Sub-GeV DM Detection using Superconducting Tunnel Junction (STJ) Sensors

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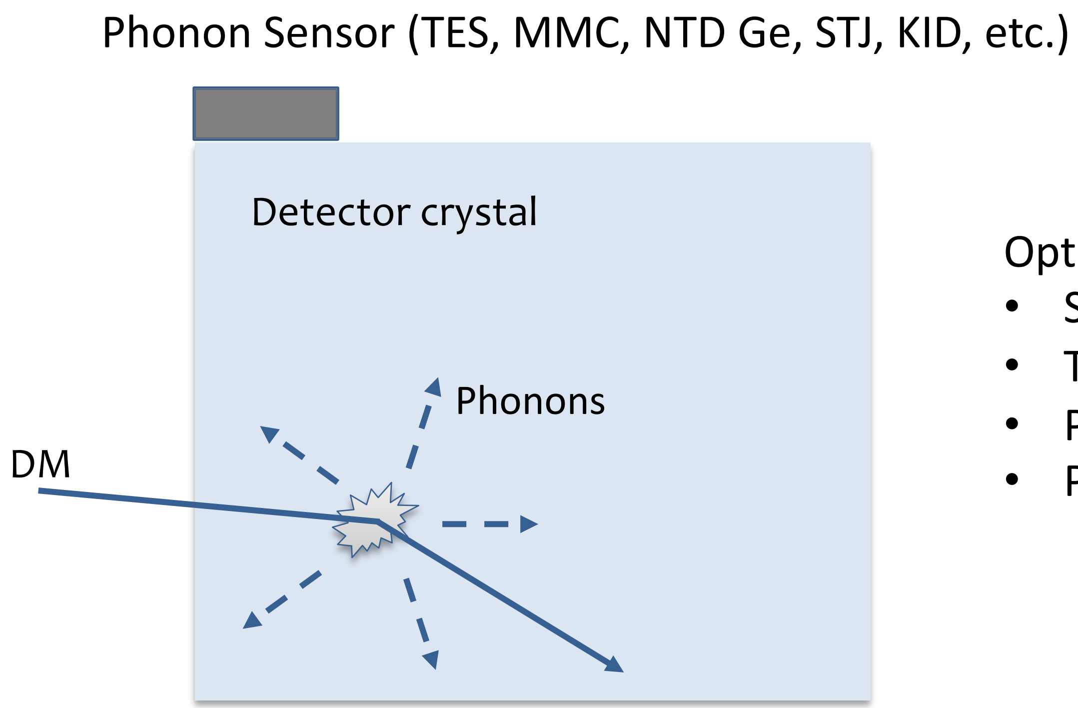
DM/Neutrino Activities at LLNL

Dark Matter Detector R&D
- LZ (GeV)
- ADMX (Axion)
- MAGNETO-DM (Sub-GeV)

Neutrino
- nEXO (0nbb)
- Prospect (short baseline)
- Project 8 (neutrino mass)
- BeEST (sub-MeV sterile)
- MAGNETO-nu (keV sterile)

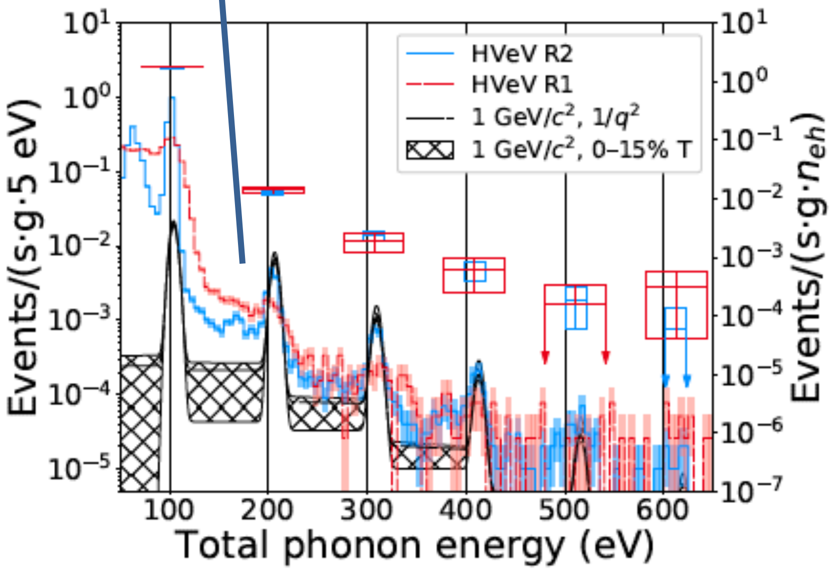
Cryogenic Particle Detectors with Crystals



Optimization:
- Sensor energy resolution
- Type of crystals
- Phonon collection efficiency
- Particle identification if applicable

Low Energy EXCESS

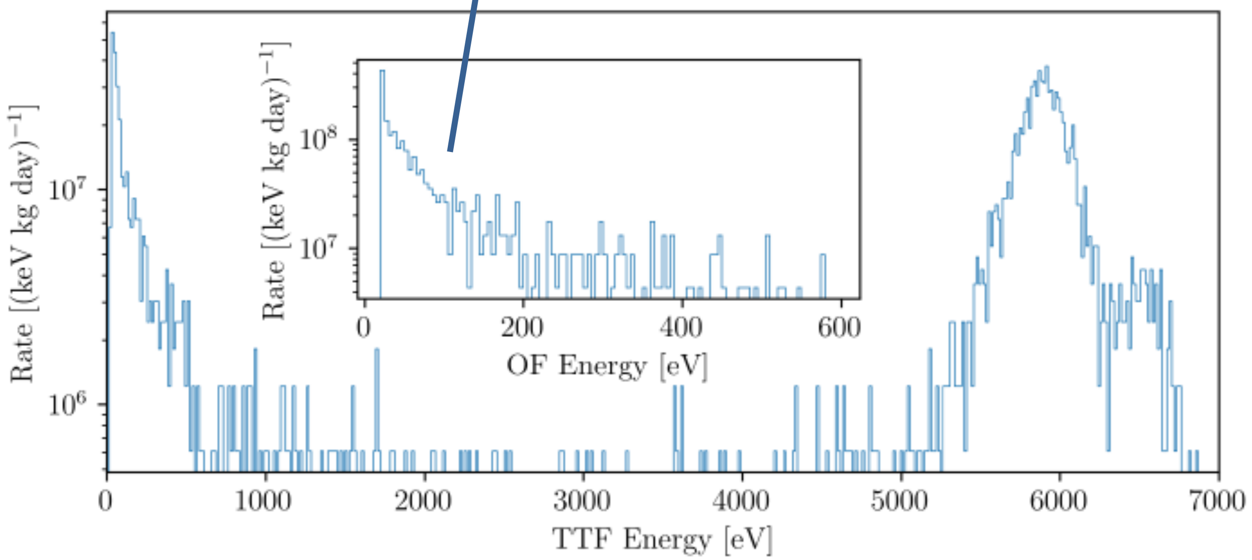
EXCESS



SuperCDMS-HVEV

Phys. Rev. D 104, 032010 (2021)

EXCESS

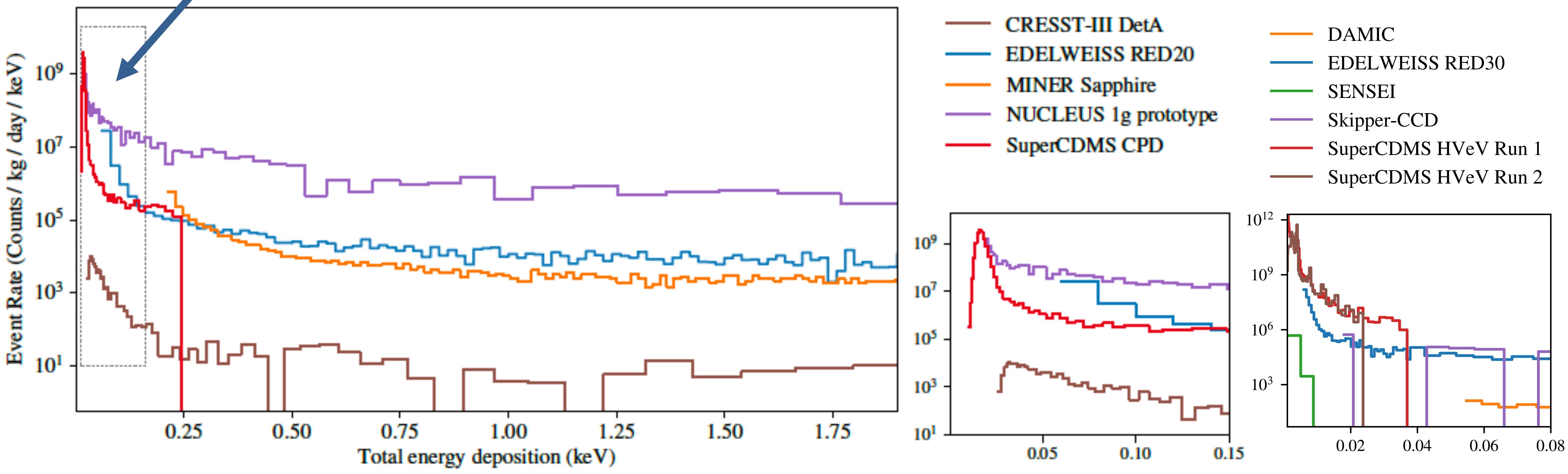


NUCLEUS-1g-prototype-2017

SciPost Physics Proceedings 9 (2022): 001

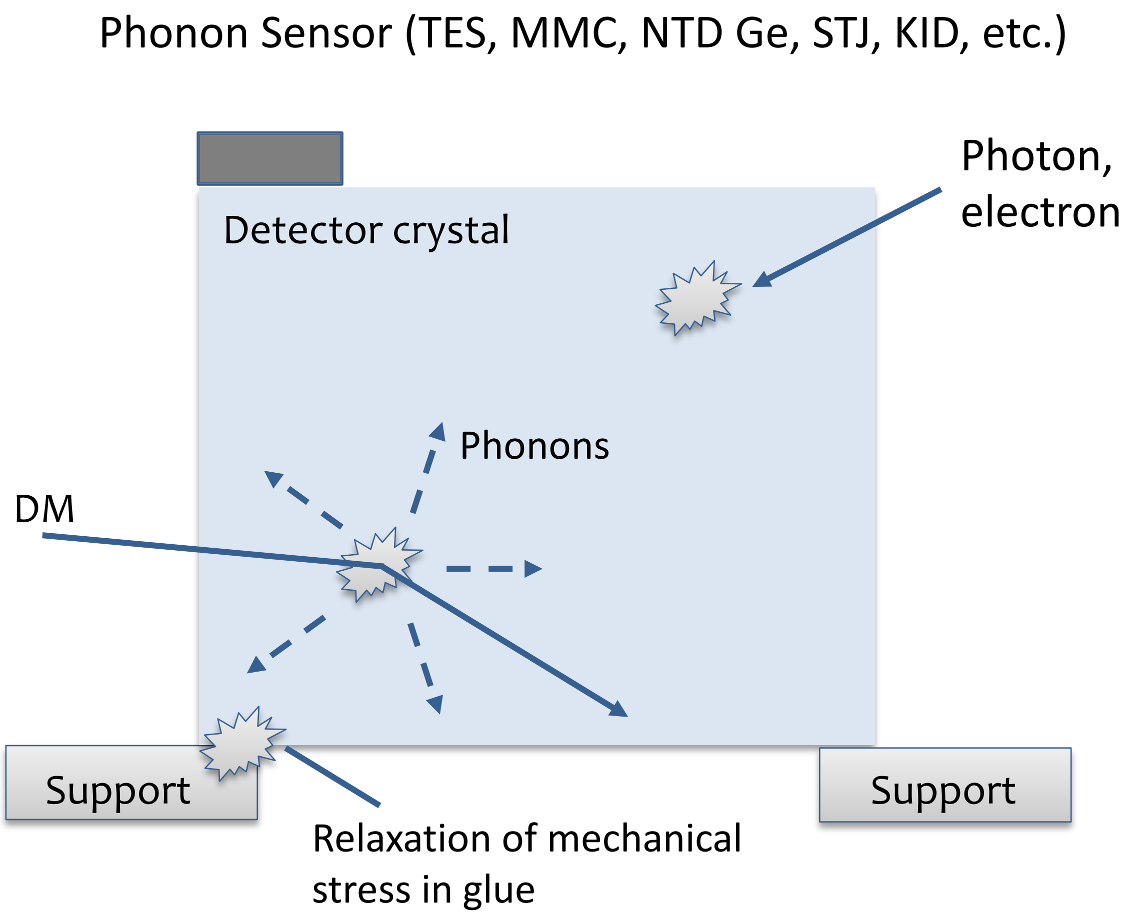
Low Energy EXCESS

SciPost Physics Proceedings 9 (2022): 001



- Most of low threshold cryogenic detectors experience excessive background rates at E < 150 eV region.
- Understanding and mitigating the excess background is one of the top R&D priorities.
  - → **Will fast phonon sensor help for understanding the origin?**

Low Energy EXCESS – Origin?

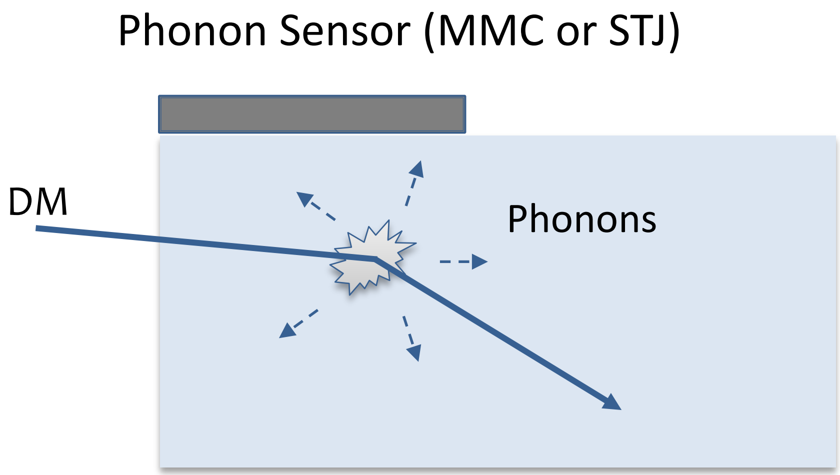


Questions for understanding EXCESS

- Nuclear or electron recoil?
- Thermal or athermal?
- Surface or bulk?

Fast phonon sensor can help understanding EXCESS
→ Let's build DM detectors with fast sensors

Fast Phonon Sensing for Understanding EXCESS

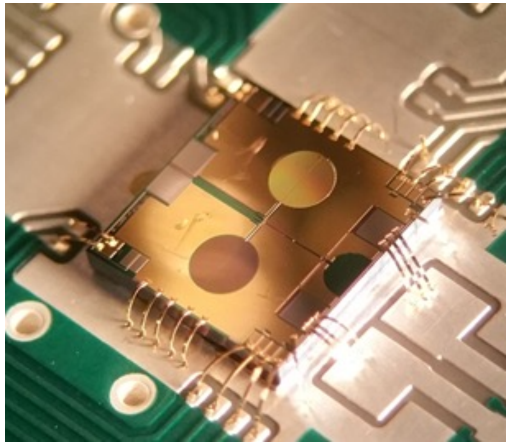


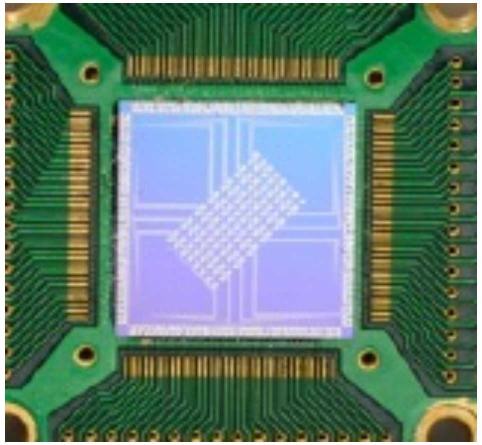
Optimization list:
Optimization:

- Sensor energy resolution
  MMC (~10 eV) vs STJ (~1 eV)
- Type of crystals and phonon collection efficiency
  MMC-based crystal screening program (MAGNETO-x)
- Particle identification if applicable
  Fast phonon sensing will improve pulse shape discrimination

Fast Phonon Sensors at LLNL

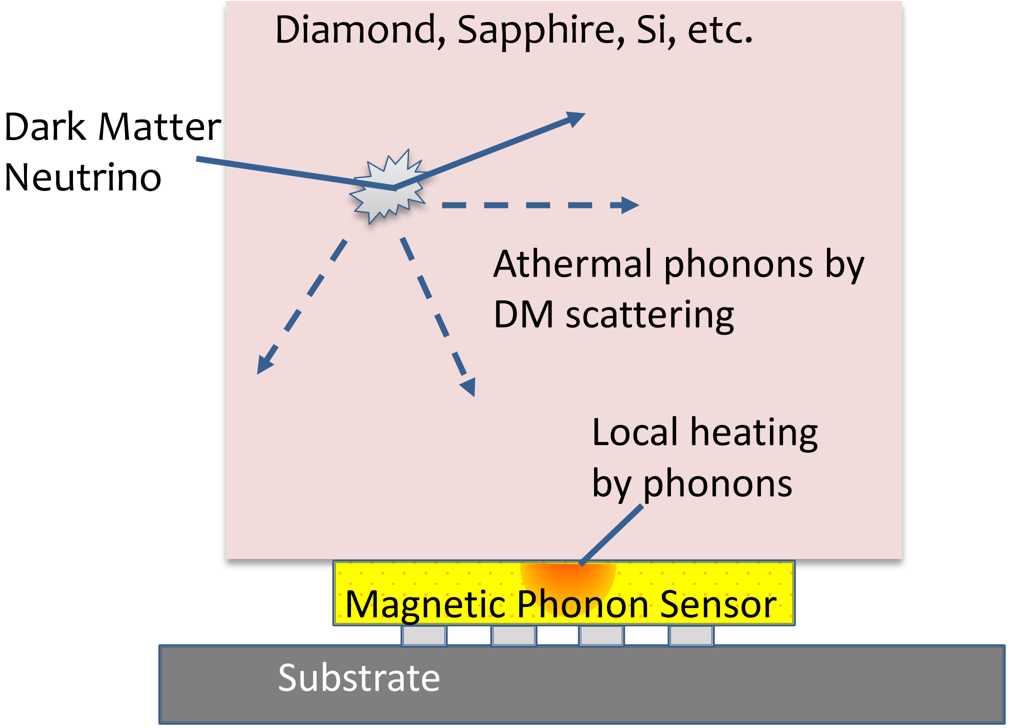
LLNL develops "fast" cryogenic sensor technologies for nuclear non-proliferation applications

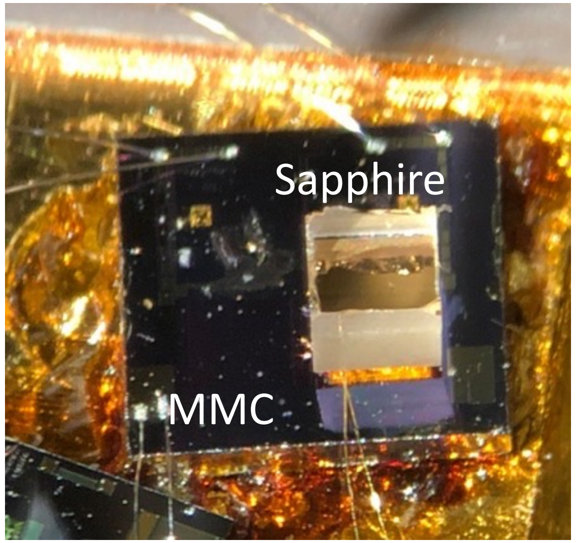




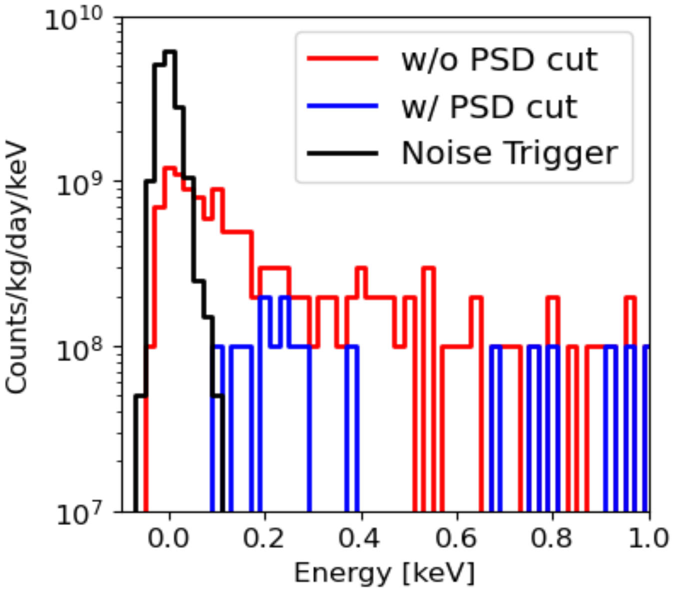
	Metallic Magnetic Calorimeter (MMC)	Superconducting Tunnel Junction (STJ)
Sensor material	Paramagnet (Au:Er, Ag:Er)	Al-AlO-Al junction
Measurement	Total magnetization	Tunneling current
Readout	Quantum magnetometer (SQUID)	JFET Current amplifier
Detector Material	**Most of any materials**	Superconductors
Resolution	O(10 eV, for LLNL technologies)	O(**1 eV,** for LLNL technologies)
Speed	O(100 ns)	O(1 us)

MMC with Crystal Absorbers





R&D experimental data



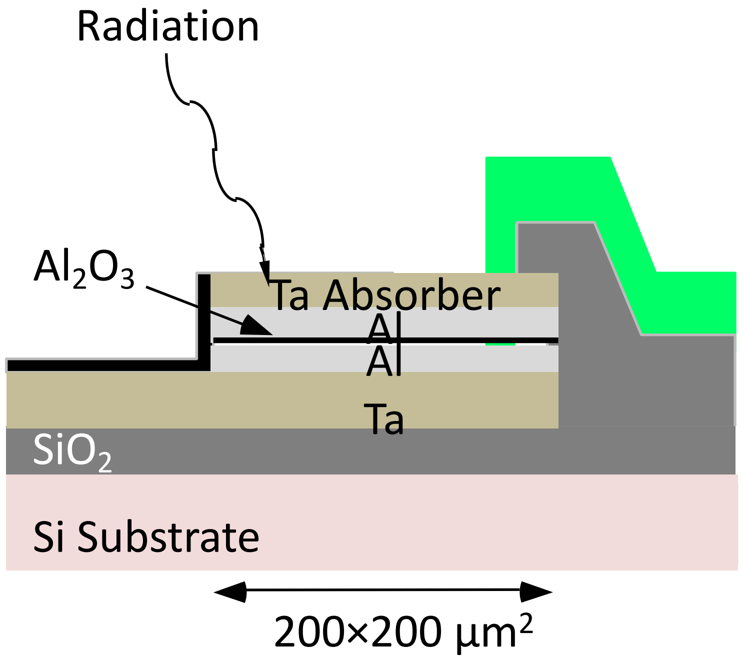
Large mass, fast timing resolution of O(100 ns) for phonon Pulse Shape Discrimination.

Applications:

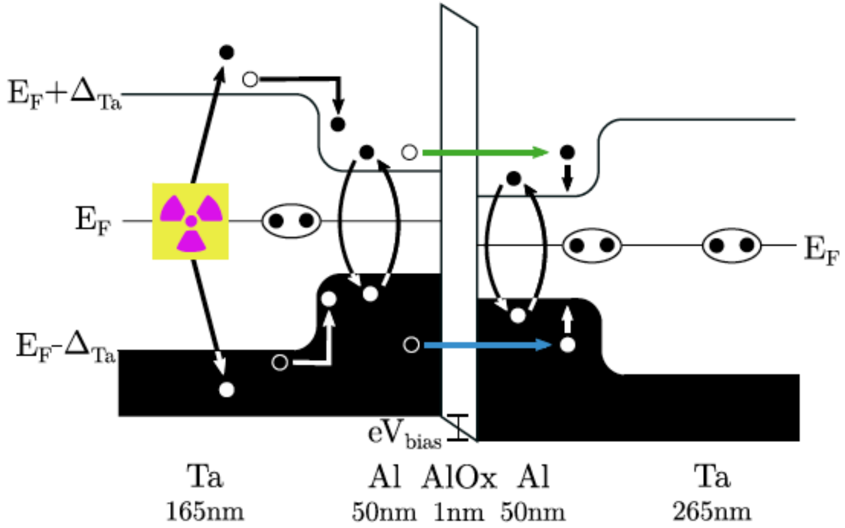
- Dark Matter Detection
- Reactor monitoring via neutrino detection

STJ Working Principle

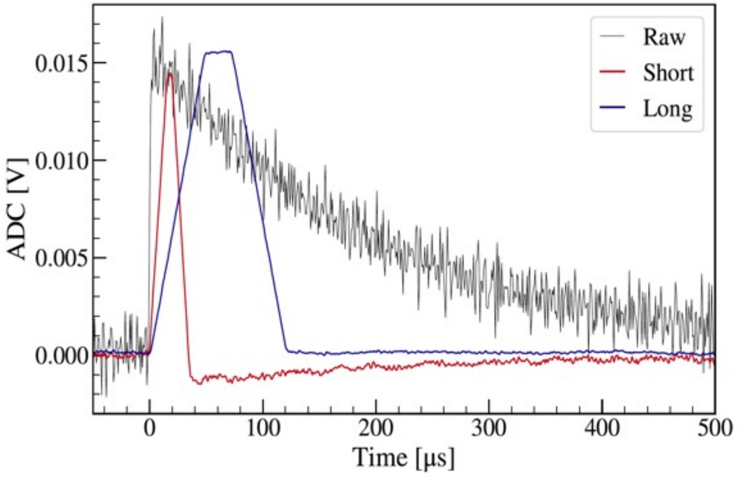
STJ Cross Section



STJ Operating Principle



STJ Signal



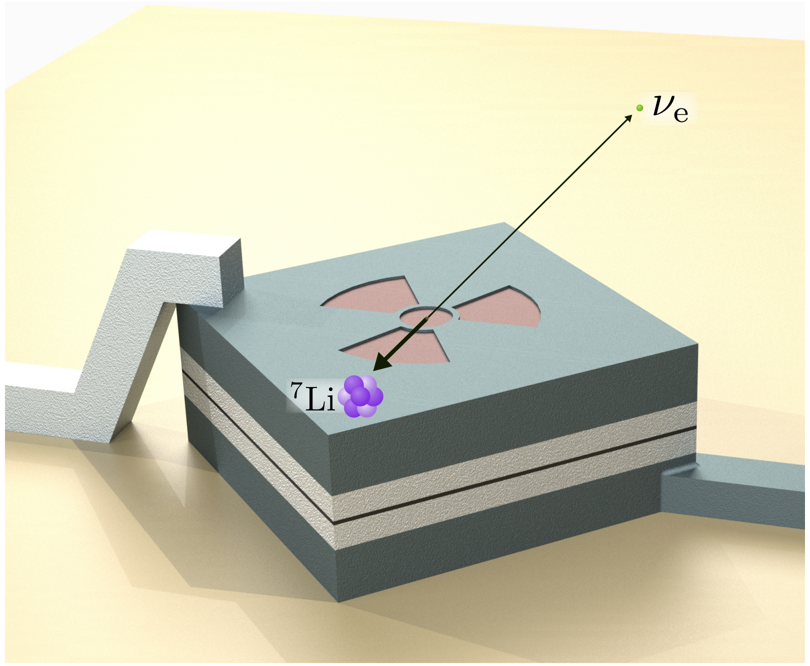
$$\text{Energy resolution } E_{FWHM} = 2.355\sqrt{1.7\Delta \cdot E_{X-ray}\left(F+1+\frac{1}{n}\right)}$$

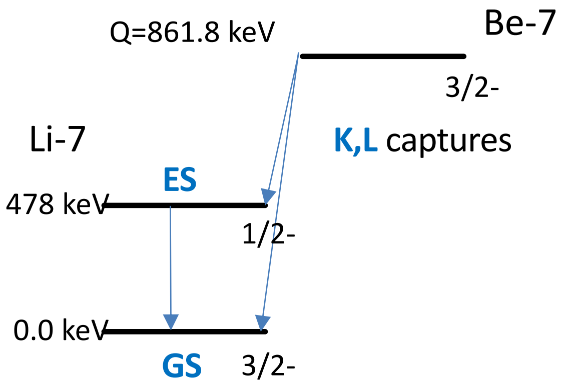
- 1 us rise-time
- 300 us decay-time
- Perfect exponential shape

- **Completely insensitive to thermal phonons (~1 meV band gap)**
- **Short excess charge life-time (~µs)**

”BeEST” Experiment with STJs

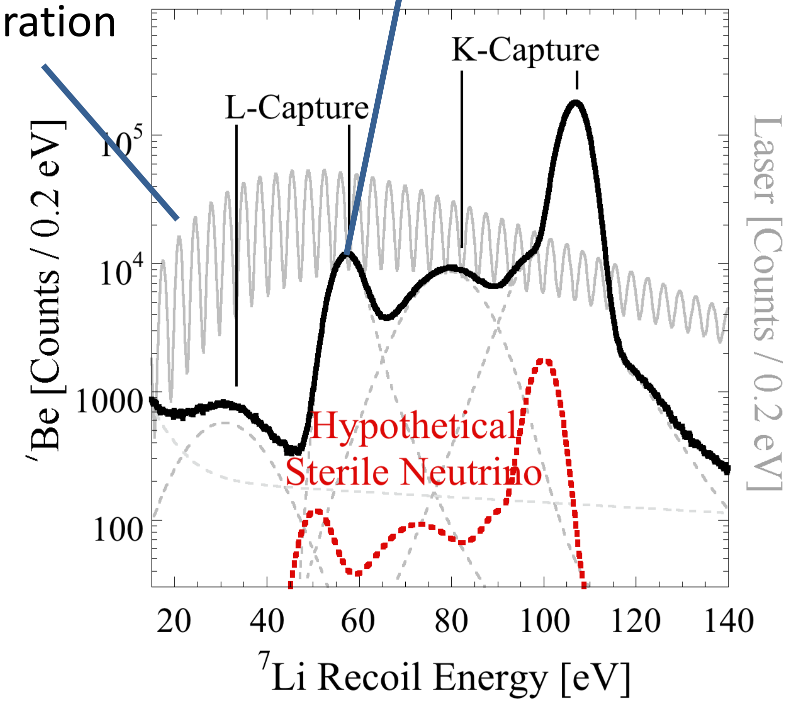
Measure eV-scale nuclear recoil peaks to search for keV neutrinos





Consistent with the calculated full recoil energy of 56.828eV

Laser Calibration



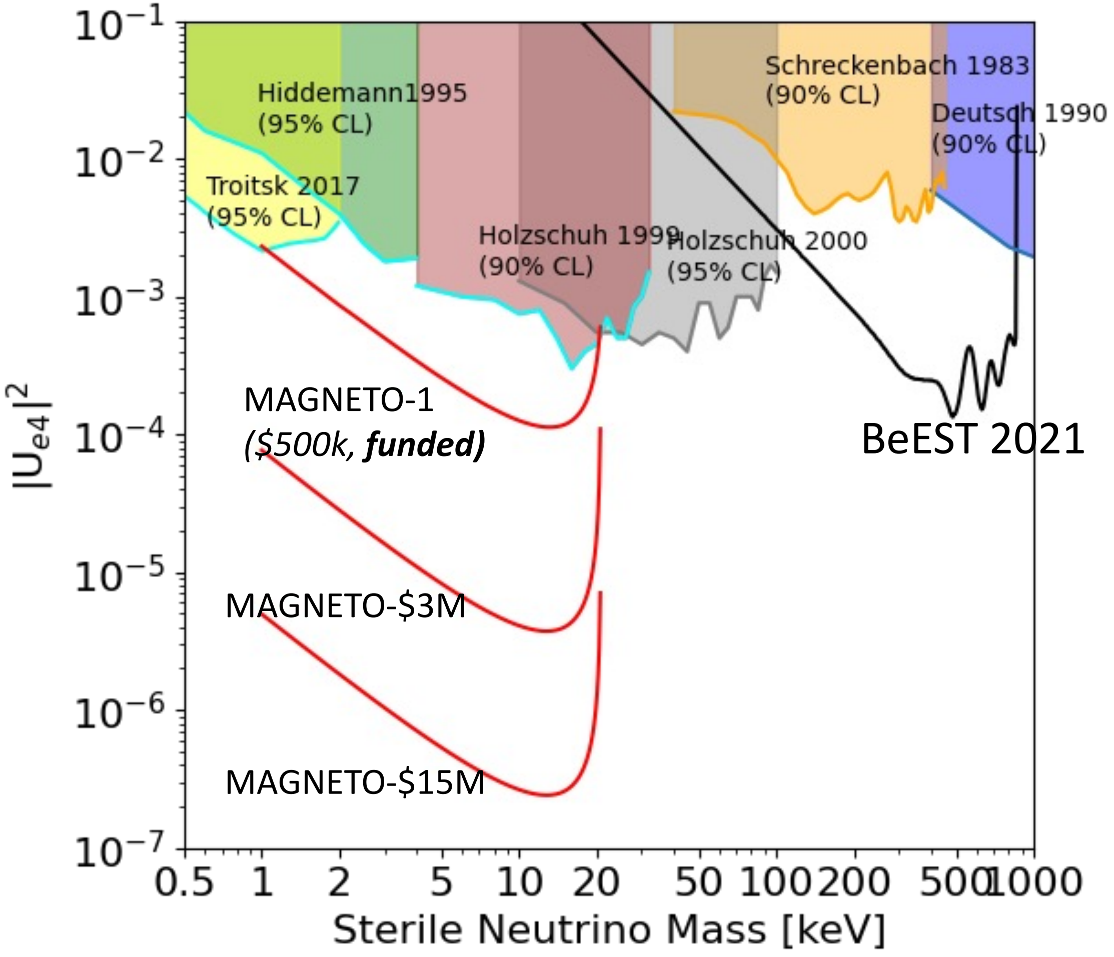
- Implant radioactive ^{7}Be into STJ detectors
- Measure nuclear recoil energy of ^{7}Li daughter

- Heavy sterile neutrinos would reduce ^{7}Li recoil
- No quenching was observed

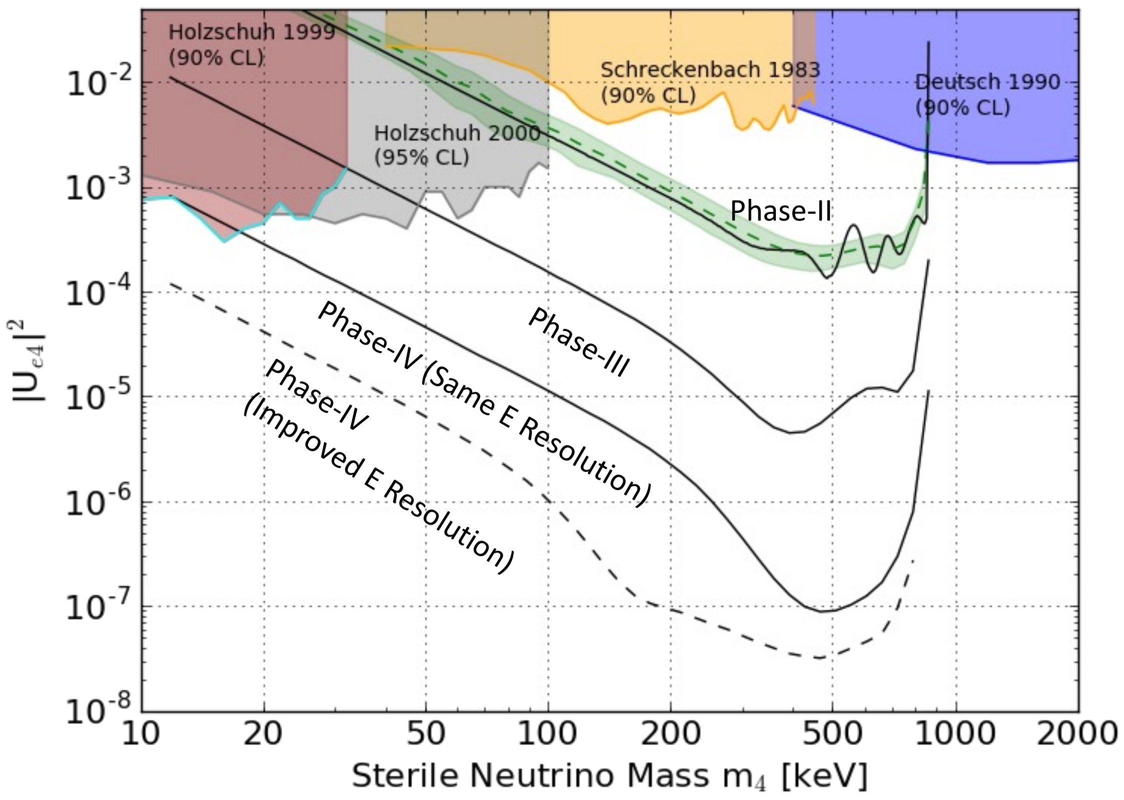
PRL 125, 032701 (2020)

keV Sterile Neutrino Searches (Warm Dark Matter Candidate)

MAGNETO-nu, keV neutrino search with ^{241}Pu

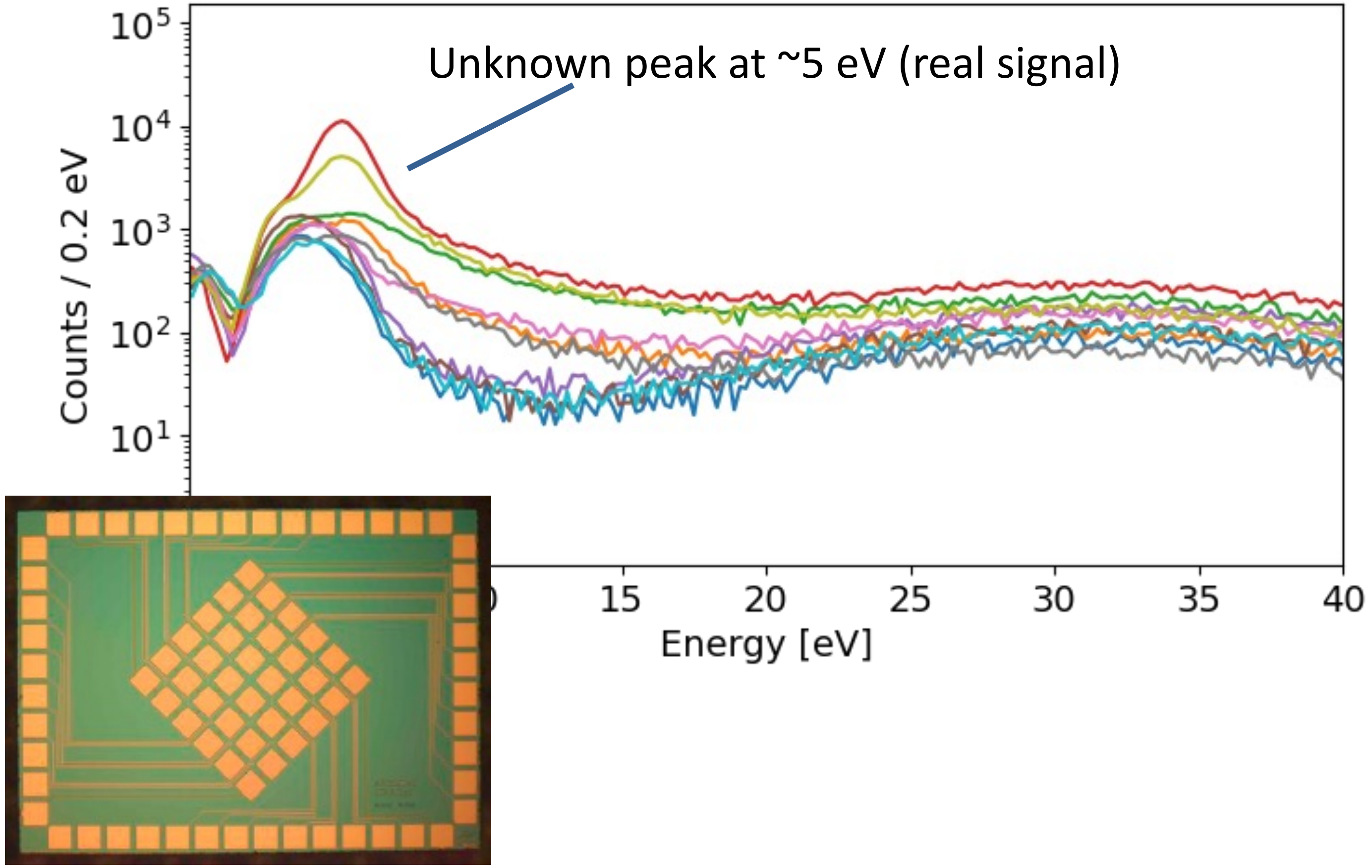


BeEST, 100 keV neutrino search with ^{7}Be

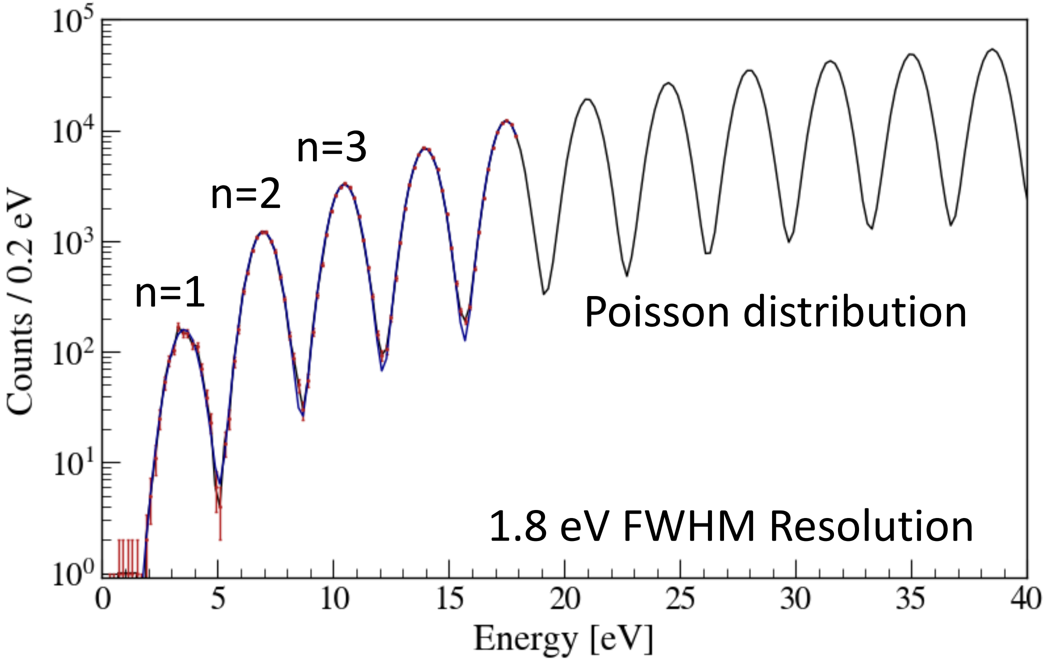


BeEST Low Energy Data – Ta events (anti-coincidence)

Single pixel spectra for 1 day. Almost all events are from ^{7}Be decays

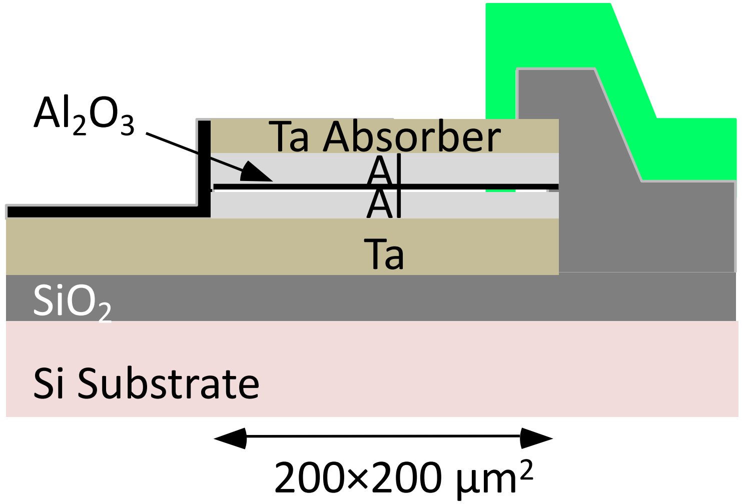


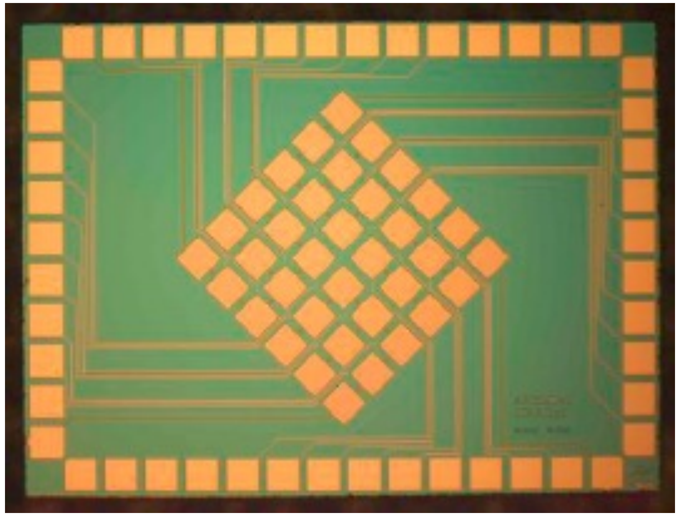
Energy calibration with 3.5 eV laser photons



DM Search using Ta Absorbers

Motivation: Existing ~1eV threshold detector. Minimal R&D cost.



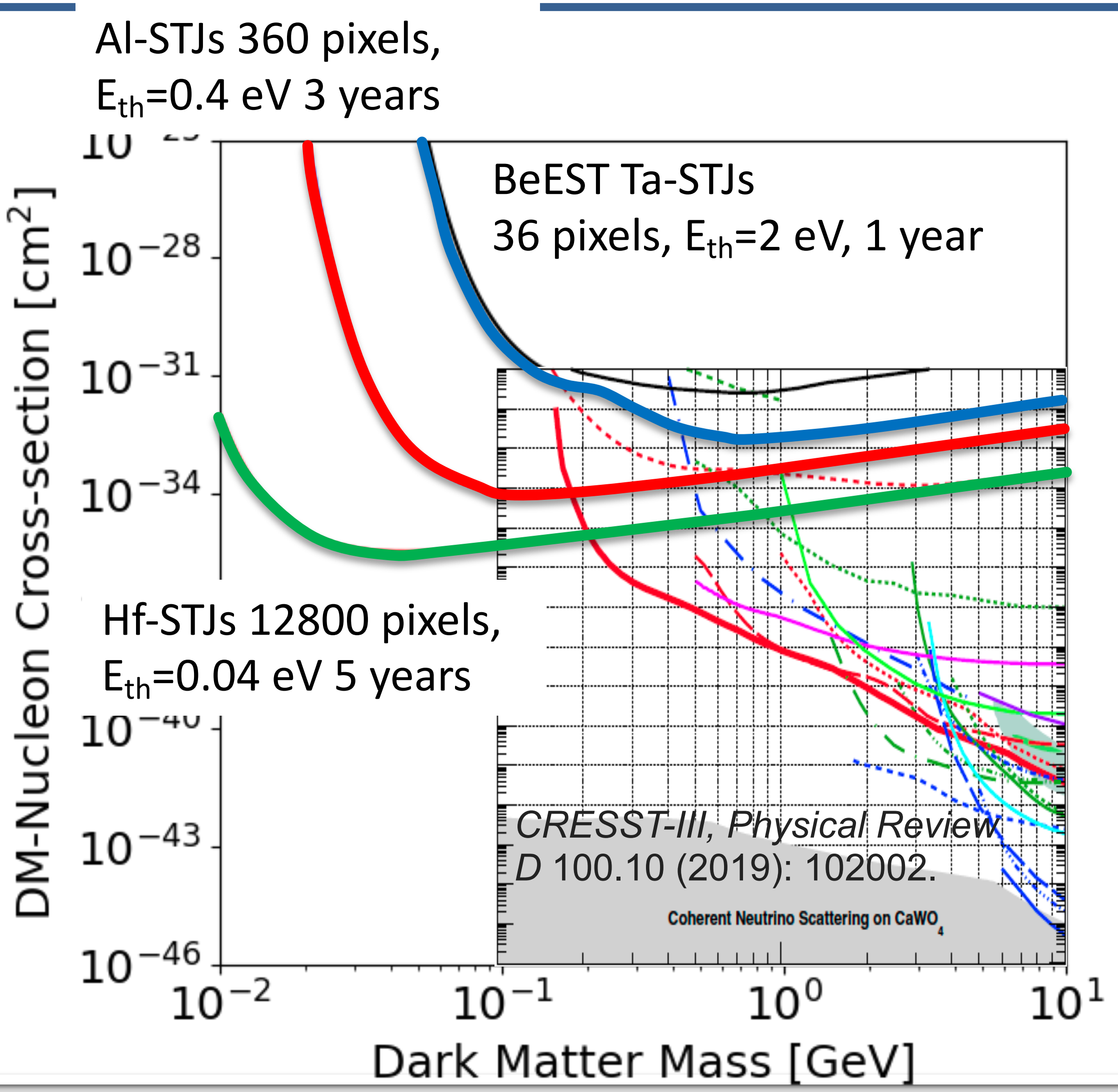


36-pixels Ta-STJs

Or, further R&D for lowering energy threshold

Ta	Tc(K)	Δ (meV)	E_{th} (eV)
Ta	4.4K	1	2
Al	1.2K	0.2	0.4
Hf	0.13	0.02	0.04

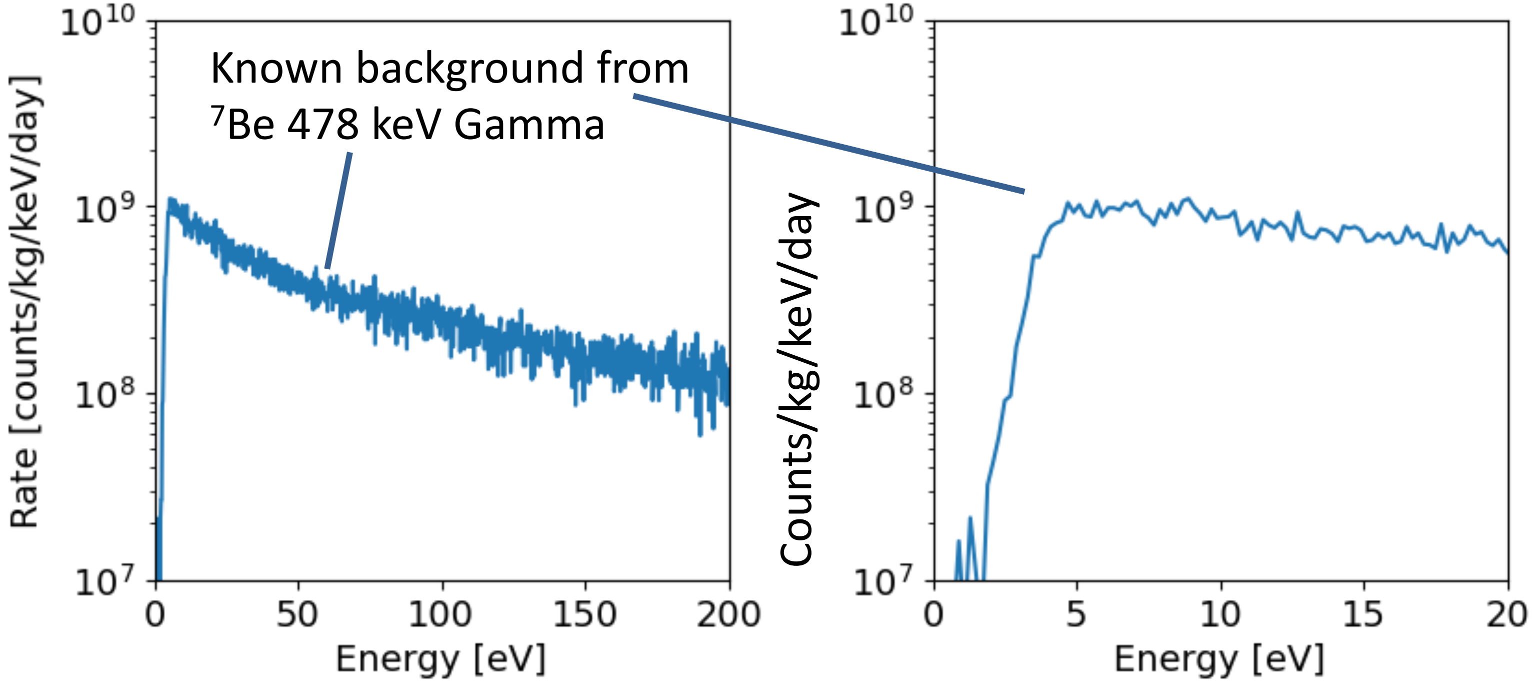
DM Search using STJ Pixels

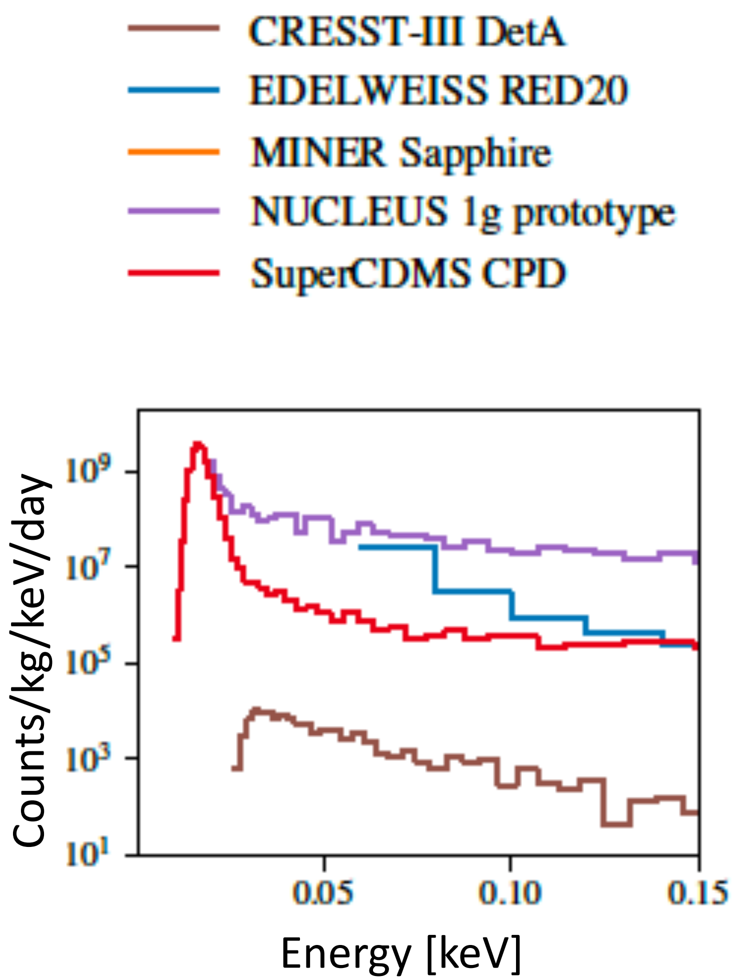


Maybe too low detector mass?

BeEST Low Energy Data – Substrate Crystal Events (coincidence spectra)

Triple+ coincidence events (Si substrate crystal events)

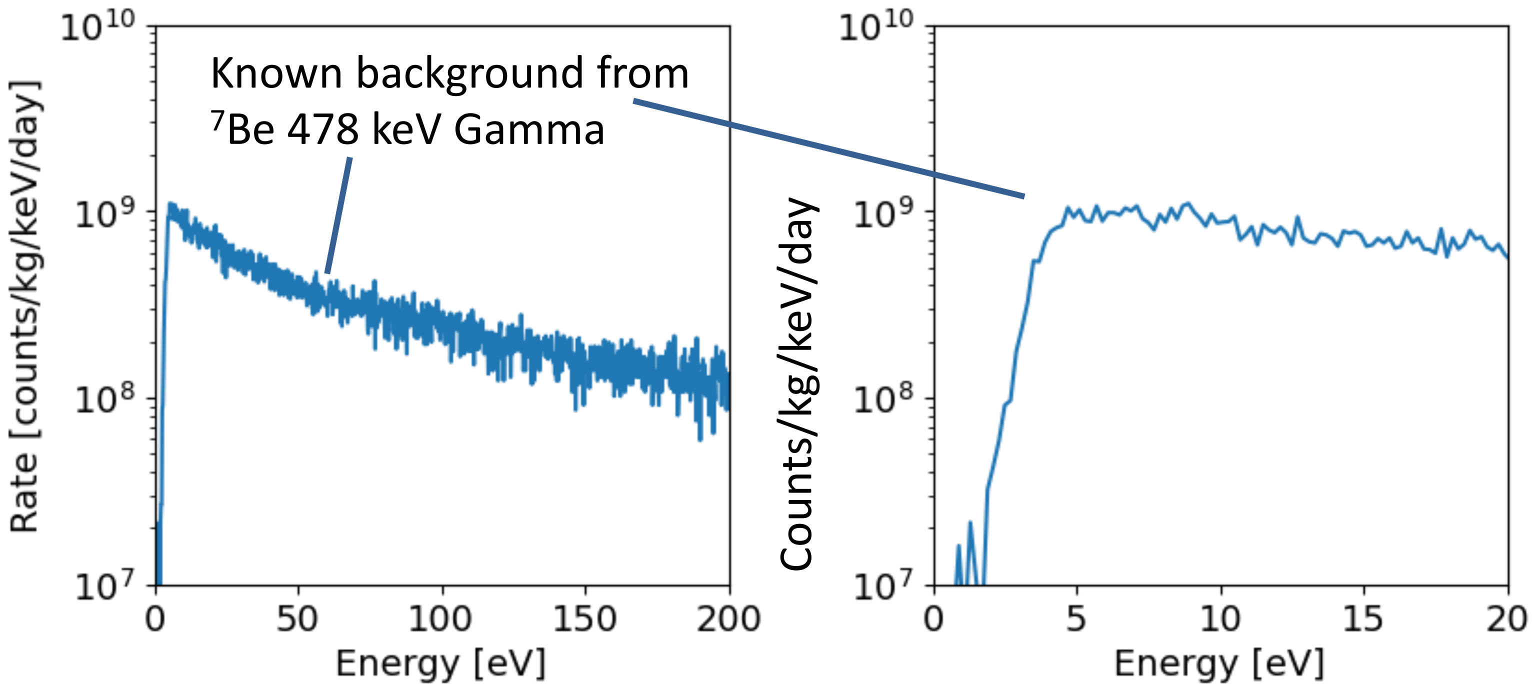


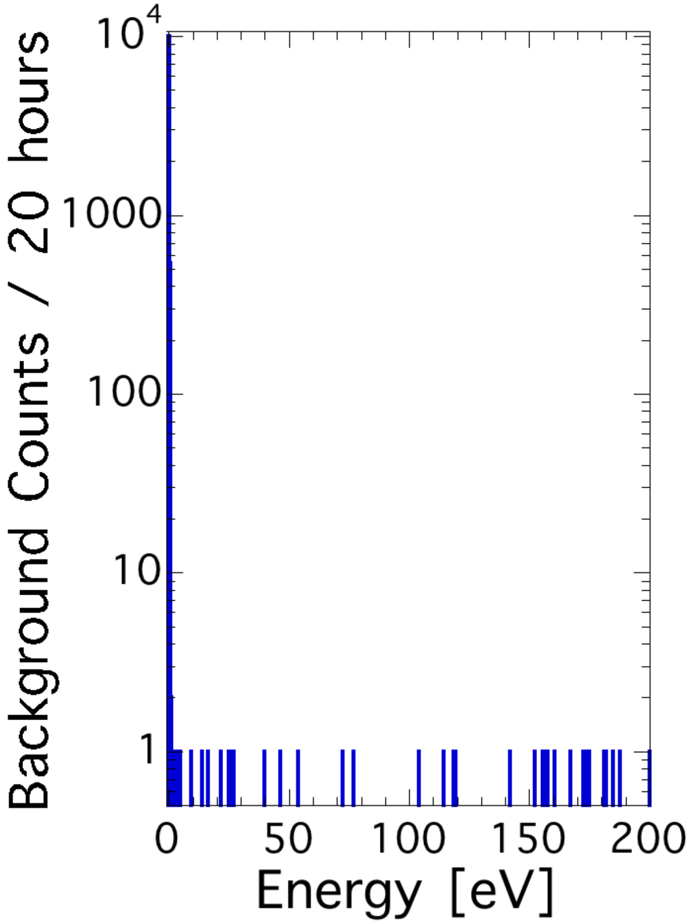


- **Will STJs see the EXCESS background?**
- **Better substrate material for DM search?**

BeEST Low Energy Data – Substrate Crystal Events (coincidence spectra)

Triple+ coincidence events (Si substrate crystal events)

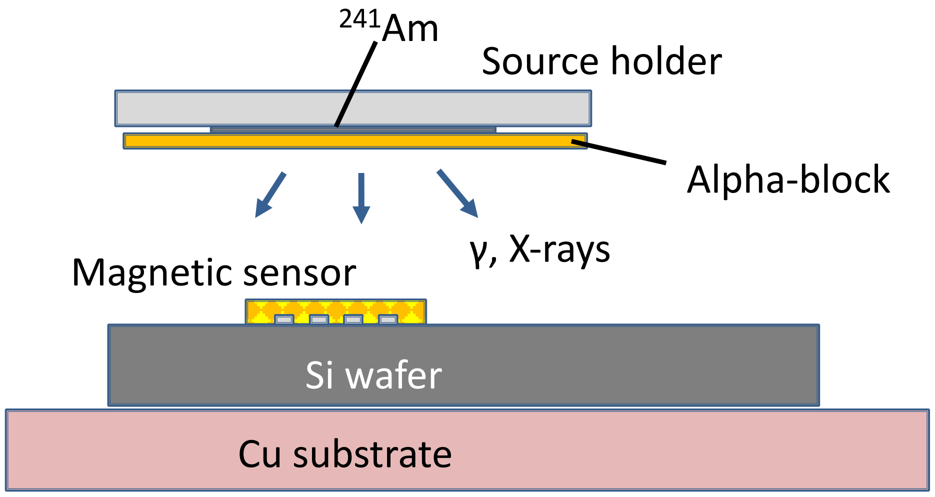




- **Will STJs see the EXCESS background?**
- **Better substrate material for DM search?**

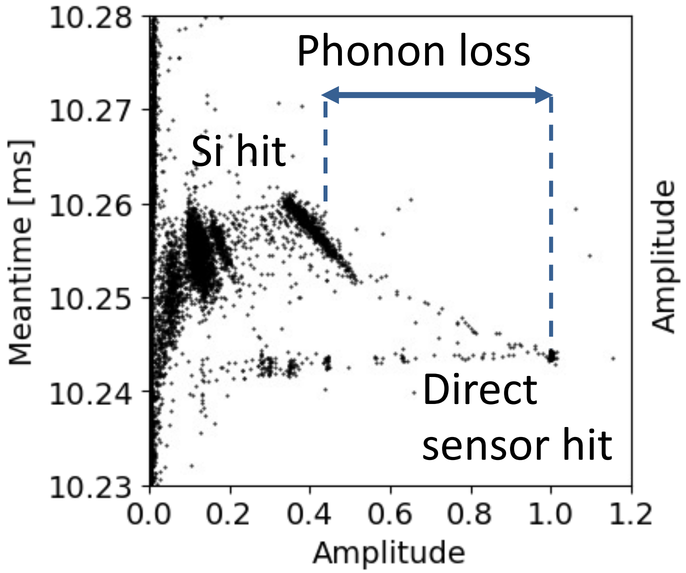
Crystal Selection (Phonon collection efficiency)

Phonon collection efficiencies are measured for various substrate crystals, using magnetic sensors

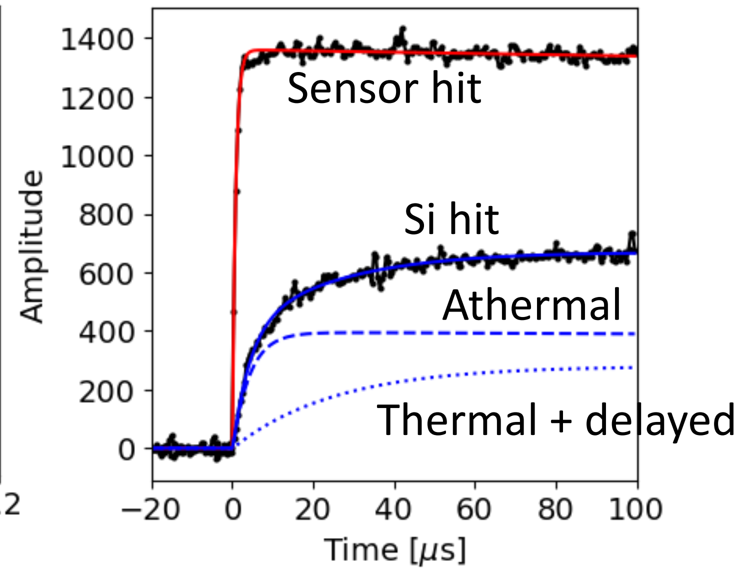


Compare sensor direct hit and crystal hit events, to extract phonon collection efficiency

Pulse Shape Distribution



Phonon Signals with model fit



- Sensor response: 0.8 μs   Athermal collection time: 4.2 μs
- Athermal collection efficiency: 28.8%
- Thermal phonon contribution: 16.2%   Energy loss to substrate: 45.1%

Crystal Selection (Phonon collection efficiency)

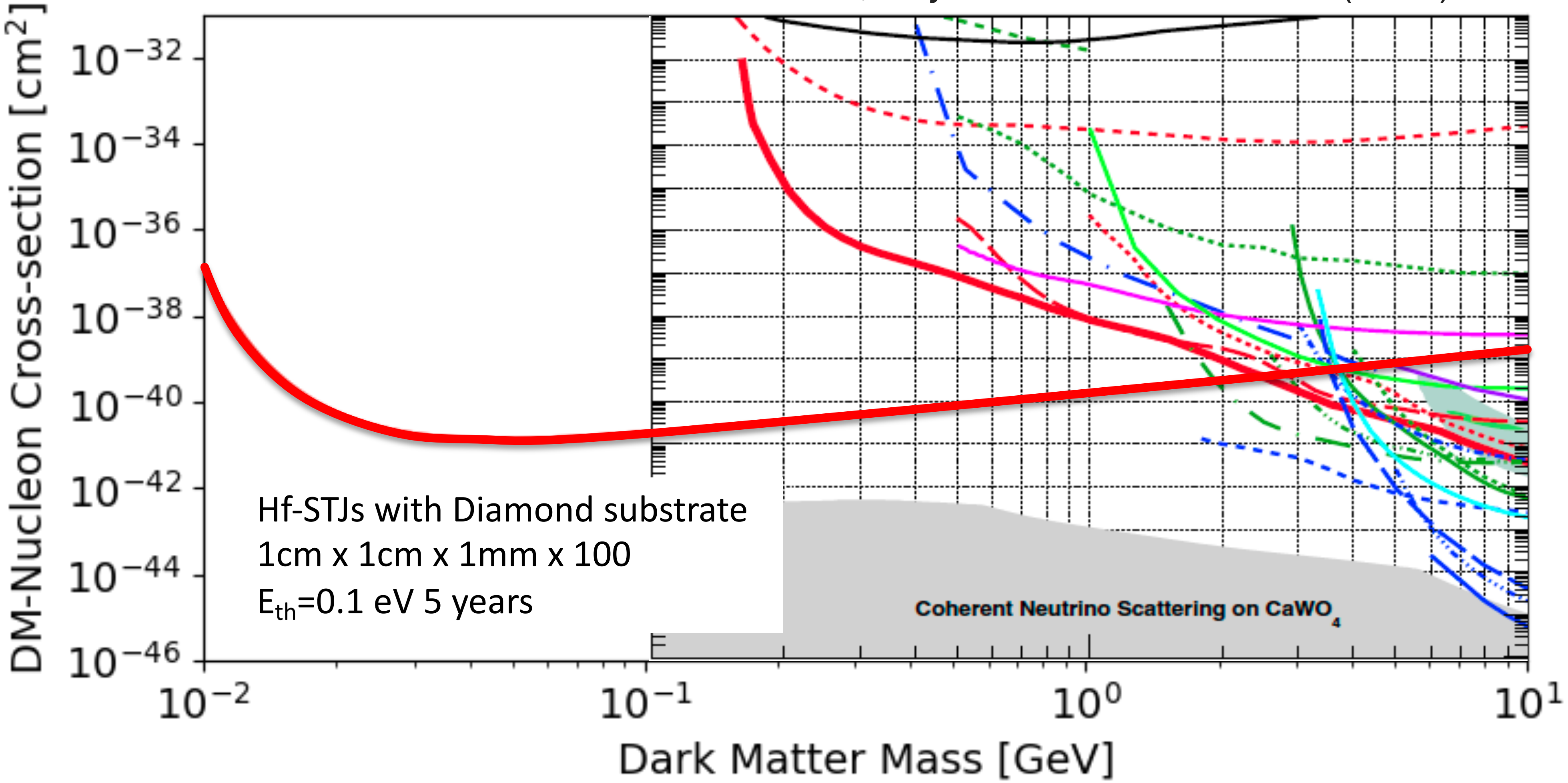
High athermal/thermal ratio indicates higher efficiency of athermal phonon collection

	Sapphire	SC-CVD	PC-CVD	Silicon
Athermal	76%	42%	Very high	29%
Thermal	15%	47%	low	16%
Loss	9%	11%	~10%	45%

Diamond crystals are from SLAC (Noah Kurinsky and OSU (Harris Kagan)

DM Search using Diamond Substrates

CRESST-III, Physical Review D 100.10 (2019): 102002.



Summary

- STJs used in BeEST experiment exhibit ~2 eV energy threshold (no quenching for NR)
- DM detection sensitivities using STJ pixels (low mass, lower threshold) and substrate crystals (higher mass, higher threshold) are calculated
- Two options might be considerable.
  - Use existing BeEST detectors (Ta-STJs) for spanning sub-GeV region, for a cost-efficient experiment.
  - Develop Hf-STJs on diamond (or sapphire) substrates for surveying more relevant DM cross-section region.

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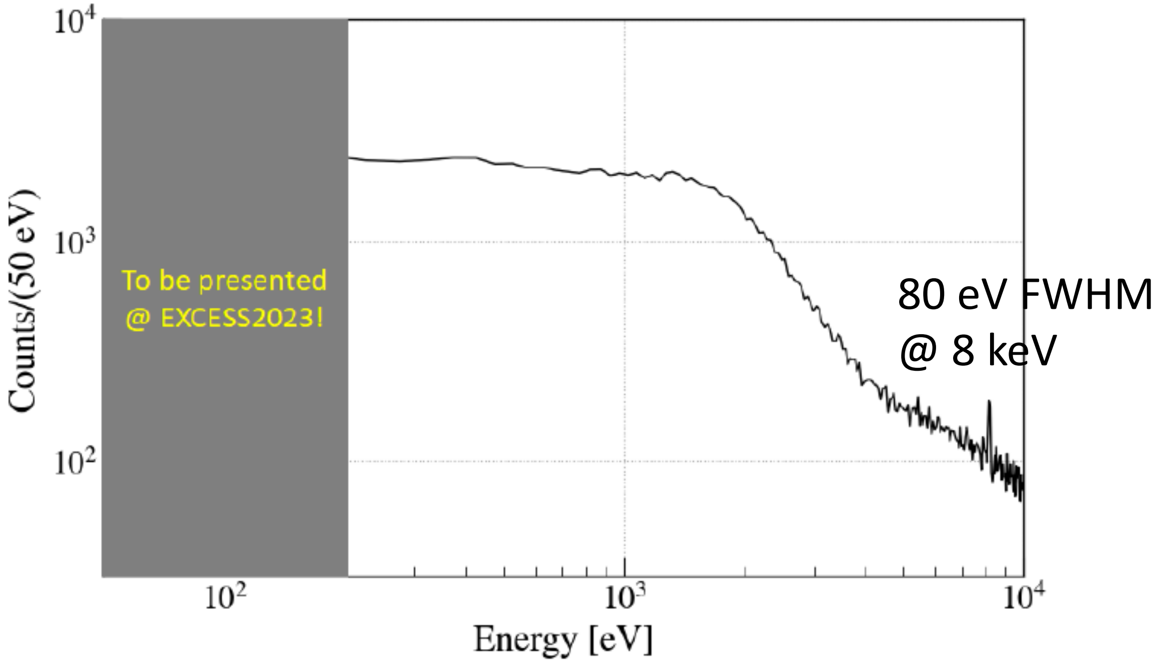
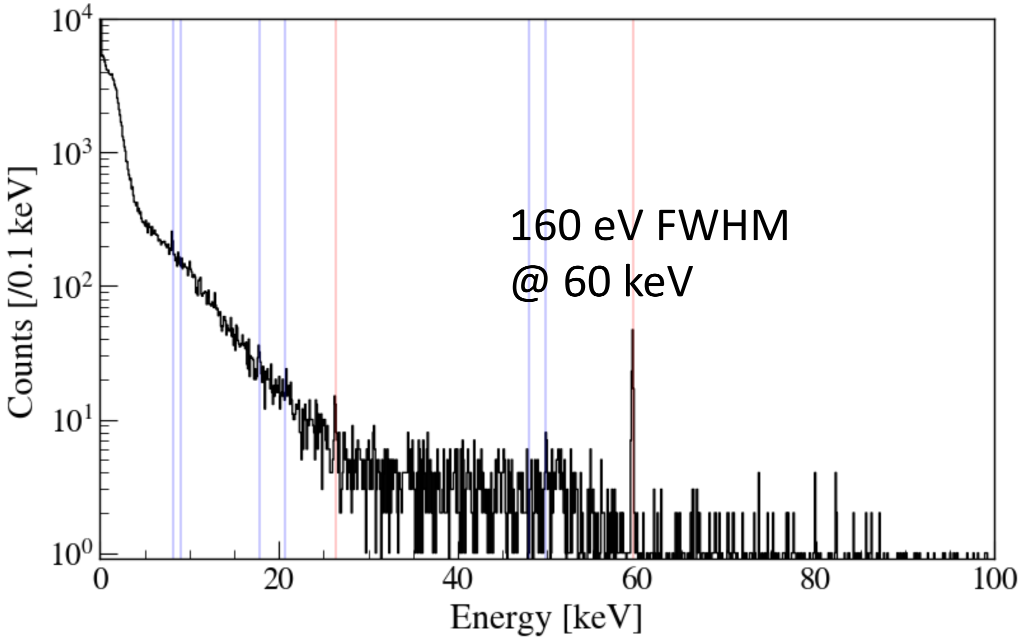
MMC with Crystal Absorbers – Diamond Crystals





- Diamond crystal detector
- 80 eV FWHM @ 8 keV X-ray
- 160 eV FWHM @ 60 keV gamma

Diamond+MMC is a very promising detection method for dark matter and reactor neutrinos