Low-Threshold Phonon-Mediated Detectors with Background Discrimination

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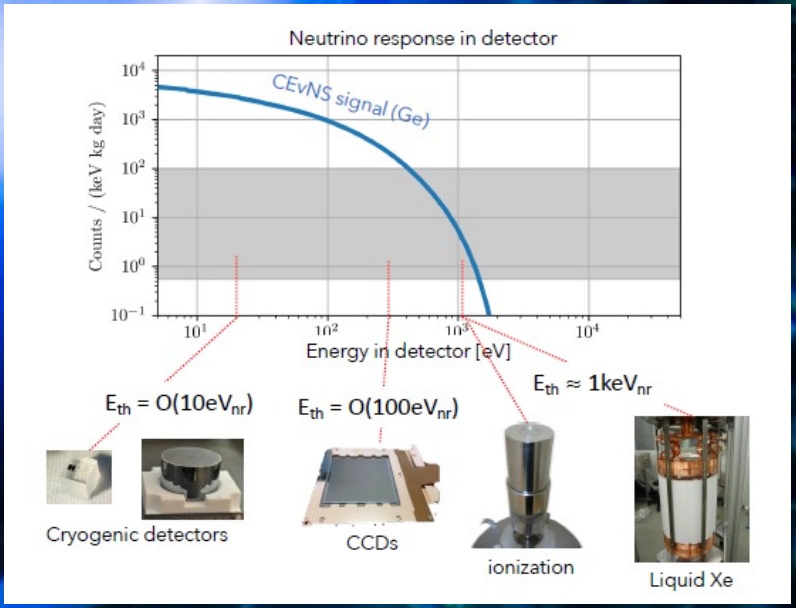
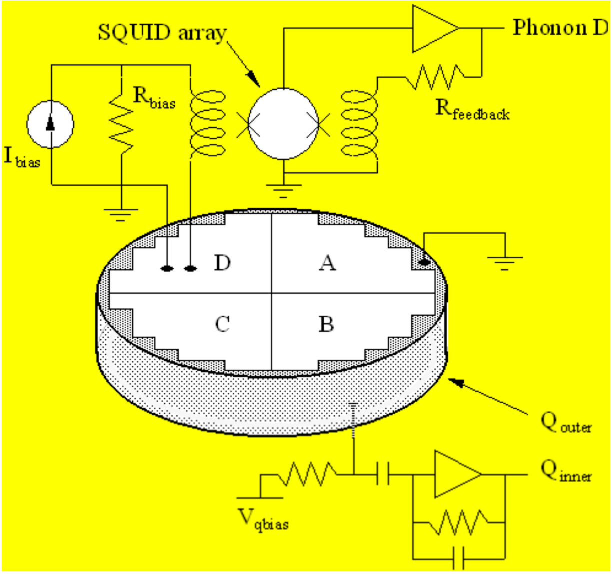
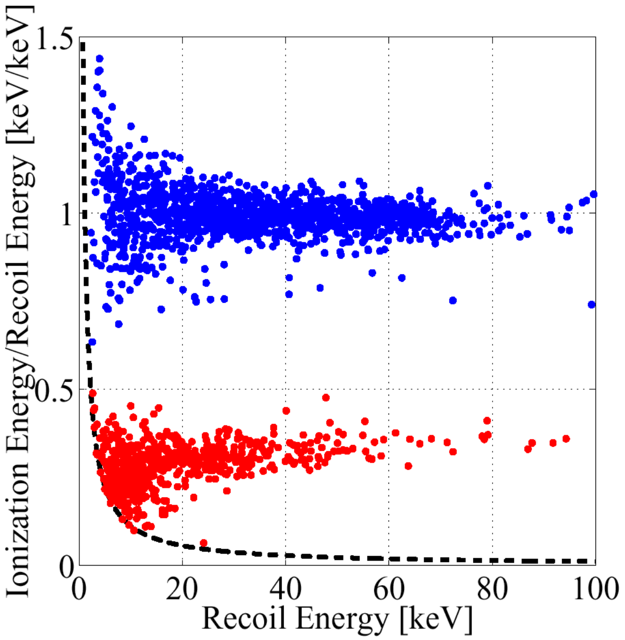
- Both low-mass dark matter and CEνNS searches require detectors with sufficiently low thresholds to detect the feeble expected signals.
- Phonon-mediated detectors are the technology of choice for searching for nuclear recoil events due to their low thresholds and lack of quenching.
- Event-by-event discrimination is highly desirable, similar to CDMS and Xenon experiments.
- We propose a new detector design that maintains both the low-threshold and low-background requirements.



CDMS early event-by-event background discrimination

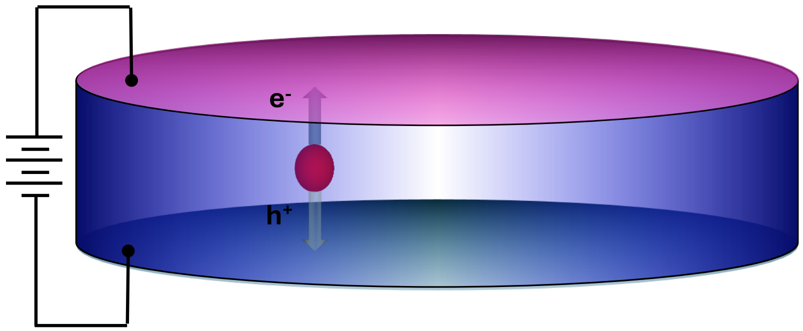
- Simultaneously measure ionization and phonon per each interaction in large Si or Ge (~ kg) crystals operating at T~20 mK.
- Superconducting Transition Edge Sensors (TES) cover one face.
- The other face covered by ionization electrodes: an inner electrode and a guard ring electrode.
- Use cold FET front-end to read charge and SQUIDs for phonon readout.
- Use ionization yield difference between electron recoil (ER) and nuclear recoil (NR) to discriminate WIMPS from background.
- Excellent discrimination for $E_r > 10$ keV . The threshold limited by ionization resolution.





Direct Ionization measurement in SC detectors

- Measure Ionization directly with a charge amplifier.
- Detectors operate at T< carrier freeze-out => No need for depletion
- Need Cold front end close to the detector : HEMT/FET.
- S/N degrades with the input capacitance.
- Limited by noise associated with high impedance readout:
  - FET or HEMT input noise.
  - Microphonics.
  - EM Pickups.
  - Ground loops…
- Best electronics RMS with CDMS detectors: $\boldsymbol{\sigma \sim 50\ \mathrm{eV}_{ee}}$



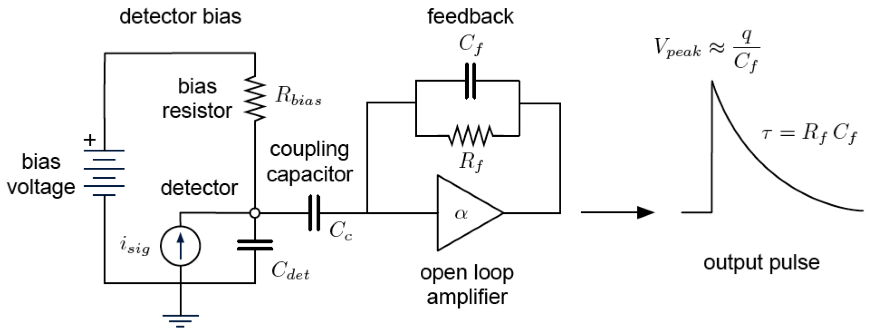


Figure 3.4: The basic charge amplifier topology.

From Arran Phipps thesis, UC Berkeley, Spring 2016

Neganov-Trofimov-Luke Effect:
Indirect Ionization measurement using phonons

Power=V.I or Energy=V.Q

- **Luke**-Neganov Gain

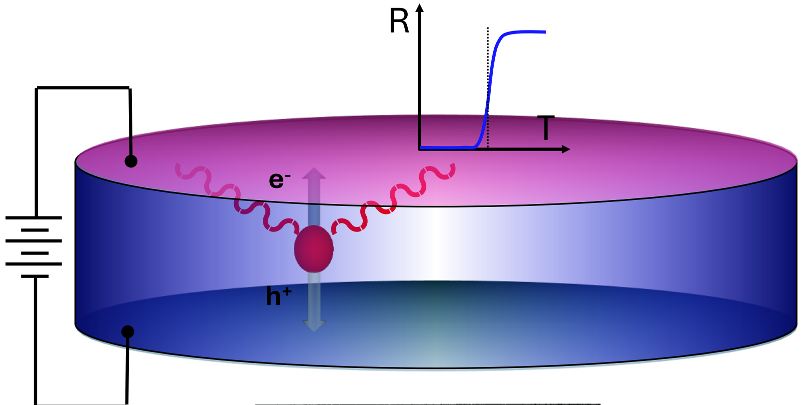
$$
\begin{aligned}
E_{tot} &= E_r + E_{luke} \\
&= E_r + n_{eh} e V_b \\
&= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)
\end{aligned}
$$

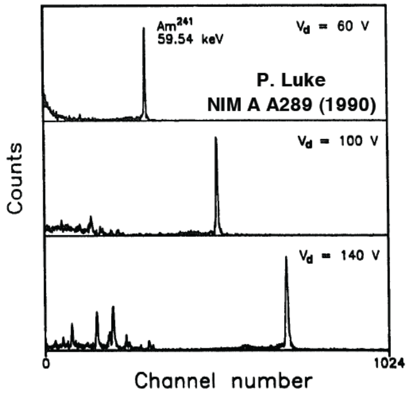
• Phonon noise doesn't scale with the ionization bias:

=> **S/N ⇧**

• In theory one can increase Bias to reach Poisson fluctuation limit!

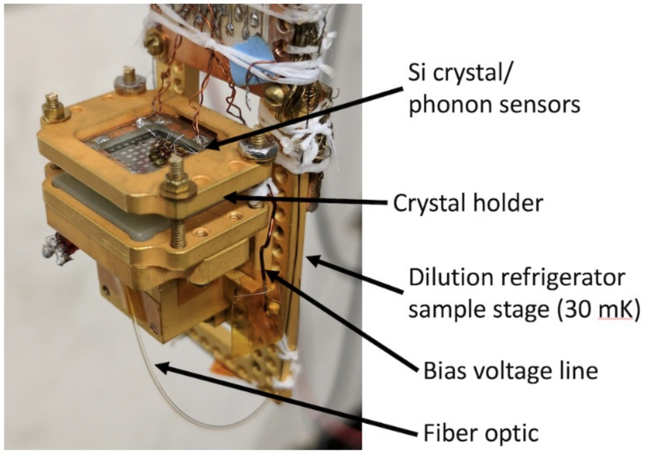
limitation: Current leakage





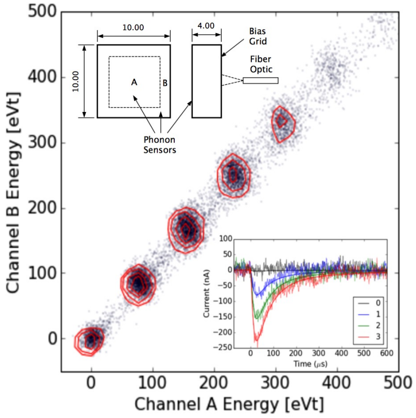
Luke et al., Nucl. Inst. Meth. Phys. Res.A 289, 406 (1990)

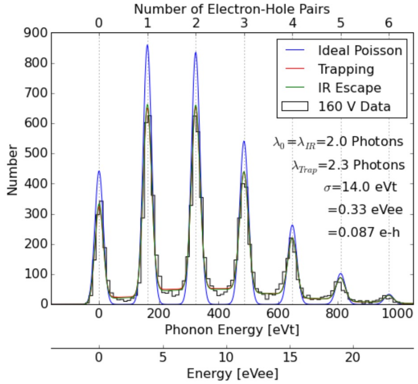
HVeV Single electron phonon mediated detectors



- Developed in Blas Cabrera group at SU
- Use 1 cm ^{2} 0.4 cm thick Si: ~ 1 g
- Use CDMS QET deisgn T_c~ 35 mK
- CDMS HV technology @ 160 Volts.
- Monochromatic Laser light: 640 nm
- Achieved ~0.1 e-h pair resoltion.
- **Clear single electron resolution!**

R. K. Romani et al., Appl. Phys. Lett. ***112****, 043501 (2018);*
https://doi.org/10.1063/1.5010699

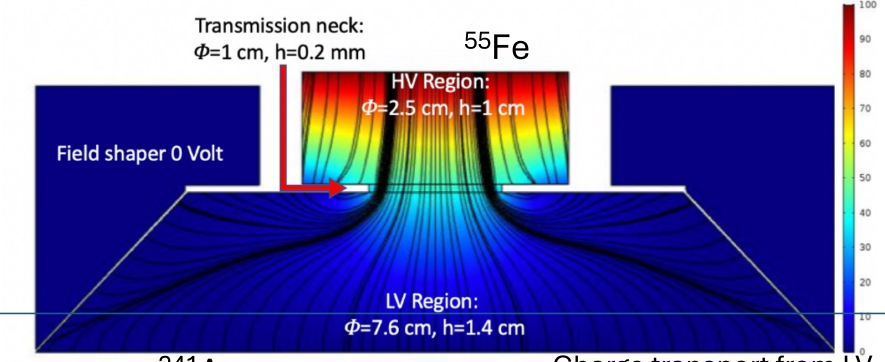




Hybrid HV Detector Principle

Funded by DOE Detector R&D for the past 4 years

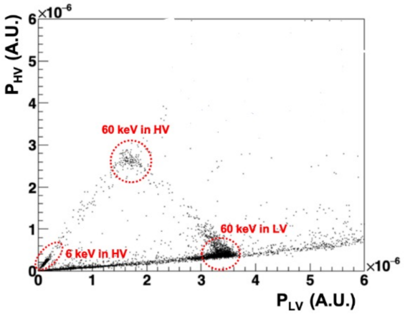
Geometry Simulation with COMSOL Multiphysics

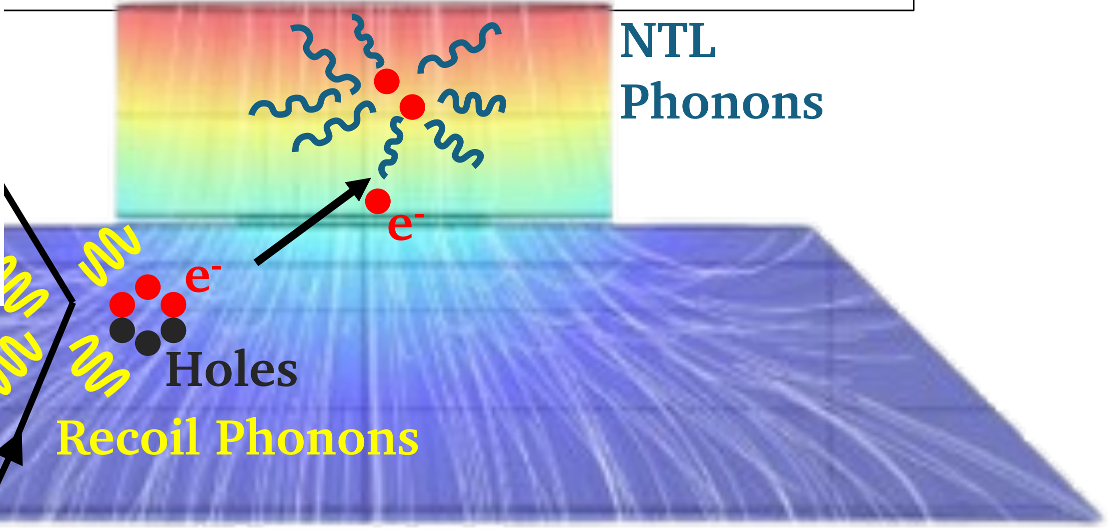


^{241}Am

Charge transport from LV region to HV almost 100%

Main idea: Monolithic detector with a low voltage (LV) and high voltage (HV) sides: LV to measure primary phonons like ZIP and HV to measure NTL phonons. Minimize HV to LV NTL phonon pollution using geometric sion at the neck

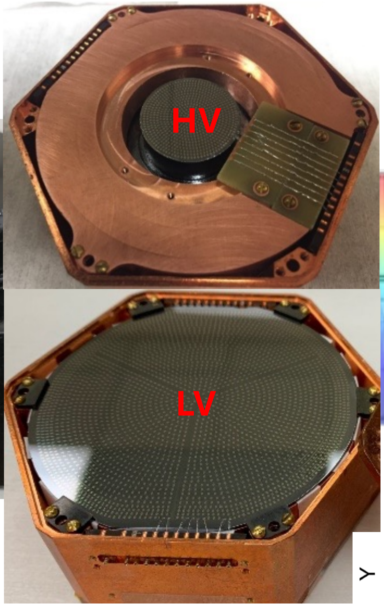


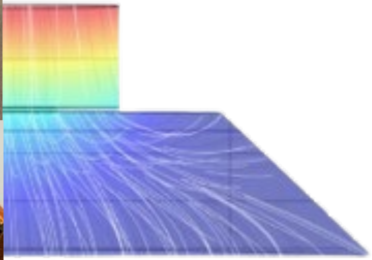


Hybrid HV Detector Principle

Main idea: Monolithic detector with a LV and a HV side – LV to measure primary phonons like iZIP and HV to measure NTL phonons. Do it without significant NTL pollution from HV to LV.
.1-1 kg

Funded by DOE Detector R&D for the past 4 years





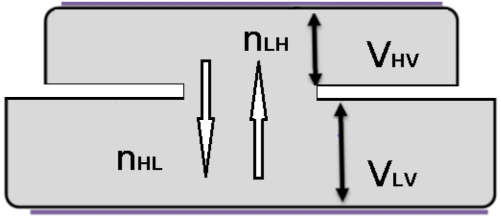
Add up phonon signal expected in HV and LV sides

$$P_{HV} = (1-\eta_{HL})E_R LV_{HV}/4 + \eta_{LH}E_R(1+LV_{LV}/4)$$

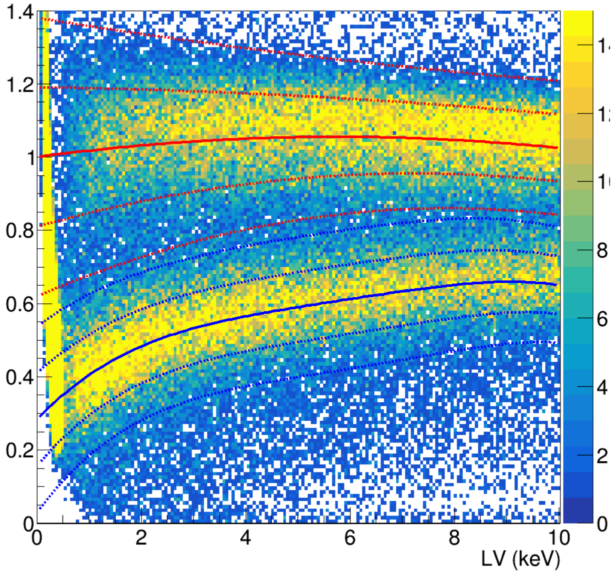
$$P_{LV} = \eta_{HL}E_R LV_{HV}/4 + (1-\eta_{LH})E_R(1+LV_{LV}/4)$$

$$\text{Discrimination:} D = \frac{P_{HV}}{P_{LV}}$$

η_{HL}, η_{LH} : phonon leakage fractions HV to LV and vice-versa
V_{HV} and V_{LV} are the estimated biased voltage across the detector
L: Lindhard factor, ϵ_{eh} : Average energy to create e-h pairs in Si



https://www.sciencedirect.com/science/article/abs/pii/S0168900222002467



Future Directions:
Larger Mass Larger Fiducial Mass

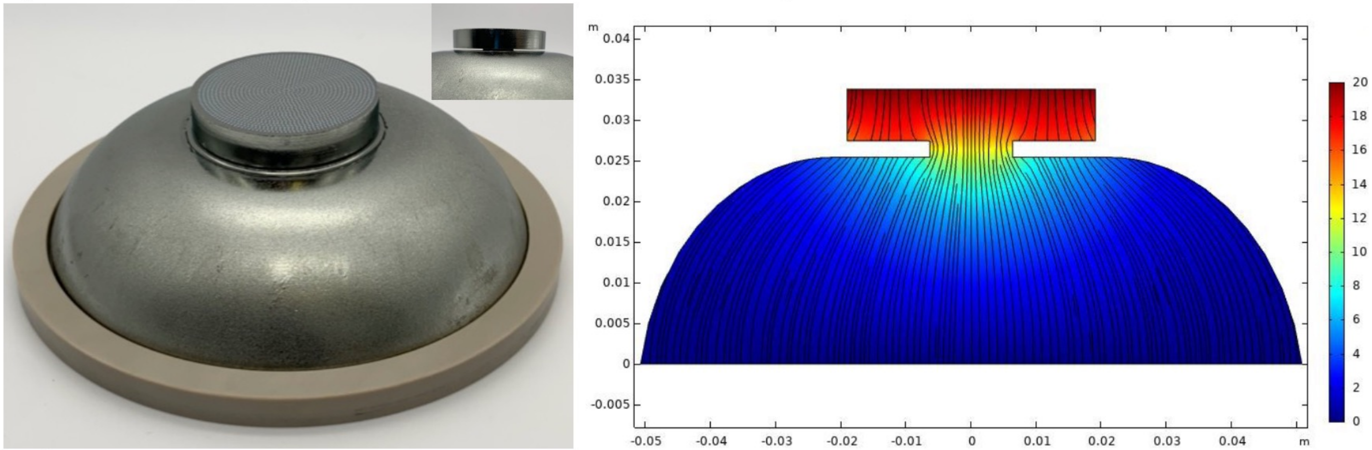
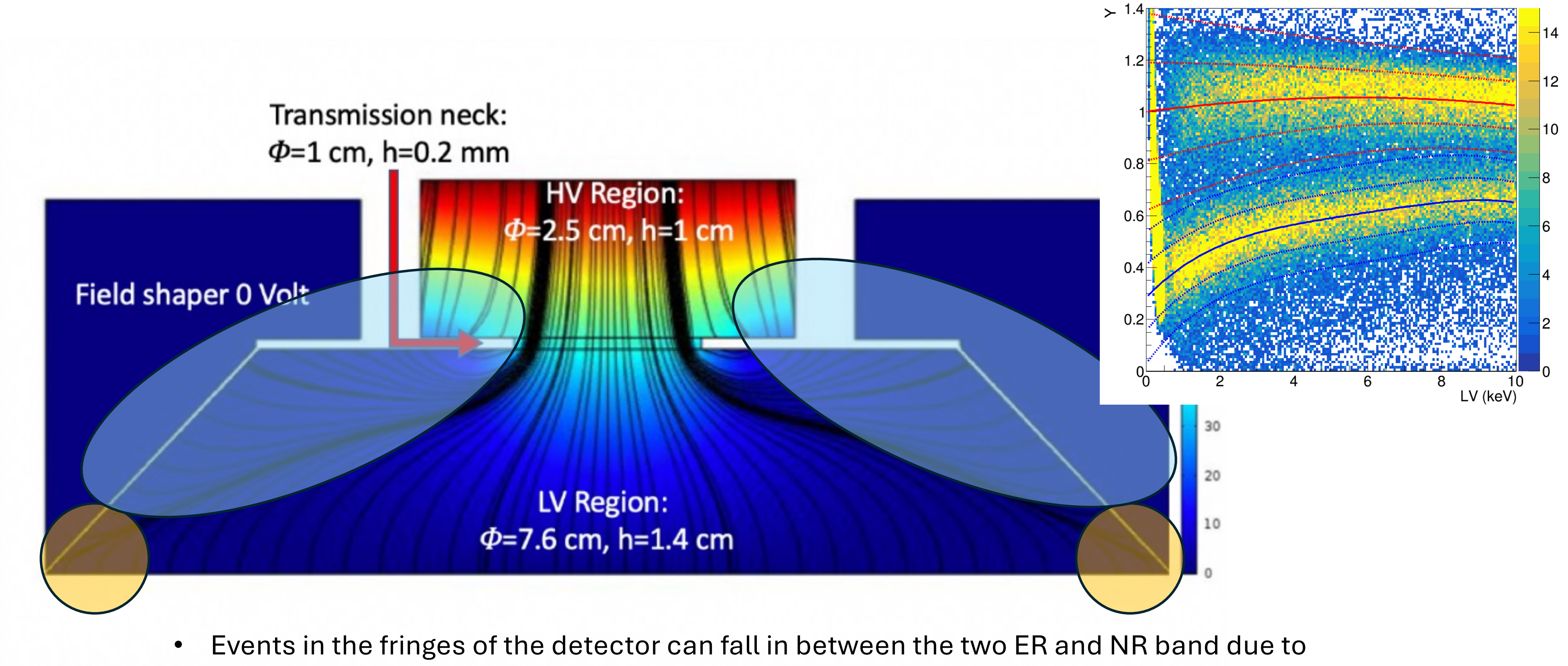


Figure 9: (a) A larger germanium hybrid detector fabricated in 2023, featuring improved fiducial efficiency and reduced phonon mixing due to a smaller diameter neck (inset). (b) COMSOL simulation of the dome-shaped detector shows most voltage drop in the top HV region. This 4"x1.33" germanium hybrid offers roughly 3 times higher fiducial volume (7.5x mass) compared to the 3"x1" silicon hybrid with a simpler conical shape.

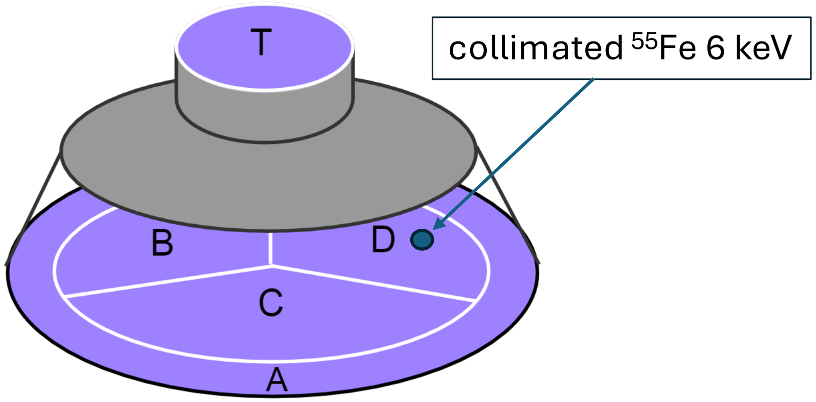
Need to Fiducialize the Detector

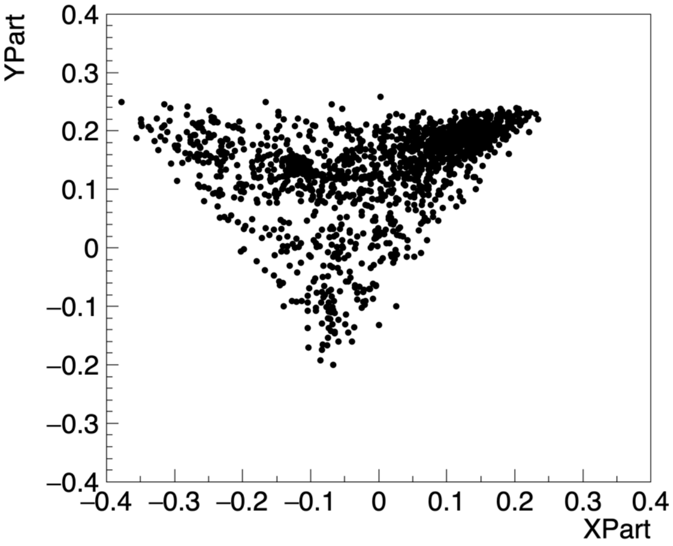


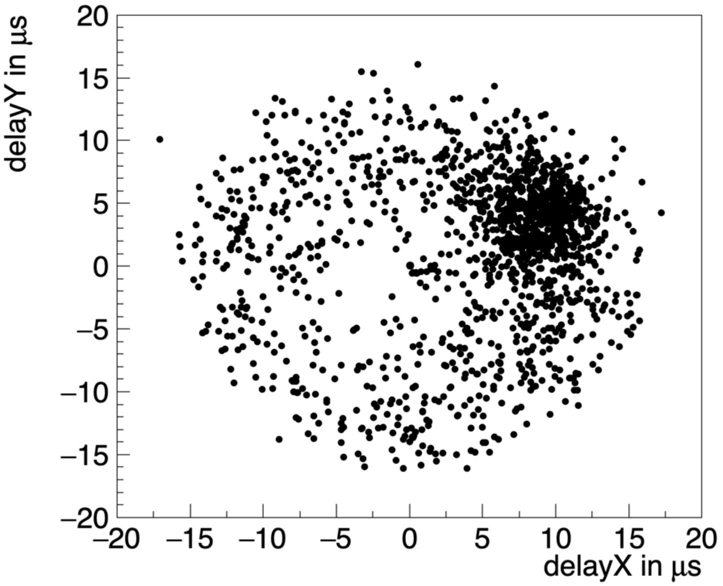
- Events in the fringes of the detector can fall in between the two ER and NR band due to incomplete charge collection.
- In particular, events in the sharp corners of the LV region see very small fields and may recombine before being drifted.

Position dependencies and need for position correction

- Our sensors are athermal phonon sensitive.
- Phonon responses depend on the location of the event
- In particular our energy estimate may depend on the location of the events.
- Need to correct the energy base on the location of the events.
- Will use a mono-energetic source and find correction bas eon the location of the events.

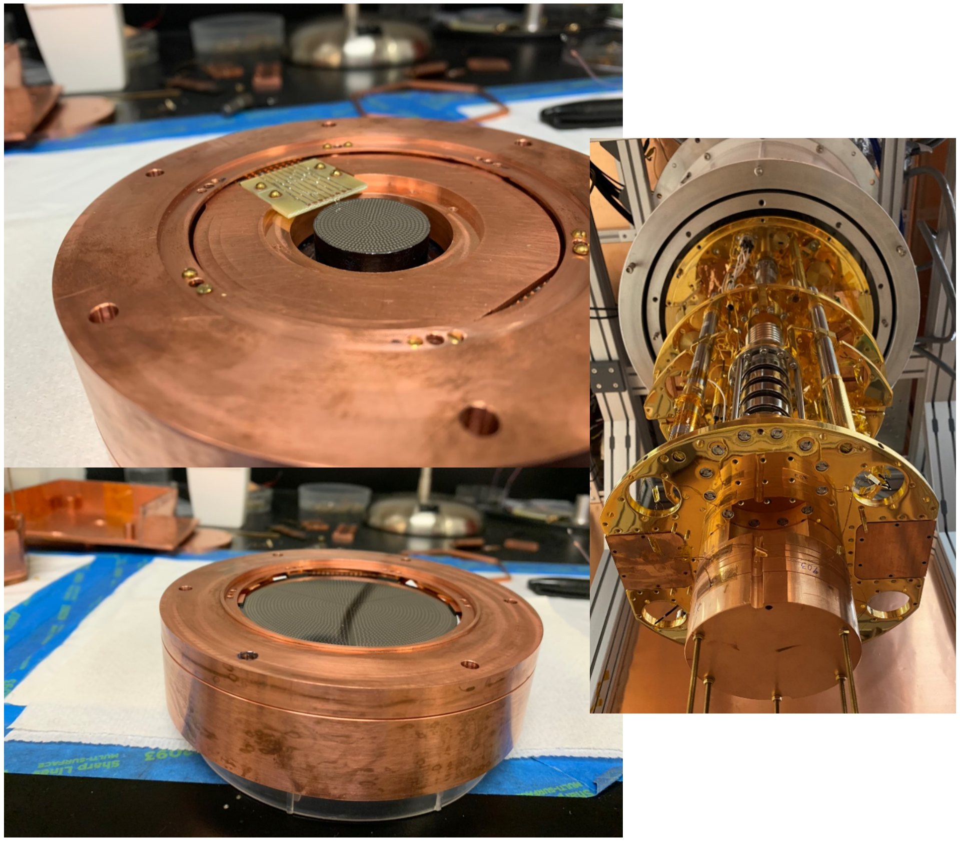






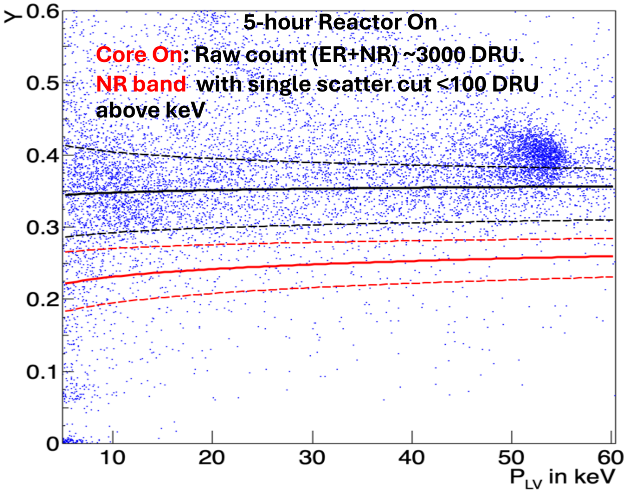
New Detector Housing for Internal Shielding

- Thick wall copper housing act as an internal shield.
- Larger mass will also reduce the effects of microphonic noise due to the pulse tube precooling stage of the dilution fridge.
- New wiring and IR have been implemented to reduce the noise from IR ionization and E/M pickup.
- Detector in its new tower structure is currently being tested in TAMU cryogenic characterization facility.



Hybrid for MIνER@HFIR – Physics Case CEνNS

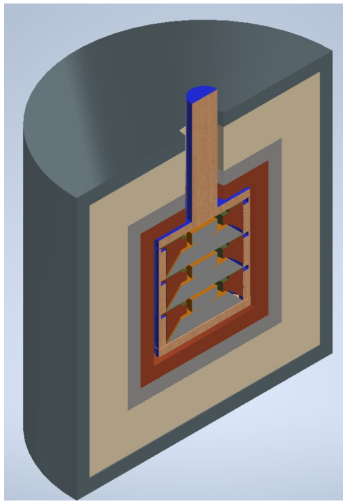
- MINER experiment moving to ORNL HFIR reactor from TAMU TRIGA reactor.
- Strong enhancement in sensitivity due to ~100x higher flux compared to TAMU TRIGA and additional factor of ~10 times higher live time due to continuous reactor operation.



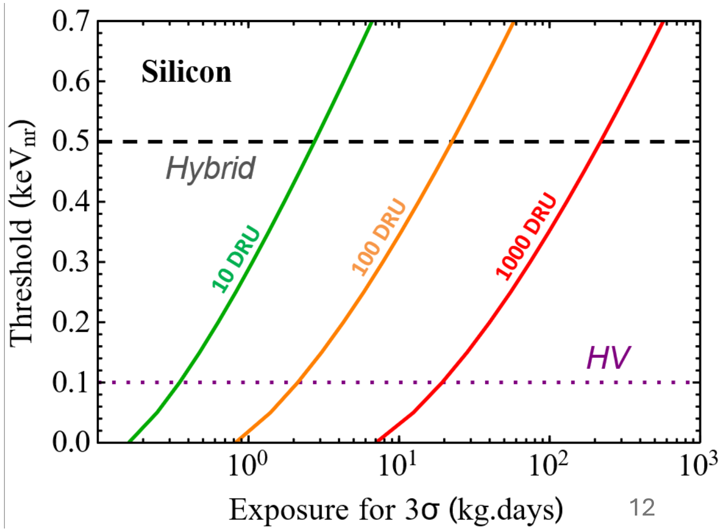
Demonstrated background ~1000 DRU without ER-NR discrimination in sapphire.

<100 DRU with Hybrid detector with ER-NR discrimination.

Benchmark recoil (NR) thresholds:
75eV for sapphire (no discrimination)
500 eV for Hybrid (ER-NR discrimination)
Single e-h sensitivity (potentially 10 eV) for HV detector (no discrimination).



Silicon detector at HFIR (5m, 85MW)



Conclusion

- Combining the two primary SuperCDMS technologies i.e. NTL-assisted low-threshold ionization measurement and ionization yield discrimination of ER/NR, The hybrid detector allows for much lower detection thresholds and maintains the NR/ER discrimination.
- The 100 g Si hybrid reached < 500 eV threshold and expected to further enhance its threshold with new detector tower and cabling.
- MINER@HFIR experiment is the first experiment using TAMU hybrid design as base detection technology.