The BeEST Experiment: A Search for keV-Scale Neutrinos in the EC Decay of ^{7}Be with Superconducting Quantum Sensors

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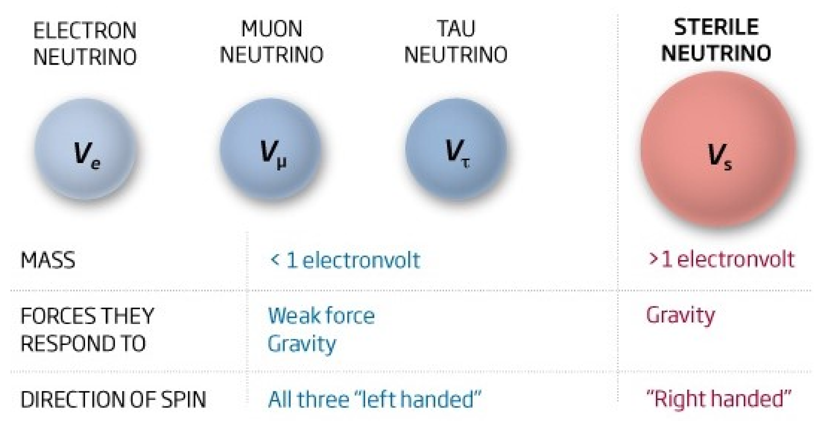
Introduction

The search for sterile neutrinos is among the brightest possibilities in our quest for understanding the microscopic nature of dark matter [1, 2]. Sterile neutrinos, unlike the active neutrinos in the Standard Model (SM), do not couple to left-handed currents in the weak interaction and are best observed via their mass–generated effects that result from momentum conservation with SM particles. This can be done through high–precision measurements of electron capture (EC) nuclear decay where the final state only contains the neutrino and a recoiling atom. This approach is a powerful, model-independent method in the search for beyond SM scenarios since it relies only on the existence of a heavy neutrino admixture to the active neutrinos, which is a generic feature of neutrino mass mechanisms, and not on the model–dependent details of their interactions. The BeEST ("beast") experiment employs the decay–momentum reconstruction technique to precisely measure the ^{7}Be→^{7}Li recoil energy spectrum in superconducting tunnel junctions (STJs).

Sterile Neutrinos on the keV Scale

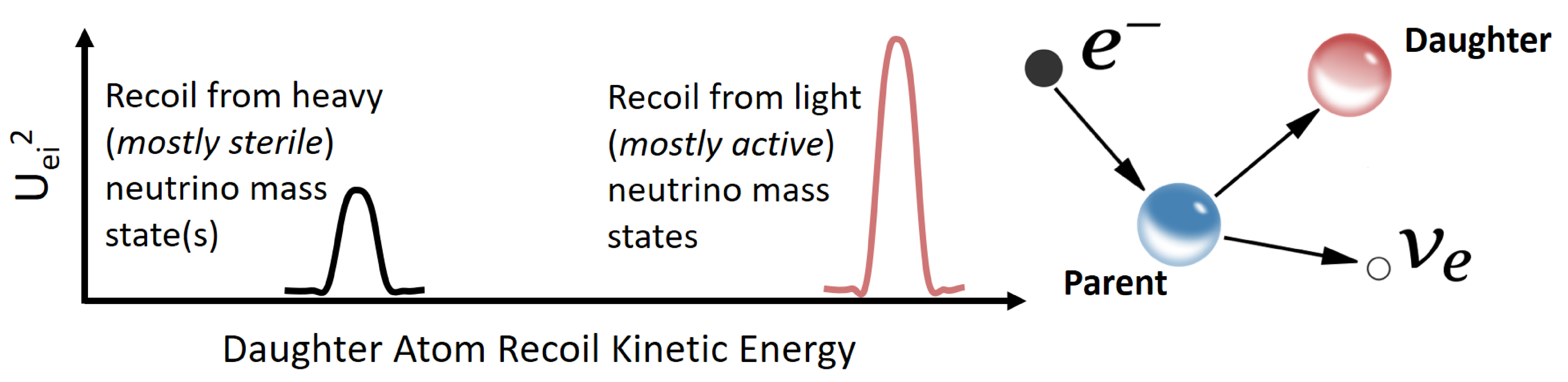
- Natural extensions to the SM that can reconcile the small "mostly active" neutrino masses by adding n RH neutrinos (νMSM and Type-I Seesaw) [3]
- Generalizes the PMNS matrix to a $(3+n)\times(3+n)$ transformation with $\nu_i \geq 4$ "mostly sterile" mass eigenstates



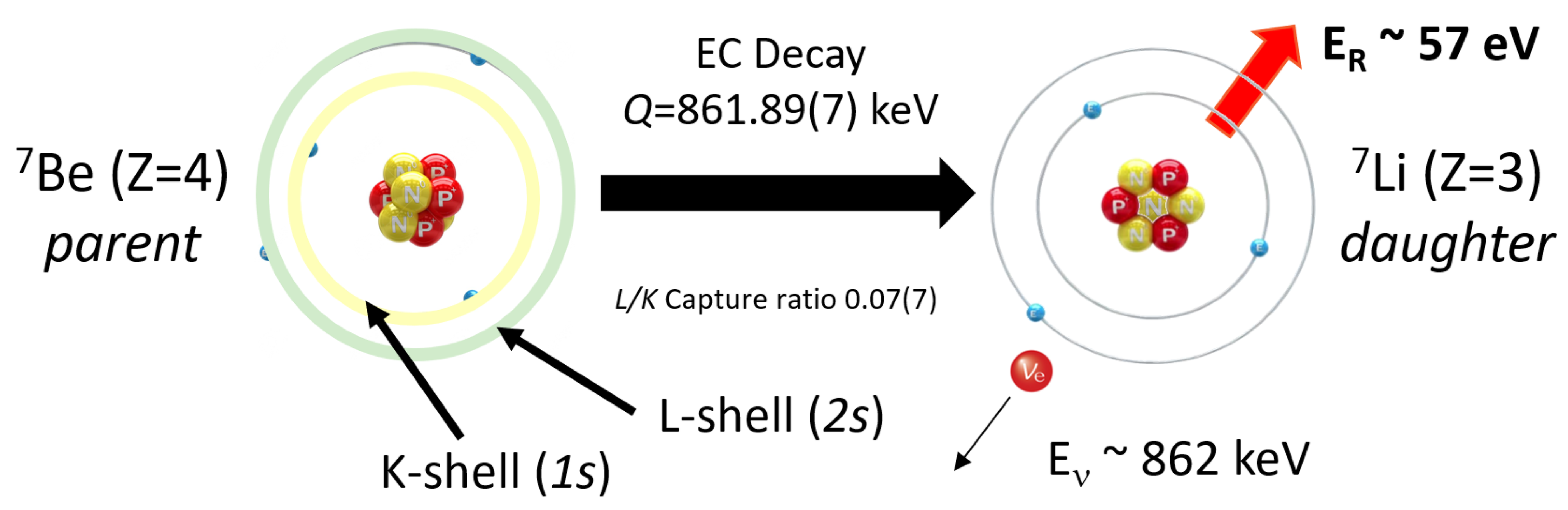
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \implies |\nu_\alpha\rangle = \sum_{i=1}^{(3+n)} U_{\alpha i}|\nu_i\rangle.$$

Decay Momentum Reconstruction as a Neutrino-Mass Probe

- The weak interaction process of orbital EC produces a two–body final state
  - Discrete kinetic energies for the emitted ν_e and daughter recoil
- Heavy neutrino admixtures to ν_e generates less energetic atomic recoil peaks.

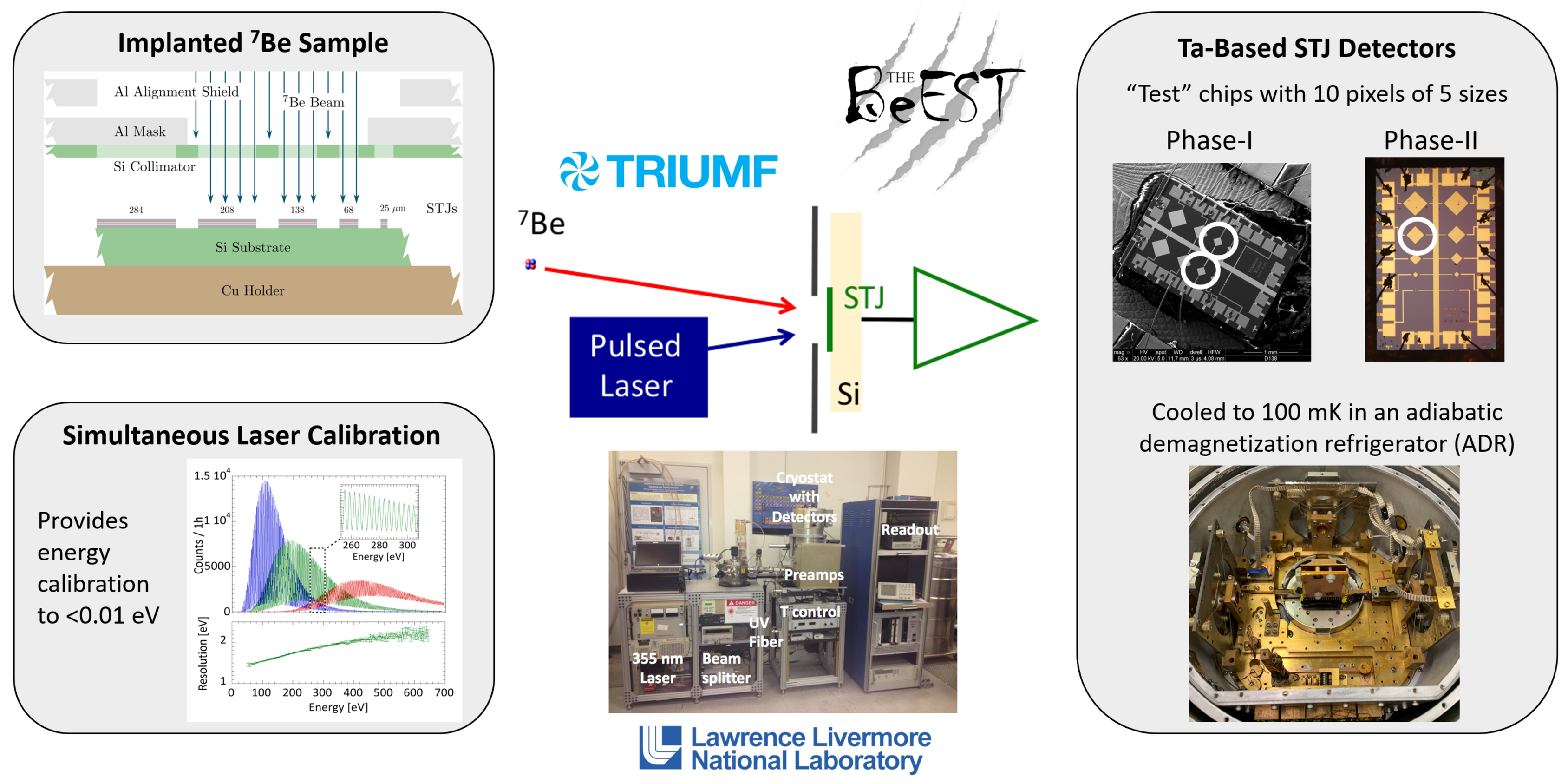


Orbital Electron Capture Decay of Beryllium-7



- ^{7}Be is the ideal system to perform these studies since it covers the widest neutrino mass range ($m_s \leq 862$ keV), and has a simple atomic ($Z=4$) and nuclear ($A=7$) structure

The BeEST Experimental Concept



Operational Principle of Superconducting Tunnel Junctions (STJs)

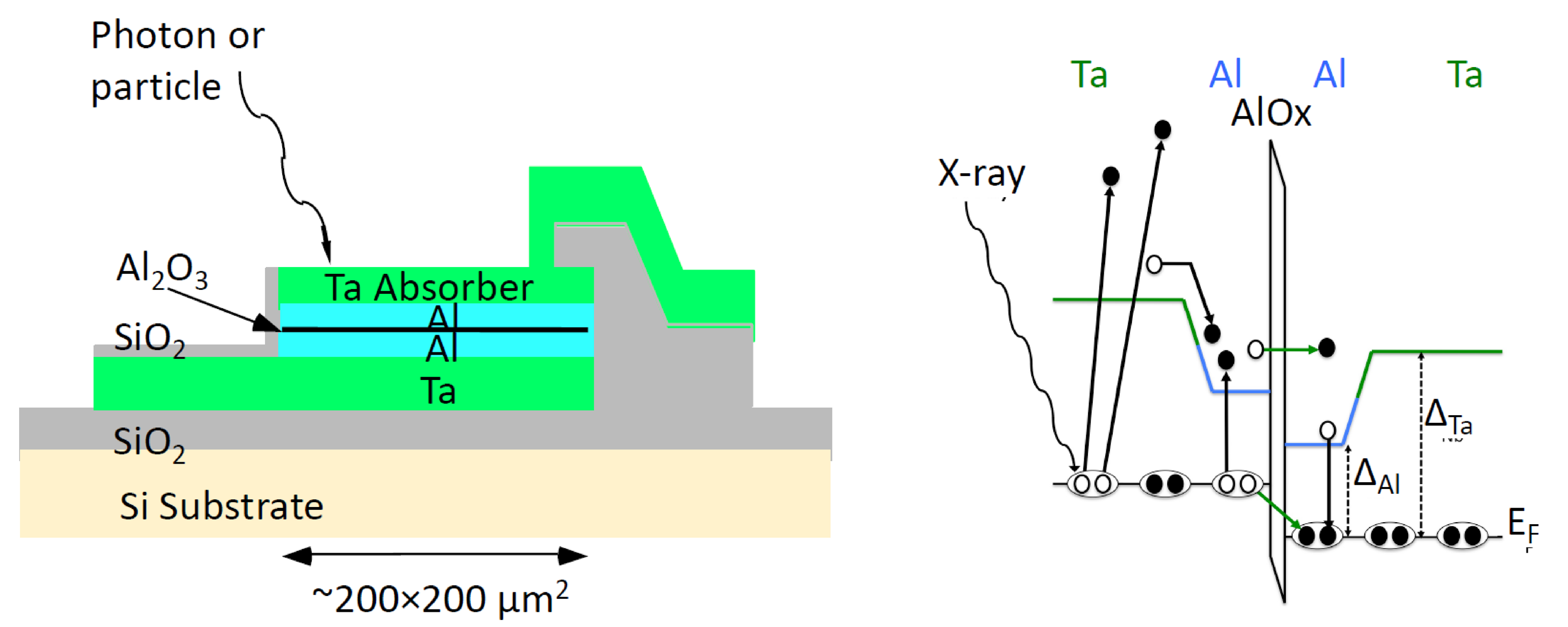
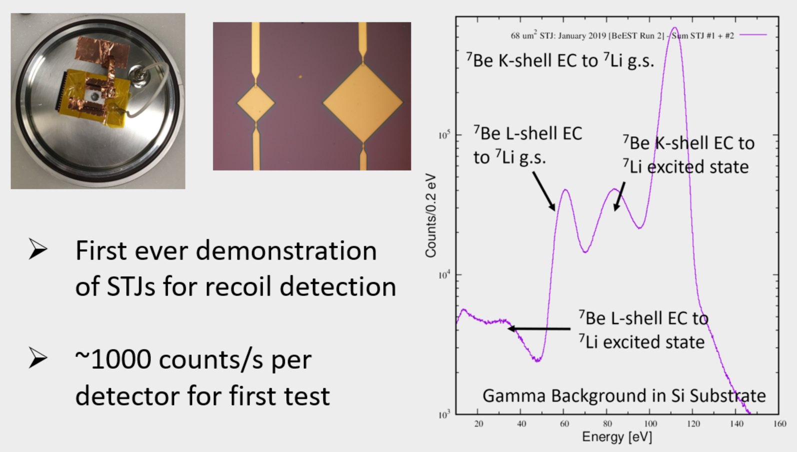


Figure 1: (left) A schematic of the Ta-based STJ detector layers [Ta (165 nm) - Al (50 nm) - Al_2O_3 (1 nm) - Al (50 nm) - Ta (265 nm)]. (right) Operational principle of STJs, where radiation breaks Cooper pairs, creates excess charge-carriers, which then tunnel across the insulating barrier generating the signal current. Present measurements are performed at $T = 0.1$ K.

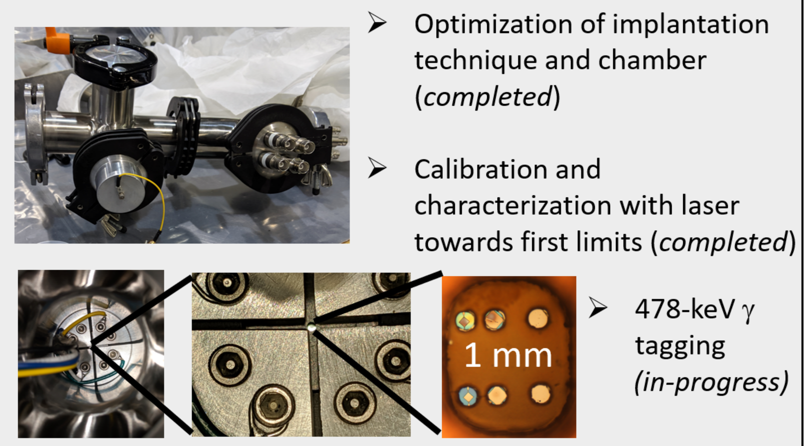
Phases of the BeEST Experiment

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



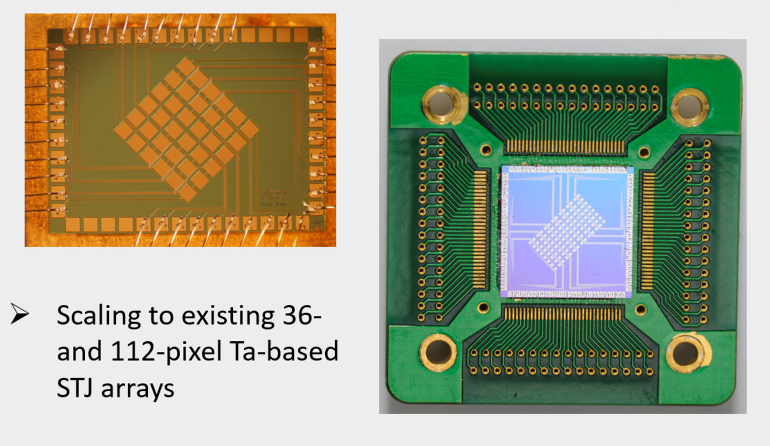
- First ever demonstration of STJs for recoil detection
- ~1000 counts/s per detector for first test

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



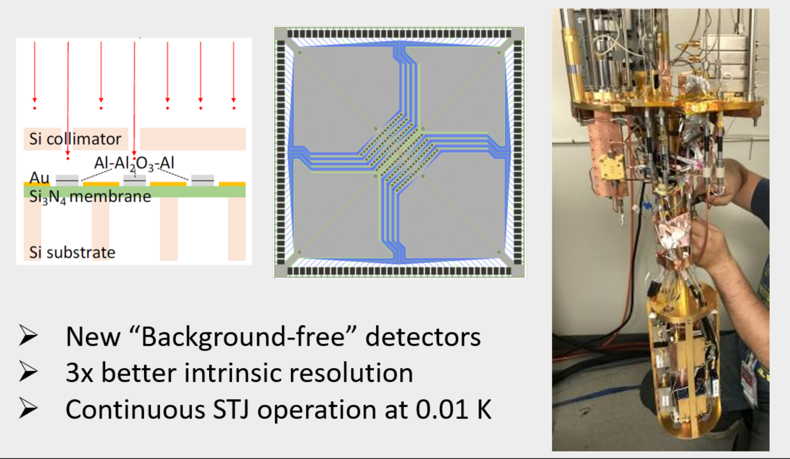
- Optimization of implantation technique and chamber (*completed*)
- Calibration and characterization with laser towards first limits (*completed*)
- 478-keV γ tagging (*in-progress*)

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

^{7}Li Recoil Energy Spectra from Calibrated Phase-II Data

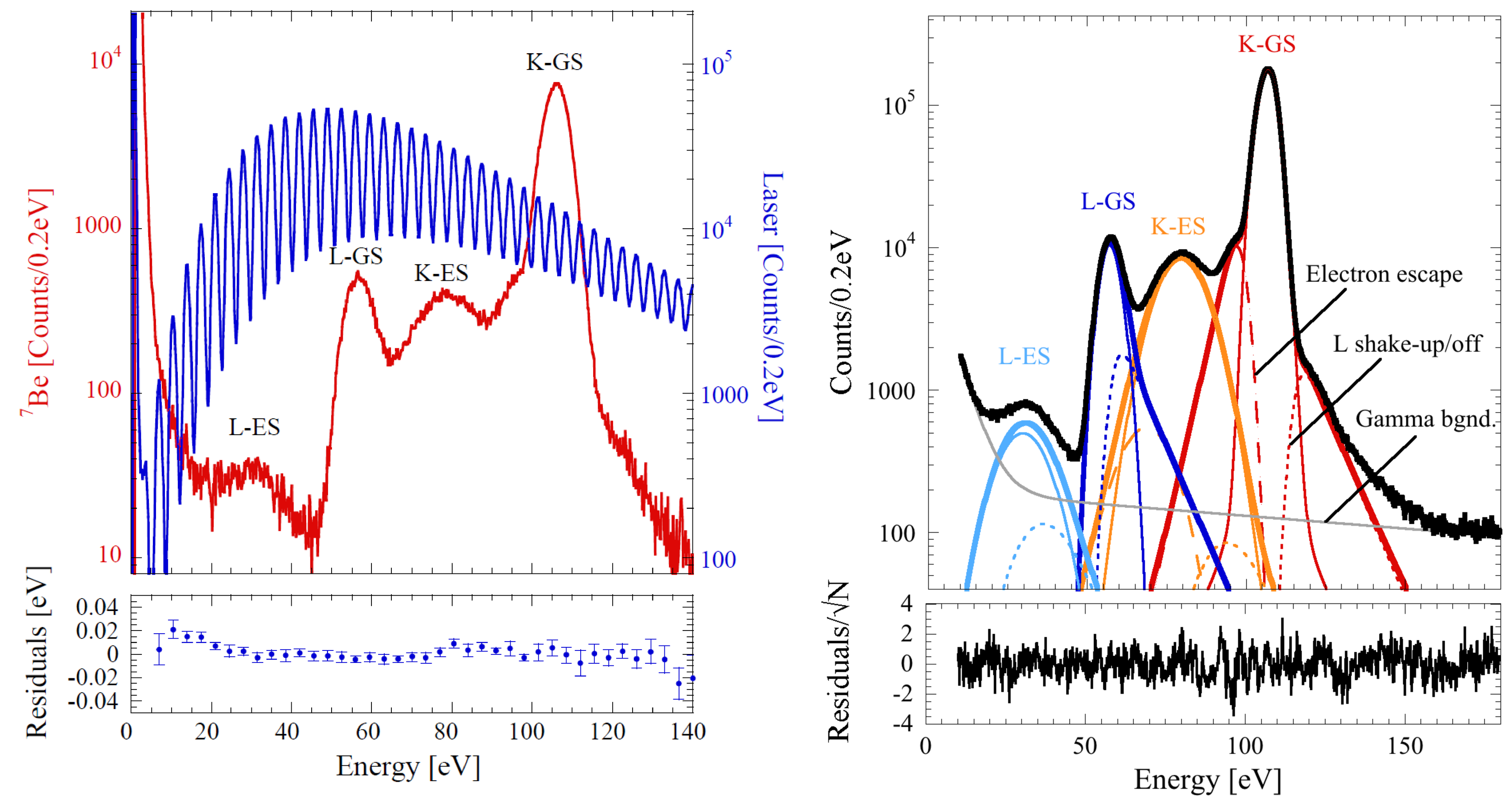
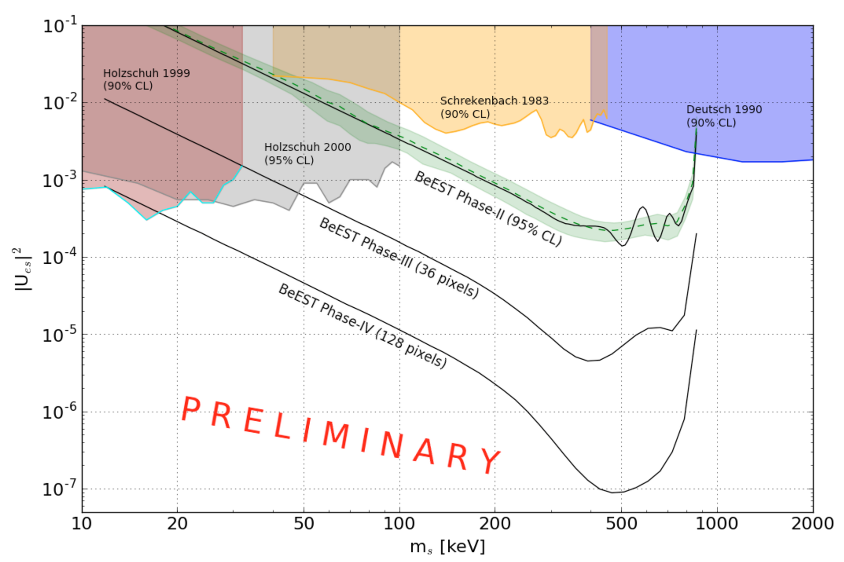


Figure 2: (left) ^{7}Li recoil energy spectrum (red) and laser calibration signal (blue) for a single 22 hour run in the "low-rate", first implantation of Phase-II. (right) Sum of all individually calibrated spectra from a single (138 μm)^2 STJ detector with a fit to all known and assumed effects in the decay ($\chi^2/\nu = 0.95$) [5].

Preliminary Limits and Outlook for the BeEST

- Preliminary "low-rate" limits from Phase-II already an order of magnitude improvement for $m_s \sim 200-800$ keV
- Ongoing quantum simulations of in-medium effects towards increased sensitivity
- Phases-III and -IV employ multi-pixel arrays and new superconducting materials
- Beyond Phase-IV is being investigated with $\geq 10^4$ pixel arrays with continuous operation



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