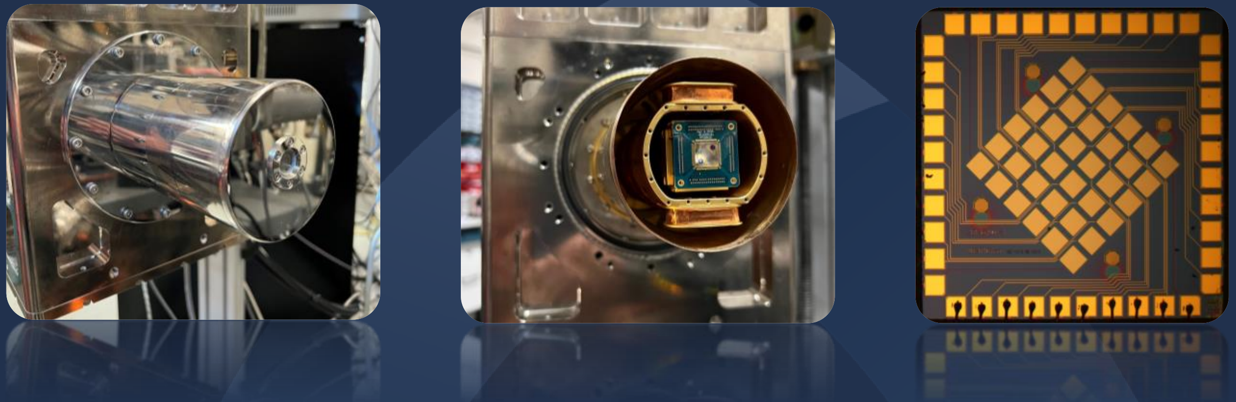


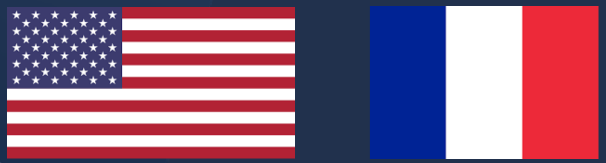
Superconducting Array for Low-Energy Radiation

Kyle Leach

Department of Physics | Quantum Engineering | Nuclear Engineering
Colorado School of Mines

and

Facility for Rare Isotope Beams
Michigan State University



SALER Co-I:
Leendert Hayen
LPC-Caen

U.S. DEPARTMENT OF ENERGY | Office of Science

GORDON AND BETTY MOORE FOUNDATION

Characterizing Nuclear β/EC Decay

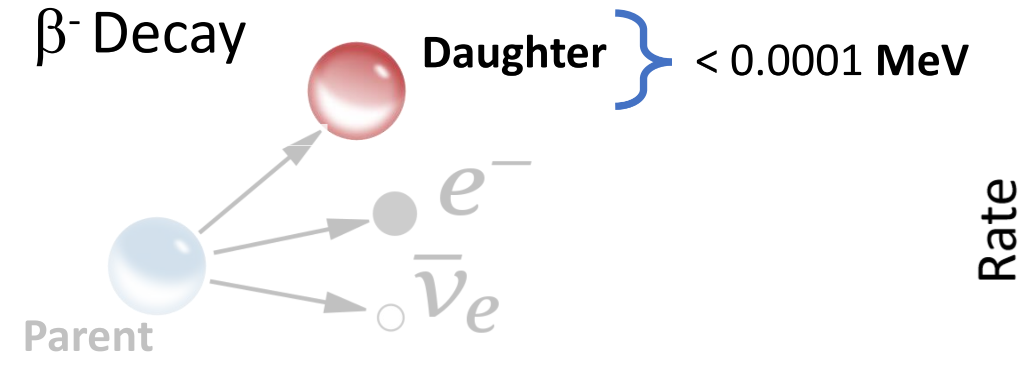
Precision β decay experiments typically performed via measurements of:

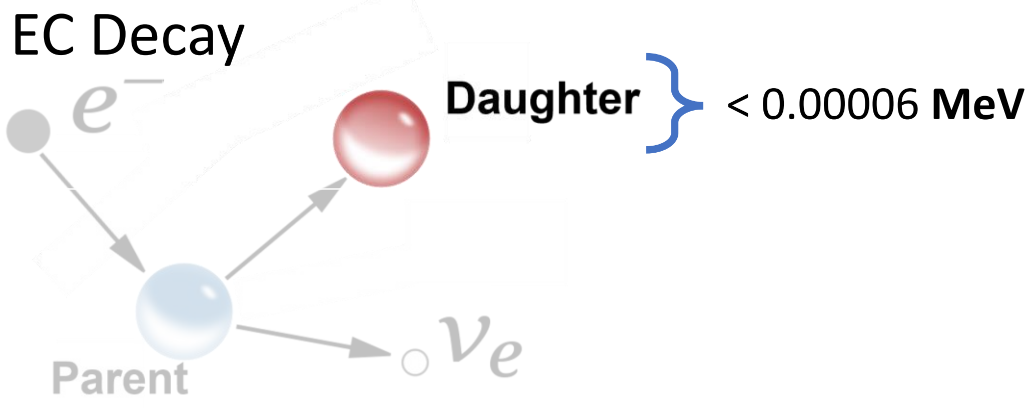
- Electrons (β^-, atomic Auger, CE, etc.)
- Positrons (β^+ and IPC)
- Photons (γ-ray, bremsstrahlung, and X-rays)

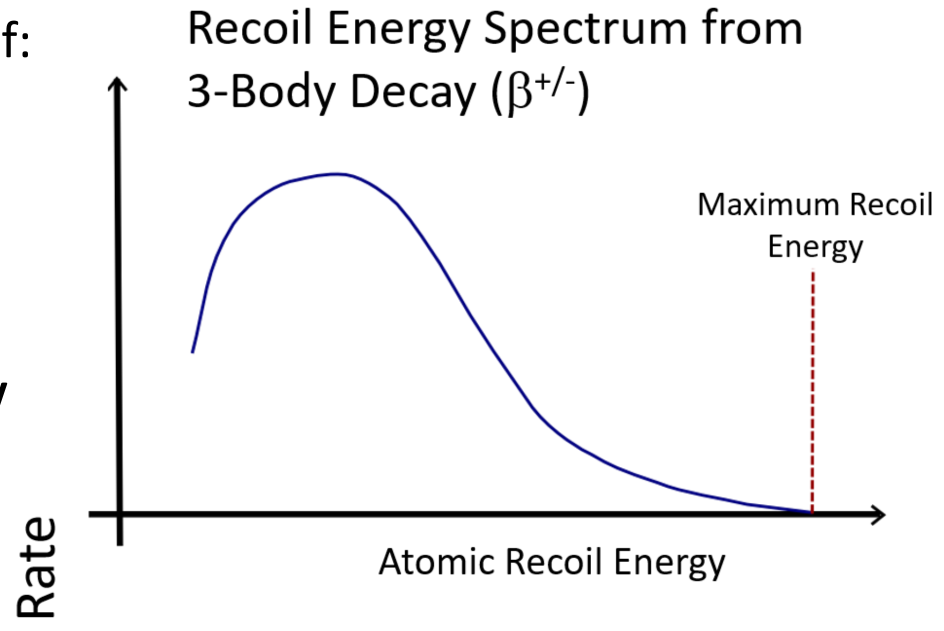
~ 0.1 – 10 **MeV**

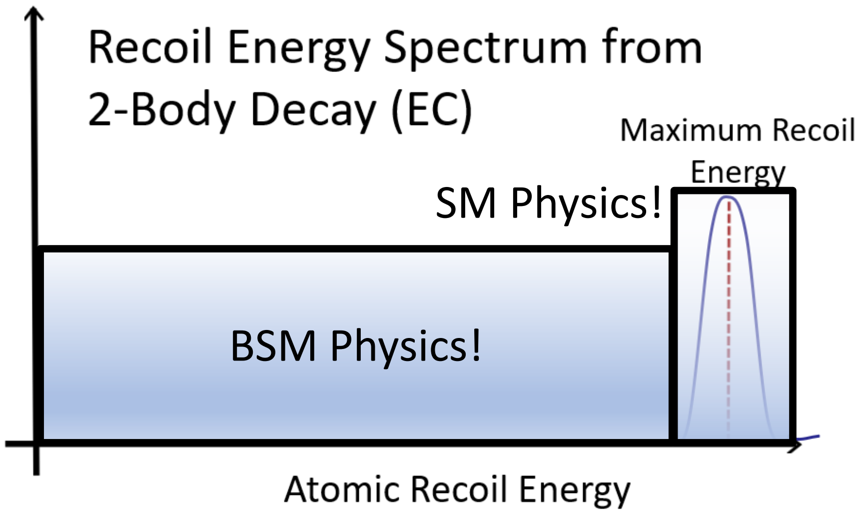
***Unique* probe of:**

- Quantum nature of radioactive decay
- Rare SM effects
- Weakly coupled new physics
- Exotic new particles and interactions









How Challenging are Nuclear Recoil Measurements?

A few current examples:

Recoils from Decay

Recoils from Interaction

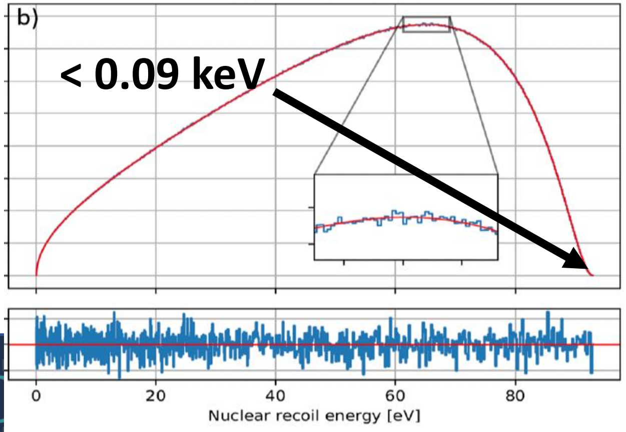
			Method
BPT@ANL	→	*A*=8 α recoils **> 700 keV** (threshold set to minimize beta) M. Sternberg et al., Phys. Rev. Lett. **115**, 182501 (2015)	**Ion Trap (Paul Trap)**
TRINAT@TRIUMF	→	"…E field accelerates the Ar^+ recoils to **4.8–5.3 keV**…" A. Gorelov et al., Phys. Rev. Lett. **94**, 142501 (2005)	**Atom Trap (MOT)**
COHERENT@ORNL	→	**> "a few keV"**, First observation of CEνNS COHERENT Collaboration, Science **357**, 1123-1126 (2017)	**Scintillator (CsI[Na])**
SuperCDMS@SNOLAB	→	Si recoils **> 0.1 keV**, "…*the lowest energy probed so far*…" CDMS Collaboration, Phys. Rev. Lett. **131**, 091801 (2023)	**Semiconductor + Superconductor (Si+TES)**

Requirements for *direct* decay recoil measurements:

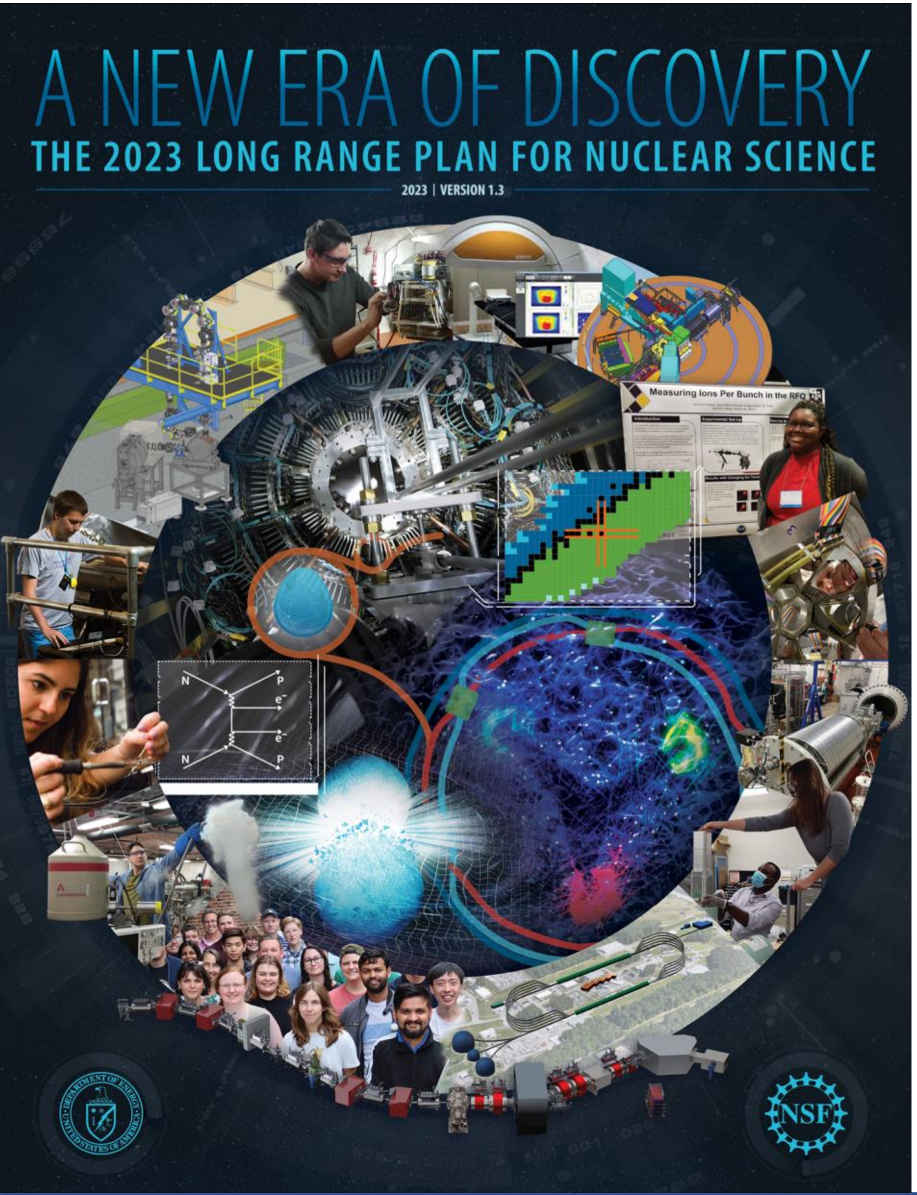
Largest EC Decay Recoil Energies:

7Be → 7Li :	**0.056826(9) keV**
37Ar → 37Cl:	**0.009618(5) keV**
67Ga → 67Zn:	**0.00804(2) keV**

^{11}C β^+ Decay Recoil Spectrum (Q=XX MeV)



The 2023 DOE/NSF NSAC Long Range Plan



A NEW ERA OF DISCOVERY

THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.3

- "Decadal Plan" for nuclear science released October 2023
- 7th since 1976 (?)
- Sets priorities for DOE-SC NP and NSF NP

- **<u>Top US Priority</u>**

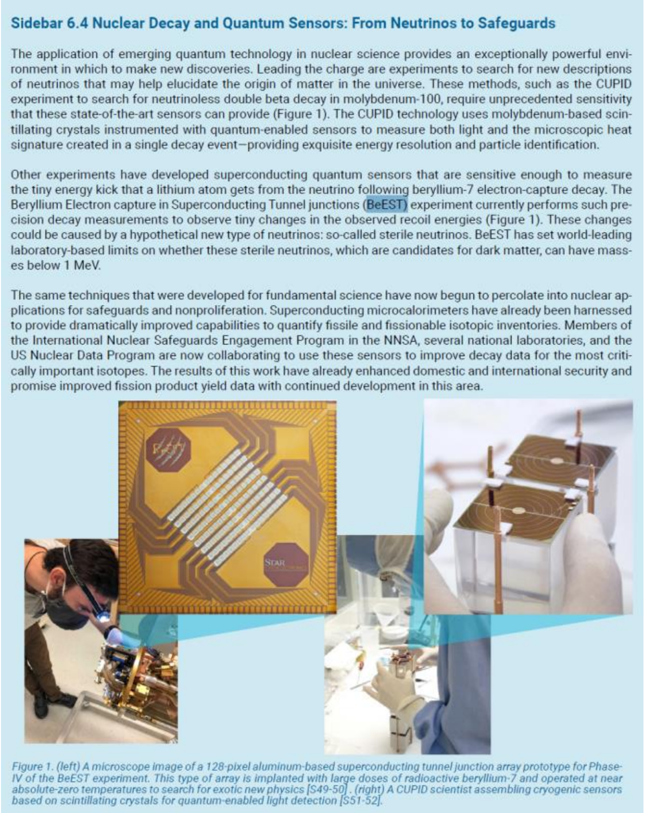
"…capitalize on past investments and operate [FRIB]…"

- **<u>BeEST</u>**

"Above 10 keV, the BeEST will provide the most sensitive search for [new neutrinos] below 1 MeV…" - $20M

- **<u>SALER and Superconducting Sensors</u>**

"Superconducting sensor technology is at the forefront of emerging ideas in precision nuclear science…" - $5M



Sidebar 6.4 Nuclear Decay and Quantum Sensors: From Neutrinos to Safeguards

The application of emerging quantum technology in nuclear science provides an exceptionally powerful environment in which to make new discoveries. Leading the charge are experiments to search for new descriptions of neutrinos that may help elucidate the origin of matter in the universe. These methods, such as the CUPID experiment to search for neutrinoless double beta decay in molybdenum-100, require unprecedented sensitivity that these state-of-the-art sensors can provide (Figure 1). The CUPID technology uses molybdenum-based scintillating crystals instrumented with quantum-enabled sensors to measure both light and the microscopic heat signature created in a single decay event—providing exquisite energy resolution and particle identification.

Other experiments have developed superconducting quantum sensors that are sensitive enough to measure the tiny energy kick that a lithium atom gets from the neutrino following beryllium-7 electron-capture decay. The Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment currently performs such precision decay measurements to observe tiny changes in the observed recoil energies (Figure 1). These changes could be caused by a hypothetical new type of neutrinos: so-called sterile neutrinos. BeEST has set world-leading laboratory-based limits on whether these sterile neutrinos, which are candidates for dark matter, can have masses below 1 MeV.

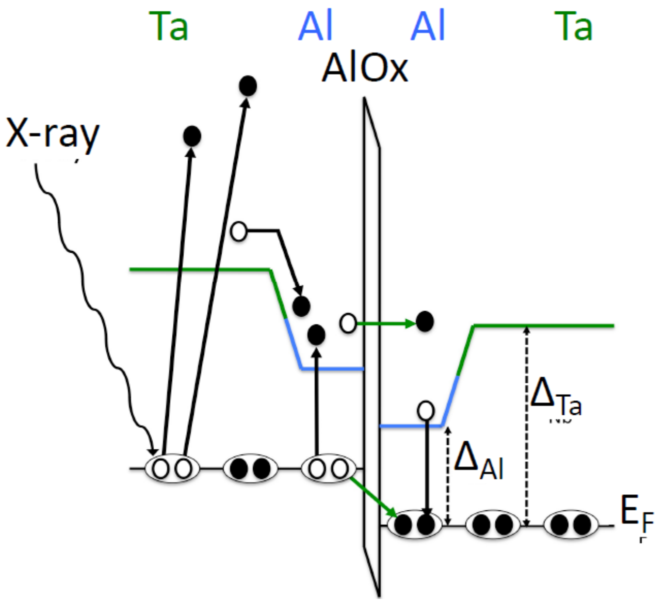
The same techniques that were developed for fundamental science have now begun to percolate into nuclear applications for safeguards and nonproliferation. Superconducting microcalorimeters have already been harnessed to provide dramatically improved capabilities to quantify fissile and fissionable isotopic inventories. Members of the International Nuclear Safeguards Engagement Program in the NNSA, several national laboratories, and the US Nuclear Data Program are now collaborating to use these sensors to improve decay data for the most critically important isotopes. The results of this work have already enhanced domestic and international security and promise improved fission product yield data with continued development in this area.

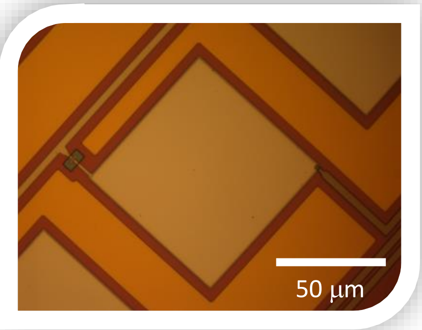
Figure 1. (left) A microscope image of a 128-pixel aluminum-based superconducting tunnel junction array prototype for Phase-IV of the BeEST experiment. This type of array is implanted with large doses of radioactive beryllium-7 and operated at near absolute-zero temperatures to search for exotic new physics [S49-50] . (right) A CUPID scientist assembling cryogenic sensors based on scintillating crystals for quantum-enabled light detection [S51-52].

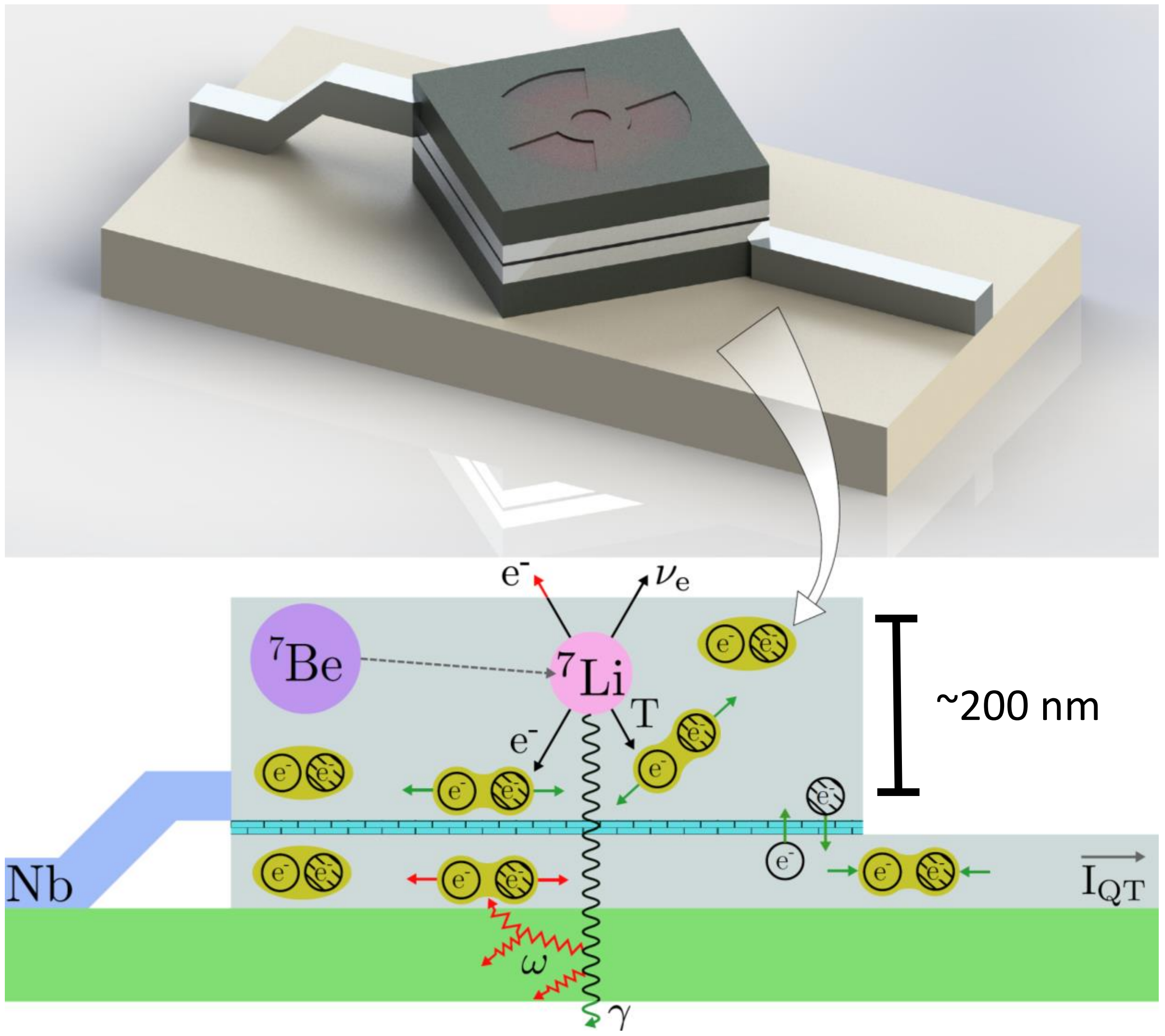
Superconducting Tunnel Junction (STJ) Quantum Sensing

- 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)

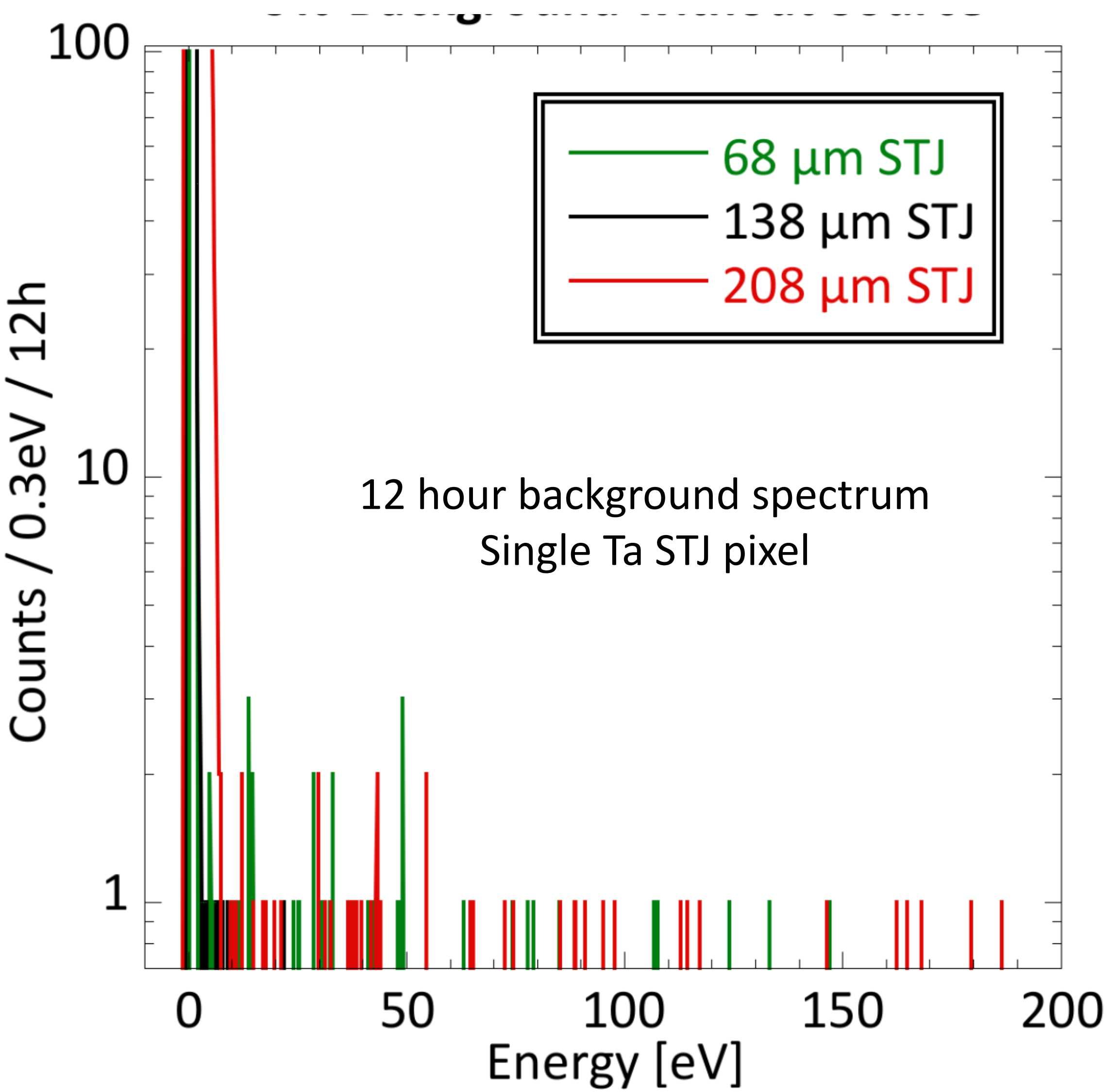
← *Optimal technology for RIB experiments*

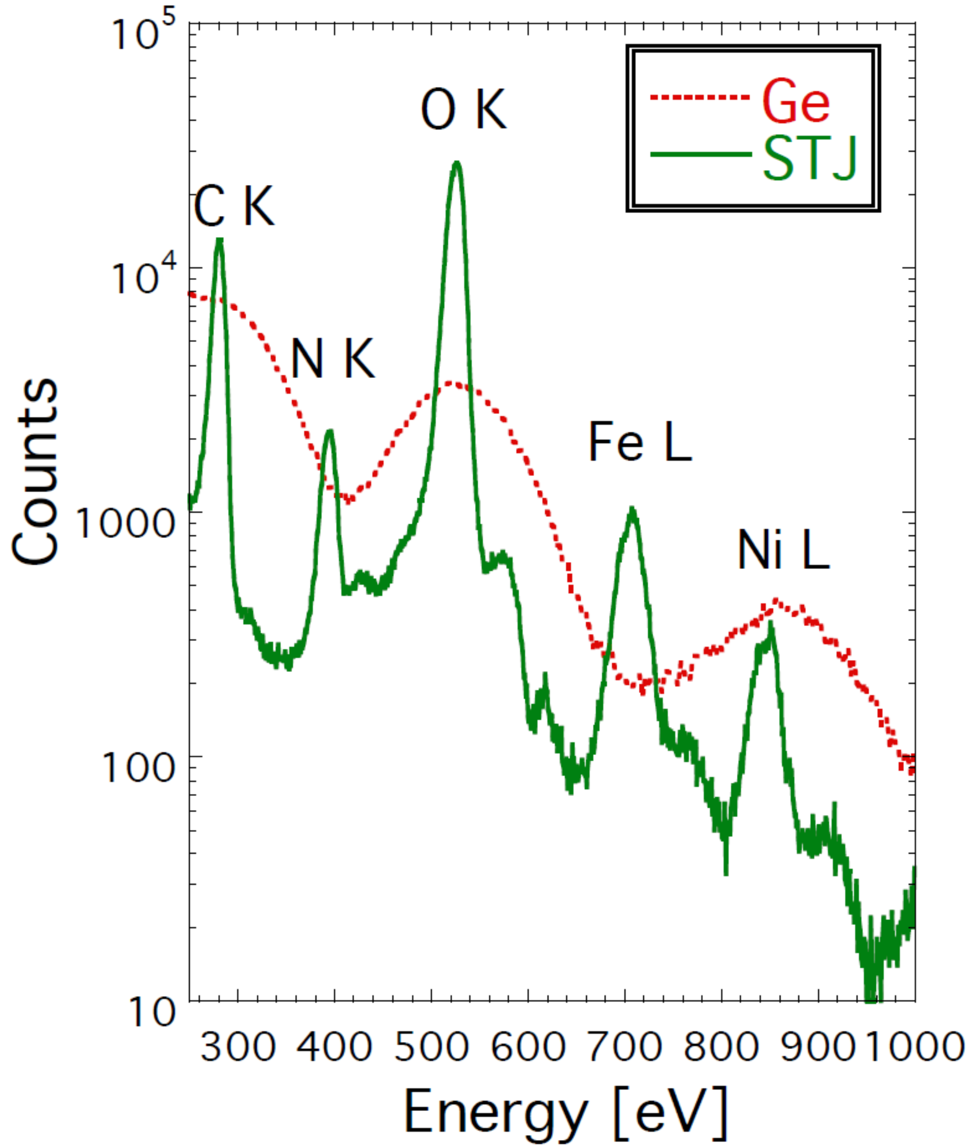






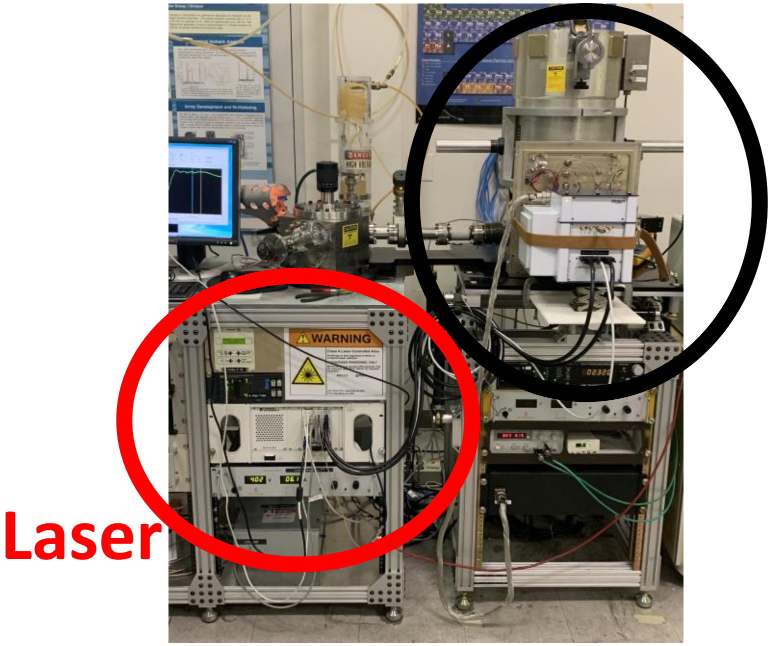
Performance of STJs to sub-keV Radiation



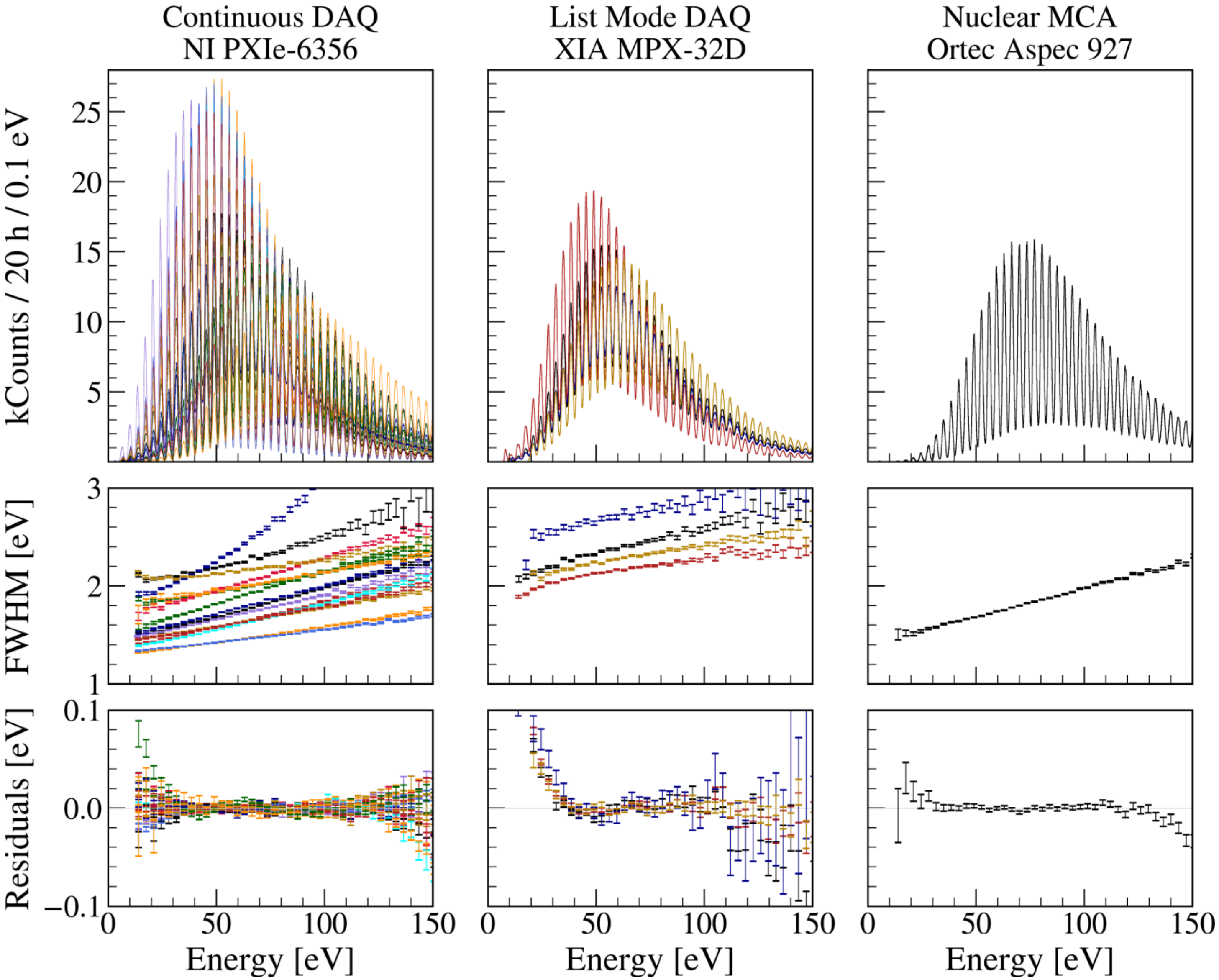


Calibration and Systematics of STJs and DAQ

ADR: Base Temp 0.07 K

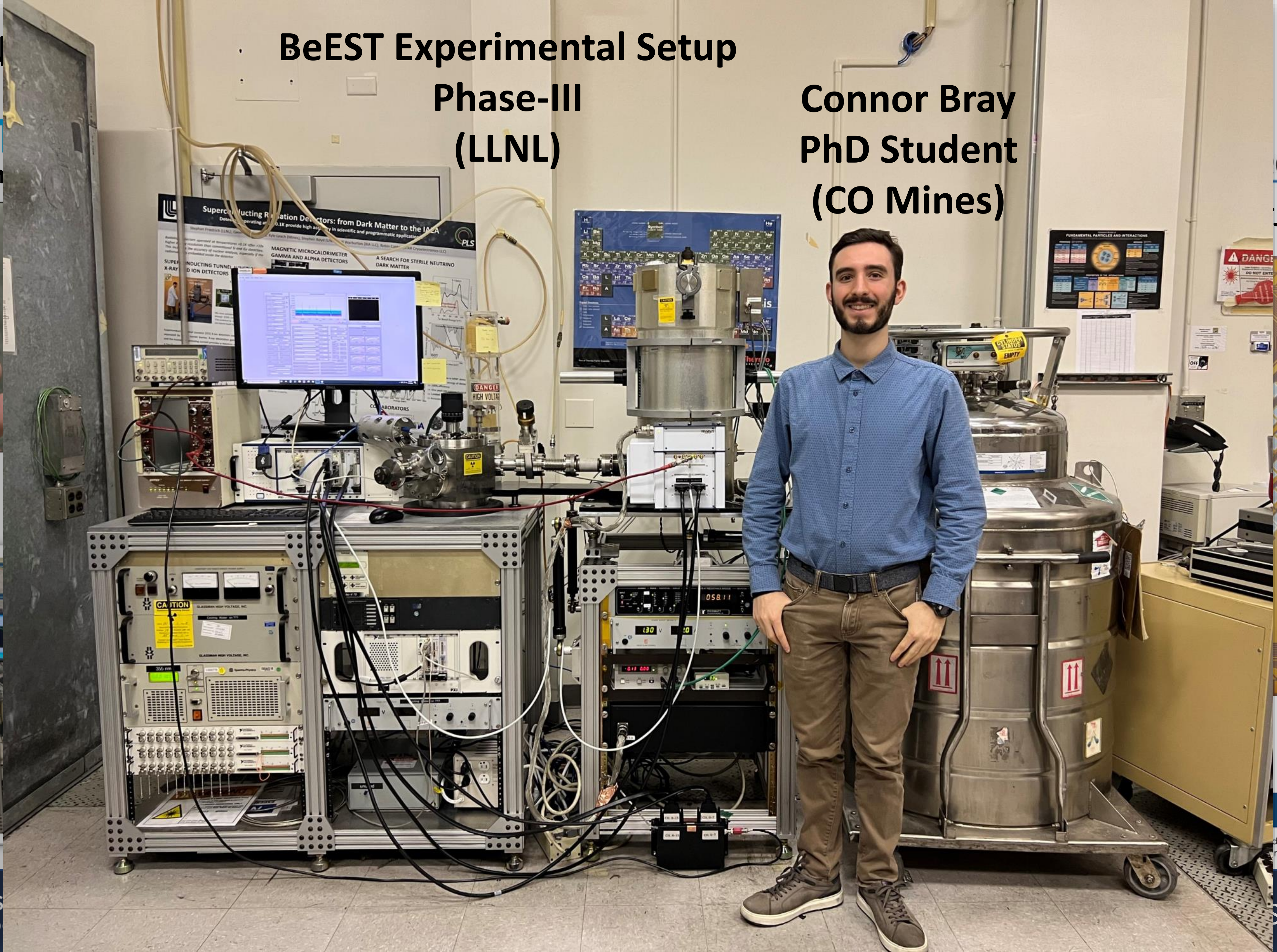


- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Stable response and small quadratic non-linearity (10^{-4} per eV)
- Evaluate signals from 3 DAQs to evaluate signals and possible systematics



Berylliu

Rare-isotope im



BeEST Experimental Setup
Phase-III
(LLNL)

Connor Bray
PhD Student
(CO Mines)

nctions

ONICS

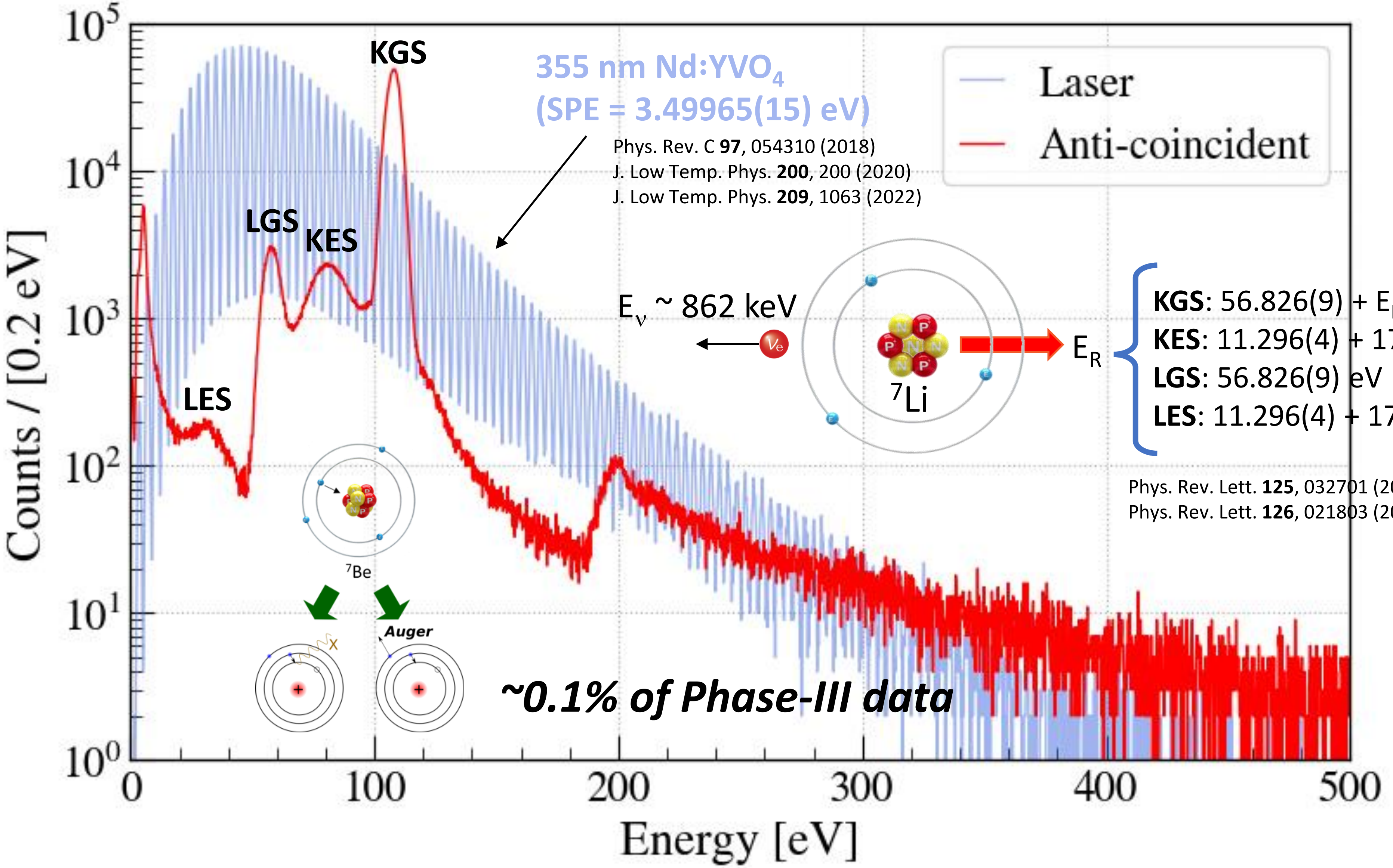
J Sensor Arrays

Office of
Science

R EURAMET

ded by the European Union's Horizon 2020
ramme and the EMPIR Participating States

^{7}Be Recoil Spectrum: A Rich Playground for Fundamental Physics



355 nm Nd:YVO_4
(SPE = 3.49965(15) eV)

Phys. Rev. C **97**, 054310 (2018)
J. Low Temp. Phys. **200**, 200 (2020)
J. Low Temp. Phys. **209**, 1063 (2022)

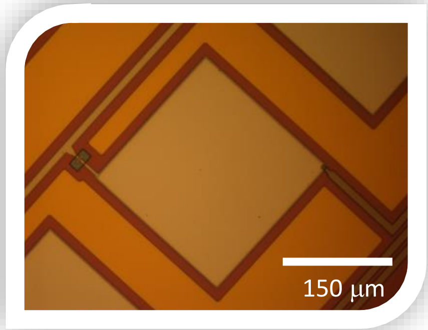
E_ν ~ 862 keV

E_R

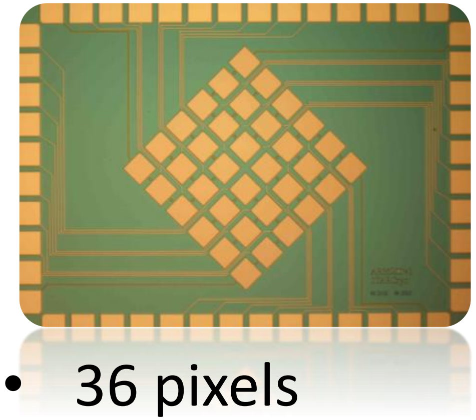
KGS: 56.826(9) + E_K
KES: 11.296(4) + 17 + E_K
LGS: 56.826(9) eV
LES: 11.296(4) + 17

Phys. Rev. Lett. **125**, 032701 (2020)
Phys. Rev. Lett. **126**, 021803 (2021)

~0.1% of Phase-III data

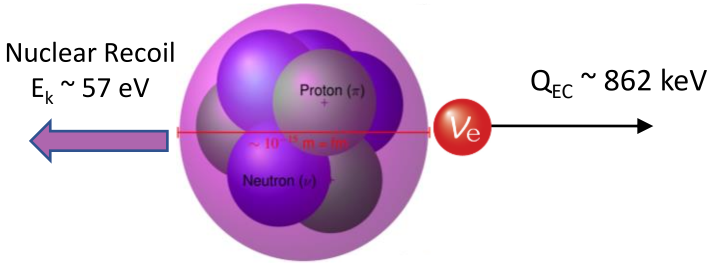


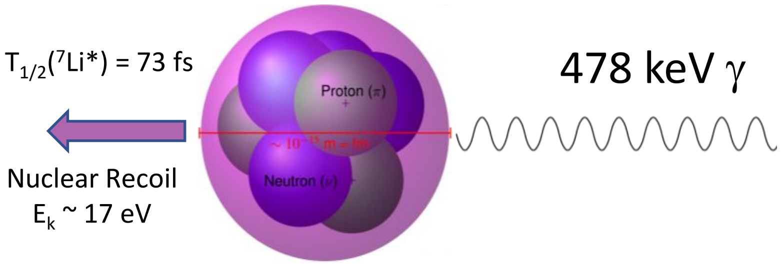
- Single pixel
- 20 hours
- 50 Bq



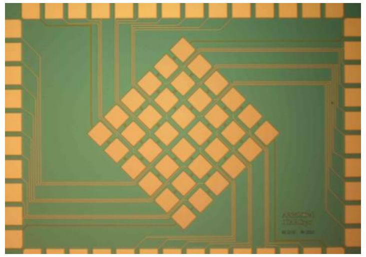
- 36 pixels
- 50 days
- 50 Bq/pixel

Nuclear Effects in 7Be EC Decay: Gamma-Recoil Coincidence

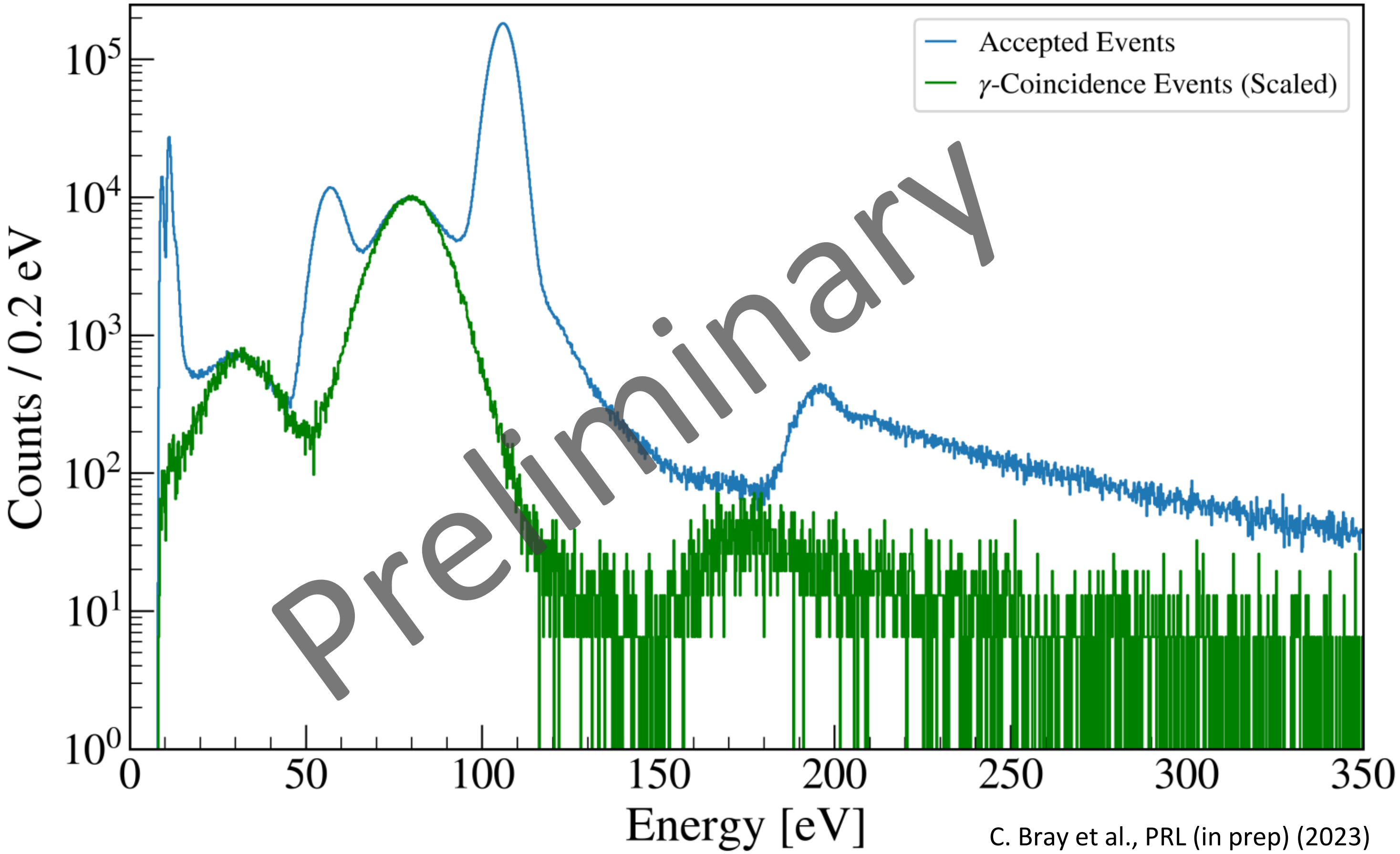




<u>Gamma-recoil coincidence</u> to select only recoils from decays to the ^{7}Li 478 keV excited state



- 20 hours
- 14 pixels
- 10 Bq/pixel



C. Bray et al., PRL (in prep) (2023)

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, Joseph Smolsky, Caitlyn Stone-Whitehead
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Lawrence Livermore National Laboratory, Livermore CA USA

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TRIUMF, Vancouver BC Canada

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CEA Saclay, Paris France

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

2023 Collaboration Meeting
Livermore, California

Fully Explore the Extensive Nuclear Toolbox

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

^{7}Be Beryllium	n 3 z 4
Jπ	3/2-
$T_{1/2}$ or Γ	53.22 d 0.06
Delta (keV)	15768.998 71
Bind/A (keV)	5371.5487 101
Mass (μAMU)	7016928.714 76
Qα (keV)	-1587.1371 708
Qβ (keV)	-11907.5551 251504
Qec (keV)	861.893 71
Sn (keV)	10677.3542 5
Sp (keV)	5606.8539 709
Decay	ec 100%

Major radiations

Type	keV	%
β+		
γ	477.6035	10.44

^{10}C Carbon	n 4 z 6
Jπ	0+
$T_{1/2}$ or Γ	19.290 s 0.012
Delta (keV)	15698.673 70
Bind/A (keV)	6032.0426 70
Mass (μAMU)	10016853.217 75
Qα (keV)	-5101.2767 5
Qβ (keV)	-23101.3545 4000000
Qec (keV)	3648.062 72
Sn (keV)	21283.6164 21378
Sp (keV)	4006.7840 9054
Decay	ec β+ 100%

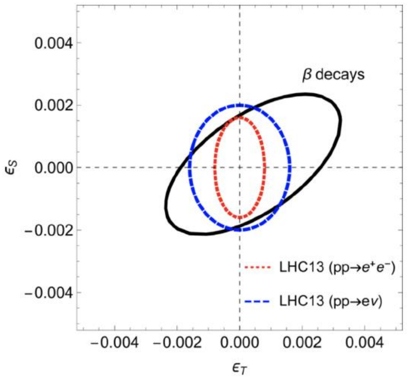
Major radiations

Type	keV	%
β+	814.3	98.50
	353.5	1.4601
γ	511.0	199.92
	718.353	100

^{14}O Oxygen	n 6 z 8
Jπ	0+
$T_{1/2}$ or Γ	70.606 s 0.018
Delta (keV)	8007.781 25
Bind/A (keV)	7052.2783 18
Mass (μAMU)	14008596.706 27
Qα (keV)	-10115.8076 747
Qβ (keV)	-23956.6215 411187
Qec (keV)	5144.364 25
Sn (keV)	23178.9686 10
Sp (keV)	4626.6710 2707
Decay	ec β+ 100%

Major radiations

Type	keV	%
β+	770.55	99.249
	1875.95	0.61
γ	511.0	199.76
	2312.593	99.388



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

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

^{229}Th Thorium	n 139 z 90
Jπ	5/2+
$T_{1/2}$ or Γ	7880 y 120
Delta (keV)	29585.517 2404
Bind/A (keV)	7634.6510 105
Mass (μAMU)	229031761.357 2581
Qα (keV)	5167.5578 10244
Qβ (keV)	-311.3310 37152
Qec (keV)	-1104.419 12
Sn (keV)	5256.7004 26090
Sp (keV)	6598.1079 27791
Decay	α 100% α 100%

Major radiations

Type	keV	%
α	4845.3	56.2
	4901.0	10.20
γ	10.622 - 19.218	80
	13.661 - 18.483	27

Isomer $T_{1/2}$ ≤ 10 μs

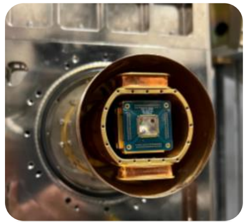
^{229}Pa Protactinium	n 138 z 91
Jπ	(5/2+)
$T_{1/2}$ or Γ	1.50 d 0.05
Delta (keV)	29896.848 3280
Bind/A (keV)	7629.8752 143
Mass (μAMU)	229032095.585 3521
Qα (keV)	5834.6274 4
Qβ (keV)	-1313.7716 66554
Qec (keV)	311.331 4
Sn (keV)	7098.0687 5
Sp (keV)	4163.0224 3
Decay	ec 99.52% α 0.48%

Major radiations

Type	keV	%
α	5580	0.173
	5670	0.089
β+		
γ	11.118 - 20.450	39.7
	93.347	29.9
	10.869 - 19.828	0.199
	90.886	0.133

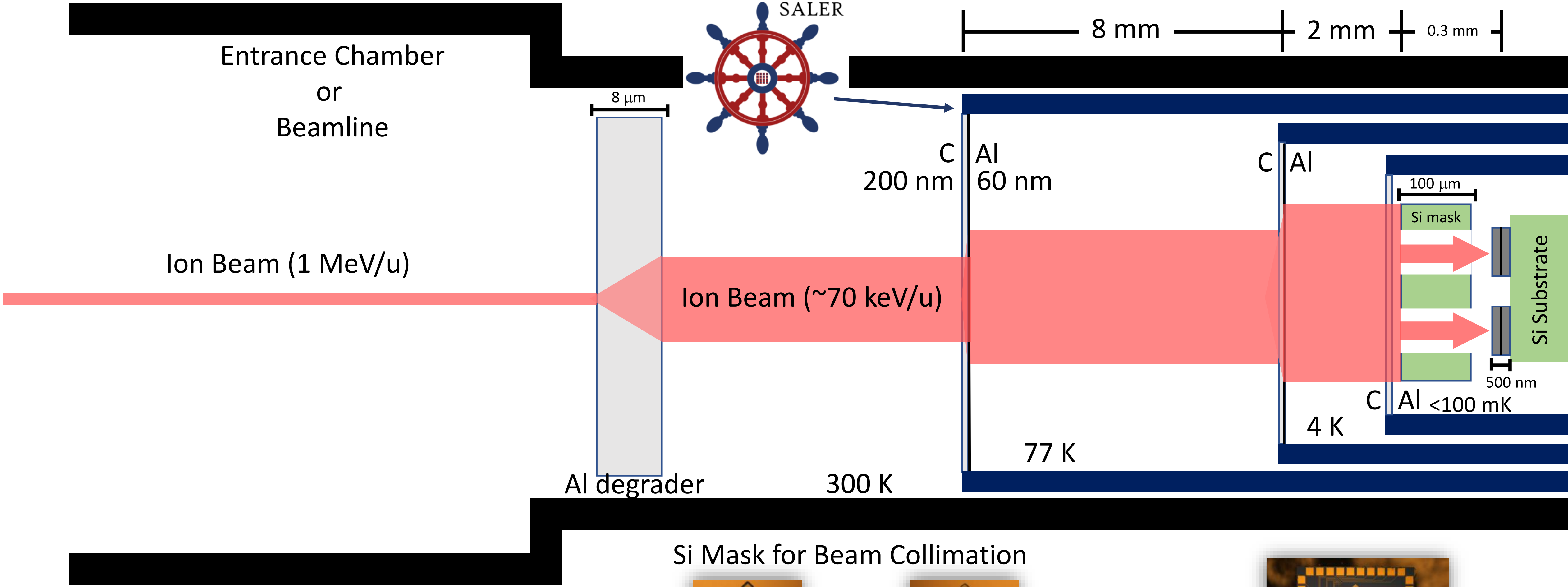
^{229}Pa (State)
10^{10} increase in e^{-} EDM sensitivity

FRIB-400 Production > 10^{9} s^{-1}



SALER

Coupling an Active Quantum Sensor Array to the RI Beamline



Entrance Chamber
or
Beamline

SALER

8 mm
2 mm
0.3 mm

8 µm

C
200 nm

Al
60 nm

C
Al

100 µm

Si mask

Ion Beam (1 MeV/u)

Ion Beam (~70 keV/u)

Si Substrate

500 nm

C
Al
<100 mK

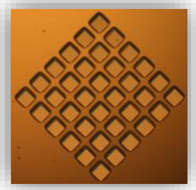
4 K

77 K

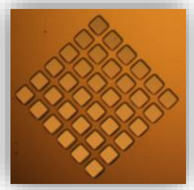
Al degrader

300 K

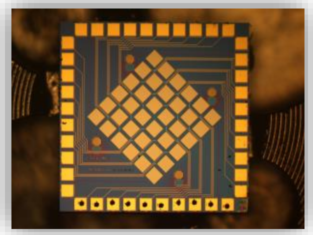
Si Mask for Beam Collimation



Before Alignment



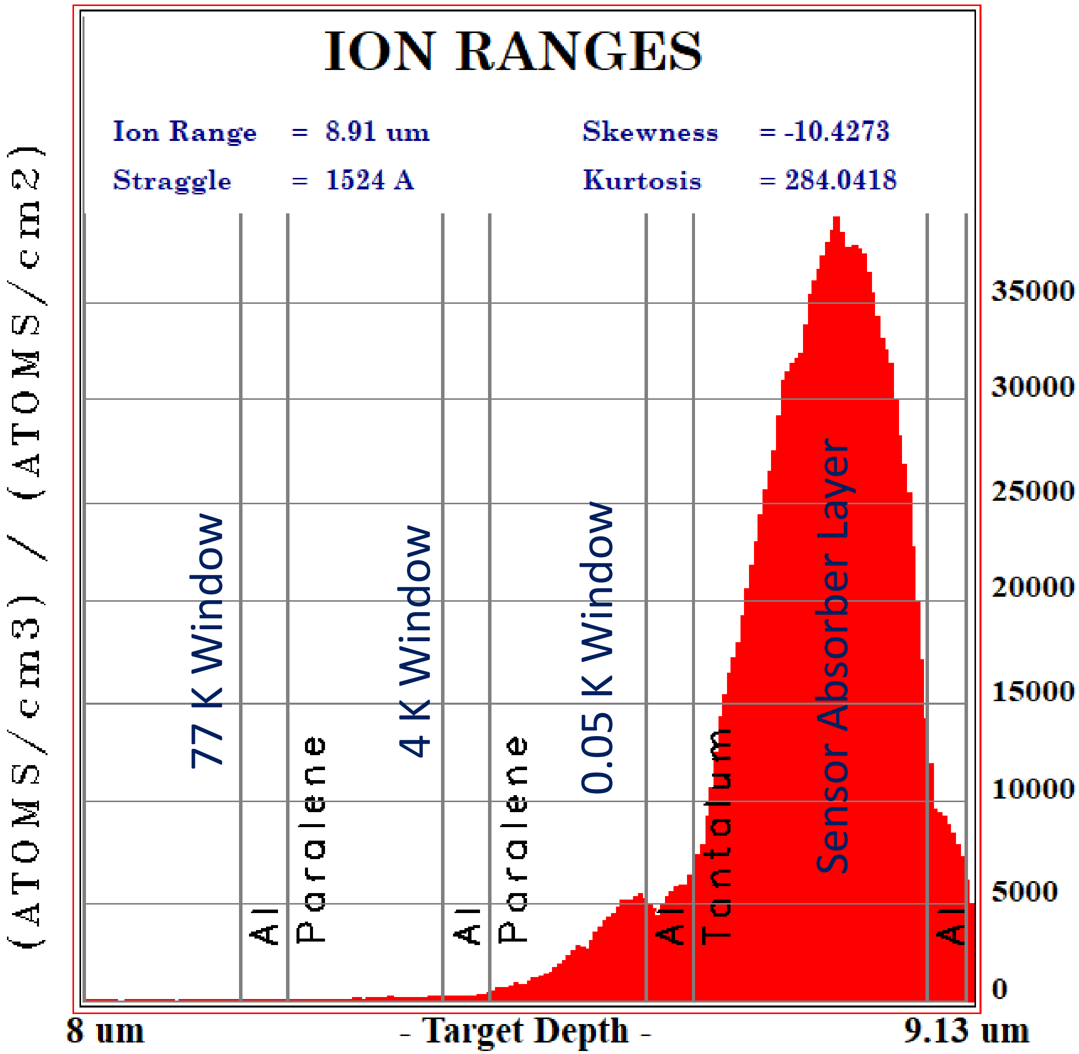
After Alignment



Mounted 36-Pixel STJ Array

* Not to scale (obviously….)

Beam Requirements – Energy and Purity



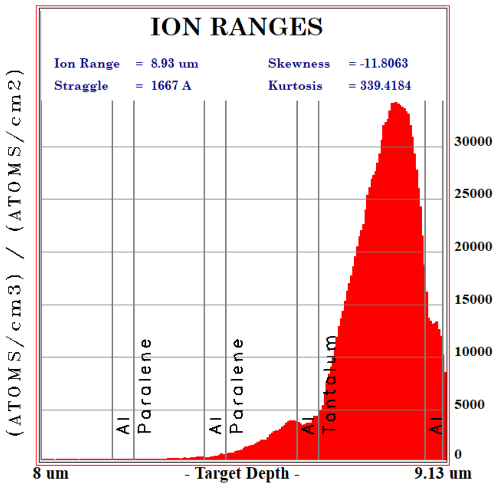
11 MeV ^{11}C Beam w/ 8μm Al foil

For a given energy, initial beam from ReA can be +/- a few % in spread

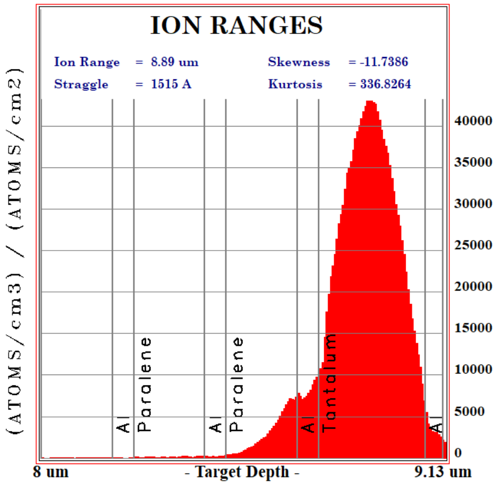
1% spread gives ~50 nm width in the depth profile

Total $^{11}C^{+}$ to achieve goal: ~10^7 (< 2 days of beam @ 100 pps)

Purity: 1 part in 10^6



11.1 MeV ^{11}C Beam

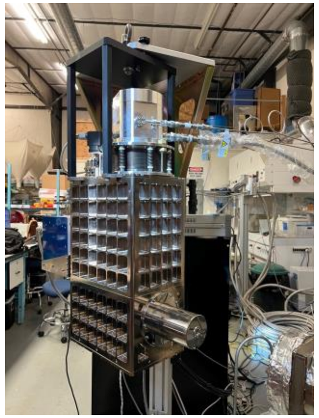


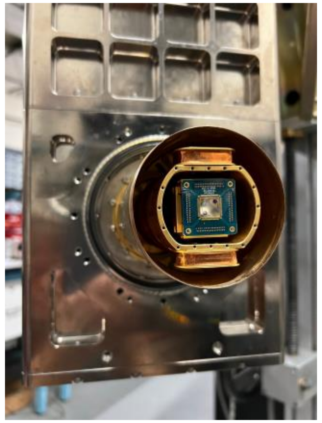
10.9 MeV ^{11}C Beam

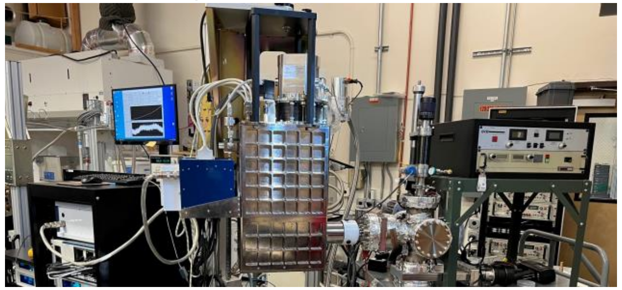
Short-Lived Isotopes in Active Sensor Arrays

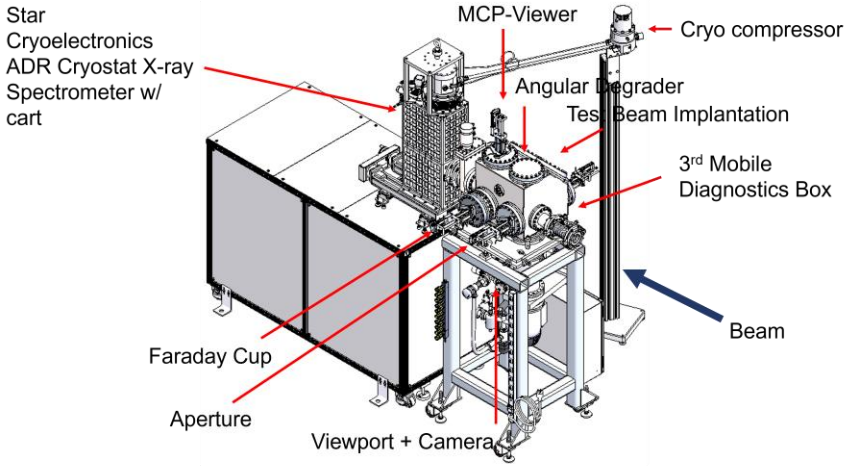
SALER @ FRIB

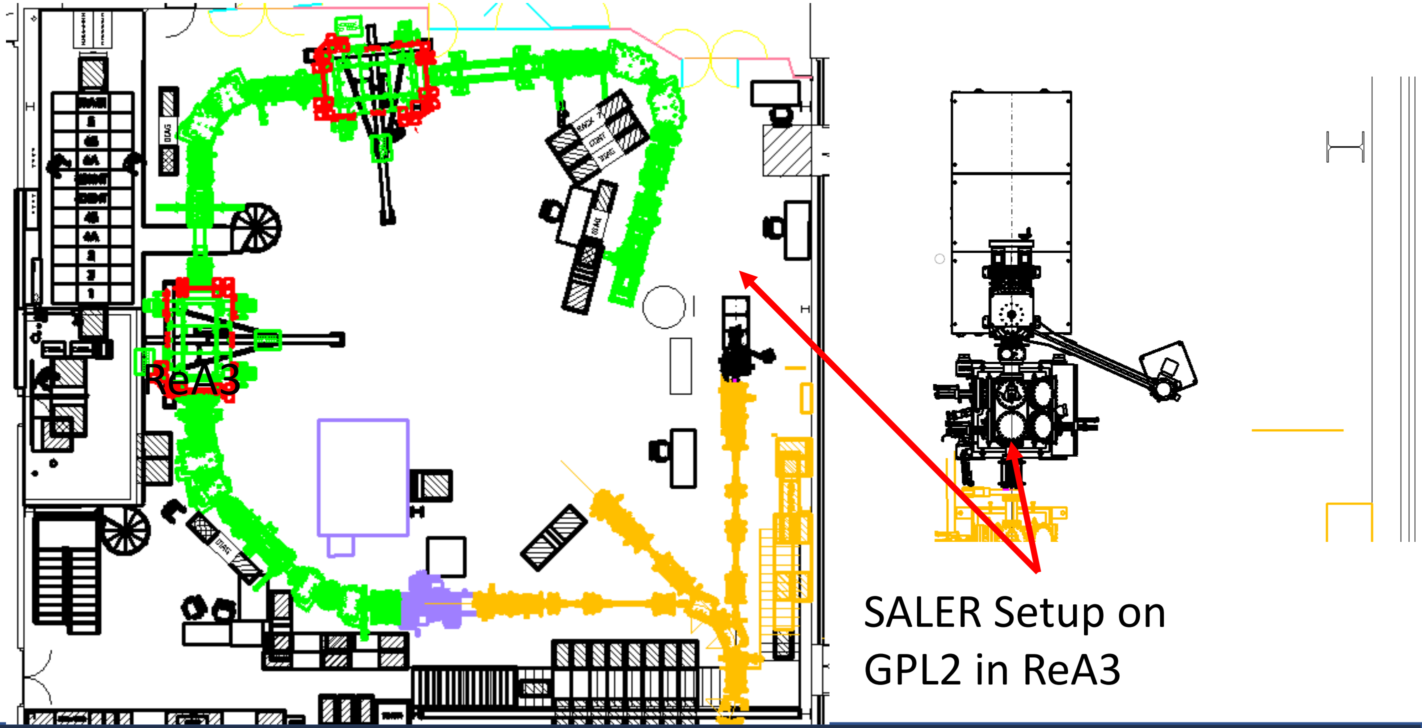
- Assembly and testing at Star Cryoelectronics is underway
- Delivery of SALER to FRIB scheduled for January 2024





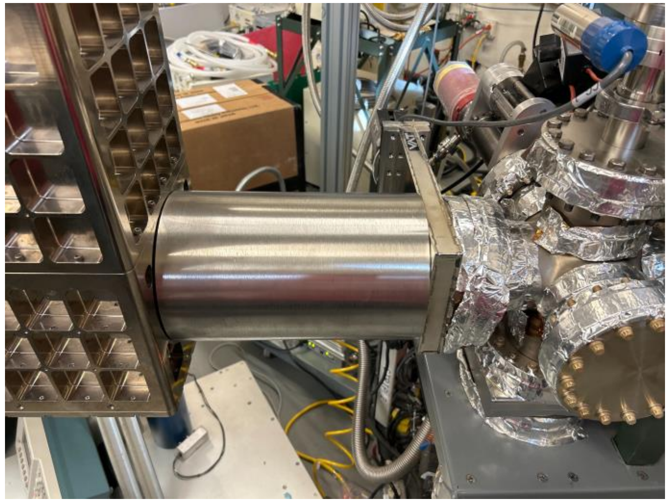


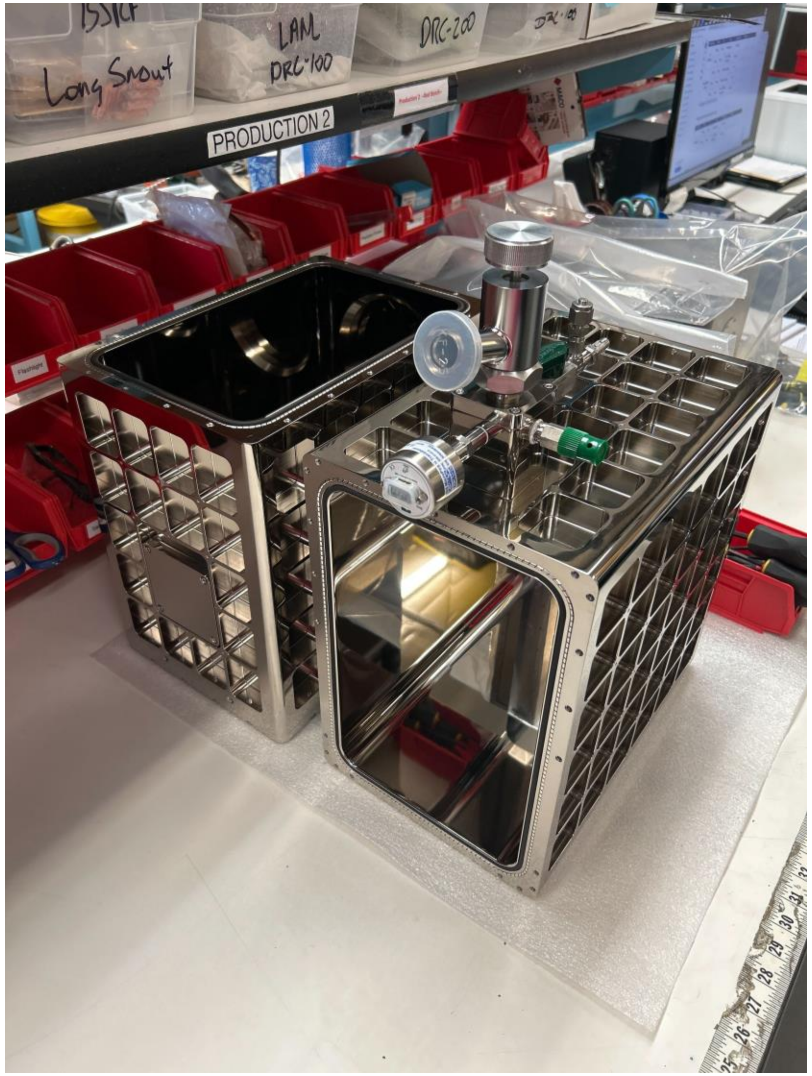




SALER Setup on GPL2 in ReA3

SALER Construction – Progress as of Today

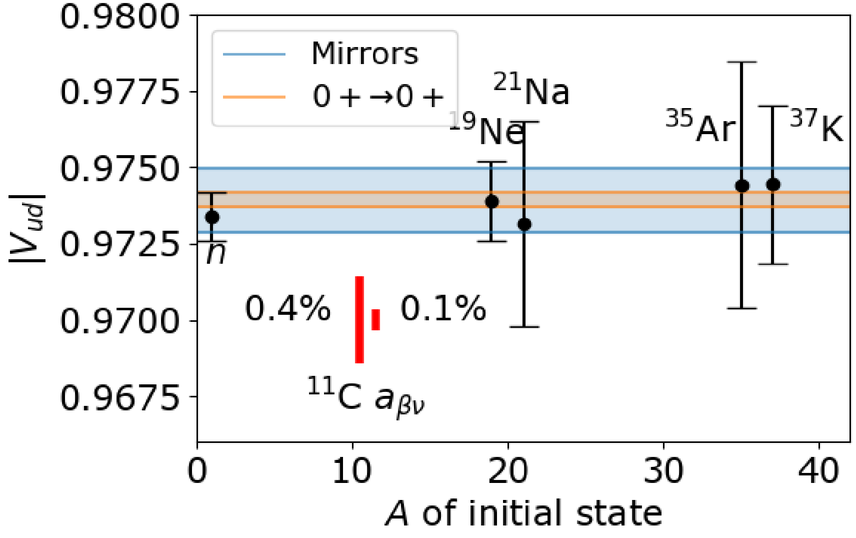




Where are we Headed with This? – Exotic Weak Currents

SALER initially aims to measure

- ^{19}Ne (current most precise)
- ^{11}C (best potential case)

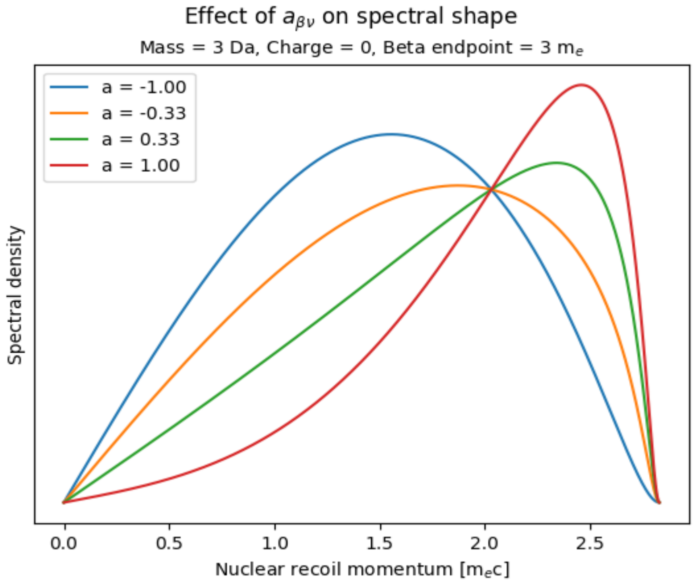


Recoil spectroscopy has O(1) sensitivity to ρ

$$\mathcal{F}t^{mirror}\left[1+\frac{f_A}{f_V}\boxed{\rho^2}\right]=\frac{K}{G_F^2\boxed{V_{ud}^2}g_v^2\left(1+\Delta_R^V\right)}$$

crucial for extraction of V_{ud}

What about *statistical sensitivity*?



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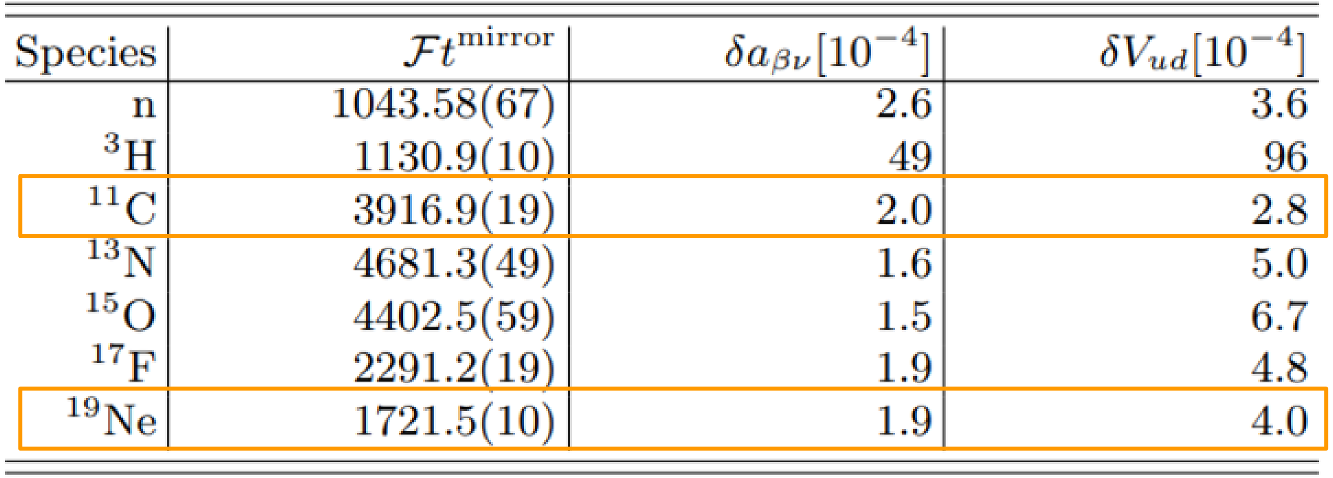
Statistical Sensitivity to BSM Physics using Recoils

Assuming **10^8 decays**, recoil spectroscopy on <u>all mirrors</u> (except ^{3}H) achieves

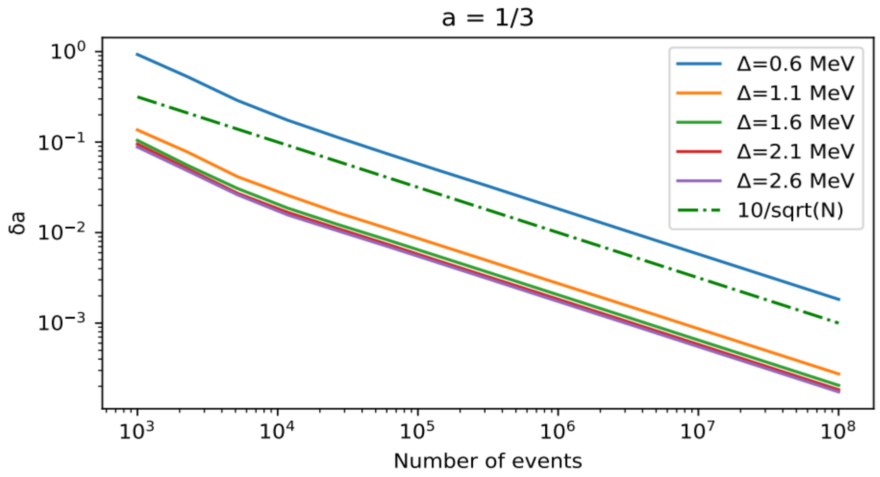
$\delta a/a \sim 10^{-4}$



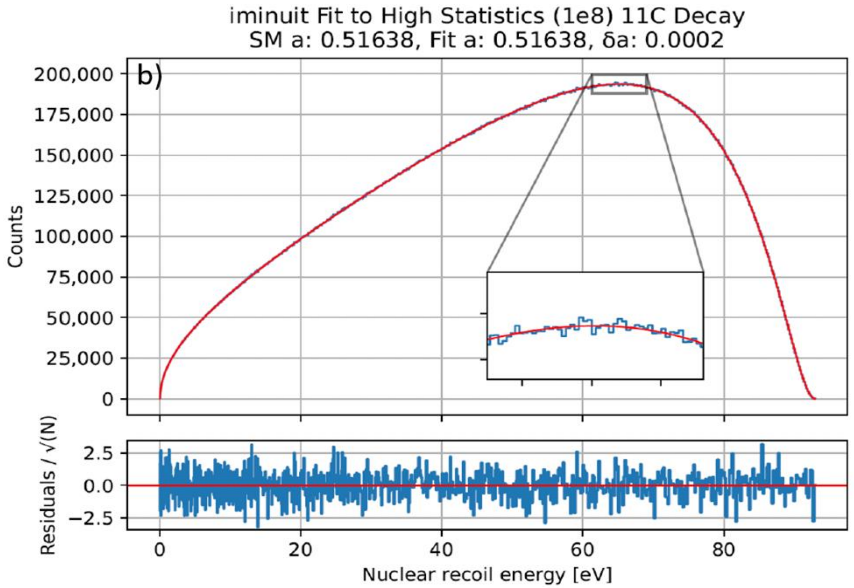
Species	$\mathcal{F}t^{\mathrm{mirror}}$	$\delta a_{\beta\nu}[10^{-4}]$	$\delta V_{ud}[10^{-4}]$
n	1043.58(67)	2.6	3.6
^{3}H	1130.9(10)	49	96
^{11}C	3916.9(19)	2.0	2.8
^{13}N	4681.3(49)	1.6	5.0
^{15}O	4402.5(59)	1.5	6.7
^{17}F	2291.2(19)	1.9	4.8
^{19}Ne	1721.5(10)	1.9	4.0

- **Can reach 10^8 decays in 1 day with ~128 pixels**
- **Systematics budget in progress**

L. Hayen and A. Marino (2023)



a = 1/3



iminuit Fit to High Statistics (1e8) 11C Decay
SM a: 0.51638, Fit a: 0.51638, δa: 0.0002

Conclusions and Opportunity for Collaboration

- SALER assembly is nearly complete
- Delivery to FRIB in January 2024
- Commissioning in Spring/Summer 2024

Partners

Lawrence Livermore National Laboratory
TRIUMF
STAR CRYOELECTRONICS
MICHIGAN STATE UNIVERSITY
McGill UNIVERSITY
NOVA SCHOOL OF SCIENCE & TECHNOLOGY
NC STATE UNIVERSITY
Yale University
XIA
BERKELEY LAB
Massachusetts Institute of Technology
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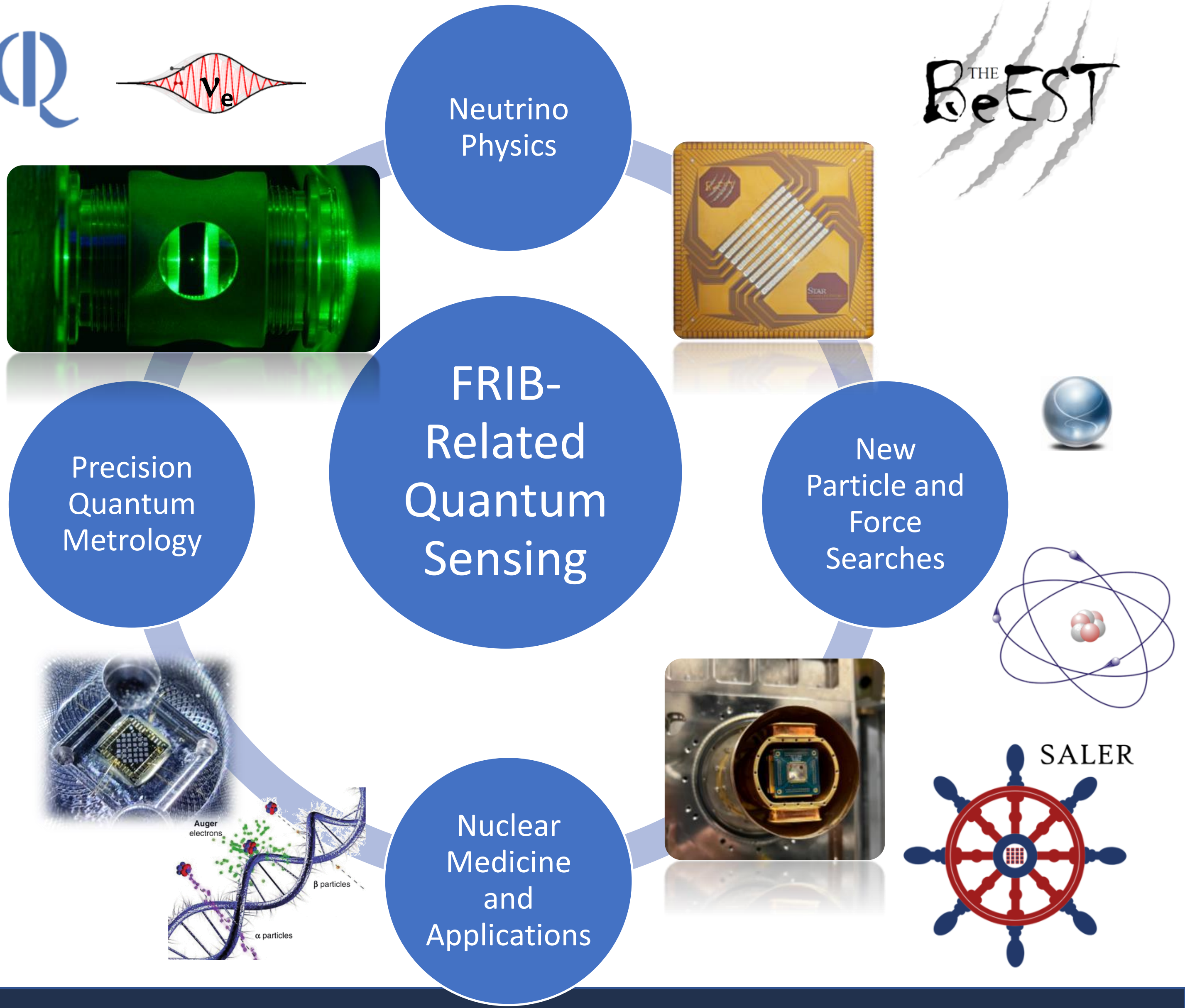
NSERC CRSNG
NSF

Specifications:

- <5 eV energy resolution
- 10 eV threshold
- Absolute energy calibration (10 meV)
- $T_{1/2}$<100 ms



FRIB-Related Quantum Sensing

Neutrino Physics

New Particle and Force Searches

Nuclear Medicine and Applications

Precision Quantum Metrology