Very Low Threshold Phonon-mediated Detectors with Background Identification

Nader Mirabolfathi
Texas A&M University
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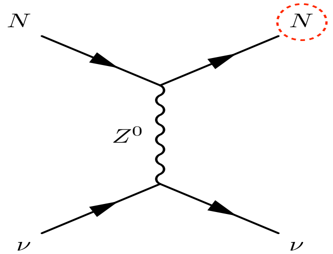
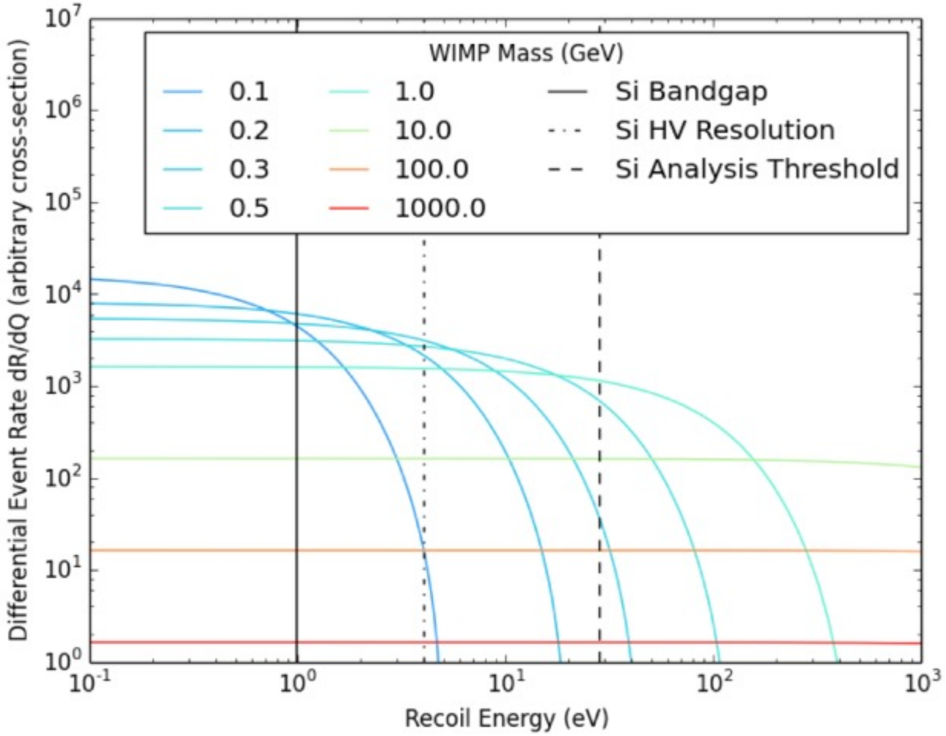
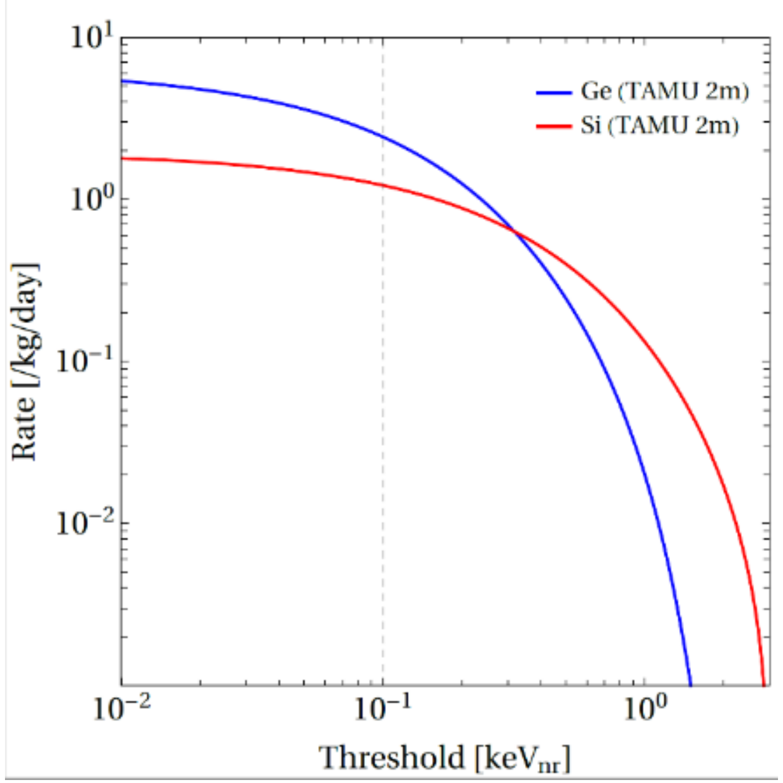
- The scientific context: **Low mass DM**, Coherent elastic neutrino nucleus scattering (**CEνNS**).
- Detection challenges: Need very low thresholds and Backgrounds.
- CDMS Ionization and phonon measurement: Excellent method to reject backgrounds on and event-by-event basis but the threshold is limited by ionization readout S/N.
- TAMU hybrid **phonon-only design with NR/ER discrimination** principle and latest results.
- Perspective.

Low Energy Nuclear Recoil (NR) Detection Challenges 1

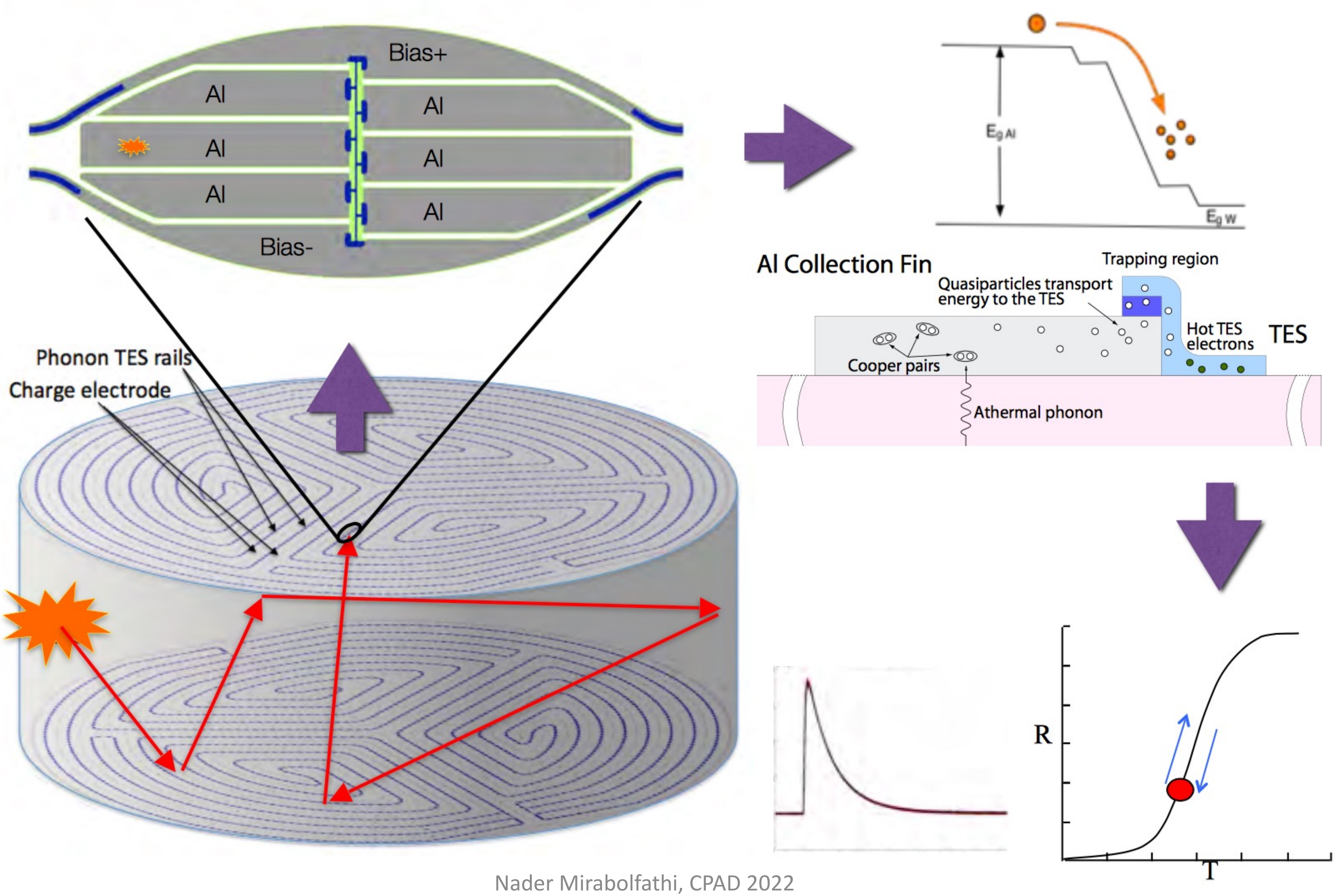
- Our main area of interest are about experiments seeking to detect low energy nuclear recoils (**Low E NR**).
- Low mass DM threshold should scale ∝ $(m_{DM})^2$.
- Similar challenges exist for low-energy CEνNS e.g. neutrinos from reactor.
- Both experiments desire detectors with very low **thresholds ~ 100 eV**.
- Among quantum excitations that are available for particle detection, **Phonons** have the lowest energy thus the best signal to noise.





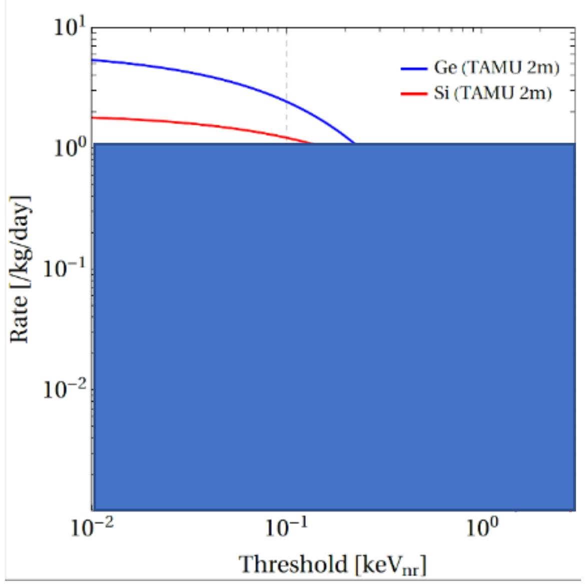


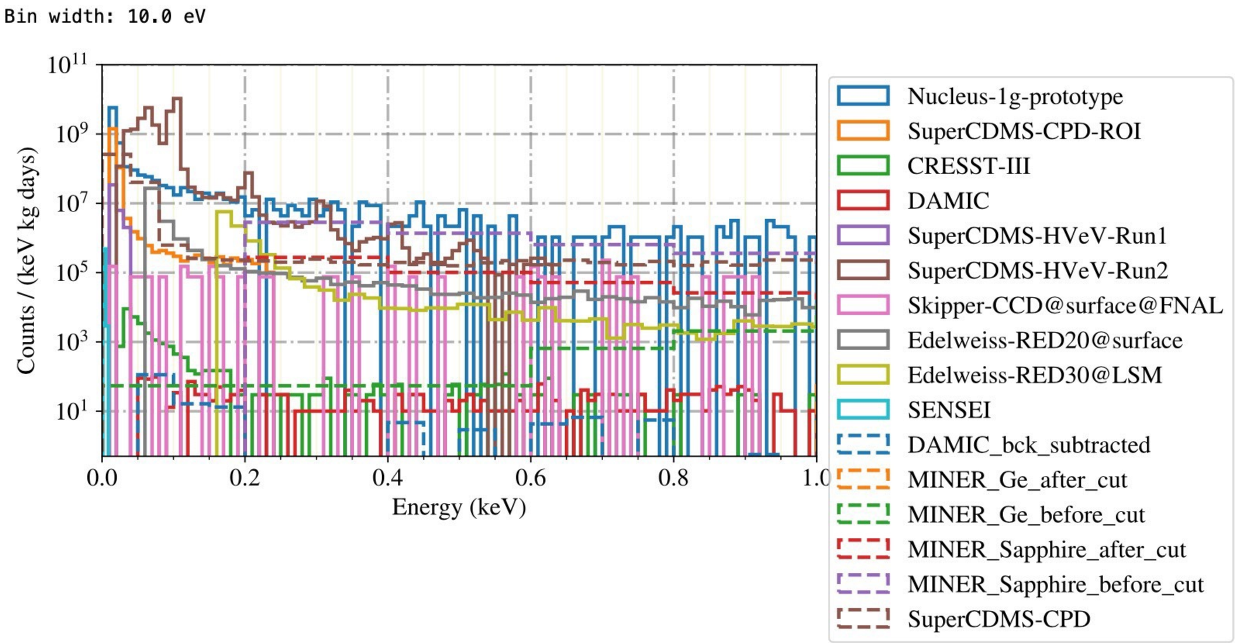
Athermal Phonon Readout: CDMS QET technology

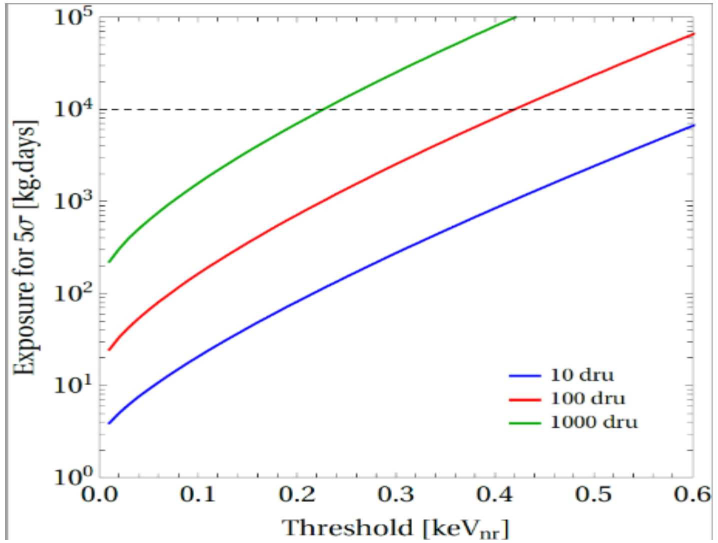


Low Energy Nuclear Recoil Detection Challenges 2

- Uncontrolled backgrounds lead to systematics that dominate the signal.
- Recently, DM and CEνNS experiments reported an excess of event rate at low energies. The origin of these events are unknown but the evidences hint backgrounds as origin: ER, stress release, defects…
- Identifying the nature of particle interaction **electron recoil (ER)** or **nuclear recoil (NR)** is very important to remove majority of the backgrounds and to identify the origin of the **EXCESS**.

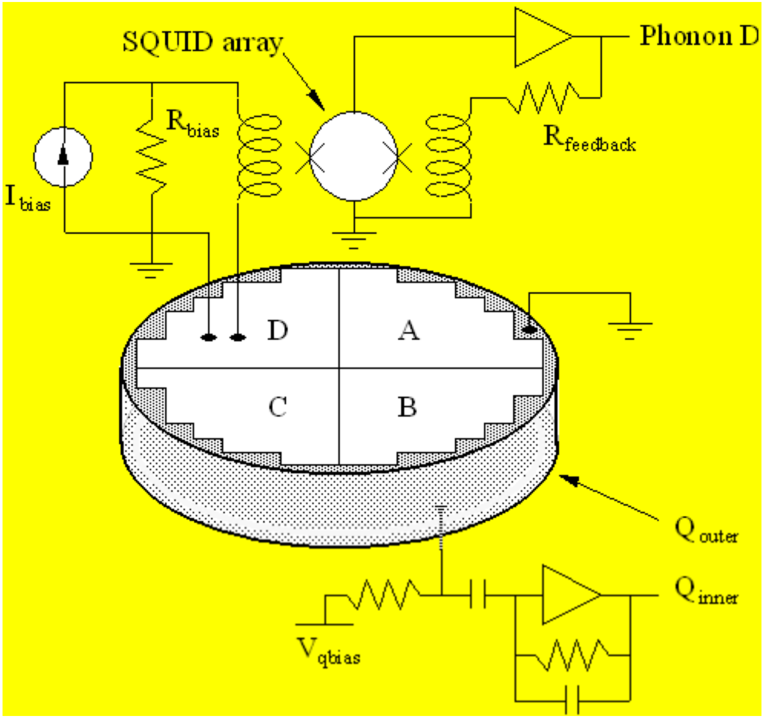


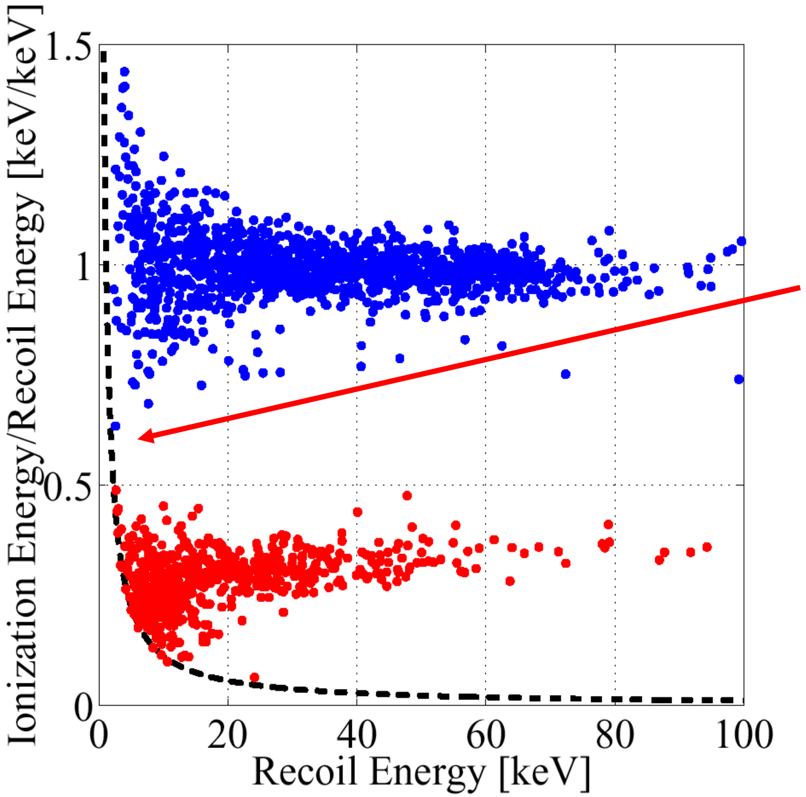




CDMS II Event-by-event Background Discrimination

- Simultaneously measure ionization and phonon after each interaction in large Si or Ge (~ kg) crystals operating at T~20 mK.
- Superconducting Transition Edge Sensors (TES) cover detector face(s).
- 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 DM from background.
- Excellent discrimination for E_r > few keV . The threshold limited by ionization resolution.



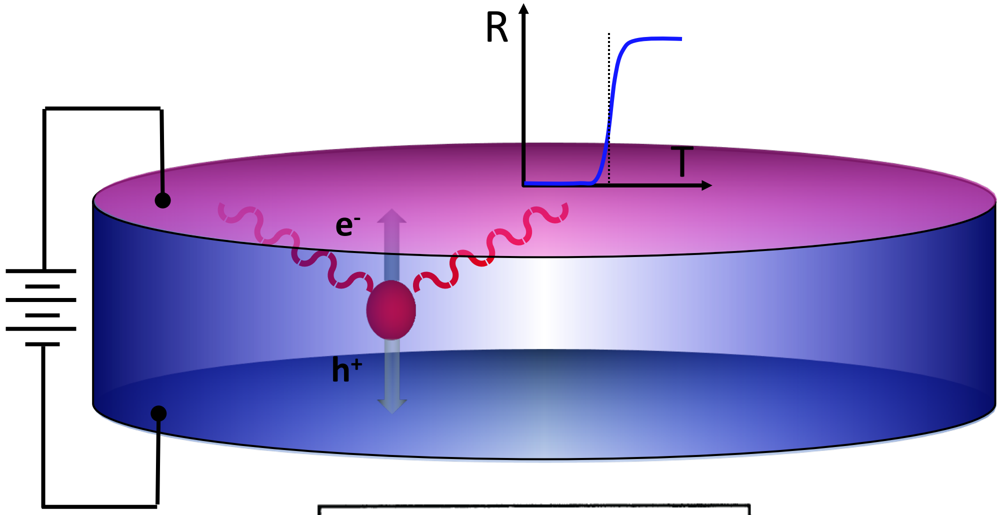


Neganov-Trofimov-Luke Effect: Indirect Ionization Measurement Using Phonons

Power=V.I or Energy=V.Q

- **Luke**-Neganov Gain

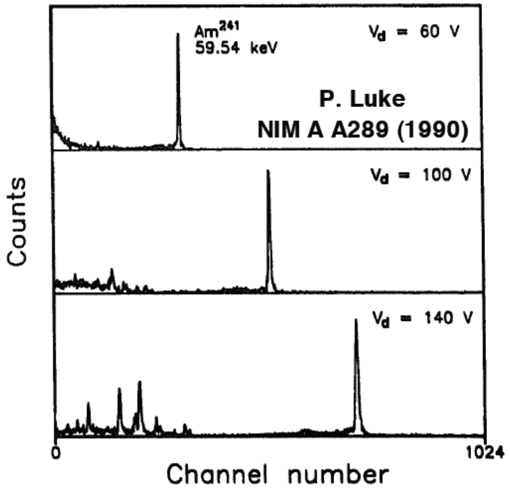
$$E_{tot} = E_r + E_{luke}$$
$$= E_r + n_{eh} e V_b$$
$$= E_r \left(1 + \frac{eV_b}{\epsilon_{eh}}\right)$$



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

=> **S/N ⇧**

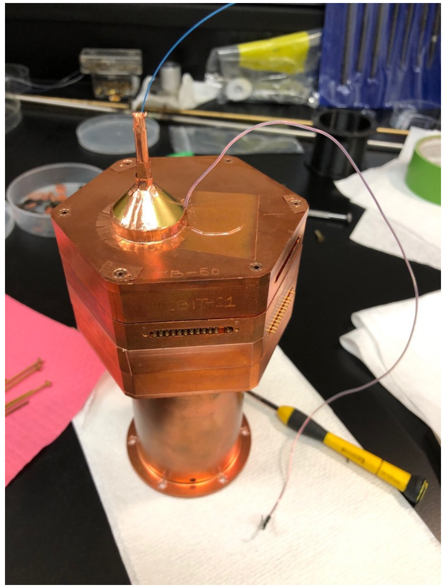
• In theory one can increase Bias to reach Poisson fluctuation limit!

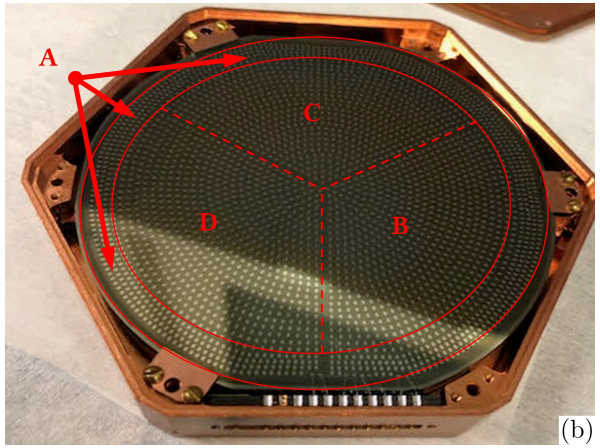


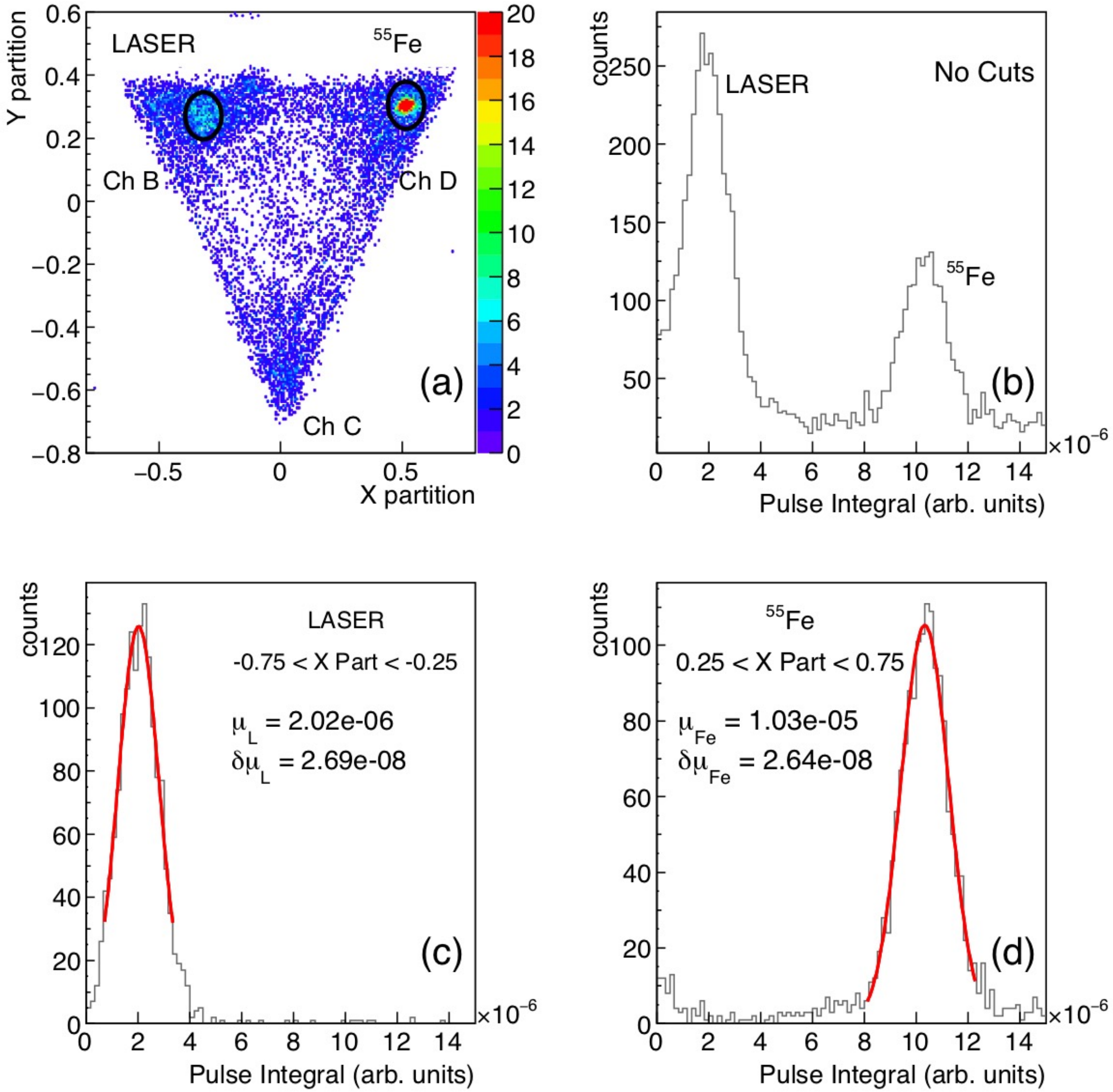
Luke et al., Nucl. Inst. Meth. Phys. Res.A 289, 406 (1990)

limitation: Current leakage

Very Low Threshold NTL-assisted Si (100g) at TAMU

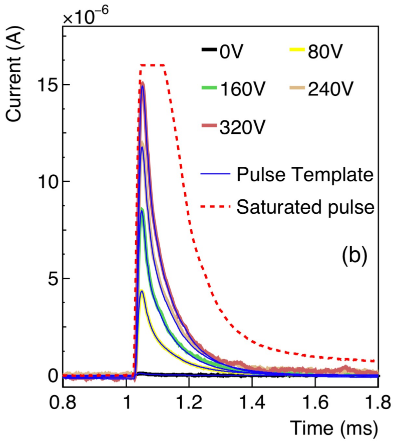


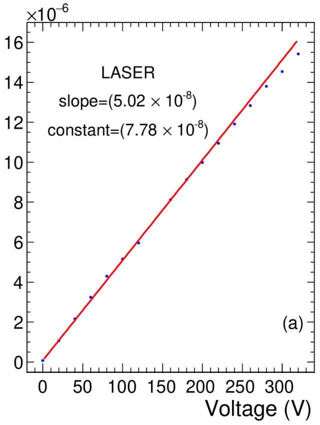


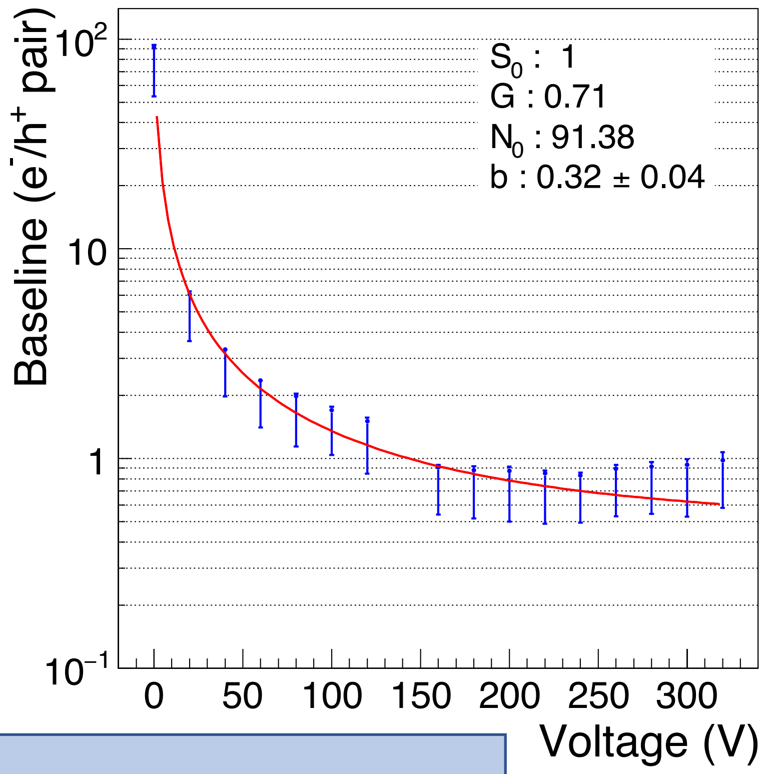


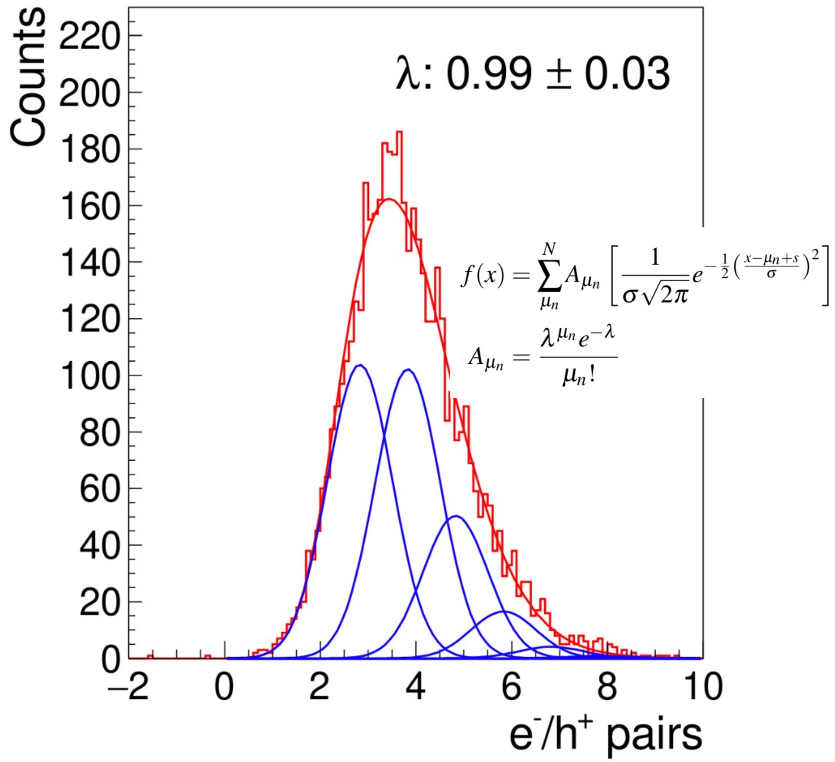
- A 100 g Si (75 mm diameter and 1 cm thick) CDMS HV phonon architecture detector prepared with one face covered by phonon sensors and the other face left bare.
- The ionization bias applied via a 500 microns gap form the bare surface. This reduces significantly the leakage.
- Use 5.9 keV line of an ^{55}Fe source to calibrate the Laser energy.
- A laser beam cross calibrate with the 6 keV line from ^{55}Fe and used to calibrate for V_{bias} > 100 V.

Recent Results with a 100 g Si









- Noise has two components: $N = \sqrt{N_0^2 + (Vb)^2}$
  - Sensor bias and readout: Independent of the HV
  - Leakage in the crystal: Linearly grows with HV
  - If $I_{leakage}$ is also a function of V => Noise increases as HV.I(V)

- Signal grows linearly with HV until:
  - Signal so large that the TES nonlinearity becomes significant
  - Joule heating due to carrier drift => $T_{crystal}$ ↑

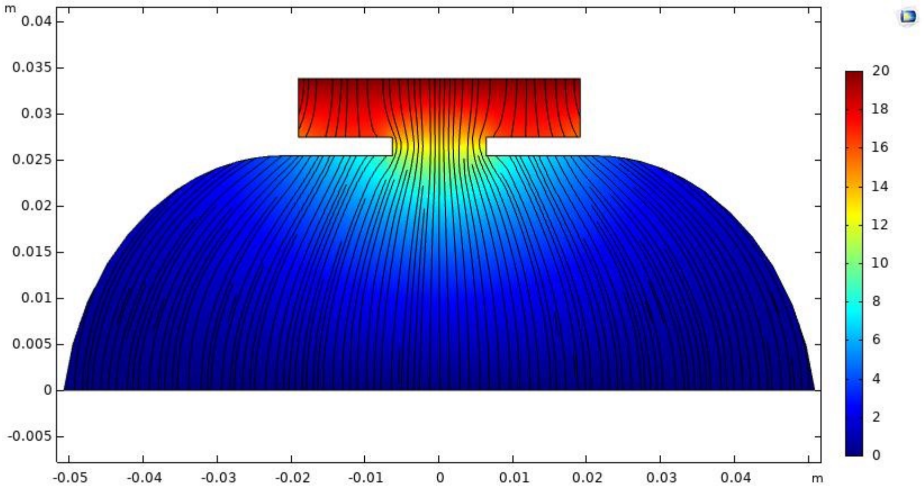
$$S = S_0 + S_0 qVG/\varepsilon$$

FIG. 5. The red histogram is the distribution of the total phonon energy measured in the detector when the LASER is incident on it. The red line is the Poisson-normalized multi Gaussian model given by Eq. 5, fit to the distribution. The blue lines are the Gaussians for different number of e^-/h^+ pairs produced by the LASER. The $\lambda = 0.99$ value represents the average number of e^-/h^+ pairs produced by the LASER.

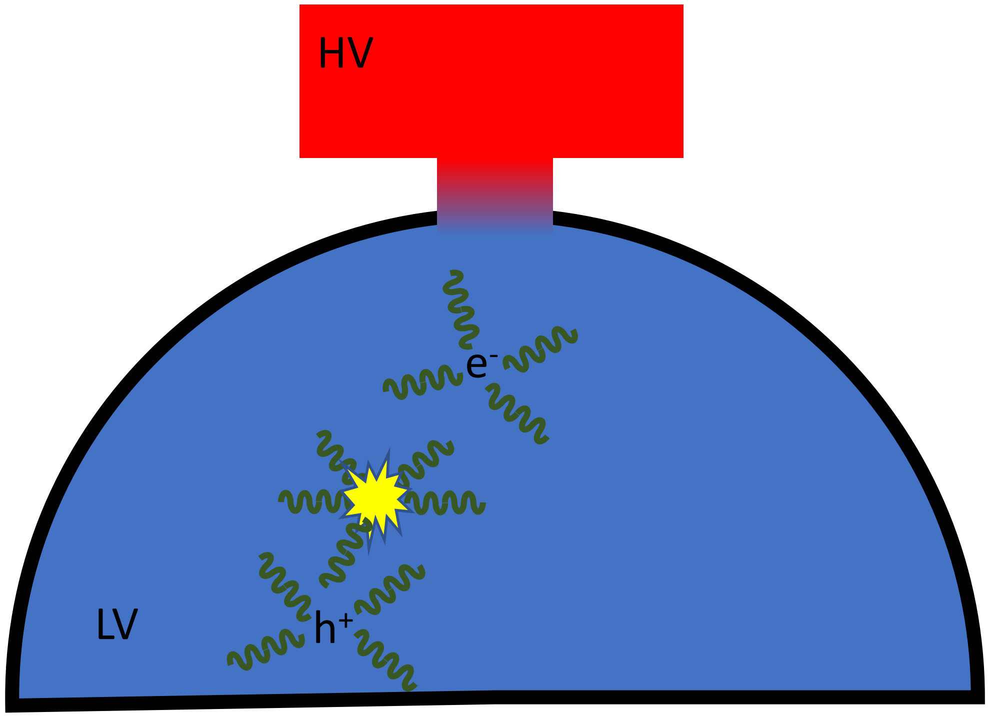
http://dx.doi.org/10.1016/j.nima.2021.165489

TAMU Event-by-event Discrimination: HV-LV Hybrid Detector Concept

- A **monolithic crystal** is shaped into **two volumes** connected via a **narrow channel**.
- The basic idea is very similar to Xenon two phase:
  - Measure impact phonons in the low voltage LV region.
  - Shape the filed to channel ionization in the HV region.
  - Measure NTL phonons in the HV region.
- Phonon sensors cover the surface of both volumes. Quasi-independently measure phonon energy for each event



High field side Phonon readout $\mathbf{P_{HV}}$
Also used to apply field



Low field side Phonon readout $\mathbf{P_{LV}}$
Set to ground together with the curved surfaces for filed shaping

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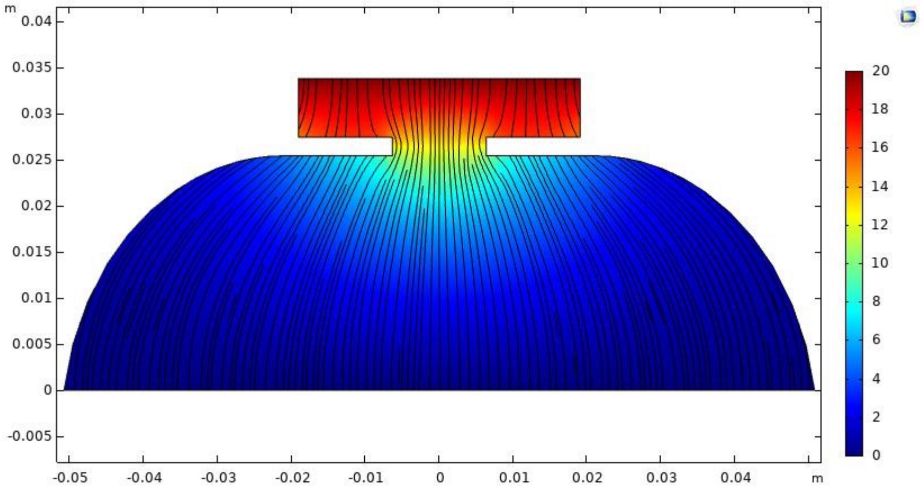

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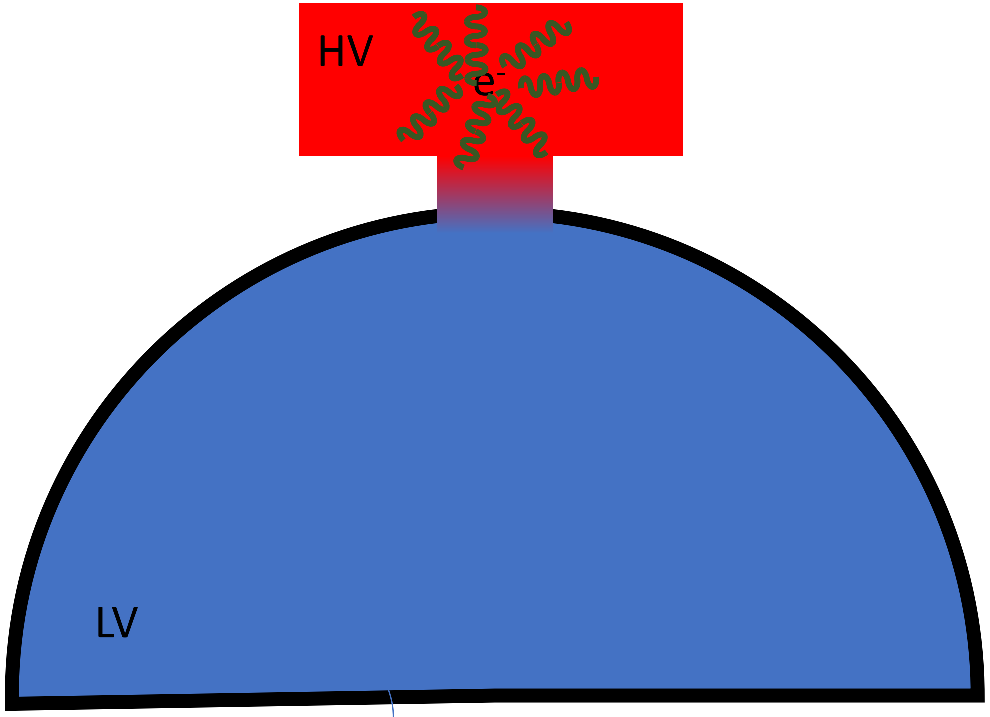

Low field side Phonon readout $\mathbf{P_{LV}}$
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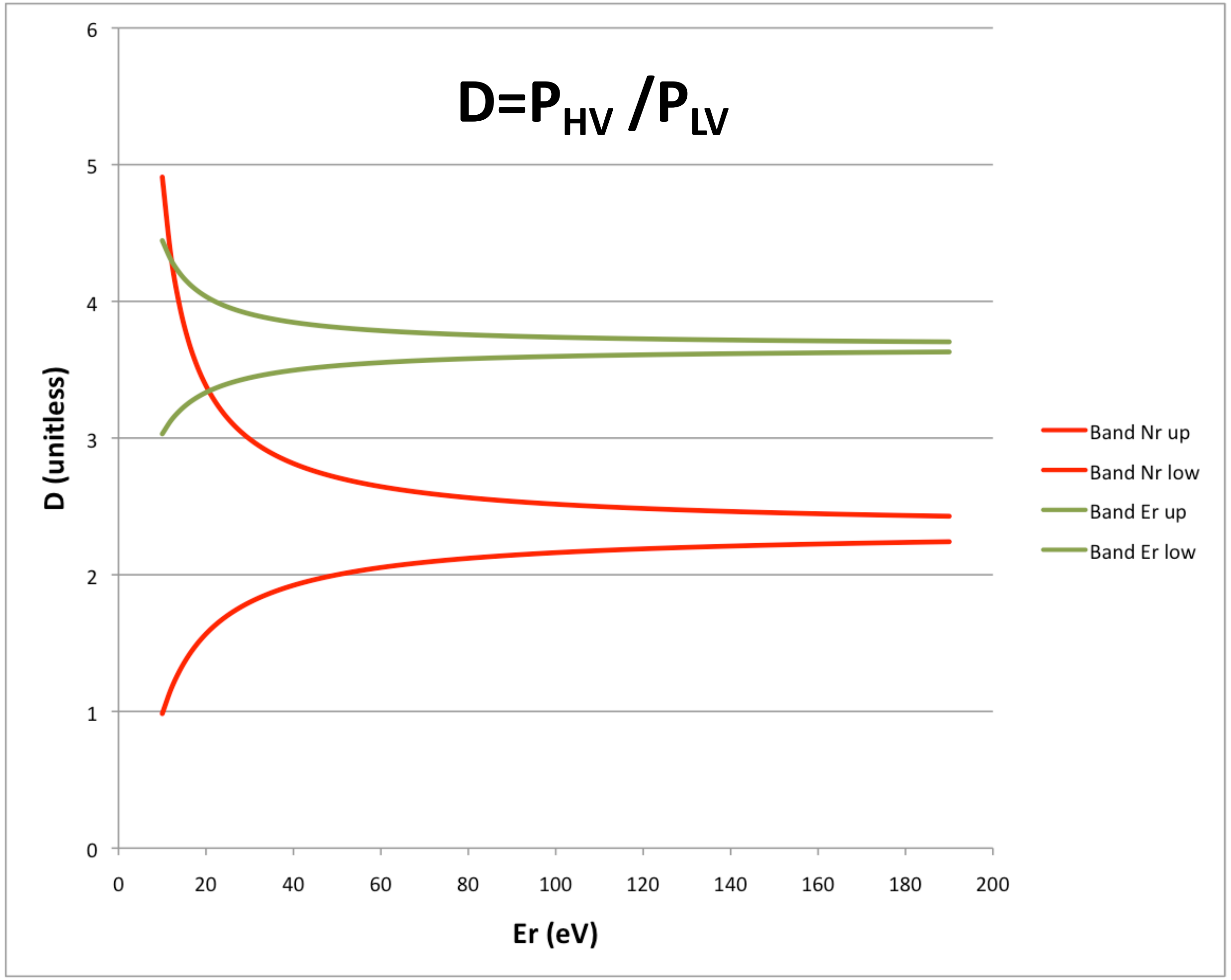
TAMU Event-by-event Discrimination: HV-LV Hybrid Detector Concept



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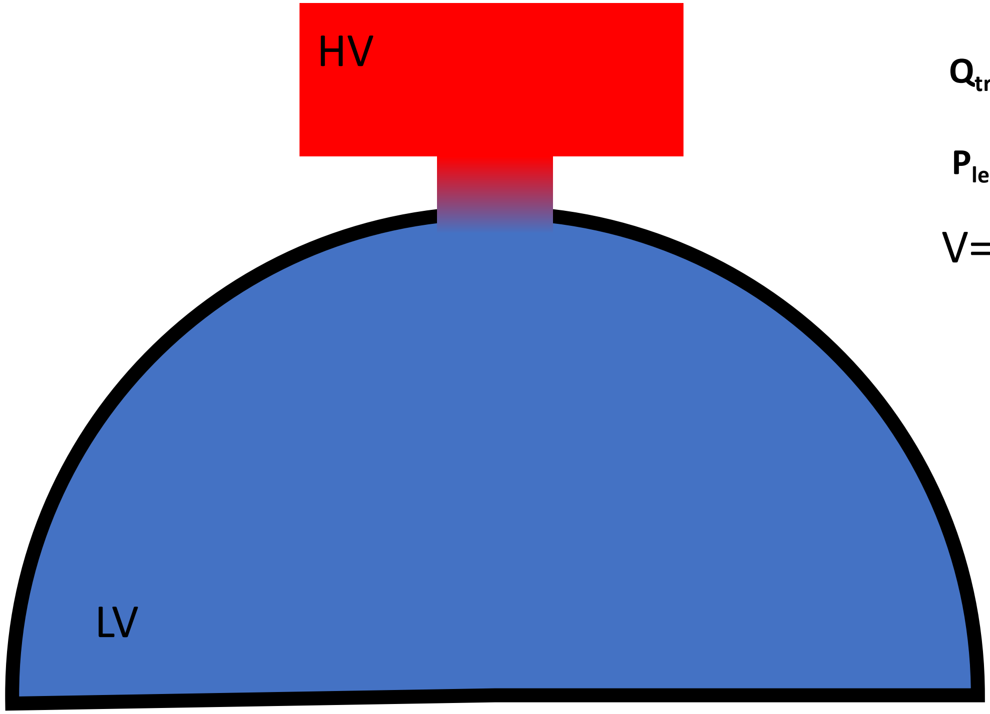


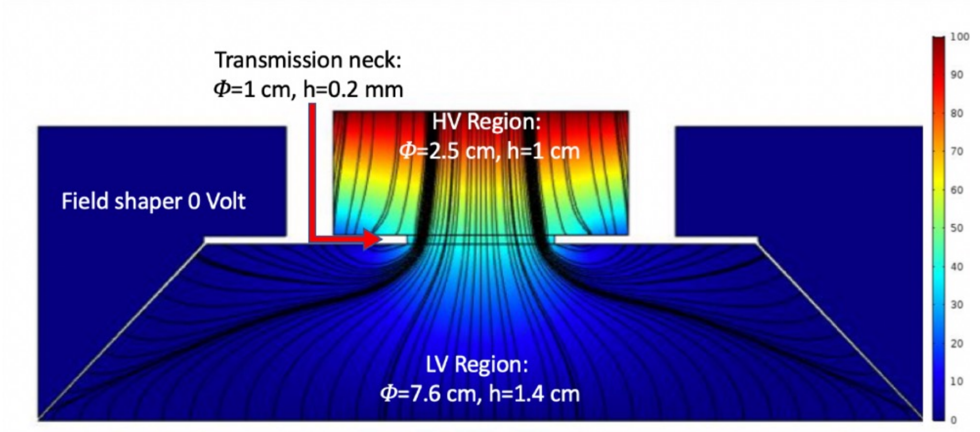
$Q_{tranfer}=\kappa Q$

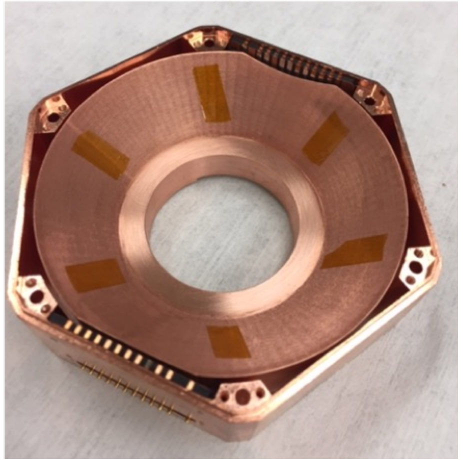
$P_{leakage}=\eta P$

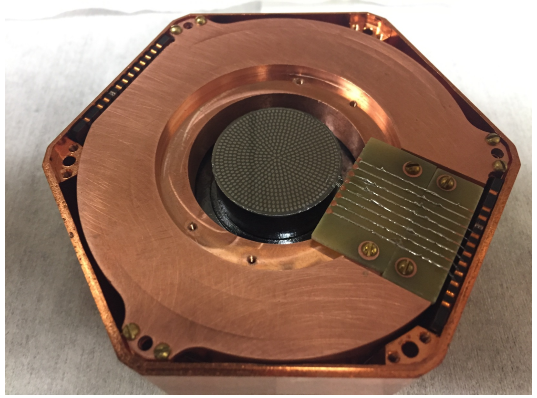
$V=V_{HV}+V_{LV}$

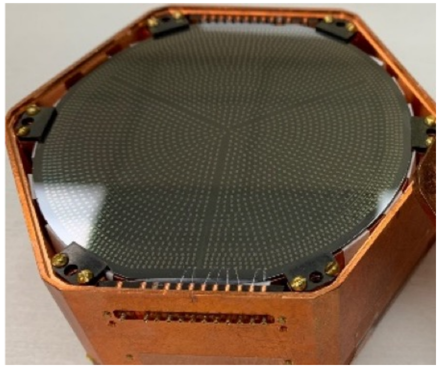
Low field side Phonon readout $\mathbf{P_{LV}}$
Set to ground together with the curved surfaces for filed shaping

TAMU Hybrid Prototype









- Si substrate shaped for the first hybrid prototype (100 g).
- Measured full charge transport from LV to HV regions. Found very good collection efficiency > 90 % for the inner regions of the LV volume.
- Phonon suppression matches model albeit being non-ideal.
- Observed clear discrimination between NR and ER calibrating with neutron source (^{252}Cf and ^{57}Co) and gamma sources.
- **Discrimination is more pronounced at low E_r**

Calibrating a Hybrid Detector

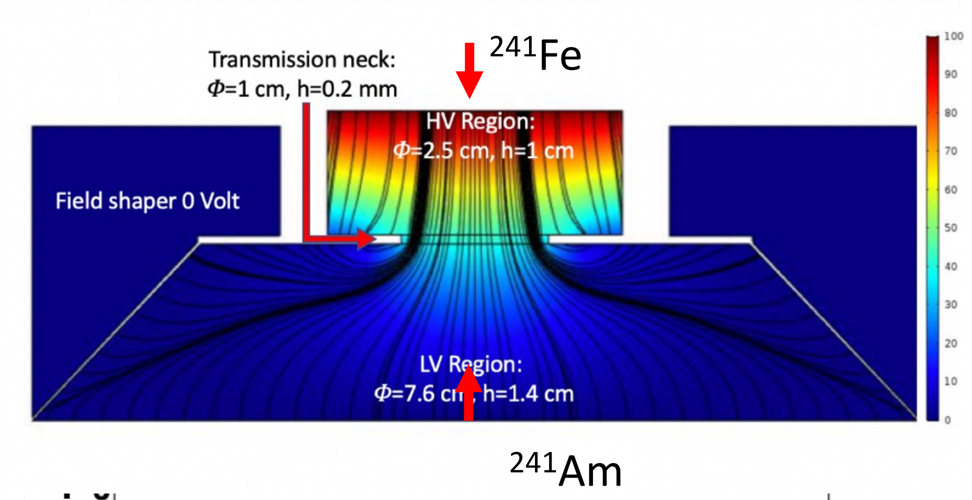
- Based on our preliminary model, one can calculate both P_{HV} and P_{LV} knowing the energy, ionization yield (NR or ER) and geometric parameters that determine the phonon leakages form HV to LV regions and voltages across the HV and LV regions.

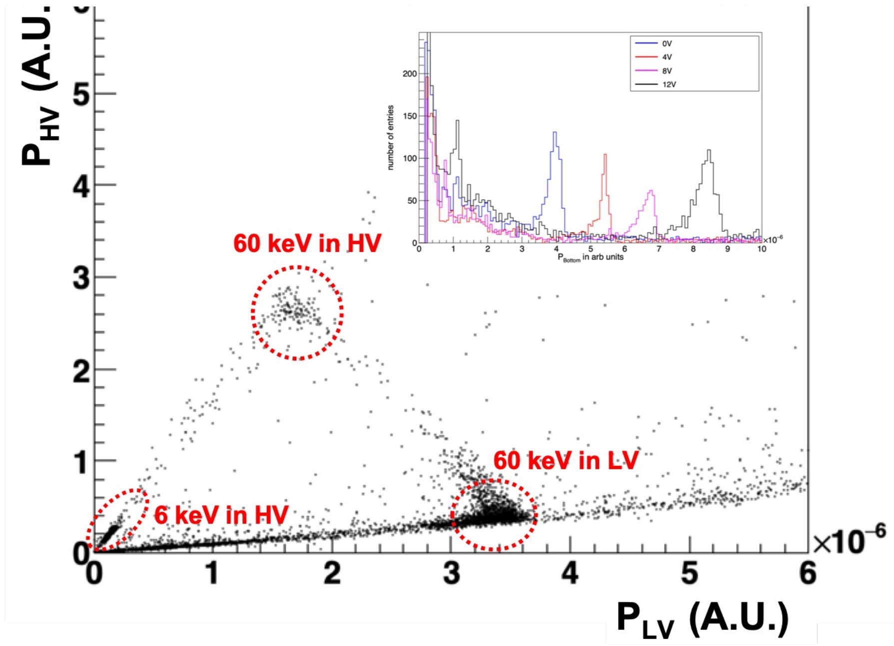
- Using the radioactive sources on both sides of the detector we estimate those geometric factors and thus using P_{HV} and P_{LV} we can compute both E_r and Y.

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

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

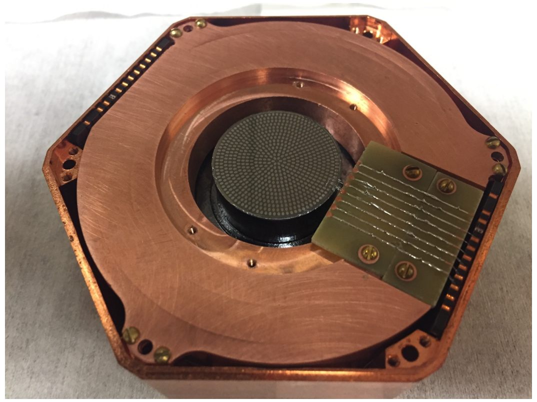
$$\text{Discrimination}: D = \frac{P_{HV}}{P_{LV}}$$

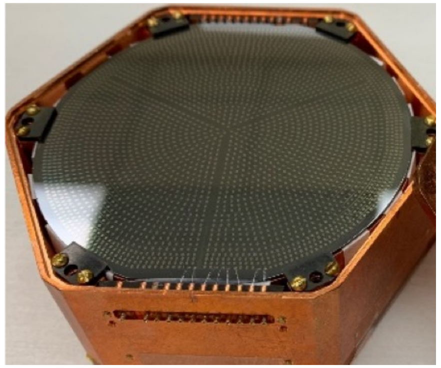


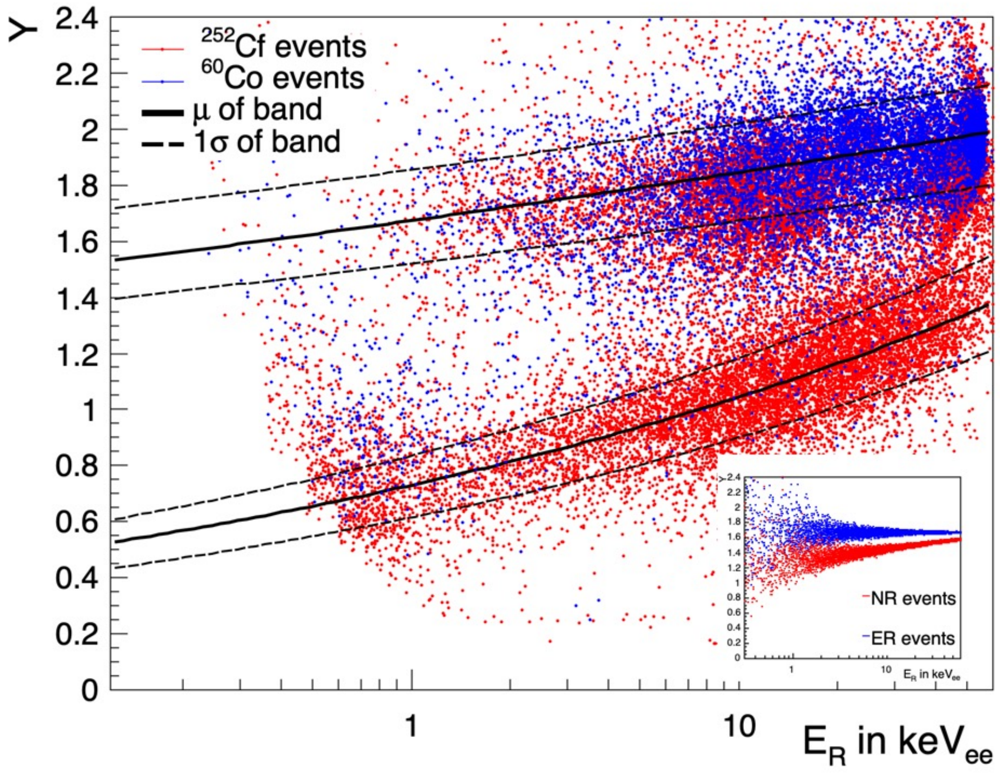


Nuclear Recoil Discrimination

- To check the NR discrimination performance of the detector, use a ^{252}Cf neutron source.
- Clearly see two bands that separate even more at lower energies 👍
- Caveat: We haven't yet performed position correction of the parameters.
- Large exposures with bulk ER is underway for this step.
- We expect significantly narrower bands once the position correction is performed.





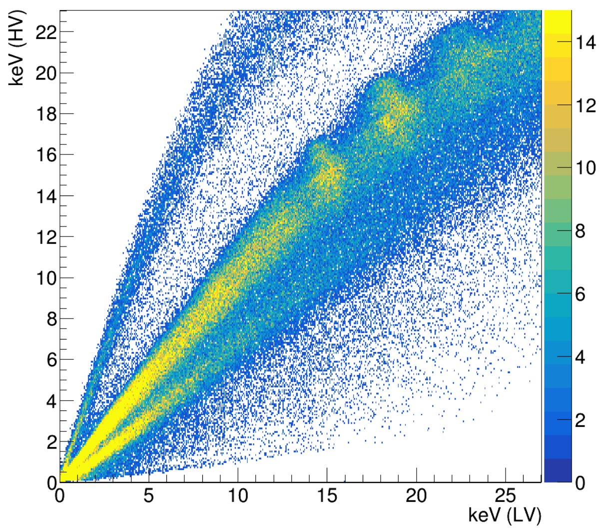


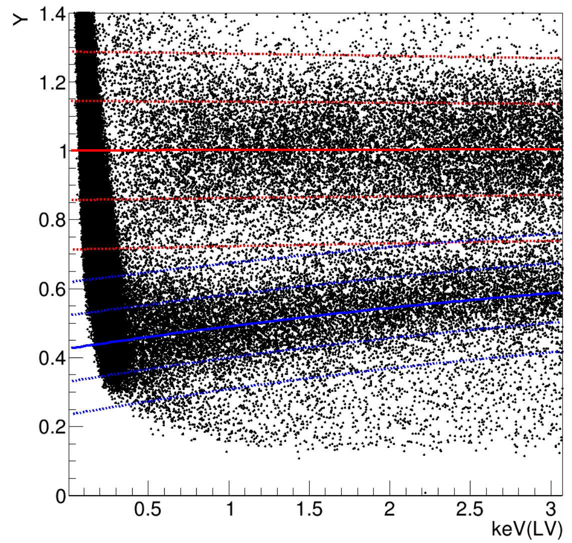
Early results with Hybrid presented at the last CPAD

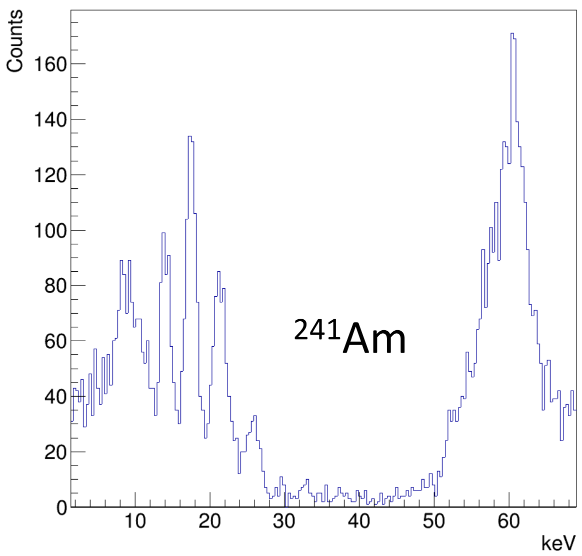
https://doi.org/10.1016/j.nima.2022.166707

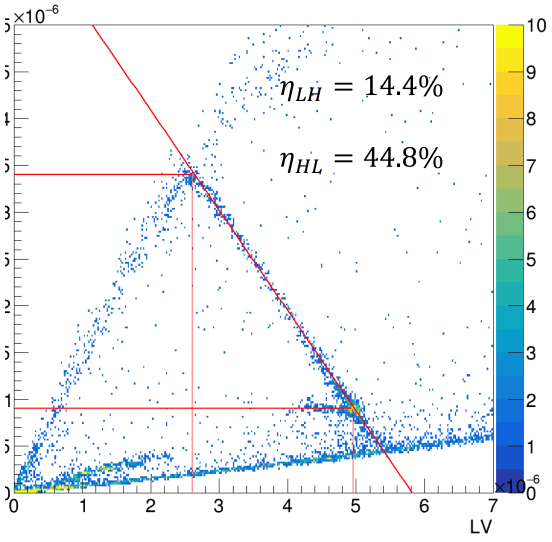
Latest Results From the TAMU Hybrid Detector

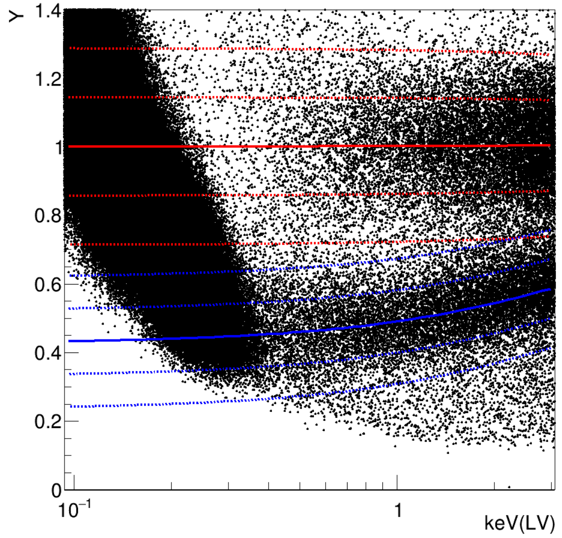
- Since last run, improved S/N for a better handling of the environmental noise.
- **Realtime Software Trigger** performed offline using **optimal filtering**.
- **Improved** the **threshold** by almost a factor of 3.
- Clearly see the **NR** and **ER bands** down to **< 500 eV_{ee}**.
- **No fiducial cut for now but in progress**.

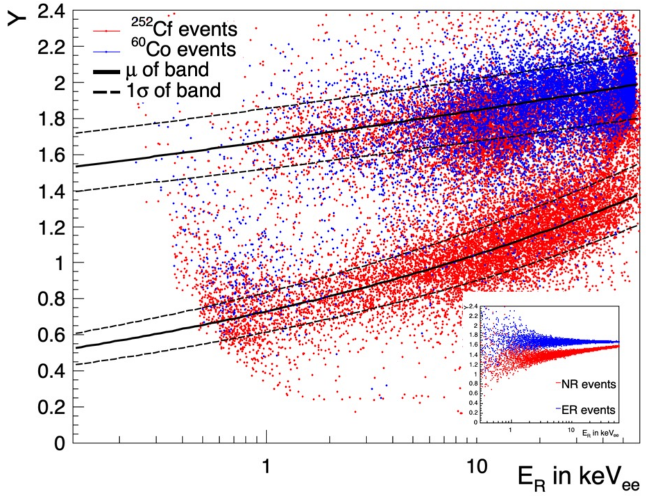






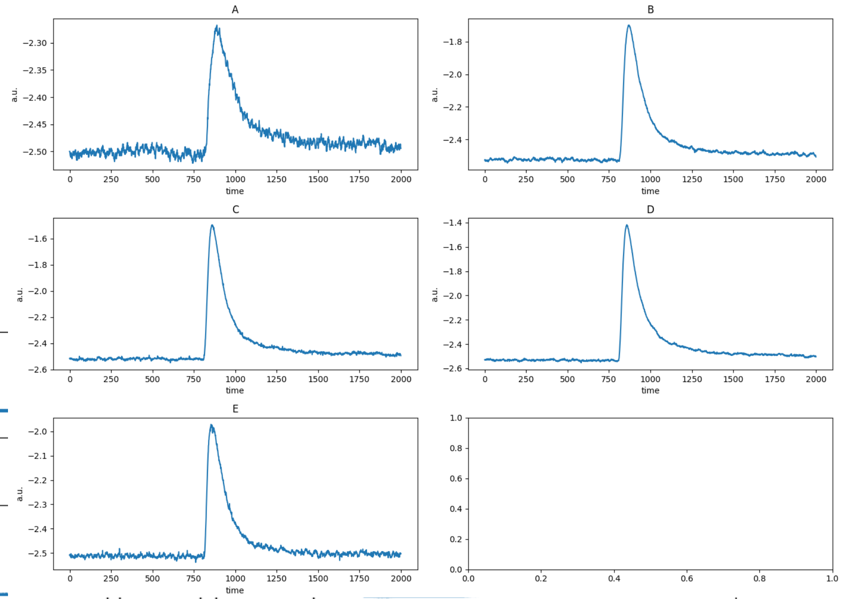


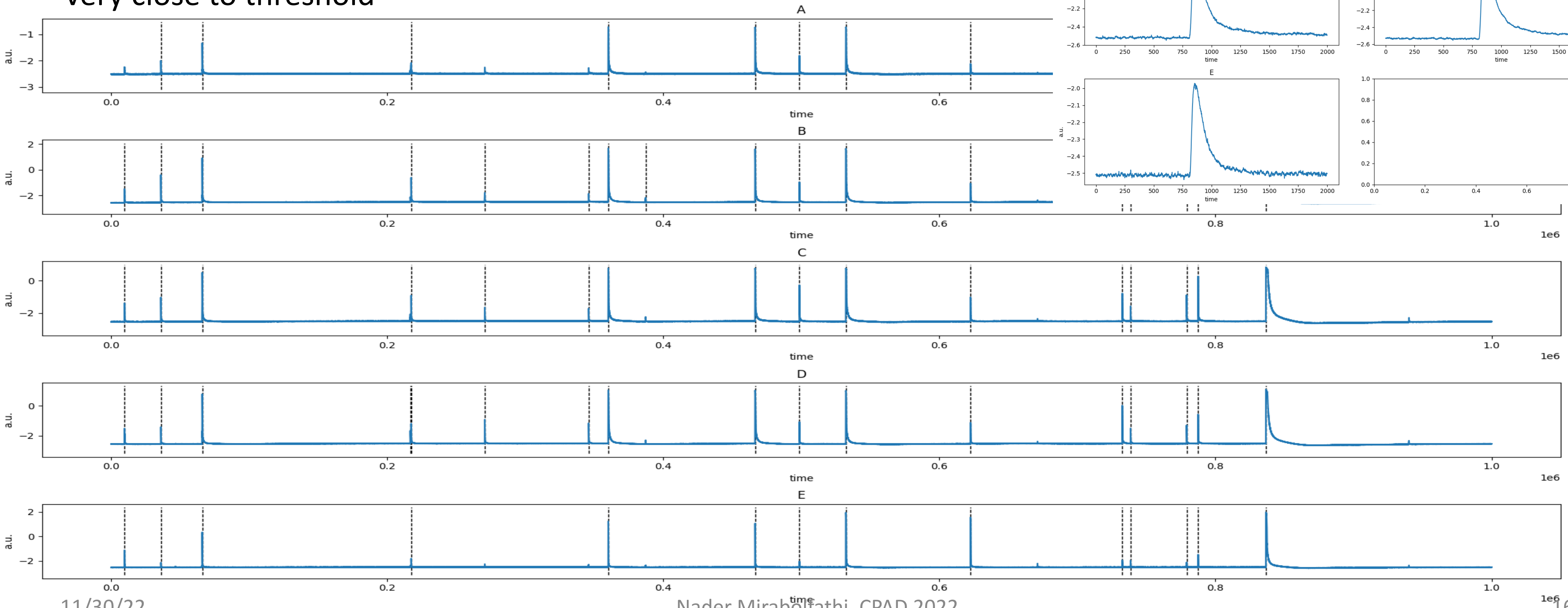




Realtime Software Trigger

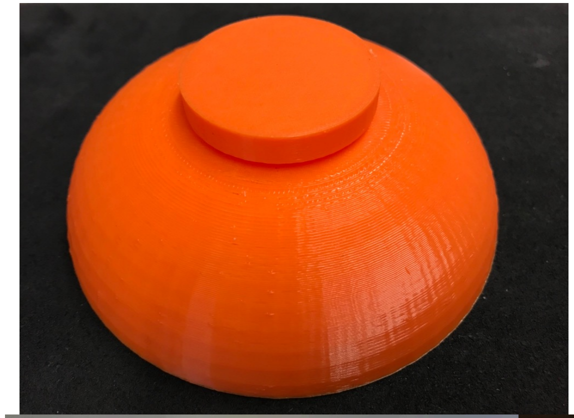
- Our previous result was limited by trigger
- An optimal filter base software trigger was developed for the most recent run with hybrid
- Very important since the region of interest for these detectors is very close to threshold

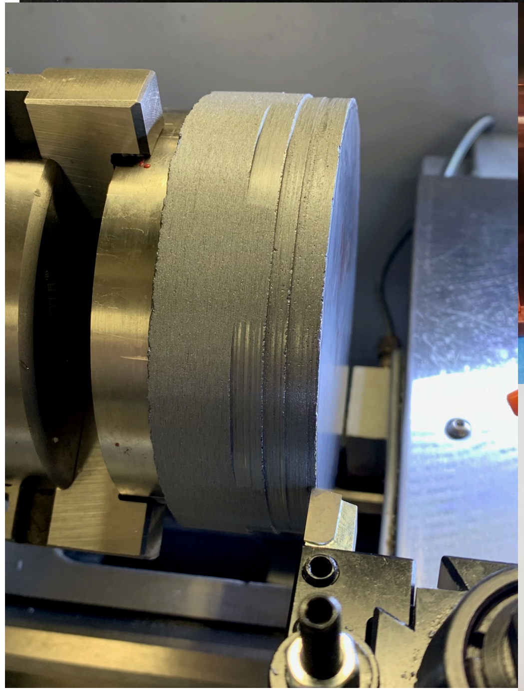
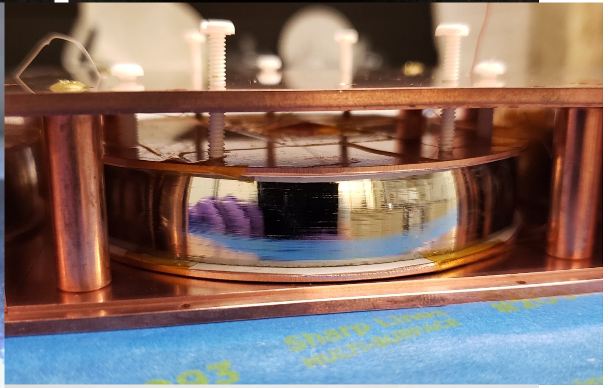
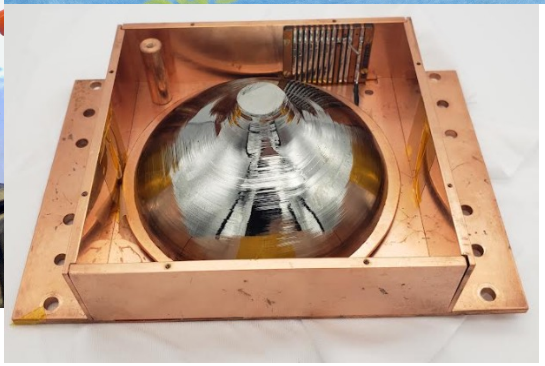
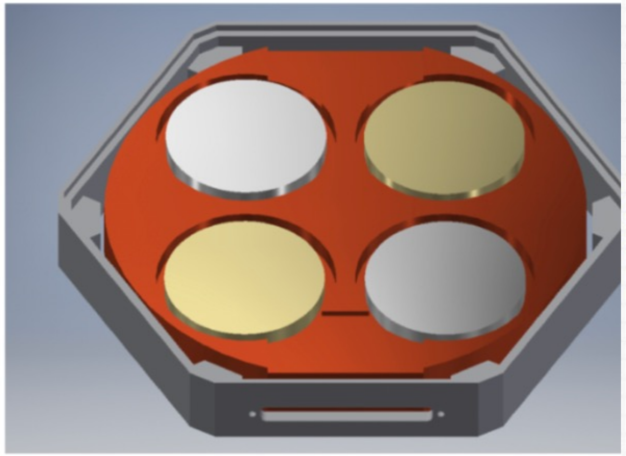
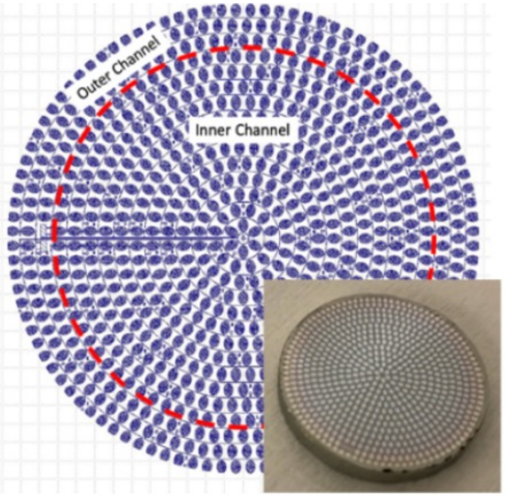




Future R&D

- Recently acquired a **crystal shaping lathe** that allows crystals in any arbitrary shape. Optimize geometry base on the field simulations.
- New contact free method to **test ionization** collection **after grinding crystals** to the desired shape.
- On the analysis side: Proceed with athermal phonon **position correction** to **narrow the NR/ER bands**.
- We further improve our S/N by better mechanical decoupling between the dilution fridge pulse tubes and the detector volume.
- In parallel we study single-electron sensitive Ge, Si devices.



Conclusion

- Two major challenges for low mass DM and low energy coherent neutrino scattering experiments: Threshold and background.
- Rapid progress in the S/N and the threshold, the backgrounds remain still a challenge as demonstrated by the EXCESS consortium.
- Identification of nuclear versus electron recoil will remove majority of the background. So far limited to > keV.
- We demonstrated a path toward NR/ER discrimination by simultaneously measuring energy using recoil phonons and indirectly measuring ionization from NTL phonons that are generated when carriers drift in a hybrid HV/LV design.
- Future generation of this technology will allow fiducialization.
- The detector actively in use for CEνNS searches in the MINER experiment and once the R&D complete can be a candidate for future low background DM searches, notably SuperCDMS at SNOLAB.