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Search for Double Electron Capture in Sn-112 using gamma-ray TES

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Motivation

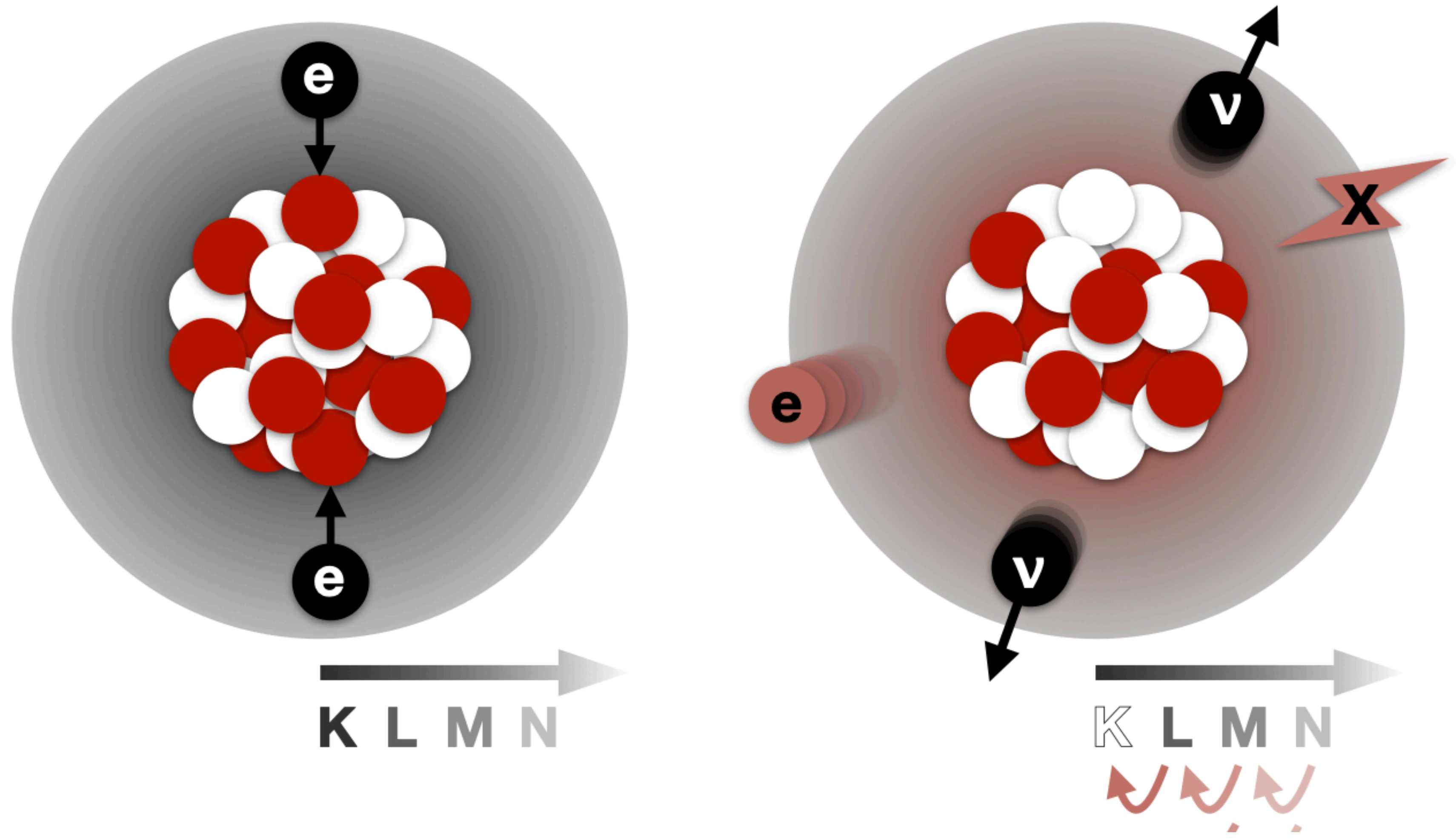
Double Electron Capture

[1]Nature, 568 25 (2019)

Double Electron Capture (ECEC)

- (A, Z) + 2e⁻ → (A, Z-2) + 2ν_e (+X-rays, Auger electrons, *O*(10 keV))
    - 34 nuclei are known to be candidates for ECEC.
    - Direct observation : Only in ^{124}Xe ($T_{1/2}=1.8\times10^{22}$ year)[1]

    → Observation of 2*ν*ECEC would provide valuable information



- If neutrino is Majorana particle, 0*ν*ECEC is also allowed : (A, Z) + 2e⁻ → (A, Z-2)

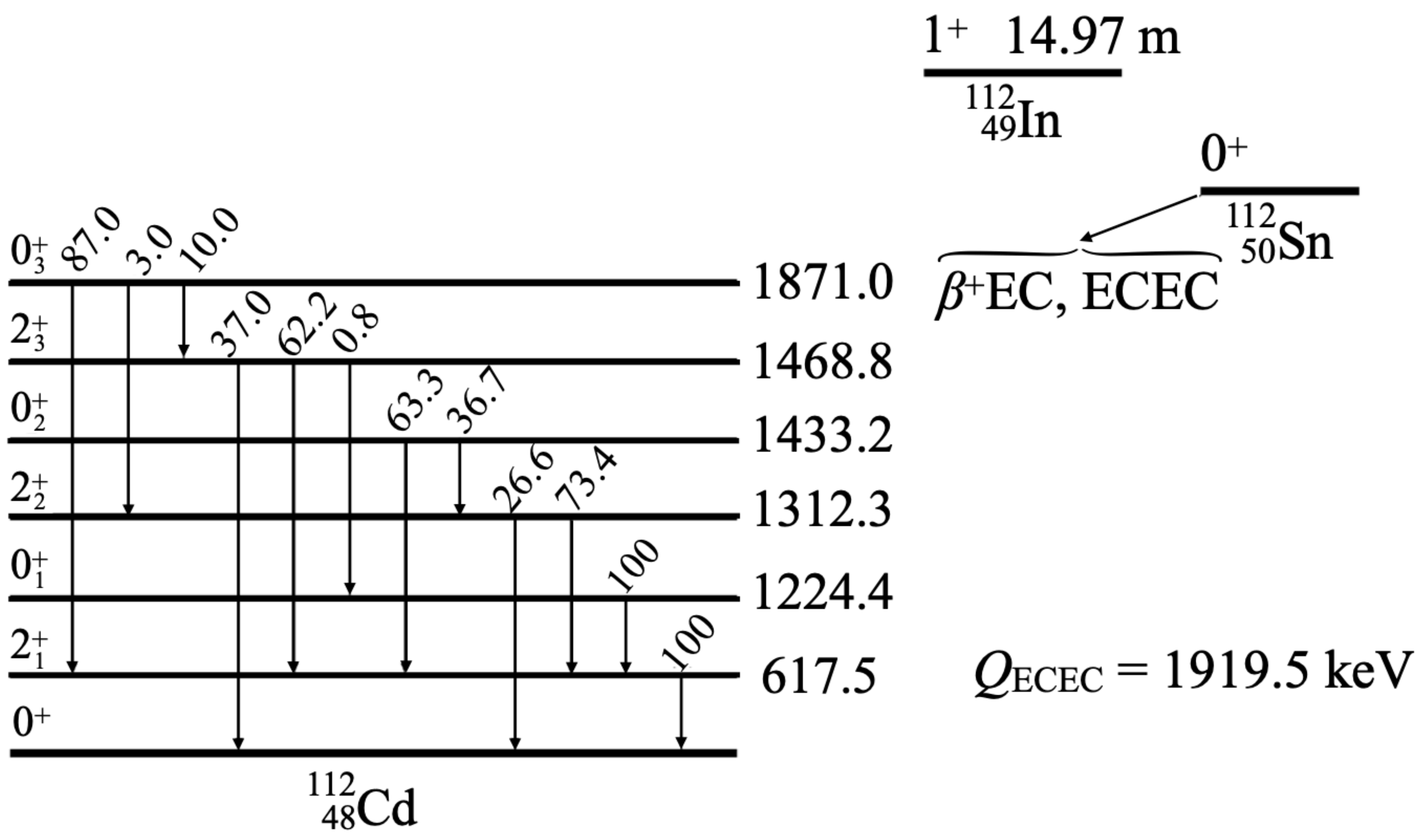
→ Can be an access to physics BSM.

Double Electron Capture in ^{112}Sn

^{112}Sn : Stable isotope of tin with the natural abundance of 0.0097

- Decay to ^{112}Cd with ECEC or β+EC (Q=1.92 MeV)
- Previous study : Searched for γ-rays from de-excitation of ^{112}Cd w/ HPGe detector[2]
  - Longer half-lives than decay to the ground state
  - Low signal efficiency : typically a few percents, at highest 13.6%

We use gamma-ray TES to overcome these difficulties.



States of ^{112}Cd	Half-lives (Theory) [yr]
g.s.	1.7×10^{22}
0_1^+	7.4×10^{24}
2_1^+	4.9×10^{28}
2_2^+	1.9×10^{32}

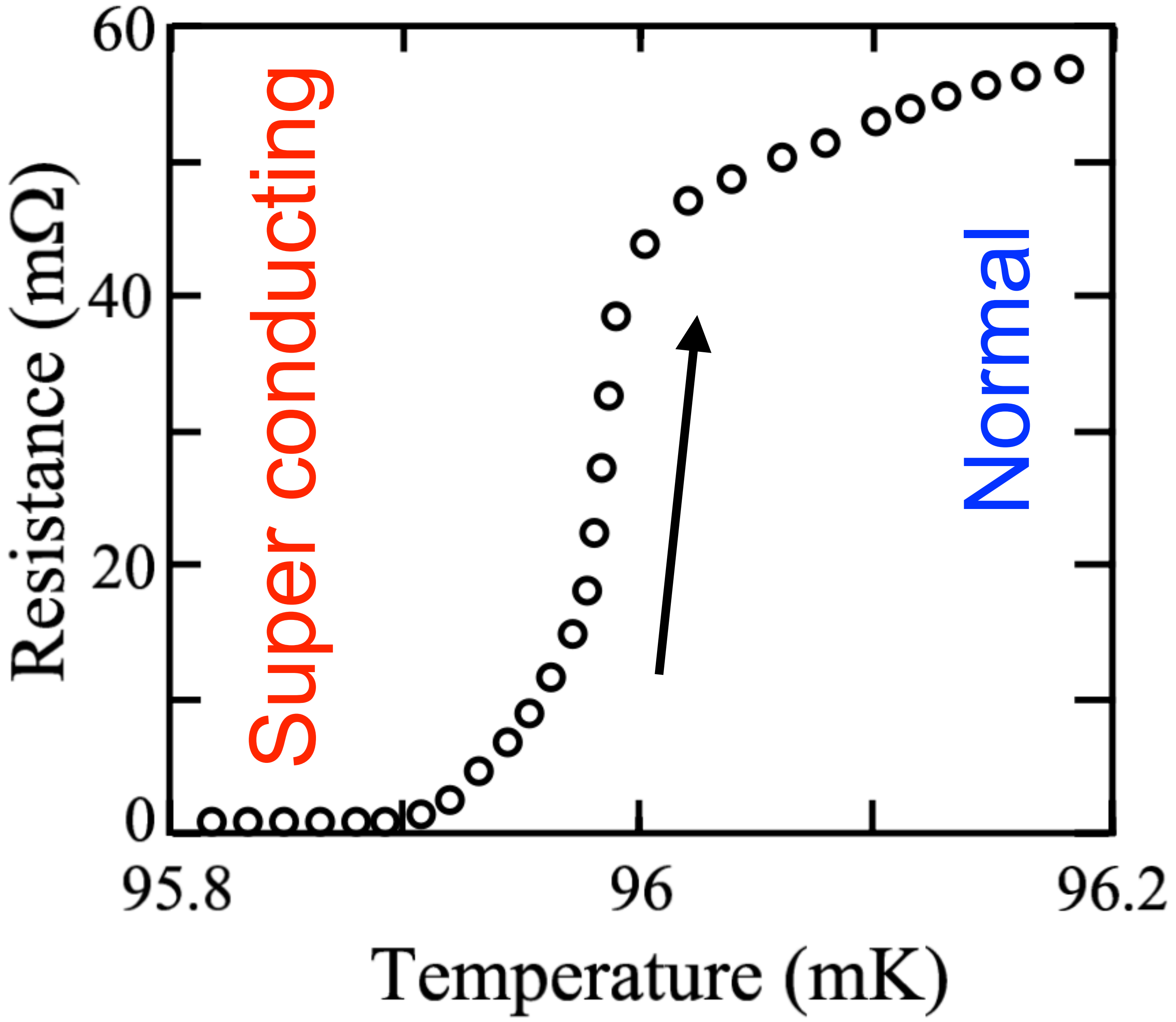
[2]Phys.Rev.C 83, 045503 (2011)

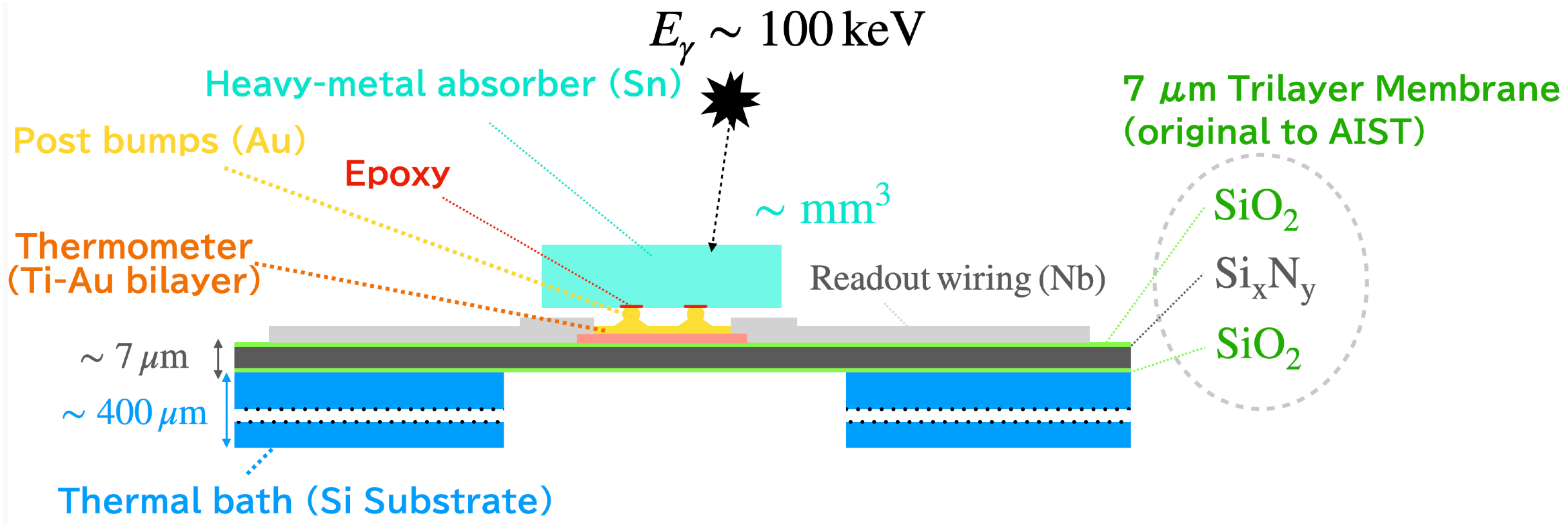
What is gamma-ray TES?

Gamma-ray TES :

- TES specialized in gamma-ray spectroscopy
  - TES + heavy-metal made absorber
- gamma-ray TES developed at AIST* : 8-pixels TES array with $^{nat.}$Sn energy absorber (Absorber size : 0.8 mm, 3.7×10^{-3} g/pixel $^{nat.}$Sn)

Resistance v.s. temperature (Mo/Cu) [3]





[3]Topics Appl. Phys. 99, 63-149 (2005)

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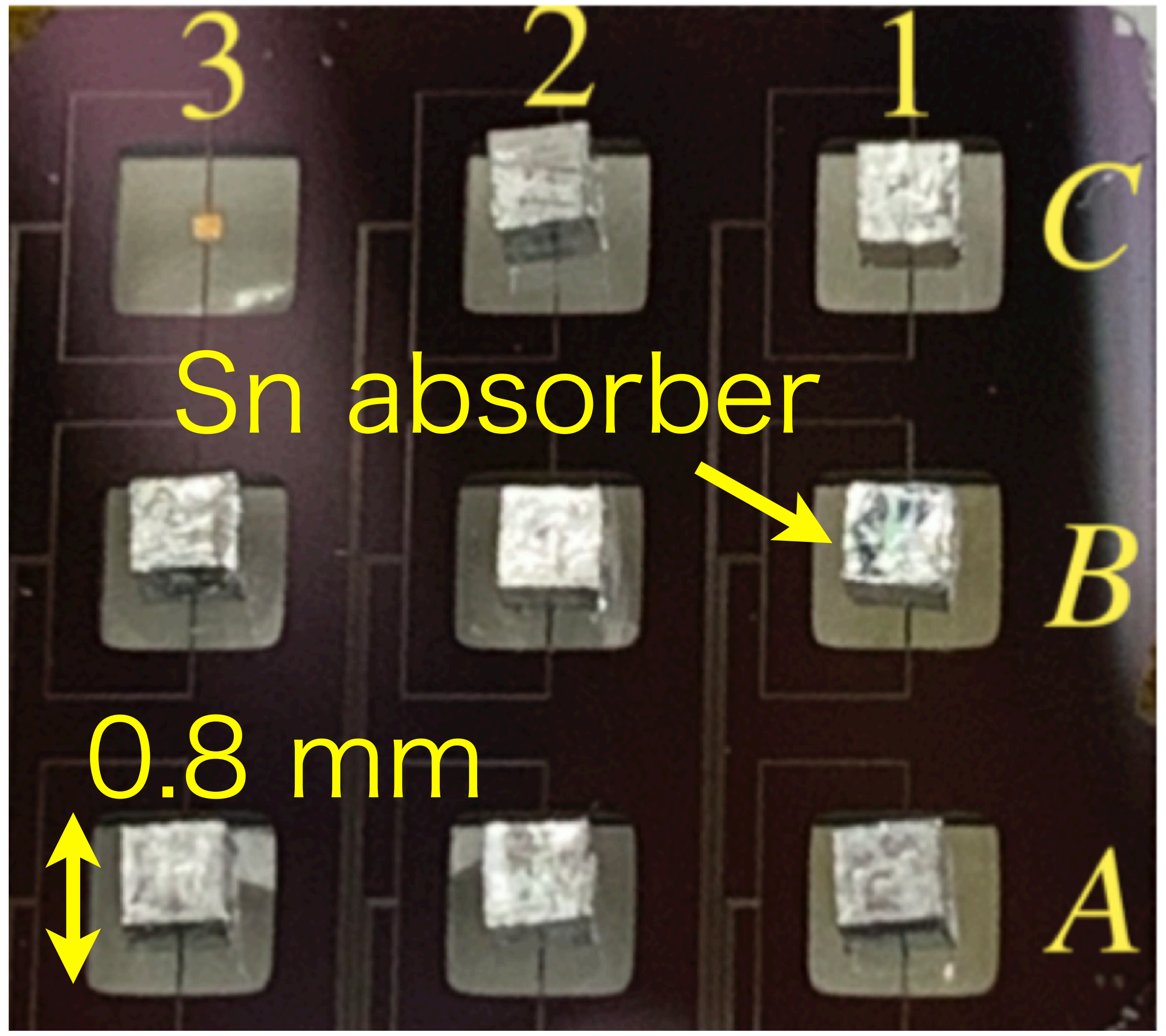
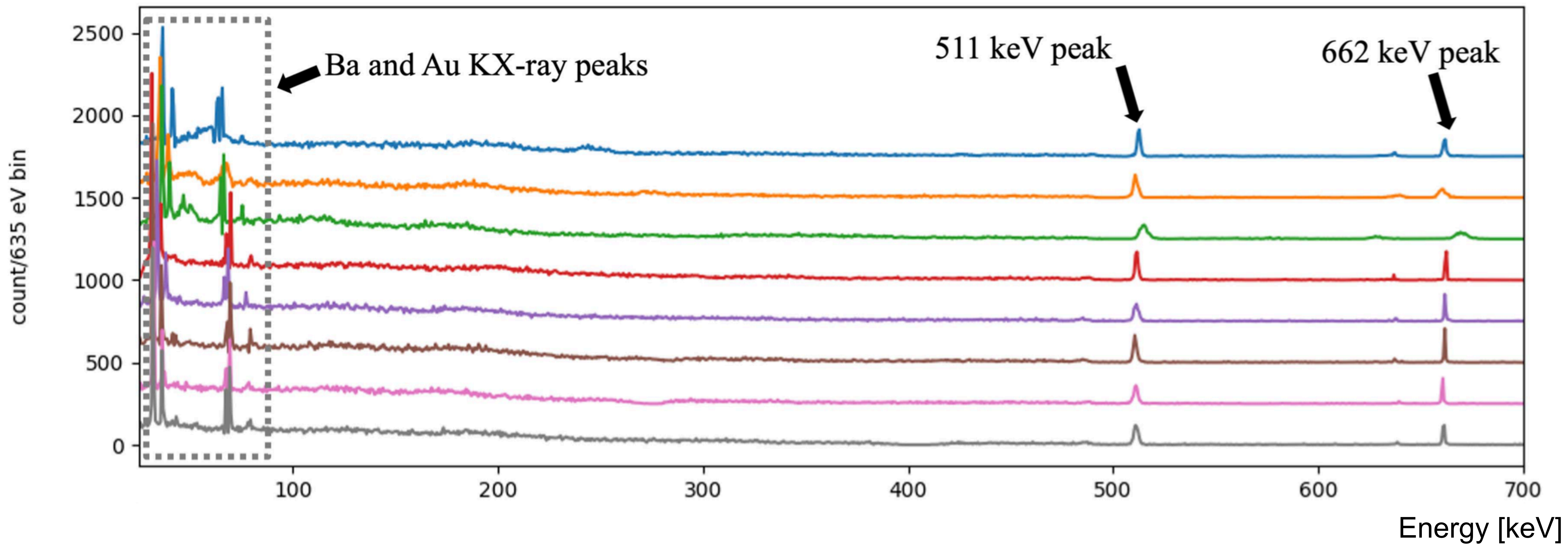
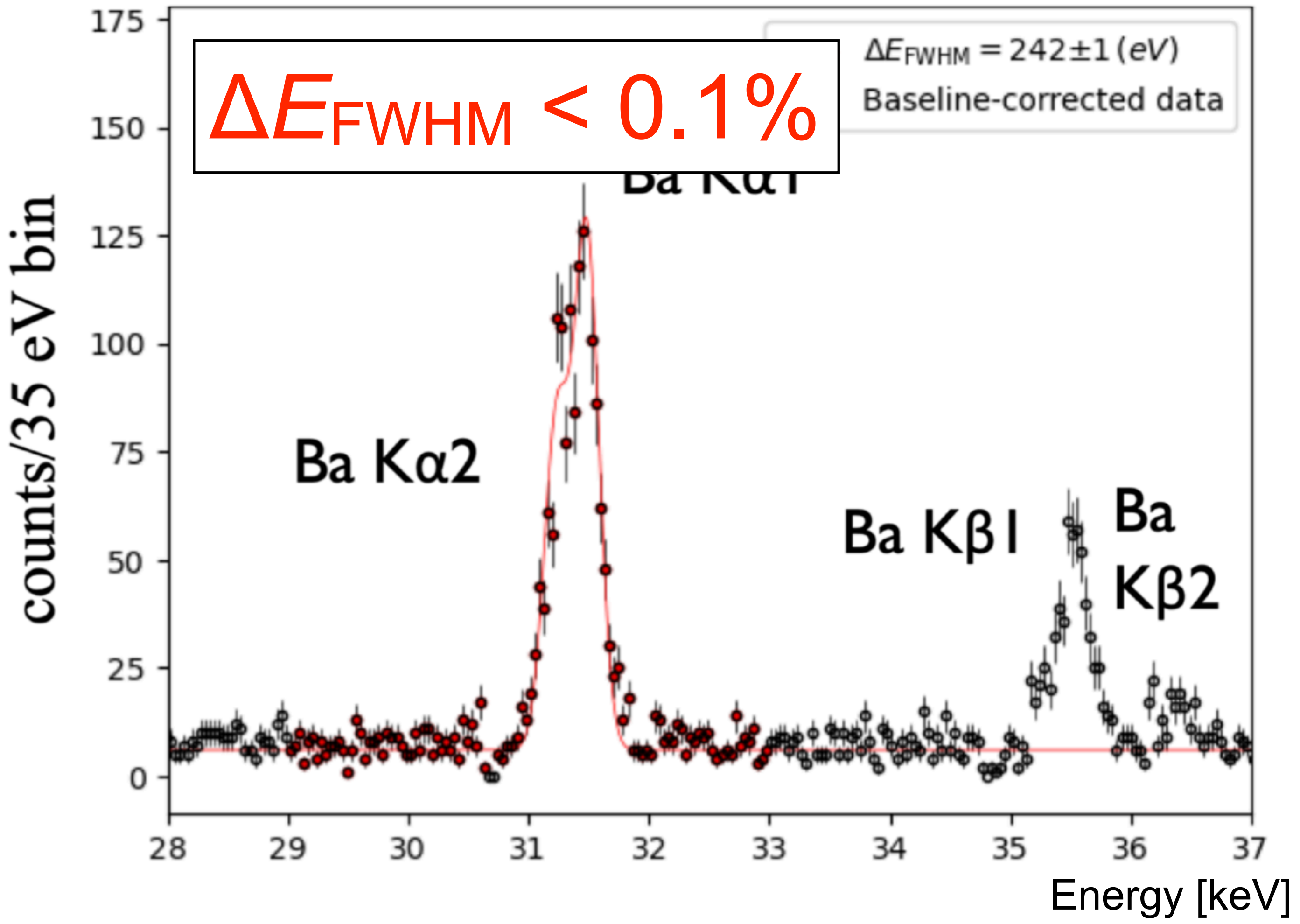
Gamma-ray TES Array @ AIST



Advantages in ^{112}Sn ECEC search

- Absorber = reaction source
  → high detection efficiency
- Available in the energy range of a few ten keV to several hundred keV with high energy resolution
  → search for ECEC to ^{112}Cd ground state by looking for X-ray and Auger electron





[4]IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 35, NO. 5, (2025)

Sensitivity Study

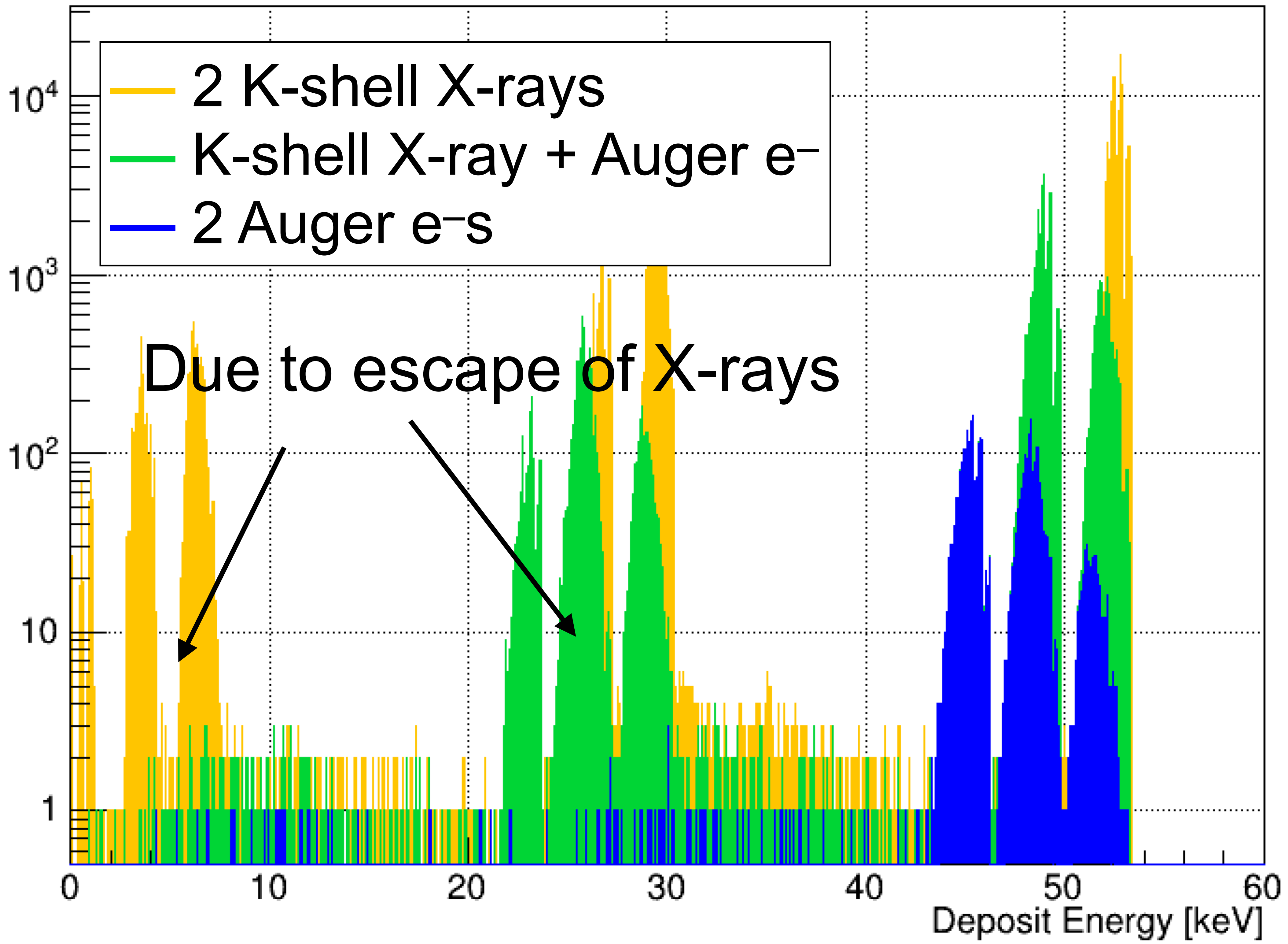
Energy Spectrum

[2]Phys.Rev.C C 83, 045503 (2011)

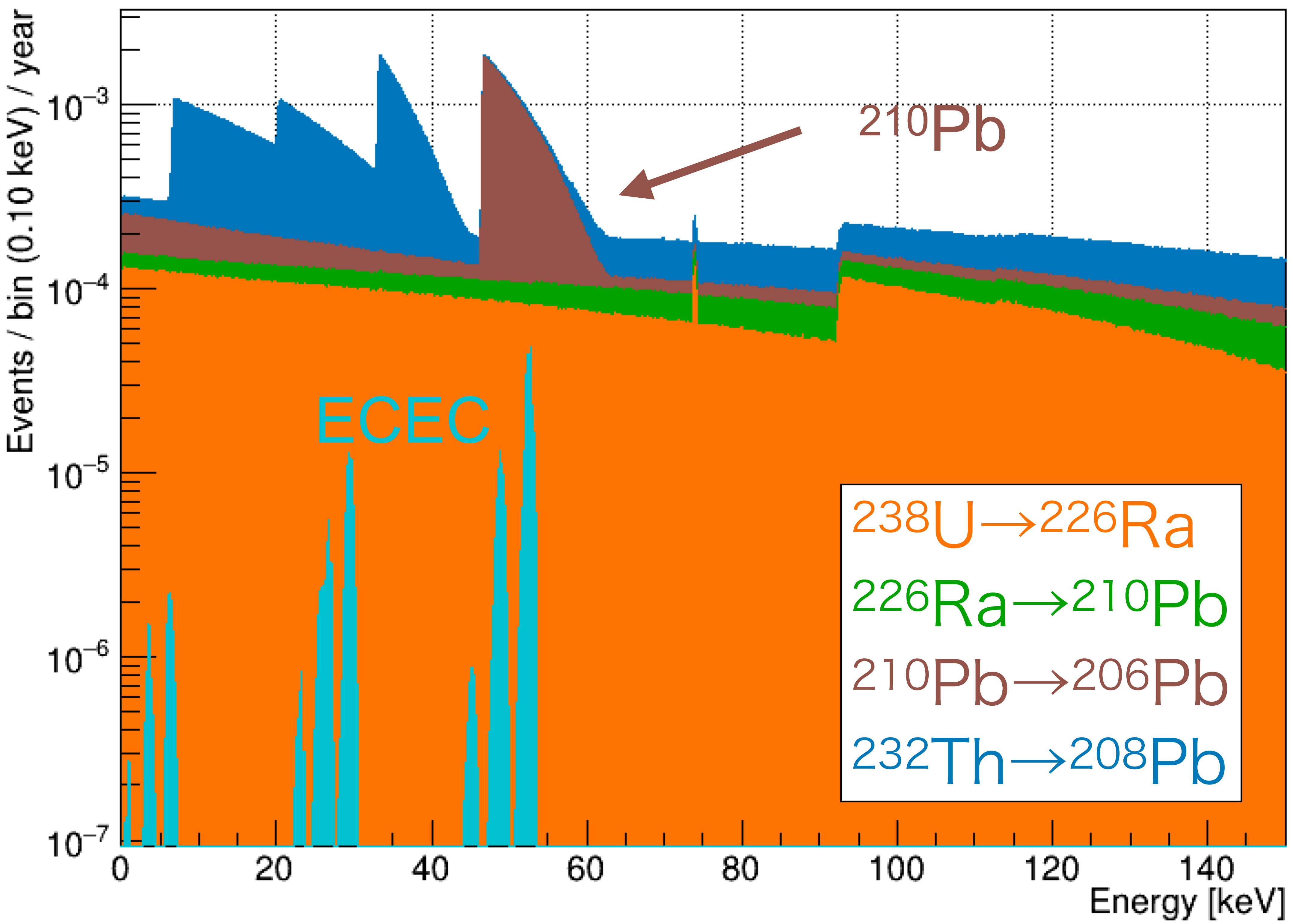
Energy deposit of ECEC and BG in Sn absorbers are simulated using Geant4

- TES with 0.8 mm x 0.8 mm x 0.8 mm cubic absorber, energy resolution of 0.1 keV
- ECEC : Two Cd atoms with a single K-shell vacancy
- BG : ^{238}U : 1.8 mBq/kg, ^{232}Th :1 mBq/kg (U.L. from [2]) and their daughters

Energy deposit of X-rays and Auger electrons of ^{112}Cd



BG spectrum (stacked)

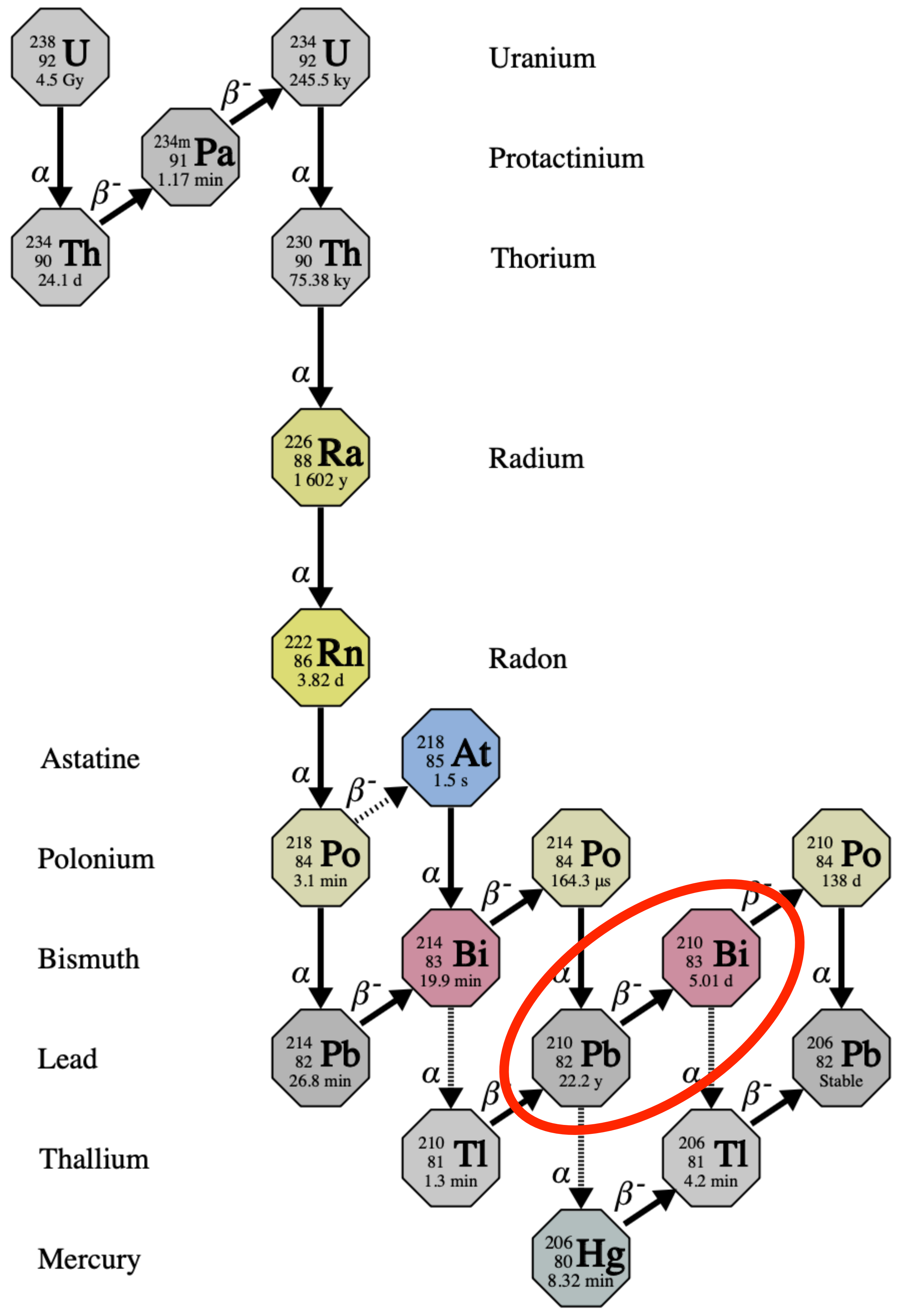


Sensitivity Study : Assumptions

- 90% C.L. rejection sensitivity is estimated using 10000 ToyMC experiments.

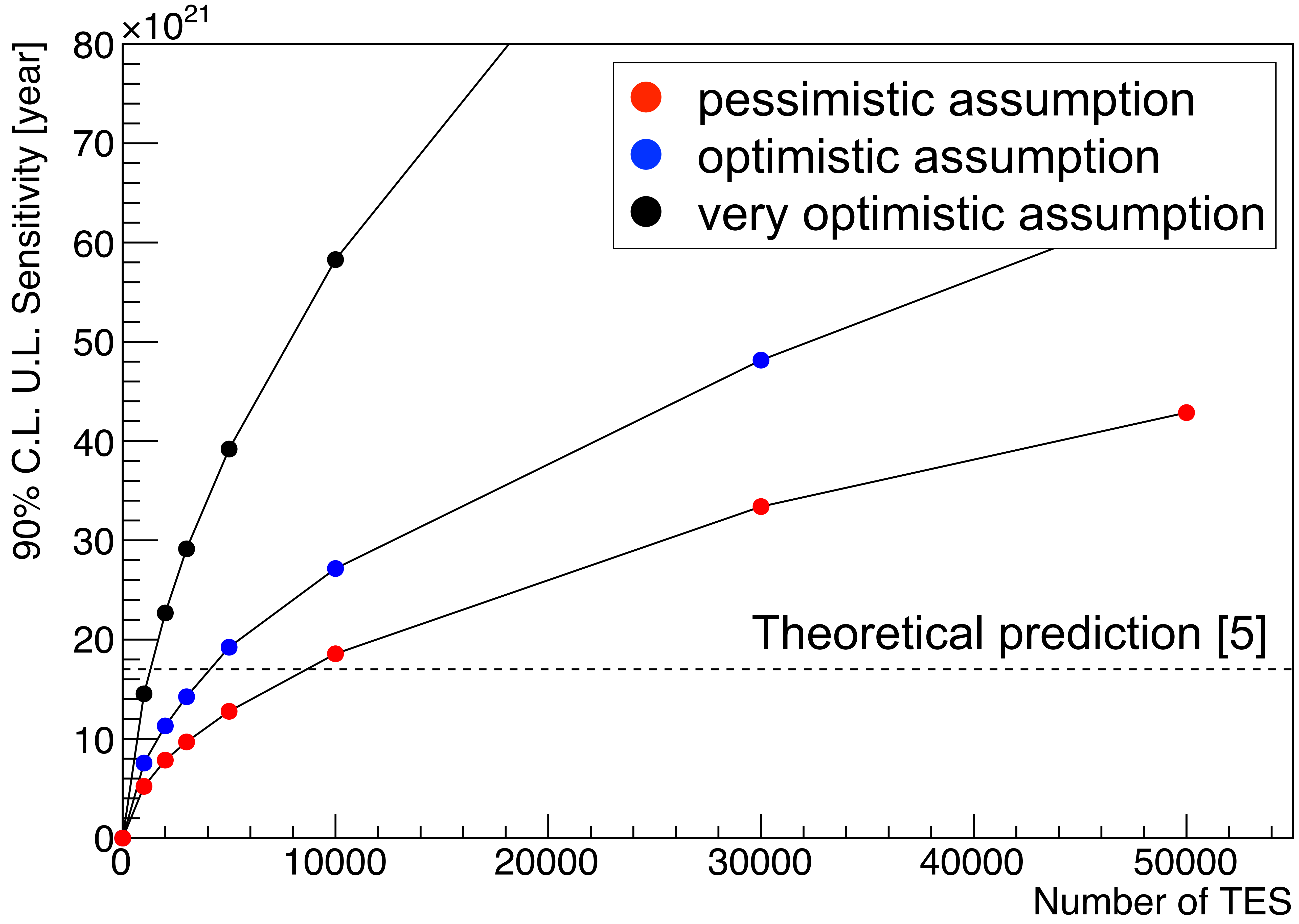
<u>Assumptions</u>

- 5 years observation using TES with (0.8 mm)^3 enriched ^{112}Sn absorber
- ^{238}U, ^{232}Th contamination … 3 assumptions
  - Pessimistic … ^{238}U : 1.8 mBq/kg, ^{232}Th :1 mBq/kg (U.L. from [2])
  - Optimistic … pessimistic case x 0.5
  - Very optimistic … pessimistic case x 0.1
- Background rejection by delayed coincidence
  - to remove ^{210}Pb
  - consecutive signals in the same TES pixel within one month will be vetoed.
    → veto : 98.4% rejection efficiency @ 12.1% signal sacrifice



[2]Phys.Rev.C C 83, 045503 (2011)

Sensitivity Study : Result



https://simonsobservatory.org/gallery/

Simons Observatory (CMB experiment)
~12000 TESs per telescope

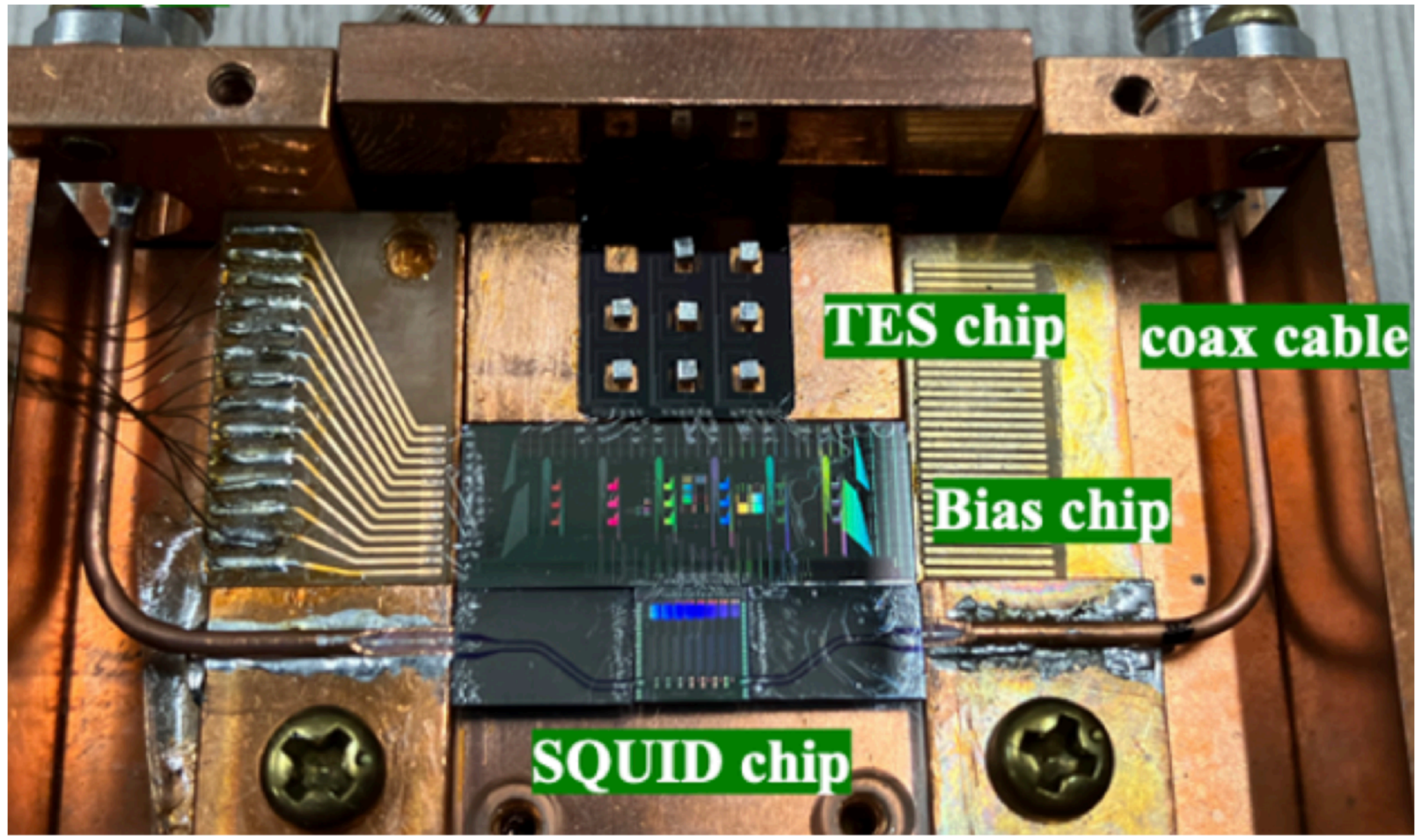
We can test a theoretical prediction using realistic numbers of TES and 5 years observation.

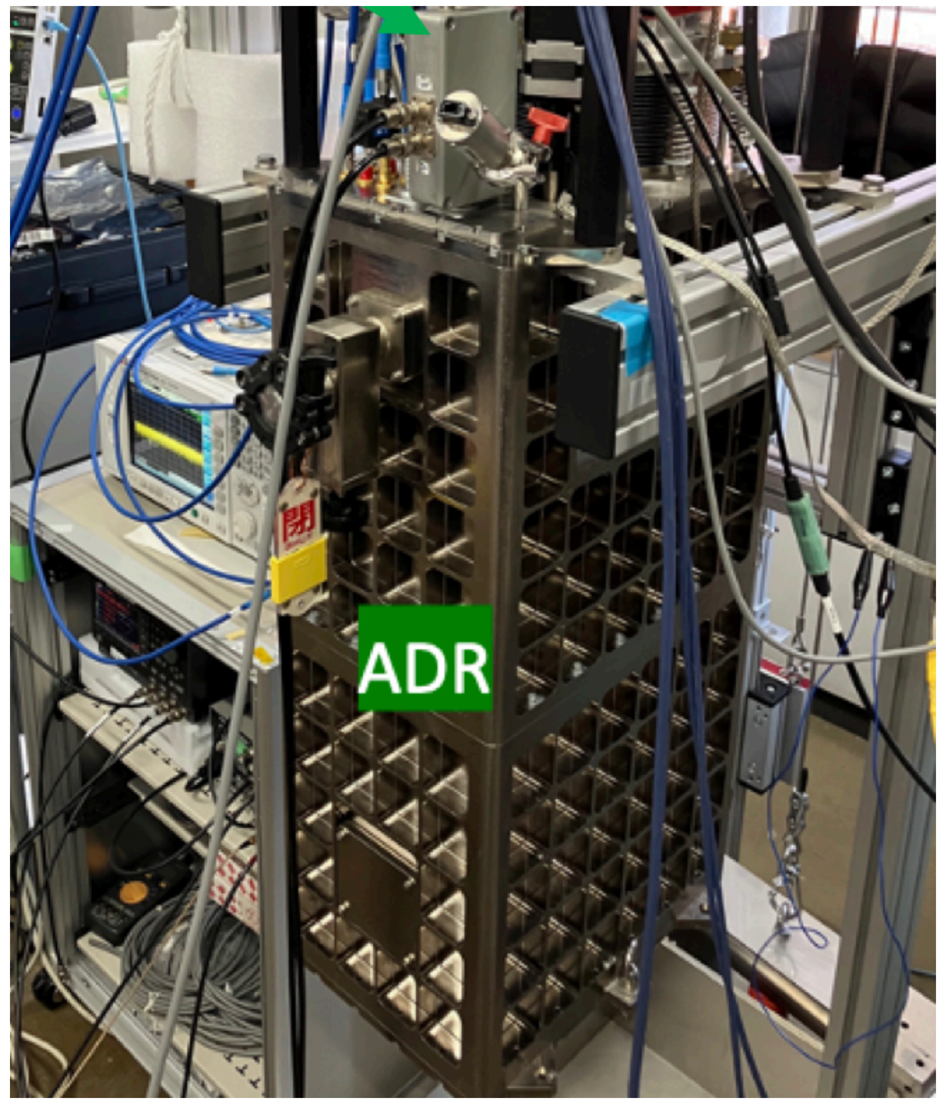
- ~10000 TESs even under pessimistic assumption
- < 5000 TESs under optimistic assumptions

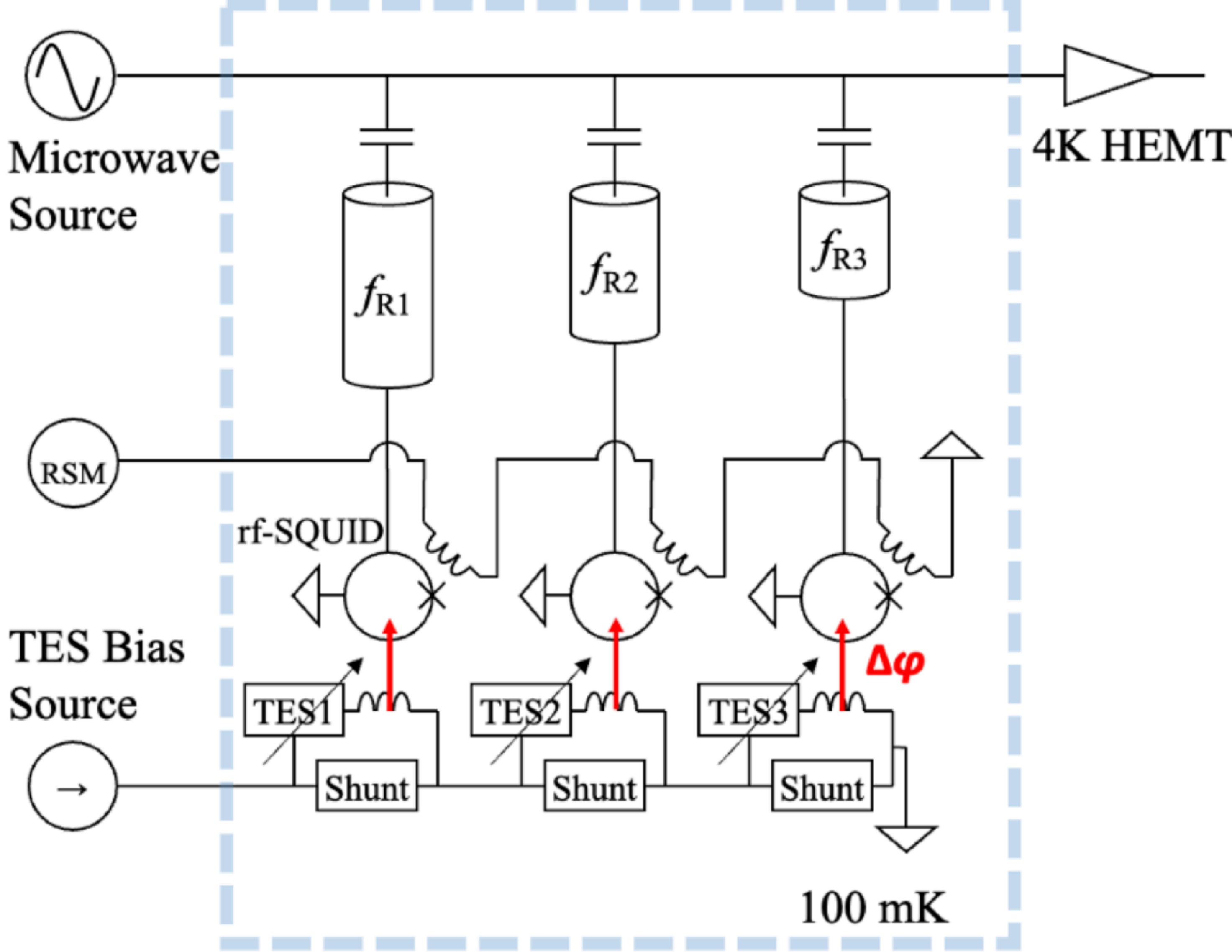
[5] Nucl. Phys. A 753 (2005) 337

Demonstration of ECEC Search Using gamma-ray TES Array

Measurement



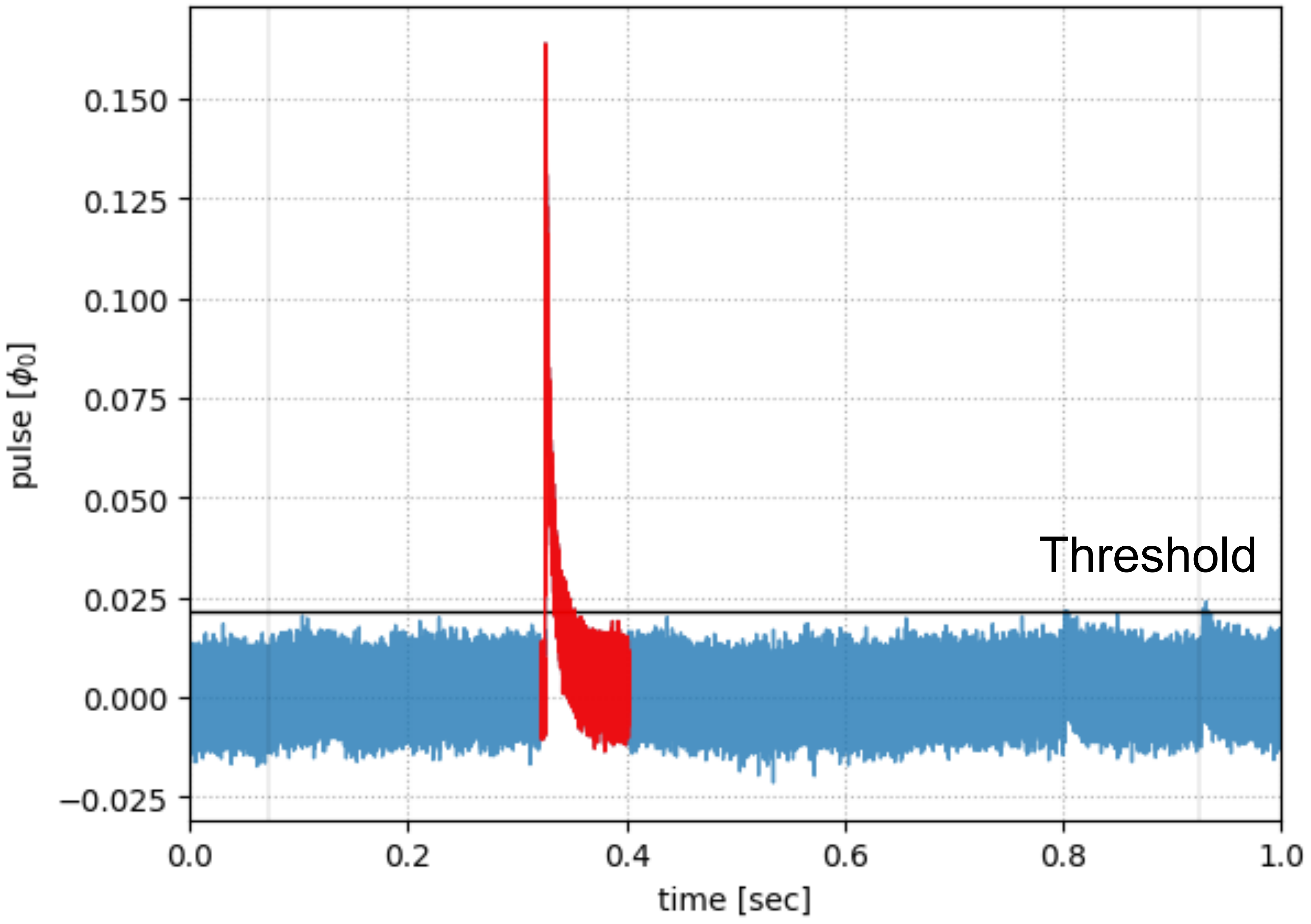




- TES module was cooled using adiabatic demagnetization refrigerator to lower than 100 mK
- 1-sec-duration waveforms were recorded repeatedly using microwave multiplexing.
- ^{130}Ba source calibration data and ECEC search data are taken.
- Measurement time for ECEC search : 22200 sec in total
  - Data from six TES pixels are used for analysis. Exposure : 1.3x10^{-10} kg*yr (^{112}Sn)

Analysis Method

- Signal waveform is extracted from 1-sec-duration data
  - Analytical threshold to pulse height : ~10keV
- Pulse Height Amplitude (PHA), that is proportion to the event energy, is calculated.
  - optimal filter method is used
- Absolute energy calibration with ^{130}Ba 81 keV peak



Calculation of PHA using optimal filtering

$$PHA = C \int_{-\infty}^{\infty} D(t)\mathcal{F}^{-1}\left(\frac{M(f)}{|N(f)|^2}\right) dt$$

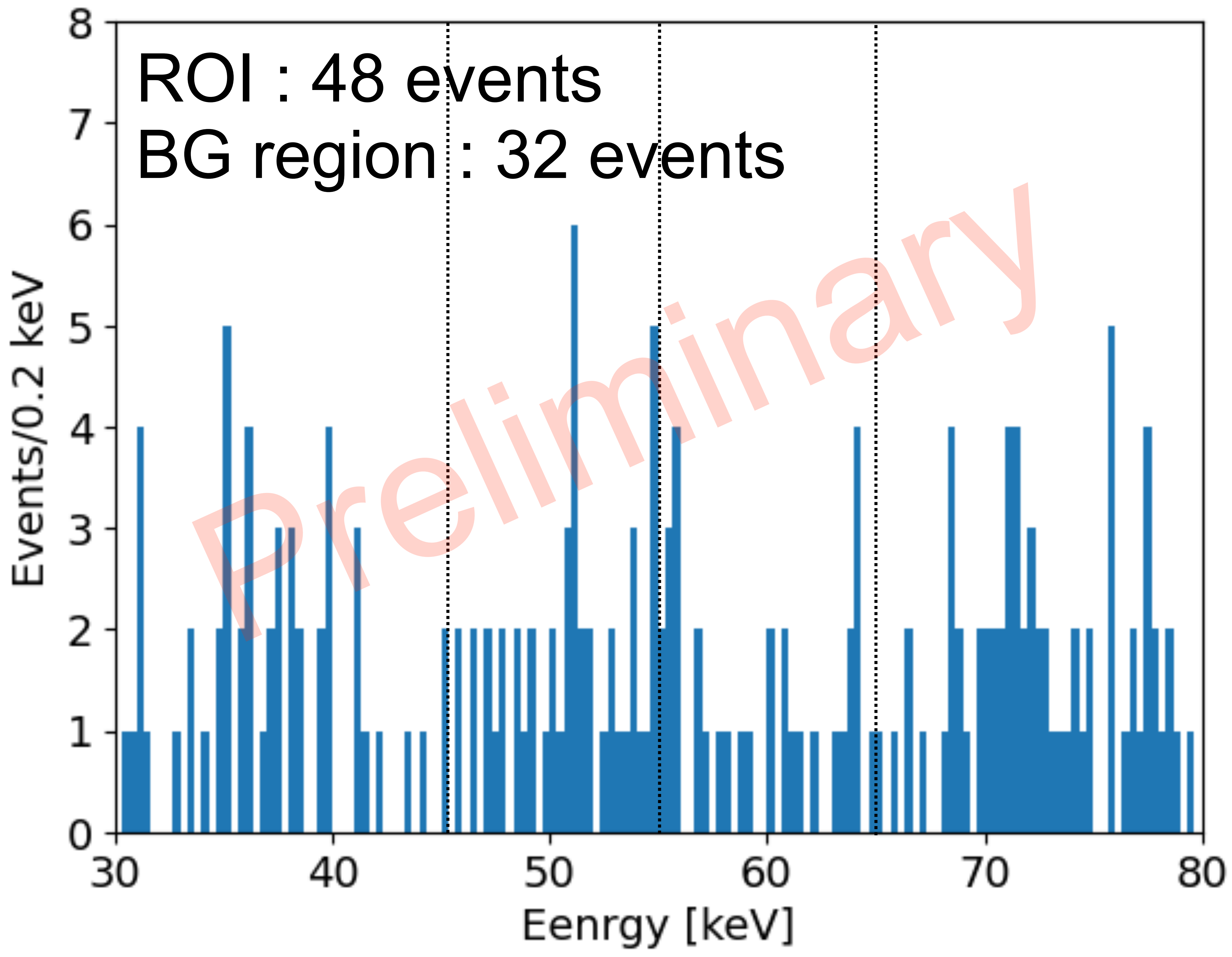
C : Normalization, $D(t)$: signal waveform, F^{-1} : IFT
$M(f)$: frequency spectrum of signal template,
$N(f)$: noise spectrum

pulse area($\propto$event energy) calculation suppressing the influence of noise.

Limit on ECEC

Set the limit on the number of ECEC events by defining 45≦Energy<55 keV and 55≦Energy<65 keV region as signal region and BG region, respectively.

- Energy selection efficiency : 73%
- Uniform distribution of BG is assumed.
- Feldman Cousins' method was used to calculate 90% C.L. U.L.



90% C.L. U.L : 28.5 events
→ $T_{1/2}$(ECEC) > 1.5x10^{12} yr (Theory : 1.7x10^{22} yr)

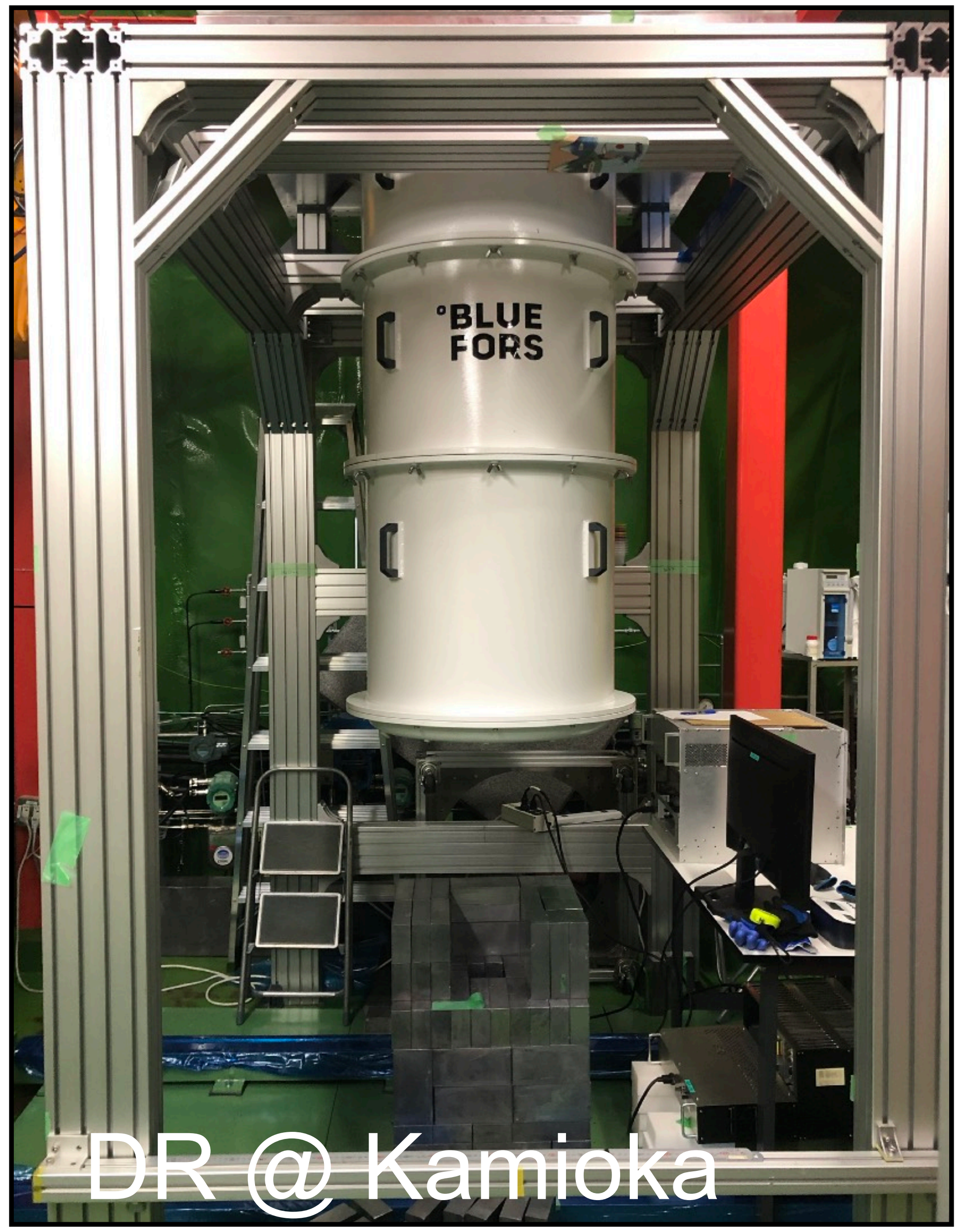
First demonstration of ECEC search using gamma-ray TES

Prospects

神岡極稀事象研究拠点

Developments in Kamioka Extremely Rare-phenomena and Neutrino-research Laboratory (KERNEL)

- KERNEL : launched in the Kamioka mine as a inter-institute collaboration hub.
- $O(10^5)$ muon flux reduction
- super clean environment
- BG measurement using HPGe detector[6] and measurement using DR in KERNEL



[6]Prog. Theor. Exp. Phys. 2023 123H01

Summary

- Double electron capture can be an input to theoretical study of nuclear structure and a key to understand Majorana nature of neutrinos.

- Simulation study shows that we can test a theoretical prediction of ECEC half-life using realistic number of TES pixels and measurement time.

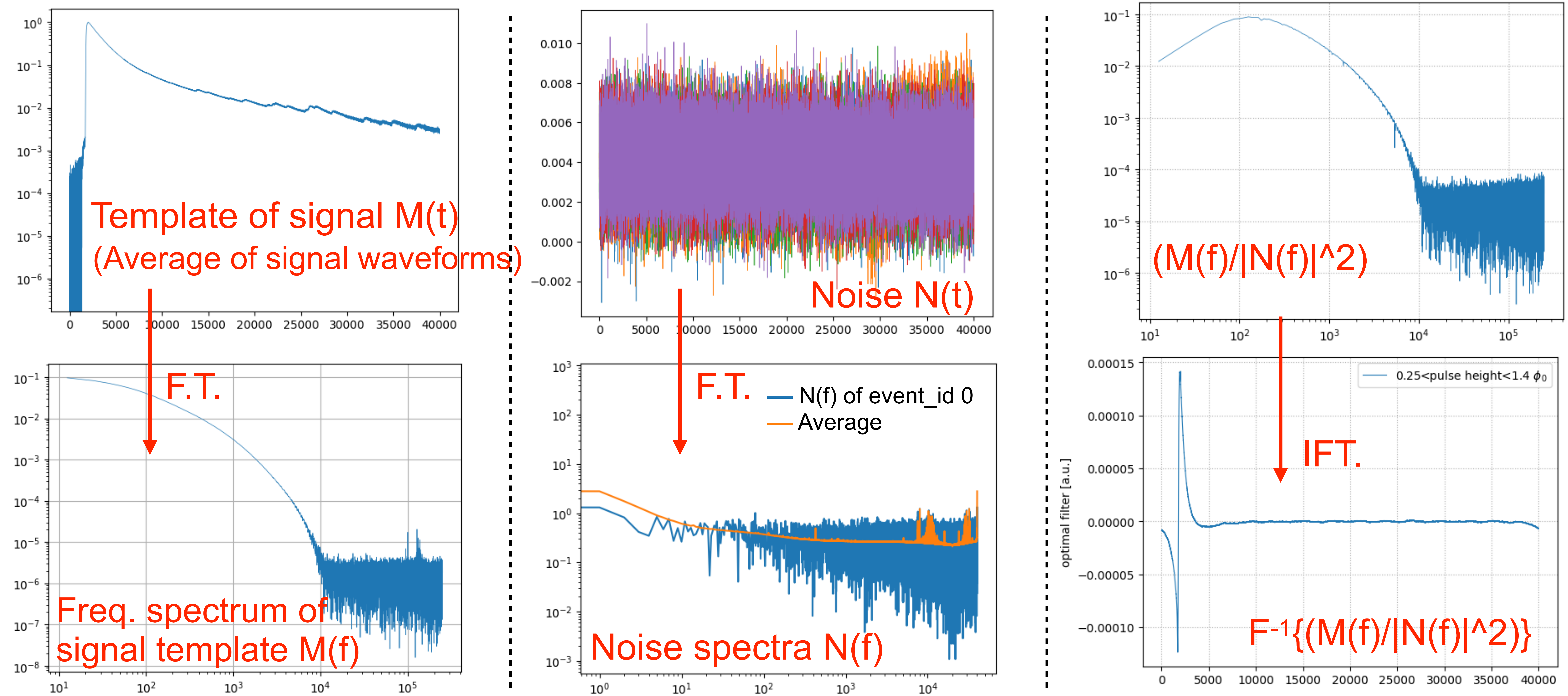
- We demonstrated ECEC search using gamma-ray TES array.
  - limit on half-life : $\underline{T_{1/2}(ECEC) > 1.5 \times 10^{12}\ \mathrm{yr}}$

- We are planning developments in KERNEL, underground laboratory in Kamioka.

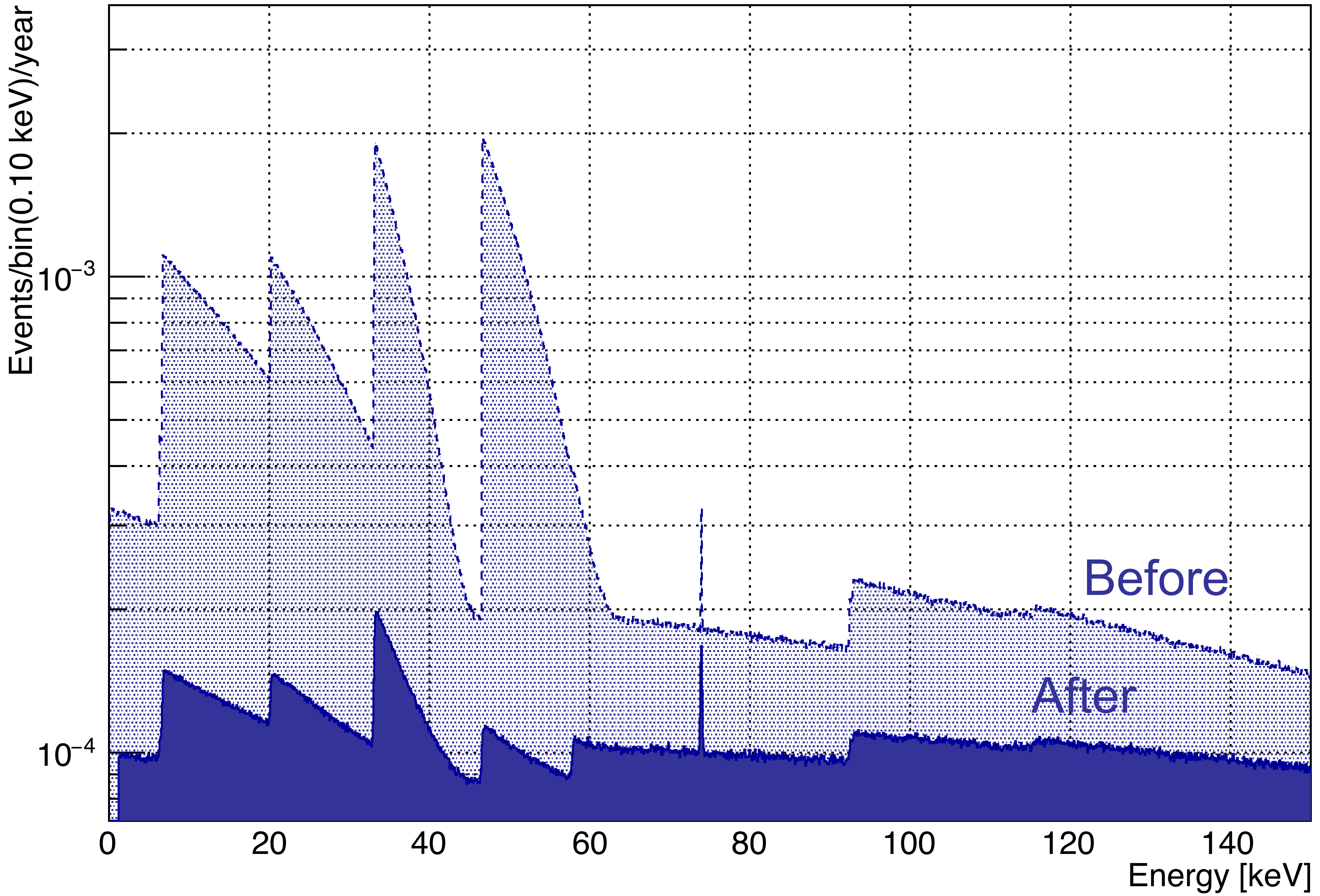
Thank you for your attention

Energy Reconstruction

$$PHA = C\int_{-\infty}^{\infty} D(t)\mathcal{F}^{-1}\left(\frac{M(f)}{|N(f)|^2}\right)\,dt$$



BG reduction by Delayed Coincidence



Details of Simulation

Energy deposit of ECEC and BG decays in Sn absorbers are simulated using Geant.4

Detector assumption

- Size of absorber : 0.8 mm x 0.8 mm x 0.8 mm
- Energy resolution : 0.1 keV

Signal

- ECEC : Two Cd atoms with a single K-shell vacancy
  - Atomic relaxation package in Geant.4 (G4AtomicDeexcitation)
  - Note : relative capture ratio of two K-shell vacancy : 73.4% (up to N5 shell)[4]
- BG : Daughter nuclei in ^{238}U and ^{232}Th series
  - Radioactive decay in Geant.4
  - Density : Upper limit from [2] … U : 1.8 mBq/kg, Th :1 mBq/kg
  - Radiation equilibrium

Sensitivity Study

- 90% C.L. rejection sensitivity is estimated.
  - 10000 Toy MC events are generated based on the simulation spectrum.
  - 90% C.L. U.L. of signal rate is calculated for each Toy MC events.
    → Median of 10000 trials is adopted as sensitivity.

Assumptions

- 5 years observation using TES with (0.8 mm)^3 enriched ^{112}Sn absorber
- ^{238}U, ^{232}Th contamination … 3 cases
  - Pessimistic assumption … ^{238}U : 1.8 mBq/kg, ^{232}Th :1 mBq/kg (U.L. from [2])
  - Optimistic assumption … worst case x 0.5
  - Very optimistic assumption … worst case x 0.1
- Background rejection by delayed coincidence
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  - consecutive signals in the same TES pixel within one month will be vetoed.
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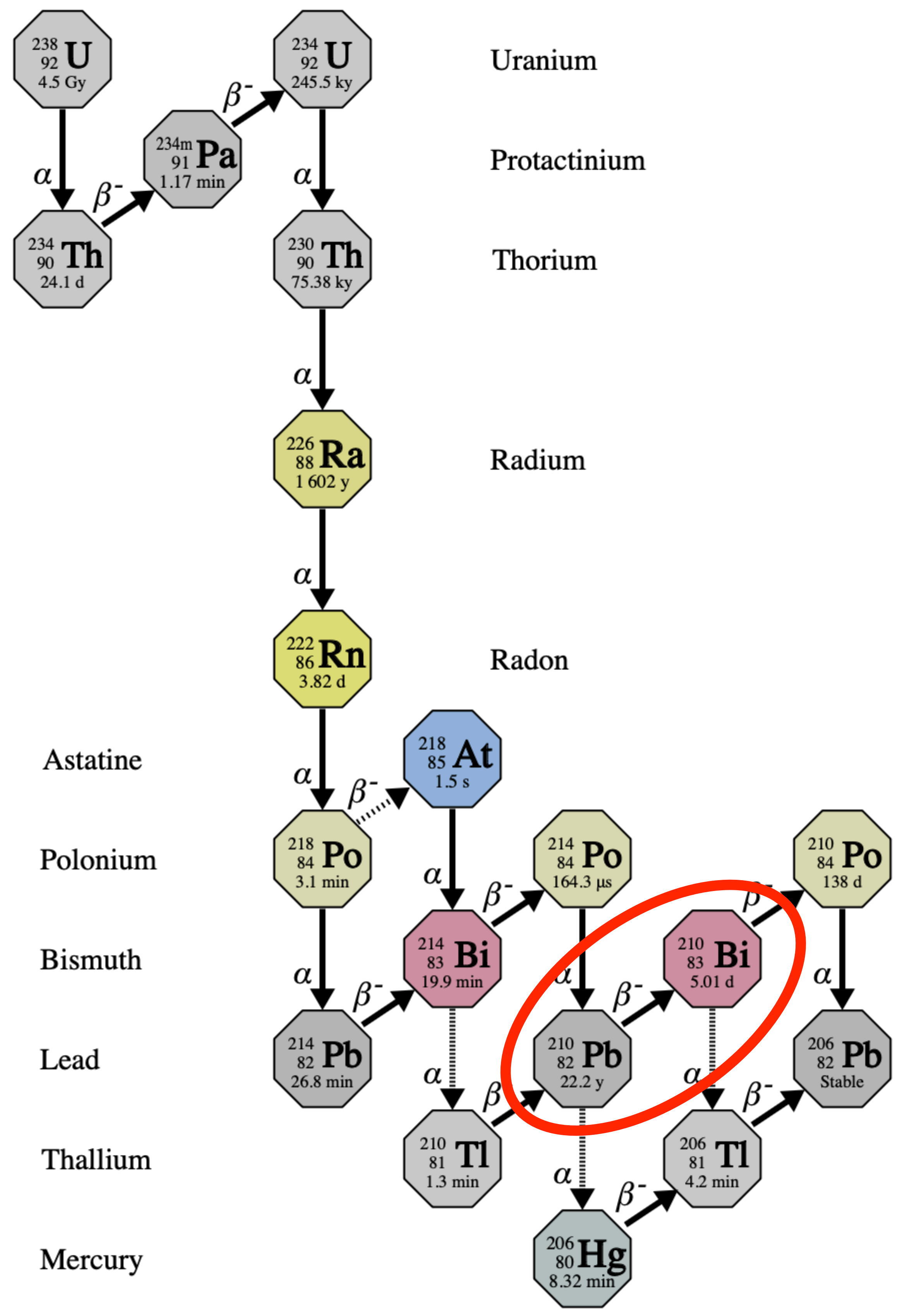


[2]Phys.Rev.C C 83, 045503 (2011)

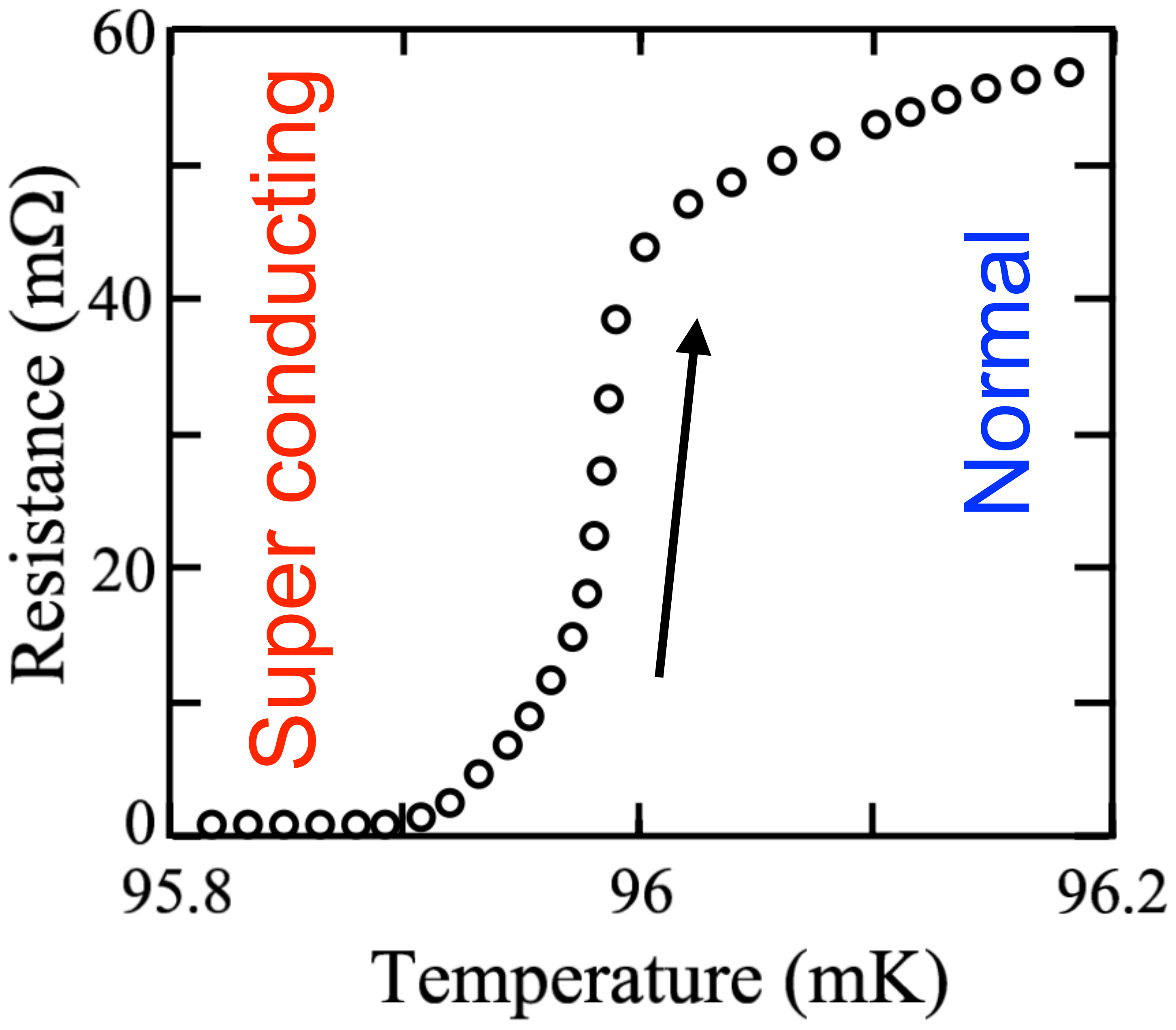
[3]Topics Appl. Phys. 99, 63-149 (2005)

What is TES?

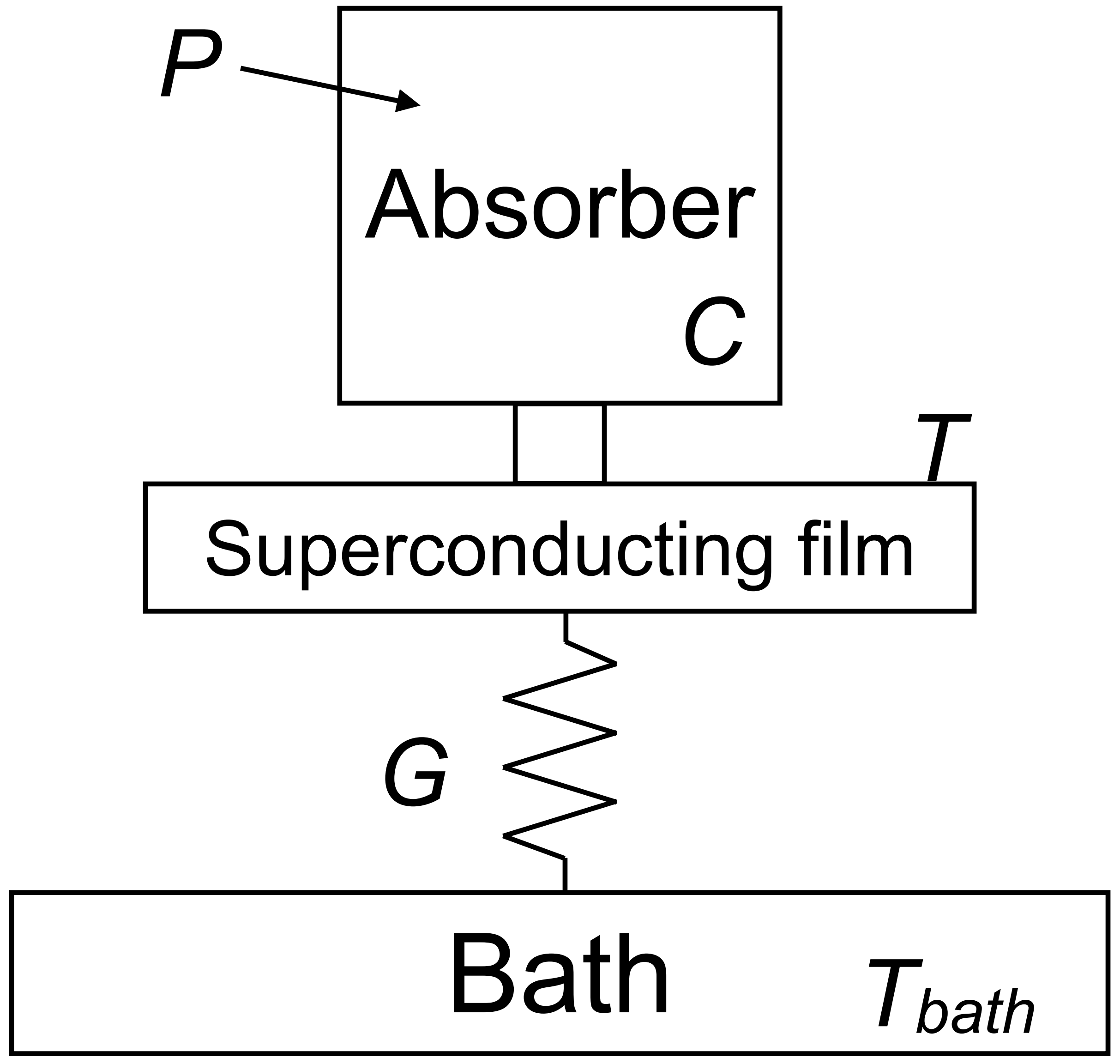
Transition Edge Sensor (TES)

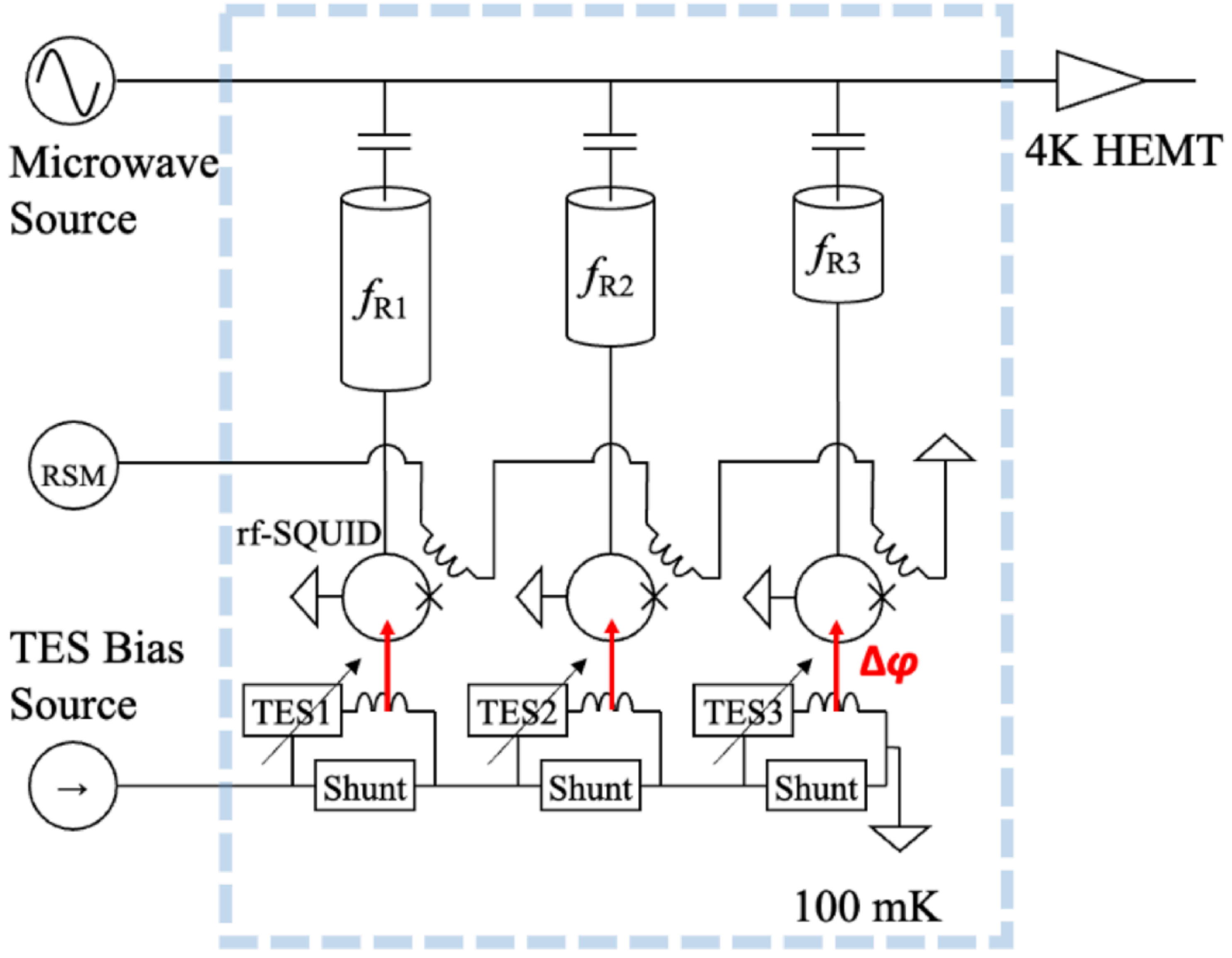
- A thermometer that operates on the sharp change in resistance of superconducting materials.
  - Energy deposit at absorber is detected as the change of resistance.
  - Technically, the change in resistance is detected as a change in current using a SQUID.
- Each absorber is small (~1mm) → multi pixelization

Resistance v.s. temperature (Mo/Cu) [3]



Conceptual design of TES

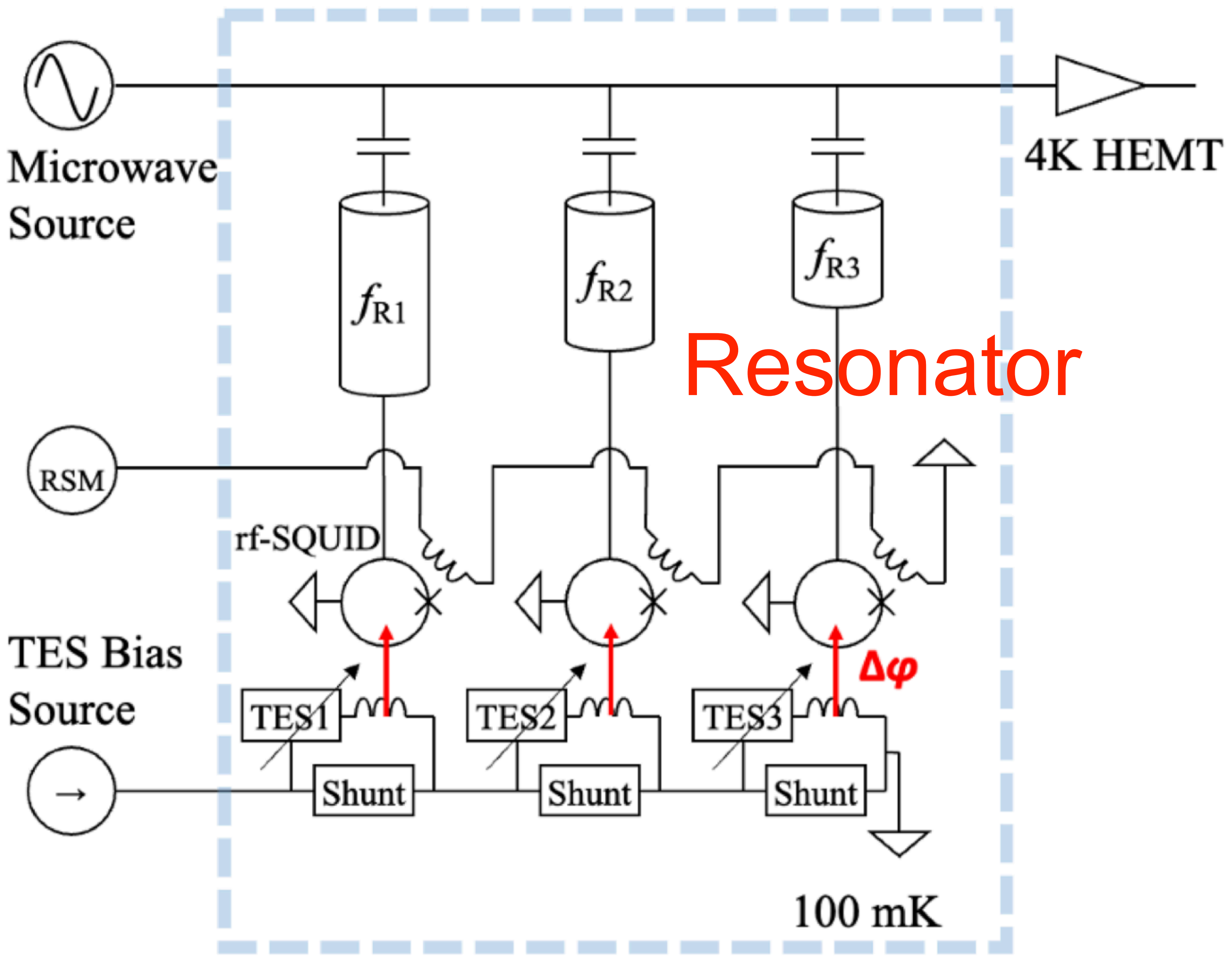


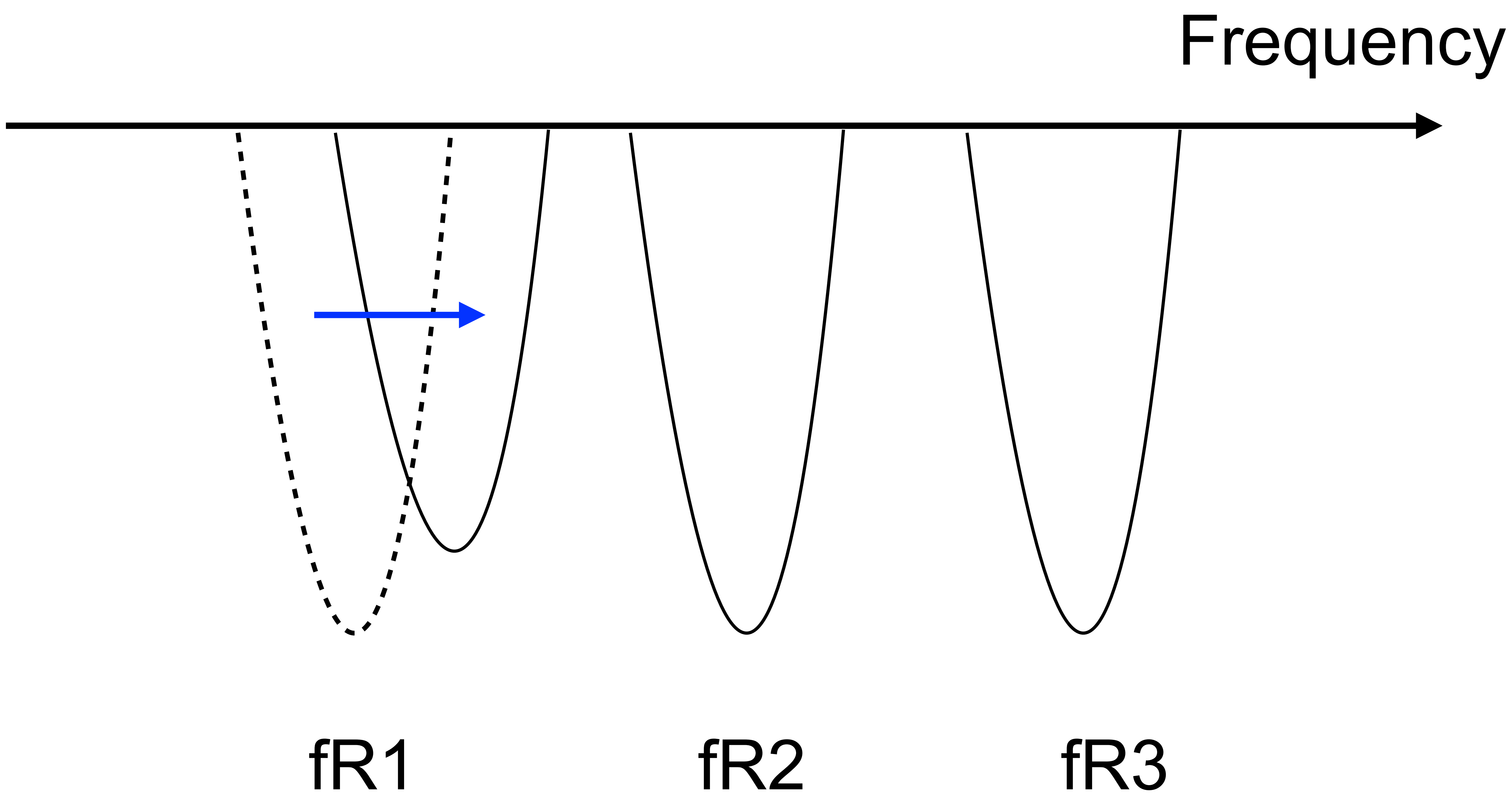


μMUX

・Multiplexed readout system

・Input coils are connected to TESs, and the change of current due to change of resistance is detected by SQUID as the magnetic signal
→ The signal is detected as the change go resonant frequency



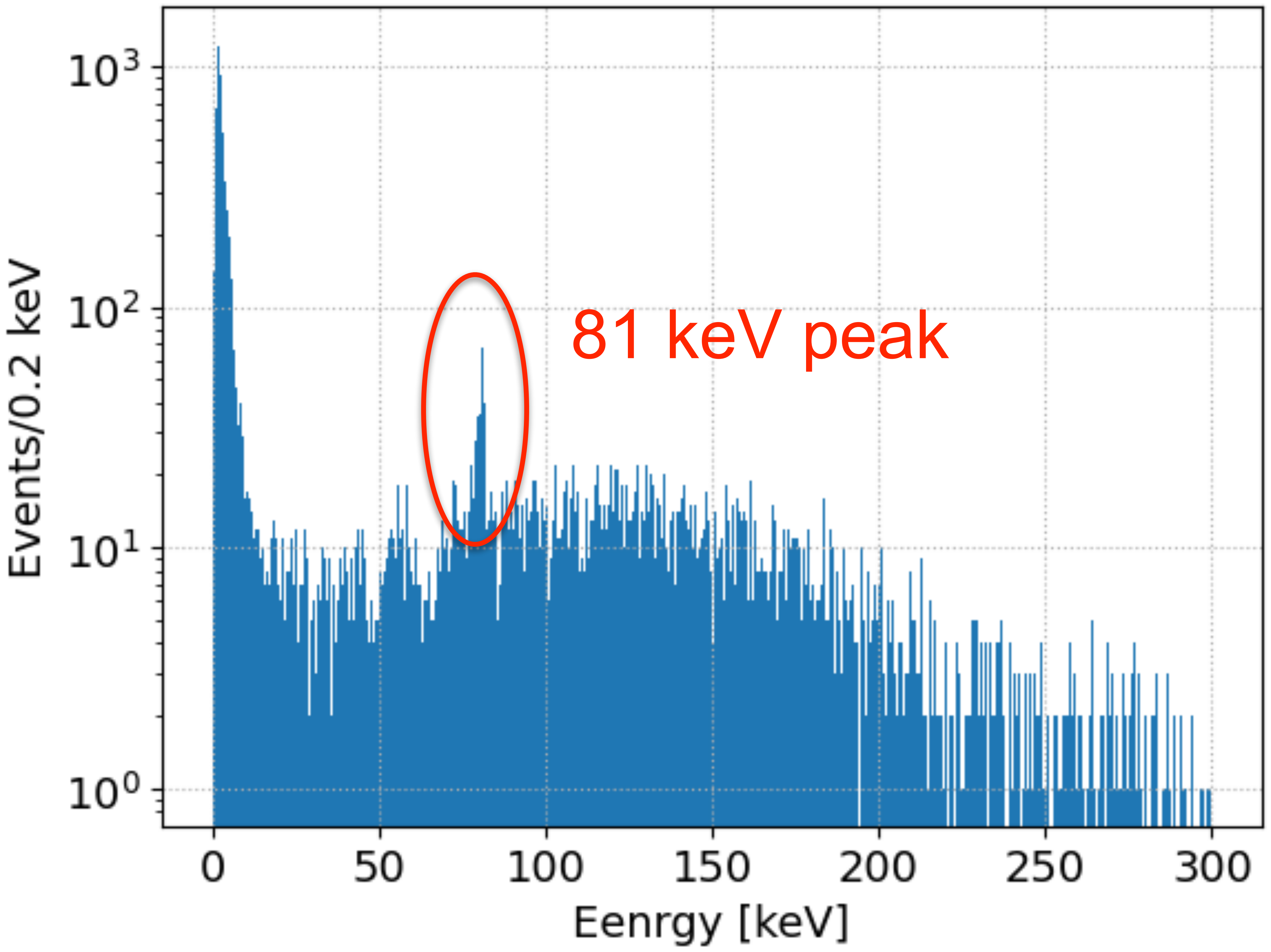


Energy Calibration

Energy spectra is obtained by multiplying calibration factor to PHA spectra.

- Calibration factor is determined by looking at the ^{130}Ba 81 keV peak in calibration data.
- Energy linearity is assumed.

Calibration data



ECEC data