

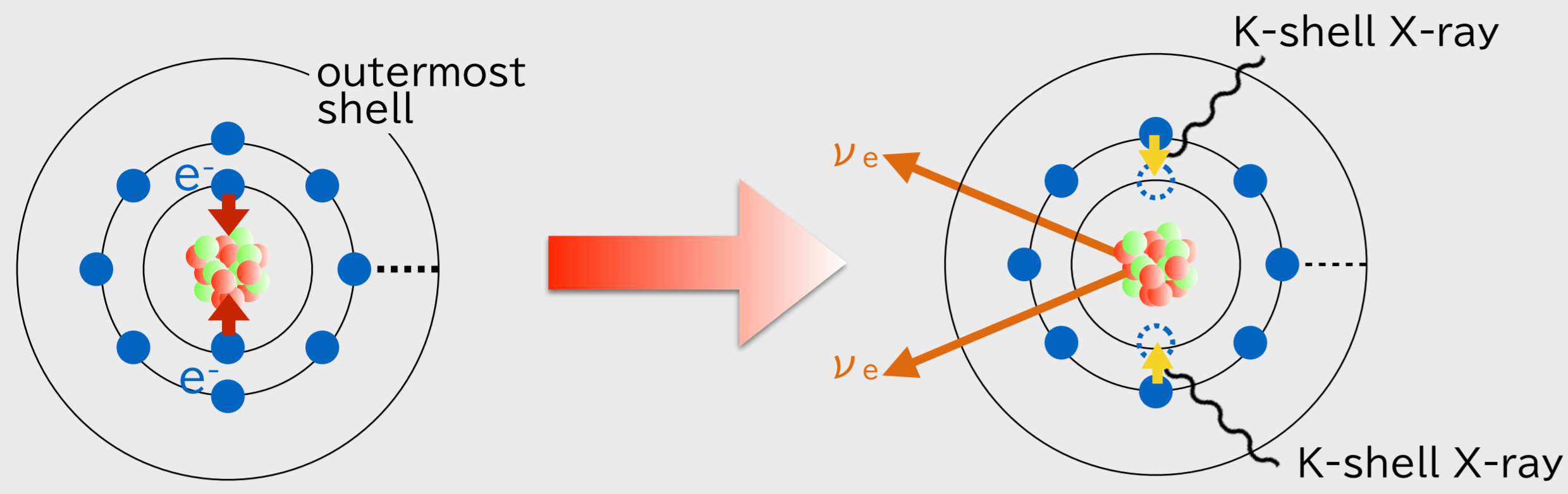
#178 Application of gamma Transition-Edge Sensor (TES) to ^{112}Sn two-neutrino double electron capture search

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I. Introduction : Double electron capture (ECEC)



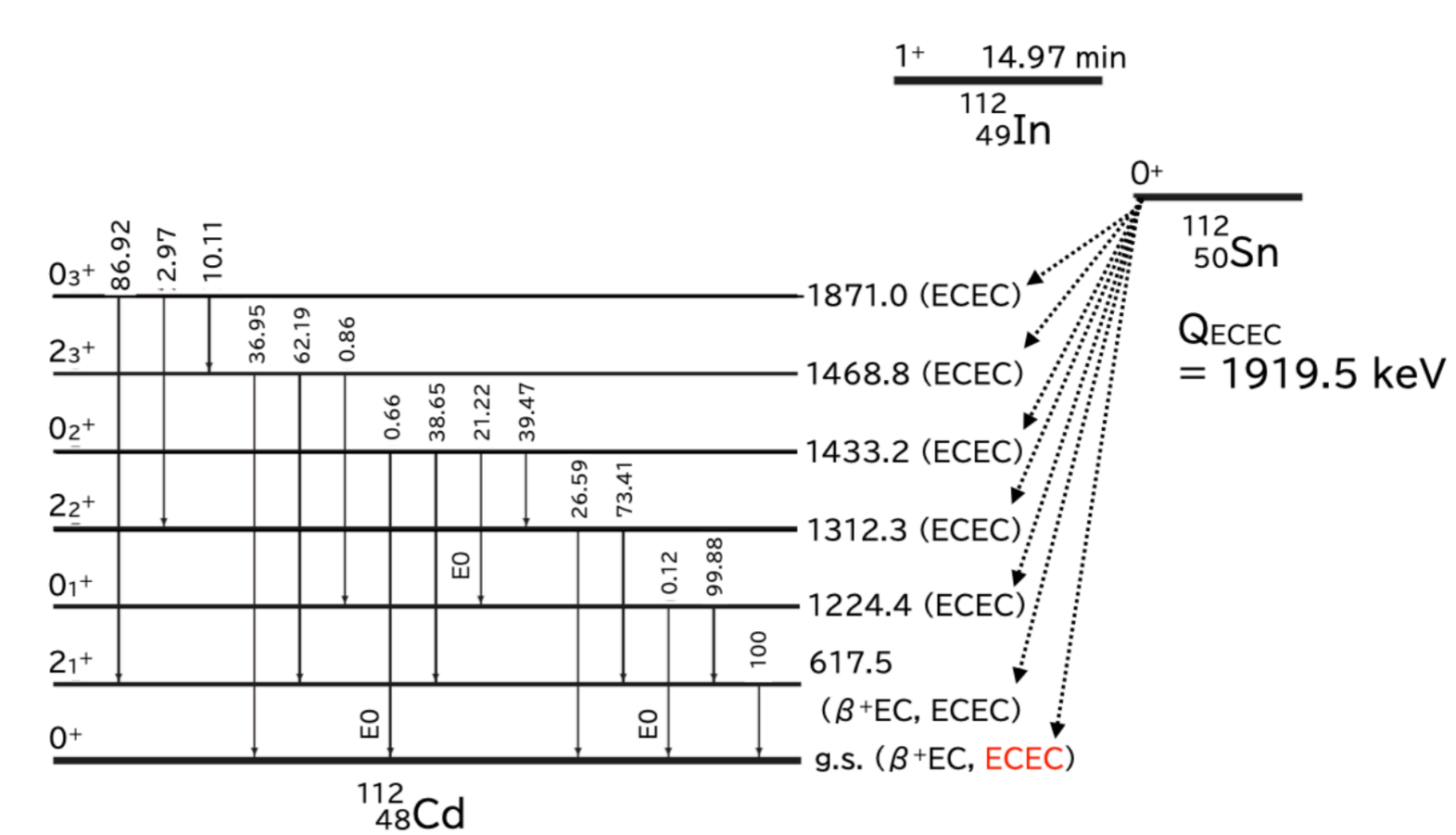
Two-neutrino two K-shell electrons capture case

- ✓ Zero-neutrino ECEC : $(A, Z) + 2e^- \rightarrow (A, Z - 2)$
 - Beyond the standard model : lepton number violation, Majorana nature of neutrino
- ✓ Two-neutrino ECEC : $(A, Z) + 2e^- \rightarrow (A, Z - 2) + 2\nu_e$
 - Rare decay, but allowed in the standard model
 - Only ^{124}Xe ECEC is observed so far ([1])
 - The observation of $2\nu\text{ECEC}$ gives some inputs for nuclear matrix element
 - **Need to observe 2 X-rays or Auger electrons.**

[1] Nature 568, 532–535 (2019)

II. Introduction : ^{112}Sn ECEC

Decay scheme of ^{112}Sn [2]



Expected half life [4]
(K-shell electrons capture case)

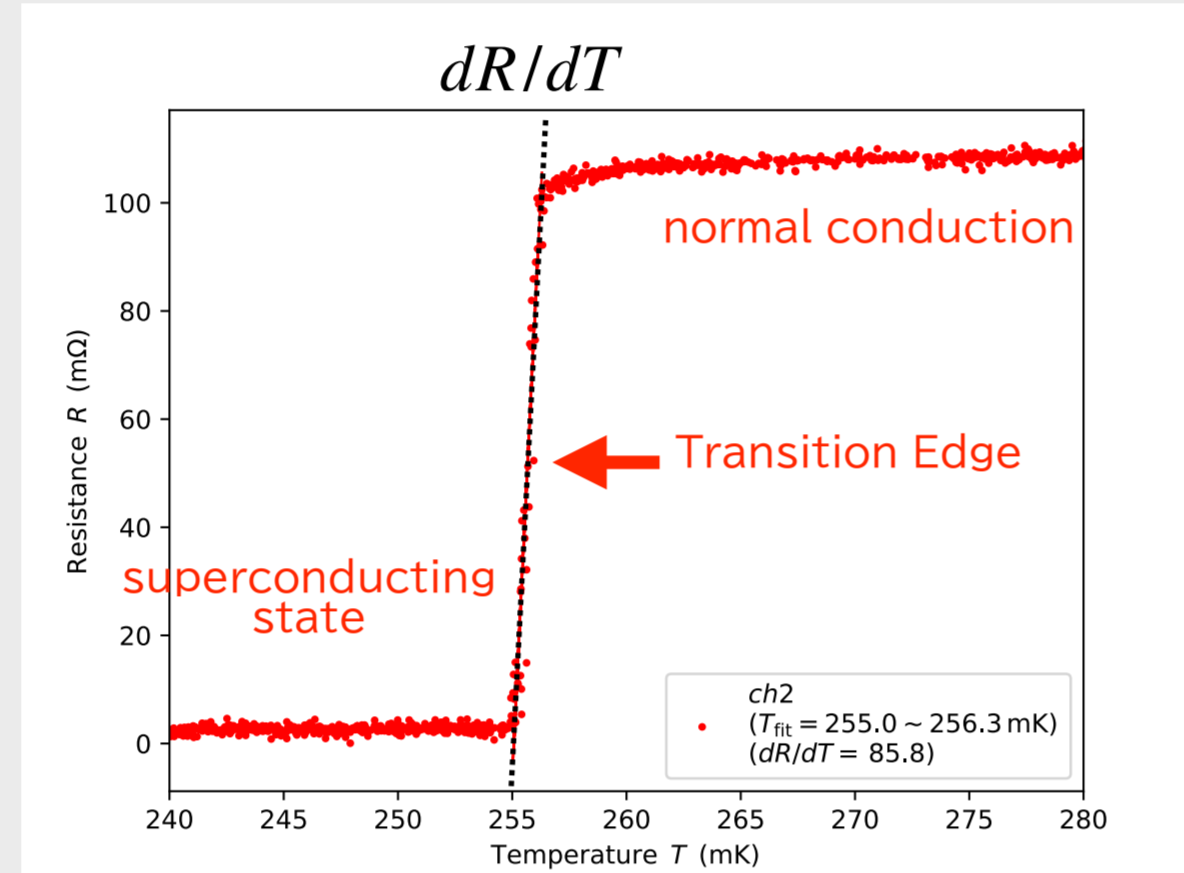
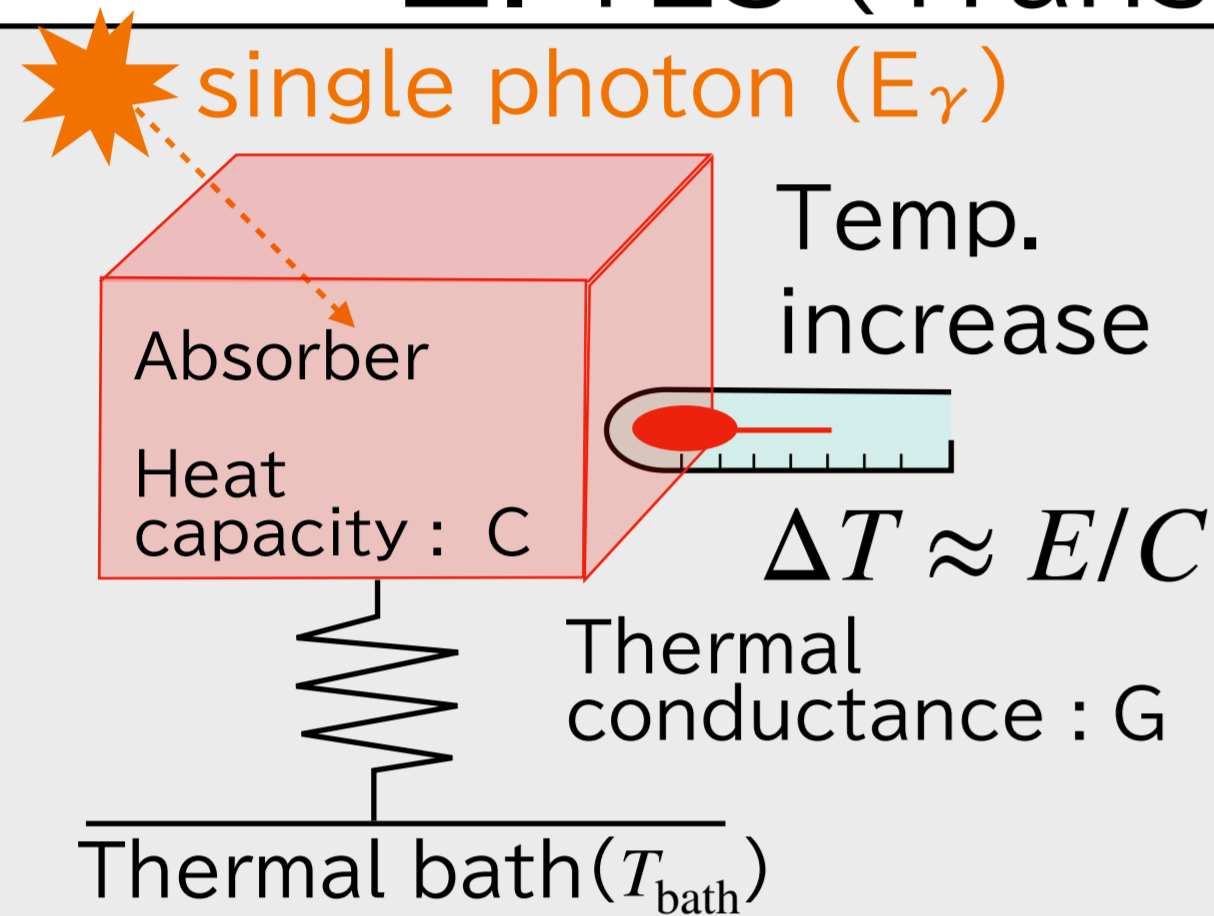
^{112}Cd energy level	$T_{1/2}(2\nu\beta^+\text{EC})$	$T_{1/2}(2\nu\text{ECEC})$
g. s.	3.8×10^{24} yr	1.7×10^{22} yr
617.5 keV	2.3×10^{32} yr	4.9×10^{28} yr
1224.4 keV	—	7.4×10^{24} yr
1312.3 keV	—	1.9×10^{32} yr
1468.8 keV	—	6.2×10^{31} yr
1871.0 keV	—	5.4×10^{34} yr

- ✓ $^{112}\text{Sn} (\text{g. s.}, 0^+) + 2e^- \rightarrow ^{112}\text{Cd} (\text{g. s.}, 0^+) + (2\nu_e) + 1.919 \text{ MeV}$
- ✓ Current experimental search : enriched sample (disk shape) + HPGe [2,3]
 - Sensitive to de-excitation γ , annihilation γ from β^+
 - Not sensitive to $2\nu\text{ECEC}$ to g.s. (shortest half life mode in ^{112}Sn decay)[4]
 - Due to X-ray absorption in sample

✓ **We propose new method to search for $2\nu\text{ECEC}$ to g.s. decay mode**

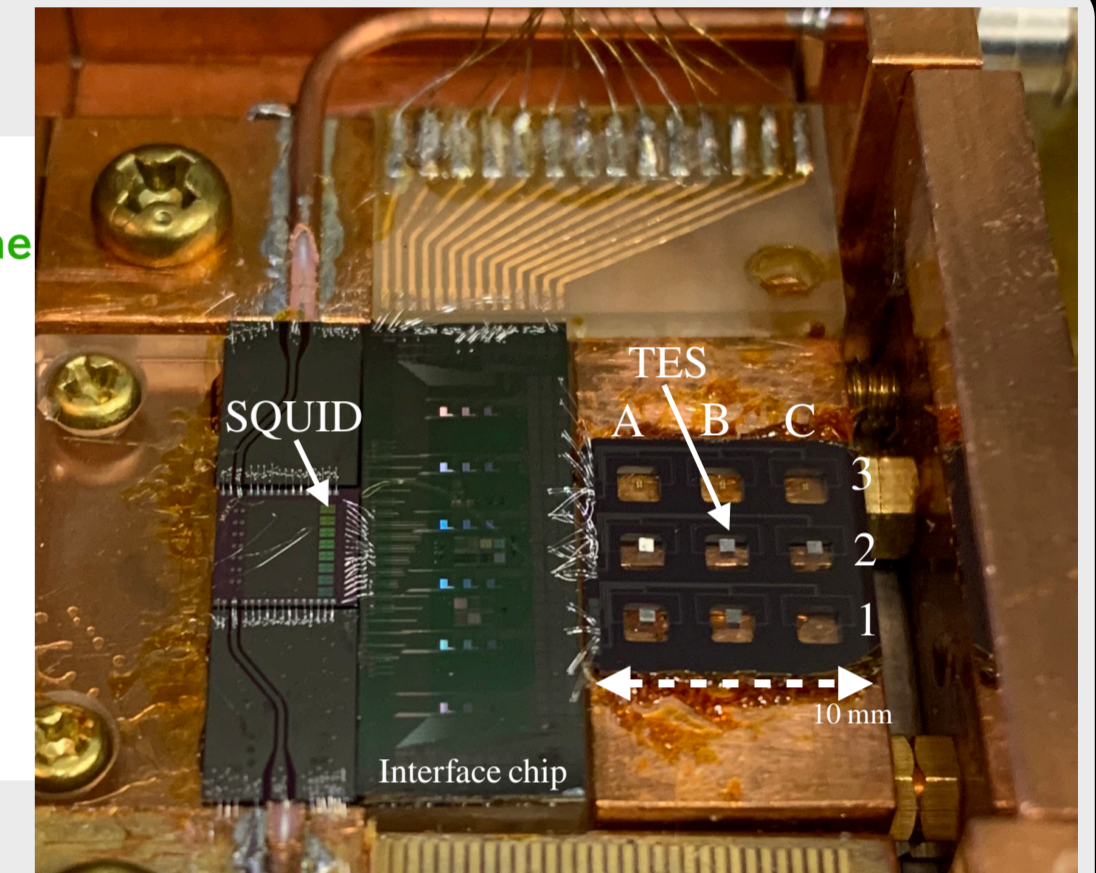
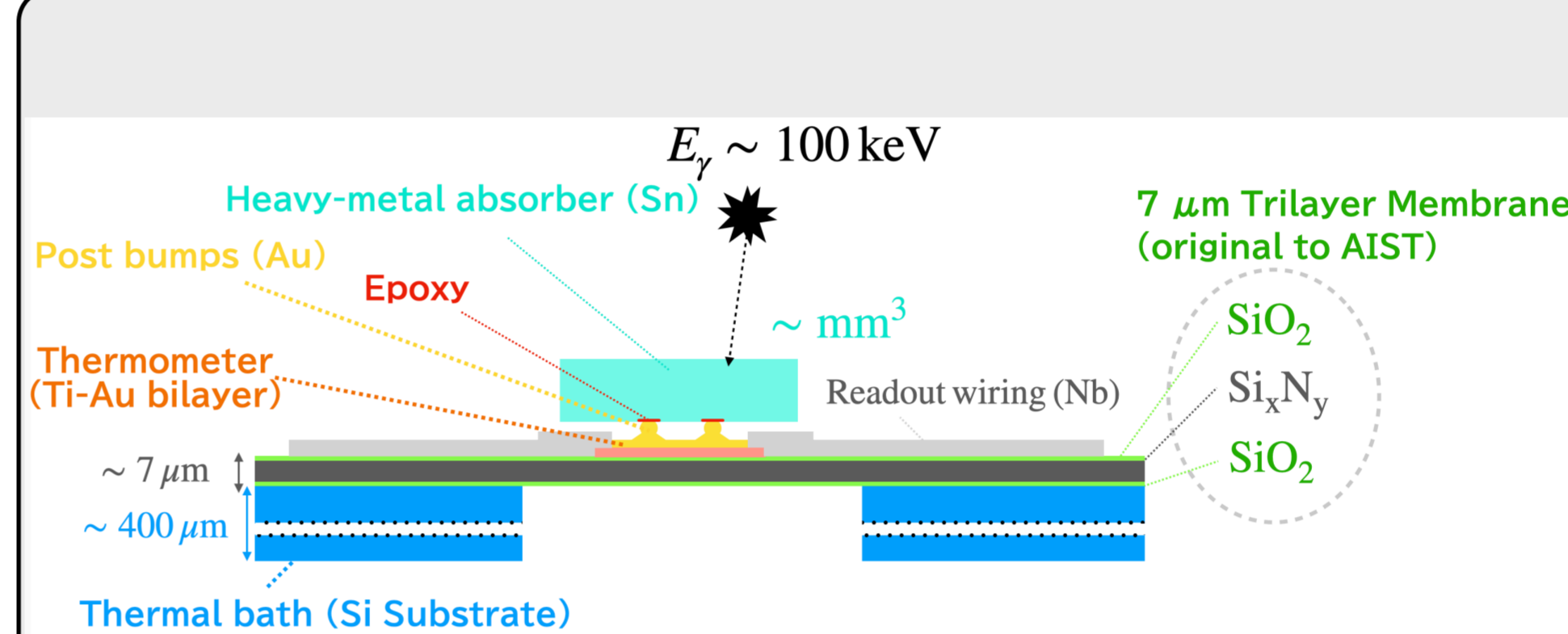
[2] Phys. Rev. C 80, 035501 (2009), [3] Phys. Rev. C 78, 035504 (2008), [4] Nucl. Phys. A 753 (2005) 337–363

III. TES (Transition-Edge Sensor)



- ✓ One of the superconducting detectors (SNSPD, MKID, MMC, STJ, etc.)
- ✓ $\gamma\text{-TES}$ calorimeter : detects individual photons, converts their energy into heat
 - Small temperature rise \rightarrow large resistance change
 - Relatively fast pulse ($T_{\text{fall}} : \text{O}(\text{msec})$)
- ✓ **Ultra high energy resolution : $\times 20$ better than semiconductor detector**
- ✓ Application of $\gamma\text{-TES}$:
 - Measurement of isotopic composition of nuclear materials
 - Monitoring transuranic radionuclides inside the human body
 - **Rare event search (source = absorber)**
 - High detection efficiency with high energy resolution

IV. AIST $\gamma\text{-TES}$ with Sn absorber

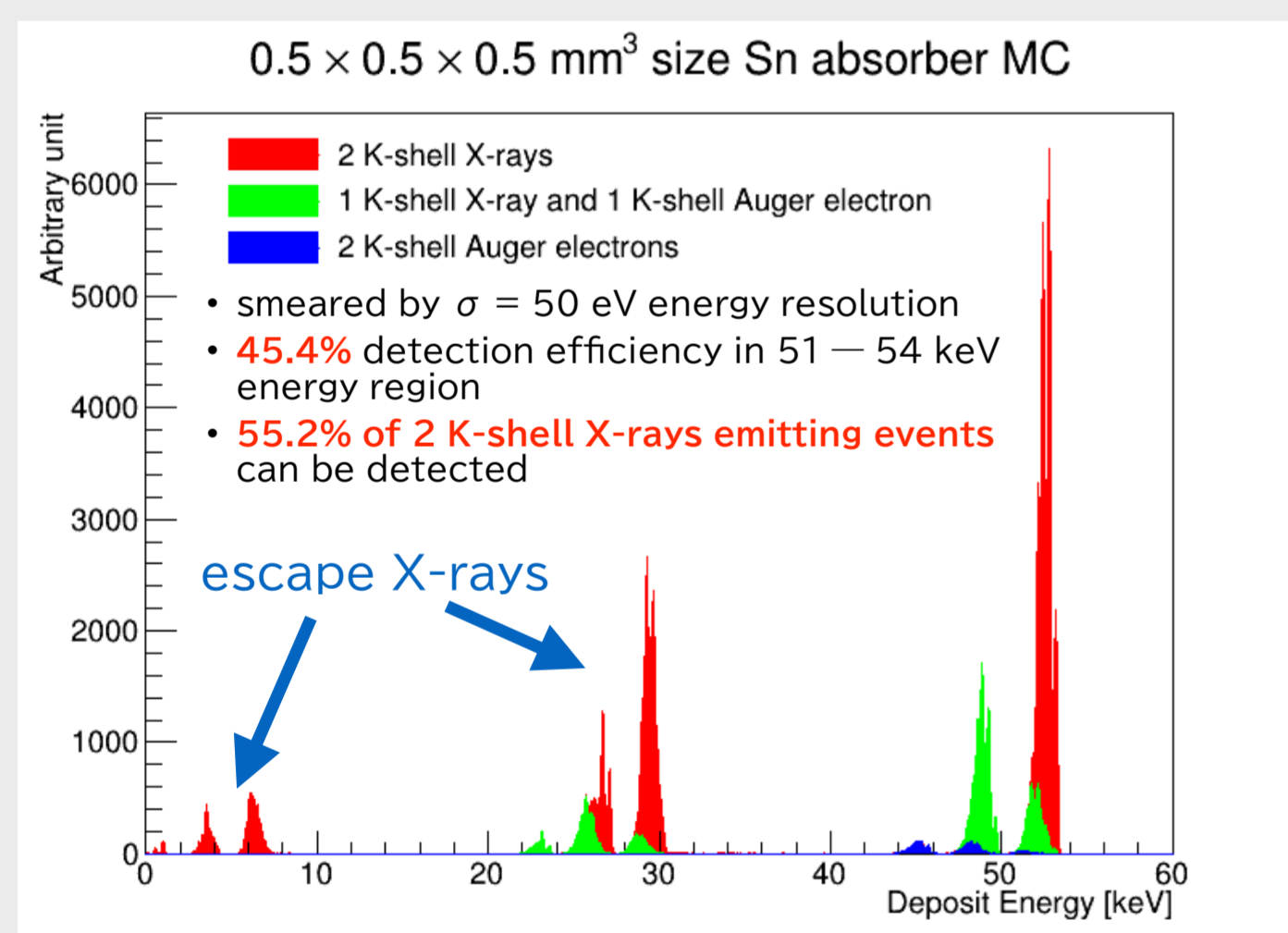


- ✓ Four ($0.5 \times 0.5 \times 0.5 \text{ mm}^3$) pixels Sn absorber
 - A2, B1, B2, C2 pixel
- ✓ Demonstrates good $^{237}\text{Np}/^{233}\text{Pa}$ γ separation with $\text{O}(40 \text{ eV})$ FWHM [5]
- ✓ **Trilayer membrane structure : unique development by AIST**
 - **7 um thickness** : suitable for heavy/large size absorber
 - Conventional SiN membrane : **1 um thickness**

➔ **In this work, 90 hr, 4 pixels ^{237}Np calibration source data is used for $2\nu\text{ECEC}$ to g.s. analysis**

[5] T. Kikuchi et al., J. Low. Temp. Phys. 211, 207–213 (2023)

V. Signal simulation

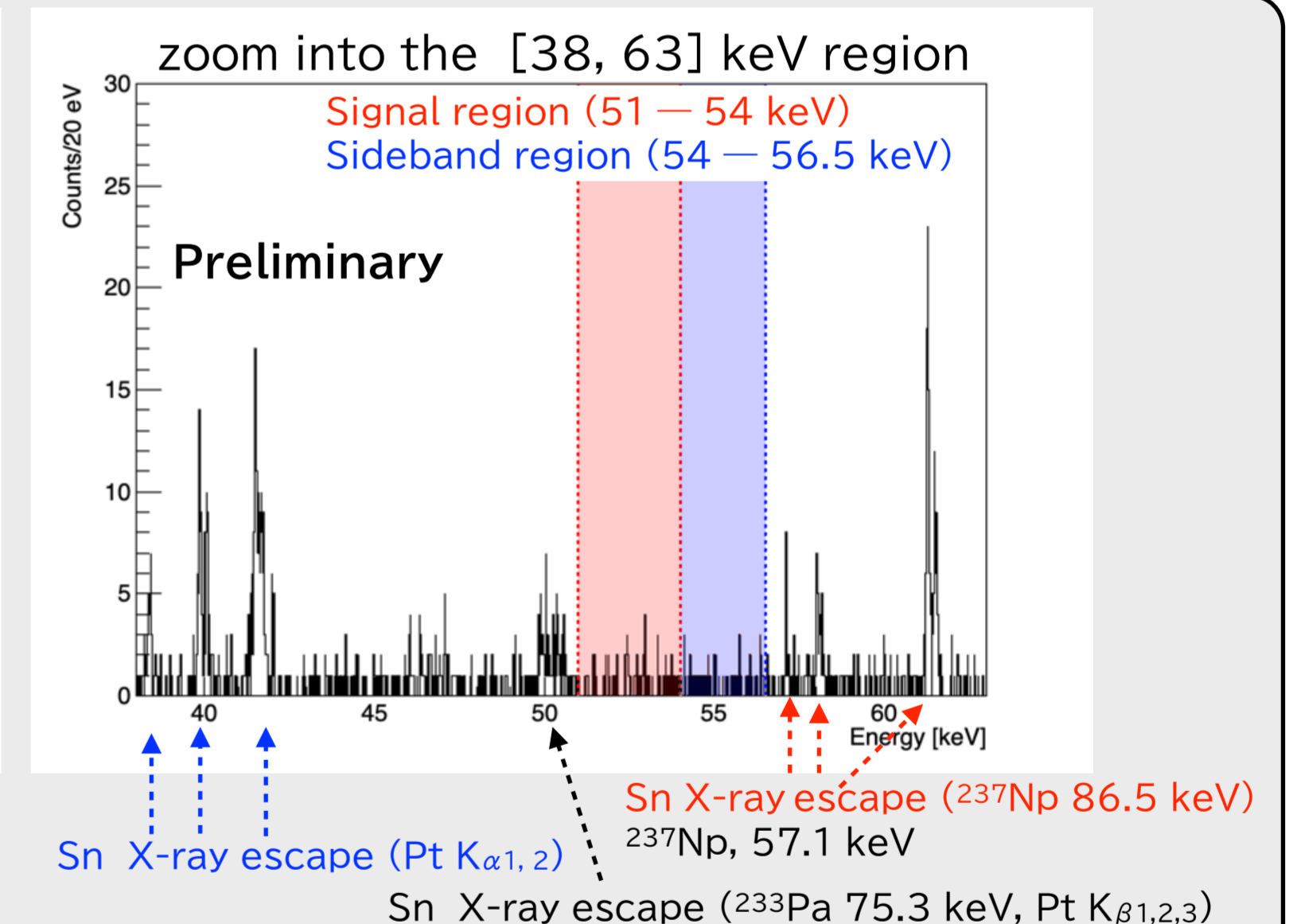
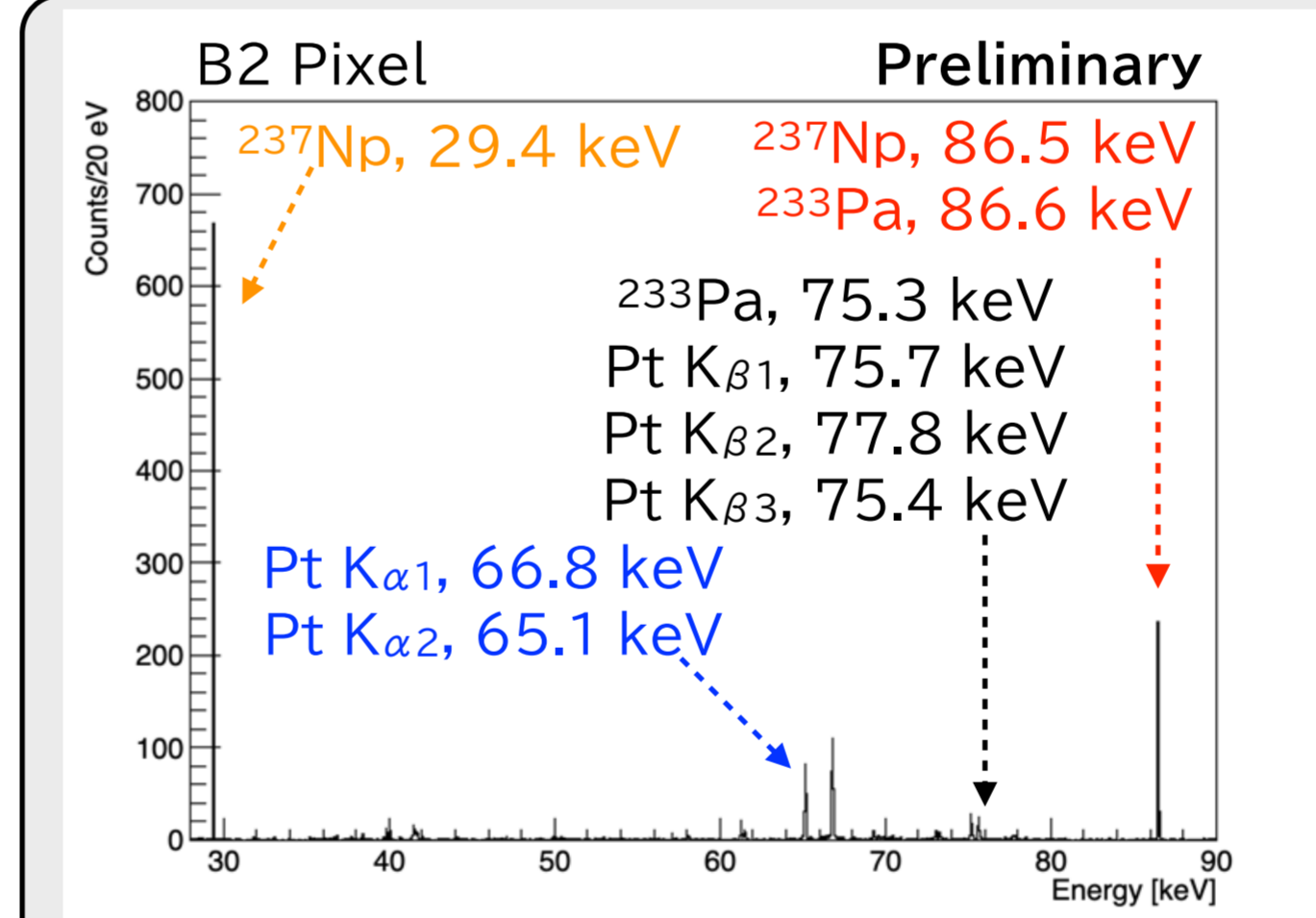


Absorber size	Detection efficiency (ROI : 51 – 54 keV)
$(0.5)^3 \text{ mm}^3$	45.4%
$(0.8)^3 \text{ mm}^3$	55.8%
$(1.0)^3 \text{ mm}^3$	59.9%
$(2.0)^3 \text{ mm}^3$	69.1%

- ✓ MC based on the atomic relaxation package in Geant4
- ✓ Signal MC : two Cd atoms with a single K-shell vacancy, uniformly generated in the Sn absorber
 - $2 \times \text{Cd K-shell binding energy} = 53.42 \text{ keV}$
 - **53.74 keV** after considering energy correction
 - The difference in the binding E of all electrons of the parent/daughter nuclei
 - The relative capture ratio of two K-shell vacancy :
 - **70.9%** (considering K and L1 shell), **73.4%** (up to N5 shell) (following [6])

[6] Phys. Rev. C 106, 024328 (2022)

VI. Analysis

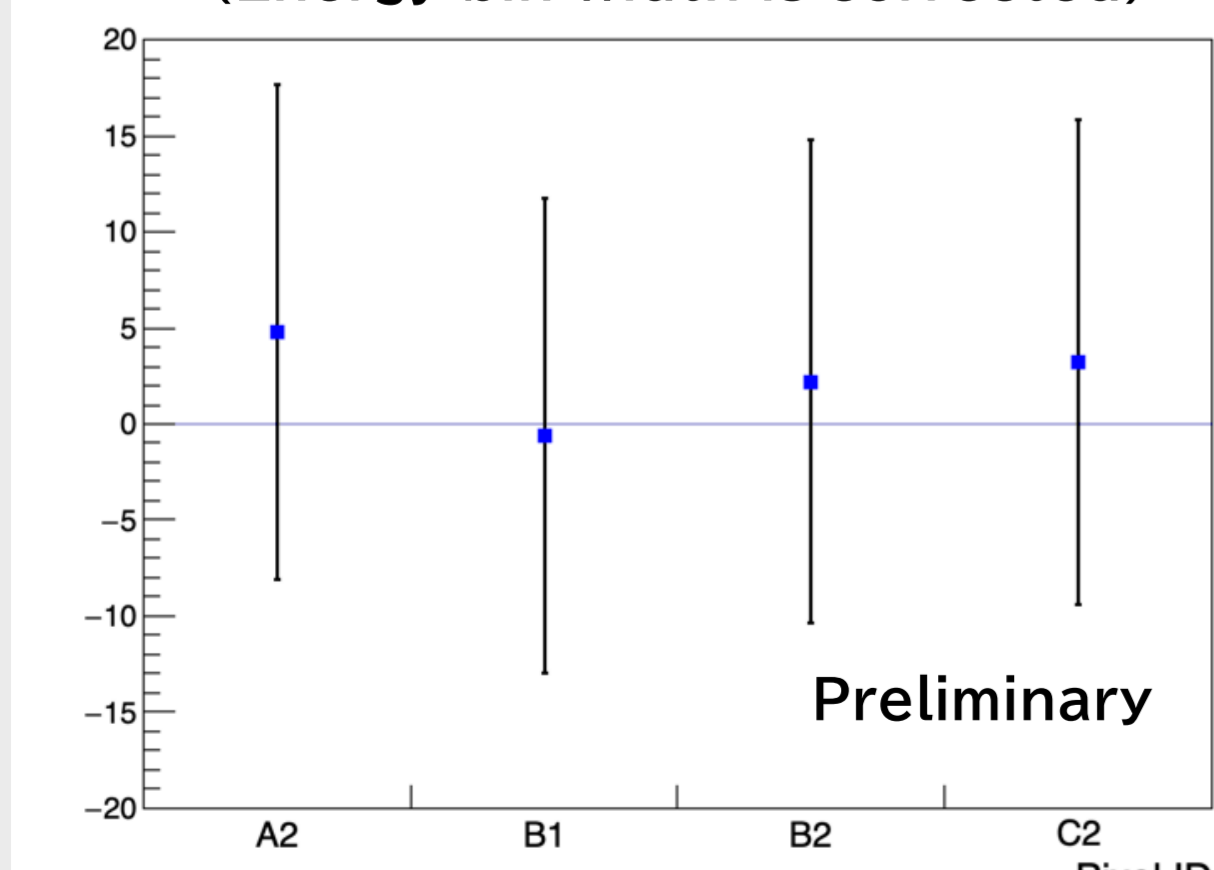


- ✓ Analyzed ^{237}Np source data used in Ref. [5]
 - 4 pixels, 90 hours data (in Ref. [5], 4 pixels, 60 hours data)
 - Clearly observed ^{237}Np γ , ^{233}Pa γ and Pt-Xray (it wraps and protects the ^{237}Np source)
- ✓ Assume flat BG in signal region and sideband region
 - Continuum component : Compton scattering of high E γ from source and environmental, minimum ionization of cosmic μ
- ✓ Count rate of signal region subtracted by the sideband region is used for this analysis

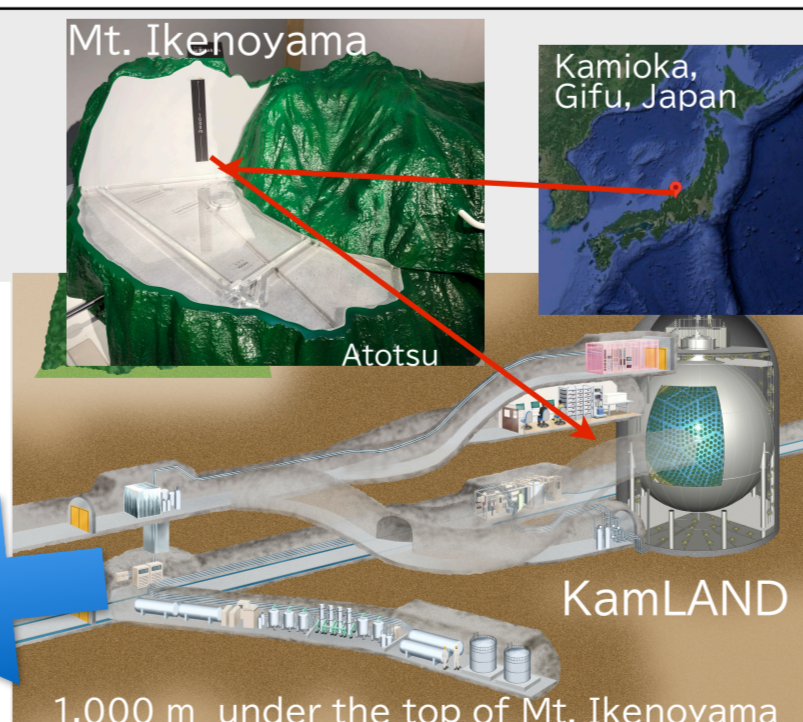
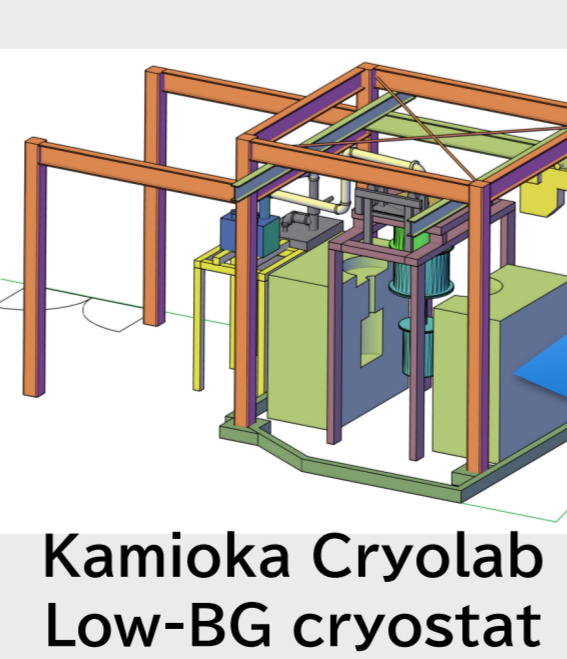
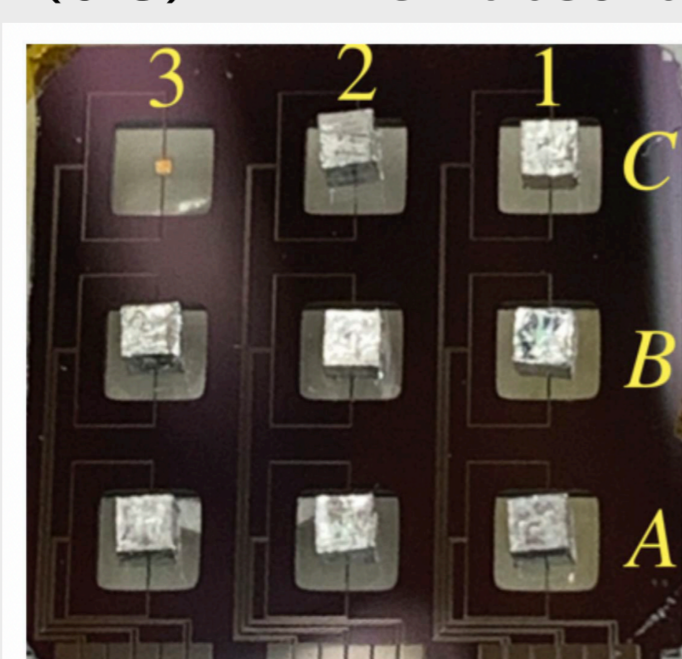
Energy info : taken from ENSDF database and table of isotopes

VII. Preliminary result and future prospect

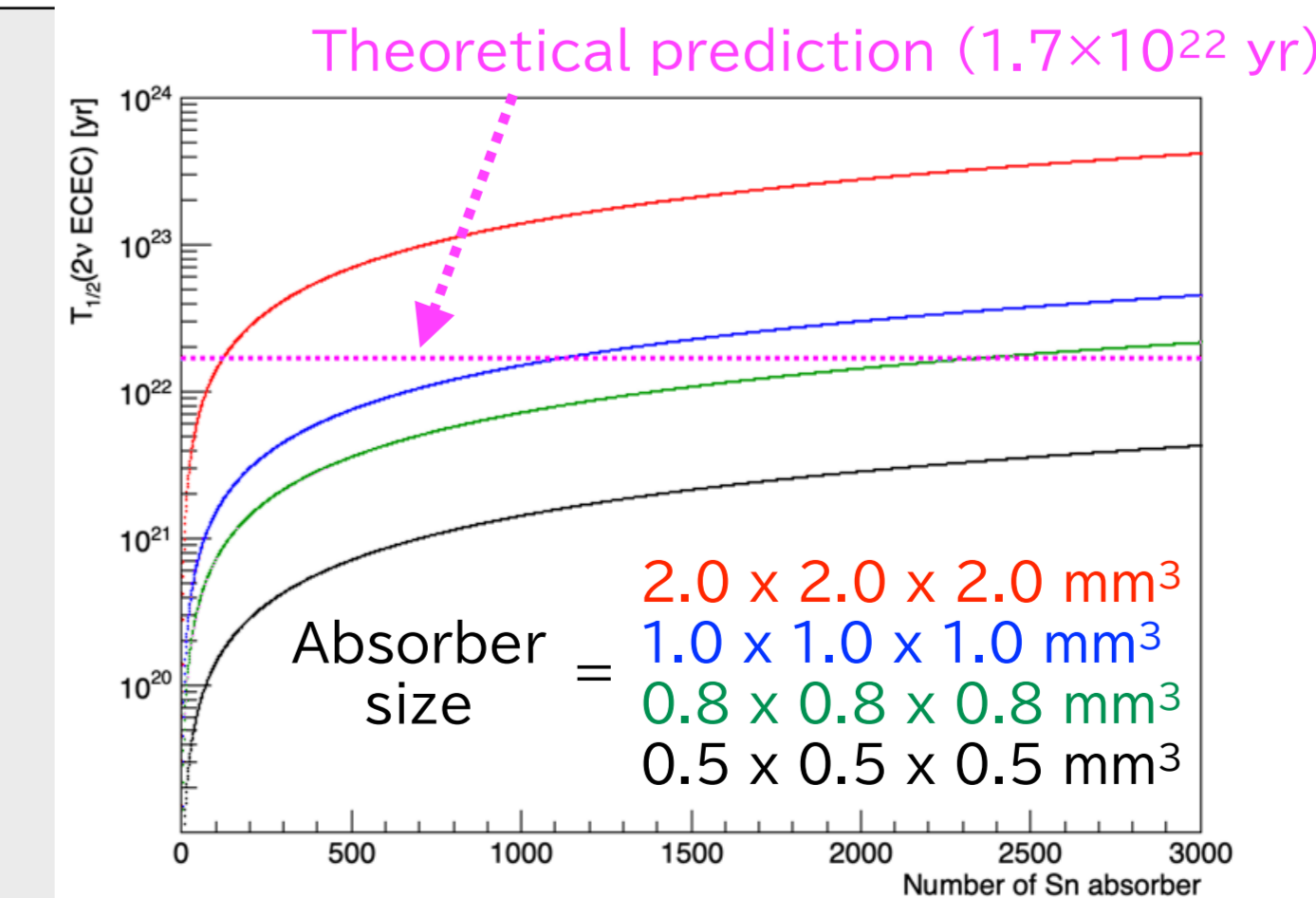
Count in Signal region - Sideband region
(Energy bin width is corrected)



8 pixel
 $(0.8)^3 \text{ mm}^3$ Sn absorber



- ✓ **Take 8 pixel data w/o ^{237}Np source in this year**
 - **$0.8 \times 0.8 \times 0.8 \text{ mm}^3$ size Sn absorber**
 - **Eventually take data with many pixels in Kamioka Cryolab**
 - **$\text{O}(10^5) \mu$ flux reduction**
 - **γ , neutron shield**
 - **Low BG cryostat**



- ✓ Optimistic assumption :
 - No events in ROI for all pixels (< 2.3 counts @ 90% C. L.)
 - 100% ^{112}Sn enrichment absorber
 - (n. a. = 0.97%) : 94.32% [2], 99.5% [3] enrichment is achieved
 - 3 year data taking
- ➔ **Could reach the theoretical prediction**

**AIST's thick membrane structure
 \rightarrow Suitable for this search**