



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Development of Carbon-based Dark Matter Detectors with Magnetic Phonon Sensors



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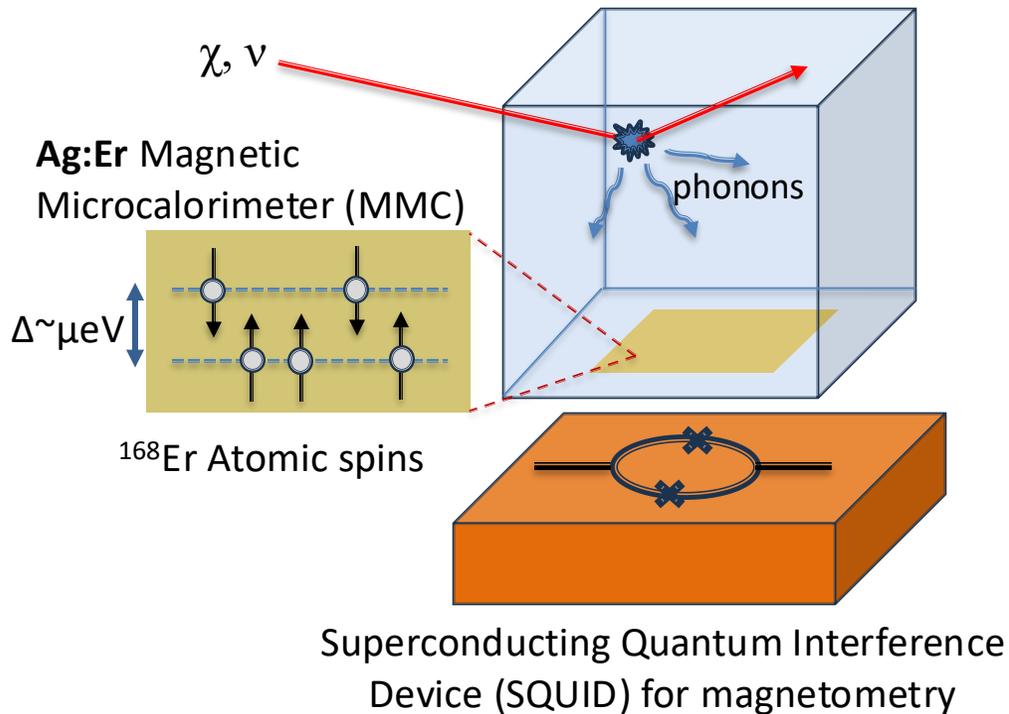
LLNL-PRES-2012137



Magnetic Phonon Sensing for DM & Neutrino Detection

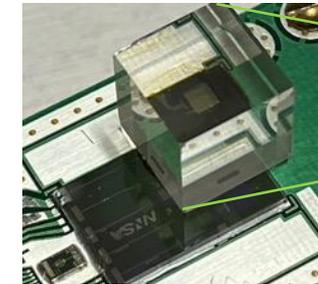
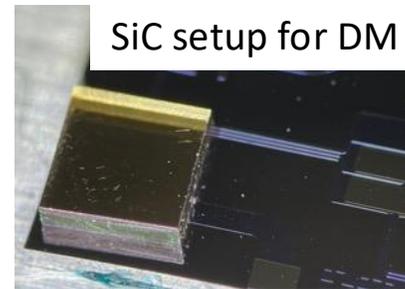
Detection Principle:

DM/ ν scattering and phonon generation \rightarrow Absorption to a magnetic sensor and spin flip \rightarrow Quantum magnetometry

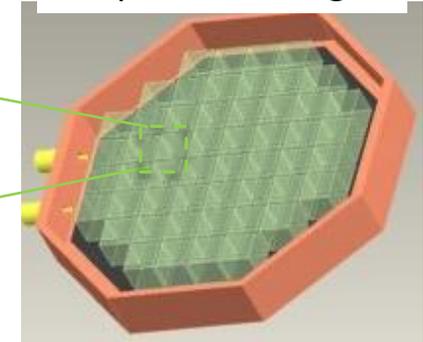


Target Crystal Selection:

- Low-Z crystals (Diamond, SiC) for low mass DM
- High-Z crystals (PbWO₄) for CEvNS



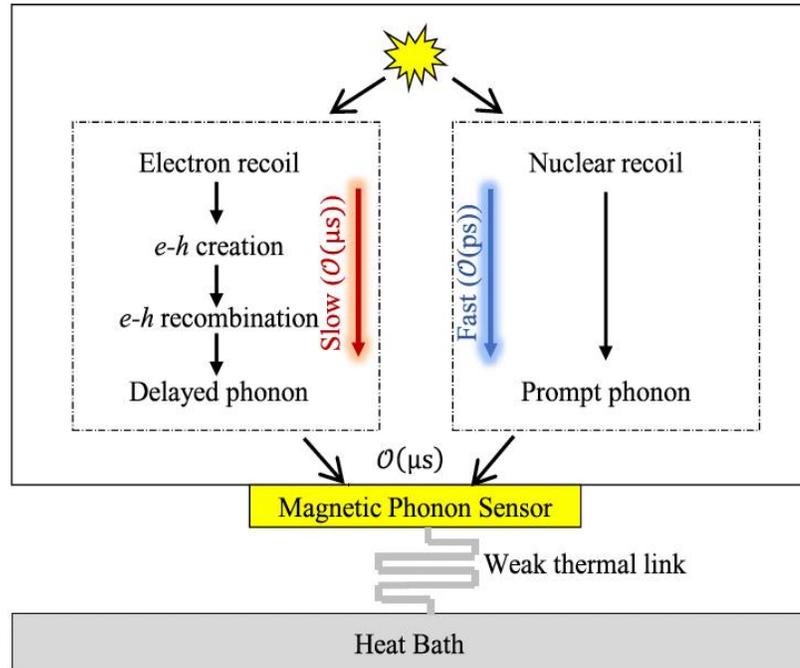
Proposed scaling



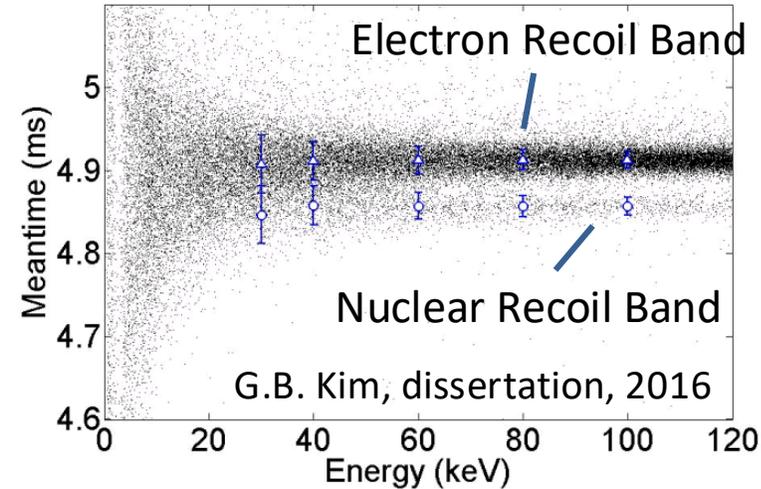
Key Features

- Not a “substrate” style. Use bulk single crystals for heavy mass.
- Fast response of O(10ns) for **Phonon Pulse Shape Discrimination** and **active background rejection**
- Compatible with “exotic” crystals (e.g., diamond, PbWO₄, Li¹⁰⁰MoO₄).
- Good scalability, without need of direct sensor fabrication on crystals

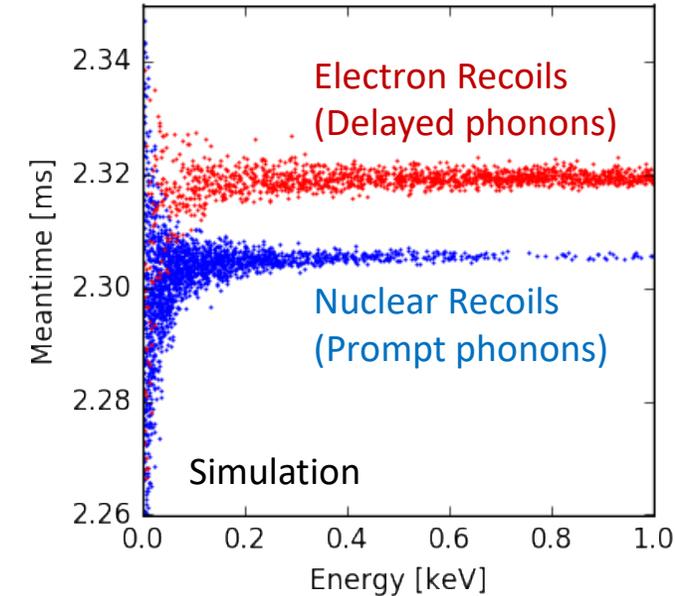
Phonon Pulse Shape Discrimination



214g CaMoO₄ AMoRE 0νββ experiment

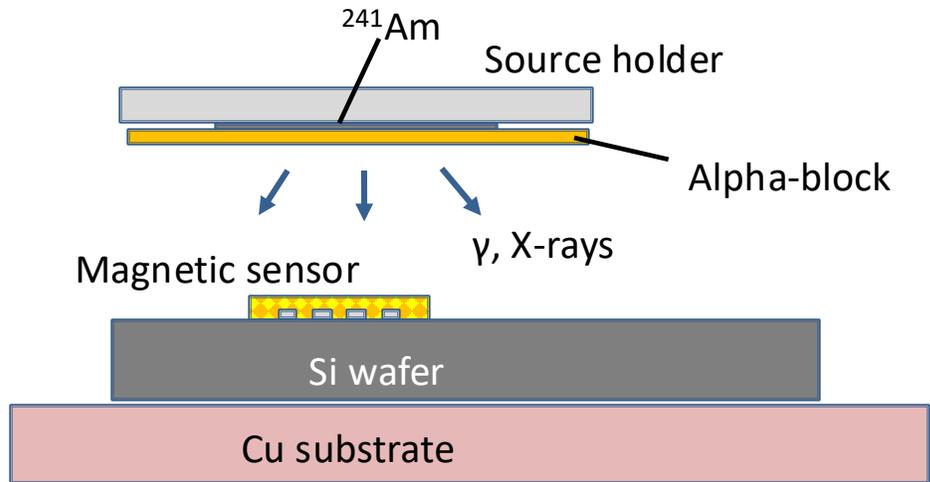


Ge with 100μs e-h lifetime

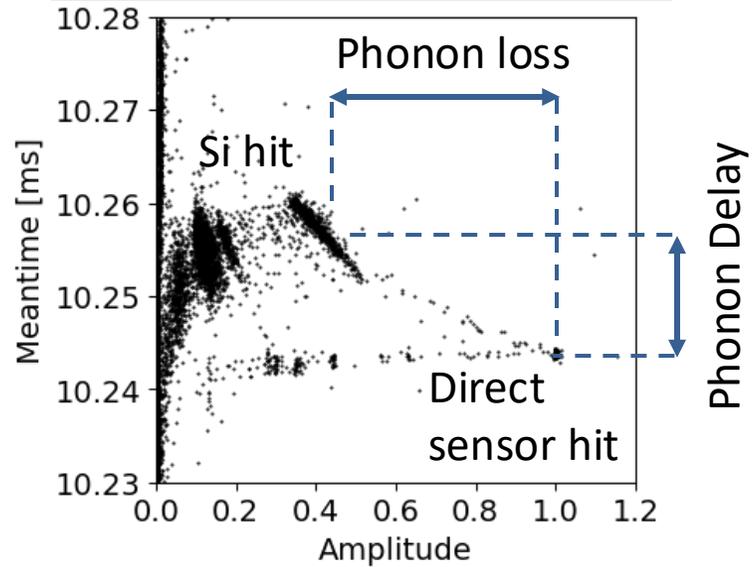


- Electron recoil background → electron excitation → delayed phonon generation → slow phonon pulse shape.
- Phonon-PSD is already proven and utilized for 0νββ.
- Phonon sensor can be as fast as O(10ns), for efficient phonon pulse shape discrimination for semiconductor crystals (SiC, Diamond, Ge.)

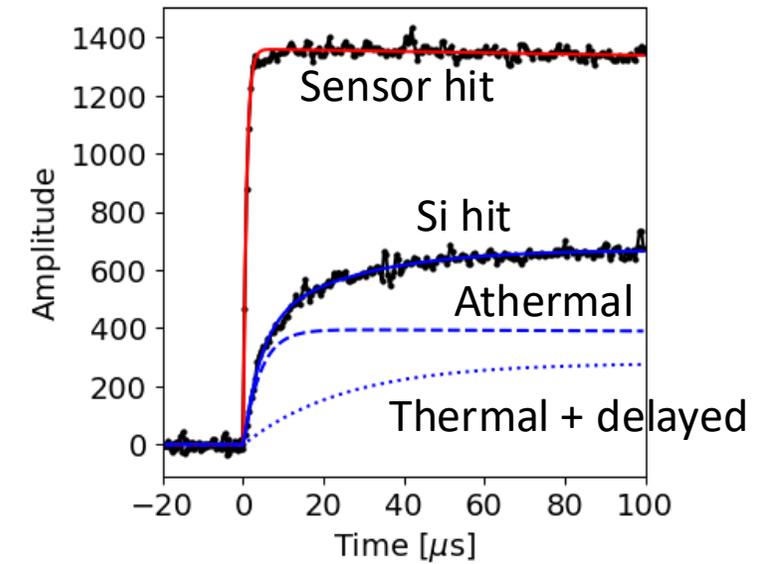
Detector Response Example



Pulse Shape Distribution



Phonon Signals with model fit



- **Faster sensing speed → better PSD power**
- **Surface events, thermal signals, and electron recoil signals could be separated out with phonon-PSD.**

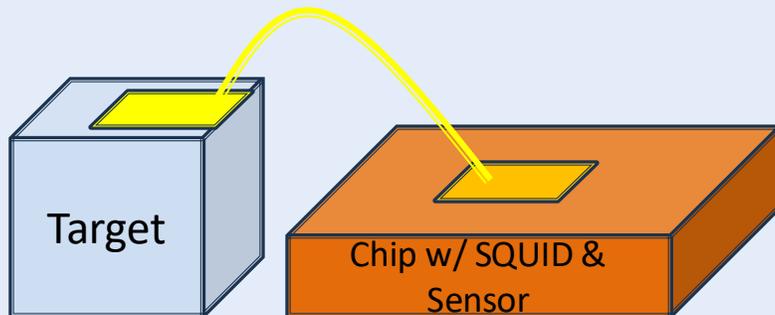
Advancement of Crystal Coupling Approach

- How do we get heat (phonons) from target into the magnetic foil?
 - Faster heat flow => Better discrimination from noise
 - Stage-2 has been demonstrated for "Decay Energy Spectrometry" experiments.

Drawing by W. Matava

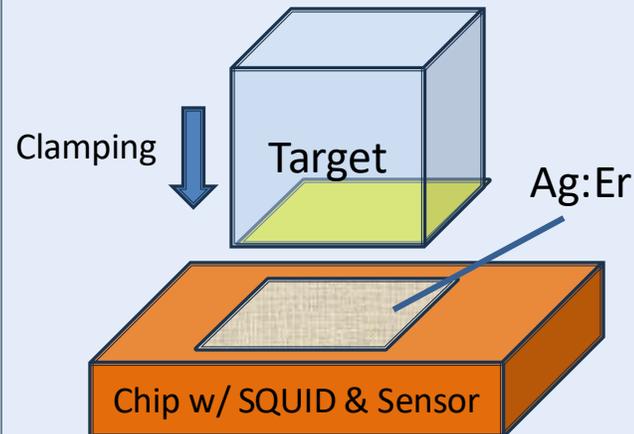
Stage 0

- Ag:Er attached to sensor
- Au foil onto target
- Thermal link made by Ag wirebond
- $\sigma_E = 170$ eV with 216g CaMoO_4 , 2014



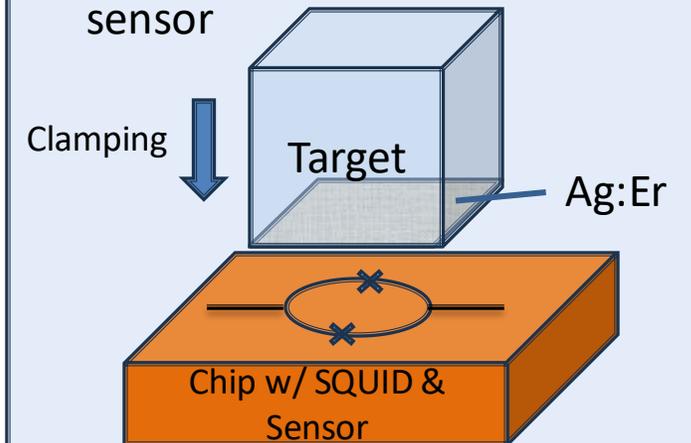
Stage 1

- Ag:Er foil attached to sensor
- Au foil onto target
- Pressure contact

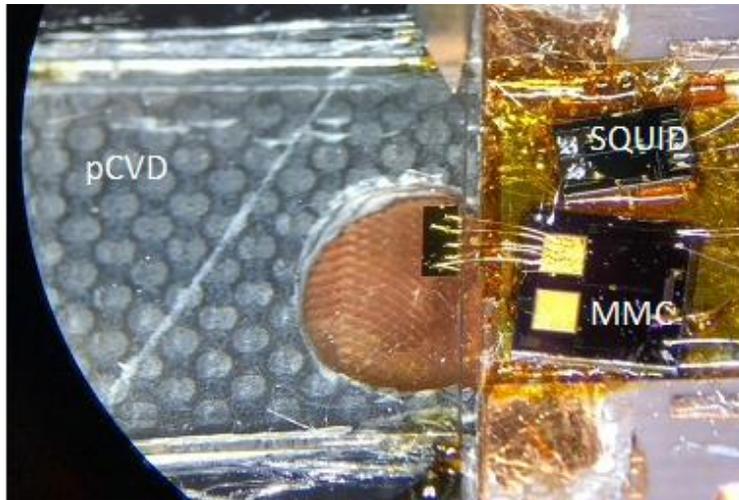


Stage 2

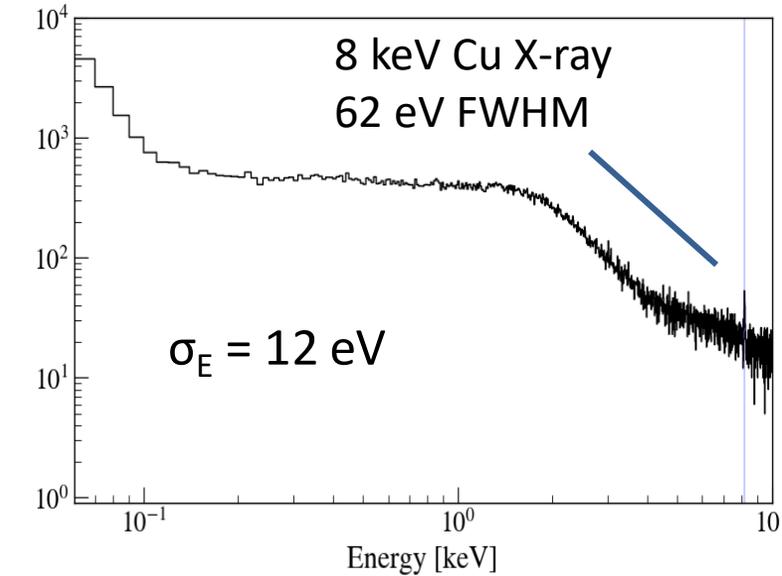
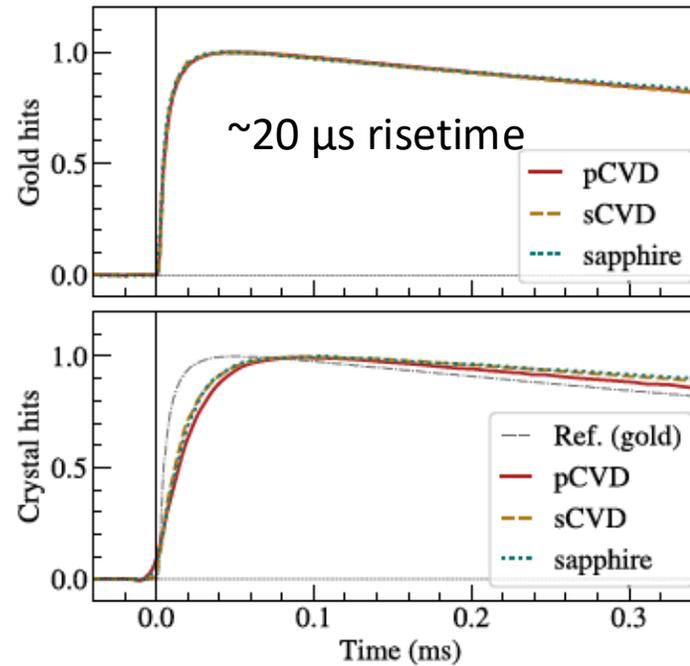
- Ag:Er foil onto **target**
- No** Au foil
- Target clamped onto sensor



Stage-0 Setup: Comparison of Diamond vs Sapphire



I. Kim et al., Physical Review D 111, 072009 (2025)



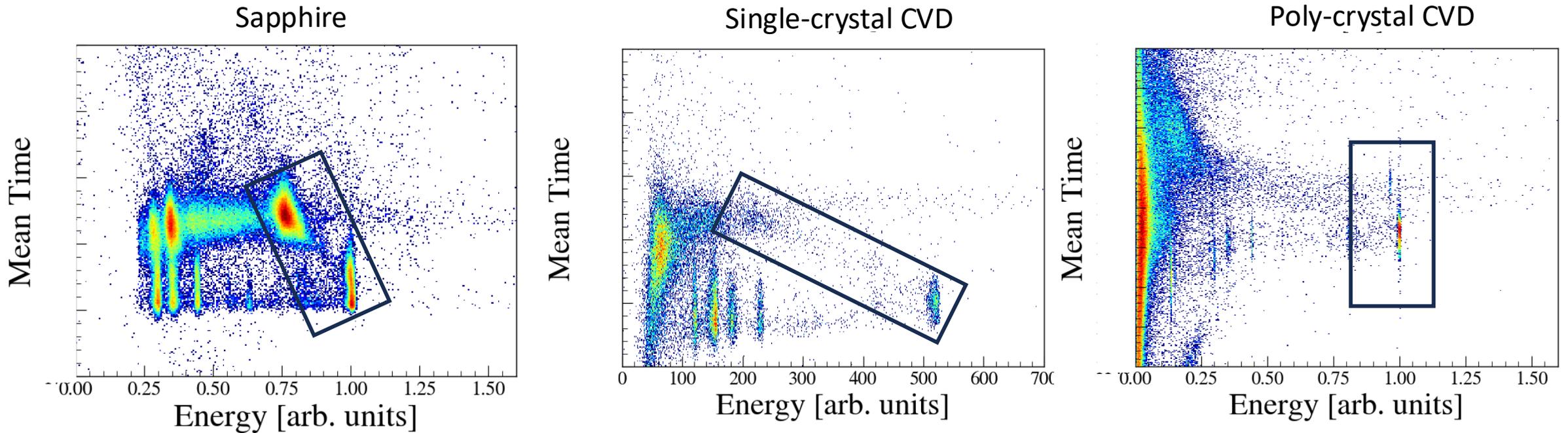
- 5mm x 5mm CVD/Sapphire + External ^{241}Am source
- Compare athermal phonon attenuation

- Phonon sensor hit vs crystal hit pulse shape analysis.
- 20 μ s risetime for sensor hit
- 12 eV energy resolution with pc-CVD

Single crystal Diamond, poly crystal diamond, and sapphire are compared

Stage-0 Setup: Comparison of Diamond vs Sapphire

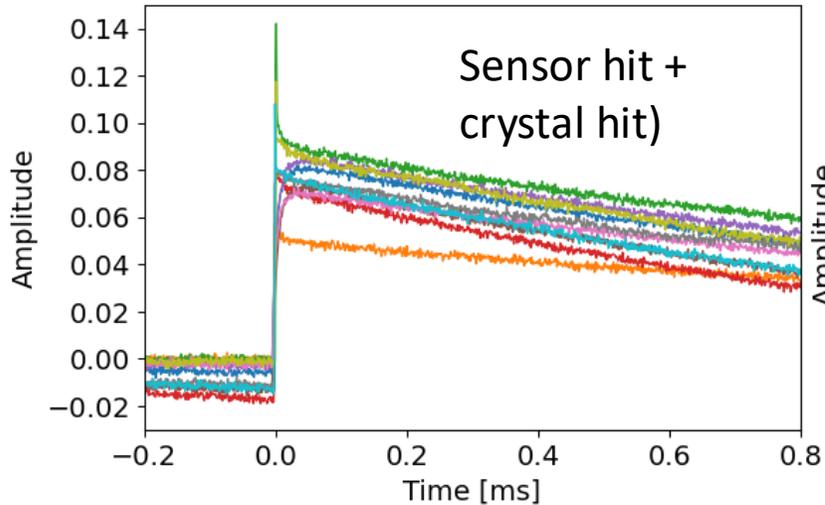
Amplitude and phonon arrival timing analysis for crystal hit vs phonon sensor hit events



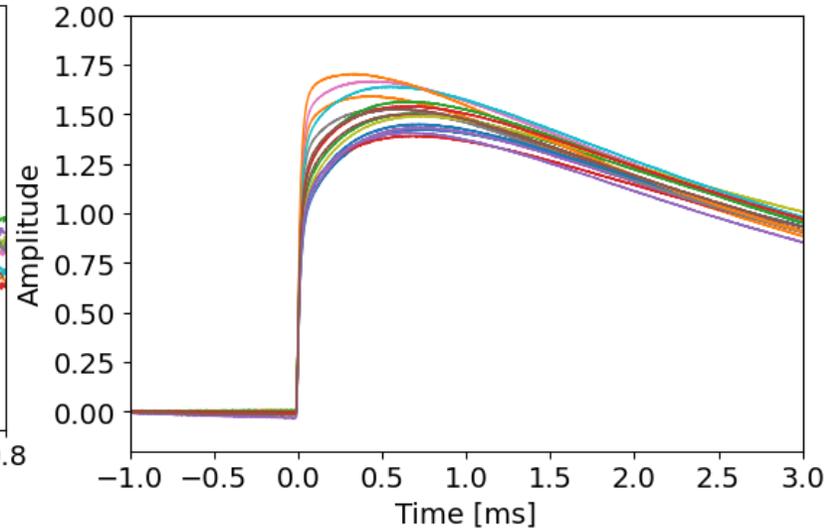
Poly-crystal CVS Exhibited Excellent Performance

Surface Event Rejection Potential

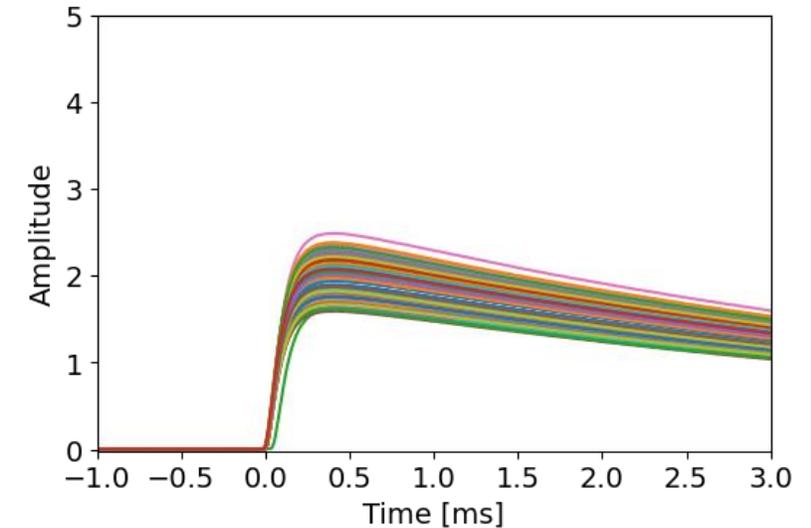
pc CVD Photon



pc CVD Alpha



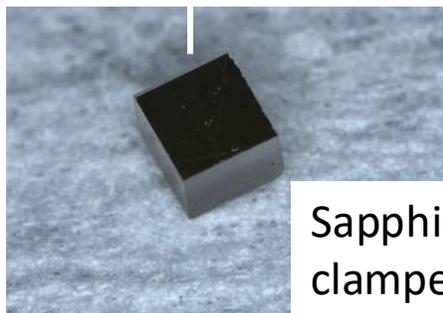
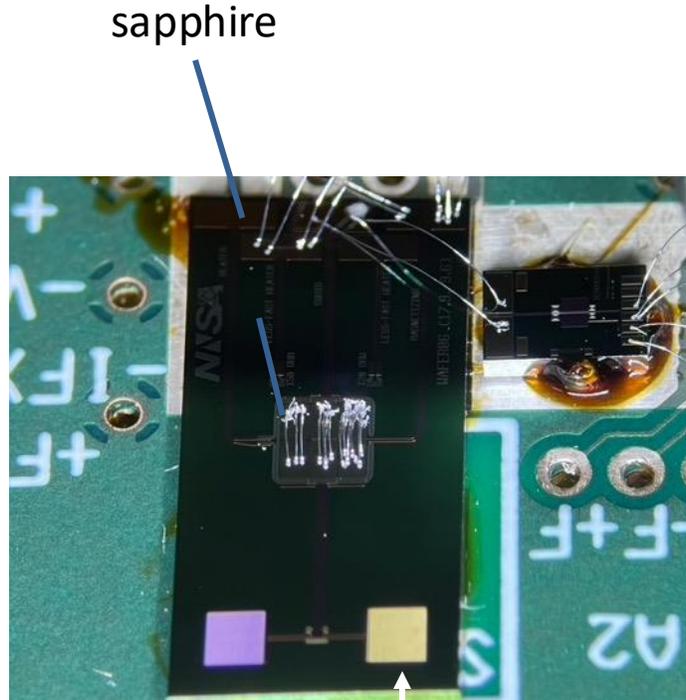
Sapphire alpha



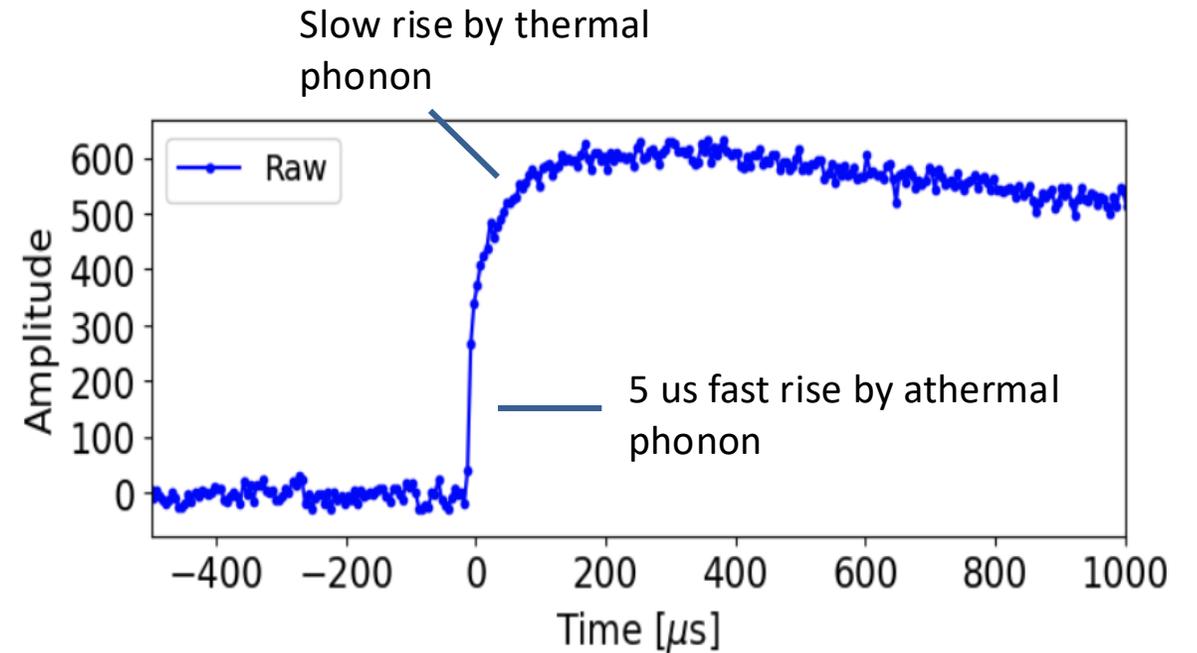
- Surface alpha events exhibited different pulse shapes in pcCVD detector (never been observed in sapphire)
- It is likely due to high thermalization rate of phonons. “Dead layer” effect?
- This is similar to the PSD of HPGc, see LEGEND talk, Wed 2:20pm by Louis Varriano

Surface Event Rejection Might be Applicable with Diamond crystals

Stage-1 Setup with a Sapphire Crystal

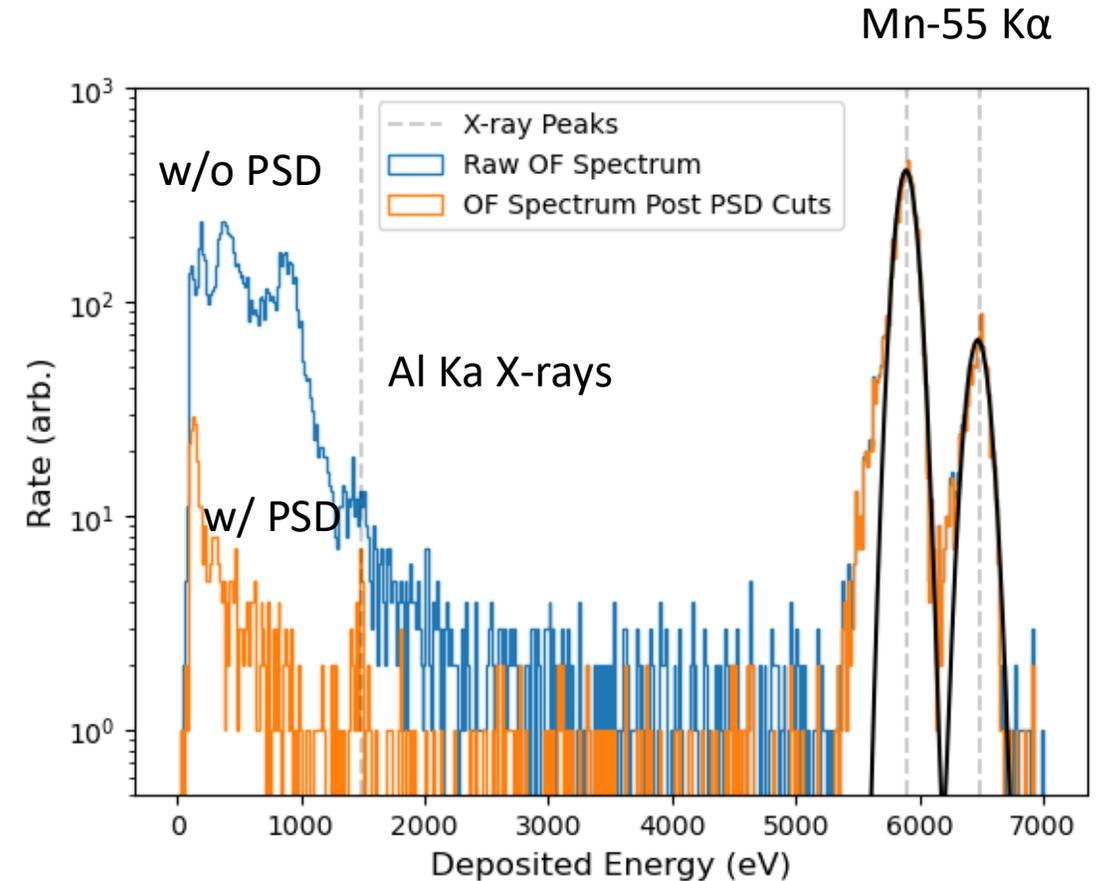
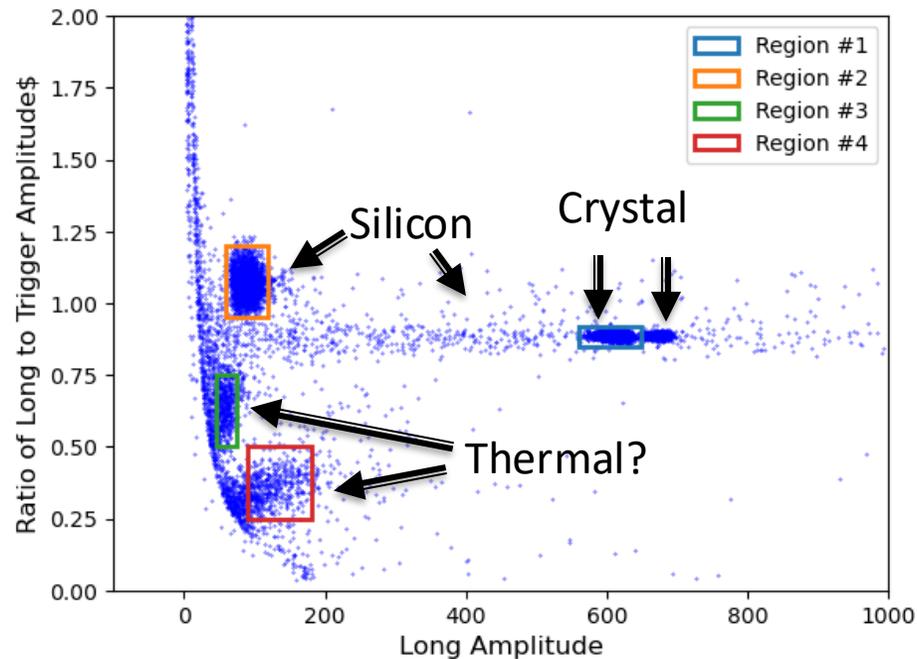


Sapphire with a gold pad is clamped on a magnetic sensor



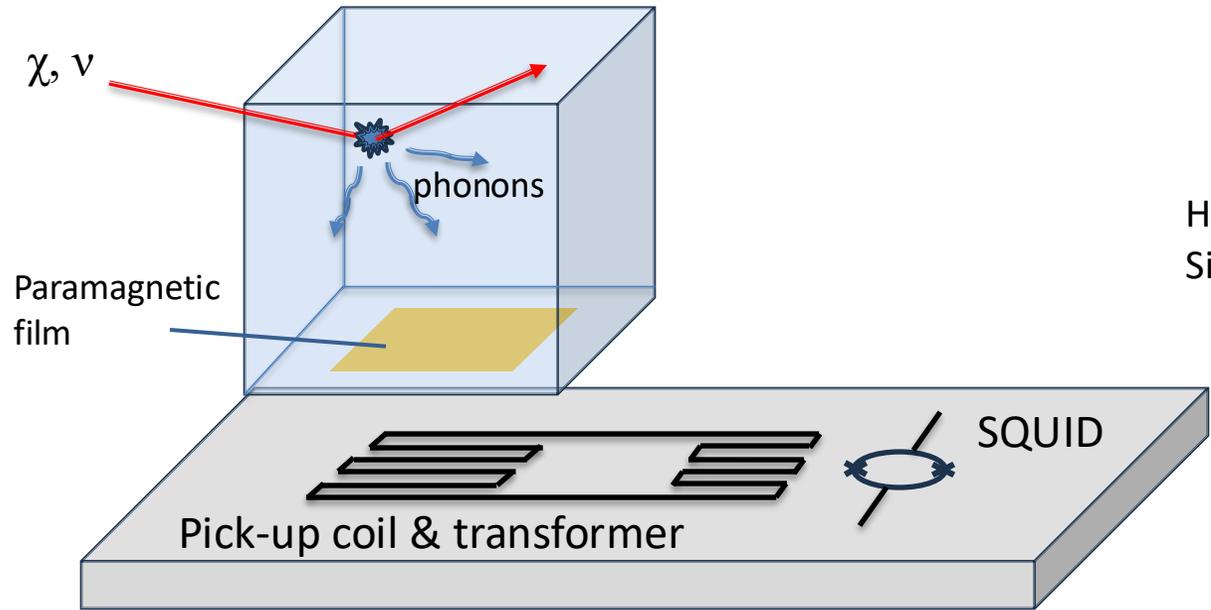
- Risetime is reduced to $\sim 5 \mu$ s
- Still a large fraction of phonons are thermalized

Stage-1 Setup with a Sapphire Crystal

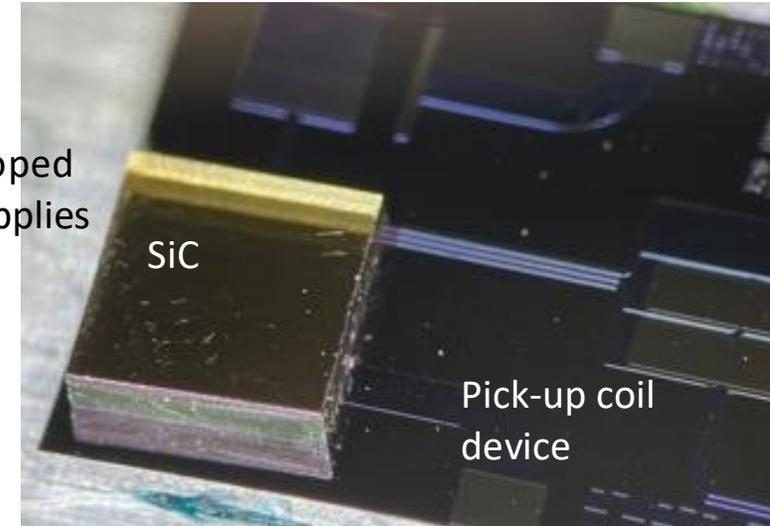


- Si substrate hit produces large background
- Non-sapphire hit events were separated by phonon PSD

Stage-2 Setup with a SiC Crystal (W. Matava)



High-purity Undoped SiC from MSE supplies



Strength

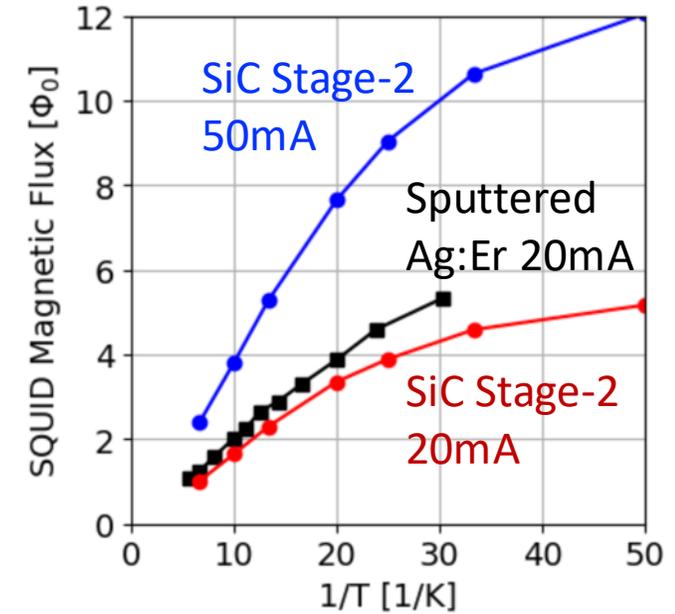
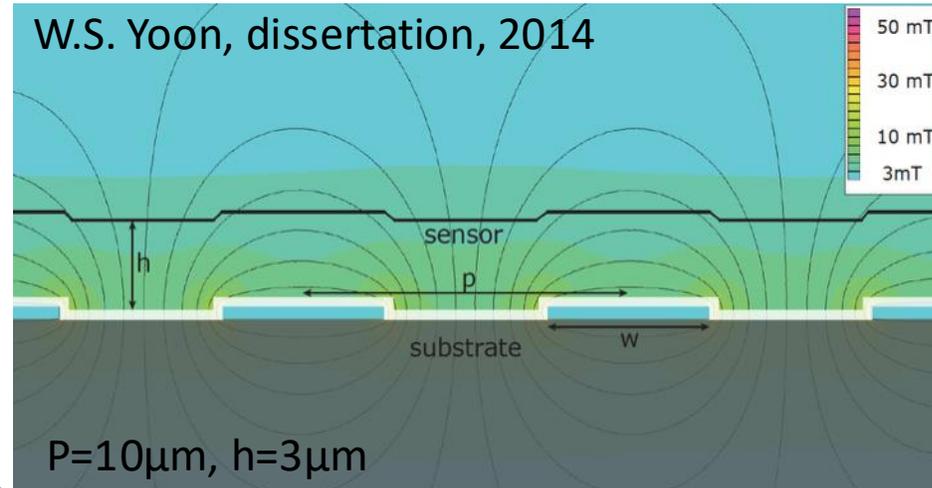
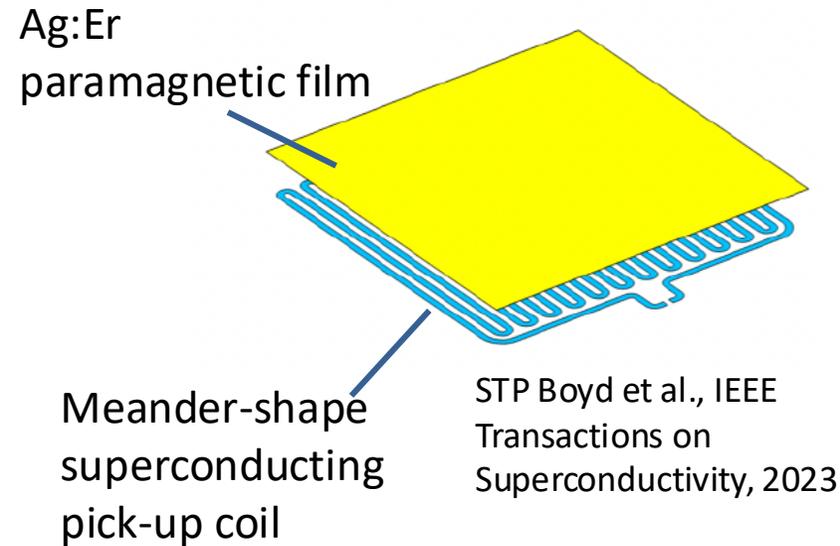
- SC circuits on Si wafer, no fabrication on the detector crystal.
- No electrical or thermal contact to the detector crystal

Risk

- Risk of magnetic contamination
- Reduced pick-up coil – sensor coupling

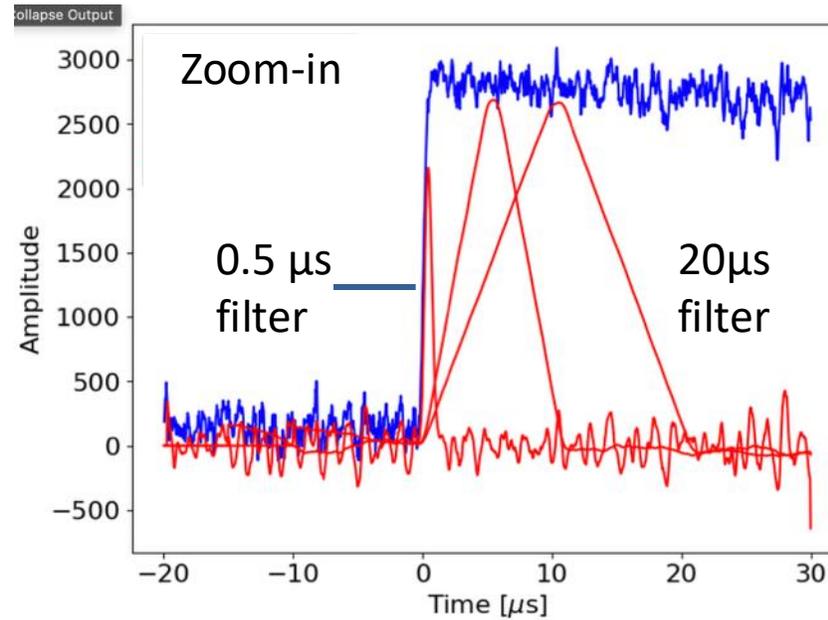
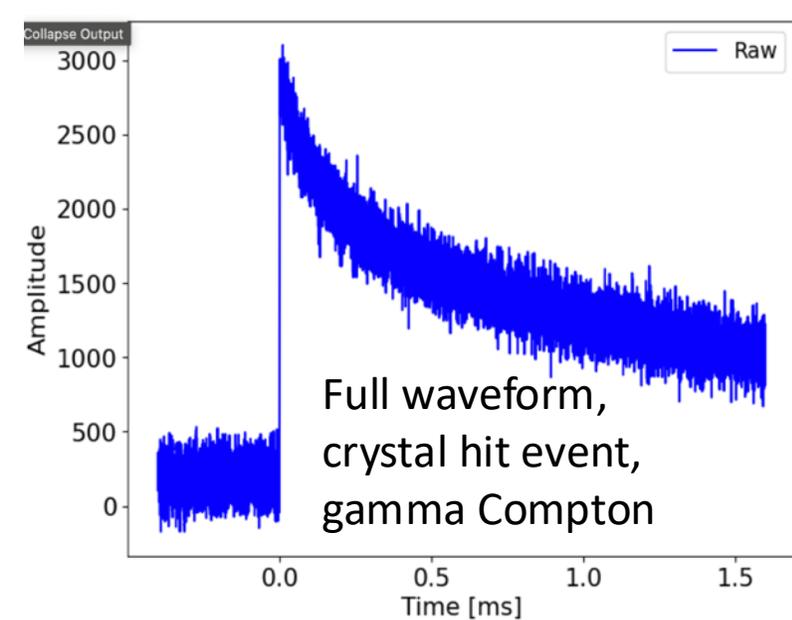
SiC results with TES: Aditi Pradeep, Advancing TES-Based Detectors for Sub-GeV Dark Matter Detection, Wed 3:20pm

Stage-2 Setup with a SiC Crystal - Magnetic Coupling Study

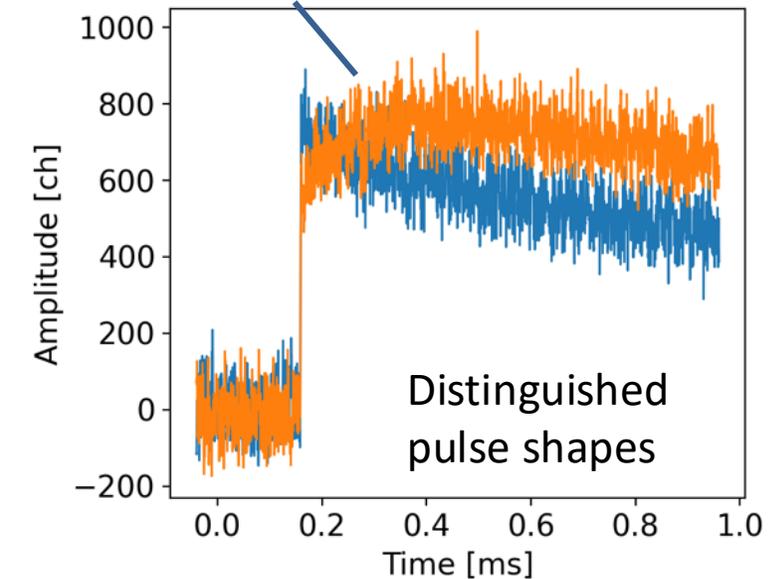


- Current $10\mu\text{m}$ pitch design has magnetic field rapidly decreasing at $h>5\mu\text{m}$.
- Need optimization to maintain coupling with finite gap in the stage2 setup.

Stage-2 Setup with a SiC Crystal



Thermal or delayed phonon ($\tau_{\text{rise}} = O(100\mu\text{s})$)



- First-ever signal with the full stage-2 setup
 - **~300 ns 10% - 90% risetime**, still limited by the SQUID electronics bandwidth (2MHz)
 - No slow rise \rightarrow very low thermal phonons?
 - Energy resolution?
 - Phonon PSD for EXCESS?
- } Will be studied

Summar and Discussion

- Stage-2 setup was demonstrated with a SiC crystal.
- **Timing resolution: 300 ns signal risetime** was observed, and it is still limited by electronics bandwidth.
- **Energy resolution: 12 eV energy resolution** was obtained with stage-0&1 setup.
- To improve E resolution for $O(1 \text{ eV})$:
 - Reduce the size of sensor film. Thickness: $1.5\mu\text{m} \rightarrow 50 \text{ nm}$. (x30). Area: $4\text{mm}^2 \rightarrow 0.04\text{mm}^2$ total x3,000 reduction \rightarrow Improving energy resolution by (x3,000 – x55)
 - Sensor-Pickup coil coupling. Achieved 80%, can further be improved.
 - Fully integrate DC-SQUID and pick-up coil (no transformer)
- Superconducting circuit needs development. Pick-up coil optimization (geometry and high critical current, SQUIDs, and multiplexing).
- archPbWO_4 crystal will be developed for CEvNS detection.

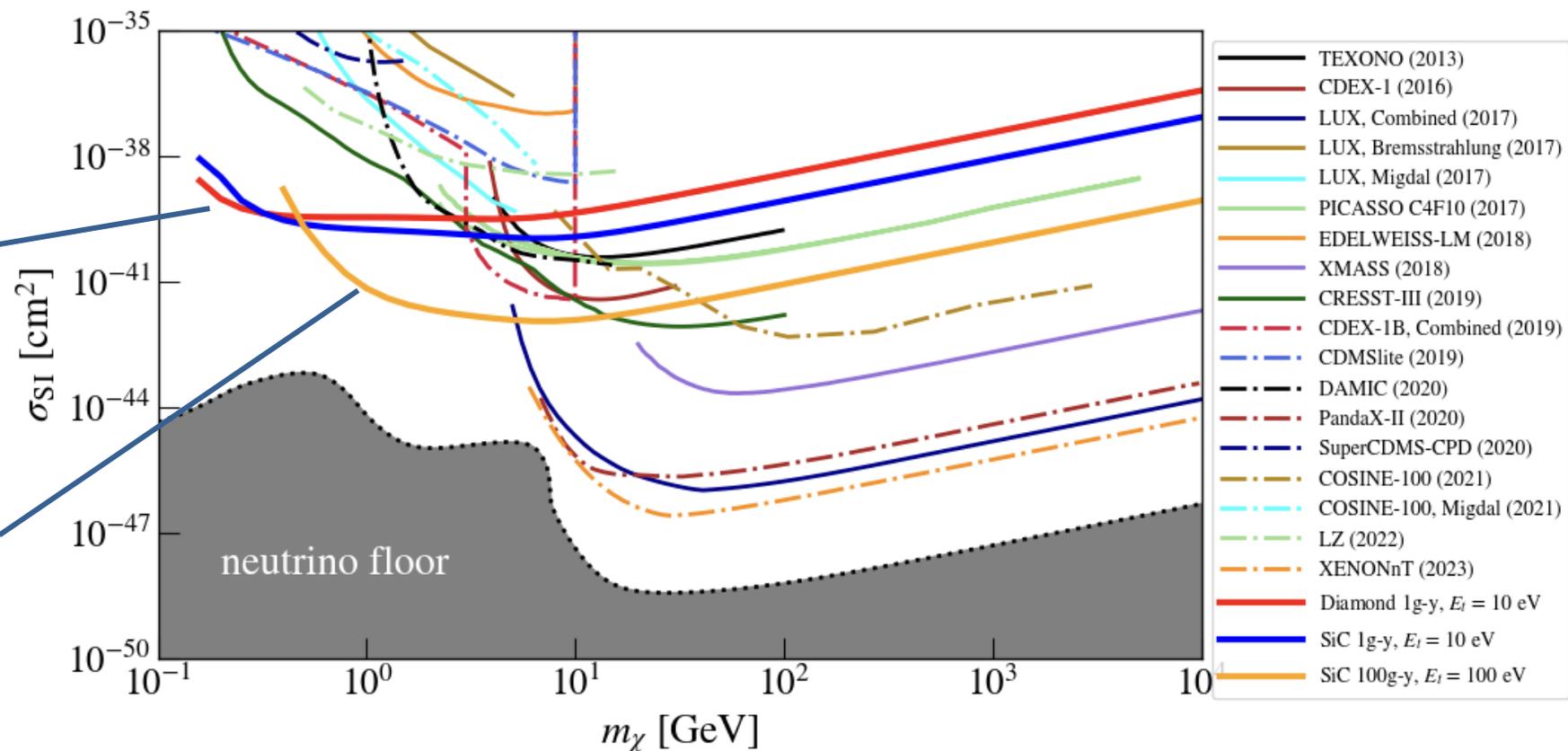
- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
- The work is funded by Office of Science of Department of Energy, under Advanced Detector Research and Development Program of High Energy Physics office.
- This work was funded by Lawrence Livermore National Laboratory via Laboratory Directed Research and Development program (22-FS-011).

Next Step

- Further improvement of energy resolution/threshold
- Select crystal types, sizes, and a total mass scale.
background, LEE, mass vs E threshold trade-off...
- Operate science runs,
for DM-nucleon scattering search

Conservative sensitivity with
1 g-year Diamond, $E_{th} = 10$ eV
100 dru background rate
(need to handle LEE)

100 g-year SiC, $E_{th} = 100$ eV
100 dru background rate
(avoid LEE)

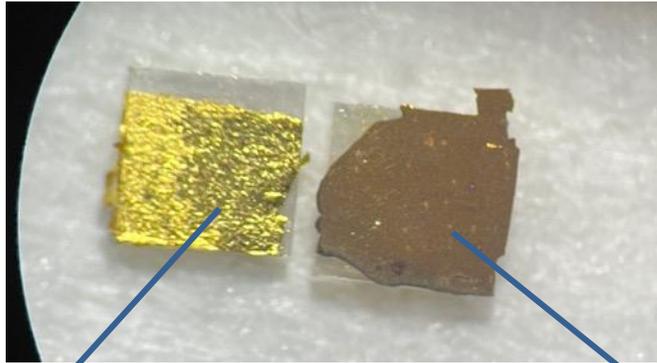




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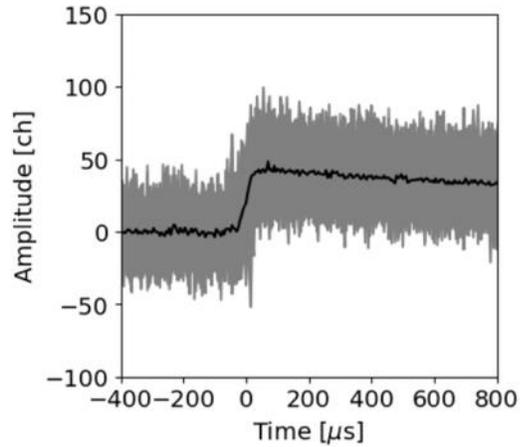
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Stage 1 vs Stage 2 SiC Setup

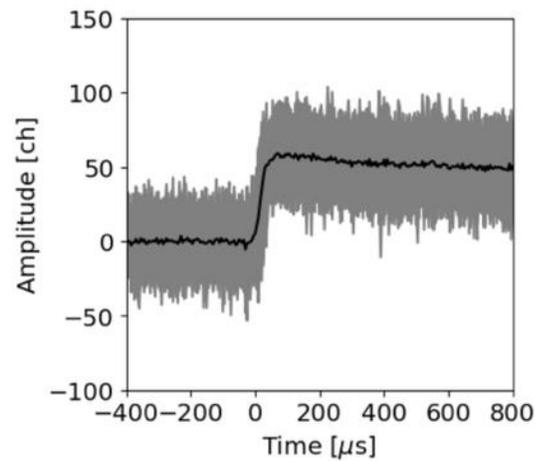


Small signal due to Stycast1266?

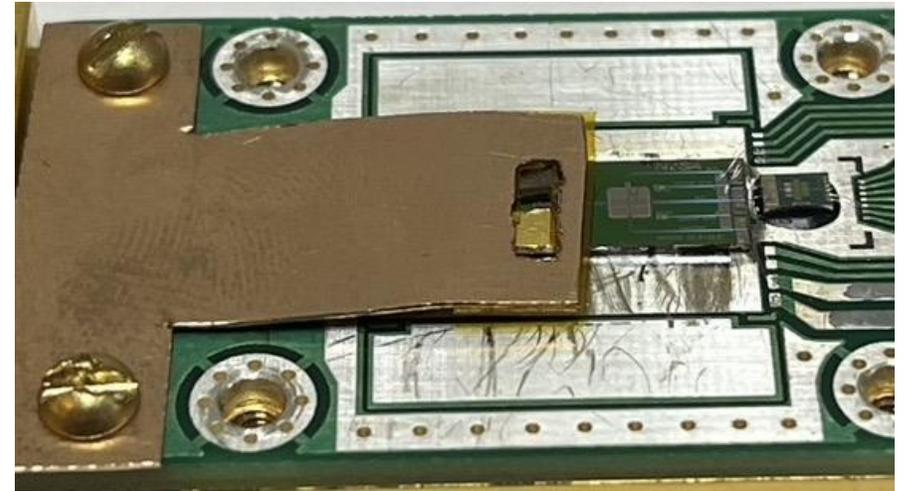
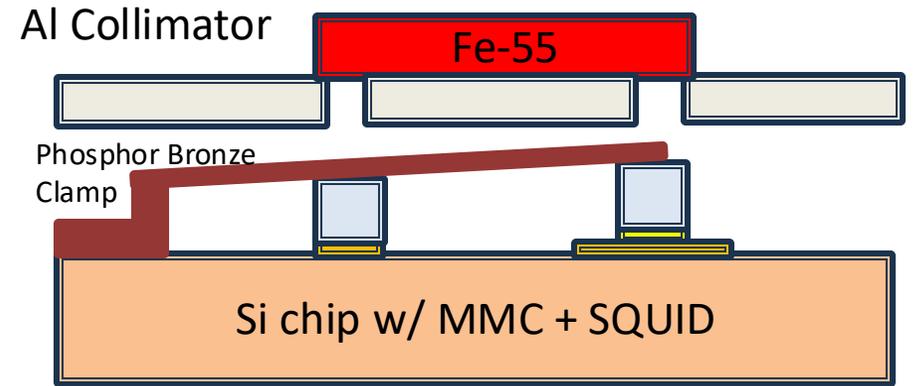
Stage-1 SiC @ 6 keV



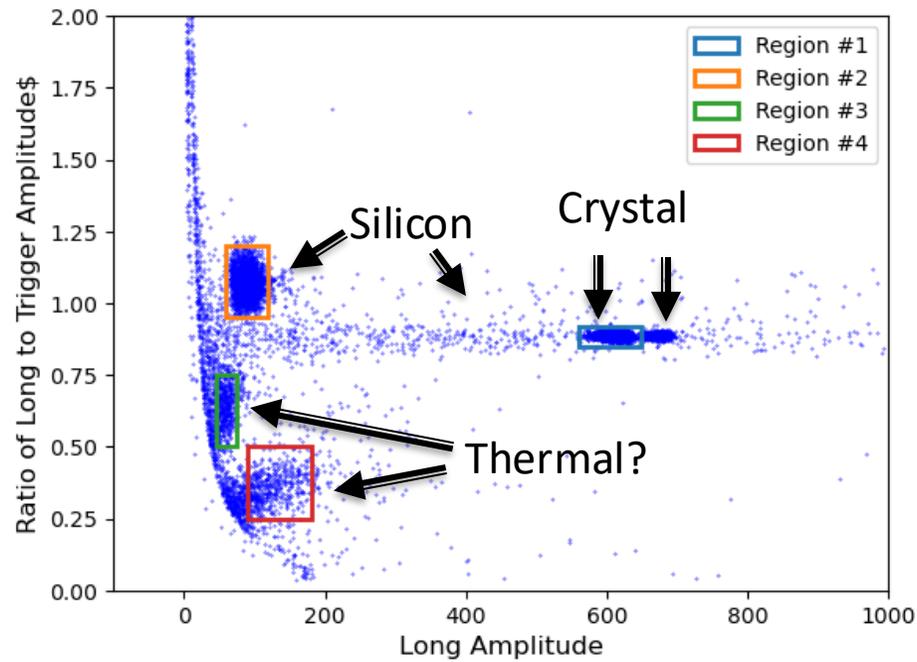
Stage-2 SiC @ 6 keV



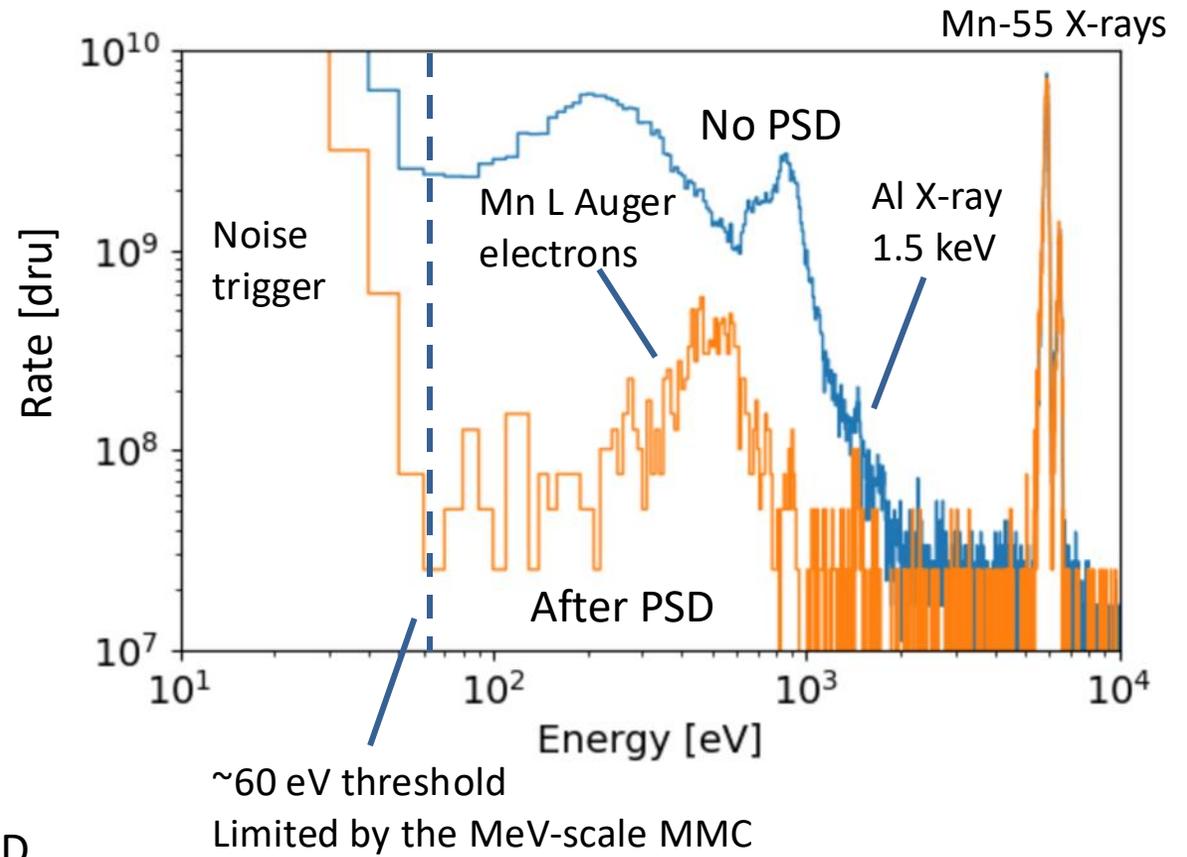
Gray: 100 individual pulses, Black: average



Stage-1 Setup with a Sapphire Crystal



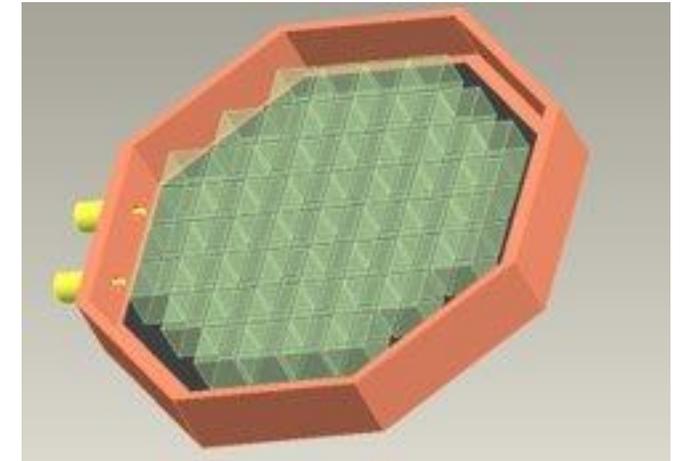
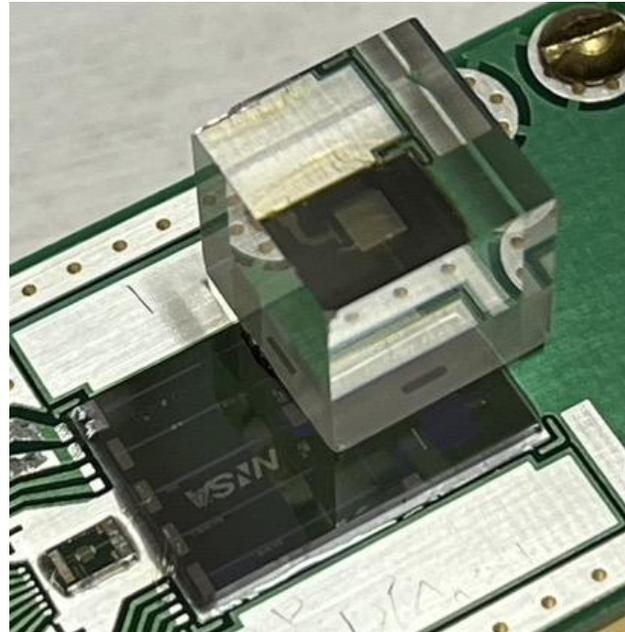
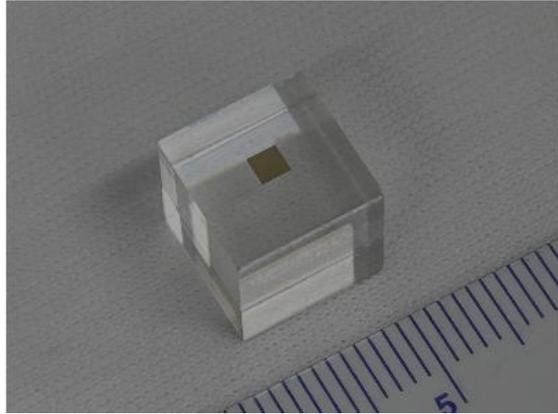
- Si substrate hit produces large background
- Non-sapphire hit events were separated by phonon PSD



~60 eV threshold
Limited by the MeV-scale MMC

Stage-2 Setup with $^{\text{arch}}\text{PbWO}_4$ for CEvNS Detection

Natural PWO, Ag:Er direct sputtering for stage-2
→ Damaged during prep



6-inch Si wafer with SQUID array + PbWO4 or SiC crystals

$^{\text{arch}}\text{PbWO}_4$ from Surge Nargony, LNGS