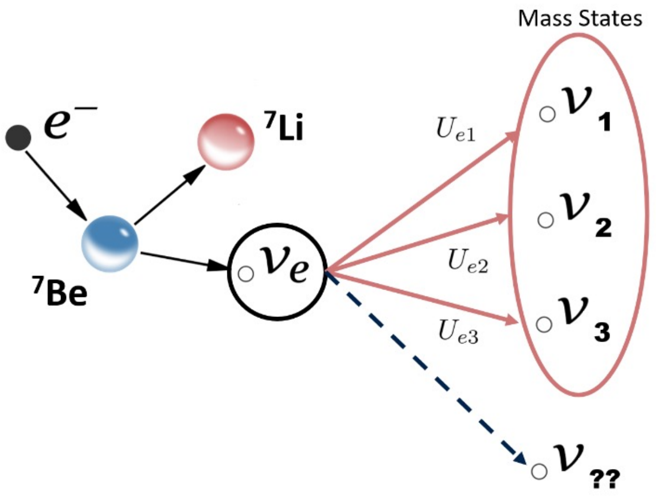
TRIUMF

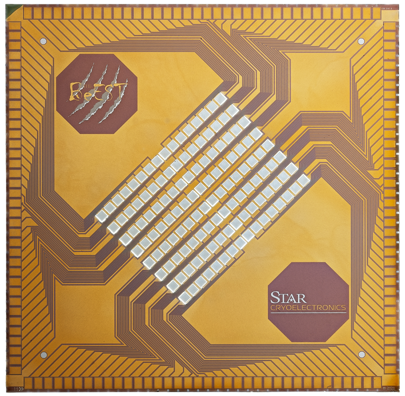
The BeEST sterile neutrino experiment

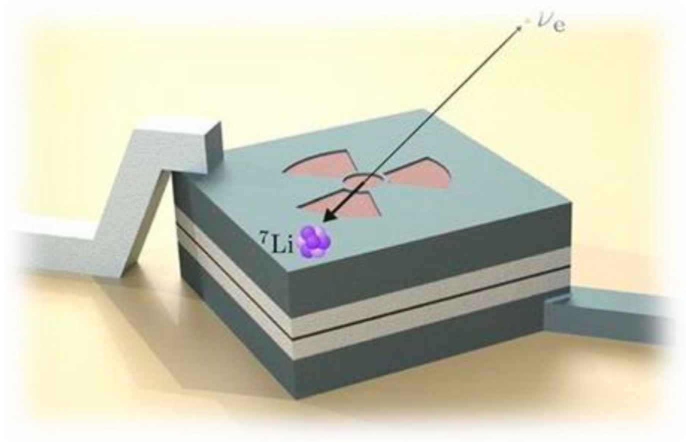
Annika Lennarz

Division of Physical Sciences, TRIUMF

on behalf of the BeEST collaboration



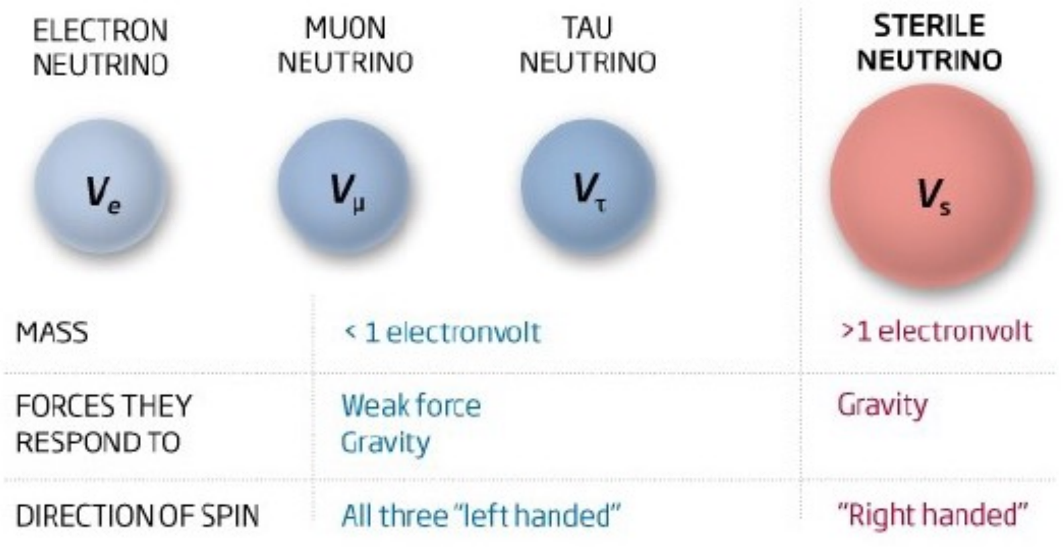




Discovery, accelerated

Motivation

- 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…

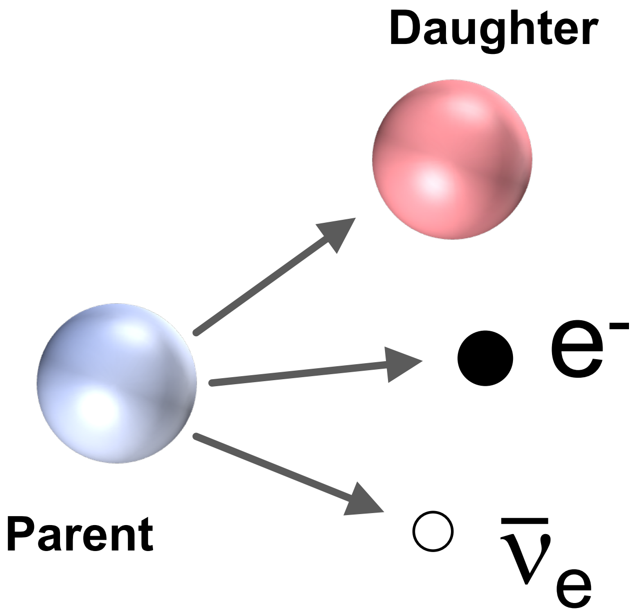
Atomic Recoils Following Nuclear β-decay

- β-decay is **powerful probe to search for BSM physics**
- Pure energy-to-matter conversion
- Complex but well understood systems (~3500)

β-decay usually characterized by measuring:

- Electrons (β^-, atomic Auger, CE, etc.)
- Positrons (β^+, IPC)
- Photons (γ-rays, Bremsstrahlung, X-rays)

MeV/keV scale!

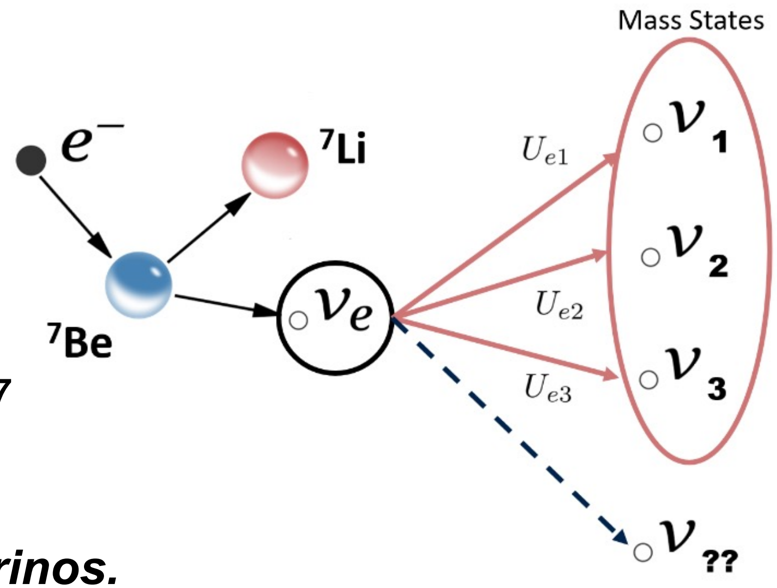


- Energy and momentum conserving system
- The **<u>daughter recoil</u>** is entangled with the other final state products!
- Contains a lot of unique but difficult to access information.
- Access to recoil energy allows access to information

For several cases, the recoil can be used as unique probe for BSM physics

The BeEST – **Be**ryllium **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
- **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
- Measurement uses **momentum reconstruction** of the ~eV-scale lithium-7 **nuclear recoil** energy spectrum following neutrino emission



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

By making a precision measurement of the low-energy recoiling atom, information on momentum conservation with the neutrino can be directly probed!

The BeEST – Beryllium Electron-capture with Superconducting Tunnel junctions

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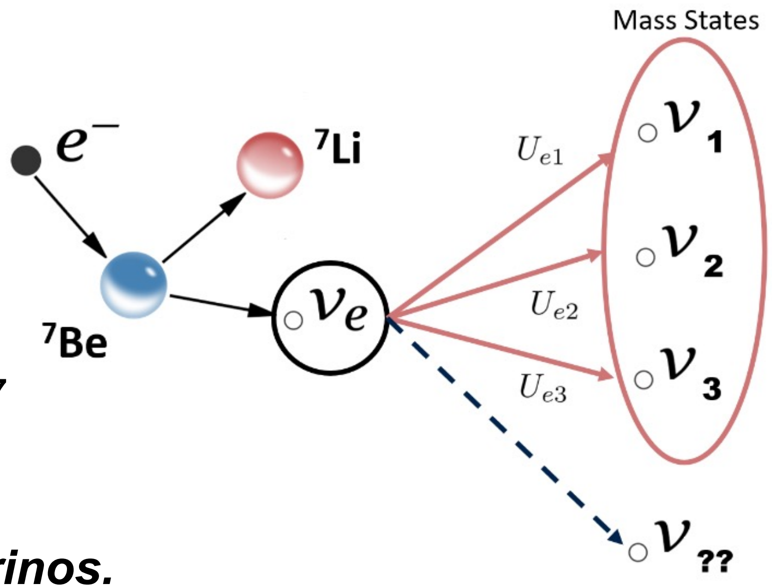


➔ ***Only relies on existence of heavy neutrino admixture to active neutrinos. Not on model-dependent details of their interactions!***

Require high resolution, low-energy detection of the recoiling atom!

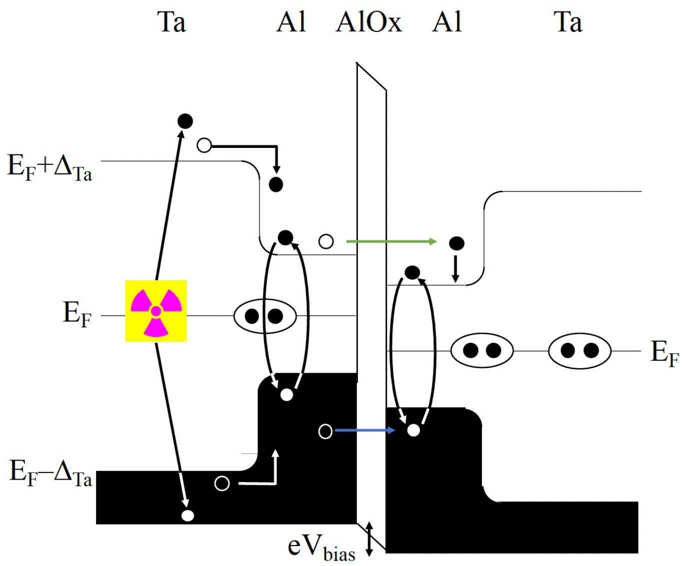
Superconducting Tunnel Junctions (STJ)

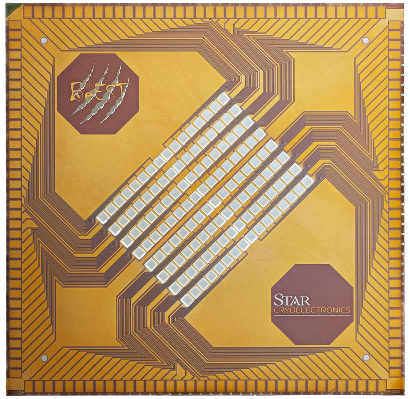
- Cryogenic charge superconducting sensors; Thin devices (~0.5 μm) optimized for **low-energy** radiation
- 2 superconducting electrodes separated by thin insulating tunnel barrier
- Superconducting energy gap Δ ~meV

  ➔ **High energy resolution (~1eV)**

- Timing resolution ~10μs ➔ fast count rates

  ➔ **High rate (10^4 /s/pixel)**





STAR CRYOELECTRONICS

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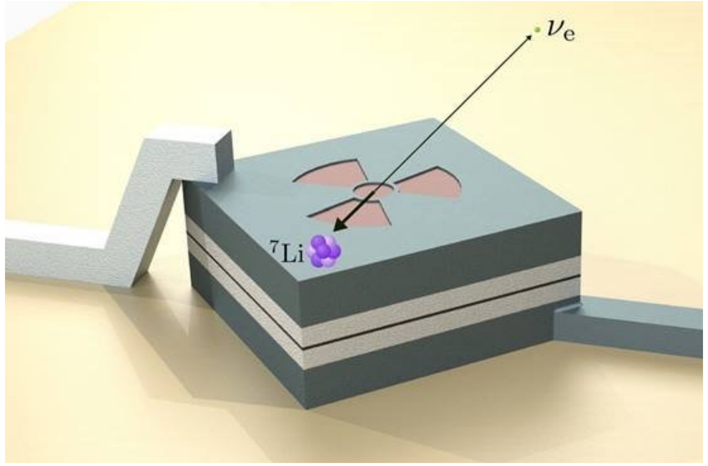
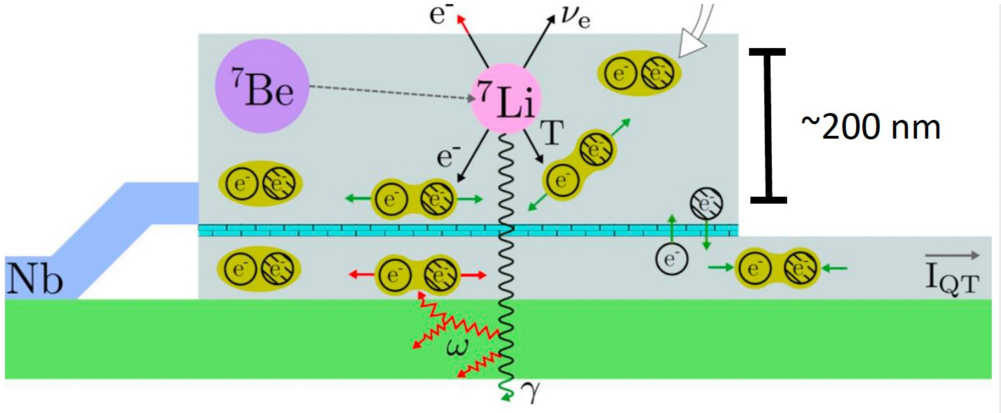
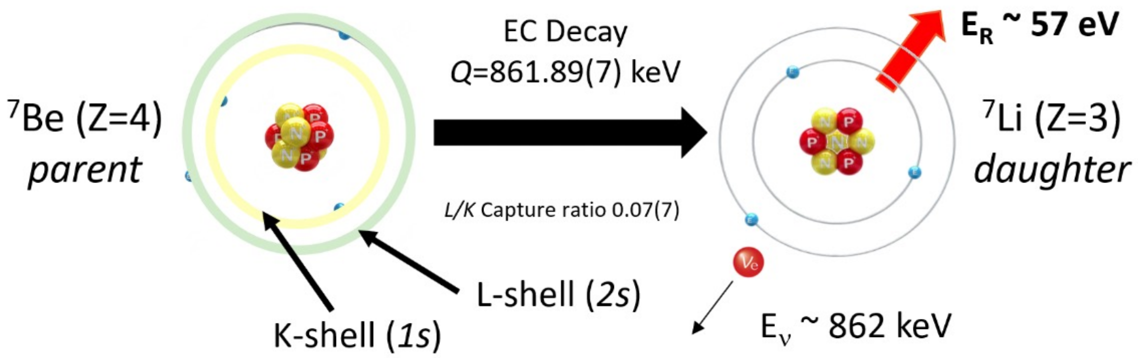
Ta, Al, and Nb-based STJ Sensor Arrays





Nuclear Recoil Spectroscopy with ^{7}Be



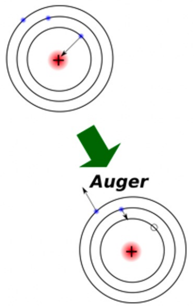
2 Atomic Capture Peaks

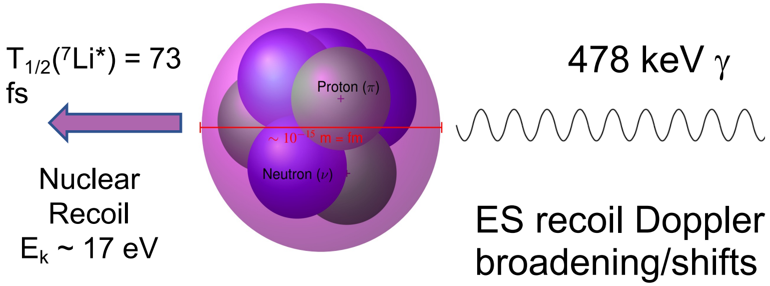
- K-shell (55 eV Auger emission)
- L-shell (no Auger emission)

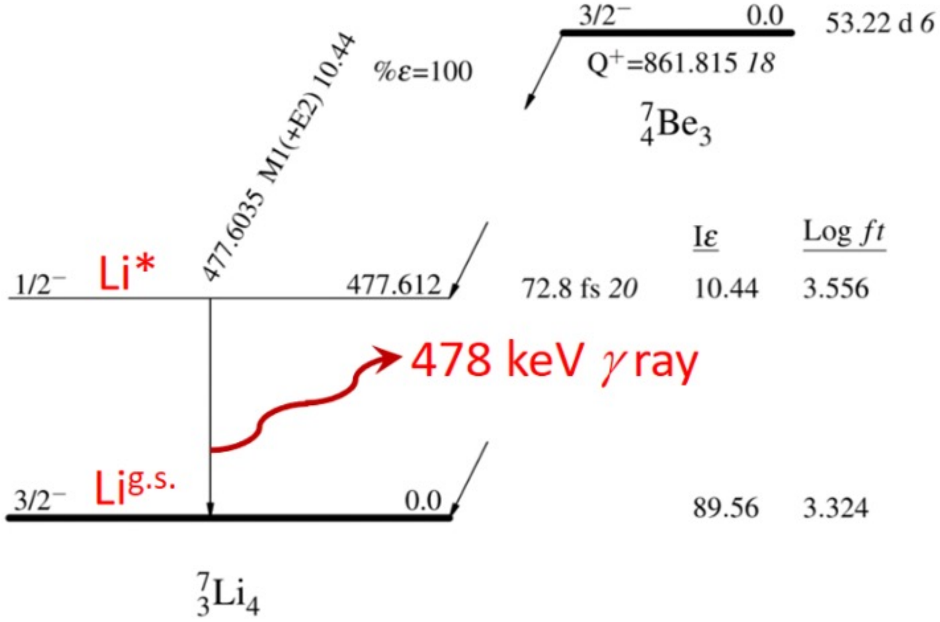
\+

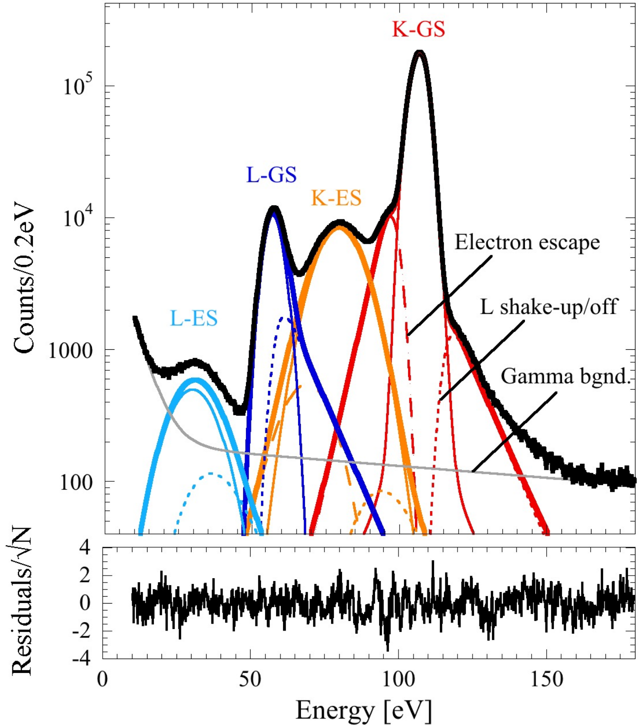
2 Nuclear Decay Branches

- Ground state
- Excited state

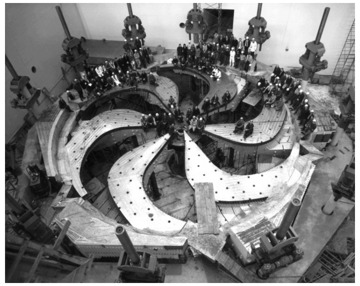






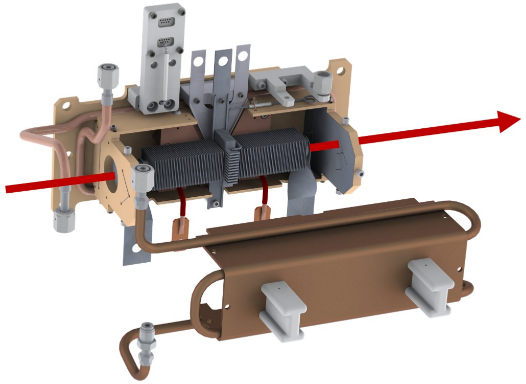


The BeEST - Experimental Concept



480 MeV p+ beam produced in cyclotron

UC_x production target

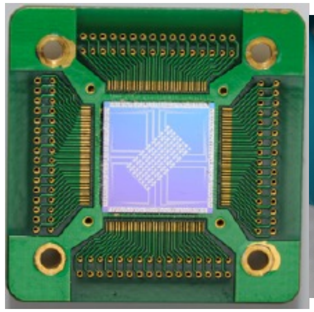


Laser ionization

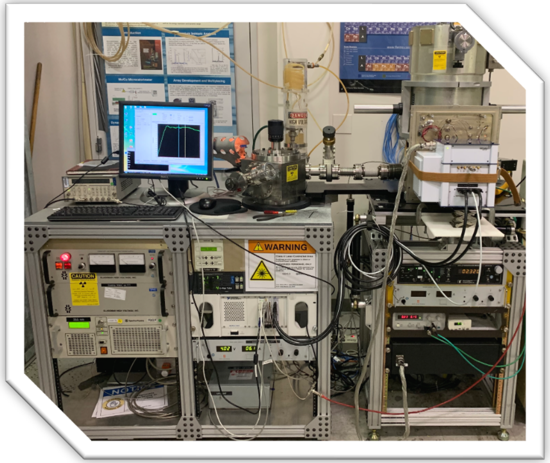
^{7}Be ($T_{1/2}$ = 53 d)

20 - 30 kV acceleration

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

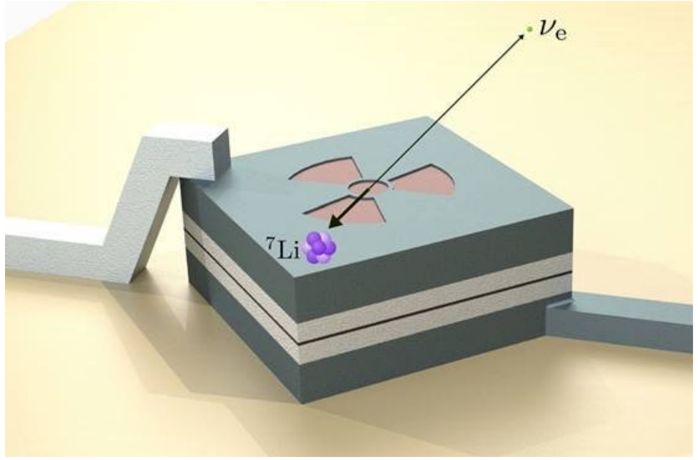


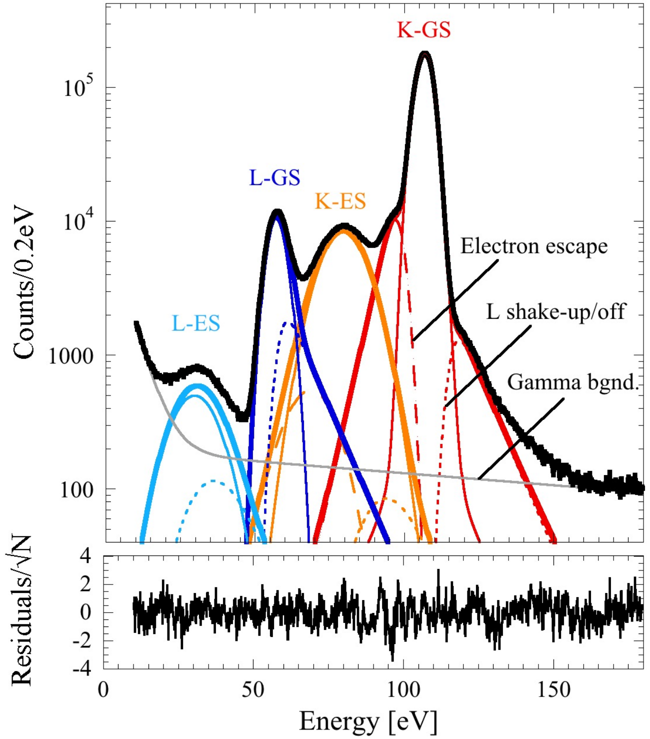
Cool to < 100mk in an Adiabatic Demagnetization Refrigerator.



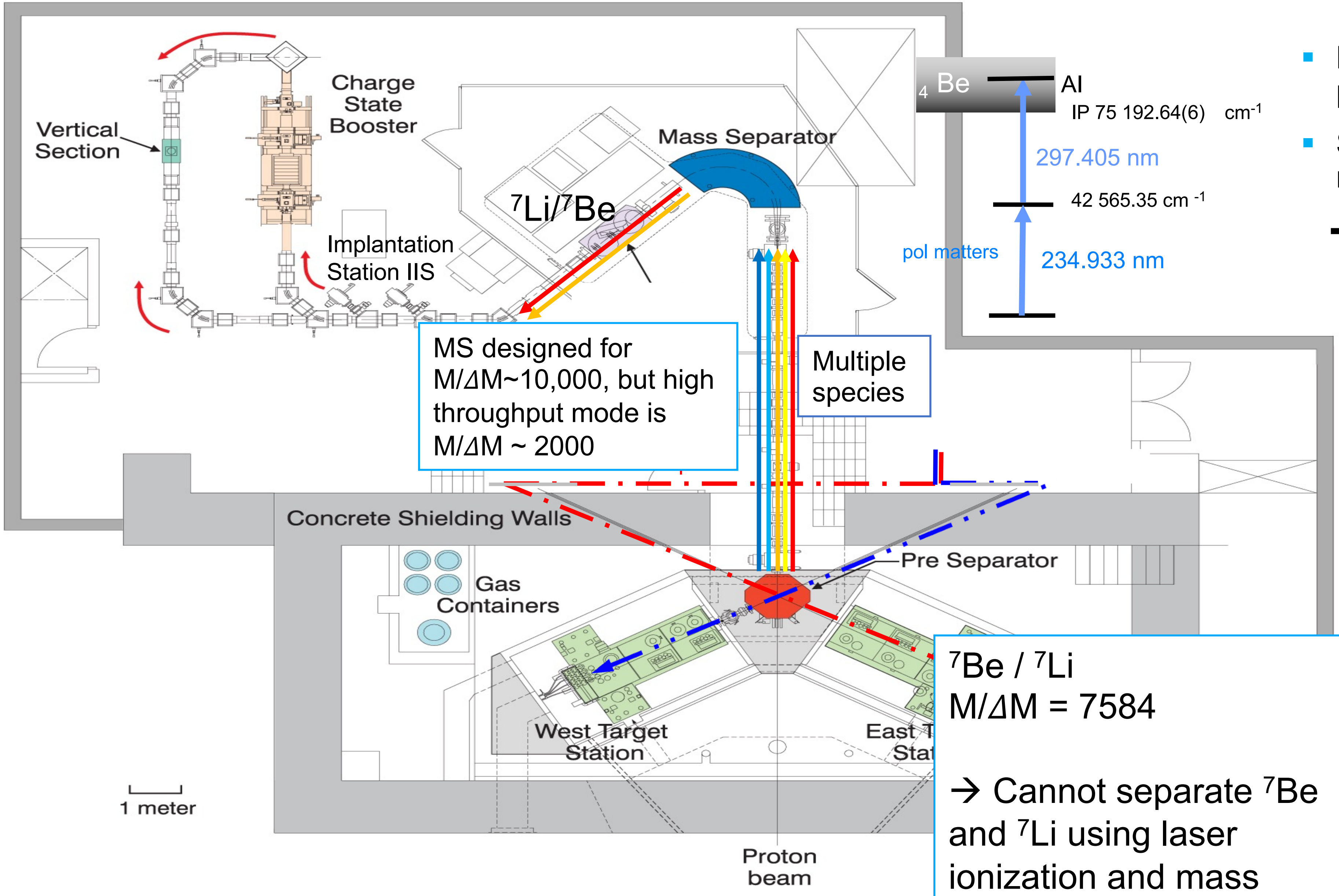
Lawrence Livermore National Laboratory

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





Beam production – ISAC target stations & mass separator



^7Be / ^7Li
M/ΔM = 7584

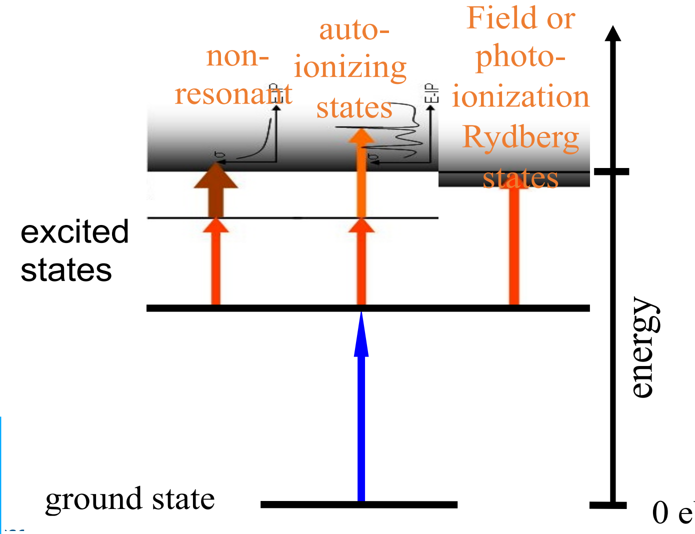
→ Cannot separate ^7Be and ^7Li using laser ionization and mass separator alone

Figure courtesy of J. Lassen (TRIUMF)

Resonant laser ionization

- **Element selective** tool for RIB production
- Selective ionization process + high-resolution mass separator

➔ suppresses neighbouring isobaric contaminations



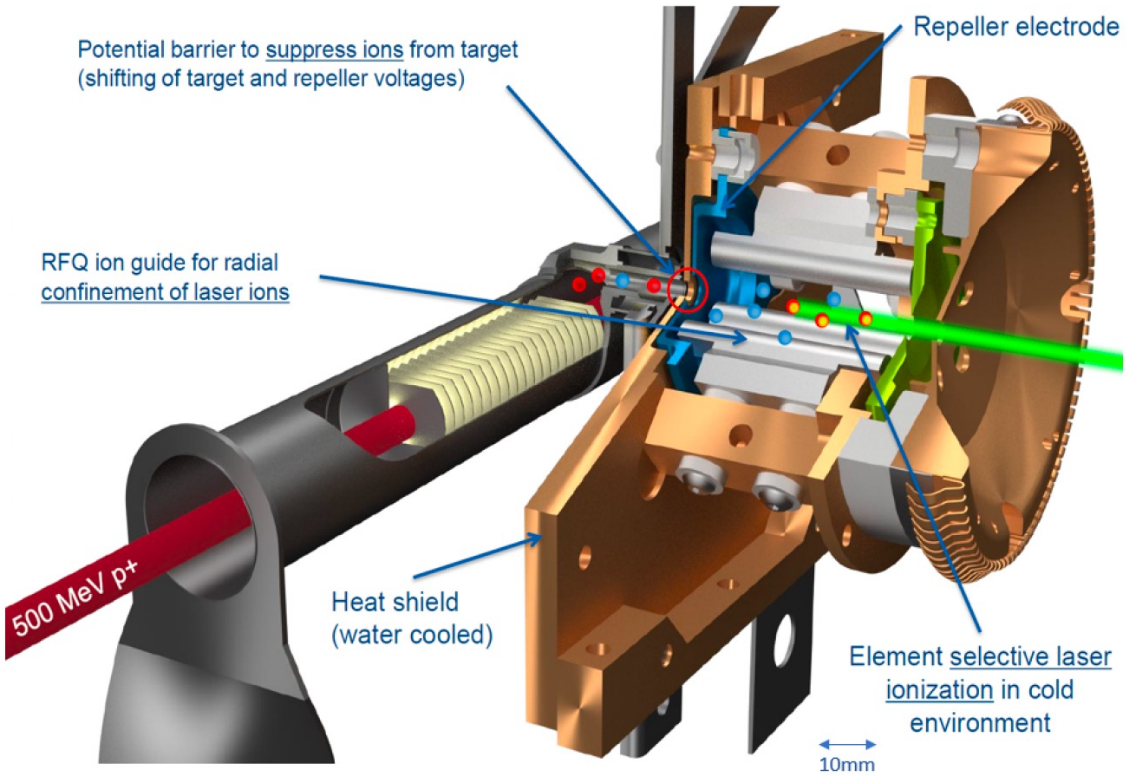
- ^7Be significantly enhanced neutrals to 1^+ (also small amount of surface ionization)
- **But**… large amounts of Li surface ionized

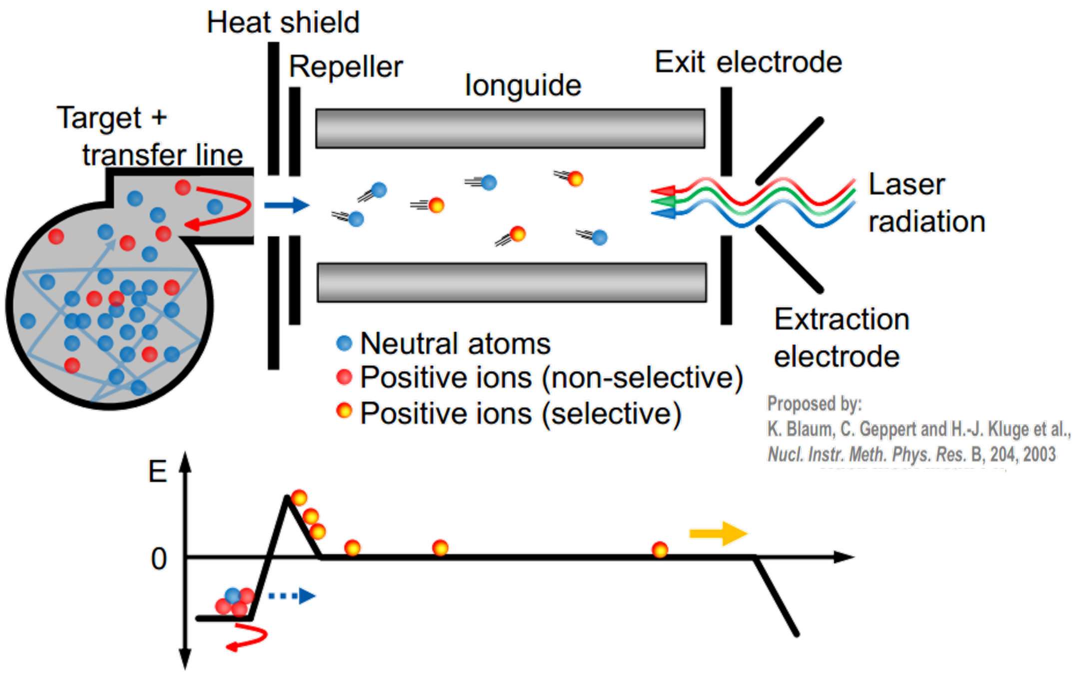
IG-LIS: Ion Guide Laser Ion Source

- The **ion guide laser ion source** (IG-LIS) decouples the hot isotope production region from the laser ionization volume
- Isobar suppression of up to 10^6 has been achieved

- Ions released from the target are efficiently suppressed by electrostatic potentials
- Neutral atoms can enter the interaction region behind the repeller electrode.

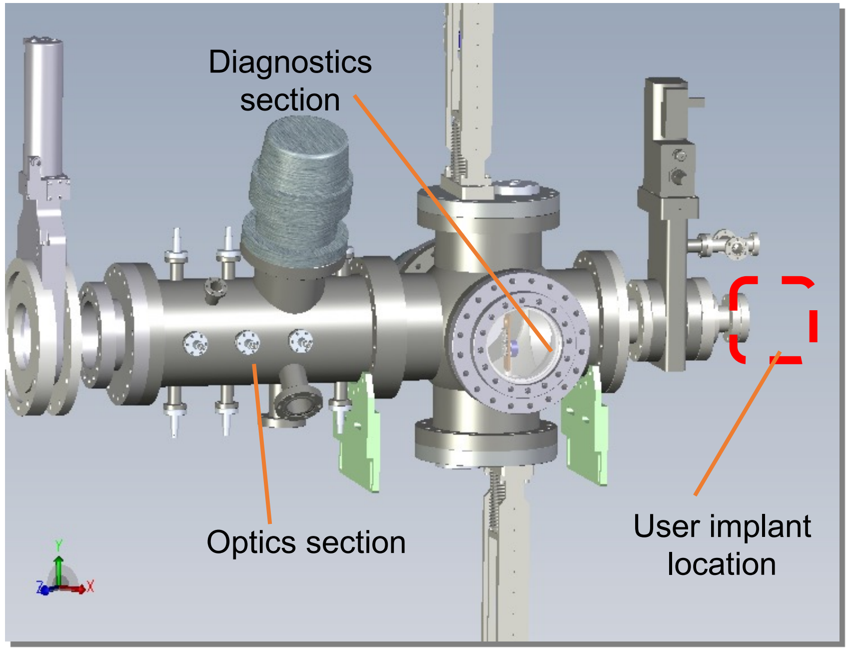
➔ Only nuclides ionized by resonant laser ionization within a cold environment behind the electrode are extracted!

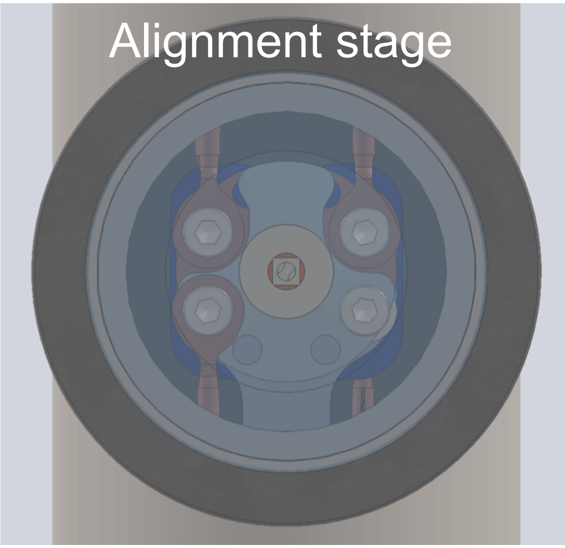


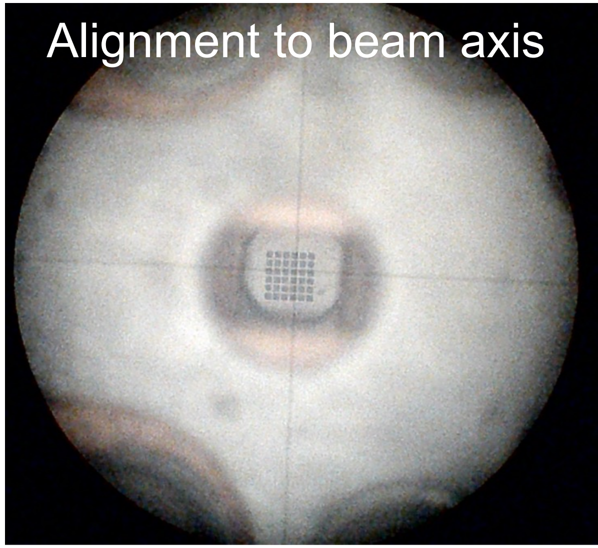


"An ion guide laser ion source for isobar-suppressed rare isotope beams"
Rev. Sci. Instrum. 85, 033309 (2014) http://dx.doi.org/10.1063/1.4868496

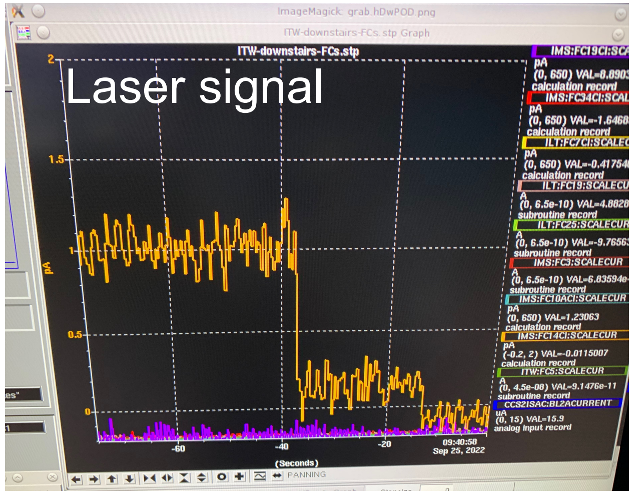
^{7}Be implantation at TRIUMF

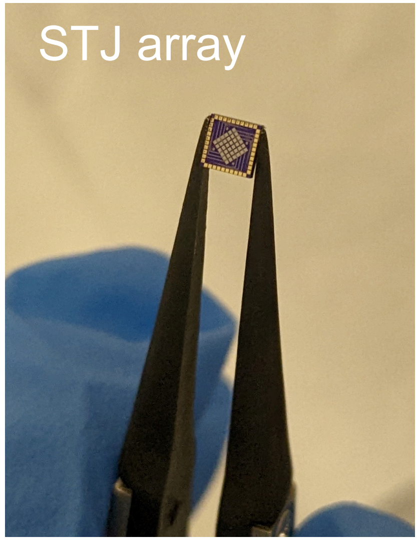






- Implantation station in exclusion area
- beam spot size ~3mm FWHM
- Bench alignment prior to implantation
- Tuning + monitoring via 7 signal readouts (slits, collimators, sample)
  ➔ Controlled implantation
- Sample removal & preparation under controlled conditions
- Plans for multi-sample irradiation in progress





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

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

Direct measurement of the ^{7}Be L/K capture ratio in Ta-based superconducting tunnel junctions

S. Fretwell,[1] K.G. Leach,[1,*] C. Bray,[1] G.B. Kim,[2] J. Dilling,[3] A. Lennarz,[3] X. Mougeot,[4] F. Ponce,[5,2] C. Ruiz,[3] J. Stackhouse,[1] and S. Friedrich[2]
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[4]CEA, LIST, Laboratoire National Henri Becquerel, CEA-Saclay 91191 Gif-sur-Yvette Cedex, France
[5]Department of Physics, Stanford University, Stanford, CA 94305, USA
(Dated: July 16, 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,†]
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[6]Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120, Palaiseau, France
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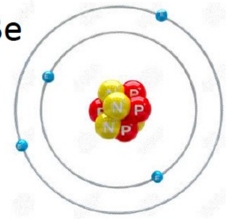
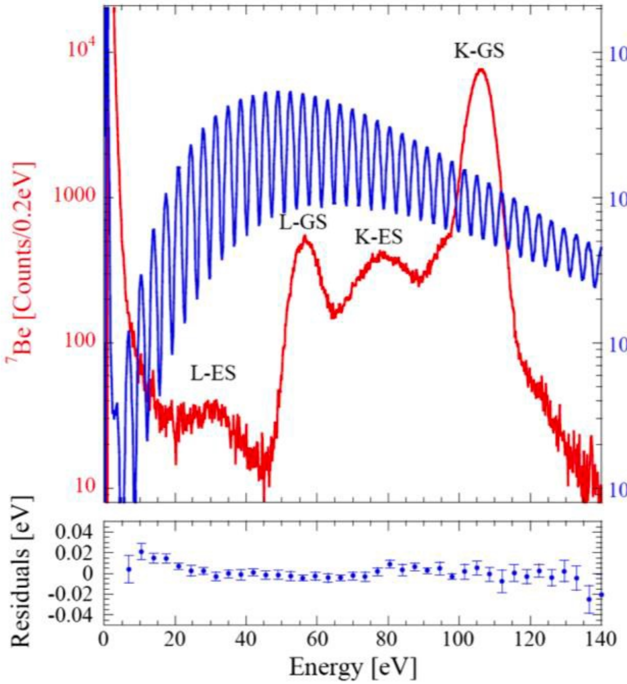
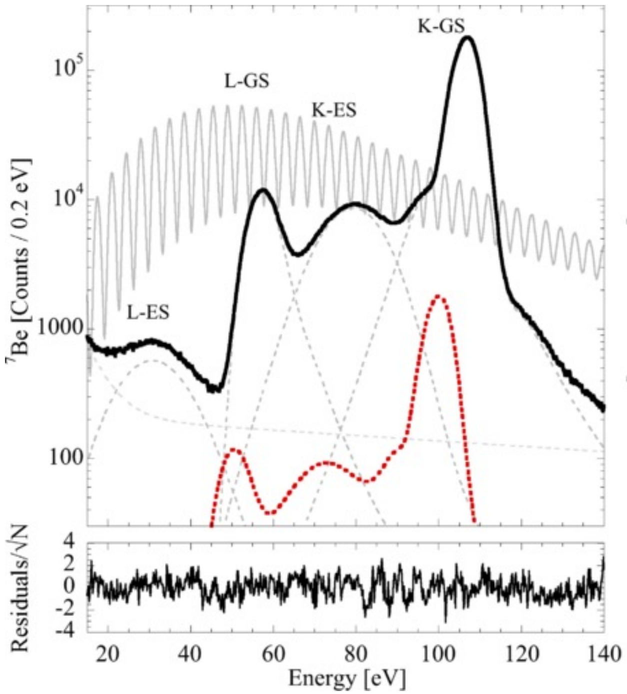
[8]XIA LLC, Hayward, CA 94544, USA
(Dated: October 20, 2020)

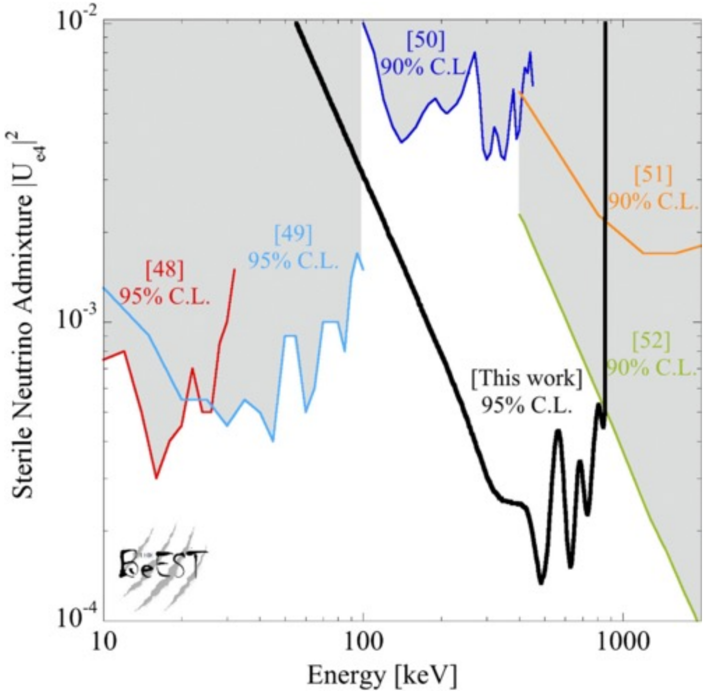
^{7}Be



L/K = 0.070(7)

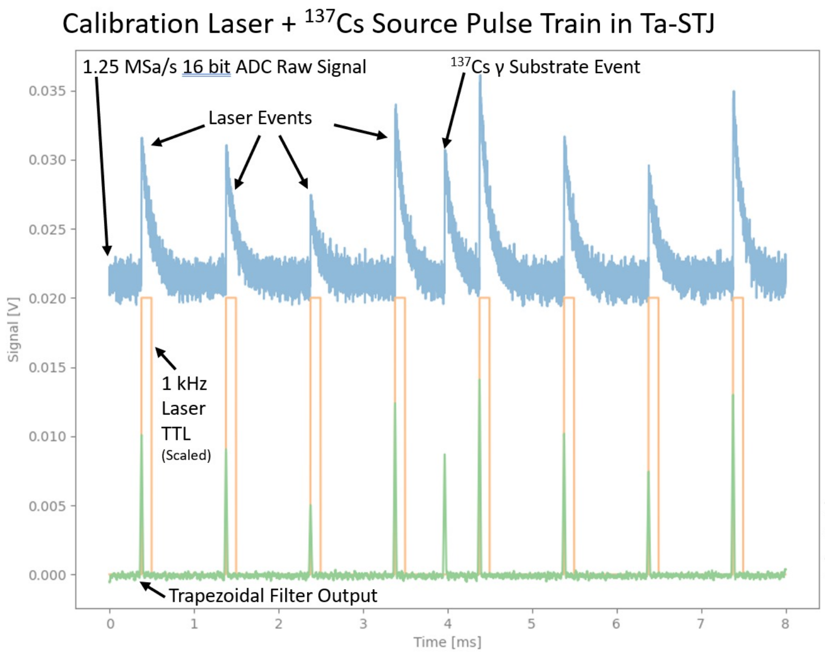




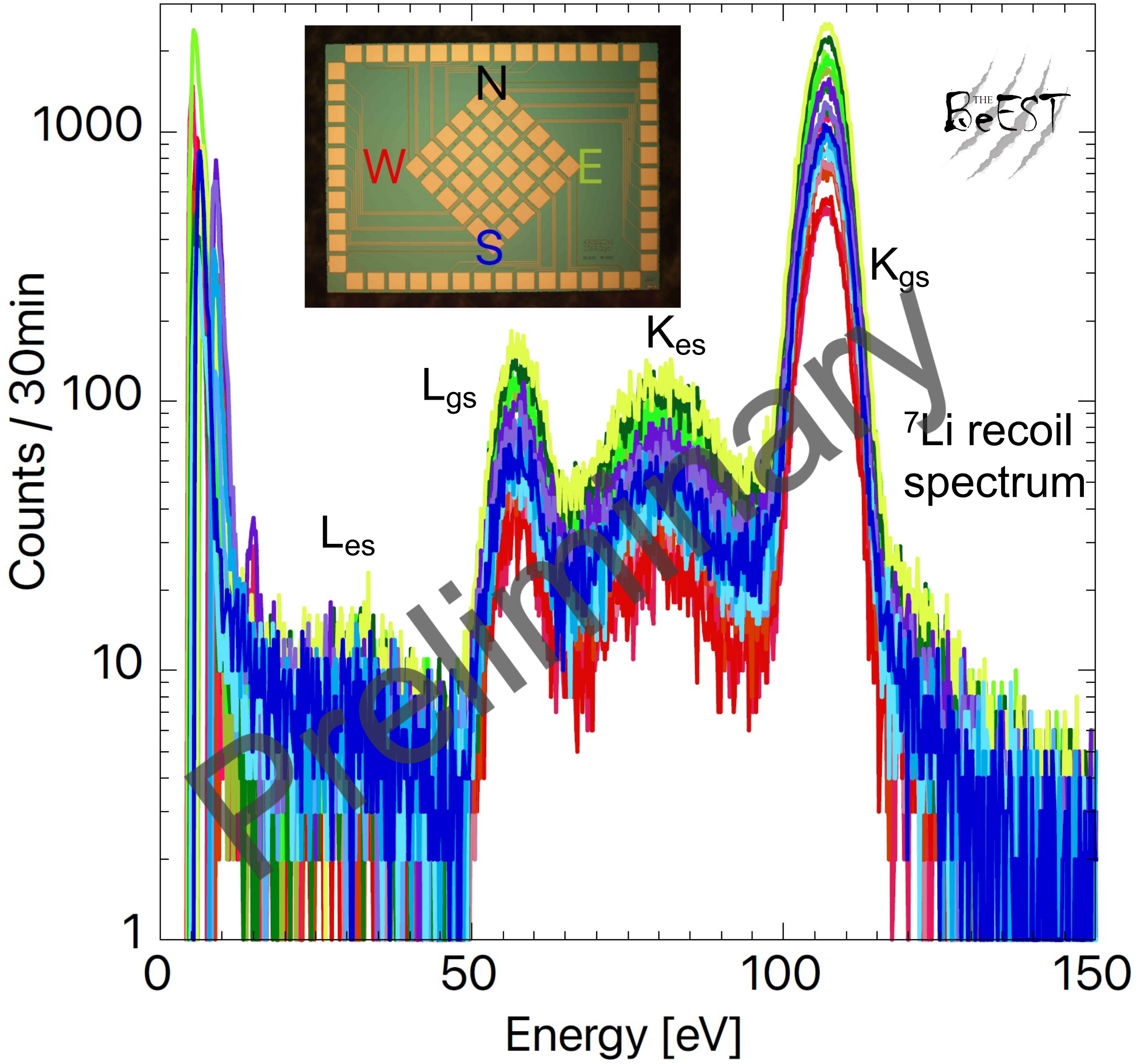


Recent Highlights – Phase III Data Run (Completed January 2023)

- 49 days of decay data from 20 pixels (~50 Bq/pixel)
  - Continuous “triggerless” DAQ (16 pixels)



- Offline processing of full signals now possible
- **90 TB of data taken!**
  - 6% of data have been released (rest is blinded)
  - Full waveform analysis and inter-pixel correlation
  - **100x statistics** over Phase-II data set
  - ➔ Improved systematics from improved spectral info

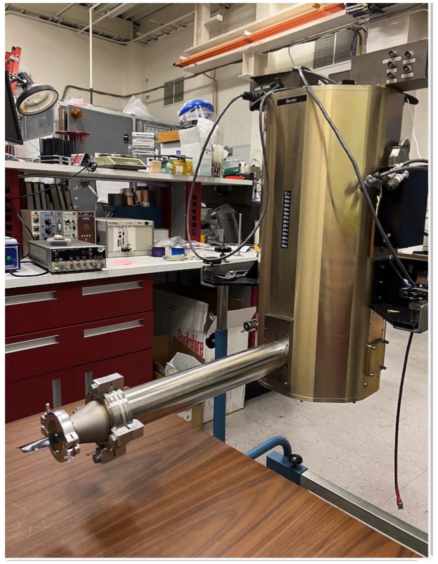


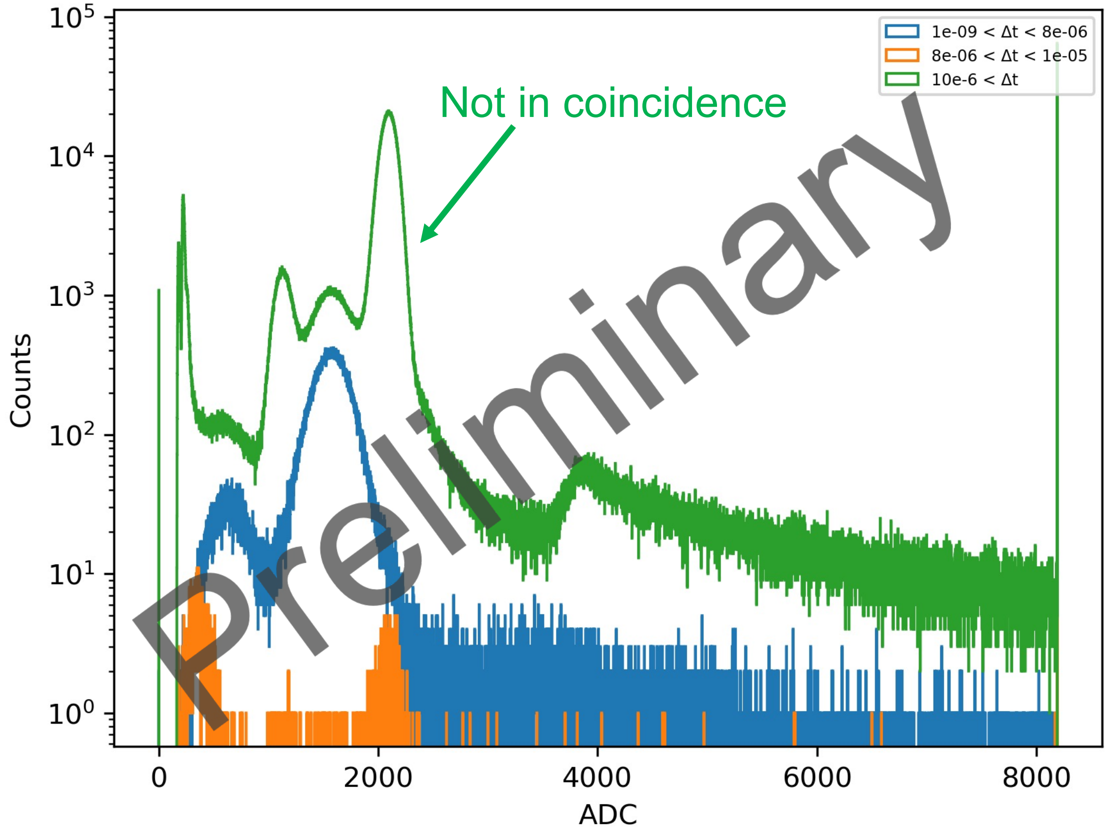
γ-Recoil Spectroscopy Run

- Used NaI detectors for **γ-coincidence** measurement (February 2023)
- gamma coincidence technique allows to separate just the excited state events

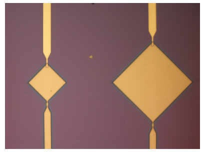
➔ Understand gamma-background & line-shape for excited state events

- Analysis ongoing



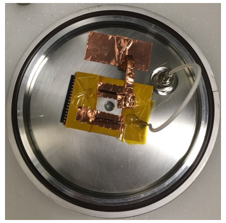


Phases of the BeEST experiment



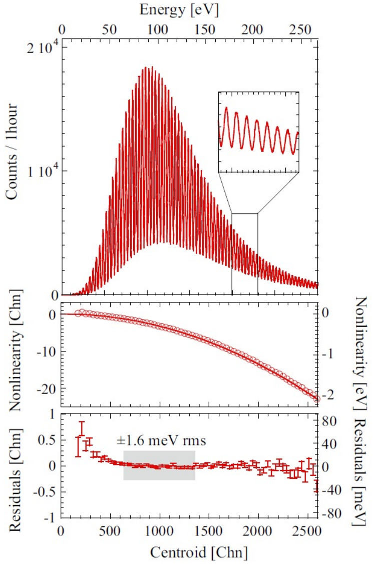
Phase-I
Proof of Concept

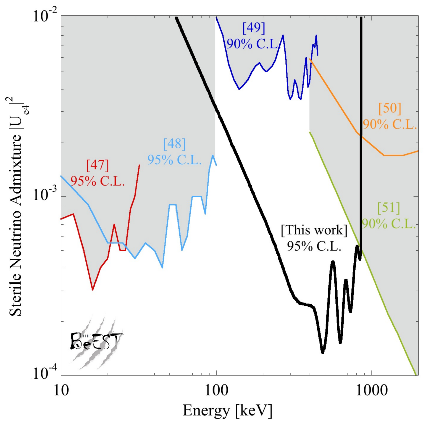
2018

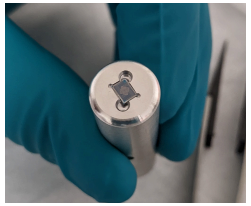


Phase-II
First Limits and Precision Device Characterization

2020

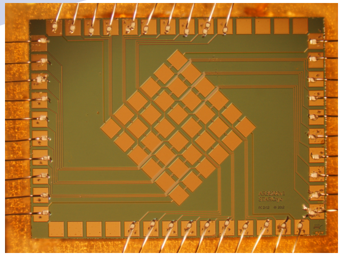


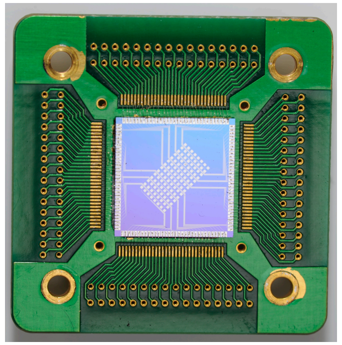




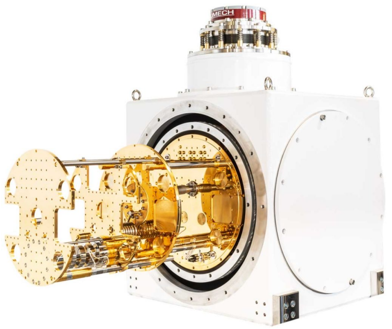
Phase-III
Scaling to 36- and 112-Pixel Arrays of Ta-Based STJs

2022



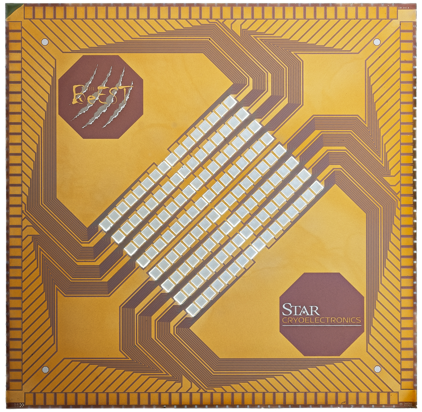


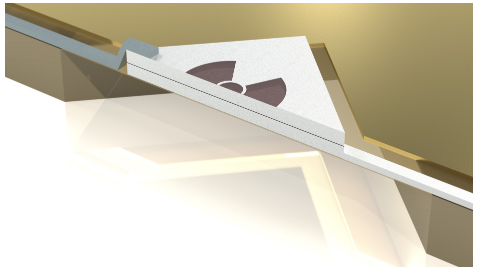
2024



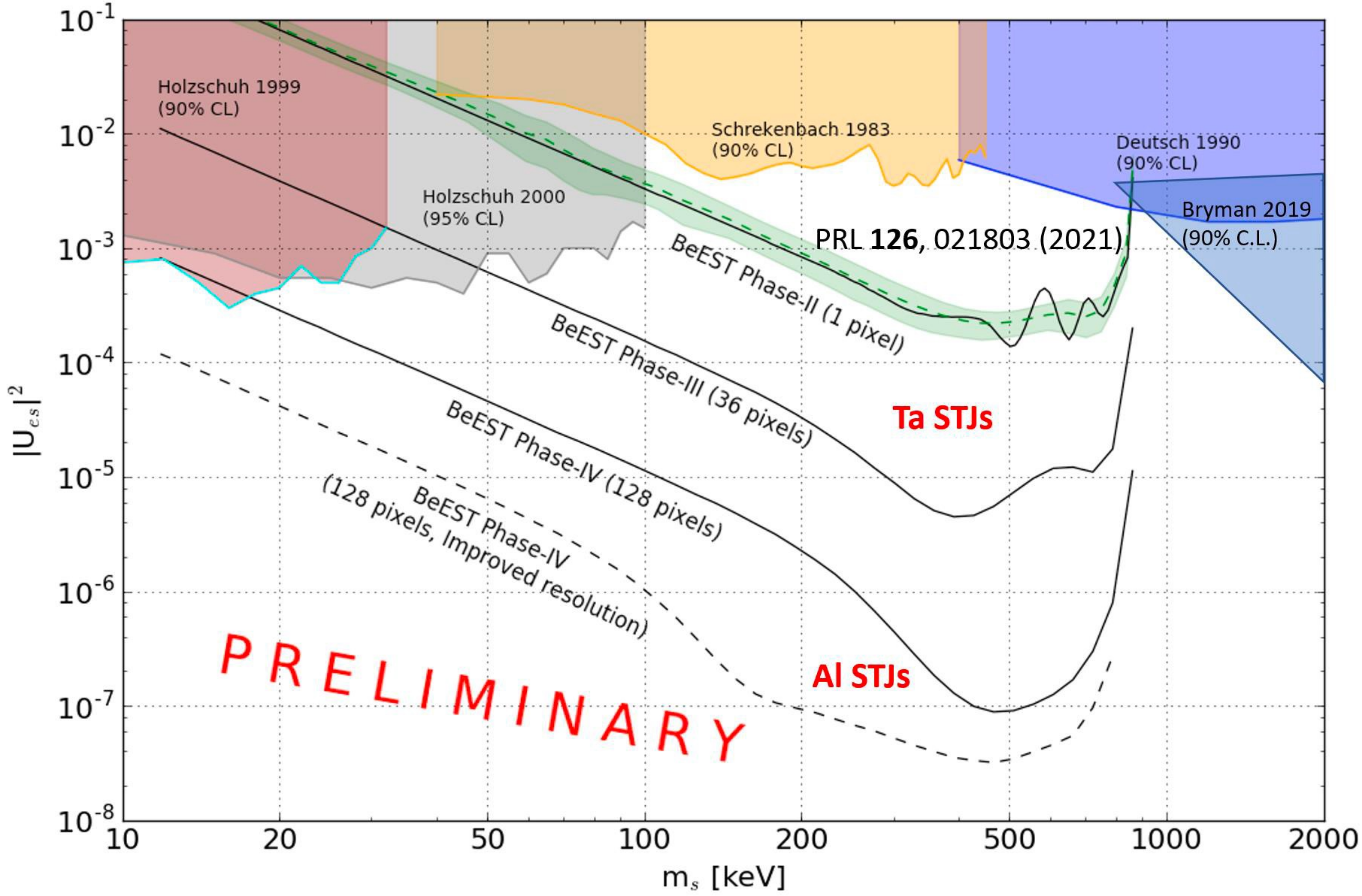
Phase-IV
Operation of 128-Pixel Arrays of Al-Based STJs in Dilution Refrigerator

2026





Projections for next phases of the BeEST



The BeEST - collaboration

Faculty/Staff
PDF
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Undergraduate

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Lawrence Livermore National Laboratory

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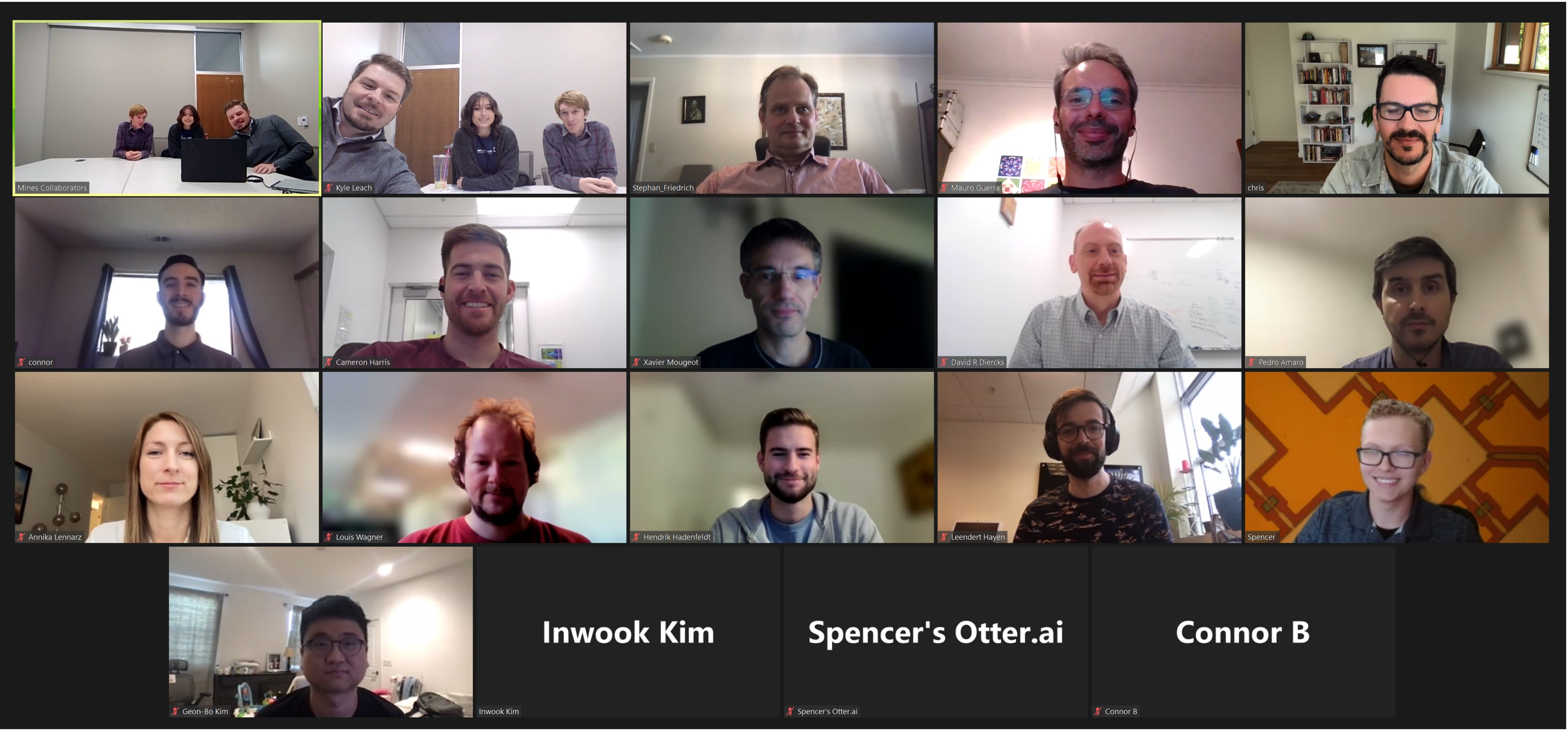
Summary

- The **Be**ryllium **E**lectron capture in **S**uperconducting **T**unnel junctions (BeEST) experiment is a new search for **sterile neutrinos** using precision measurements of the electron capture decay of ^{7}Be
- Implanting rare isotope beams into superconducting tunnel junctions is a powerful new tool to perform **sub-keV nuclear decay spectroscopy**
- Since 2018 the BeEST collaboration has performed precision measurements in the EC decay of ^{7}Be to search for beyond standard model physics
- High statistics data from 2022 Ta-array implantation! Terabytes of data need to be analyzed!
- 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

The BeEST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Thank you
Merci

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Discovery, accelerated

References

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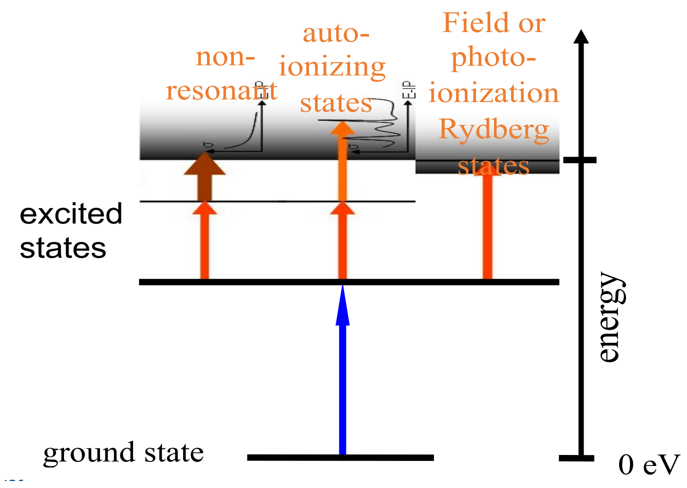
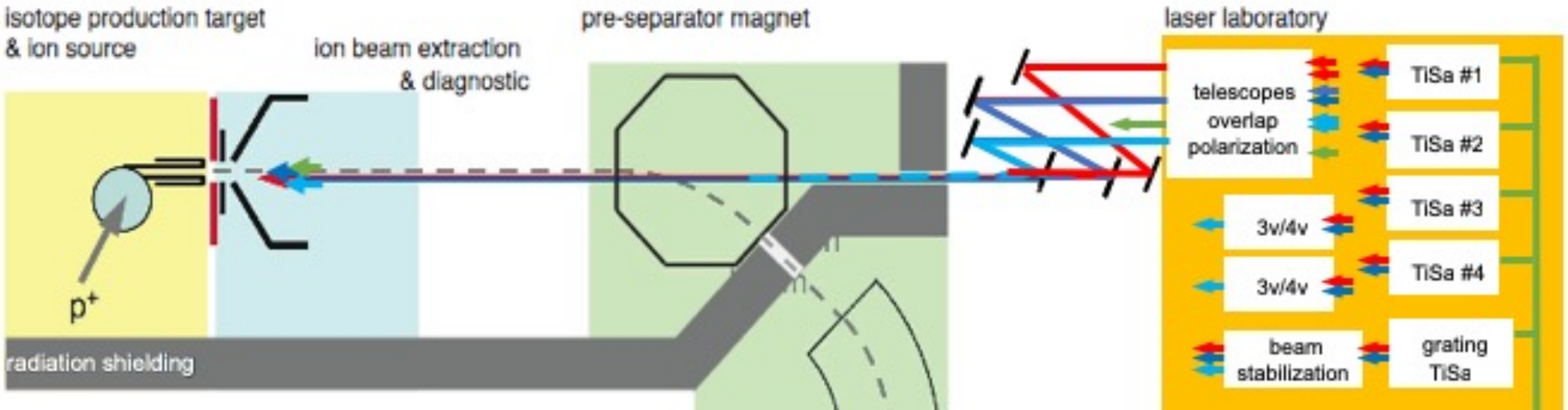
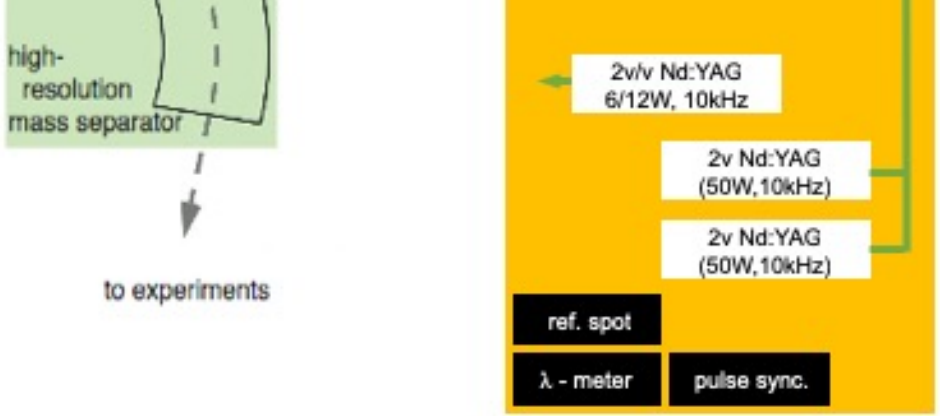
Back-up slides

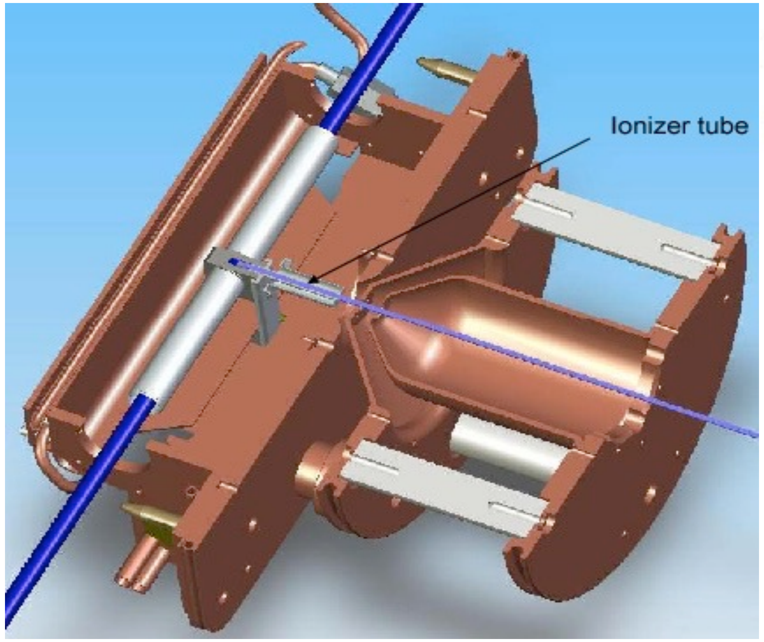
Beam production - TRILIS (TRIUMF Resonant Ionization Laser Ion Source)

- **Element selective** tool for RIB production
- Selective ionization process + high-resolution mass separator

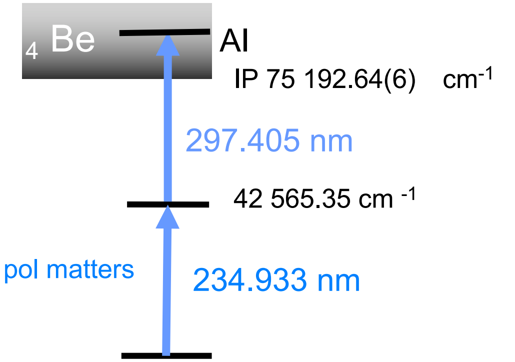
  ➔ suppresses neighbouring isobaric contaminations





- ^{7}Be significantly enhanced neutrals to 1^{+} (also small amount of surface ionization)
- **But**… large amounts of Li surface ionized

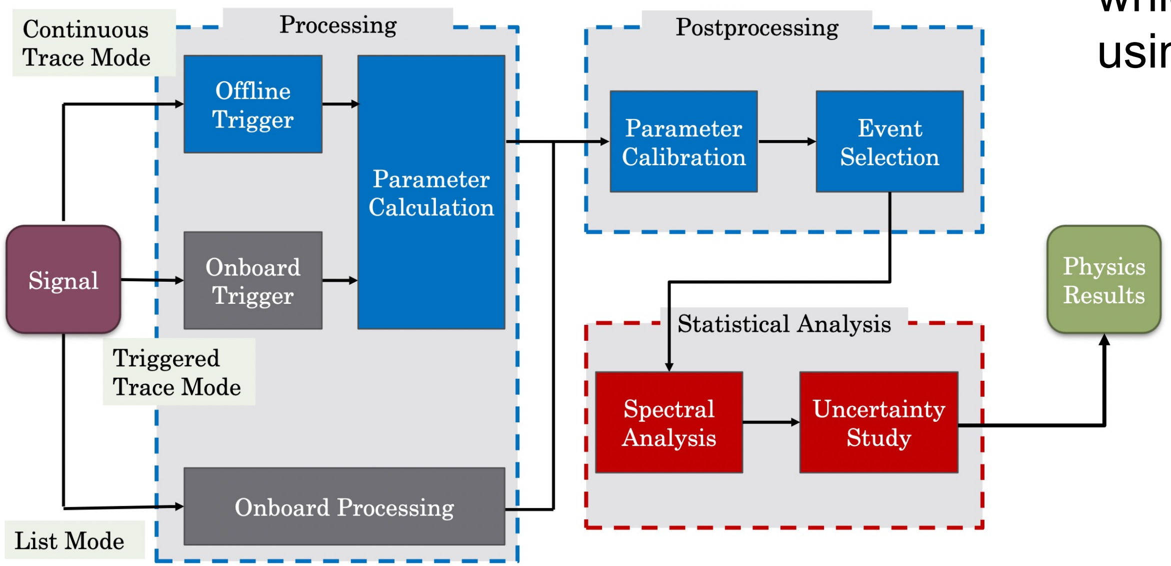


Details in: "polarization dependent resonance ionization of Be" for "Spectrochimica Acta B" R. Li et al. (2020)

Slide courtesy of J. Lassen

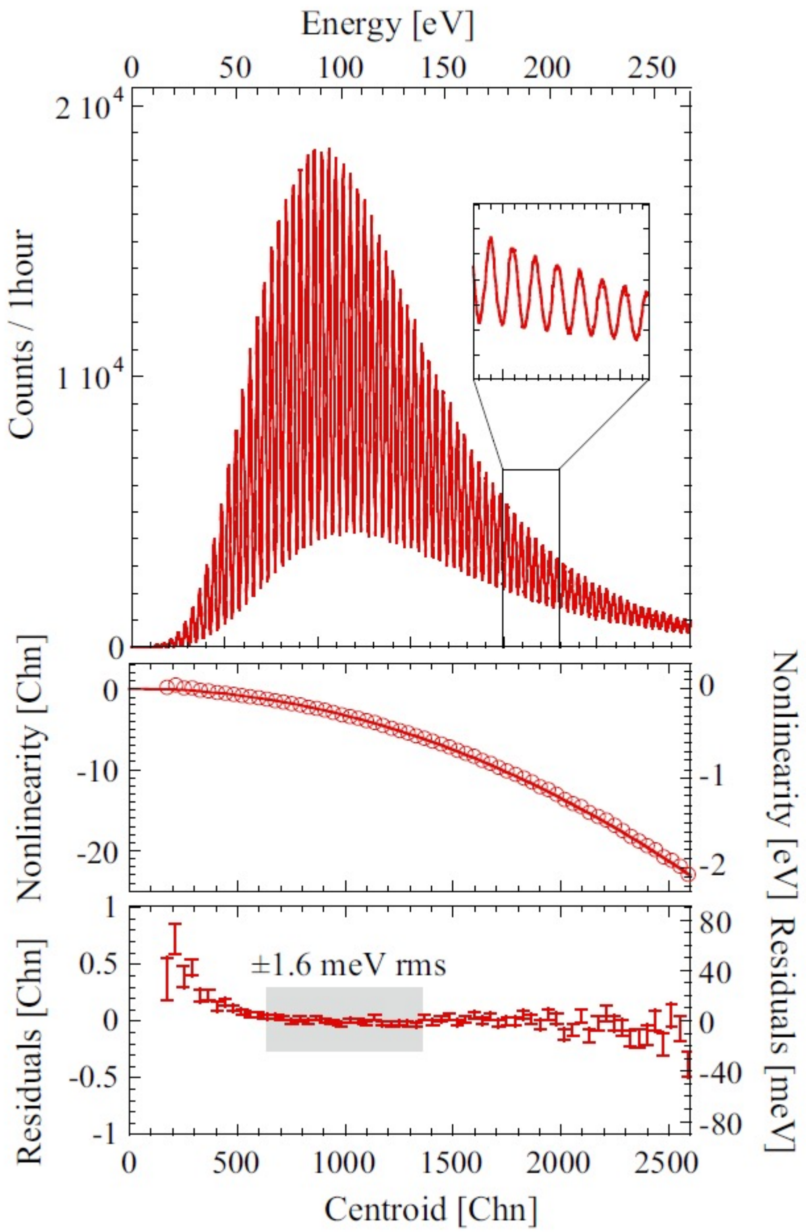
Data processing

- Past limit-setting results from the experiment used a list-mode ADC with a hardware trapezoidal filter to trigger the pulses from the STJ array.
- To improve our signal analysis capabilities, we have constructed a continuously sampling data acquisition system which allows for advanced offline characterization of events using pulse shape and timing information.



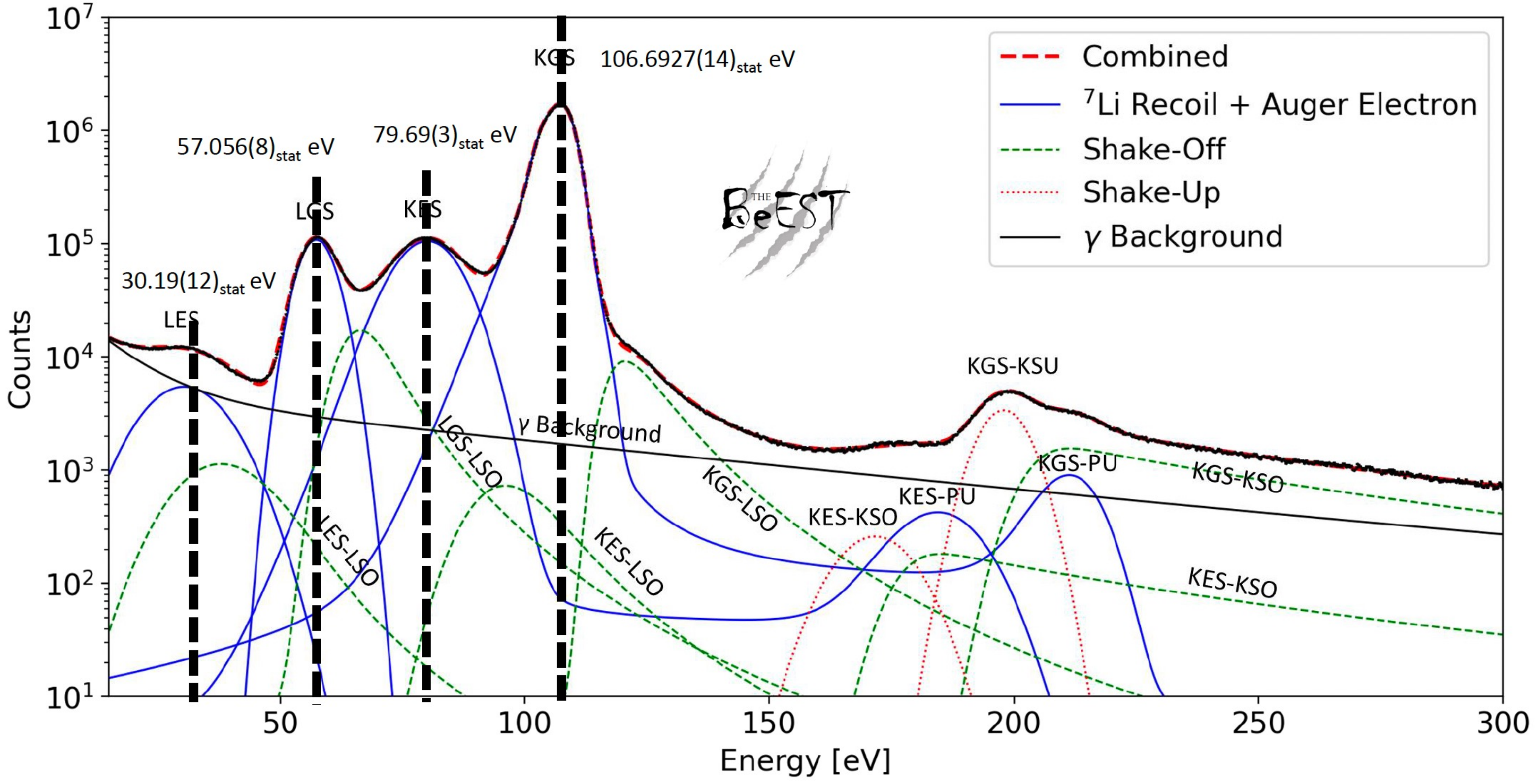
- **New:** Continuous "triggerless" I PXIe DAQ (16 pixels)
- Old system: List-mode XIA system (4 pixels)
  - Signal readout with specialised current-sensitive preamp from XIA LLC
  - Processed with analog spec-amp (Ortec 627, shaping time 10 μs)
  - Captured with 2-channel MCA (Ortec Aspec927)
- 1 Ortec MCA channel for monitoring

Energy calibration



- For energy calibration, the STJs were simultaneously exposed to 3.49965(15) eV photons from a pulsed Nd:YVO4 laser
- Triggered at a rate of 100 Hz
- The laser intensity was adjusted such that multi-photon absorption provided a comb of peaks over the energy range from 20-120 eV.
- The calibration spectrum was recorded in coincidence with the laser trigger and the 7Li recoil spectrum in anti-coincidence.

7Li recoil spectrum



Be-7 EC spectrum with Heavy Sterile Neutrinos

$$T_D = \frac{Q_{EC}^2 - m_\nu^2 c^4}{2(Q_{EC} + m_D c^2)}$$

- Neutrino mass and Li-7 recoil energy

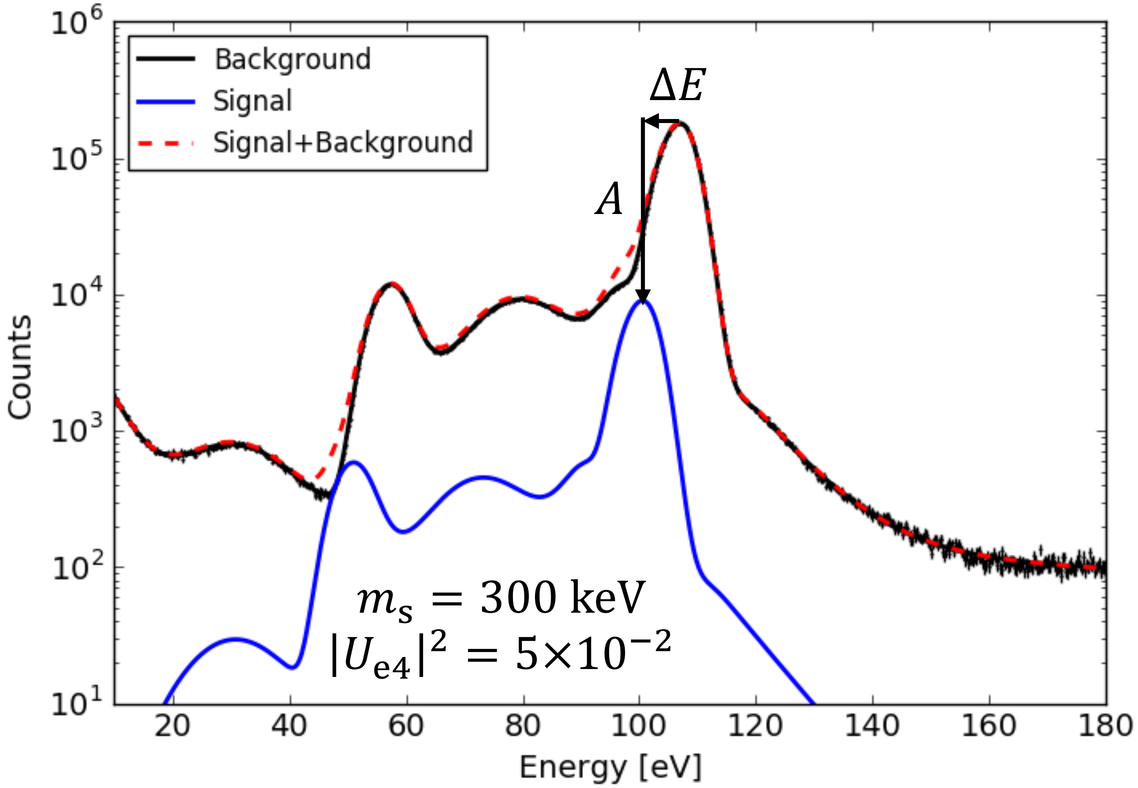
$$\boldsymbol{E_r} = (Q^2 - \boldsymbol{m_4^2})/2(Q + M_{7Li})$$

- EC probabilities

$$\lambda \propto \underbrace{(1 - |\boldsymbol{U_{e4}}|^2)Q^2}_{\text{Active neutrinos}} + \underbrace{|\boldsymbol{U_{e4}}|^2 Q\sqrt{Q^2 - m_4^2}}_{\text{Sterile neutrino addition}}$$

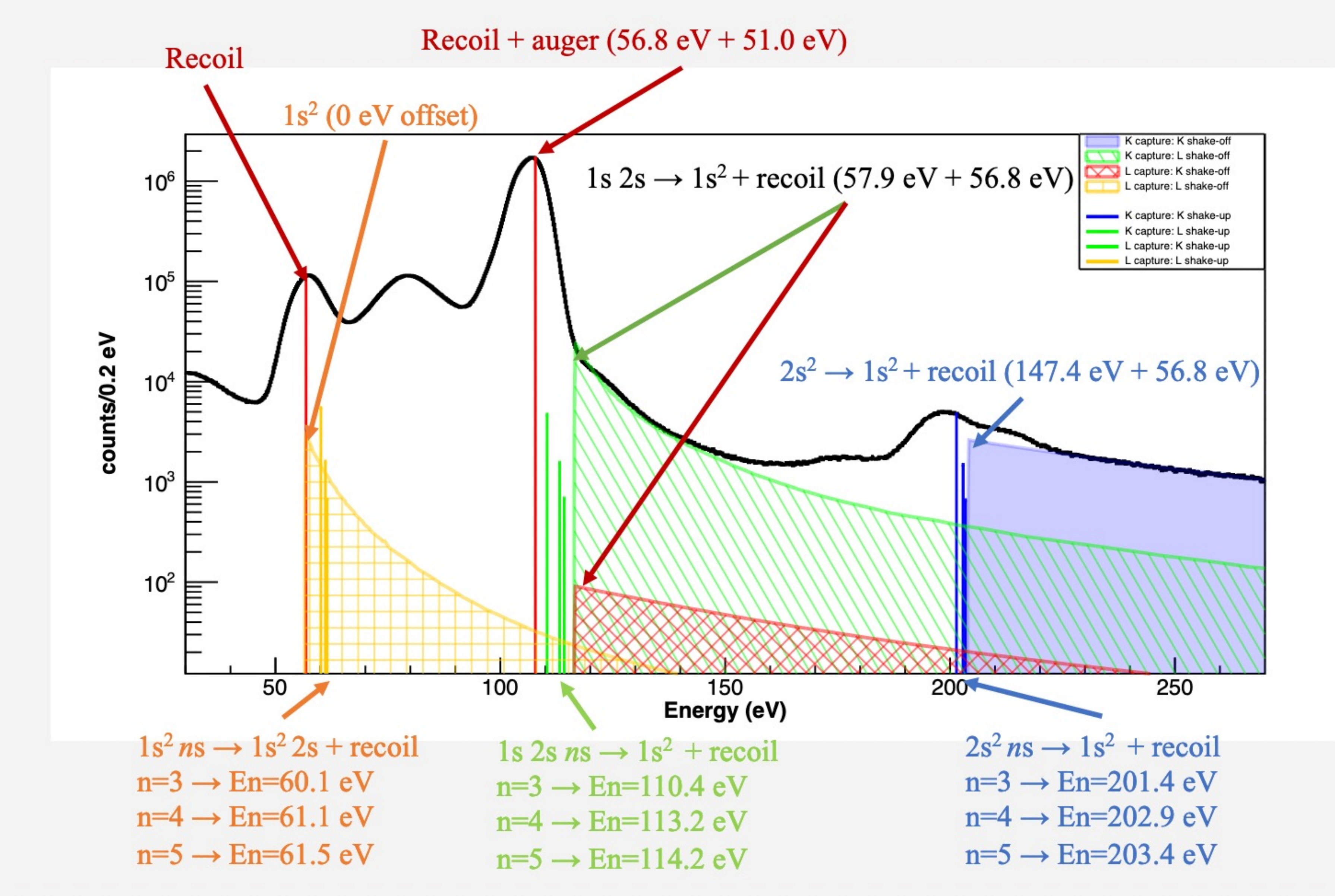
- Spectral shape

$$f(E) = \underbrace{[1 - A(U_{e4})]\, f_0(E)}_{\text{Active neutrinos}} + \underbrace{A(U_{e4})\, f_0(E - \Delta E)}_{\text{Sterile neutrino addition}}$$



Sterile neutrino will add a similar spectrum with:
1) Shifted recoil energy $\Delta E(m_4)$
2) Reduced amplitude ($A \propto |U_{e4}|^2$)

Atomic effects



The BeEST in context