The BeEST Experiment:
A Search for sub-MeV BSM Physics in the Neutrino Sector using Superconducting Tunnel Junctions

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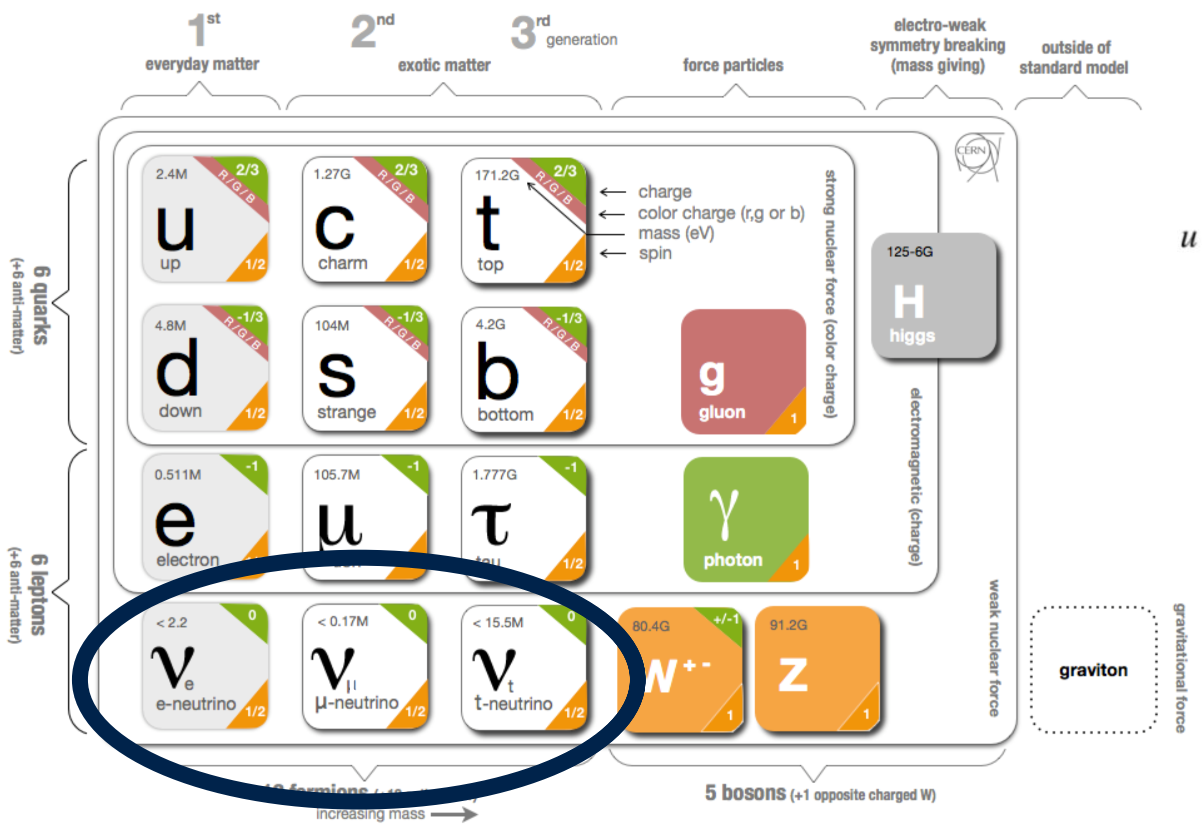
22nd Particles and Nuclei International Conference (PANIC)
September 8, 2021

beest.mines.edu

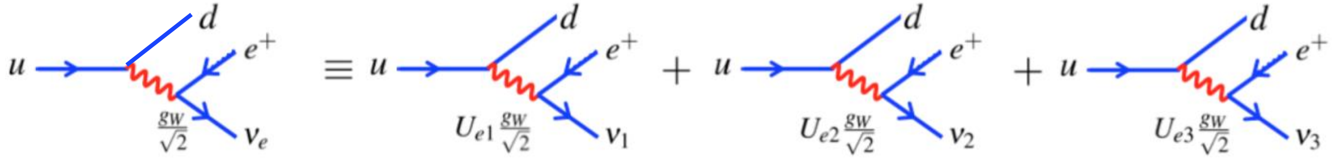
Neutrinos in the Standard Model

- In the SM, there are three generations of neutrino that are defined in terms of their weak-interaction eigenstates.



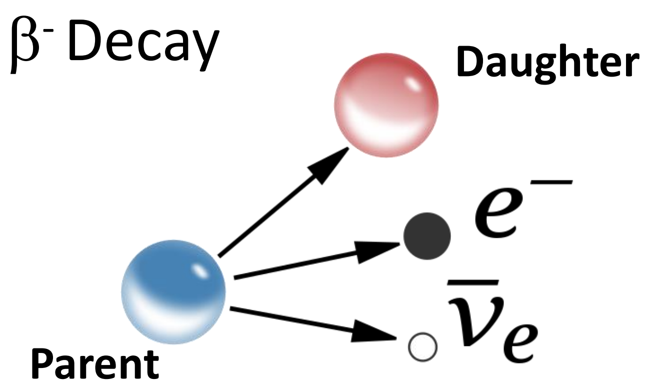
- These weak interaction eigenstates are not equal to the mass eigenstates, and are related via a unitary transformation – the PMNS matrix (analogous to CKM).

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- The existence of massive neutrinos makes extensions to the SM description of leptons unavoidable
- Extensions that provide this accommodation also include massive “right handed” neutrino flavours that do not couple to the weak interaction
- We need ***model-independent*** searches for new physics!

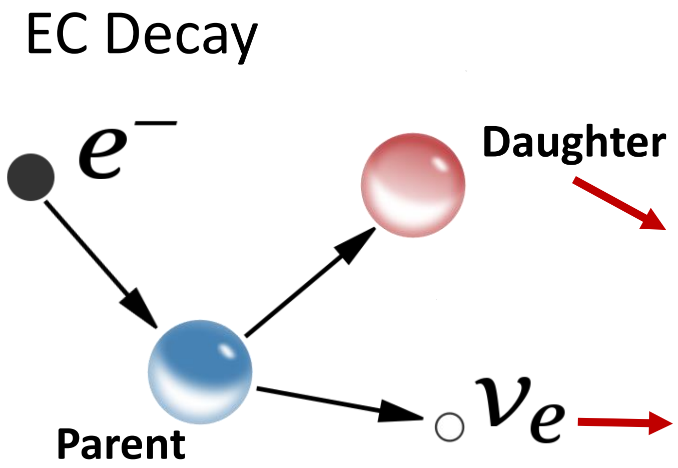
The Model Independent Nature of Beta Decay



- Decay momentum reconstruction is a simple, model-independent approach to heavy neutrino searches

  R. Davis, Phys. Rev. **86**, 976 (1952)
  R. Shrock, Phys. Lett. B **96**, 159 (1980)
  G. Finocchiaro and R.E. Shrock, Phys. Rev. D **46**, R888(R) (1992)
  M.M. Hindi *et al.*, Phys. Rev. C **58**, 2512 (1998)

- The process is tremendously simplified for electron capture (EC) since there are only two final bodies that share energy/momentum



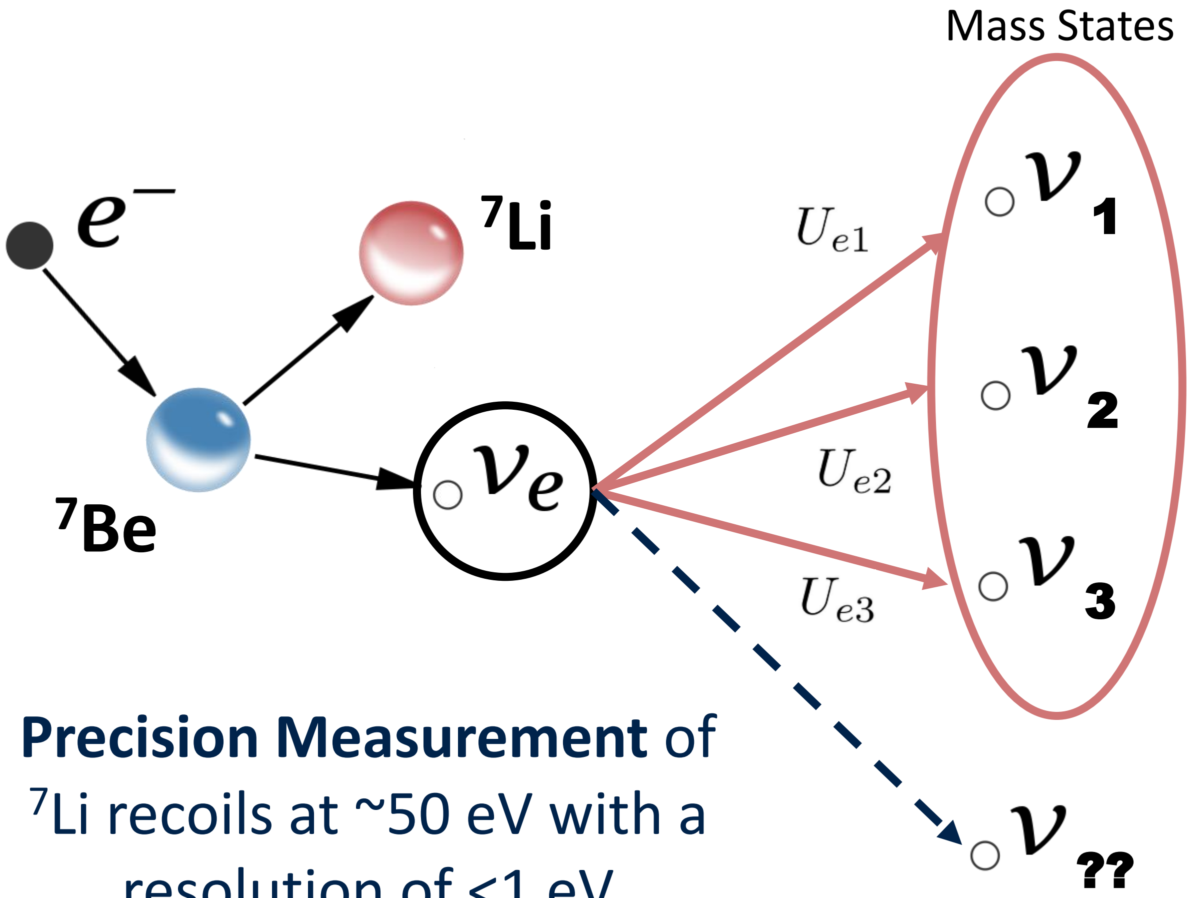
$$T_d = \frac{Q_{EC}^2 - m_\nu^2 c^4}{2\left(Q_{EC} + m_d c^2\right)}$$

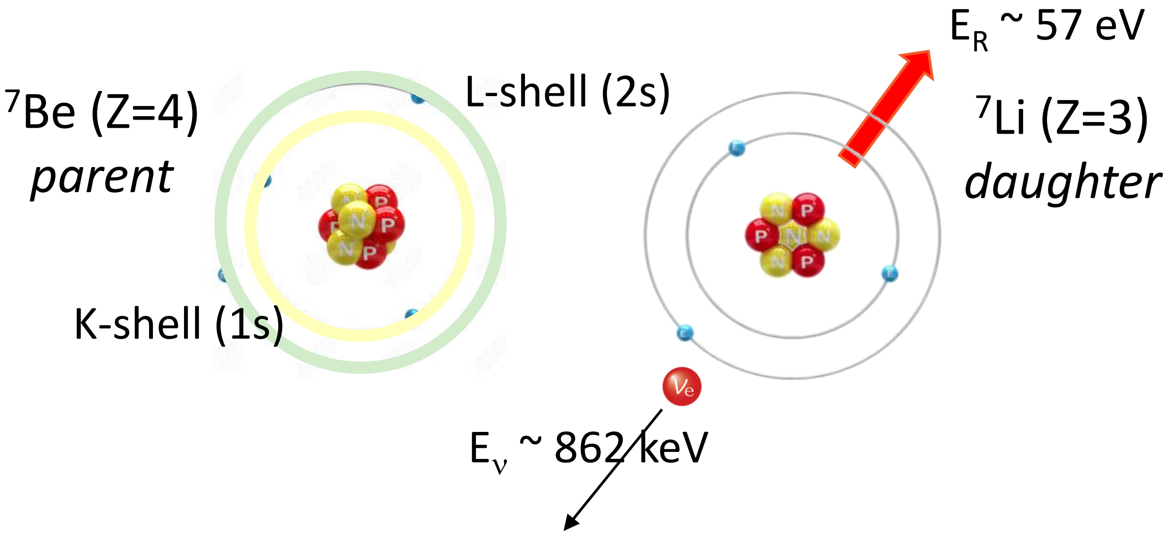
$$T_\nu = \frac{\left(m_\nu c^2 - Q_{EC}\right)\left(c^2(m_\nu - 2m_d) - Q_{EC}\right)}{2\left(m_d c^2 + Q_{EC}\right)}$$

Takeaway: Beta decay provides a sensitive, model independent probe of any new physics in the neutrino sector that couples to their mass states

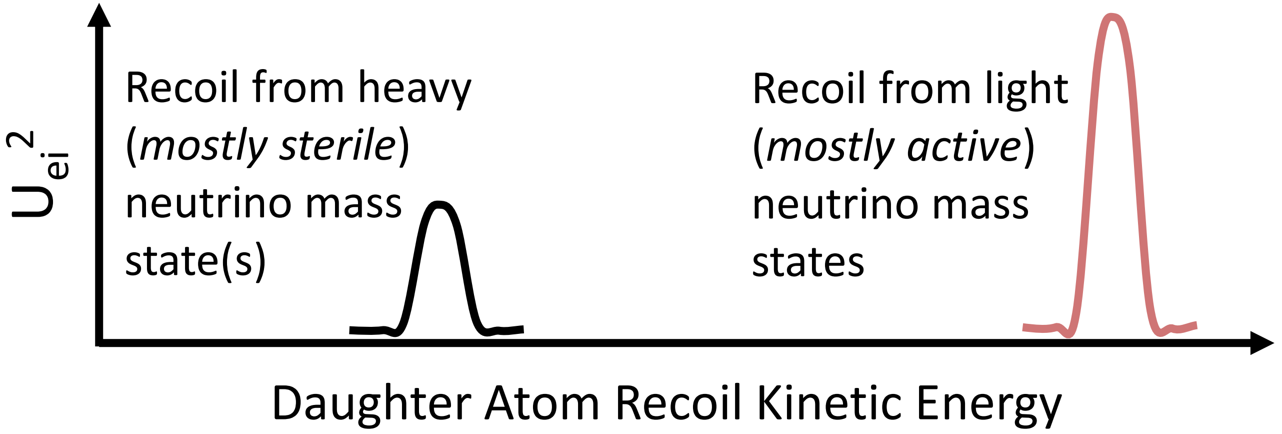
Neutrino Studies with the Electron Capture Decay of ^{7}Be

- **^{7}Be is the ideal case for neutrino studies using decay momentum reconstruction.**
  - Simple atomic and nuclear structure and largest *Q*-value (862 keV) of all pure EC cases
    ➔ Highest maximum recoil energy





Precision Measurement of ^{7}Li recoils at ~50 eV with a resolution of <1 eV



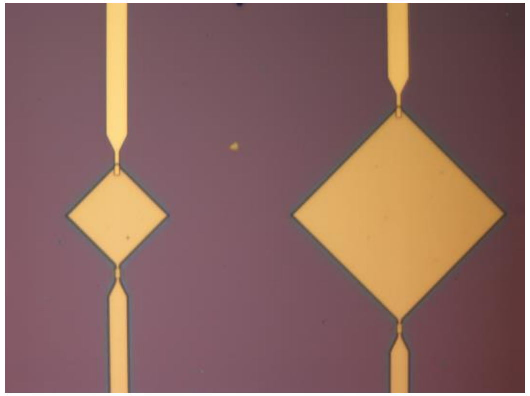
Superconducting Tunnel Junction (STJ) Quantum Sensing

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

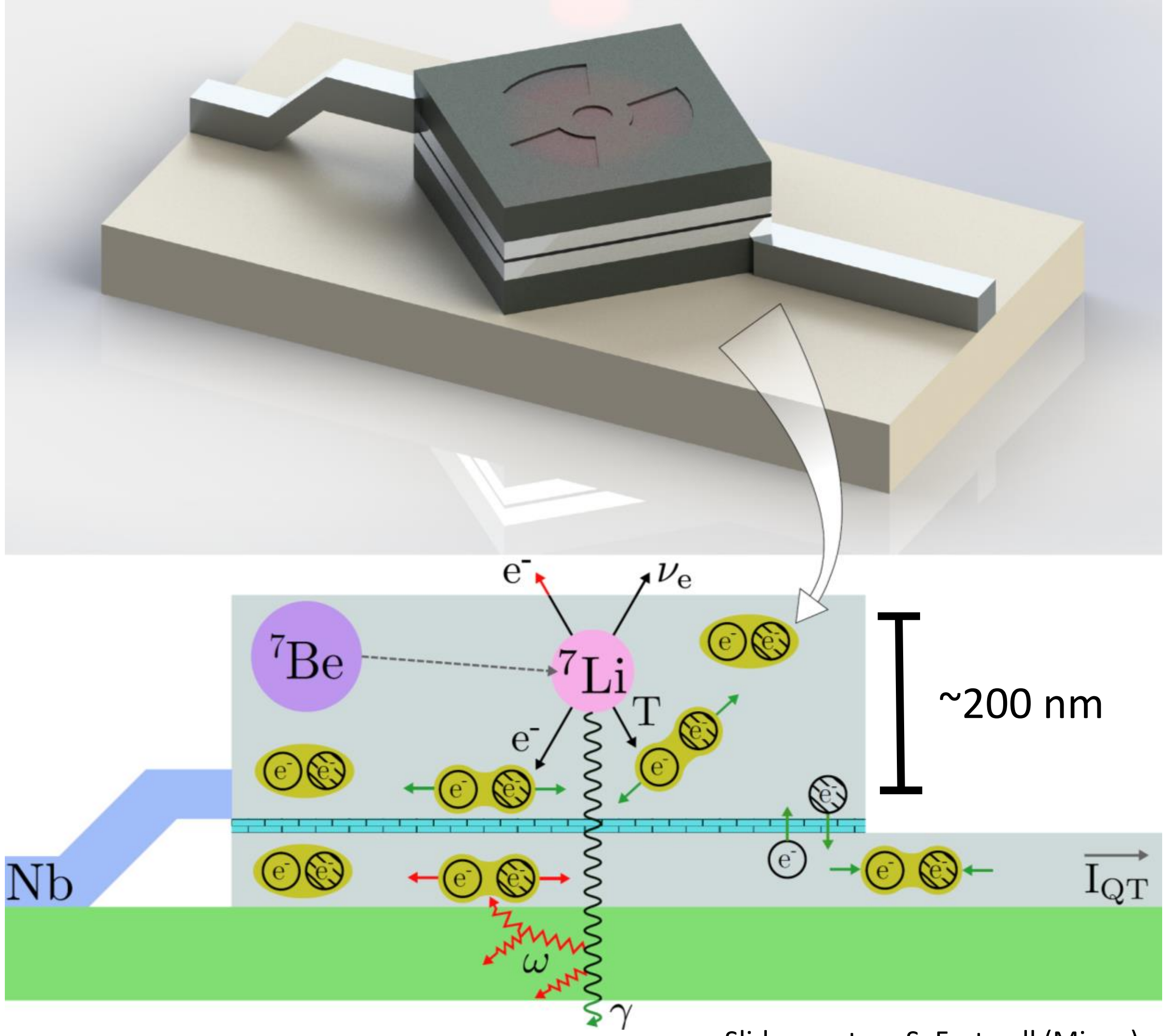
Can exploit strength of BSM searches with rare isotopes

Josephson Junctions

68 x 68 μm^2

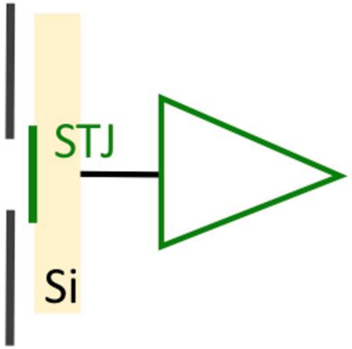


138 x 138 μm^2



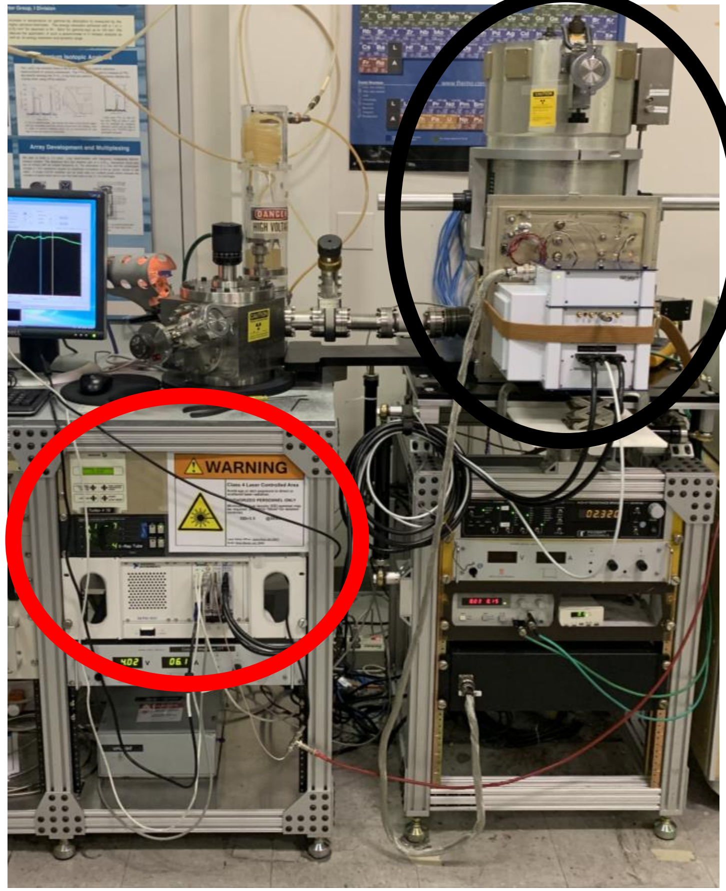
Slide courtesy S. Fretwell (Mines)

STJ Performance and Characterization



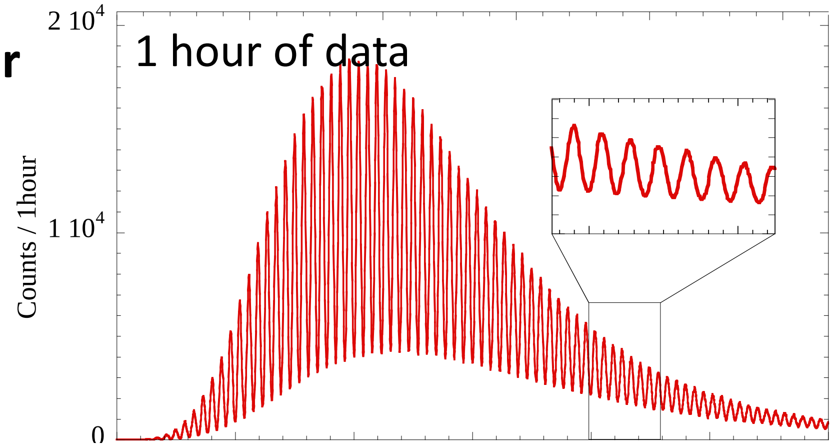
- Pulsed 355 nm (3.5eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK



Laser

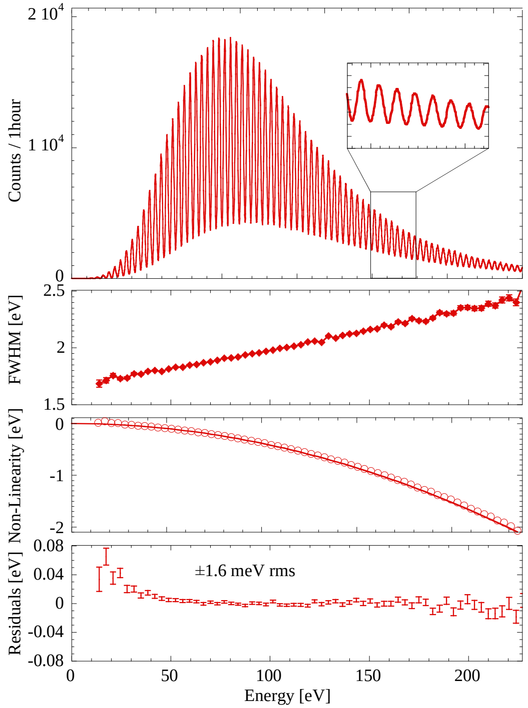
Lawrence Livermore National Laboratory



S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

The BeEST Experiment

Rare-isotope implantation at TRIUMF-ISAC

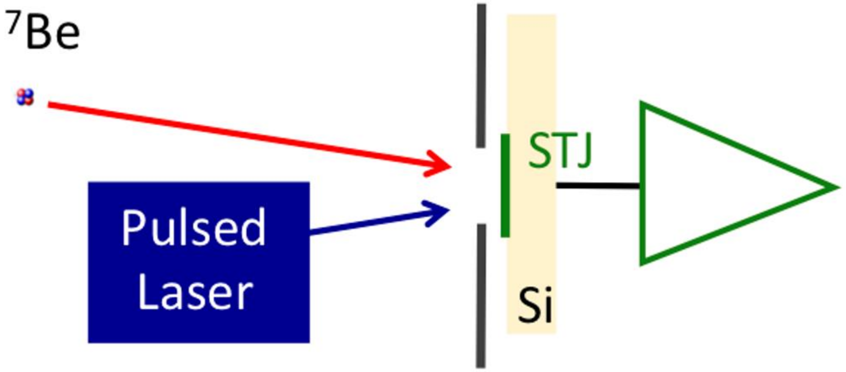


S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

THE BeEST

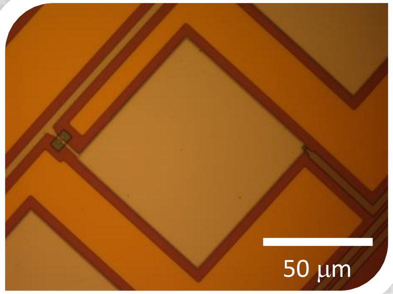
TRIUMF

STAR CRYOELECTRONICS

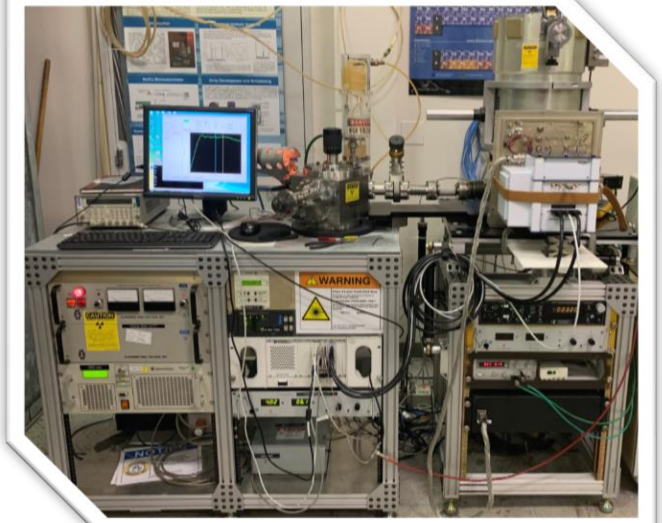


High-precision *In-situ* calibration and characterization

Ta, Al, and Nb-based STJ Sensors



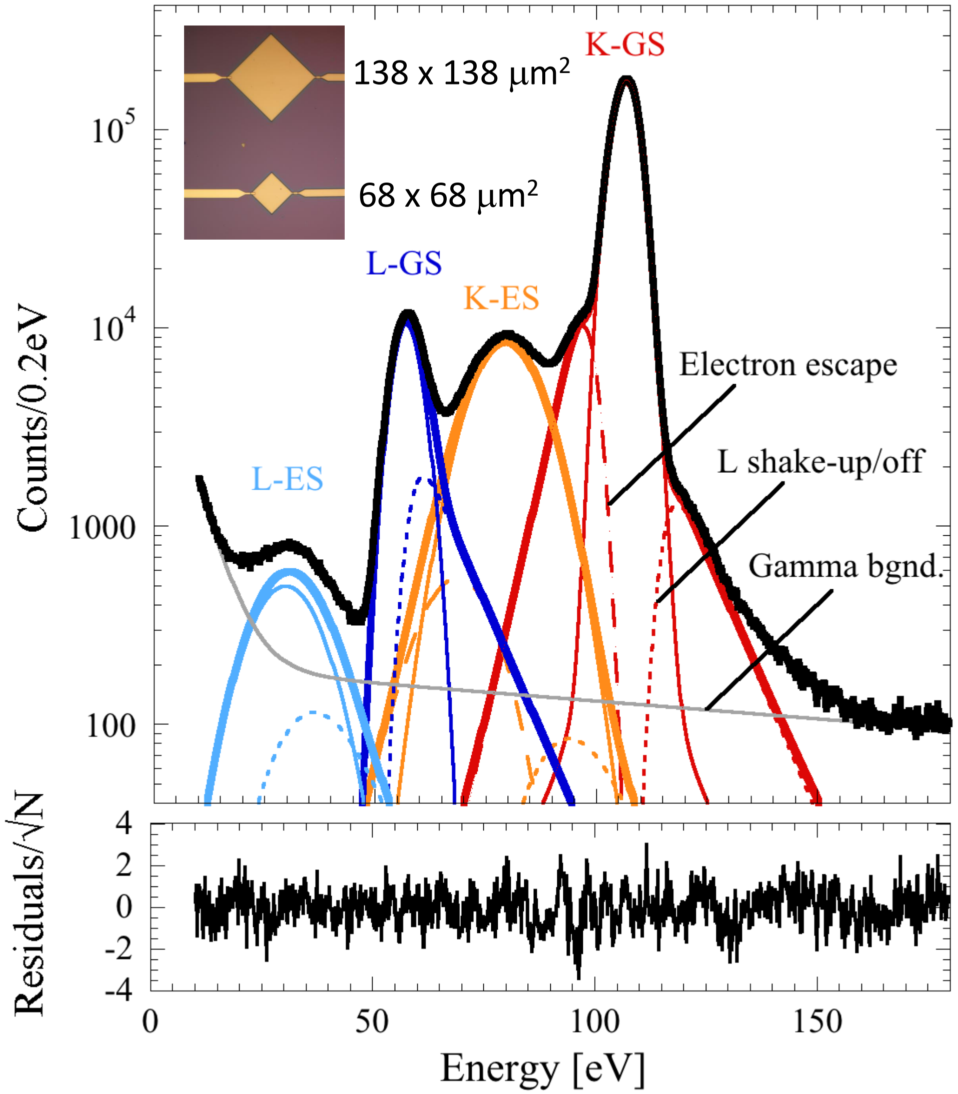
Lawrence Livermore National Laboratory



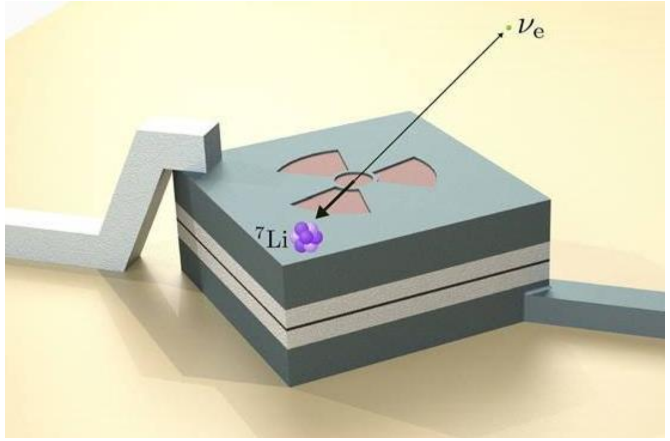
Cooling (<0.1 K) and measurement in ADR at LLNL

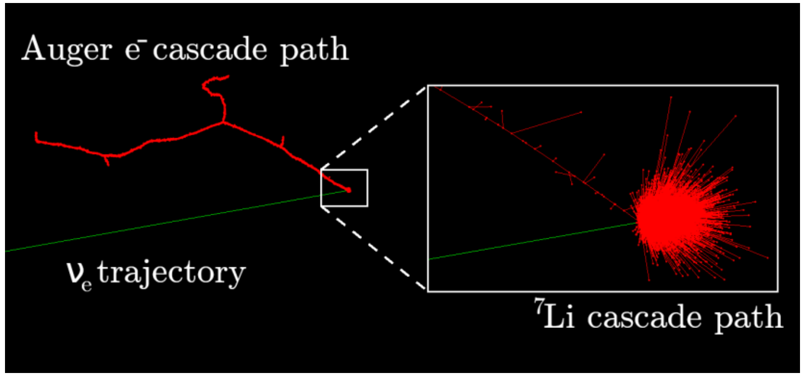
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

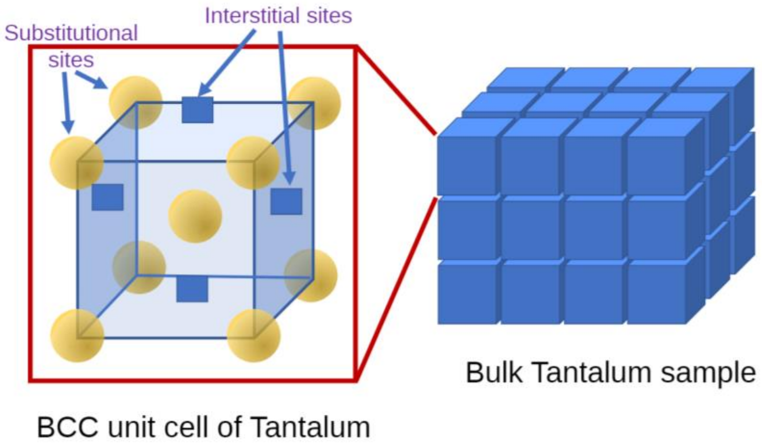
First Nuclear Recoil Experiments with STJs

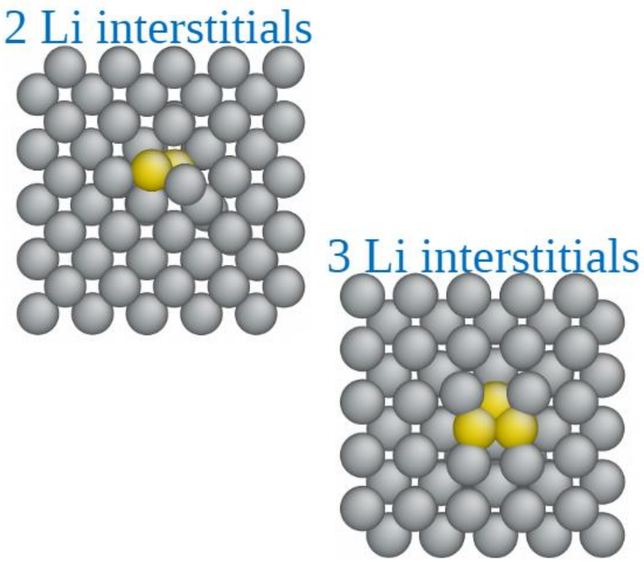


S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)







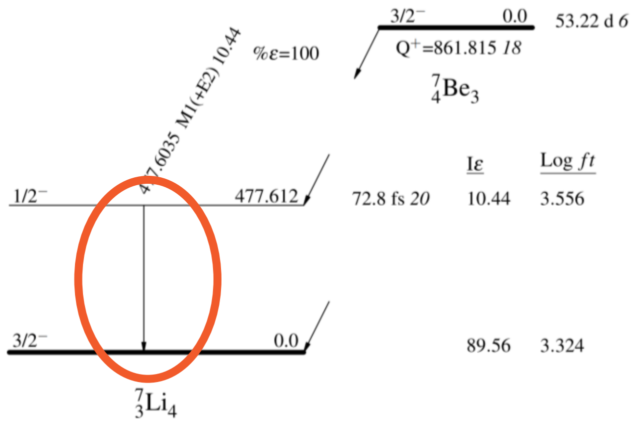


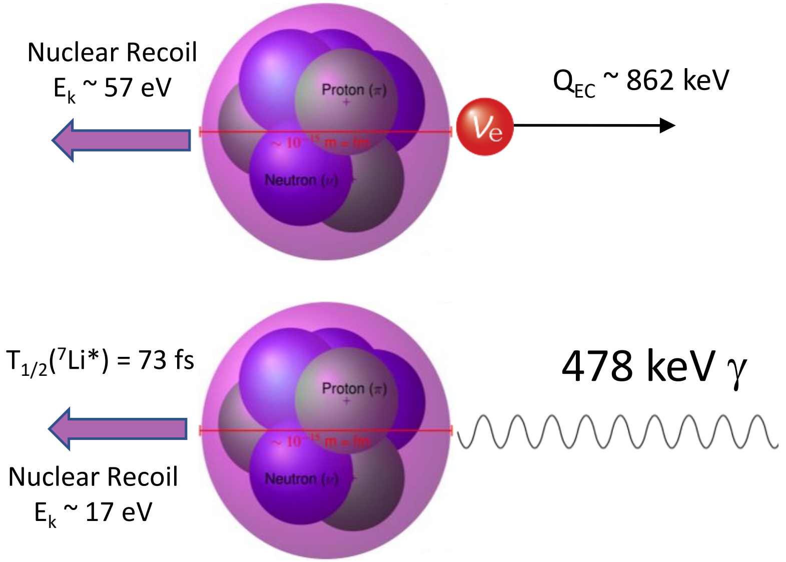
- Intrinsic resolution (laser): 1.4 to 2.9 eV
- Recoil peak resolution: 6 eV
- In-medium effects of Be/Li in Ta matrix

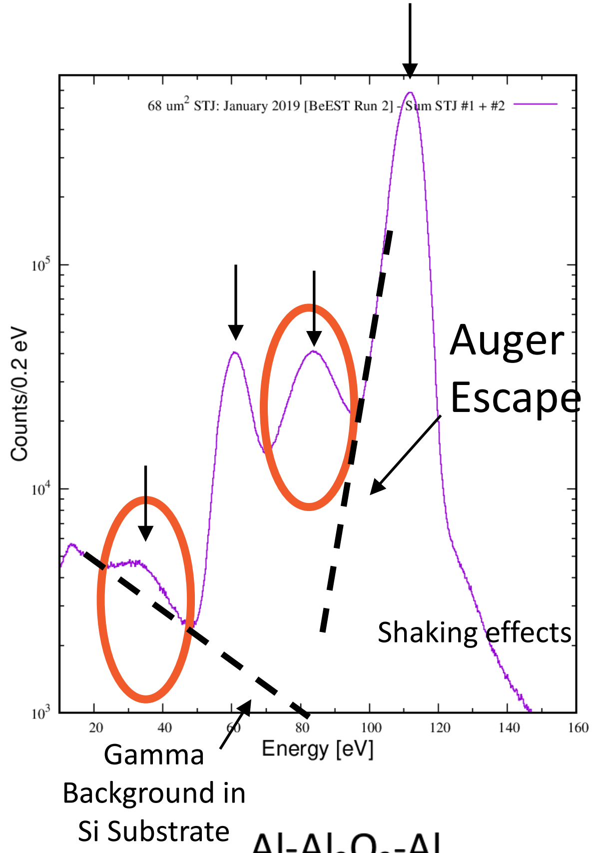
A. Samanta, S. Friedrich, K.G. Leach, and V. Lordi (2021)

Known (and Unknown) Features in the the Data

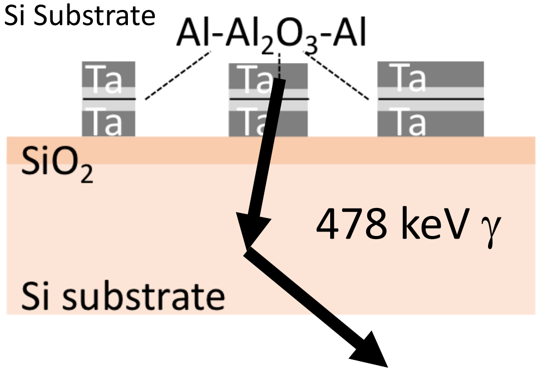
- Doppler broadening of recoil from excited state decay







- Interaction of 478 keV photon in Si substrate (low-energy background)
- Low implantation depth from limited ISAC energy (escape tails)
- Shake-up/off (autoionization) electrons following EC decay (higher energy features)



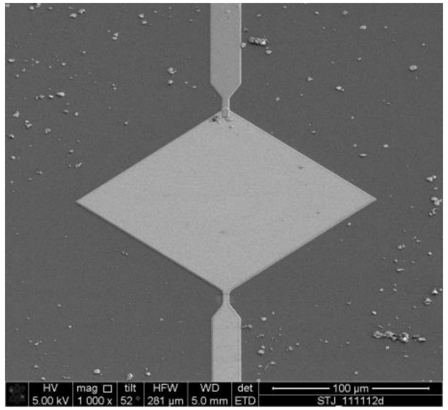
- Quenching of STJ response to electrons or recoils vs calibration photons AND material dependent effects (slight difference in measured energies)

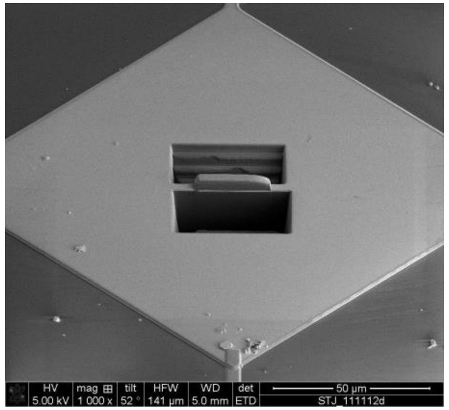
Atom-by-Atom Characterization of the BeEST

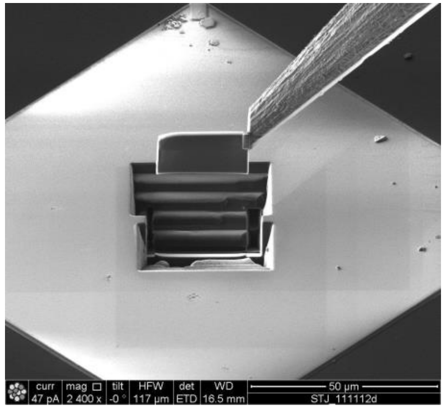
- The sensitivity of our experiment (and technique in general) is currently limited by our understanding of where the atoms we implanted are, and how they interact with the detector

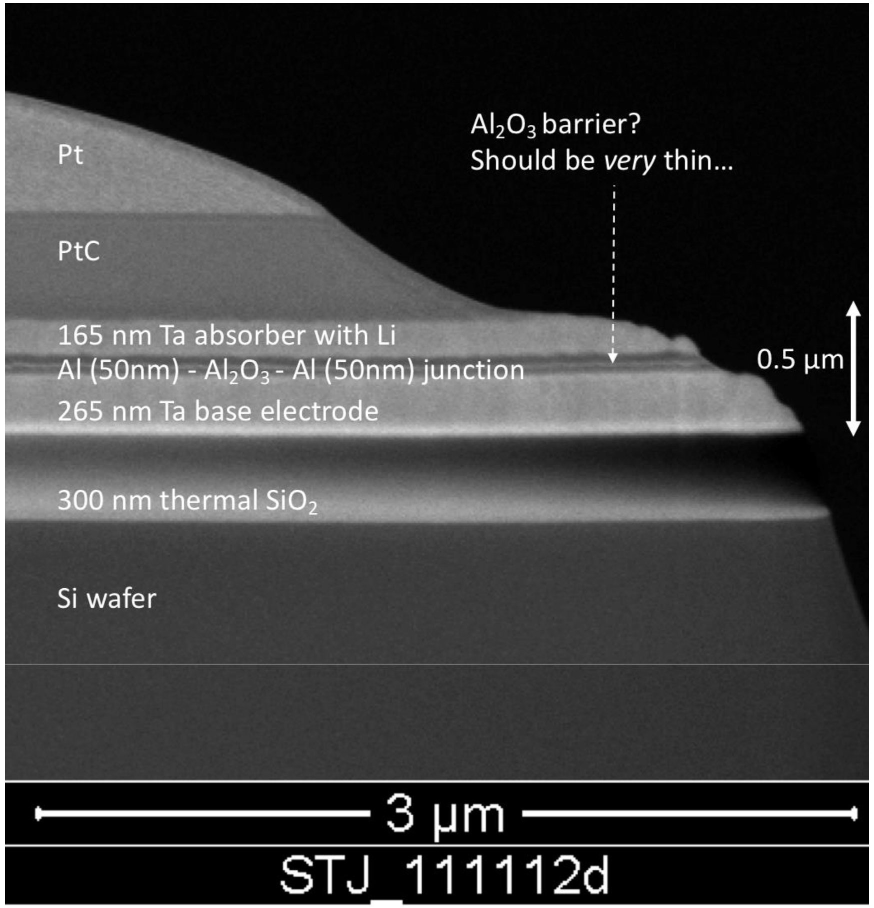
THE GOAL: Create an atom-by-atom map of the detector

"How does Be location in the matrix affect binding and emission energies?"

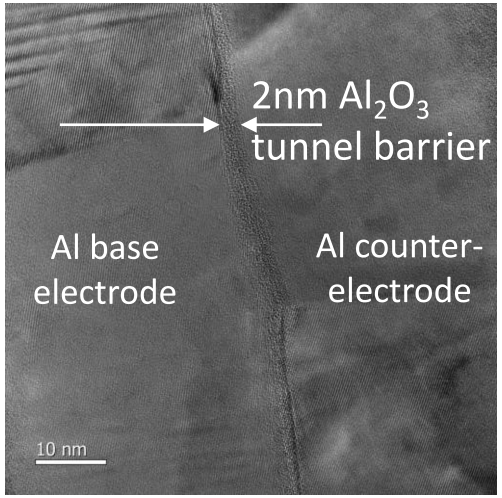






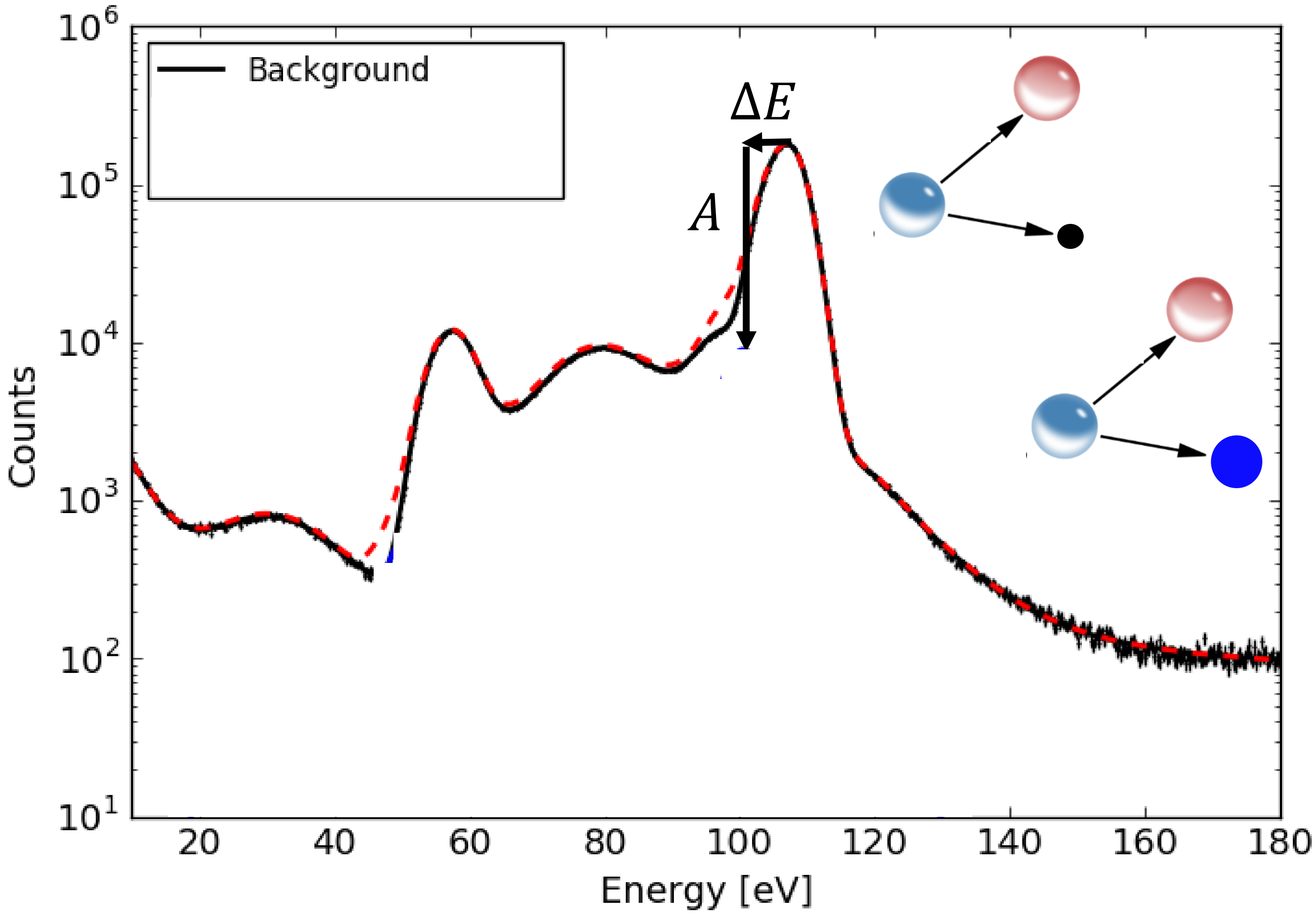


- Materials imaging done at Mines, Berkeley, and LLNL
- DFT quantum simulations performed at LLNL using the supercomputers to map material-dependent energies



A. Samanta, D. Diercks, S. Friedrich, K.G. Leach, and V. Lordi (2021)

Searching for Heavy Neutrinos in the BeEST Data



Sterile neutrino will add a similar spectrum with:
1) Shifted recoil energy $\Delta E(m_s)$
2) Reduced amplitude ($A \propto |U_{e4}|^2$)

$$f(E) = \underbrace{[1 - A(U_{e4})]\, f_0(E)} + \underbrace{A(U_{e4})\, f_0(E - \Delta E)}$$

Background:
Active neutrino contribution
+ other background

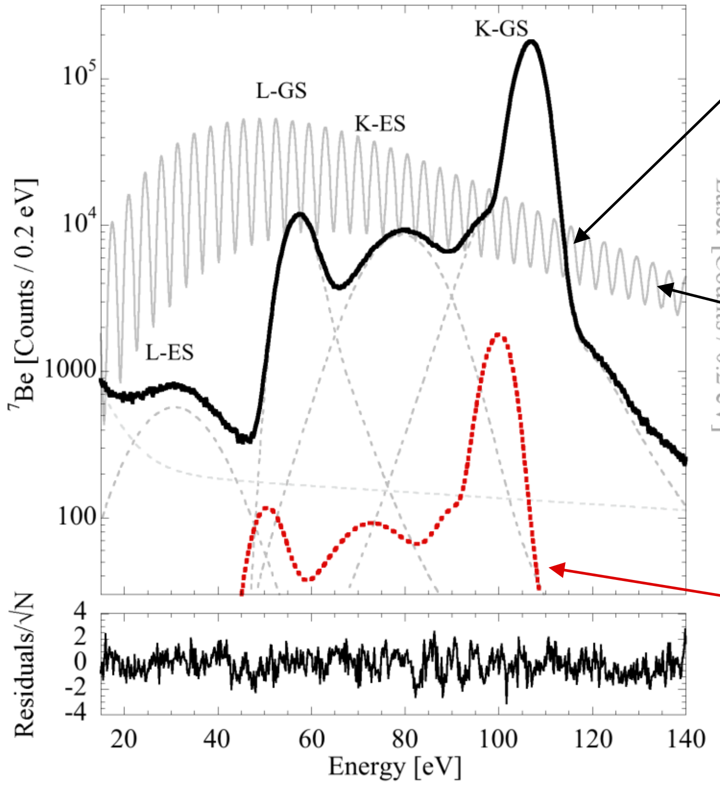
Signal:
Sterile neutrino contribution

f_0= EC spectral shape with active neutrinos

Slide Courtesy: Geon-Bo Kim (LLNL)

First Limits from BeEST Phase-II Data

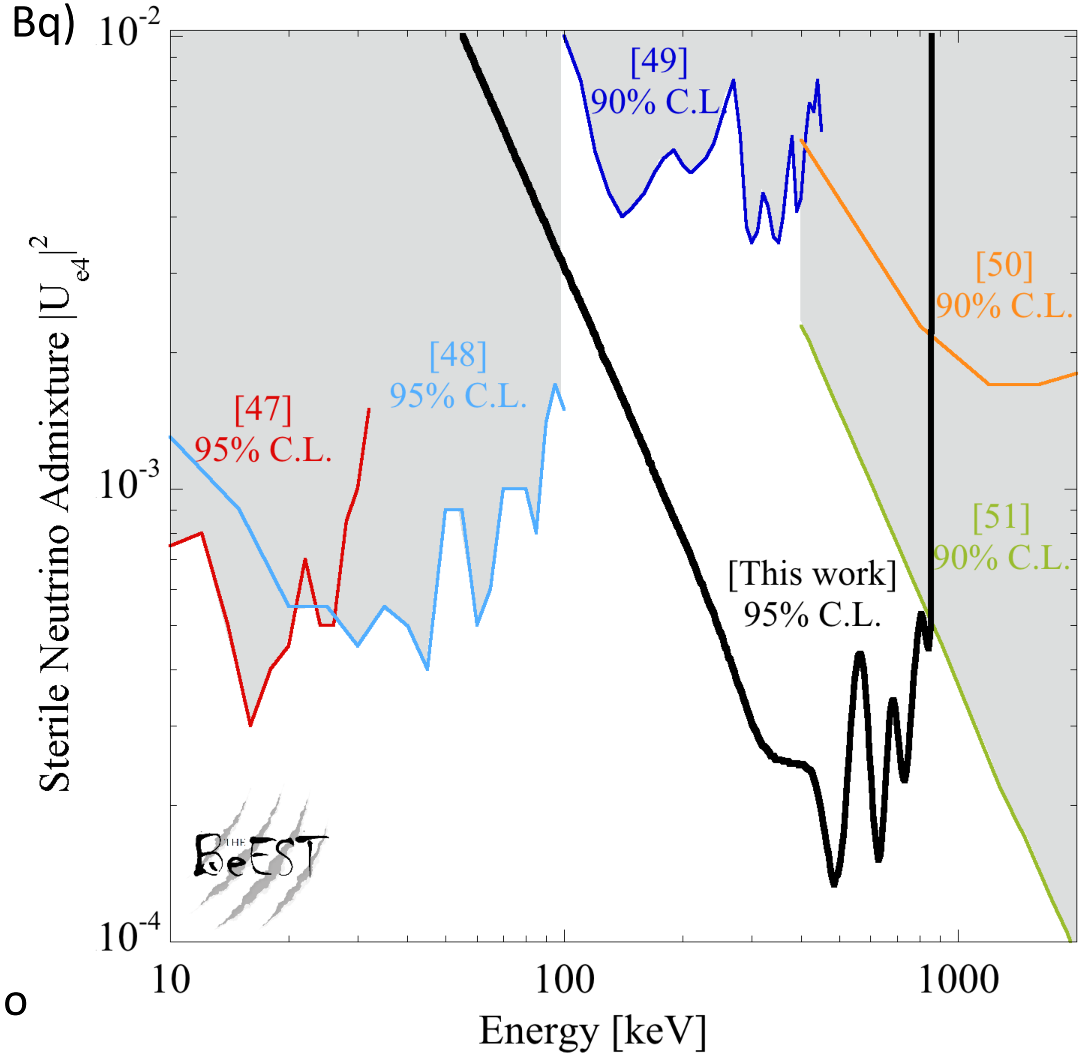
- Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq)



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Simultaneously acquired laser calibration spectrum

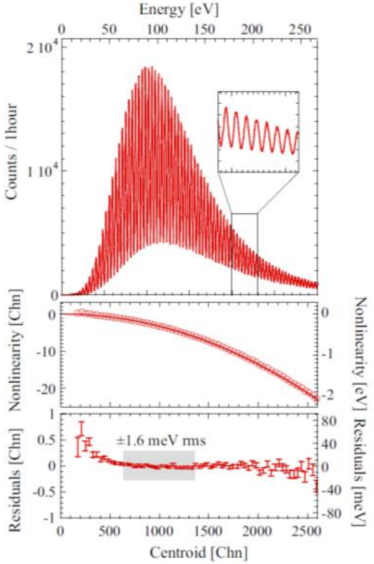
Example of signal that would be generated by 300 keV neutrino with 1% mixing

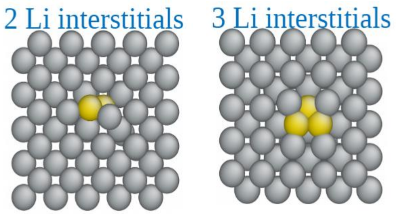


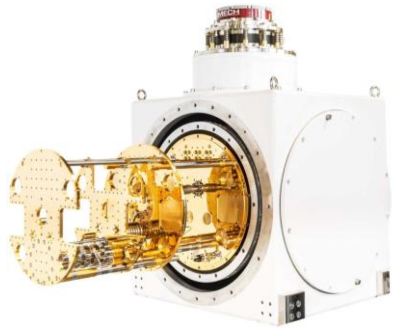
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

- Up to an order of magnitude improvement for limits on heavy neutrino admixtures to ν_e for masses of 100 – 850 keV

Phases of the BeEST Experiment







Phase-IV

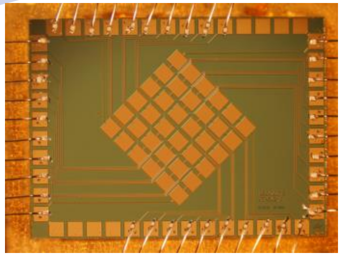
Operation of 128-Pixel Arrays of Al-Based STJs in Dilution Refrigerator

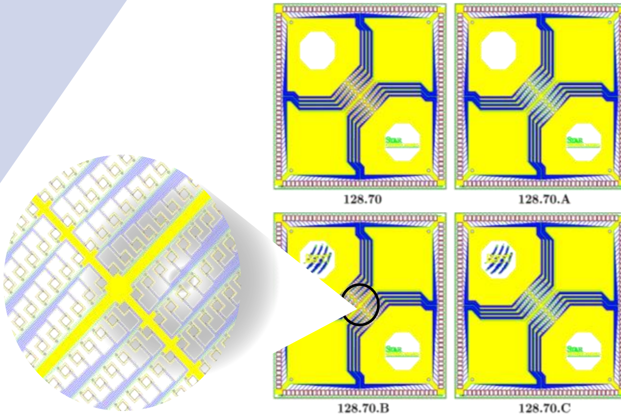
2025

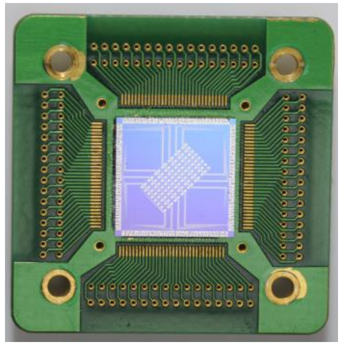
Phase-III

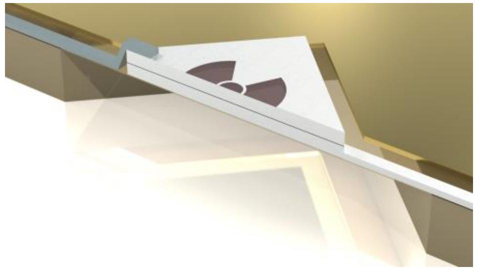
Scaling to 36- and 112-Pixel Arrays of Ta-Based STJs

2022







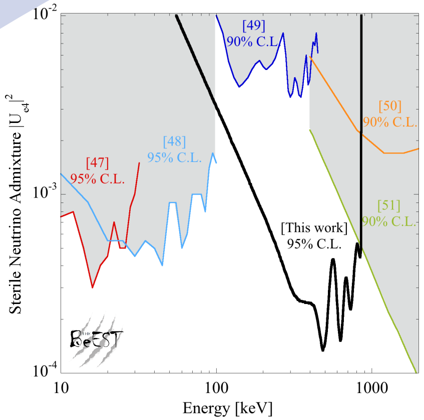


Phase-II

First Limits and Precision Device Characterization

- J. Low Temp. Phys. **200**, 200 (2020)
- PRL **126**, 021803 (2021)

2021

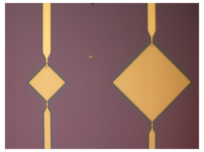


2020

Phase-I

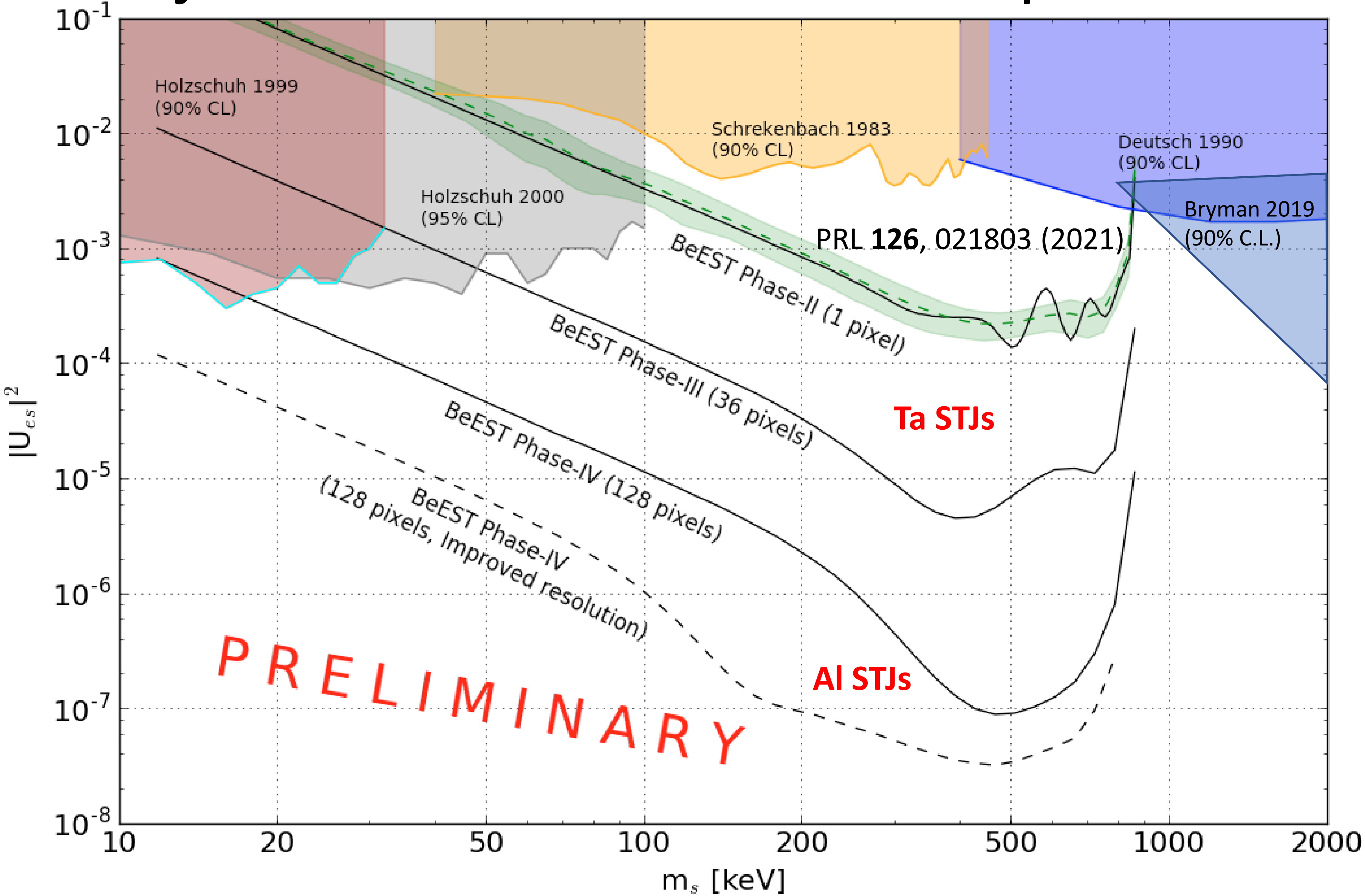
Proof of Concept

- PRL **125**, 032701 (2020)



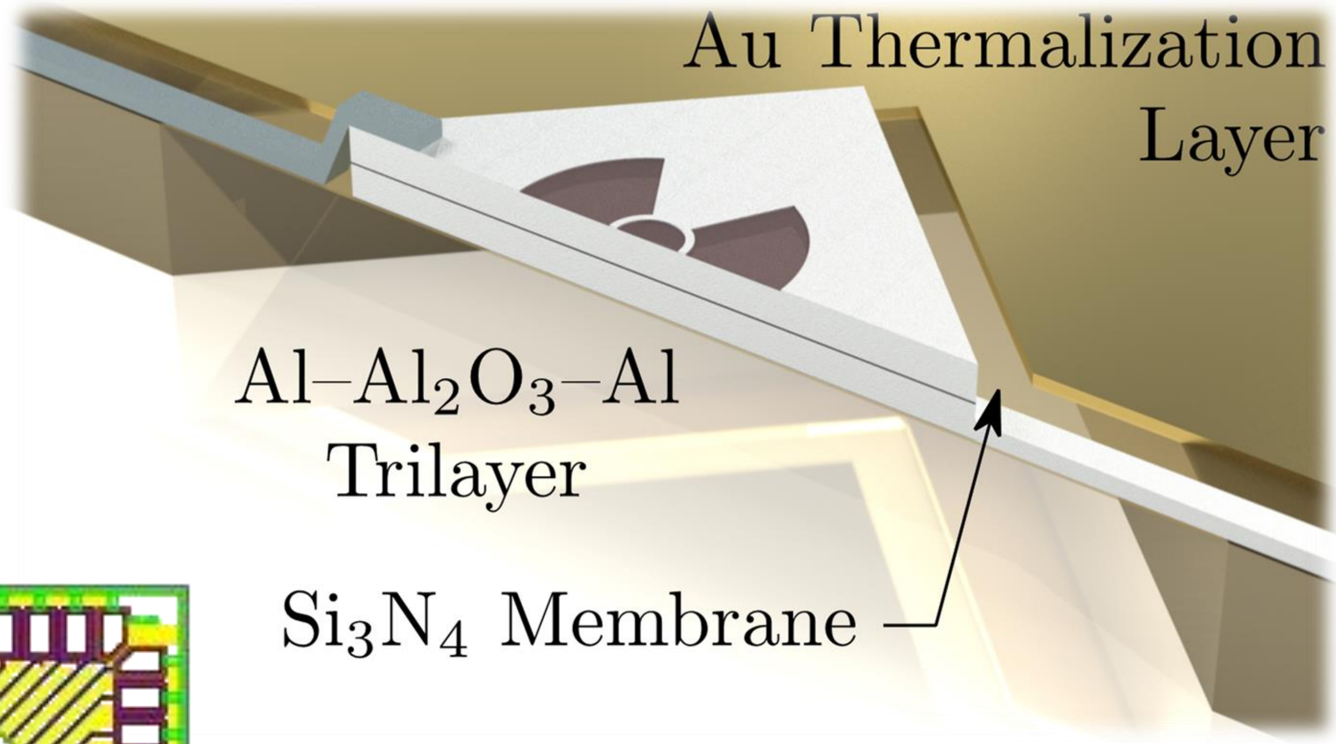
2018

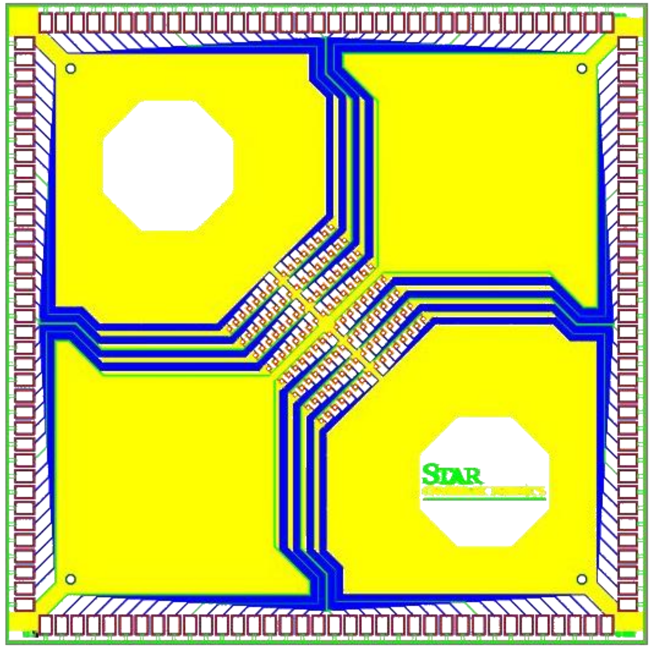
Projected Limits of the BeEST Experiment



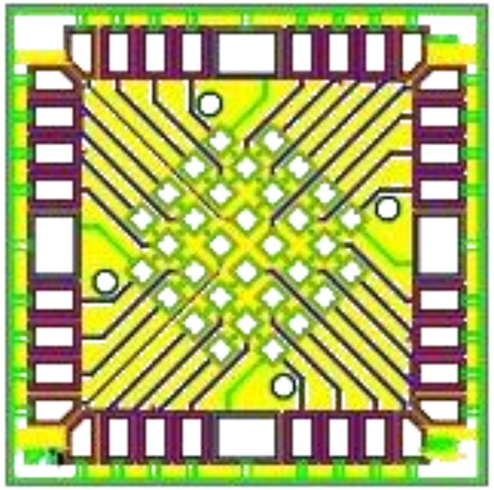
April 2021 - First Set of Al STJ Arrays

- STJs for Phase-IV
  - Al junctions (higher resolution and depth)
  - SiN and Au Surface Features (Background)
  - Large arrays (statistics)

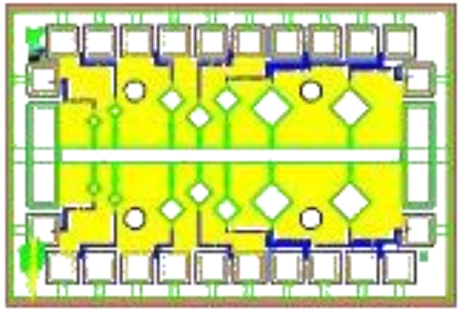




128.70



32.130



Test Chip

Slide courtesy S. Fretwell (Mines)

Testing the First Set of Al STJ Arrays

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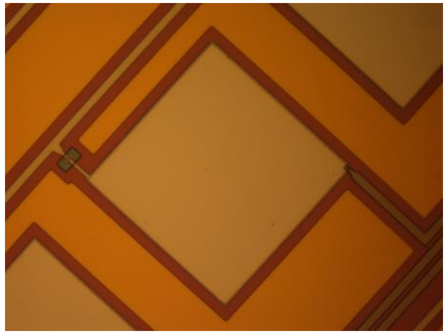
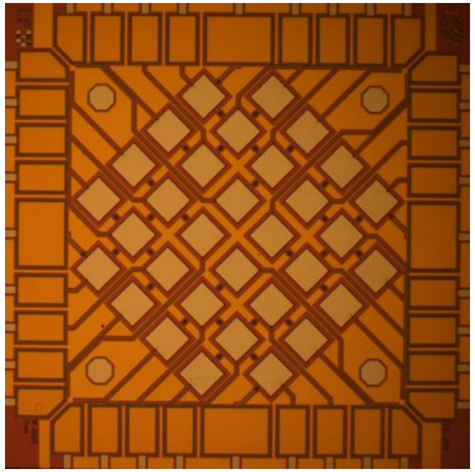
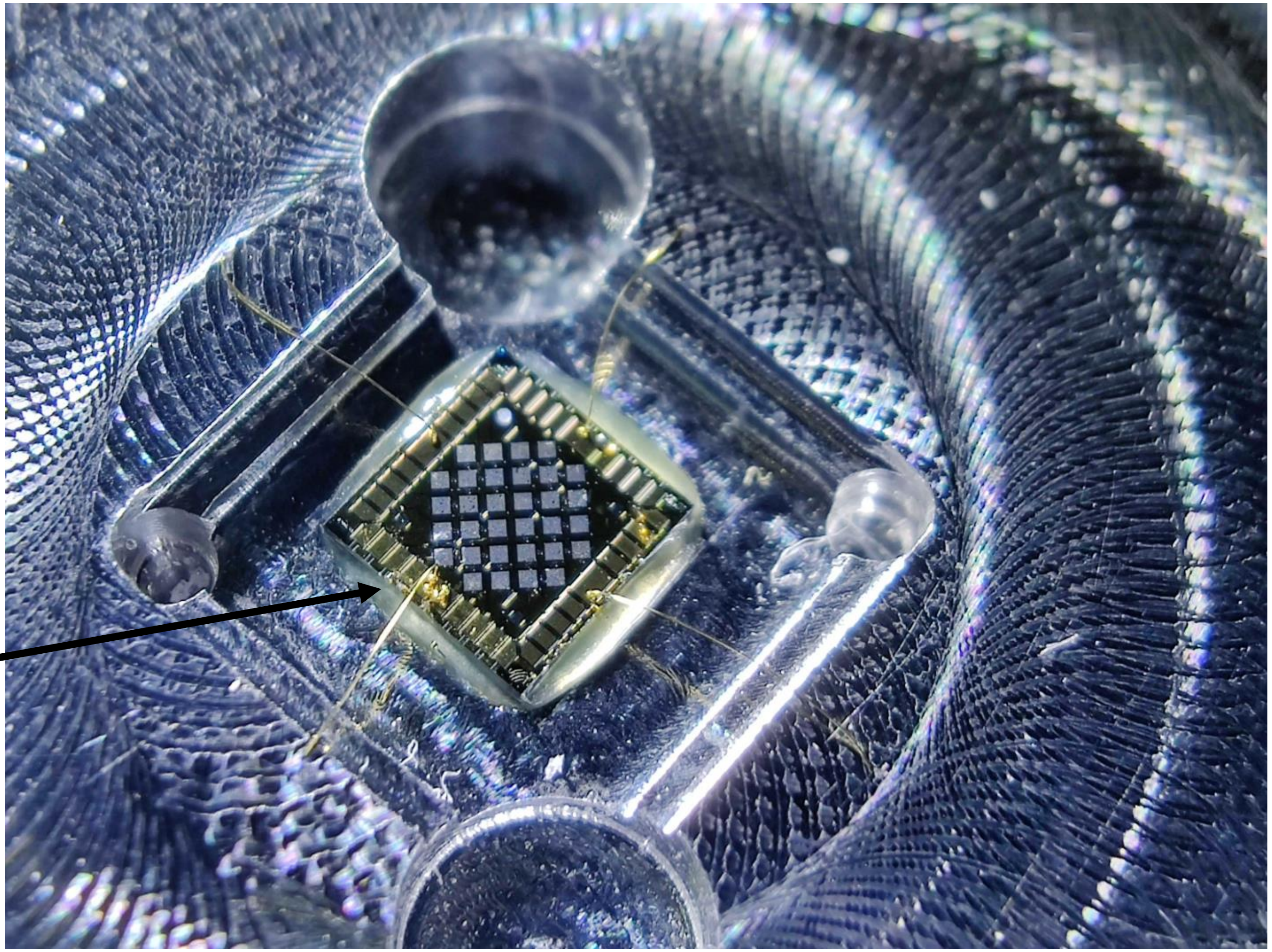
STAR CRYOELECTRONICS



Single Junction





First 32-pixel Al STJ array

- First set of junctions for Phase-IV have been fabricated (including test detectors and arrays)
- First ^{7}Be implantation completed in August, currently being tested at Livermore

Conclusions

- Quantum sensors can be powerful tools in our search for BSM physics using nuclei/atoms. In particular, STJs allow for high-rate experiments to probe weak BSM physics

- The scalability of the technology allows for implementation of large-scale arrays and readouts at low temperatures for increased sensitivity.

- The Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment uses momentum reconstruction in the EC decay of ^{7}Be to search for heavy neutrino masses (ultimately) in the 5-860 keV range.

- This method is a model-independent approach to heavy neutrino searches that is complementary to future efforts using nuclear decay of ^{3}H (KATRIN, Project 8), ^{131}Cs (HUNTER), and ^{163}Ho (ECHo, HOLMES) to provide high-sensitivity searches from the eV to MeV scale.

The BeEST

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APS physics

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