Superconducting Tunnel Junction (STJ) Radiation Detectors

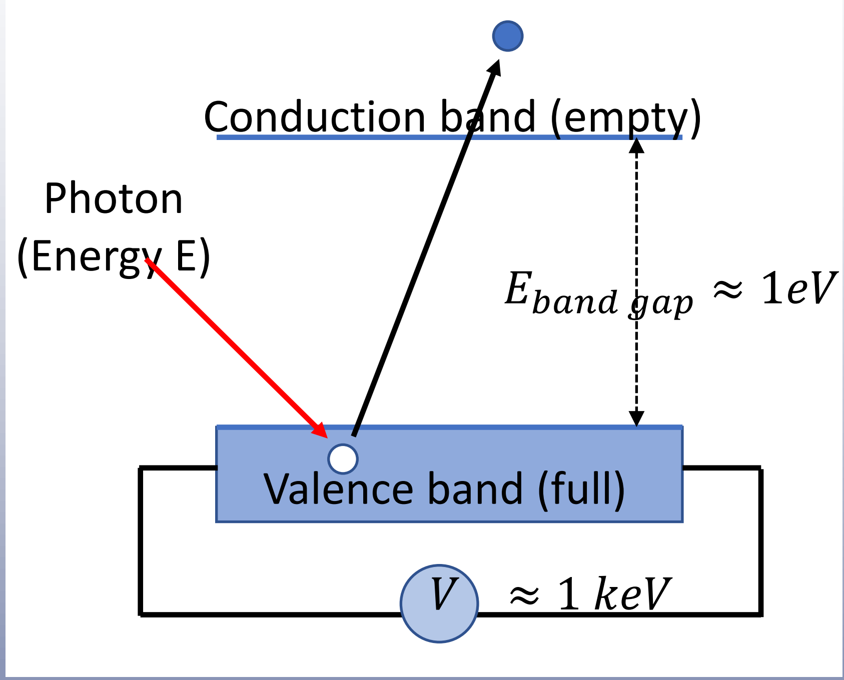
Stephan Friedrich, LLNL

Part 1: What are STJs?

Part 2: The BeEST Sterile Neutrino Search

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
LLNL-PRES-811064

Refresher: Si and Ge Semiconductor Detectors



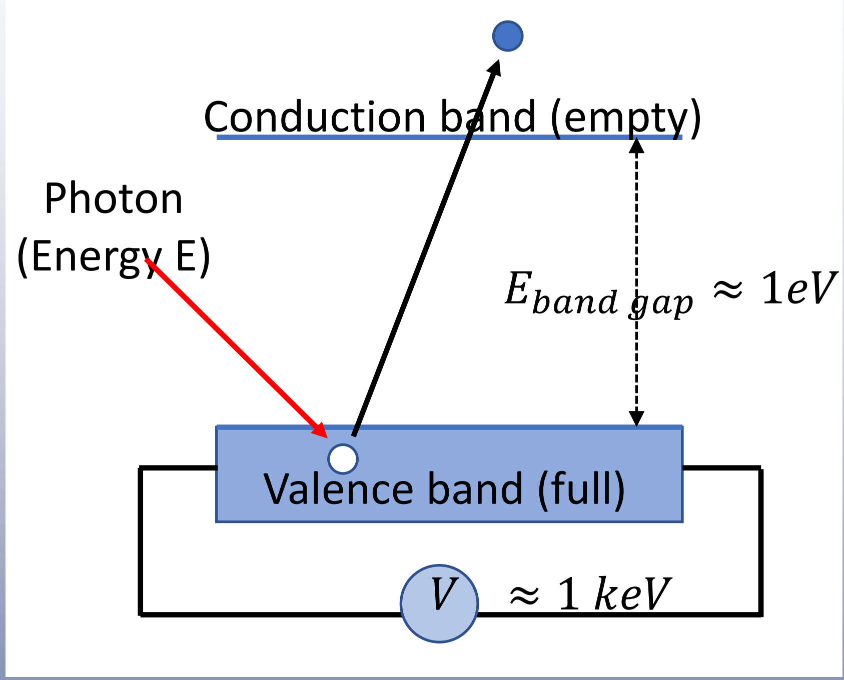
1) Energy resolution is proportional to $1/\sqrt{band\ gap}$
2) Cooling is required to reduce thermal excitations $N_{thermal}$.

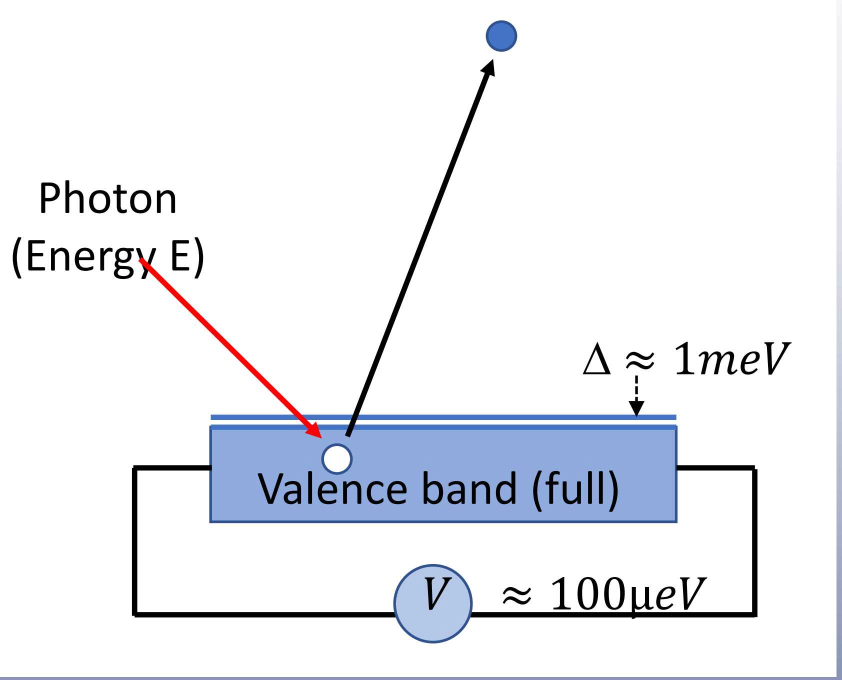
Signal: $Q_S = eN$ with $N = E/\varepsilon$ and $\varepsilon \approx 3E_{band\ gap}$

Noise: $Q_N = e\sqrt{FN}$

$\Rightarrow$ S/N: $Q_S/Q_N = \sqrt{N/F} \propto 1/\sqrt{E_{band\ gap}}$

Semiconducting vs Superconducting Detectors





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$\Rightarrow$ S/N: $Q_S/Q_N = \sqrt{N/F} \propto 1/\sqrt{E_{band\ gap}}$

Signal: Q_S = eN with N = E/ε and $\varepsilon \approx 1.7\Delta$

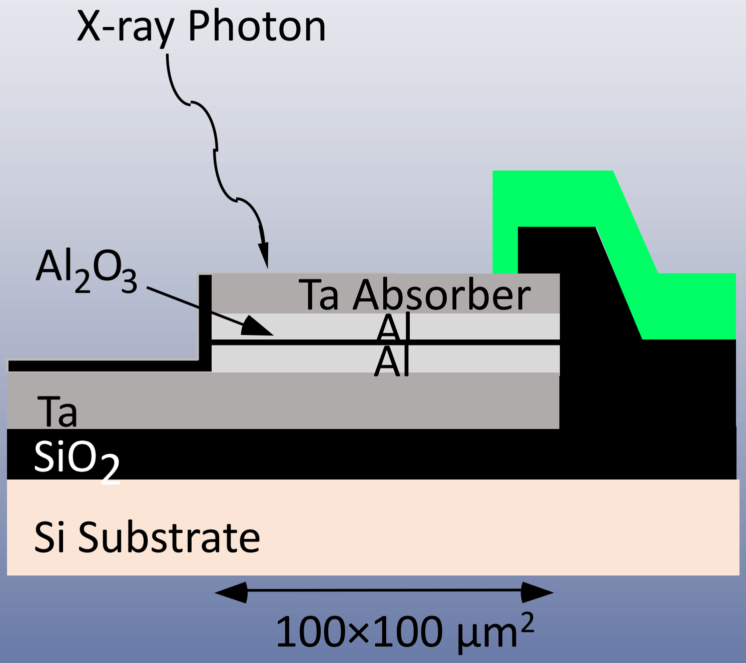
Noise: Q_N = e$\sqrt{FN}$

1000x smaller gap $\Rightarrow$ ~30x higher resolution

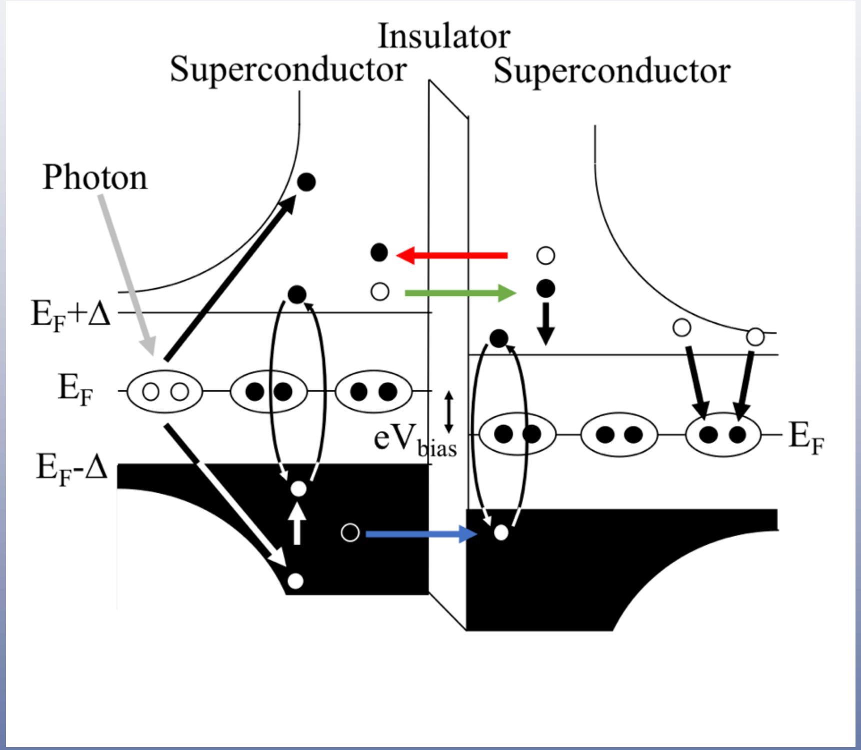
(and 1000x lower T needed)

Superconducting Tunnel Junctions (STJs)

STJ Cross Section



STJ Band Diagram



1) Small ~1 meV energy gap Δ ⇒ High resolution: ~few eV FWHM
2) Short ~μs charge lifetime ⇒ High speed: >1000 counts/s

Statistical Noise in STJ Detectors

Charge Generation

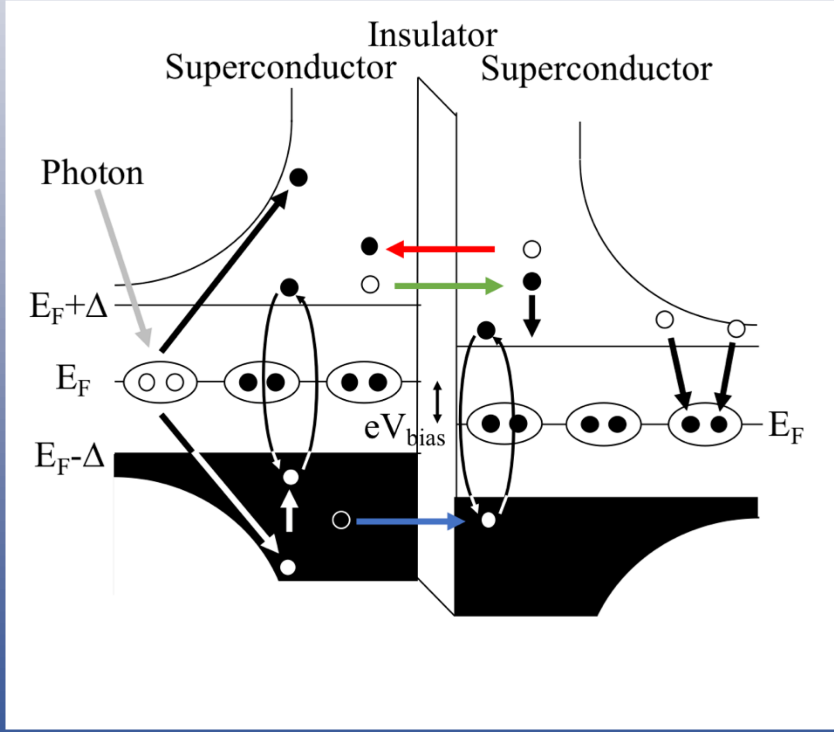
$$F = 0.2$$

Due to Backtunneling

$$F = 1 + \frac{1}{\langle n \rangle}$$

Due to Reverse Tunneling

$$F = \frac{4\gamma(1-\gamma)}{(1-2\gamma)\char`^2}$$



Refresher: Electronic Noise in Si and Ge Detectors

Current and Voltage Noise

Leakage Current (in Detector and FET)

$\Rightarrow$ Current (shot) noise $i_n = \sqrt{2eI_{leak}}$

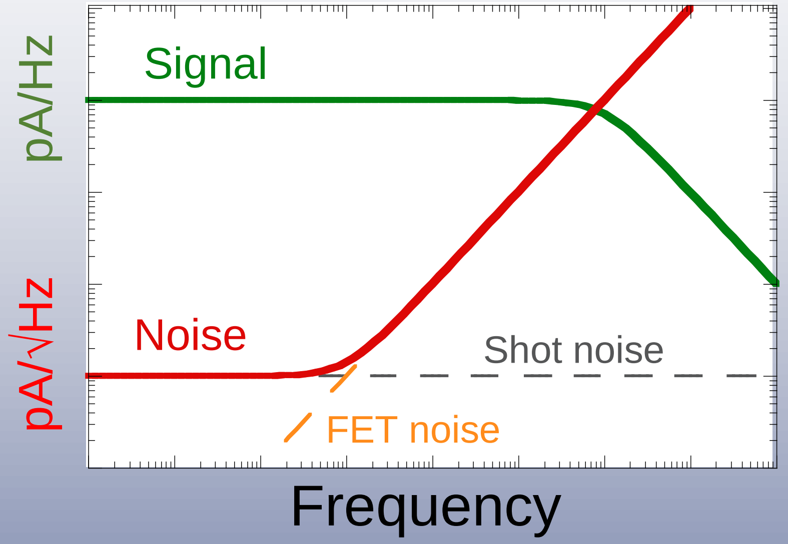
Thermal Noise (in Resistors and FET)

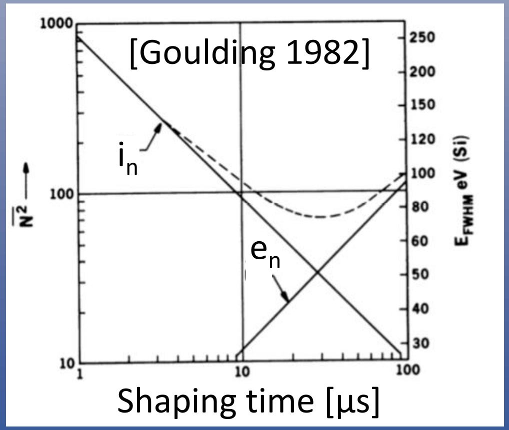
$\Rightarrow$ Voltage (Johnson) noise of FET $e_{FET} = \sqrt{4k_BT\left(\frac{2}{3g_m}\right)}$

$\Rightarrow$ Equivalent current noise $\frac{e_n}{|Z_{detector}|} \approx |e_n i\omega C_{detector}| \propto e_n\omega C$

FET noise and Si / Ge detector capacitance set electronic noise.

Noise vs Frequency





Electronic Noise in STJ Detectors

Current and Voltage Noise

Leakage Current (in Detector and FET)

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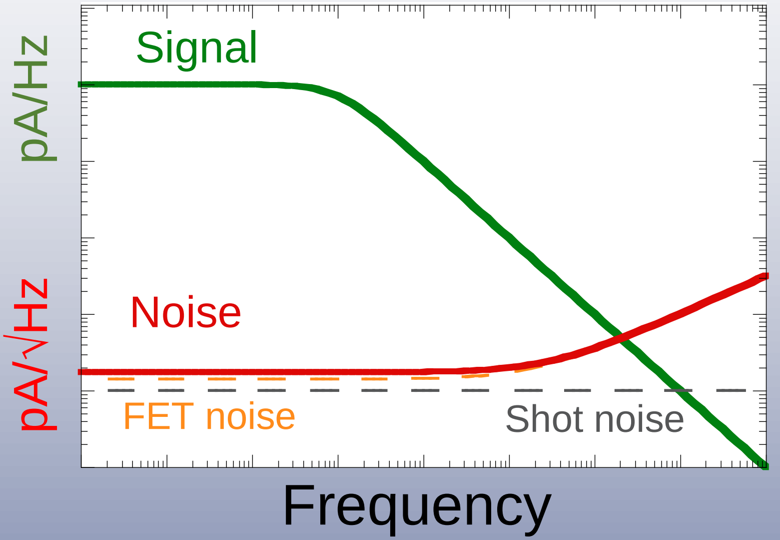
Thermal Noise (in Resistors and FET)

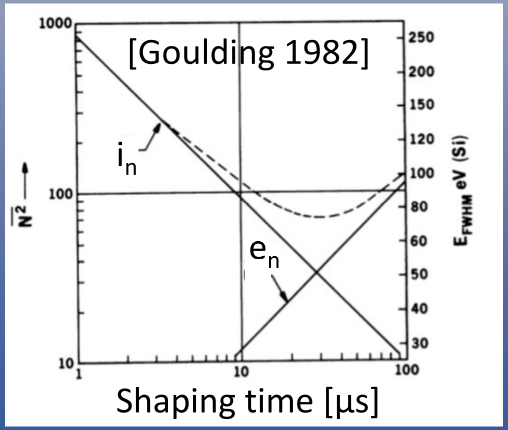
$\Rightarrow$ Voltage (Johnson) noise of FET $e_{FET} = \sqrt{4k_B T\left(\frac{2}{3g_m}\right)}$

$\Rightarrow$ Equivalent current noise $\frac{e_n}{|Z_{detector}|} \approx \left|\frac{e_n}{R_{STJ}||C_{STJ}}\right| \propto \frac{e_n}{R_{STJ}}$

FET noise and STJ detector <u>resistance</u> set electronic noise.

Noise vs Frequency





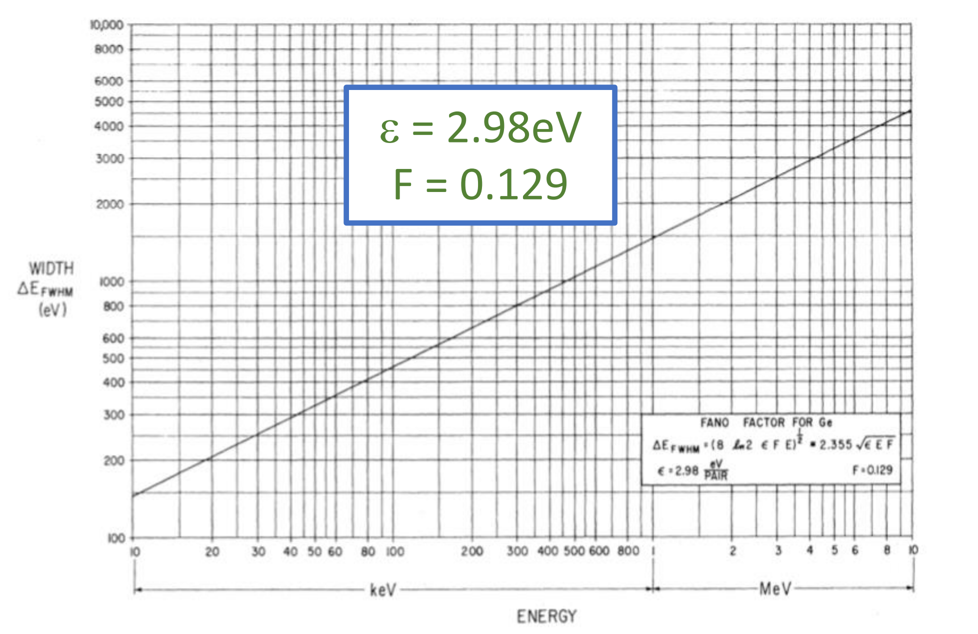
STJs vs Ge:

- *Slower* signal
- *Resistive* detector

Measuring Statistical and Electronic Noise

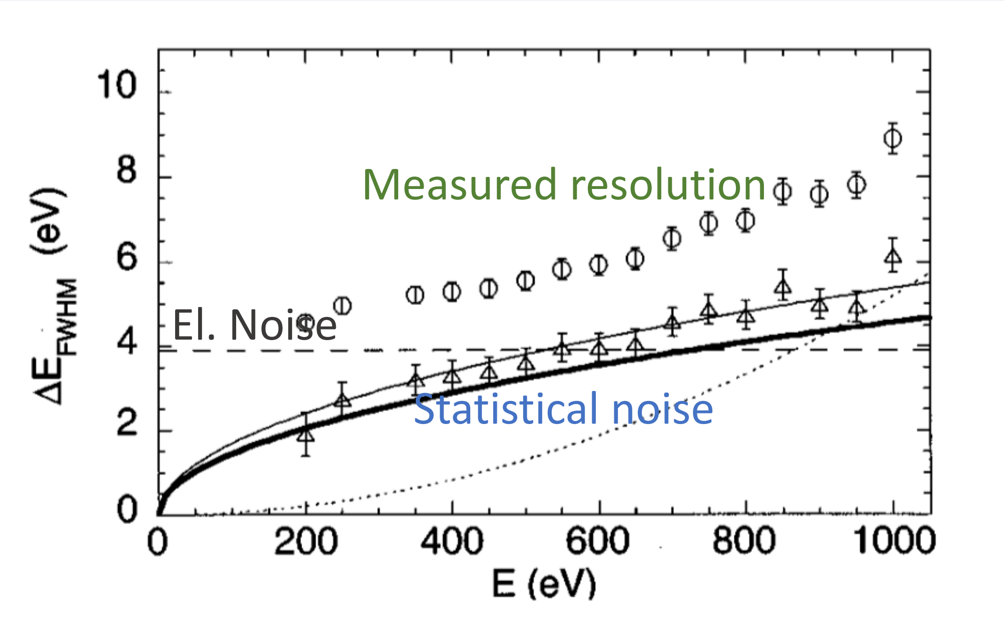
Ge Detectors

Bilger, Phys. Rev. **163**, 238 (1967)



STJ Detectors

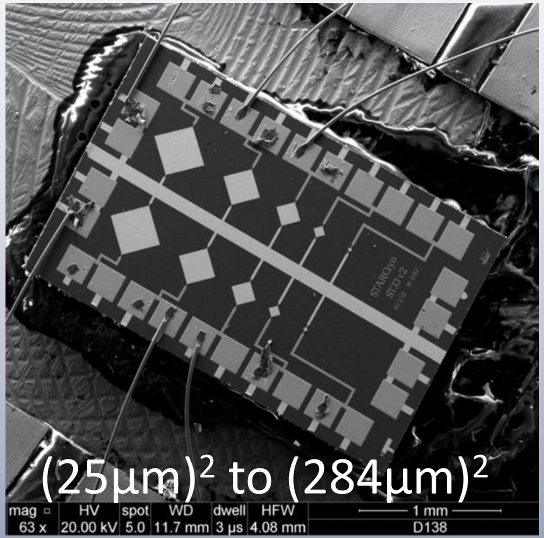
le Grand et al., Appl. Phys. Lett. **73**, 1295 (1998)



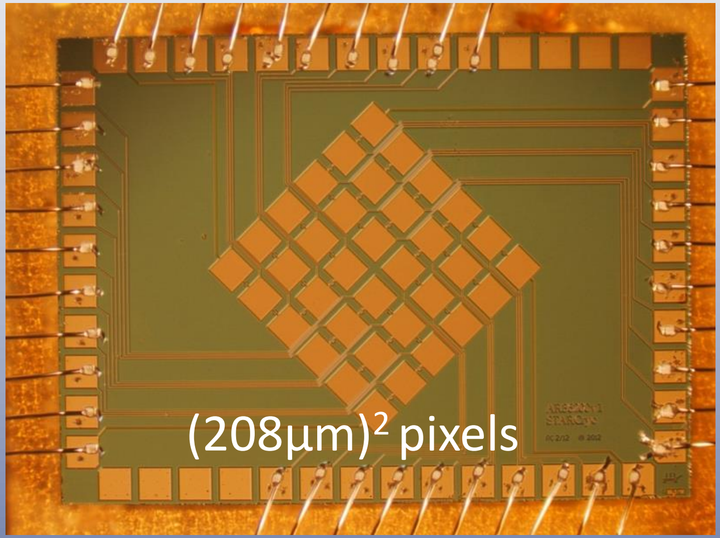
- Statistical noise ∝ √E
- Electronic noise is constant with E
- Inhomogeneity causes broadening ∝ E

STJ Fabrication

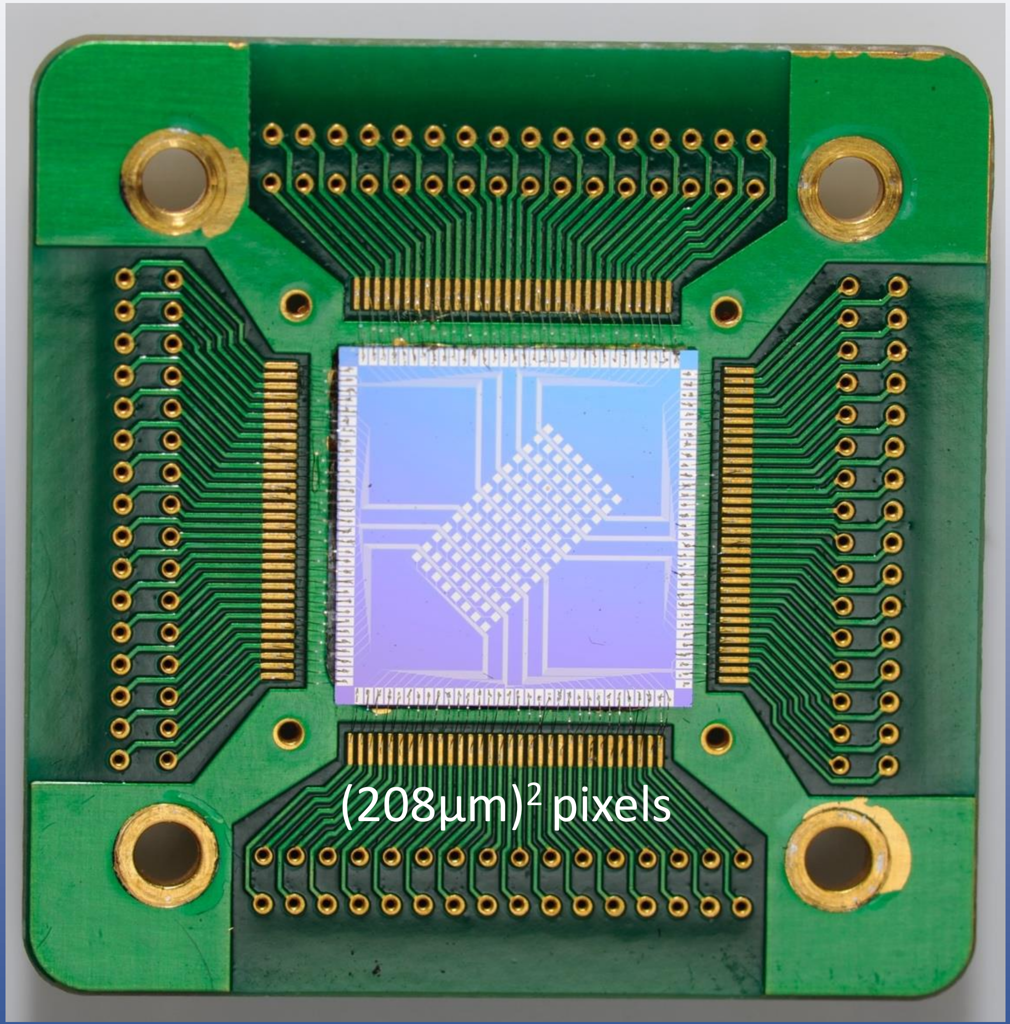
Few Pixels



36 Pixels



128 Pixels

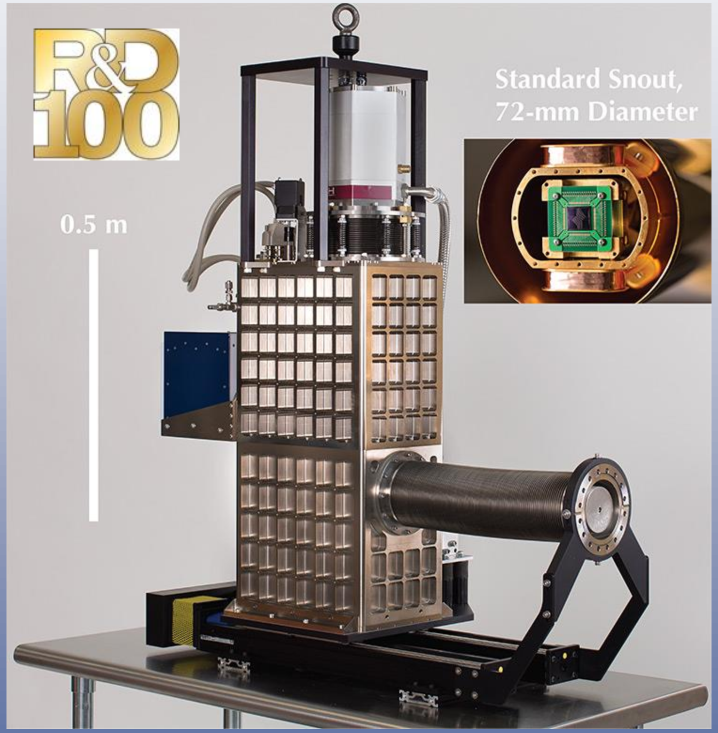


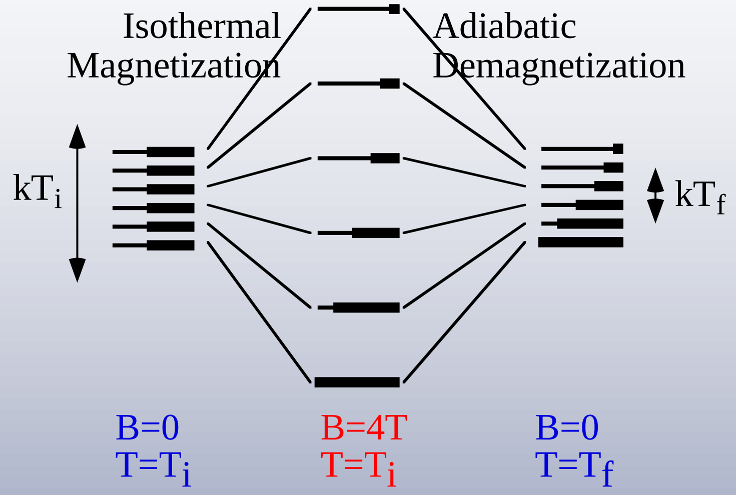
Our STJs are fabricated by photolithography at STAR Cryo in Santa Fe.

Automated STJ Cooling to 0.1K

1990s:
Liquid N_2 and He pre-cooling
Single-stage ADR

2010s:
Pulse-tube pre-cooling ("dry")
Two-stage ADR



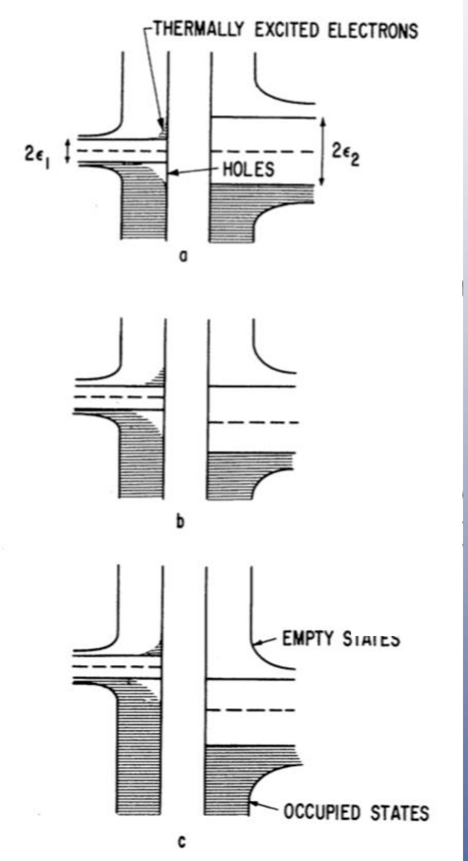


1) Close heat switch
2) Apply B (lower entropy S)
3) Open heat switch (decouple T)
4) Reduce B slowly (keeping entropy constant $\Rightarrow$ reduce T)

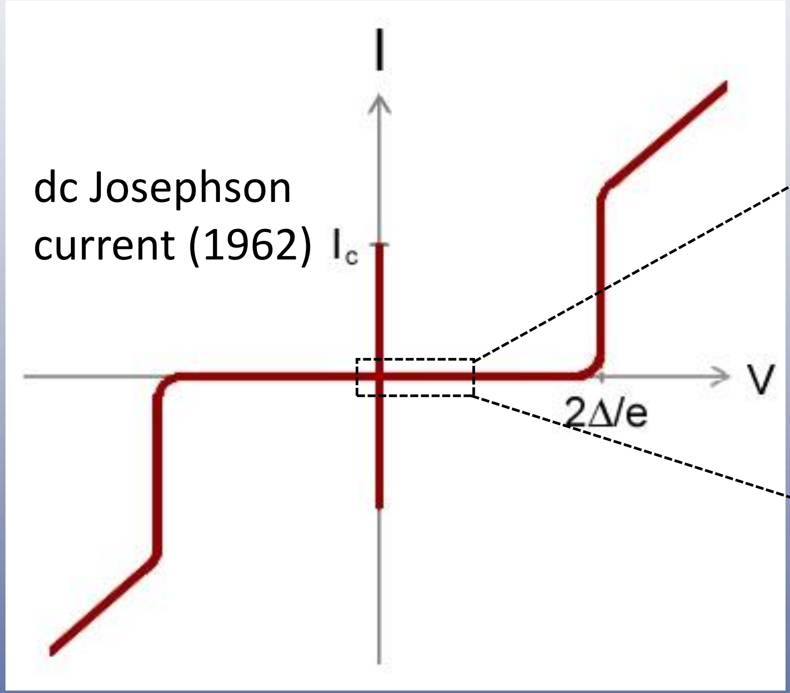
Adiabatic Demagnetization Refrigerators (ADRs) are compact, reliable, automated and commercially available.

STJ Operation

Current-Voltage I(V) Curve (Textbook Version)

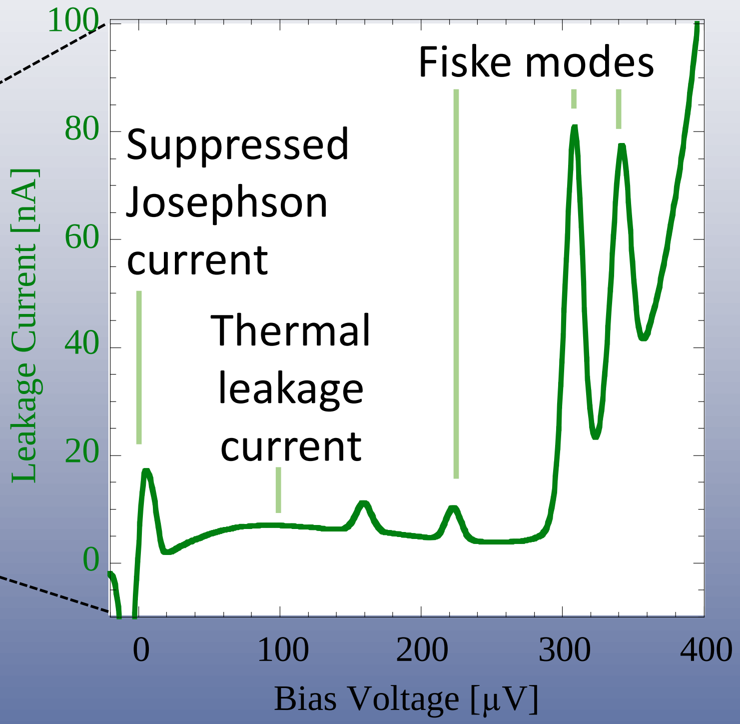


I. Giaever (1960)



Cool to ≤ $0.1T_C$ to suppress thermal current.

I(V) Curve (Real Life)

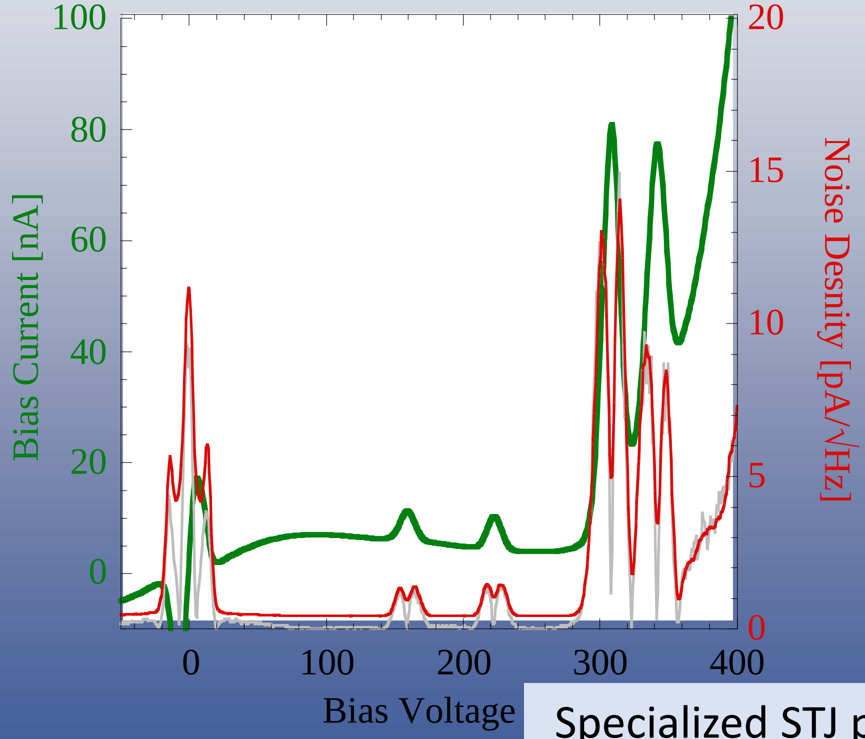


Apply B to suppress dc Josephson current.

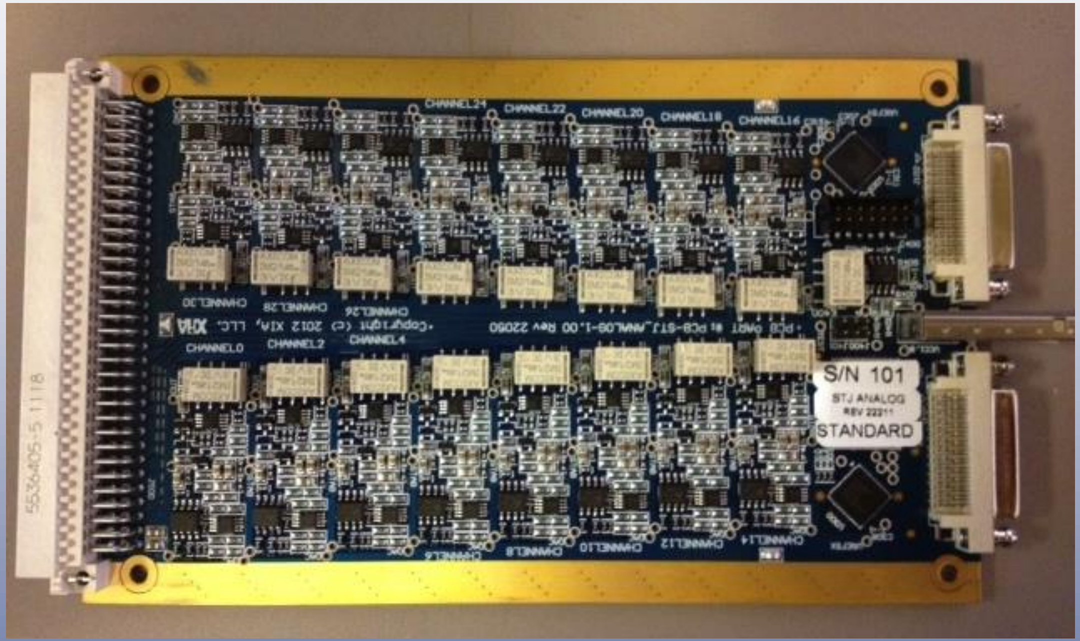
STJ Electronics

Readout Requirements

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



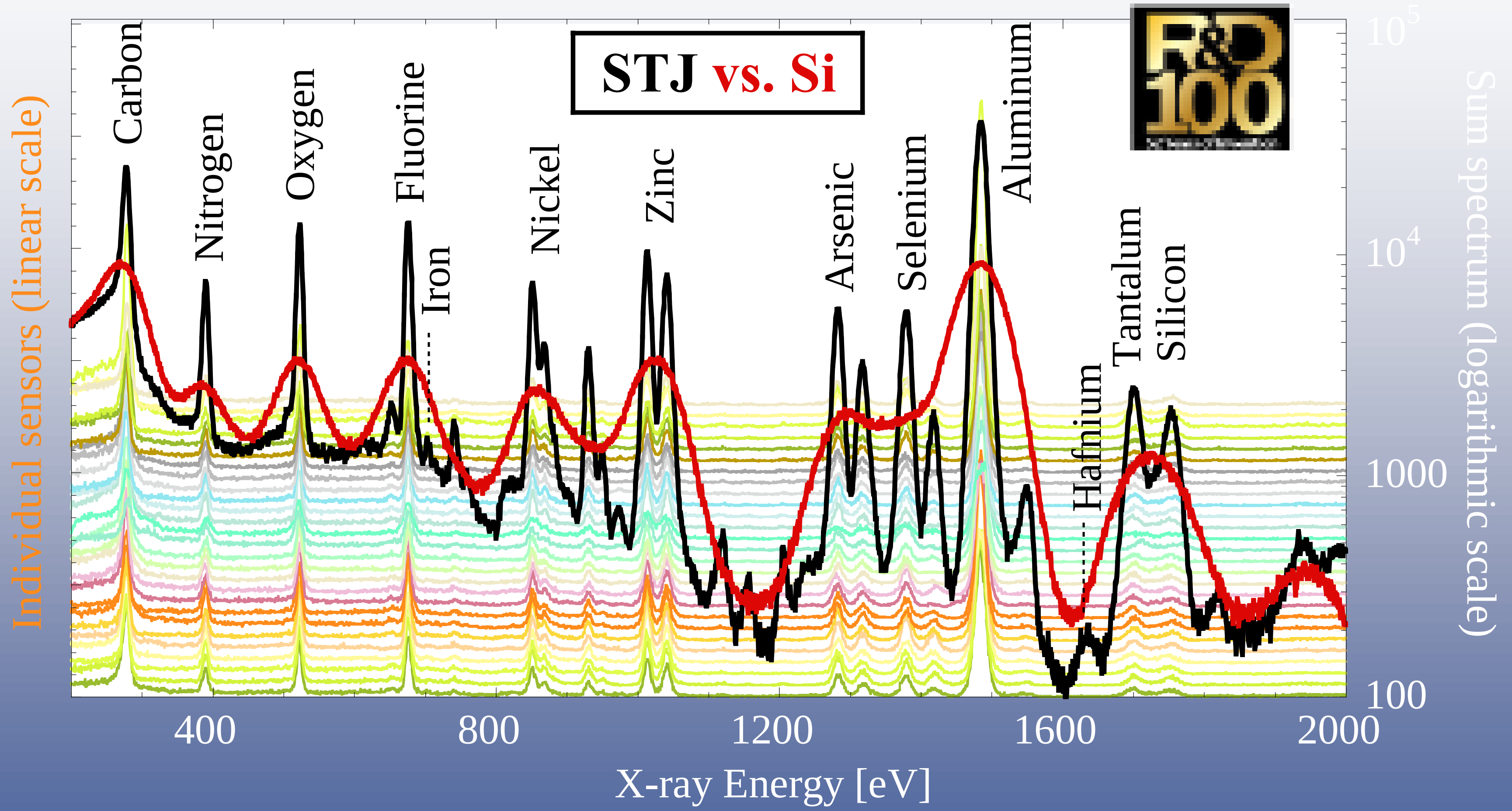
Computer-Controlled Preamplifier (XIA)



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

Specialized STJ preamplifiers are commercially available, too.

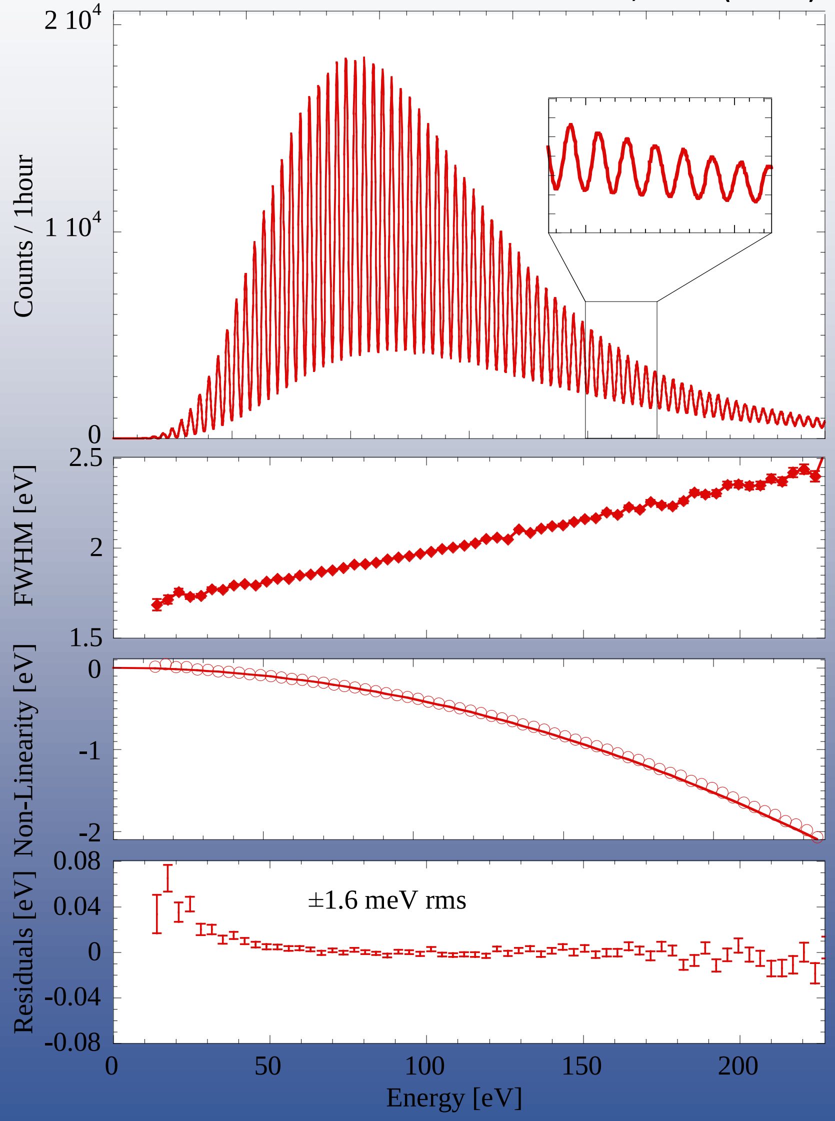
STJ vs. Si Detectors



High resolution is important at low energies where lines are closely spaced.

STJ Performance: Resolution and Linearity

S. Friedrich et al., JLTP (2020)



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

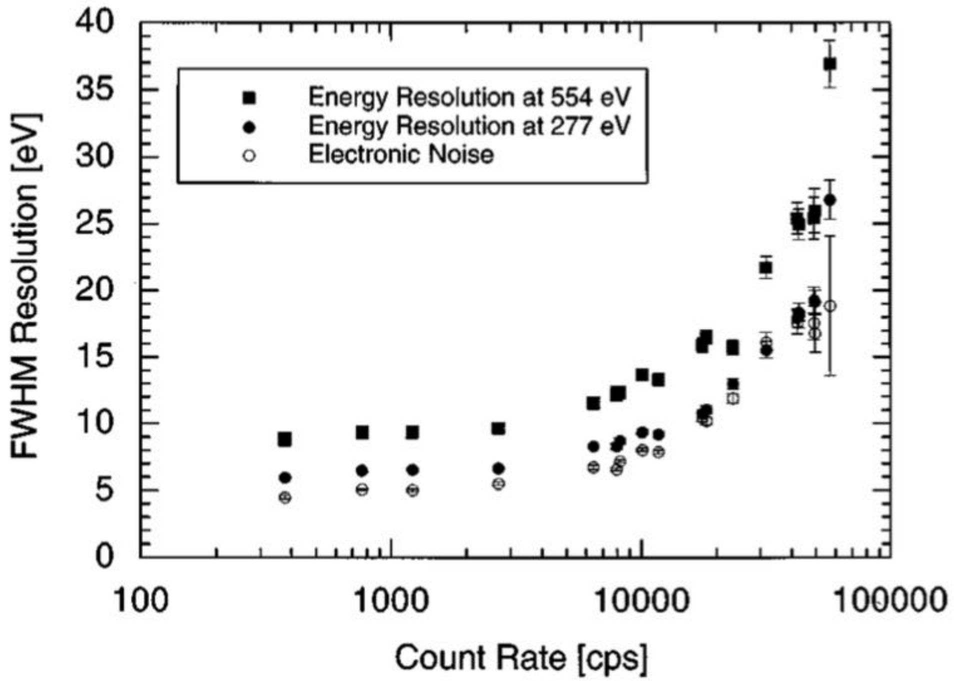
⇒ Calibration accuracy of order ±1 meV in 1 hour

STJ Performance: Speed

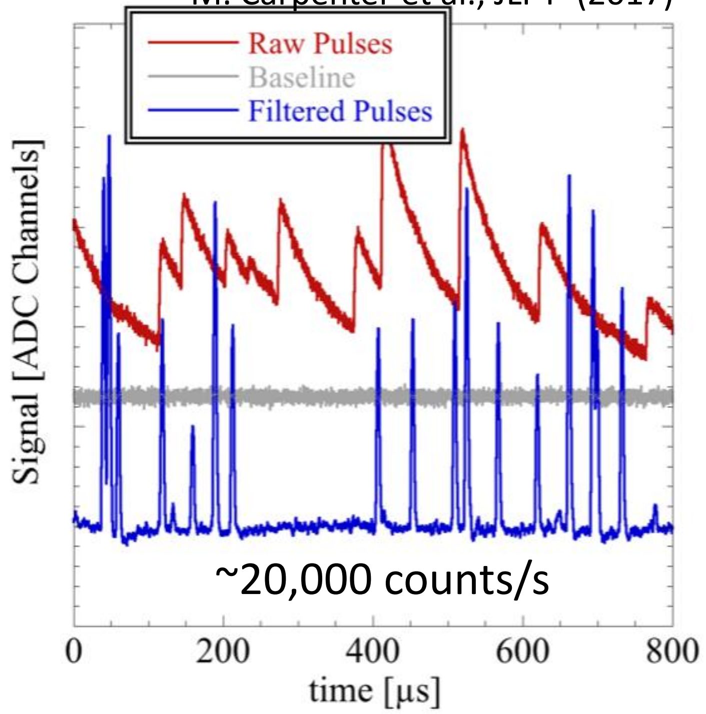
Nb-STJs (τ_{decay} ≈ few µs)

Ta-STJs (τ_{decay} ≈ few 10 µs)

M. Frank et al, RSI (1998)



M. Carpenter et al., JLPT (2017)



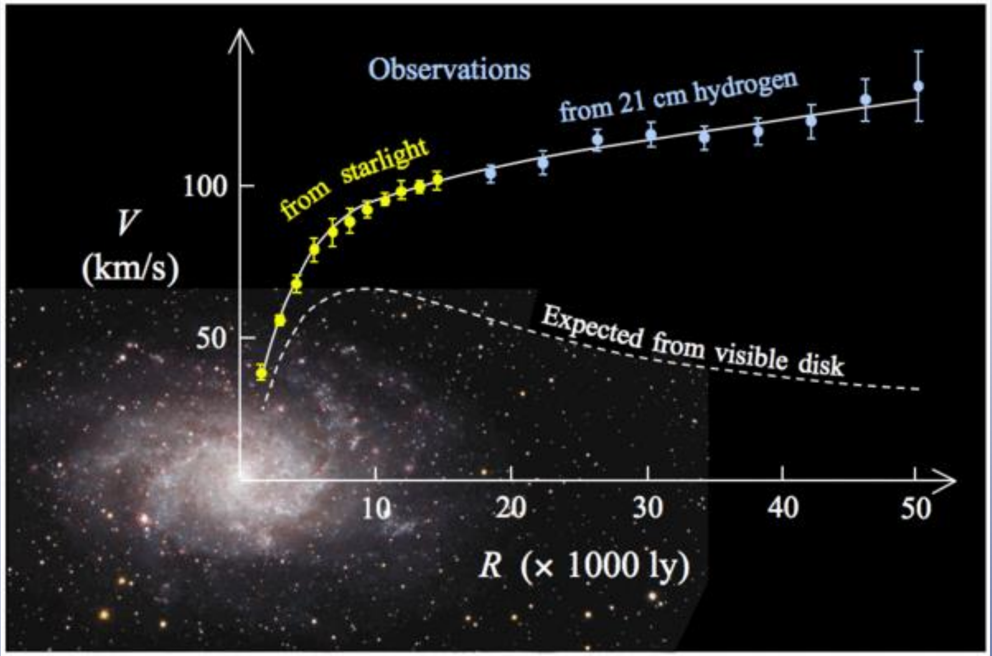
STJ Signal:
- Single exponential decay constant

DSP pulse processing:
- Trapezoidal filter
- Pile-up rejection

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

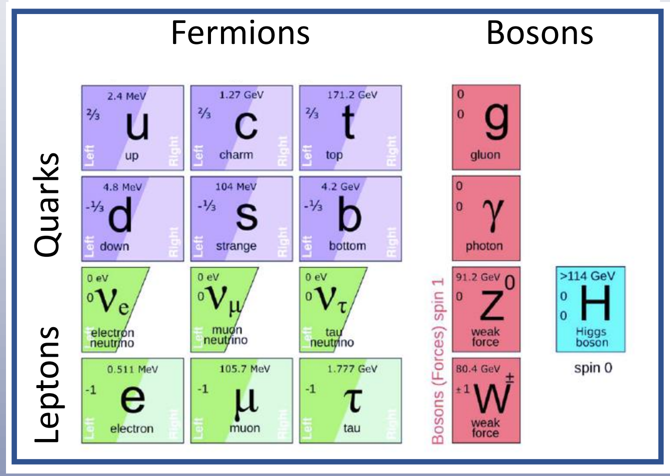
Part II: The BeEST Sterile Neutrino Search

What is Dark Matter?



- What is 85% of the mass in the Universe?
- Why the matter-antimatter asymmetry?

Do Right-Handed (Sterile) Neutrinos Exist?



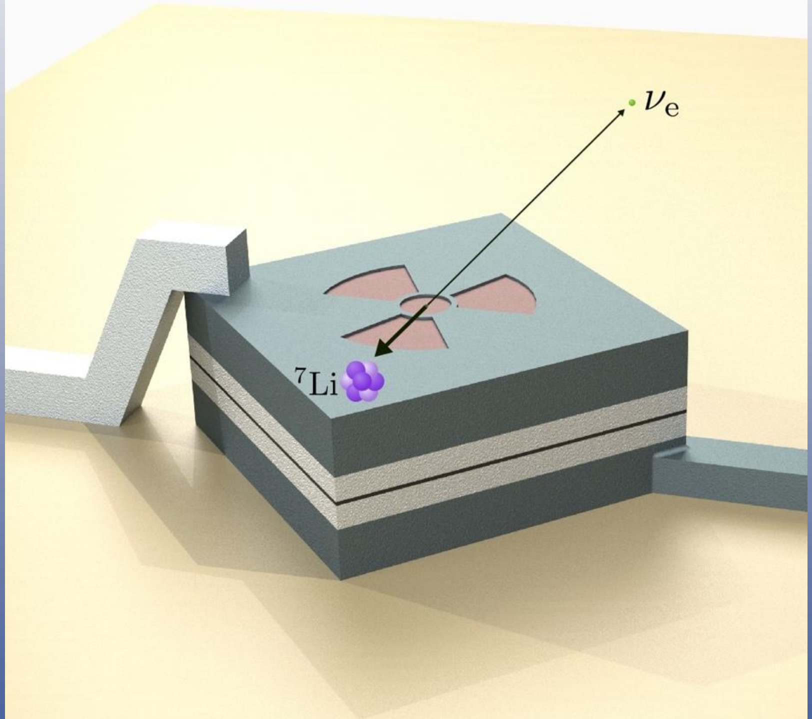
- Why are all neutrinos left-handed?
- Why do neutrinos have mass?

How to Find Something that

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

How to Find Something that

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



From the recoil it causes!

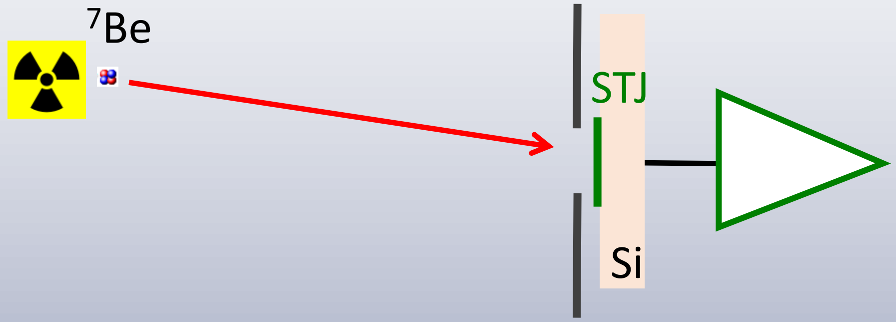
$|p_{Li\text{-}7}| = |p_\nu|$

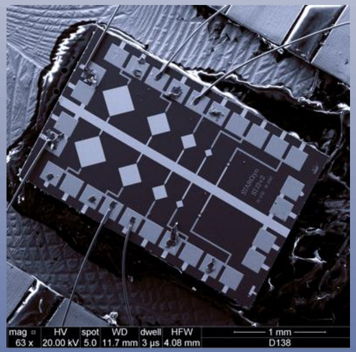
(Missing momentum experiment.)

A Sterile Neutrino Search with STJ Detectors

Implant ^{7}Be
at TRIUMF

Superconducting Detector
from LLNL





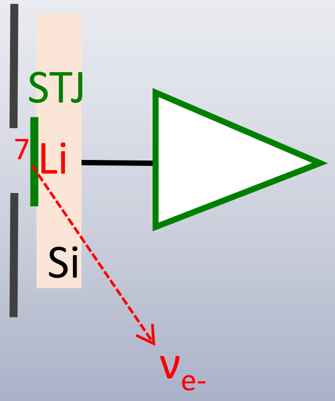
Implant ^{7}Be into STJ detectors.

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

Beryllium-7 Electron Capture in STJ Detectors

Implant ^{7}Be
at TRIUMF

Detect ^{7}Be Decay
at LLNL



$$^{7}\mathbf{Be} + \mathbf{e-} \longrightarrow {}^{7}\mathbf{Li} + \boldsymbol{\nu}_{\mathbf{e-}}$$

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

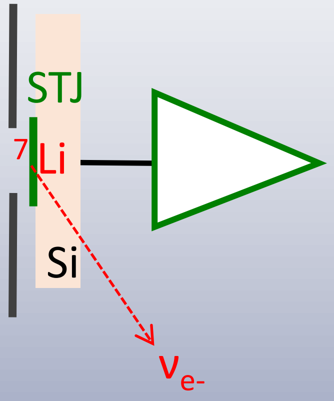
Measure electron capture decay of ^{7}Be to ^{7}Li.

2-body decay ⇒ Monochromatic recoil (in principle)

Be-7 Electron Capture in STJs: The BeEST Experiment

Implant ^{7}Be
at TRIUMF

Detect ^{7}Be Decay
at LLNL



$$E_{^{7}Li\ recoil} = \frac{Q^2 - m_\nu^2 c^4}{2(Q - m_{^{7}Li}c^2)}$$
$$\rightarrow 56.826(9) eV\ for\ m_\nu \approx 0$$

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

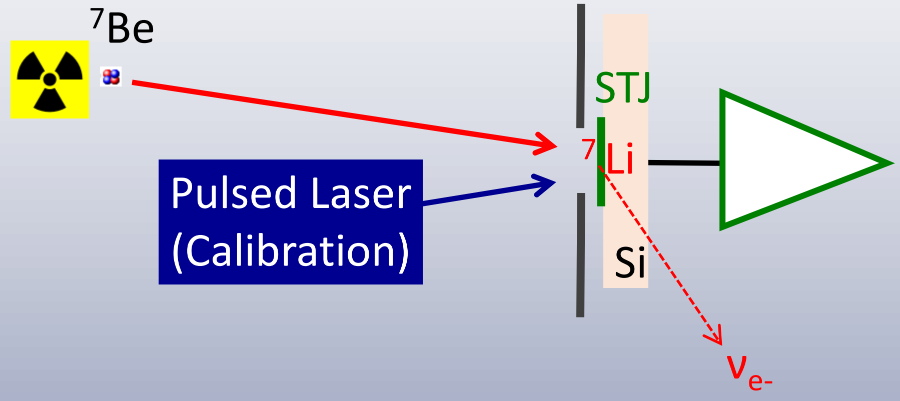
Heavy sterile neutrinos would change ^{7}Li recoil energy.

Look for new peaks in recoil spectrum.

The BeEST Sterile Neutrino Search

Implant ^{7}Be
at TRIUMF

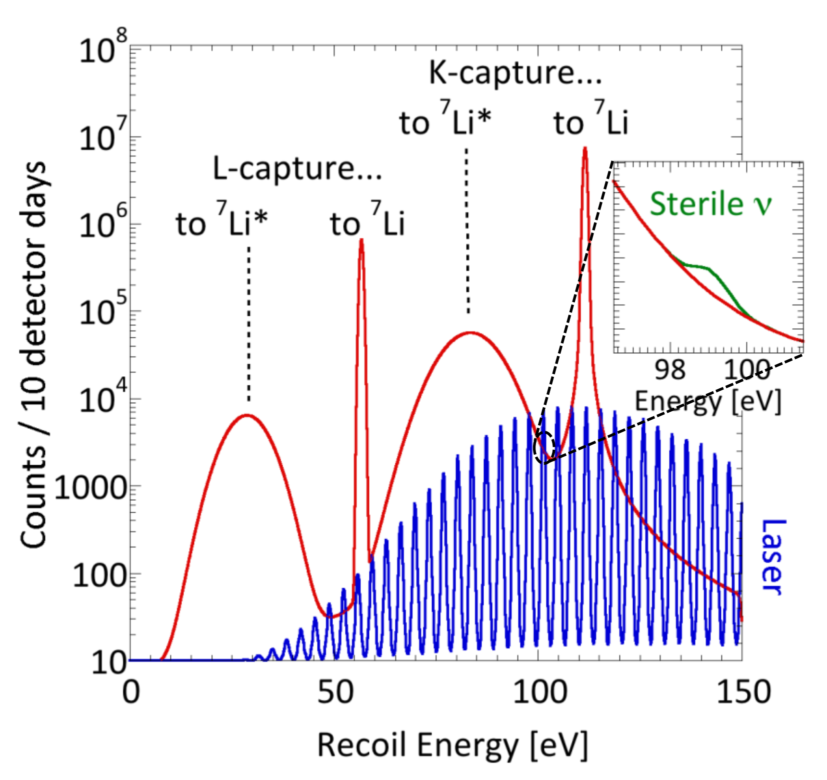
Detect ^{7}Be Decay
at LLNL



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

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

High-Resolution Recoil Simulation



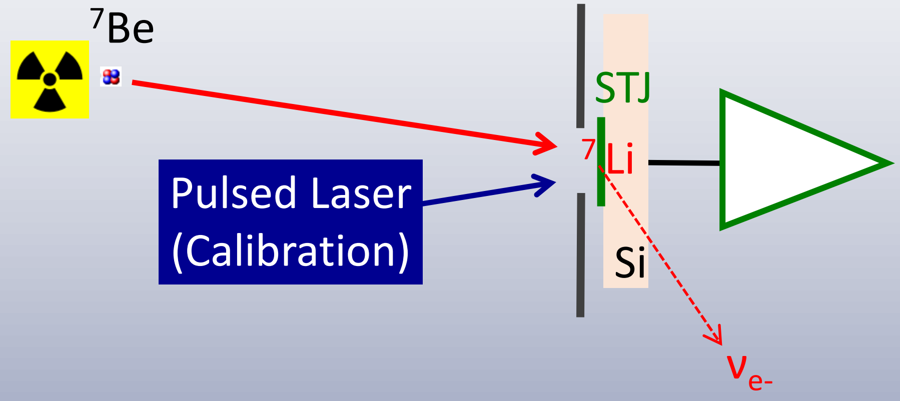
Calibrate STJ with pulsed laser.

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

The BeEST Sterile Neutrino Search

Implant ^{7}Be
at TRIUMF

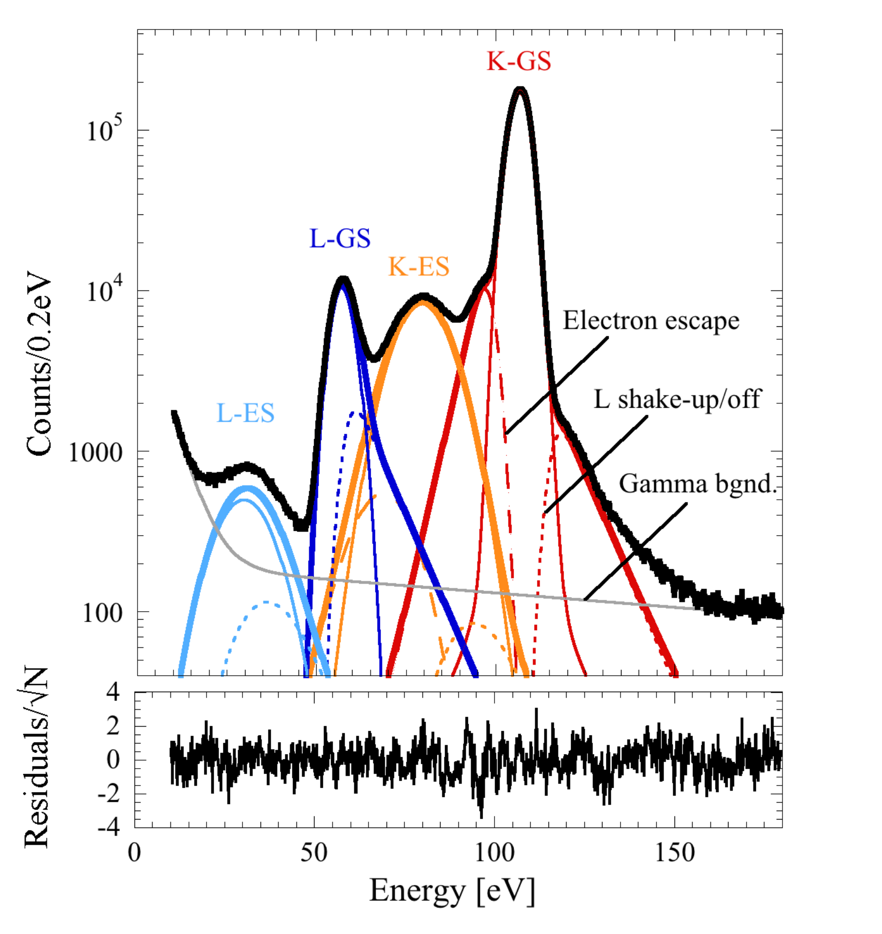
Detect ^{7}Be Decay
at LLNL



^{7}Be + e- ⟶ ^{7}Li + ν_{e-}

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

Data from 1 Ta-STJ Detector for 28 Days



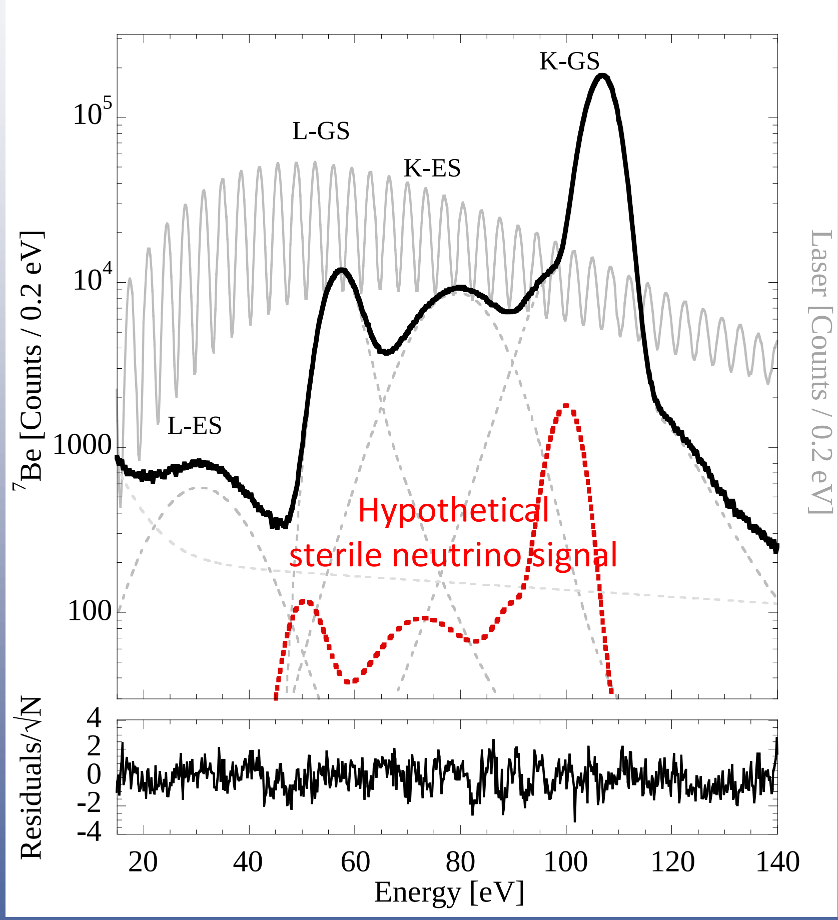
- 4 primary peaks
  - 2 x K-capture, 2x L-capture
  - to ^{7}Li ground state and to ^{7}Li*
- 4 high-energy tails
  - Shake-off effects
- 2 low-energy tails
  - (Partial) Auger e- energy loss
- 1 broad background
  - 478 keV γ's in substate

L/K Ratio = 0.070(7)

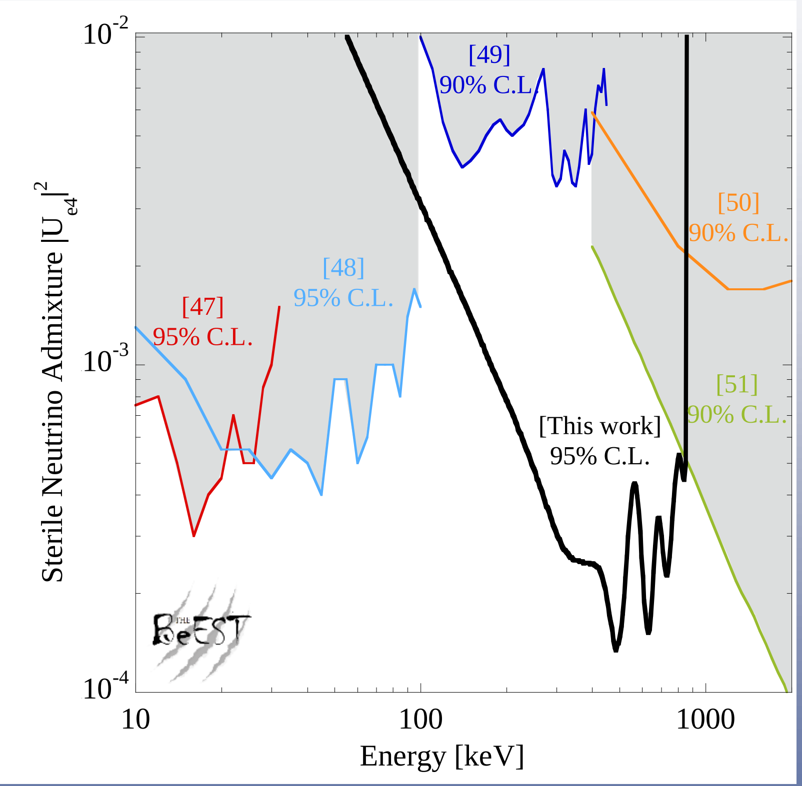
PRL **125**, 032701 (2020)

The BeEST Sterile Neutrino Search

Data with Hypothetical Sterile ν Signal



Exclusion Plot

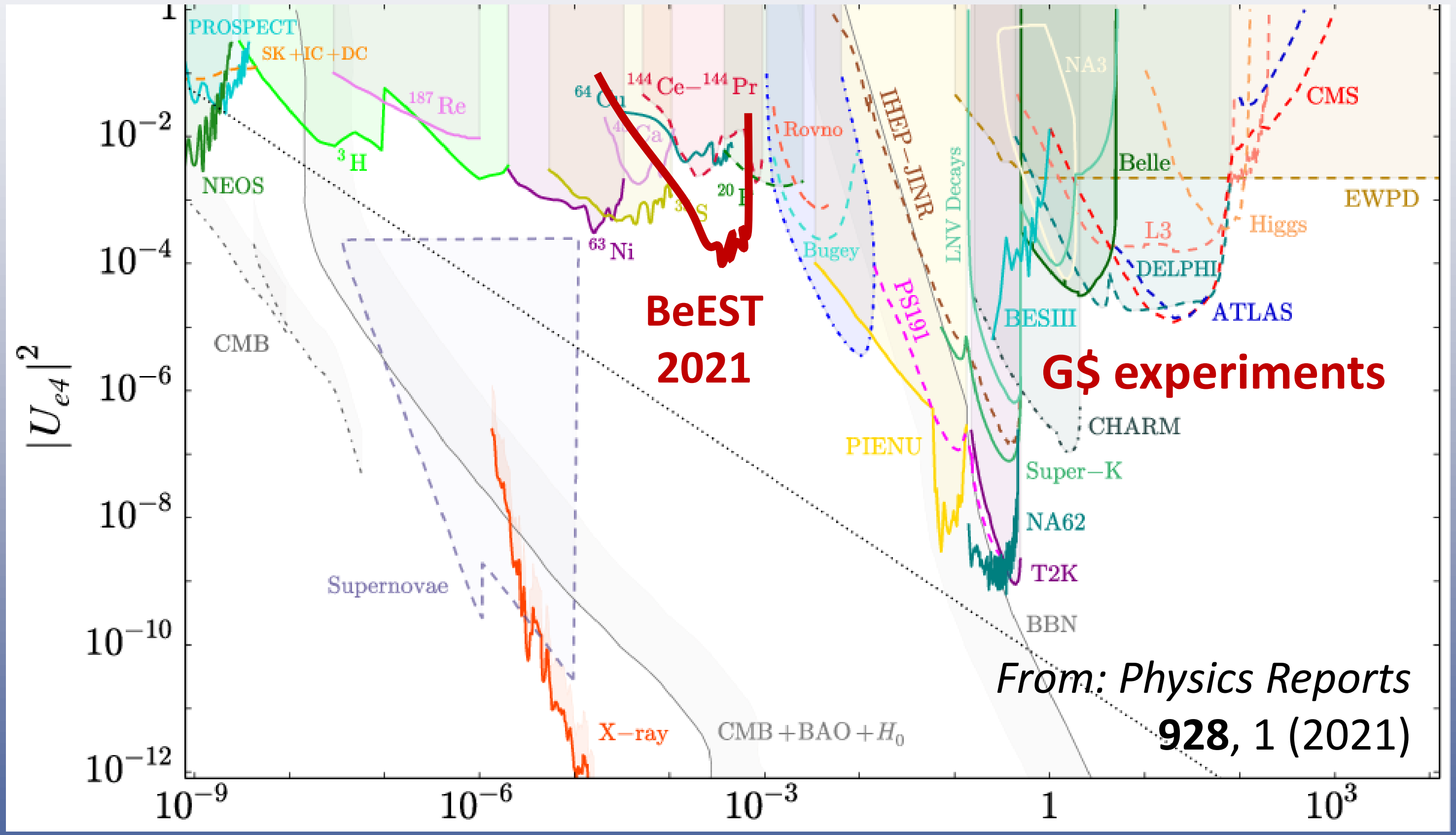


10x improvement with 1 pixel.

PRL **126**, 021803 (2021)

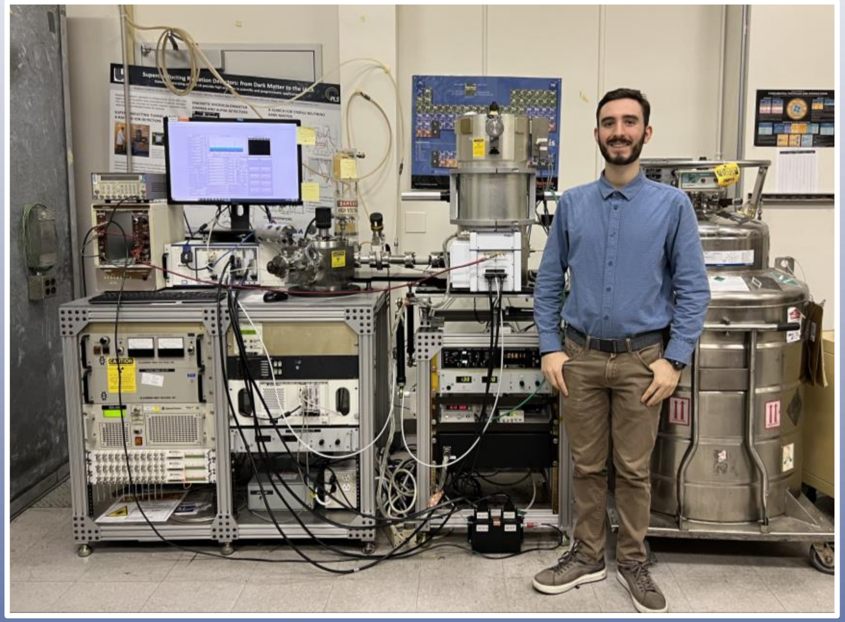
The BeEST in Context

Summary of Sterile Neutrino Searches (2021)



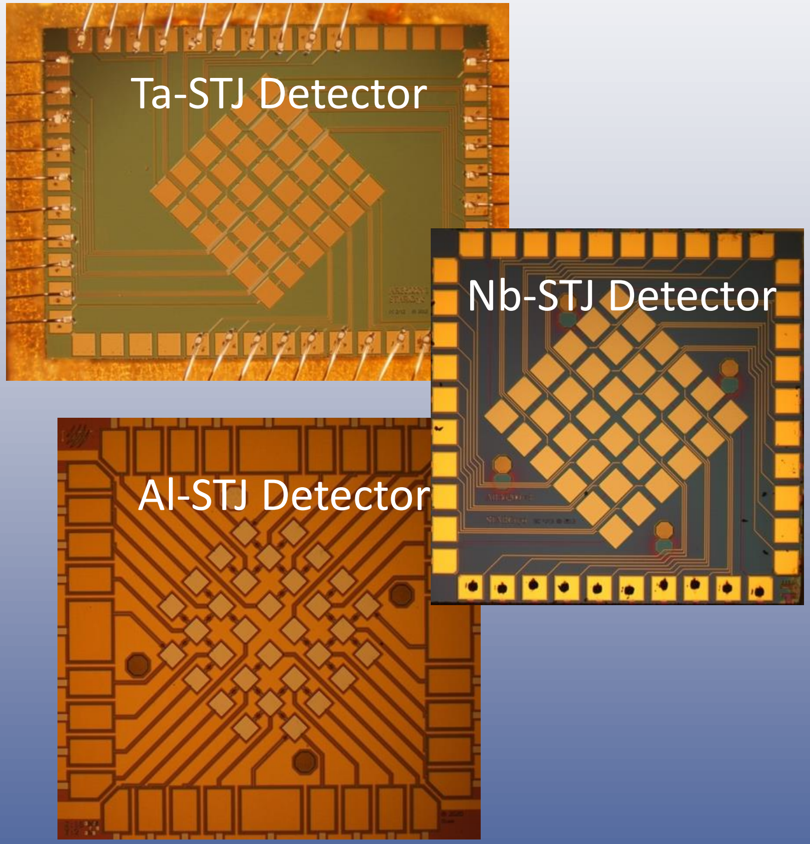
m_4 [GeV]

Tabletop BeEST Experiment



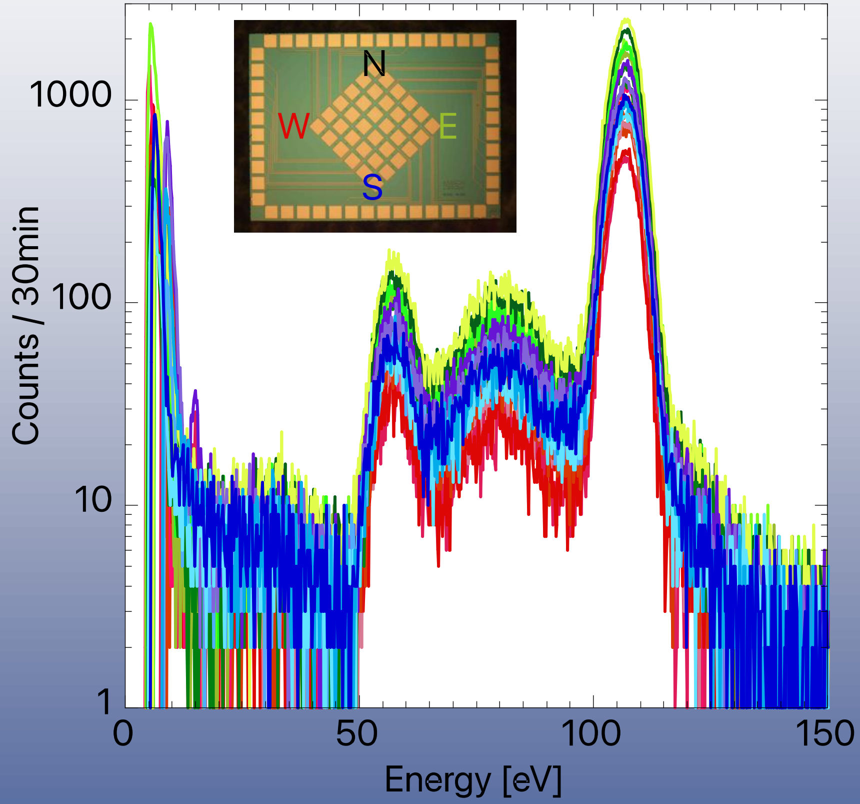
Current Work: New Materials and More Pixels

STJs from Different Materials



Separate BSM physics from material effects.

Currently Taking Data with Ta-STJ Array

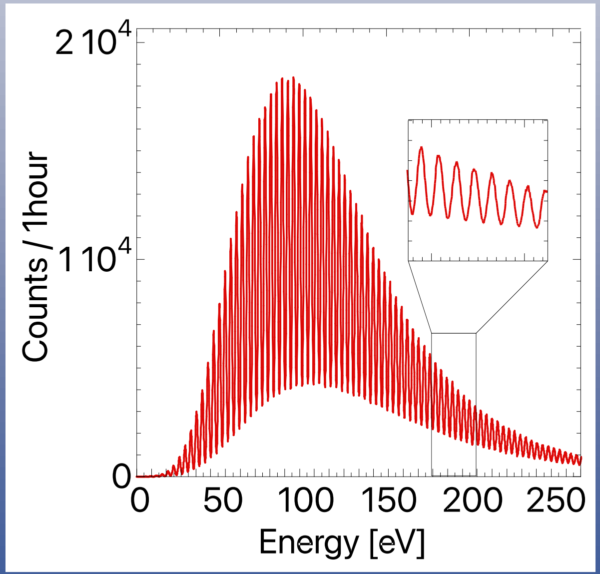


Stay tuned!

Summary: STJs and the BeEST

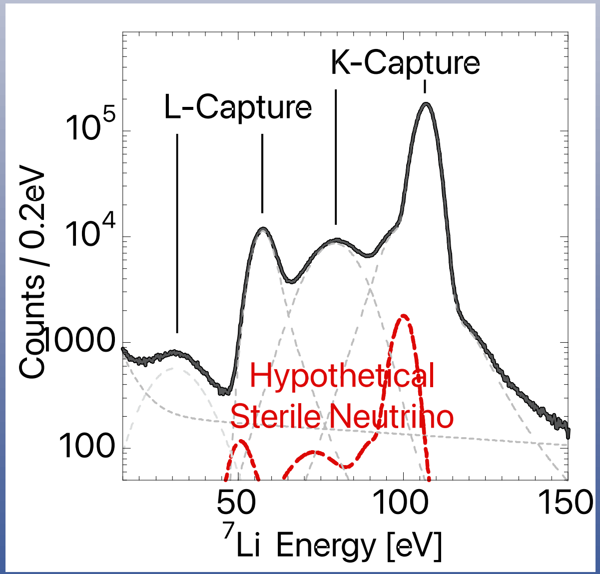
Superconducting Tunnel Junctions

- High energy resolution: ~1 – 5 eV
- High speed: >1000 counts/s per pixel
- No quenching



Beryllium-7 Electron Capture in STJs

- High-sensitivity recoil measurement
- Exclusion to $|U_{e4}|^2$ to $\sim 10^{-4}$ with 1 pixel
- Currently scaling to arrays



Stephan Friedrich
G.-B. Kim, I. Kim, A. Samanta, V. Lordi

⇒ BeEST Experiment
⇒ DFT Simulations
⇒ TEM Imaging

Kyle Leach
S. Fretwell, C. Bray, A. Marino, C. Harris

⇒ Weak Interaction Physics
⇒ Monte-Carlo Simulations

Chris Ruiz
A. Lennarz, P. Machule, D. McKeen

⇒ ^{7}Be Implantation
⇒ Cosmology

Robin Cantor
Ad Hall

⇒ STJ Fab

Thank You!

Xavier Mougeot

⇒ EC Decay Simulations

Bill Warburton
J. Harris

⇒ STJ Electronics

Cynthia Volkert
H. Hadenfeldt, J. Arlt

Jose-Paolo Santos
J. Machado, M. Guerra

⇒ Shake-up/off Simulations