Constraints on Generalized Neutrino Interactions in the keV Region of the Tritium β-Decay Spectrum

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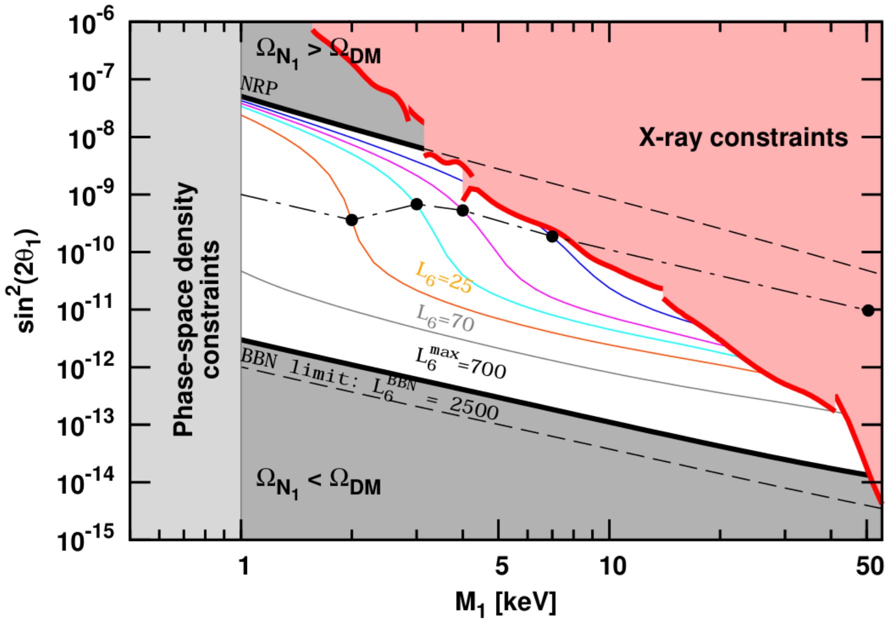
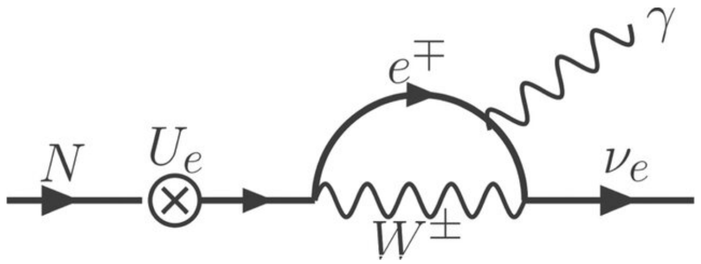
Motivation



- Neutrino oscillation: massive neutrino in BSM
- What is made of the dark matter?
- Can sterile neutrino solve above problems?
- X-ray in decay of heavy neutrino
  : But pretty depending on cosmological heavy neutrino production
  : such as DW, Shi-Fuller mech., Reheating temperature(MeV? GeV?).
- **Need model independent measurement: Tritium Beta decay**



$$m_N = 2E_{X-ray\,peak}$$

$$\Gamma_{N\to\nu\gamma} = \frac{9\,\alpha\,G_F^2}{1024\,\pi^4}\,\sin^2(2\theta)\,M^5 \simeq 1.38\times10^{-22}\,\sin^2(2\theta)\left(\frac{M}{1\,\mathrm{keV}}\right)^5\,\mathrm{s}^{-1}$$

Why **tritium** beta spectrum?

- Very well studied comparably easy in approximation.
  : Only 3 nucleons(pnn), 1 or 2 electorns.
  : Well defined effective Lagrangian, atomic and relativistic correction
- WDM for keV-scale mass, Q=18.59keV.
- Enough reliable precedent experiment (e.g. KATRIN, Mainz, Troitsk)

The invariant β-decay amplitude is given by

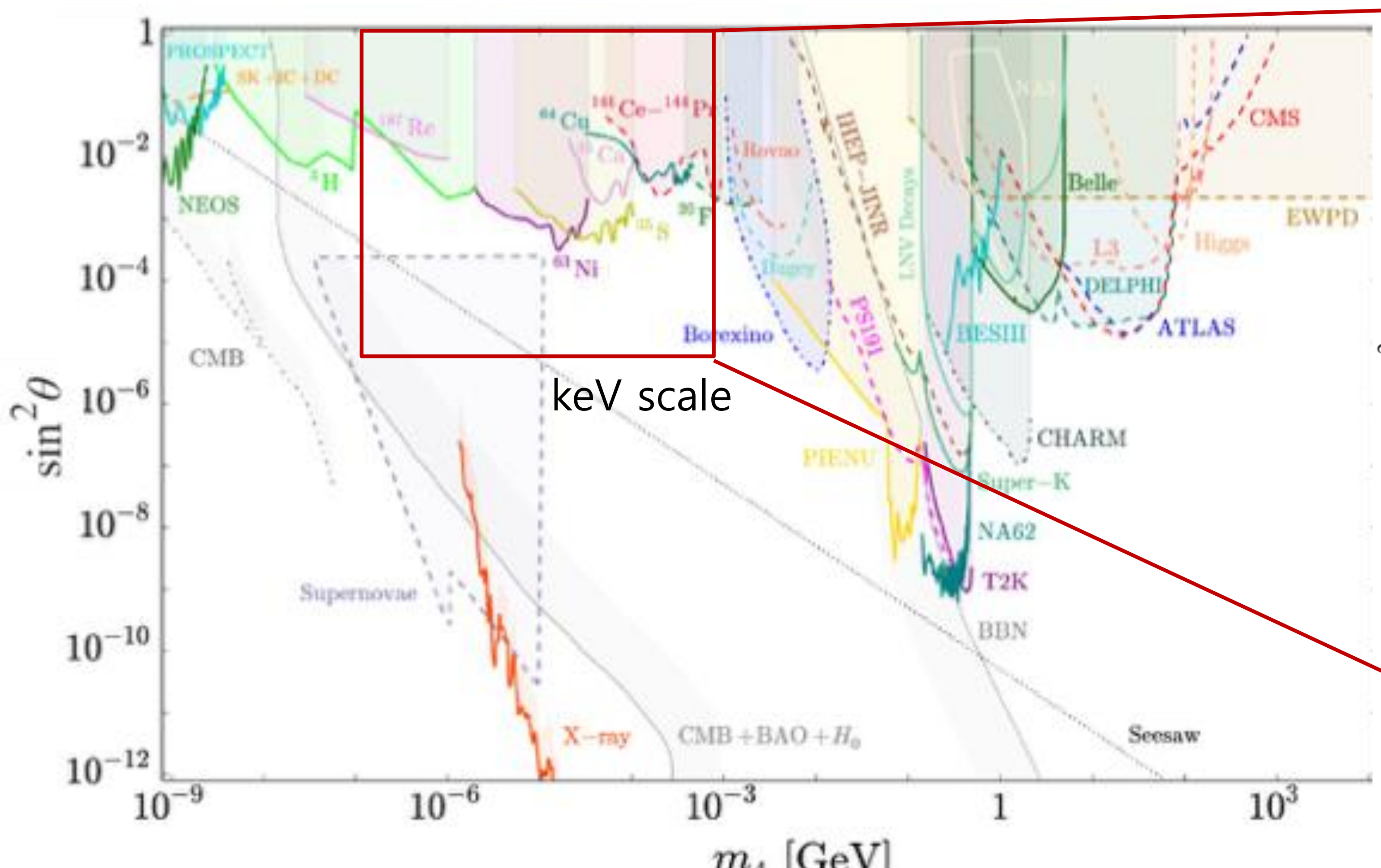
$$M = \frac{G_F V_{ud}}{\sqrt{2}} \bar{u}(P_e)\gamma_\alpha(1-\gamma_5)\upsilon(P_\nu)$$
$$\times \bar{u}(P_f)\Big[G_V(q^2)\gamma^\alpha + i\frac{G_M(q^2)}{2M_i}\sigma^{\alpha\beta}q_\beta$$
$$-G_A(q^2)\gamma^\alpha\gamma_5 - G_P(q^2)q^\alpha\gamma_5\Big]u(P_i).$$

$$G_V(q^2) = \frac{g_V}{\left(1-\frac{q^2}{M_V^2}\right)^2}, \qquad G_M(q^2) = \frac{g_M}{\left(1-\frac{q^2}{M_V^2}\right)^2},$$

$$G_A(q^2) = \frac{g_A}{\left(1-\frac{q^2}{M_A^2}\right)^2}.$$

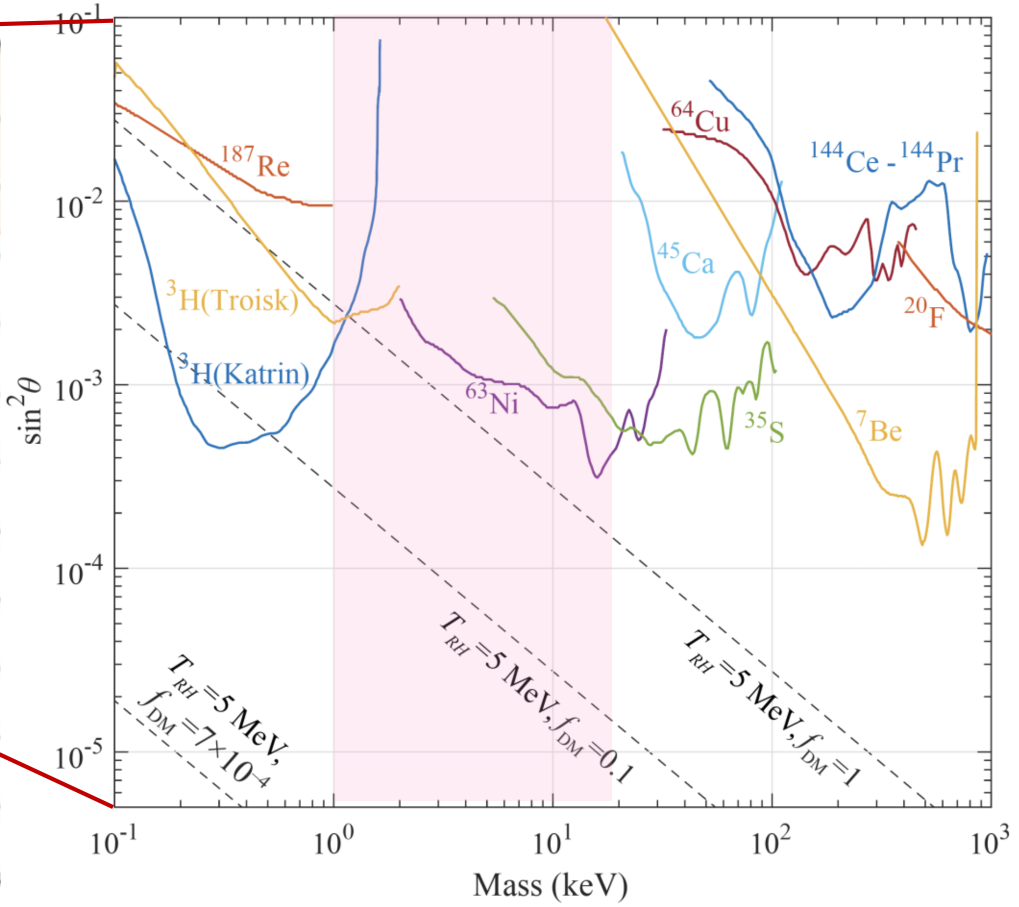
PhysRevC.77.055502

ROI for measurement



Dasgupta, Phys Rep(2021)

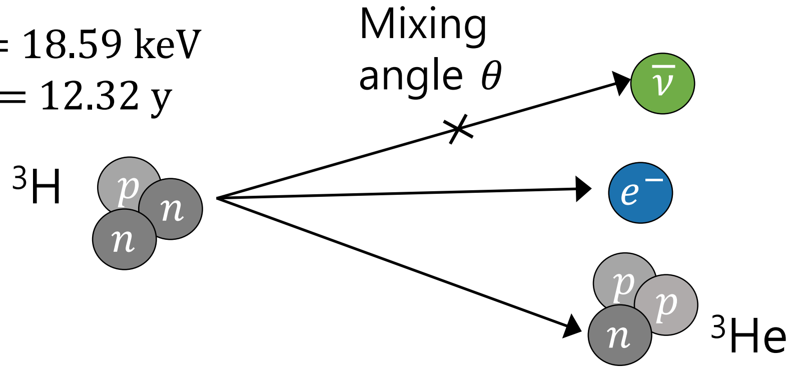
ROI of this work

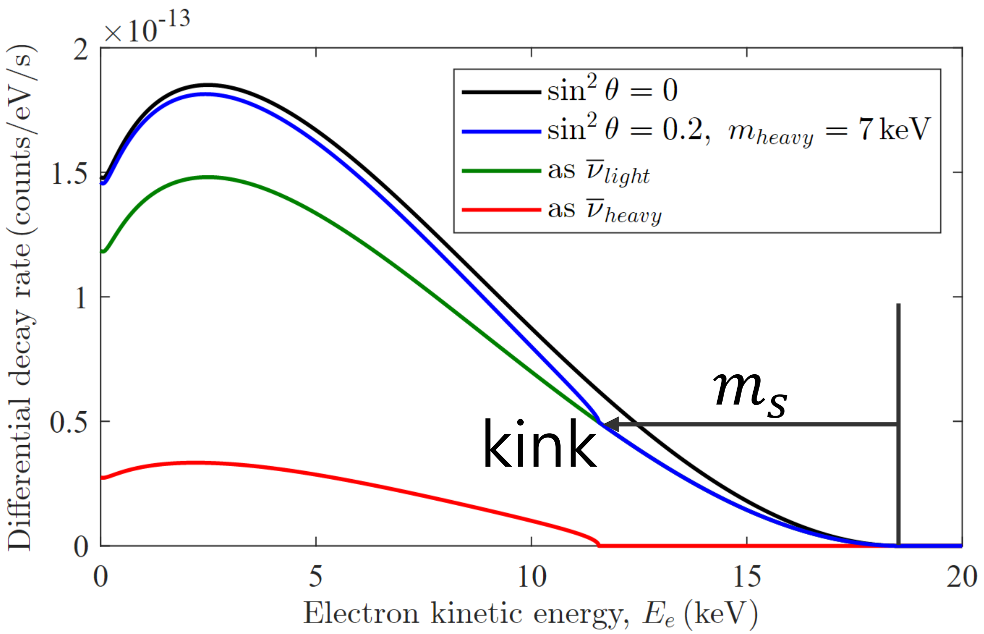


The dashed lines from Low Reheating Temperature (LRT) model Abazajian, PRD (2023)

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

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





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

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

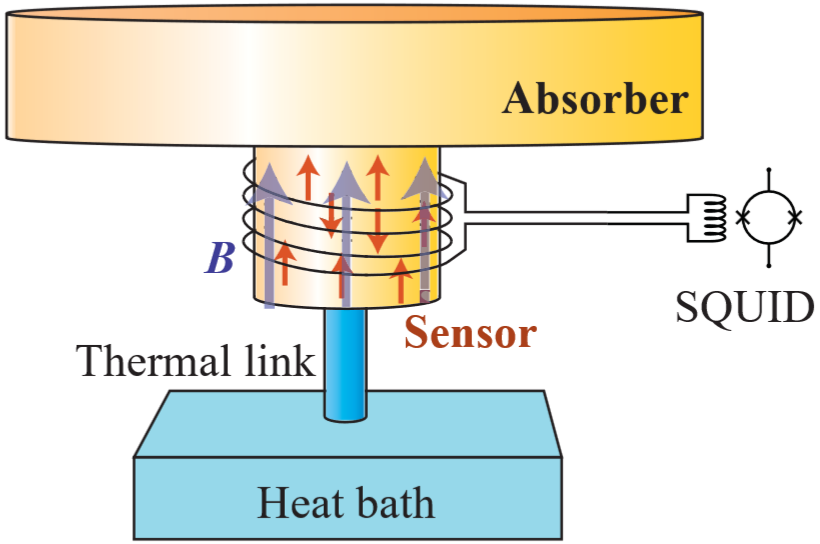
$$\frac{d\Gamma_{\text{tot}}}{dE}(E_e; m_{\text{light}}, m_{\text{heavy}})$$

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

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

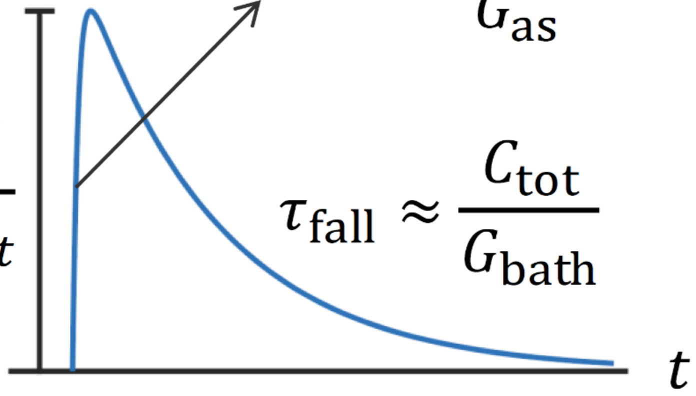
Measurement of decay event

- Beta with kinetic energy → heat in crystal → Heated Ag:Er under current coil → Induced current in coil → Signal



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

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

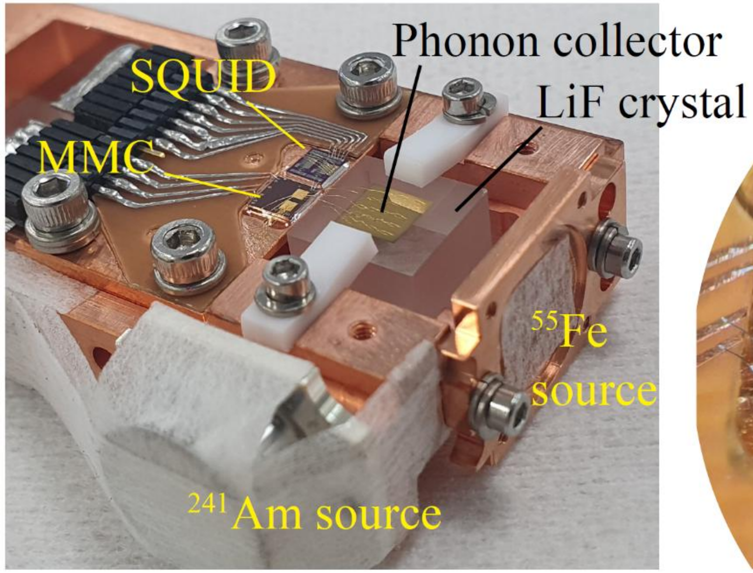


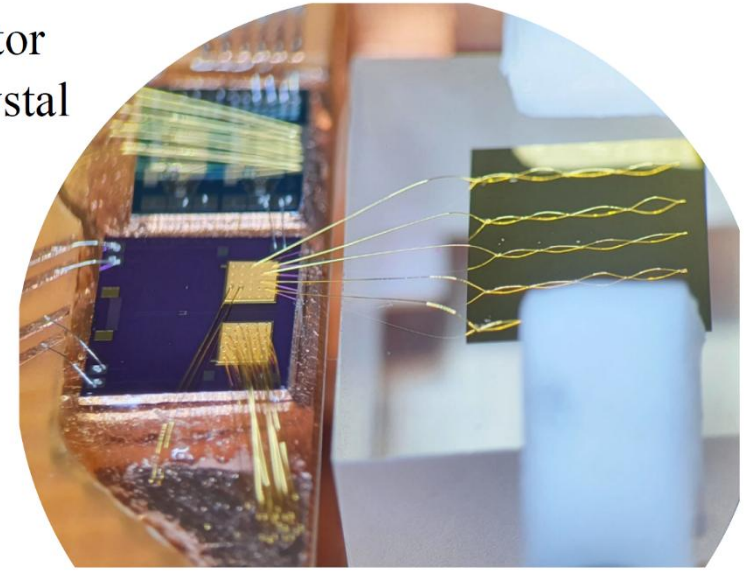
$$\tau_{\mathrm{rise}} \approx \frac{C_{\mathrm{eff}}}{G_{\mathrm{as}}}$$

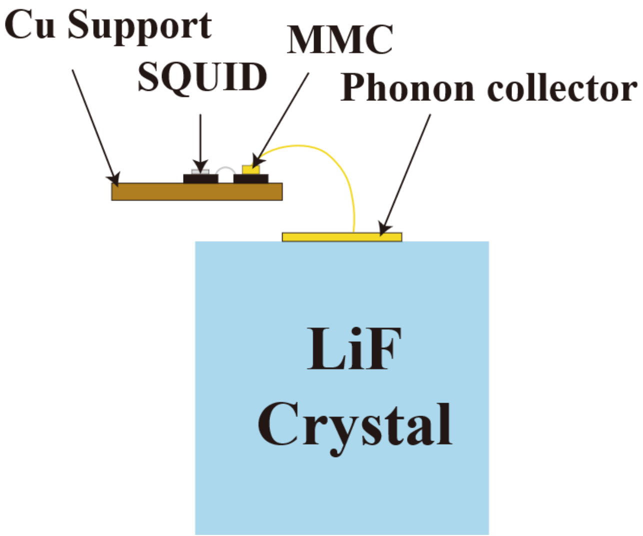
$$\tau_{\mathrm{fall}} \approx \frac{C_{\mathrm{tot}}}{G_{\mathrm{bath}}}$$

Measurement of decay event

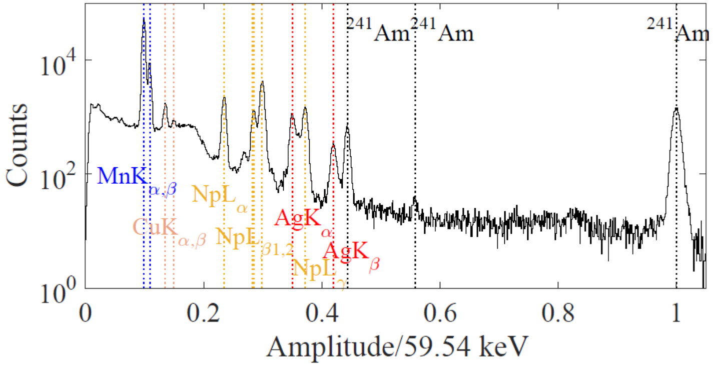
- Beta with kinetic energy → heat in crystal → Heated Ag:Er under current coil → Induced current in coil → Signal

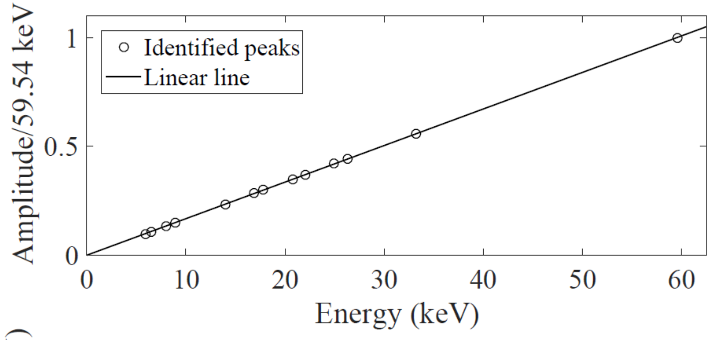


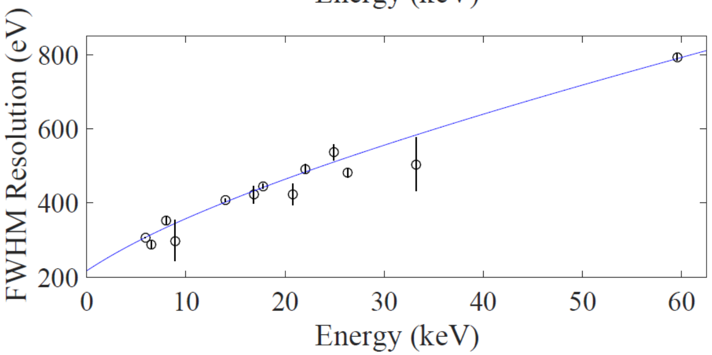


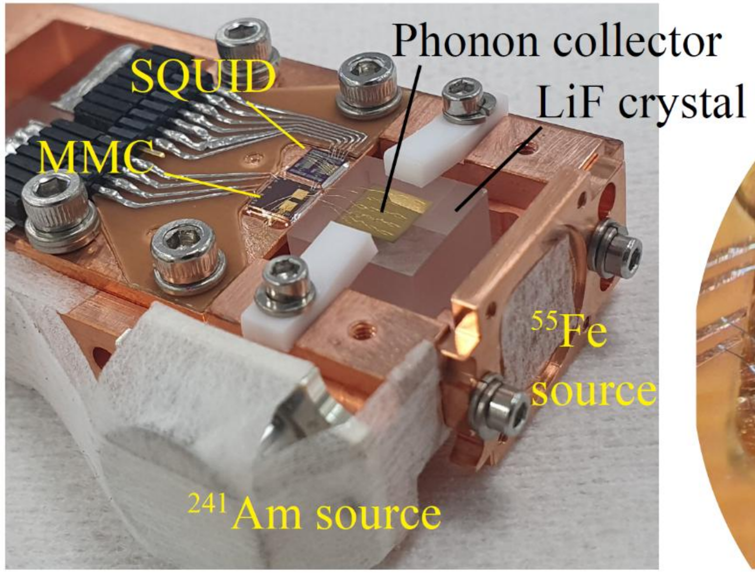


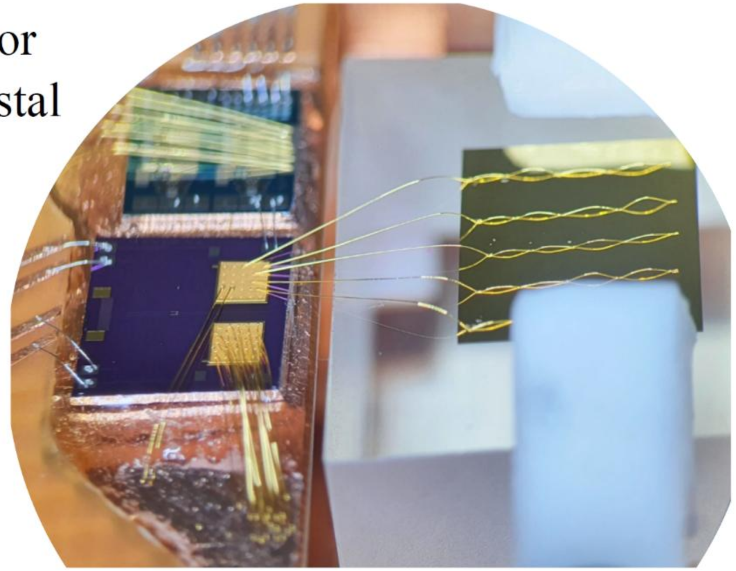
Detector Performance Basics
(**Before** neutron activation)





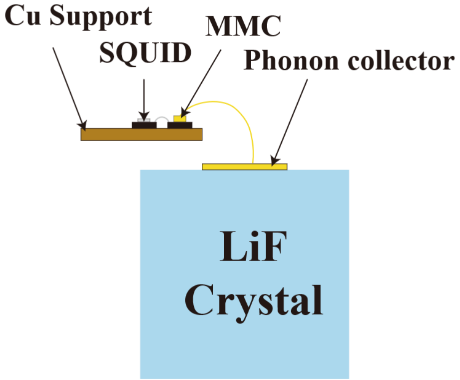






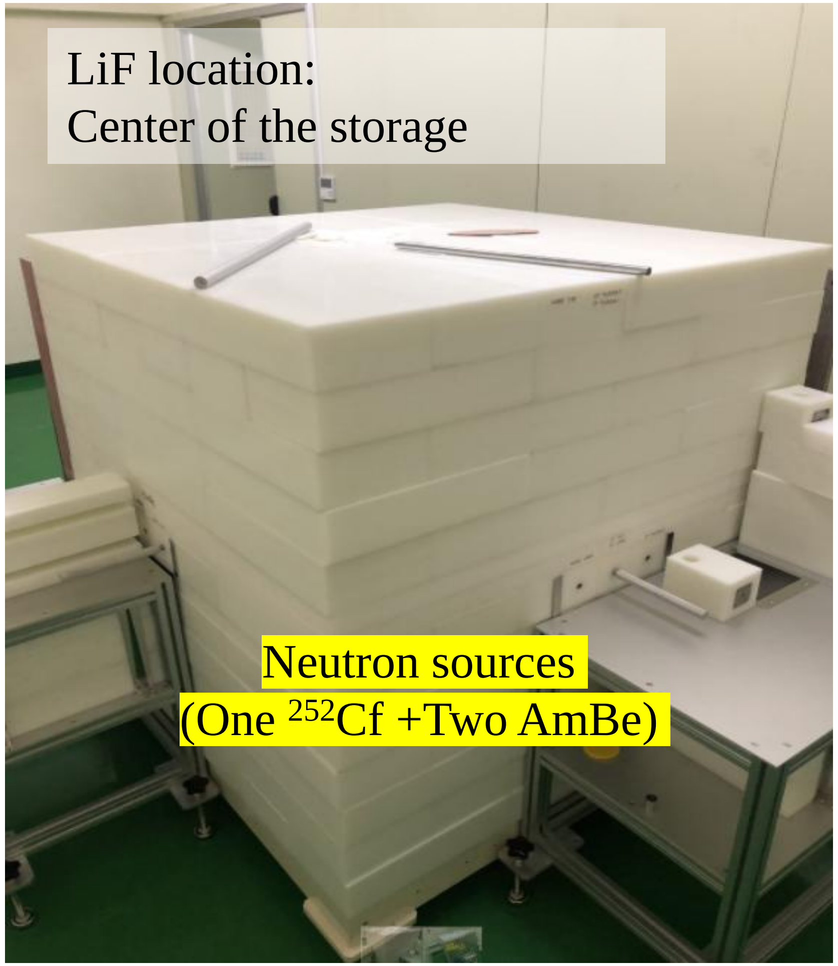
Measurement with internal ^{55}Fe and ^{241}Am sources

- 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

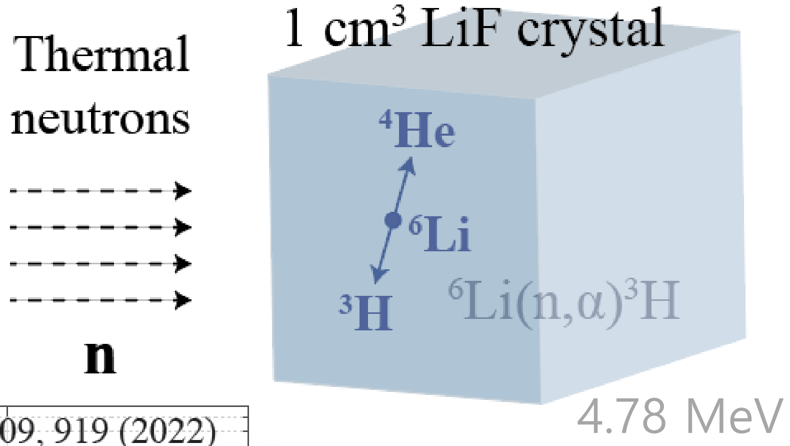


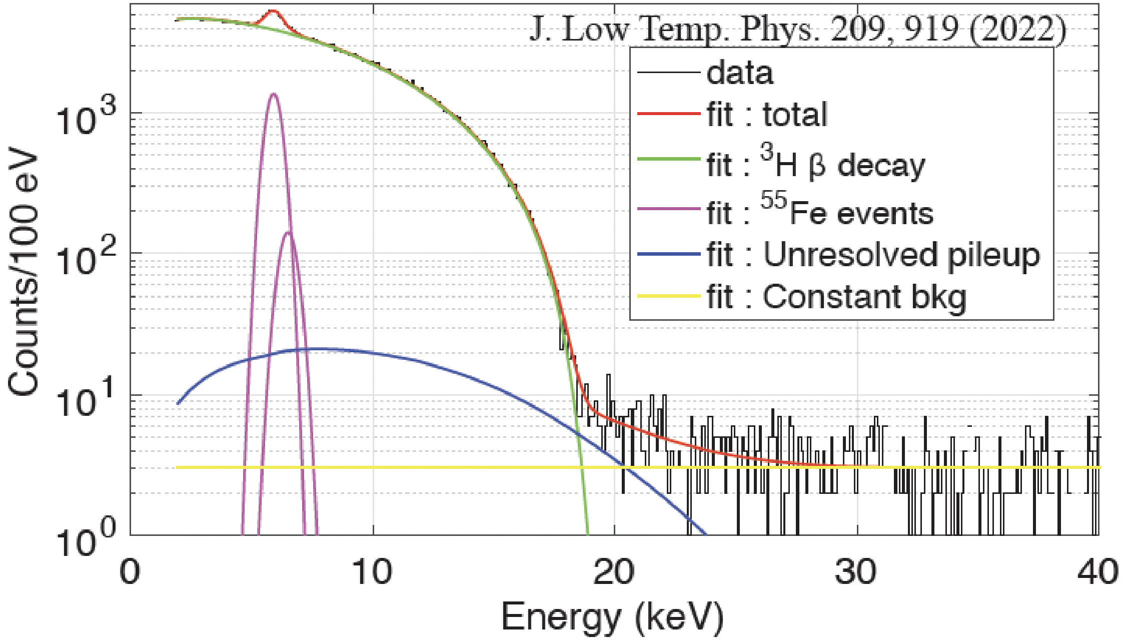
^{3}H Production in LiF Cubic Crystals

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



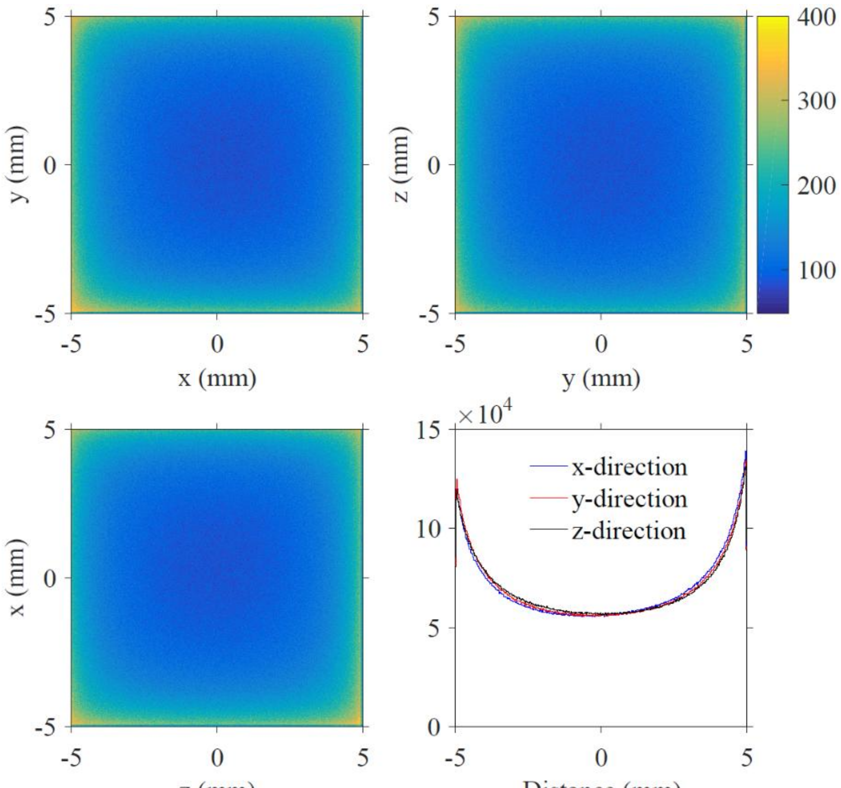
Neutron irradiation at KRISS
Week exposure → 20 Bq ^{3}H



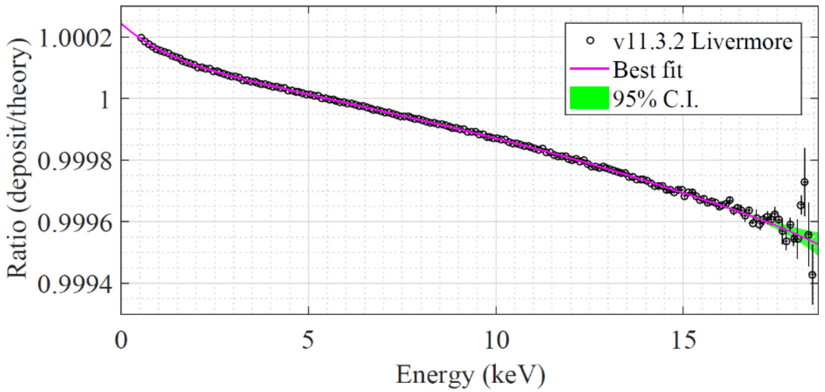


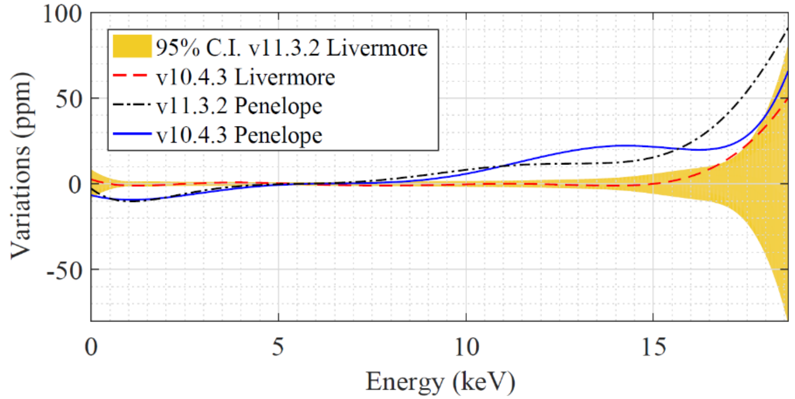
10-hour spectrum using the first LiF(^{3}H) with ^{55}Fe source

Surface issues (^3H distribution and energy loss)



20 μm bin





- ✓ Non-uniform ^3H distribution LiF
  : $\lambda_n = 2.3mm, r_{stop,\mathrm{T}} = 33\mu m$
- ✓ Possible energy loss for escape
  : $r_{stop,\beta(18keV)}$ in LiF = 0.5 μm
- ✓ Correction uncertainty
  : Up to GEANT4 library, 10ppm different in energy spectrum

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

Background spectrum

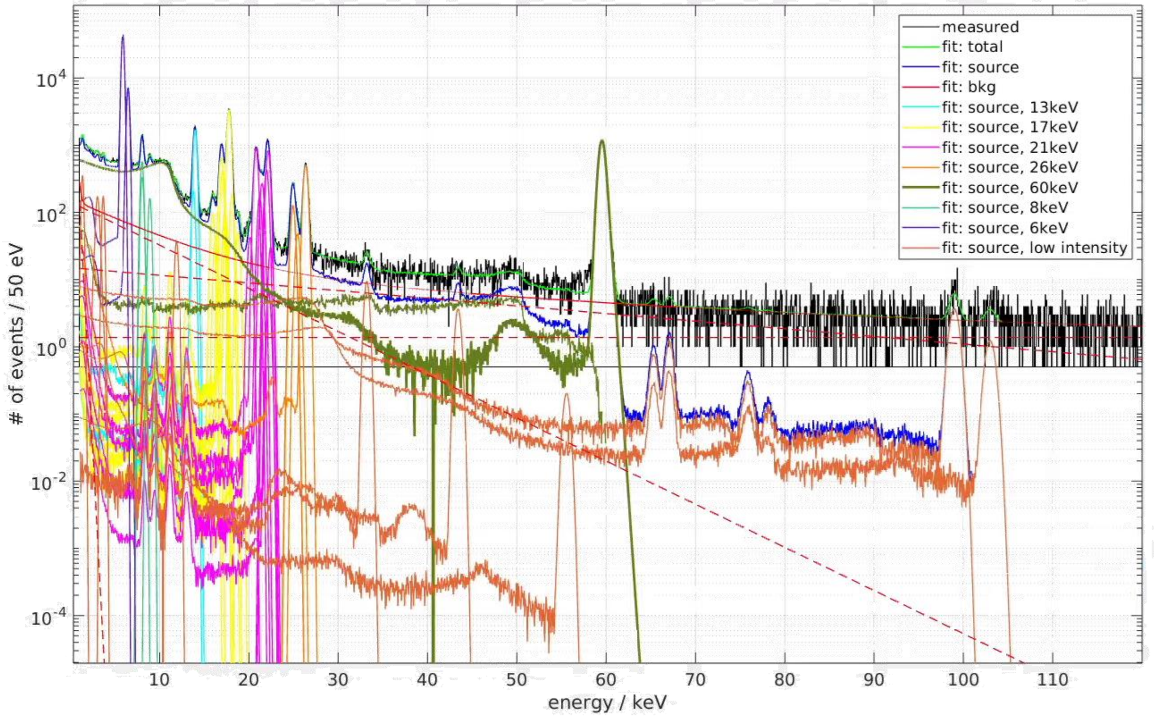
- Fit range: 1~120keV

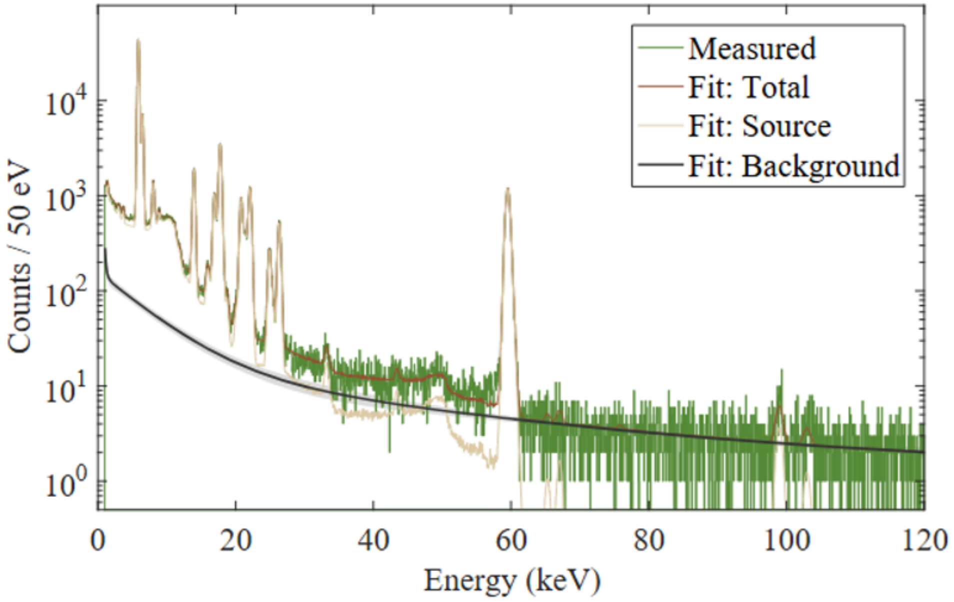
- Expect spectrum: full peak + continuum + bkg(3 exponential + constant)

• Full peak: Gaussian or tailed Gaussian function fitted to measured spectrum
• Continuum: from simulation, share same normalization with full peak

*** special treat: for 60keV, separate continuum into (secondary el's) and (not by secondary el's). Full peak and (not by secondary el's) share same normalization, and (secondary el's) has own normalization parameter -> X 3.2 (fit result)

- chi^2 / ndf = 2640.8 / 2335



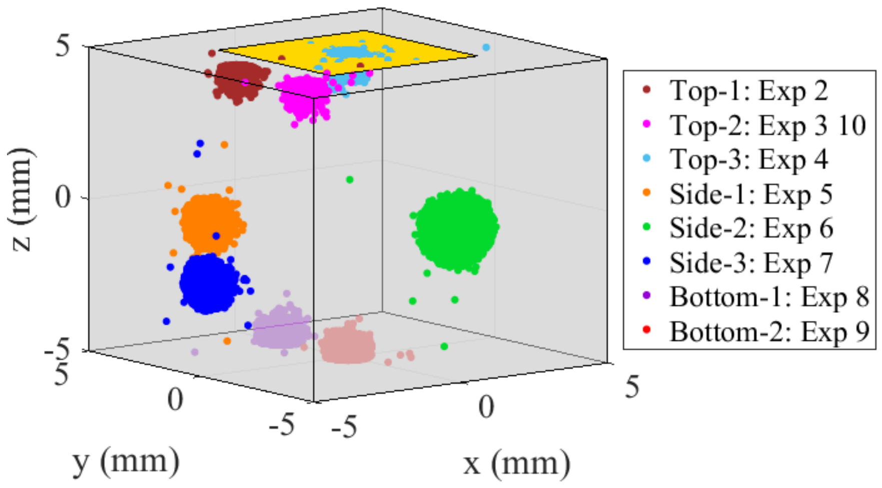


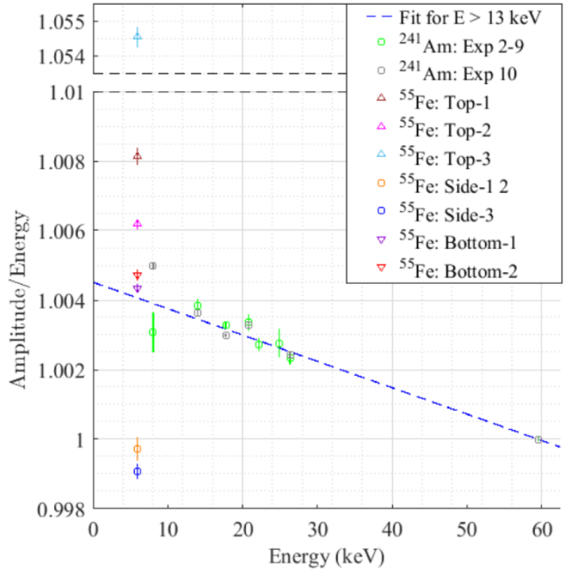
Calibration (Energy + Position)

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

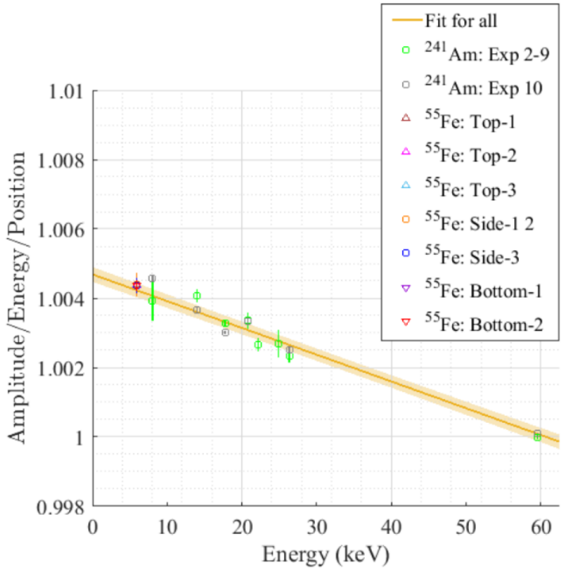
[a] Exp. 11 was carried out after neutron activation.
[b] Characteristic X-rays of Ag and W could be activated from external γ sources during the calibration run.

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

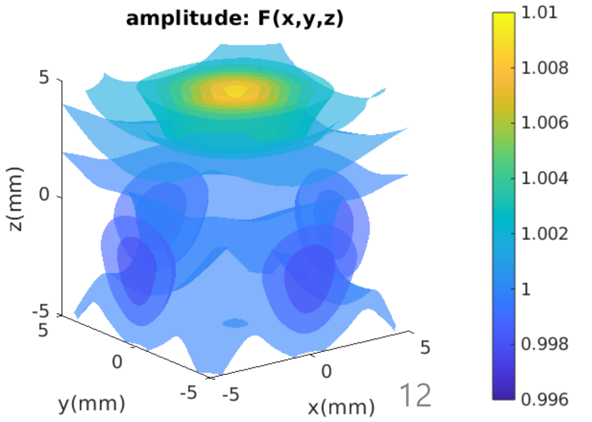




Position calibration



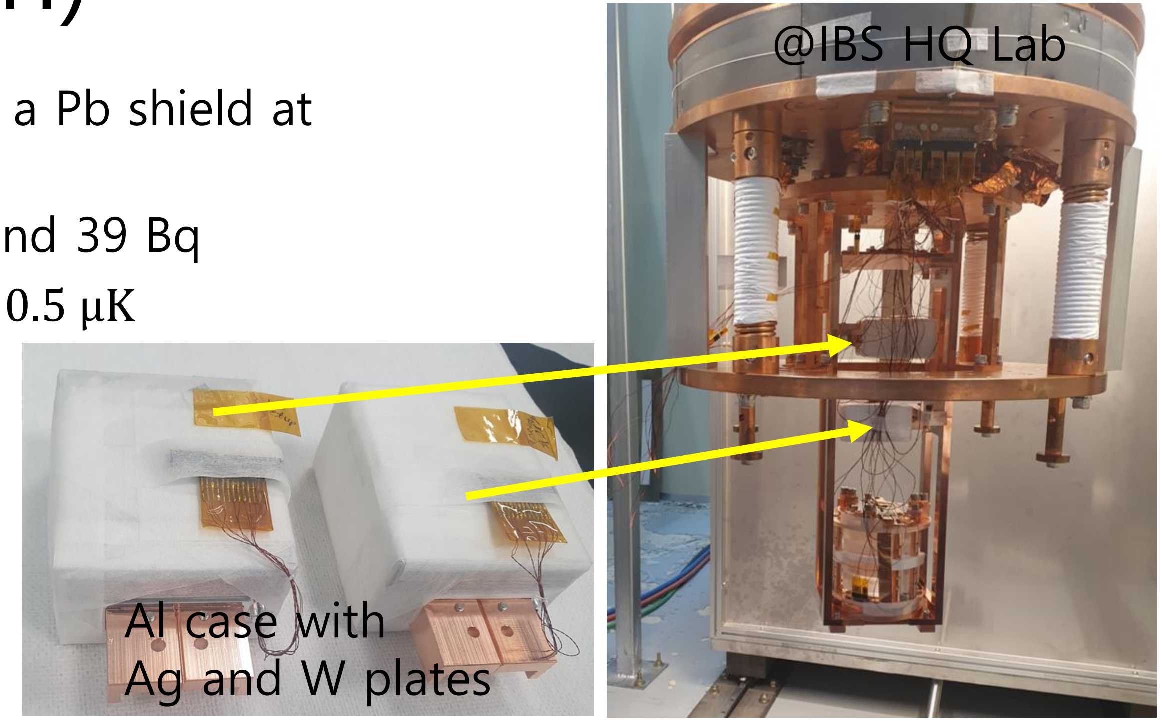
$$\mathrm{Amp} = (Position\ fuction)(\alpha \mathrm{E}^2 + \beta \mathrm{E})$$



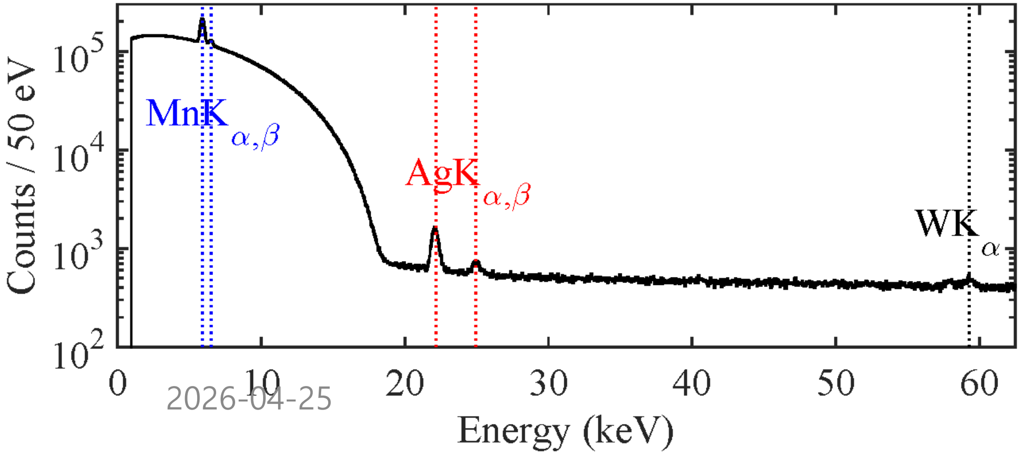
- Each calibration peak corresponds to the energy and position of the events in the crystal.
- Calibration measurements were carried out in various source locations (^{55}Fe and ^{241}Am) for 21 event sets for energy-position calibrations.

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
- Two-stage temperature control system with $\Delta T_{rms} \sim 0.5\ \mu K$
- An internal ^{55}Fe source is employed on each crystal.
- Data taking period: May~Dec/2024



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

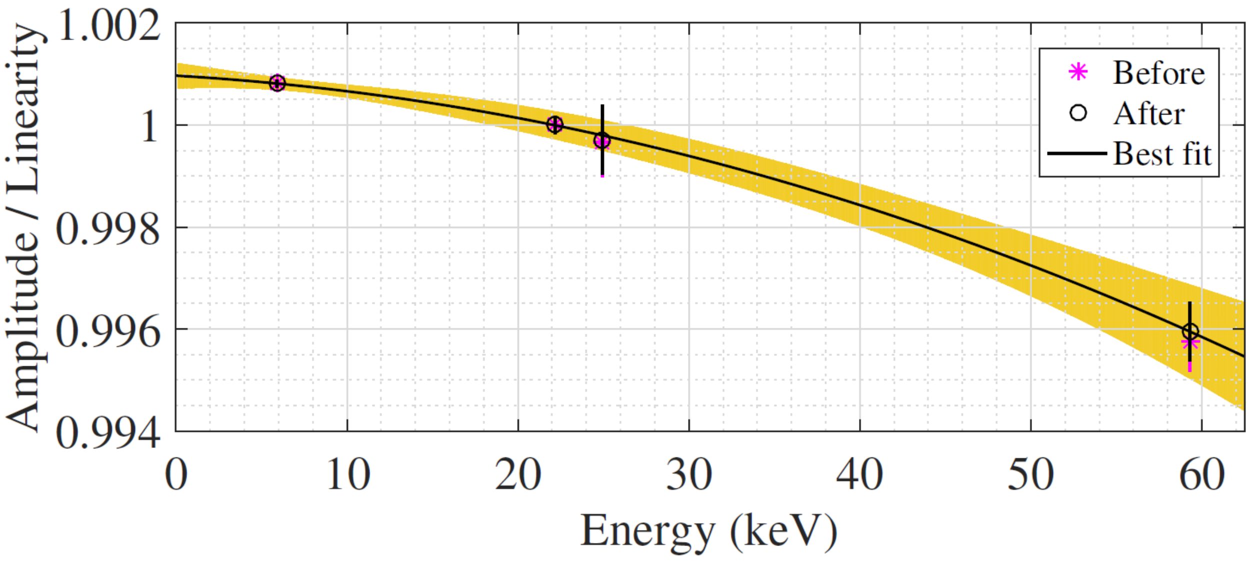


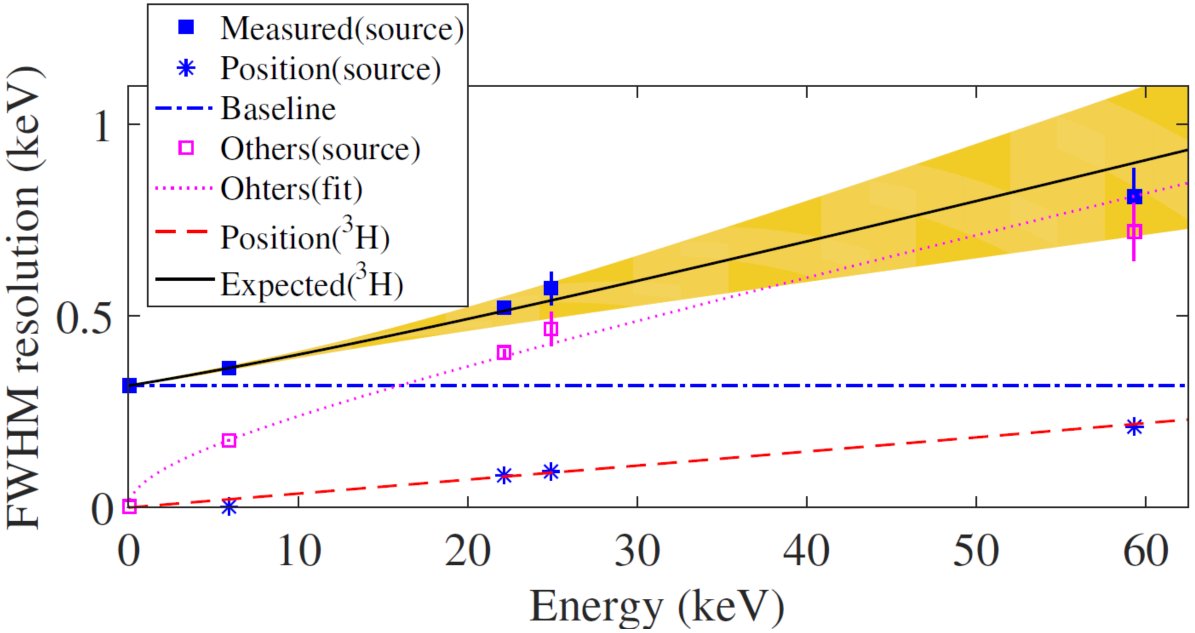
After neutron irradiation, internal ^{55}Fe + X-ray fluorescence

- 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





- Reasonable linearity and resolution are found.
- The calibration with the position correction function works for calibration lines.
- The uncertainties of the calibration curve and the resolution curve were incorporated as systematic errors.

Theoretical ^{3}H spectrum

3eV @ endpoint

✓ 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

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

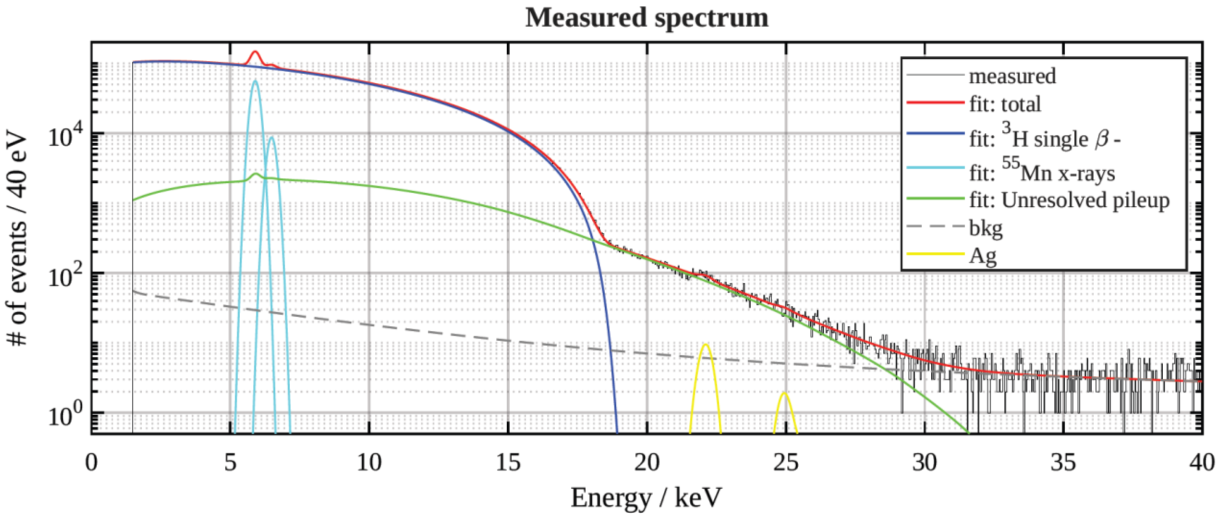
- Fermi function, Recoiled coulomb potential, Finite nuclear size correction, Screened Coulomb correction
- Radiative correction
- Spectral shape is determined by initial and final atomic states

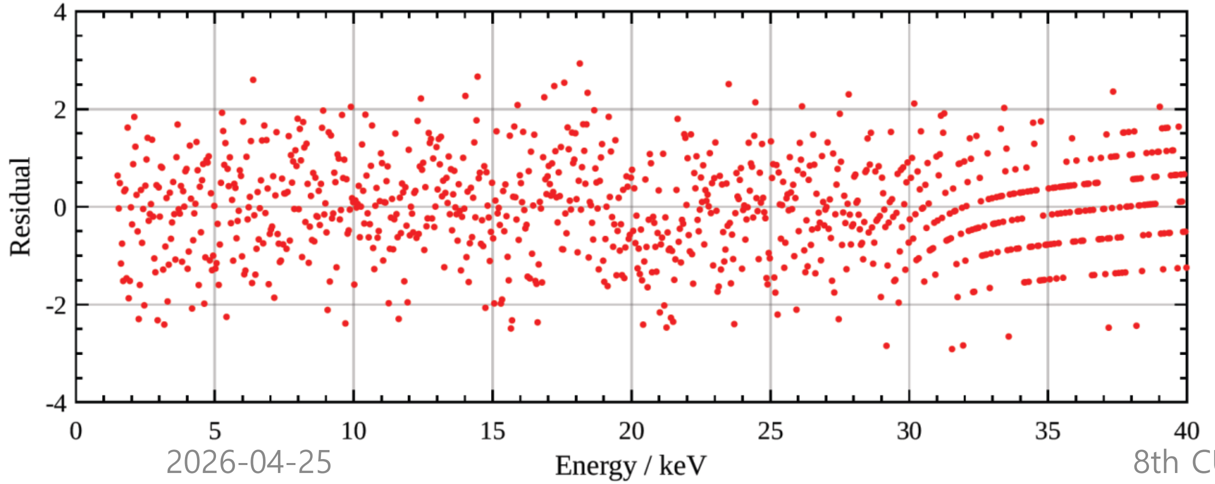
  Transition probability accounting for exchange effect between β^- and electron (bound).

  $^3H^0 \rightarrow \nu + \beta^- + {}^3He^+$ + 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 β decay spectrum fit: Using 10 days of one channel





Null hypothesis

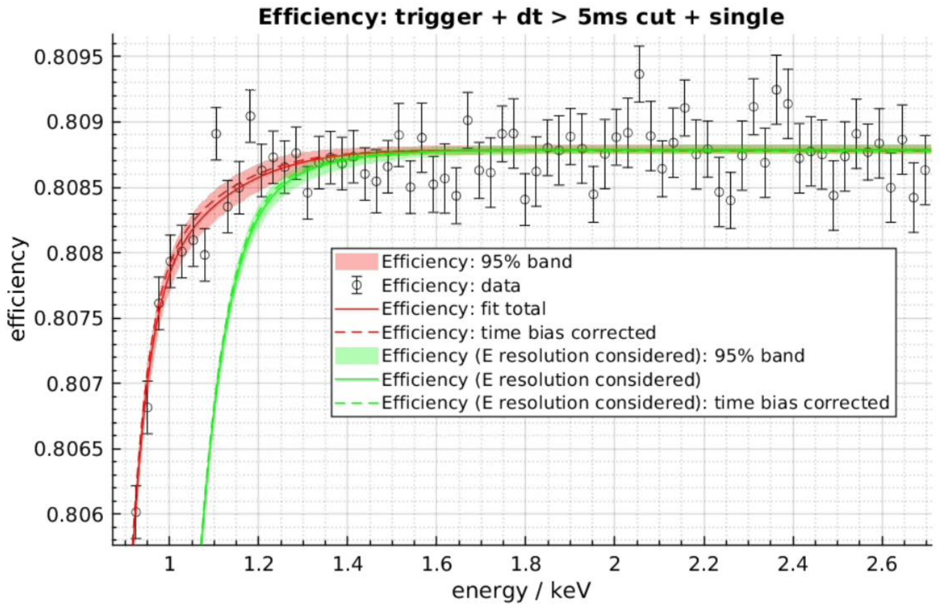
χ^2/NDF = 991.43/953 in the analysis range 1.5~40 ke

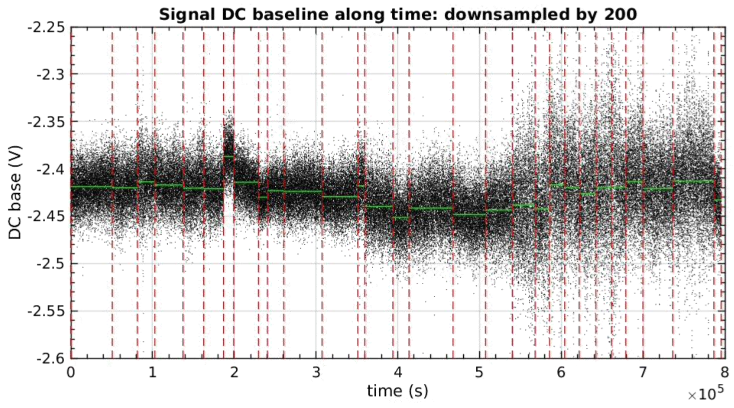
➔ Good agreement between the measured and expected values.

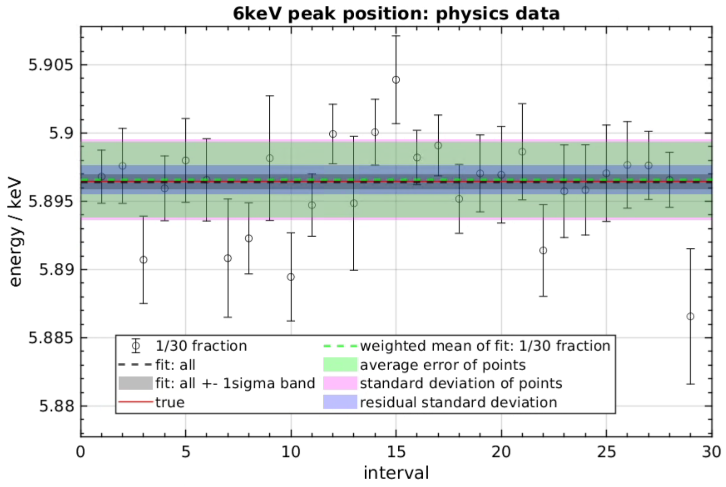
➔ We can activate the routine for sterile branch search.

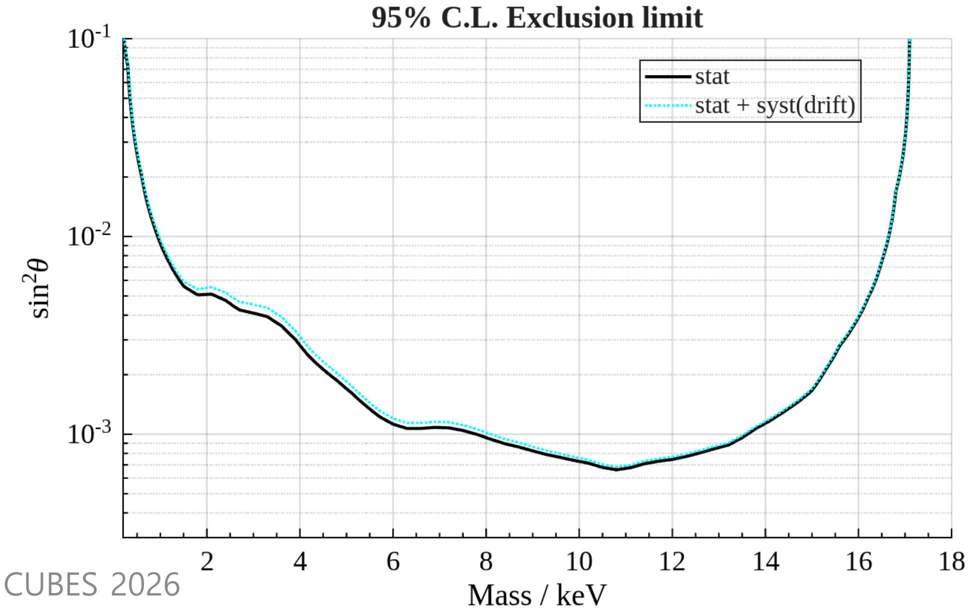
We included
- ^{3}H distribution in the LiF crystal
- Position calibration function
- One channel 10-day data
  (~1/20 of the measured data)

Systematic Uncertainty









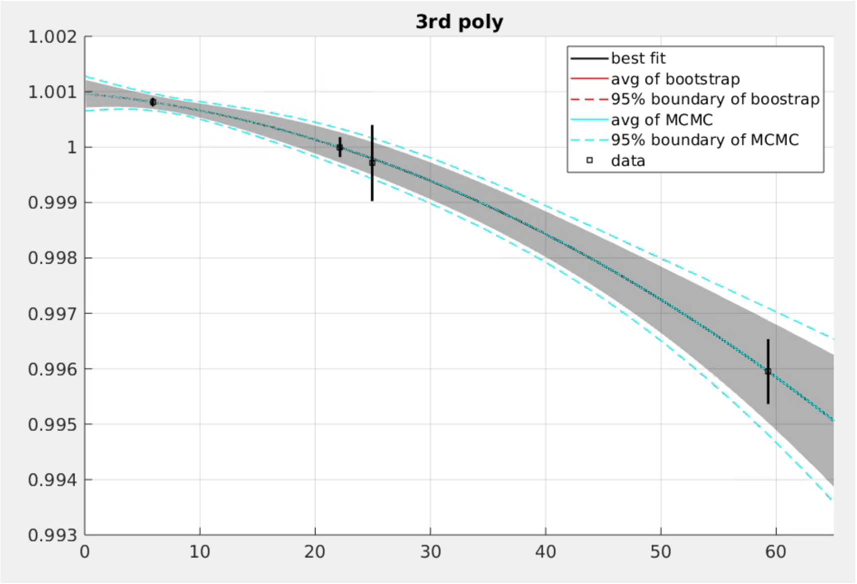
- Scaled templates are injected into the real data stream, and the fraction that passes the same data processing pipeline as the real data is evaluated.
- Negligible deviation from flatness above 1.5keV (Total 45 ppm deviation @ 1.5keV region)

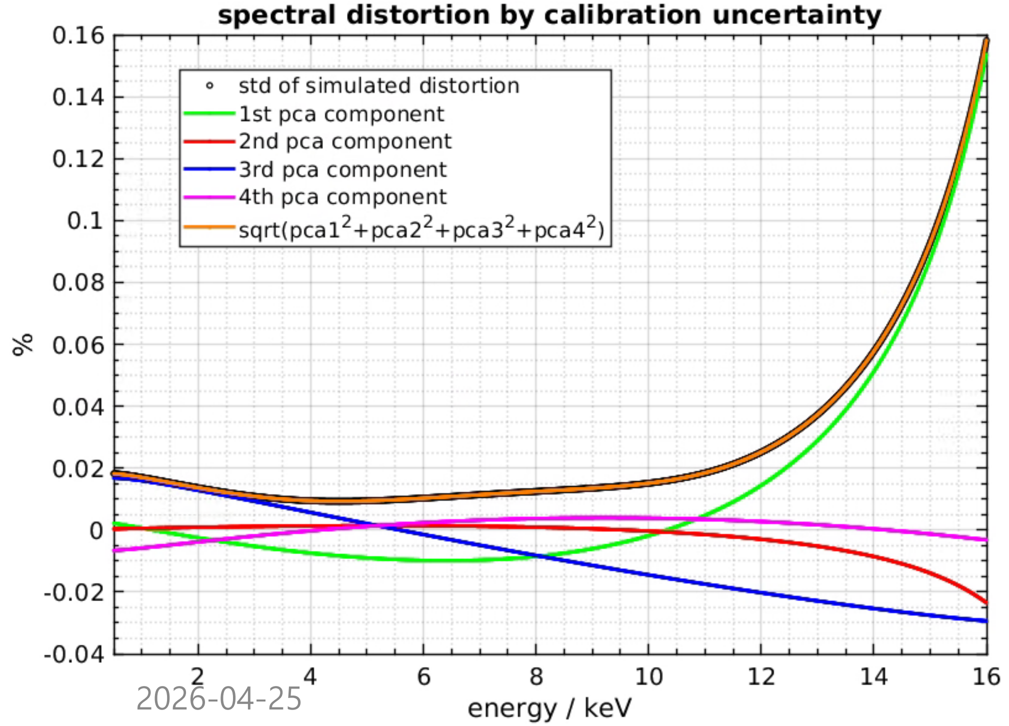
3. Uncertainty in energy calibration

- The calibration curve, modeled as a third-order polynomial constrained to pass through the origin, is constructed from four calibration points. Its uncertainty arises from the limited number of points (four, corresponding to two degrees of freedom) as well as the statistical uncertainties of each point.

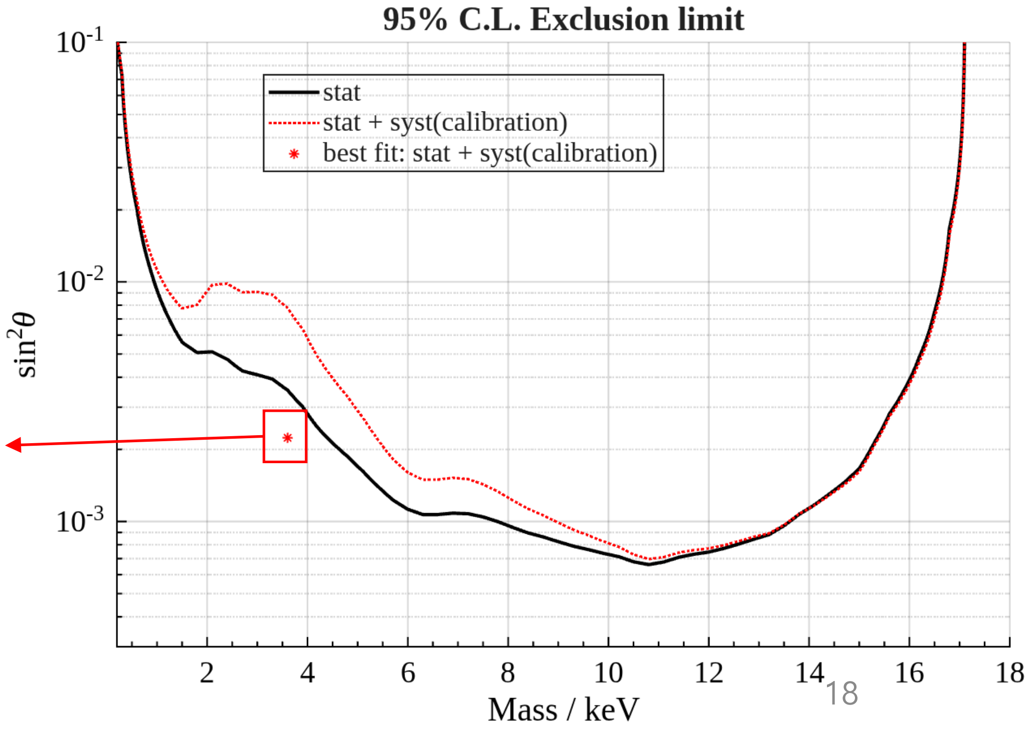
- A bootstrap method, taken as a conservative approach, is applied to generate random realizations of the energy calibration curve and to evaluate the resulting distortions in the spectrum.

- Most of the spectral distortion is captured by four PCA components.

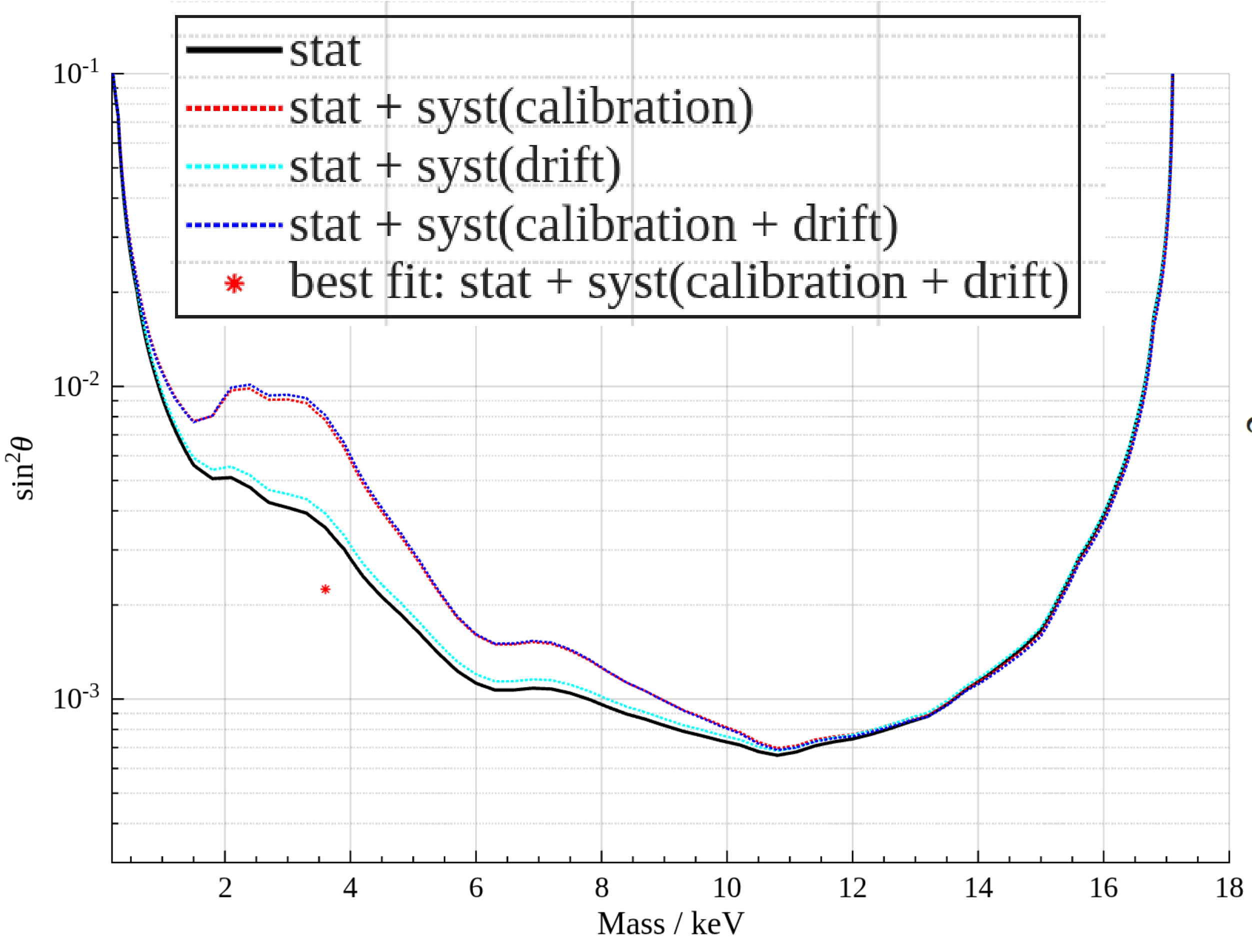




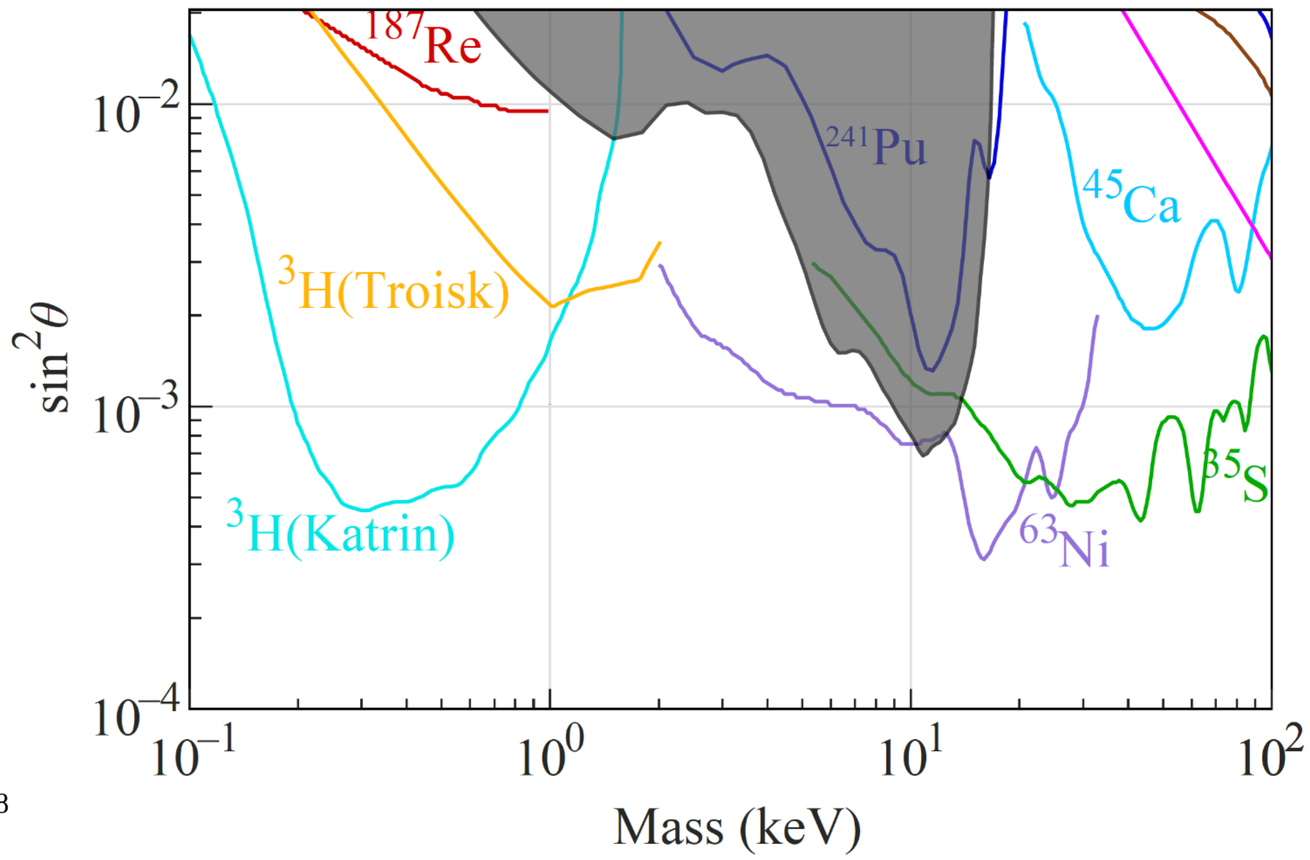
- In the statistical-only fit, the null model provides the best fit.
- When this systematic is included, a global minimum appears at 3.5 keV; however, the improvement over the null model is not significant ($\Delta\chi^2 \approx -1$).



Exclusion limit with 1-ch 10-day data



1ch, 10-days



General Neutrino Interaction

- Actually, sterile neutrino is one of GNI.

CKM matrix (mixing between quarks)

$$\mathcal{L}^{\mathrm{CC}}_{\mathrm{GNI}} = -\frac{G_{\mathrm{F}} V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,\mathrm{ud}} \right)^{\alpha\beta\gamma\delta} (\bar{\mathrm{e}}_\alpha \mathcal{O}_j \nu_\beta)(\bar{\mathrm{u}}_\gamma \mathcal{O}'_j \mathrm{d}_\delta) + \mathrm{H.c.},$$

(under Lorentz invariant)

Flavour index with PMNS matrix (neutrino mixing)

- If there is no mixing,

: $-\frac{G_F}{\sqrt{2}} \left((g_V^2 + 3g_A^2) + \sum \epsilon_j (\bar{e} O_j \nu)(\bar{u} O'_j d) \right) + h.c.$

- For other experiment $\epsilon \sim 10^{-3}$, so if our sensitivity for mixing angle ~10^{-3}, we can test further BSM parameters.

j	ϵ_j	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_{L}	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
2	$\tilde{\epsilon}_{\mathrm{L}}$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
3	ϵ_{R}	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
4	$\tilde{\epsilon}_{\mathrm{R}}$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
5	ϵ_{S}	$(\mathbb{1}-\gamma^5)$	$\mathbb{1}$
6	$\tilde{\epsilon}_{\mathrm{S}}$	$(\mathbb{1}+\gamma^5)$	$\mathbb{1}$
7	$-\epsilon_{\mathrm{P}}$	$(\mathbb{1}-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_{\mathrm{P}}$	$(\mathbb{1}+\gamma^5)$	γ^5
9	ϵ_{T}	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}-\gamma^5)$
10	$\tilde{\epsilon}_{\mathrm{T}}$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}+\gamma^5)$

KATRIN PRL134, 251801 (2025)

GNI terms

For N instead of β, $\mathrm{U} \to S$, $\mathrm{T} \to \mathrm{V}$

SM model

$$\xi_\beta = |U_{ei}|^2[(g_V^2+3g_A^2)(1+|\epsilon_L|^2+|\epsilon_R|^2+2\mathrm{Re}(\epsilon_L)) + 2(g_V^2-3g_A^2)(\mathrm{Re}(\epsilon_R\epsilon_L^*)+\mathrm{Re}(\epsilon_R)) + g_S^2|\epsilon_S|^2 + 48g_T^2|\epsilon_T|^2] + |T_{ei}|^2[(g_V^2+3g_A^2)(|\tilde\epsilon_L|^2+|\tilde\epsilon_R|^2) + 2(g_V^2-3g_A^2)\mathrm{Re}(\tilde\epsilon_R\tilde\epsilon_L^*) + g_S^2|\tilde\epsilon_S|^2 + 48g_T^2|\tilde\epsilon_T|^2],$$

$$\xi_\beta b_\beta = |U_{ei}|^2[2g_Sg_V\mathrm{Re}(\epsilon_S(1+\epsilon_L+\epsilon_R)^*) - 24g_Ag_T\mathrm{Re}(\epsilon_T(1+\epsilon_L-\epsilon_R)^*)] + |T_{ei}|^2[2g_Sg_V \mathrm{Re}(\tilde\epsilon_S(\tilde\epsilon_L+\tilde\epsilon_R)^*) + 24g_Ag_T\mathrm{Re}(\tilde\epsilon_T(\tilde\epsilon_L-\tilde\epsilon_R)^*)]$$

$$\left(\frac{d\Gamma}{dE}\right)_j = \frac{G_F^2V_{ud}^2}{2\pi^3}\sqrt{(E+m_e)^2-m_e^2}\,(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_j^2}\;\xi\left[1+b\frac{m_e}{E+m_e} - b'\frac{m_j}{E_0-E} - c\frac{m_em_j}{(E+m_e)(E_0-E)}\right]$$

~ 1 $\qquad \sim -(b'+c)*\frac{m_N}{E_\nu} \to -b'\frac{m_N}{E_\nu}$

$$\xi_\beta b'_\beta = \mathrm{Re}(U_{ei}T_{ei})\big[2g_Vg_S\{\mathrm{Re}(\tilde\epsilon_S(1+\epsilon_L+\epsilon_R)^*) + \mathrm{Re}(\epsilon_S(\tilde\epsilon_L+\tilde\epsilon_R)^*)\} - 24g_Ag_T\{\mathrm{Re}(\tilde\epsilon_T(1+\epsilon_L-\epsilon_R)^*) - \mathrm{Re}(\epsilon_T(\tilde\epsilon_L-\tilde\epsilon_R)^*)\}\big],$$

$$\xi_\beta c_\beta = \mathrm{Re}(U_{ei}T_{ei})[2g_V^2\mathrm{Re}((\tilde\epsilon_L+\tilde\epsilon_R)(1+\epsilon_L+\epsilon_R)^*) - 6g_A^2\mathrm{Re}((\tilde\epsilon_L-\tilde\epsilon_R)(1+\epsilon_L-\epsilon_R)^*) + 2g_S^2\mathrm{Re}(\epsilon_S\tilde\epsilon_S^*) + 96g_T^2\mathrm{Re}(\epsilon_T\tilde\epsilon_T^*)].$$

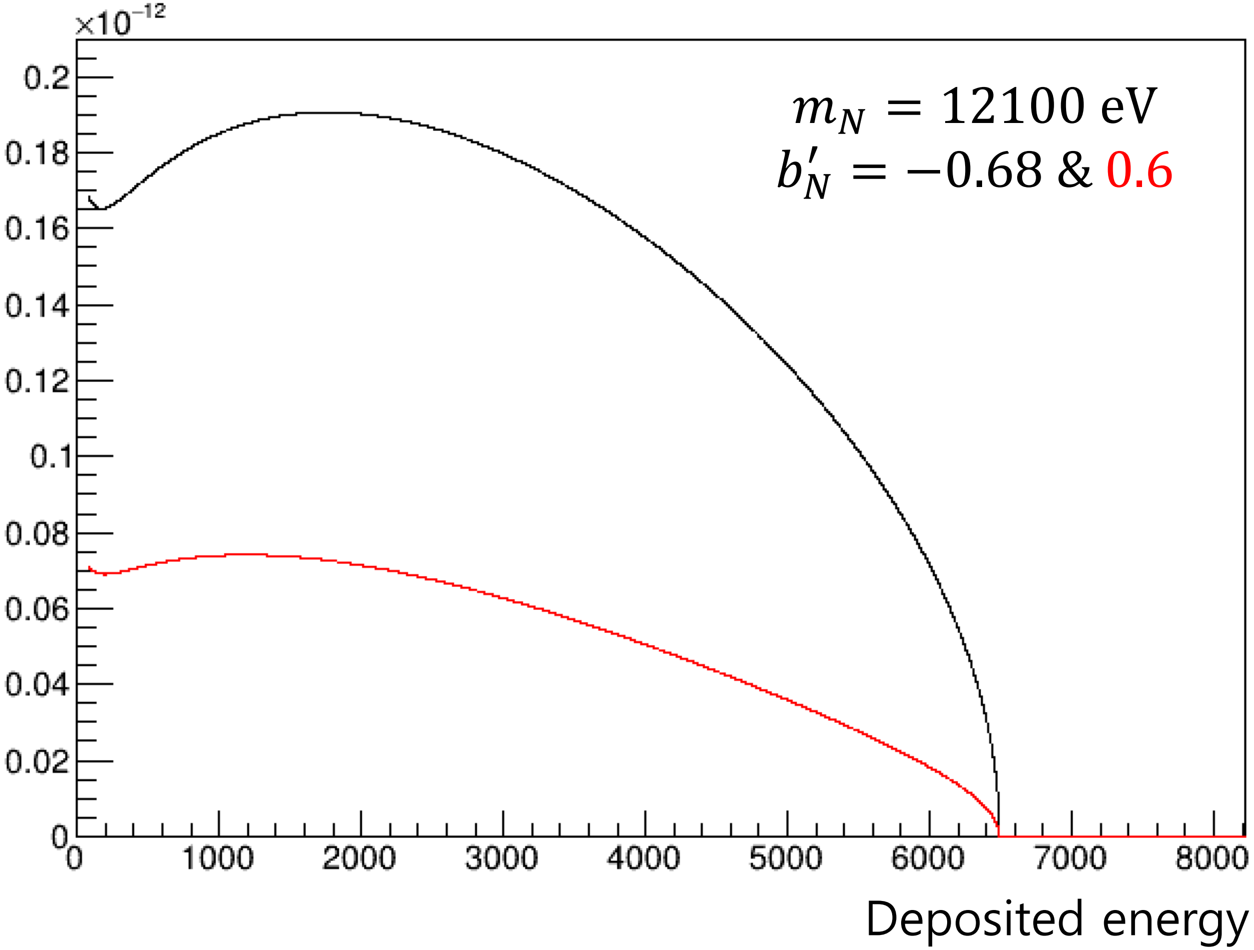
- ξ : Normalization like mixing angle
- $b' m_N/\mathrm{E}_\nu$
  : Distortion of energy spectrum
  : Heavy mass induces large distorition

Tritium beta spectrum

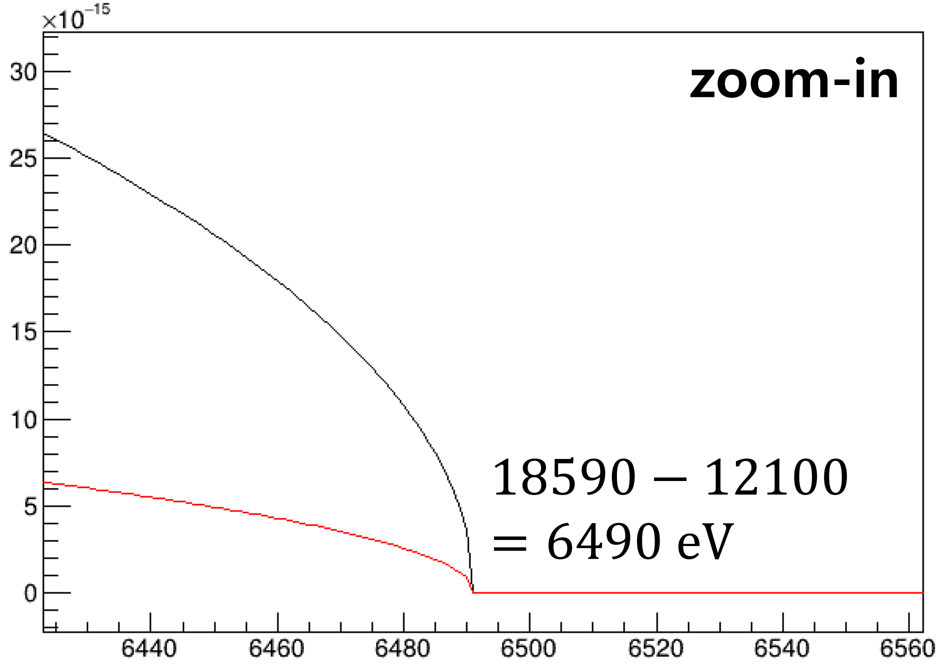
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \frac{G_\mathrm{F}^2 V_\mathrm{ud}^2}{2\pi^3} F(E,2) \sqrt{(E+m_\mathrm{e})^2 - m_\mathrm{e}^2}(E+m_\mathrm{e}) \cdot \sum_j \sum_{k=\beta,\mathrm{N}} \zeta_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_k^2} \xi_k \left[1 - b_k' \frac{m_k}{\varepsilon_j}\right] \Theta(\varepsilon_j - m_k).$$

- Additional corrections : Relativistic Fermi function, Exchange effect, radiative correction, Recoiled Coulomb correction, Finite nuclear size correction, Screened Coulomb correction.
- j stands for 30 atomic states (shake-up) and continuum state (shake-off)
- β : electron neutrino, N : sterile neutrino
- GNI effect : $\xi_{k=\beta,N}$, $b_{k=\beta,N}{}'$

Spectrum shape for (m_N, b'_N)



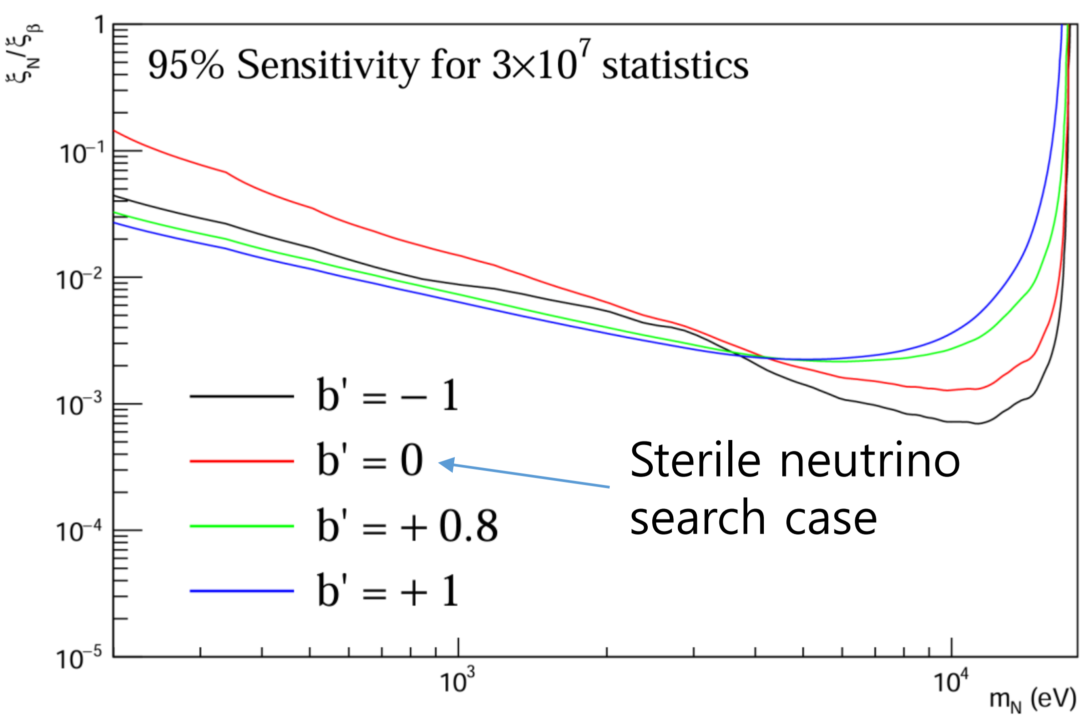
$$\frac{d\Gamma}{dE} = A(E, m_e) \sum_j \zeta_j \, \varepsilon_j \left(\sqrt{\varepsilon_j^2 - m_N^2} \, \cancelto{1}{\xi_N} (1 - b'_N \frac{m_N}{\varepsilon_j}) \right)$$

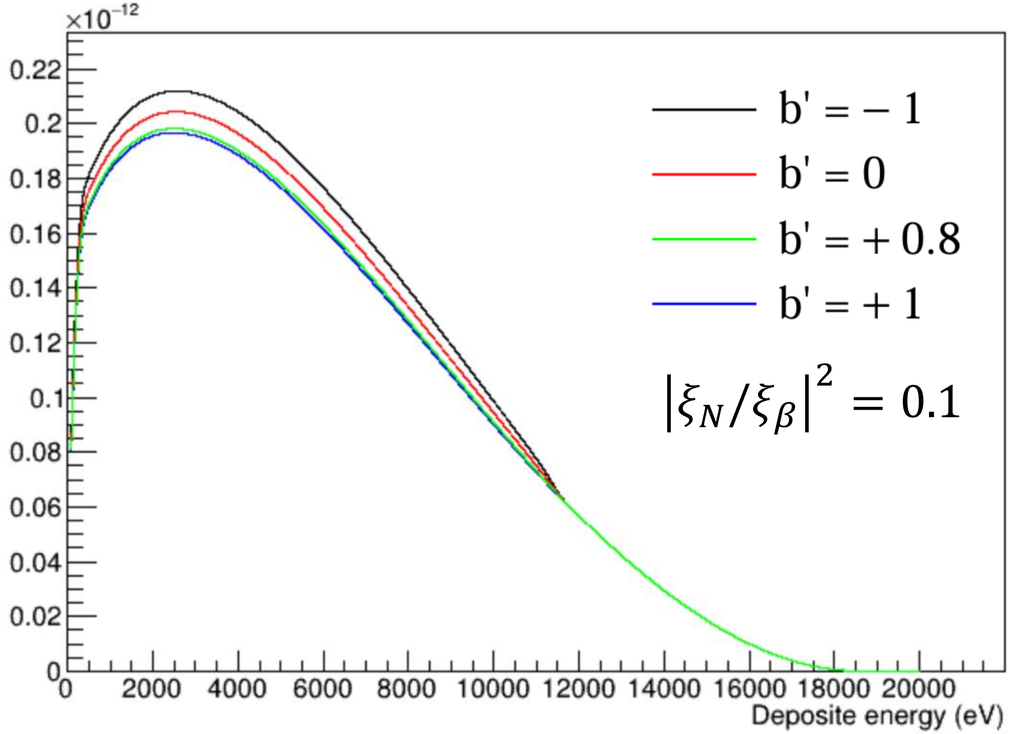


Grid of parameters for sensitivity

- Parameters: $\xi_\beta,\ \cancel{b'_\beta},\ \cancel{m_\beta} = 0,\ \xi_N,\ b'_N,\ m_N$
- $\frac{d\Gamma}{dE} = A(E, m_e)\sum_j \zeta_j \varepsilon_j \left(\left(\sqrt{\varepsilon_j^2 - m_N^2}\ \xi_N (1 - b'_N \frac{m_N}{\varepsilon_j})\right) + \left(\sqrt{\varepsilon_j^2 - \cancel{m}_\beta^2}\ \xi_\beta\ (1 - \cancel{b'_\beta} \frac{\cancel{m_\beta}}{\varepsilon_j})\right)\right)$
- GNI effect $\propto$ ξ_k and $\xi_k b'_k m_k$
- For SM & sterile neutrino,
- $\xi_\beta \sim |U_{eN}|^2 (g_V^2 + 3g_A^2)(1 + |\epsilon_R^2|) \sim 5.79\ (\pm 0.5\%)$: fix as 1
- $\xi_N \sim (g_V^2 + 3g_A^2)(|S_{eN}|^2 + |V_{eN}|^2 |\tilde{\epsilon}_L|^2)$, leading term $|S_{ei}|^2$ means mixing. : 201 in [5E-5, 10]
- $b'_N \sim |S_{eN}||T_{eN}|\tilde{\epsilon}_{L,R,S,T}(1 + \tilde{\epsilon}_{L,R,S,T} \pm \tilde{\epsilon}_{L,R,S,T})/\xi_N$ can varies $-5\sim5$: 101 in [-5,5]
- m_N : 111 in [0,18590] eV (bin=169eV)

Shape distortion of b'

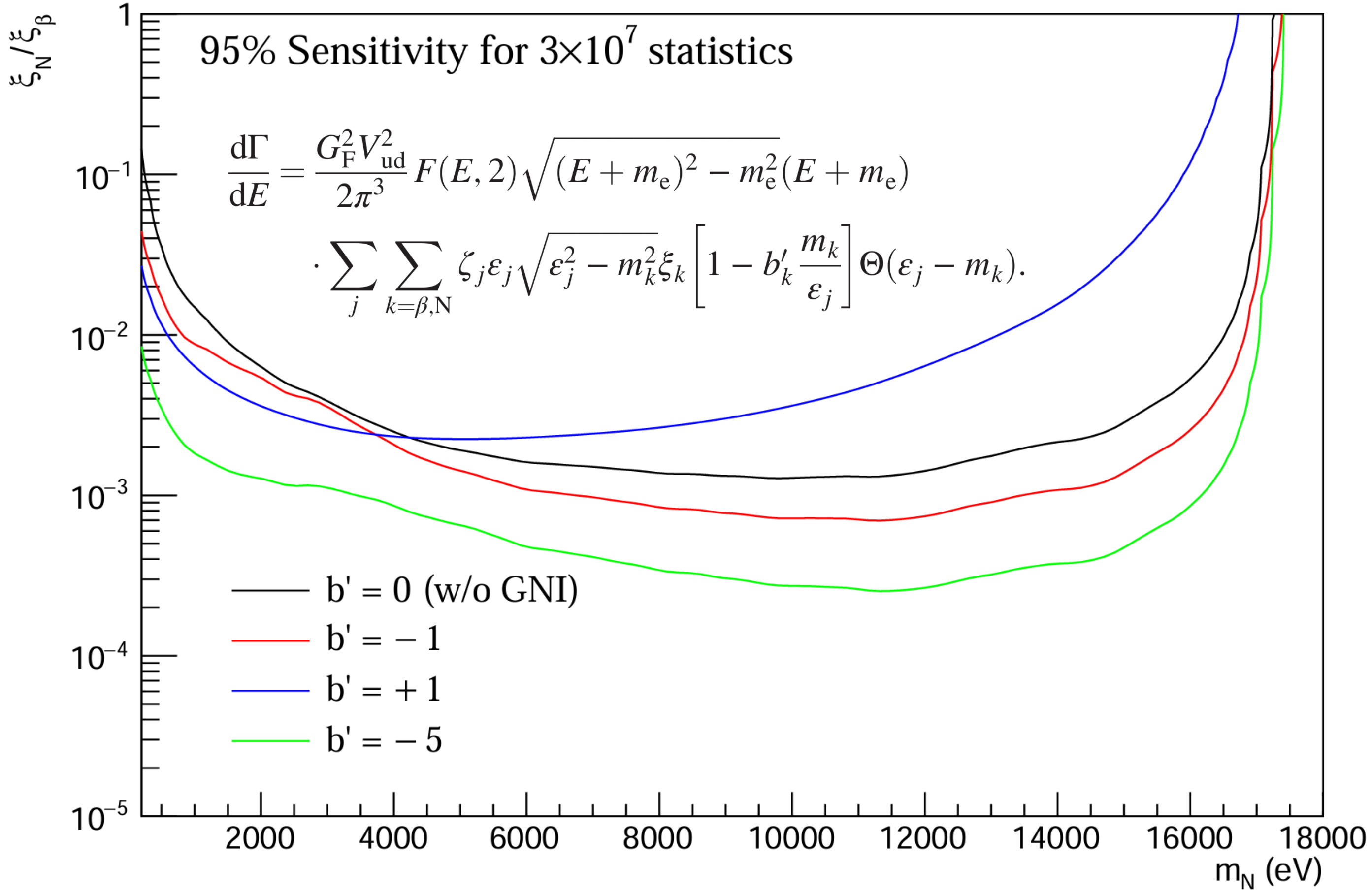




b′=-5 b′=0 b′=0.2 b′=1 b′>1 Non-physical

$@E = m_\nu$ concave kink +Kink small kink no kink

Sensitivity and ROI for GNI effect



1. $|S|^2$: mixing between heavy mass and light mass state ($< 0.001, |V|^2 = 1 - |S|^2$)
2. $\tilde{\epsilon}_S < 10^{-2}$
3. $\tilde{\epsilon}_T < 10^{-3}$ *PhysRevLett.134.251801*

Leading term (1st order of ϵ, $g_{V,A,S,T} = 1$)

: $b' = \frac{V}{S} * 2(\tilde{\epsilon}_S - 12\tilde{\epsilon}_T) > 60 * (\tilde{\epsilon}_S - 12\tilde{\epsilon}_T)$

if $-\tilde{\epsilon}_S + 12\tilde{\epsilon}_T$ is enough large, $b' = -5$

Most sensitive at $m_N = 11\text{keV}$ for tritium beta spectrum

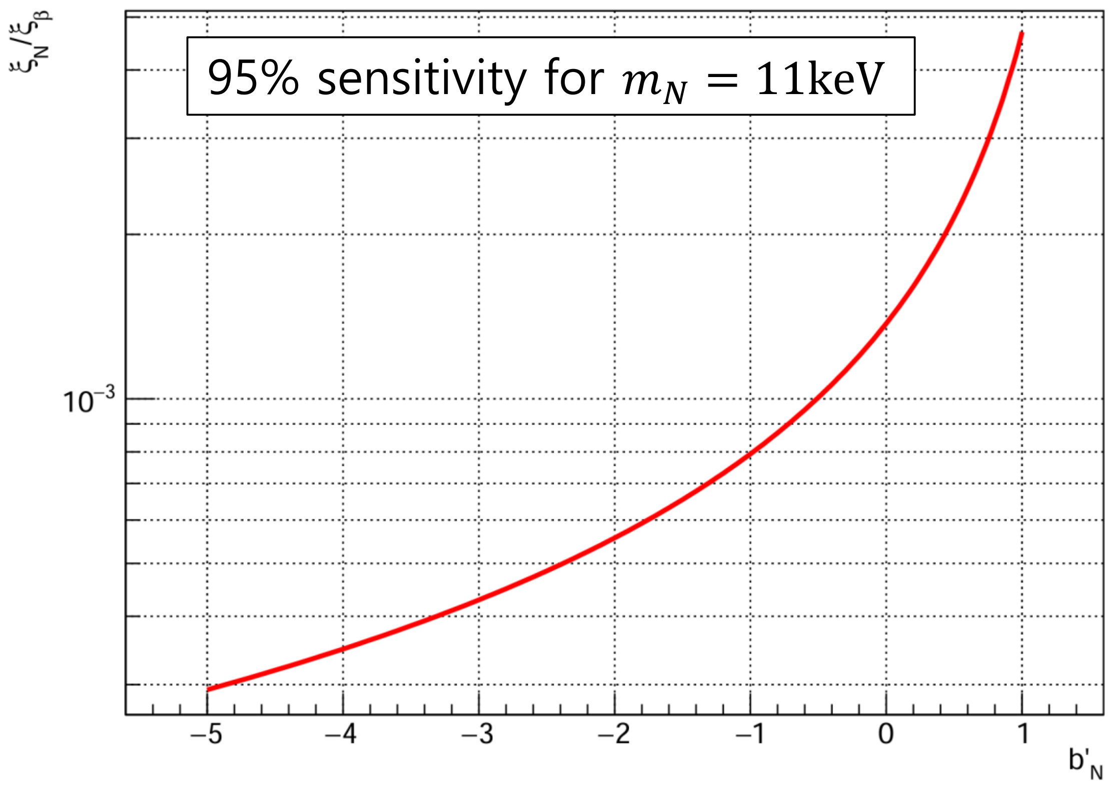
	m_ν<4keV	4keV<m_ν
b'	-5~0	-5~1

Sensitivity (ξ_N/ξ_β, b'_N) for $m_N = 11\text{keV}$

- At $m_\nu = 11\text{keV}$ for 2 cases
  : $|S|^2 = 1 \times 10^{-3}, 1 \times 10^{-5}$
- For 95% sensitivity,

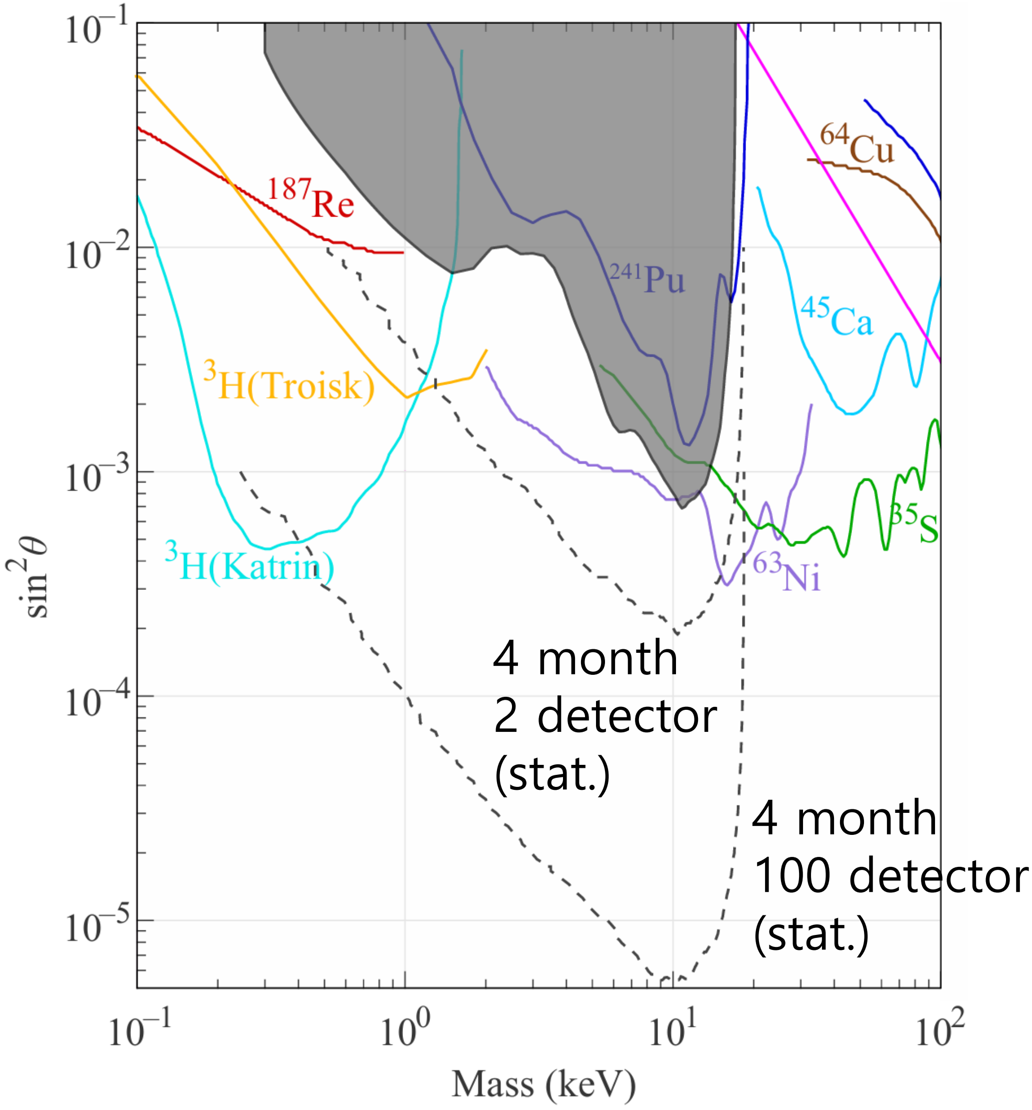
  $\xi_N(b' = -5) = 2.93 \times 10^{-4}$

  $\xi_N(b' = 1) = 4.69 \times 10^{-3}$
- Input values
  $g_V = 1.0$, $g_A/g_V = 1.2646$, $g_S = 1.02$
  $g_P = 349$, $g_T = 1.02$



Summary

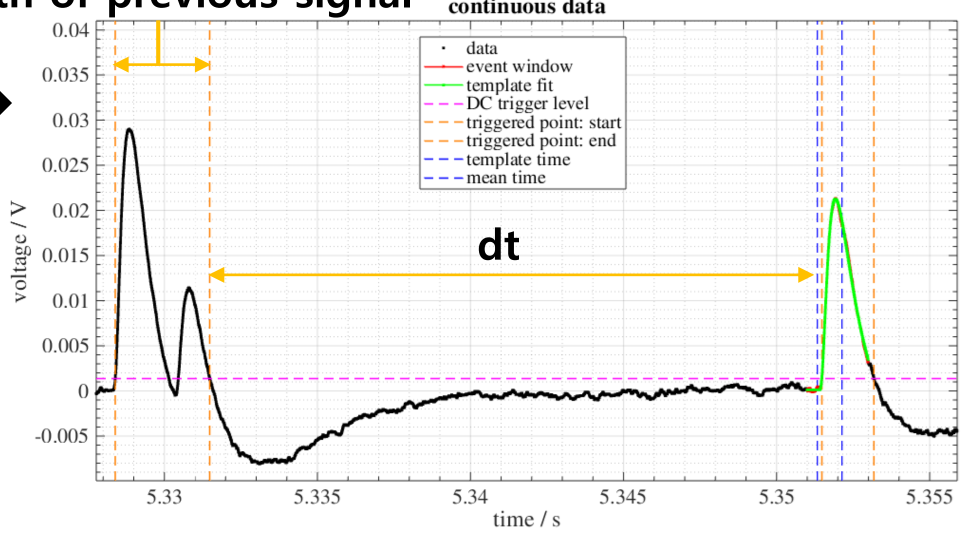
- For sterile neutrino search, we can reach lowest limit 10^{-3} at 11keV mass using only 10 day data-set (1 crystal).
- For 4 month data-set(for 2crystal), we expect best limit in 1-18keV region.
- We would make first result for GNI for search full range in tritium beta spectrum soon.



Data processing

Relation to previous signal ➡

width of previous signal

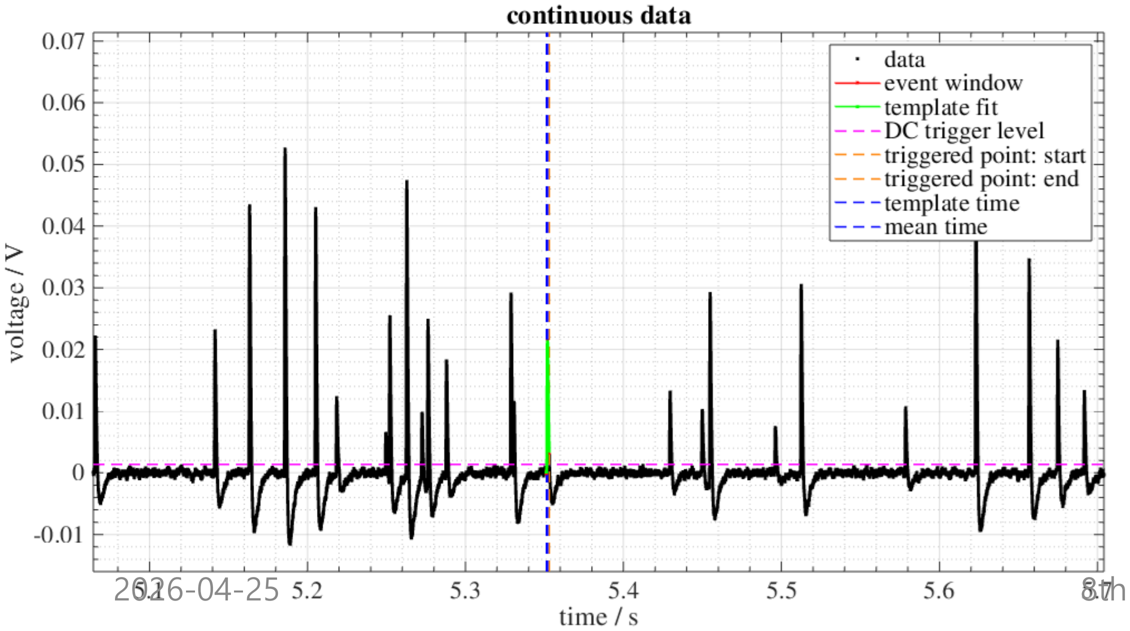


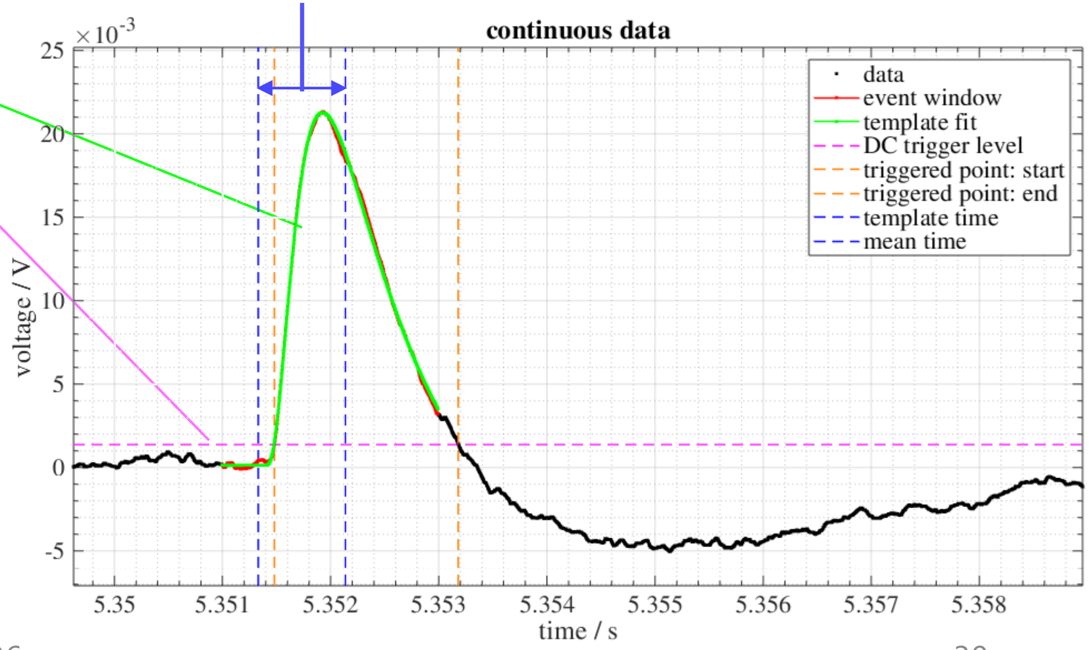
For continuous data

1. Applying frequency filter with band pass: [0.1kHz 1.5kHz]
2. Event trigger with DC trigger level(360eV) and 1ms dead time
3. Template fit to triggered event to calculate pulse amplitude
4. Event cut with 3 parameters:

- **1. loose cut for width of previous signal & dt > 8ms,**
- **2. Mean time cut**

Mean time





Pseudo data

Make continuous pseudo data with long(~100ms) **signal template** and **noise** and **event rate**(3H, Mn 6keV peaks) from real data and expected energy spectrum of 3H decay

- Template is scaled along energy calibration
- Apply same trigger logic, event selection criteria as real data

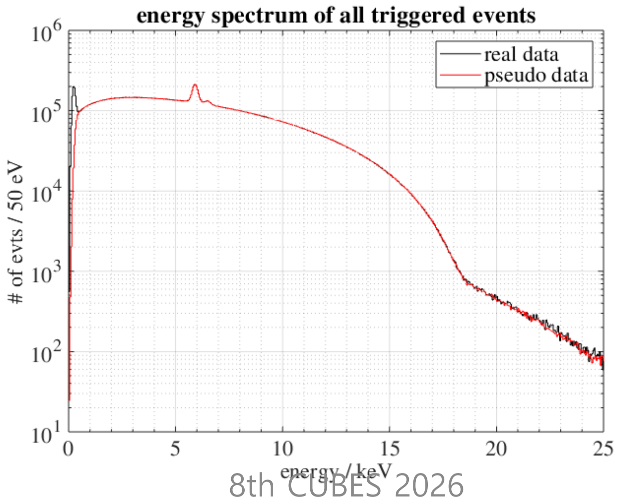
To calculate

- Efficiency estimation, **especially for single event**
- Bias correction in pulse amplitude for low energy signal
- Unresolved pileup spectrum

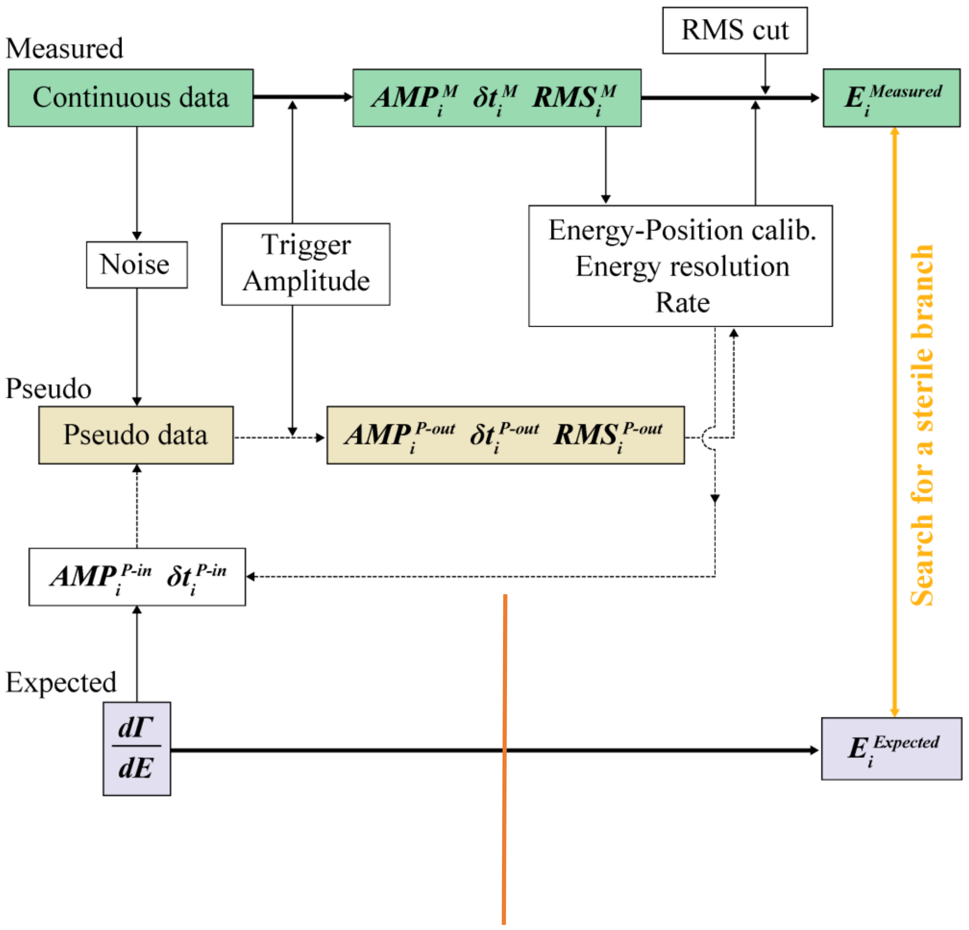
Expect spectrum T(E) to fit measured

$T(E) = \int_{-\infty}^{\infty} (S(E')/Eff(E')) * R(E,E')dE' + D(E) + bkg(E)$

- S(E): theoretical 3H spectrum,
- Eff(E′): efficiency for single event,
- R: detector resolution,
- D(E): Unresolved pileup spectrum
- bkg(E): background spectrum



Schematic of analysis flow



2-3 times iteration needed to saturate the value of event rate & bias correction