Model-Independent Search for sub-MeV Sterile Neutrinos with Superconducting Quantum Sensors

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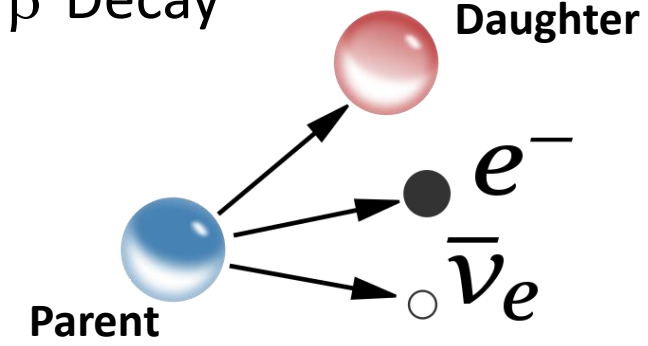
beest.mines.edu

The Model Independent Nature of Beta Decay

β^- Decay

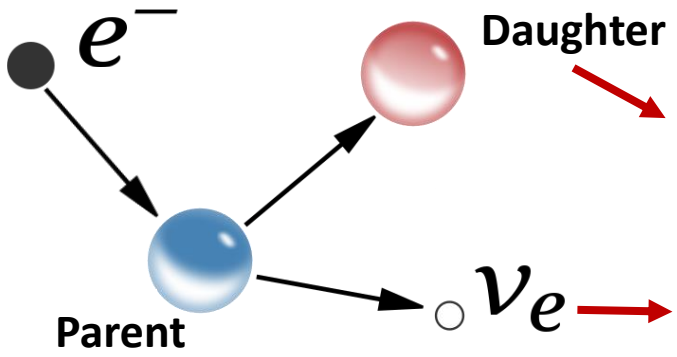


- Decay momentum reconstruction is a simple, model-independent approach to heavy neutrino searches

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

EC Decay



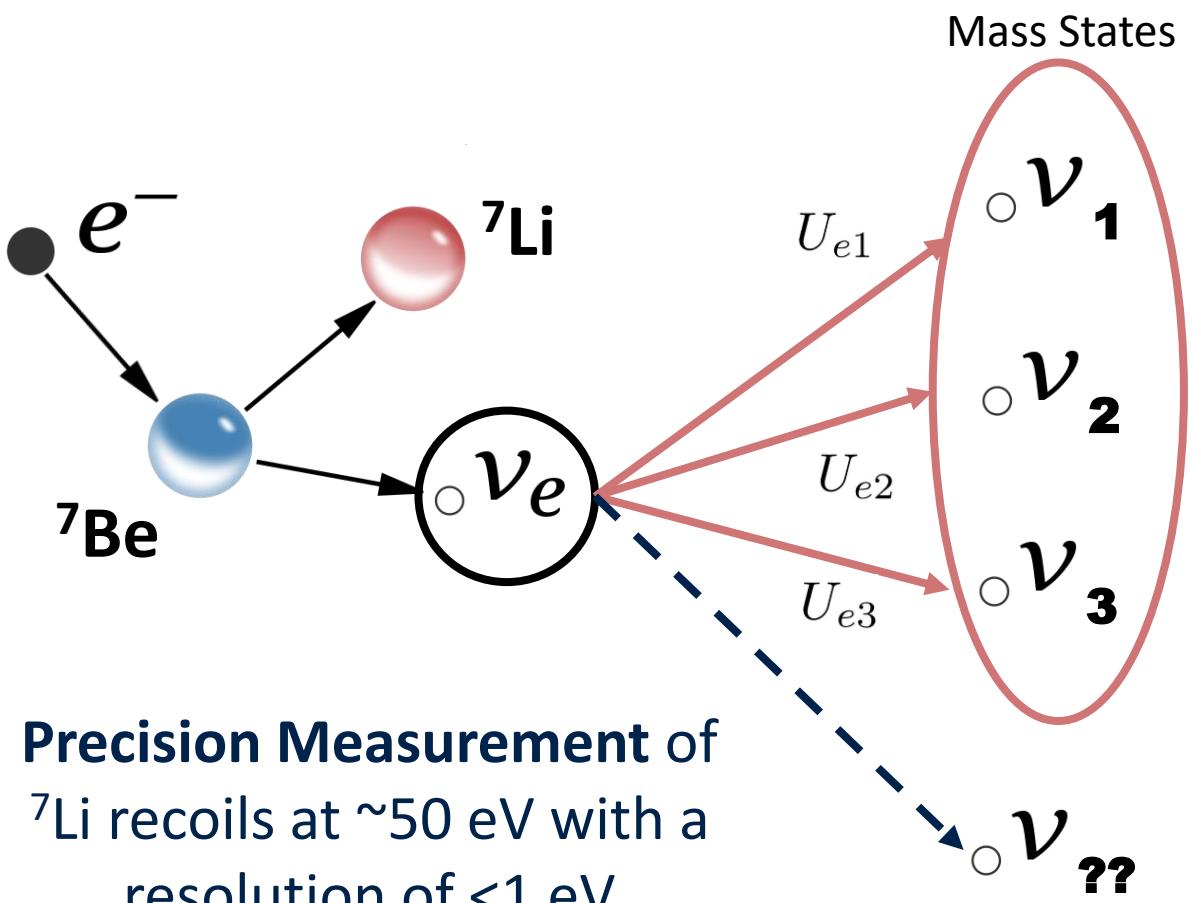
$$T_d = \frac{Q_{EC}^2 - m_\nu^2 c^4}{2\left(Q_{EC} + m_d c^2\right)}$$

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

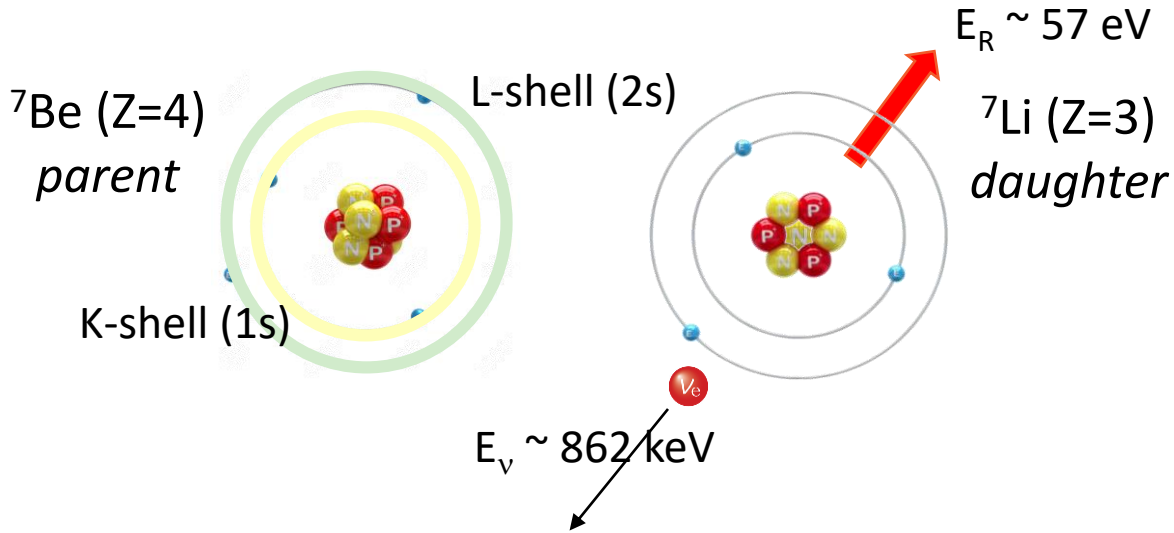
Takeaway: Beta decay provides a sensitive, model independent probe of any new physics in the neutrino sector that couples to their mass states

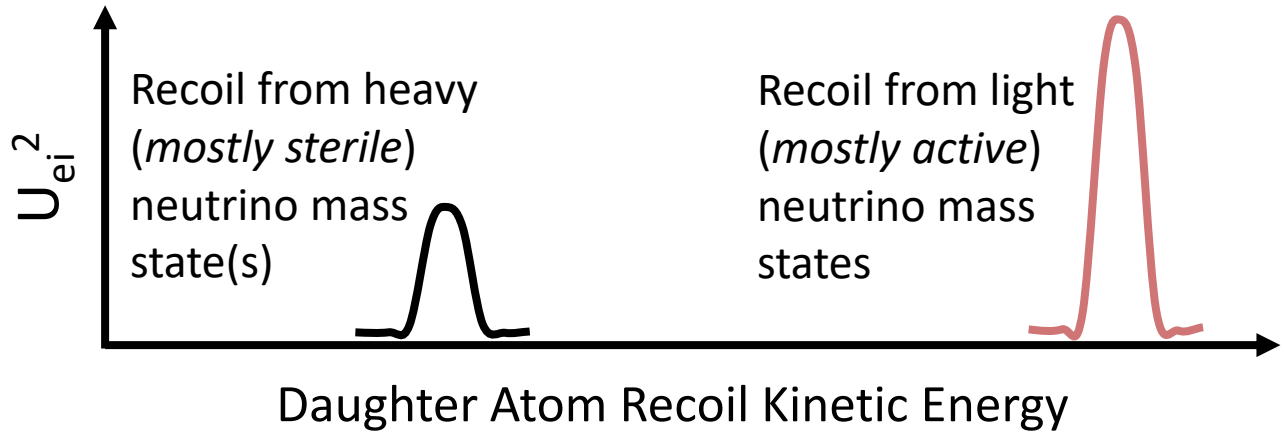
Neutrino Studies with the Electron Capture Decay of ^{7}Be

- **^{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

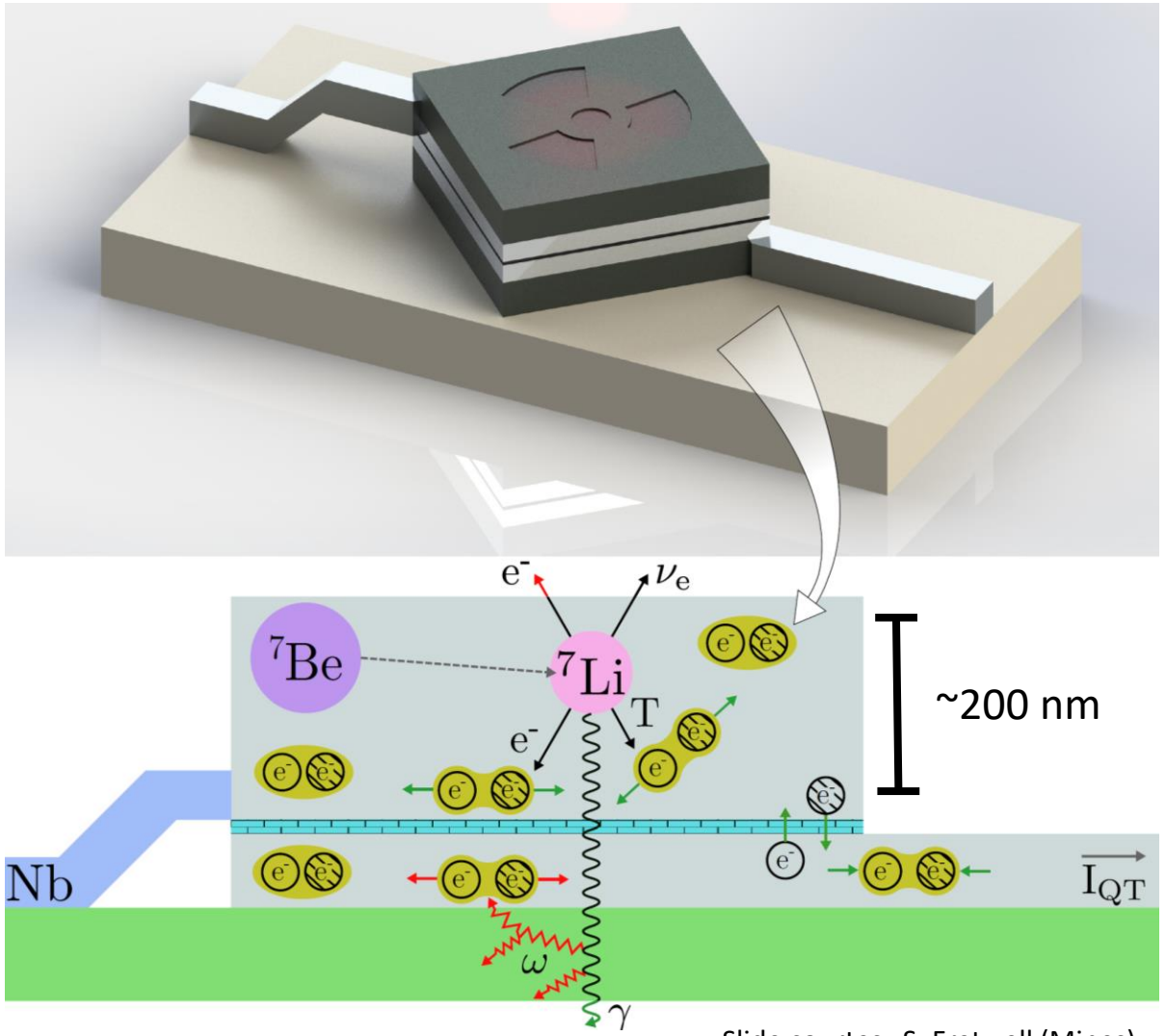




Superconducting Tunnel Junction (STJ) Quantum Sensing

- 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)

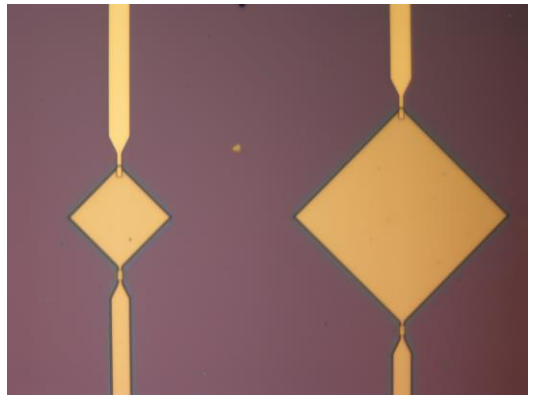
Can exploit strength of BSM searches with rare isotopes



Slide courtesy S. Fretwell (Mines)

Josephson Junctions

68 x 68 μm^2



138 x 138 μm^2

The BeEST Experiment

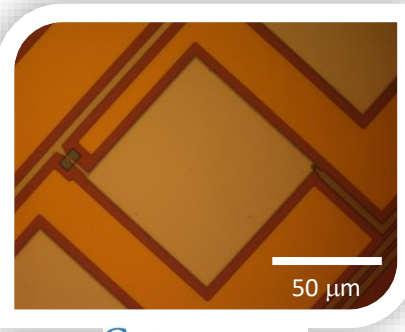
TRIUMF

Rare-isotope implantation at TRIUMF-ISAC

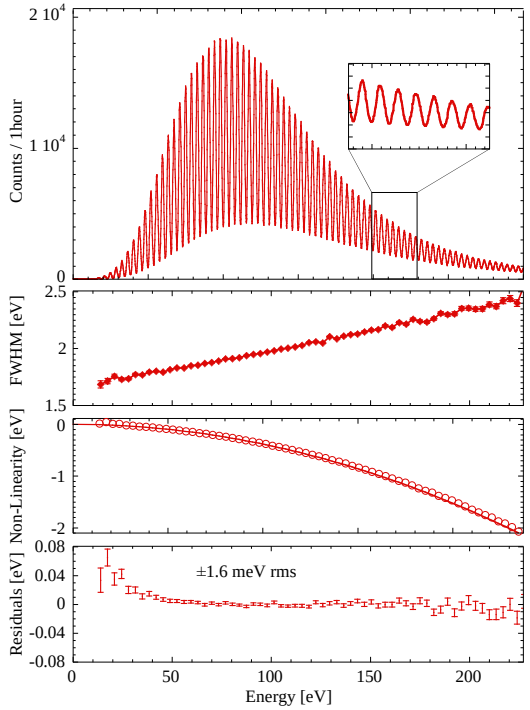
THE BeEST

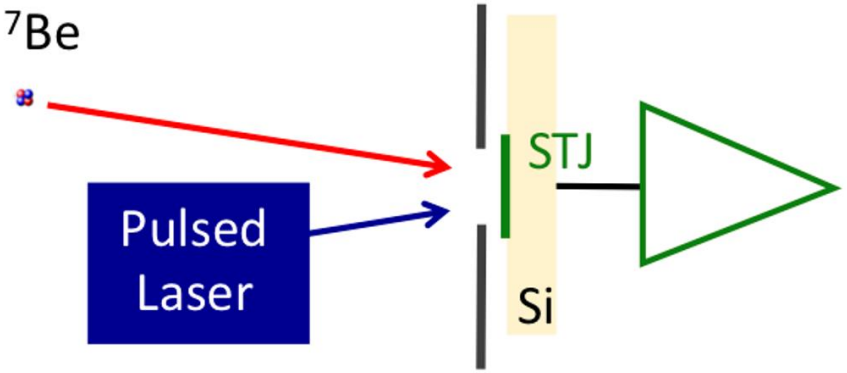
K.G. Leach and S. Friedrich, arXiv:2112.02029 (2021)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

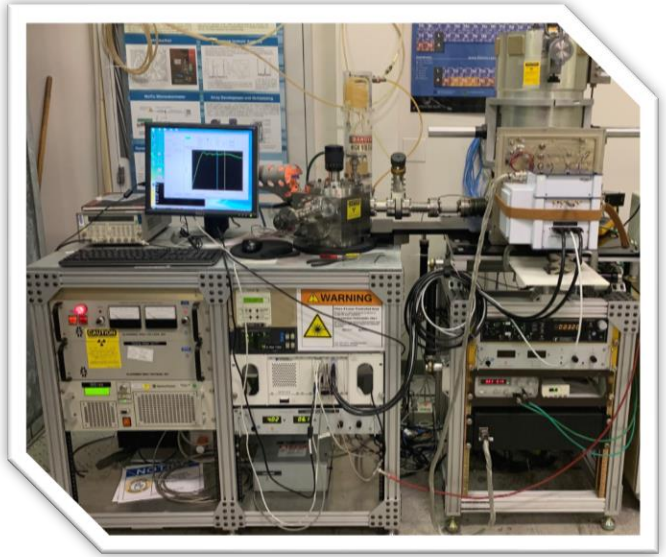
Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS







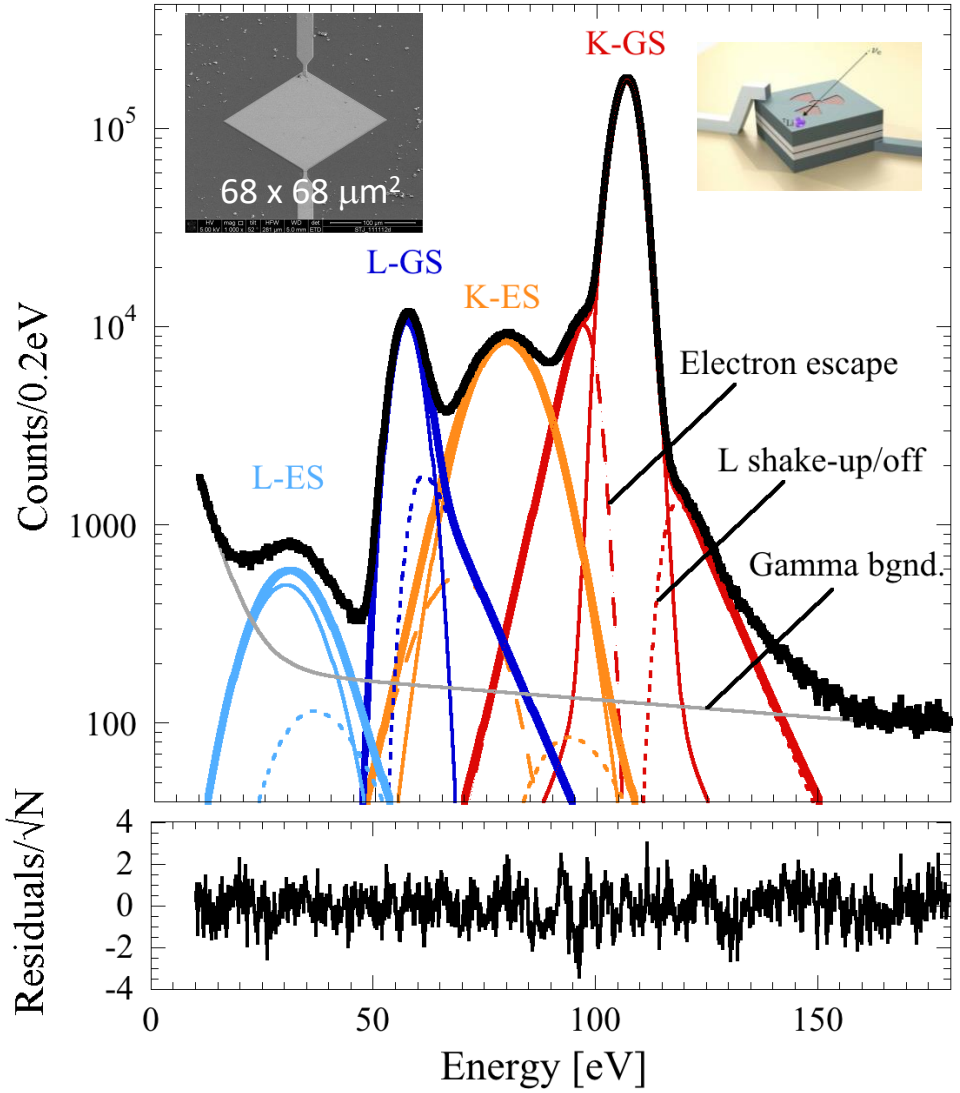
High-precision *In-situ* calibration and characterization

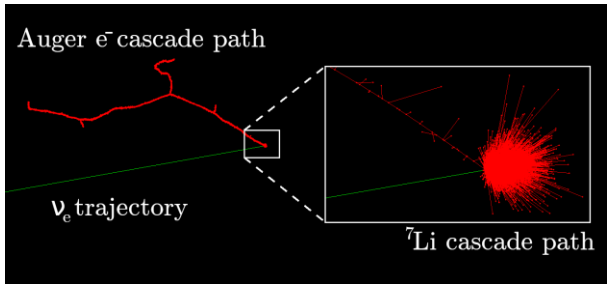
Lawrence Livermore National Laboratory

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

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

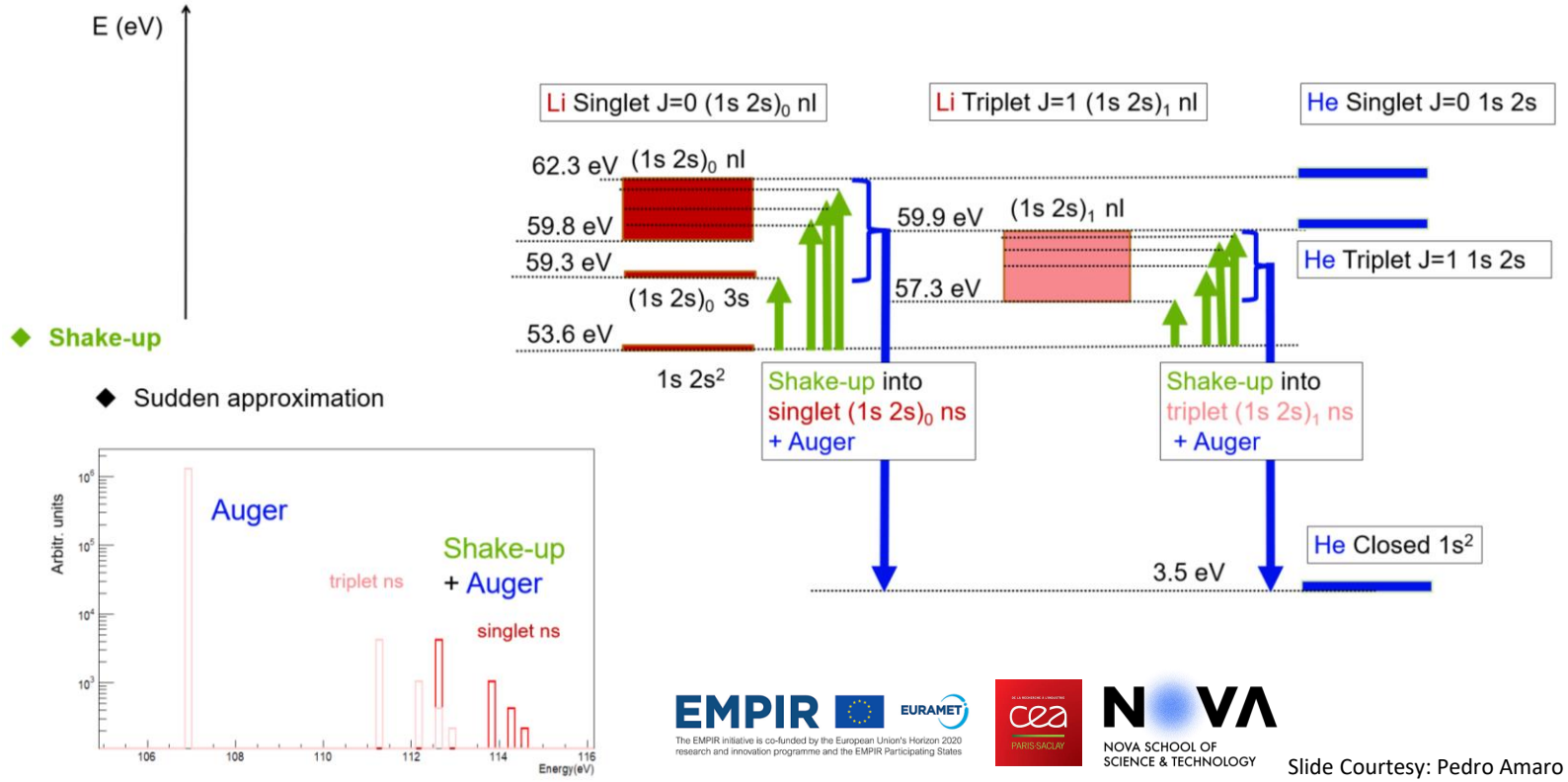
Phases-I and –II: First Nuclear Recoil Experiments with STJs





- Nuclear and atomic relaxation modeling
- High precision possible due to simplicity of atomic system

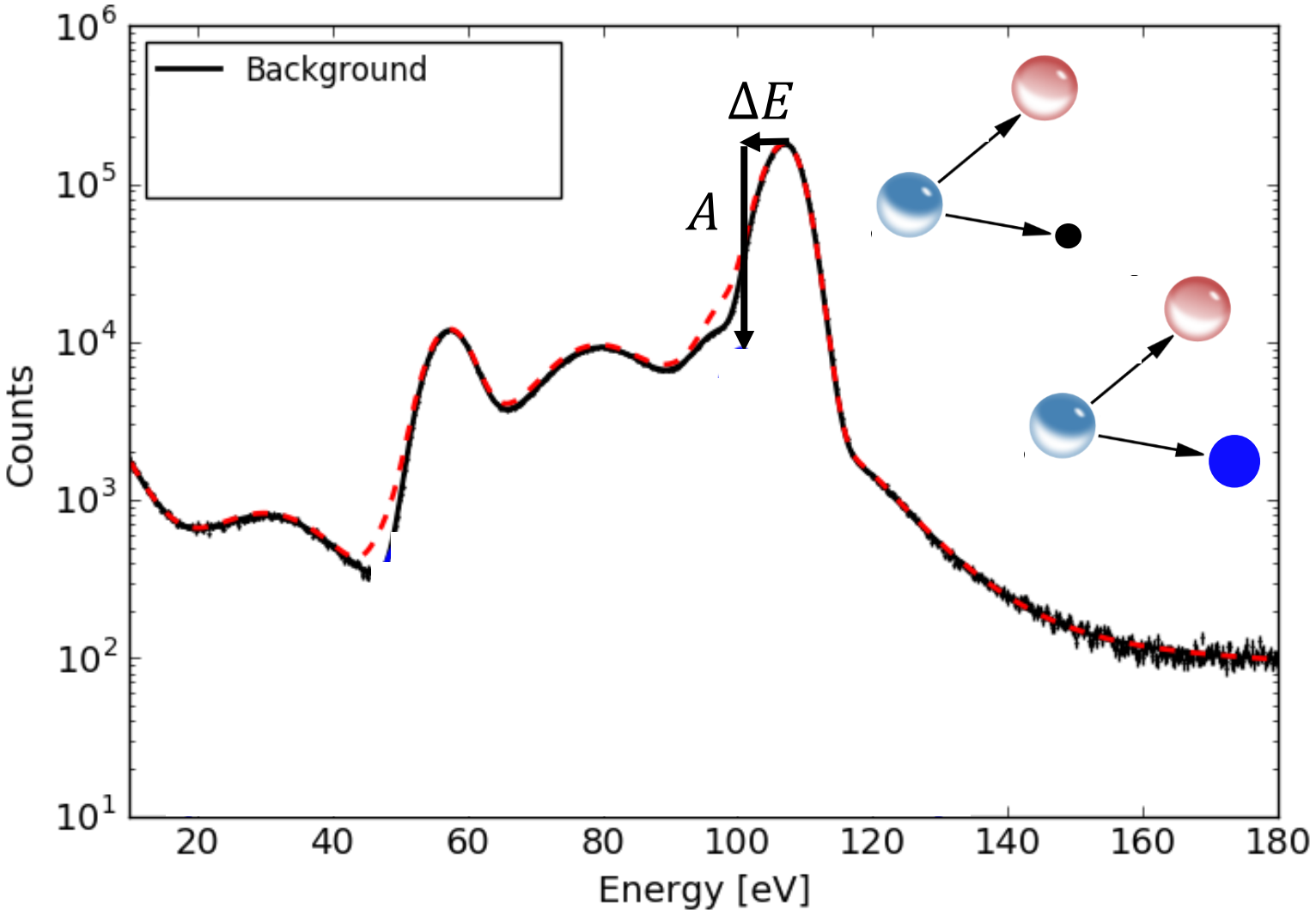
Energy structure of Li and He: L Shake-up + Auger



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

Slide Courtesy: Pedro Amaro

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 ($A \propto |U_{e4}|^2$)

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

Background:
Active neutrino contribution
+ other background

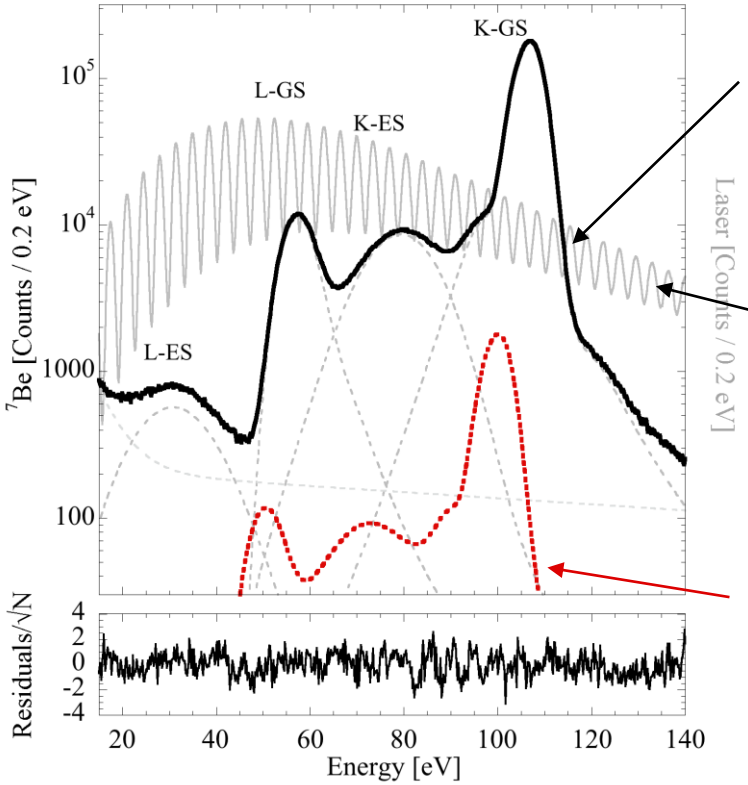
Signal:
Sterile neutrino contribution

f_0= EC spectral shape with active neutrinos

Slide Courtesy: Geon-Bo Kim (LLNL)

First Limits from BeEST Phase-II Data

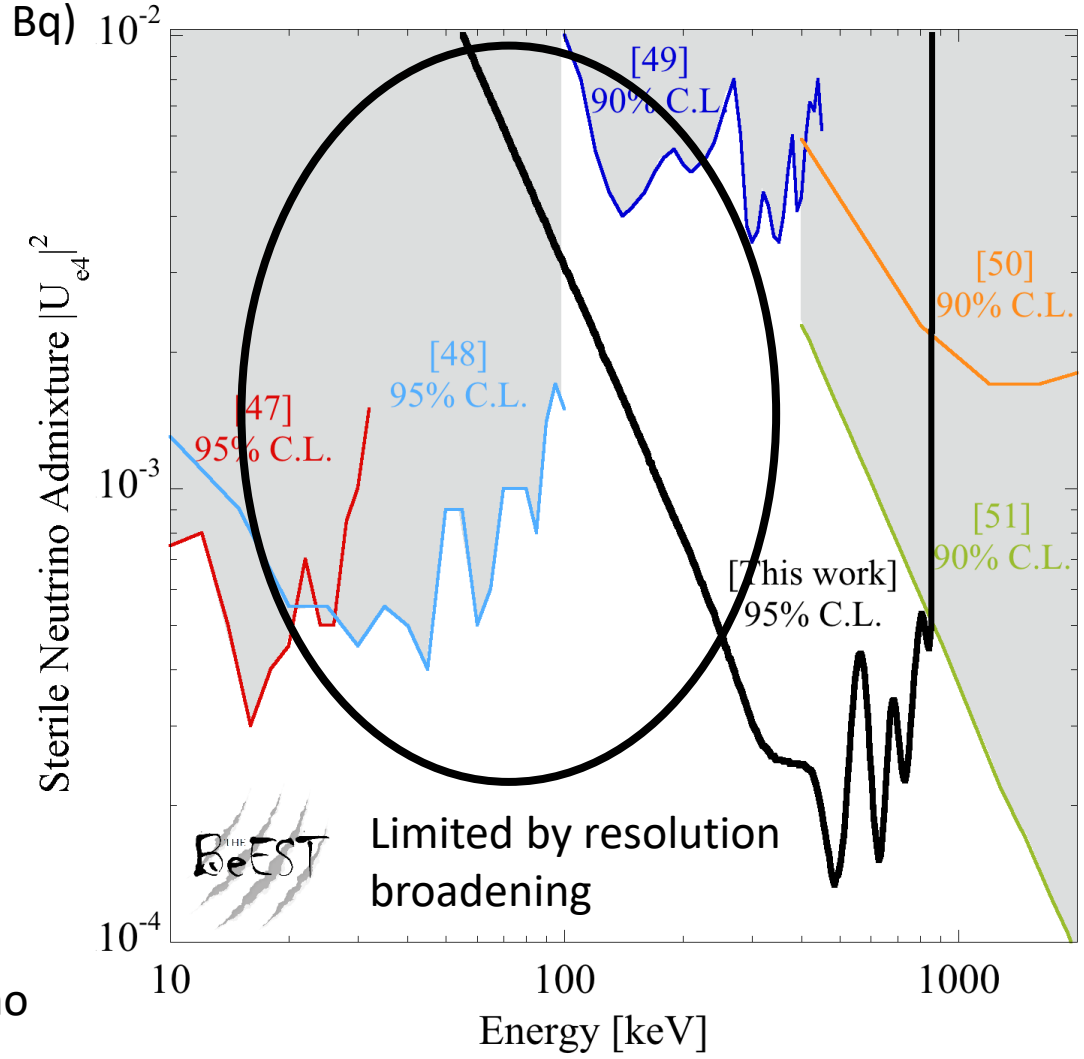
- Phase-II data from a single 138x138 μm² STJ counting at low rate (~10 Bq)



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



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

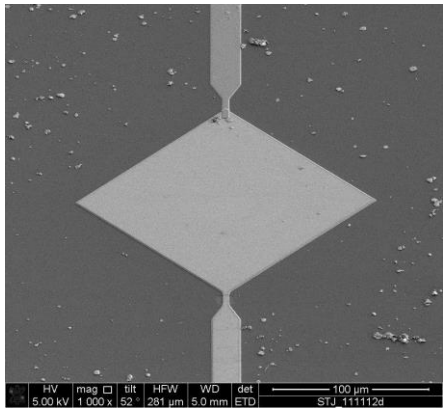
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

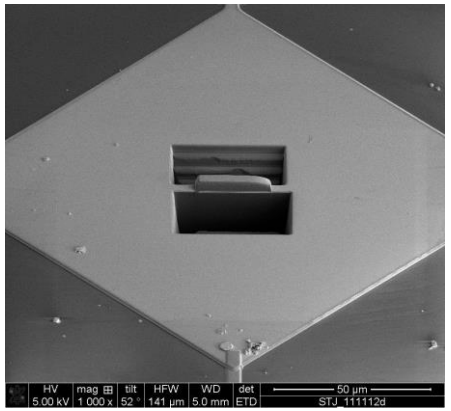
Atom-by-Atom Characterization of the BeEST

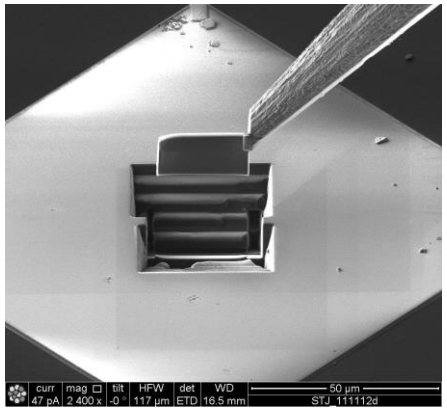
- The sensitivity of our experiment (and technique in general) is currently limited by our understanding of where the atoms we implanted are, and how they interact with the detector

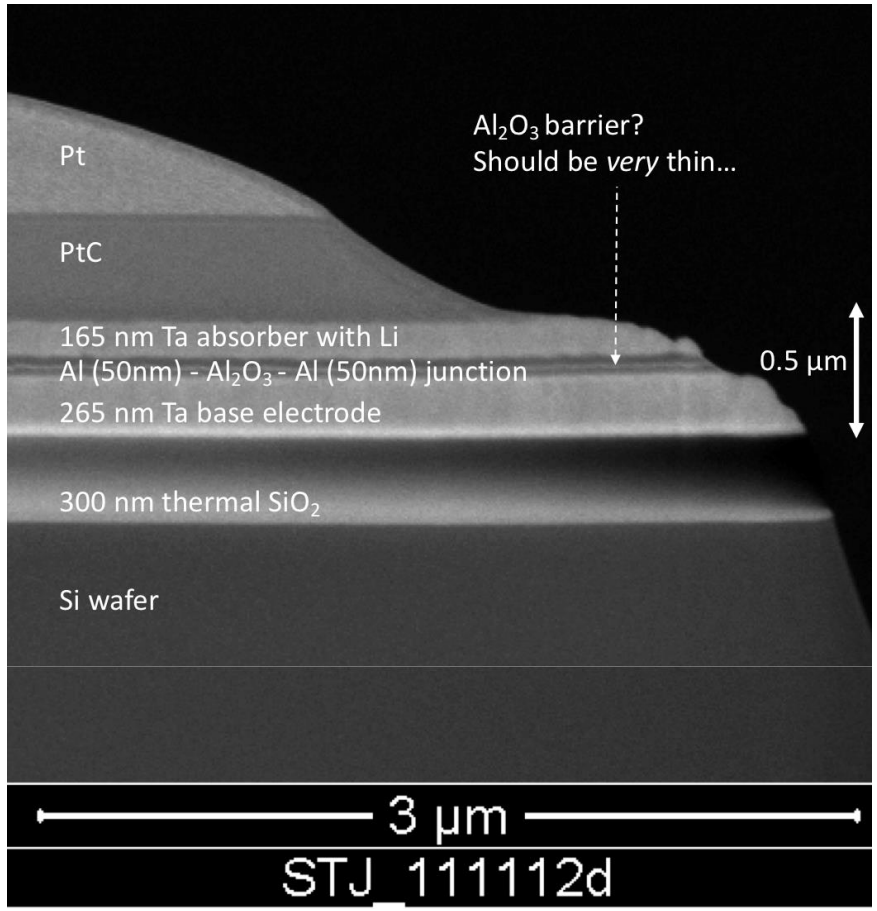
THE GOAL: Create an atom-by-atom map of the detector

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

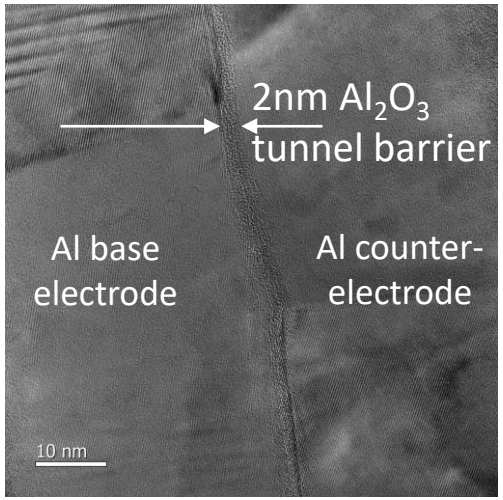






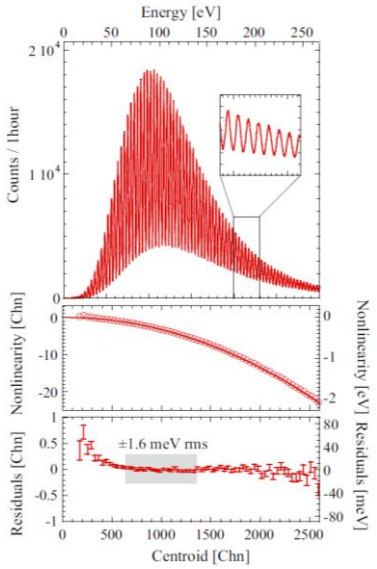


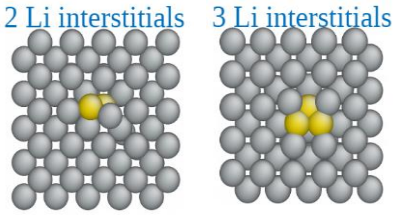
- Materials imaging done at Mines, Berkeley, and LLNL
- DFT quantum simulations performed at LLNL using the supercomputers to map material-dependent energies



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

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

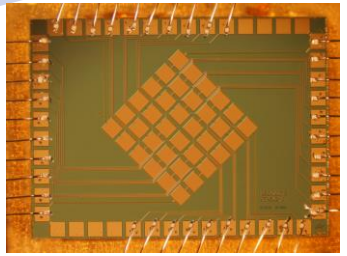
2022

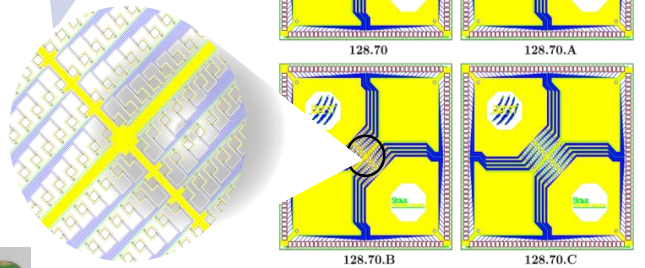
Phase-II

First Limits and Precision Device Characterization

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

2021



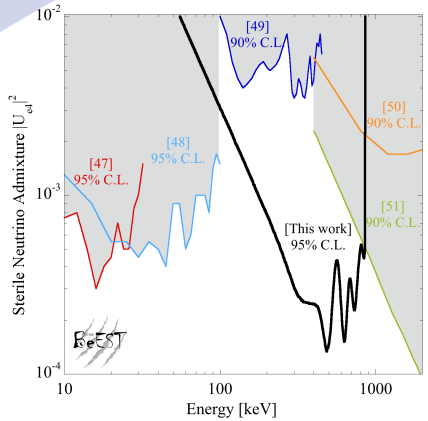


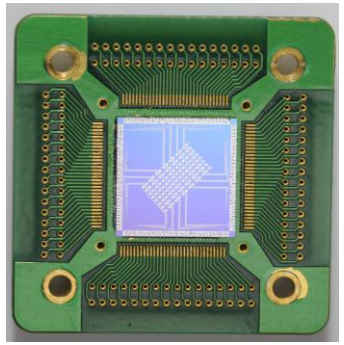
Phase-I

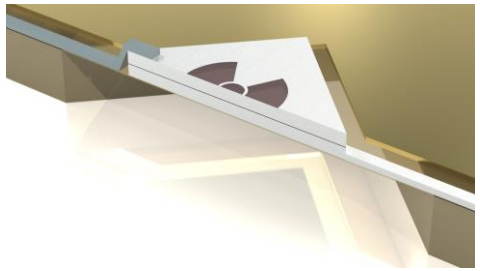
Proof of Concept

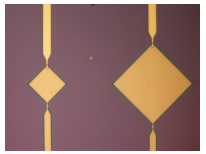
- PRL **125**, 032701 (2020)
- arXiv:2112.02029 (2021)

2020



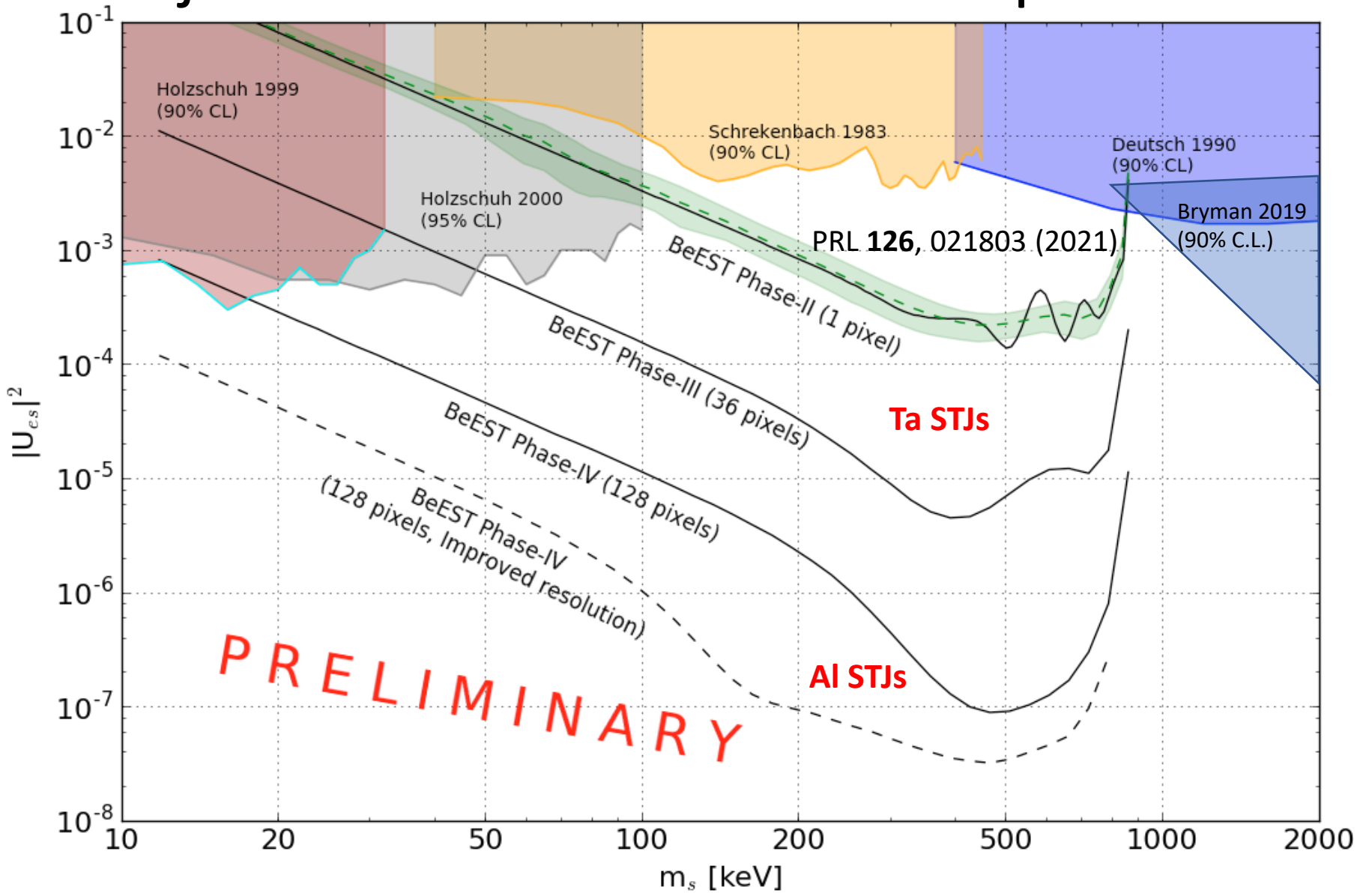




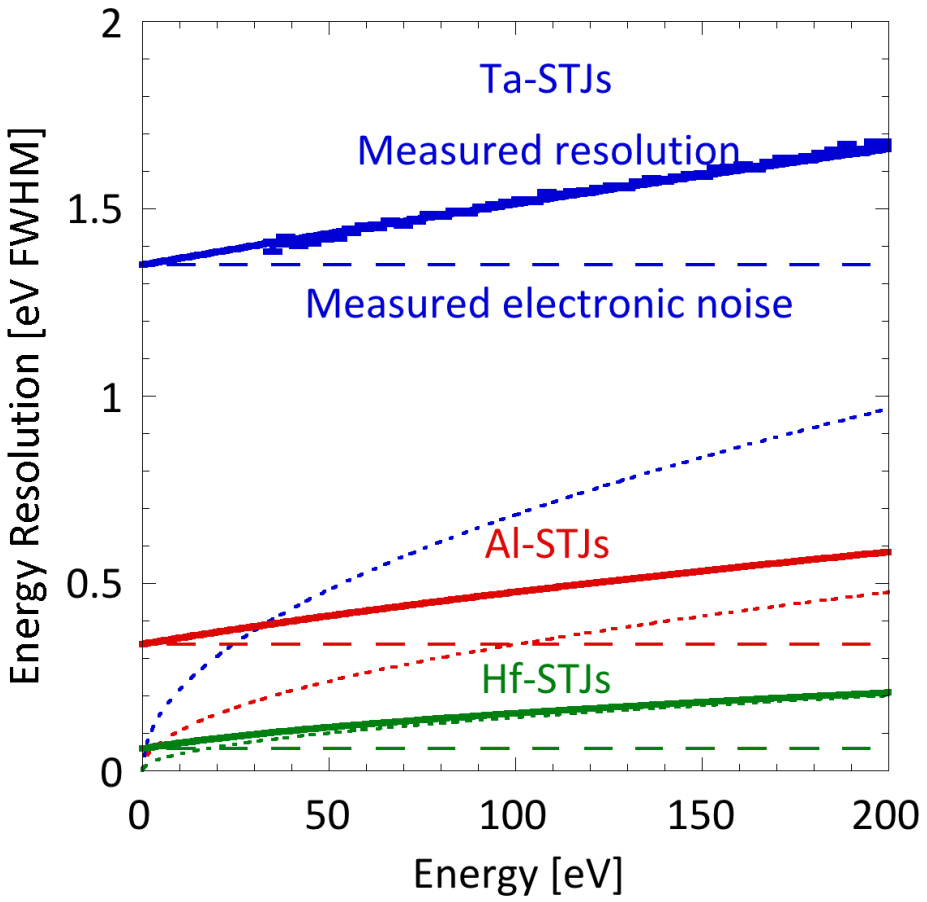


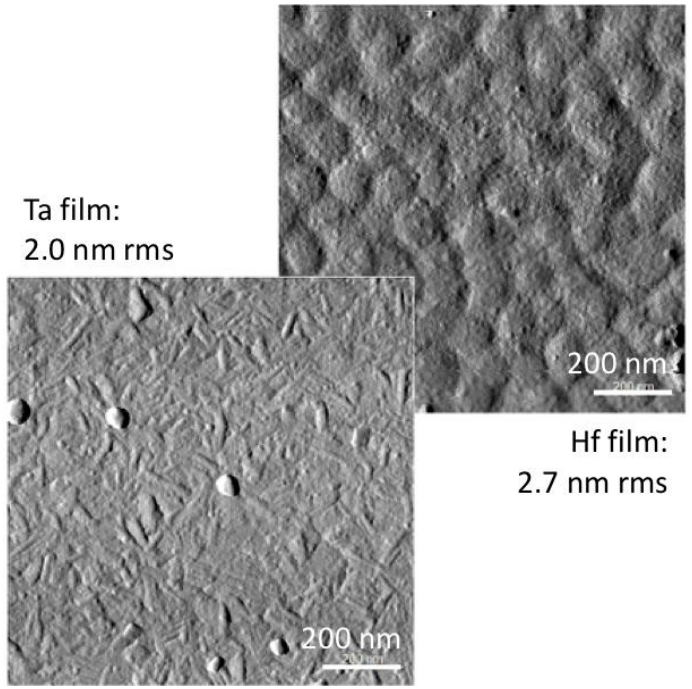
2018

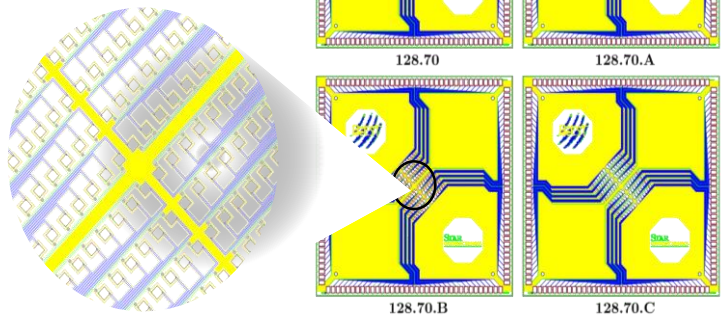
Projected Limits of the BeEST Experiment

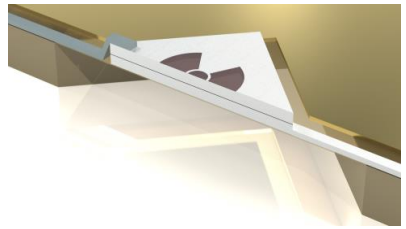


Beyond the BeEST – 10,000 Pixel Hf-Based Experiment



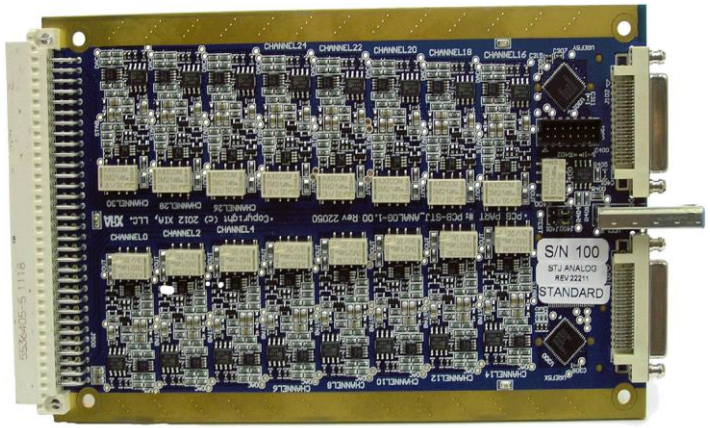






STAR CRYOELECTRONICS

XIA



Time	Detector	Resolution	Count Rate	Run Time	ν Mass	ν_s Admixture
Now	1 Ta STJ pixel	6 eV	10 cps	30 days	>100 keV	~1e-4
5 years	100 Al STJs	1 eV	1000 cps	100 days	>10keV	<1e-6
10 years	10 000 Hf STJs	0.2 eV	3000 cps	1000 days	> 5keV	<1e-9

Slide courtesy S. Friedrich (LLNL)

Conclusions

- 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 mass states (sub-MeV).

- Phase-II of the experiment uses only a single Ta-based STJ counting at 10 Hz for 28 days to acquire the first low-statistics data set.

- These first limits using this approach are up to an order of magnitude more stringent than all previous model-independent decay-based measurements in the 100 – 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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EMPIR EURAMET

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STAR CRYOELECTRONICS

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