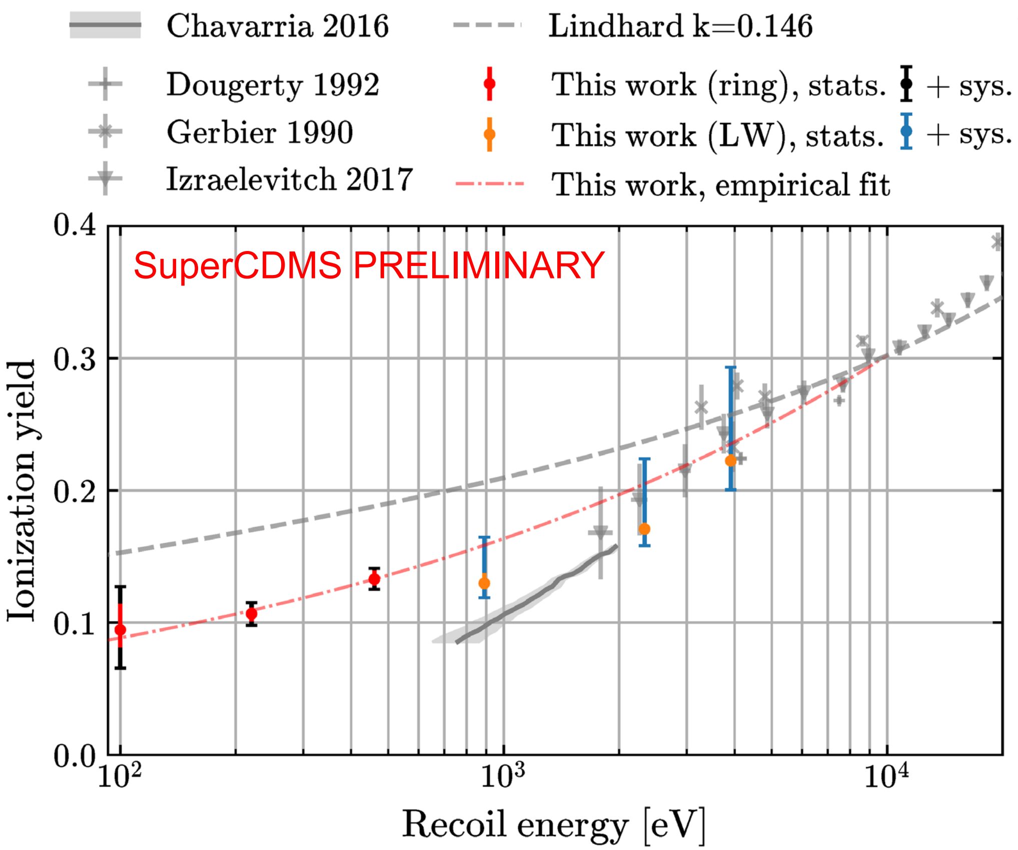




Nuclear recoil ionization

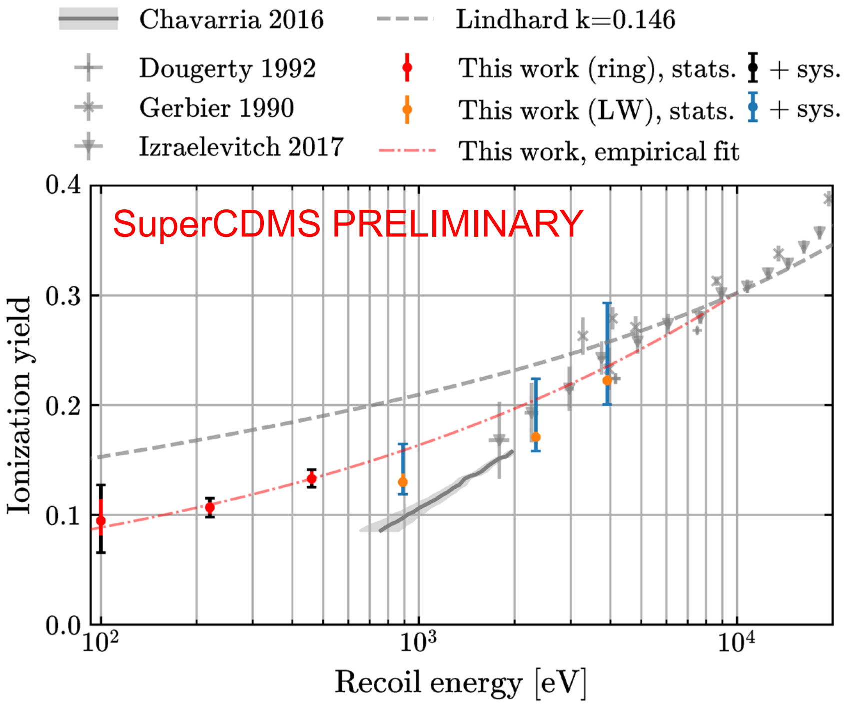
First ionization yield measurement in silicon down to 100 eV

- deviation from the Lindhard model
- no indication of an ionization production threshold down to 100 eV



Conclusions

- A silicon SuperCDMS HVeV detector was operated in a ~56 keV neutron beam at TUNL (North Carolina, US)
- The nuclear recoil ionization yield was measured in silicon at six different energies
- A nuclear recoil measurement in silicon down to 100 eV was performed for the first time

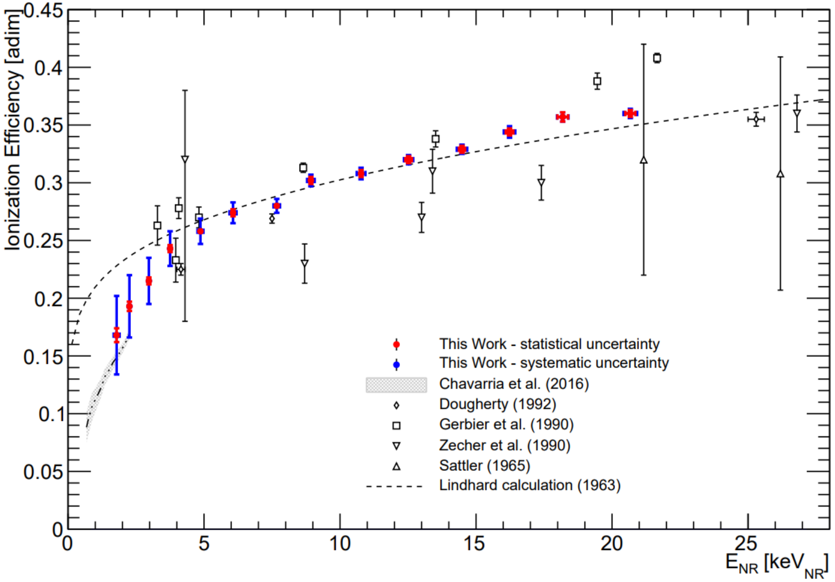


Extra…

Lindhard theory and previous measurements

In 1963, Lindhard et al. published a theoretical study on damage effects caused by particle radiations in matter, which includes the expected ionization yield for the nuclear recoil.

Measurements down to 3-4 keV_{NR} are compatible with Lindhard et al.'s study, but more recent measurements suggest a suppressed yield at low energies

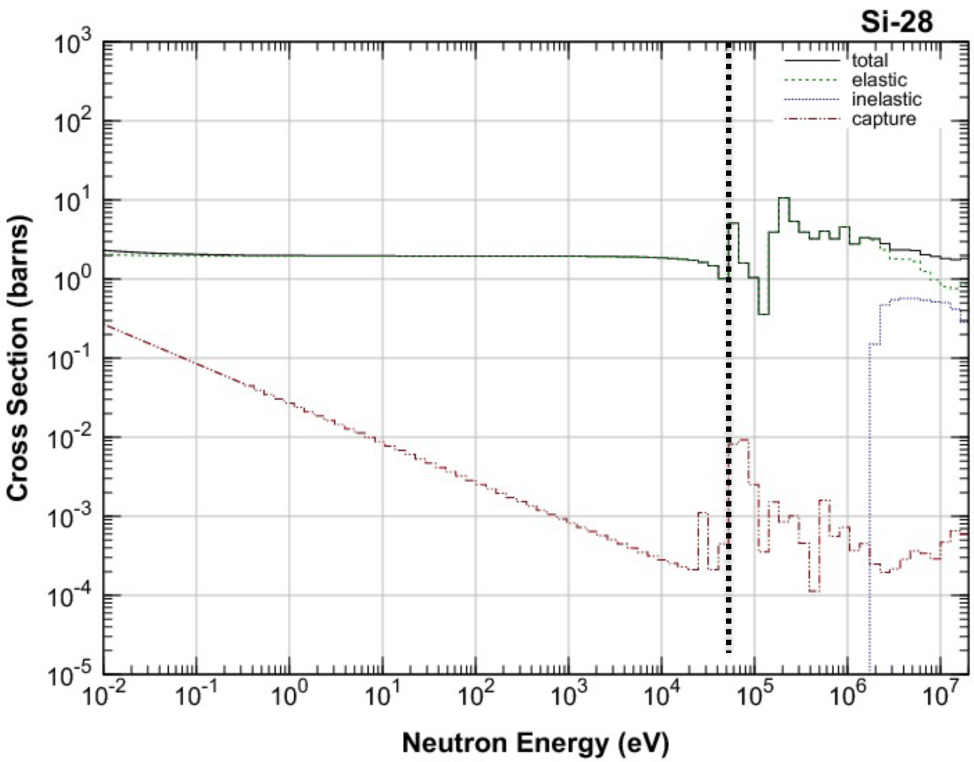


F. Izraelevitch, et al., J. Inst., 12, P06014 (2017)

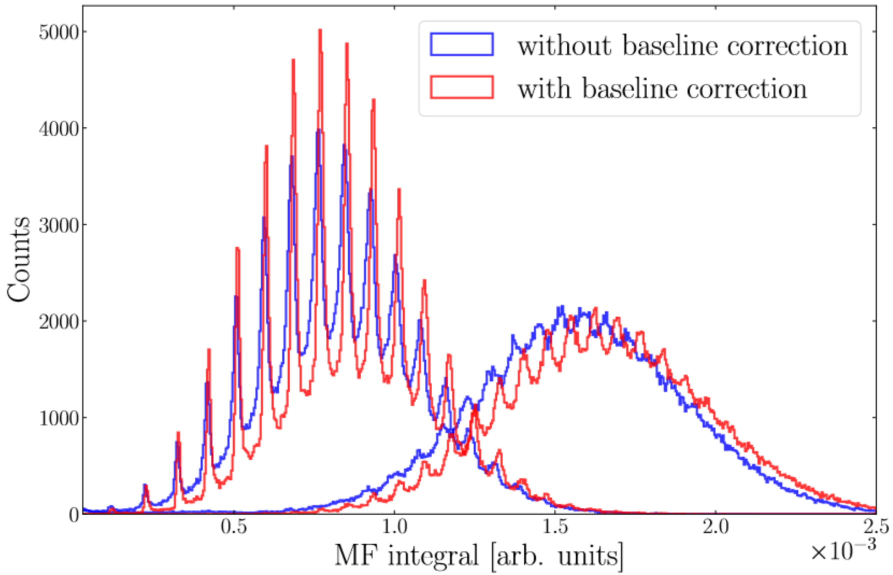
J.Lindhard, et al.,Mat. Fys. Medd.Dan. Vid. Sels.,33, 10(1963)

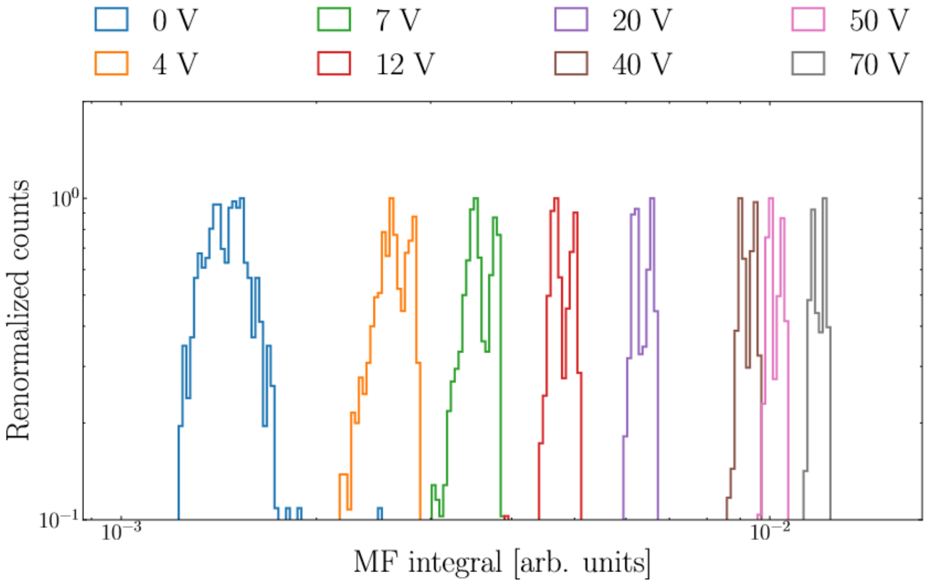
Neutron to silicon cross section

56 keV neutron energy



Calibration





R. Ren *et al.*, Phys. Rev. D 104, 032010, 2021

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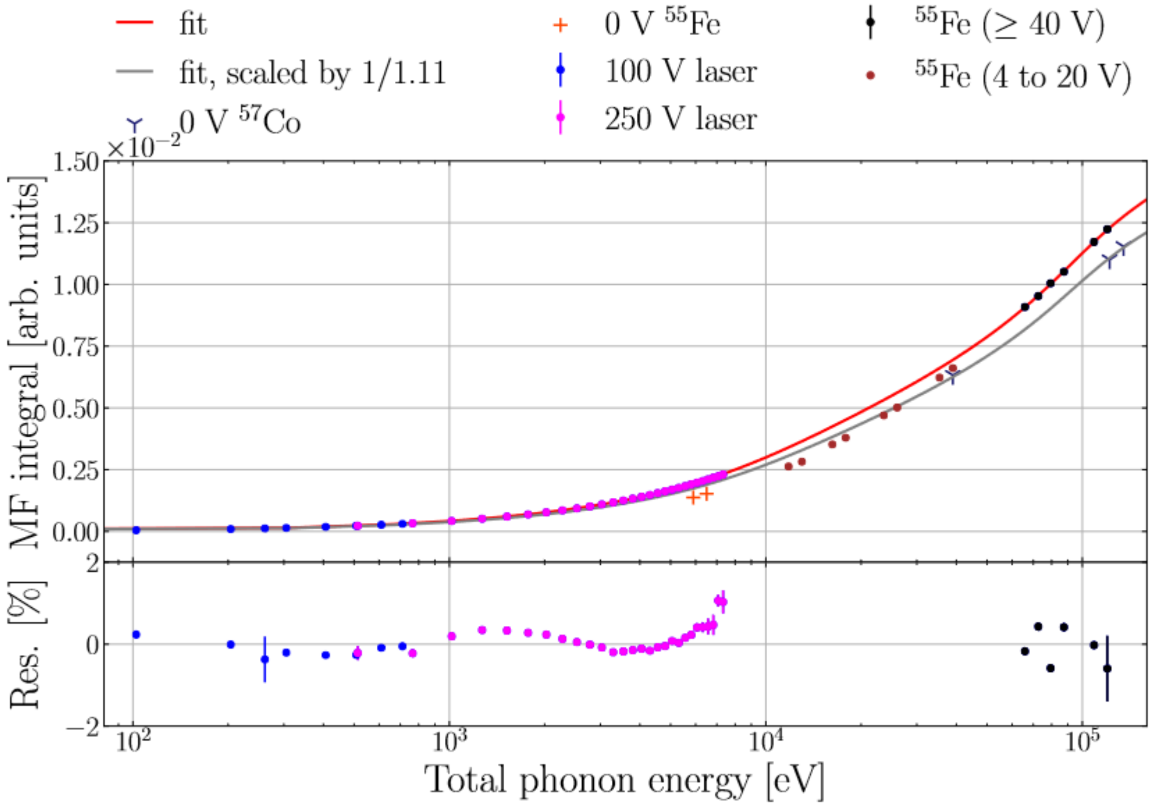

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Systematic uncertainties