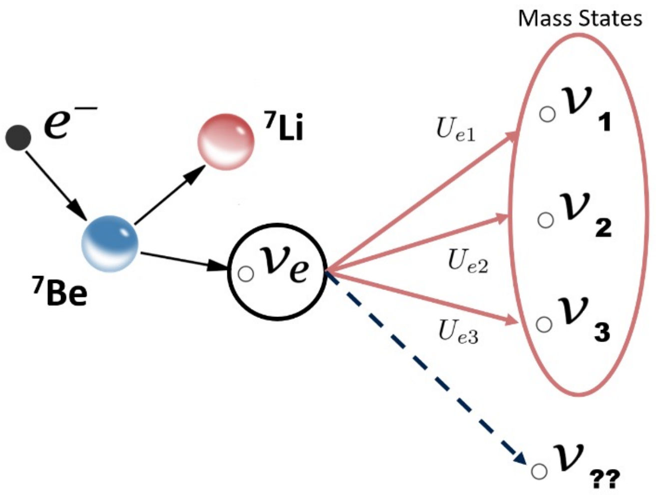
TRIUMF

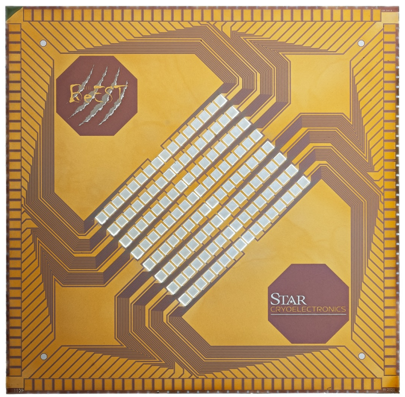
The BeEST experiment

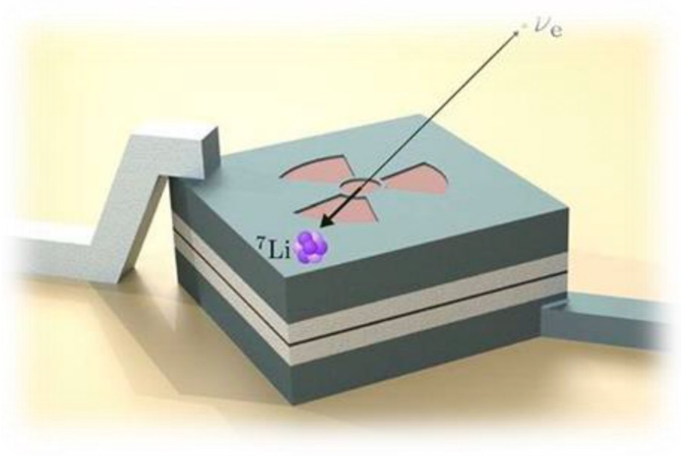
Annika Lennarz

TRIUMF Science Week 2023

August 3rd, 2023



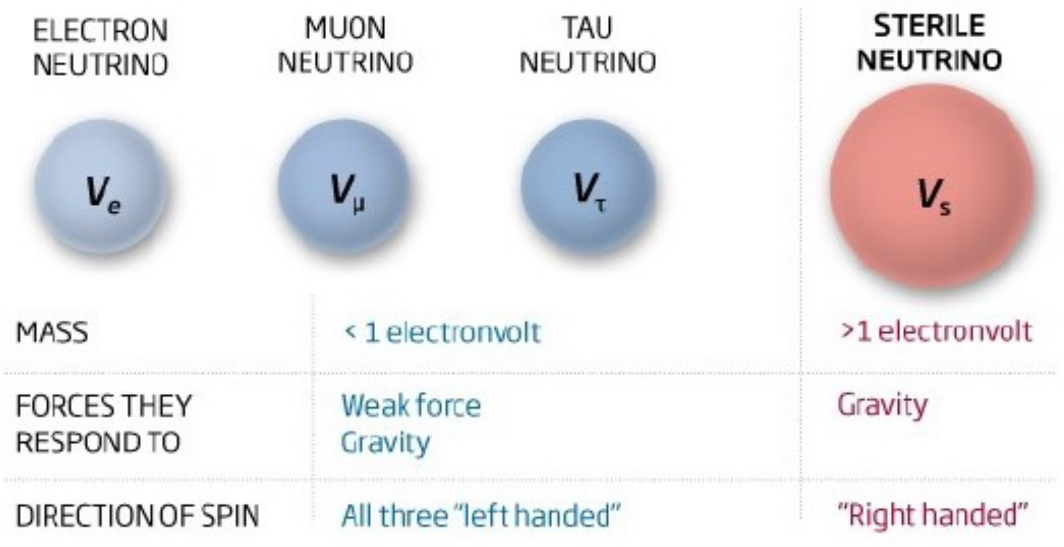




Discovery, accelerated

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 **<u>model-independent</u>** and cover a large area of the allowed parameter space.

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

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 elec**... (STJ) radiati...
- Based on m... spectrum fol...

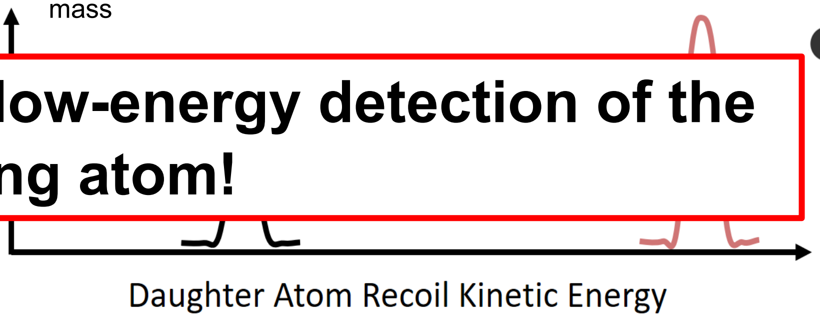
Pure two-... of the re...

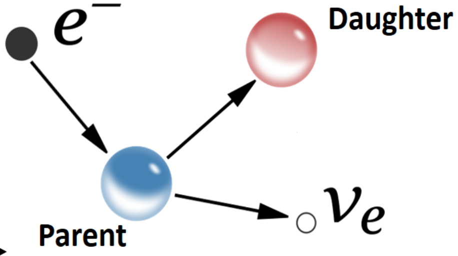
- ^{7}Be is ideal
  - pure two-body final state
  - Relatively lar...
  - Relatively hig...
  - Simple atomi...

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

→*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!





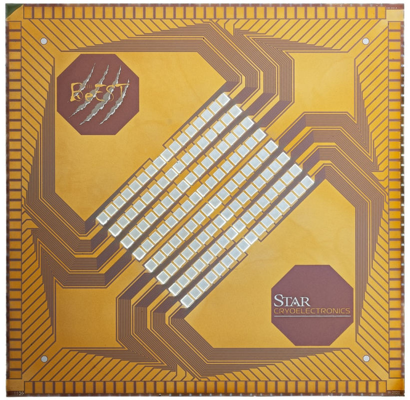
Superconducting Tunnel Junctions (STJ)

- 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)

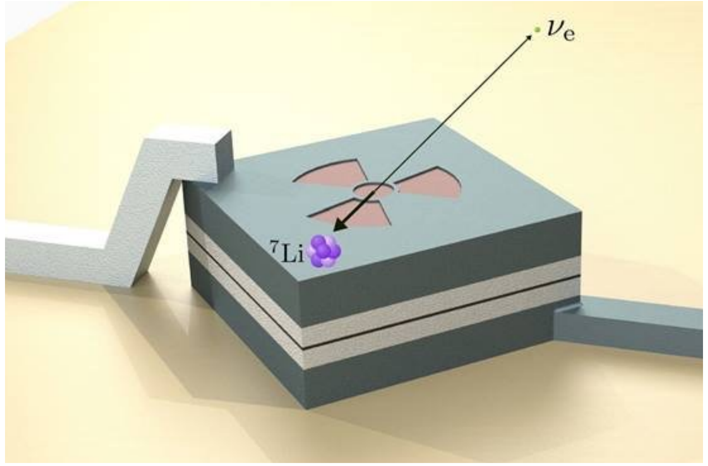
- Short access charge lifetime ~μs ➔ fast count rates

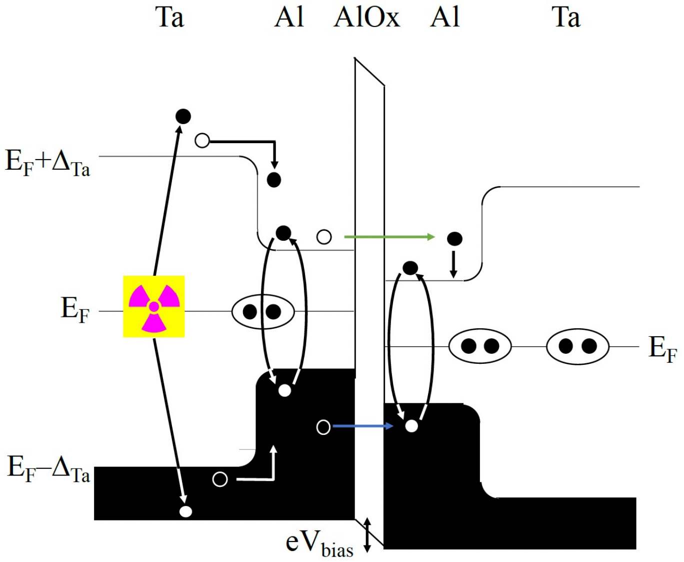
  ➔ High rate (10^4 counts /s /pixel)

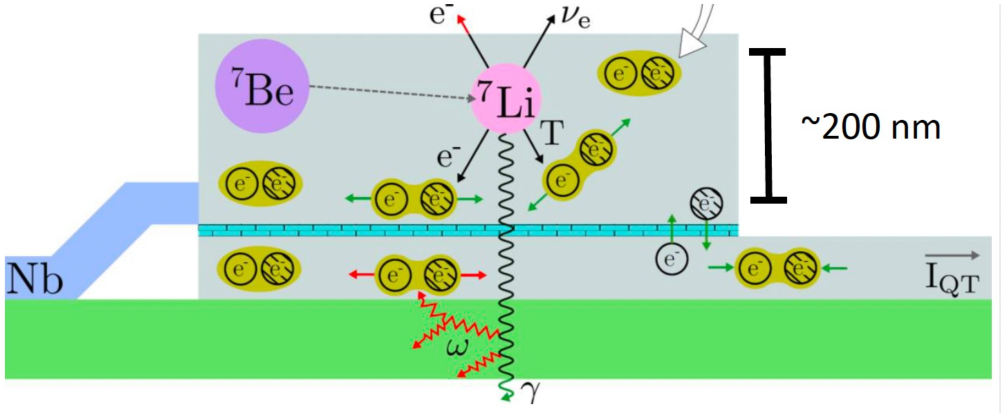


STAR CRYOELECTRONICS

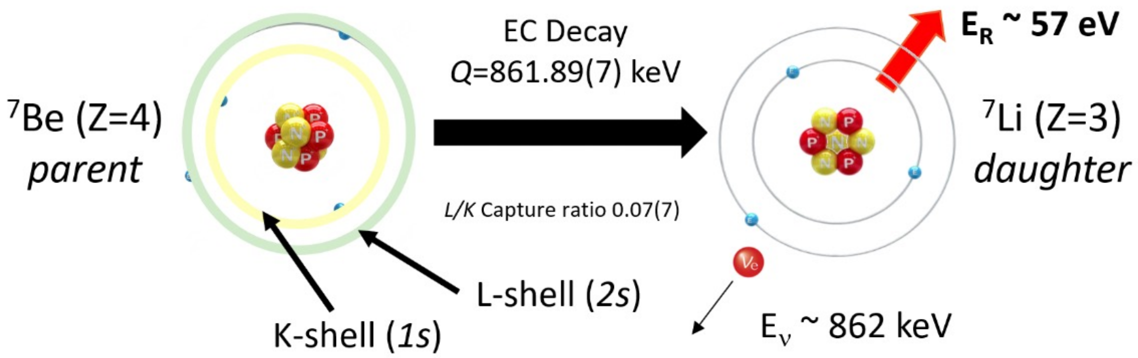
Development on Ta, Al, and Nb-based STJ Sensor Arrays

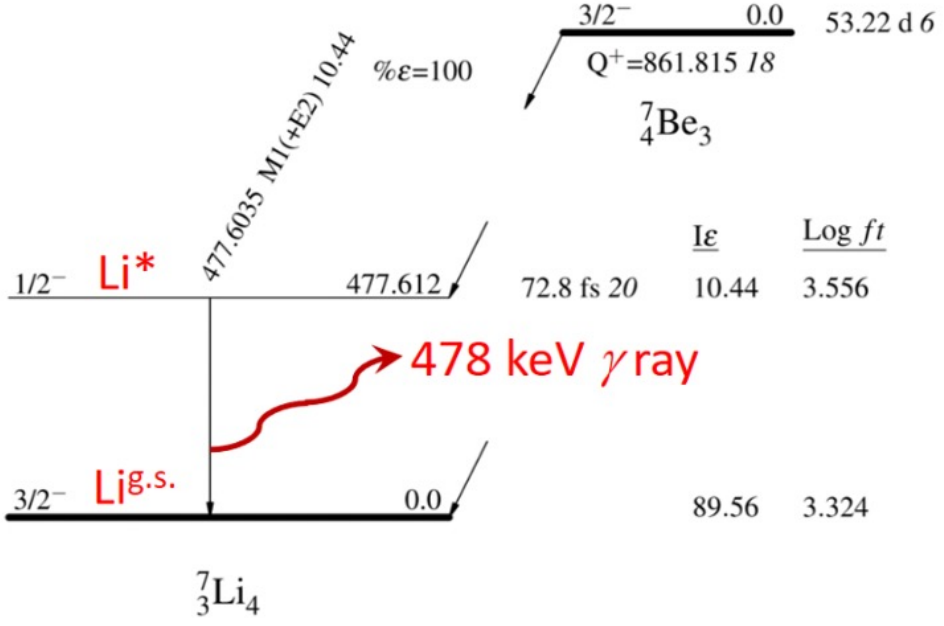






Nuclear Recoil Spectroscopy with ^{7}Be





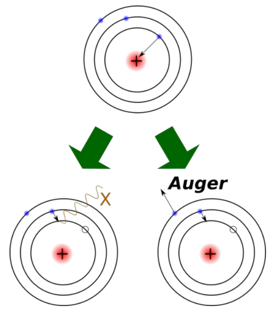
2 Atomic Capture Peaks

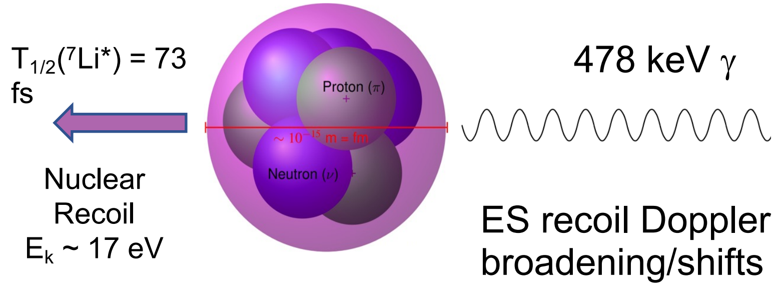
- K-shell (55 eV Auger emission)
- L-shell (no Auger emission)

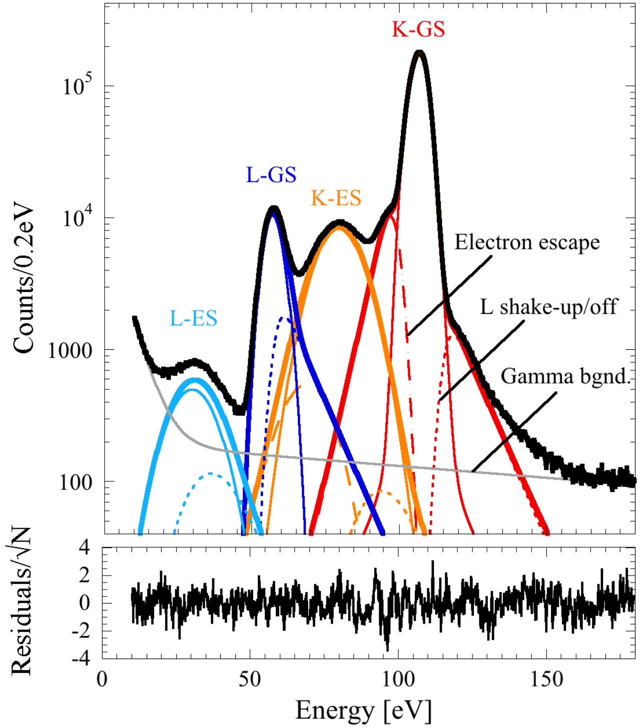
\+

2 Nuclear Decay Branches

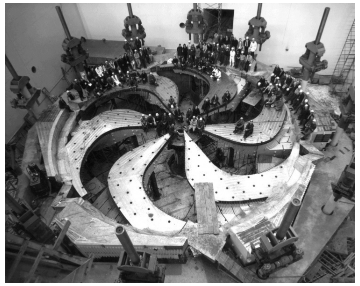
- Ground state
- Excited state





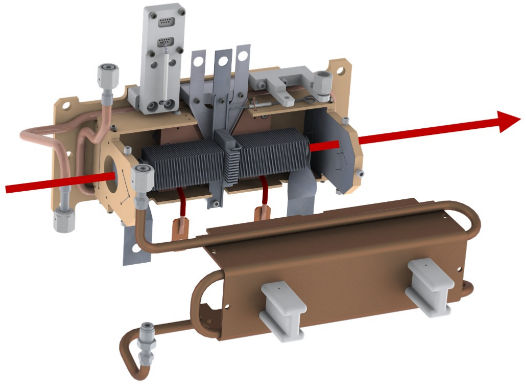


The BeEST - Experimental Concept



480 MeV p+ beam produced in cyclotron

UC_x production target

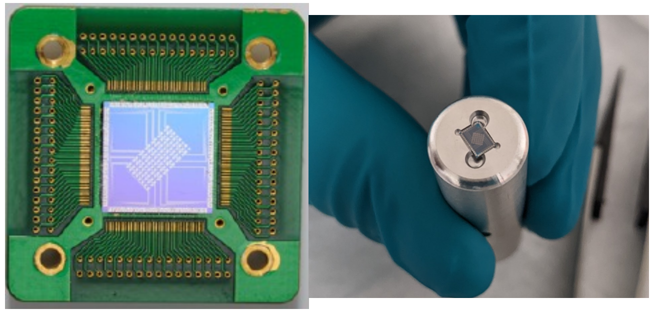


Laser ionization

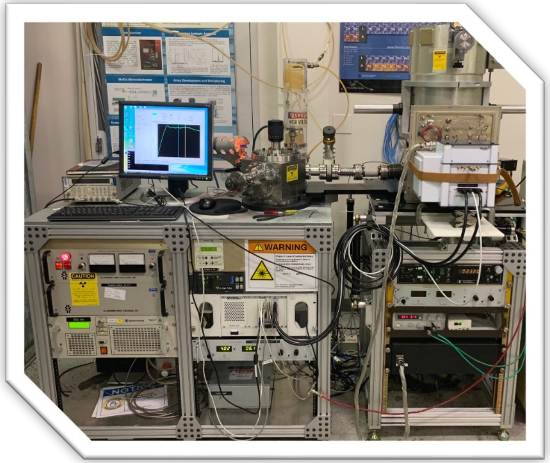
^{7}Be ($T_{1/2}$ = 53 d)

20 - 30 kV acceleration

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

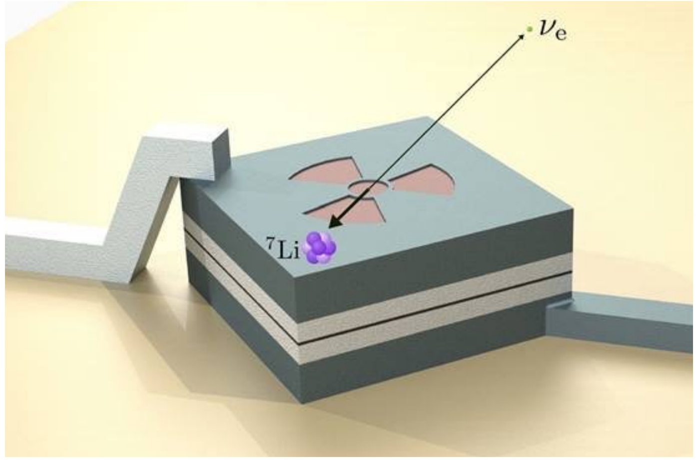


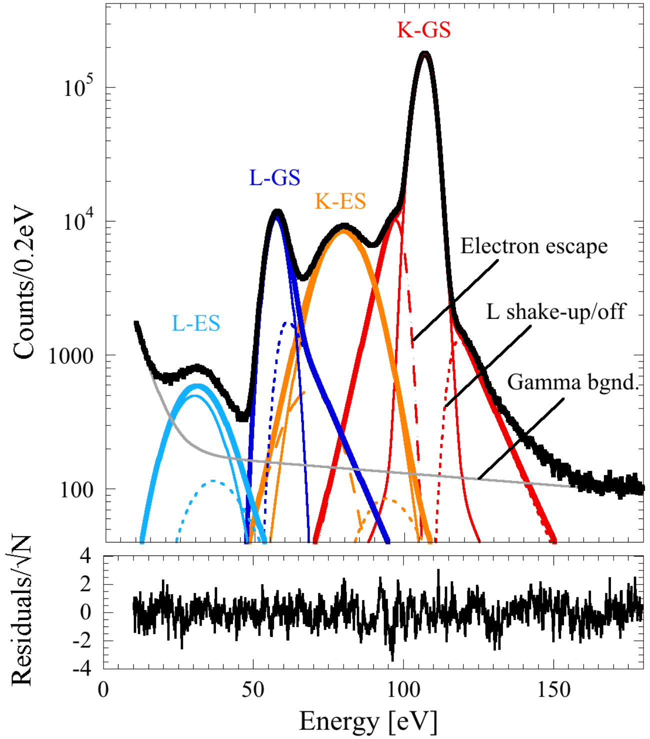
Cool to < 100mk in an Adiabatic Demagnetization Refrigerator.



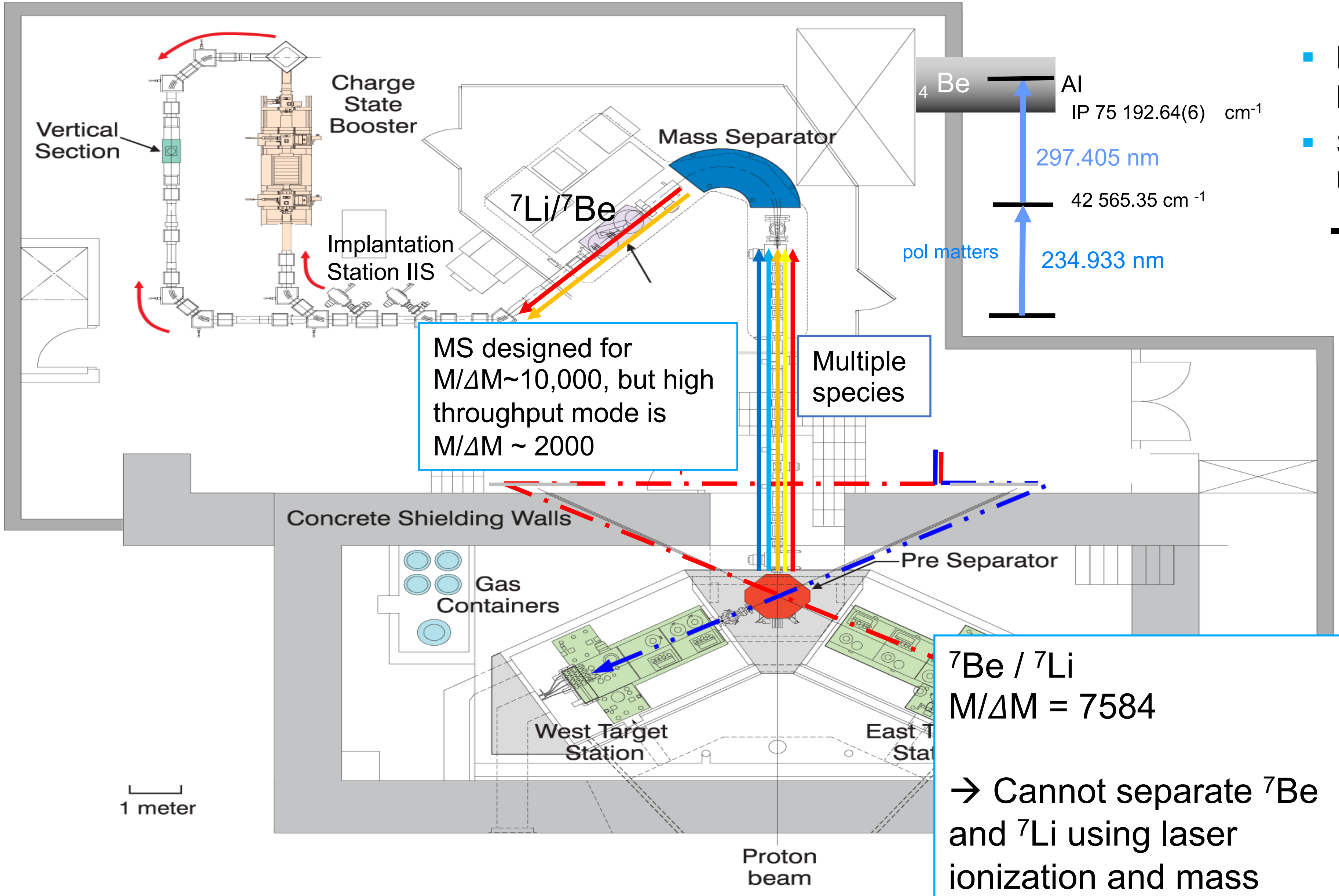
Lawrence Livermore National Laboratory

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





Beam production – ISAC target stations & mass separator



MS designed for M/ΔM~10,000, but high throughput mode is M/ΔM ~ 2000

^{7}Be / ^{7}Li
M/ΔM = 7584

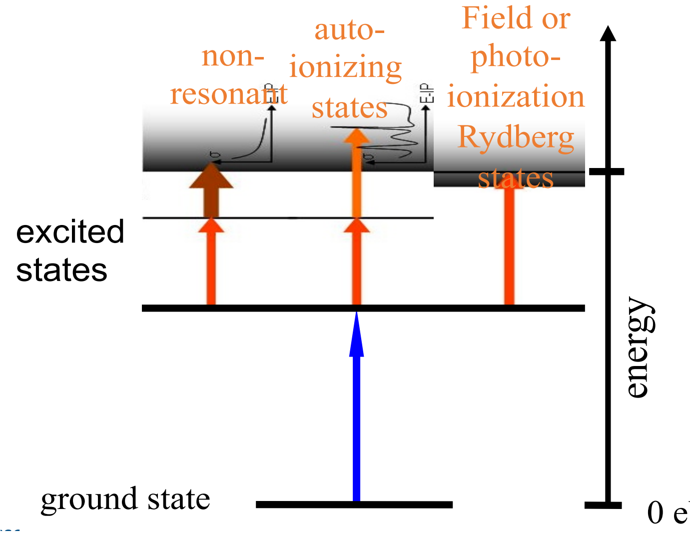
→ Cannot separate ^{7}Be and ^{7}Li using laser ionization and mass separator alone

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



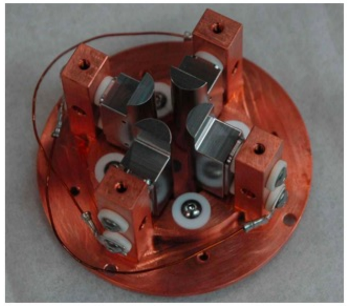
- ^{7}Be significantly enhanced neutrals to 1^{+} (also small amount of surface ionization)
- **But**… large amounts of Li surface ionized

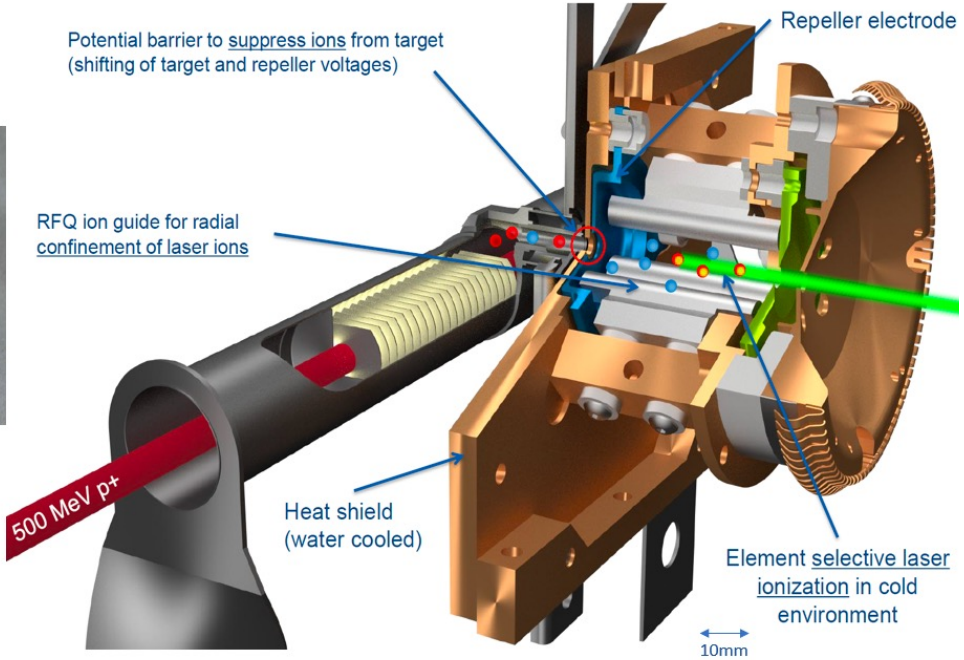
IG-LIS: Ion Guide Laser Ion Source

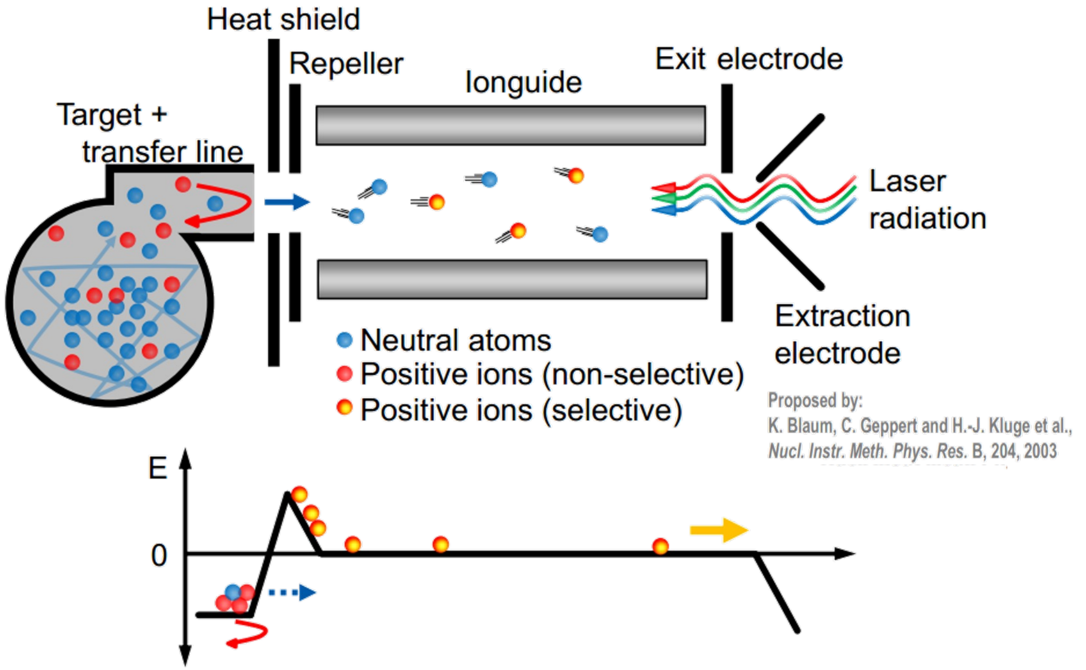
- The **ion guide laser ion source** (IG-LIS) decouples the hot isotope production region from the laser ionization volume
- Isobar suppression of up to 10^6 has been achieved in some cases

- 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!

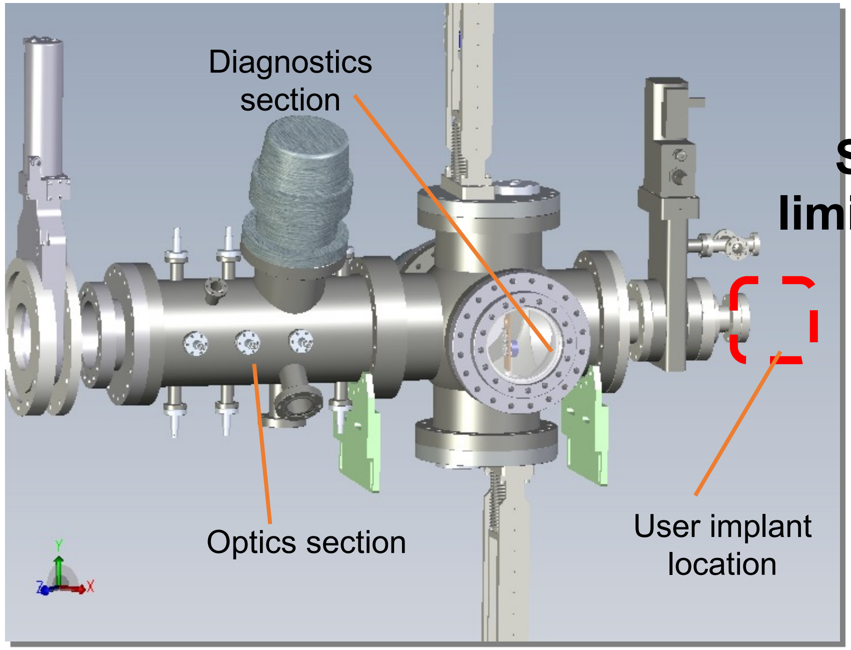






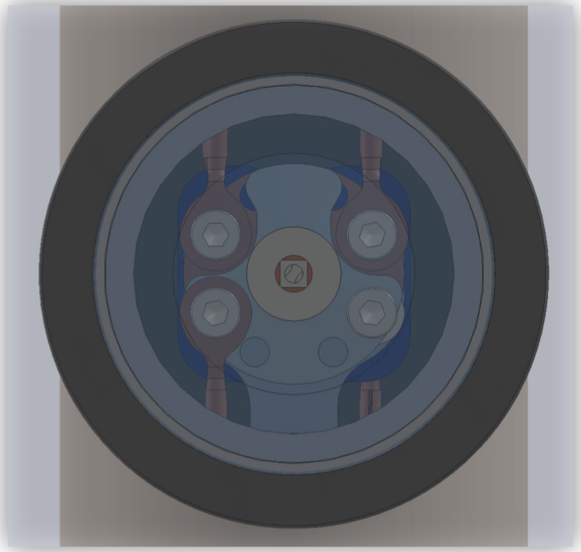
"An ion guide laser ion source for isobar-suppressed rare isotope beams"
Rev. Sci. Instrum. 85, 033309 (2014) http://dx.doi.org/10.1063/1.4868496

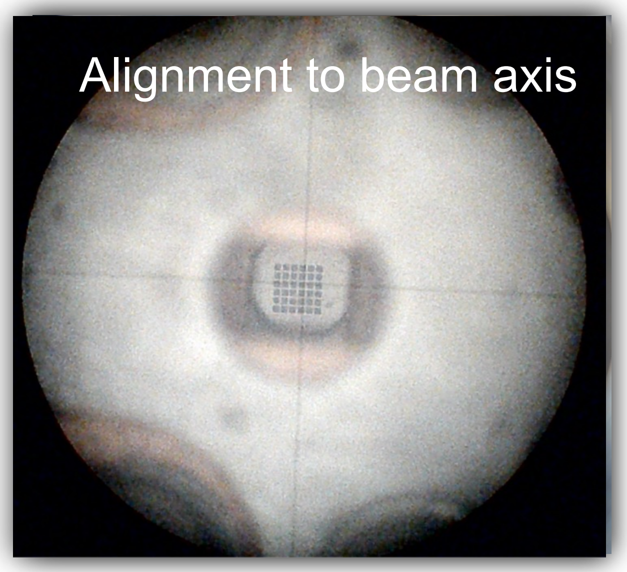
^{7}Be implantation at TRIUMF



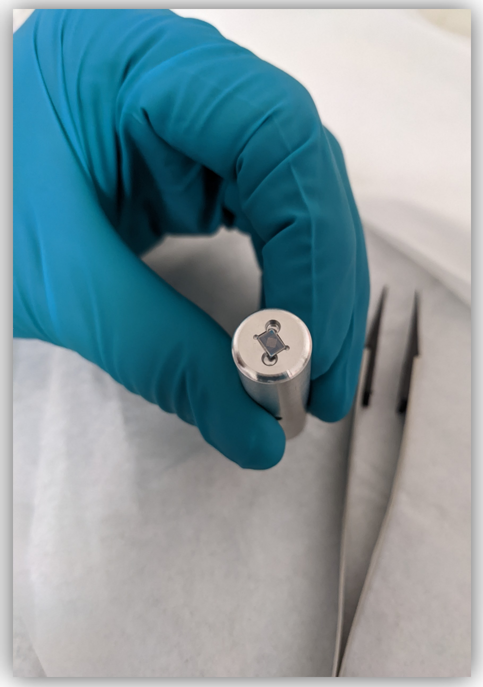
Space limitations!

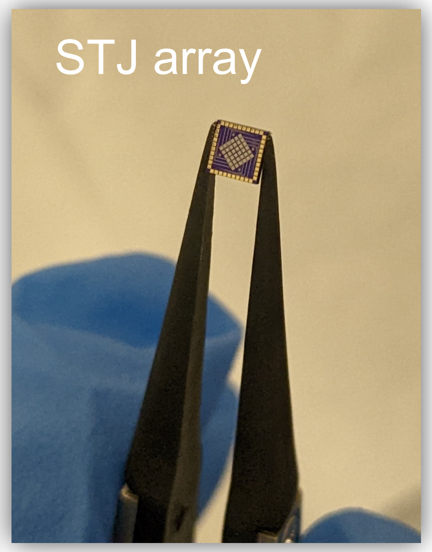
Alignment stage





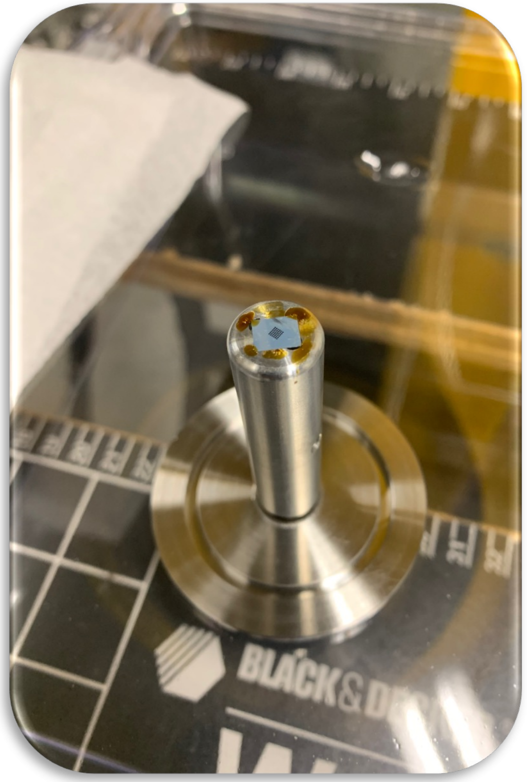
- Implantation station in exclusion area
- beam spot size ~3mm FWHM
- Bench alignment prior to implantation
- Tuning + monitoring via 7 signal readouts (slits, collimators, sample)
  ➔ Monitor implantation
- Sample removal & preparation under controlled conditions
- Plans for multi-sample irradiation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





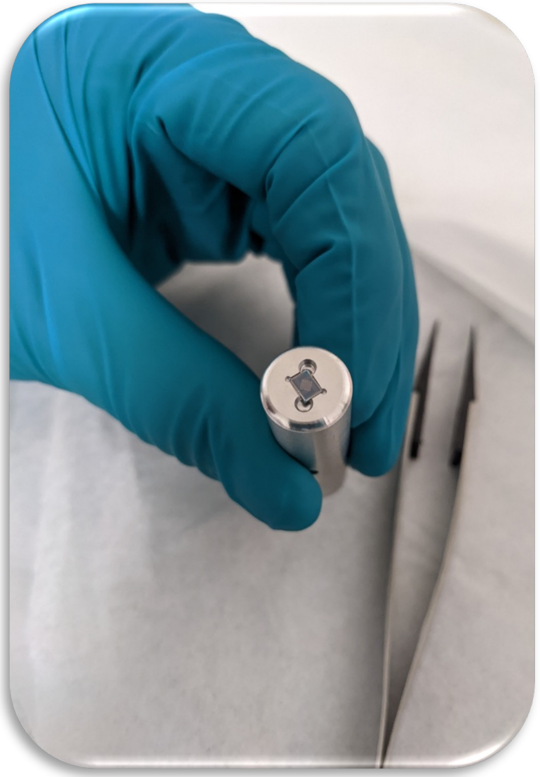
Sample retrieval & preparation (September 2022)

DRAGON postdocs Sriteja (Teja) Upadhyayula & Louis Wagner preparing beamline opening



STJ array with Si collimator (after implantation) mounted on holder on pin connector

Holder + STJ array in ethanol bath



STJ array without Si collimator (removal after ethanol rinse with carbon-tip tweezers)

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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[3] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[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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[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
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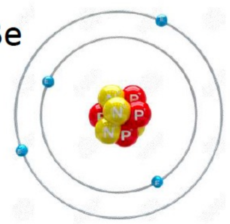
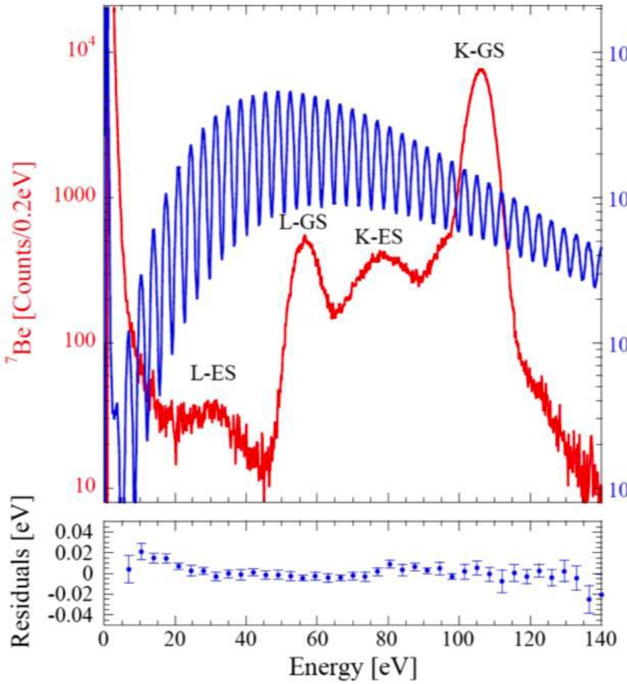
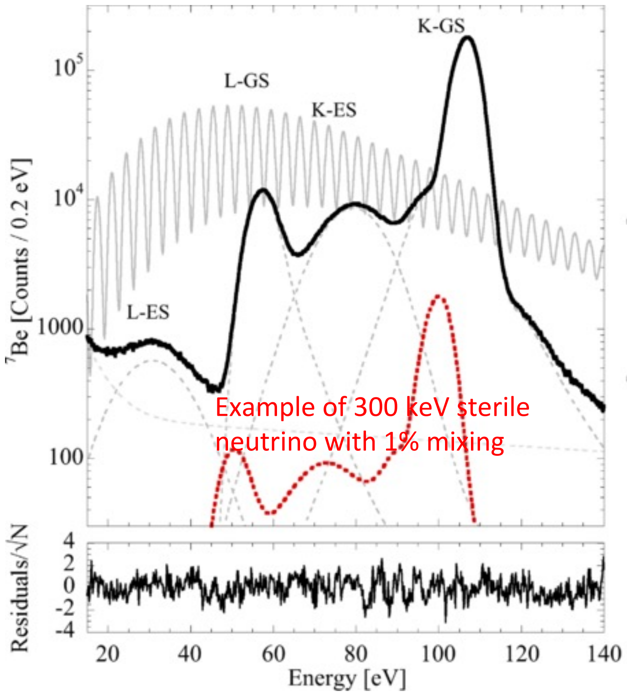
[6] Université Paris-Saclay, CEA, List, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120, Palaiseau, France
[7] Department of Physics, Stanford University, Stanford, CA 94305, USA
[8] XIA LLC, Hayward, CA 94544, USA
(Dated: October 20, 2020)

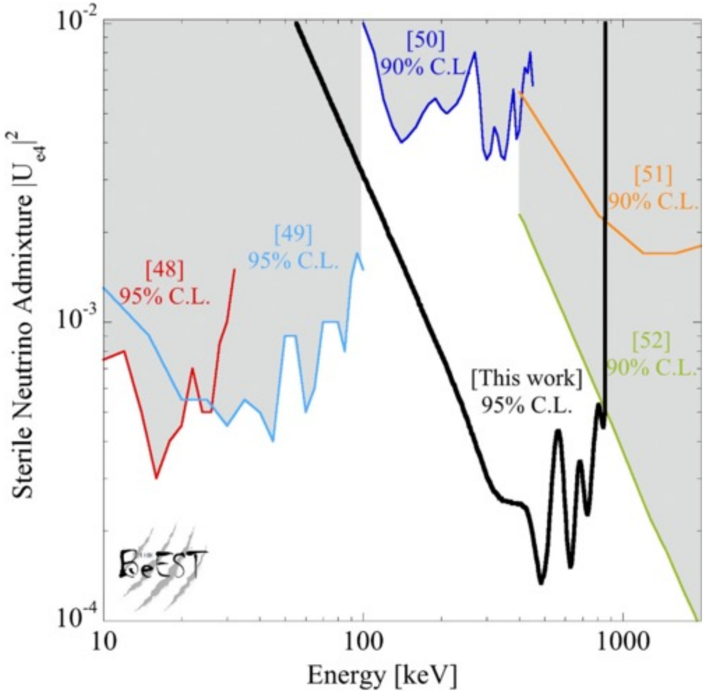
^{7}Be



L/K = 0.070(7)



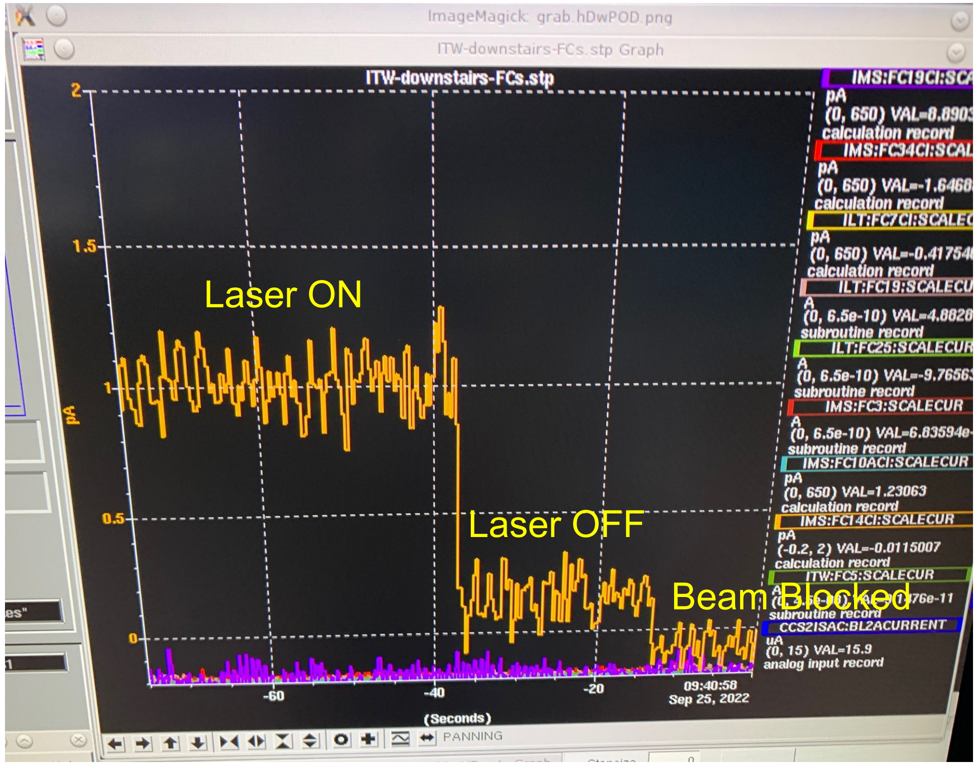




Phase III data: Implantation 2022 – First run with significant ^{7}Li suppression!

Date	25th Sep, 2022	22nd Nov, 2022
Target + Source	UC + IG-LIS	Graphite + RILIS
Mode (Trans/Supp)	Suppression	N/A
^{7}Be intensity (pps)	6.2×10^6 (x44 reduction c.f. UC + RILIS)	Not measurable. No laser on/off difference.
^{7}Li intensity (pps)	8.1×10^5 (x4,000 Li suppression)	6×10^{11}
Li/Be	**1:7** ☺	300:1 ☹
Implant Time	~24 hrs	~10 min.
Implant energy	Ta (30 kV)	Nb (20 kV)

- Plan was to at least run again in transmission mode with better beam alignment and an “okay” Li:Be ratio

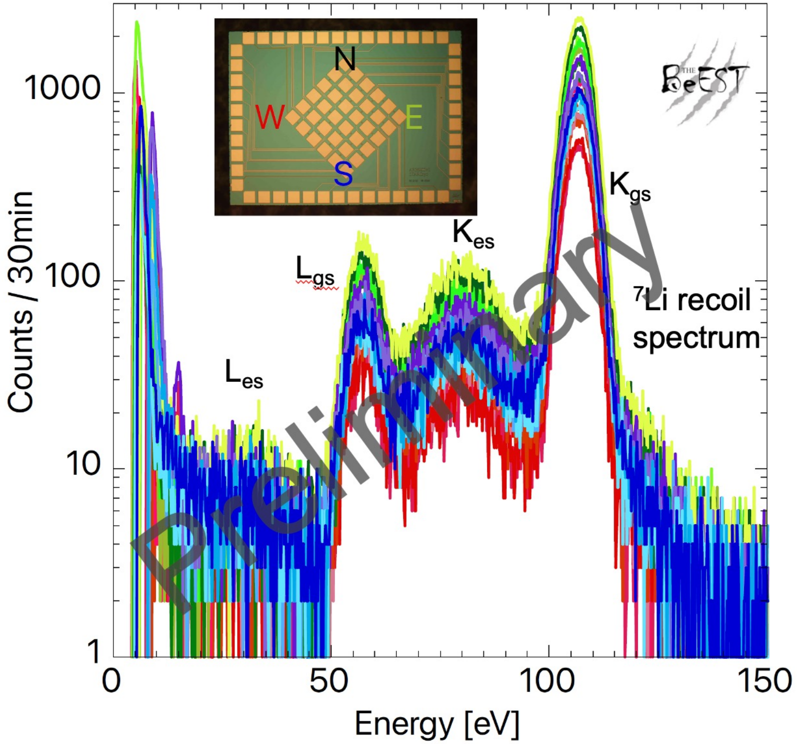


- Successful suppression mode was attributed to a better RF-power transmission line into this target station, as this was the first time IG-LIS was used here.
- RF cabling and generator were exchanged.
- However, suppression is still difficult compared to heavier masses. (Jens Lassen – Laser Applications Group)

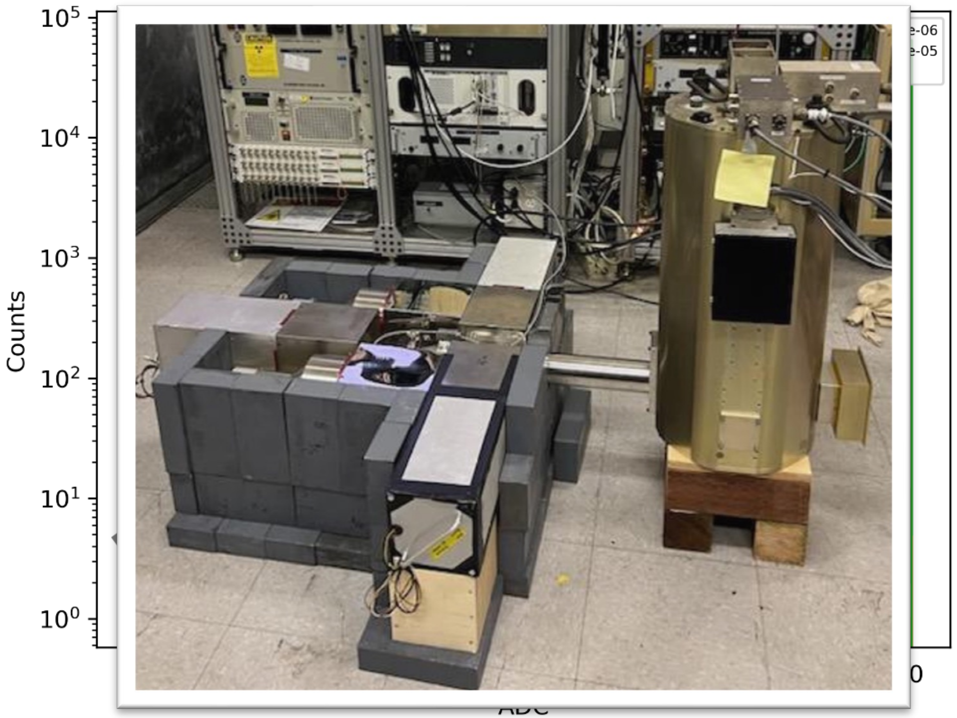
Recent Highlights – Phase III Data Run (Completed January 2023)

- 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

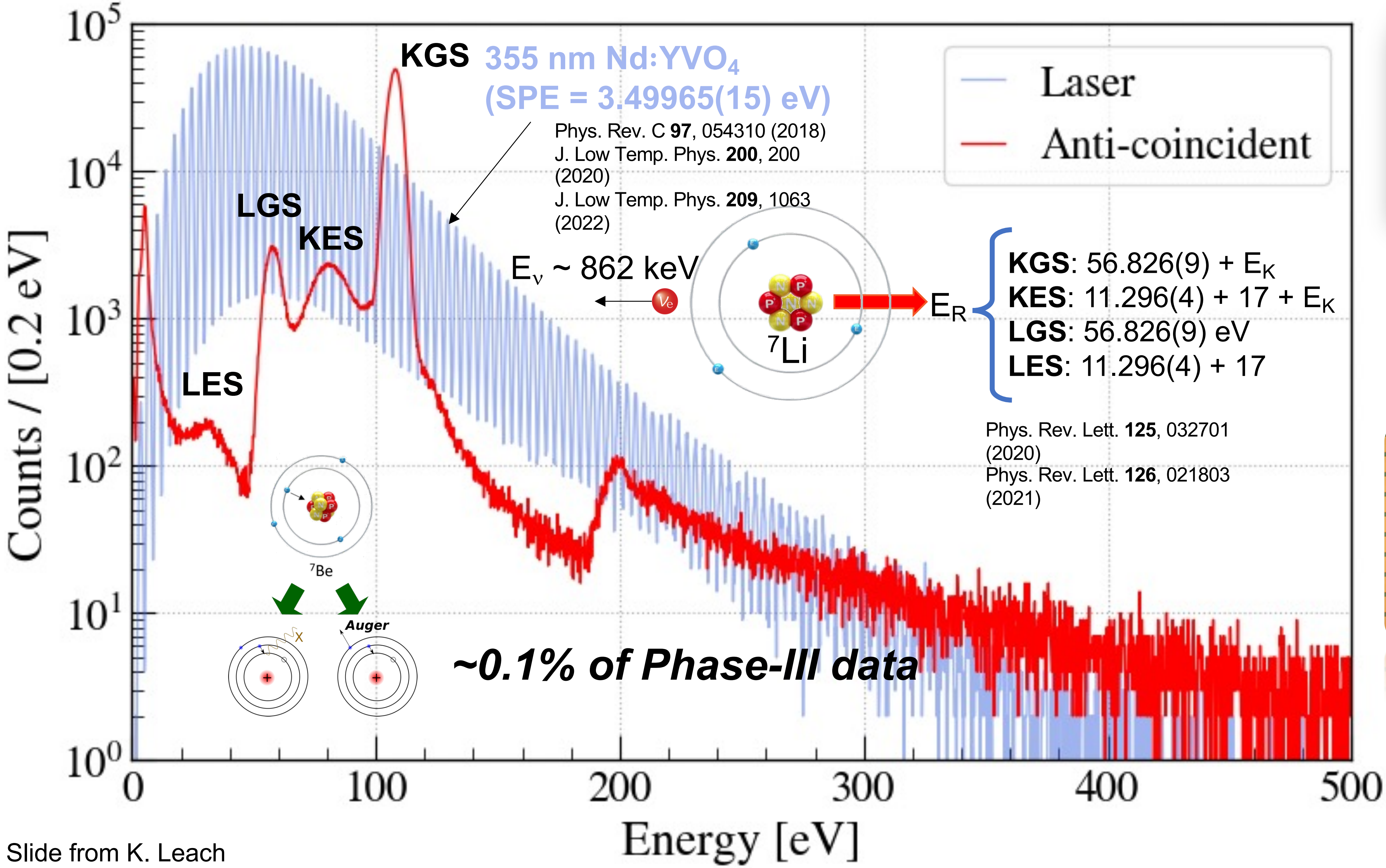


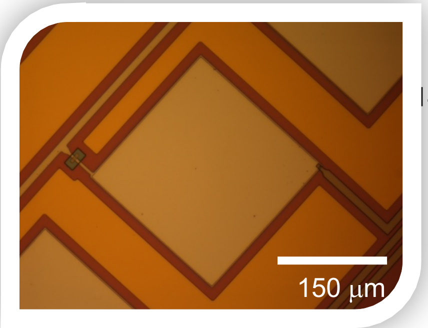
- Used NaI detectors for **γ-coincidence** measurement (February 2023)
- Gamma-coincidence technique allows to separate just the excited state events

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

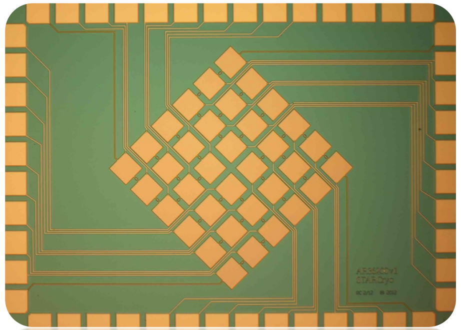
- Analysis ongoing

Recoil Spectrum from Phase III data





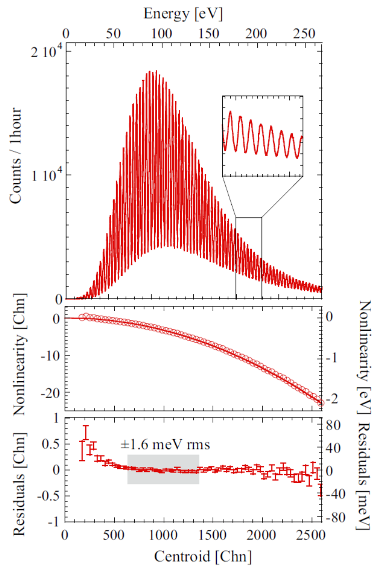
- Single pixel
- 20 hours
- 50 Bq

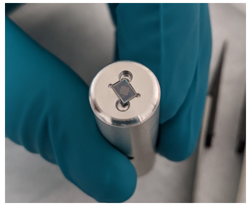


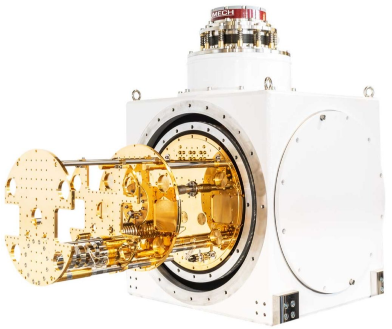
- 36 pixels
- 50 days
- 50 Bq/pixel

Slide from K. Leach

Phases of the BeEST experiment







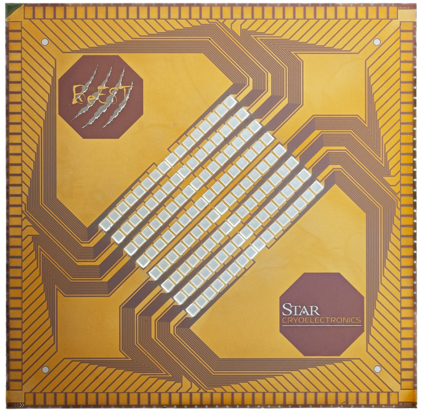
Phase-IV
Operation of 128-Pixel Arrays of Al-Based STJs in Dilution Refrigerator

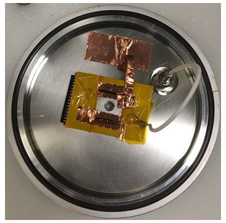
2026

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

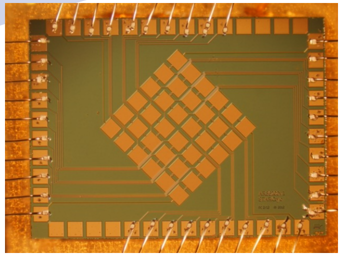
2024

2022



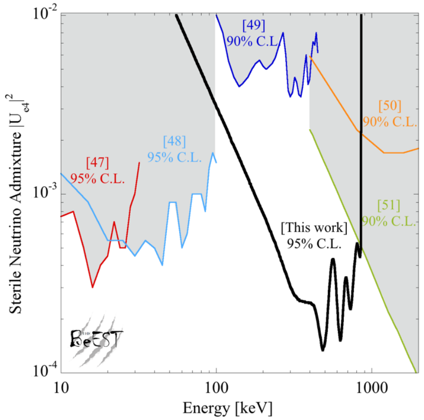


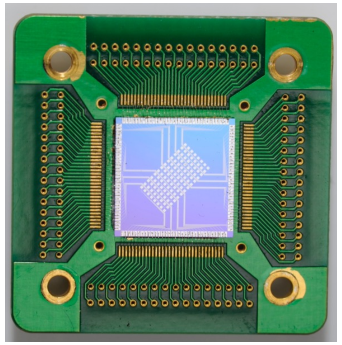
Phase-II
First Limits and Precision Device Characterization

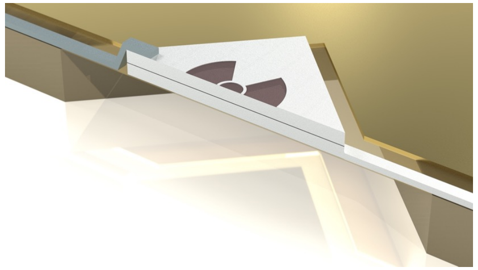


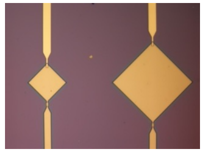
2020

Phase-I
Proof of Concept



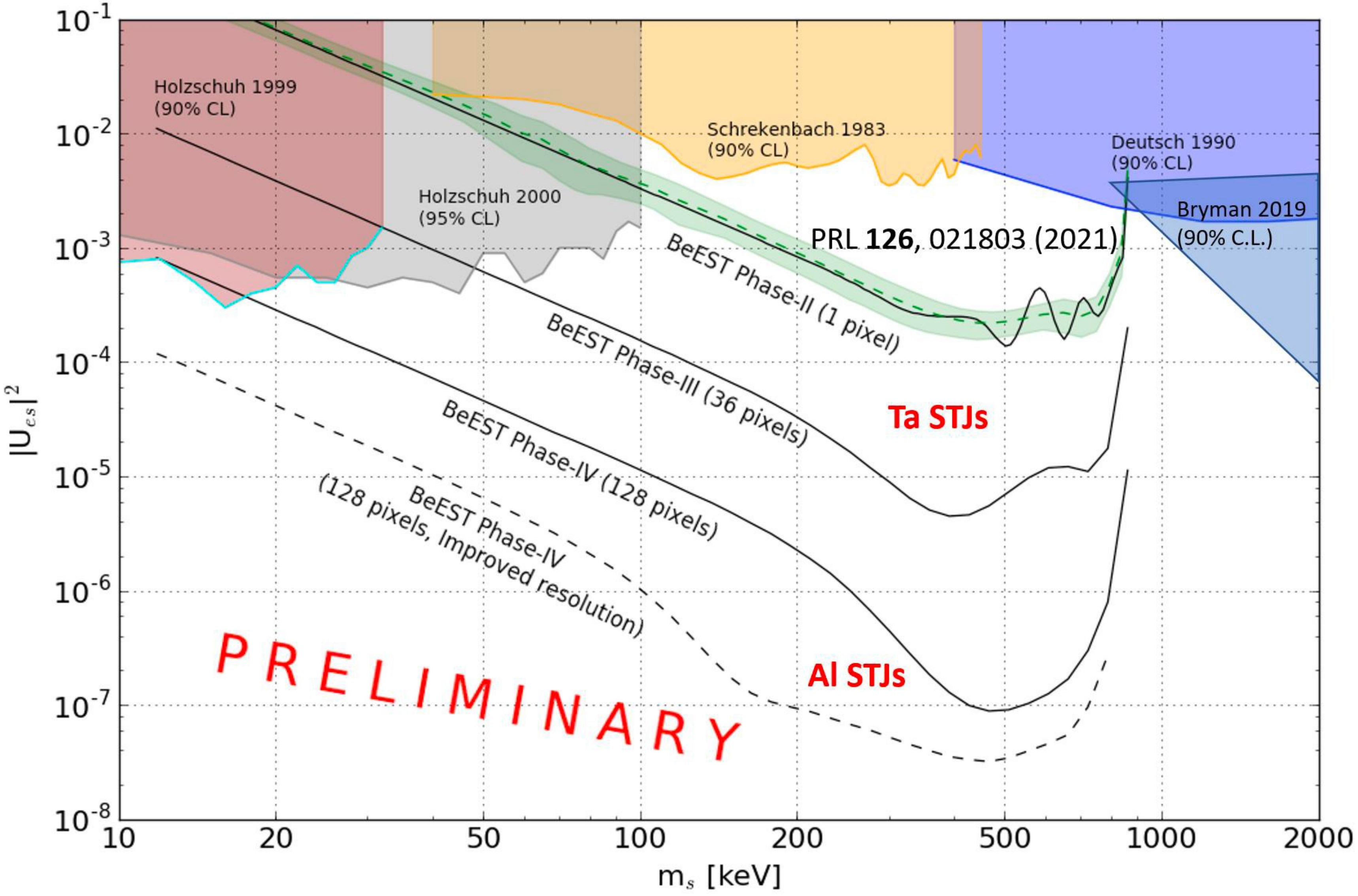






2018

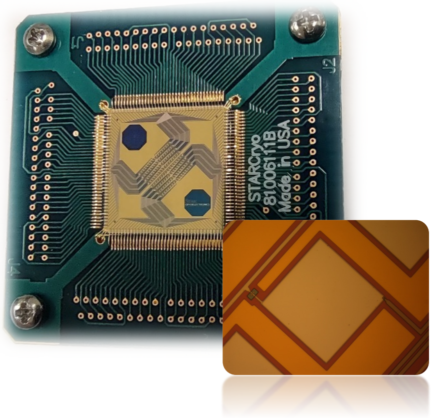
Projections for next phases of the BeEST

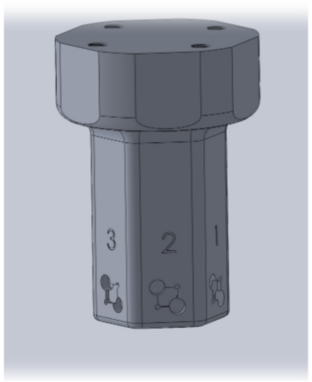


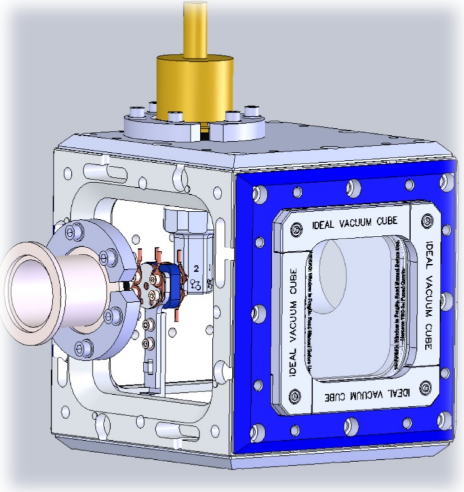
How will *the BeEST* benefit from ARIEL?

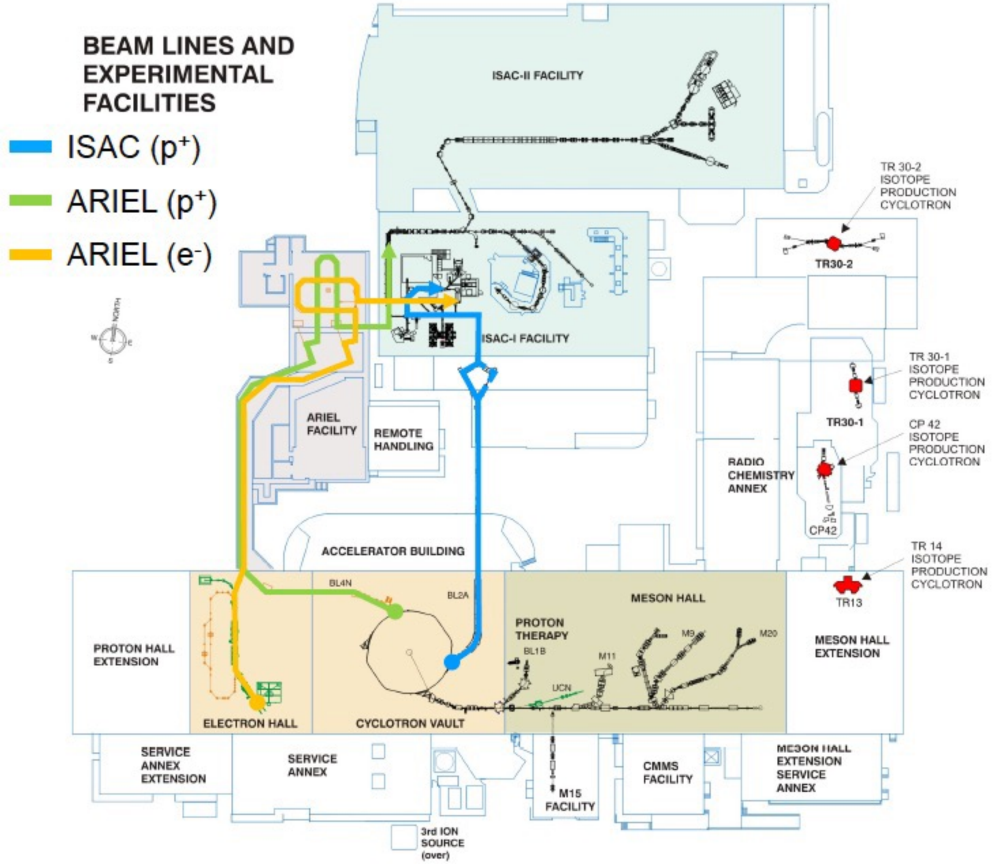
Phases III & IV require detailed understanding of STJ response & material effects to reach projected limits

- Requires data taking with many iterations of STJ arrays (variations in material, thickness, pixel sizes/numbers (scaling up from hundreds to thousands))
- Requires **reliable** implantation with **pure ^{7}Be beams**
- Requires **long run times** of multiple weeks at a time (currently not feasible)
- Ideally operate outside of exclusion area









How will *the BeEST* benefit from ARIEL?

Concept:

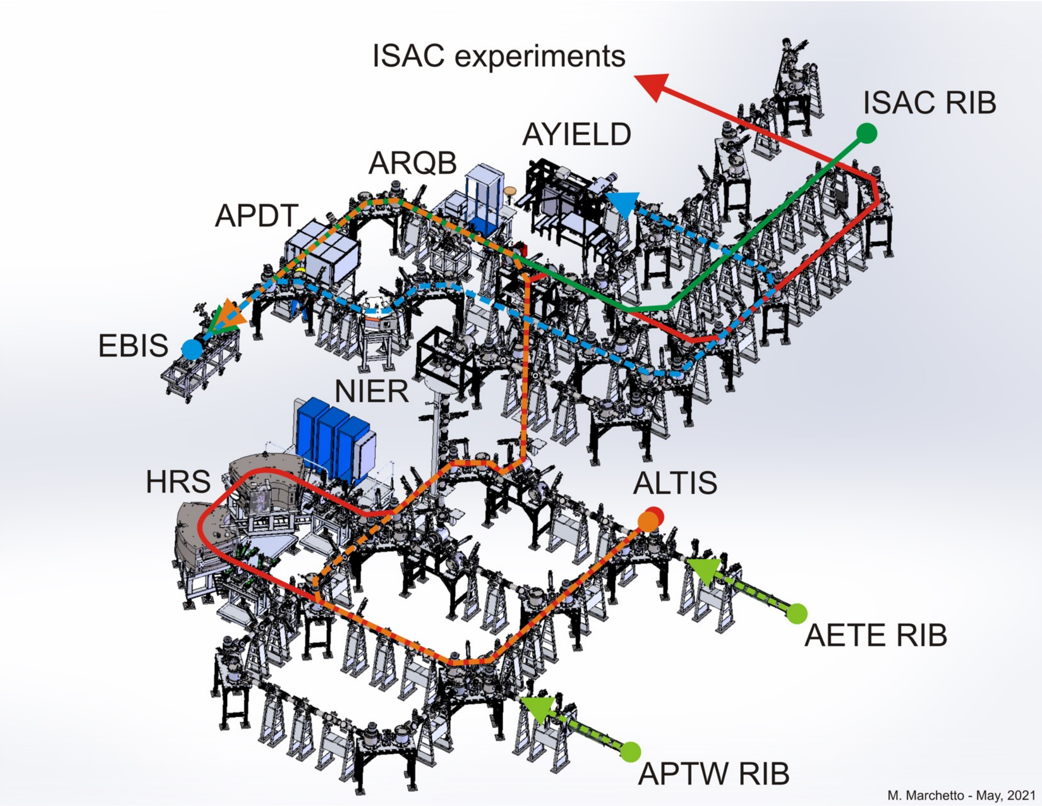
- Use **multi-target chamber with ARIEL beams** cleaned through High Resolution Separator (~1:20,000) (or 100% ^{7}Li suppression with IG-LIS)

Requirements:

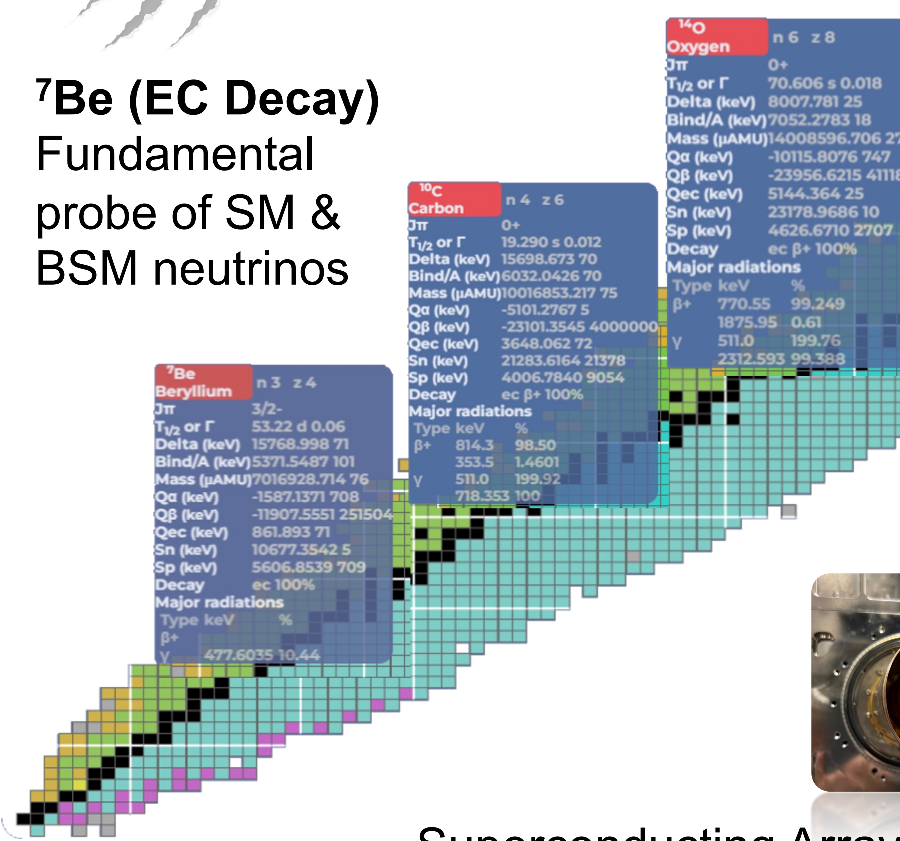
- Need ARIEL to come online
- AETE: predicted in-target production ~5e+10pps (based on 100kW)

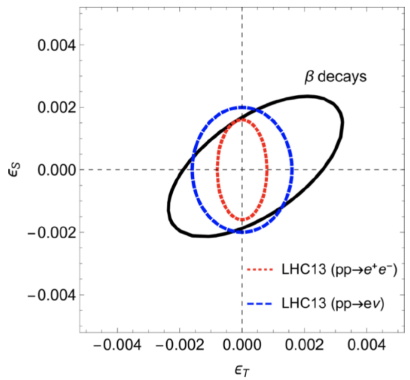
➔ ~1e9 pps through the HRS & **No Lithium.**

- Earliest tests 2026/27
- APTW & BL4N (earliest 2027)



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)

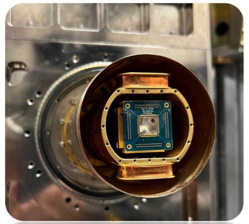
$T_{1/2}$ ≤ 1 min

THE BeEST

^{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



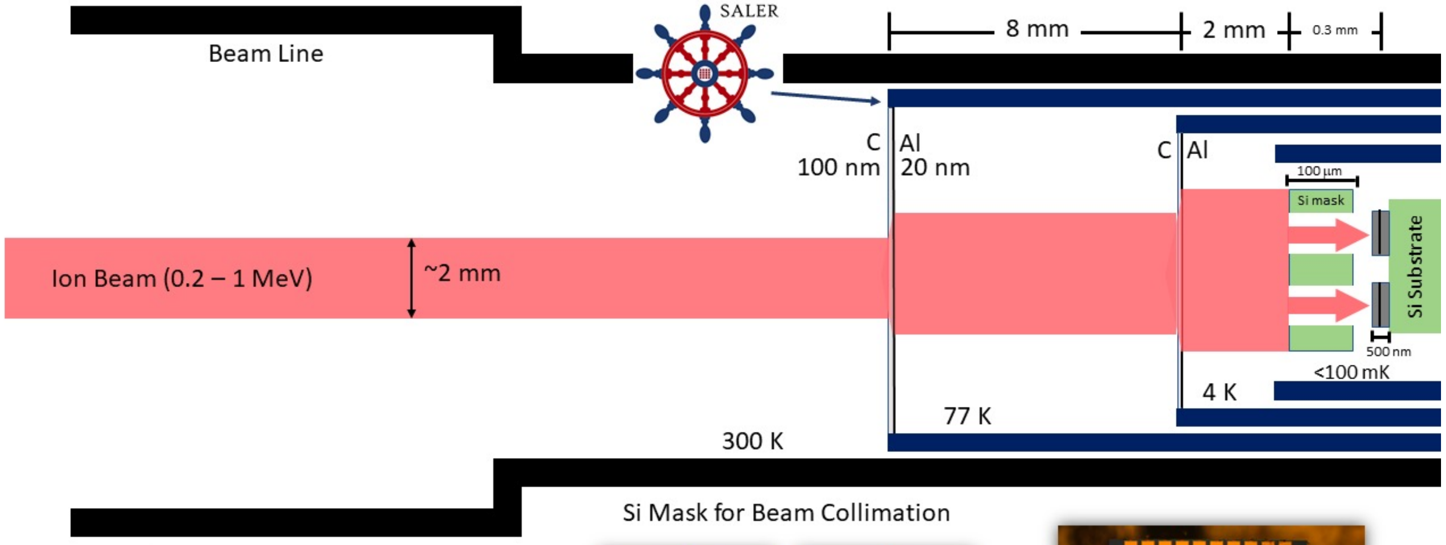
SALER

Superconducting Array for Low-Energy Radiation

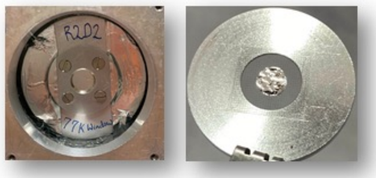
Slide from K. Leach

SALER – Superconducting Array for Low-Energy Radiation

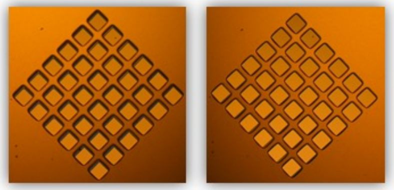
Extended application for STJs for short lived rare isotopes $T_{1/2}$ > 0.1s



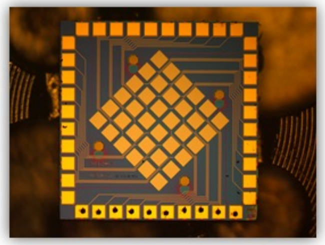
Si Mask for Beam Collimation



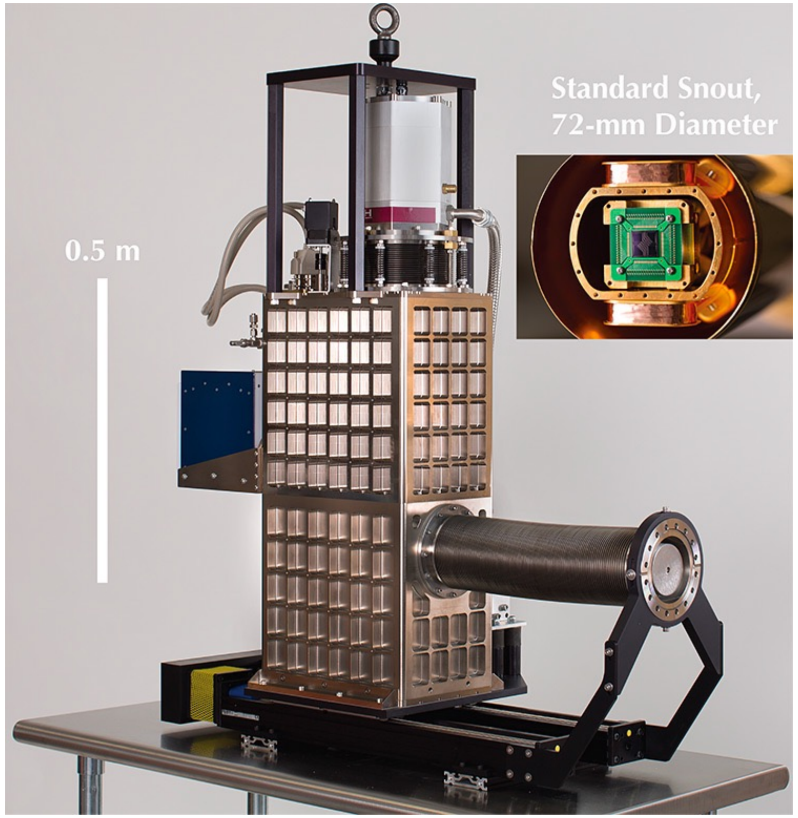
Ultra-Thin (120 nm) Thermal windows



Before Alignment After Alignment



Mounted 36-Pixel Nb STJ Array



FRIB

- 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 beamline
- **ARIEL** would enable efficient commissioning & detector development
- **Beams from CANREB-EBIS**
- Science cases beyond LOI to be identified

Summary

- Implanting rare isotope beams into superconducting tunnel junctions is a powerful new tool to perform **sub-keV nuclear decay spectroscopy**
- Using STJs, we are able to measure radiation from ~2.5 eV to 1 keV with ~ meV precision at decay rates of up to 10 kBq
- The **Be**ryllium **E**lectron capture in **S**uperconducting **T**unnel junctions (BeEST) experiment is a new search for **beyond standard model physics** using precision measurements of the EC decay of ^{7}Be
- 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 to 5 years ➔ **ARIEL needed to achieve goals!**
- BeEST concept has been extended to develop the superconducting array for low-energy radiation (SALER) to perform nuclear recoil spectroscopy using short-lived RIBs on-line (proposals FRIB & TRIUMF) ➔ expand number of systems to study to search for BSM physics!

The BeEST - collaboration

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Xavier Mougeot

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Jens Dilling

GORDON AND BETTY MOORE FOUNDATION
U.S. DEPARTMENT OF ENERGY — Office of Science
Lawrence Livermore National Laboratory
NSERC CRSNG
EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
NNSA — National Nuclear Security Administration
TRIUMF

Collaboration meeting at LLNL in April 2023

TRIUMF

Thank you
Merci

www.triumf.ca

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Discovery, accelerated

Back-up slides

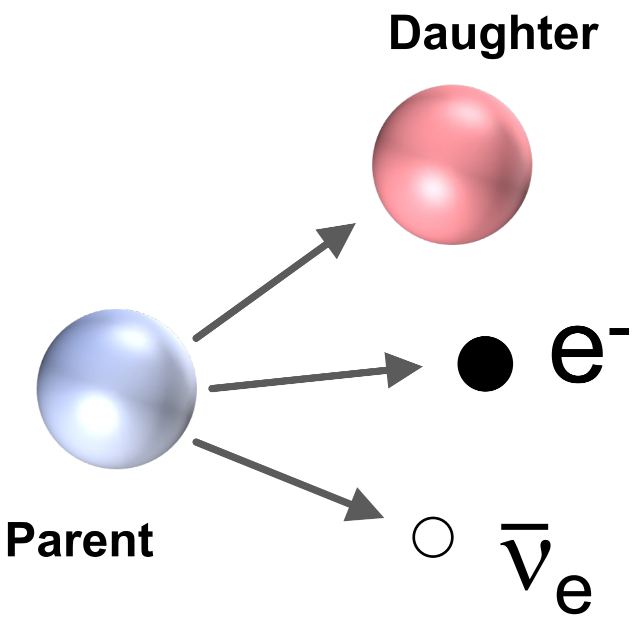
Atomic Recoils Following Nuclear β-decay

- 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 **daughter recoil** 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

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

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

- EC probabilities

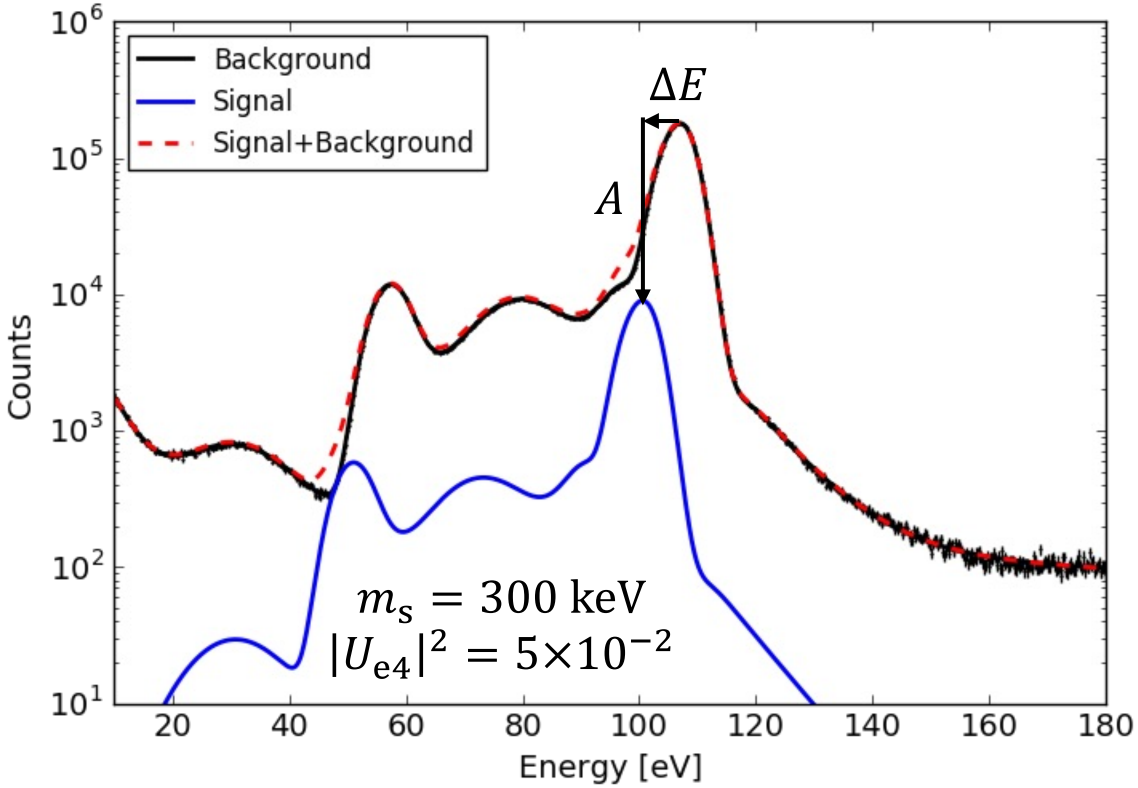
$$\lambda \propto \left(1 - |\boldsymbol{U_{e4}}|^2\right)Q^2 + |\boldsymbol{U_{e4}}|^2 Q\sqrt{Q^2 - m_4^2}$$

Active neutrinos — Sterile neutrino addition

- Spectral shape

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

Active neutrinos — Sterile neutrino addition



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

Because we're measuring an entire spectrum being shifted, this removes danger of false identification of random peak!

Material effects

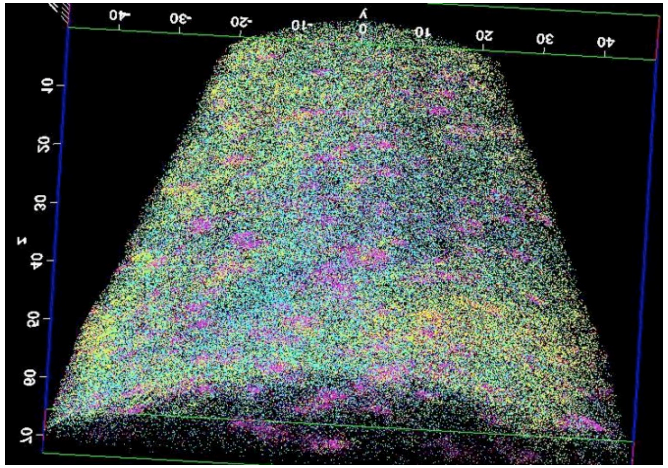
Systematics Studies

- Improvements in theoretical understanding of the EC spectrum – atomic/nuclear effects
- Study on materials effect on-going
- Simulation on background helps reducing systematics

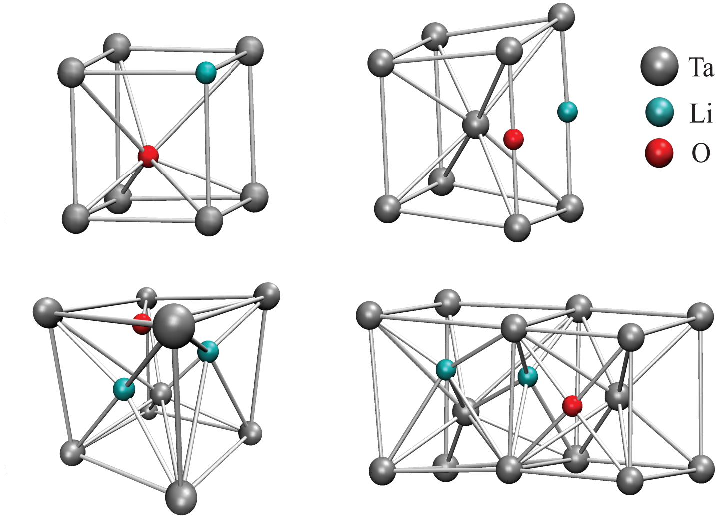
Detector characterization

- Energy resolution as low as 1.3 eV FWHM @ 100 eV
- Improved background rejection

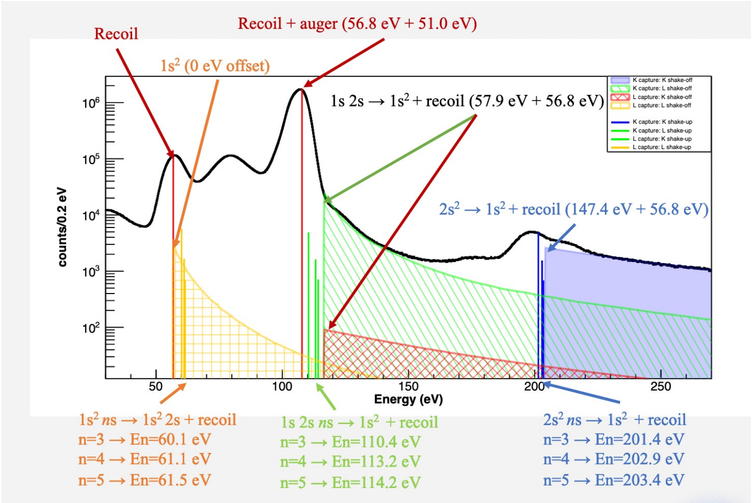
TEM scans, atom by atom mapping



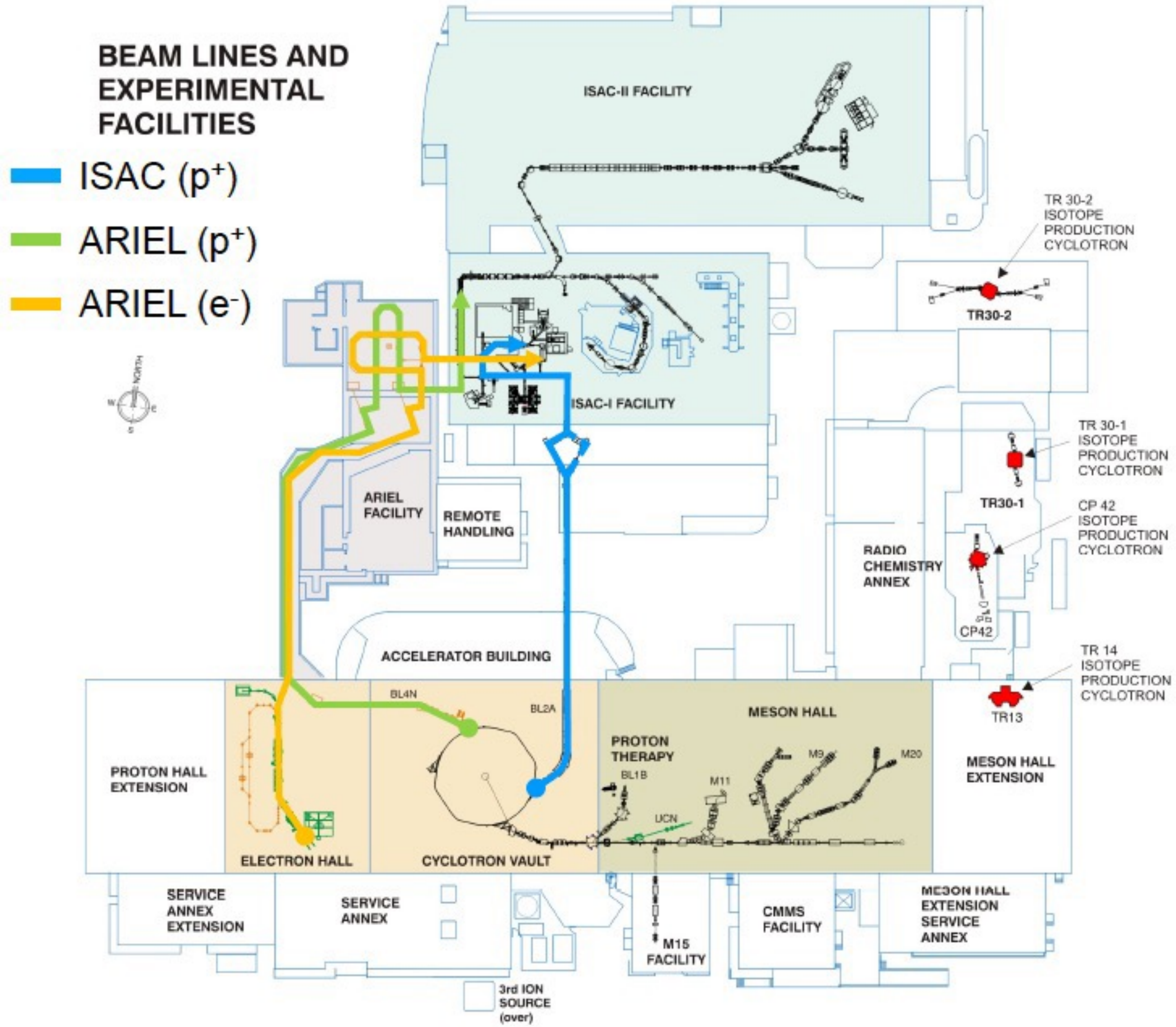
Hybridization



Atomic effects (Shake-up & Shake-off)



TRIUMF – A High-Power Target Laboratory, based on world’s largest cyclotron



TRIUMF (since 1968)
Meson facility (π, & thus μ beams)
520 MeV H$^-$ cyclotron
200 kW protons
on average 3000 proton beam hours annually

ISAC (since 1995)
2 target stations
500 MeV, 50 kW proton beam
Post-Acc. RIB: 2.1 MeV/u & 15 MeV/u

ARIEL (since 2010)
2 target stations under construction
AETE (electron target)
- **35 MeV, 100 kW electron beam**
- **Construction to be finished by 2025**
- **First beam to yield station anticipated in 2026**

APTW (proton target)
- **500 MeV, 50 kW proton beam**
- **Construction to be finished by 2026**
- **First beam to yield station anticipated in 2027**

Previous implantations - Overview

Sched.	Shifts	Target/Source	^{7}Be Rates [pps] (Be:Li)	Notes (STJ type, implant energy etc)
135 (2018)	2 (discretionary)	UC_x + RILIS	~7.4 x 10^8 (26/1)	Proof of principle with Ta chip (26 kV)
136 (2019)	1 (discretionary)	UC_x + RILIS	~2 x 10^8 (74/1)	Ta chip (25 kV), 30min implantation
139 (2020)	5	Graphite + RILIS	~1 x 10^9 (1:100)	Two Ta arrays (HV bias – chips damaged)
140 (2021)	6	UC + RILIS	7 x 10^7 (1:120)	2 Ta arrays, 1 Nb array, and 1 Al array. Ta arrays were damaged (likely in transit). Dose in Nb and Al chips was low. Some Al chips still produced usable data for test purposes.
141 (2021)	3	UC + IGLIS (transmission mode)	5 x 10^7 (1:86) 1.5 x 10^8 (1:13)	1 Nb array – STJ failed. Cause unknown. 1 Al array – First Al physics data tests
142 (2022)	3	UC + IGLIS (suppression mode)	6.2 x 10^6 (7:1)	Ta (30 keV). Phase-III physics implant
143 (2022)	<1	Graphite + RILIS	~1 x 10^8 (1:300)	Nb test chip – low activity on sample
140	12	OLIS	~1 x 10^{11} at 30 keV	Stable ^{7}Li beam implantation at GRIFFIN, 12 samples

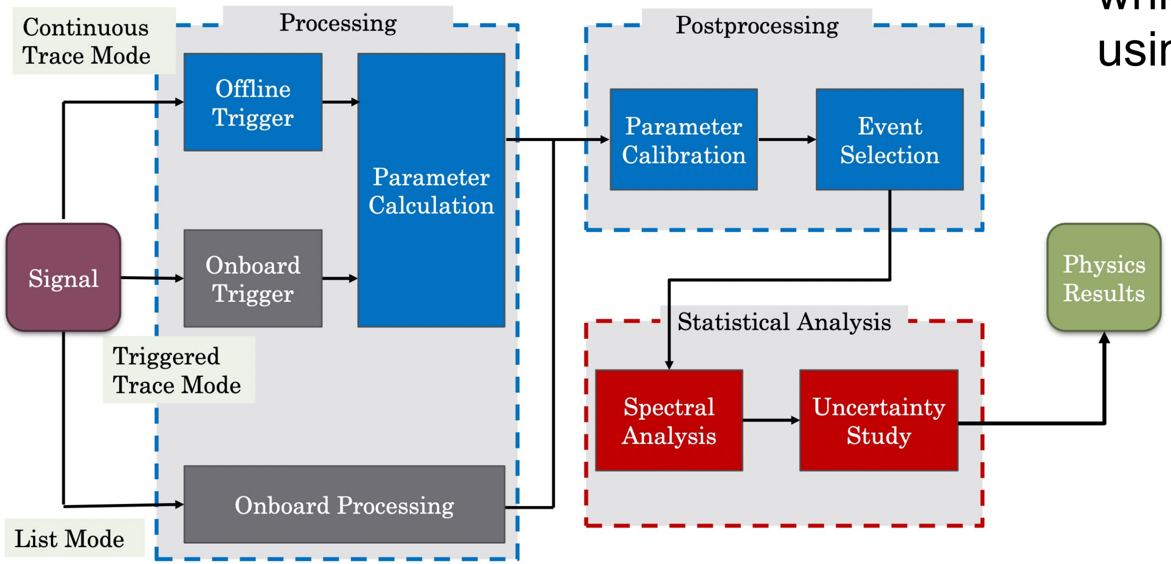
First limits data set

Under analysis

24 new shifts requested and approved by EEC with high priority

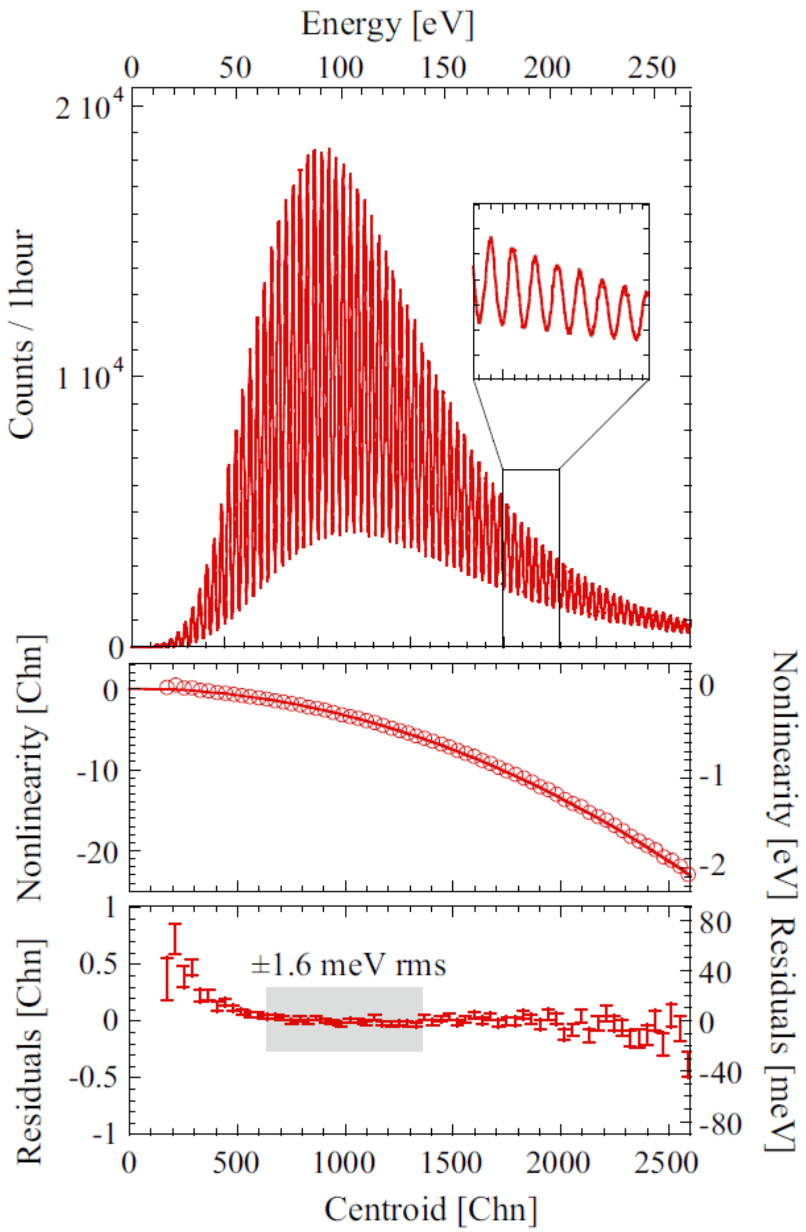
Data processing

- 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

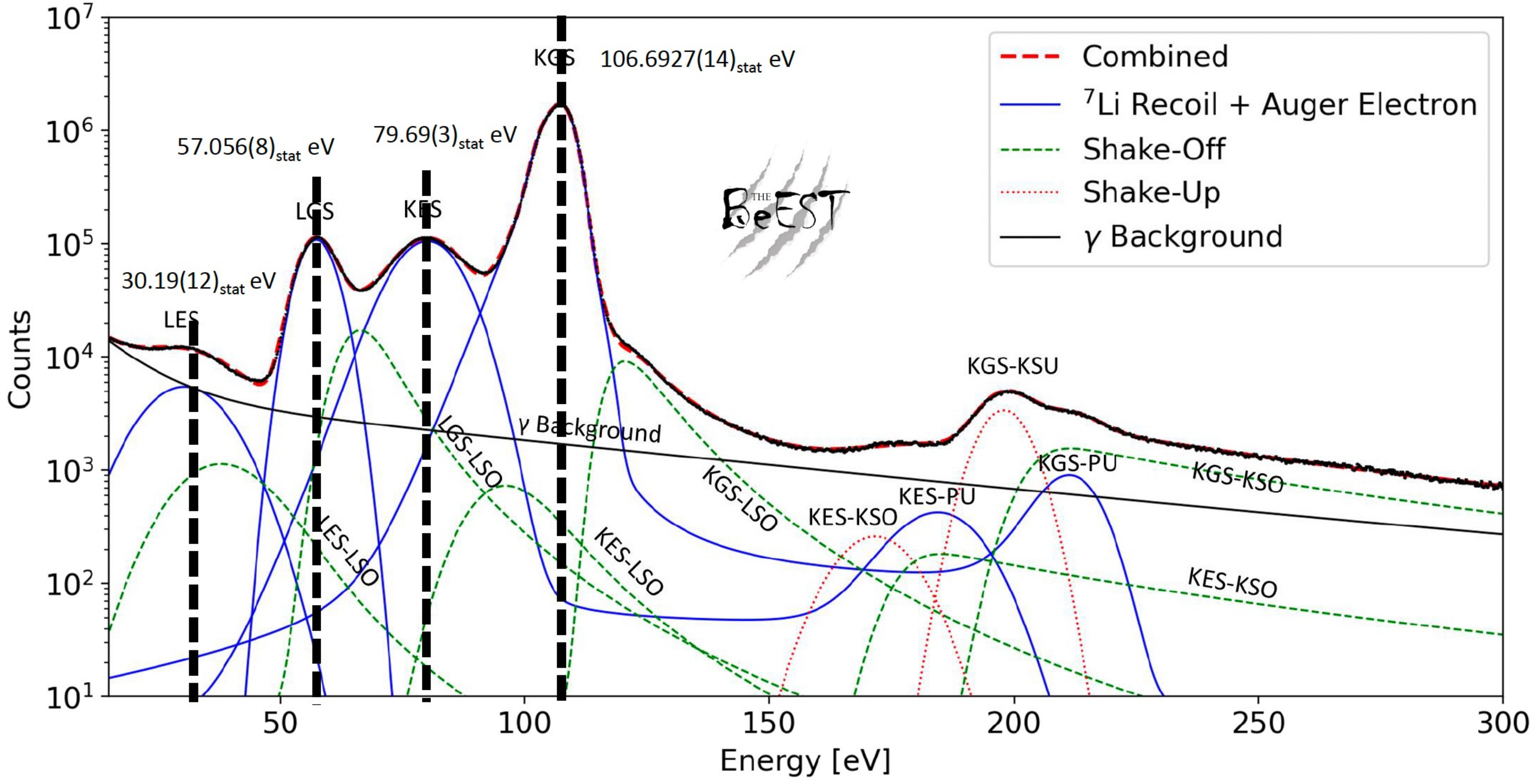
Energy calibration



- For energy calibration, the STJs were simultaneously exposed to 3.49965(15) eV photons from a pulsed Nd:YVO4 laser (355nm)
- 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.
- Since the STJ absorbs an integer number of photons per pulse, the spectrum consists of a comb of equidistant peaks with a Poissonian distribution
- The calibration spectrum was recorded in coincidence with the laser trigger and the 7Li recoil spectrum in anti-coincidence.

Friedrich et al., *Journal of Low Temperature Physics* **volume 200**, pages 200–205 (2020)

7Li recoil spectrum



The BeEST in context