

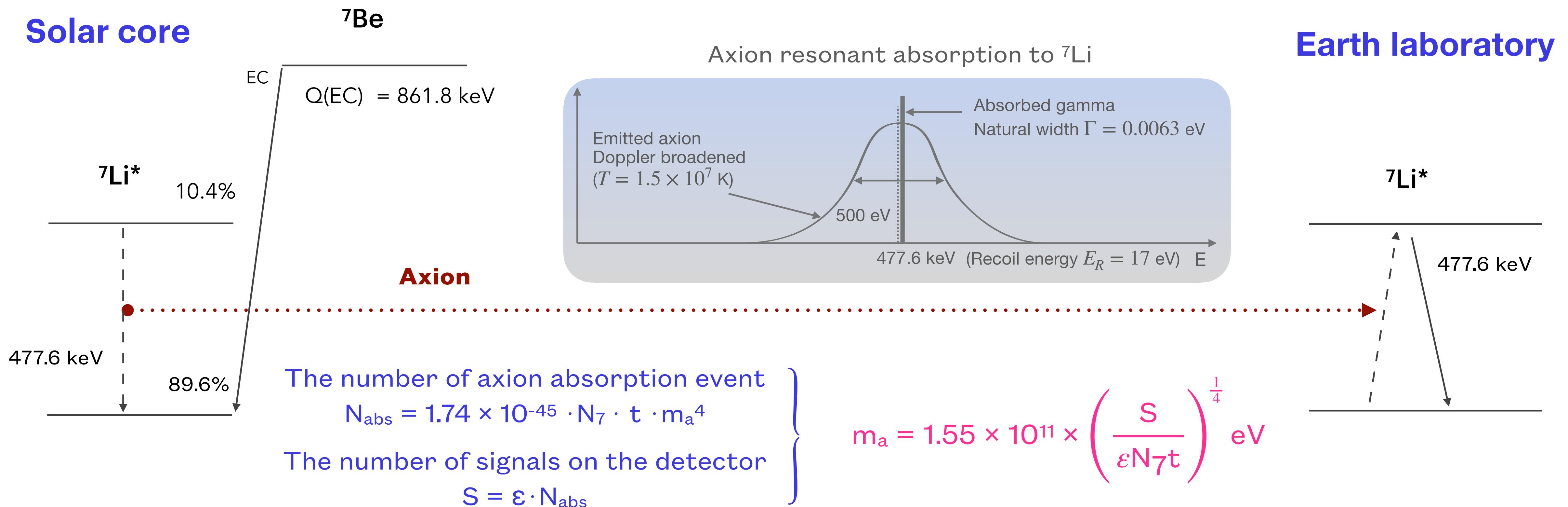
A search for ${}^7\text{Li}$ axions with Li_2MoO_4 detectors in the AMoRE experiment

Jeewon Seo

¹ IBS School, University of Science and Technology (UST)

² Center for Underground Physics, Institute for Basic Science (IBS)

Motivation for solar axion search



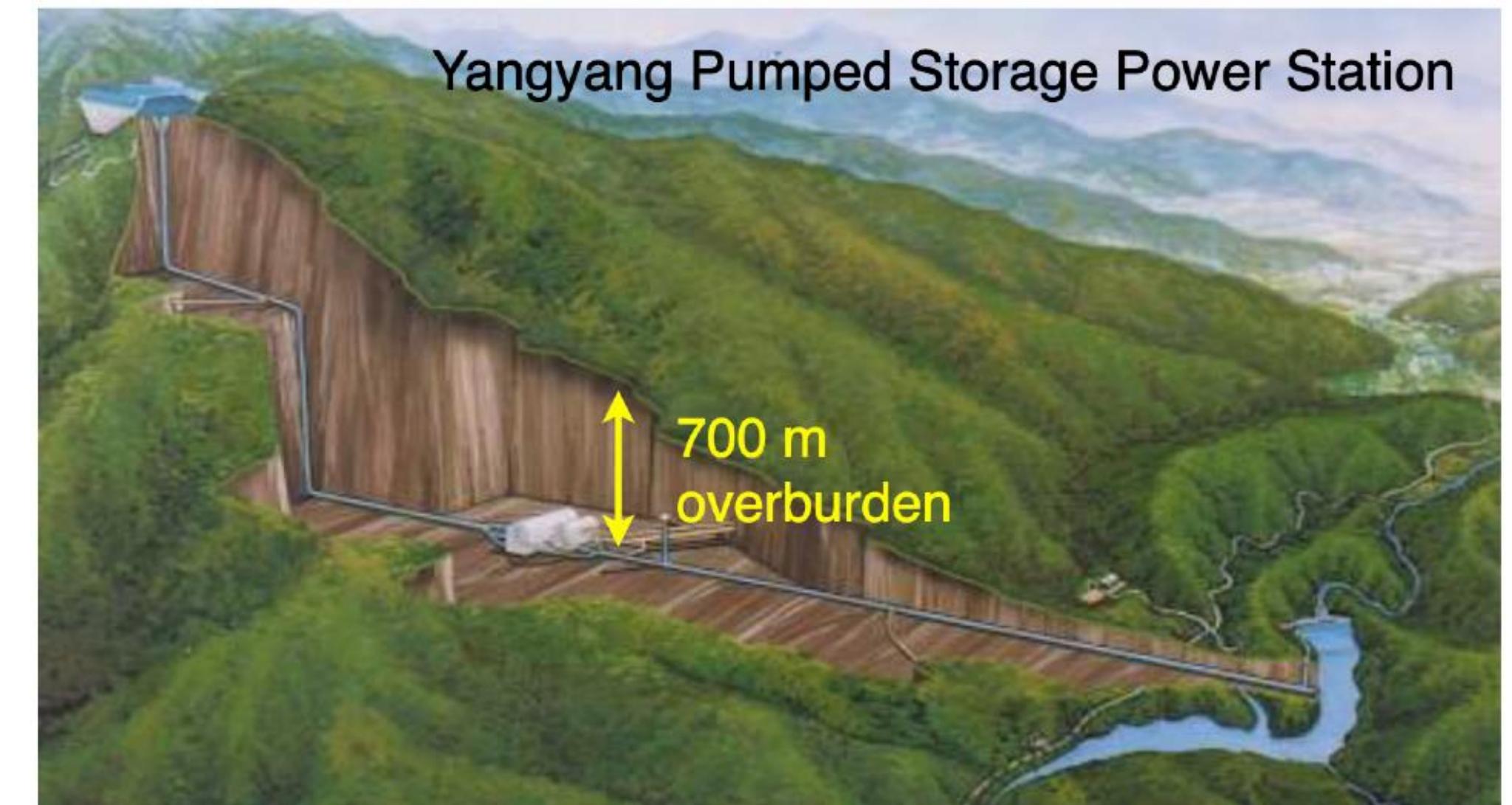
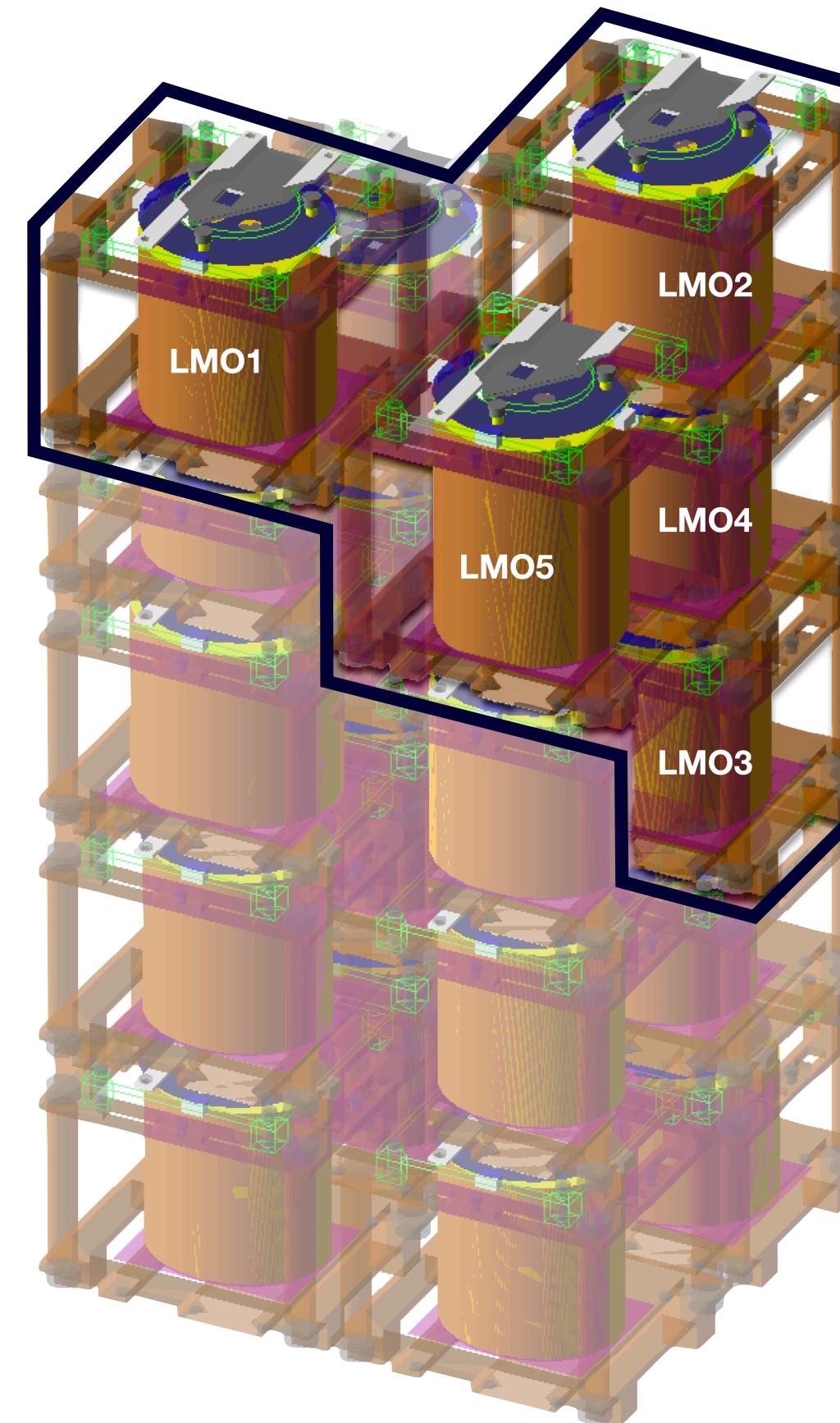
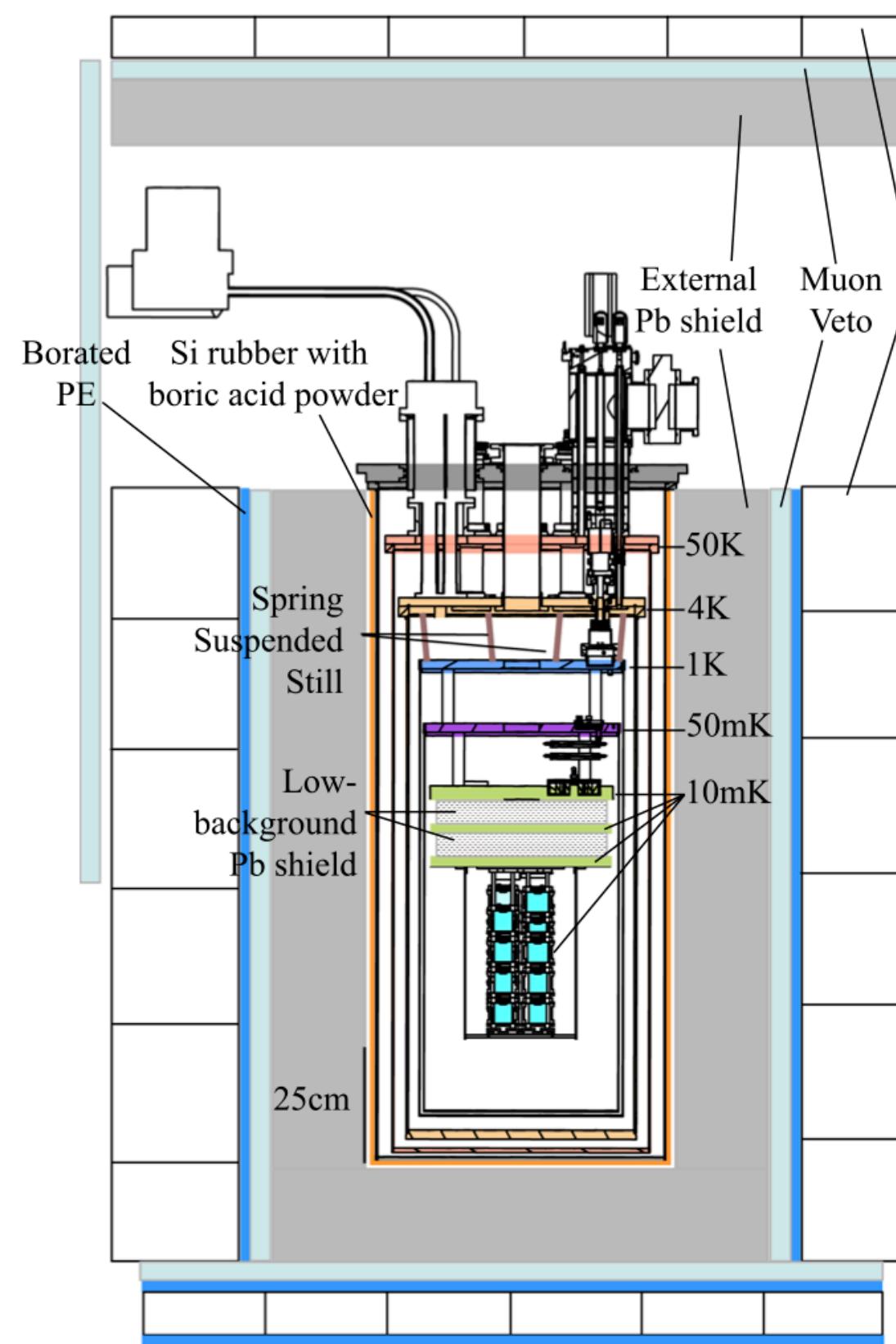
N_7 : The number of ^{7}Li in the crystal, t : live time (sec), m_a : axion mass, ε : detection efficiency

For this relation, isoscalar and isovector coupling constants of the KSVZ axion model were used.

$$g_{aN}^0 = -3.51 \times 10^{-8} m_a, \quad g_{aN}^3 = -2.8 \times 10^{-8} m_a$$

Solar axion search with AMoRE-I

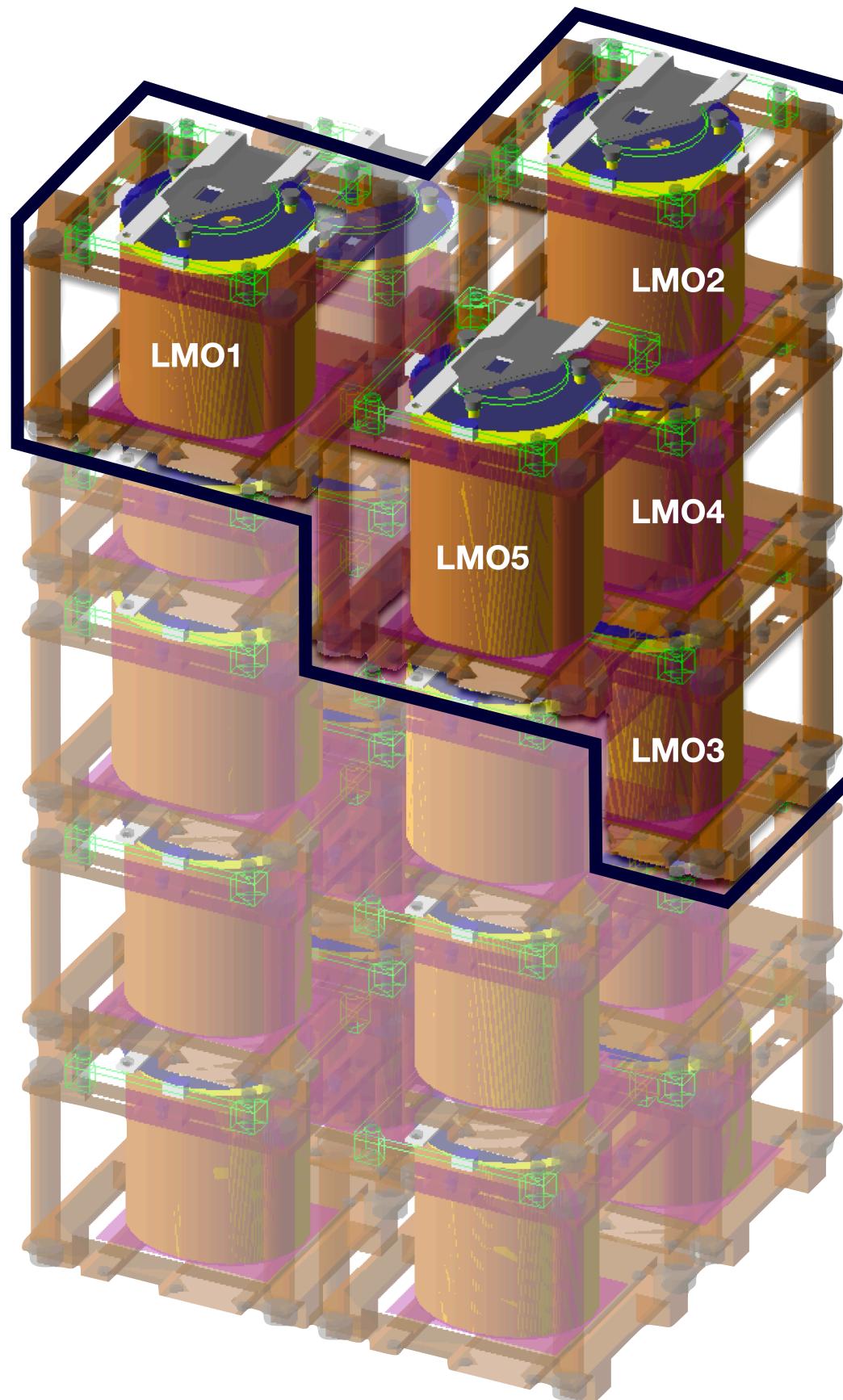
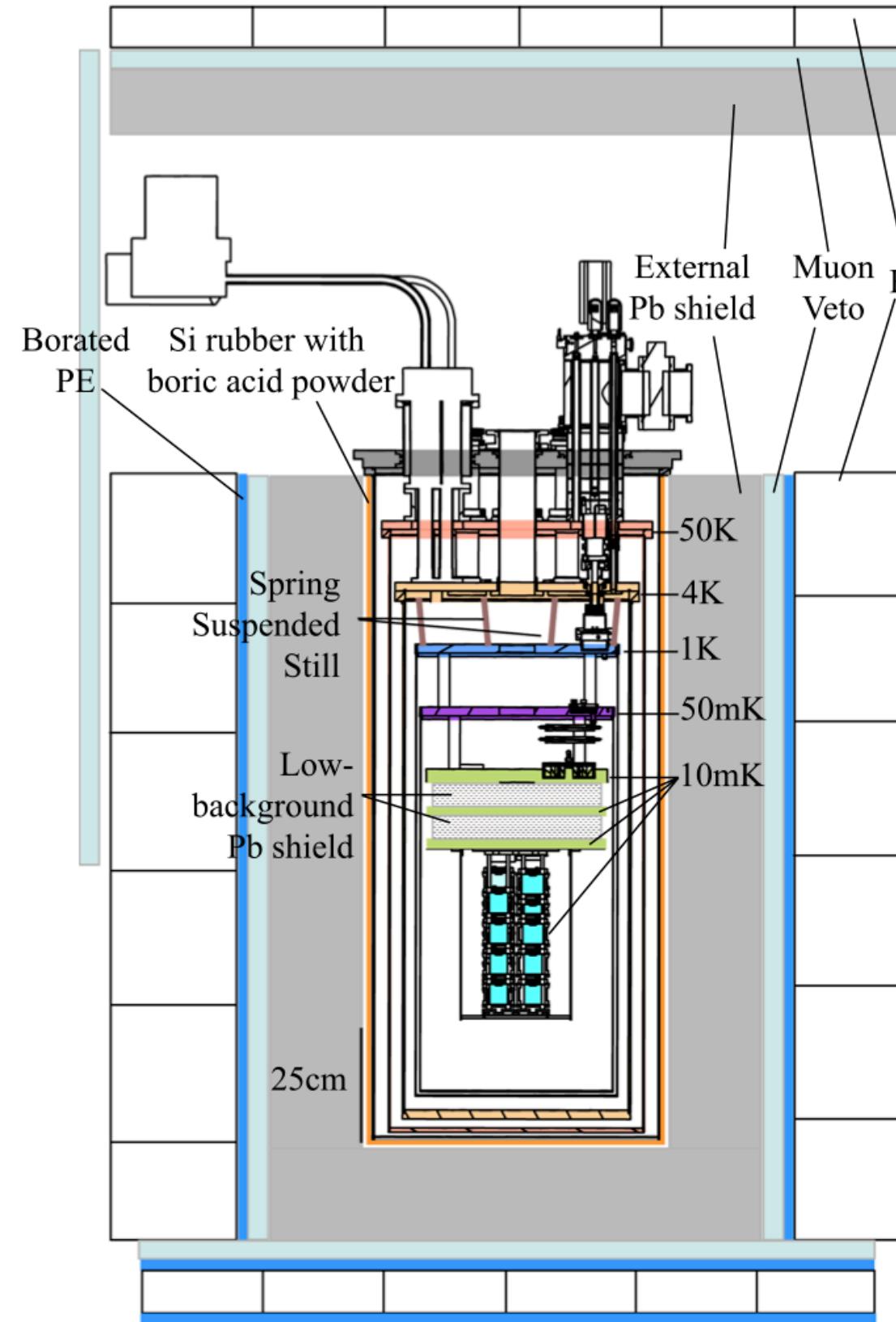
AMoRE-I detector



- Yangyang Underground laboratory (Y2L)
 - ~ 700 m vertical depth (2000 m.w.e)
 - Detector module with enriched Li₂¹⁰⁰MoO₄ crystals and ^{depl}Ca¹⁰⁰MoO₄
 - Phonon detector is located at the bottom of the module
 - Photon detector is located on top of the module

Solar axion search with AMoRE-I

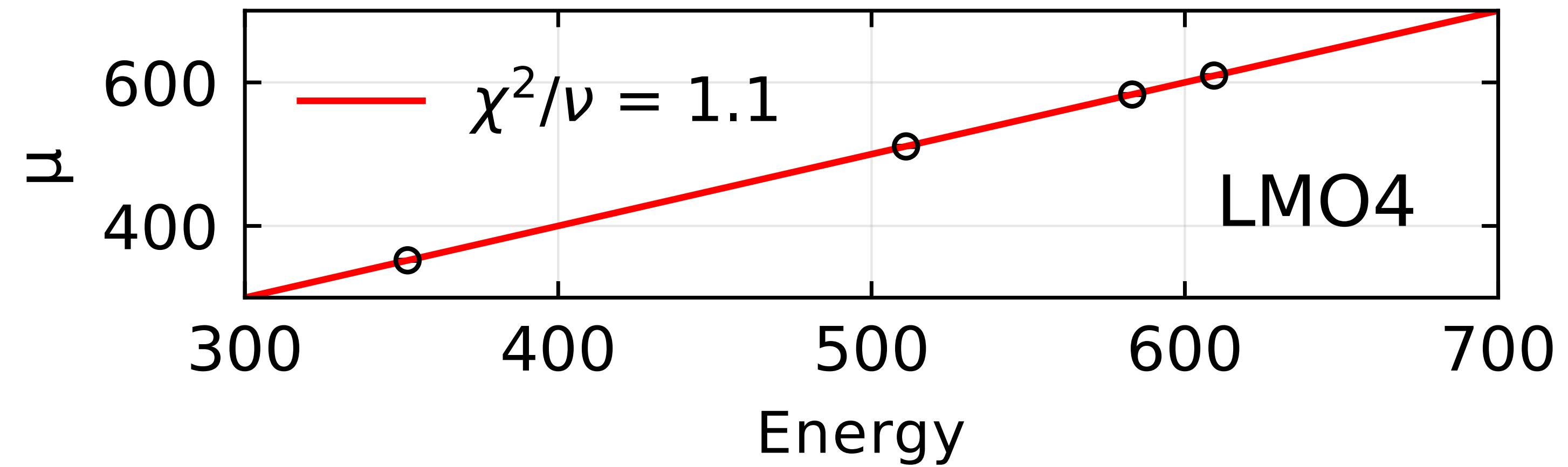
AMoRE-I detector



- Full peak detection efficiency for the 5 crystals obtained by Geant4 simulation.
- The measurement time is 333 days.
- Our system has 50 ms dead-time for each event.

Crystal	Mass (g)	N_7 ($\times 10^{24}$)	Exposure ($\times 10^{24} \cdot \text{Li} \cdot \text{day}$)	Efficiency (%)
LMO1	300	1.92	606.72	2.38
LMO2	312	2.00	632.00	2.92
LMO3	312	2.00	632.00	2.57
LMO4	308	1.97	622.52	2.86
LMO5	378	2.42	764.72	3.46
Total	1610	10.31	3257.96	14.19

Energy calibration and events selection

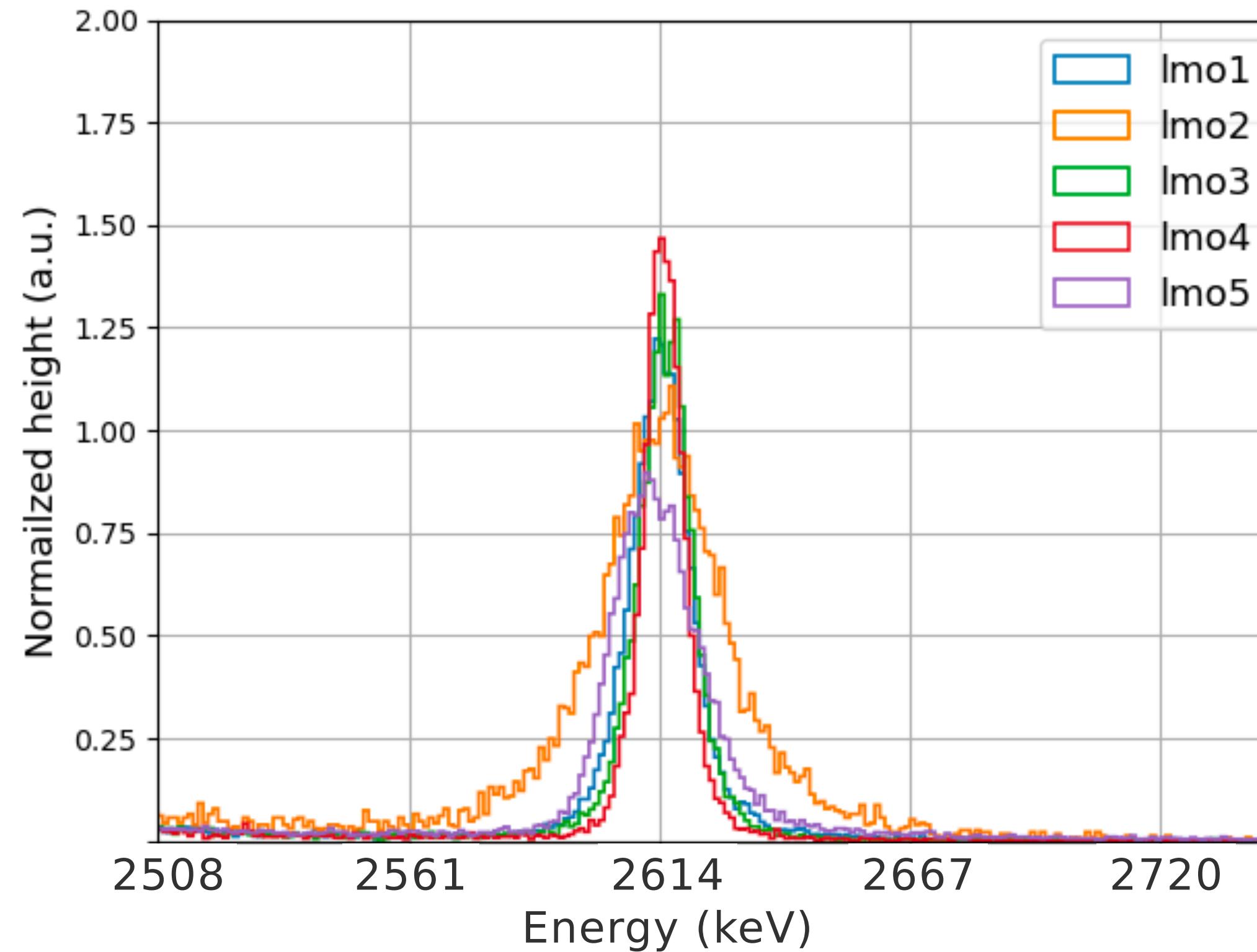


- Literature energy: 351.9, 511, 583.2, 609.2, 1120.3, 1173.2, 1332, 2614.5 keV
- The mean energy (μ) obtained after Gaussian + background fitting for each crystal
- μ as a function of literature energy was fitted with $p_0x + p_1x^2$

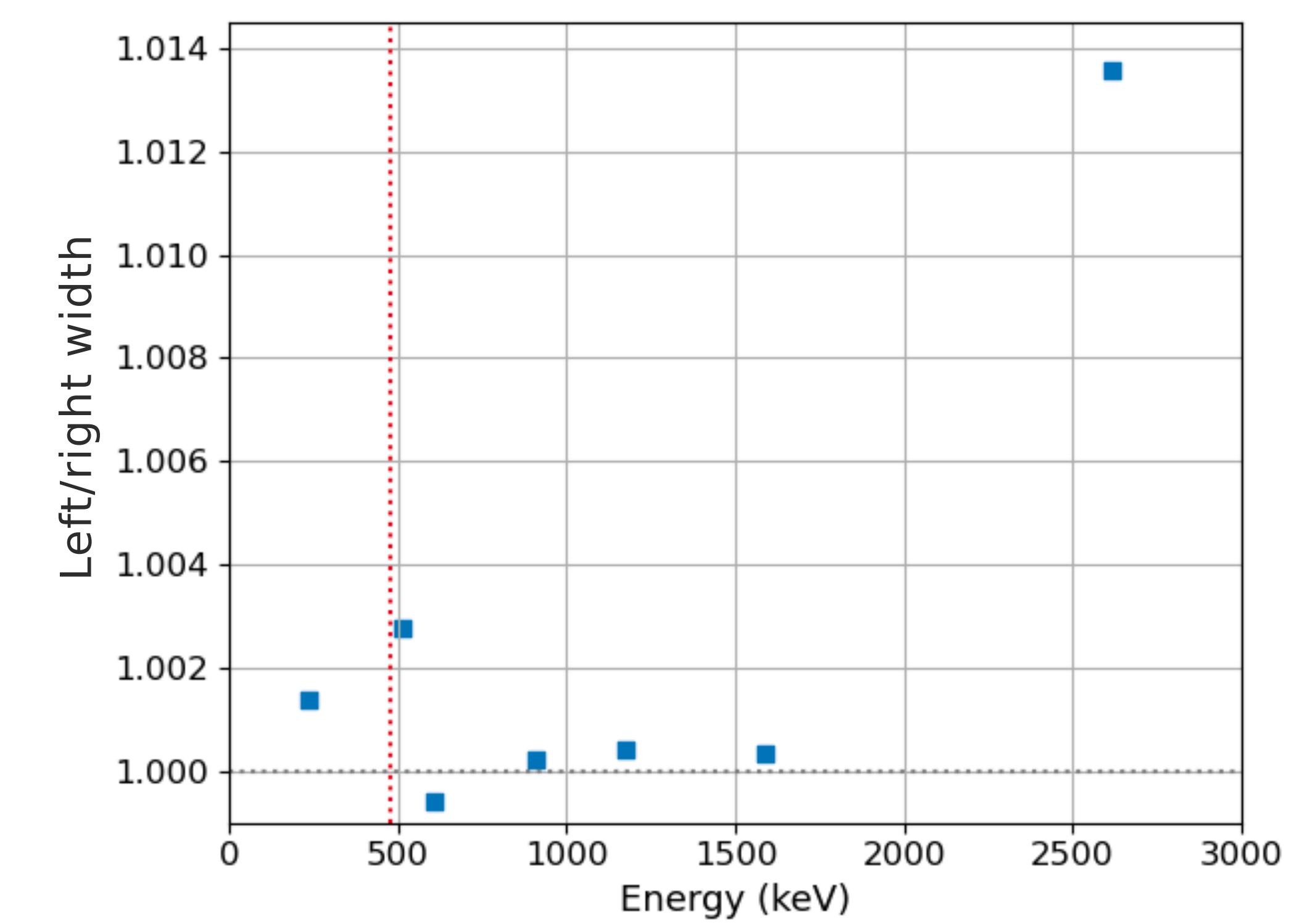
Cut	Efficiency at 478 ± 10 keV (%)
LH ratio	96.00 ± 0.11
Rising time	97.93 ± 0.10
Muon veto	99.78 ± 0.11
Total	93.22 ± 0.11

Signal shape

The shape of the 2.6 MeV energy peak



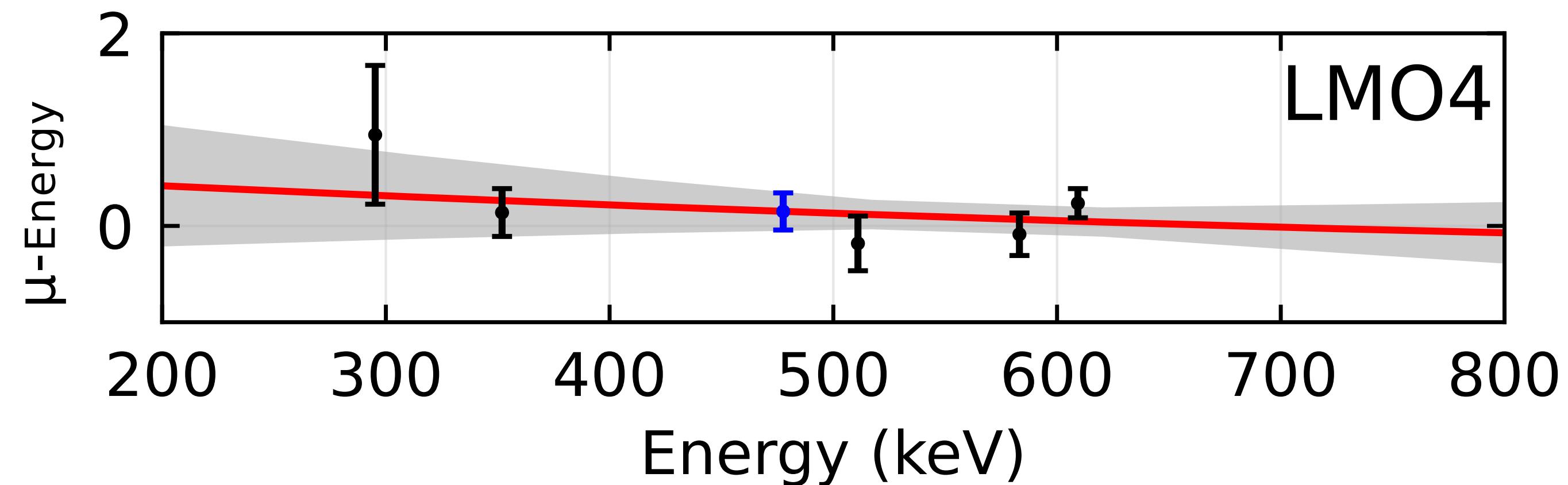
The ratio of left and right width of the peak



- The resolution is different between crystals. → We decided to fit and analyze them before merging.
- The peak shape is almost Gaussian at the low energy region. → We use the Gaussian function for the fitting model.

Systematic uncertainty

Energy scale bias

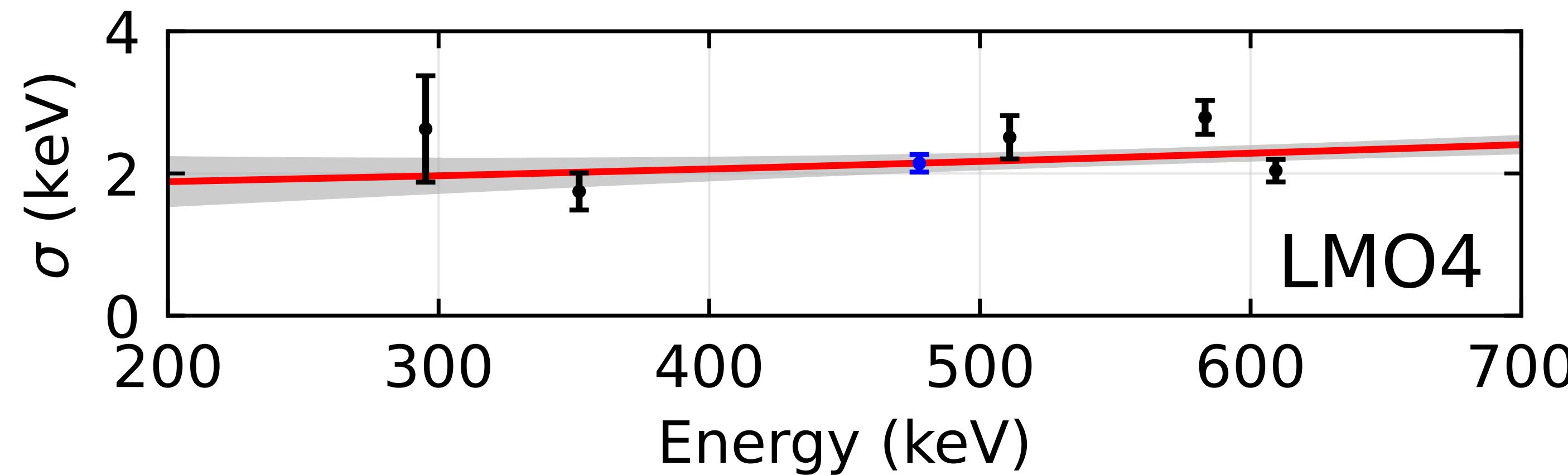


Crystal	μ - Energy	
	478 keV	511 keV
LMO1	0.72 ± 0.27	0.62 ± 0.31
LMO2	-4.24 ± 2.40	-4.17 ± 2.39
LMO3	-0.18 ± 0.19	-0.17 ± 0.18
LMO4	0.24 ± 0.16	-0.21 ± 0.11
LMO5	0.10 ± 0.28	0.06 ± 0.22

- Second-order polynomial fit on the difference between the fitting result and literature energy as a function of energy.
- The uncertainty band is a sum of the uncertainty from changing the fitting function.

Systematic uncertainty

Energy resolution



- The energy resolution (σ) of the gamma peaks can be fitted by

$$\sigma = \sqrt{p_o^2 + p_1^2 E + p_2^2 E^2}$$

Crystal	σ	
	478 keV	511 keV
LMO1	3.31 ± 0.24	3.84 ± 0.24
LMO2	6.72 ± 2.43	6.73 ± 2.41
LMO3	3.07 ± 0.19	3.14 ± 0.19
LMO4	1.99 ± 0.13	2.12 ± 0.12
LMO5	3.97 ± 0.22	4.01 ± 0.21

Least square fit

$$\chi_i^2 = \sum_i \left(\sum_j \frac{(f_i(x_{ij}) - y_{ij})^2}{\sigma_{y_{ij}}^2} + \sum_k \frac{(a_k - p_k)^2}{\Delta a_k^2} \right)$$

The number of parameters = 41

i = crystal id

j = data point

k = systematic source

p = parameter

y = data

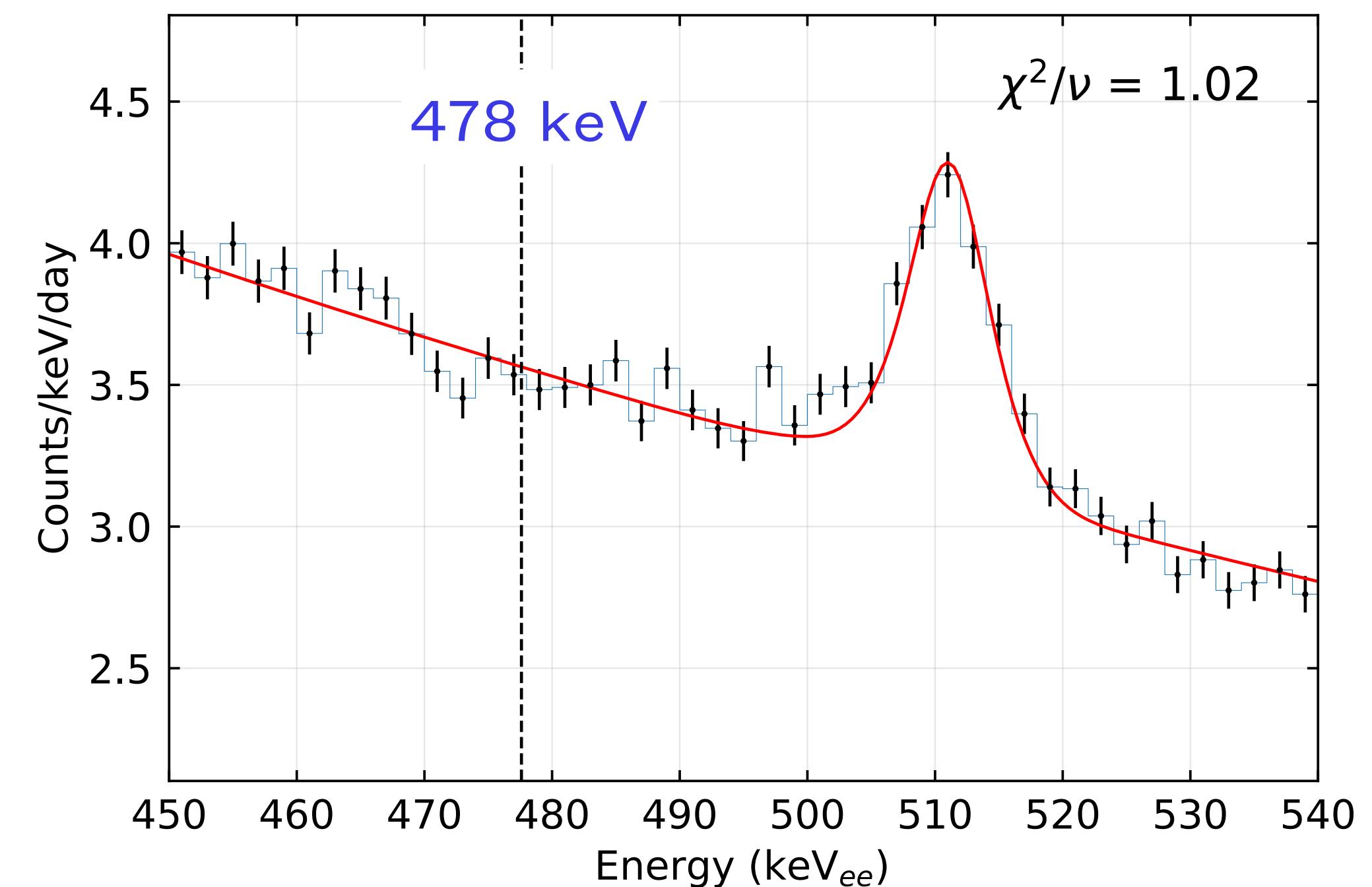
$f(x)$ = fitting model

a = central value of the systematic source

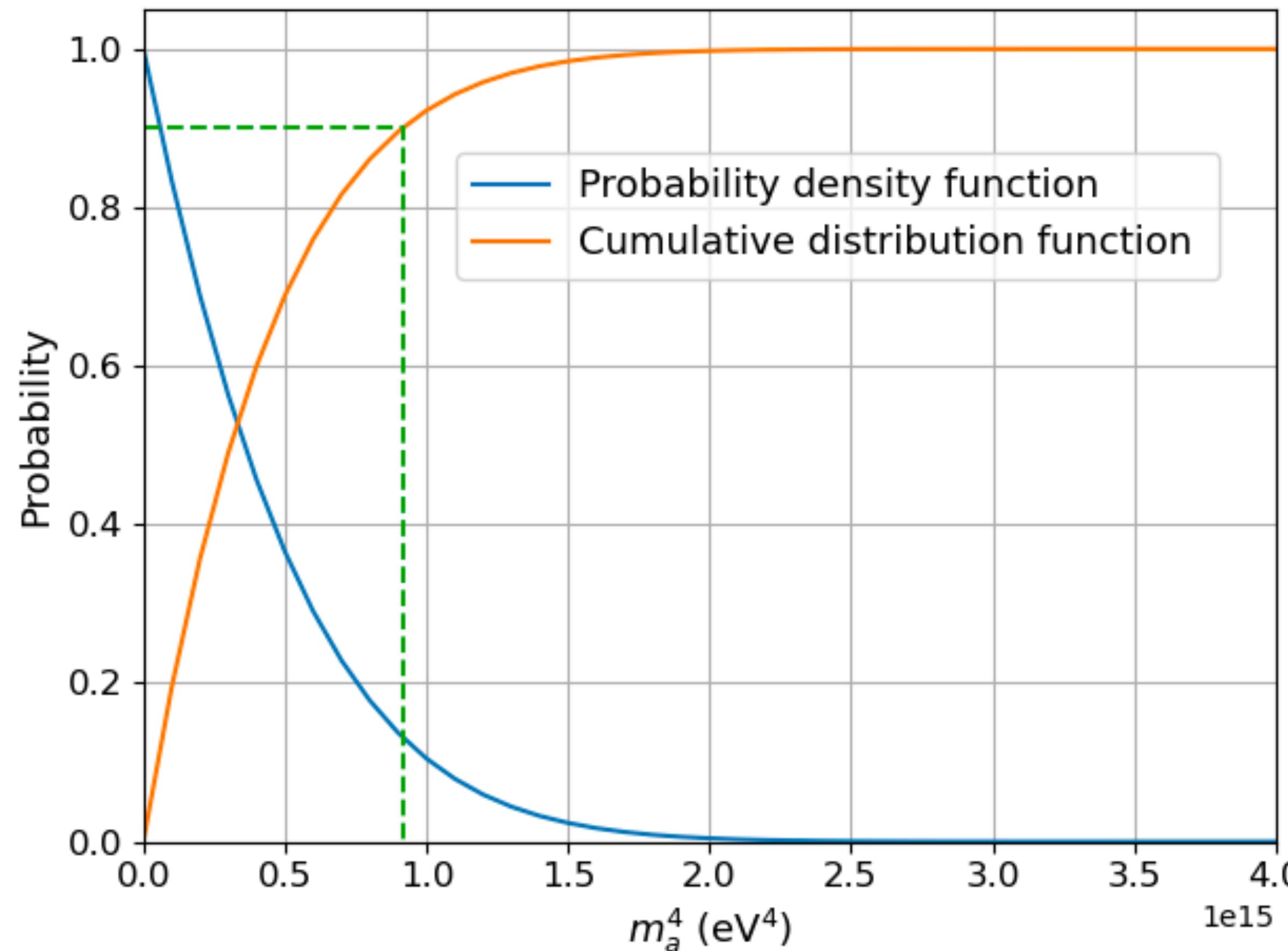
Δa = systematic uncertainty

$$f_i(x_{ij}) = \underbrace{\mathbf{A} \mathbf{p}_0 \frac{1}{\sqrt{2\pi} p_{2_i}} \exp \left[-\left(\frac{x_{ij} - p_{1_i}}{\sqrt{2} p_{2_i}} \right)^2 \right]}_{\text{Gaussian for } 478 \text{ keV}} + \underbrace{p_{3_i} \exp \left[-\frac{x_{ij} - p_{4_j}}{p_{5_j}} \right]}_{\text{exponential background}}$$

$$+ \underbrace{p_{6_i} \frac{1}{\sqrt{2\pi} p_{8_i}} \exp \left[-\left(\frac{x_{ij} - p_{7_i}}{\sqrt{2} p_{8_i}} \right)^2 \right]}_{\text{Gaussian for } 511 \text{ keV}}$$



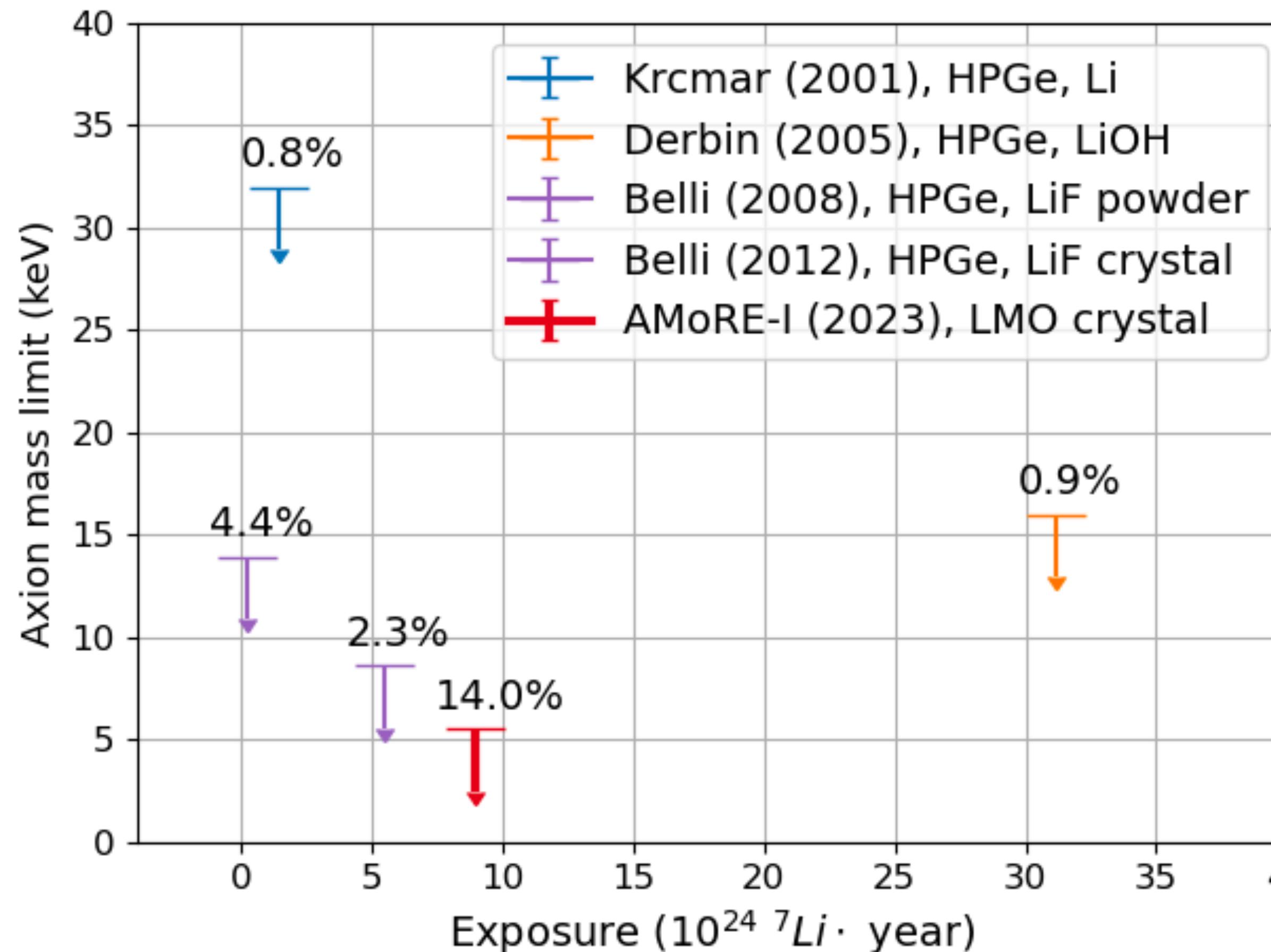
Axion mass limit



- Full peak detection efficiency at ROI: 14.2%
- Exposure : $3.258 \times 10^{27} {}^7\text{Li}\cdot\text{day}$
- Simultaneous shape analysis at ROI with exponential background for each crystal

$m_a < 5.5 \text{ keV}$ at 90% C.L.

Summary



	AMoRE-I	AMoRE-II
Crystal size	$\varnothing 50 \text{ mm} \times 50 \text{ mm}$	$\varnothing 50 \text{ mm} \times 50 \text{ mm}$ $\varnothing 60 \text{ mm} \times 60 \text{ mm}$
Total mass	1.6 kg	180 kg
N_{Li7}	1.13×10^{25}	1.28×10^{27}
Efficiency (%)	14.19	21.83
Axion mass (keV)	< 5.5	~ 2

BACKUP SLIDE

Motivation for solar axion search

The rate of the absorption of solar axions per ${}^7\text{Li}$ nucleus in the laboratory

$$R_a = \int_{-\infty}^{\infty} dE_a \frac{d\Phi(E_a)}{dE_a} \sigma(E_a) = \sqrt{\frac{\pi}{2}} k \sigma_0 \Gamma \left(\frac{\Gamma_a}{\Gamma_\gamma} \right)^2 \int_0^{R_\odot} \frac{d\Phi_\nu^{Be}(r)}{\sqrt{\sigma(T)^2 + \sigma(T_E)^2}}$$

Axion flux

Axion resonance absorption cross-section

$$\frac{d\Phi(E_a)}{dE_a} = \int_0^{R_\odot} d\Phi_\nu^{Be}(r) k \frac{1}{\sqrt{2\pi}\sigma_s(T)} \times \exp \left[-\frac{(E_a - E_\gamma)^2}{2\sigma_s(T)^2} \right] \frac{\Gamma_a}{\Gamma_\gamma}$$

$$\sigma(E_a) = \sqrt{\pi} \sigma_{0\gamma} \frac{\Gamma_a}{\Gamma_\gamma} \exp \left[-\frac{4(E_a - E_\gamma)^2}{\Gamma^2} \right]$$

Probability of axionic emission

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha} \left(\frac{k_a}{k_\gamma} \right)^3 \frac{1}{1 + \delta^2} \left(\frac{g_{aN}^0 \beta + g_{aN}^3}{(\mu_0 - \frac{1/2}{}) \beta + \mu_3 - \eta} \right)^2 = 4.12 \times 10^{-15} m_a^2$$

R_\odot : solar radius, $d\Phi_\nu^{Be}$: fraction of the $\nu_{\gamma Be}$ flux at the earth,

$\sigma_s(T)$: standard deviation of the axion energy spectrum

$\sigma_{0\gamma} = \frac{2I_1 + 1}{2I_0 + 1} \frac{2\pi\lambda^2}{1 + \alpha}$: maximum resonant cross-section of gamma rays

I_0 and I_1 : spin of the ground and excited states of ${}^7\text{Li}$ nucleus
electron conversion factor $\alpha \approx 0$