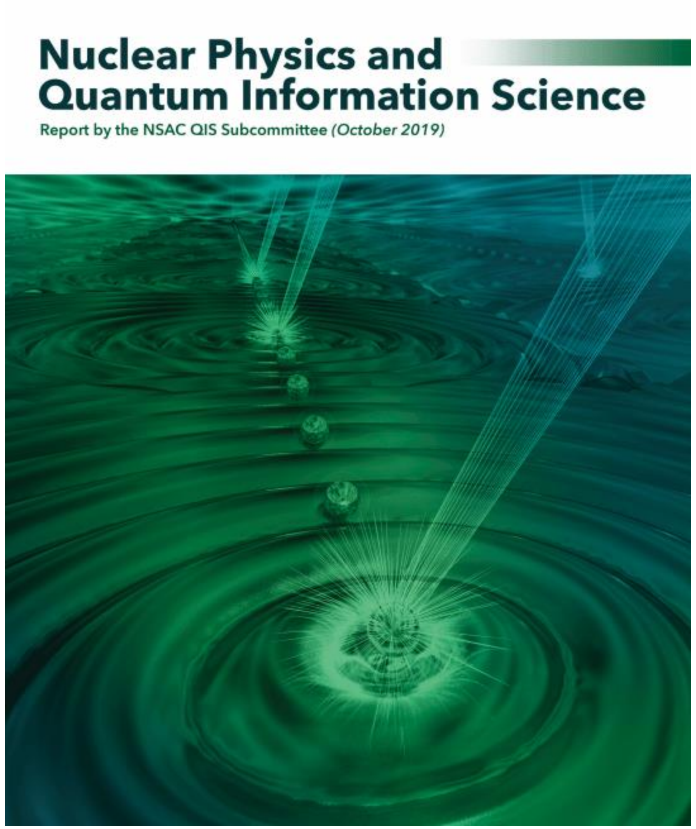
Low-Energy Quantum Sensing Methods with Rare-Isotopes at ISAC

Kyle Leach, Colorado School of Mines

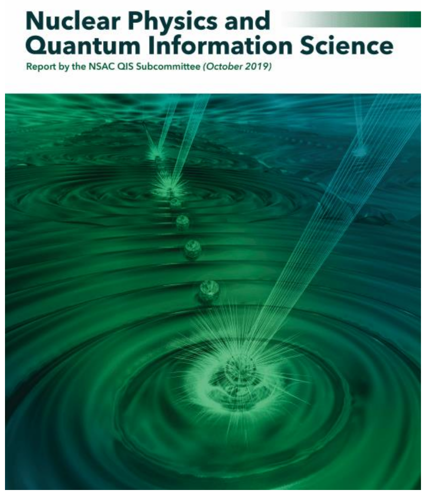
https://beest.mines.edu

TRIUMF Science Week
Thursday August 20, 2020



https://science.osti.gov/np/Research/Quantum-Information-Science

Quantum Sensing and Nuclear Physics



"The need for quantum sensors permeates the entire field of NP, encompassing [all] physics arguments and scientific objectives.."

Quantum Sensors 1.0: Devices such as transition edge sensors (TESs), superconducting nanowire single photon detectors (SNSPDs), microwave kinetic inductance detectors (MKIDs), Josephson parametric amplifiers (JPAs), [and Superconducting Tunnel Junctions (STJs)]. Their use essentially spans all subfields, including condensed matter, atomic, molecular and optical physics, NP, HEP, and astronomy. **They play critical roles in cosmic microwave background searches, sub-millimeter astrophysics, and dark matter searches.**

In use currently for NP

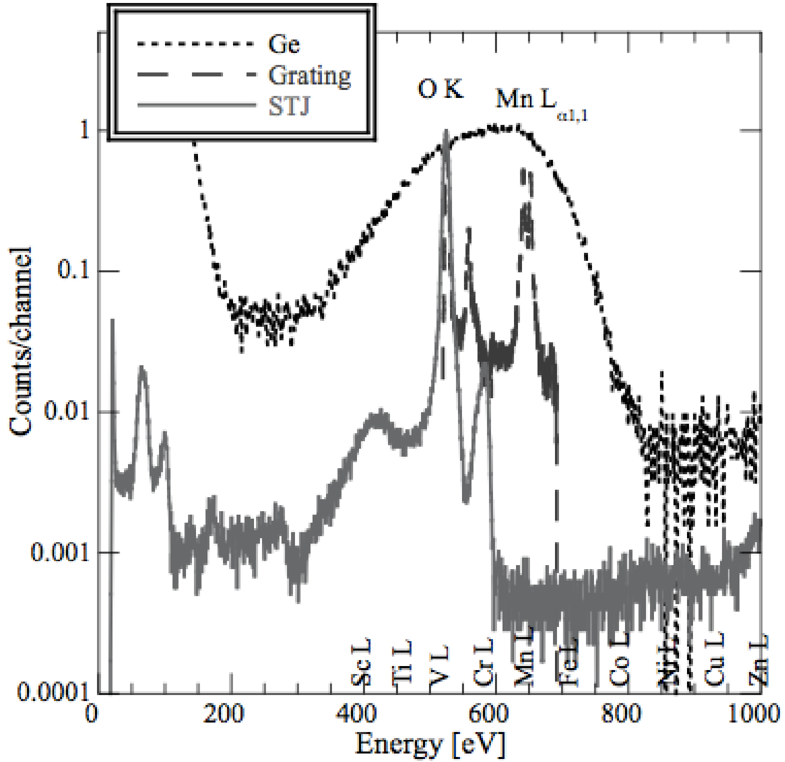
Quantum Sensors 2.0: Devices whose operation depends explicitly on quantum phenomena such as superposition of states (coherence) and/or entanglement to achieve superior performance. **These devices use quantum systems and quantum manipulations that frequently share basic elements with those used for QC with qubits.** However, their design is specific to sensing applications.

On the horizon for NP

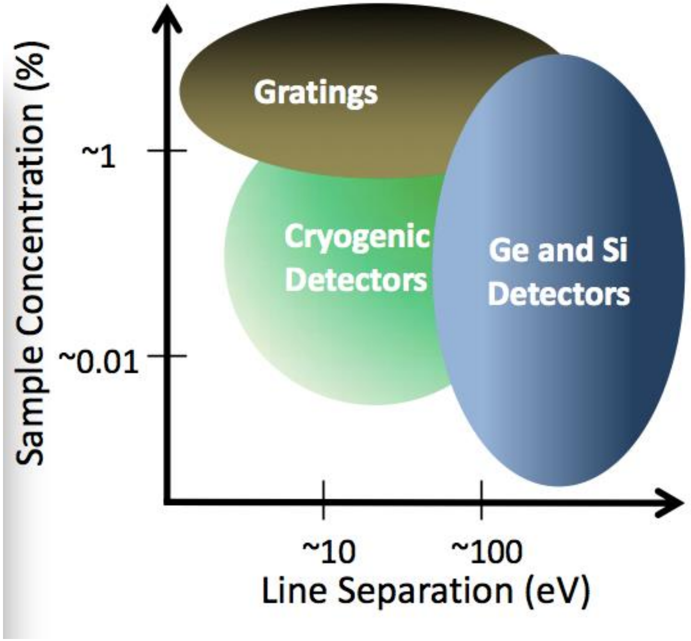
Since optical manipulation and ion/atom trapping (clocks, EDMs) are well covered already at Science Week, I will focus here on quantum sensing in the Low-Temperature Detector (LTD) regime – "Quantum Sensors 1.0".

High-Resolution Low-Temperature Detectors

O. Drury, IEEE Tr. Appl. Sc **15**, 613 (2005)

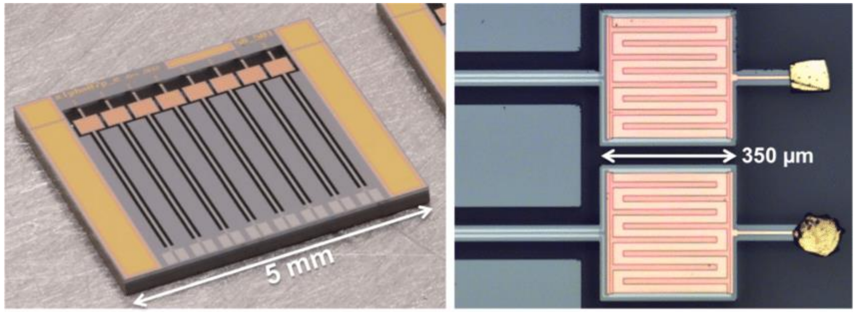


Higher resolution than Si or Ge,
Higher efficiency than gratings.

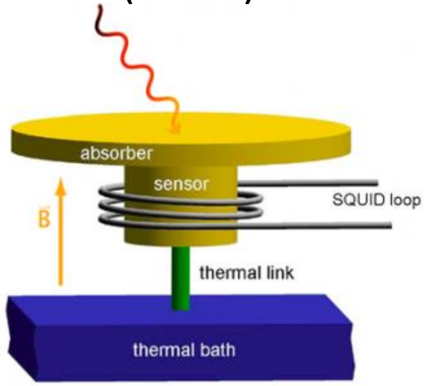


Soft X-ray spectroscopy of dilute samples.

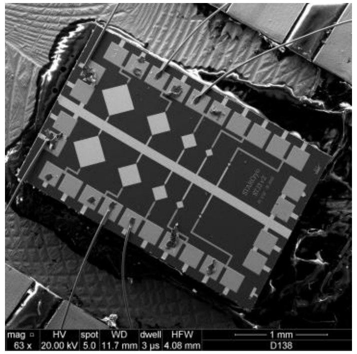
Transition Edge Sensor (TES)



Magnetic Microcalorimeter (MMC)



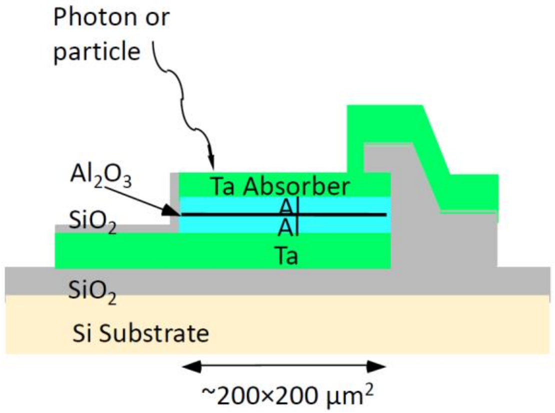
Superconducting Tunnel Junction (STJ)

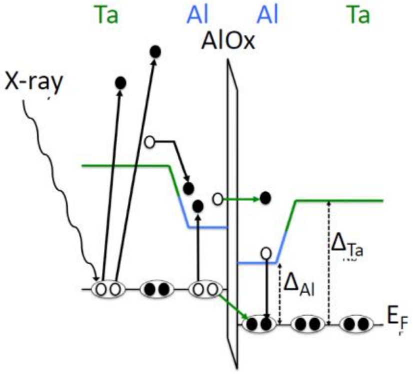


Slide Courtesy S. Friedrich (LLNL)

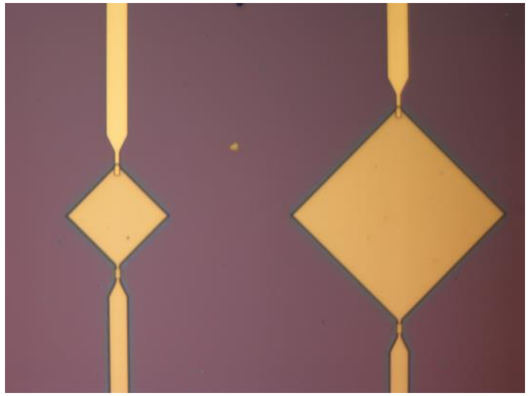
Superconducting Tunnel Junctions as Radiation Detectors

- Two electrodes separated by a thin insulating tunnel barrier
- Absorbed energy breaks the Cooper pairs of the superconducting ground state and excites charges above the energy gap Δ in proportion to the deposited energy E
- Since the superconducting energy gap Δ is of order ~meV, radiation generates roughly 1000x more excess charges in a superconductor than in conventional semiconductor
  → High Energy Resolution (~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)



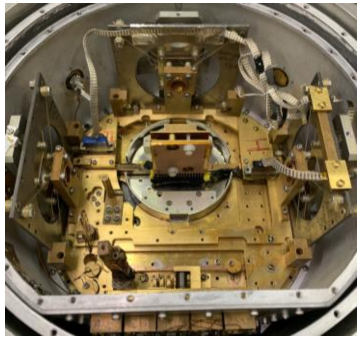


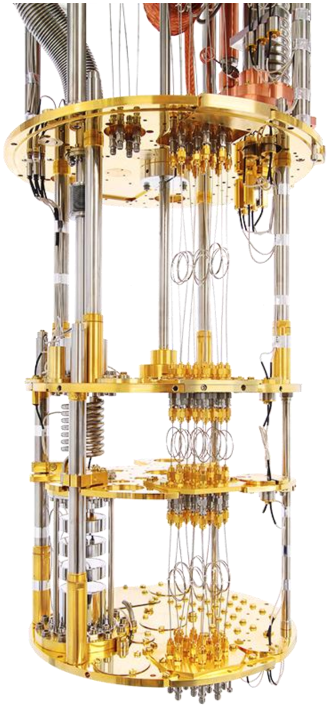
Josephson Junction



Applications of Tunnel Junctions and MMCs/TES'

	Tunnel Junctions	Microcalorimeters
Operating principle	$E \rightarrow \Delta Q$ (electrons)	$E \rightarrow \Delta T$ (phonons)
→ Max volume	low (E_{max} < 10 keV)	high (E_{max} < MeV)
Energy resolution	$\sim[2\Delta_{sc}E]^{1/2}$	$\sim[k_B T^2 C_{abs}]^{1/2}$
	~0.2 - 20 eV FWHM	~1 - 5 eV FWHM
Max. count rate	**<10,000 cts/s**	~10-100 cts/s
Device resistance	High, > 1000 Ω	Low, < 0.1 Ω
→ Electronic readout	**FET at room T**	SQUID at 4 K
Max. operating T	<0.5 K (ADR)	<0.1 K (Dil Fridge)





X-ray astrophysics

Nuclear security, Rare-Event Searches, Dark Matter

Microcalorimeters and TES' are preferred for highest energy resolution and large volume absorbers.
Superconducting Tunnel junctions are preferred for high speed applications at low energies.

Synchrotron science, Solar physics, **BeEST and SALER**

Slide Courtesy S. Friedrich (LLNL)

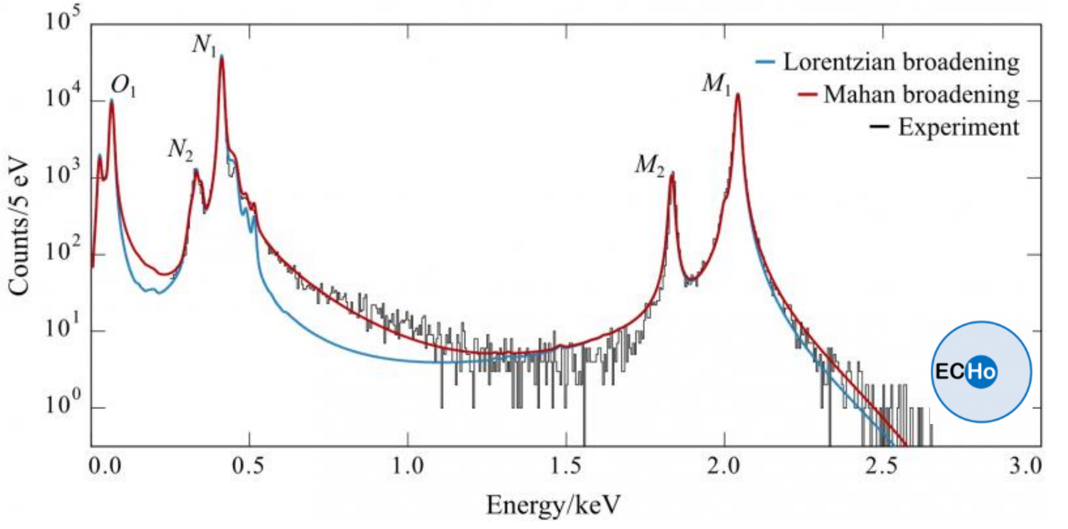
Recent Examples of Quantum Sensing in NP

MMC

TES

Determination of the Absolute Mass Scale of the Neutrino

- ^{163}Ho electron capture decay (Q_{EC}=2.8 keV) spectroscopy to achieve a sensitivity to the "normal matter" neutrino mass of better than 0.2 eV

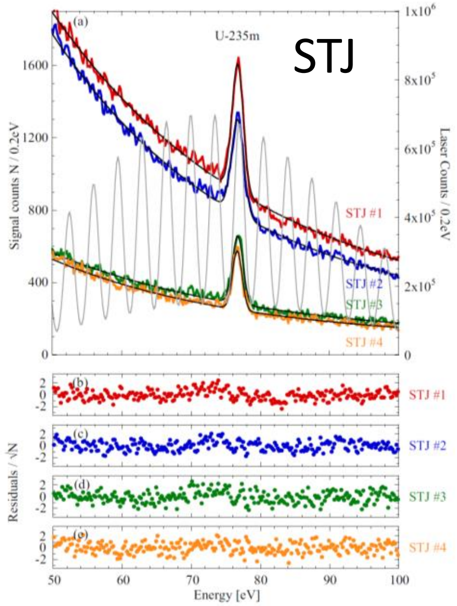


C. Velte et al., Eur. Phys. J. C **70**, 1026 (2019)

Ultra-Low Energy Spectroscopy Towards Nuclear Clock Transitions

- Development towards spectroscopy of ^{229m}Th 8 eV nuclear clock transition energy
- ^{235m}U low-energy measured to high precision: 76.737(18) eV

STJ



F. Ponce et. al., Phys. Rev. C **97**, 054310 (2018)

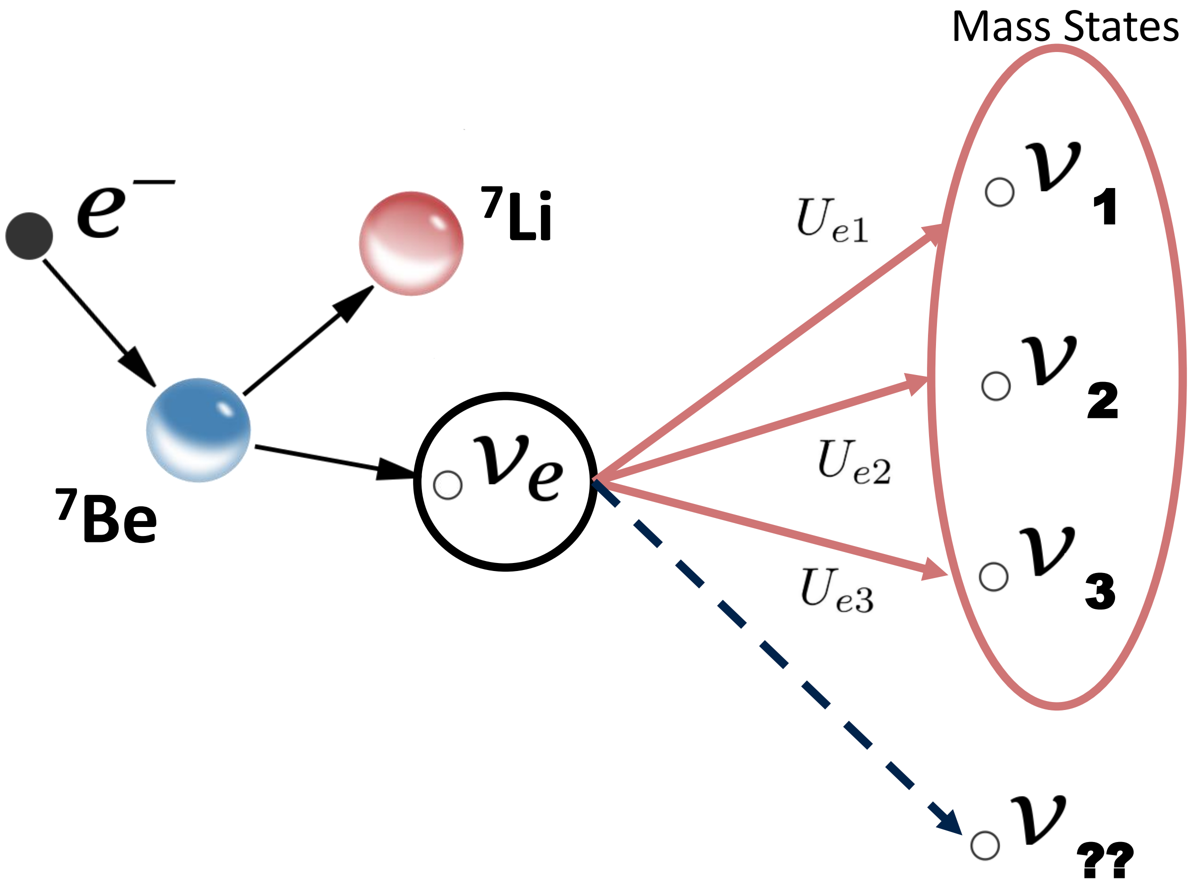
Two Approved RIB Experiments at ISAC (January 2020 EEC)

S2005: 7Be Implantation into Superconducting Tunnel Junctions for the BeEST Sterile Neutrino Search Experiment

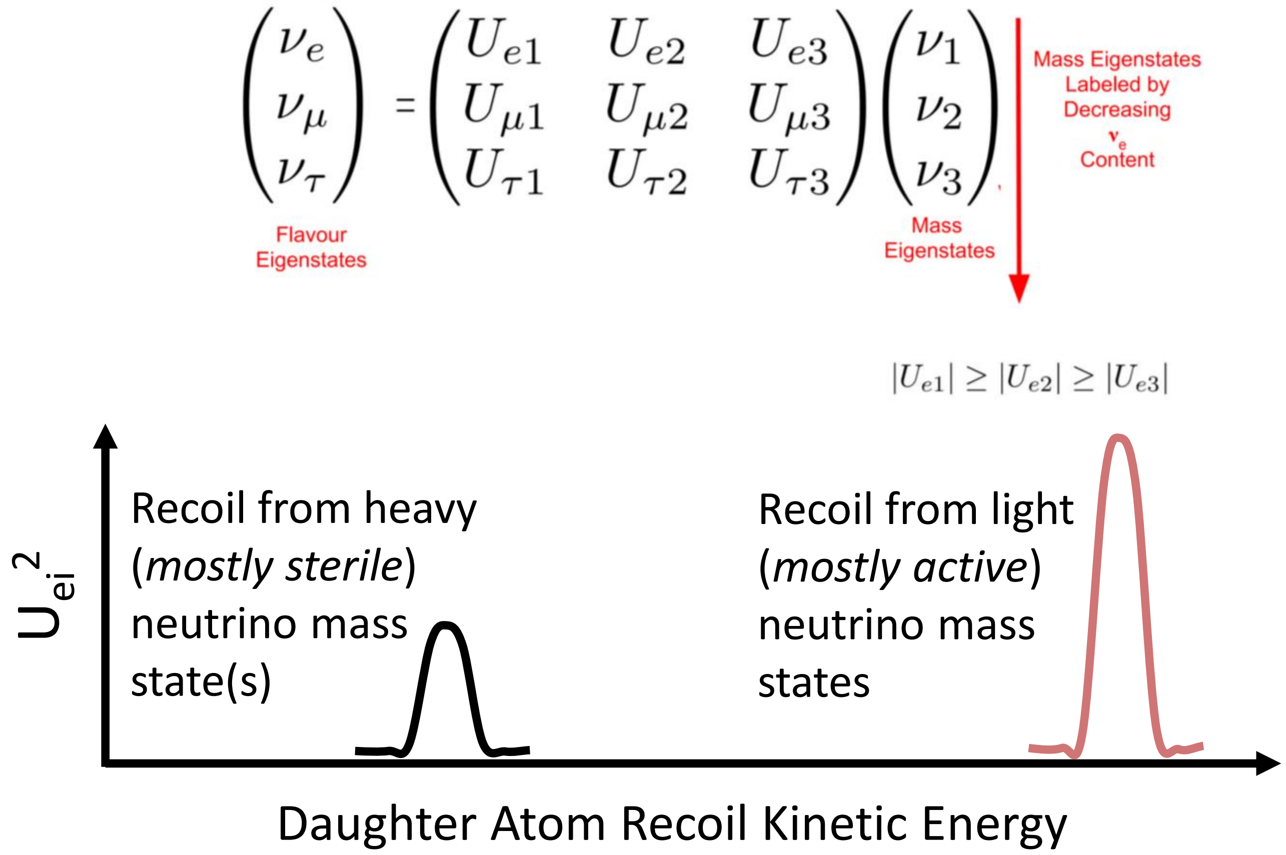
S2048: Redefining the Geologic Timescale of the Solar System by Accurately Determining the ^{146}Sm Half-Life with Magnetic Microcalorimeters

A Search for BSM Physics in the Neutrino Sector

- ^{7}Be is the ideal case for neutrino studies momentum reconstruction
- Simple atomic and nuclear structure and largest *Q*-value (862 keV) of all pure EC cases
  - ➔ Highest-energy recoil from EC decay (~50 eV)

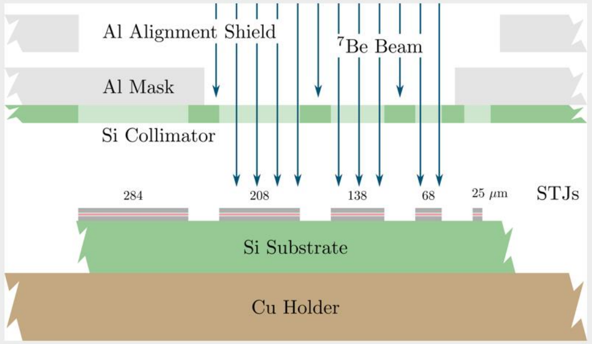


$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



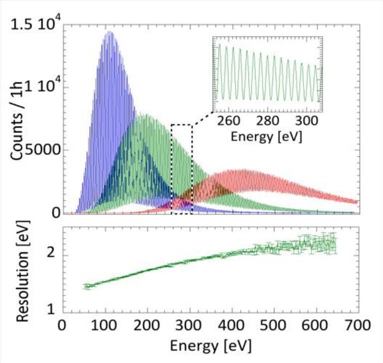
The BeEST Experimental Concept

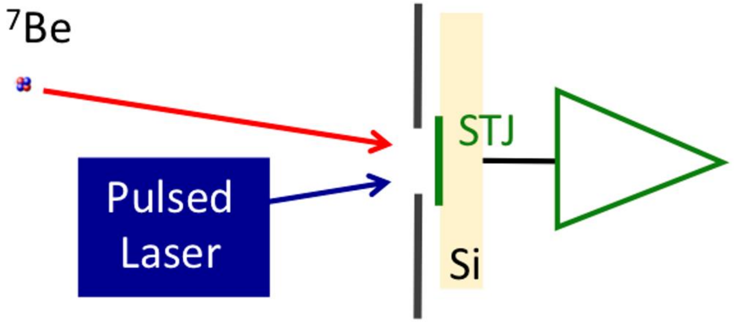
Implanted ^{7}Be Sample

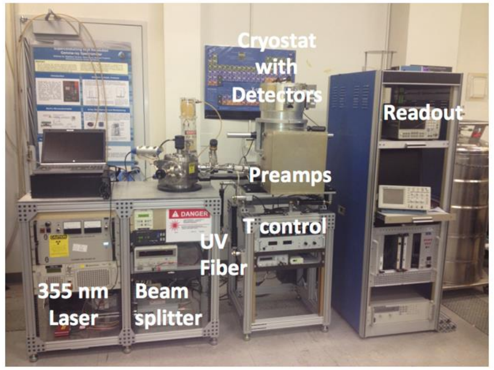


Simultaneous Laser Calibration

Provides energy calibration to <0.01 eV



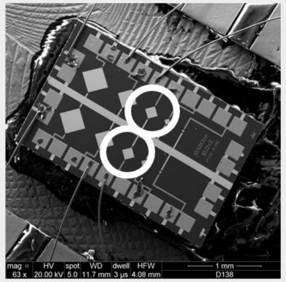




Ta-Based STJ Detectors

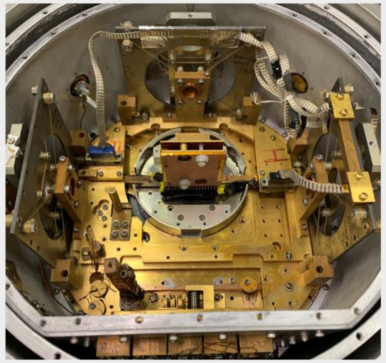
"Test" chips with 10 pixels of 5 sizes

Phase-I



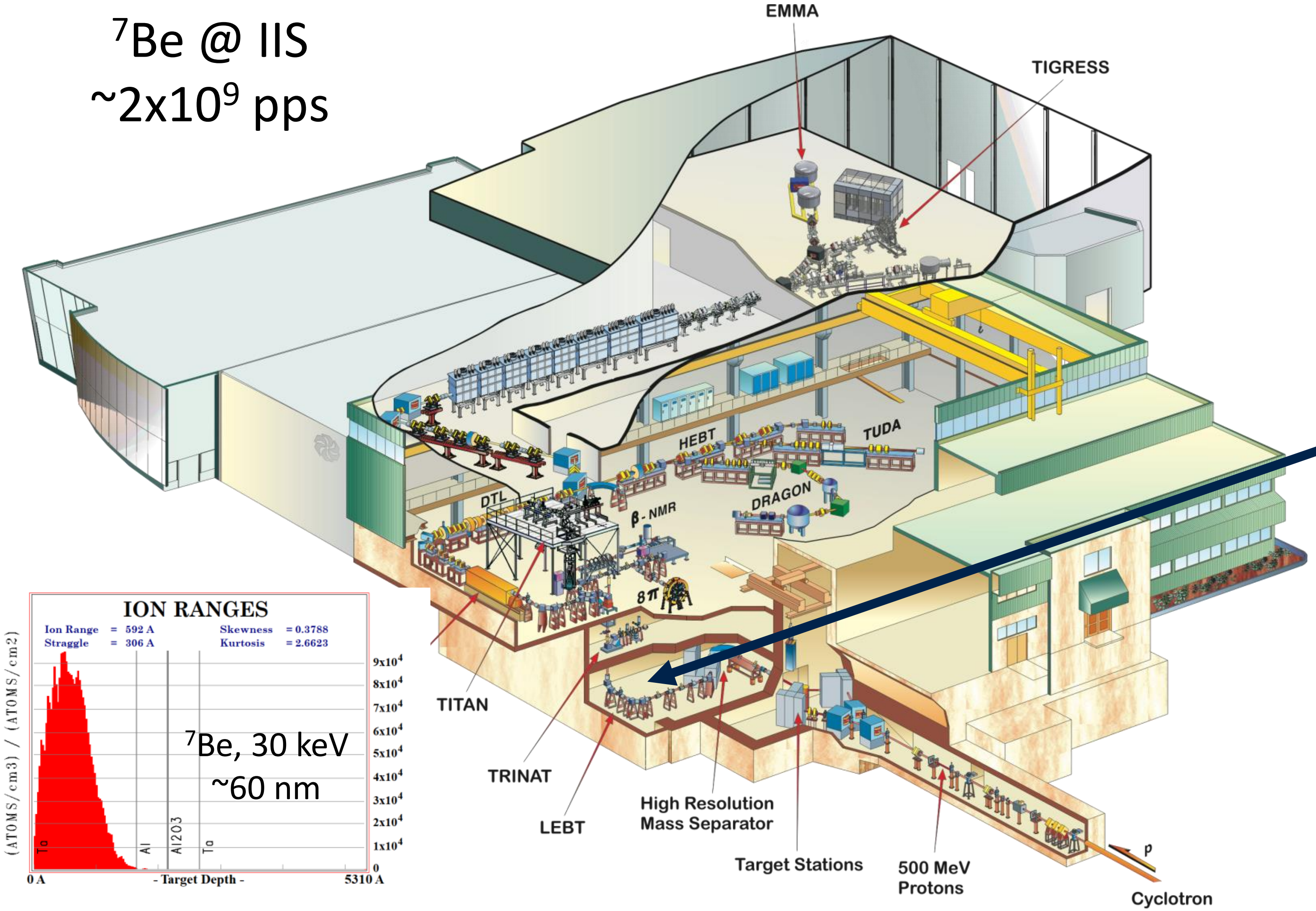
Phase-II

Cooled to 100 mK in an adiabatic demagnetization refrigerator (ADR)



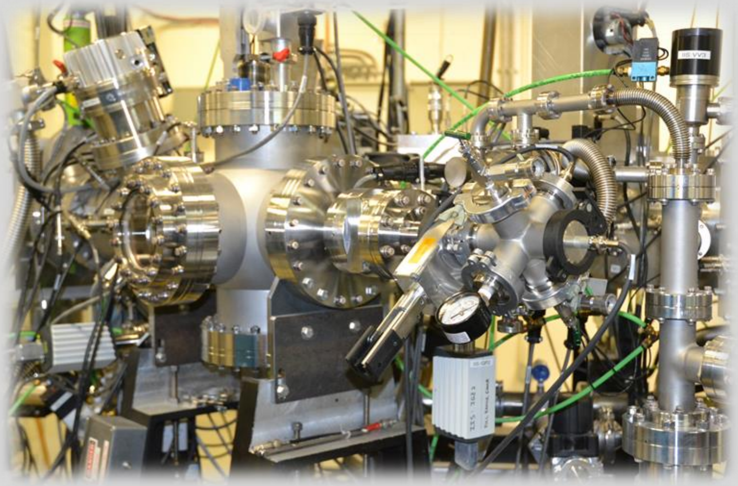
Direct Implantation of ^{7}Be at ISAC

^{7}Be @ IIS
~2x10^9 pps

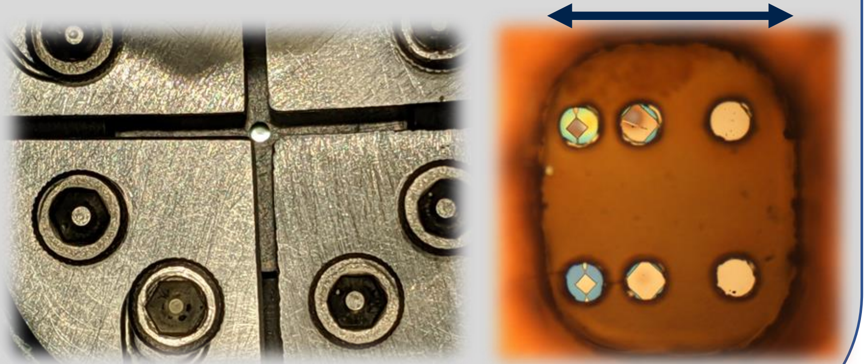


^{7}Be, 30 keV
~60 nm

The ISAC Implantation Station



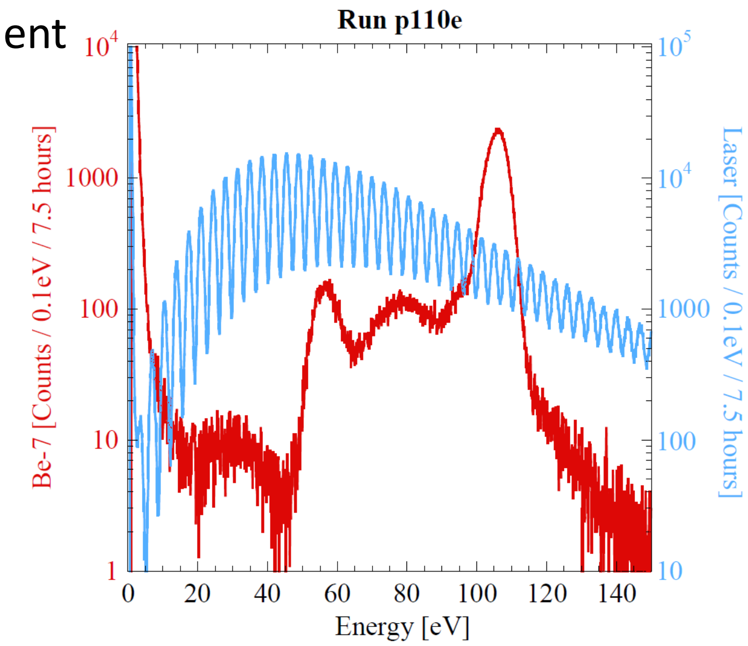
1 mm

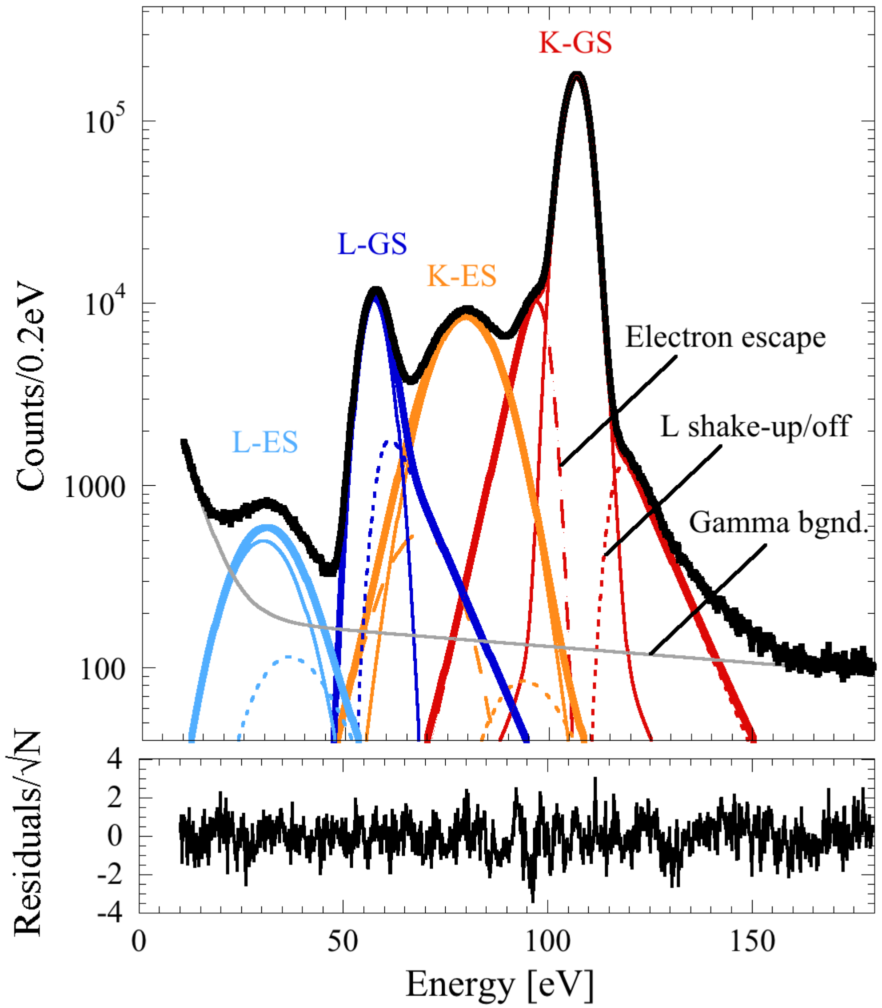


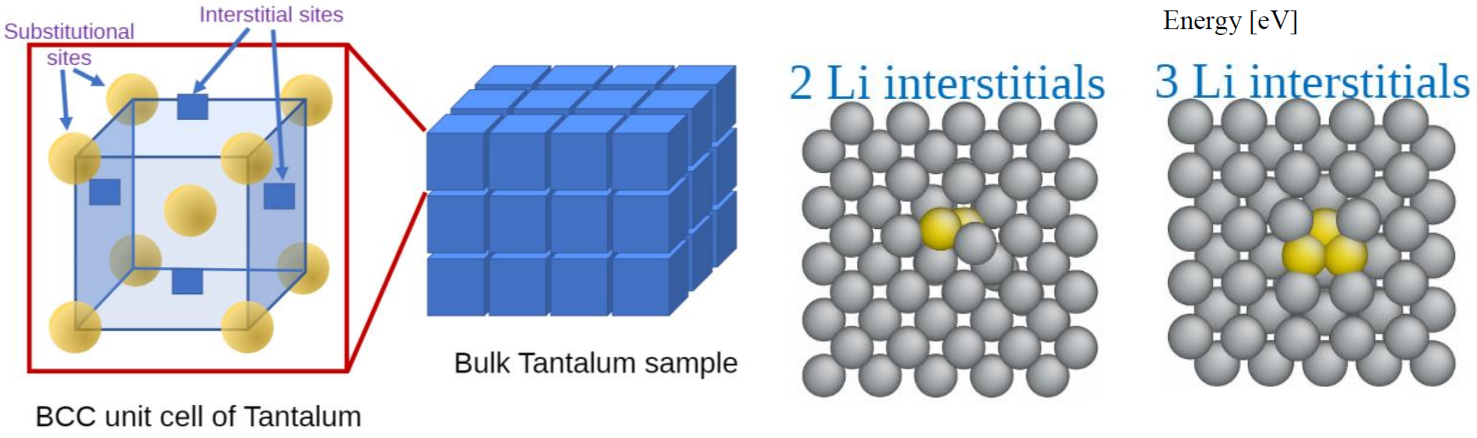
First Nuclear Recoil Experiments with Tantalum STJs

- High-statistics L/K capture ratio measurement
- Laser calibration precision <10 meV
  - Non-linearity of order 10^{-4} per eV

    S. Friedrich et al., J Low Temp Phys (2020)
  - Energy Resolution:
    - Laser peaks: 1.4 to 2.9 eV
    - Recoil peaks: 6 eV
      - Likely due to in-medium effects of Be/Li in Ta





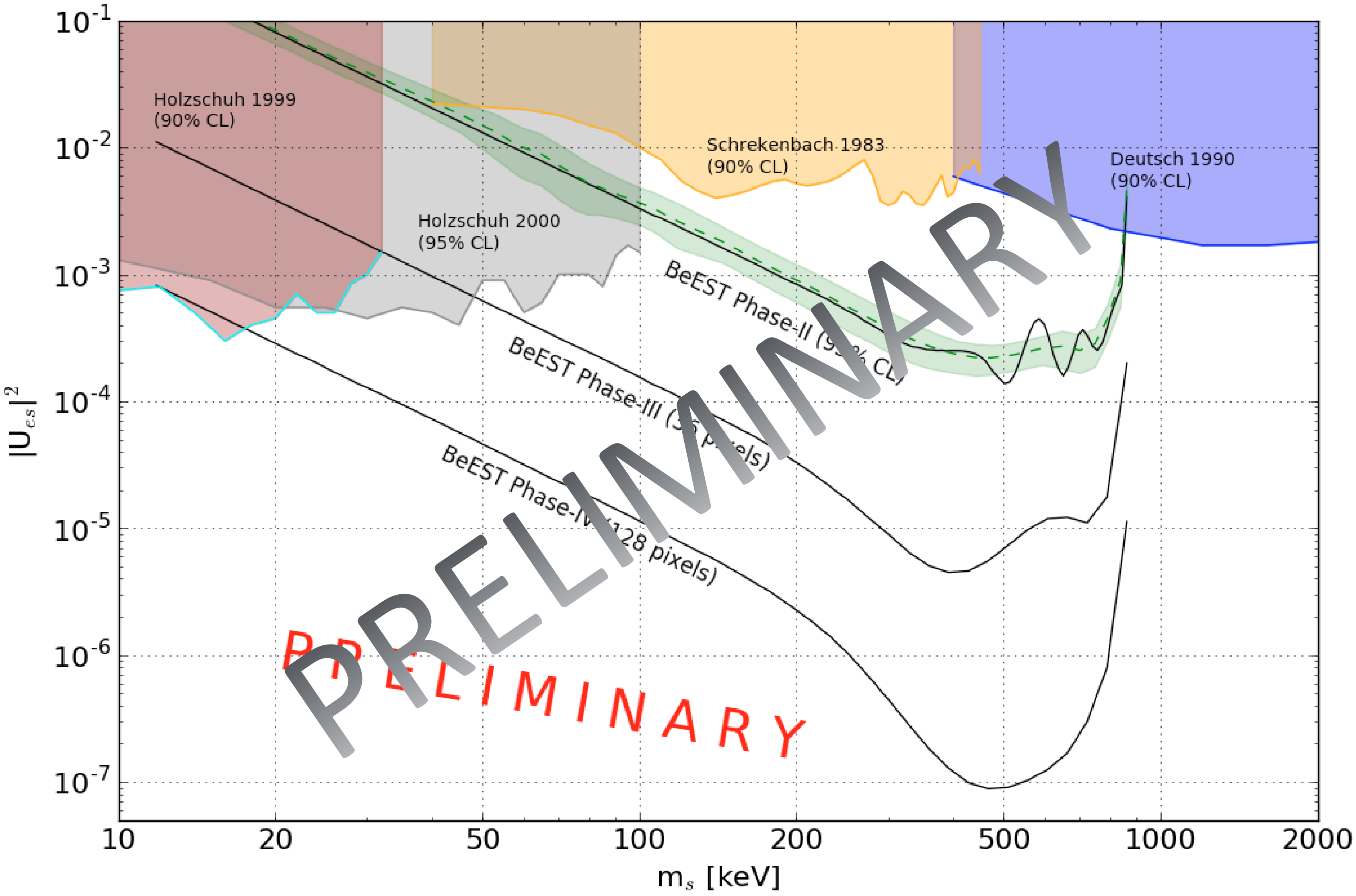


Vince Lordi and Amit Samanta – Quantum Simulation Group (LLNL)

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

Preliminary Exclusion Limits from "Low-Rate" Phase-II Data

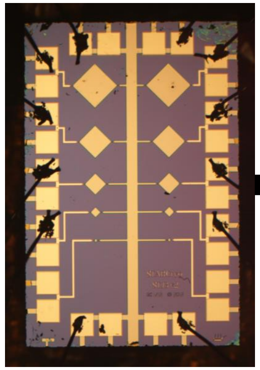
- Limits from Phase-II are derived from a single detector counting for a month (~20 hours/day) at a few Hz
- This rate is more than *three orders of magnitude* lower than the counting limit for these detectors
- The power of high-rate/intensity RIB with STJs has not fully been explored, but may have tremendous potential



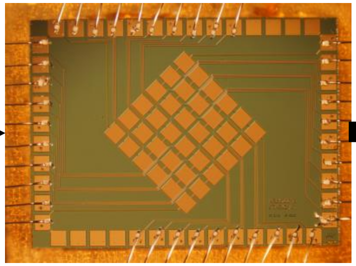
STJ Detector Development for NP

Stephan Friedrich
Lawrence Livermore National Laboratory

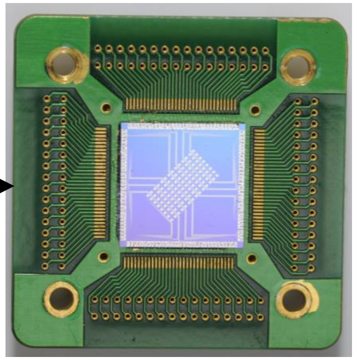
10 "Test" Pixels



36-Pixel Array



112-Pixel Array

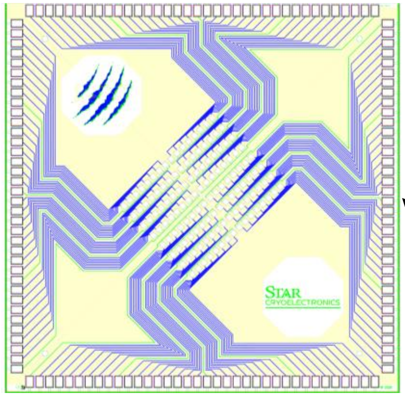


U.S. Department of Energy Office of Science
NNSA National Nuclear Security Administration

NNIS Fellow

Spencer Fretwell
Colorado School of Mines
Earth • Energy • Environment

128-Pixel Al Array



STAR CRYOELECTRONICS

BeEST (current)

BeEST (in-progress)

Future BeEST

Superconductor used as absorber	² (energy gap)	Theoretical ² E at 6 keV (single tunneling)	Theoretical ² E at 6 keV (multiple tunneling)	² E Achieved at 6 keV	Resolution at 0.1 keV
Niobium	1.52 meV	4.3 eV	10.6 eV	24 eV (LLNL)	3 eV
Tantalum	0.71 meV	2.9 eV	7.2 eV	13 eV (Yale)	1.5 eV
Aluminum	0.17 meV	1.4 eV	3.5 eV	12 eV (T.U. Munich)	0.8 eV
Titanium	0.052 meV	0.8 eV	2.0 eV		
Hafnium	0.017 meV	0.46 eV	1.1 eV		0.2 eV

Table Courtesy C.K. Stahle (NASA Goddard)

The BeEST

Colorado School of Mines

Kyle Leach
Connor Bray
Spencer Fretwell
Josh Stackhouse

Lawrence Livermore National Laboratory

Stephan Friedrich
Jack Henderson
Geon-Bo Kim
Vince Lordi
Amit Samanta

TRIUMF

Jens Dilling
Annika Lennarz
Dave McKeen
Chris Ruiz

Faculty/Staff
PDF
Graduate
Undergraduate

Michigan State University / NSCL

Sean Liddick

Stanford University

Francisco Ponce

XIA

Bill Warburton

Central Michigan University

Matt Redshaw
Ramesh Bhandri

CEA Paris-Saclay

Xavier Mougeot

LPC Caen

Oscar Naviliat-Cuncic

STAR Cryoelectronics

Robin Cantor

Funding

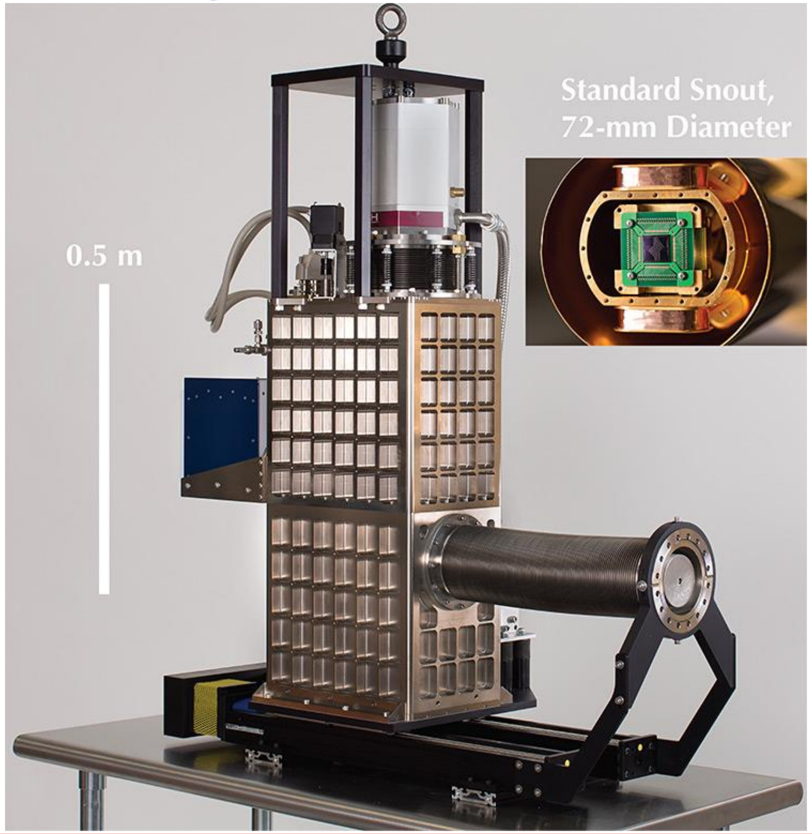
U.S. Department of Energy, Office of Science
Lawrence Livermore National Laboratory
Colorado School of Mines
TRIUMF
APS physics
Gordon and Betty Moore Foundation

Superconducting Array for Low-Energy Radiation

SALER

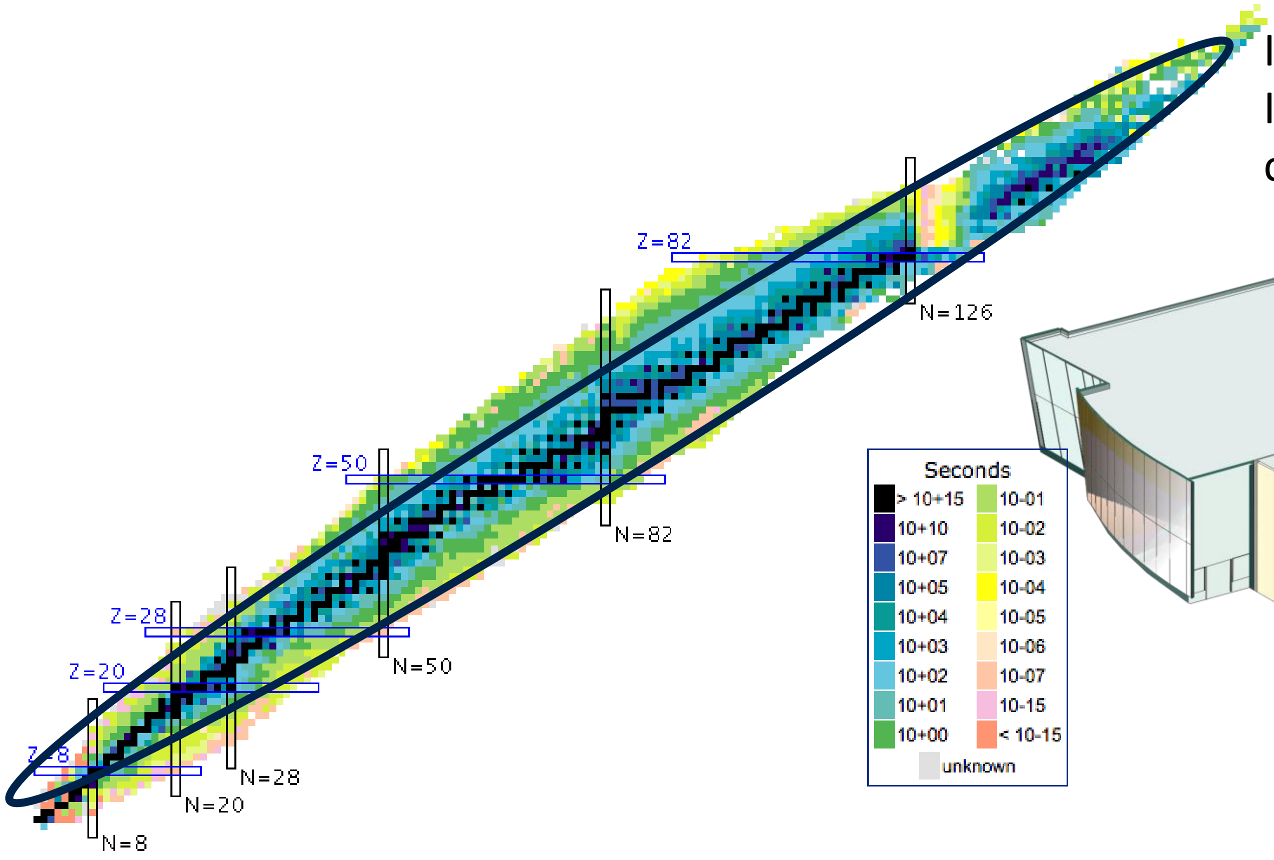
- Adaptation of commercial STJ units designed for synchrotron beamline science and other high-resolution X-ray measurements.

STAR CRYOELECTRONICS

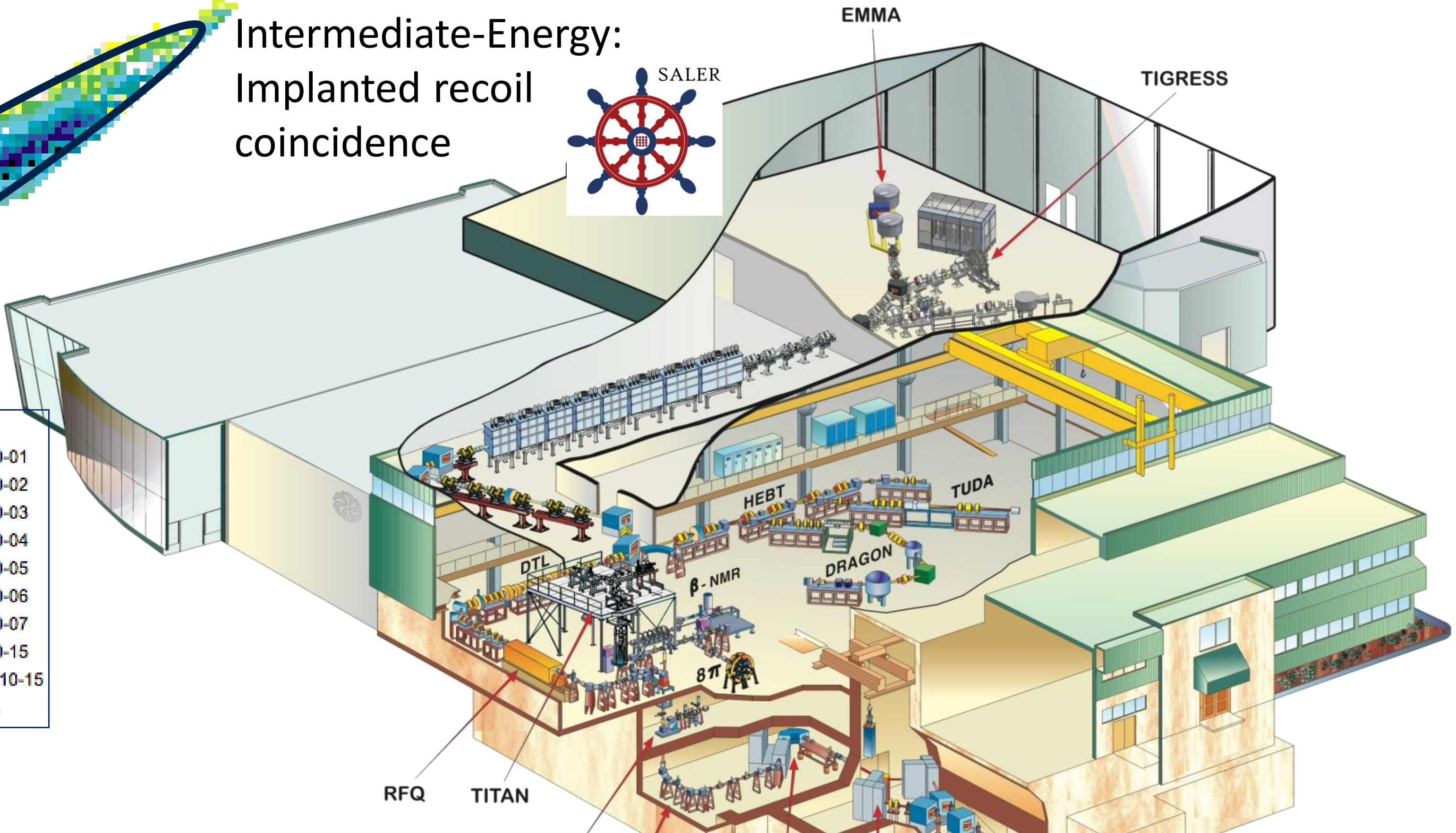


- 128-pixel array of detectors that cover an area of ~5mm^2 with electron/photon energy resolution of <10 eV at ~500 eV.
- Cryogen-free dry ADR (0.1 K) with room-temperature electronics.
- Choice of STJs leverages the high-intensities (count rates) of RIBs at ISAC – with the trade-off of E<10 keV
- Nuclear recoil measurements via direct implantation may be possible for nuclei with $T_{1/2}$~ seconds or longer

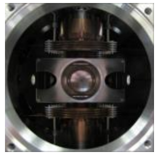
Synergy with SALER as a High-Resolution Spectrometer at ISAC



Intermediate-Energy: Implanted recoil coincidence



Low-Energy: Photons, electrons, or recoils



Summary

- Quantum sensors can be powerful tools in our search for BSM physics using nuclei/atoms
- Physics case and device selection is critical as these devices are not "one size fits all" options for all nuclear spectroscopy
- Devices such as TESs, MMCs, and STJs are already being used for high-precision measurements of low-energy radiation from nuclear decay (HOLMES, ECHo, BeEST)
- Given the high-rate capability of STJs, there is potential to use them as low-energy nuclear recoil spectrometers for structure and fundamental symmetry studies at RIB facilities
- As we look to the future, we should be ready to leverage the tremendous development efforts that have been made in the QIS community to make groundbreaking (and unique) measurements in Nuclear Physics

BACKUP SLIDES

Commercial Beam-Line Ready Options for 10 mK Operation

Technical Specifications

Note: Cooling power is measured on experimental flange outside MXC.

LH250	GUARANTEED
Base temperature	10 mK
Cooling power @ 20 mK	10 µW
Cooling power @ 100 mK	250 µW
Cooling power @ 120 mK	360 µW
Cool-down time to base	24 hrs

LH400	GUARANTEED
Base temperature	10 mK
Cooling power @ 20 mK	12 µW
Cooling power @ 100 mK	400 µW
Cooling power @ 120 mK	575 µW
Cool-down time to base	24 hrs

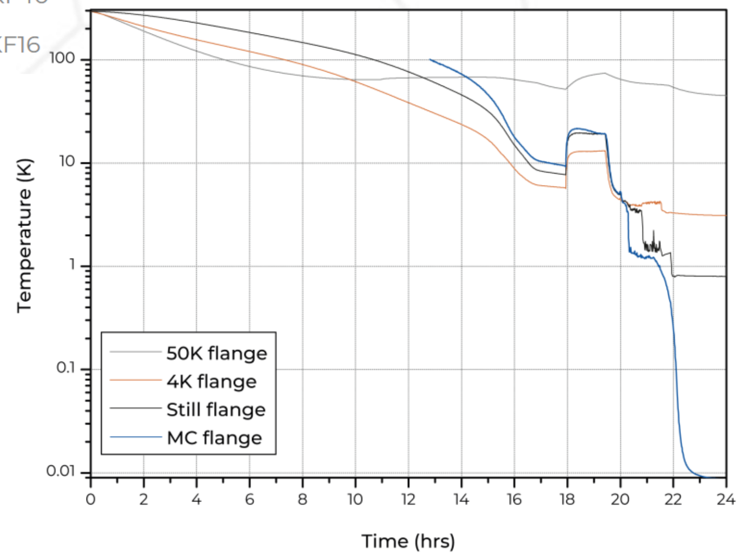
LH System

The horizontal model LH is a low-height, compact and truly horizontal dilution refrigerator system capable of operation under different tilt angles. It is ideal for beamline, telescope or detector experiments.

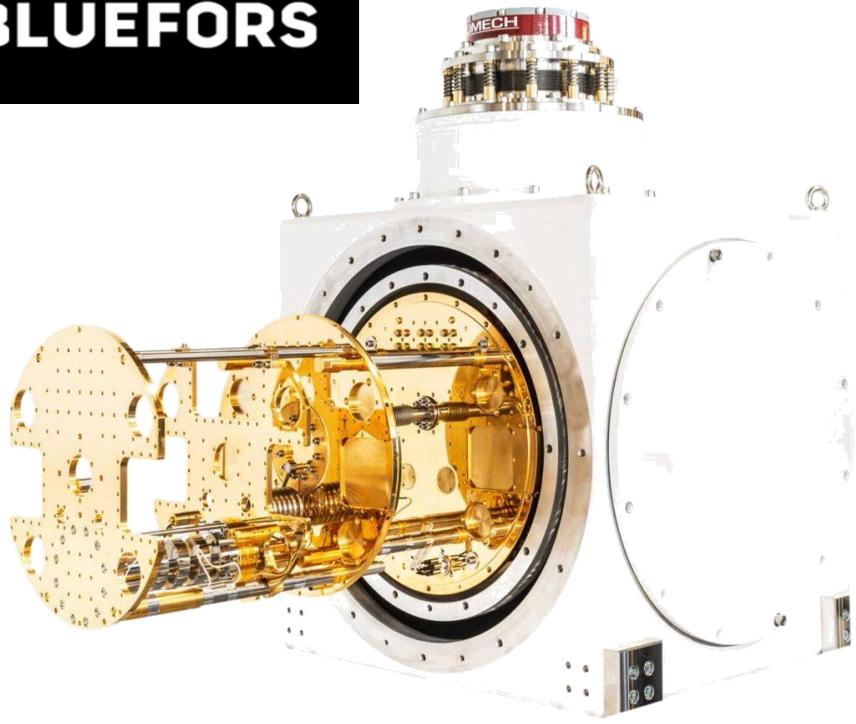
Eight LOS Access Ports

All line-of-sight ports reach from room temperature to mixing chamber.

- 2 x KF63 slotted in all flanges
- 4 x KF40
- 2 x KF16

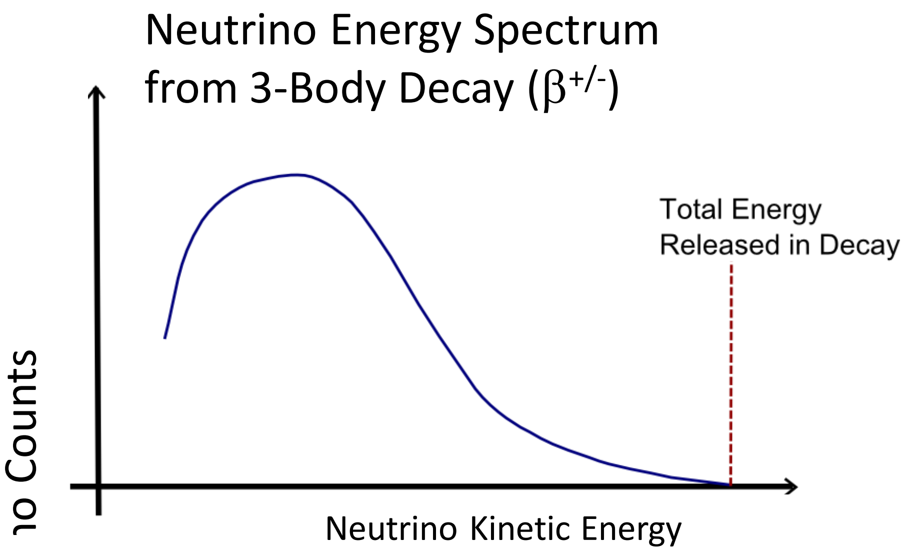


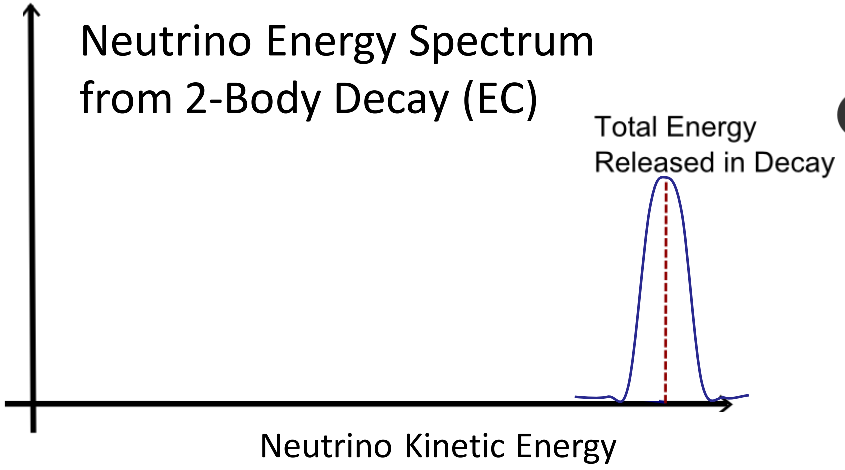
BLUEFORS



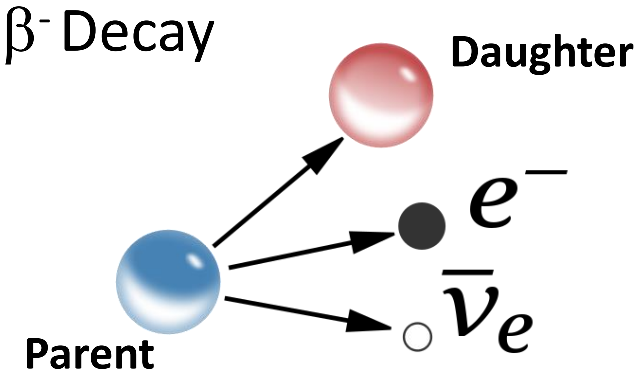
Kyle Note:
I add this here for completeness based on other Science Week discussions

Neutrino Mass Studies via Momentum Reconstruction

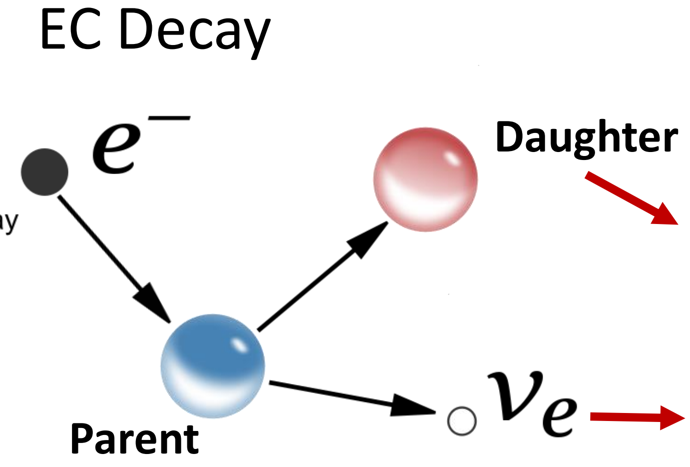




β- Decay



EC Decay



- Decay momentum reconstruction is perhaps the best way to access information on the neutrino mass in an absolute way.

- The process is tremendously simplified for electron capture (EC) since there are only two final bodies that share energy/momentum

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

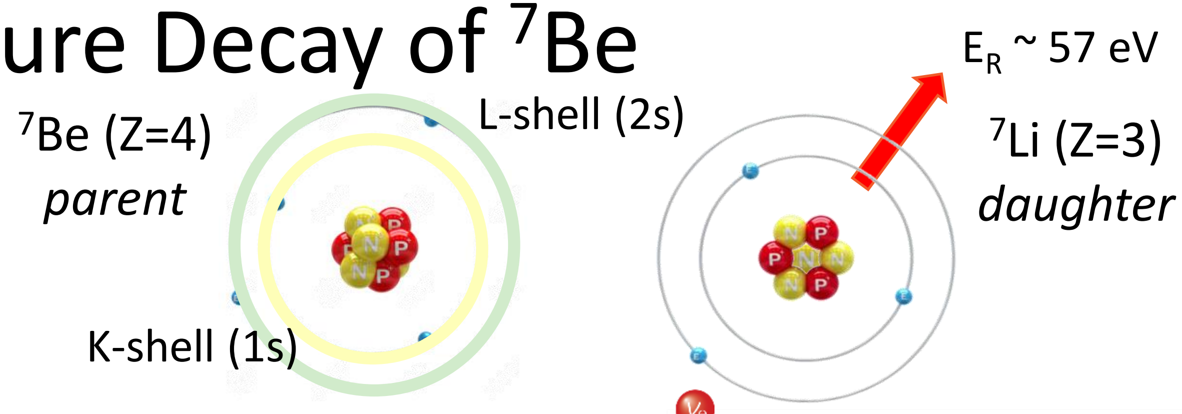
$$T_\nu = \frac{\left(m_\nu c^2 - Q_{EC}\right)\left(c^2(m_\nu - 2m_d) - Q_{EC}\right)}{2\left(m_d c^2 + Q_{EC}\right)}$$

K.G. Leach
Low-Energy Quantum Sensing Methods at ISAC
TRIUMF Science Week
August 20, 2020

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

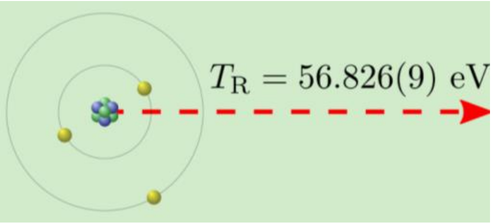
The Electron Capture Decay of ^{7}Be

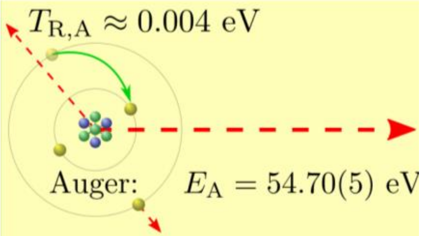
- **^{7}Be is the ideal case for neutrino studies using this method.**
  - Simple atomic and nuclear structure
  - Largest *Q*-value (862 keV) of all pure EC cases
  - ➔ Highest-energy recoil from EC decay
- The decay is followed by the Li atomic recoil that (to first order) can be detected at 4 different discrete energies.

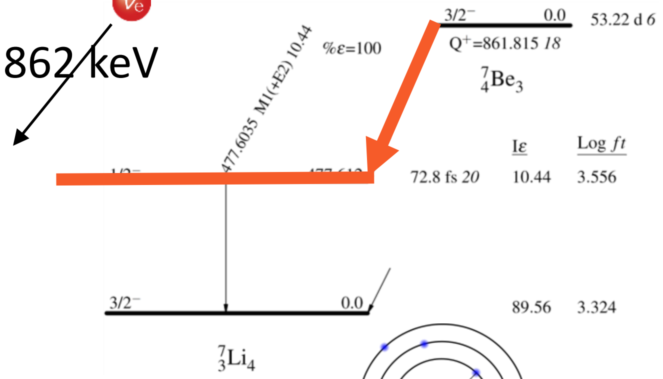


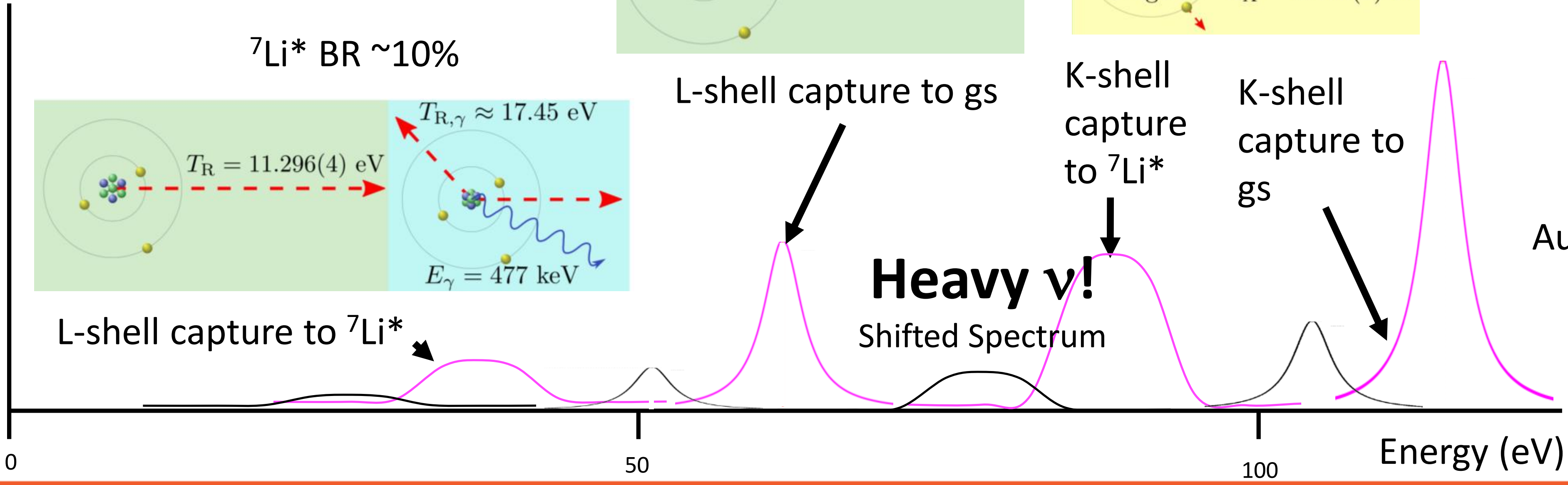
L/K capture ratio = 0.07(7)

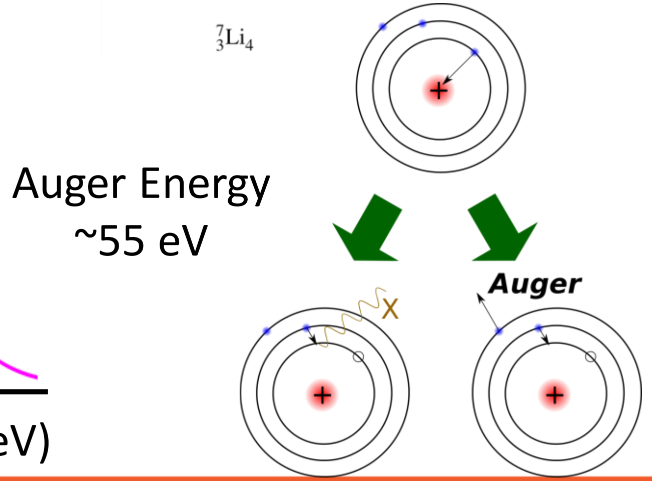
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)











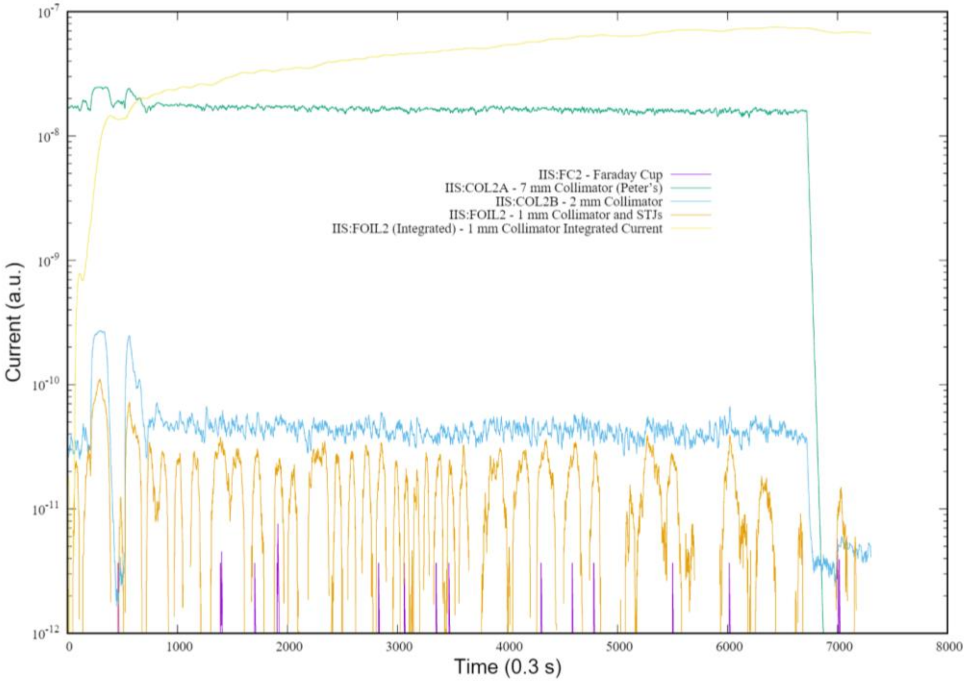
The BeEST Phase-II: Implantation - September 2019

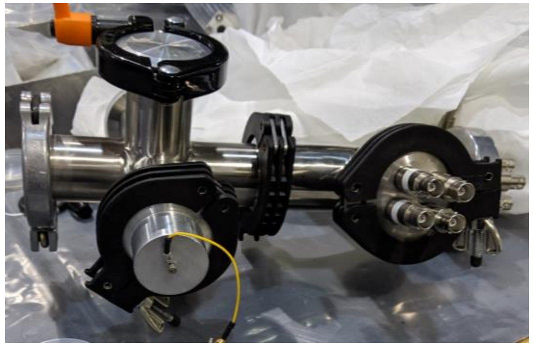
- **Goal: Precision calibration and elimination of known broadening/tail effects**

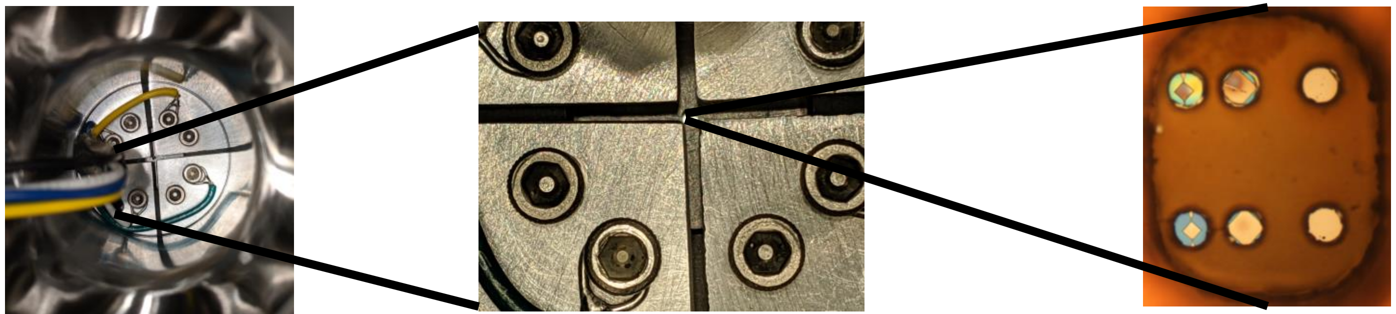
- Need:
  - >40 keV implantation energy ☹
  - Less Li implanted ☺
  - Better diagnostics in chamber ☺

- Second implantation chip from same fabrication run, already at LLNL

- New implantation chamber designed and fabricated by Mines undergraduate students







1 mm

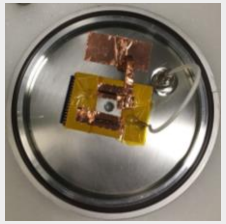
30 min. implantation:

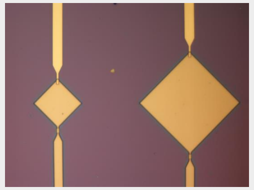
Total Implanted (Li+Be)	1.2E+11
7Be Implanted	1.7E+09

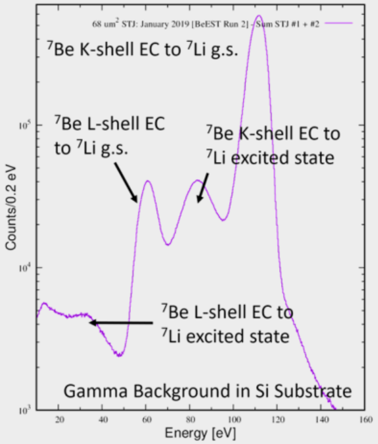
Activity on STJs: 0.25(1) kBq

What’s Next for the BeEST

Phase-I: Proof of Concept – Complete (Mar. 2019)

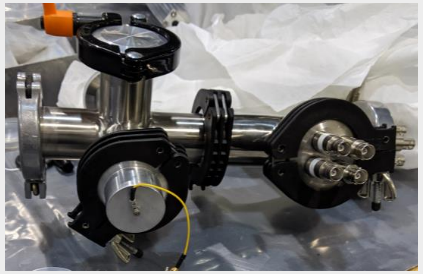




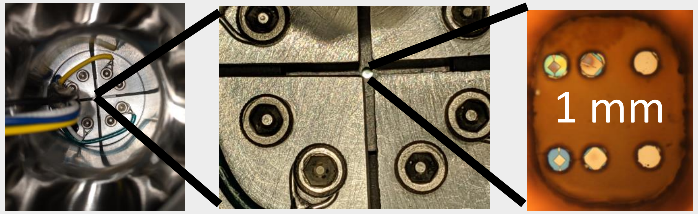


- First ever demonstration of STJs for recoil detection
- ~1000 counts/s per detector for first test

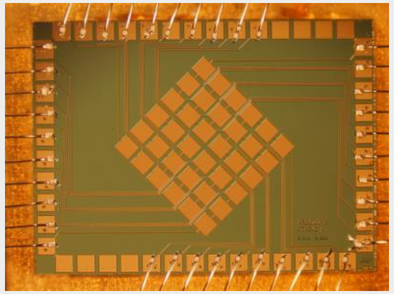
Phase-II: Calibration and Characterization – *In Progress*

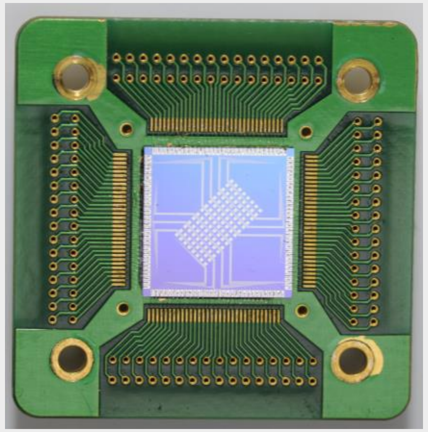


- Optimization of implantation technique and chamber (*completed*)
- Calibration and characterization with laser towards first limits (*completed*)



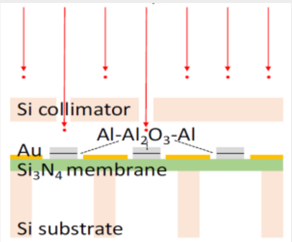
Phase-III: Scaling to Multi-Pixel Arrays – *In Progress*

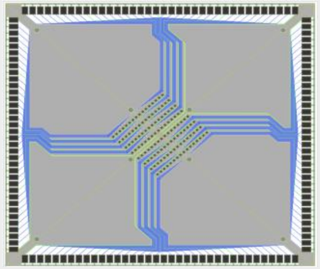


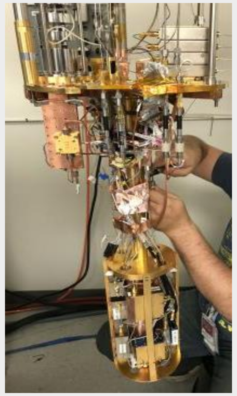


- Scaling to existing 36- and 112-pixel Ta-based STJ arrays

Phase-IV: Al STJ Arrays in Dilution Fridge – *Design*







- New “Background-free” detectors
- 3x better intrinsic resolution
- Continuous STJ operation at 0.01 K