Search for keV-Scale Sterile Neutrinos via ^3H Beta Decay in LiF Crystals

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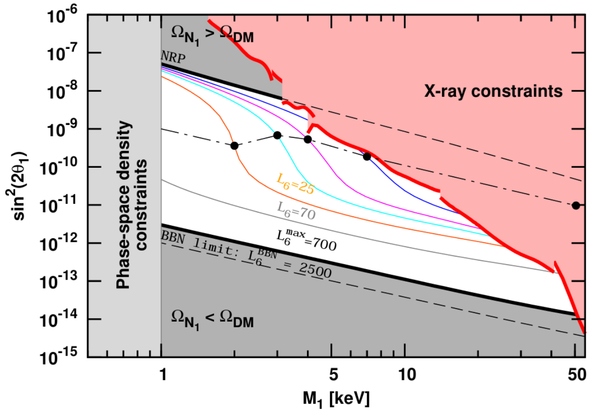
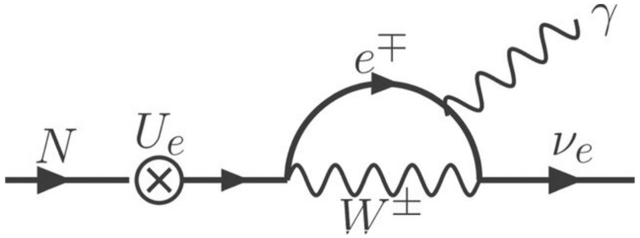
Motivation for keV-scale Sterile Neutrino Searches

- Neutrino oscillations → Beyond Standard Model physics
  - ▶ Suggest **existence of sterile neutrinos**
- Cosmological production (Dodelson–Widrow, Shi–Fuller, ...)
  - ▶ keV sterile neutrinos are **Dark Matter candidates**
- X-ray observations
  - ▶ but depend on **cosmological models**



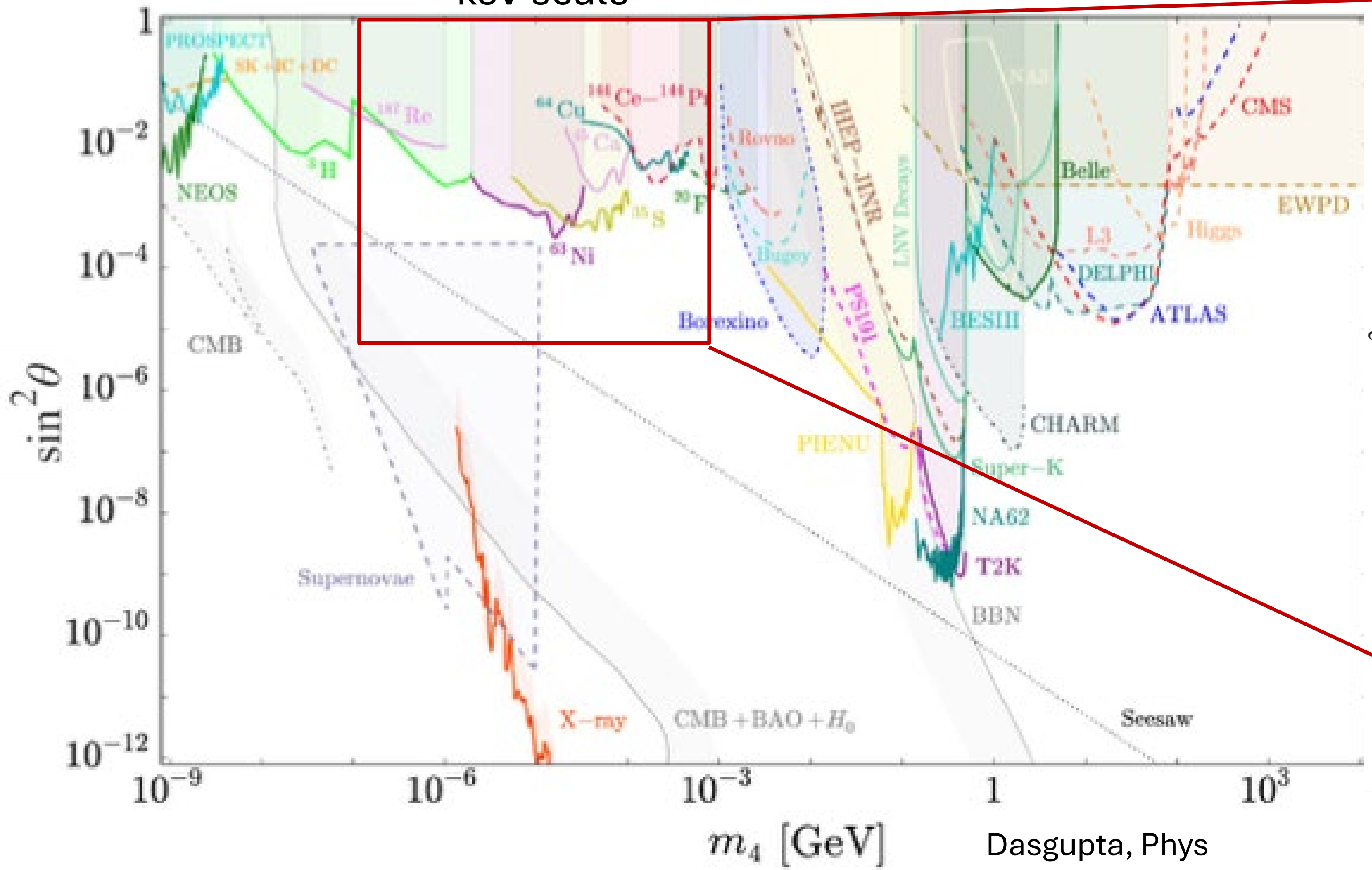


$$\sin^2(2\theta) < \mathcal{O}(10^{-10})$$

Model-independent search for a sterile neutrino emission branch in beta decay

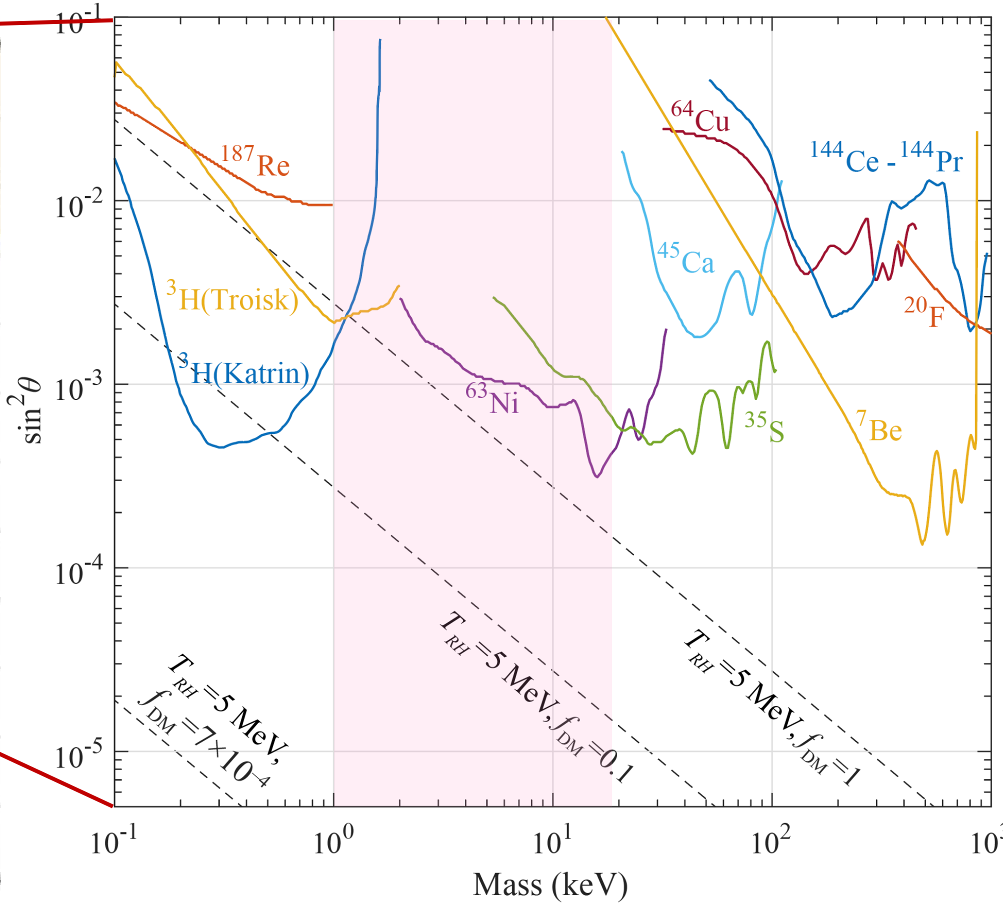
Current limit for $\sin^2\theta$ and m_s

keV scale



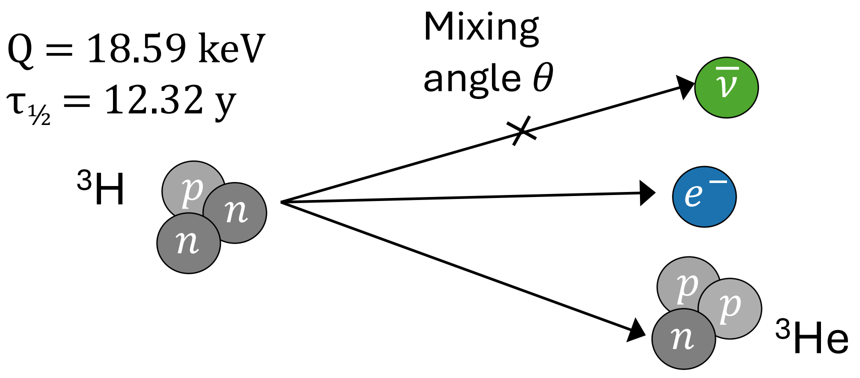
Dasgupta, Phys Rep(2021)

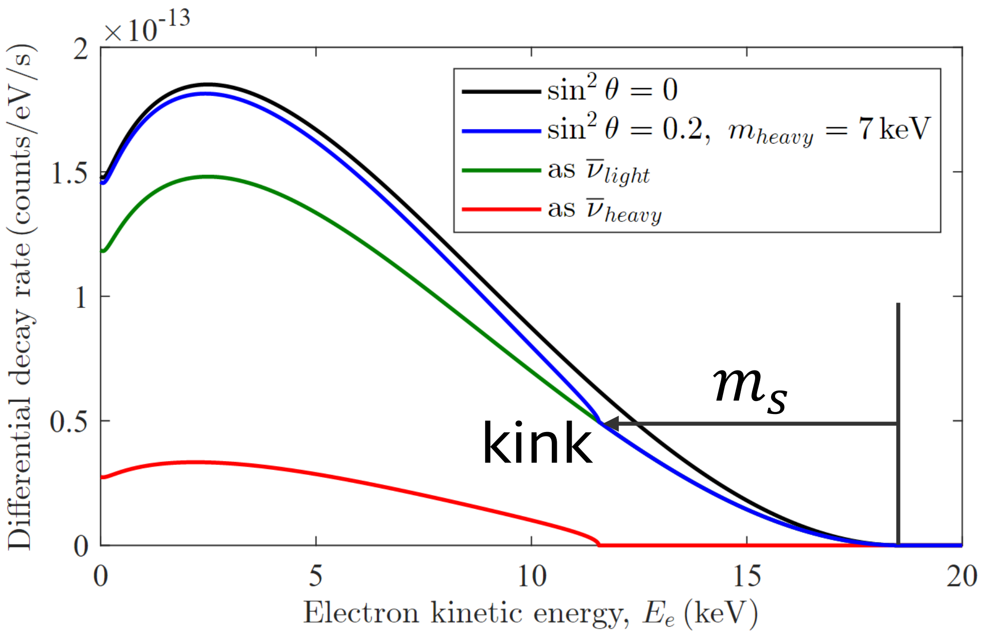
ROI of this work



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

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





- Sterile neutrino (ν_s) feebly mixing with active neutrino (ν_e)

$$\begin{pmatrix}\nu_e\\ \nu_s\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_{\text{light}}\\ \nu_{\text{heavy}}\end{pmatrix}$$

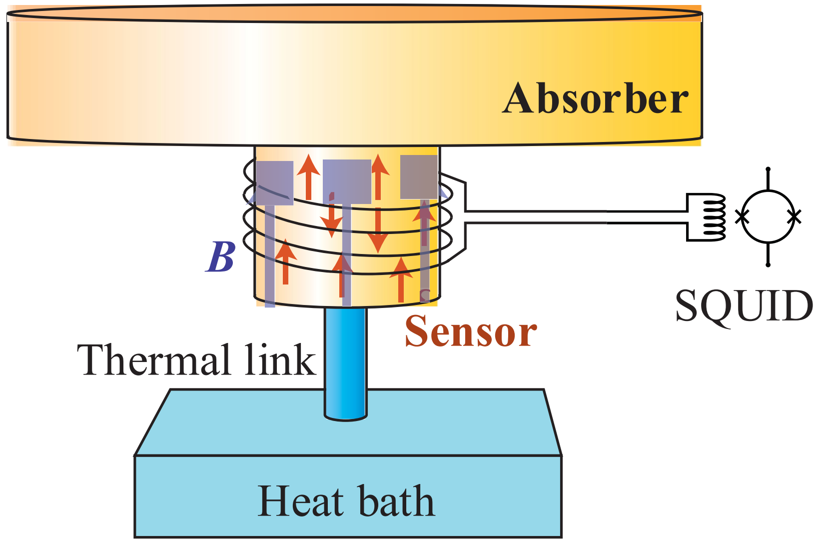
$$\frac{d\Gamma_{\text{tot}}}{dE}(E_e; m_{\text{light}}, m_{\text{heavy}})$$

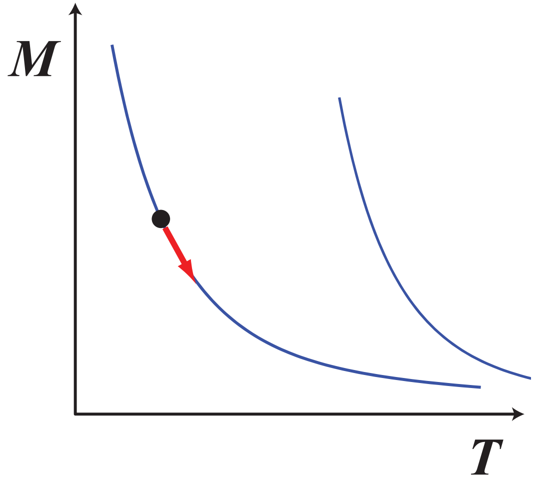
$$= \cos^2\theta\,\frac{d\Gamma}{dE}(E_e; m_{\text{light}}) + \sin^2\theta\,\frac{d\Gamma}{dE}(E_e; m_{\text{heavy}})$$

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

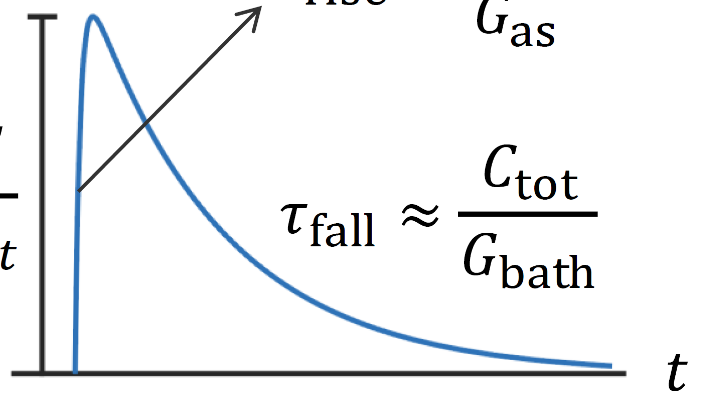
Low Temperature Detector (LTD)
Magnetic MicroCalorimeters (MMC)

C : Heat capacity
G : Thermal conductance
M : Magnetization
T : Temperature
$\delta\Phi$: Magnetic flux





$$\delta T \approx \frac{\delta E}{C_{tot}}$$

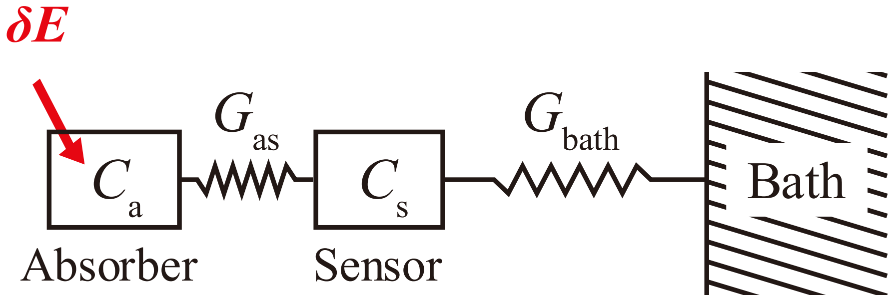


$$\tau_{\text{rise}} \approx \frac{C_{\text{eff}}}{G_{\text{as}}}$$

$$\tau_{\text{fall}} \approx \frac{C_{\text{tot}}}{G_{\text{bath}}}$$

$$\delta E \rightarrow \delta T \rightarrow \delta M \rightarrow \delta\Phi$$

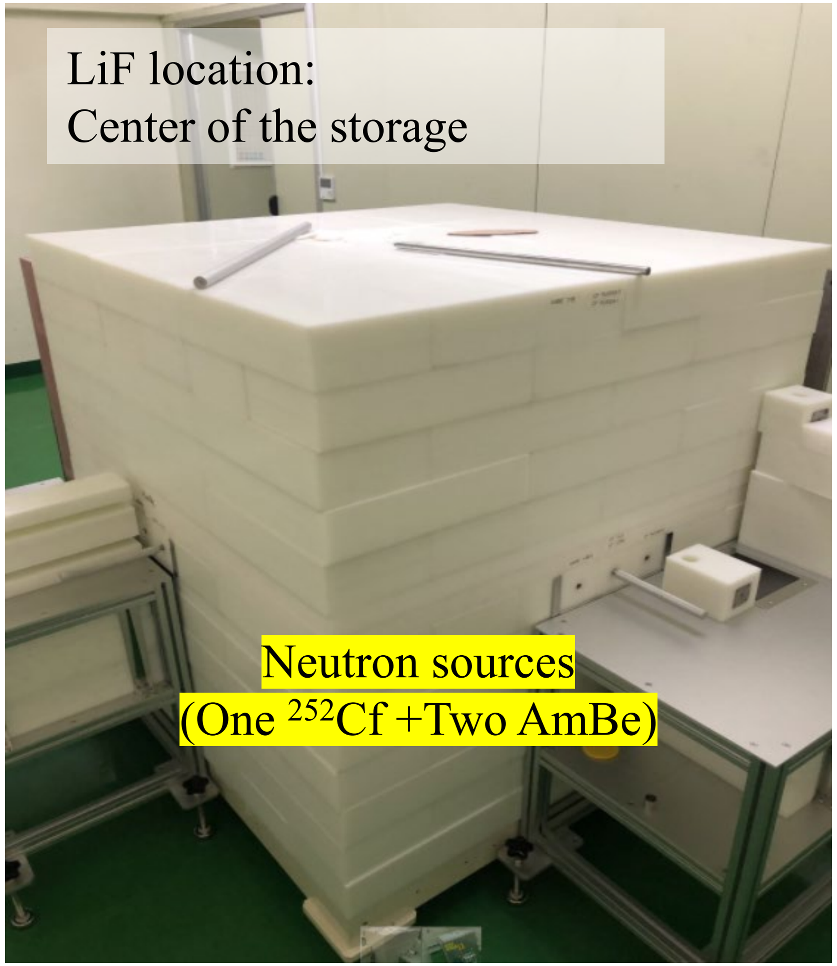
- Paramagnetic alloy in a magnetic field
- Au:Er, Ag:Er (300-1000 ppm)
- Metal host - Fast thermalization
- High resolution
- Good linearity
- Large dynamic range



$$\delta\Phi \propto \frac{\partial M}{\partial T}\frac{\delta E}{C_{tot}}$$

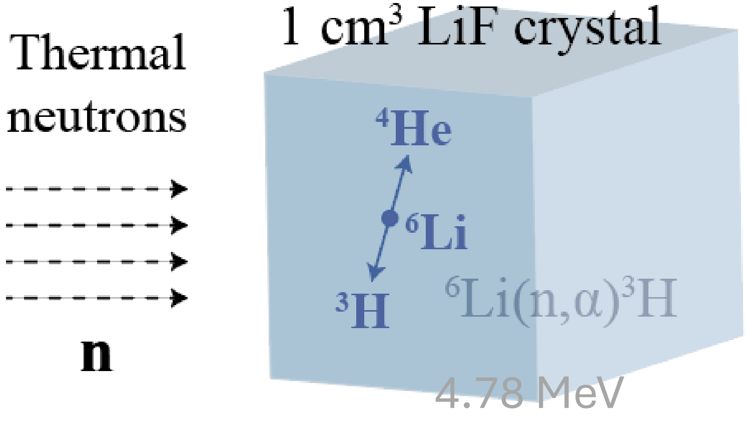
^{3}H Production in LiF Cubic Crystals

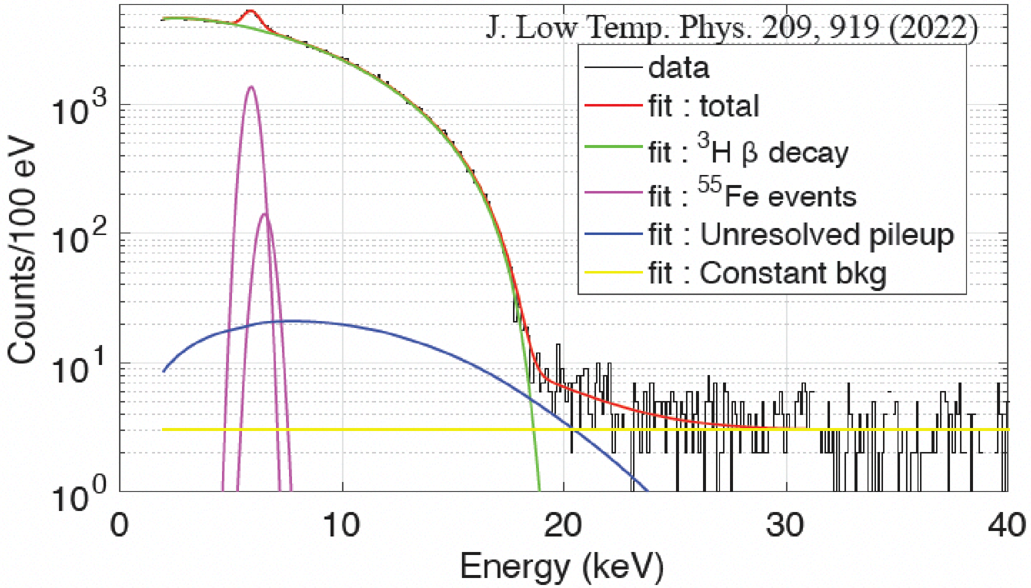
Mean free path:
2.3 mm in LiF with 7.6 % ^{6}Li



Neutron irradiation at KRISS

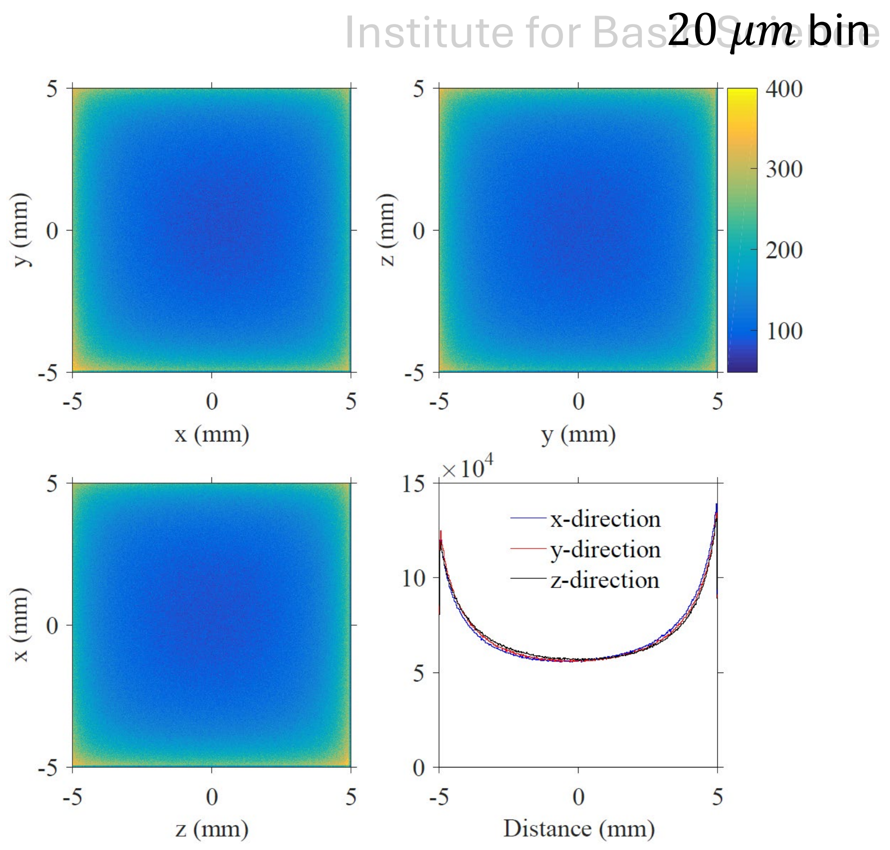
Week exposure → ~ 20 Bq in a LiF





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

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

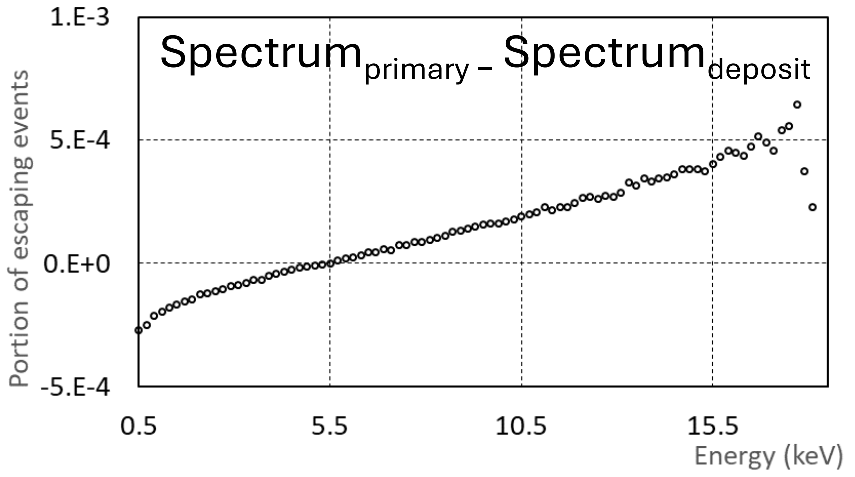


✓ Non-uniform ^{3}H distribution in 1×1×1 cm^3 LiF

- 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

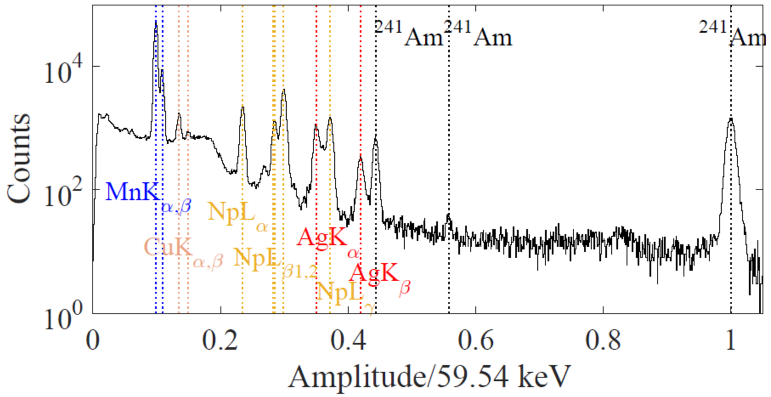
✓ Possible energy loss of decay energy other than neutrino

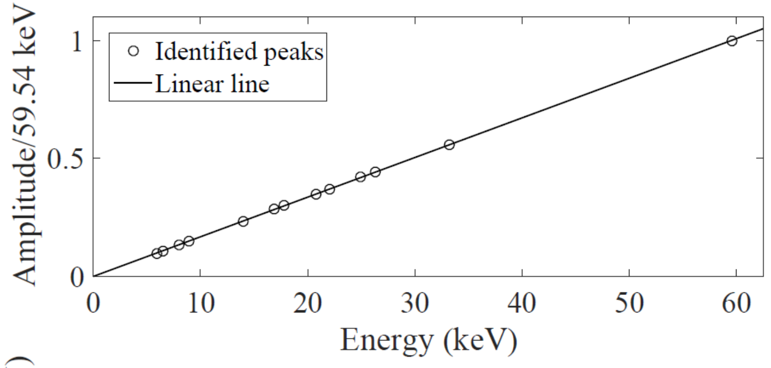
- MC simulation includes surface escapes of electrons and bremsstrahlung X-ray
- Stopping range of 18 keV β^- in LiF ~ 0.5 μm

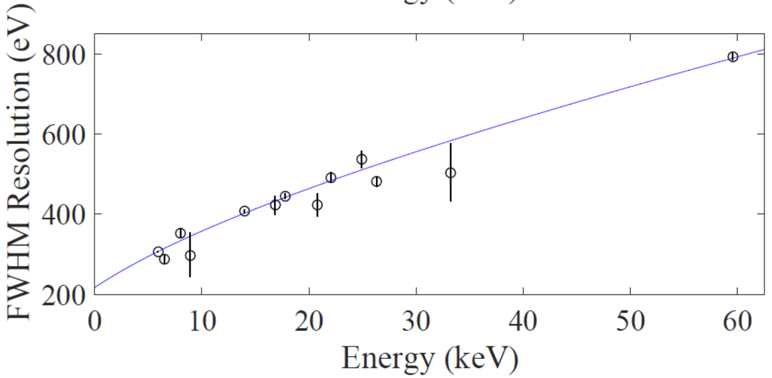


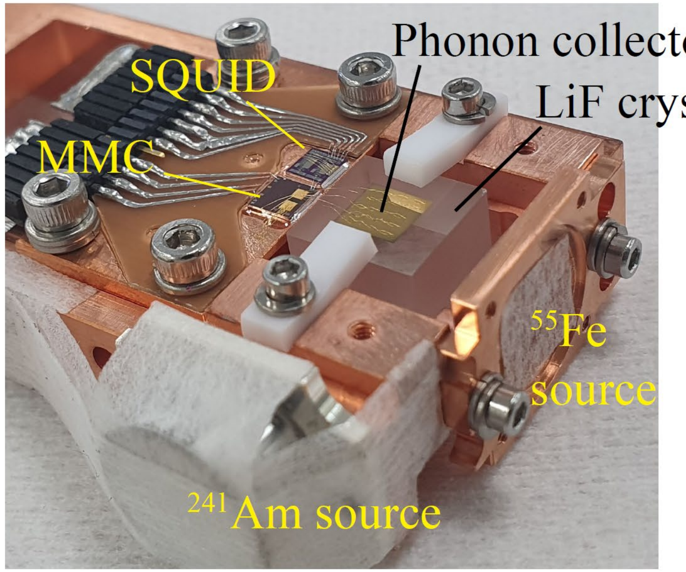
These effects are well understood from MC simulation and accounted for in the analysis.

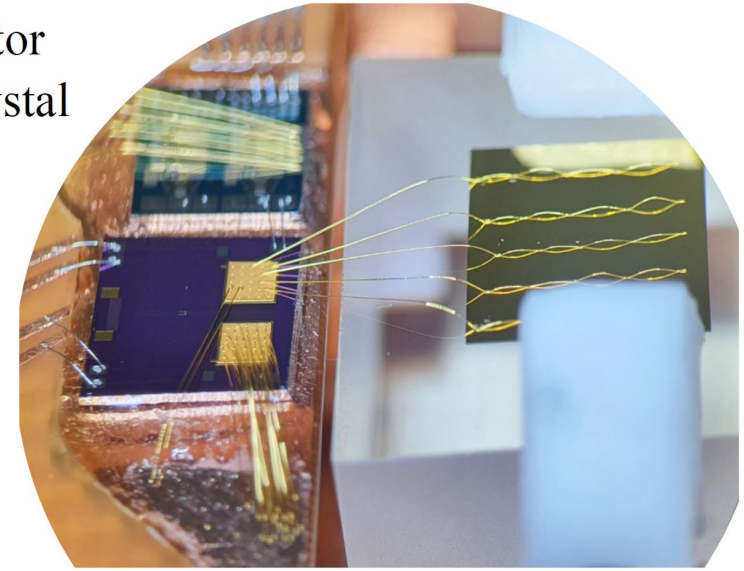
Detector Performance Basics (**Before** neutron activation)



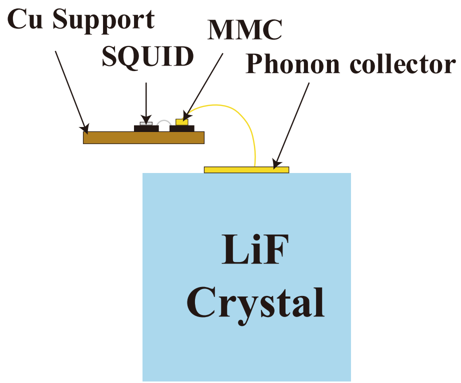








Measurement with internal ^{55}Fe and ^{241}Am calibration sources



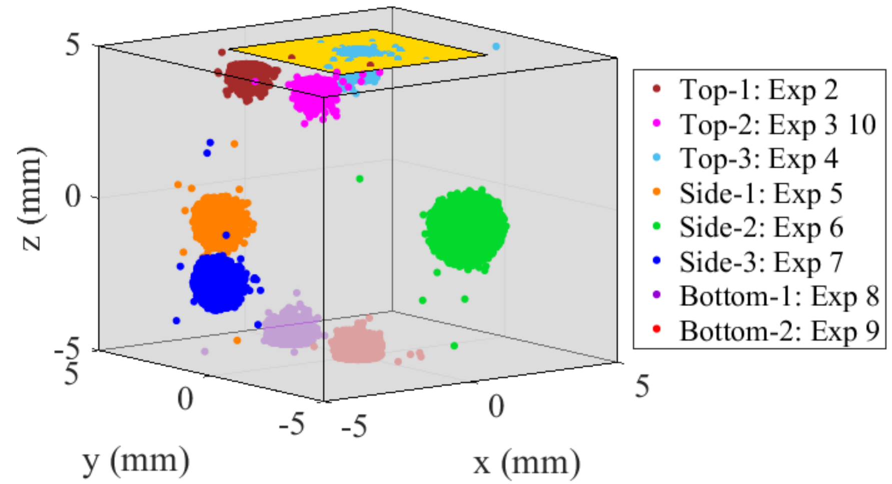
- Backgound measurement
- All the peaks are clearly identified.
- Excellent linearity in energy calibration
- Excellent energy resolution (0.2~0.4 keV FWHM) in the ROI

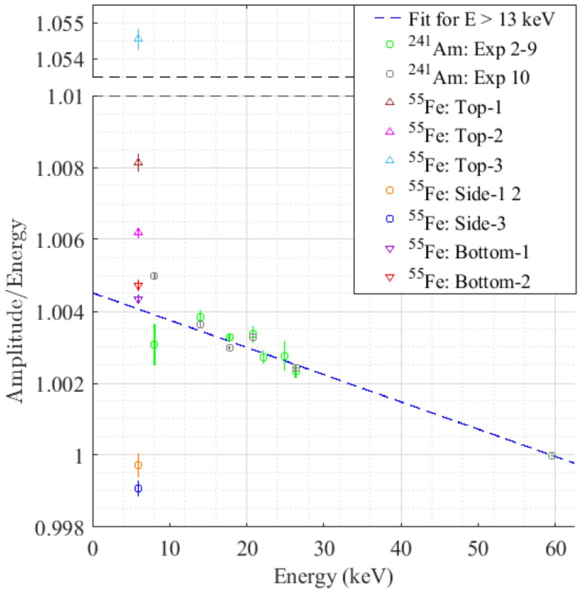
Calibration (Energy + Position)

Exp.		Refrigerator	Calibration sources
1		DR	^{55}Fe, ^{241}Am with Ag collimator
2–9		ADR	^{55}Fe, ^{241}Am with Ag collimator
10		ADR	^{55}Fe, ^{241}Am with Cu collimator
11[a]	Calibration	DR	^{55}Fe, (Ag, W)[b]
	β-spectrum	DR	^{55}Fe

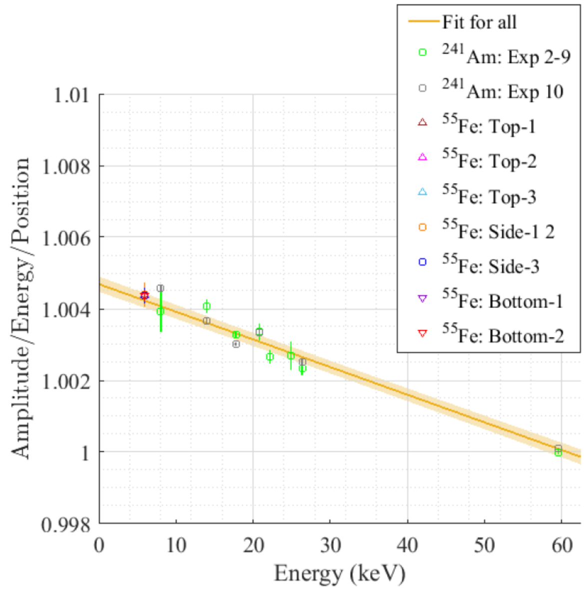
[a] Exp. 11 was carried out after neutron activation.
[b] Characteristic X-rays of Ag and W could be activated from external γ sources during the calibration run.

Simulated positions of 5.9 keV X-ray events (Mn K_α) absorbed in the LiF crystal from various ^{55}Fe source locations used in Exp. 2–10.





Position calibration

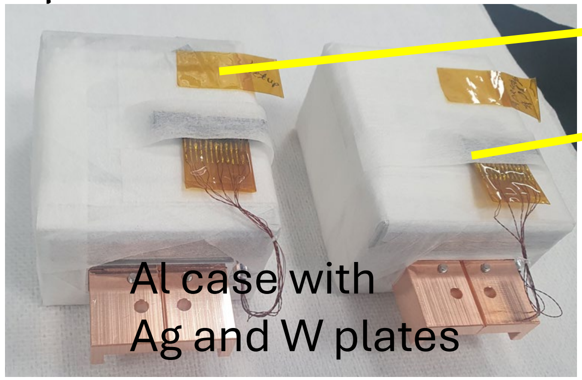


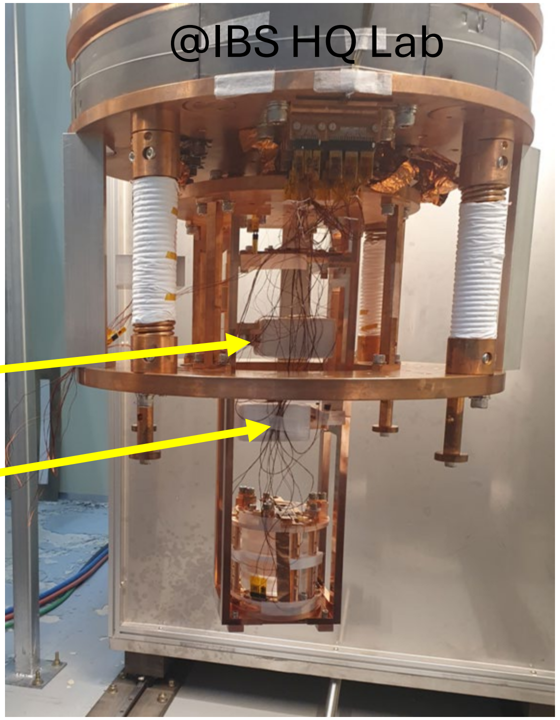
$$\mathrm{Amp} = (Position\ fuction)(\alpha \mathrm{E}^2 + \beta \mathrm{E})$$

- 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.

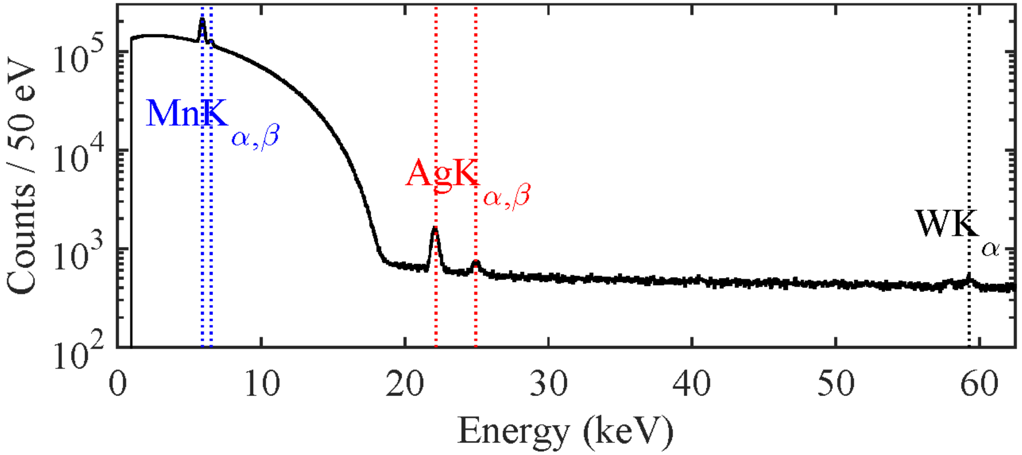
LiFE-SNS Phase1: two setups (**After** neutron activation)

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





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

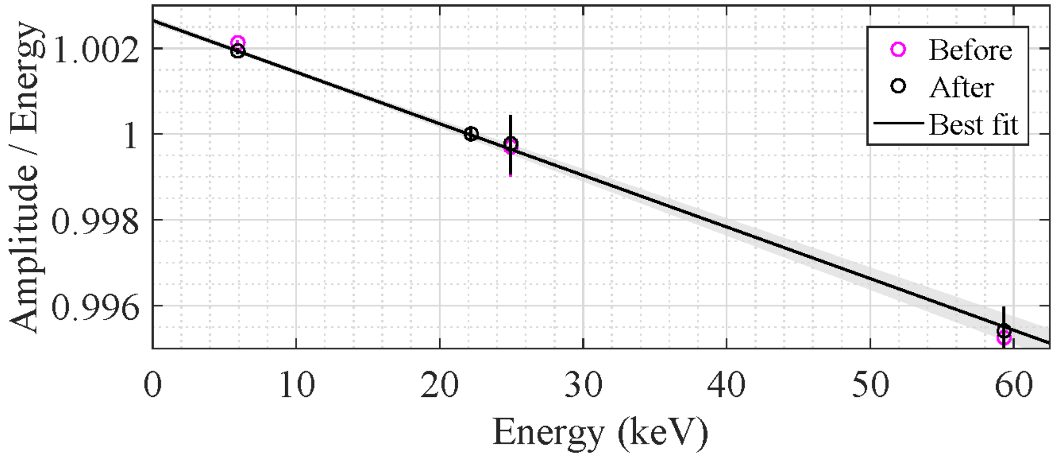


After neutron irradiation, internal ^{55}Fe + X-ray fluorescence

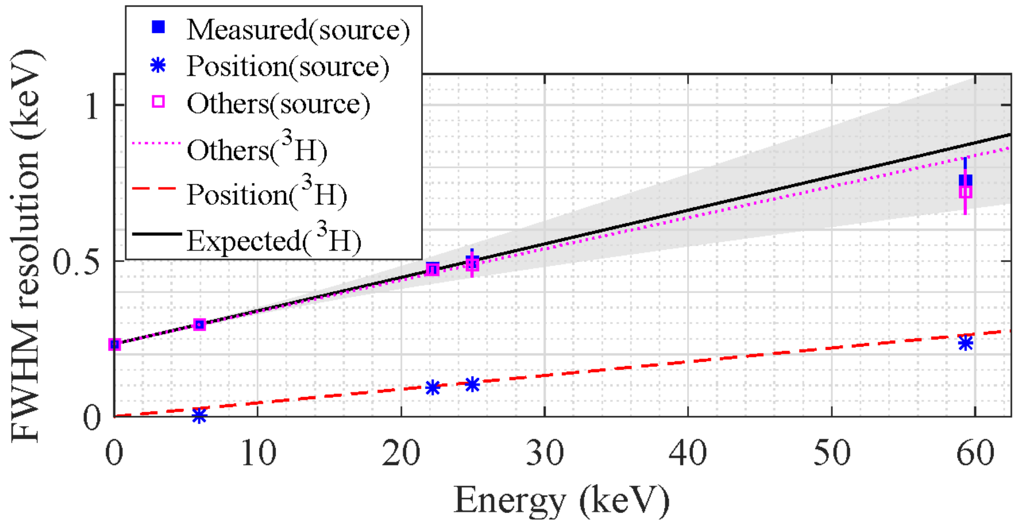
- Metal plates of (Ag, W on s.c. shield)
- Activated by external gamma sources
- ^{55}Fe(5.9, 6.5 keV): On
- Ag(22 keV, 25 keV), W(59 keV), Pb(75 keV): On and Off

Energy calibration result (**After** neutron activation)

Position dependence correction



Normalized to the expected amplitude for the 22.16 keV Ag K_α template



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

24.5873(1+), 79.0052(2+) eV

✓ Theoretical expectations are well-studied.

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

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

- 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.

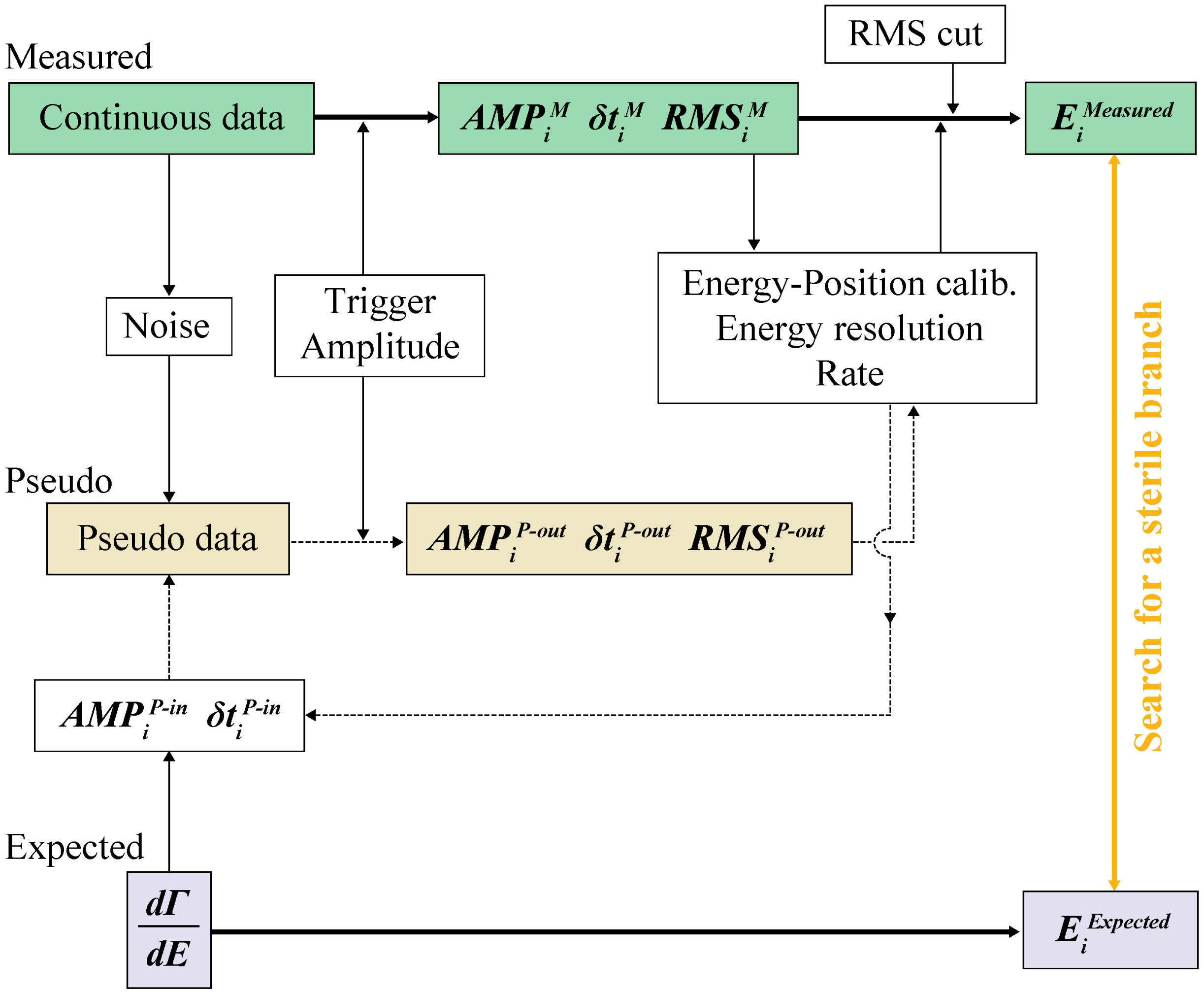
AMP : Amplitude of the signal, proportional to the deposited energy
δt : Time interval between signals
RMS : Difference in shape between the measured and the reference signal (Template)

Analysis method

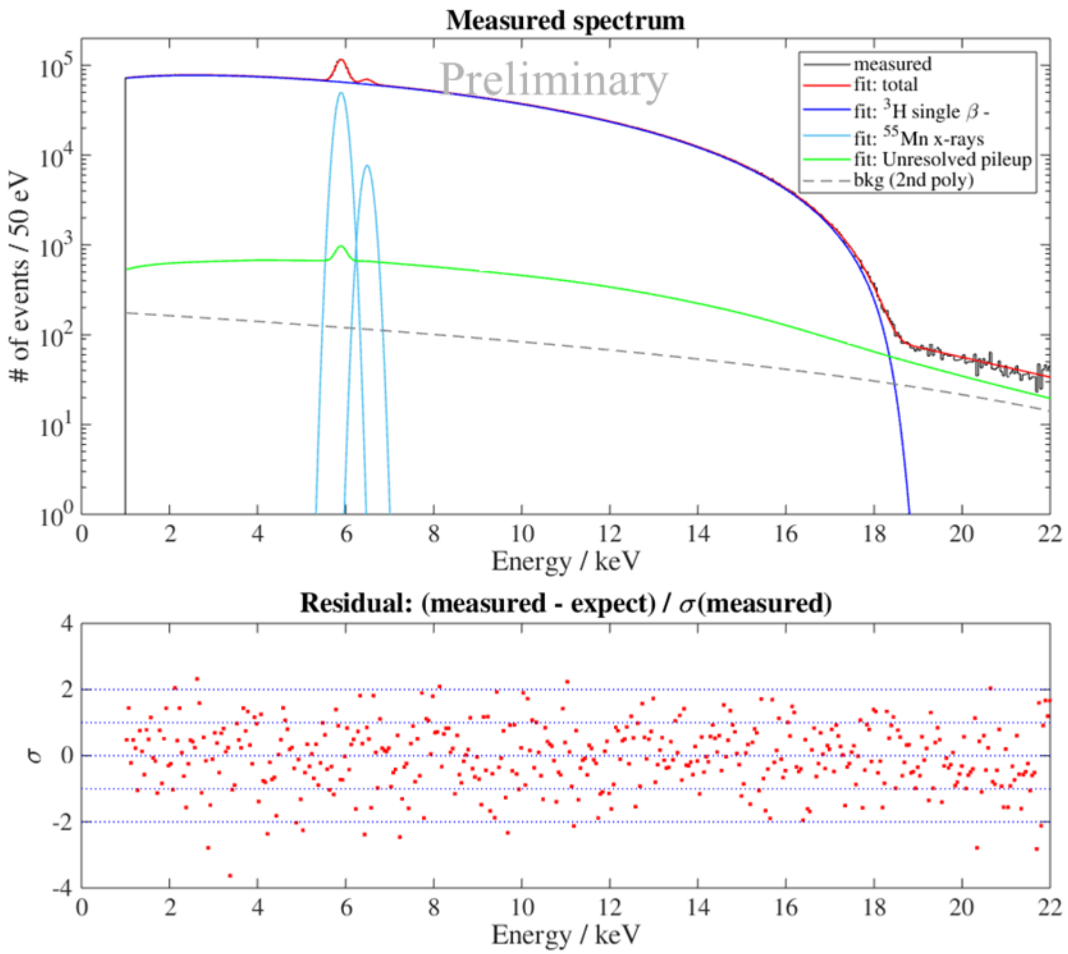
$$RMS = \sqrt{\frac{\sum_{n=1}^{N}(S_n - AMP \cdot T_n)^2}{N}}$$

S : The signal in time series
T : Template signal in time series
N : Number of bins in analysis window

- Noise
- Template
- Expected distribution
- Event rate



$^{3}\mathrm{H}\ \beta$ decay spectrum fit: Using one week (7 days) of one channel



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

➔ Good agreement between the measured and expected values.

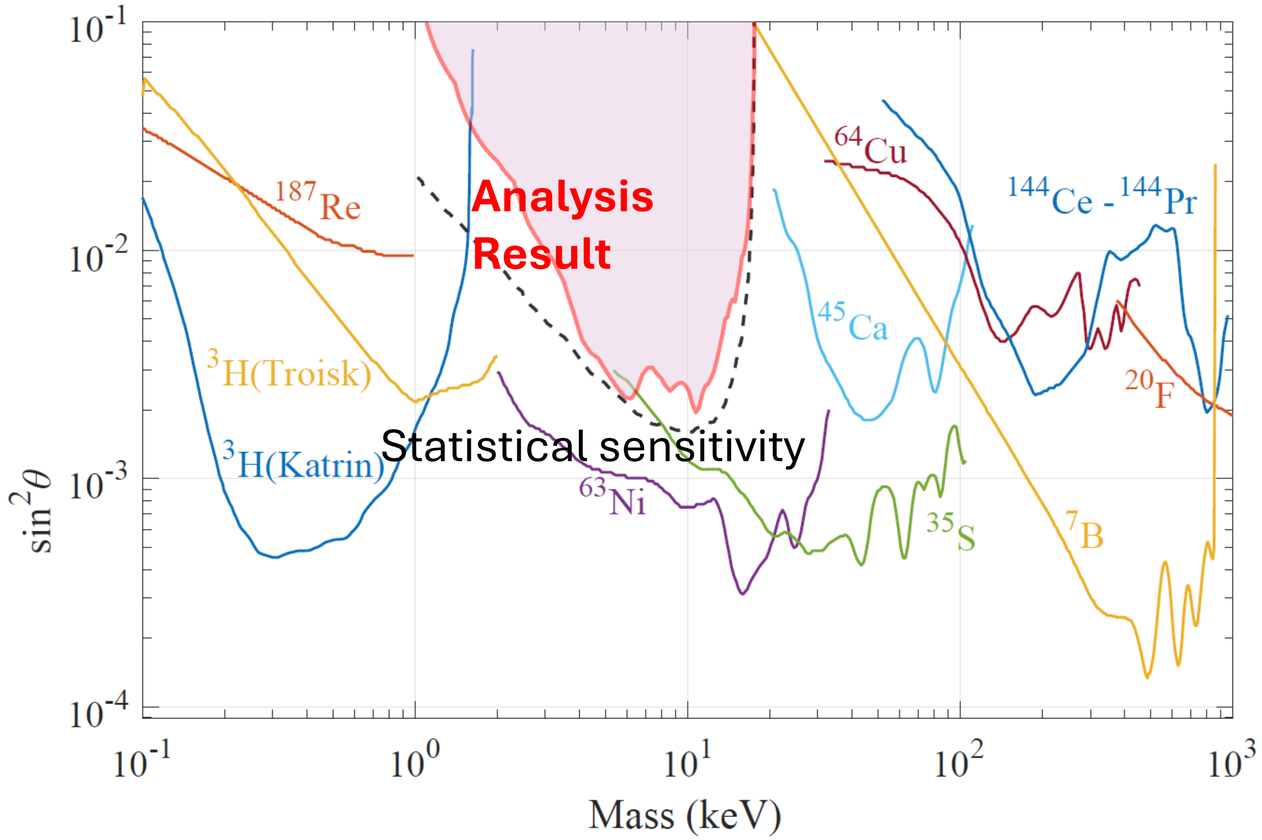
➔ We can activate the routine for sterile branch search.

We included

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

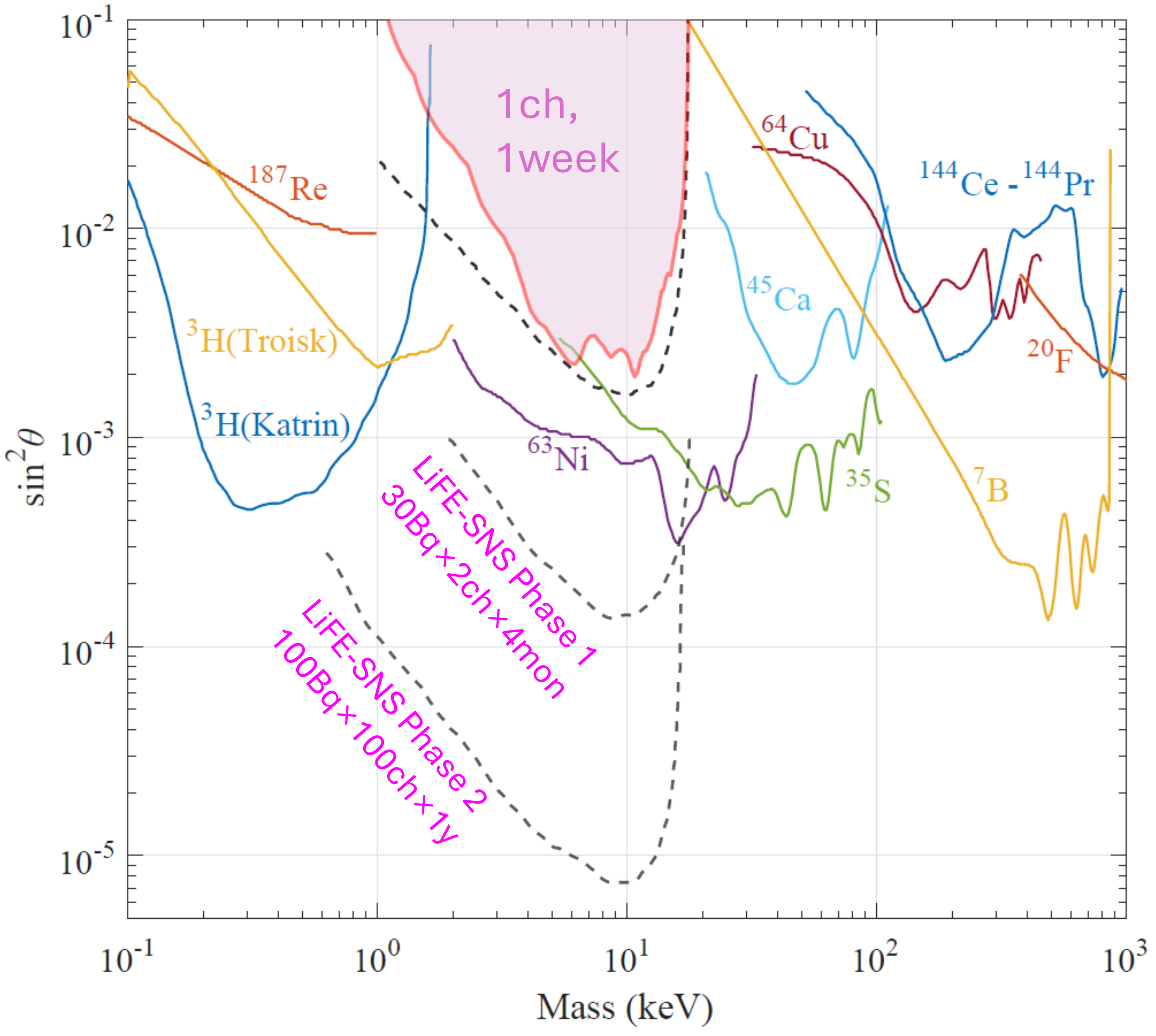
Exclusion limit with 1-ch 7-day data

The null hypothesis is preferred.



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

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.
  - 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 being considered.

Stay tuned to LiFE-SNS