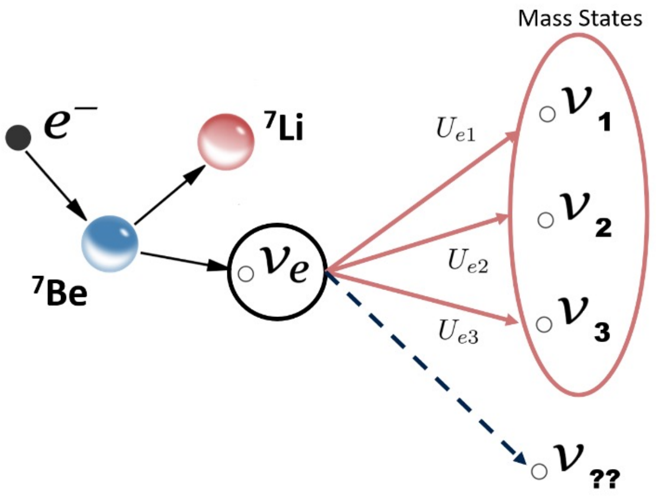
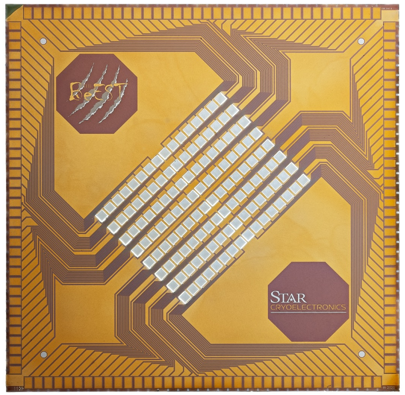
The BeEST sterile neutrino experiment

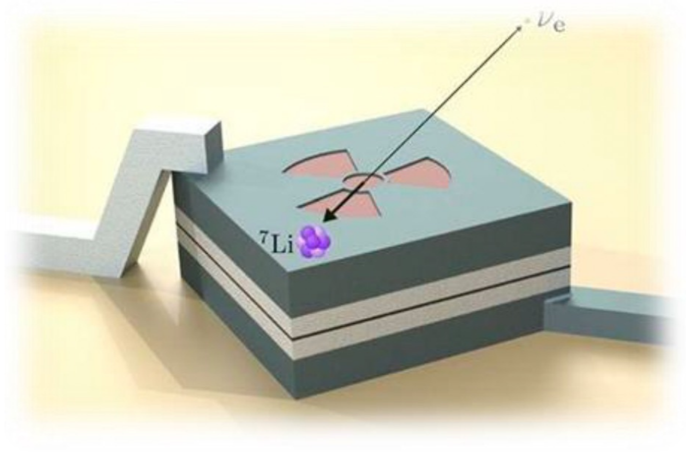
Annika Lennarz

Division of Physical Sciences, TRIUMF

on behalf of the BeEST collaboration







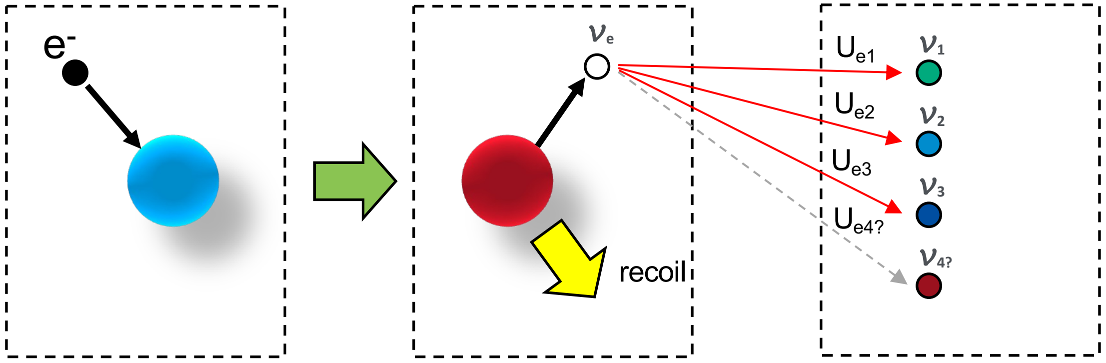
LLWI 2024 – Feb. 19th – 23rd

Discovery, accelerated

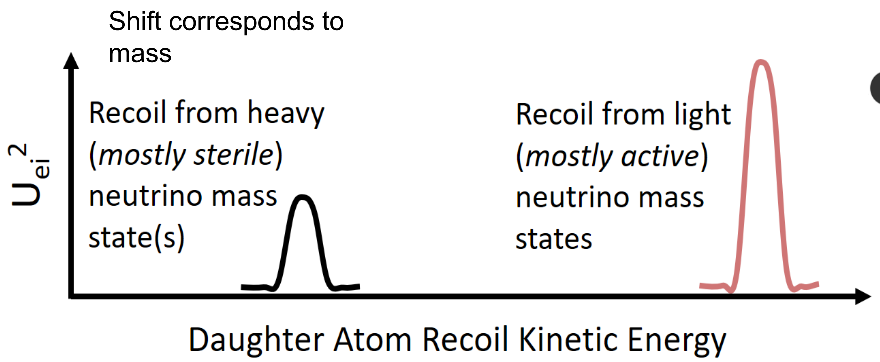
The BeEST – **B**eryllium **E**lectron-capture with **S**uperconducting **T**unnel junctions

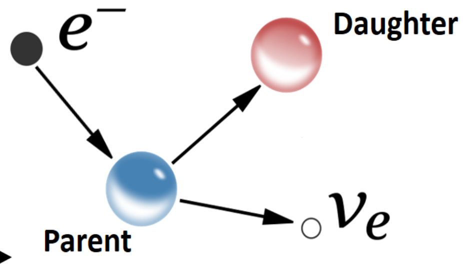
- The BeEST experiment searches for **sterile neutrinos in the keV mass range** using the **nuclear electron capture decay of ^{7}Be** implanted into superconducting tunnel junction (STJ) radiation detectors
- Based on **momentum reconstruction** of the ~eV-scale lithium-7 **nuclear recoil** energy spectrum following neutrino emission

Pure two-body final state that consists of the recoiling daughter nucleus and the emitted ν_e



- ^{7}Be is ideal candidate because of its:
  - pure two-body final state
  - Relatively large decay energy (862 keV)
  - Relatively high recoil energy (~ 50 eV)
  - Simple atomic and nuclear structure





The BeEST – Beryllium Electron-capture with Superconducting Tunnel junctions

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(STJ) radiati
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spectrum fol

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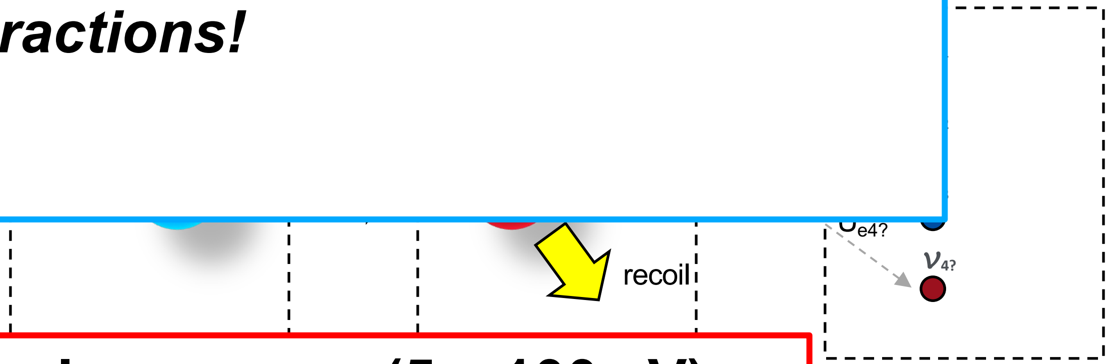
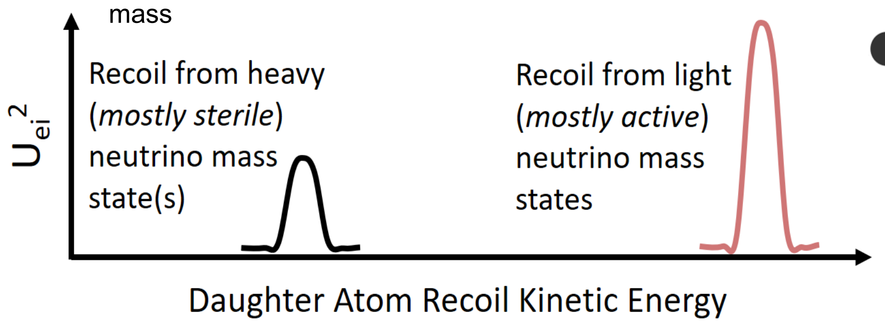
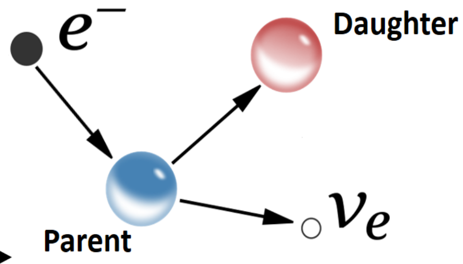


➔ ***Only relies on existence of heavy neutrino admixture to active neutrinos. Not on model-dependent details of their interactions!***

Require high resolution, low-energy (5 – 100 eV) detection of the recoiling atom!

- ^7Be is ideal candi
  - pure two-body final state
  - Relatively large decay energy (862 keV)
  - Relatively high recoil energy (~ 50 eV)
  - Simple atomic and nuclear structure





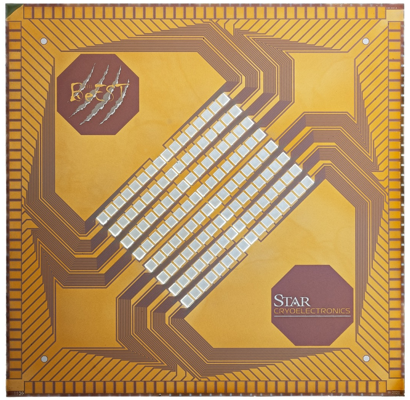
Superconducting Tunnel Junctions (STJ)

- High-speed cryogenic charge superconducting sensors; Thin devices (~0.5 μm) optimized for **low-energy** radiation
- 2 superconducting electrodes separated by thin insulating tunnel barrier (nm scale)
- Superconducting energy gap Δ ~meV

  ➔ **High energy resolution (~1eV)**

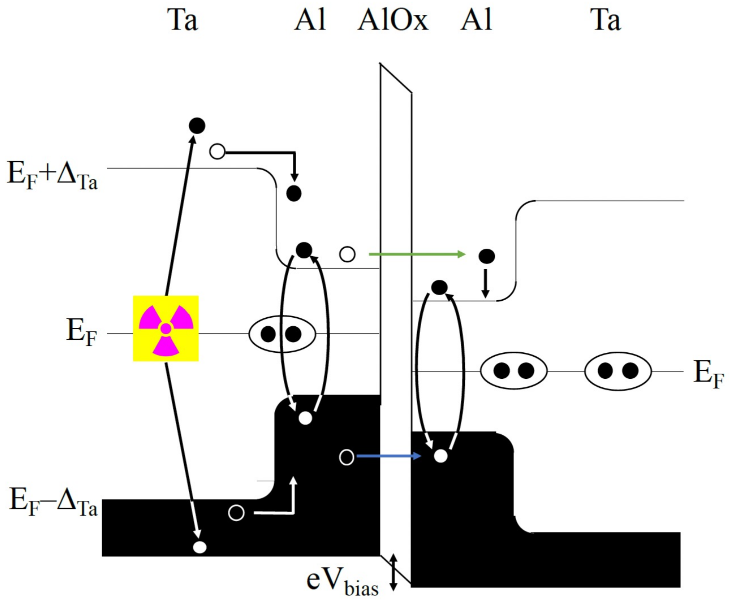
- Timing resolution ~10μs ➔ fast count rates

  ➔ **High rate (10^4 /s/pixel)**

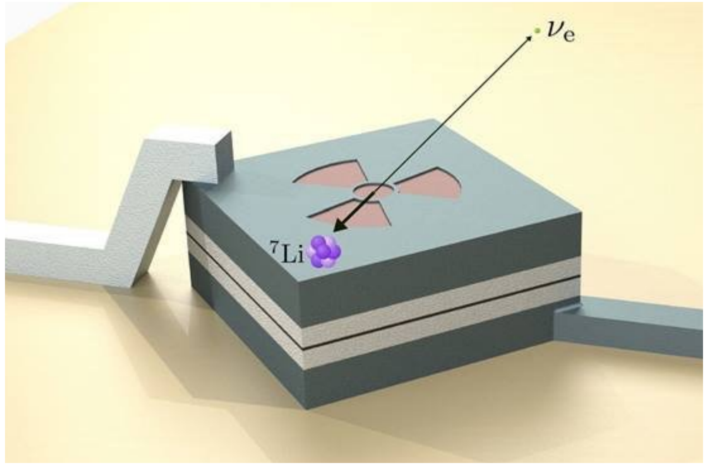


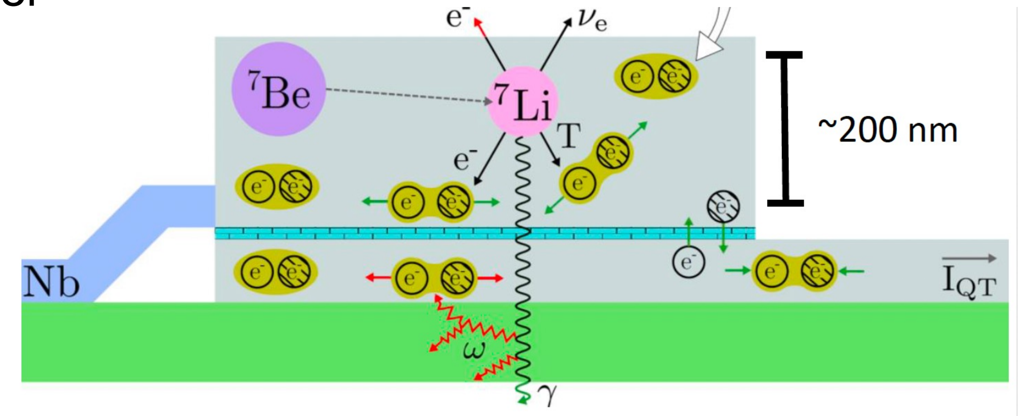
STAR CRYOELECTRONICS

Ta, Al, and Nb-based STJ Sensor Arrays

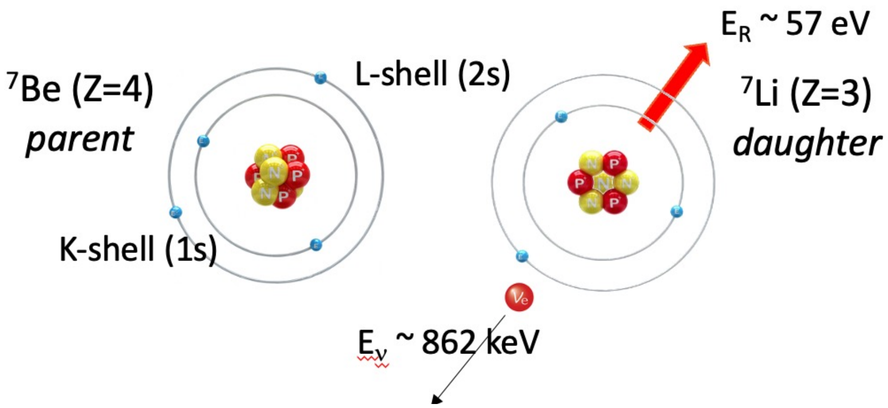


Don't measure thermal changes, but the breaking of cooper pairs

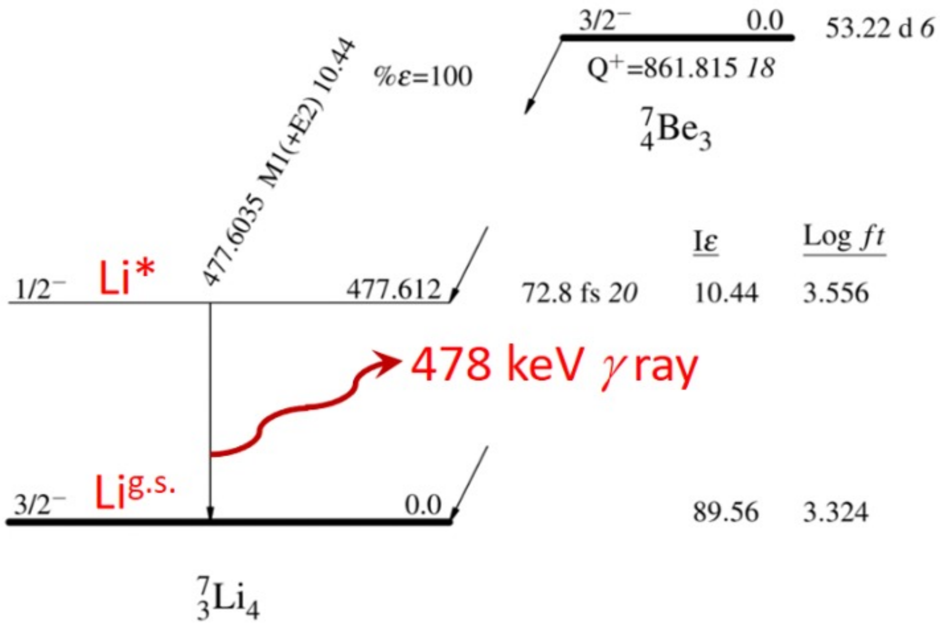




Nuclear Recoil Spectroscopy with ^{7}Be



b) Nuclear Decay Process



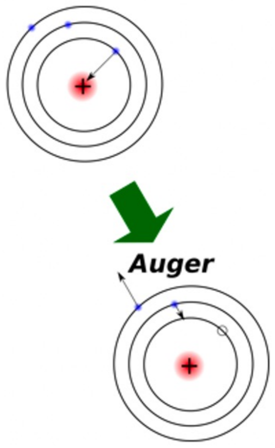
2 Atomic Capture Peaks

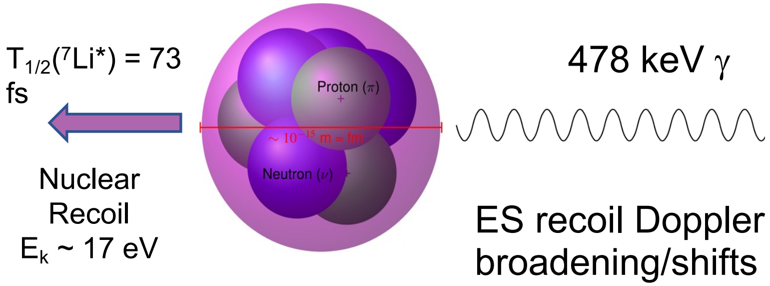
- K-shell (55 eV Auger emission)
- L-shell (no Auger emission)

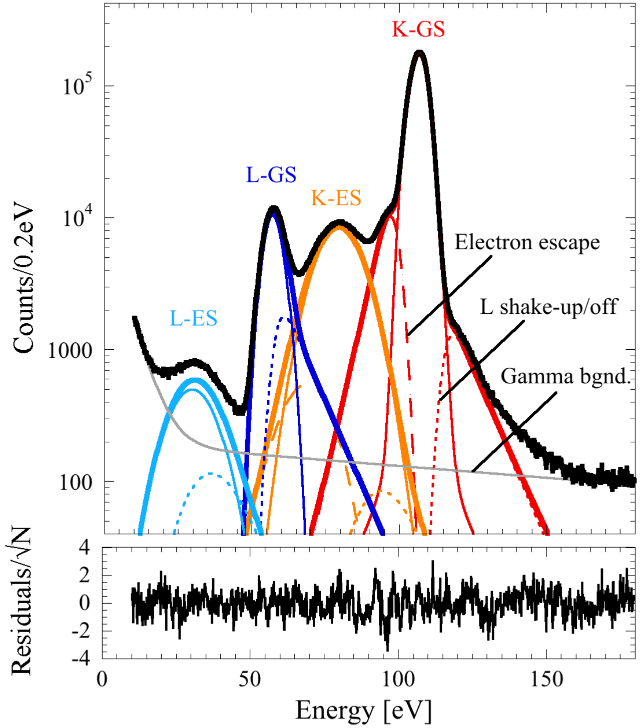
+

2 Nuclear Decay Branches

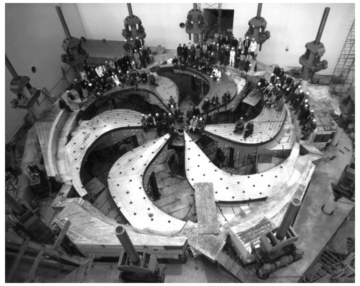
- Ground state
- Excited state





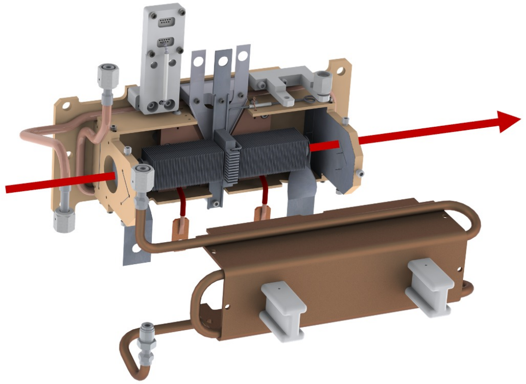


The BeEST - Experimental Concept



480 MeV p+ beam produced in cyclotron

UC_x production target

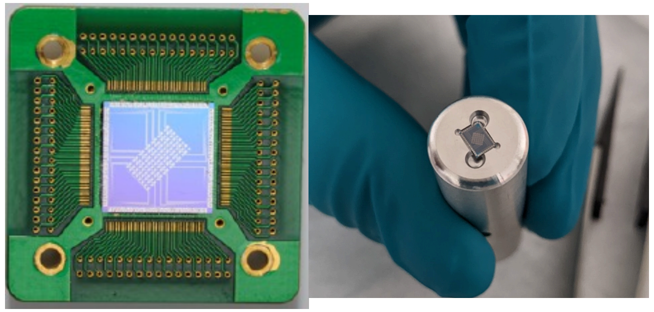


Laser ionization

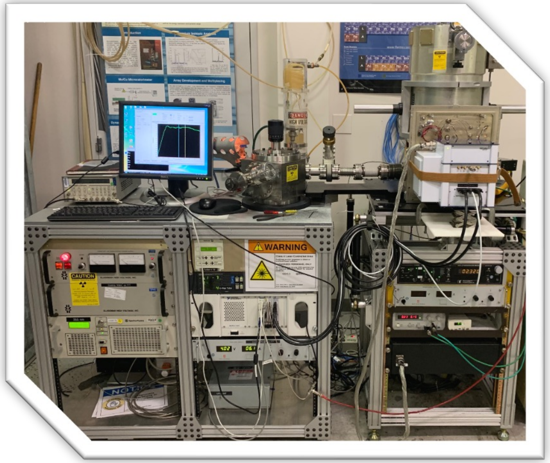
^7Be ($T_{1/2}$ = 53 d)

20 - 30 kV acceleration

Implant into Superconducting Tunnel Junction (STJ) Sensors at TRIUMF-ISAC

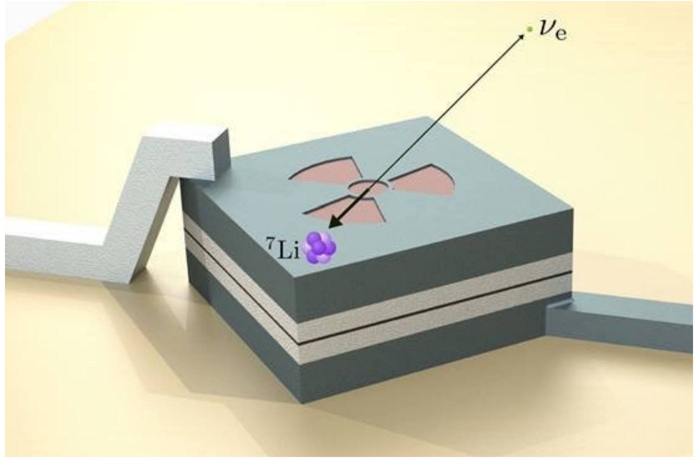


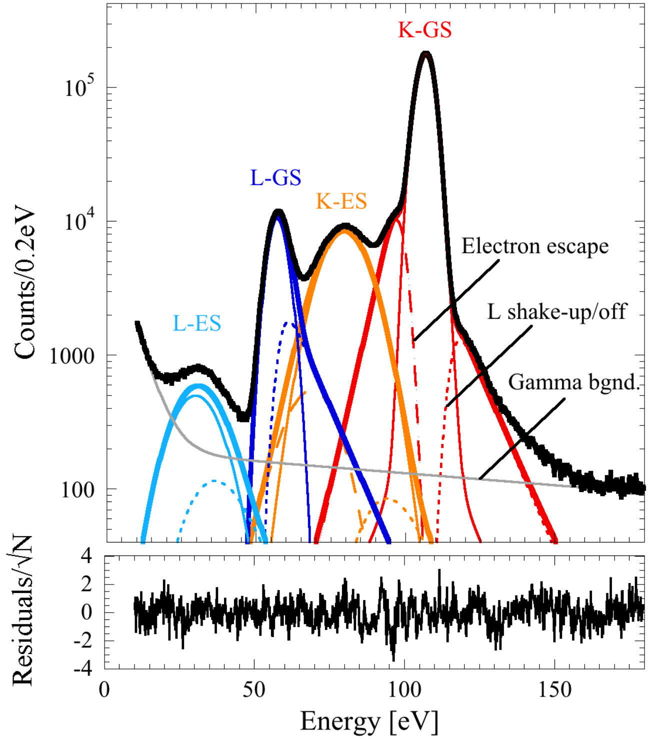
Cool to < 100mk in an Adiabatic Demagnetization Refrigerator.



Lawrence Livermore National Laboratory

Measure eV-scale nuclear recoils from ^7Be EC decays in STJ sensors at LLNL.





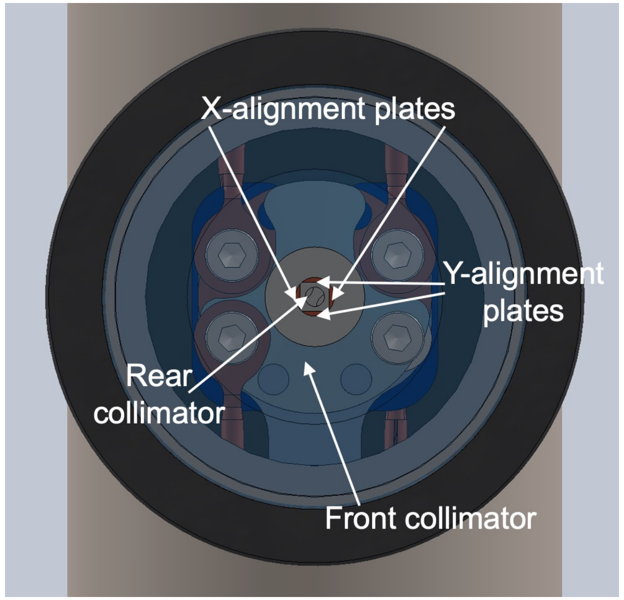
Production & Implantation of ^{7}Be in STJs

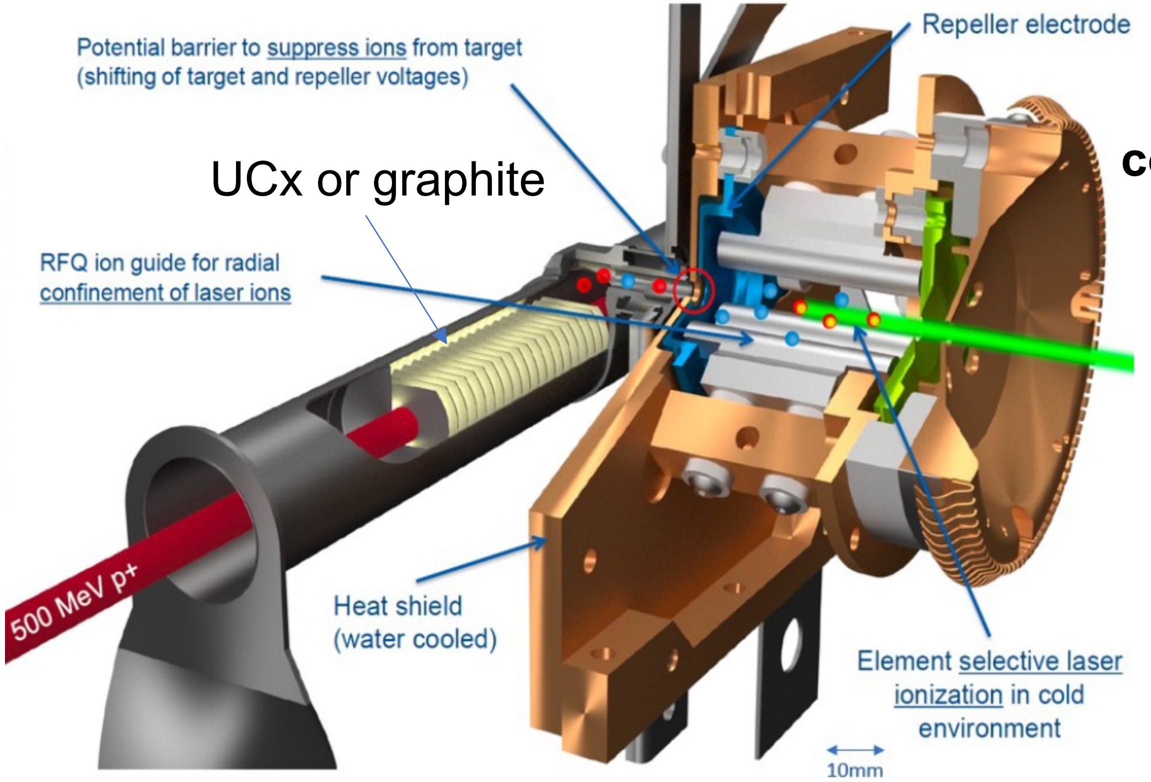
TRIUMF

Isotope Separation On-Line (ISOL) Method

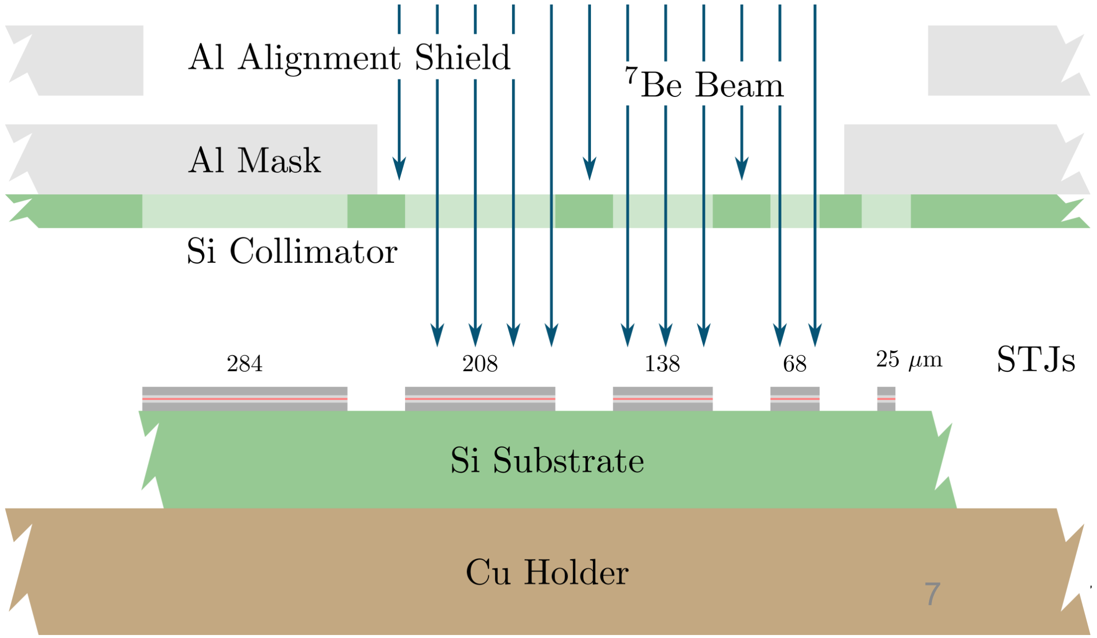
Element- and mass-selective delivery of ^{7}Be:

- Purity > 80%
- Rate > 1e8 pps

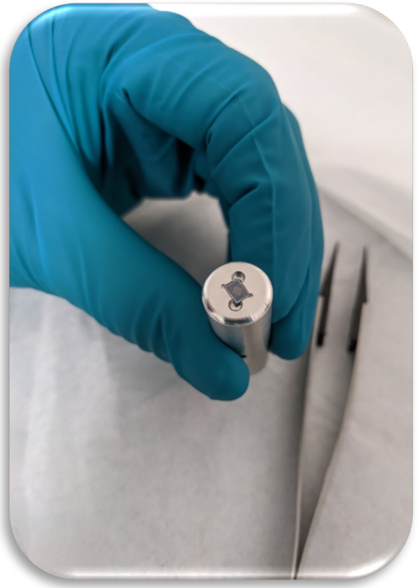


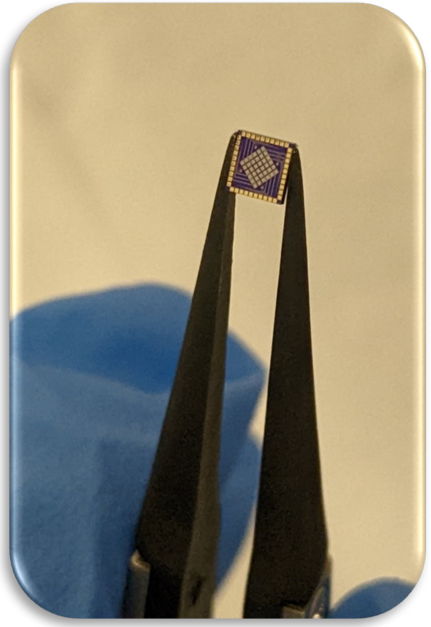


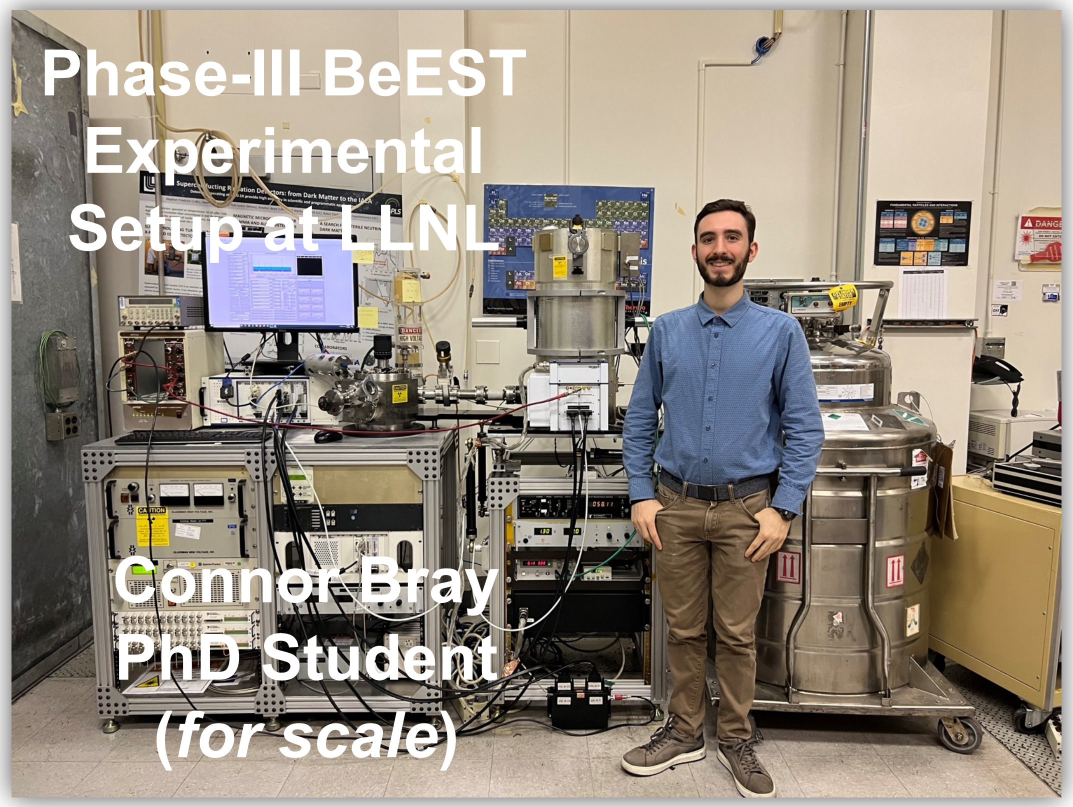
Remove ^{7}Li contamination!

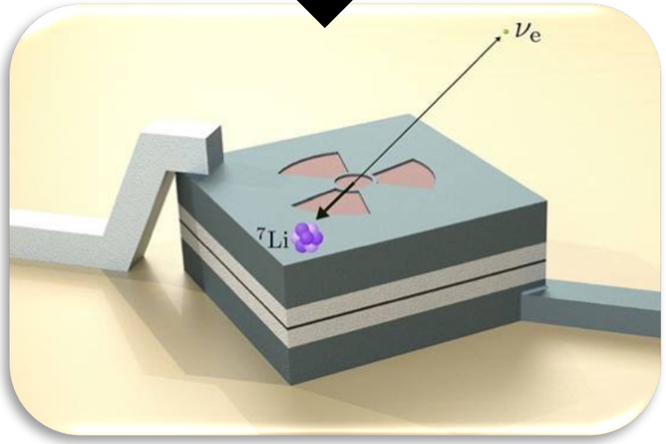


Implantation of ^{7}Be in STJs



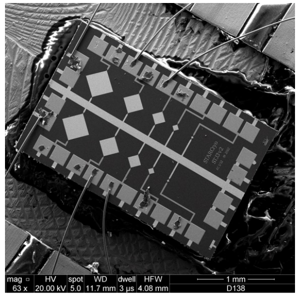






Results from first nuclear recoil experiments using STJs – Phase II exclusion limits

The BeEST group's initial experiment placed significant new limits on the existence of sterile neutrinos in the mass range of 100-800 keV (with single pixel)



"First Light" Dec 9th, 2018
…"Be-7 signals visible"…

"Direct measurement of the **7Be L/K capture ratio** in Ta-based superconducting tunnel junctions"
Phys. Rev. Lett. **125**, 032701 (2020)

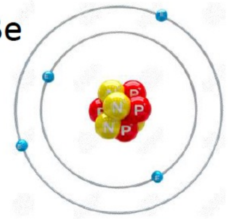
Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of ^{7}Be in Superconducting Quantum Sensors

S. Friedrich,[1,*] G.B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J.A. Hall,[3] A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4] A. Samanta,[1] W.K. Warburton,[8] and K.G. Leach[2,†]

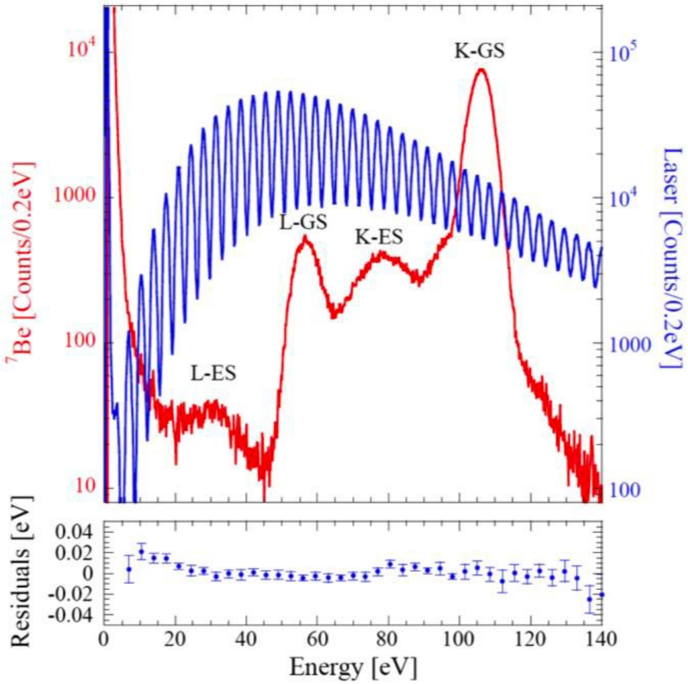
[1] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[2] *Department of Physics, Colorado School of Mines, Golden, CO 80401, USA*
[3] *STAR Cryoelectonics LLC, Santa Fe, NM 87508, USA*
[4] *TRIUMF, Vancouver, BC V6T 2A3, Canada*
[5] *Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada*
[6] *Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120, Palaiseau, France*
[7] *Department of Physics, Stanford University, Stanford, CA 94305, USA*
[8] *XIA LLC, Hayward, CA 94544, USA*

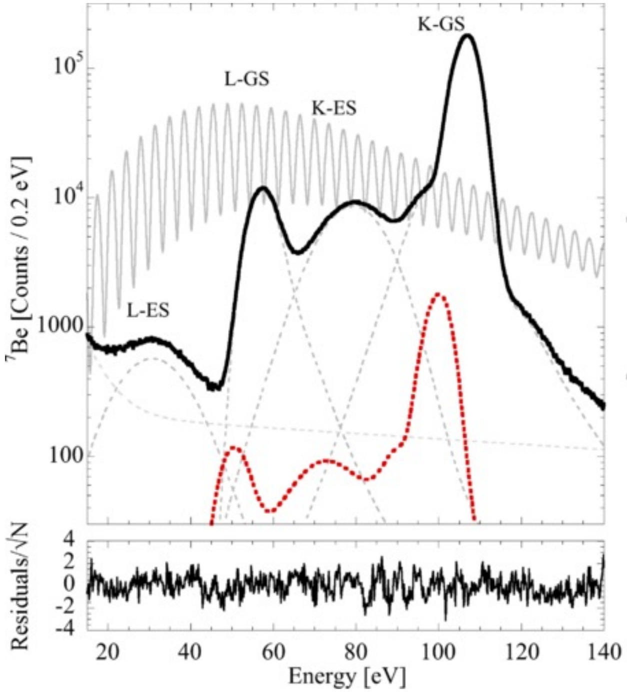
(Dated: October 20, 2020)

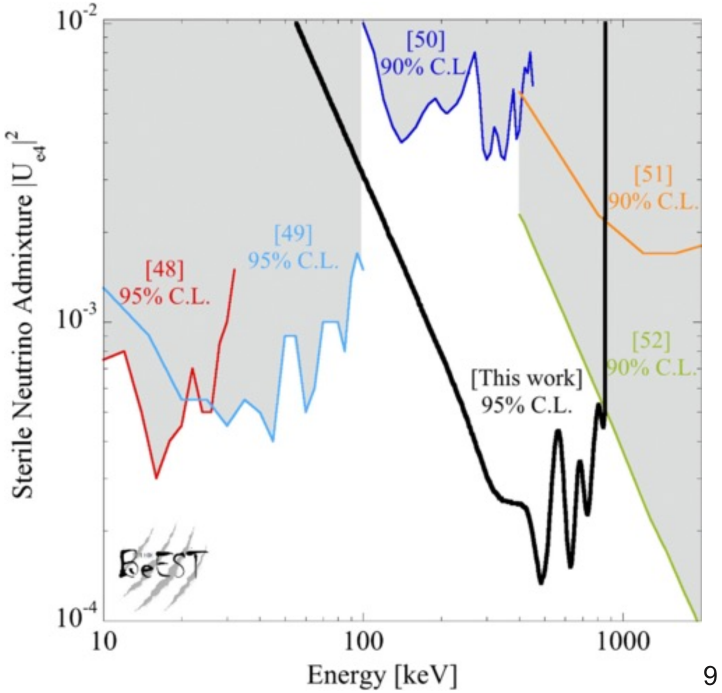
^{7}Be



L/K = 0.070(7)

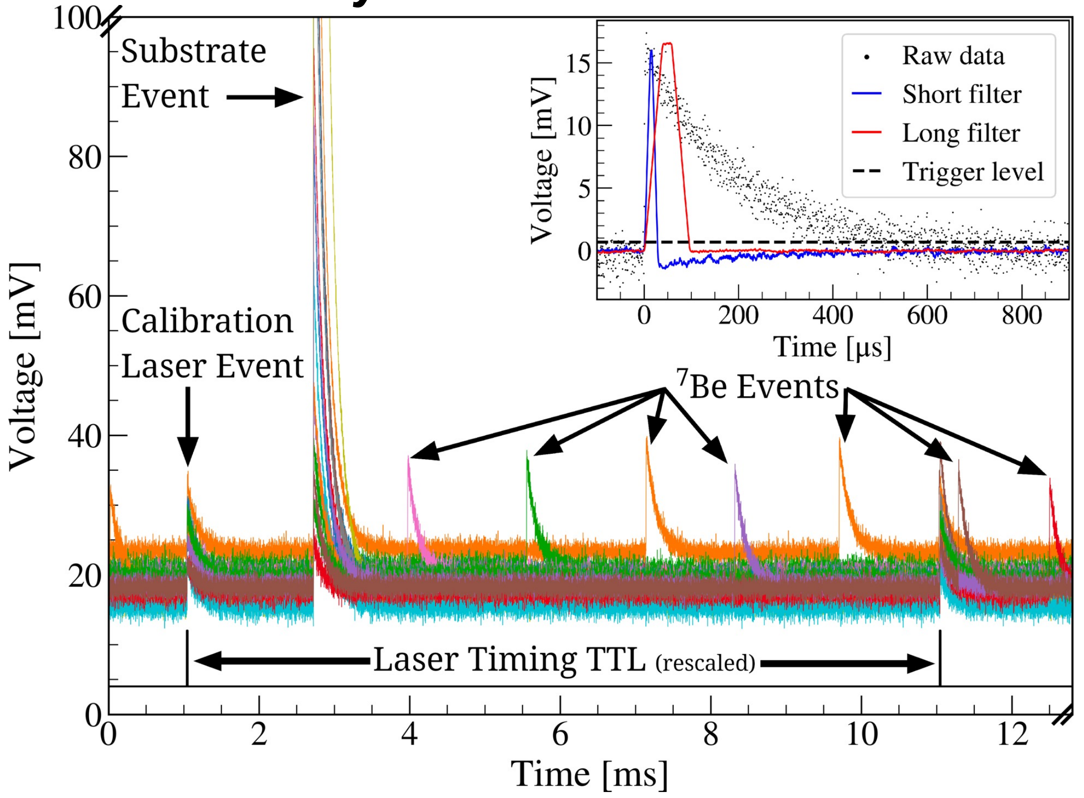


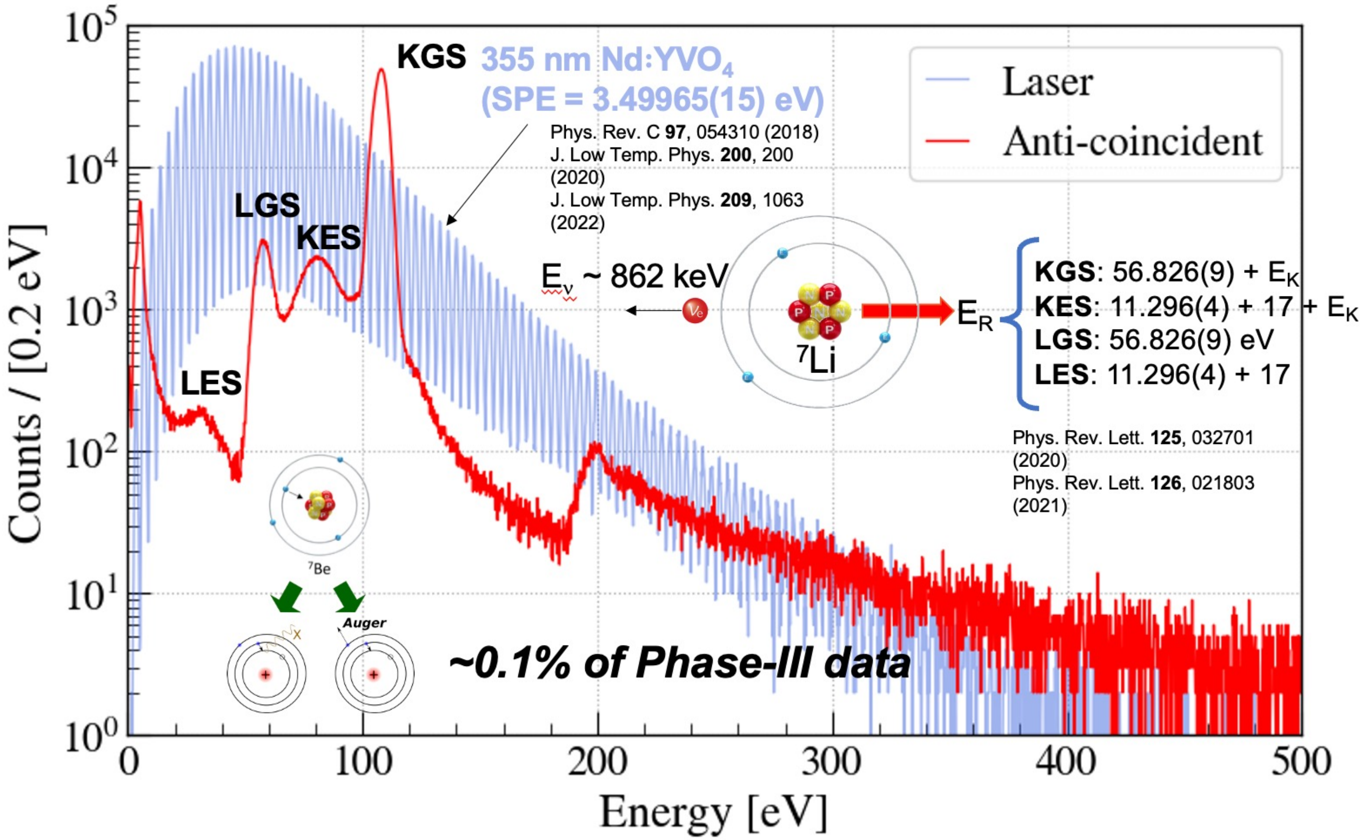




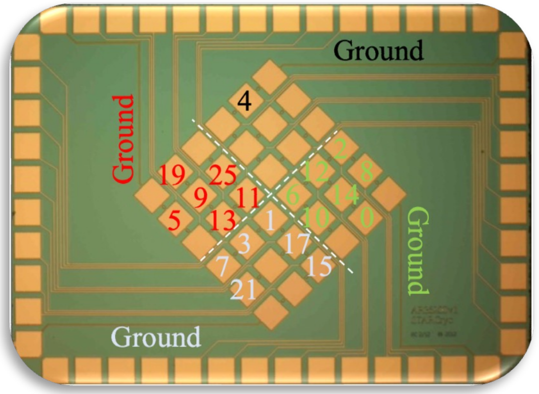
Phase-III data collection – scaling to multi-pixel arrays

continuous synchronous waveform collection



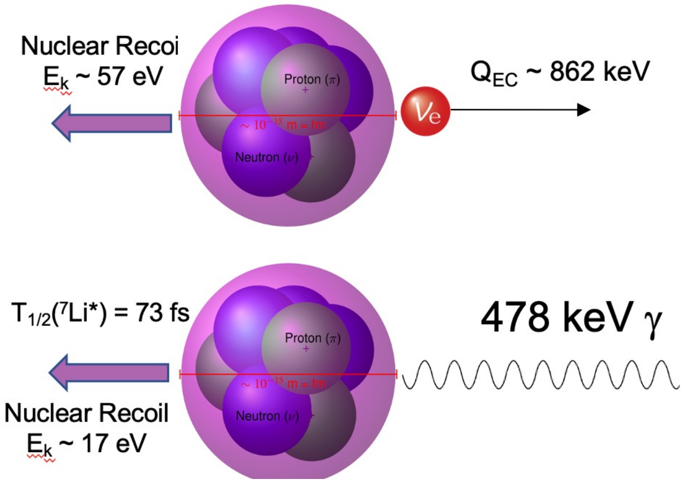


- ADC raw signal (1.25 MSa/s 16 bit)
- Signal rise time of ~1 μs & decay time of ~100 μs
- In-situ energy calibration with a pulsed 355 nm laser at 100 Hz (0.01eV)
- 100x statistics over Phase-II data set



- 36 Ta-pixels
- 49 days
- 50 Bq/pixel
- Over 90 TB of data
- 7Be/7Li ~7/1

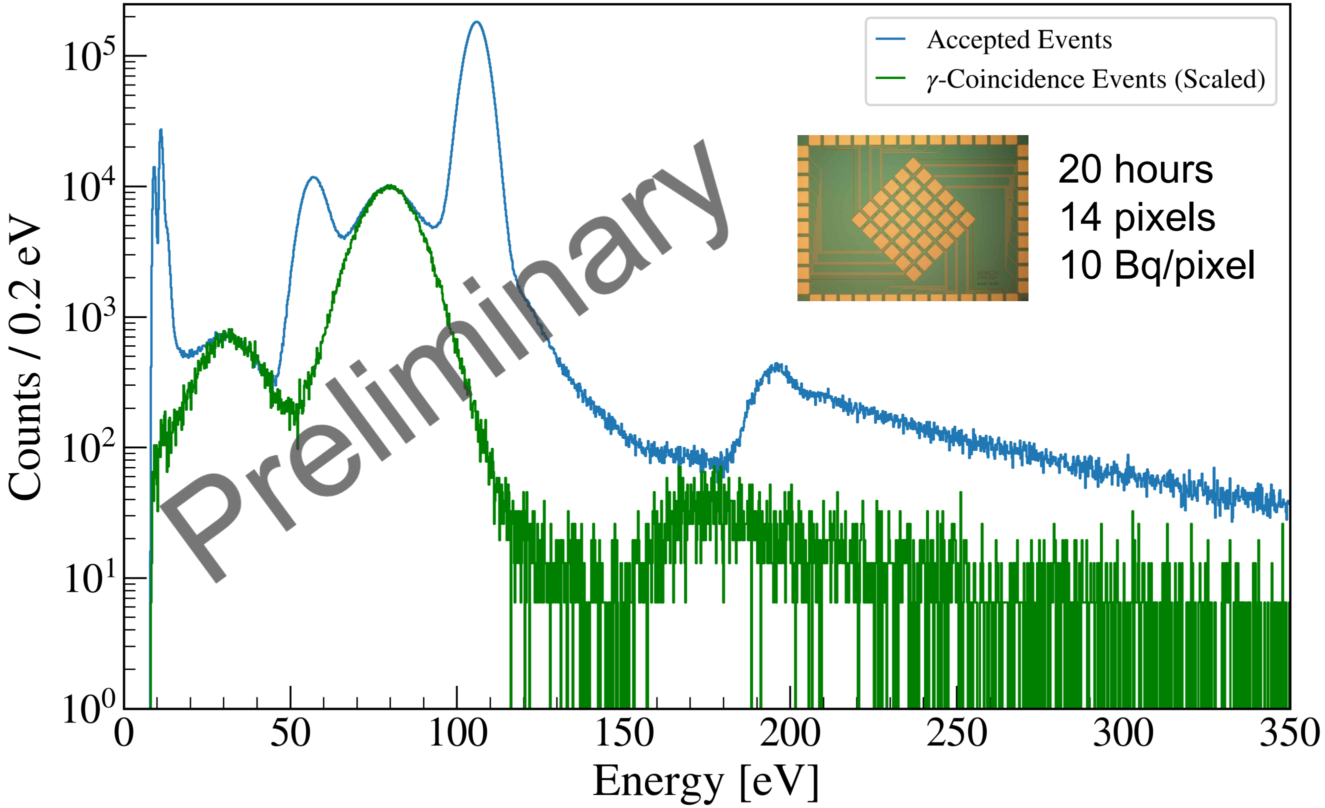
Gamma-Recoil Coincidence measurement



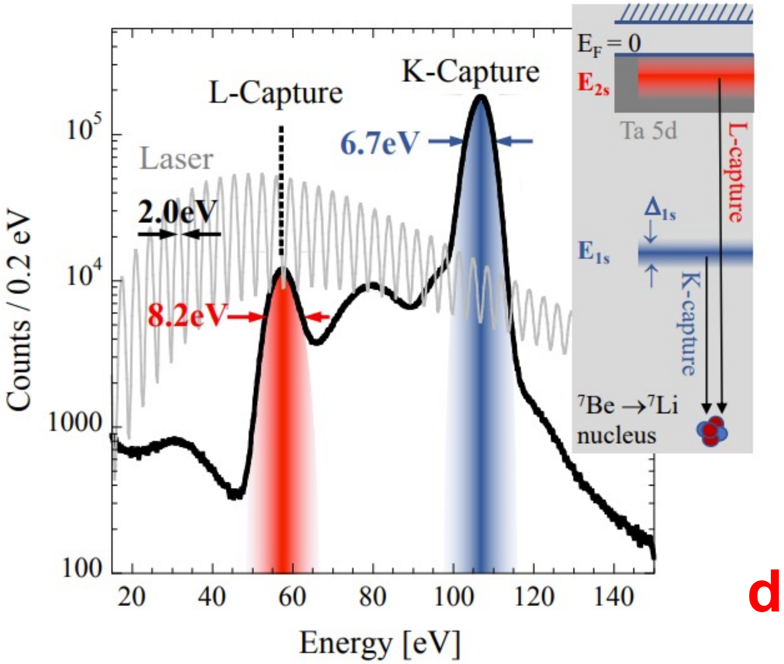
- gamma coincidence technique allows to select only recoils from decays to ^{7}Li 478 keV excited state

➔ Understand γ-background & line-shape for excited state events

NaI detectors for γ-**coincidence** measurement



Material Effects

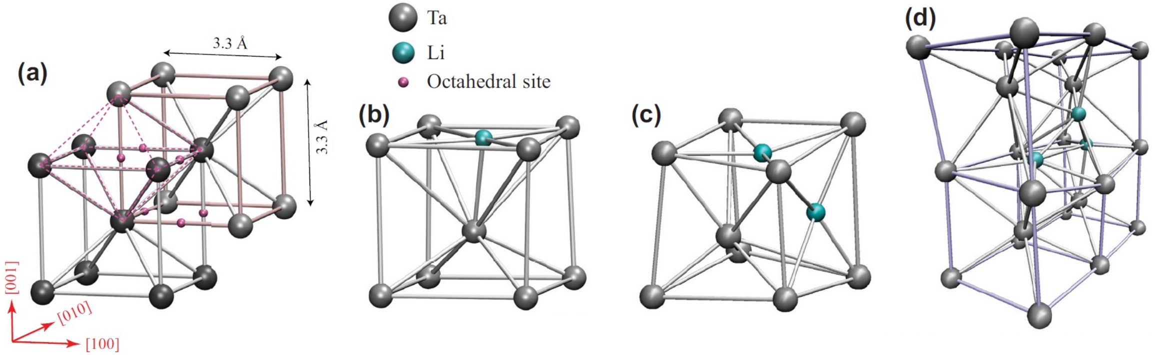


EC decay peaks broadened well beyond the intrinsic energy resolution

➔ Matrix-dependent effects

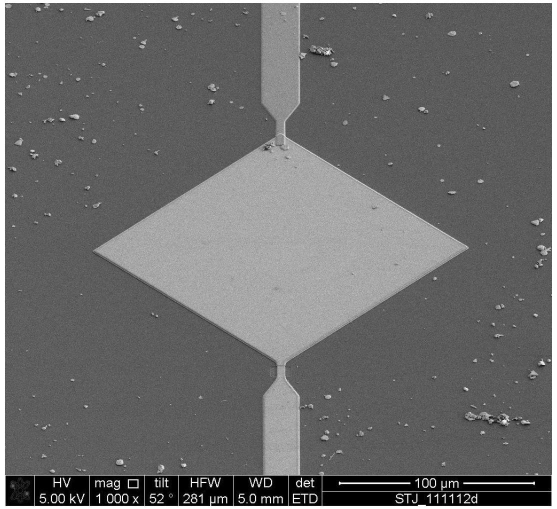
Theory: Molecular Hybridization of ^7Li in Ta

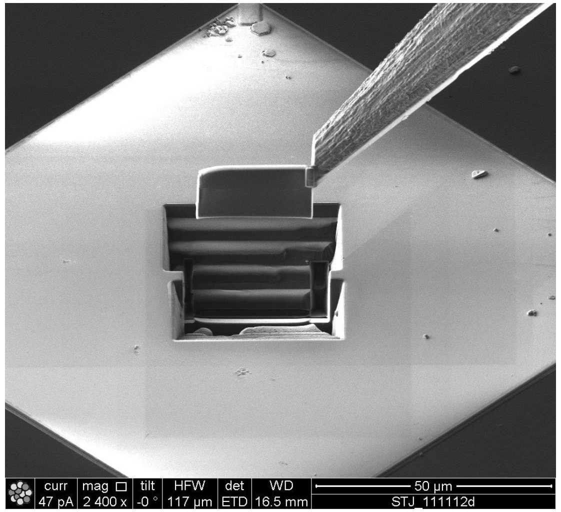
(Inter., Subs., Clustering, Impurities, etc.)

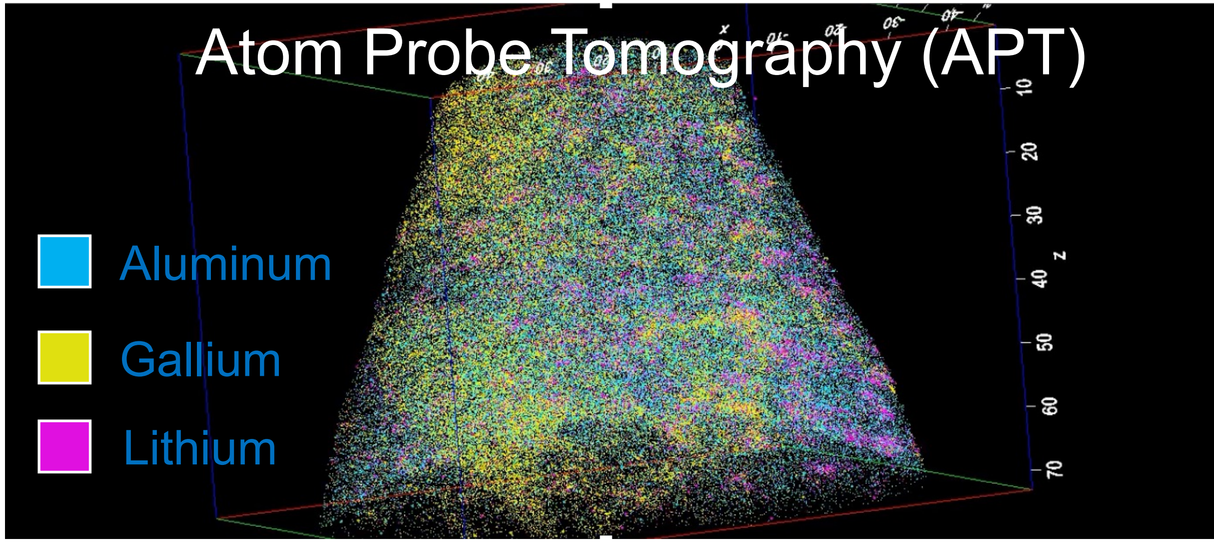


A. Samanta, et. al, Phys. Rev. Applied **19**, 014032 (2023)

Experiment: "Atom-by-Atom Mapping" (3D reconstruction)

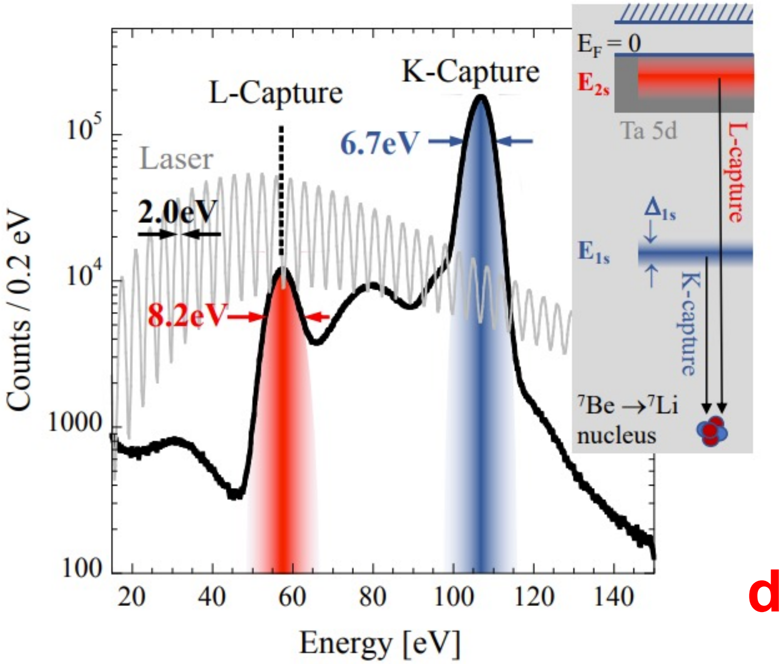






C. Harris, et. al, Phys. Rev. Mat. (in prep.) (2024)

Material Effects



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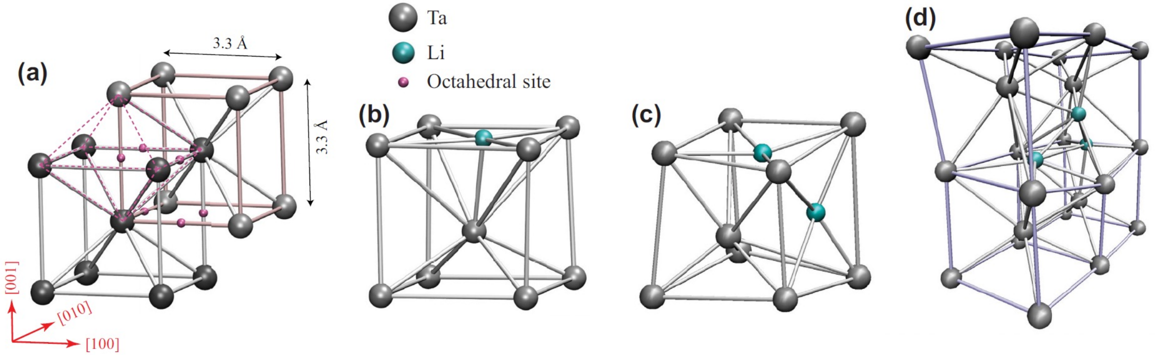

A. Samanta, et. al, Phys. Rev. Applied **19**, 014032 (2023)

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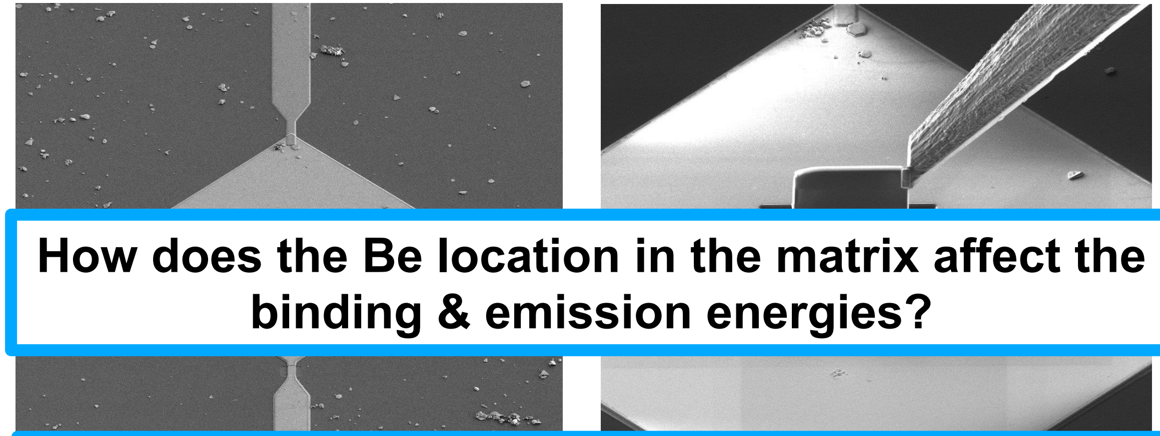
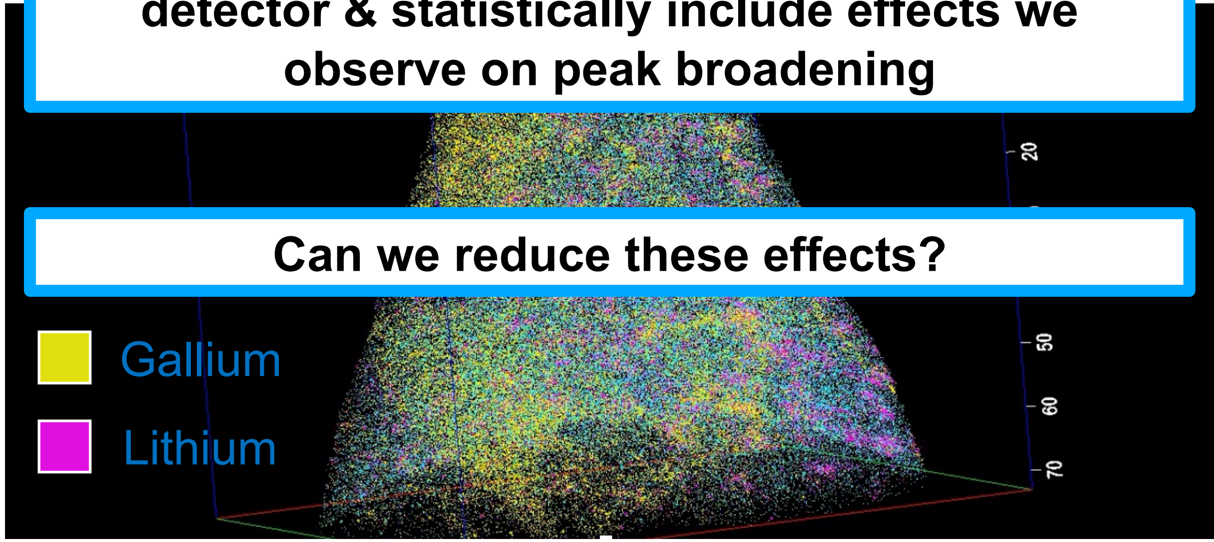


How does the Be location in the matrix affect the binding & emission energies?

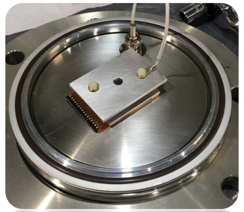
Goal: Create complete atom-by-atom map of our detector & statistically include effects we observe on peak broadening



Can we reduce these effects?

C. Harris, et. al, Phys. Rev. Mat. (in prep.) (2024)

A phased approach to the BeEST

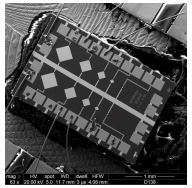


Phase-I: Proof of Concept

- First implantation of rare isotopes into STJs
- L/K capture ratio
- "First Light" December 2018 – concept demonstrated

2018-2020

- PRL **125**, 032701 (2020)
- JLTP **200**, 205 (2020)
- JLTP **209**, 796 (2022)

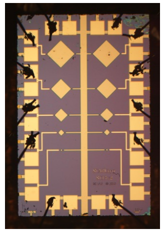


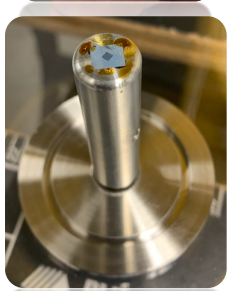
Phase-II: First Search for Heavy Neutrinos

- First precision calibration *in-situ*
- Characterization of decay-induced backgrounds
- First physics limits

2019-2021

- PRL **126**, 021803 (2021)
- JLTP **209**, 857 (2022)
- JLTP **209**, 1063 (2022)



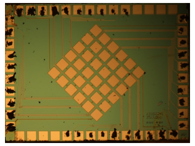


Phase-III: Scaling to Multi-Pixel Arrays

- 36-Pixel Ta STJ array
- Pure ^{7}Be beam (TRIUMF)
- First atomic/materials estimates
- Wavepacket, masses, particles search

2021-2024 (Finalizing Analysis)

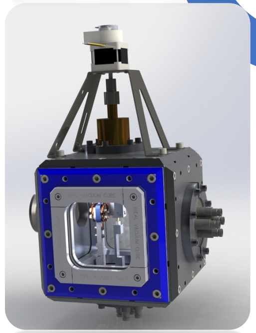
- Phys. Rev. Applied **19**, 014302 (2023)

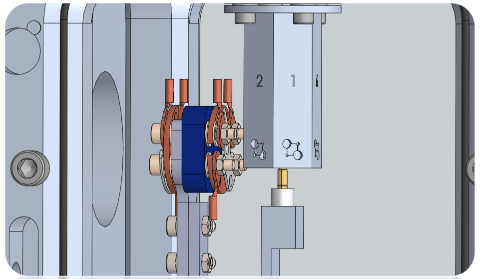


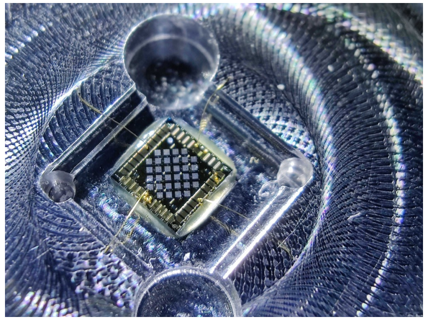
Phase-IV: High-Sensitivity Search with 128-Pixel Al STJ Array

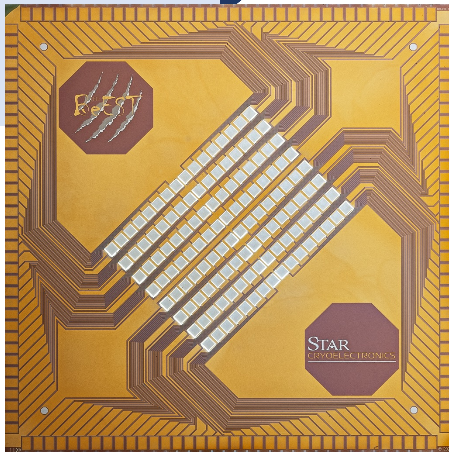
- Development of new Al STJs (higher resolution)
- Experimental running in Dilution Refrigerator
- Improved searches

2022-2026 (Development)



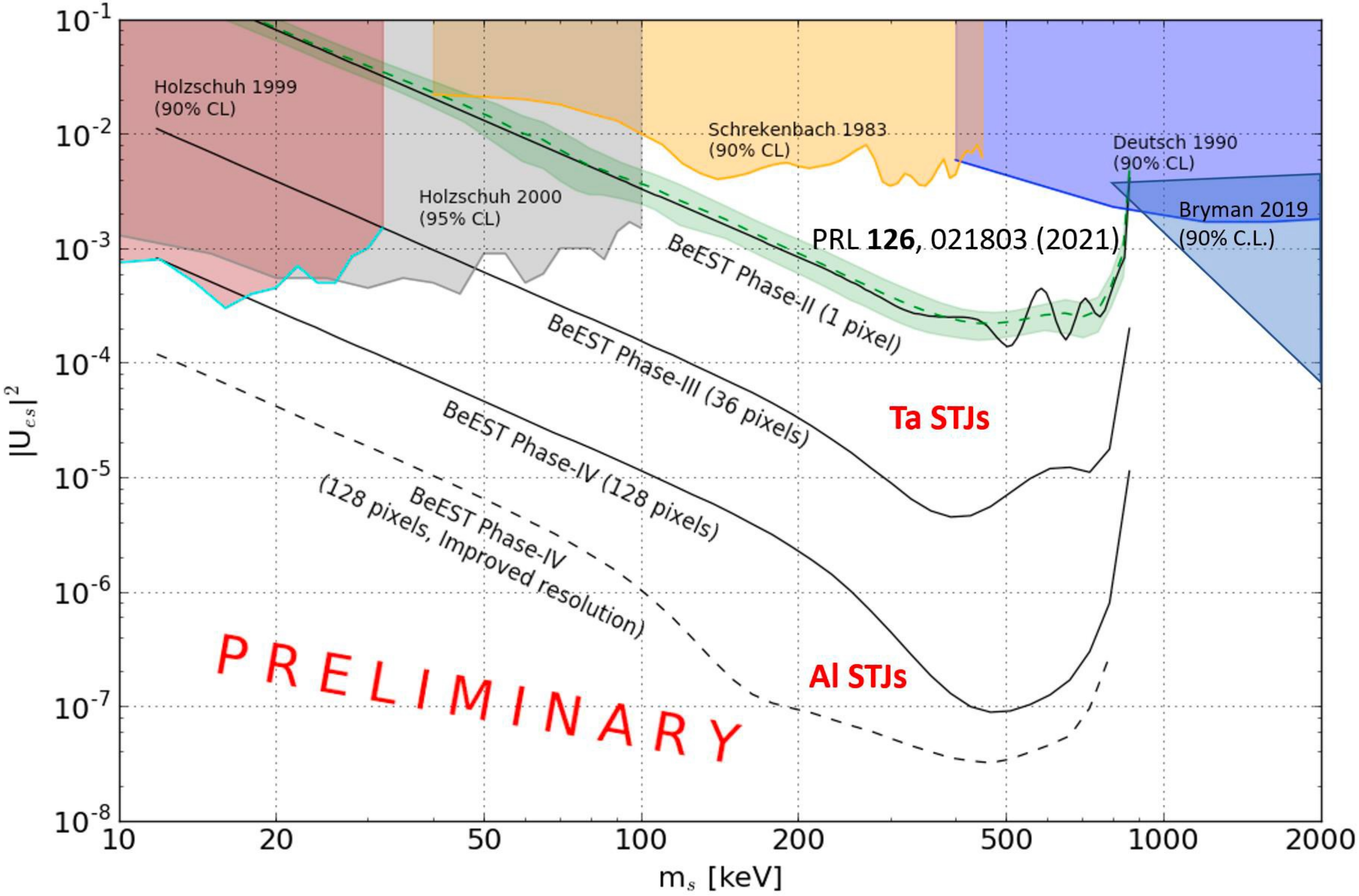


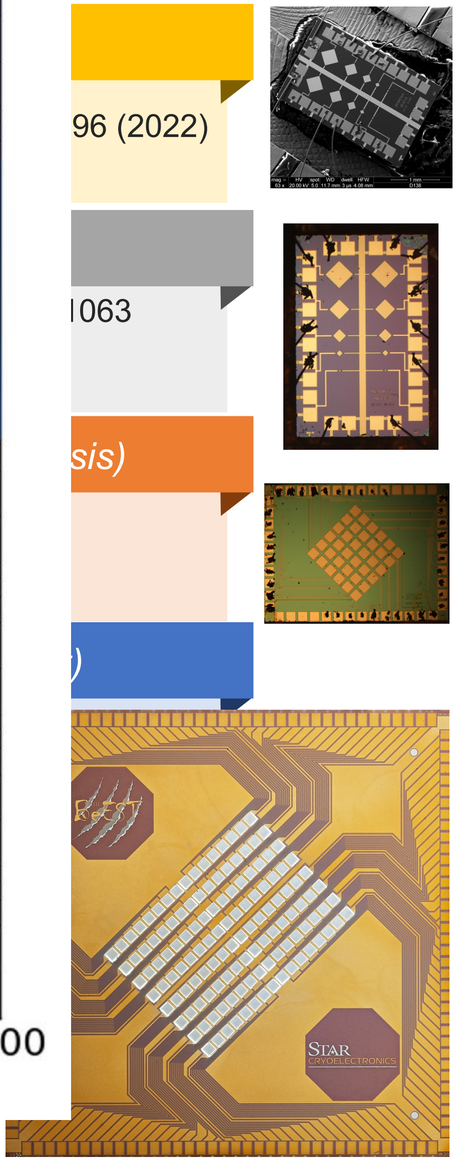




Slide courtesy of K. Leach

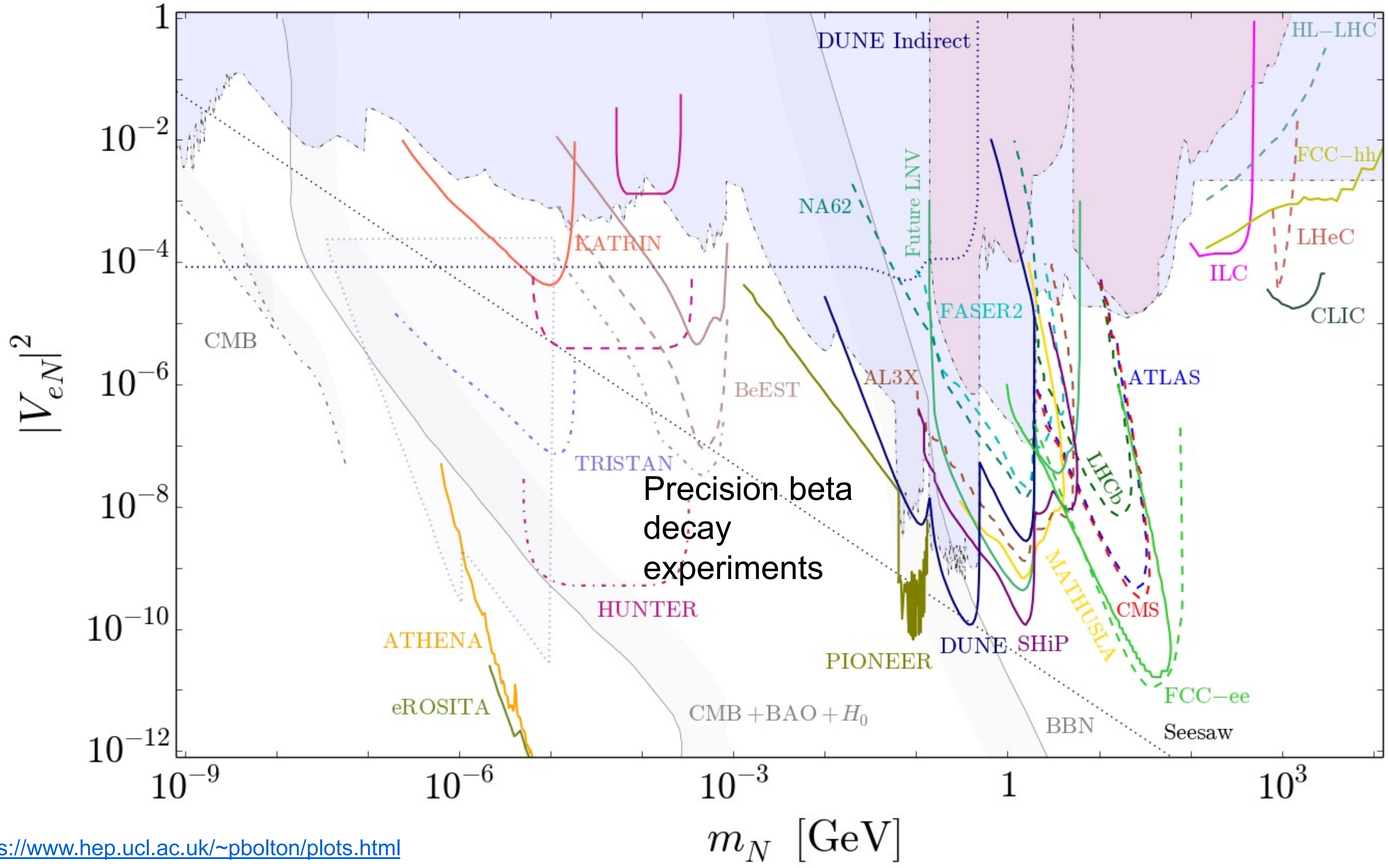
A phased approach to the BeEST





Slide courtesy of K. Leach

The BeEST in context



Precision beta decay experiments

https://www.hep.ucl.ac.uk/~pbolton/plots.html

Summary

- Weak nuclear decay is a broadband, **high-sensitivity probe of BSM physics in the lab**
- The *BeEST* experiment is a new search for **sterile neutrinos in the EC-decay of ^{7}Be** (since 2018)
- Implanting rare isotope beams into STJs is a powerful new tool to perform **sub-keV nuclear decay spectroscopy**
- High statistics multi-pixel data from 2022 Ta-array implantation under analysis

Outlook:

- The BeEST has already obtained the **best laboratory mixing limits** in the range between 100–800 keV, planning to improve these limits by 3 orders of magnitude in the next 4 years.
- Experimental technique to be applied for isotopes beyond ^{7}Be (including short-lived isotopes)
- What other BSM physics may the BeEST be sensitive to? – Stay tuned!

The BeEST - collaboration

Keith Borbridge, Connor Bray, Harris Crocker, David Diercks, Spencer Fretwell, Abbi Gillespie, Cameron Harris, Calvin Hinkle, Amii Lamm, Kyle Leach, Drew Marino, John Taylor, Ben Waters, Joe Smolsky, Caitlyn Stone-Whitehead
Colorado School of Mines, Golden CO USA

Stephan Friedrich, Geon-Bo Kim, Inwook Kim, Vincenzo Lordi, Amit Samanta
Lawrence Livermore National Laboratory, Livermore CA USA

Michael Greenough, Annika Lennarz, Peter Machule, Dave McKeen, Chris Ruiz
TRIUMF, Vancouver BC Canada

Pedro Amaro, Mauro Guerra, Jorge Machado, José Paulo Santos
NOVA School of Science and Technology, Lisbon Portugal

Adrien Andoche, Paul-Antoine Hervieux
Université Strasbourg, Strasbourg France

Robin Cantor, Ad Hall
Star Cryoelectronics LLC, Santa Fe NM USA

Jack Harris, Bill Warburton
XIA LLC, Oakland CA USA

Leendert Hayen
LPC Caen, Caen France

Xavier Mougeot
CEA Paris-Saclay, Paris France

Francisco Ponce
Pacific Northwest National Laboratory, Richland WA USA

GORDON AND BETTY MOORE FOUNDATION

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NNSA National Nuclear Security Administration

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Thank you
Merci

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Discovery, accelerated

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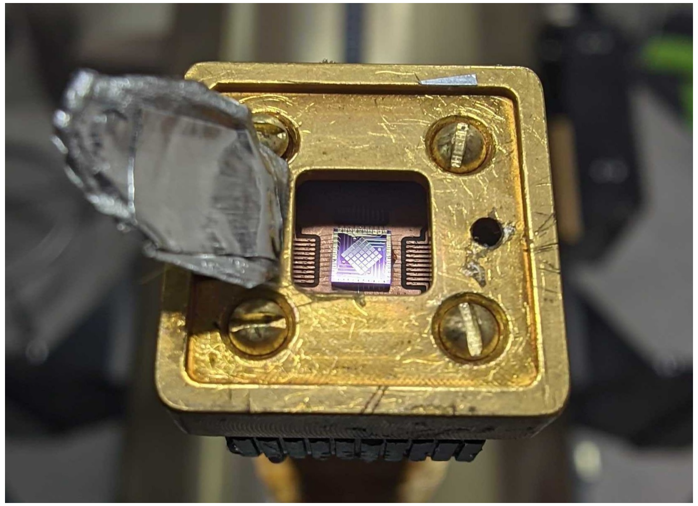
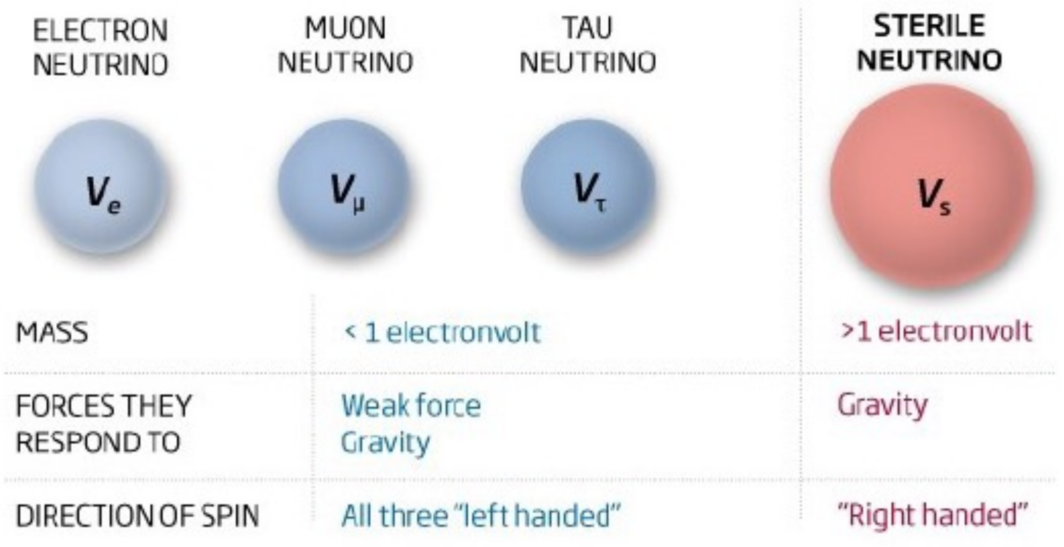
- Sebastian Raeder, Henning Heggen, Jens Lassen et al. - "An ion guide laser ion source for isobar-suppressed rare isotope beams" Rev. Sci. Instr. 85, 033309 (2014) http://dx.doi.org/10.1063/1.4868496

Back-up slides



Introduction

- Standard Model is known to be incomplete
- Lepton sector of Standard Model (SM) provides window into Beyond SM physics (confirmed observation of non-zero ν mass)
- Sub-MeV **“sterile neutrinos**” are well motivated, natural extensions to the SM
- Neutrino masses on the keV scale are a promising **candidate** for so-called “warm" **dark matter**
- Right-handed, non-interacting with respect to SM forces
- Probe via mixing of active neutrinos

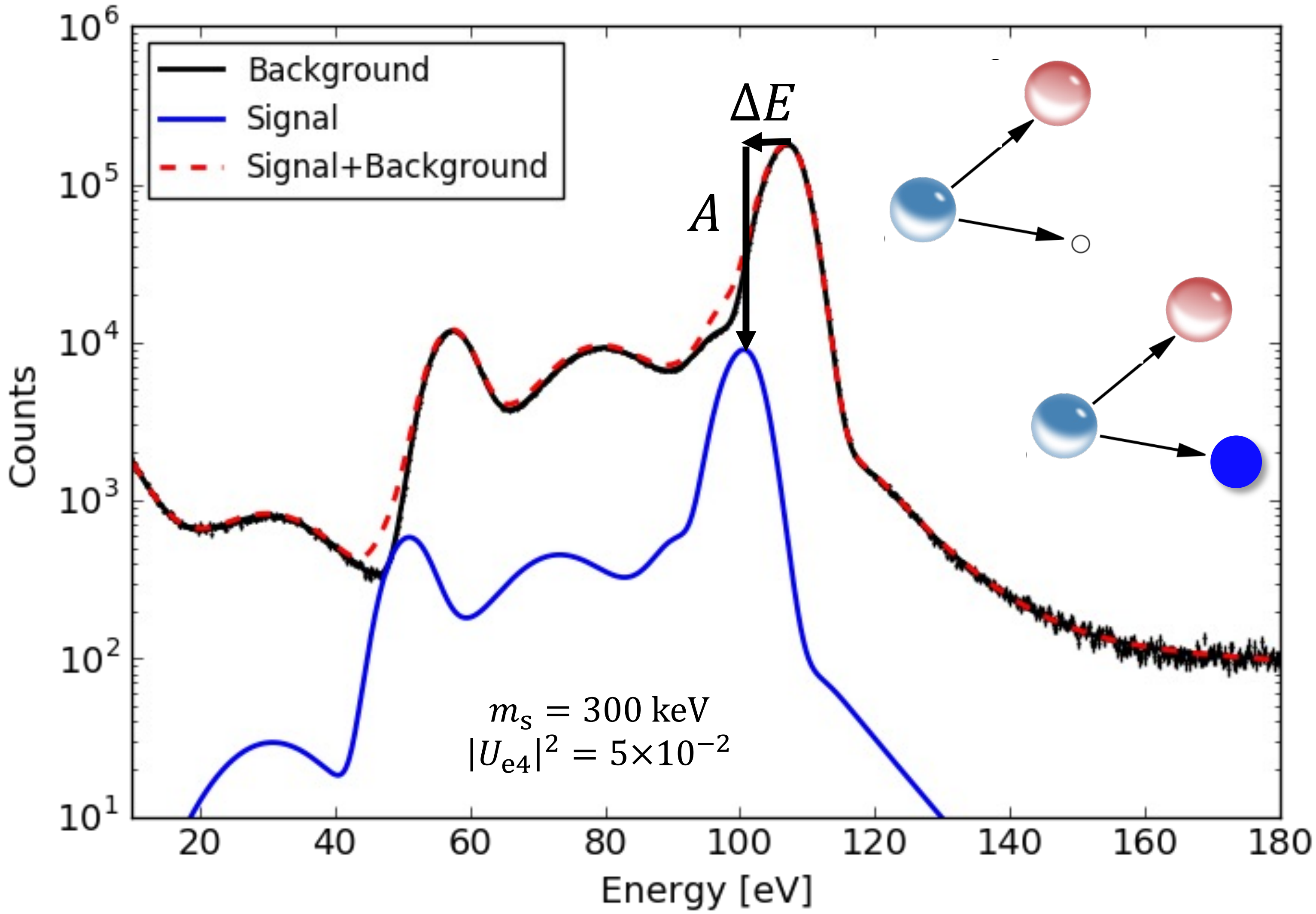


There exist a wide range of masses and couplings from model predictions for heavy beyond Standard Model neutrinos

➔ effective experimental searches for these particles should be **model-independent** and cover a large area of the allowed parameter space.

➔ One conceptually simple approach is through energy and momentum conservation in nuclear β-decay…

Searching for Heavy Neutrinos in the BeEST Data



Heavy neutrino signature is overlayed 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

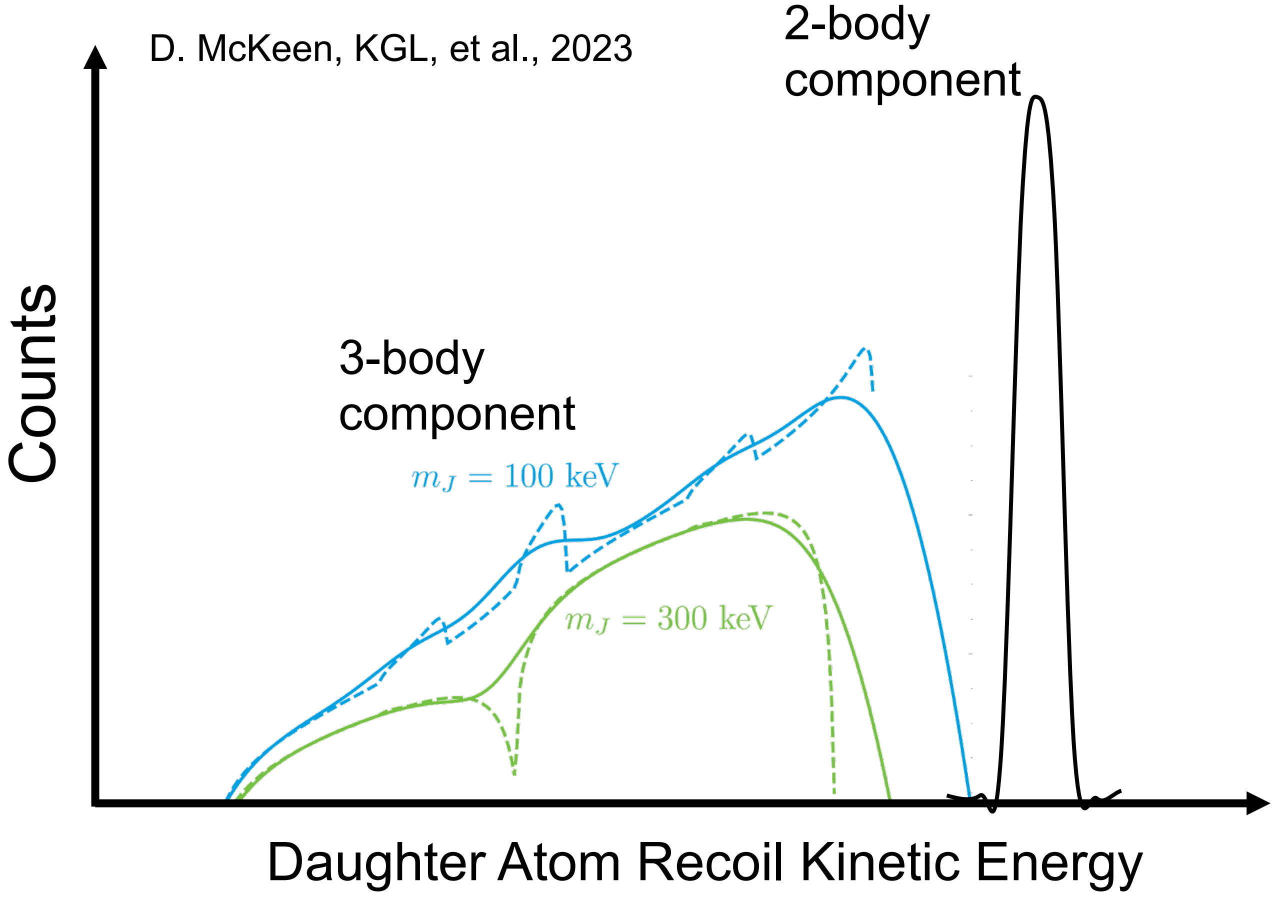
Outlook: Sensitive to All New Physics that Couples to Neutrino

- Momentum reconstruction in EC decay is sensitive to any deviation from the SM recoil signal (e.g. Majoron emission)

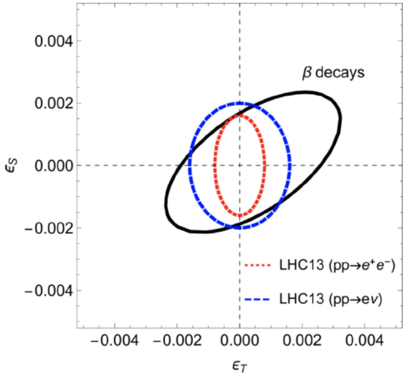
- New bosons coupled to neutrinos can address problems in cosmology

Potentially extract limits from Phase-III Data (stay tuned!)

Example: *Majoron signature in the BeEST Data*



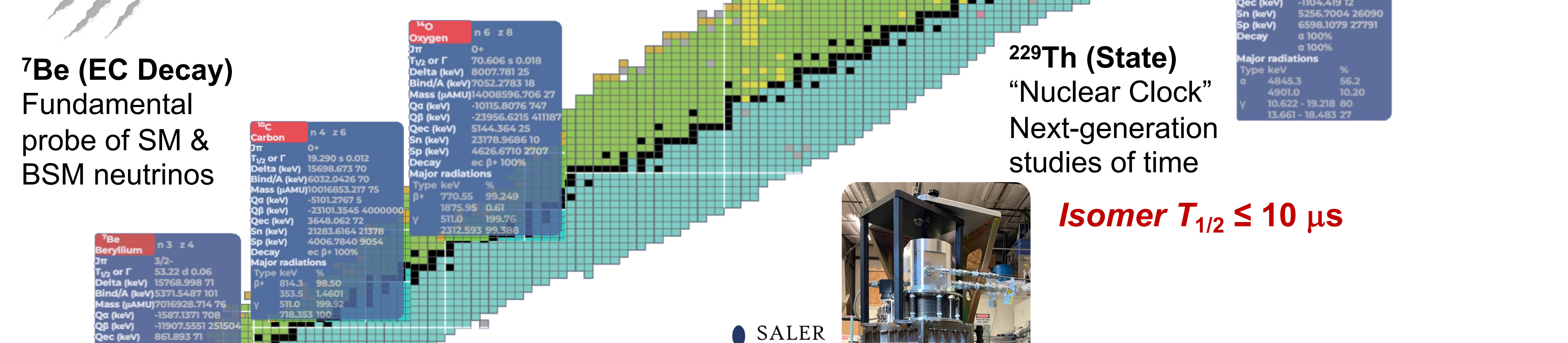
Outlook: Fully Explore the Extensive Nuclear Toolbox with STJs



N≈Z Systems (β⁺ Decay)
Most sensitive laboratories for CKM unitarity tests and searches for exotic currents (~10 TeV scale)

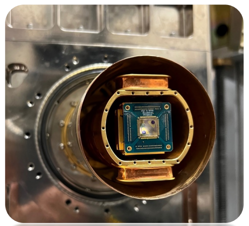
$T_{1/2}$ ≤ 1 min

^{7}Be (EC Decay)
Fundamental probe of SM & BSM neutrinos



^{229}Th (State)
"Nuclear Clock"
Next-generation studies of time

Isomer $T_{1/2}$ ≤ 10 μs



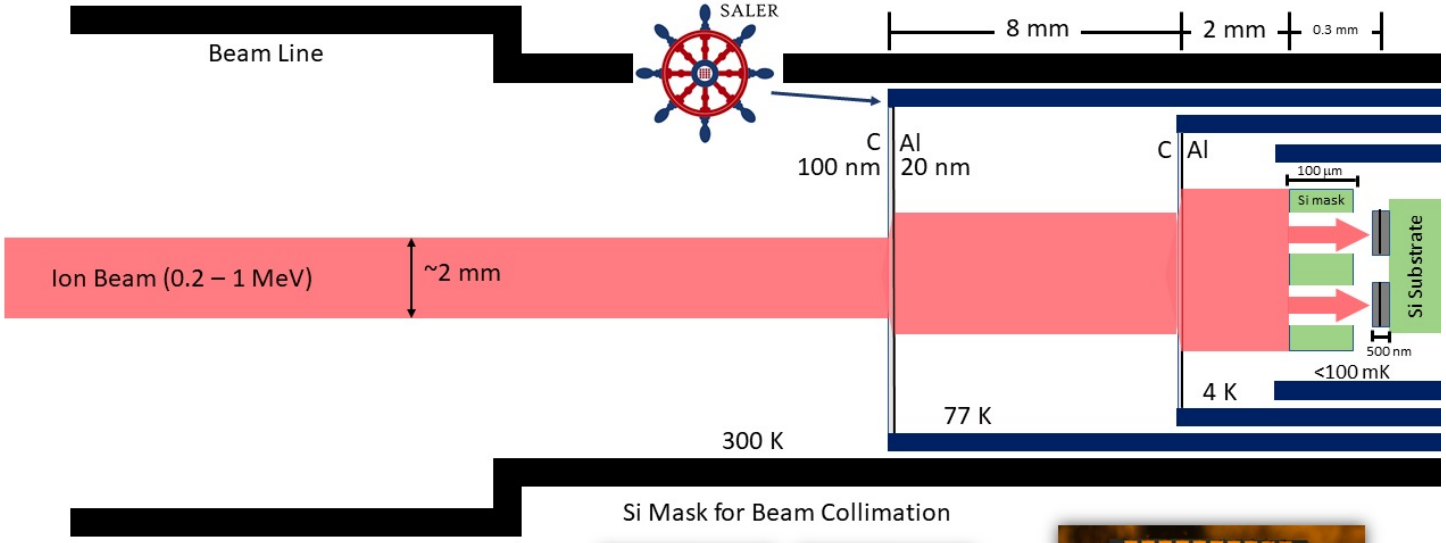
SALER

Superconducting Array for Low-Energy Radiation

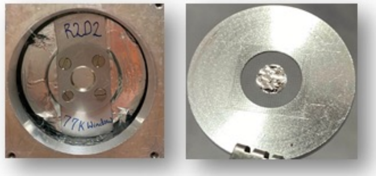
Slide from K. Leach

SALER – Superconducting Array for Low-Energy Radiation

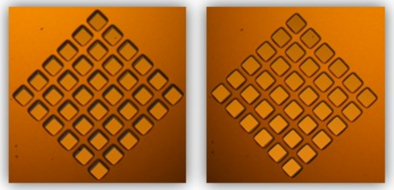
Extended application for STJs for short lived rare isotopes $T_{1/2}$ > 0.1s



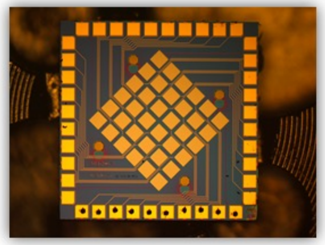
Si Mask for Beam Collimation



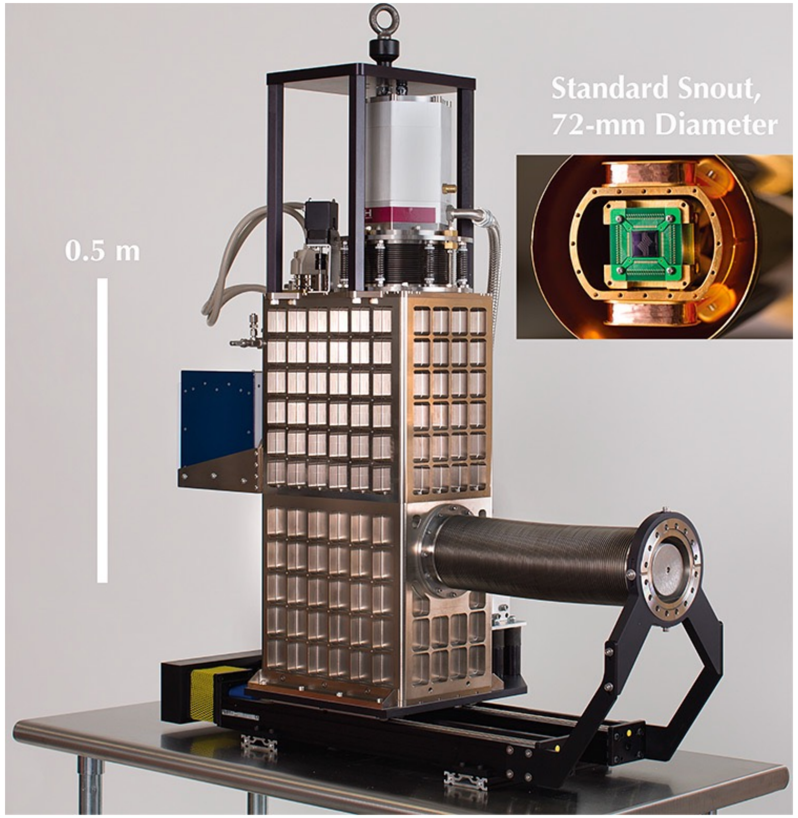
Ultra-Thin (120 nm) Thermal windows



Before Alignment After Alignment



Mounted 36-Pixel Nb STJ Array



- Couple active sensor array to beamlines at RIB facilities (FRIB (online commissioning in 2025), TRIUMF-ISAC (LOI), CERN-Isolde)

- In-situ measurements with ADR coupled to RIB beamline
- Beam energies 0.2 – 1 MeV

FRIB