Beyond Standard Model Neutrino Studies with Rare Isotopes in Quantum Sensors

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Colorado School of Mines

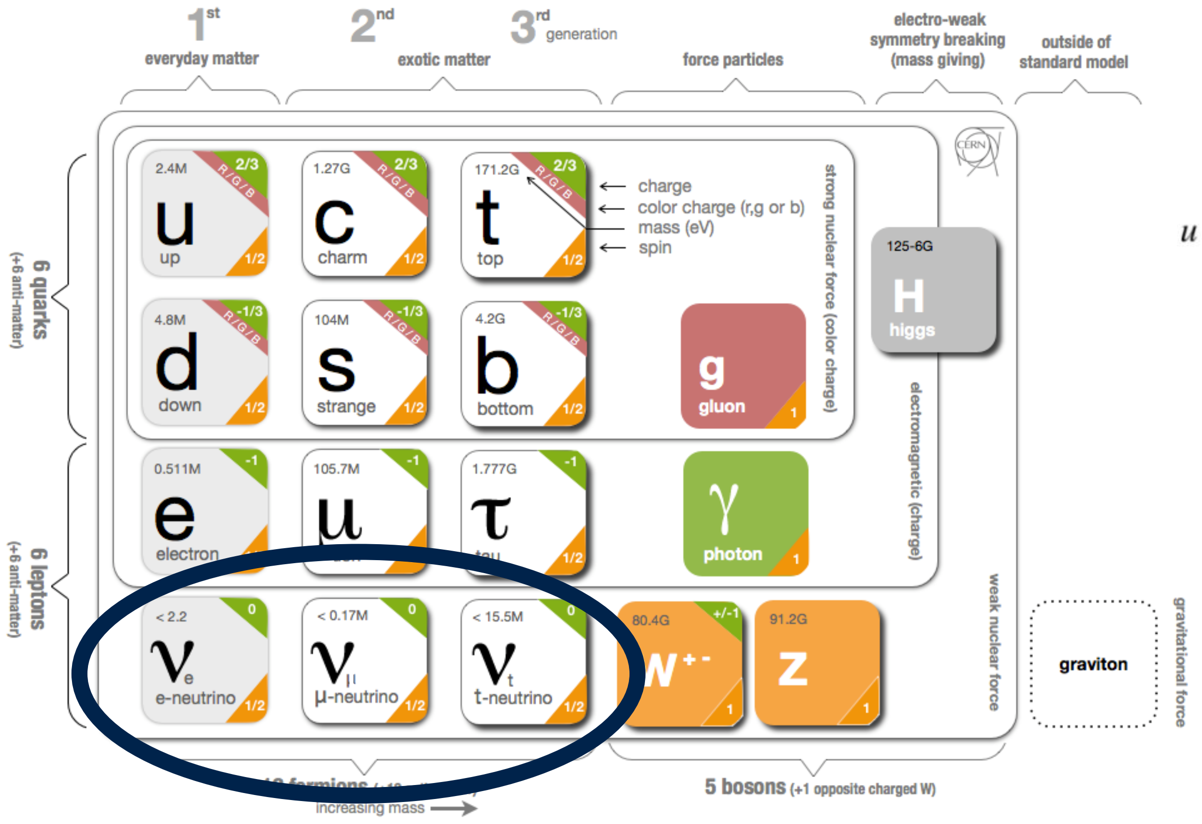
Developing New Directions in Fundamental Physics (DND)
New Physics with Radioactives
November 5, 2020

THE BeEST

beest.mines.edu

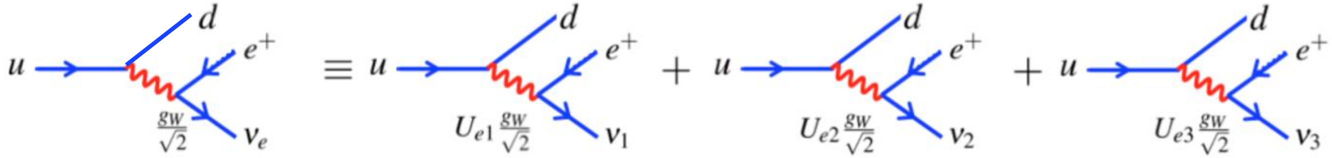
Neutrinos in the Standard Model

- In the SM, there are three generations of neutrino that are defined in terms of their weak-interaction eigenstates.



- These weak interaction eigenstates are not equal to the mass eigenstates, and are related via a unitary transformation – the PMNS matrix (analogous to CKM).

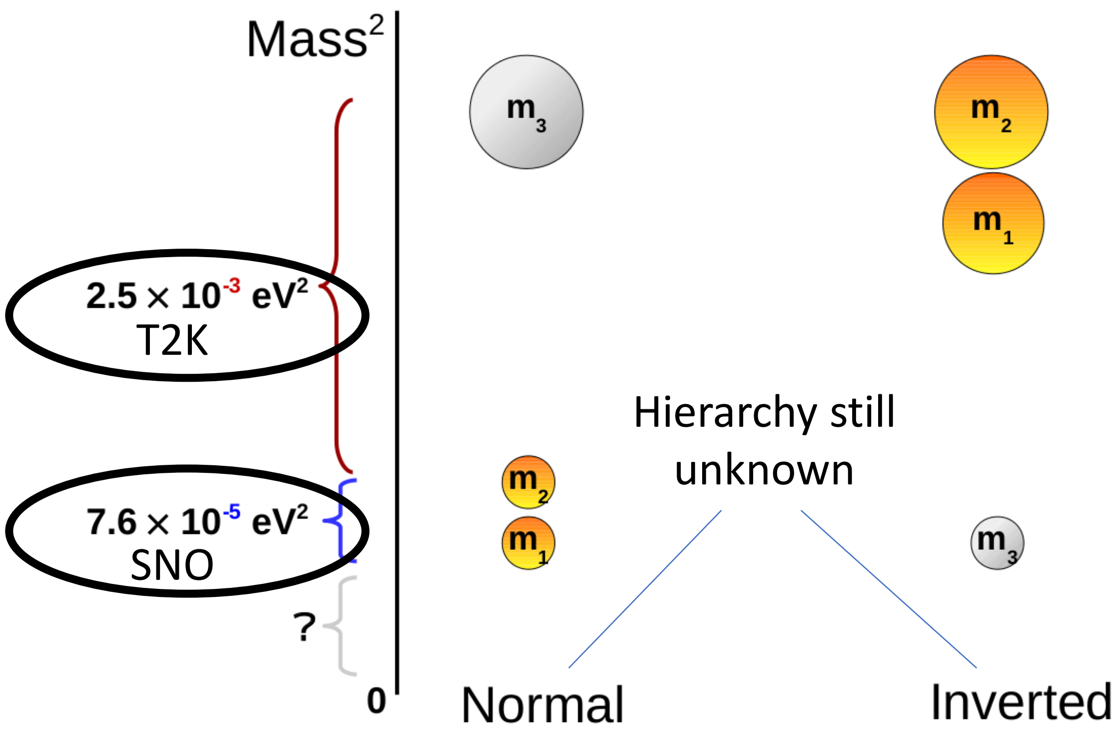
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



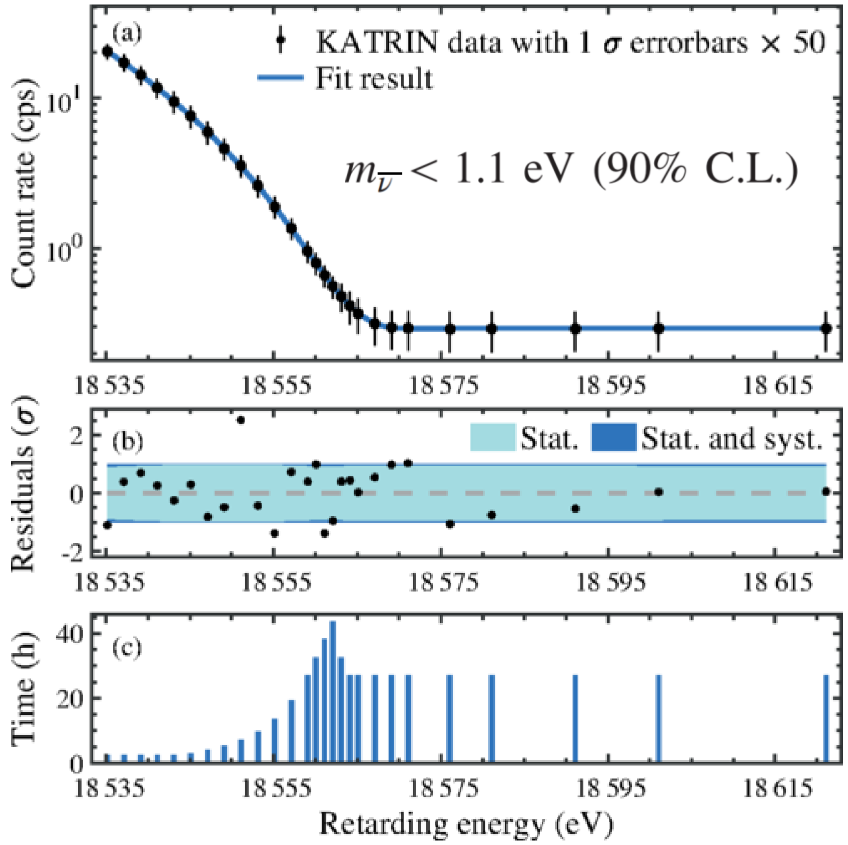
- Unlike the CKM matrix in the quark sector, the PMNS matrix is not diagonal, and shows significant mixing – the origin of which has garnered much speculation.
- This is known as the flavour puzzle, and is one of the big open questions in subatomic physics.

Neutrino Masses: What do (we think) we Know?

Neutrino Mass Splittings
(Oscillation Experiments)



Absolute anti-neutrino mass limits
(β^- Decay Experiments)



KATRIN Collaboration, PRL **123**, 221802 (2019)

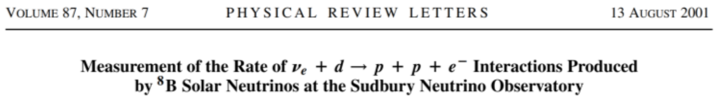
BSM Physics in the Neutrino Sector

Oscillation experiments have been a powerhouse for neutrino physics studies for nearly 30 years
…..but precision β decay measurements are catching up

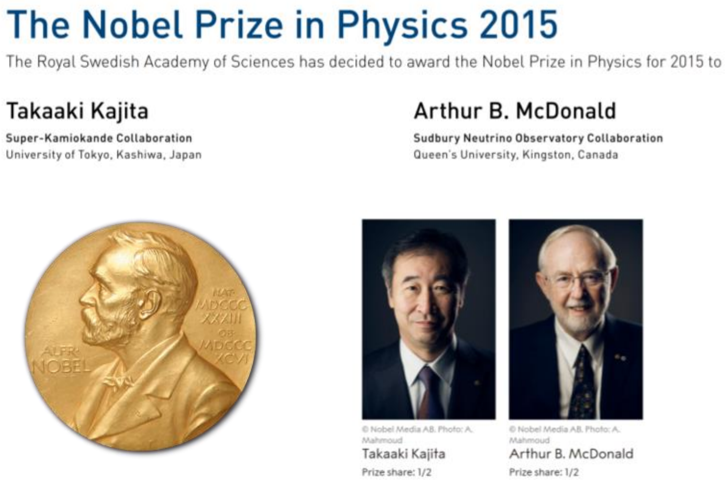
Massive Neutrinos!


VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos


VOLUME 87, NUMBER 7 PHYSICAL REVIEW LETTERS 13 AUGUST 2001

Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory


The Nobel Prize in Physics 2015

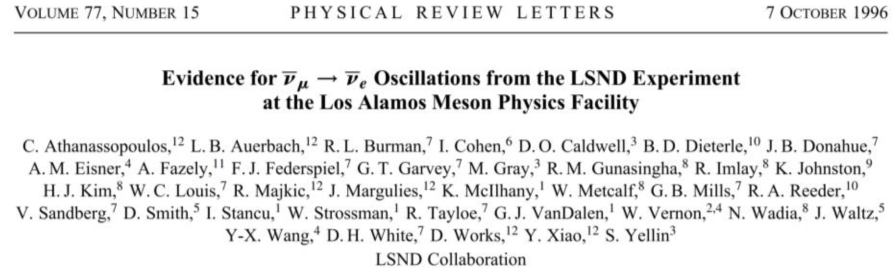
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

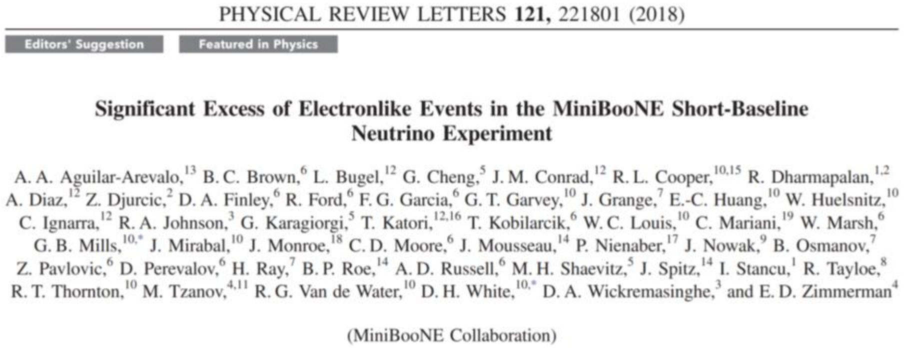
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Discovery of eV Sterile Neutrinos?


VOLUME 77, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1996

Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from the LSND Experiment at the Los Alamos Meson Physics Facility

C. Athanassopoulos,[12] L. B. Auerbach,[12] R. L. Burman,[7] I. Cohen,[6] D. O. Caldwell,[3] B. D. Dieterle,[10] J. B. Donahue,[7] A. M. Eisner,[4] A. Fazely,[11] F. J. Federspiel,[7] G. T. Garvey,[7] M. Gray,[3] R. M. Gunasingha,[8] R. Imlay,[8] K. Johnston,[9] H. J. Kim,[8] W. C. Louis,[7] R. Majkic,[12] J. Margulies,[12] K. McIlhany,[1] W. Metcalf,[8] G. B. Mills,[7] R. A. Reeder,[10] V. Sandberg,[7] D. Smith,[5] I. Stancu,[1] W. Strossman,[1] R. Tayloe,[7] G. J. VanDalen,[1] W. Vernon,[2,4] N. Wadia,[8] J. Waltz,[5] Y-X. Wang,[4] D. H. White,[7] D. Works,[12] Y. Xiao,[12] S. Yellin[3]
LSND Collaboration


PHYSICAL REVIEW LETTERS **121,** 221801 (2018)

Editors' Suggestion Featured in Physics

Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment

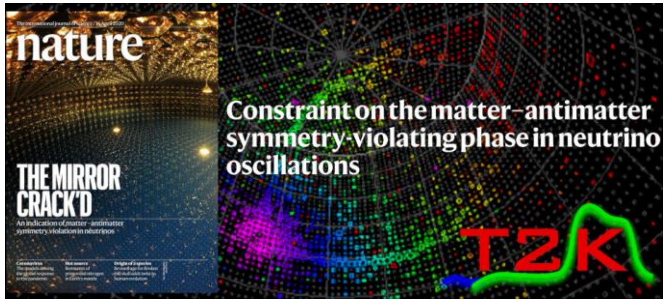
A. A. Aguilar-Arevalo,[13] B. C. Brown,[6] L. Bugel,[12] G. Cheng,[5] J. M. Conrad,[12] R. L. Cooper,[10,15] R. Dharmapalan,[1,2] A. Diaz,[12] Z. Djurcic,[2] D. A. Finley,[6] R. Ford,[6] F. G. Garcia,[6] G. T. Garvey,[10] J. Grange,[7] E.-C. Huang,[10] W. Huelsnitz,[10] C. Ignarra,[12] R. A. Johnson,[3] G. Karagiorgi,[5] T. Katori,[12,16] T. Kobilarcik,[6] W. C. Louis,[10] C. Mariani,[19] W. Marsh,[6] G. B. Mills,[10,*] J. Mirabal,[10] J. Monroe,[18] C. D. Moore,[6] J. Mousseau,[14] P. Nienaber,[17] J. Nowak,[9] B. Osmanov,[7] Z. Pavlovic,[6] D. Perevalov,[6] H. Ray,[7] B. P. Roe,[14] A. D. Russell,[6] M. H. Shaevitz,[5] J. Spitz,[14] I. Stancu,[1] R. Tayloe,[8] R. T. Thornton,[10] M. Tzanov,[4,11] R. G. Van de Water,[10] D. H. White,[10,*] D. A. Wickremasinghe,[3] and E. D. Zimmerman[4]

(MiniBooNE Collaboration)

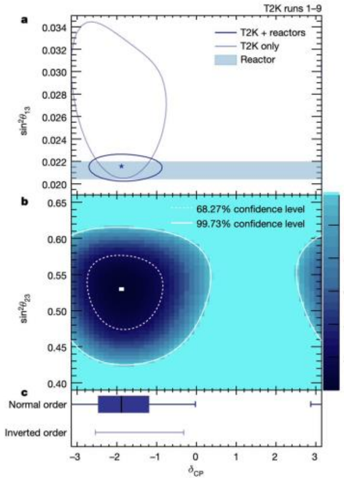
Combined LSND and MiniBooNE fit:
$\Delta m^2 = 0.041$ eV^2 @ 6.0σ

Hints of CP Violation?

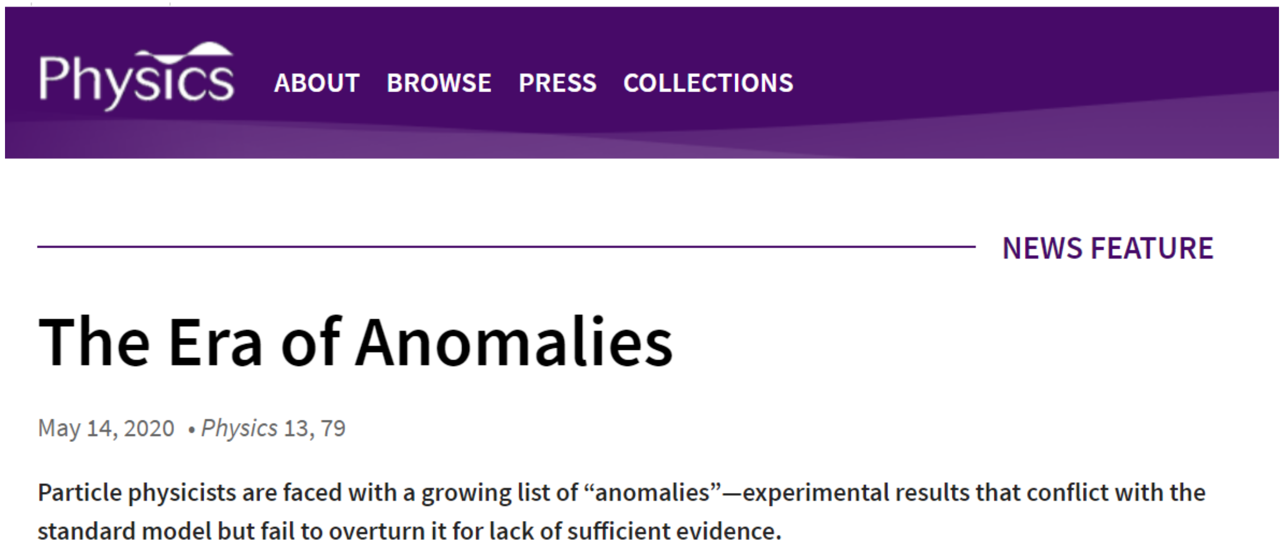
Nature **580,** 339–344 (2020)



- δ_{CP} = 0 or π, excluded @ 95% C.L
- 3σ limits on δ_{CP}



“The Era of Anomalies”



NEWS FEATURE

The Era of Anomalies

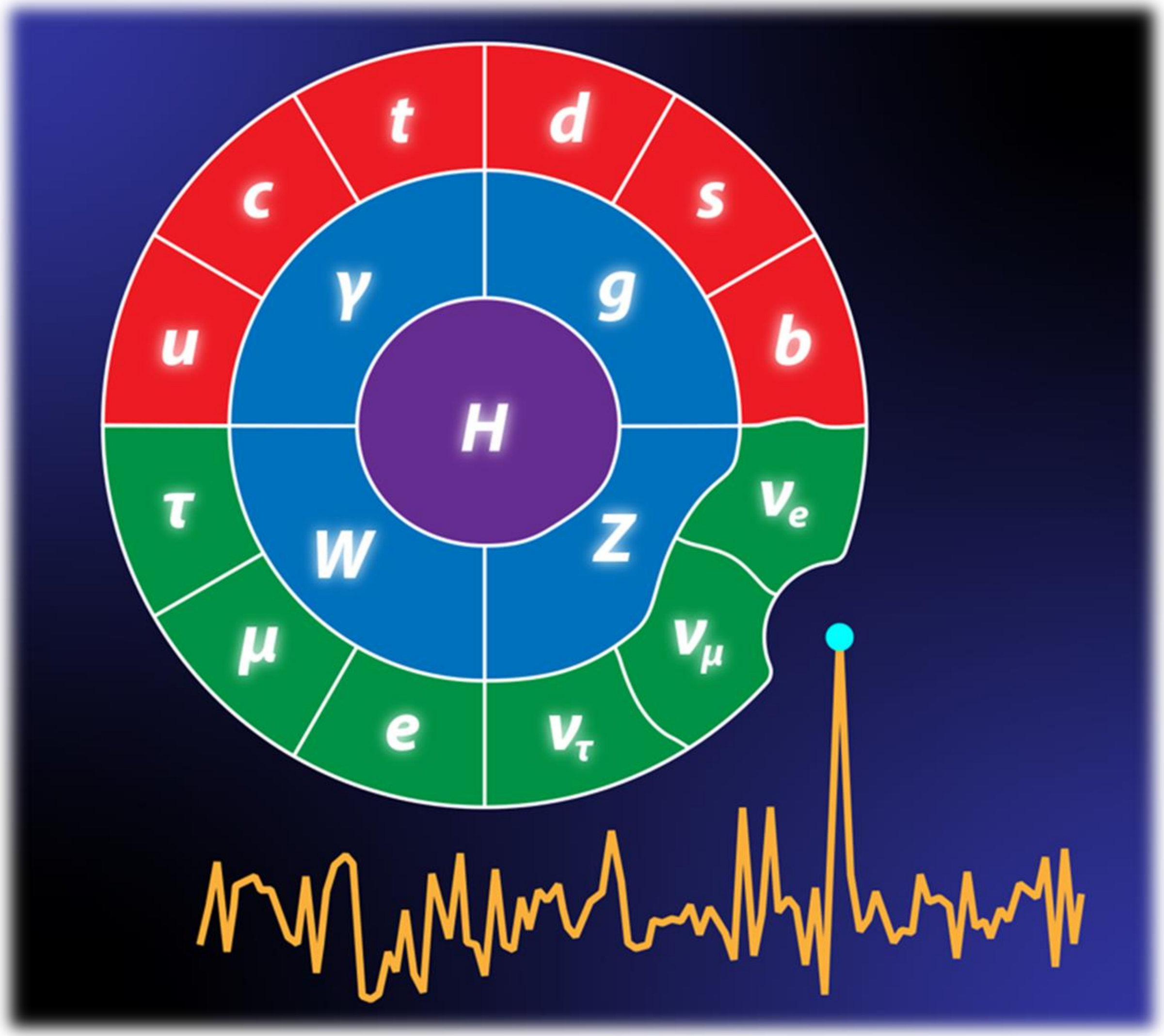
May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of “anomalies”—experimental results that conflict with the standard model but fail to overturn it for lack of sufficient evidence.

- These statistical “anomalies” (in the 3 σ range) provide some hints to what might lie beyond our SM

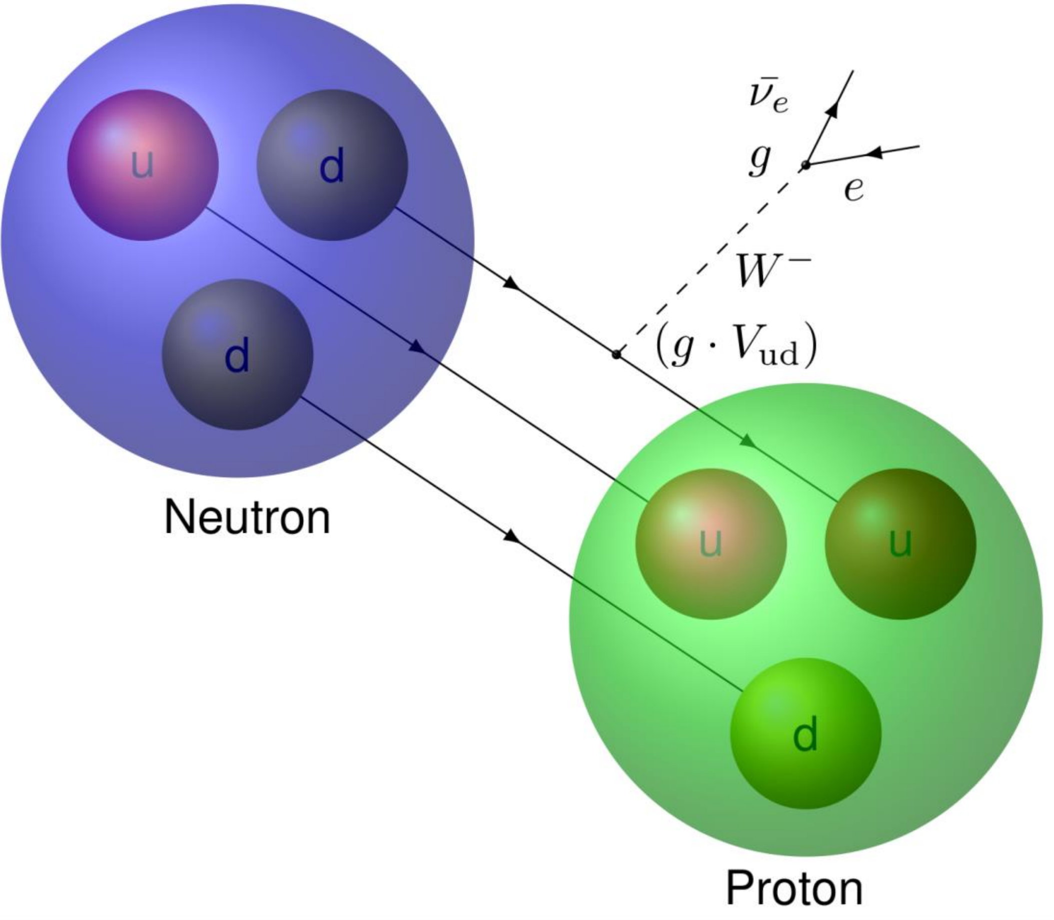
- They can help point us in the direction where new searches, with new detection methods (different associated systematics) and more control should focus.

There is significant need for definitive, model independent searches for BSM physics in the neutrino sector

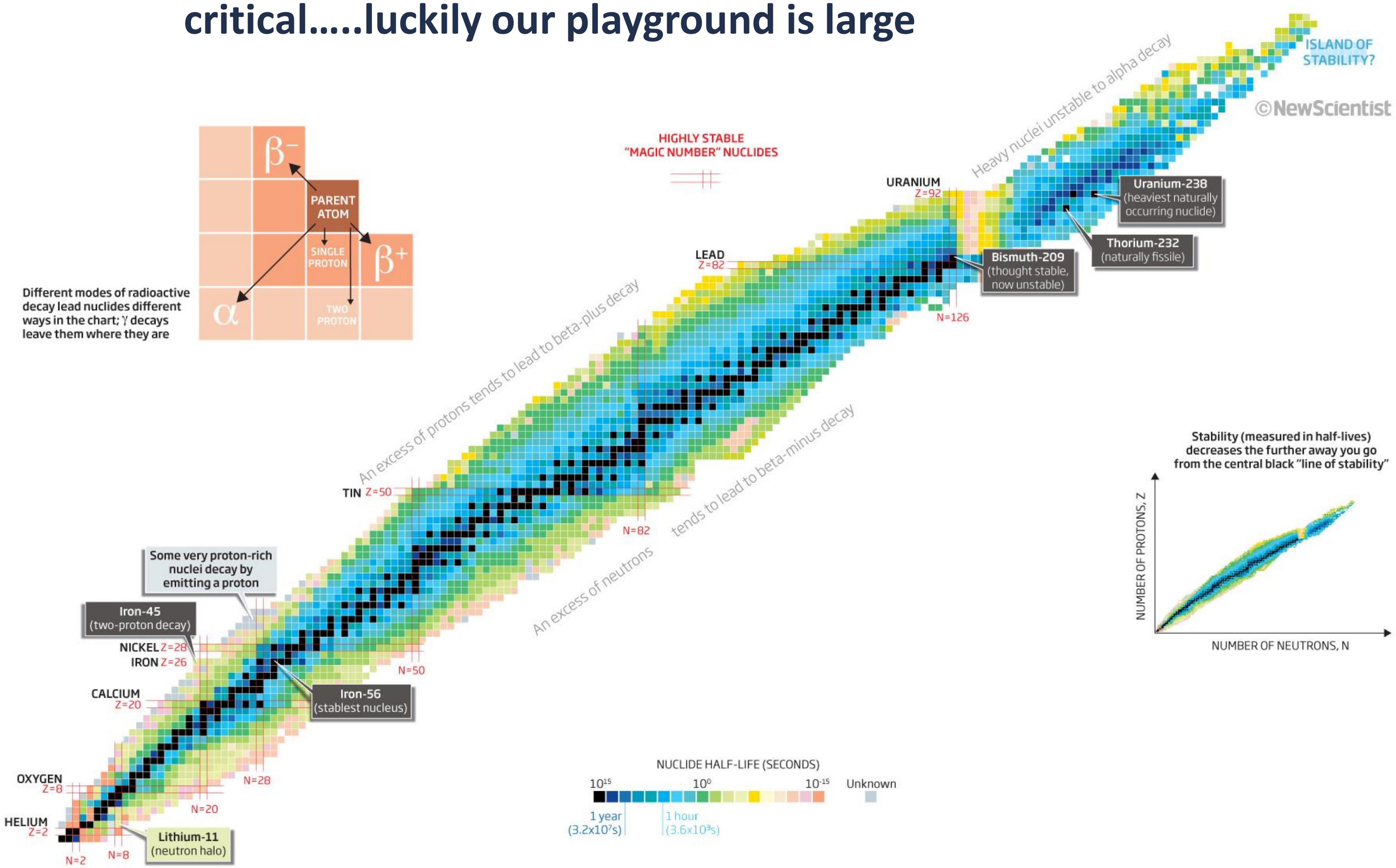


Nuclear β Decay as a Probe of New Physics

(………New Physics with Radioactives?)

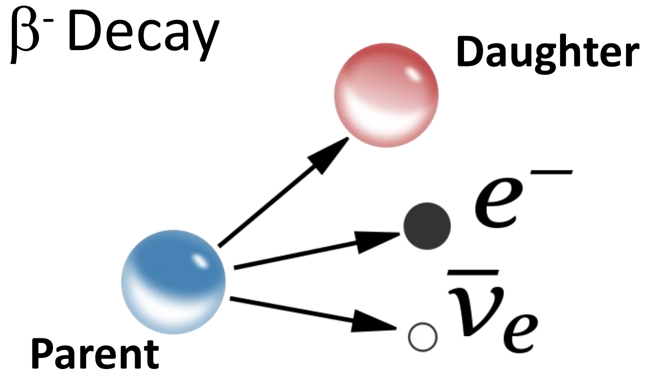


Selection of initial and final quantum states is critical…..luckily our playground is large



P. Walker, New Scientist Magazine (2011)

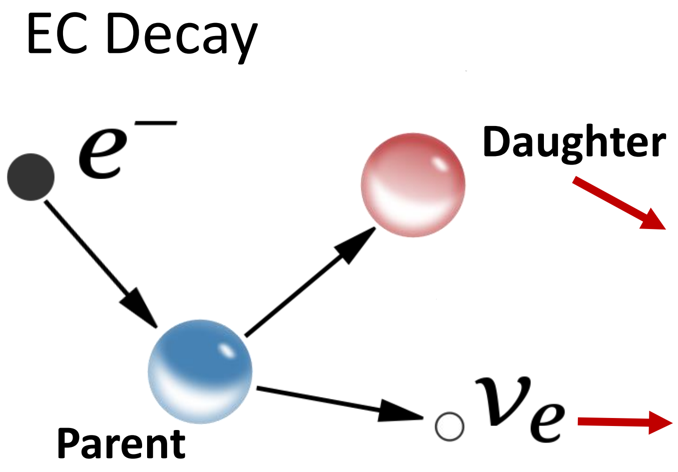
The Model Independent Nature of Beta Decay



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

R. Davis, Phys. Rev. **86**, 976 (1952)
R. Shrock, Phys. Lett. B **96**, 159 (1980)
G. Finocchiaro and R.E. Shrock, Phys. Rev. D **46**, R888(R) (1992)
M.M. Hindi *et al.*, Phys. Rev. C **58**, 2512 (1998)

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



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

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

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

Model Independent Searches for BSM Neutrinos

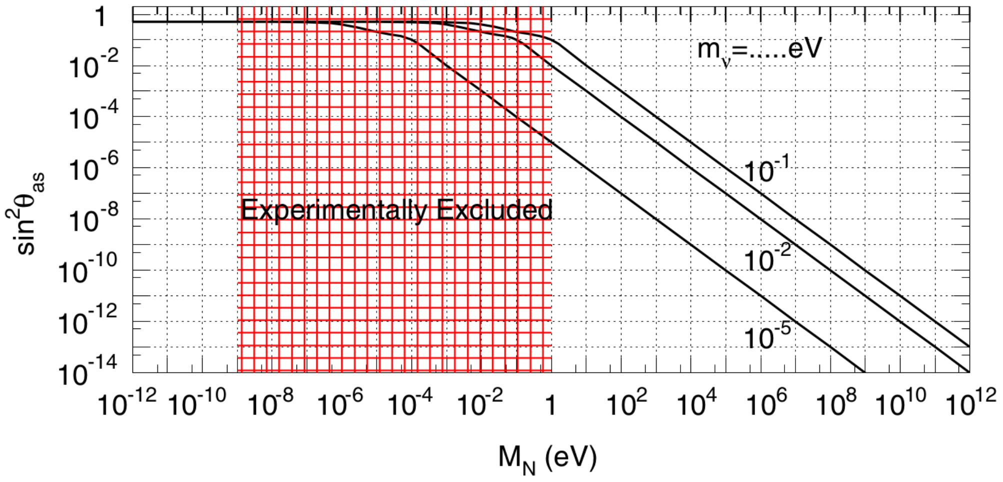
electron neutrino

muon neutrino

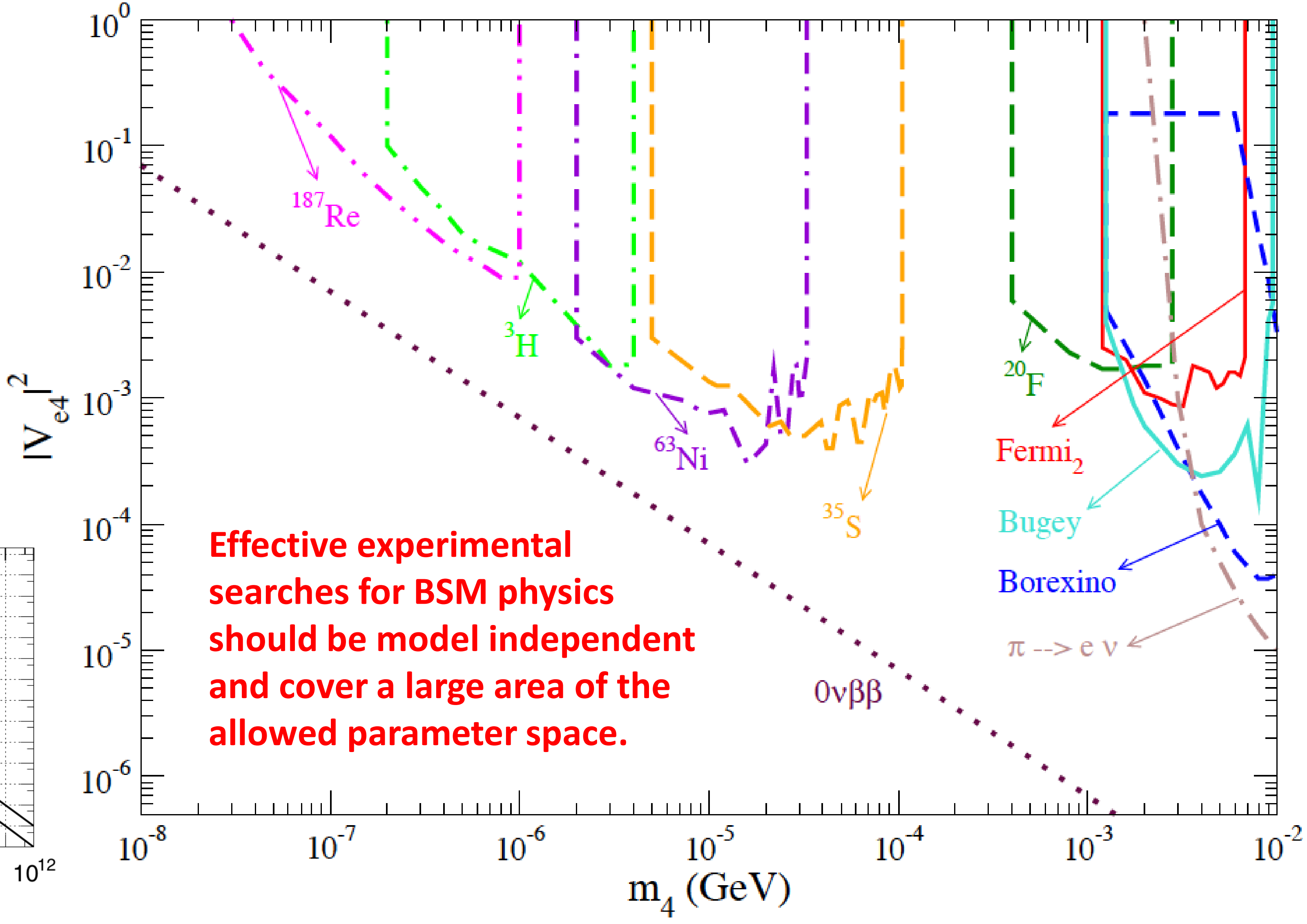
tau neutrino

sterile neutrino

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \nu_{s2} \\ \nu_{s3} \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & U_{e6} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & U_{\mu 6} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & U_{\tau 6} \\ U_{s11} & U_{s12} & U_{s13} & U_{s14} & U_{s15} & U_{s16} \\ U_{s21} & U_{s22} & U_{s23} & U_{s24} & U_{s25} & U_{s26} \\ U_{s31} & U_{s32} & U_{s33} & U_{s34} & U_{s35} & U_{s36} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{bmatrix}$$



Andre de Gouvea, Wei-Chih Huang, and James Jenkins, Phys. Rev. D **80**, 073007 (2009)



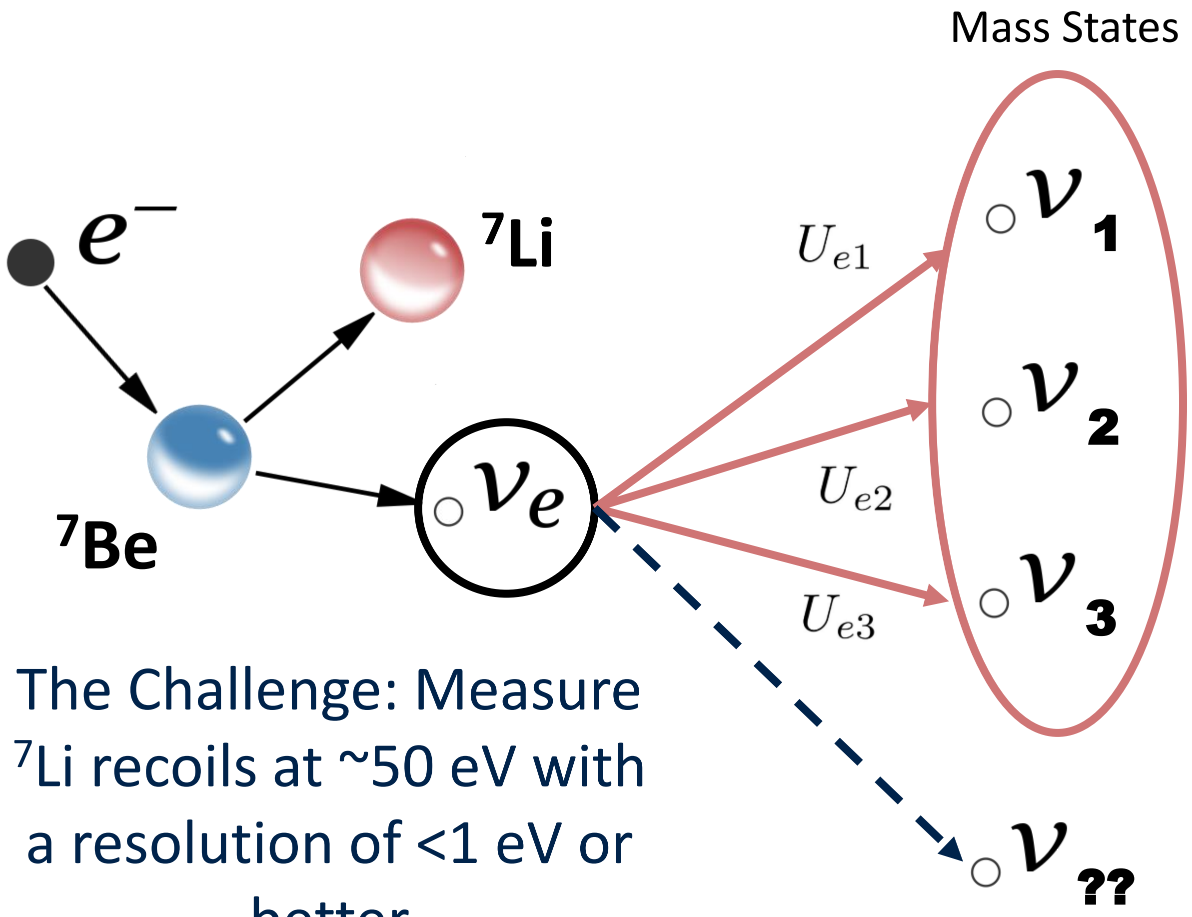
Effective experimental searches for BSM physics should be model independent and cover a large area of the allowed parameter space.

J. Barea, J. Kotila, and F. Iachello, Phys. Rev. D **92**, 093001 (2015)

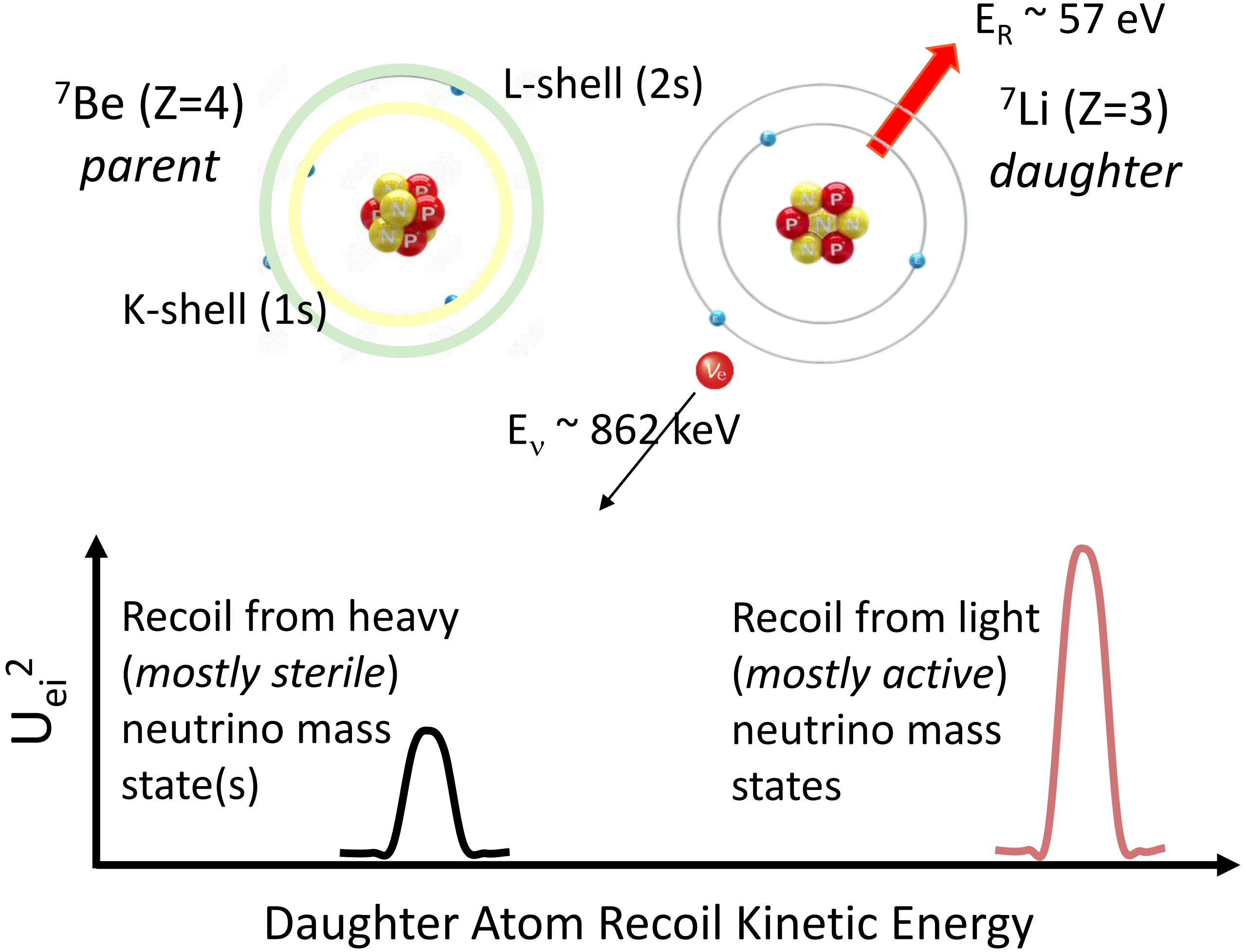
Neutrino Studies with the Electron Capture Decay of ^{7}Be

- **^{7}Be is the ideal case for neutrino studies using this method.**
  - Simple atomic and nuclear structure and largest *Q*-value (862 keV) of all pure EC cases

    ➔ Highest maximum recoil energy

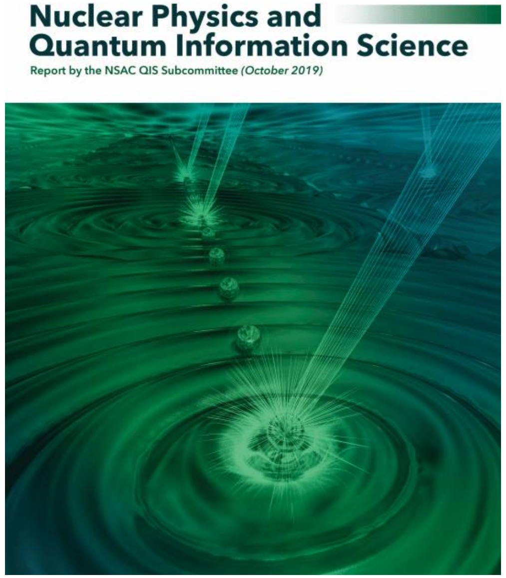


The Challenge: Measure ^{7}Li recoils at ~50 eV with a resolution of <1 eV or better



Quantum Sensing and Nuclear Physics

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



Nuclear Physics and Quantum Information Science

Report by the NSAC QIS Subcommittee *(October 2019)*

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

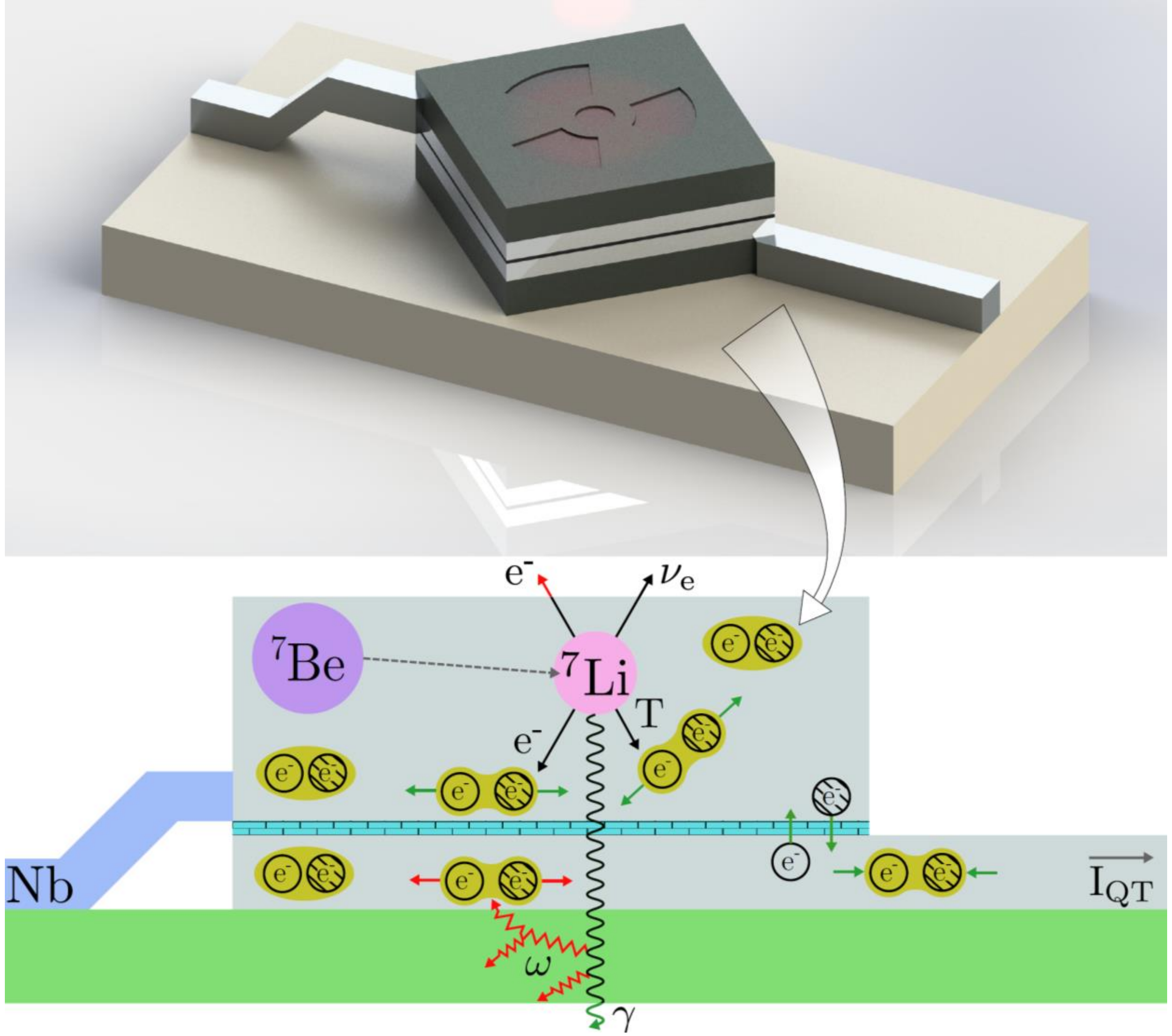
Quantum Sensors 2.0: Devices whose operation depends explicitly on quantum phenomena such as superposition of states (coherence) and/or entanglement to achieve superior performance. **These devices use quantum systems and quantum manipulations that frequently share basic elements with those used for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

← On the horizon for NP

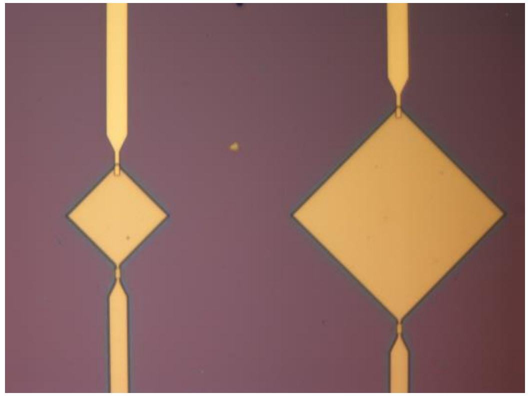
Superconducting Tunnel Junction (STJ) Quantum Sensing

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

Can exploit strength of BSM searches with RIBs



Josephson Junctions

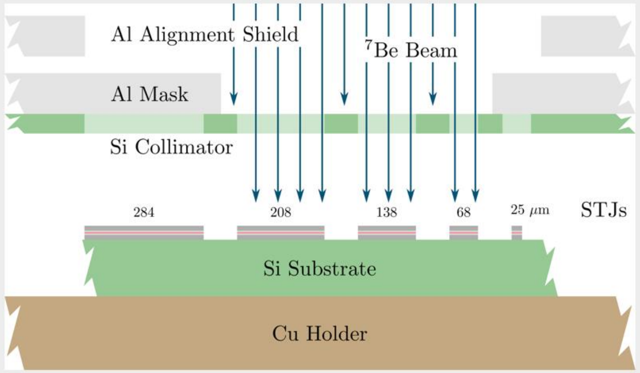


68 x 68 μm^2

138 x 138 μm^2

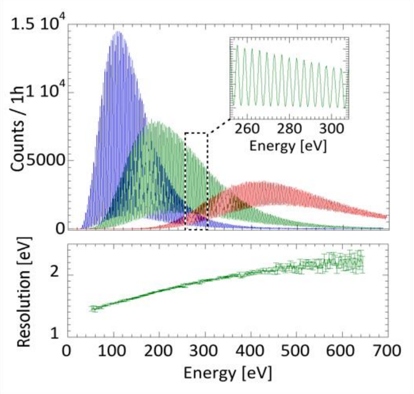
The BeEST Experimental Concept

Implanted ^{7}Be Sample



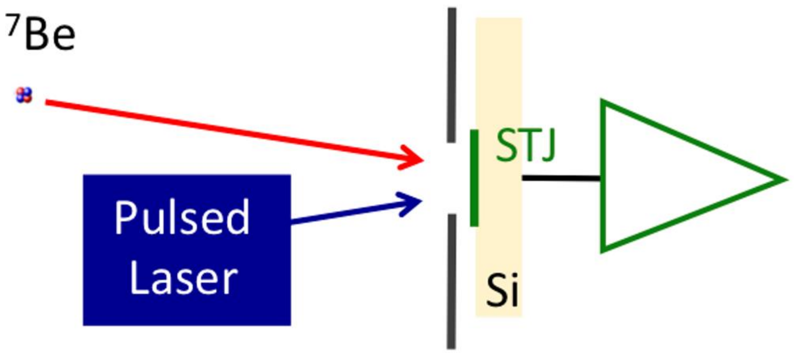
Simultaneous Laser Calibration

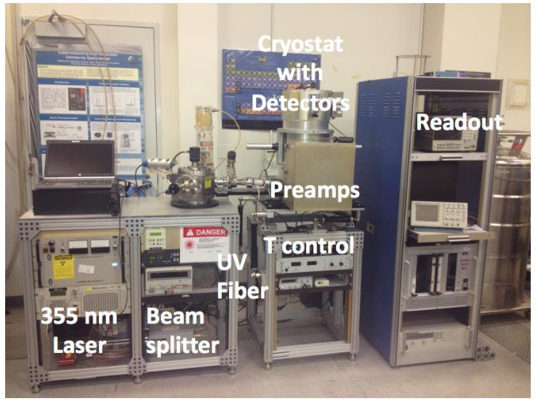
Provides energy calibration to <0.01 eV



THE BeEST

TRIUMF



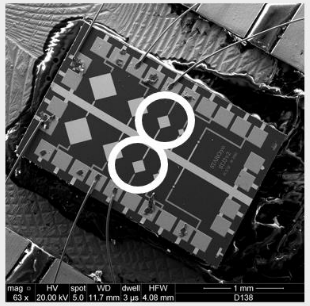


Lawrence Livermore National Laboratory

Ta-Based STJ Detectors

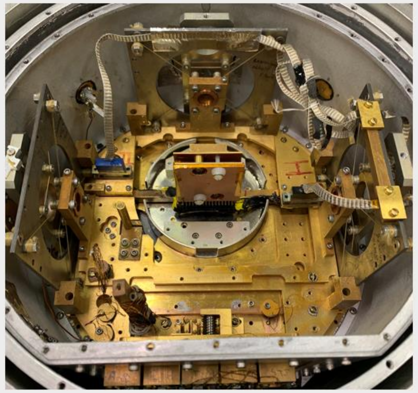
"Test" chips with 10 pixels of 5 sizes

Phase-I



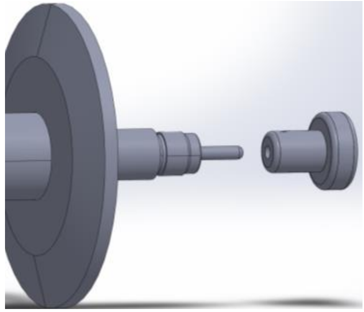
Phase-II

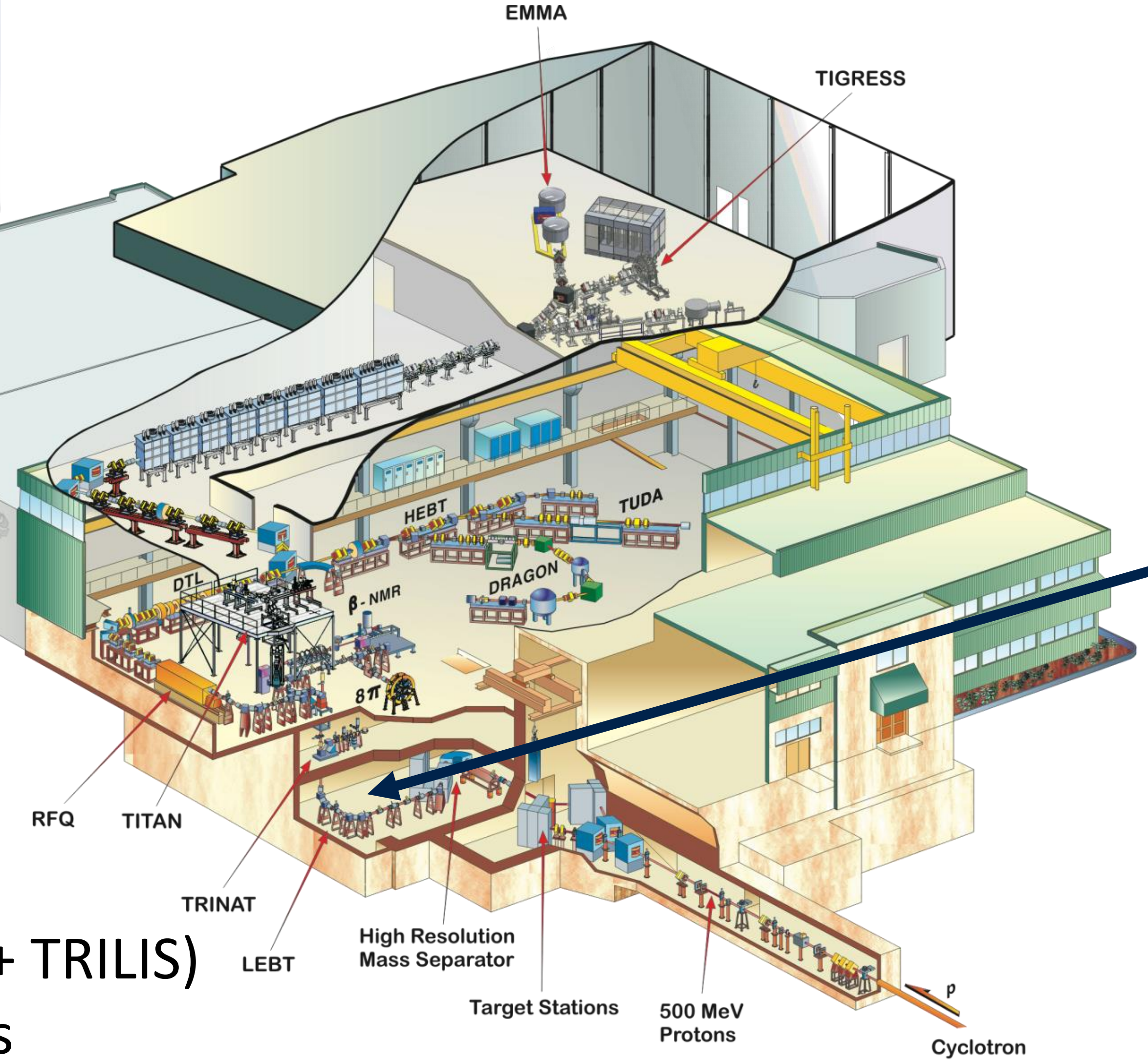
Cooled to 100 mK in an adiabatic demagnetization refrigerator (ADR)



S. Fretwell *et al*., Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al*., arXiv:2010.09603 (2020)

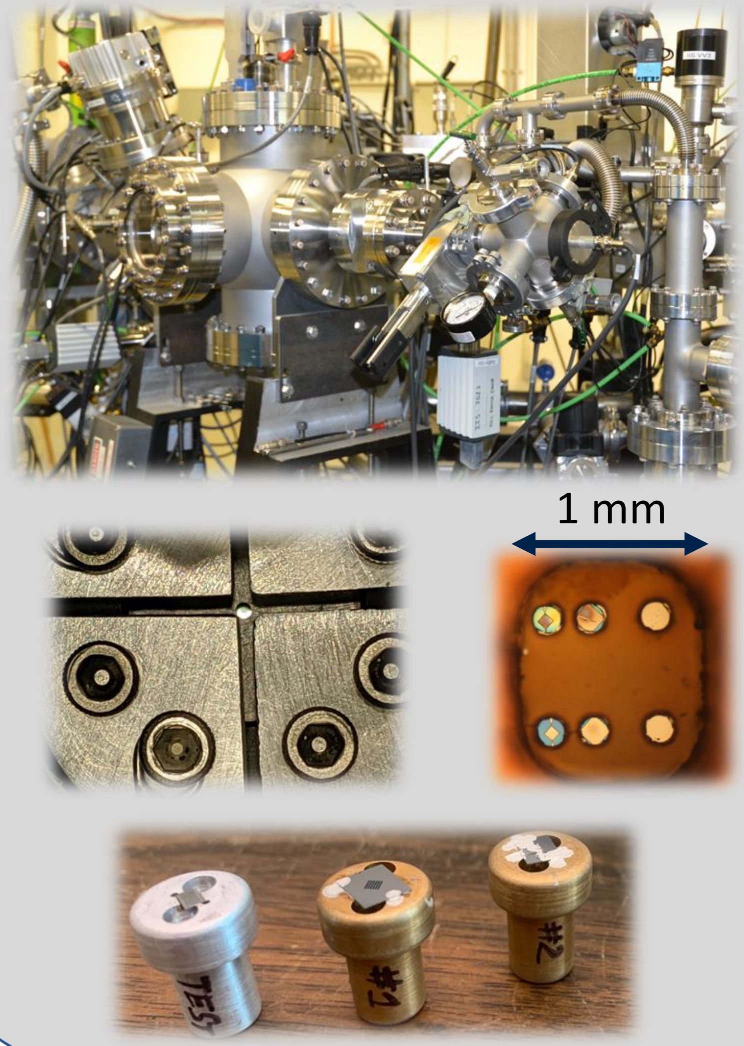
Harvesting ^{7}Be at ISAC





^{7}Be @ IIS (UCx + TRILIS)
$>10^{9}$ pps

The ISAC Implantation Station

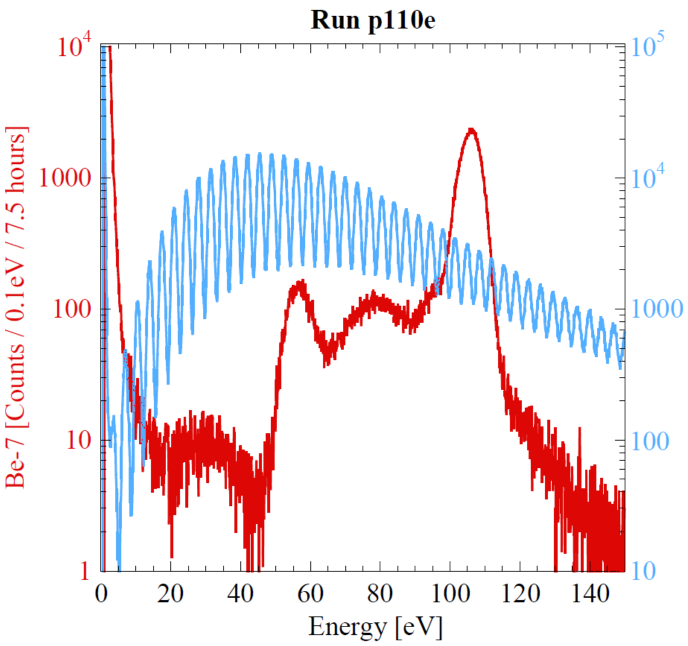


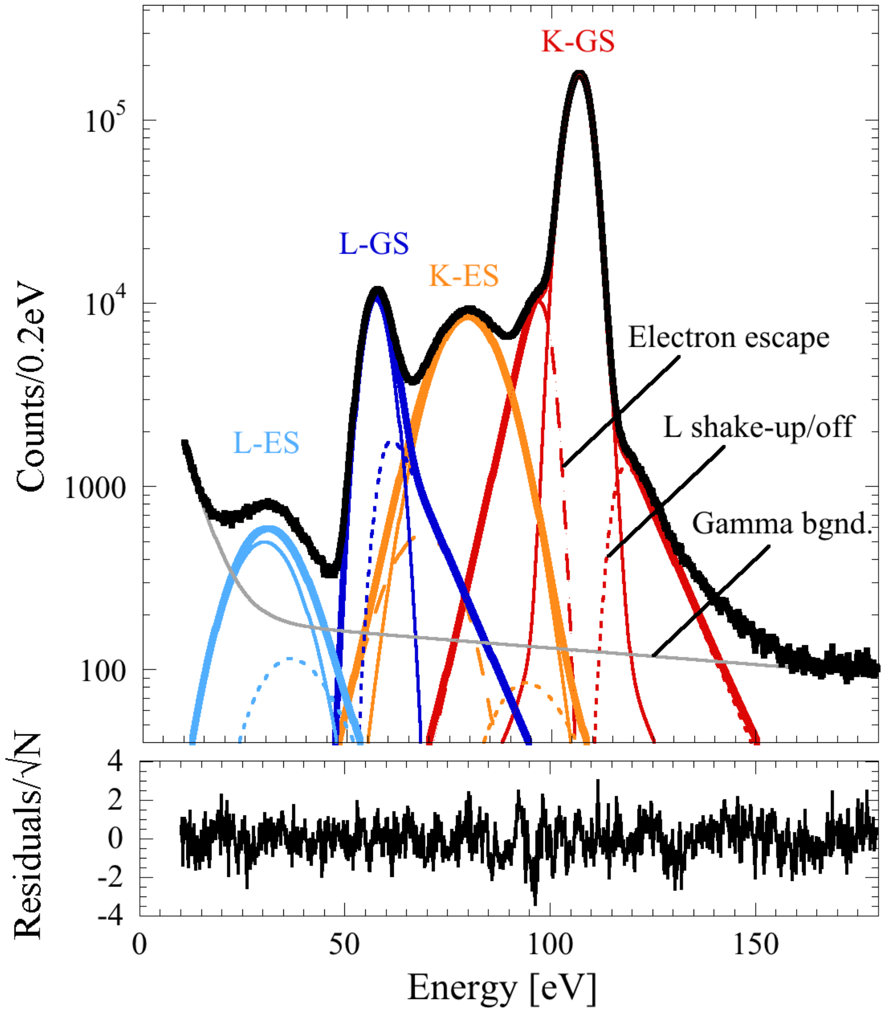
First Nuclear Recoil Experiments with STJs

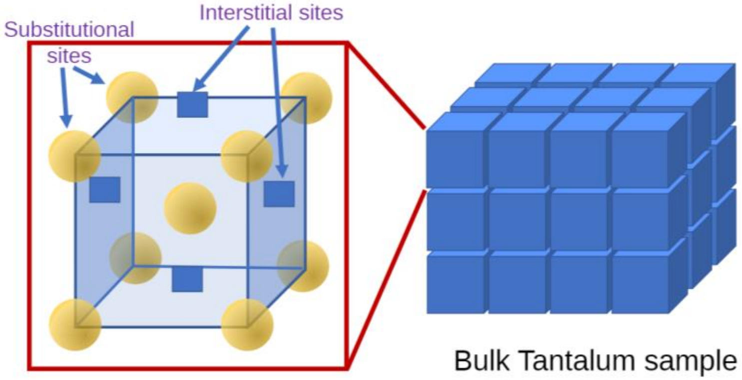
- Proof-of-concept
- Laser calibration precision <10 meV
    - Non-linearity of order 10^{-4} per eV

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

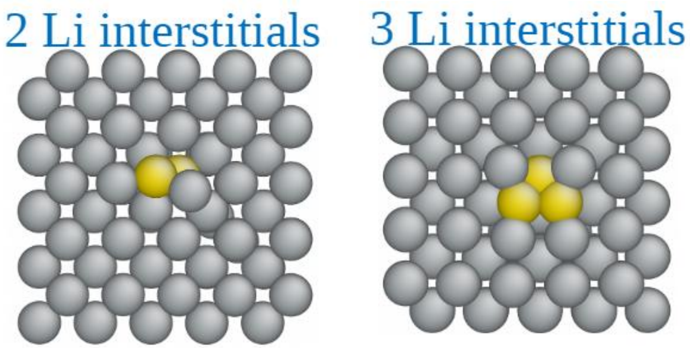






Bulk Tantalum sample

BCC unit cell of Tantalum

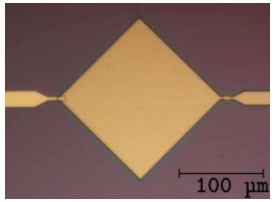


Vince Lordi and Amit Samanta – Quantum Simulation Group (LLNL)

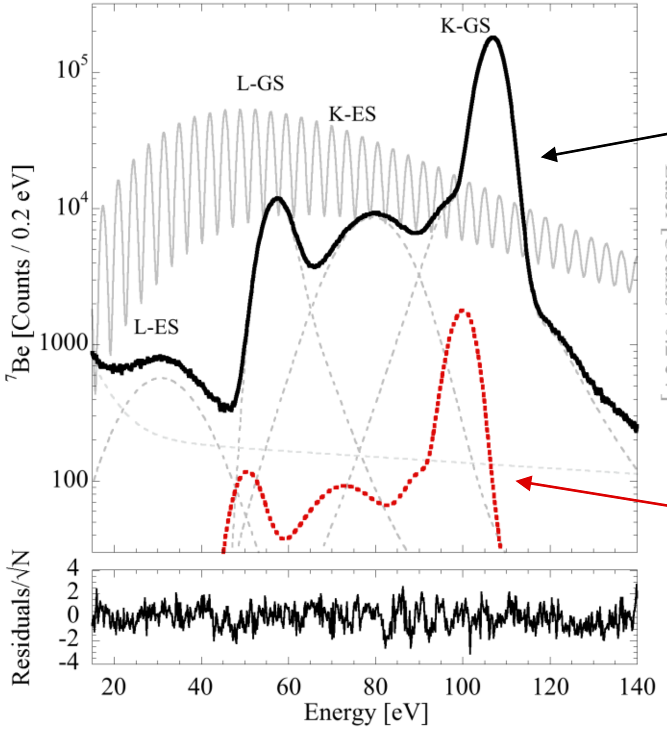
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

First Limits from “Low-Rate” Phase-II Data

- Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq)



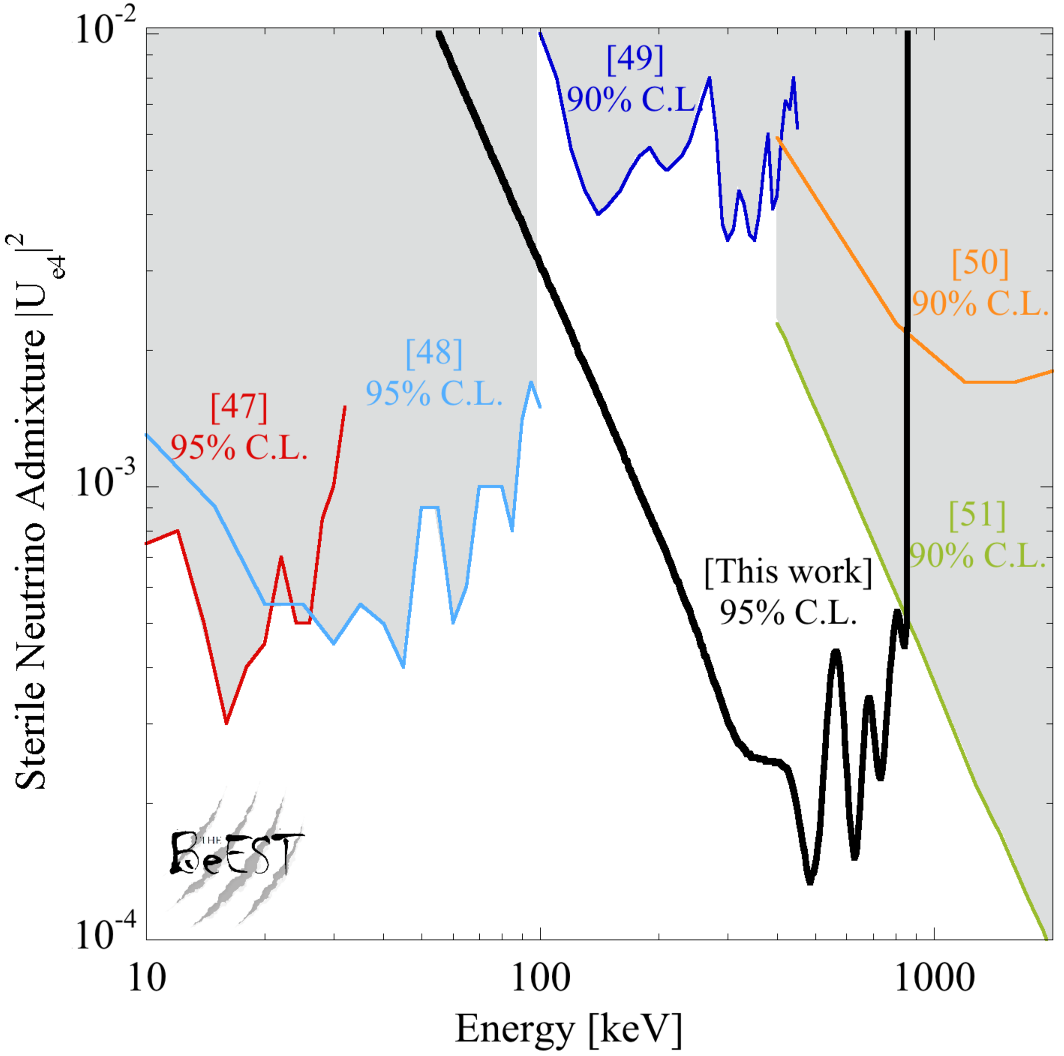
- Novel laser calibration scheme via individual photon counting
  - Precision characterization and energy calibration (<0.01 eV)



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

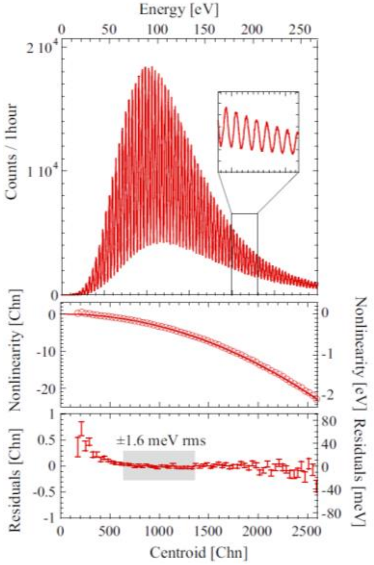
Example of signal that would be generated by 300 keV neutrino with 1% mixing

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



S. Friedrich *et al.*, arXiv:2010.09603 (2020)

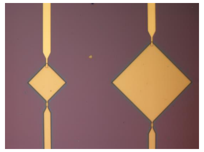
Phases of the BeEST Experiment



Phase-I

Proof of Concept

- PRL **125**, 032701 (2020)



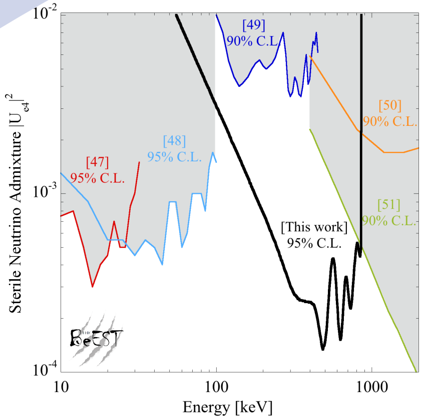
2018

Phase-II

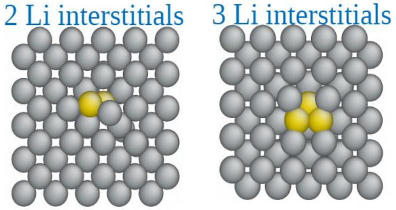
First Limits and Precision Device Characterization

- J. Low Temp. Phys. **200**, 200 (2020)
- arXiv:2010.09603 (2020)

2020

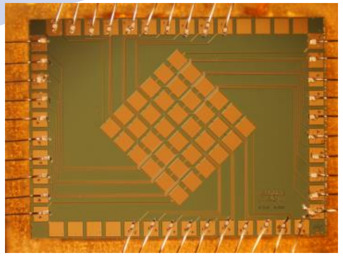


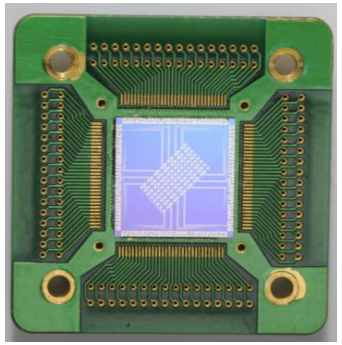
2021



Phase-III

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



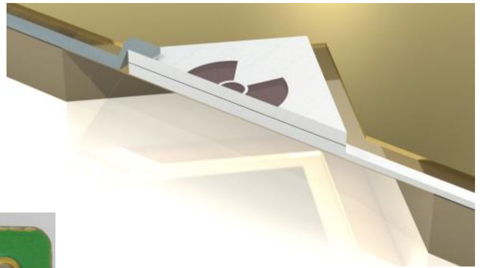


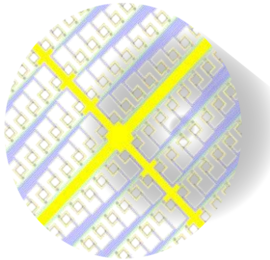
2022

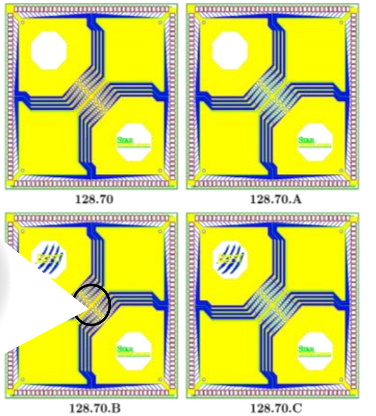
Phase-IV

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

2025

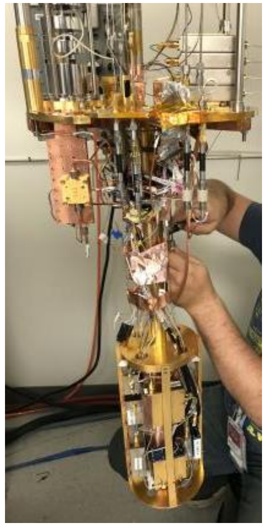






>2026: SuperBeEST

10,000-pixels of Hf-based STJs

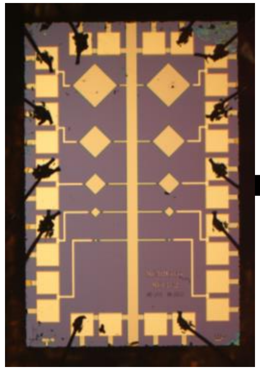


STJ Detector Development for NP

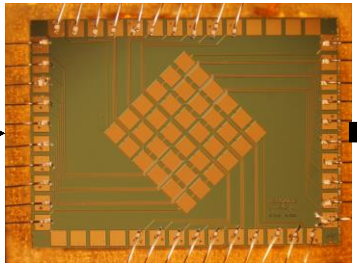
Stephan Friedrich

Lawrence Livermore National Laboratory

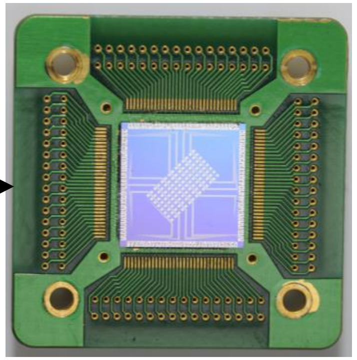
10 "Test" Pixels



36-Pixel Array



112-Pixel Array



U.S. DEPARTMENT OF ENERGY Office of Science

NNSA National Nuclear Security Administration

NNIS Fellow

Spencer Fretwell

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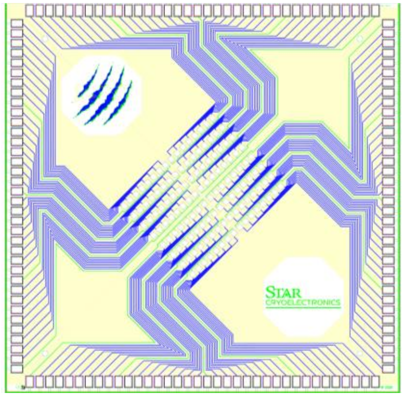
128-Pixel Al Array

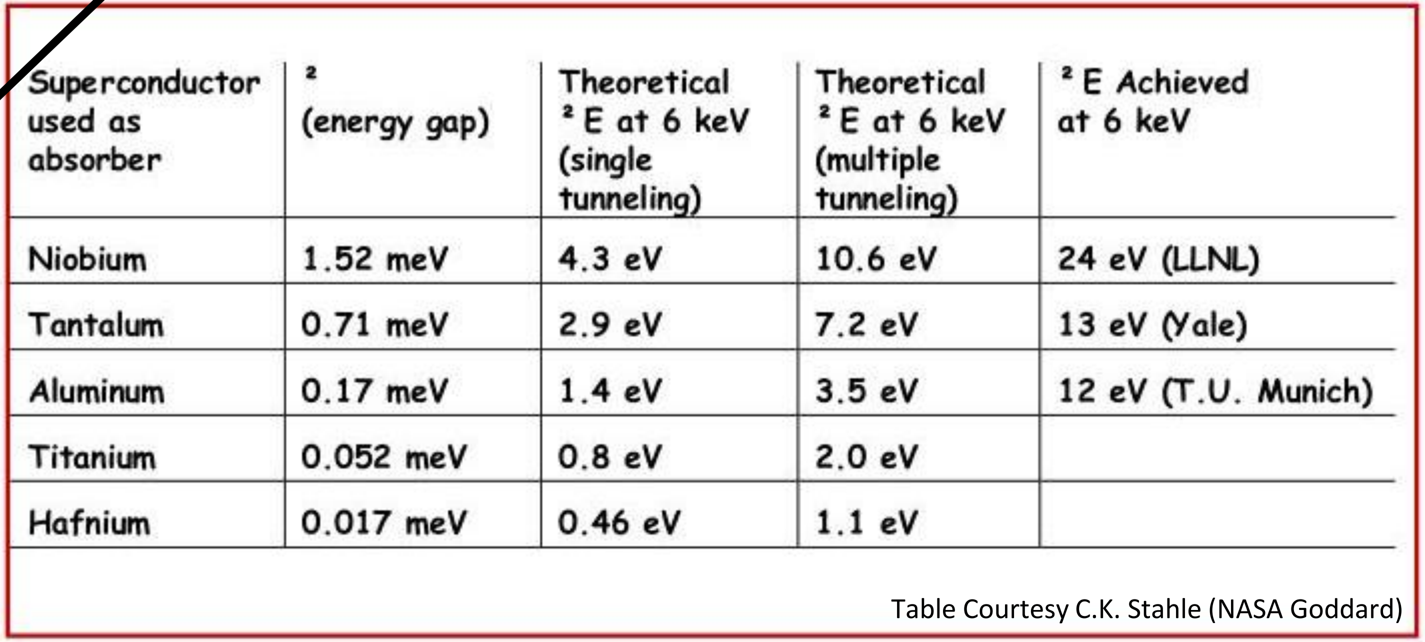


STAR CRYOELECTRONICS

BeEST (current)

BeEST (in-progress)

SuperBeEST



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
Niobium	1.52 meV	4.3 eV	10.6 eV	24 eV (LLNL)
Tantalum	0.71 meV	2.9 eV	7.2 eV	13 eV (Yale)
Aluminum	0.17 meV	1.4 eV	3.5 eV	12 eV (T.U. Munich)
Titanium	0.052 meV	0.8 eV	2.0 eV	
Hafnium	0.017 meV	0.46 eV	1.1 eV	

Table Courtesy C.K. Stahle (NASA Goddard)

Resolution at 0.1 keV

3 eV

1.5 eV

0.8 eV

0.2 eV

Gentle nudge from John this morning:

"I hear a convenor kindly reminding the goal is to help TRIUMF and CENPA figure out what to do :) "

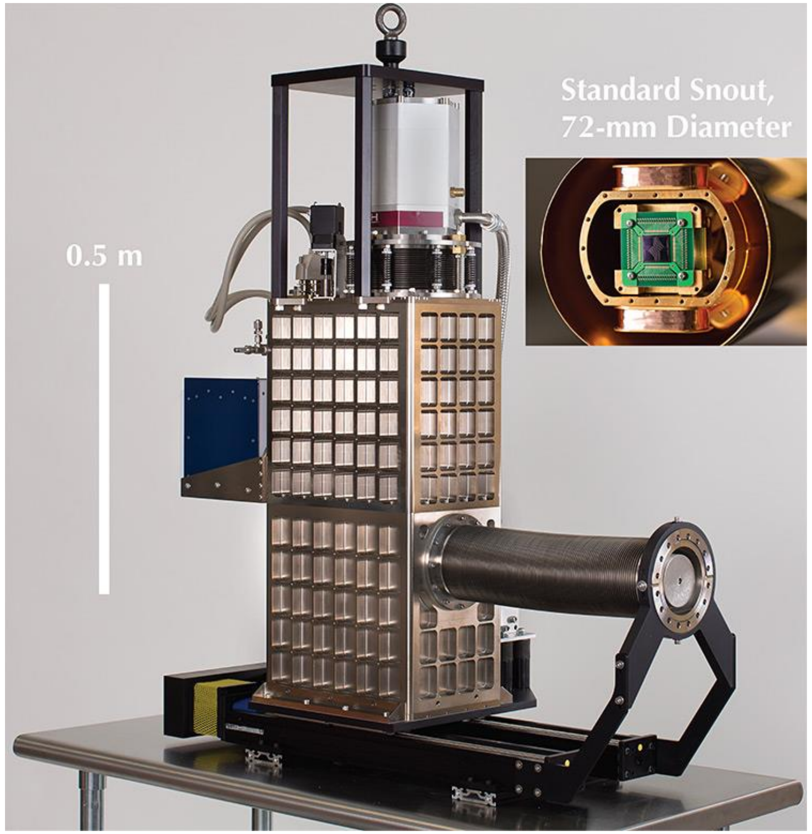
So, how can TRIUMF or CENPA exploit these ideas?

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

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

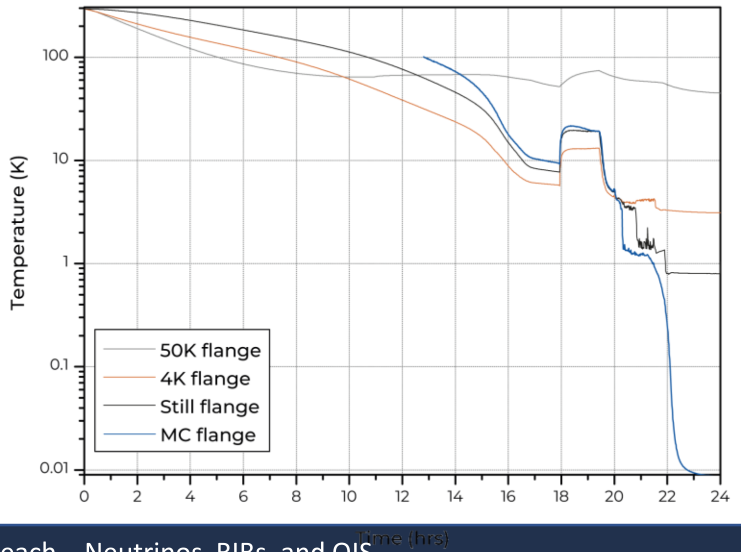
LH System

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.

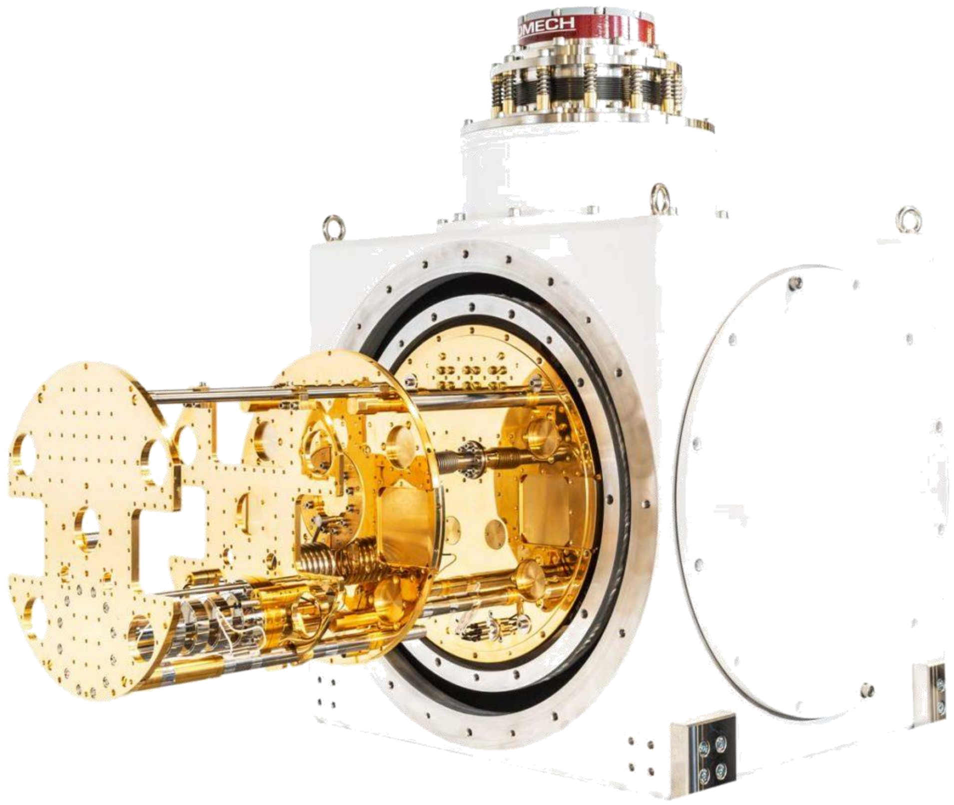
Eight LOS Access Ports

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

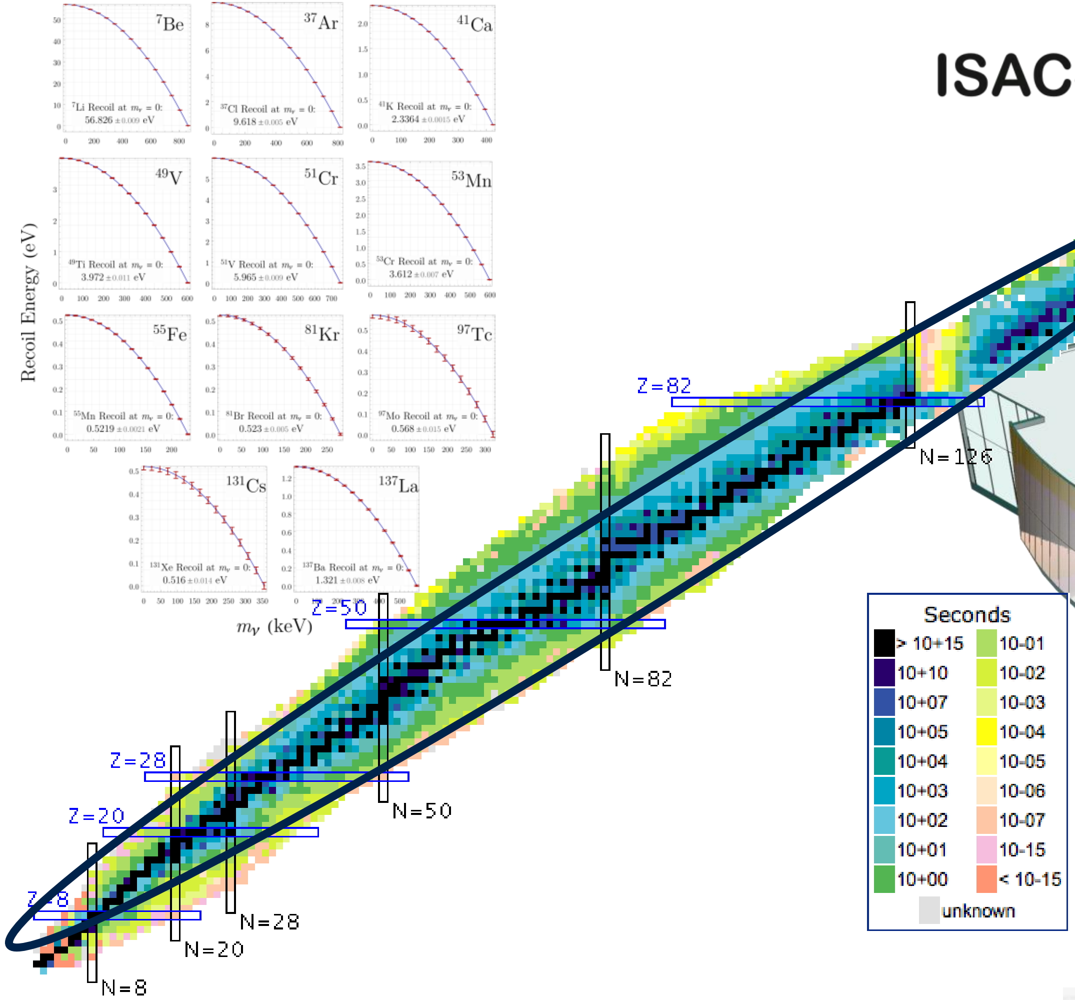
- 2 x KF63 slotted in all flanges
- 4 x KF40
- 2 x KF16



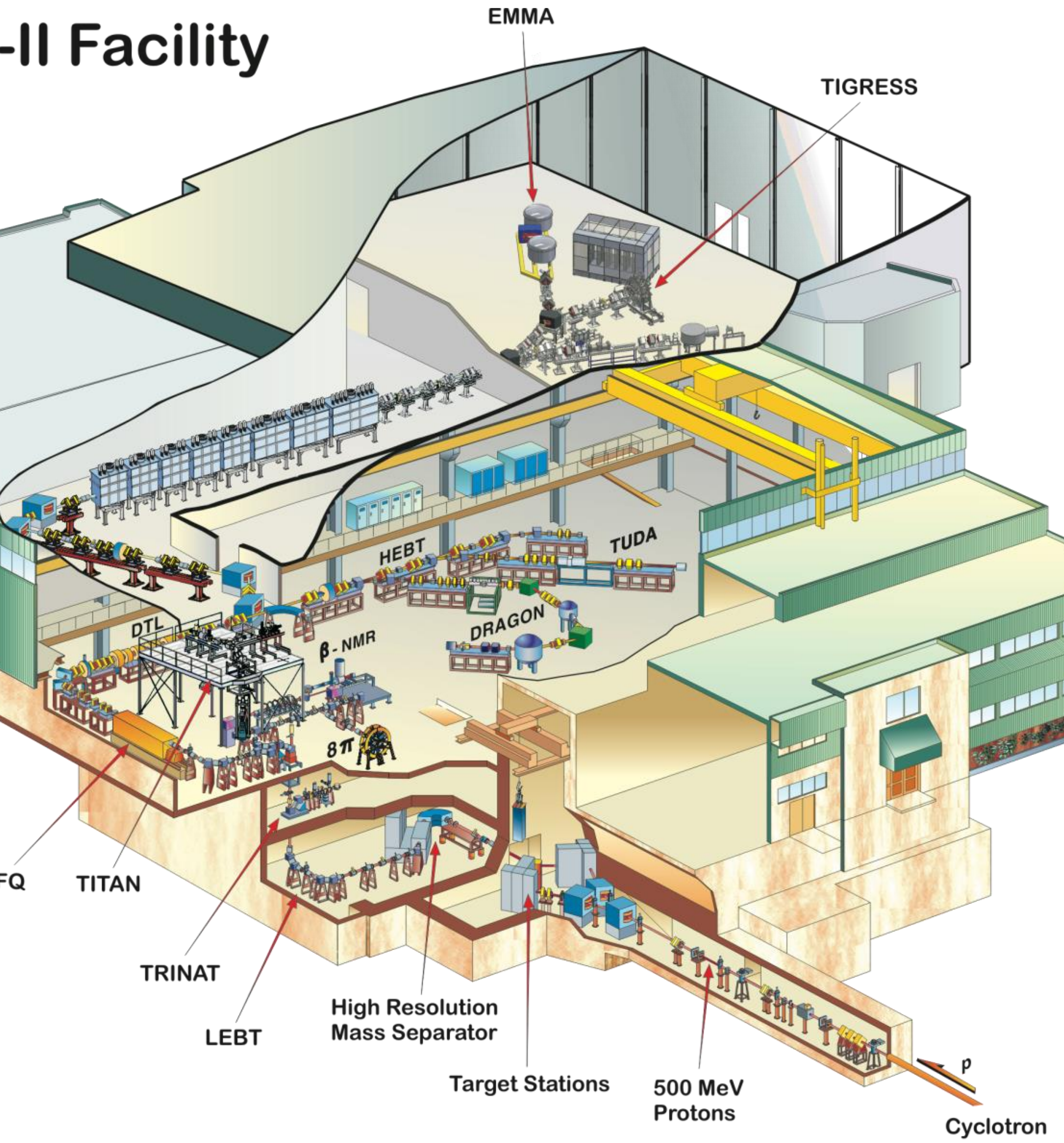
°BLUEFORS



Quantum Sensors and Short-Lived RIBs at ISAC



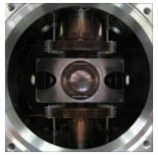
ISAC-I and ISAC-II Facility



Low-Energy: Photons, electrons, or recoils

SALER

GRIFFIN



Conclusions

- Quantum sensors can be powerful tools in our search for BSM physics using nuclei/atoms. In particular, STJs allow for high-rate experiments to probe weak BSM physics S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

- Physics case and device selection is critical as these devices are not "one size fits all" options for all nuclear spectroscopy

- The Beryllium Electron capture in Superconducting Tunnel junctions (BeEST) experiment uses momentum reconstruction in the EC decay of ^{7}Be to search for heavy neutrino mass states in the 5-860 keV range.

  S. Friedrich *et al.*, arXiv:2010.09603 (2020)

- In the near future, we will have sensitivity to heavy mass states from 5-860 keV with couplings as low as 10^{-7}.

- Decay momentum reconstruction is a simple, model-independent approach to heavy neutrino searches, and will also be employed in future complementary efforts using nuclear decay of ^{3}H (KATRIN, Project 8), ^{131}Cs (HUNTER), and ^{163}Ho (ECHo, HOLMES) to provide high-sensitivity searches from the eV to MeV scale.

- At ISAC, in particular, one could envision using short-lived species to do direct implantation, or measure low-energy radiation to very high precision.

The BeEST

COLORADO SCHOOL OF MINES
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STAR CRYOELECTRONICS

Robin Cantor

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NNSA National Nuclear Security Administration
APS physics
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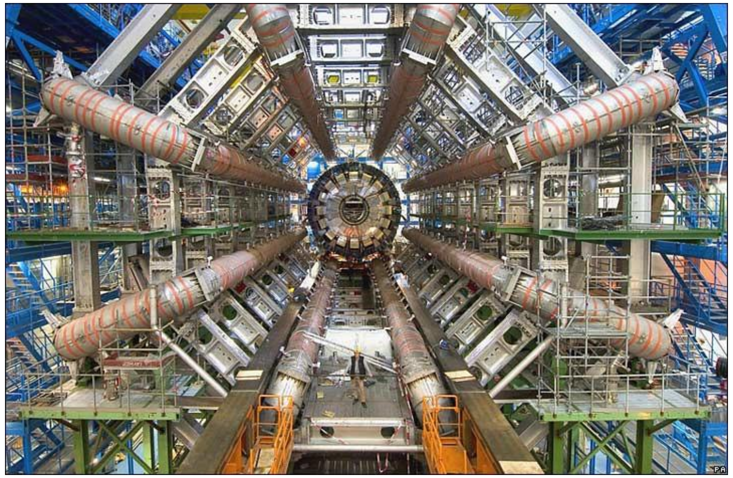
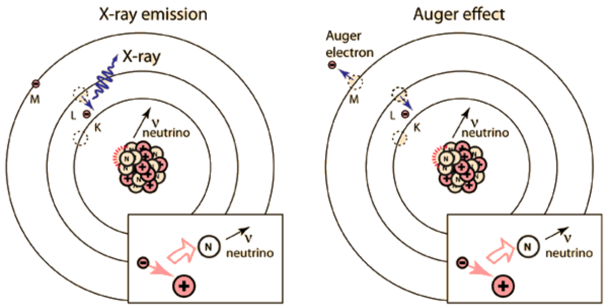
Backup Slides

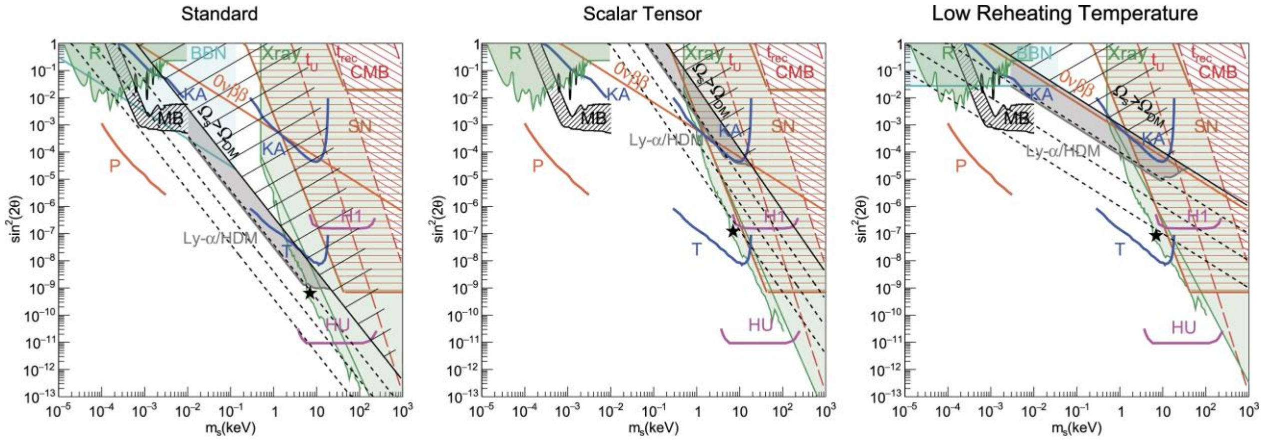
Nuclear β Decay as a Probe of New Physics

First, we need to ask a few questions:

1. What can we uniquely probe in the era of the LHC?
2. Are model predictions of observable couplings to BSM physics within reach?
3. Do we understand the nuclear and atomic structures well enough to make definite conclusions?





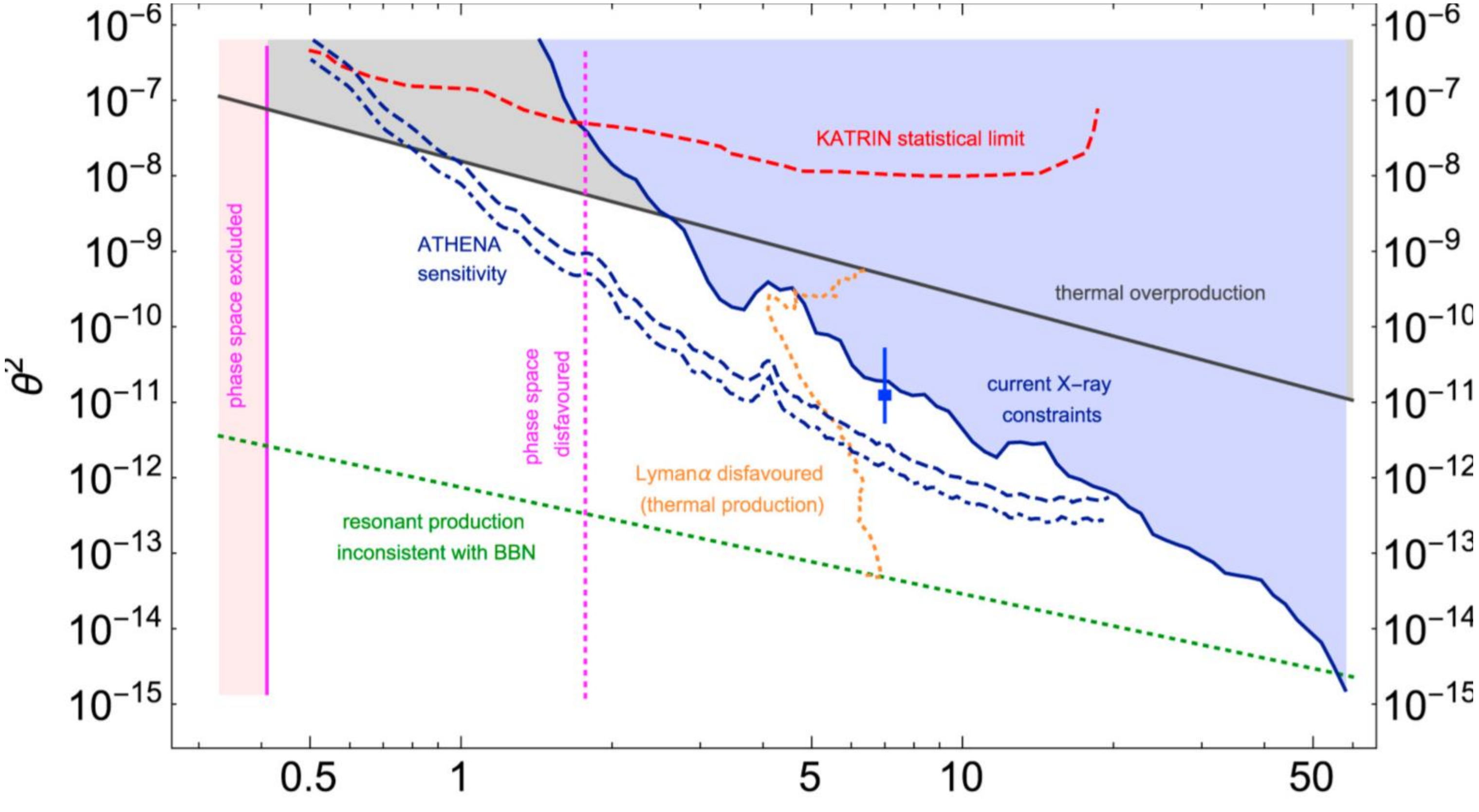


Graciela B. Gelmini, Philip Lu, Volodymyr Takhistov, PLB **800**, 135113 (2020)

keV-Scale Sterile Neutrinos as Dark Matter

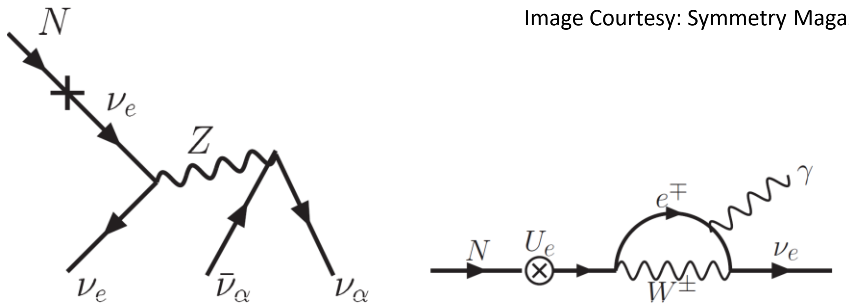
- Extensions to the SM that extend the PMNS matrix (eg. type-I seesaw mechanism) can generate a heavy neutrino that is on the keV mass scale - an excellent candidate for DM

Image Courtesy: Symmetry Magazine



M [keV]

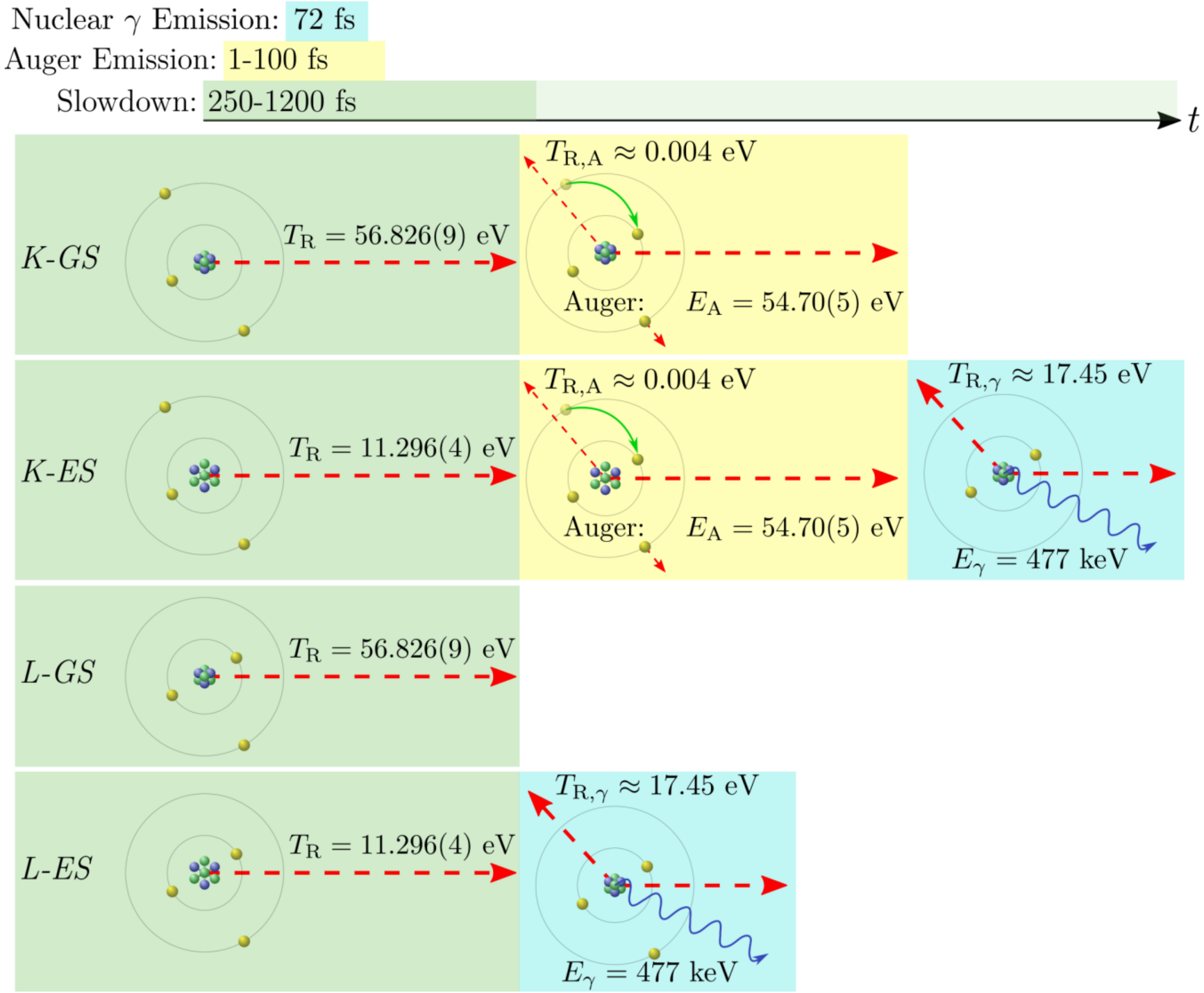
A. Boyarsky et al., PPNP **104**, 1-45 (2019)

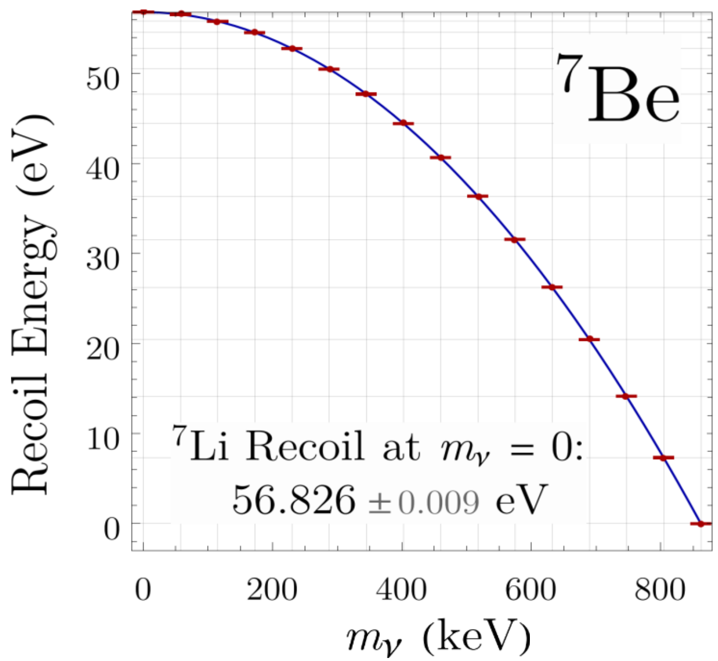


R. Adhikari et al., JCAP **25** (2017)

These limits can be powerful, but are heavily model dependent and only provide useful limits *if* (for example) they have an observable annihilation or decay mode

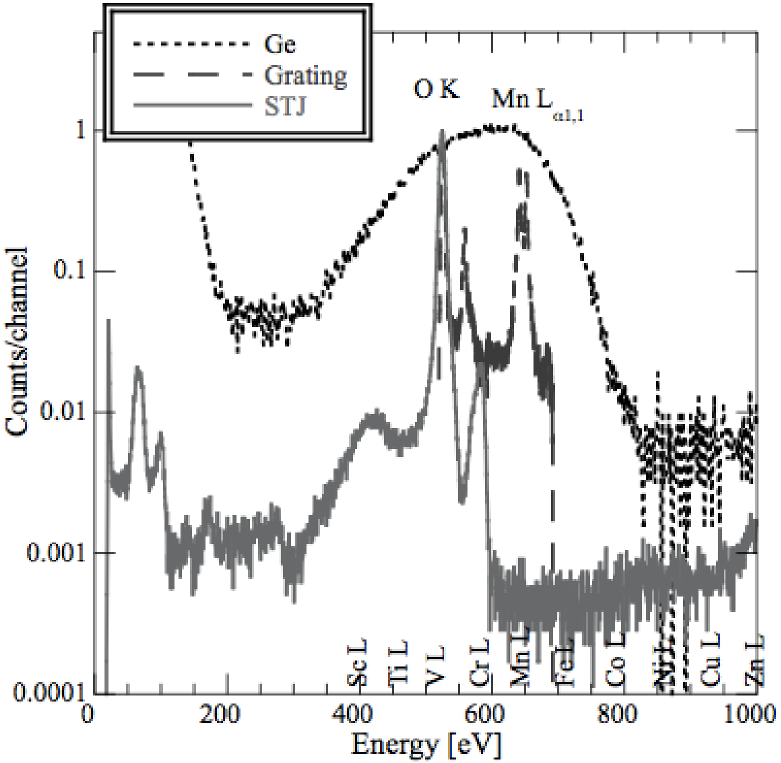
^{7}Be Decay Processes



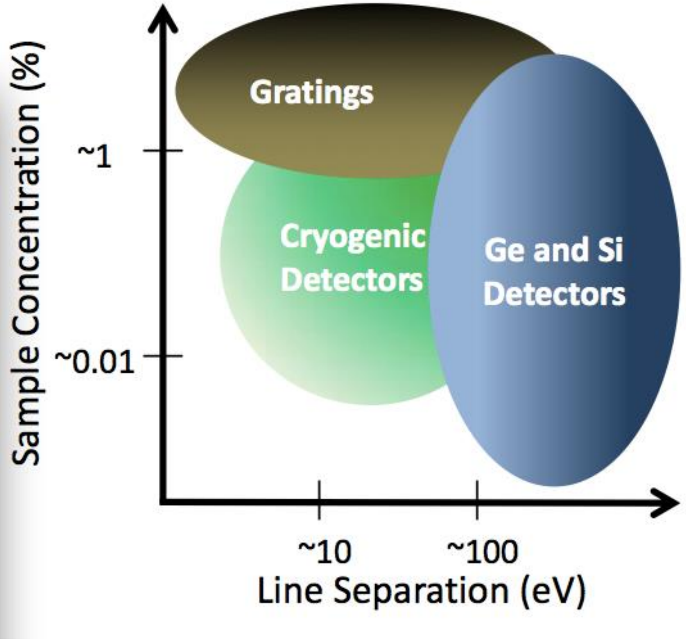


High-Resolution Low-Temperature Detectors

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

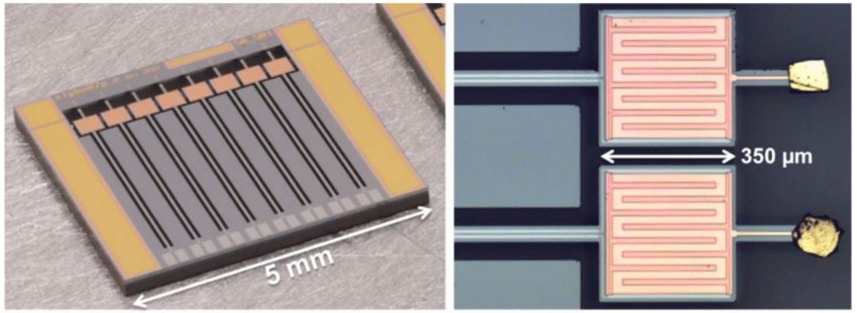


Higher resolution than Si or Ge,
Higher efficiency than gratings.

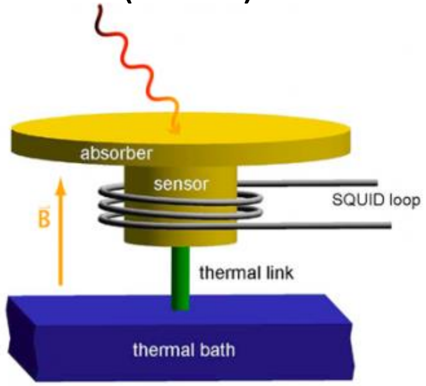


Soft X-ray spectroscopy of dilute samples.

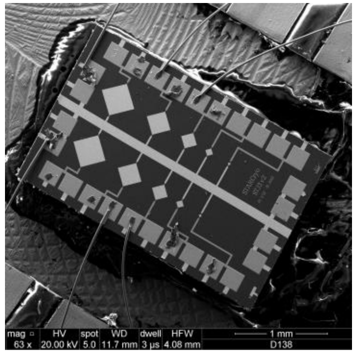
Transition Edge Sensor (TES)



Magnetic Microcalorimeter (MMC)



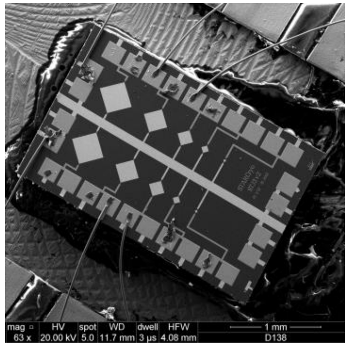
Superconducting Tunnel Junction (STJ)



Slide Courtesy: Stephan Friedrich

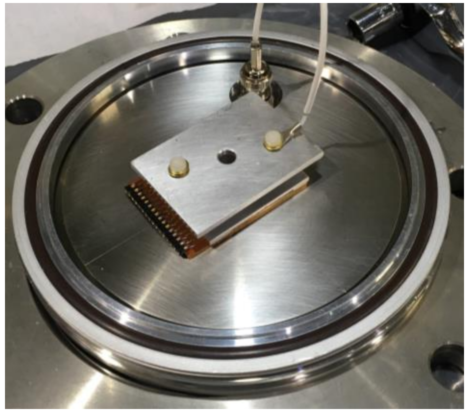
Our Proof of Concept (Implantation 1 - Dec 2018)

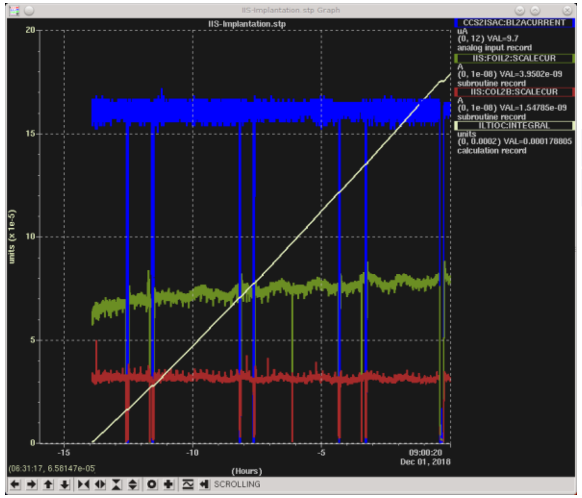
- **Goal: Demonstrate the BeEST concept**
- “Test” chip from LLNL



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

- Implantation chamber designed, fabricated, and tested by M.S. Student Spencer Fretwell in 3 weeks



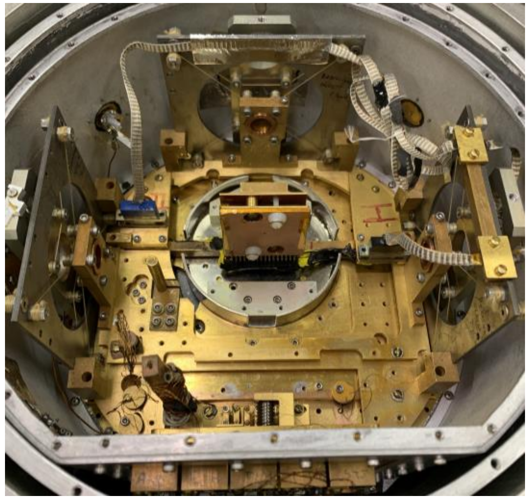


```
CCS2ISAC:BL2ACURRENT
uA
(0, 12) VAL=9.7
analog input record
IIS:FOIL2:SCALECUR
A
(0, 1e-08) VAL=3.9502e-09
subroutine record
IIS:COL2B:SCALECUR
A
(0, 1e-08) VAL=1.54785e-09
subroutine record
ILTIOC:INTEGRAL
units
(0, 0.0002) VAL=0.000178805
calculation record
(06:31:17, 6.58147e-05
```

12 hr implantation:

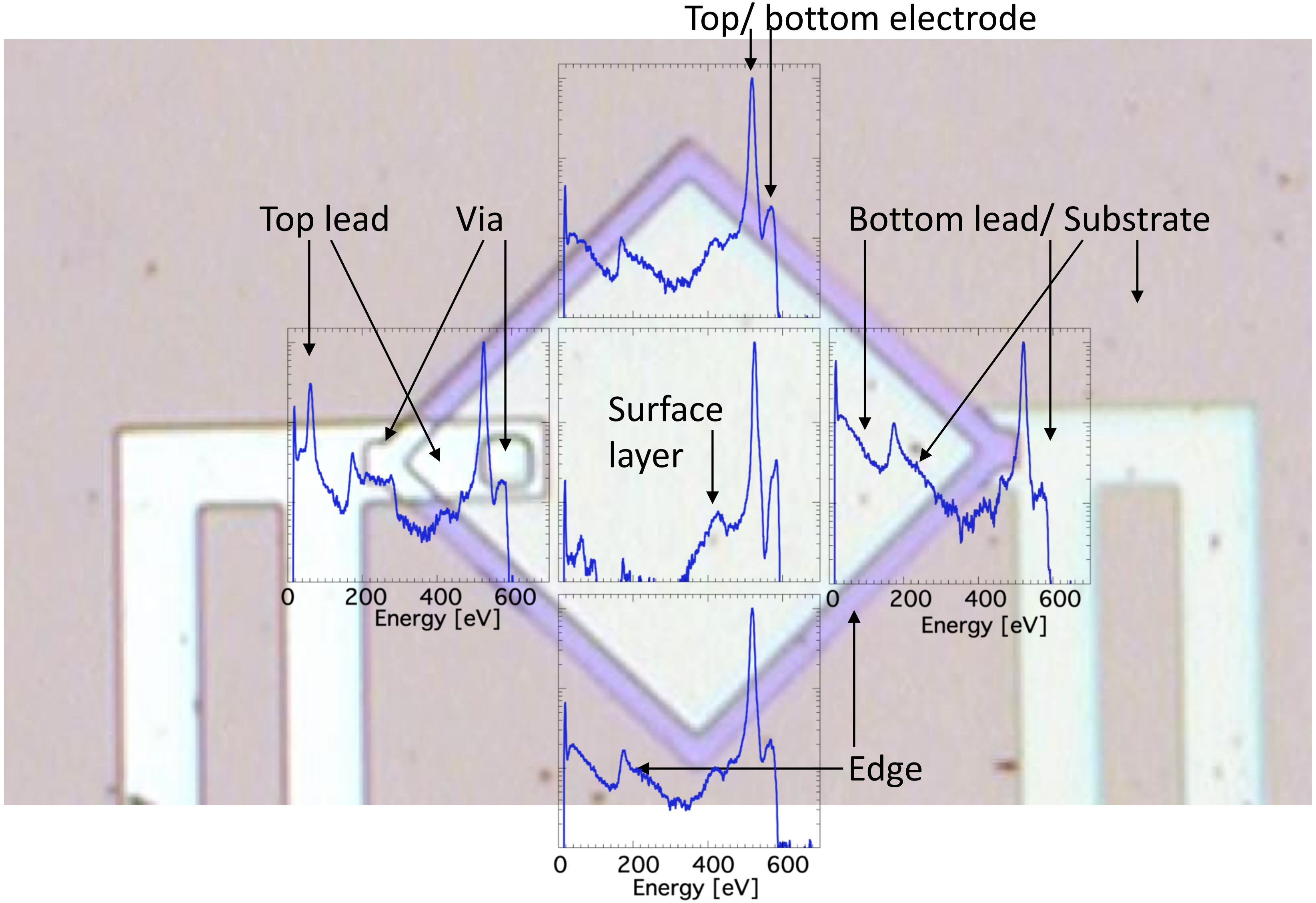
Total Implanted (Li+Be)	1.23E+12
7Be Implanted	4.68E+10

Measured activity on chip: 7.5(4) kBq



→ TRIUMF → Lawrence Livermore National Laboratory

STJ Line Shape (of very old Nb-STJs)



Experiment:

- Illuminate different parts of STJ
- Use focused 500 eV X-ray beam
- Identify source of artifacts

STJ Improvements since then:

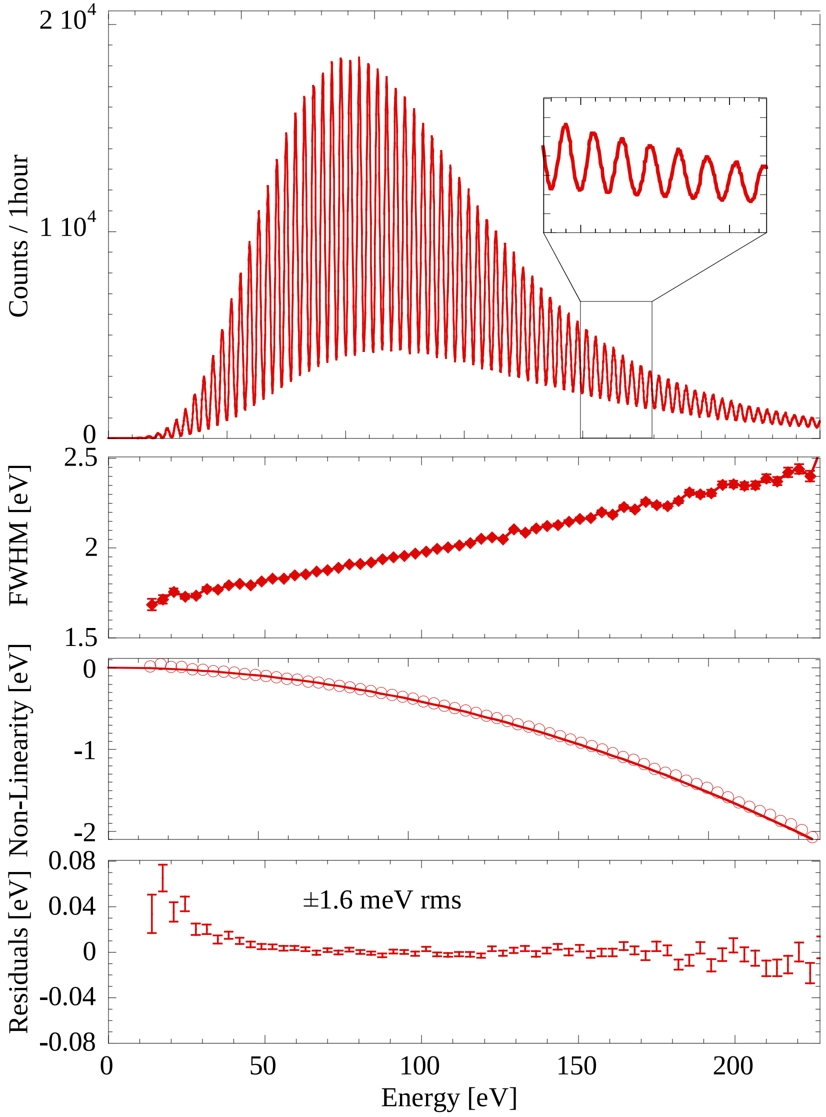
- Replace Nb by Ta ⇒ Line splitting ↓
- No SiO_2 on surface ⇒ No artifact
- Narrower base layer edge
- Smaller overlap of top lead

Planned Improvements

- Replace Ta by thick Pb, no Ta base ⇒ Higher efficiency at high E
- STJ on membrane, use collimator ⇒ No substrate and edge effects

Slide Courtesy: Stephan Friedrich

STJ Performance: Resolution and Linearity



Pulsed 355 nm (3.5eV) laser at 5,000 Hz

⇒ Comb of peaks at integer multiples of 3.5 eV

⇒ Energy resolution between ~1.5 and ~2.5 eV FWHM

⇒ Only quadratic non-linearity

⇒ Calibration accuracy of order ±1 meV in 1 hour

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