INPC 2025

The 29th International Nuclear Physics Conference

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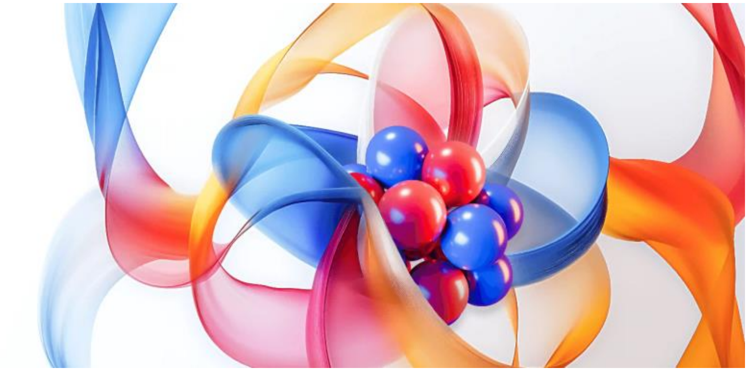
DCC, Daejeon, Korea



Precise measurement of ^{3}H beta decay spectrum and keV-scale sterile neutrino search

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CENTER FOR UNDERGROUND PHYSICS

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Motivation

- Standard Model cannot explain

  Matter-antimatter imbalance, Nature of neutrino mass

  Existence of dark matter and dark energy.

- Sterile neutrino: hypothesized by neutrino minimal standard model (νMSM) in the Seesaw model

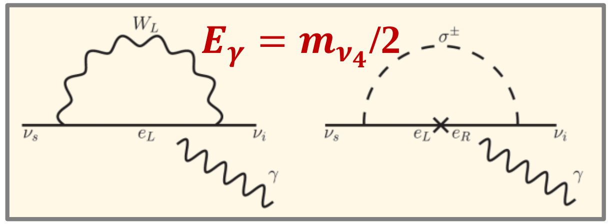
- Sterile neutrinos in keV scale are (warm) dark mater candidate.

  ν_{heavy} may have been generated in the reheating epoch of the early Universe. (Model dependent)

  ν_{heavy} may decay to an active neutrino and an X-ray. (Model dependent)

  Cosmic X-rays ➔ probe for mass and mixing of the sterile states. .

  Strong exclusion limit (Model dependent) : $\sin^2\theta < \mathcal{O}(10^{-11})$



Benso, et al. PRD (2019)

- Searching for a sterile decay branch in beta decay with possible ν_s emission : (Model-independent)

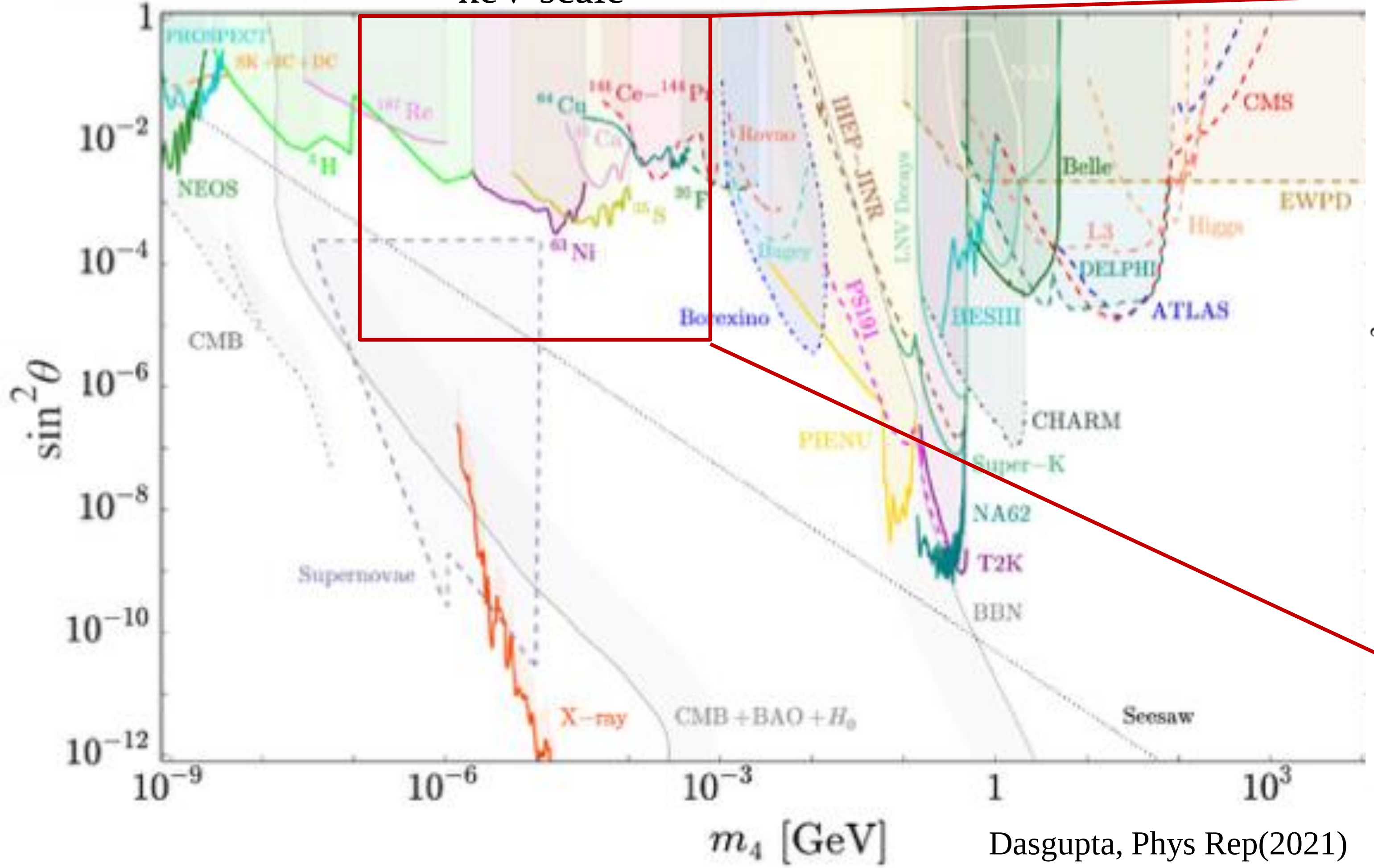
Possible mixing with active ν_{light}

$$\nu_e = \cos\theta\,\nu_{light} + \sin\theta\,\nu_{heavy}$$

$$\nu_s = -\sin\theta\,\nu_{light} + \cos\theta\,\nu_{heavy}$$

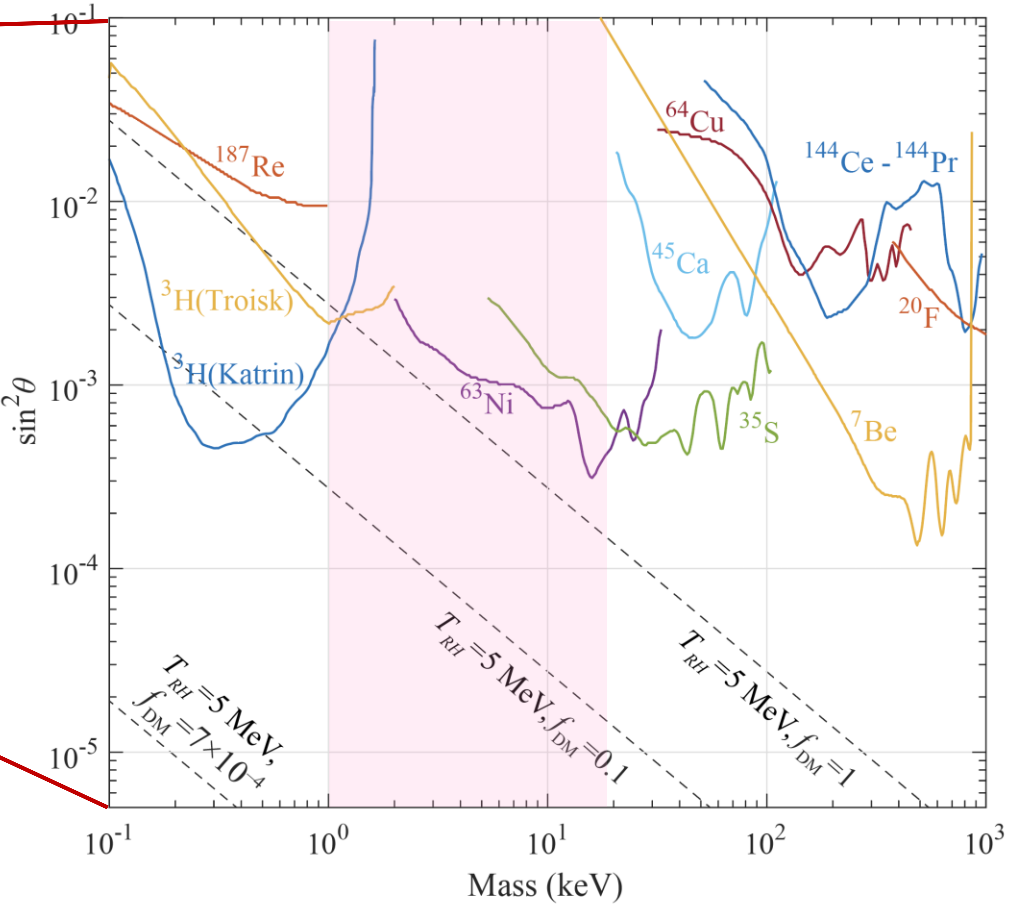
Current limit for $\sin^2\theta$ and m_s

keV scale



Dasgupta, Phys Rep(2021)

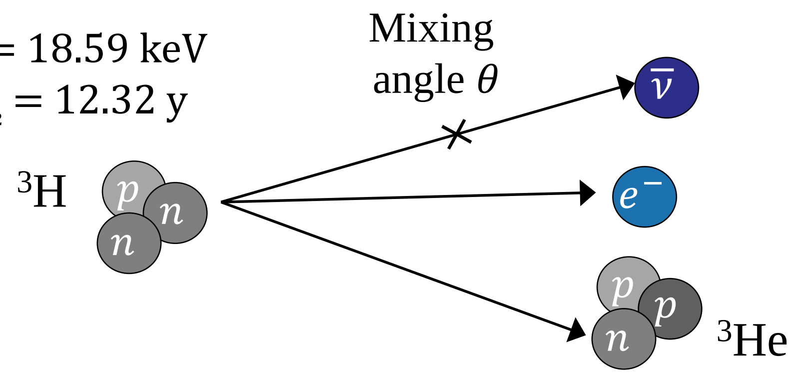
ROI of this work

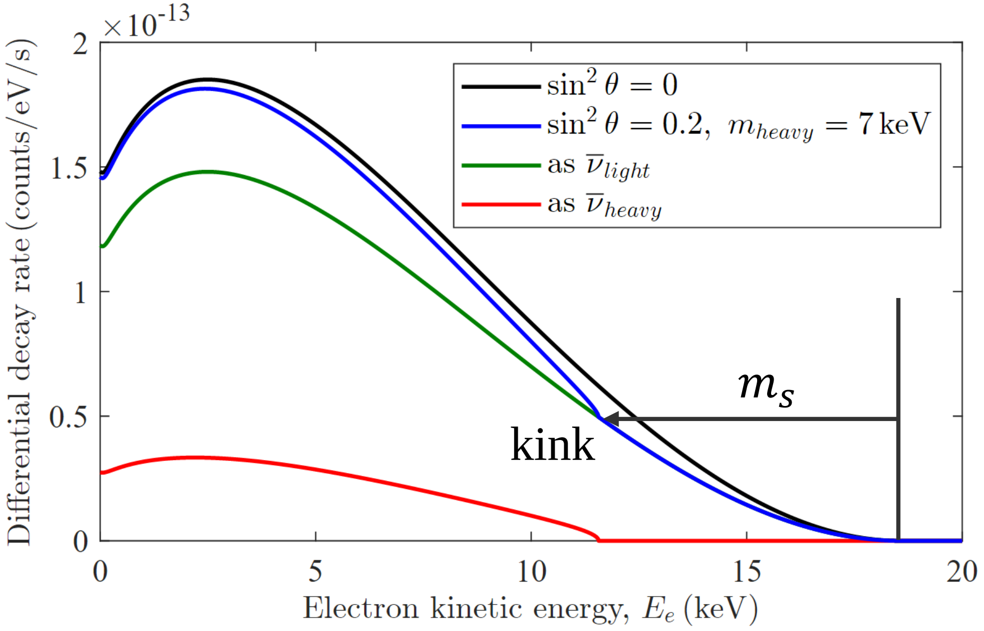


The dashed lines from Low Reheating Temperature (LRT) model
Abazajian, PRD (2023)

^{3}H β-decay Spectrum with sterile ν emission

Q = 18.59 keV
$\tau_{1/2}$ = 12.32 y





- Sterile neutrino (ν_{heavy}) feebly mixing with active neutrino (ν_{light})

$$\bar{\nu}_e = \cos\theta\,\bar{\nu}_{light} + \sin\theta\,\bar{\nu}_{heavy}$$

$$\frac{d\Gamma_{\rm tot}}{dE}(E_e; m_{light}, m_{heavy}) = \cos^2\theta\,\frac{d\Gamma}{dE}(E_e; m_{light}) + \sin^2\theta\,\frac{d\Gamma}{dE}(E_e; m_{heavy})$$

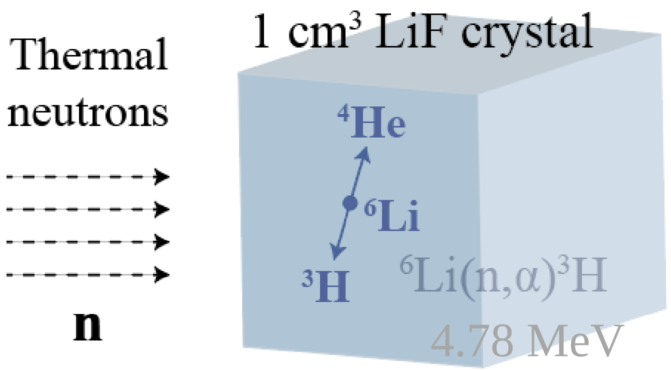
- β-decay spectrum for ν_{heavy} is added to that for ν_{light} with angle normalization factor.
- Non-differentiable point at $Q - m_s$

LiFE-SNS

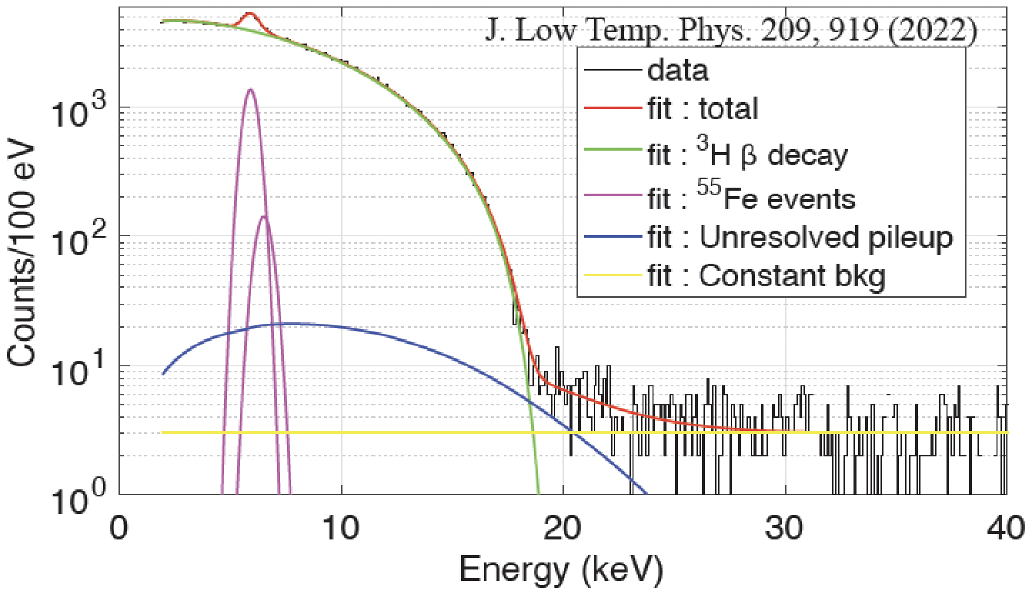
LiF Experiment

for keV Sterile Neutrino Search

^{3}H Production in LiF Cubic Crystals



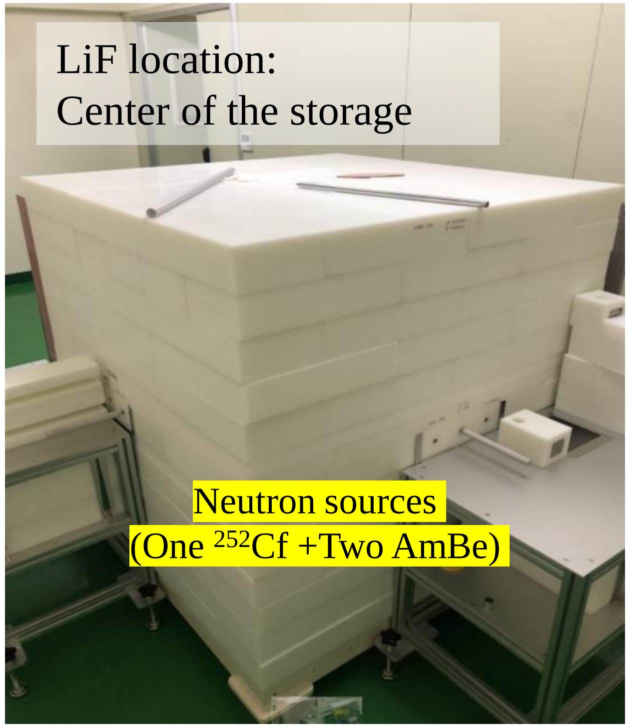
Thermal neutrons in a ^{6}Li target
Mean free path: 2.3 mm in LiF with 7.6% ^{6}Li



10-hour spectrum
using the first LiF(^{3}H)
w. ^{55}Fe source

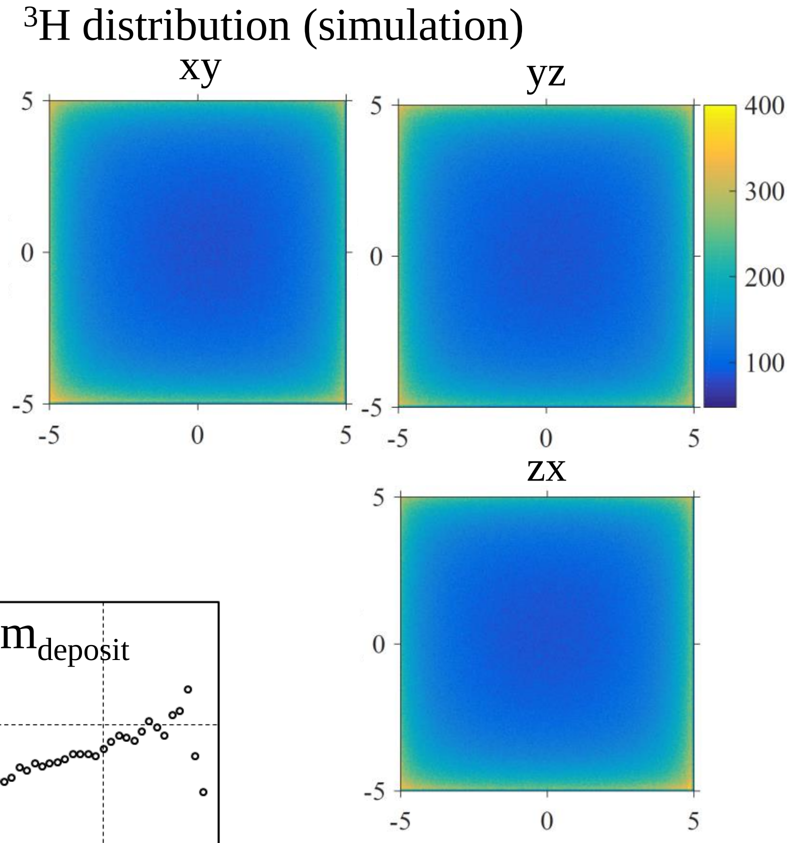
Neutron irradiation at KRISS

Week exposure → ~ 20 Bq in a LiF

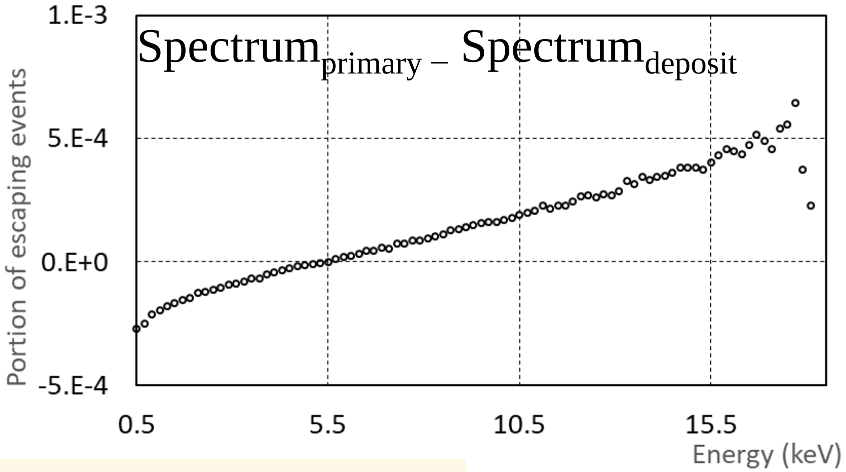


Surface issues (^{3}H distribution and energy loss)

- ✓ Non-uniform ^{3}H distribution in 1×1×1 cm^3 LiF
- - Expected from neutron capture and beta decay simulations
- - Mean free path of thermal neutron in LiF: 2.3 mm
- - Stopping range of 2.7 MeV ^{3}H in LiF: ~ 33μm

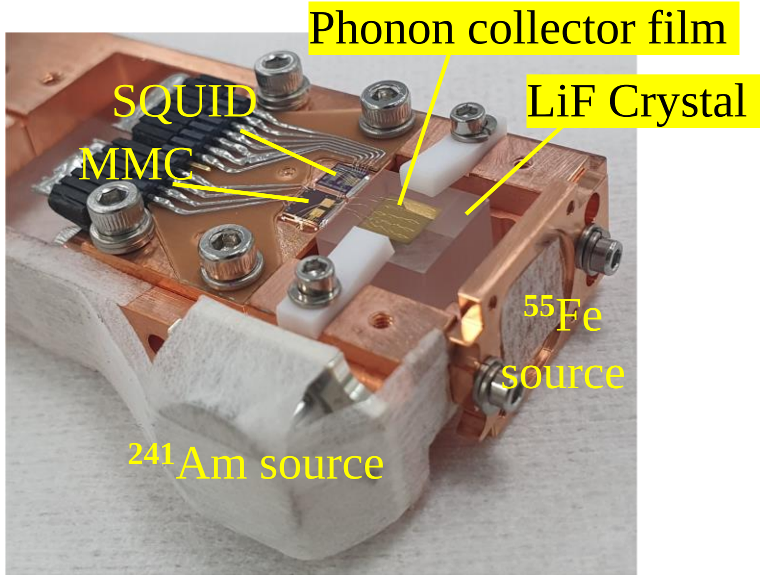


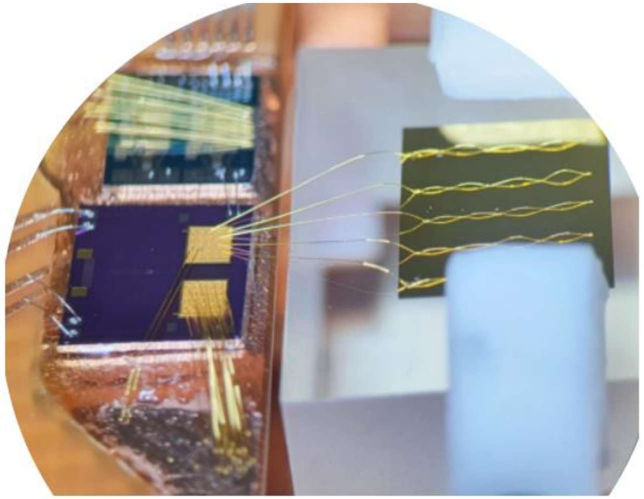
- ✓ Possible energy loss of decay energy other than neutrino
- - MC simulation includes surface escapes of electrons and X-rays
- - Stopping range of 18 keV β^- in LiF ~ 0.5 μm
- - ~ 0.1% spectrum shape shifted to lower energy

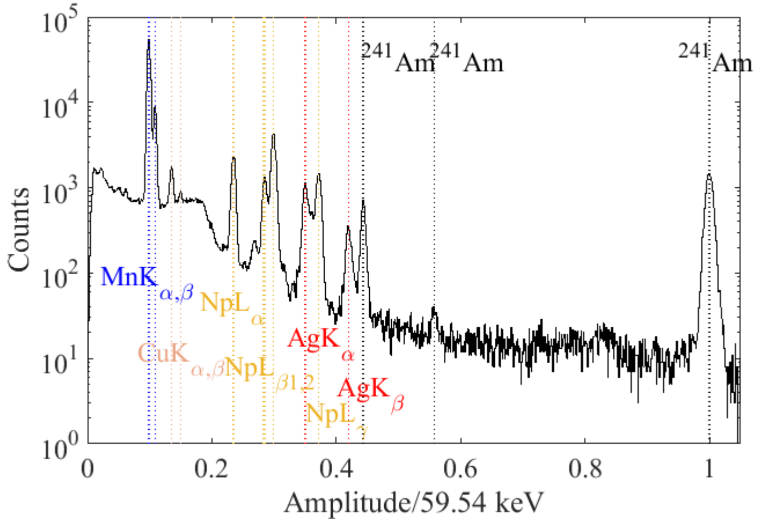


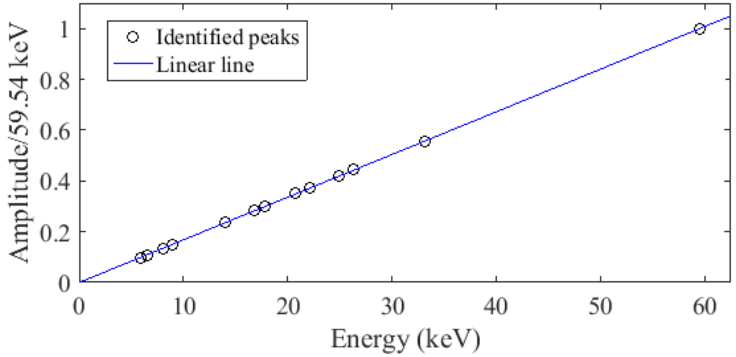
These effects are well understood from MC simulation and accounted for in the analysis.

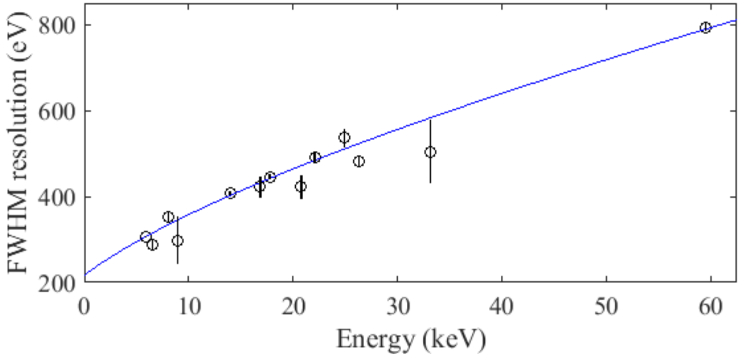
Detector Performance Basics (before neutron activation)











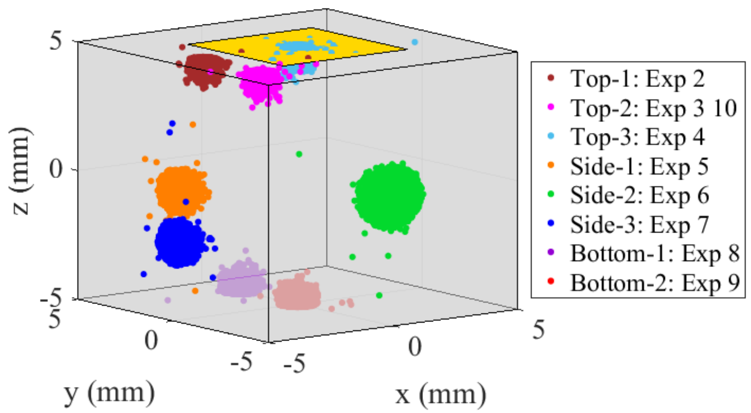
Measurement with internal ^{55}Fe and ^{241}Am calibration sources

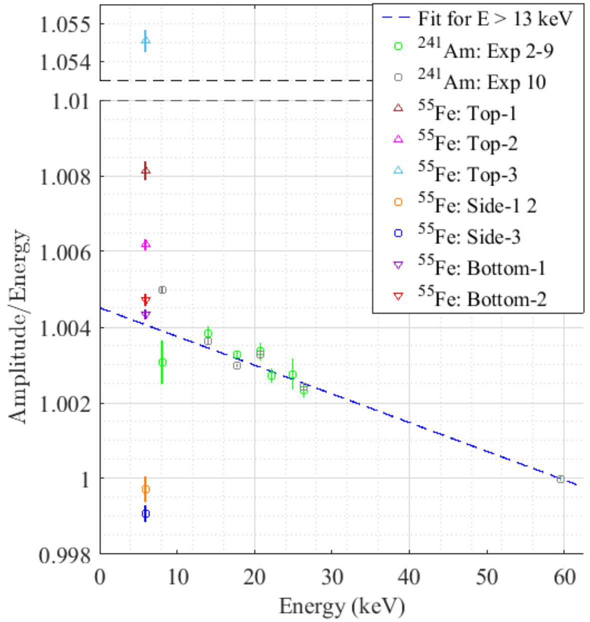
- All the peaks are clearly identified.
- Excellent linearity in energy calibration
- Excellent energy resolution (0.2~0.4 keV FWHM) in the ROI

Calibration (Energy + Position)

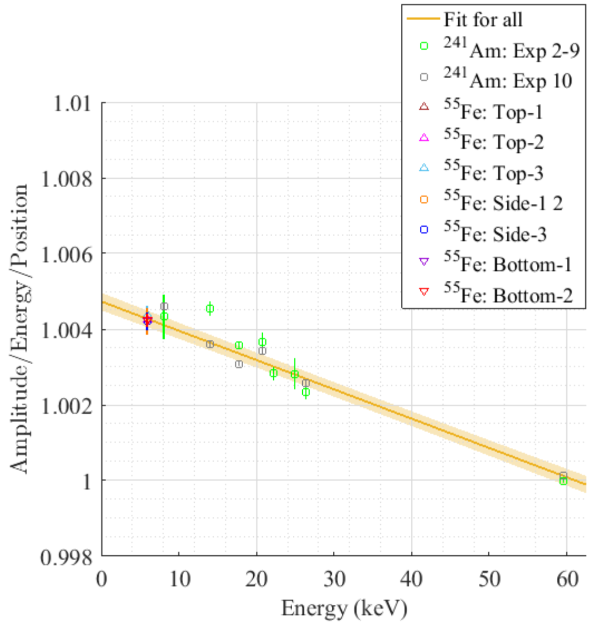
Some deviations are apparent from perfect linearity in the scale of Amp/Energy

Event locations of 5.9 keV X-ray absorption in LiF





Position calibration



$$\mathrm{Amp} = (\mathit{Position\ fuction})(\alpha \mathrm{E}^2 + \beta \mathrm{E})$$

$$\mathrm{Amp/Energy} = \overline{\mathrm{F}(x, y, z)}\,(\alpha \mathrm{E} + \beta)$$

- Each calibration peak corresponds to the energy and position of the events in the crystal.
- Calibration measurements were carried out in various source locations (^{55}Fe and ^{241}Am) for 21 event sets for energy-position calibrations.

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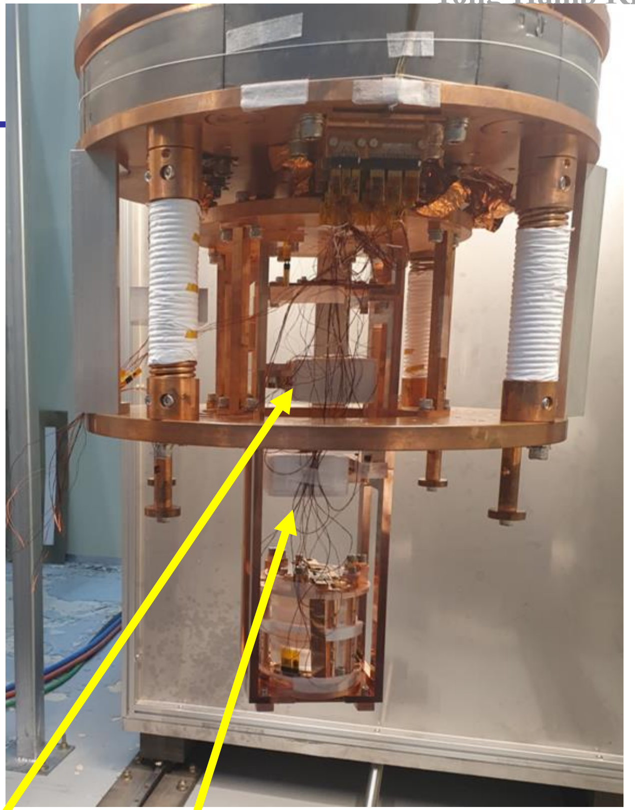
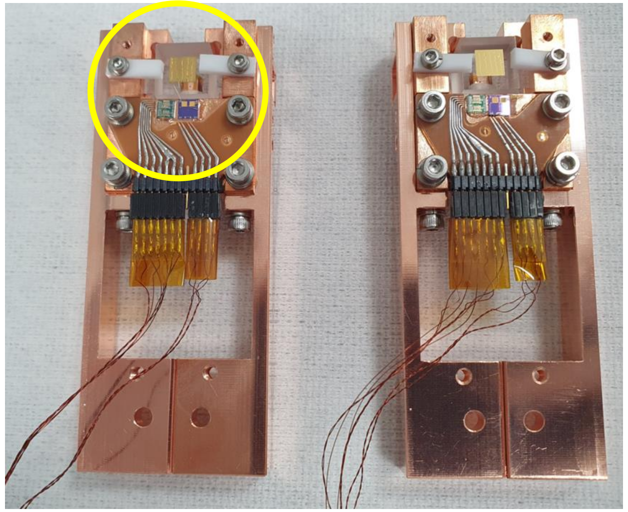
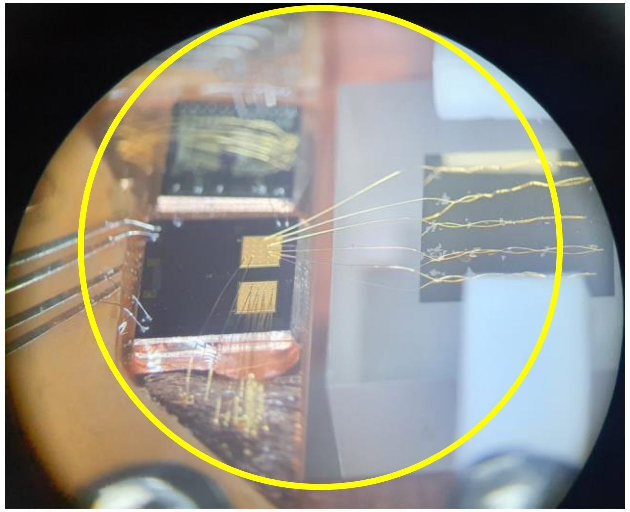
LiFE-SNS Phase1: two setups

- Two detector modules: $LiF(^3H)$ + MMC with 30 Bq and 39 Bq
- An internal ^{55}Fe source is employed on each crystal.
- The setups are attached to a dry DR surrounded by a Pb shield at the Daejeon HQ lab.
- Two-stage temperature control system with $\Delta T_{rms} \sim 0.5\ \mu K$
- Data taking period: May~Dec/2024

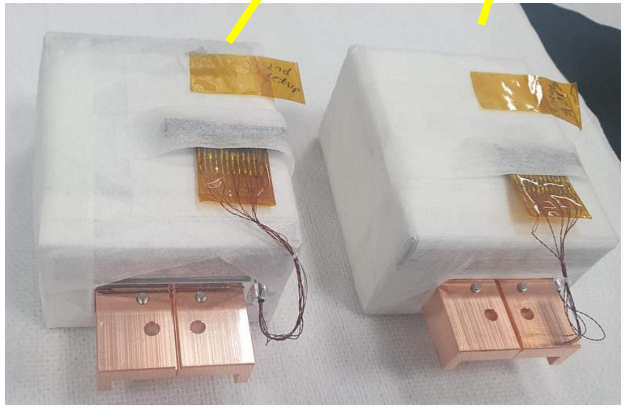


@IBS HQ Lab





Yong Chang Lee, SNU



Al case with
Ag and W plates

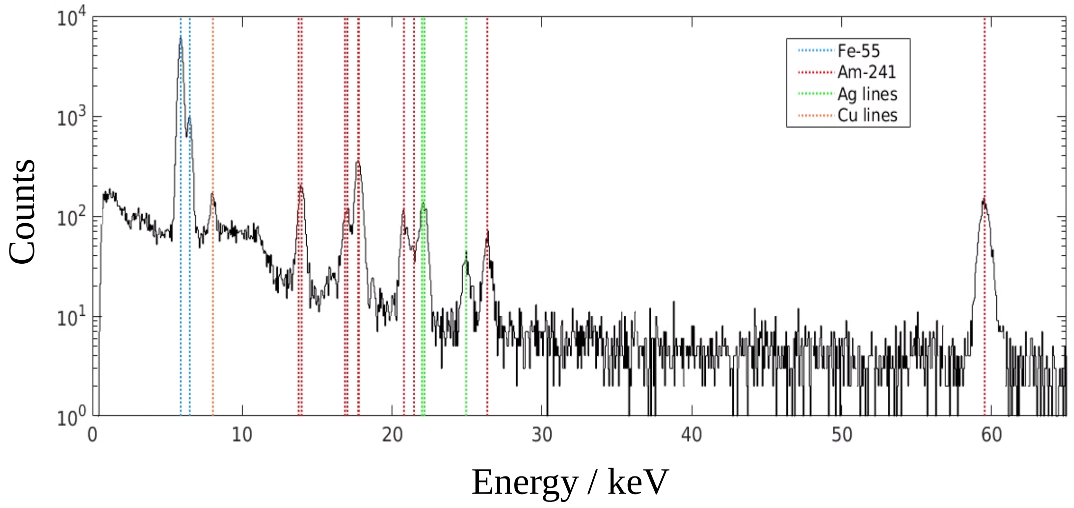
Calibration with ^{3}H β activities

Before neutron irradiation, internal sources (^{241}Am, ^{55}Fe).

➔ All the peaks were identified with good linearity.

The position calibration function was found.

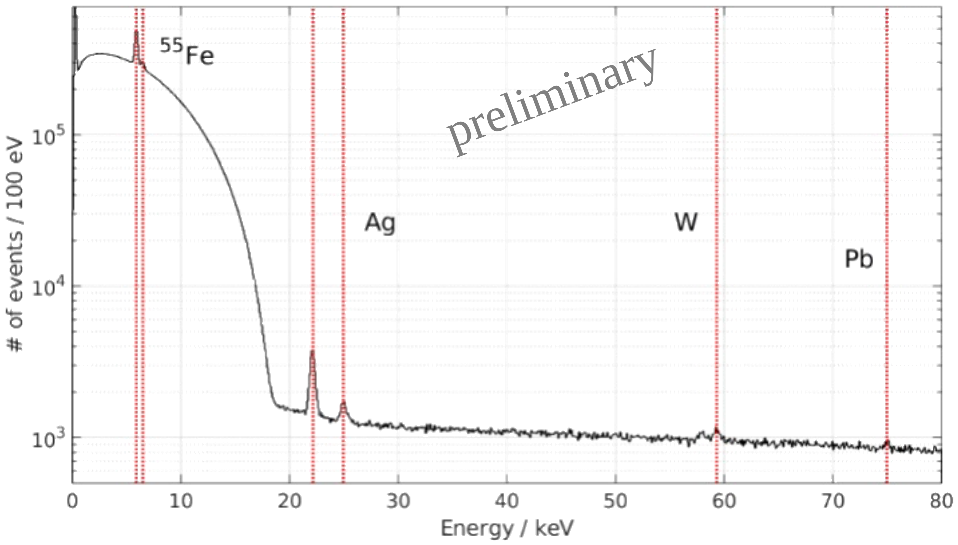
Calibration without ^{3}H in LiF



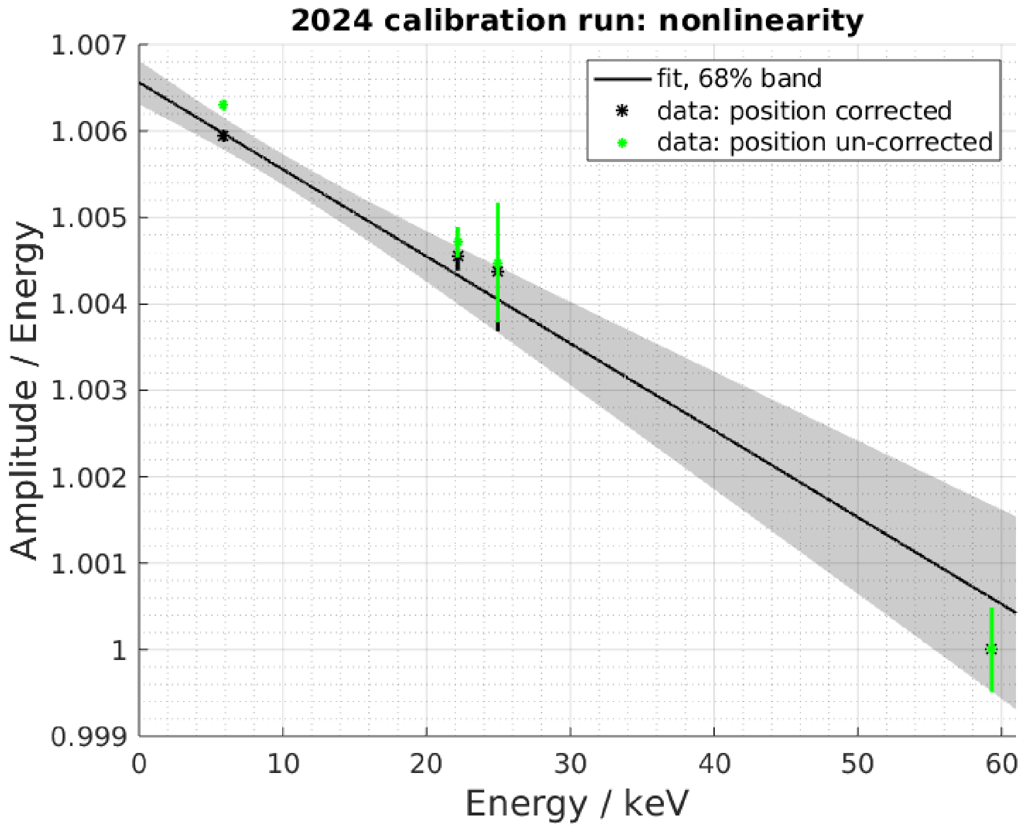
After neutron irradiation, internal ^{55}Fe + X-ray fluorescence

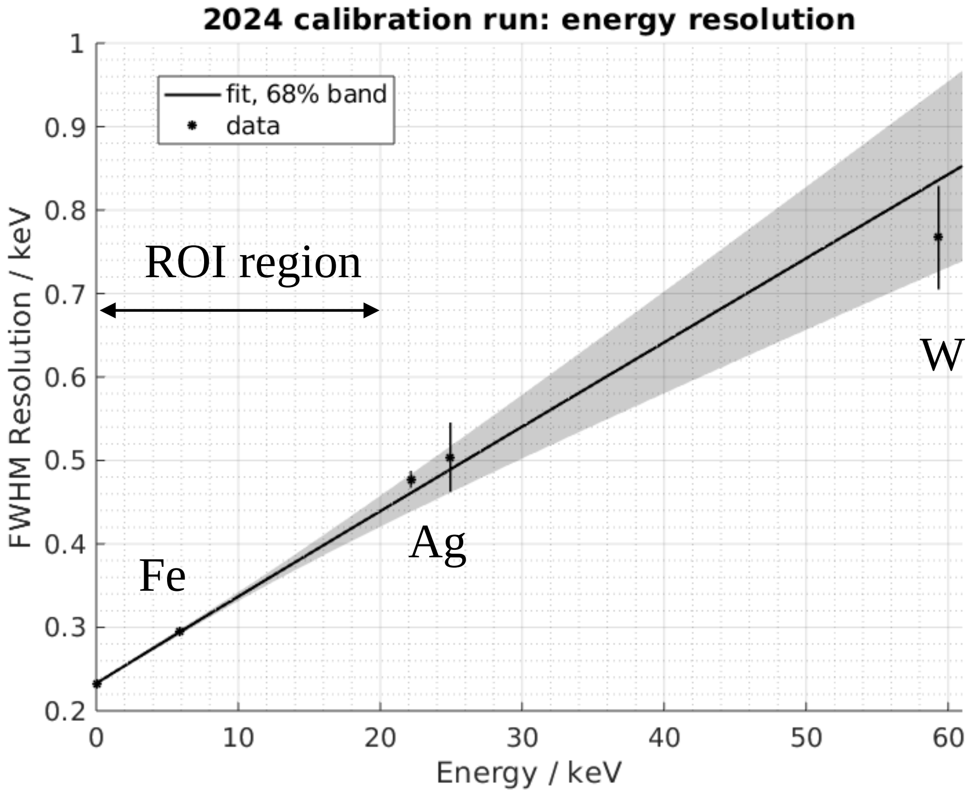
- Metal plates of (Ag, W on s.c. shield)
- Activated by external gamma sources
- ^{55}Fe(5.9, 6.5 keV): On
- Ag(22 keV, 25 keV), W(59 keV), Pb(75 keV): On and Off

Two week calibration run with ^{3}H in LiF



Energy calibration result





- Reasonable linearity and resolution are found.
- The calibration with the position correction function works for calibration lines.
- Systematic error from energy calibration and resolution is not dominant over the statistical error with 10^9 β events.

Theoretical ^{3}H spectrum

✓ Energy deposit in LiF: $E_{deposit} = E_{\beta^-} + E_{Recoil} + E_{Deexcitation} + E_{neutralization} = Q - E_\nu$

✓ Theoretical expectations are well-studied.

- Relativistic ^{3}H β spectrum including V-A, Weak magnetism current

$$M = \frac{G_F V_{ud}}{\sqrt{2}} \bar{u}(P_e)\gamma_\alpha(1-\gamma_5)v(P_\nu)\bar{u}(p_f)\left[G_V(q^2) + \frac{iG_M(q^2)}{2M_N}\sigma^{\alpha\beta}q_\beta - G_A(q^2)\gamma^\alpha\gamma_5\right]u(p_i)$$

- Fermi function, Recoiled coulomb potential, Finite nuclear size correction, Screened Coulomb correction
- Radiative correction
- Spectral shape is determined by initial and final atomic states

  Transition probability accounting for exchange effect between β^- and electron (bound).

  $^3H^0 \rightarrow \nu + \beta^- + {}^3He^+$ + neutralization : many He^+ states from $n = 1\sim30$

  $^3H^0 \rightarrow \nu + \beta^- + {}^3He^{2+} + e^-$ + neutrailzation : He^{2+} continuum

Refs: PRC 77, 055502 (2008), PRC 76, 045501 (2007), JCAP08(2014)038, JHEP 2016, 40 (2016), RMP. 90, 015008 (2018), JCAP02(2015)020, .JHEP 2023, 144 (2023)

✓ ^{3}H states in LiF (Solid state effect)

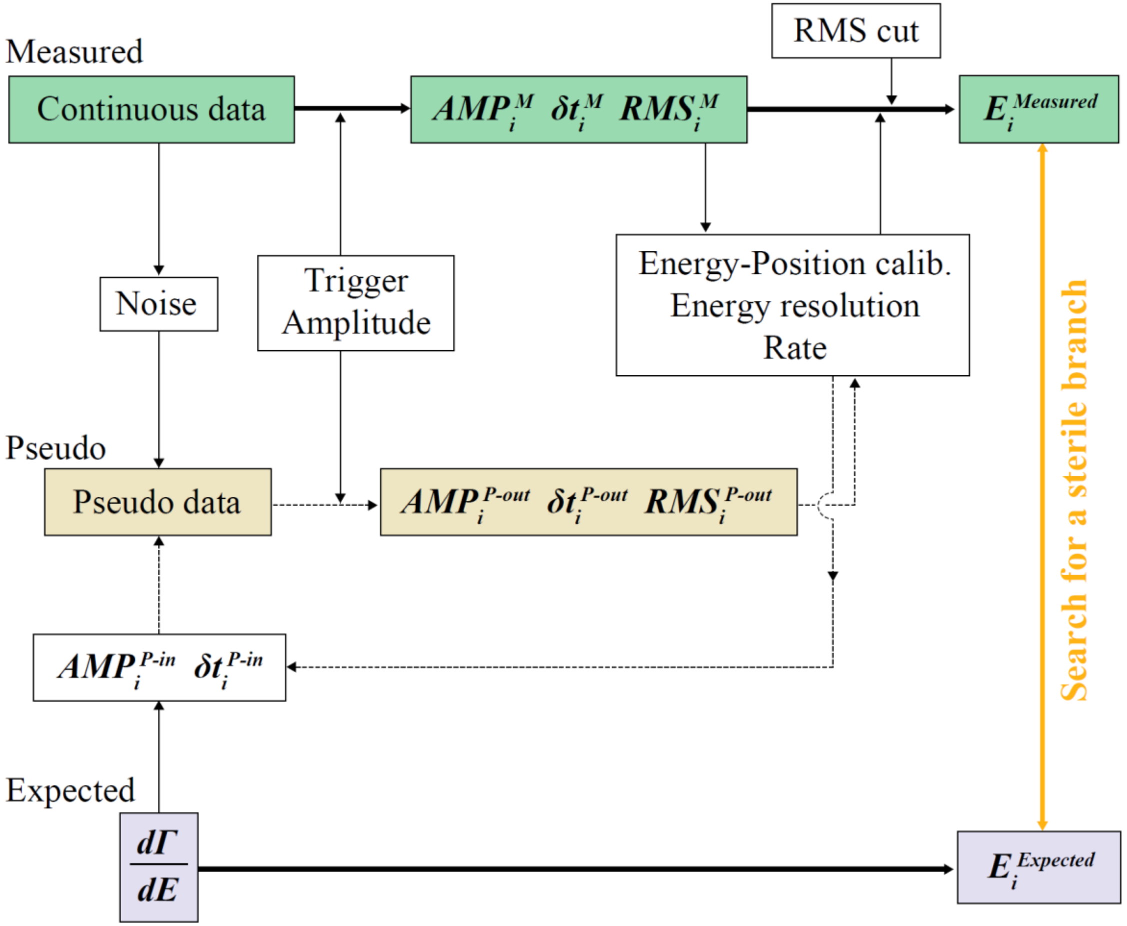
- Kazumata, Journal of the Physical Society of Japan 35(5), 1442 (1973):

  Tritiums in LiF may occupy interstitial lattice sites

- Quantum hybridization of the atomic orbitals should be considered between ^{3}H and the surrounding atoms (Li and F), requiring further theoretical modeling.

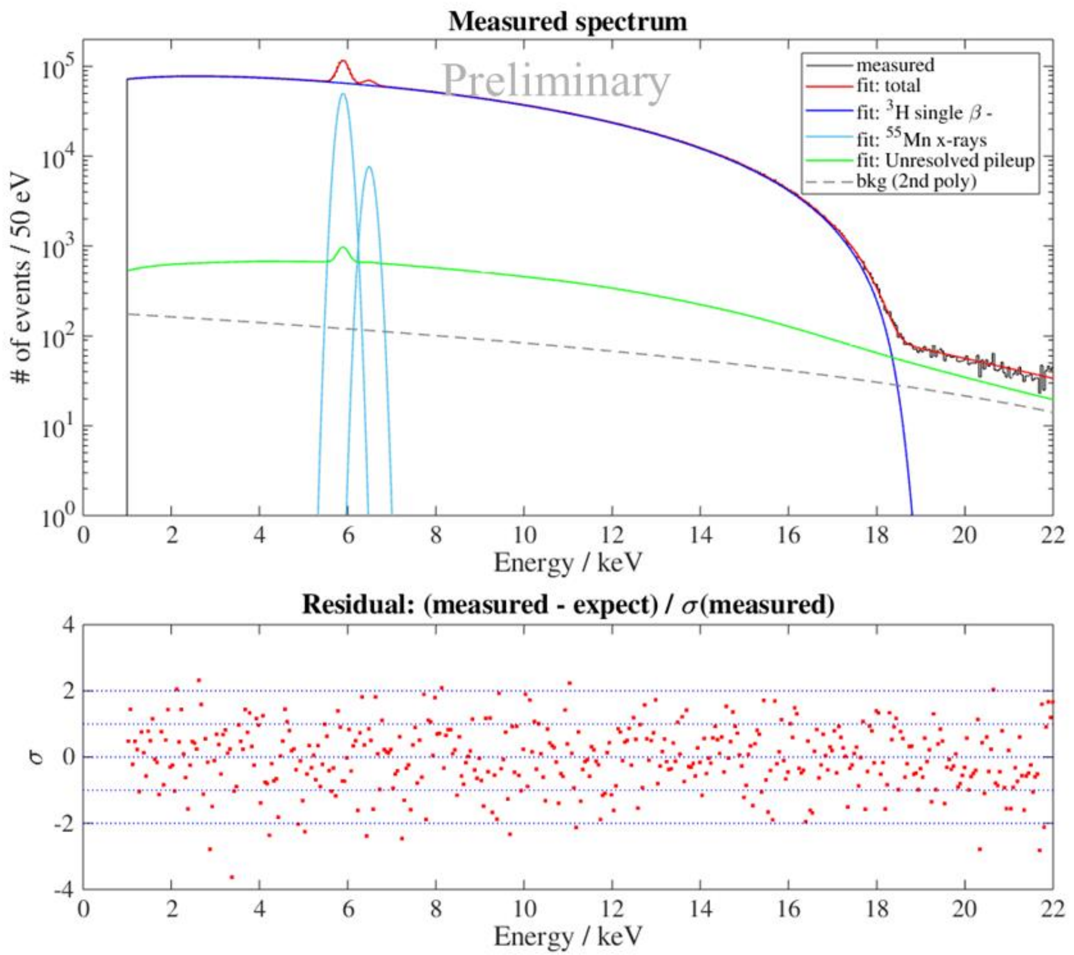
Analysis method for a decay branch with a heavy neutrino

- ✓ Amp → E (the energy spectrum) using calibration and any bias correction from simulation with measured noise data
- ✓ Comparison between the measured and expected spectra to find out any additional branch.



^{3}H β decay spectrum fitting

<Using one week of one channel data>



✓ $\chi^2/\mathrm{NDF} = 308.6/314$ in the analysis range 1~17 keV

➔ Good agreement between the measured and expected values.

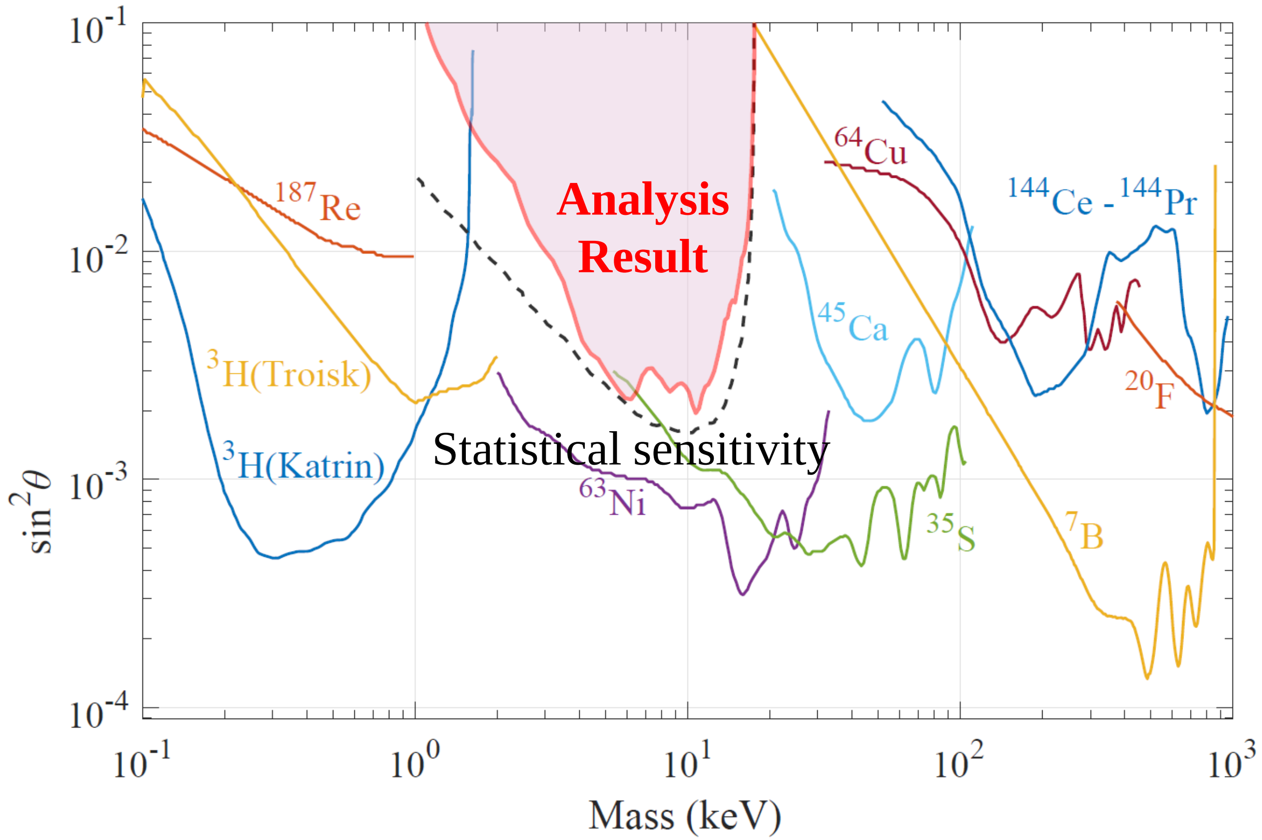
➔ We can activate the routine for sterile branch search.

We included
- ^{3}H distribution in the LiF crystal
- Position calibration function
- One channel 7-day data
  (~1/30 of the measured data)

Exclusion limit with 1-ch 7-day data

The null hypothesis is preferred.

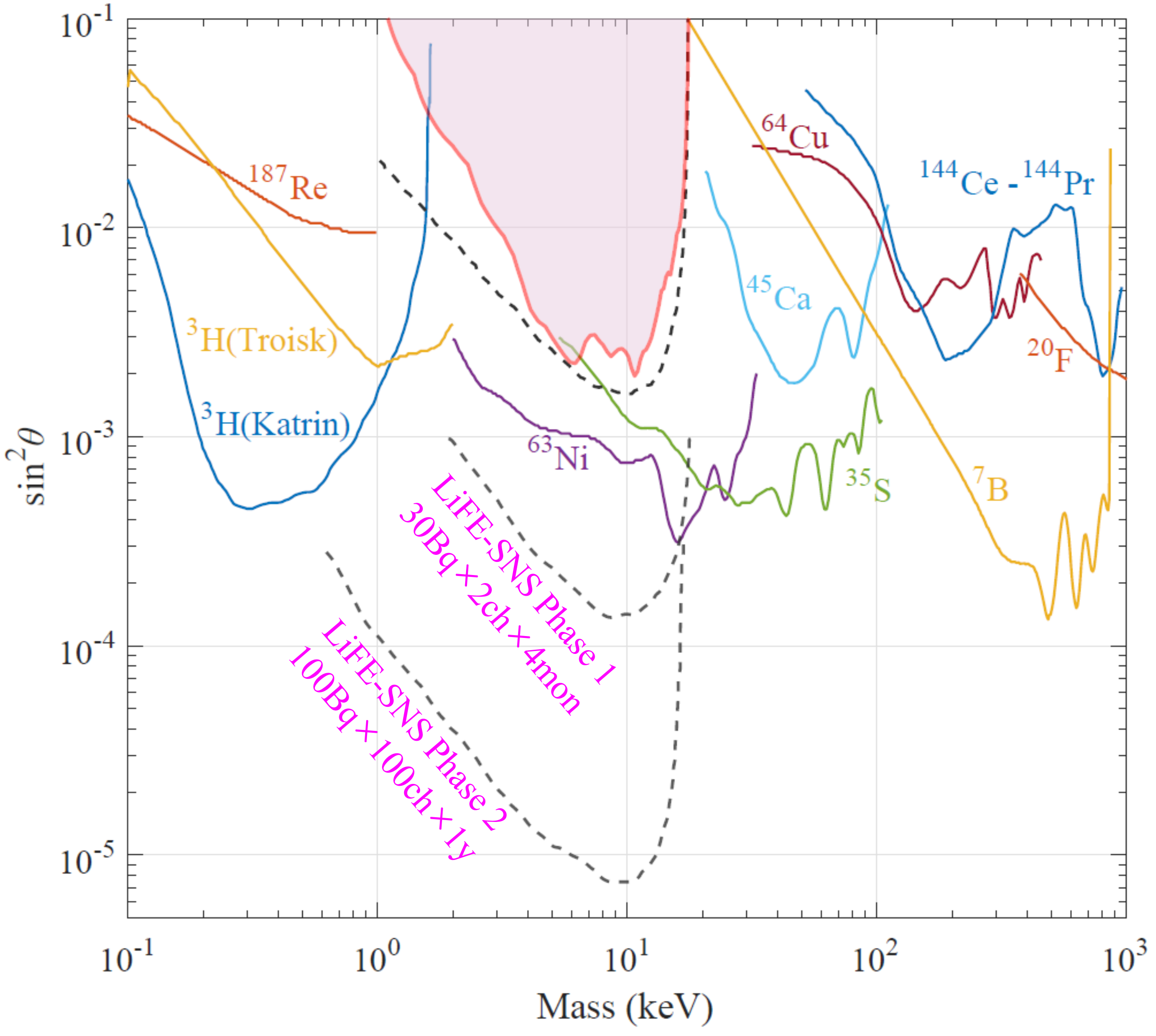
Close to the best limit in 10 keV region



The exclusion limit with 1-ch 7-day data reaches to a $\sin^2\theta$ sensitivity of 10^{-3}

in the 10 keV region, comparable to the current best limits.

Expected limit (LiFE-SNS)



2024 measurement: LiFE-SNS Phase 1
- 2 detectors × 35 Bq × 4 month: 0.8 B β events
- Aboveground measurement
- $\sin^2\theta$ sensitivity:
  - ~ 10^{-3} found with only 1/30 data
  - ~ 2×10^{-4} expected (analysis result will come soon)
- Most stringent limit near 10 keV region
- Further systematics are being investigated

LiFE-SNS Phase 2
- When low systematic error is confirmed.
- 100 detectors × 100 Bq × 1 year
- $\sin^2\theta$ sensitivity: ~ 7×10^{-6}
- Underground measurement

Stay tuned for the signal from LiFE-SNS

Yong-Hamb Kim

Summary LiFE-SNS

- The precise spectrum of ^{3}H β decays measured in LiFE-SNS provides a suitable tool to investigate sterile ν's.

- The Phase-1 measurement was finished for 2ch × 35 Bq × 4 months.
  - A preliminary analysis shows **a good agreement** between the measured and expected spectra **within 1.05 σ statistical deviations.**
  - This analysis results in **a $\sin^2\theta$ sensitivity of 10^{-3} found with 1-ch 7-day data**.
  - A complete analysis will have **an expected sensitivity of ~10^{-4}**, which would be **the most stringent limit** of sterile neutrino search **near m_s ~ 10 keV.**

- Phase 2, with 100 channels, is to be prepared.

Stay tuned to LiFE-SNS