***Be**ryllium-7 **E**lectron Capture in **S**uperconducting **T**unnel Junctions: The **BeEST** Sterile Neutrino Search*

Stephan Friedrich

Lawrence Livermore National Laboratory

for the BeEST Collaboration

LLNL-PRES-836503

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52- 07NA27344.

Outline

A Very Brief History of Radiation Detection

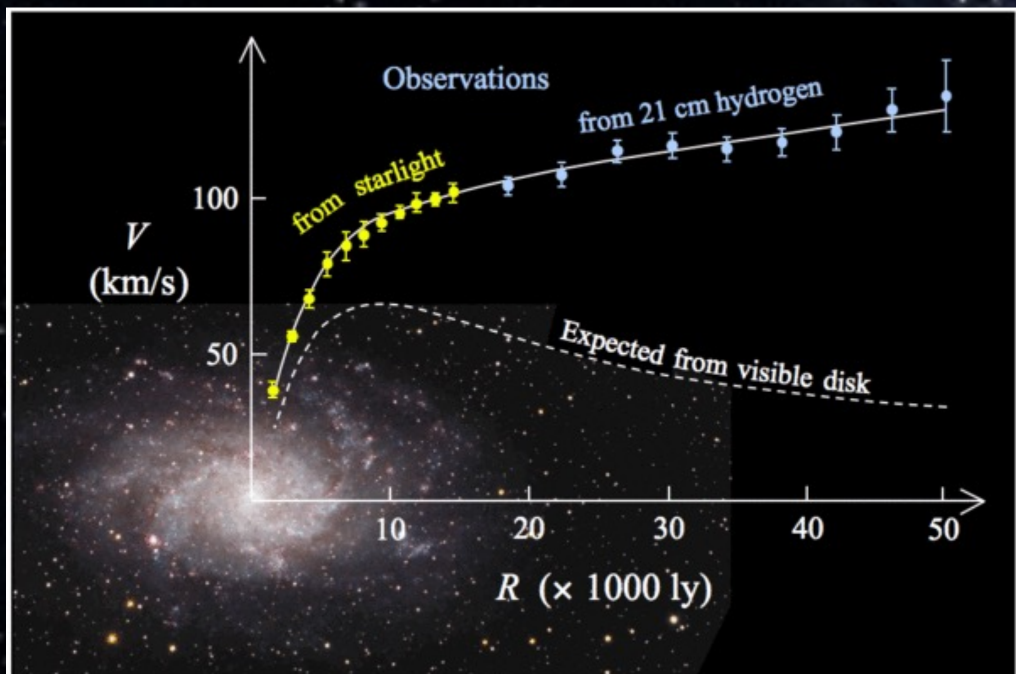
1) Dark Matter and Sterile Neutrinos
2) Superconducting Tunnel Junction (STJ) Radiation Detectors
3) The BeEST Sterile Neutrino Search
4) Material Effects in Superconducting (STJ) Sensors
5) Next: Increased Sensitivity with Arrays and New Materials

Tabletop BSM Physics.

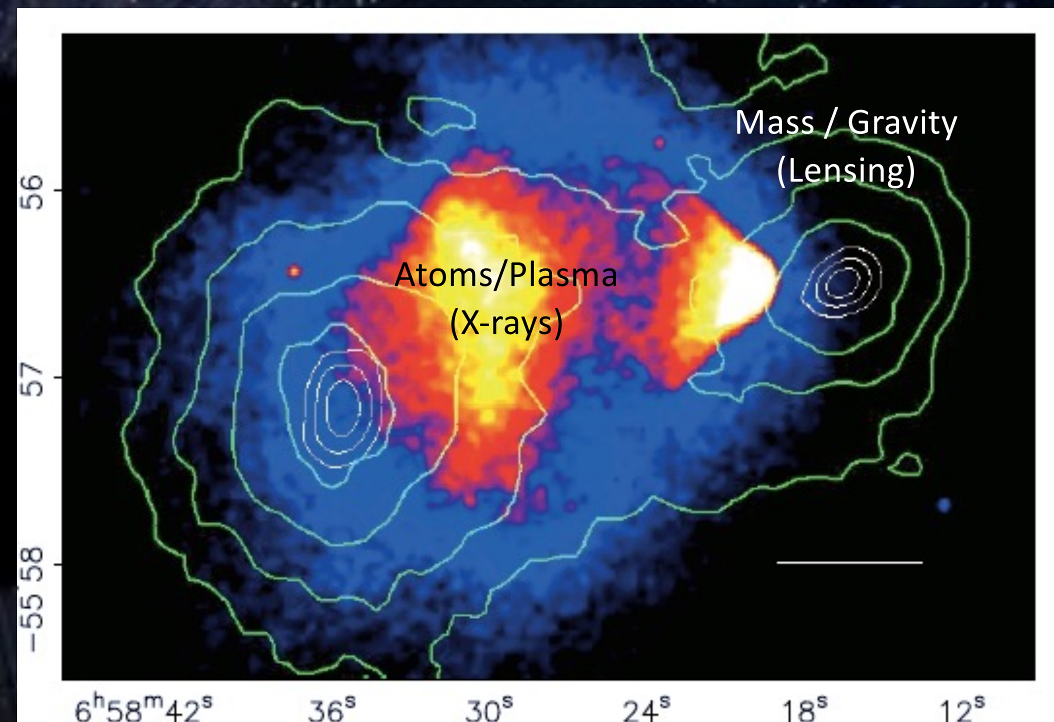
Dark Matter

A Very Brief History of Radiation Detection

Galaxy Rotation Curves



Merging "Bullet Cluster"



The composition of ~85% of the mass in the universe is unknown.

Sterile Neutrinos

Questions in Cosmology:

- What is dark matter?
- Why is there more matter than antimatter in the universe?

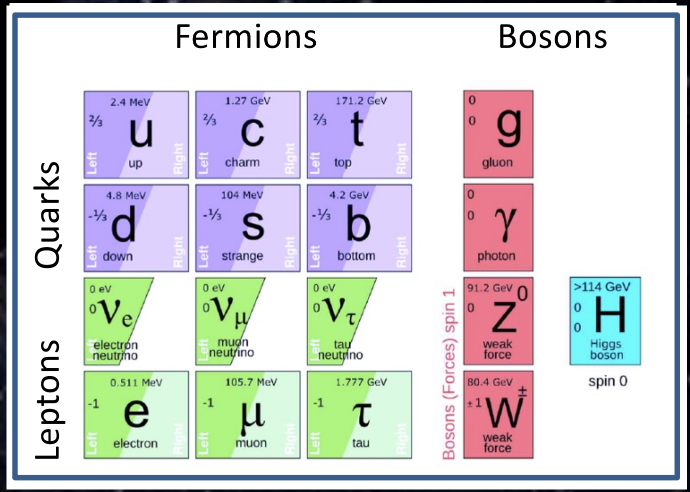
Questions in Particle Physics:

- What is nature of neutrinos mass?
- Do right-handed neutrinos exist?


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

A White Paper on keV sterile neutrino Dark Matter

Editors: M. Drewes, T. Lasserre, A. Merle and S. Mertens
E-mail: marcodrewes@gmail.com, thierry.lasserre@cea.fr, amerle@mpp.mpg.de, smertens@lbl.gov



Sterile neutrinos are an appealing dark matter candidate.

But they are well-motivated without dark matter, too.

1) (Active) neutrinos exist   2) (Sterile) neutrinos could explain *several* big questions

How to Find Something that

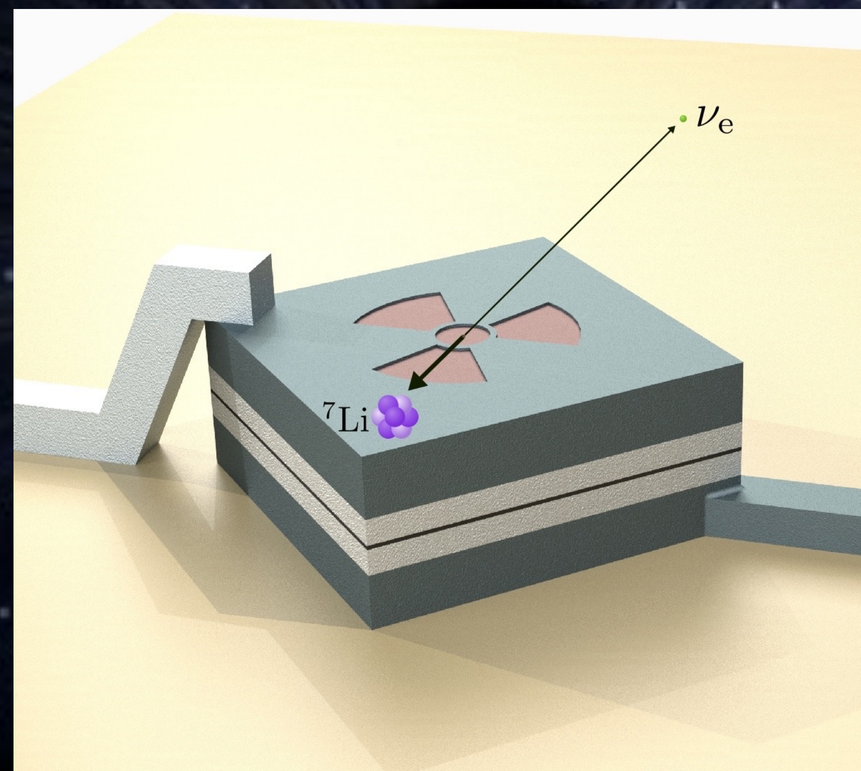
A Very Brief History of Radiation Detection

1) Doesn't emit light
2) Doesn't absorb light
3) Doesn't interact (except through its mass)?

How to Find Something that

A Very Brief History of Radiation Detection

1) Doesn't emit light
2) Doesn't absorb light
3) Doesn't interact (except through its mass)?



Use $|p_{neutrino}|$ = $|p_{Li\text{-}7}|$ to search for missing momentum in nuclear decay of ^{7}Be.

Why ^{7}Be?

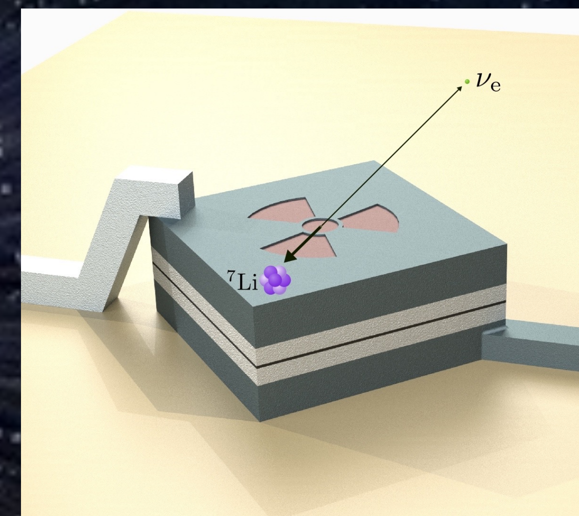
Why ^{7}Be?

1) 2-body Electron Capture decay $^7Be + e^- \Rightarrow {}^7Li + \nu$
   $\Rightarrow$ Monochromatic recoil
2) Long half life of 53 days
   $\Rightarrow$ Easy handling
3) Low Z = 7
   $\Rightarrow$ Manageable calculations
4) Large Q = 861 keV
   $\Rightarrow$ "Large" recoil signal E = 56 eV

Why Not ^{7}Be?

1) 10% EC decay into excited state $^7Li^*$
   $\Rightarrow$ Doppler-broadened secondary peaks

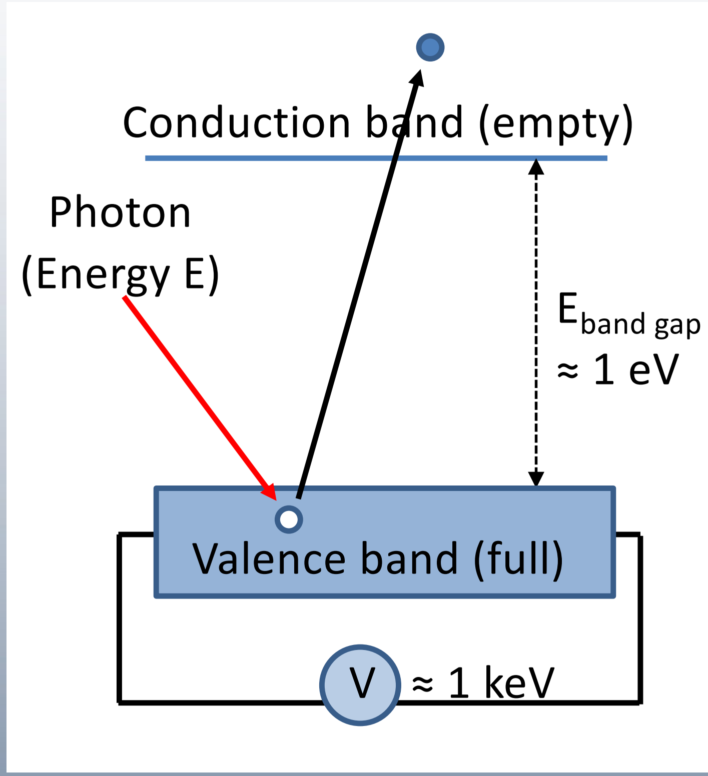
Superconducting Tunnel Junction Detector



1) High energy resolution
2) High speed, >1000 counts/s
3) Sensitive to phonons

Use $|p_{neutrino}| = |p_{Li\text{-}7}|$ to search for missing momentum in nuclear decay of ^{7}Be.

2) Semiconducting vs Superconducting Detectors

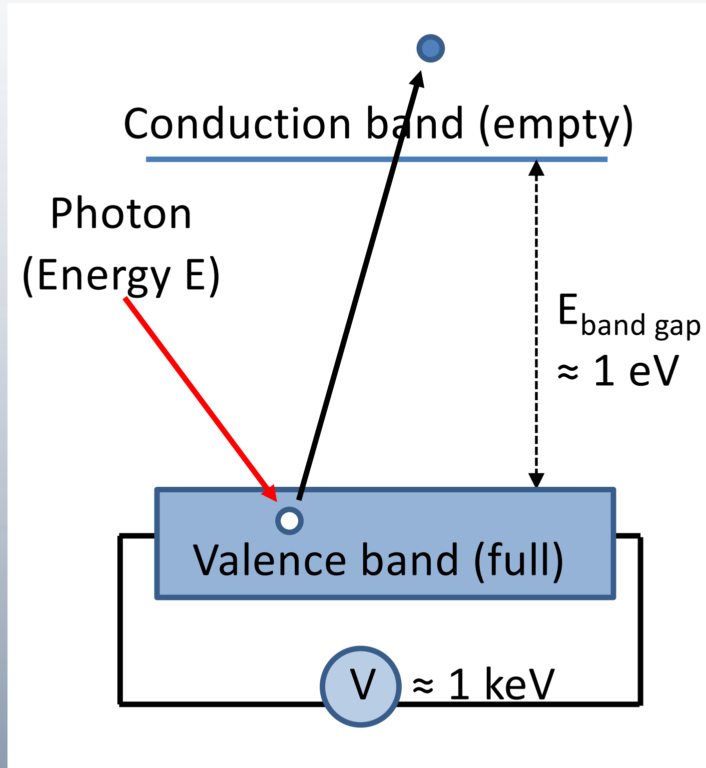


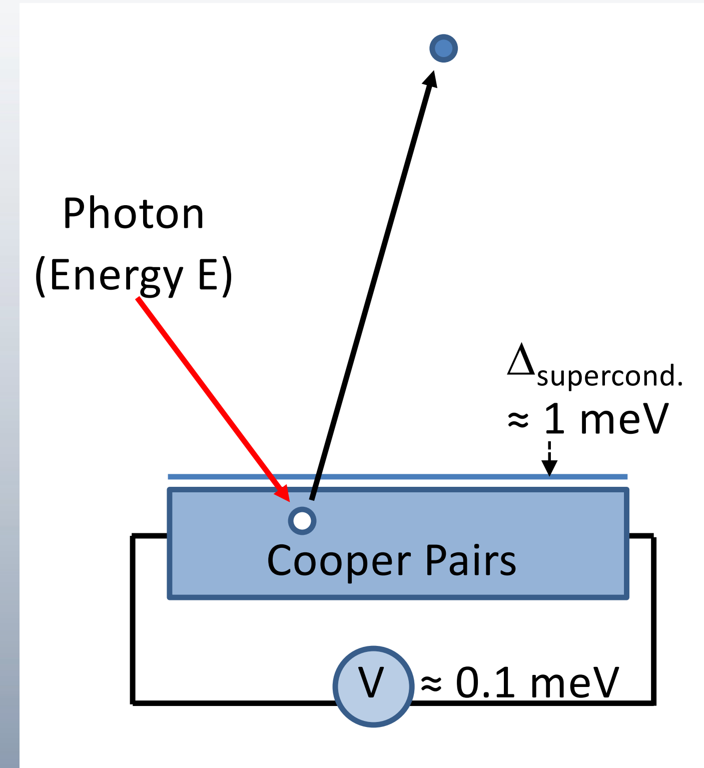
$$\text{Signal} = eN \approx e \frac{E}{3E_{bandgap}}$$

$\text{Noise} = (FN)^{1/2}$ with $F \approx 0.1$

$\text{Signal/Noise} \propto 1/\sqrt{E_{bandgap}}$

2) Semiconducting vs Superconducting Detectors





$\text{Signal} = eN \approx e\,\dfrac{E}{3E_{bandgap}}$

$\text{Noise} = (FN)^{1/2}$ with $F \approx 0.1$

$\text{Signal/Noise} \propto 1/\sqrt{E_{bandgap}}$

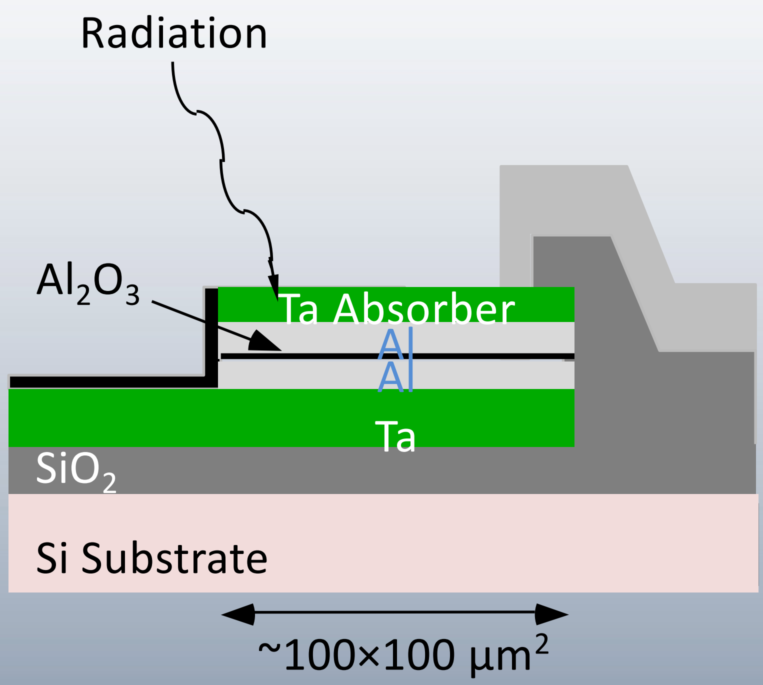
$\text{Signal} = eN \approx e\,\dfrac{E}{1.7\Delta_{supercond.}} \rightarrow$ ~1000x larger !

$\text{Noise} = (FN)^{1/2}$ with $F \approx 0.2 \rightarrow$ ~30x larger

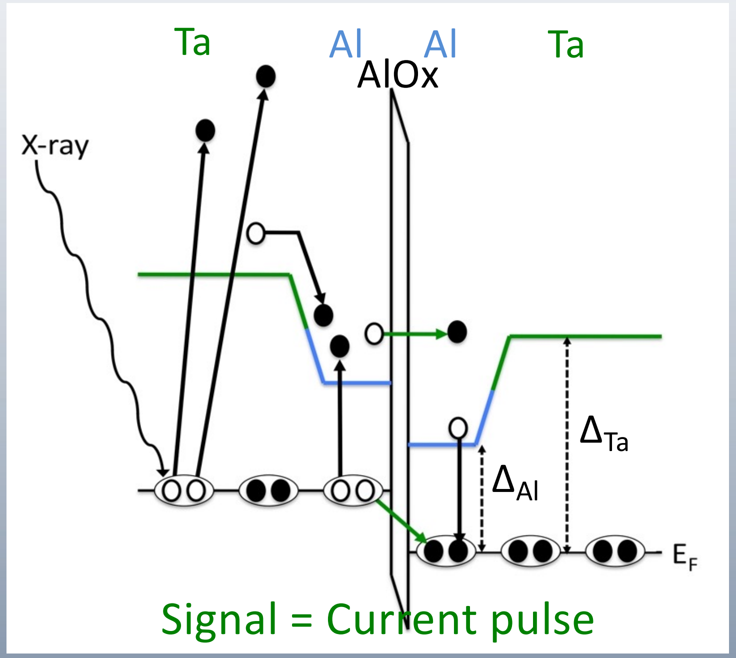
~30x higher energy resolution, no quenching.

Superconducting Tunnel Junction (STJ) Radiation Detectors

STJ Cross Section



STJ Operating Principle

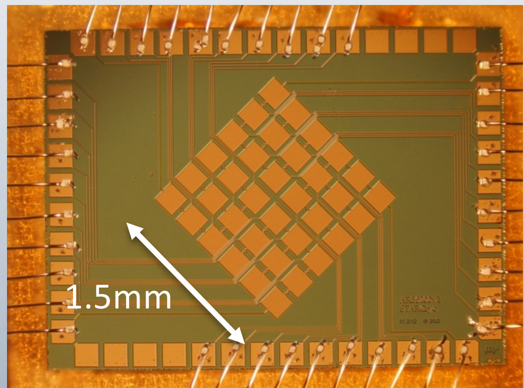


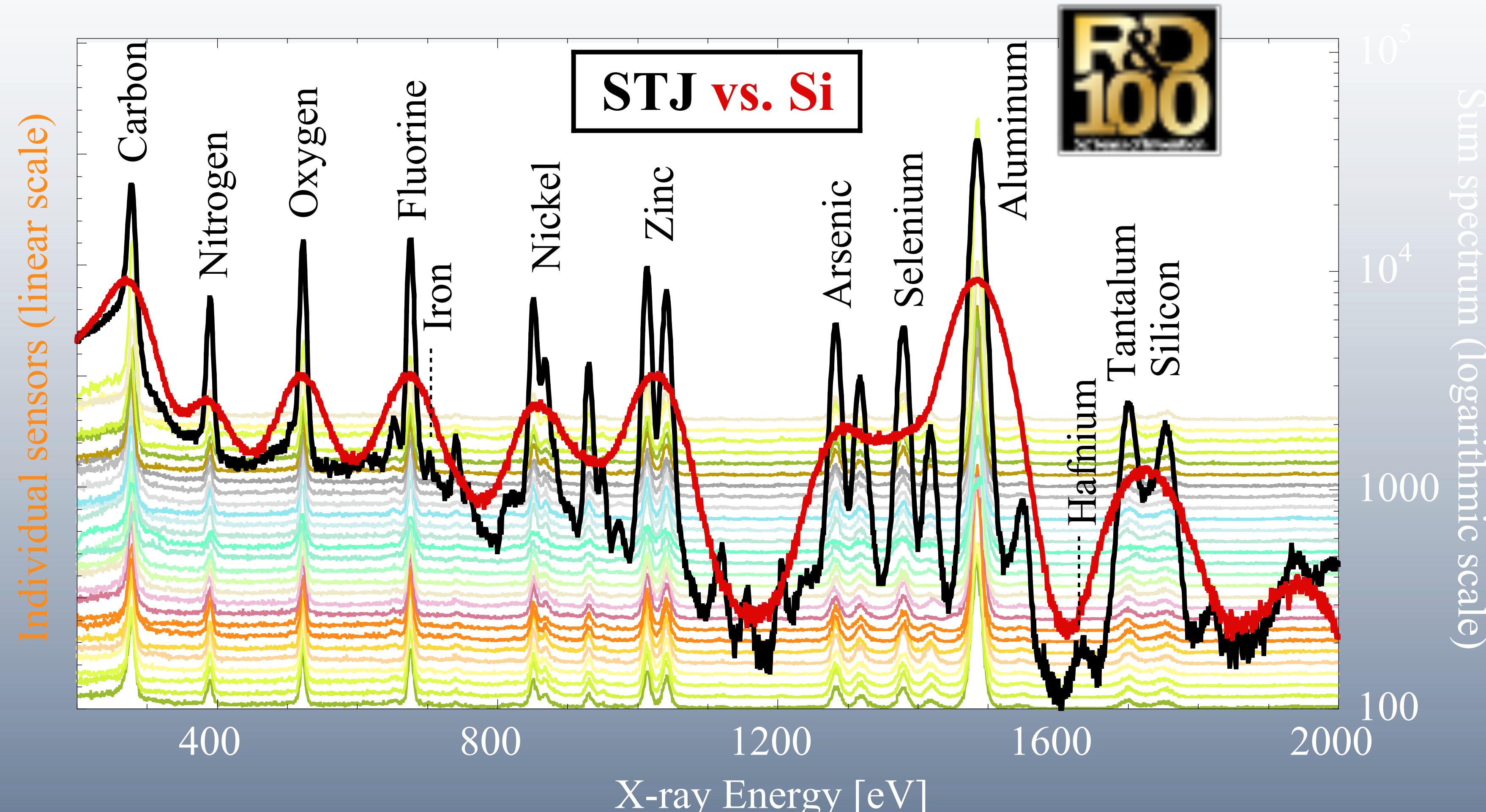
Energy resolution $E_{FWHM} = 2.355\sqrt{1.7\Delta \cdot E_{X-ray}\left(F+1+\frac{1}{n}\right)}$

Small superconducting energy gap (Δ ≈ 1meV) ⇒ High resolution (<10 eV FWHM)
Short excess charge life-time (~µs) ⇒ High count rate (>1,000 counts/s/pixel)

STJ Soft X-ray Detectors

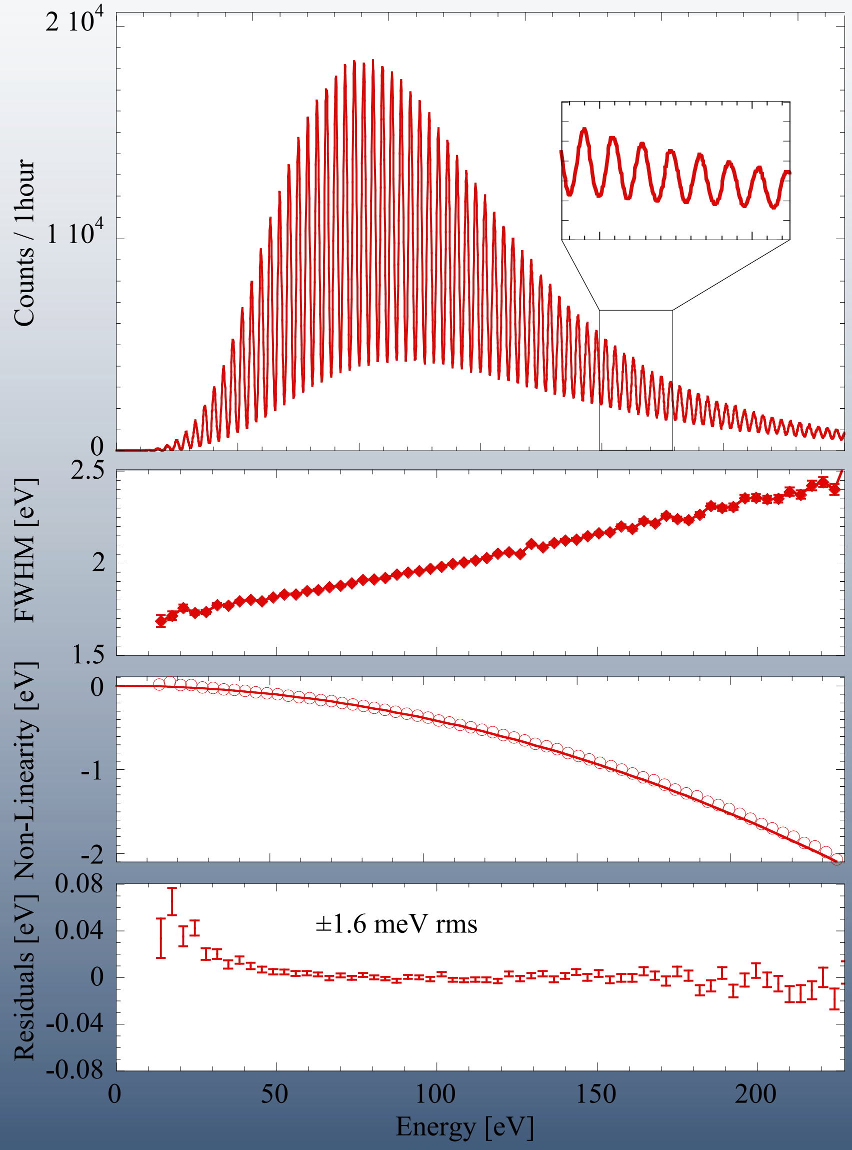
36-pixel STJ Array





STJs were initially developed for high-resolution spectroscopy with soft X-rays where lines are closely spaced.

STJ Characterization with Pulsed UV Laser



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

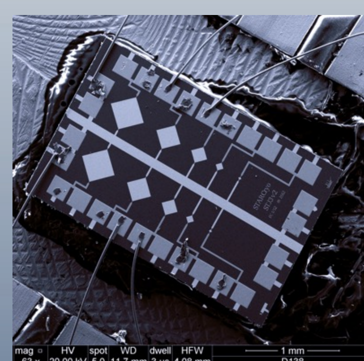
⇒ Only quadratic non-linearity

⇒ Calibration accuracy of order ±1 meV in 1 hour

3) A Sterile Neutrino Search with Superconducting Tunnel Junctions

Implant ^{7}Be
at TRIUMF

Superconducting Detector
from LLNL



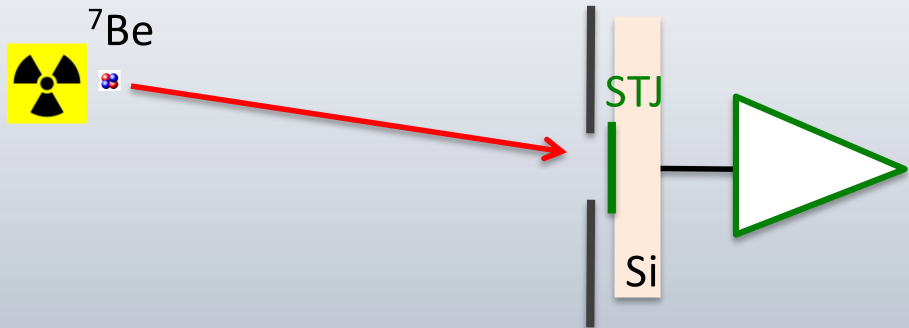
Implant ^{7}Be into STJ detectors.

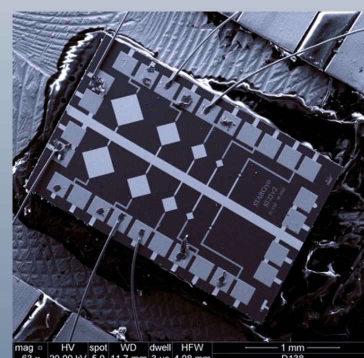
$\tau_{1/2}$ = 53 days, Q = 861 keV

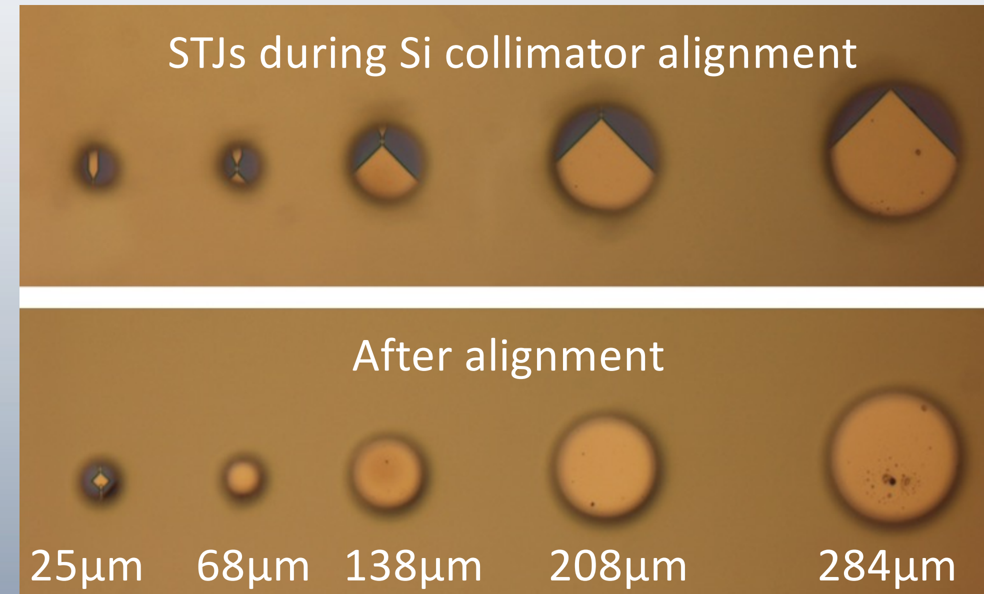
3) A Sterile Neutrino Search with Superconducting Tunnel Junctions

Implant ^{7}Be
at TRIUMF

Superconducting Detector
from LLNL







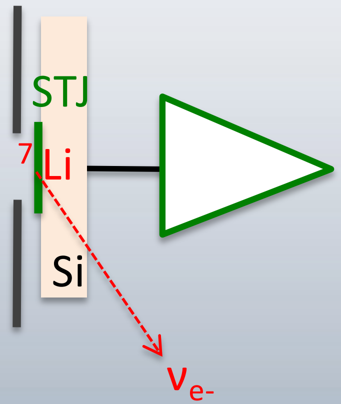
Implant ^{7}Be into STJ detectors.

$\tau_{1/2}$ = 53 days, Q = 861 keV

Beryllium-7 Electron Capture in Superconducting Tunnel Junctions

Implant ^{7}Be
at TRIUMF

Detect ^{7}Be Decay
at LLNL



$$^7\mathbf{Be} + \mathbf{e}- \longrightarrow {}^7\mathbf{Li} + \boldsymbol{\nu}_{e-}$$
with $\nu_{e-} = \boldsymbol{\Sigma}\, |U_{ea}|^2 \nu_{active}$

Measure electron capture decay of ^{7}Be to ^{7}Li.

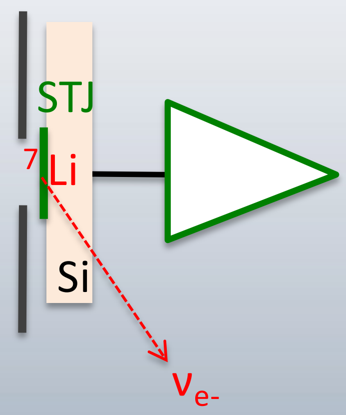
2-body decay $\Rightarrow$ Monochromatic recoil (in principle)

Beryllium-7 Electron Capture in Superconducting Tunnel Junctions

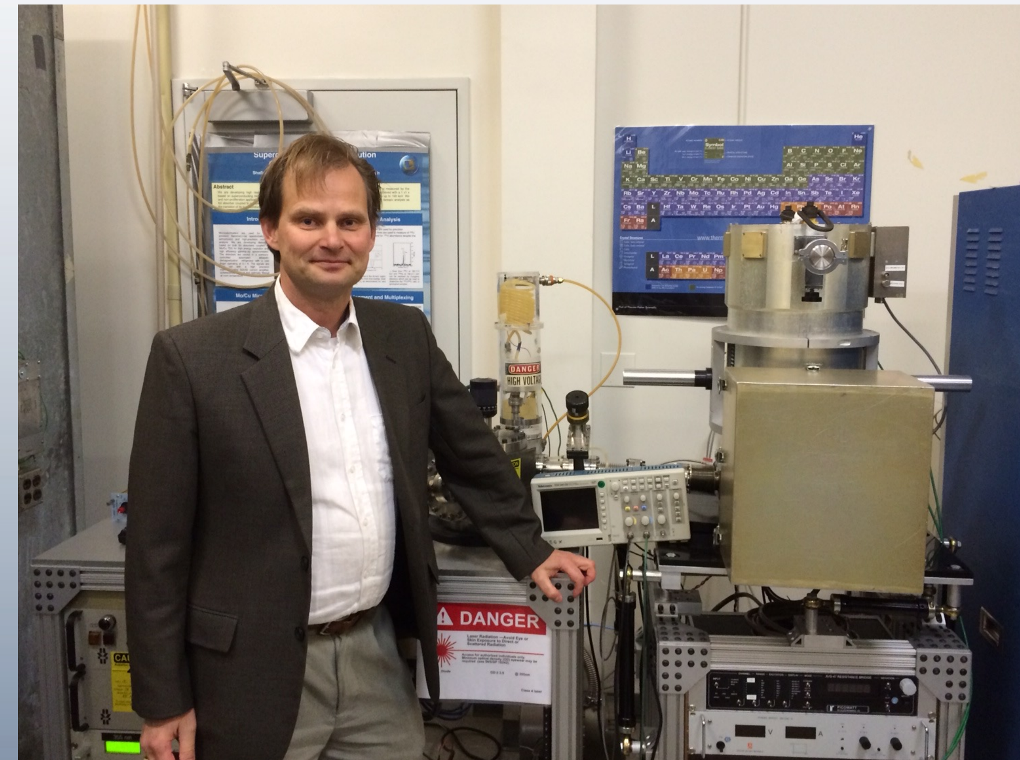
Implant ^{7}Be
at TRIUMF

^{7}Be

Detect ^{7}Be Decay
at LLNL



$^{7}Be + e- \longrightarrow {}^{7}Li + \nu_{e-}$
with $\nu_{e-} = \Sigma \; |U_{ea}|^2 \nu_{active}$



Measure electron capture decay of ^{7}Be to ^{7}Li.

2-body decay $\Rightarrow$ Monochromatic recoil (in principle)

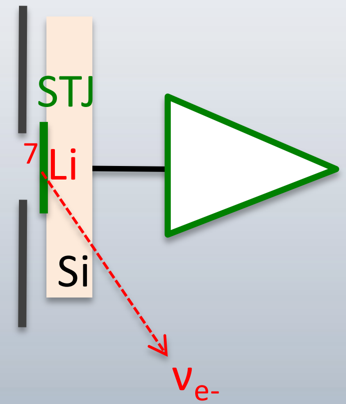
Be-7 ***E***lectron Capture in ***ST***Js: The ***BeEST*** Experiment

Implant ^{7}Be

at TRIUMF

Detect ^{7}Be Decay

at LLNL



$$E_{^7Li\ recoil} = \frac{Q^2 - m_\nu^2 c^4}{2(Q - m_{^7Li} c^2)}$$

$$\rightarrow 56.826(9) eV\ for\ m_\nu \approx 0$$

$^7Be + e^- \longrightarrow {}^7Li + \nu_{e-}$

with $\nu_{e-} = \Sigma\ |U_{ea}|^2 \nu_{active} + |U_{es}|^2 \nu_{sterile}$

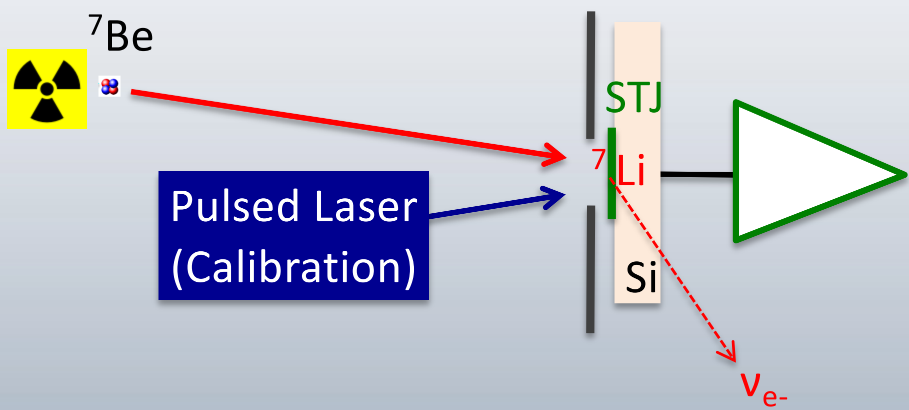
Heavy sterile neutrinos would reduce ^{7}Li recoil energy.

Look for shifted peaks in the recoil spectrum.

The BeEST Sterile Neutrino Experiment

Implant ^{7}Be
at TRIUMF

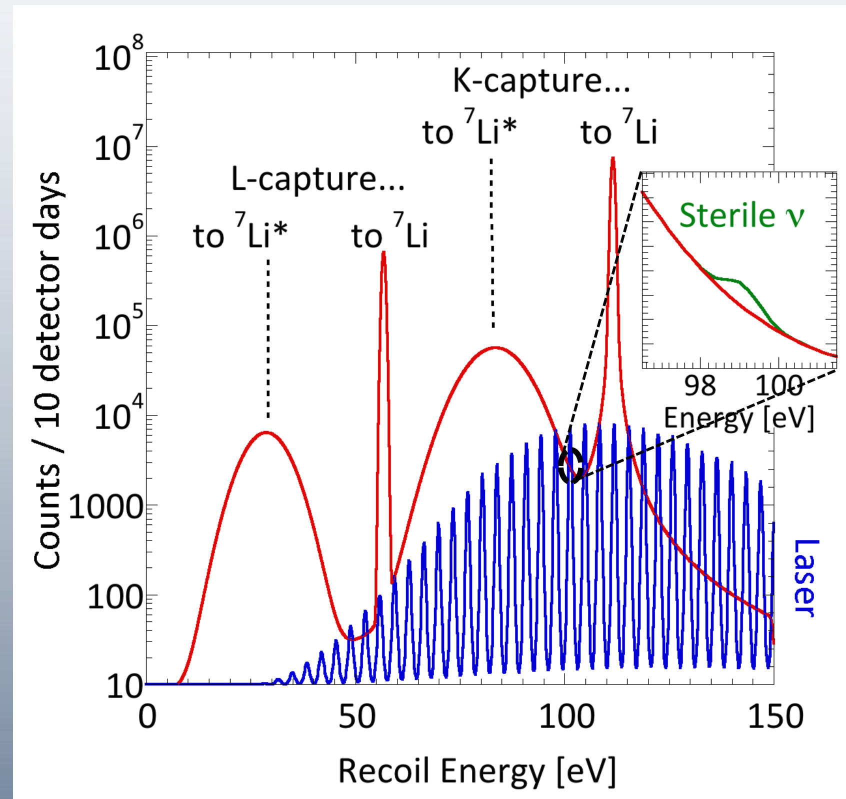
Detect ^{7}Be Decay
at LLNL



$$^7\text{Be} + e- \longrightarrow {}^7\text{Li} + \nu_{e-}$$

with $\nu_{e-} = \Sigma \, |U_{ea}|^2 \nu_{active} + |U_{es}|^2 \nu_{sterile}$

High-Resolution Recoil Simulation



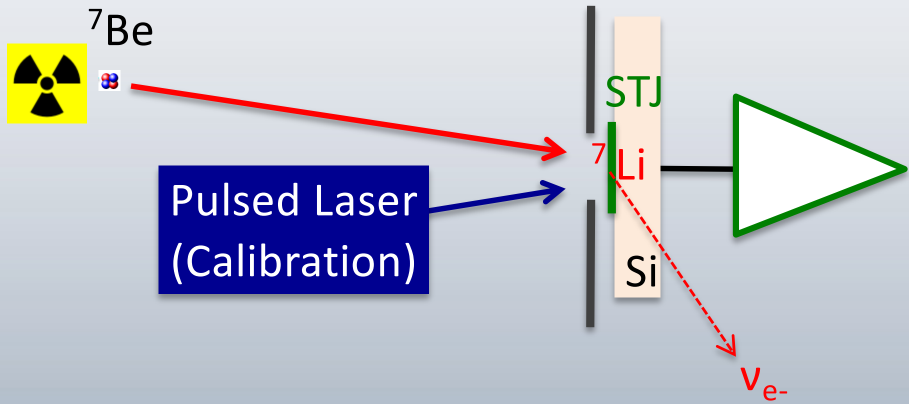
Calibrate STJ with pulsed laser.

Four peaks due to K- and L- capture into ^{7}Li ground and excited state

The BeEST Sterile Neutrino Experiment

Implant ^{7}Be
at TRIUMF

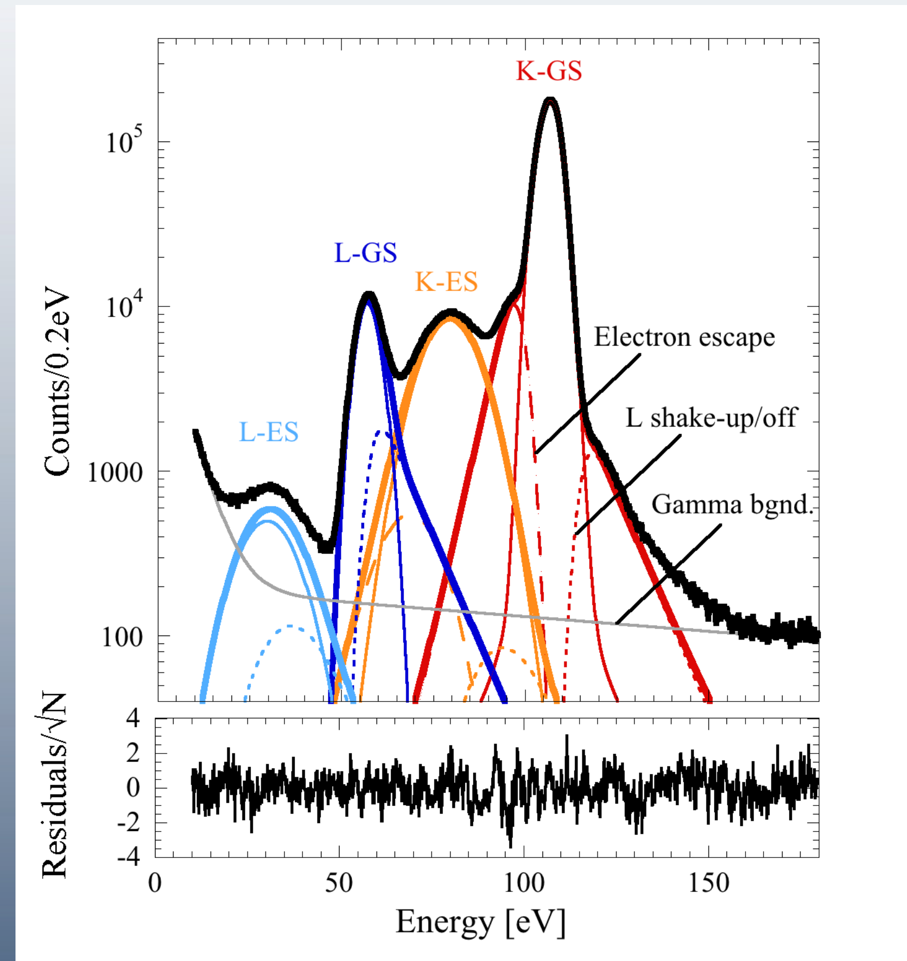
Detect ^{7}Be Decay
at LLNL



$$^7\mathrm{Be} + e^- \longrightarrow {}^7\mathrm{Li} + \nu_{e^-}$$

with $\nu_{e-} = \Sigma\ |U_{ea}|^2 \nu_{active} + |U_{es}|^2 \nu_{sterile}$

Data from 1 Ta-STJ Detector for 28 Days



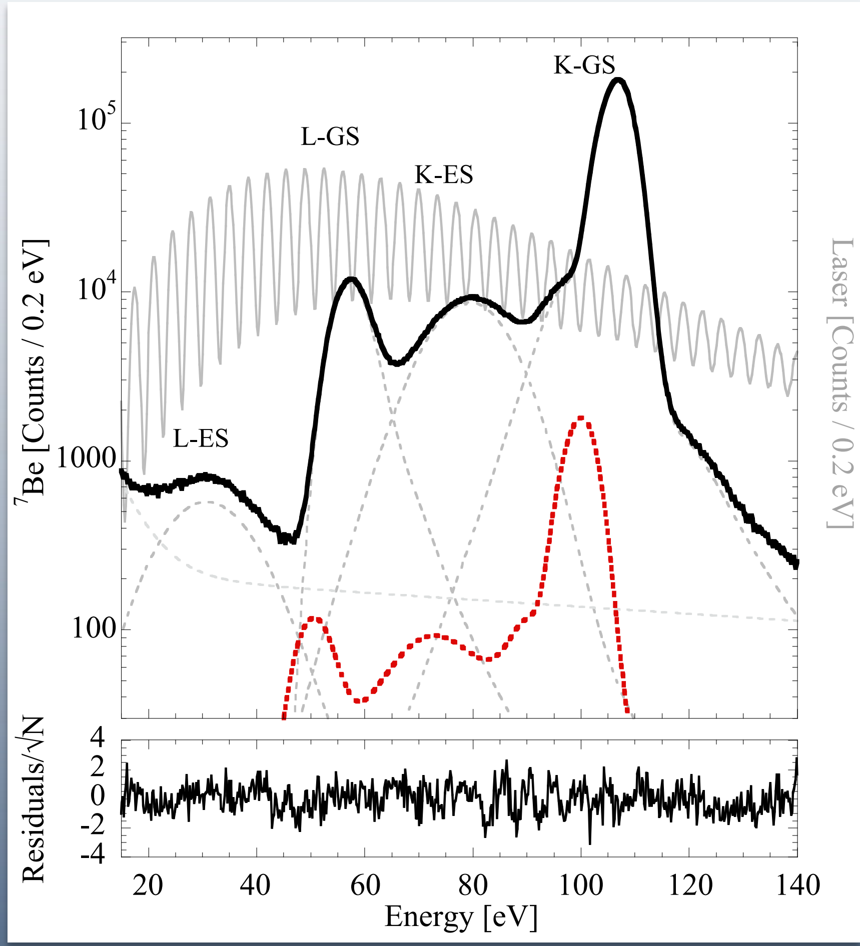
- 4 primary peaks
  - 2 x K-capture, 2x L-capture
  - to ^{7}Li ground state and to ^{7}Li*
- 4 high-energy tails
  - Shake-off effects
- 2 low-energy tails
  - (Partial) Auger e- energy loss
- 1 broad background
  - 478 keV γ's in substate

L/K Ratio = 0.070(7)

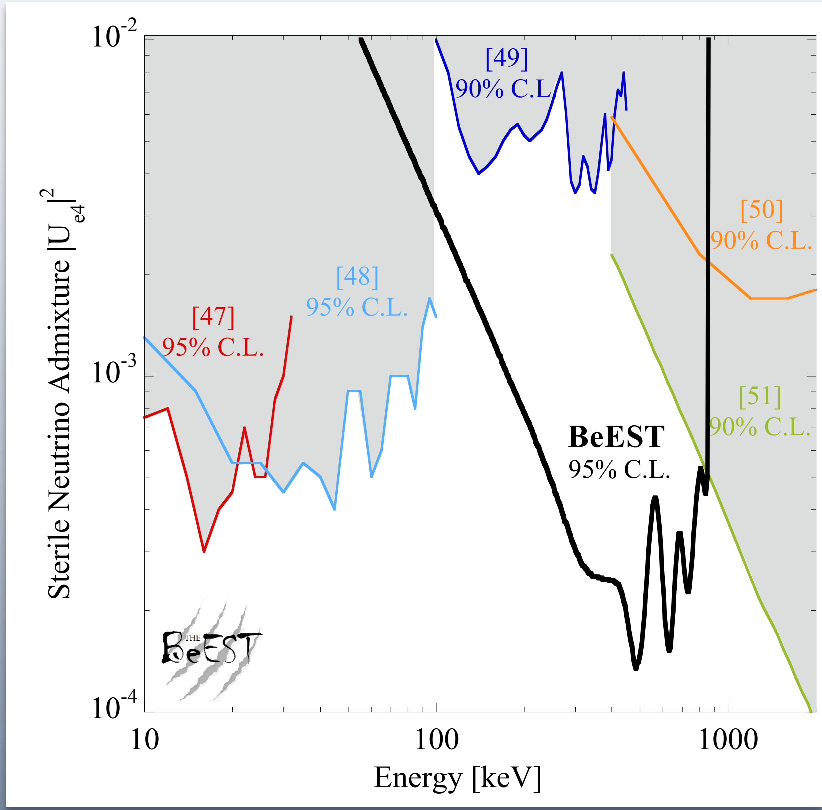
PRL **125**, 032701 (2020)

The BeEST Sterile Neutrino Experiment

Data with Hypothetical Sterile ν Signal



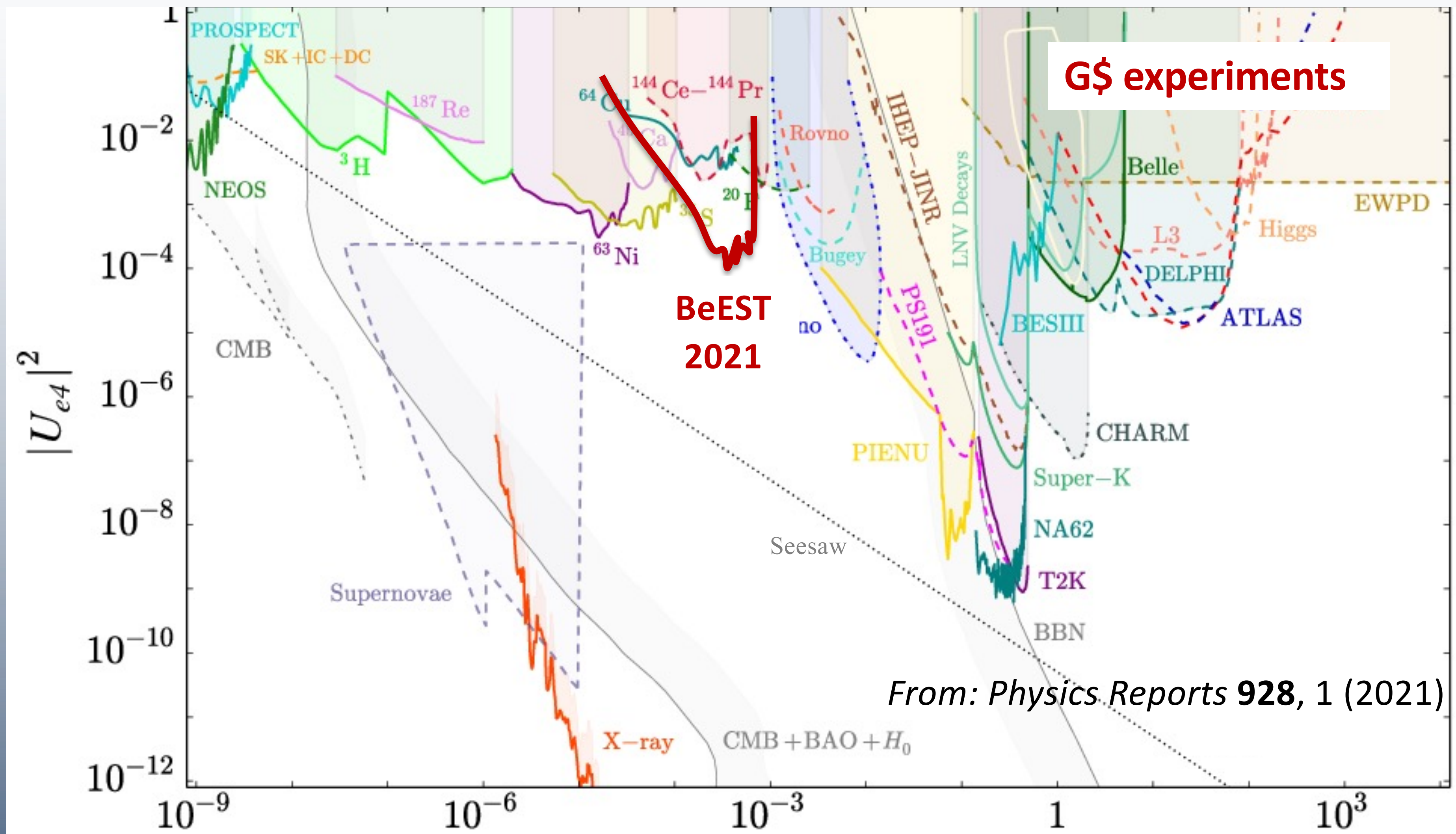
Exclusion Plot



10x improvement with 1 pixel at 10 counts/s.

PRL **126**, 021803 (2021)

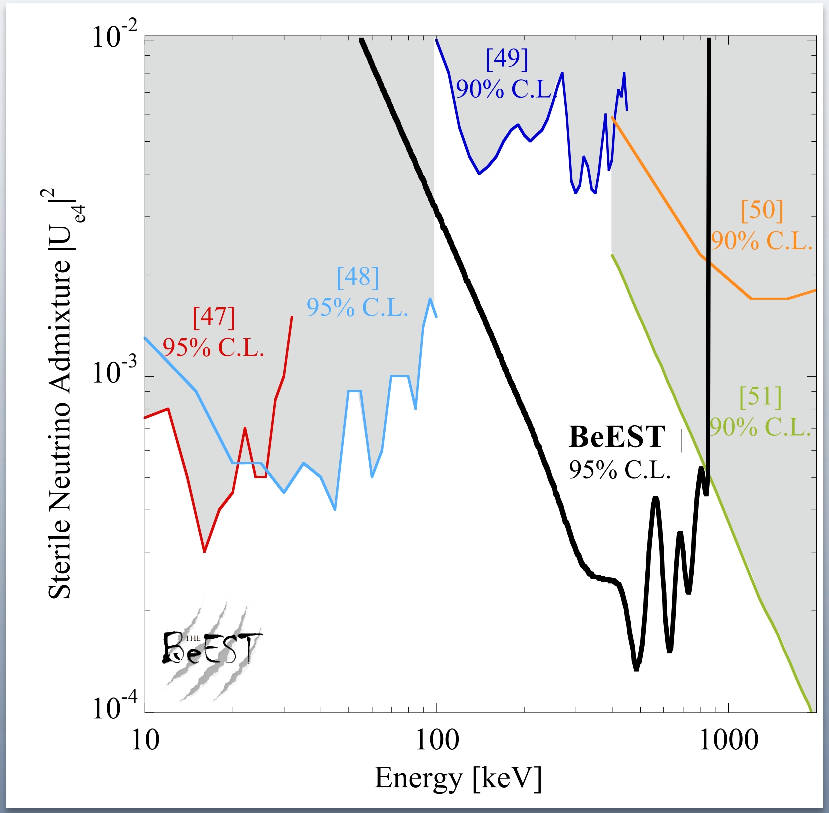
The BeEST in Context



m_4 [GeV]

4) Why Are The Capture Peaks so Broad?

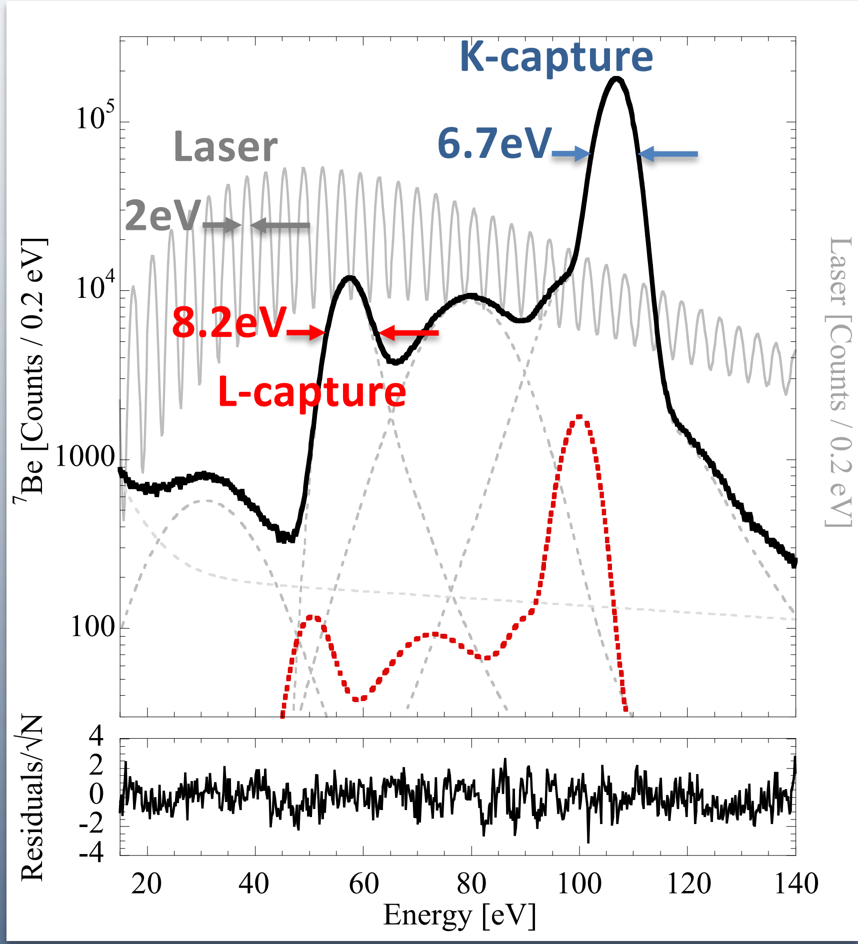
Exclusion Plot

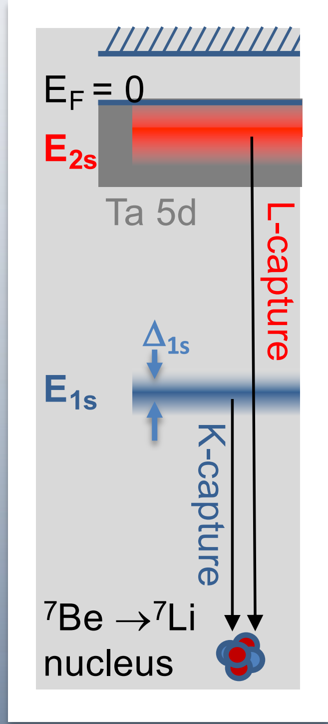


10x improvement with 1 pixel at 10 counts/s.

PRL **126**, 021803 (2021)

Data with Hypothetical Sterile ν Signal



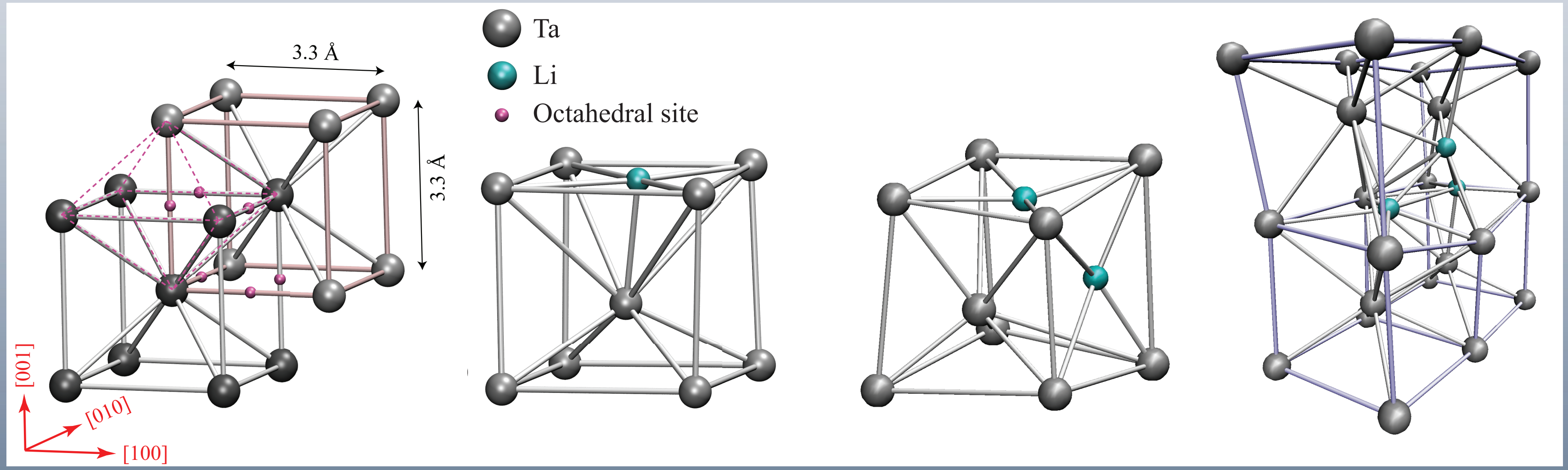


Chemical Broadening?

Density Functional Theory (DFT) Simulations of Li 1s Energy Shift

Li Configuration:	Substitutional Li	1 Li Intersititial	2 Li Intersititals	3 Li Intersititals	Li_{Ta}-V_{Ta} Complex
1s Energy Shift:	0 (reference case)	1.18 eV	1.58 eV	1.30 eV	1.67 eV
Formation E:	1.23 eV	4.07 eV	7.63 eV	11.23 eV	2.50 eV
Binding E / Li atom	–	–	-0.26 eV	-0.33 eV	-1.53 eV

vs. separate interstitials

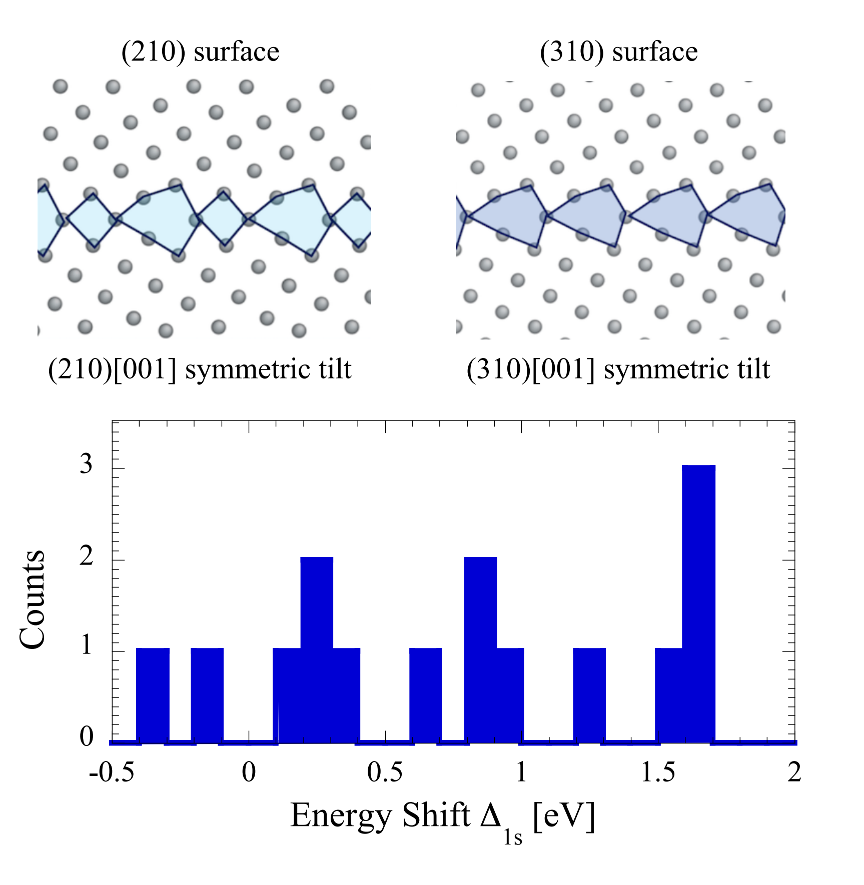


Simple configuration changes can alter Li 1s energy levels by >1 eV.

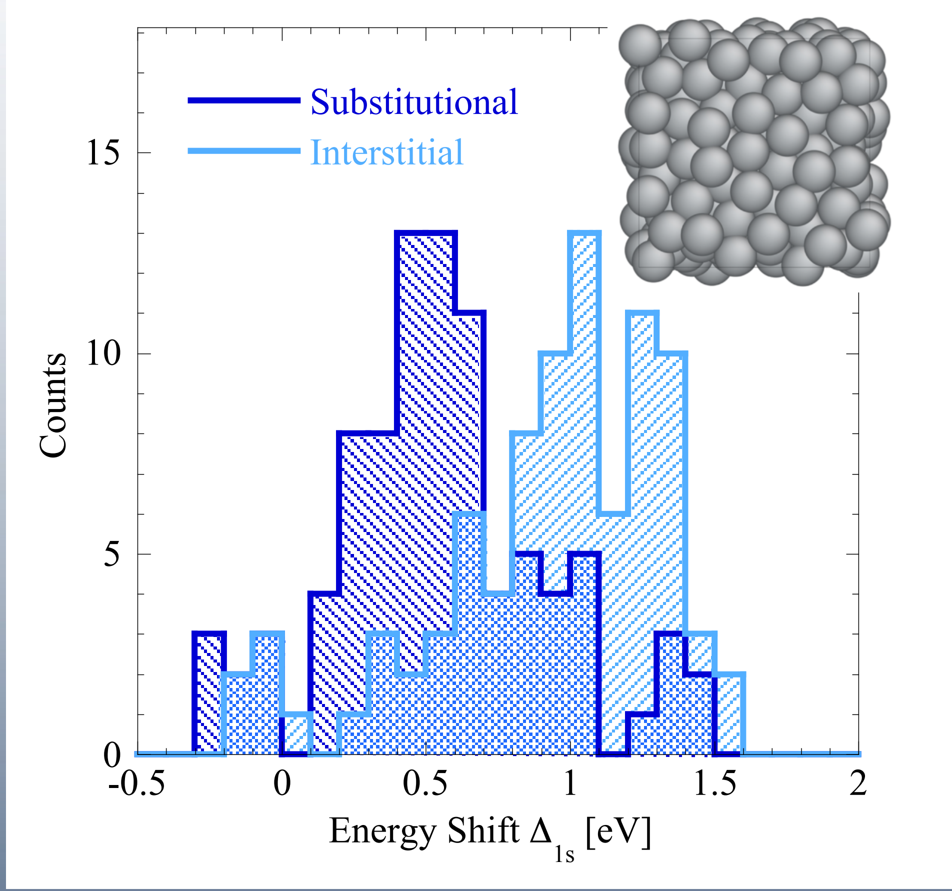
A. Samanta et al., submitted to Phys. Rev. Applied and arXiv: 2206.00150

DFT Simulations in Disordered / Amorphous Ta

Li at Grain Boundaries



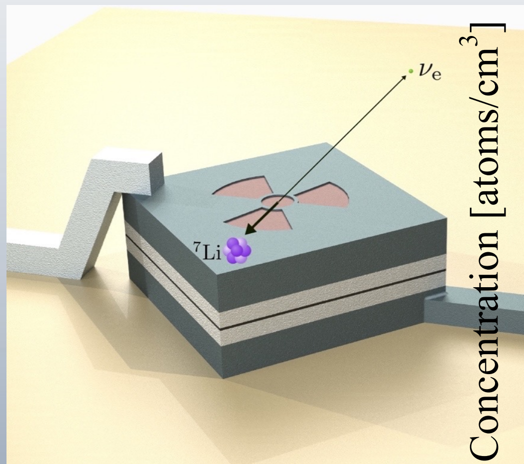
Li in in Amorphous Ta

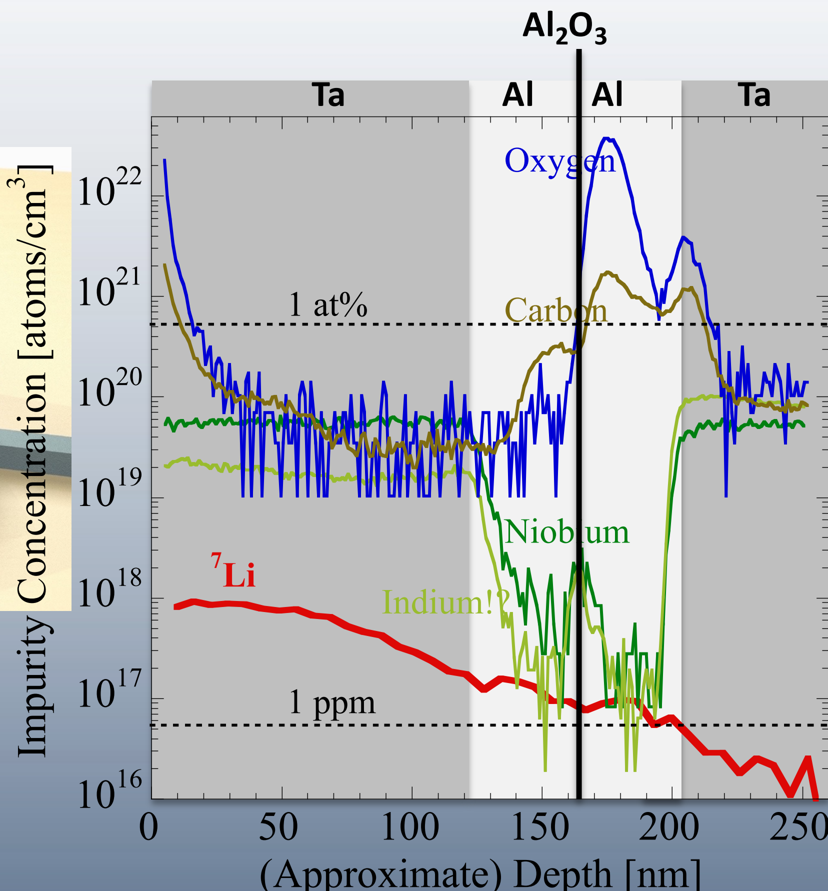


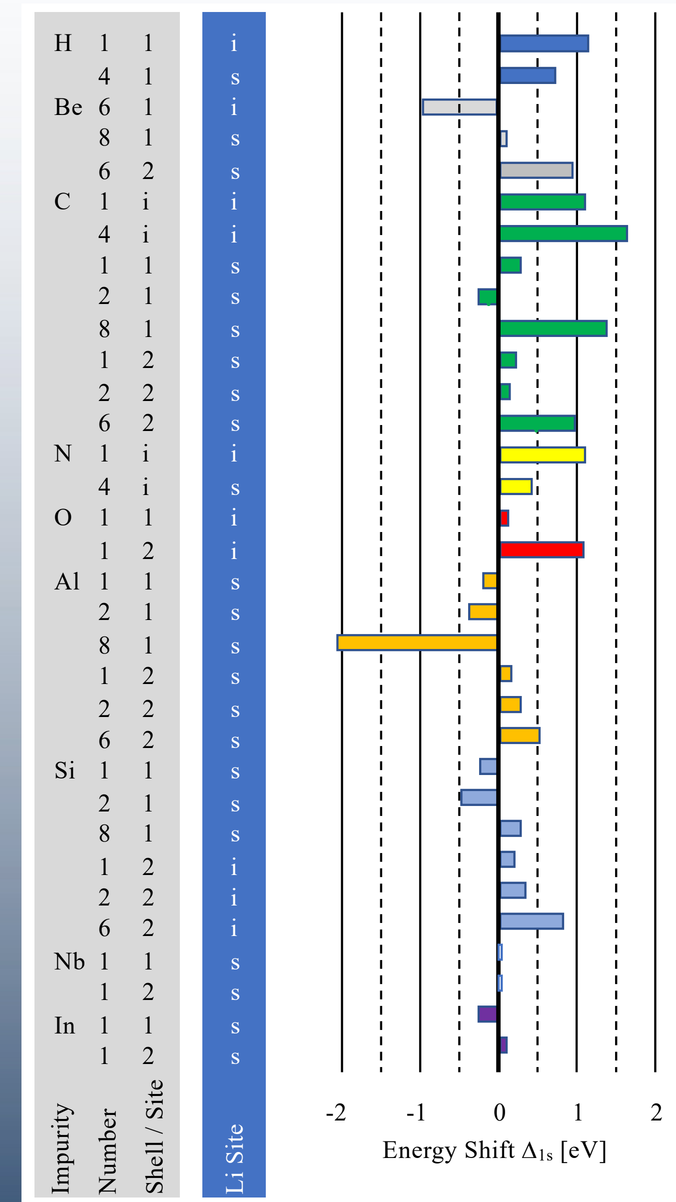
Even extreme disorder only shifts 1s levels by ~2 eV and cannot explain the observed 6.7 eV broadening

DFT Simulations of Li 1s Energy Shifts due to Impurities

TOF-SIMS Analysis of Impurities in STJ Detector





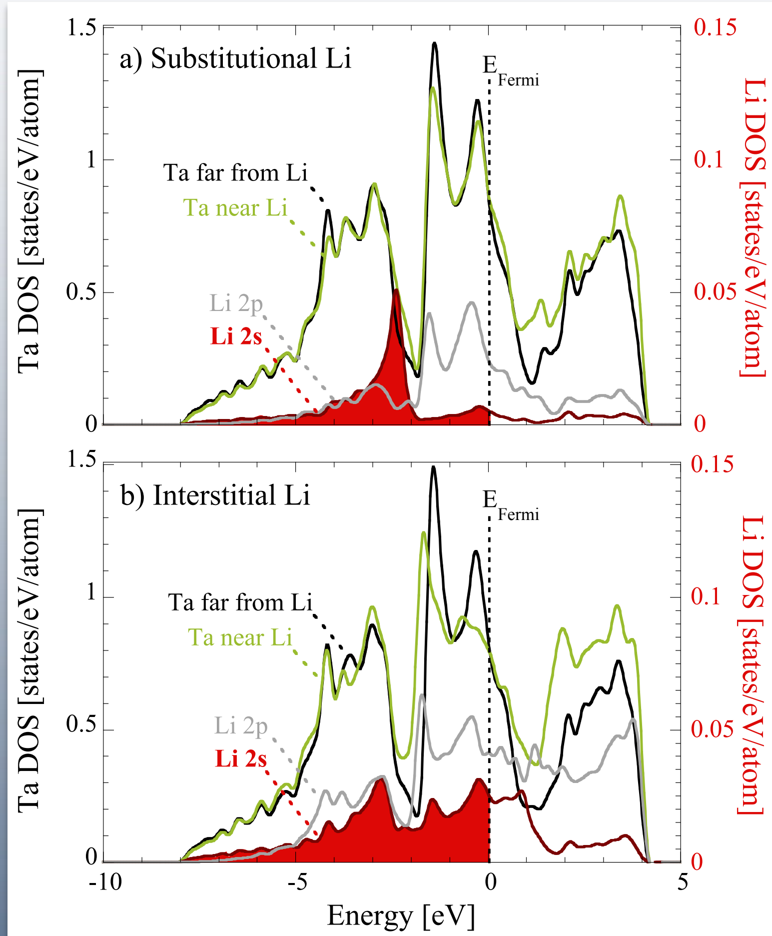


Impurities can change the Li 1s energy levels by ~2eV

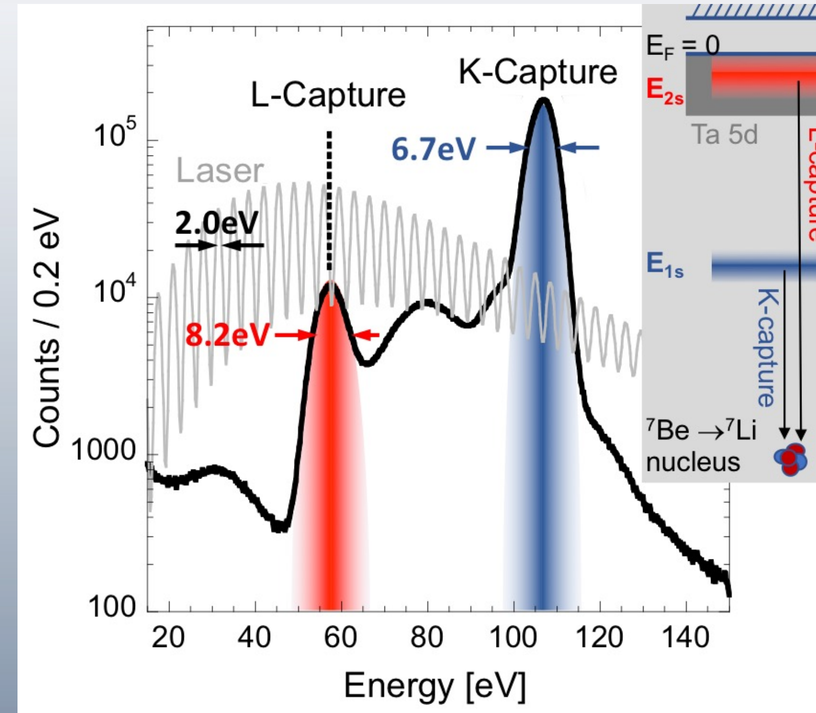
(Again, much less than observed experimentally.)

DFT Simulations of Li 2s Energies in bcc Ta

Li 2s Levels in Ta 5d Band



L-Capture is Broader than K-Capture Peak



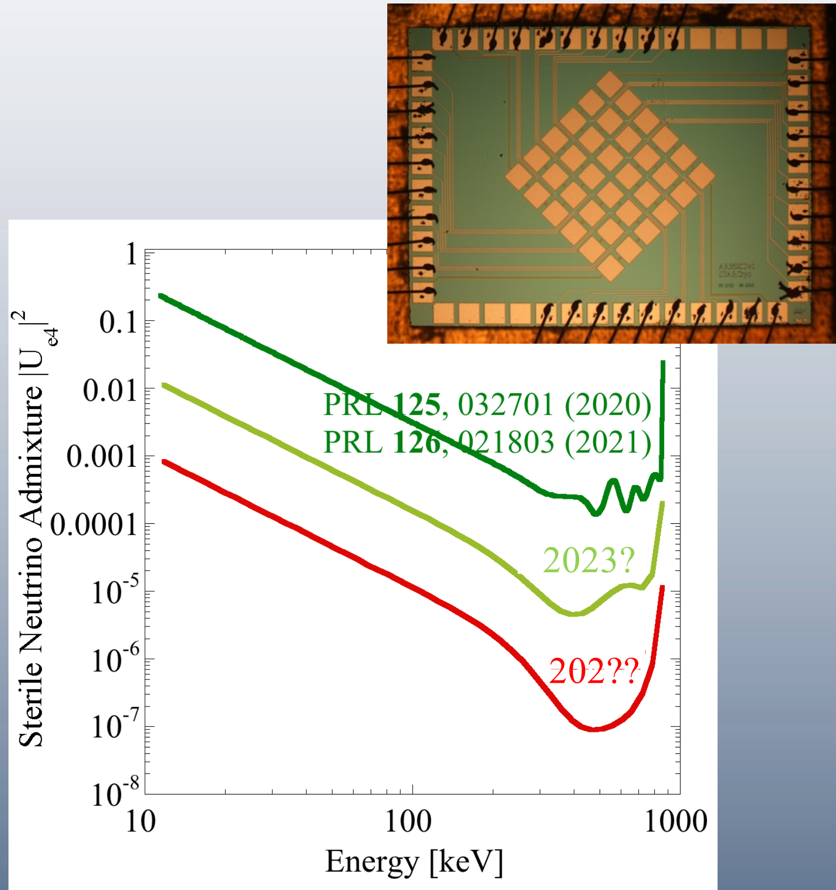
A. Samanta et al., arXiv: 2206.00150

Hybridization of Li 2s with Ta 5d-6s band with explains why L-capture peak is broader than K-capture peak.

Material effects matter but _cannot_ explain entire observed broadening.

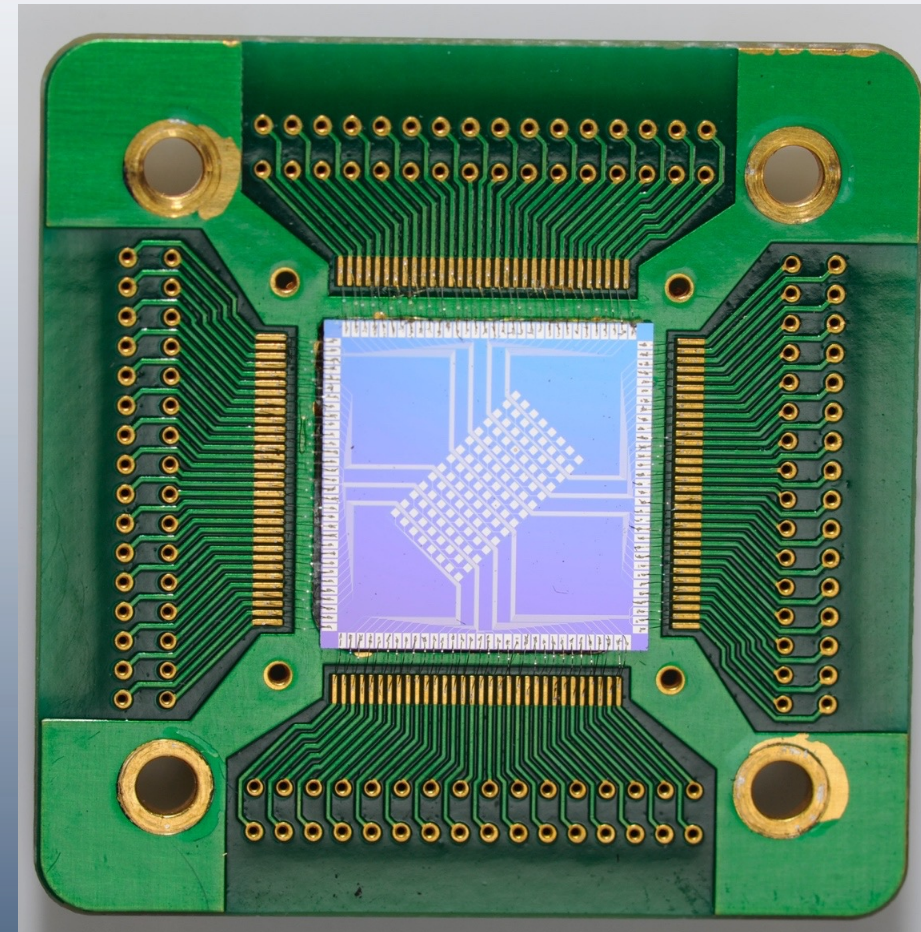
5) Next: Bigger Detector Arrays, Higher ^{7}Be Dose

Improved Sensitivity with Ta-STJ Arrays



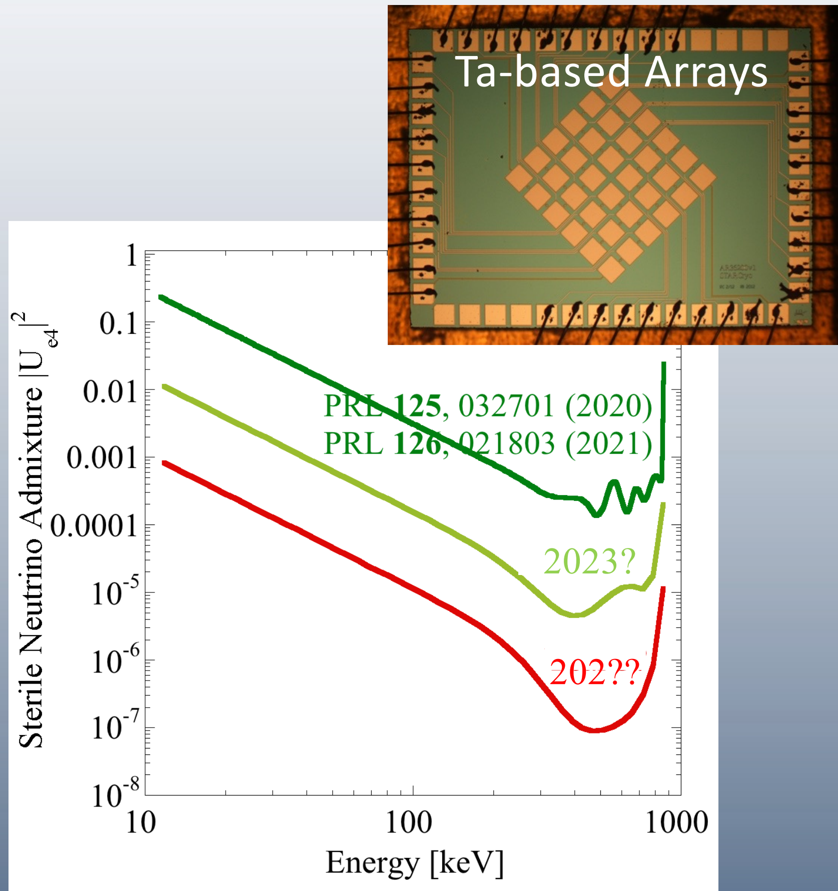
Next ^{7}Be implantation on 09/22/22

112-pixel Ta-STJ Array



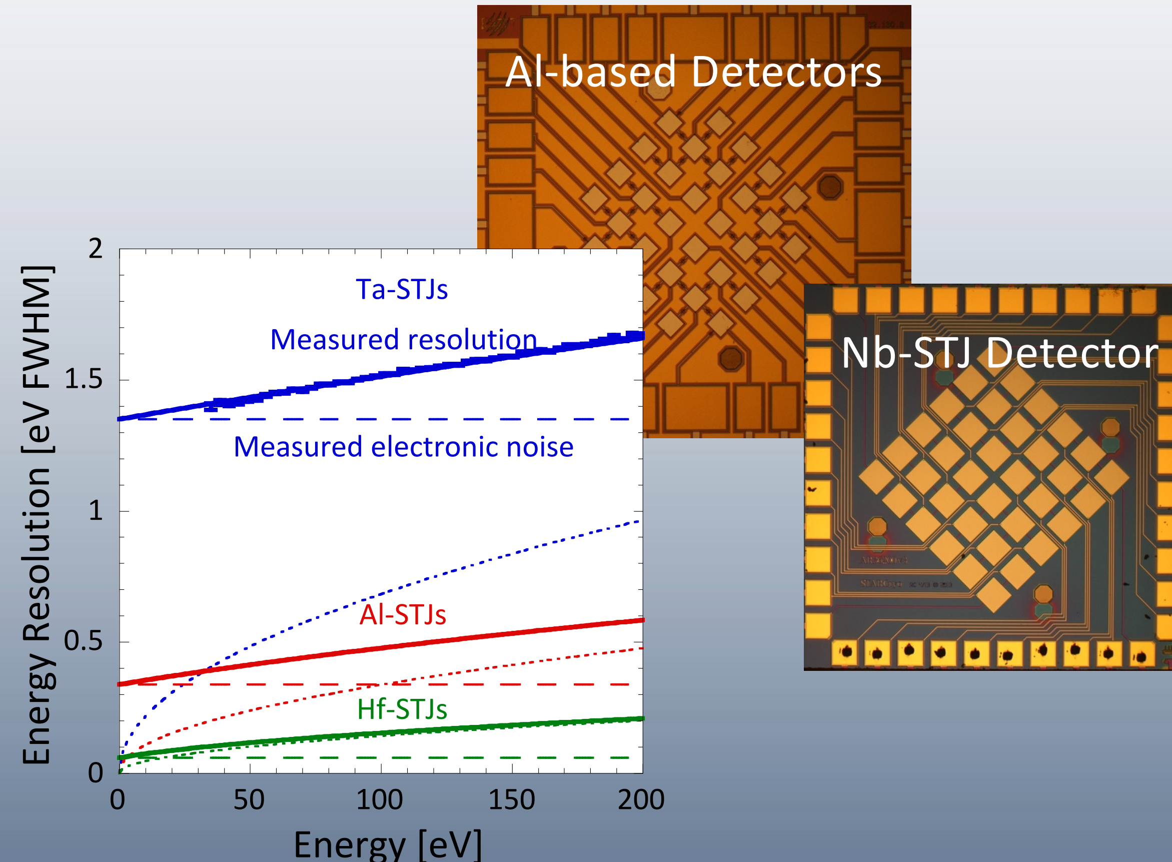
Next: New Materials

Improved Sensitivity with Ta-STJ Arrays



Next ^{7}Be implantation on 09/22/22

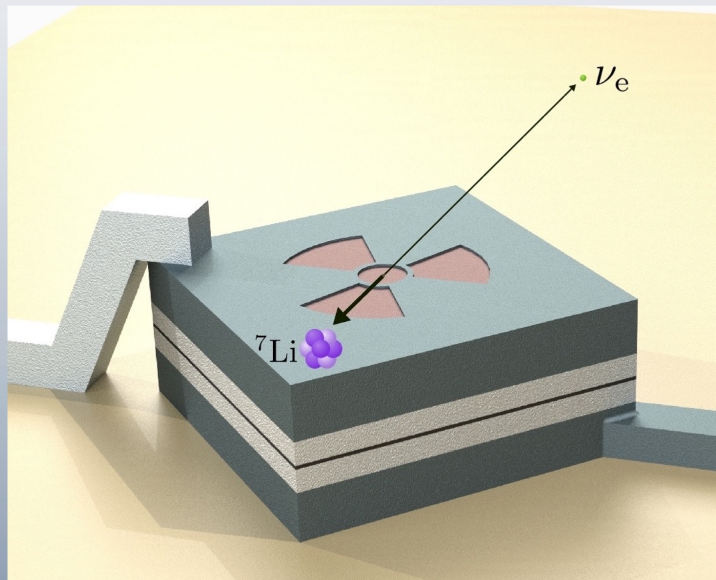
STJ Detectors from Different Materials



Distinguish material effects from BSM physics

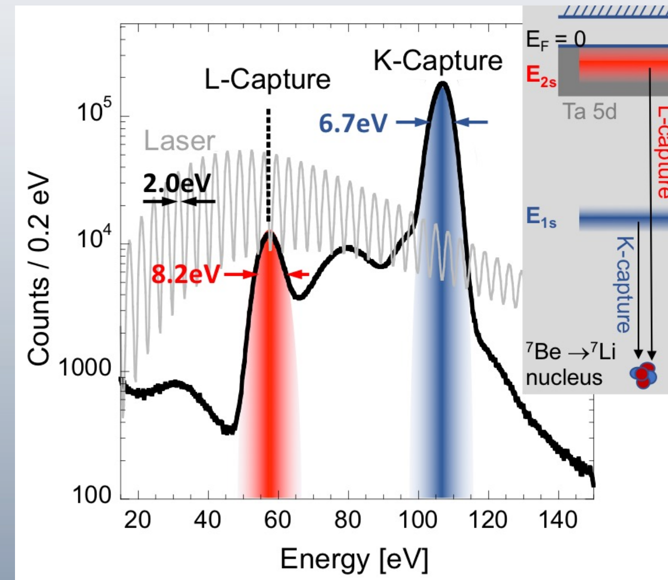
The *BeEST* Sterile Neutrino Search

^{7}Be in STJ detectors ⇒ Missing Momentum Search



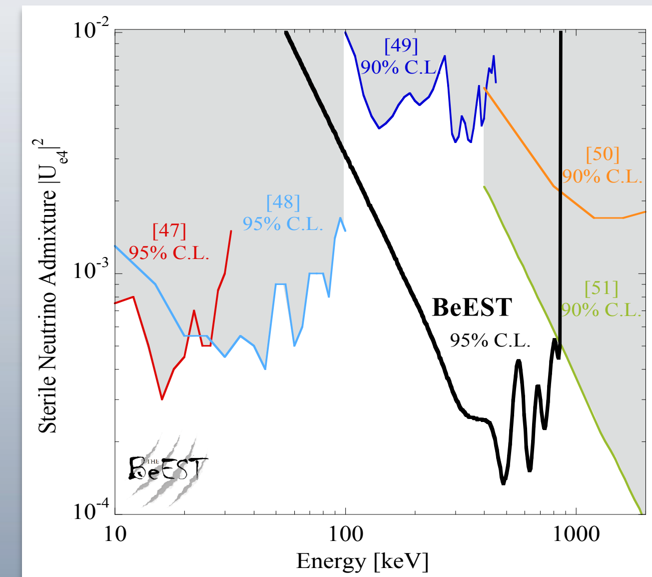
- High resolution: ~2 eV at 100 eV
- High speed: >1,000 counts/s/pixel
- No quenching

2 eV FWHM and 2-body decay ⇒ High Sensitivity



- Accurate laser calibration
- Material effects non-negligible

1STJ at 10 counts/s ⇒ Exclusion to O(10^{-4})



- O(10^{-7}) with 128-pixel arrays
- New Al- and Nb-STJs ⇒ Separate BSM physics from material effects

Thank You!

STJ Fabrication
(STAR Cryo)
Robin Cantor
Ad Hall

STJ Experiments
(LLNL)
Stephan Friedrich
Inwook Kim

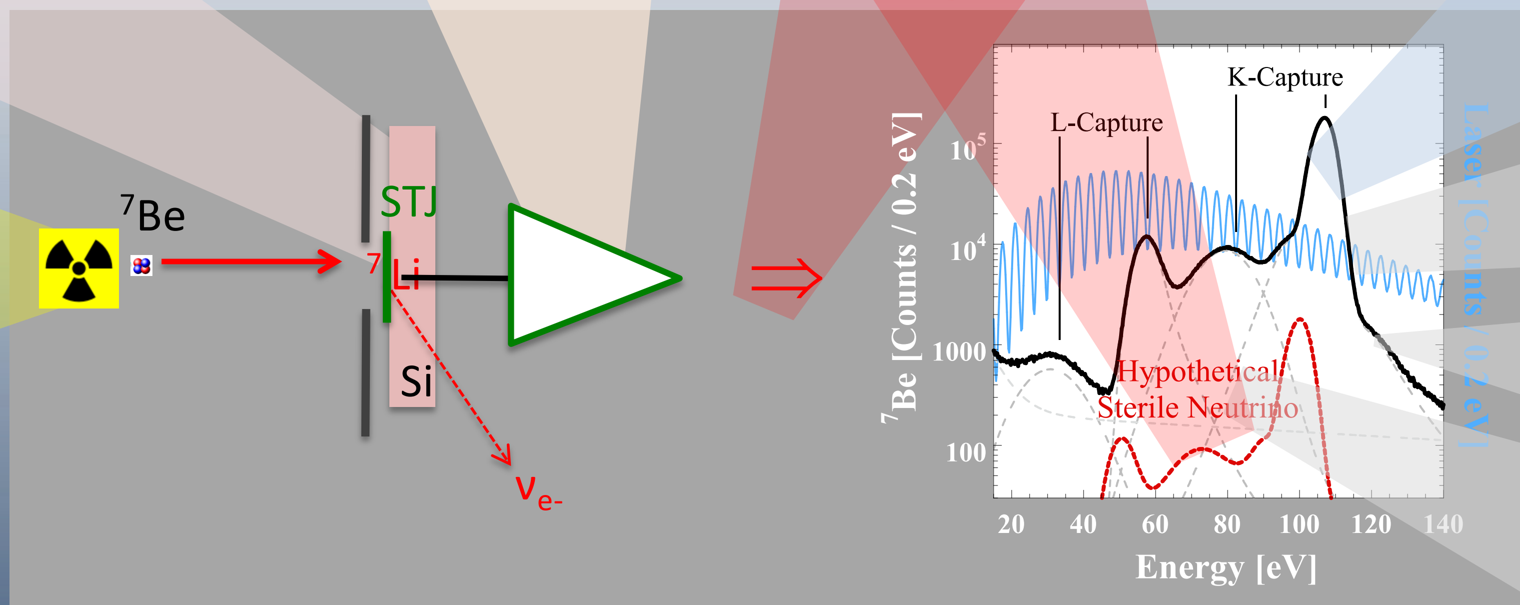
STJ Preamplifier
(XIA)
Bill Warburton
Jack Harris

Processing / Analysis
Francisco Ponce (PNNL)
Geon-Bo Kim (LLNL)
Spencer Fretwell

BSM Physics
(Mines)
Kyle Leach
Dave McKeen

Material Characterization
Dave Diercks (Mines)
Tony Li (LLNL)
Yi-De Chuang (ALS)
Cameron Harris

^{7}Be Implantation
(TRIUMF)
Chris Ruiz
Annika Lennarz



Simulations

Broadening (LLNL)
Vince Lordi
Amit Samanta

Shake-up/-off (UNL)
Jose-Paolo Santos
Jorge Machado
Mauro Guerra
Padro Amaro

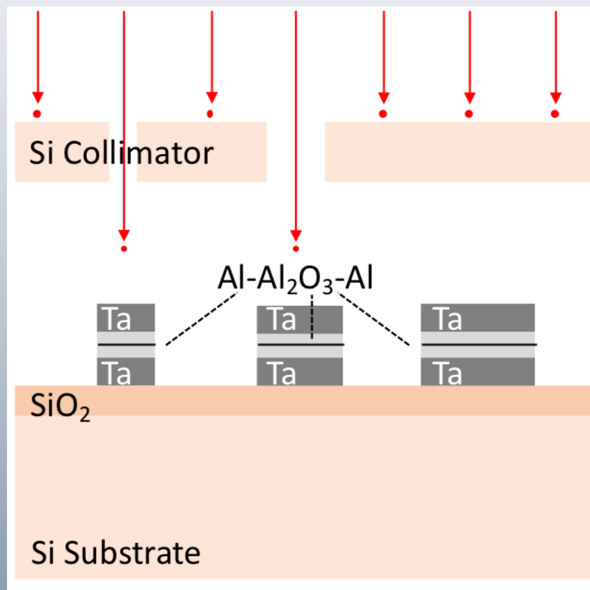
Escape Tails
Connor Bray

Electron Capture
Xavier Mougeot (CEA)

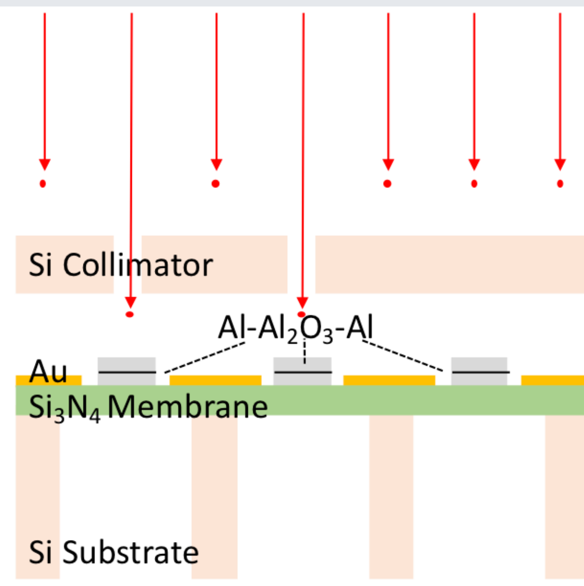
Back-up Slides

Different STJ Detectors

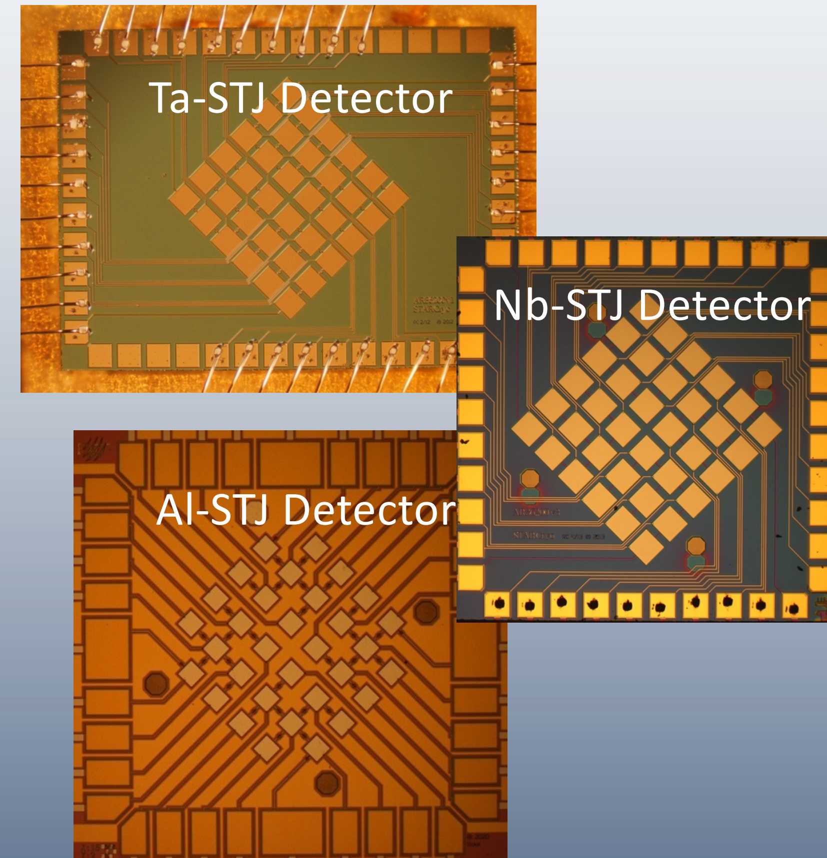
Current Geometry



Next Geometry



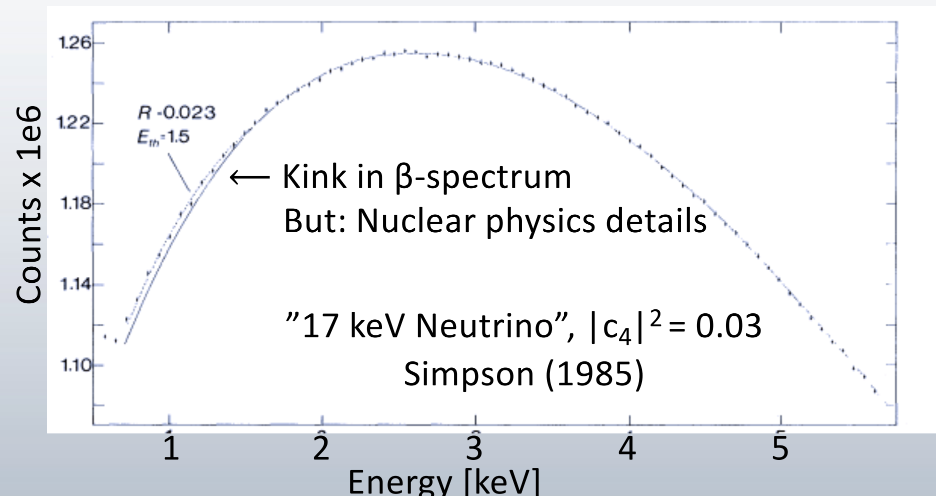
Different Materials



Complementary experiments and simulations of different materials might separate BSM physics from material effects.

Competing Sterile Neutrino Experiments

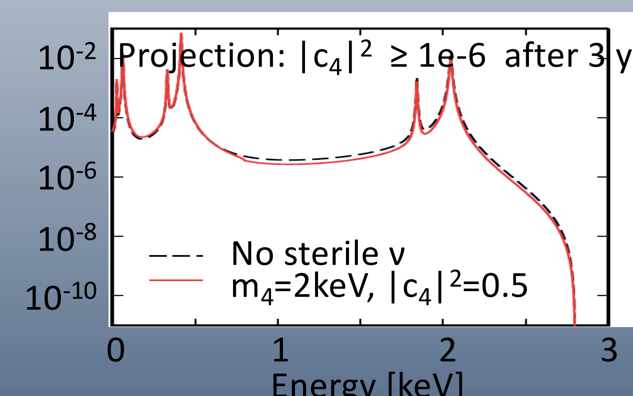
^{3}H Beta Decay



KATRIN = *KA*rlsruhe *TRI*tium *N*eutrino Expt

Troitsk “nuMass” ^{3}H

ECHo = Electron Capture in Ho



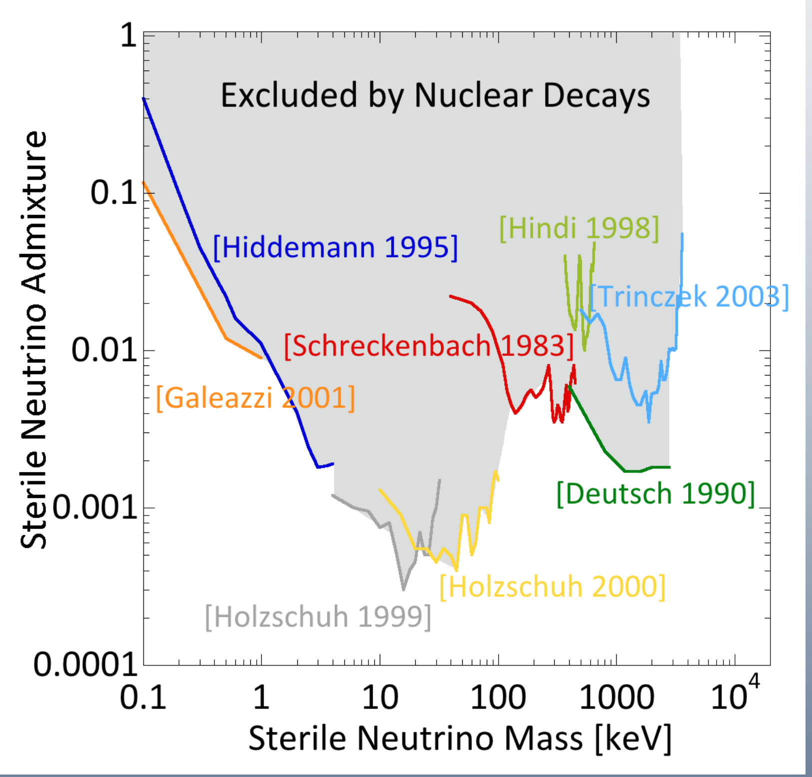
We are more sensitive *and* much cheaper than competing experiments

(which admittedly are not optimized for sterile neutrinos.)

Experimental Limits on Sterile Neutrino Dark Matter

Limits from Nuclear Decays

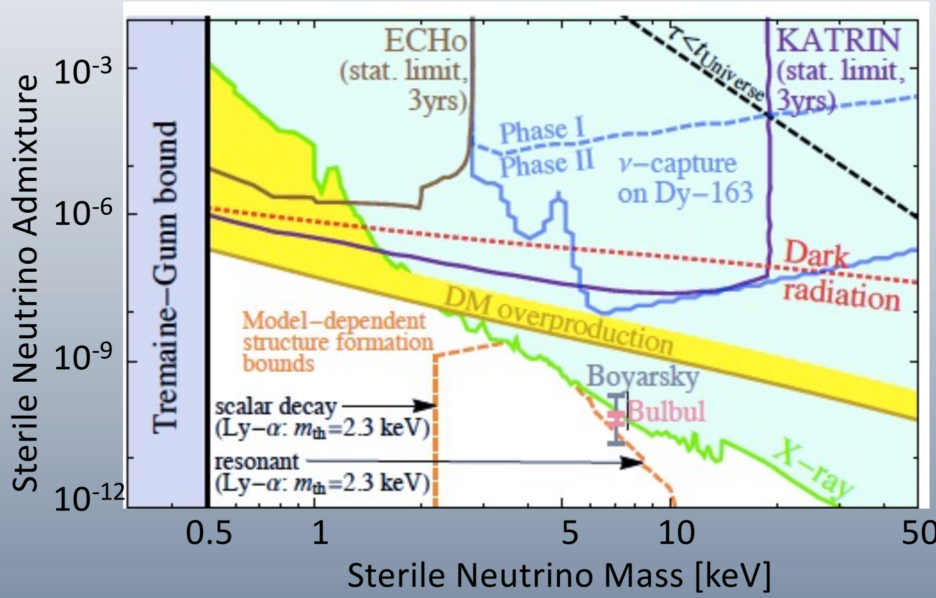
Look (in vain) for kink in beta spectrum



Limits from Astronomy

Look (in vain) for decay X-rays from galaxies

[Adhikari, JCAP **1**, 25 (2017)]



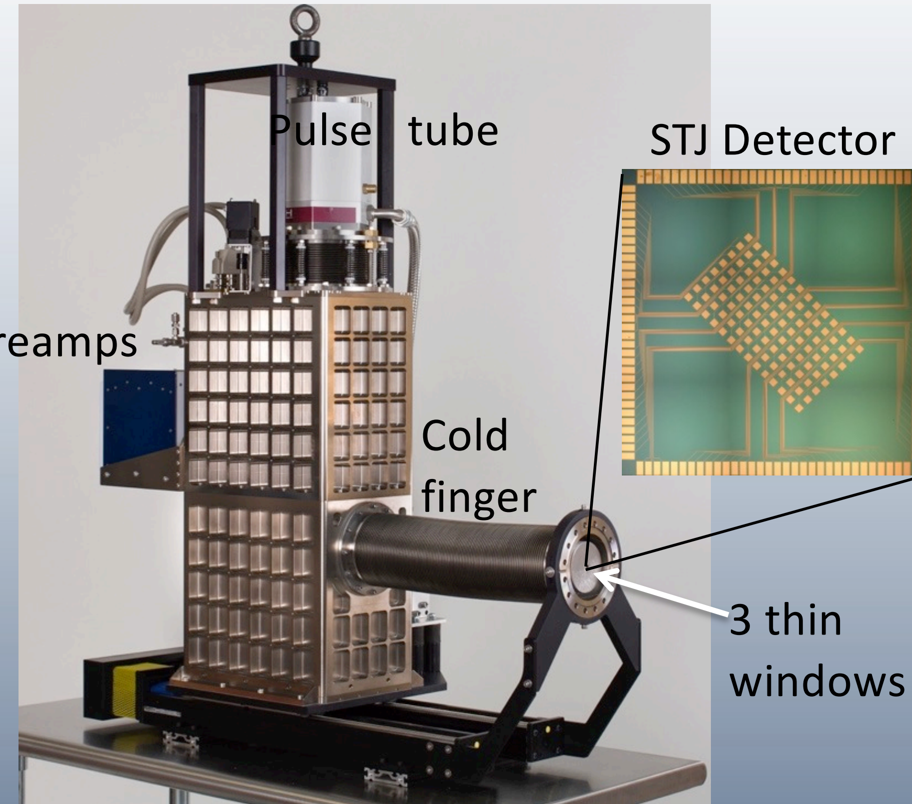
So we're looking for ~keV neutrinos, 10^{-12} to 10^{-3} of which are mixed to active neutrinos.

Astronomy limits depend on underlying assumptions and models.

Adiabatic Demagnetization Refrigerators (ADRs)

“Wet” Cryodetector ADR (2001)

Commercial “Dry” ADR (2016)

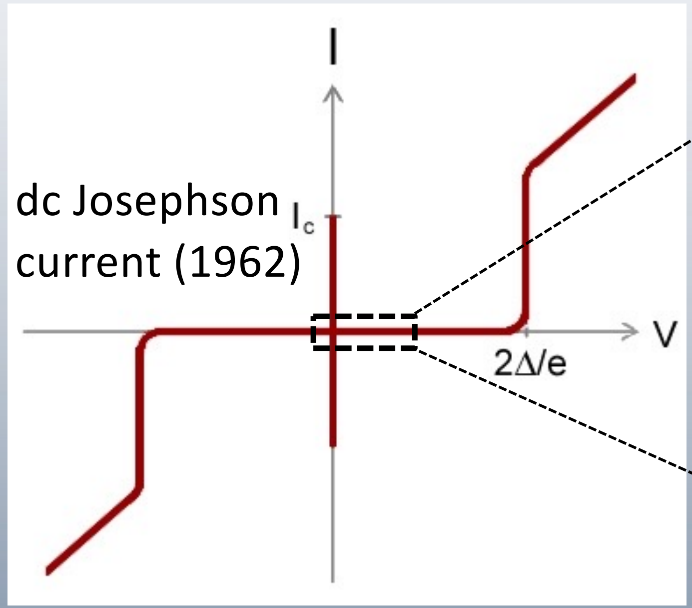


ADR refrigerators for automated cooldown to <0.1K are commercially available (~$500k).

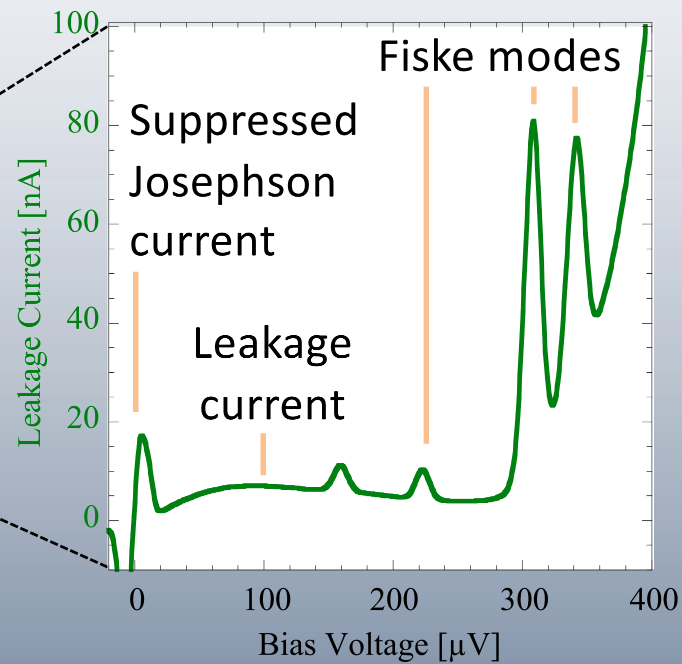
STJ Electronics

STJ Biasing

…in Textbooks

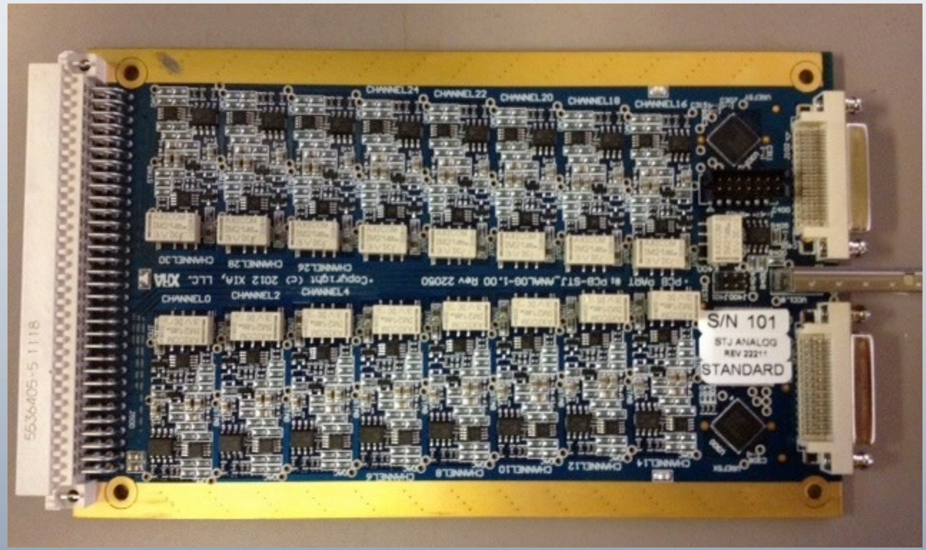


…in Real Life



- Low noise ($e_n \leq 1$ nV/√Hz)
- Stable biasing (to ±few µV)
- Voltage bias (dc load line <100 Ω)

32-channel STJ Preamplifier (XIA)

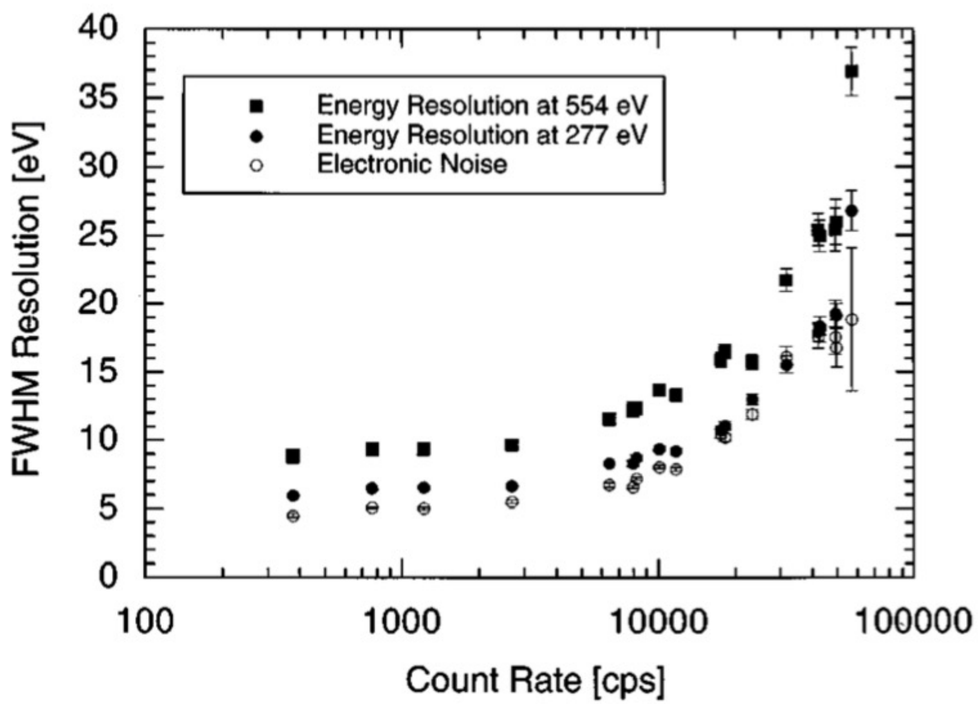


- Low noise, stable biasing, dc voltage bias
- Computer-controlled
- 32 preamplifiers per board

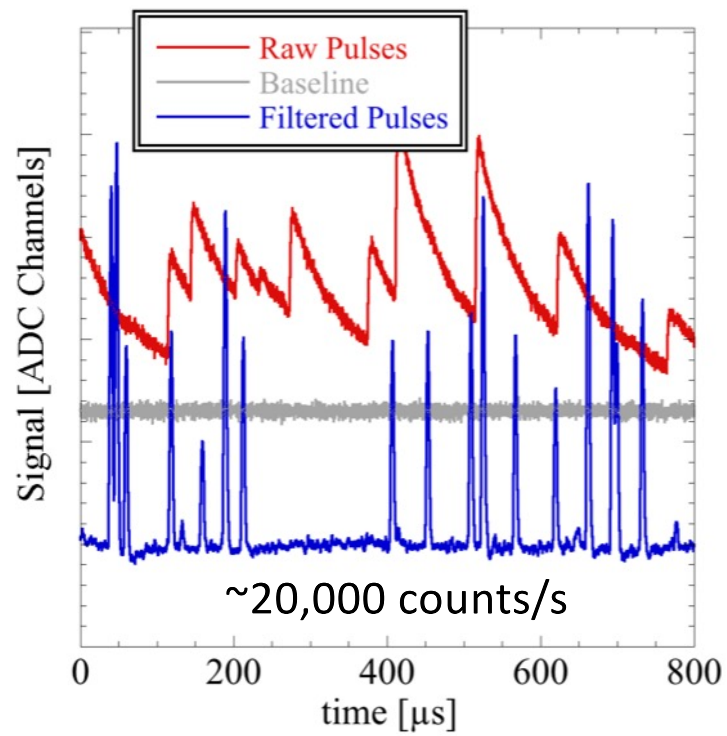
Specialized preamplifiers for STJs are commercially available.

STJ Characterization at High Speed

Nb-STJs (τ_{decay} ≈ few µs)



Ta-STJs (τ_{decay} ≈ few 10 µs)



STJ Signal:

- Single exponential decay constant

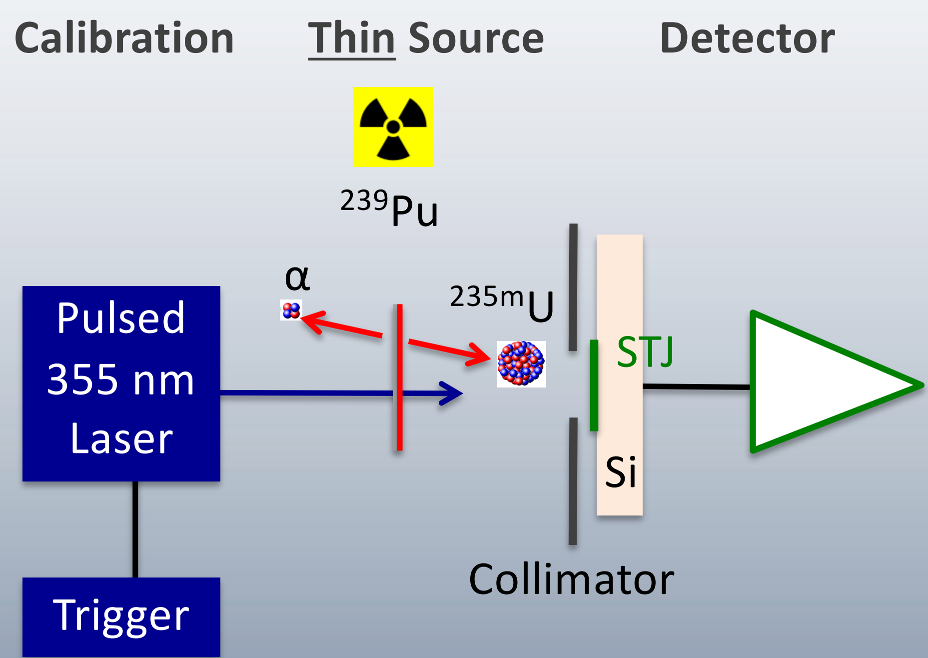
DSP pulse processing:

- Trapezoidal filter
- Pile-up rejection

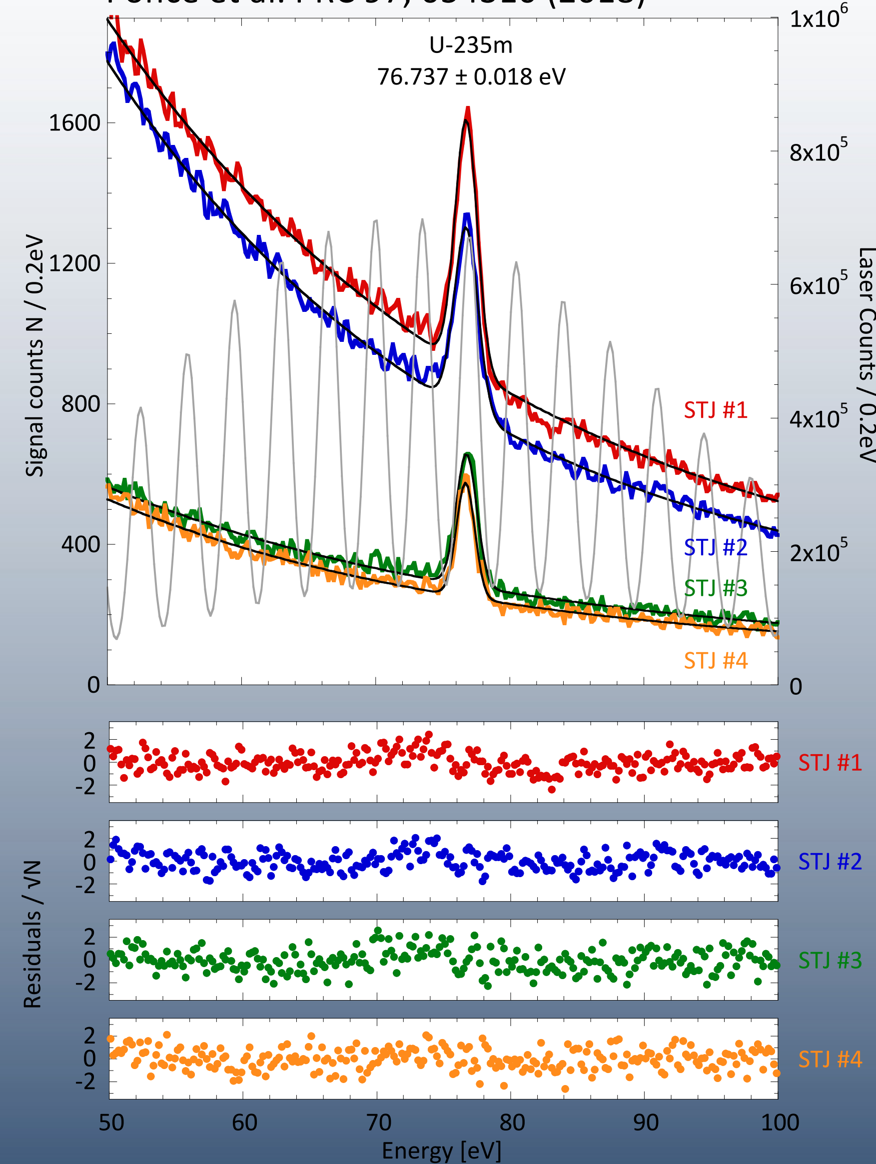
STJs detectors can be operated at rates well above 1000 counts/s per pixel.

Nice, but only at low energies.

Low-Energy Nuclear Spectroscopy of ^{235m}U



Ponce et al. PRC 97, 054310 (2018)



- Absorb ^{235m}U from ^{239}Pu decay in STJ
- Measure ^{235m}U decay with 2 eV resolution
- Result: ^{235m}U energy: 76.737 ± 0.018 eV