Development of Remote Magnetic Phonon Sensing for Rare Event Detection

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Oct-21, 2026

LLNL-CFPRES-2024006



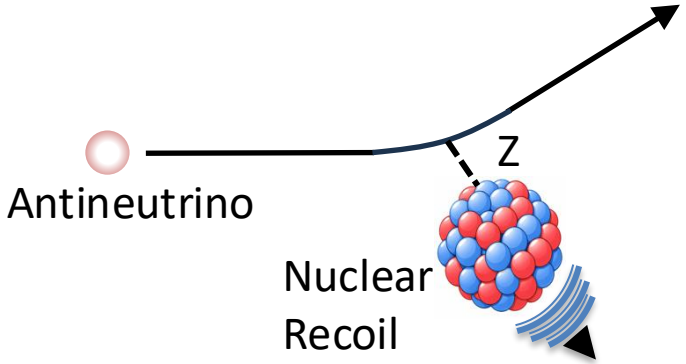
LLNL-PRES-
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

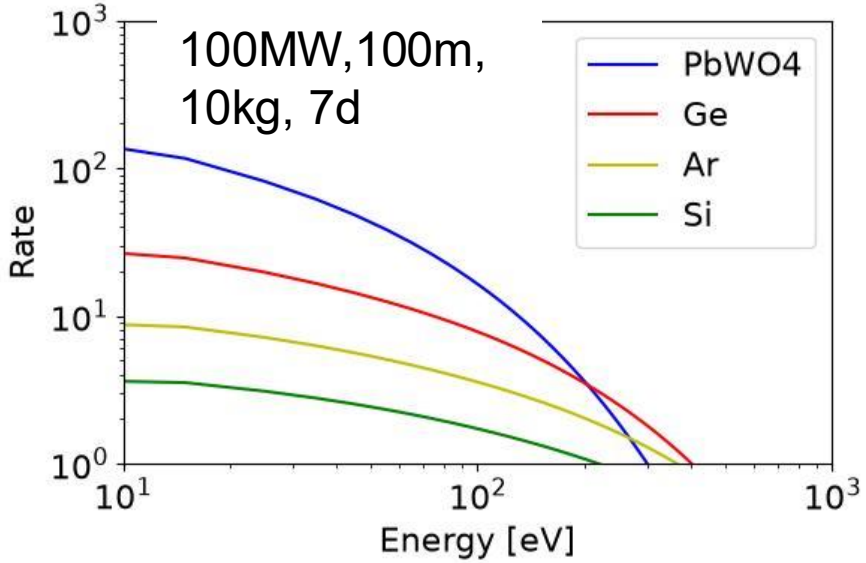
Motivation: Remote Reactor Monitoring via Neutrino Detection



"Floating Nuclear Power Plant"
(www.ans.org/news/article-4061)

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)



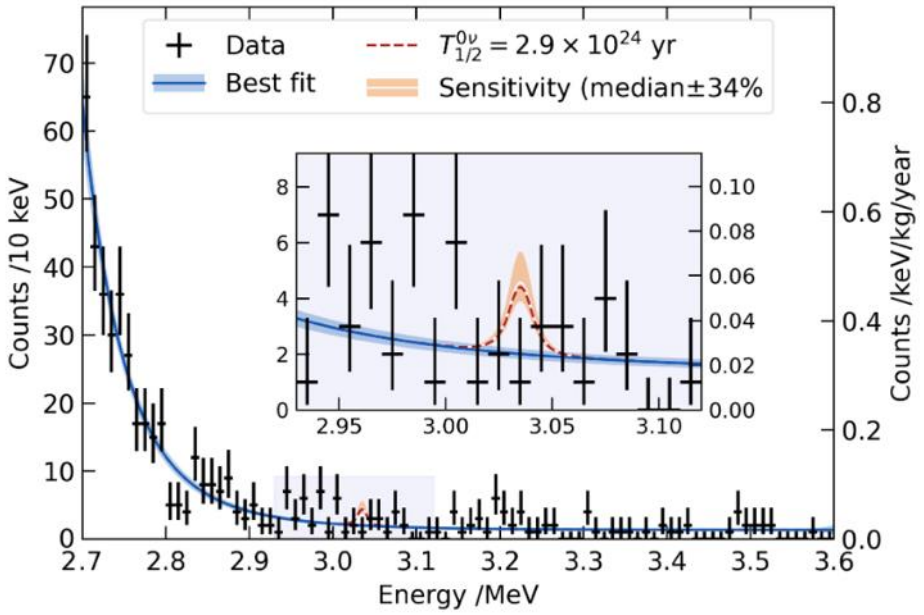


- Signal rate can be significantly increased with CEvNS detection, if the detector has
  1) Heavy element (e.g., Pb)
  2) Large detector mass (>>1kg)
  3) Low background.

Time required to detect 100 MW reactor at 100 m

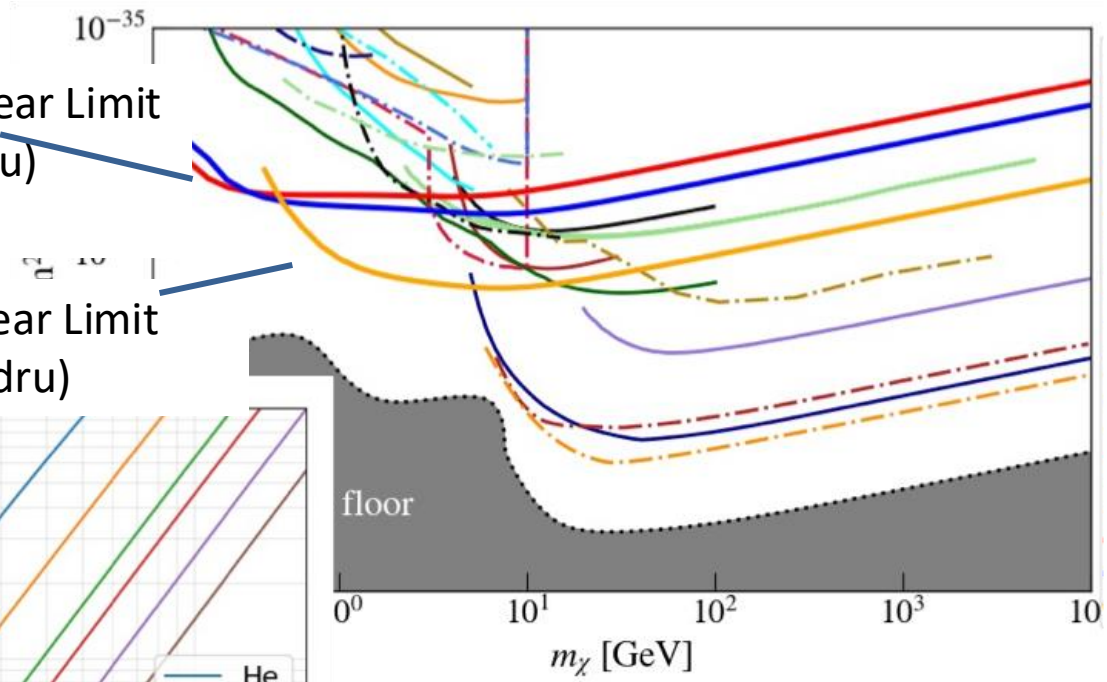
1-ton Liquid Scintillator (current state-of-the-art)	10-kg $PbWO_4$ CEvNS Detector
69 days	2 days

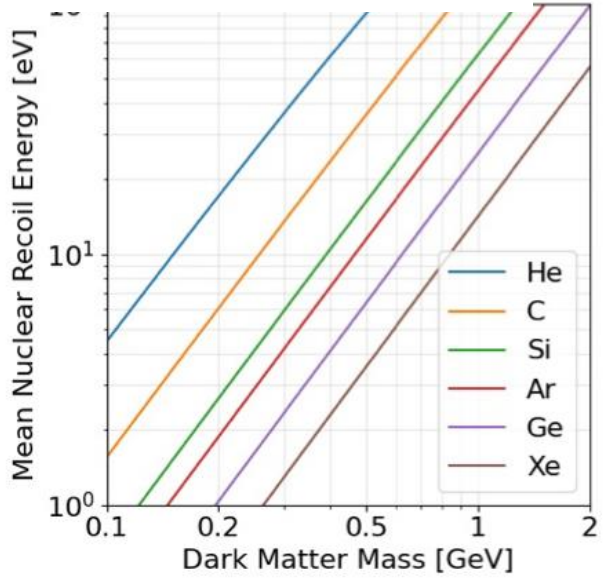
Other Rare Event Detection Experiments

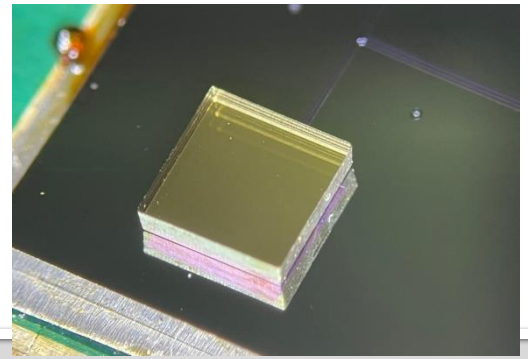


- AMoRE 0νββ experiment
- $Ca^{100}MoO_4$, $Li^{100}MoO_4$
- Magnetic Microcalorimeter

- Diamond 1g year Limit (10 eV E_{th}, 100 dru)
- SiC 100 g year Limit (100 eV E_{th}, 1 dru)







State-of-the-art Superconducting & Quantum Calorimeters

Direct fabrication on detector material
CDMS, TASSERACT, CRESST, NUCLEUS, BULLKID, ….

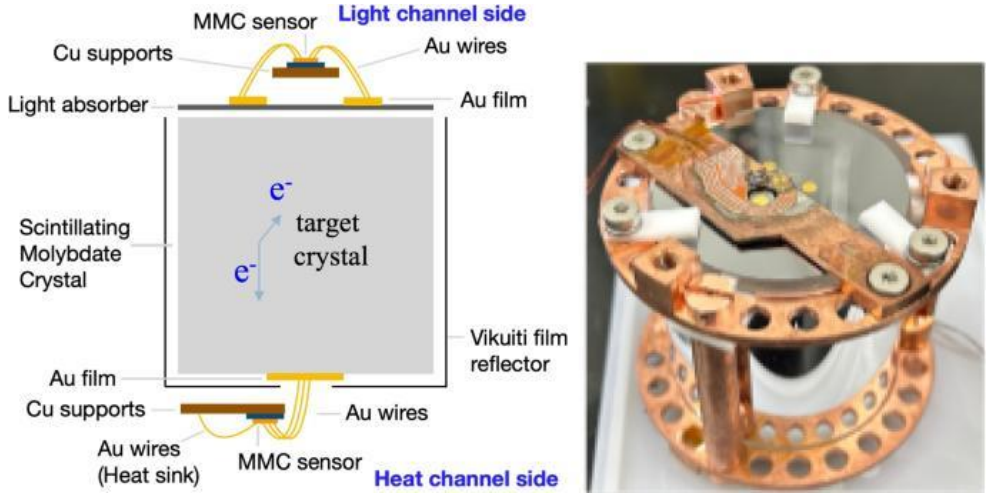
Pros: Best energy resolution
Cons: Limited choice of detector material



https://www.symmetrymagazine.org/article/a-new-search-for-dark-matter-6800-feet-underground?language_content_entity=und

Gold pad and wirebonding
AMoRE, RICOCHET, COSINUS, ….

Pros: flexible material choice
Cons: additional heat capacity of gold pads



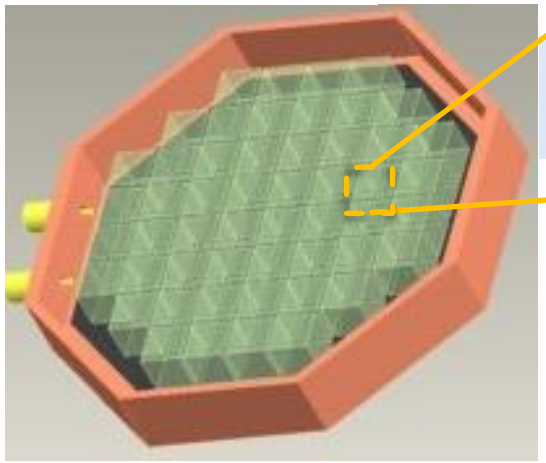
https://link.springer.com/article/10.1007/s43673-024-00132-8

Magneto-DM: Magnetometry for Dark Matter/CEvNS/0νββ Detection

Detection Principle:

1) Phonon generation by particle interactions → 2) phonon absorption and magnetic field change → 3) Quantum magnetometry

Proposed scaling



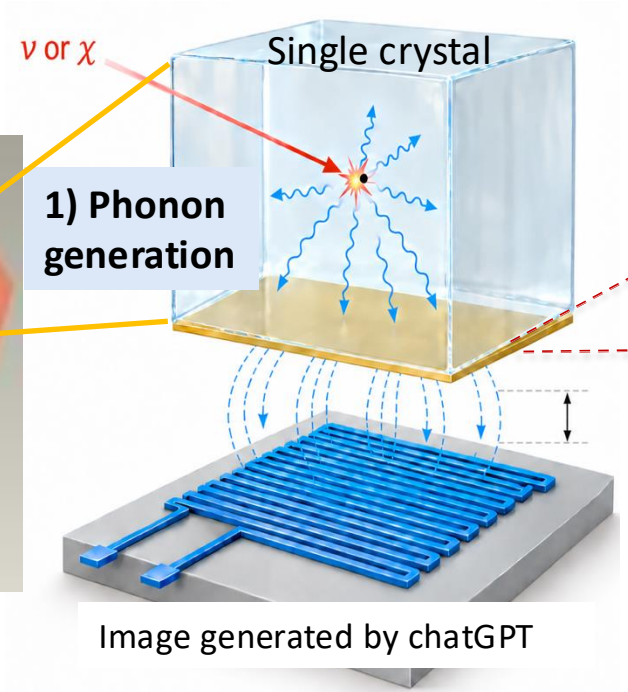
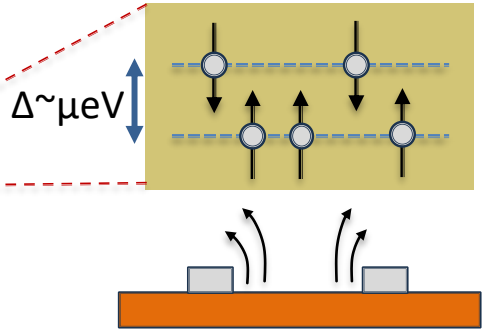


Image generated by chatGPT

3) SQUID-based magnetometry

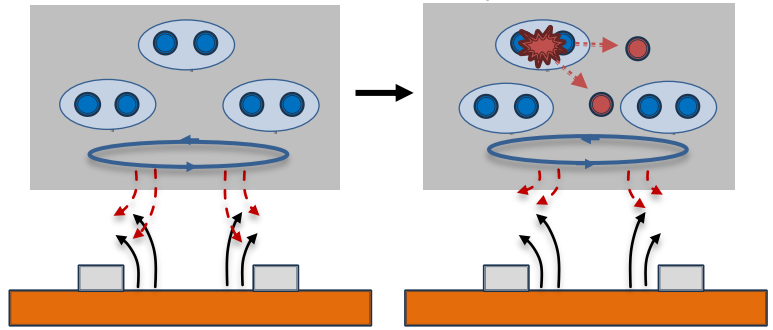
2-a) Spin flip

Ag:Er **M**agnetic **M**icro**C**alorimeter



2-b) cooper pair breaking

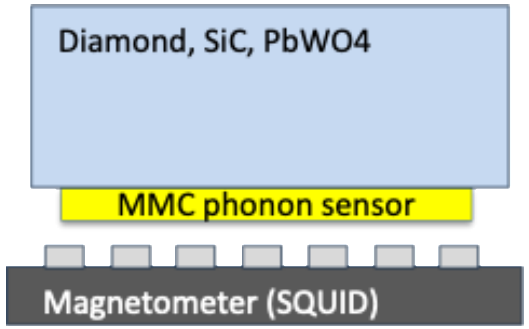
Superconducting film (**M**agnetic **P**enetration **T**hermometer)

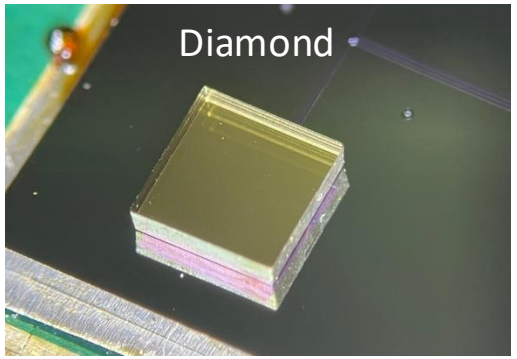


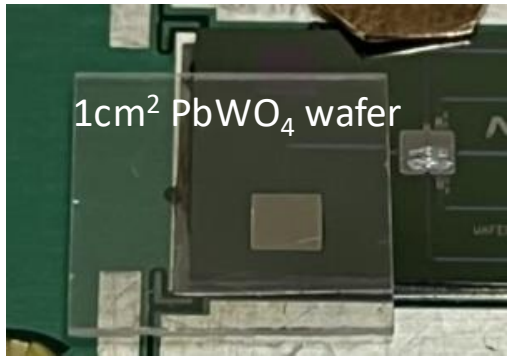
Key advantages

1) Flexible choice of detector material (Diamond, PbWO4, LiMoO4).
2) Scalable, as no direct fabrication is needed.
3) Active background rejection by phonon pulse shape discrimination with sub-μs timing resolution.

Cm-scale $PbWO_4$ Quantum Calorimeters for CEvNS

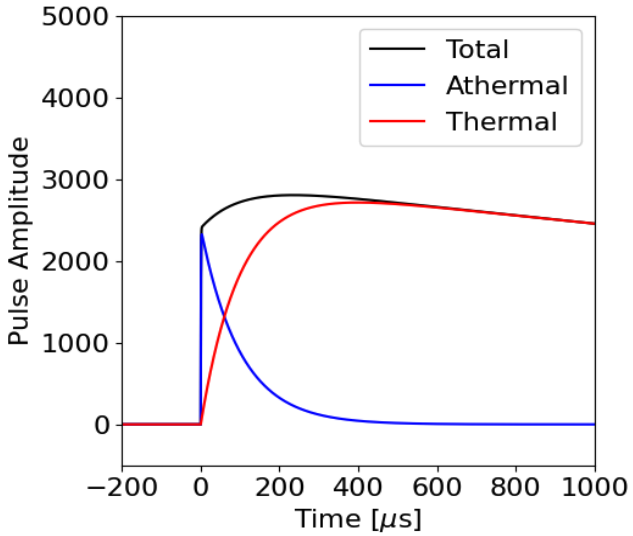




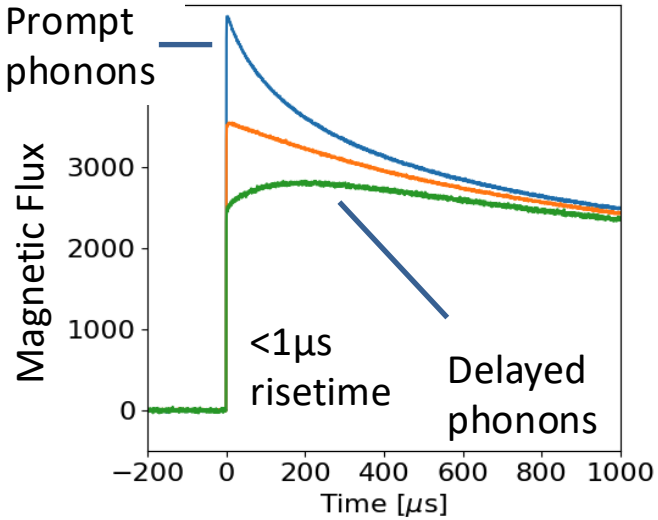




Phonon Signal Model



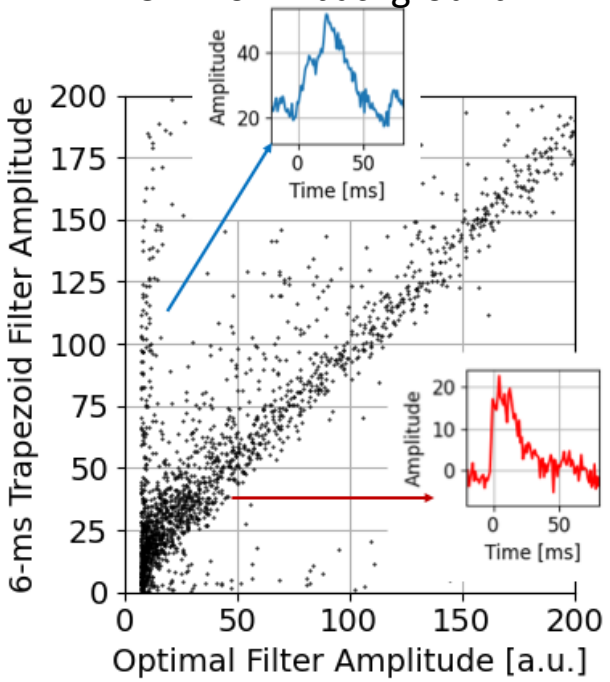
Experimental Phonon Pulses



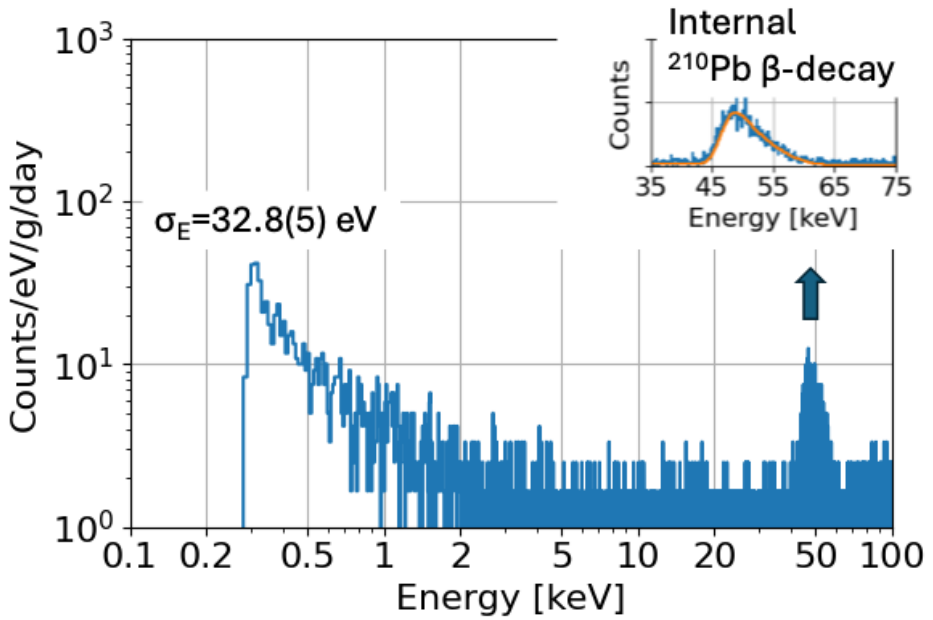
- Demonstrated compatibility with various crystals (Diamond, SiC, CaMoO4, PbWO4)
- Demonstrated sub-microsecond sensing speed.

Cm-scale $PbWO_4$ Quantum Calorimeters

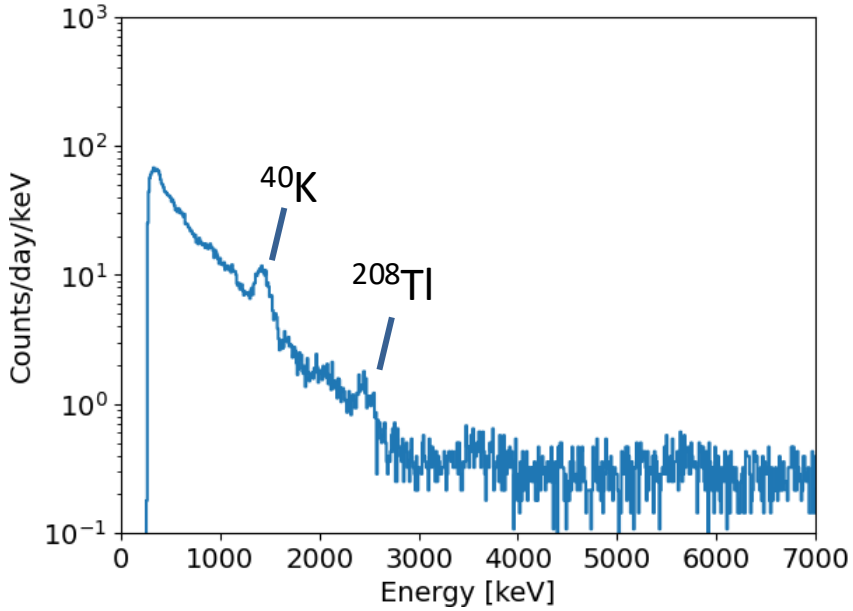
Unknown background



natPWO 0.5g

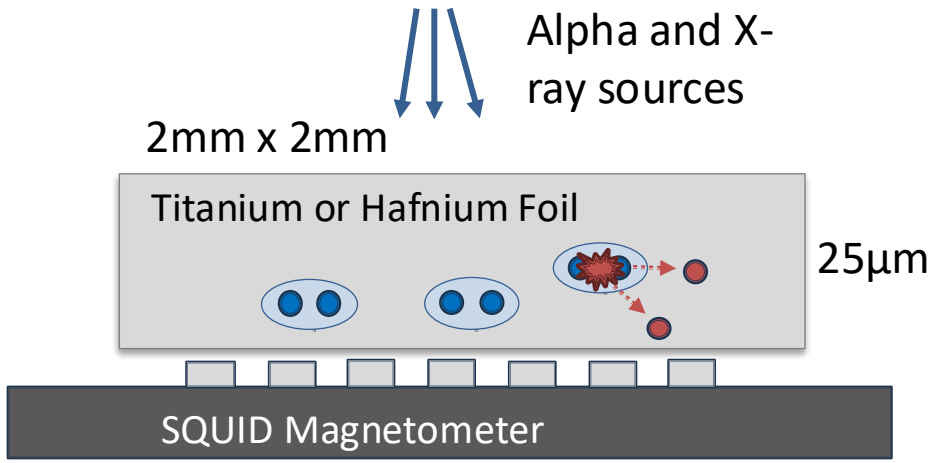


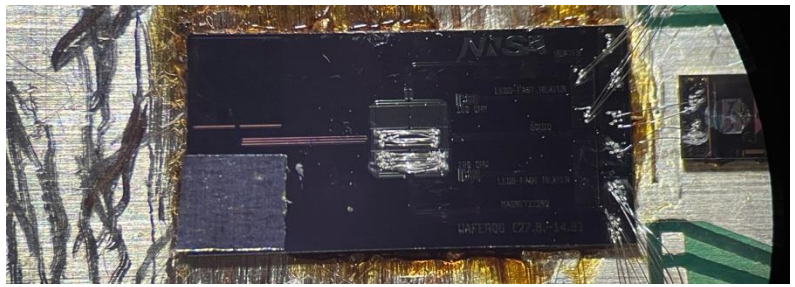
arch PWO 9g



- Risetime-based event type classification
- 33 eV rms resolution and 300 eV energy threshold was achieved with 1cm wafer $PbWO_4$.
- The $1cm^3$ $^{arch}PbWO_4$ detector had poor athermal phonon collection.

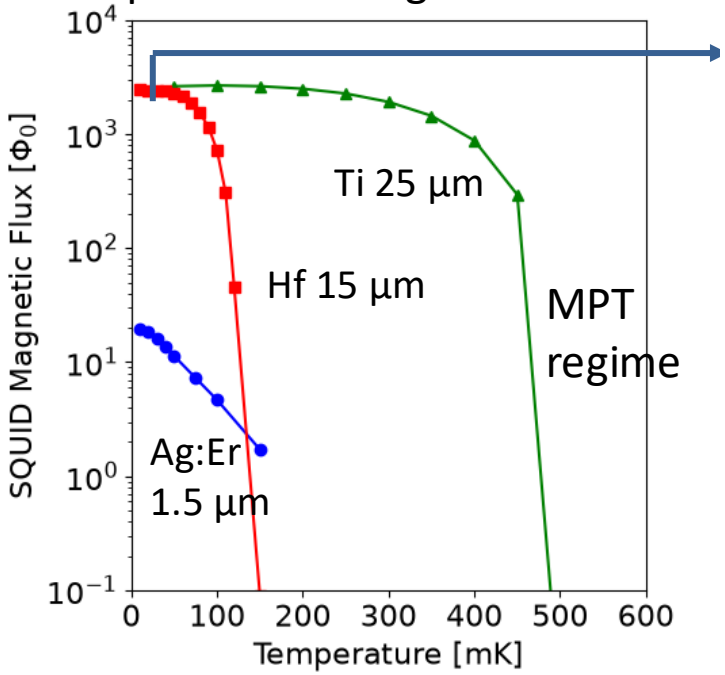
Magnetic Penetration Phonon Sensor (MPPS) Characterization



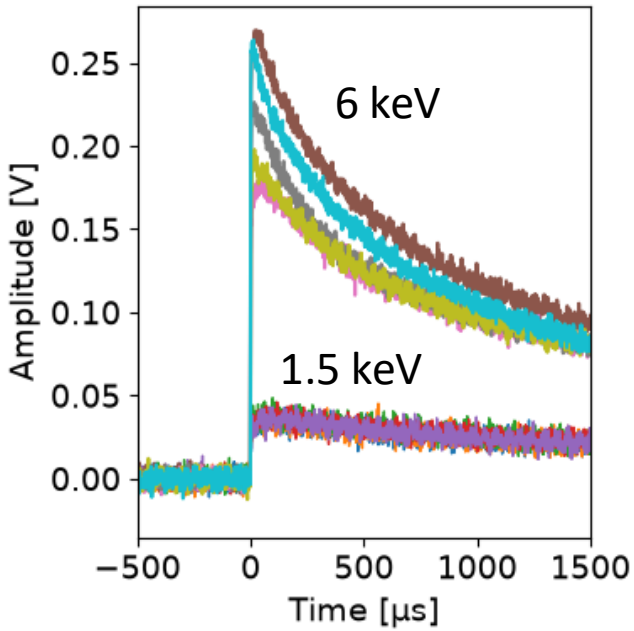


Directly measure surface QP density with sub-microsecond resolution

Temperature – Magnetic Flux Curve



X-ray pulses

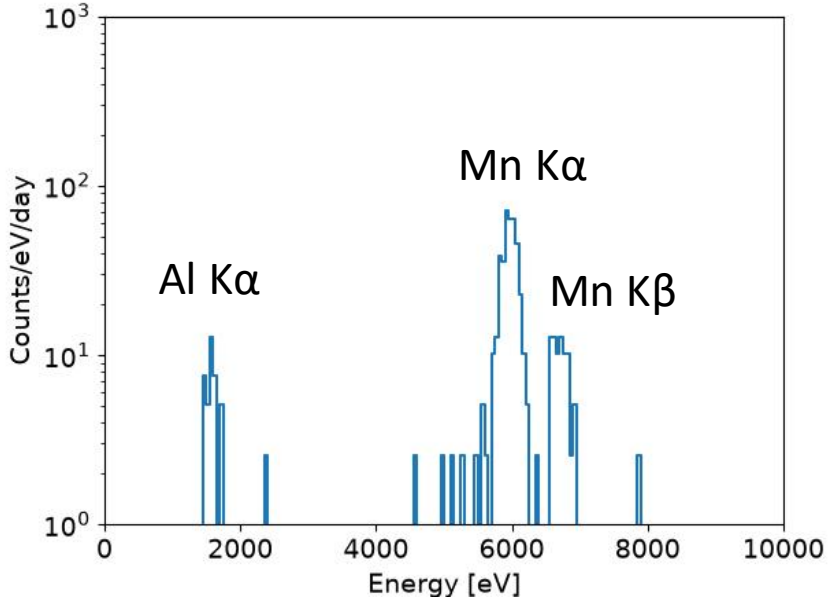


Moody, M. V., et al. "A superconducting penetration depth thermometer." *Proceedings of the 17th Intl. Conf. on Low Temp. Phys*. 1984.

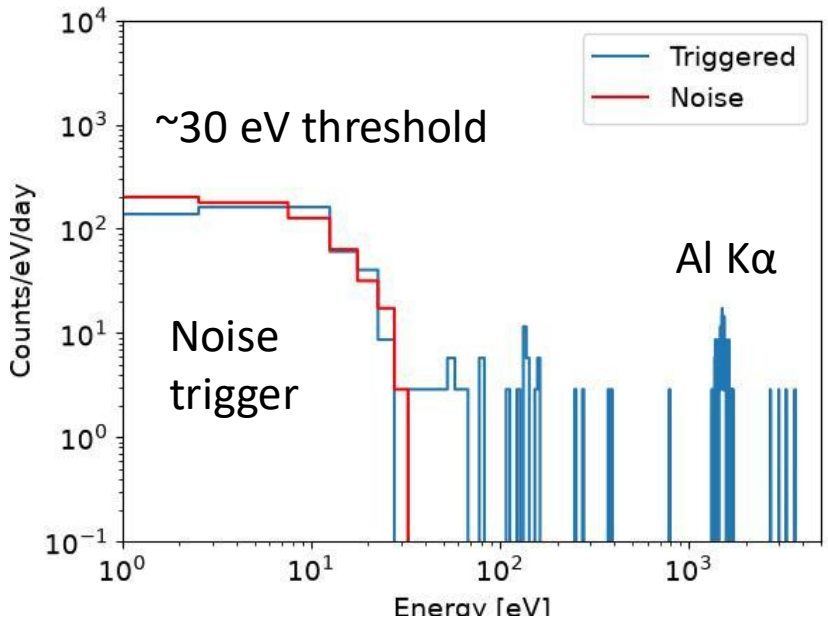
Nagler, P. C., et al. "Performance of magnetic penetration thermometers for x-ray astronomy." *J. Low Temp. Phys.* 167.3 (2012): 455-460.

Hafnium Sensor Fe-55 Energy Spectrum

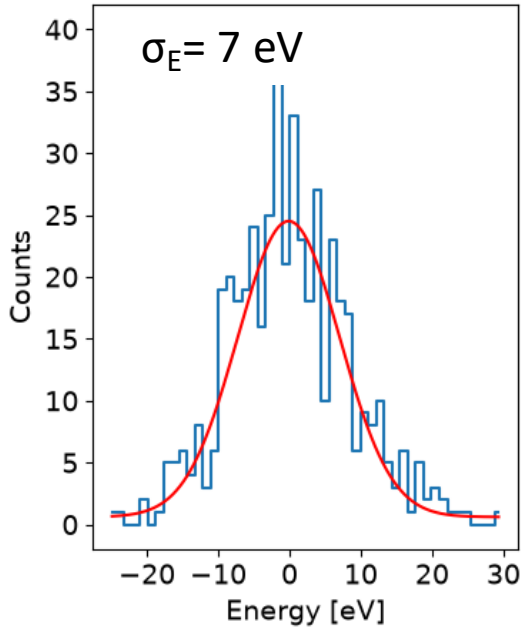
Fe-55 source spectrum



Fe-55 source spectrum

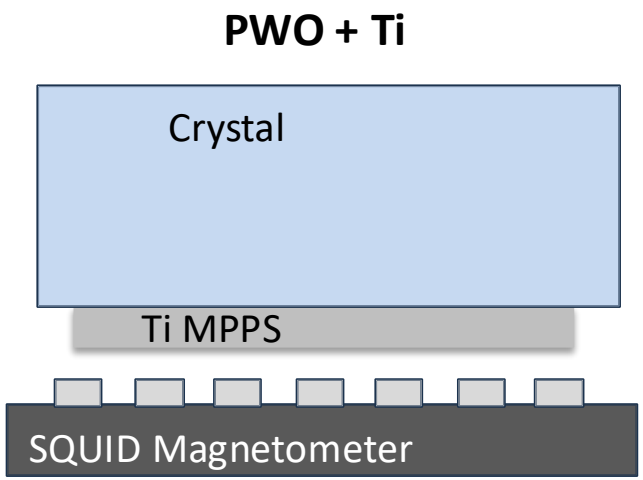


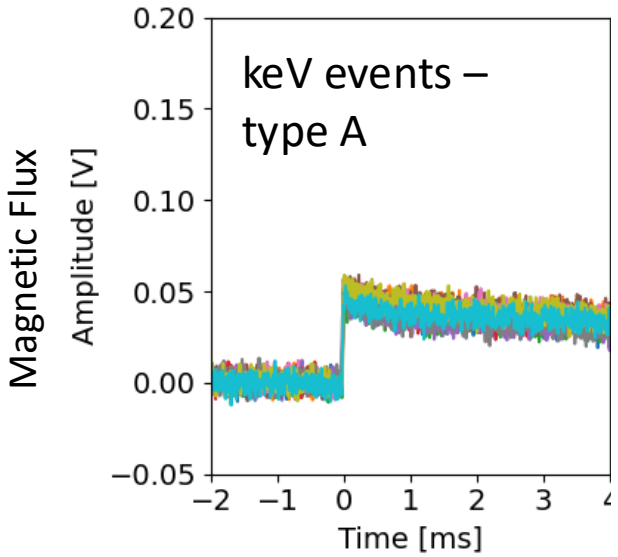
Baseline Resolution

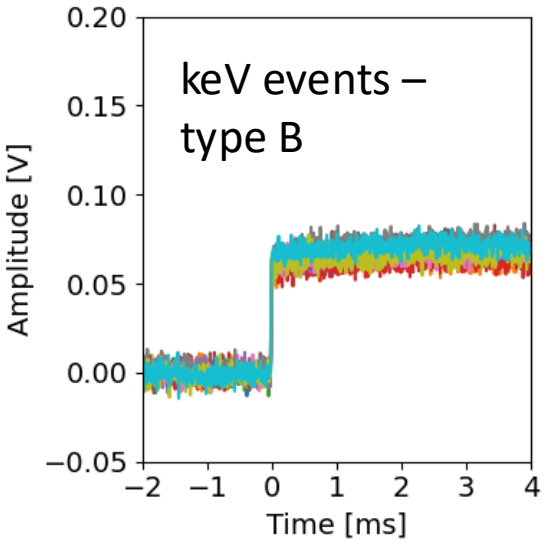


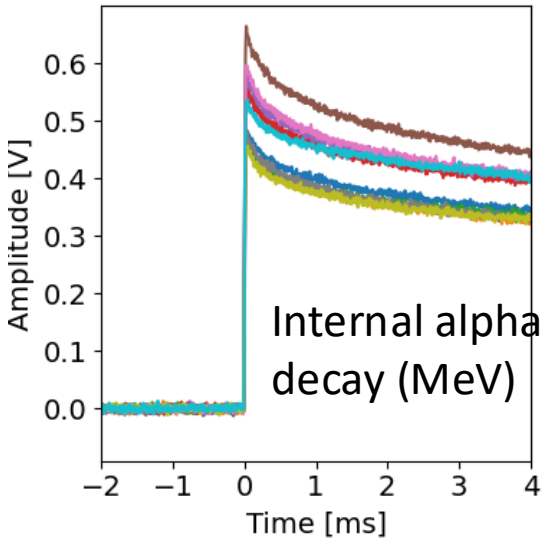
- Long measurement will be performed for LEE study
- Better SQUID (on the way), smaller sensor (currently 2mm x 2mm x 15um) for improved resolution
- Test with crystals

Proof of Concept - PbWO4 + Ti Magnetic Penetration Phonon Sensor





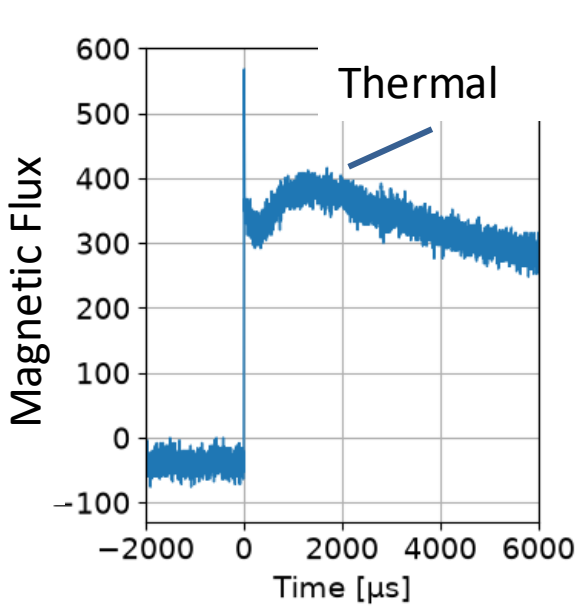


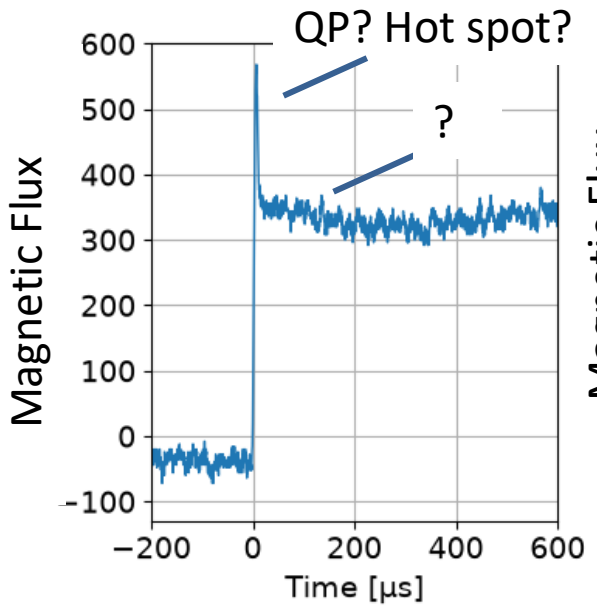


- First observation of MPPS-based phonon signals
- Uniform signal shapes.
- Alpha signals produced larger fast component.
- No significant non-equilibrium QP signals is observed.

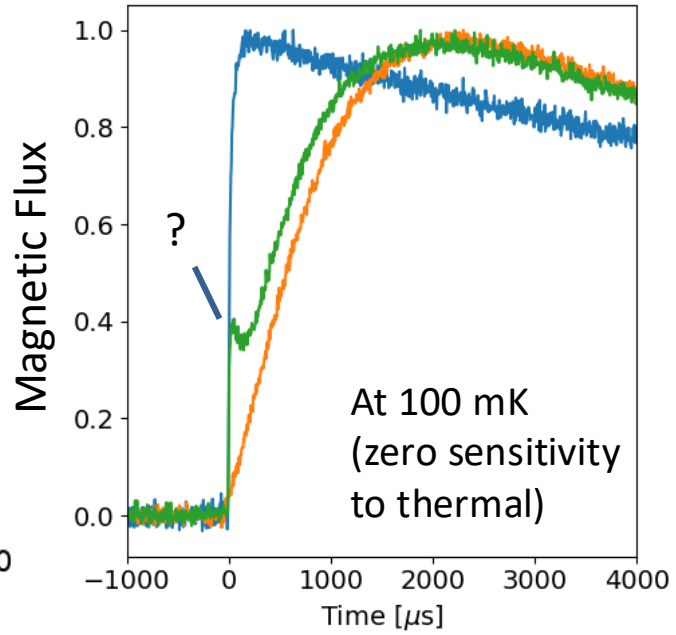
Quasiparticle Dynamics Study

Alpha events in Hf sensor



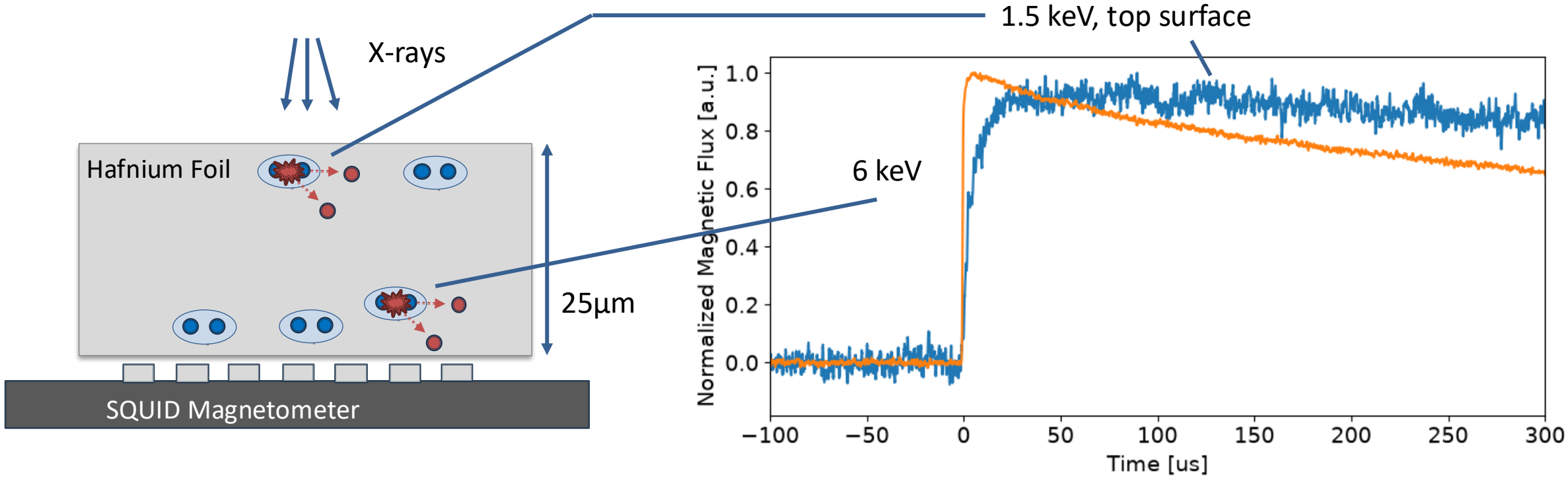


Alpha in Ti sensor

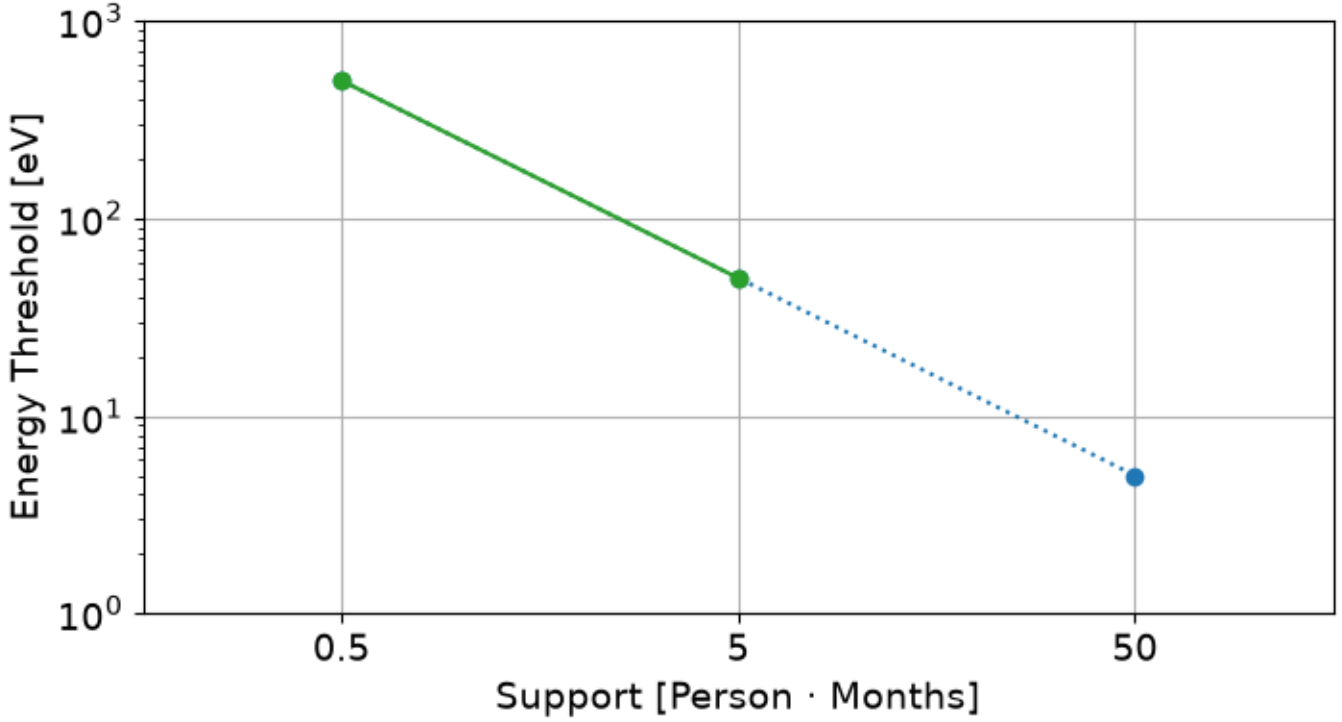


- MPPS directly measures surface QP density → support QP transport modeling and radiation impact on superconductor.
- Any separate samples with arbitrary superconducting pattern can be measured (does not require sensor integration)

QP Diffusion Time



Summary and Future Work



Looking for collaborators for

- Superconductor modeling & calculation (under B field)
- Low Tc film fabrication
- Crystal growing
- Full time graduate student

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was funded by the National Nuclear Security Administration of the Department of Energy, Office of Defense Nuclear Nonproliferation Research and Development (NA-22). This work was supported by the Laboratory Directed Research and Development program of LLNL (22-FS-011) and DOE Office of Science HEP Advanced Detector R&D program.



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