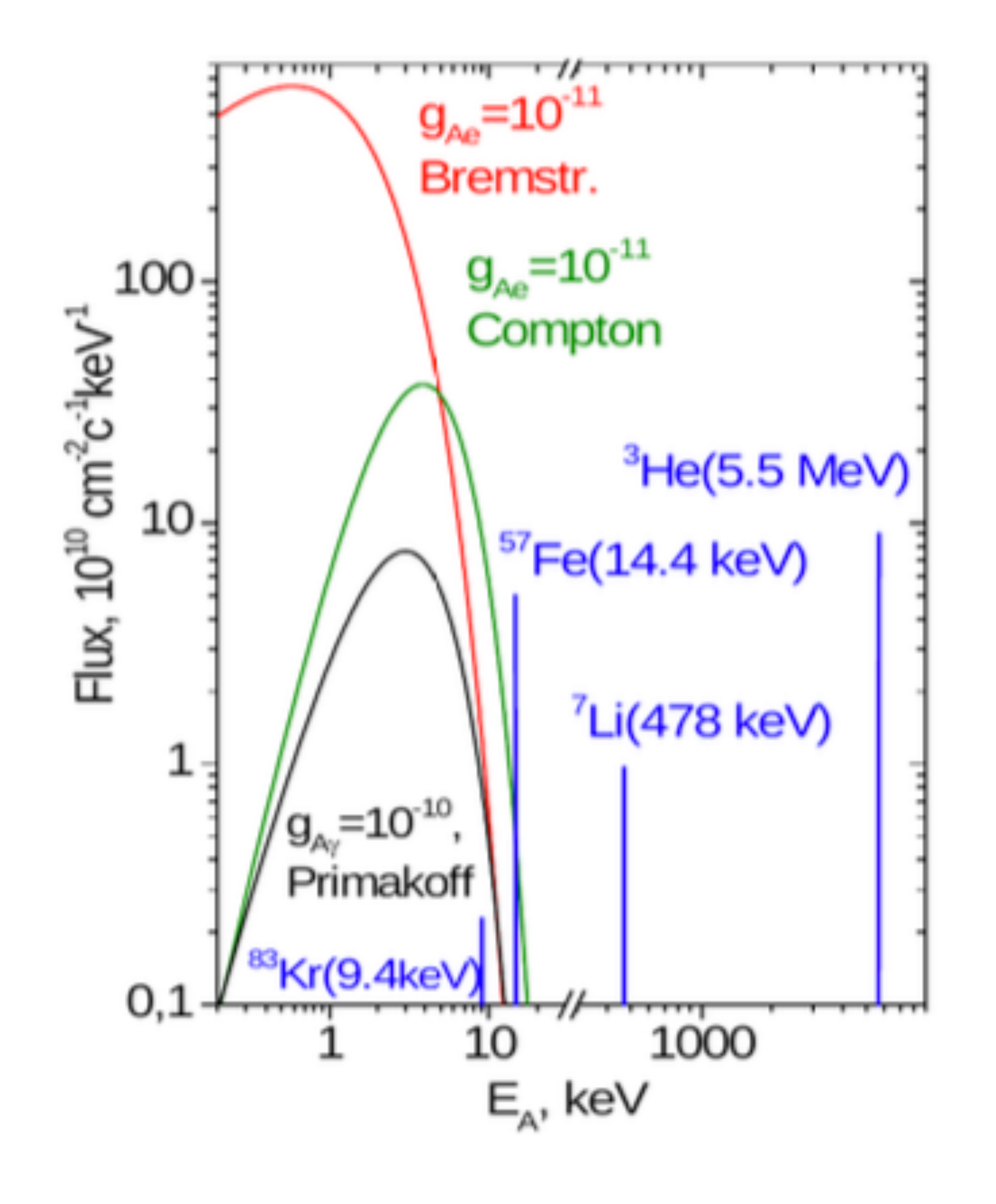
A solar axion search with the Li_2MoO_4 crystal detector at the AMoRE-I experiment

Jeewon Seo
Center for underground physics, Institute for basic science

ibs Institute for Basic Science
CENTER FOR UNDERGROUND PHYSICS

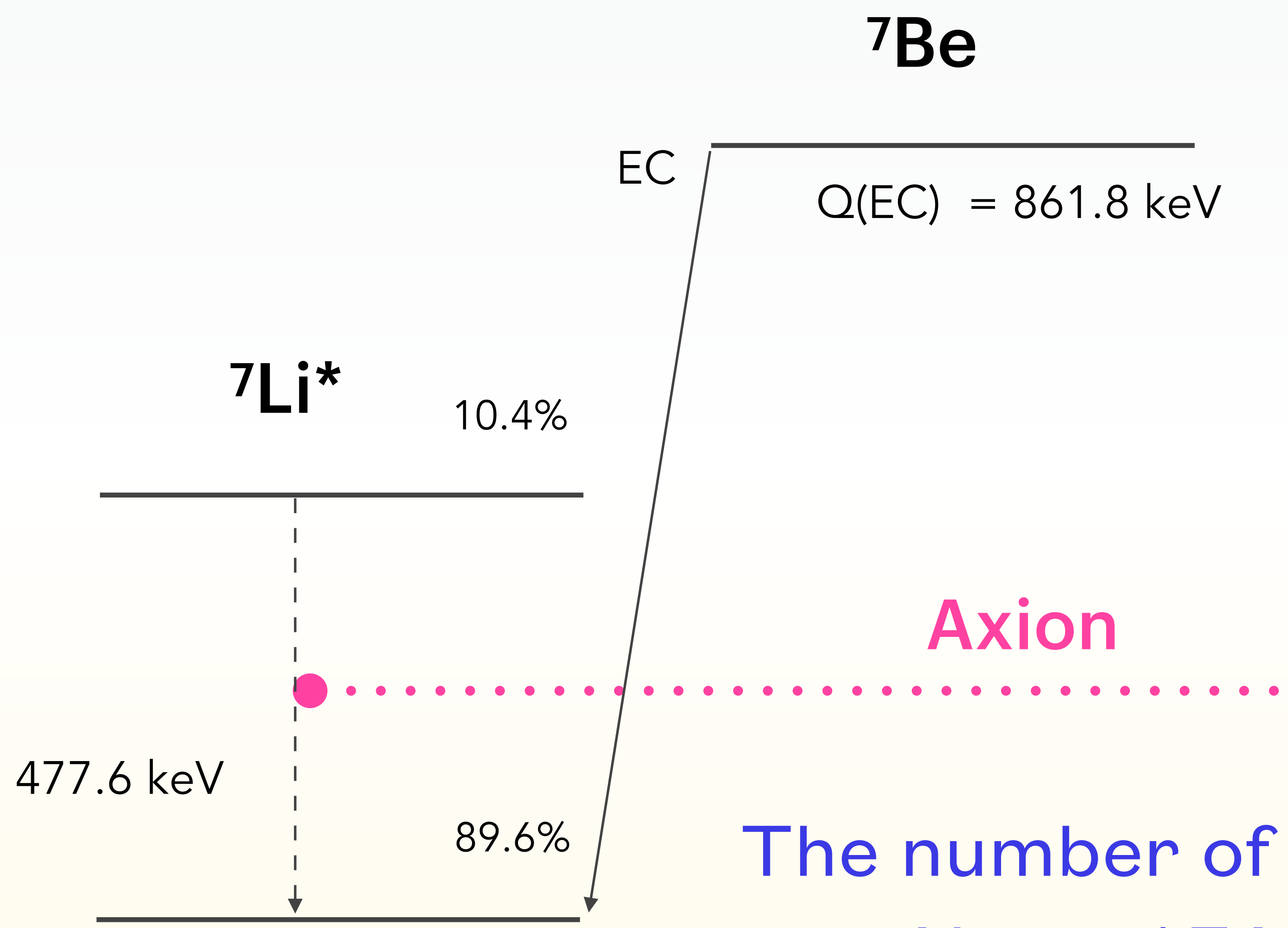
Introduction for solar axion search

- Proposed to solve the strong CP problem in QCD by R.Peccei and H.Quinn (1977)
- Light, electrically neutral, and zero spin
- Considered as candidates for dark matter
- Sun can be a very intense source of axion.
- The 7Li resonance events are associated only with the axion-nucleon coupling.

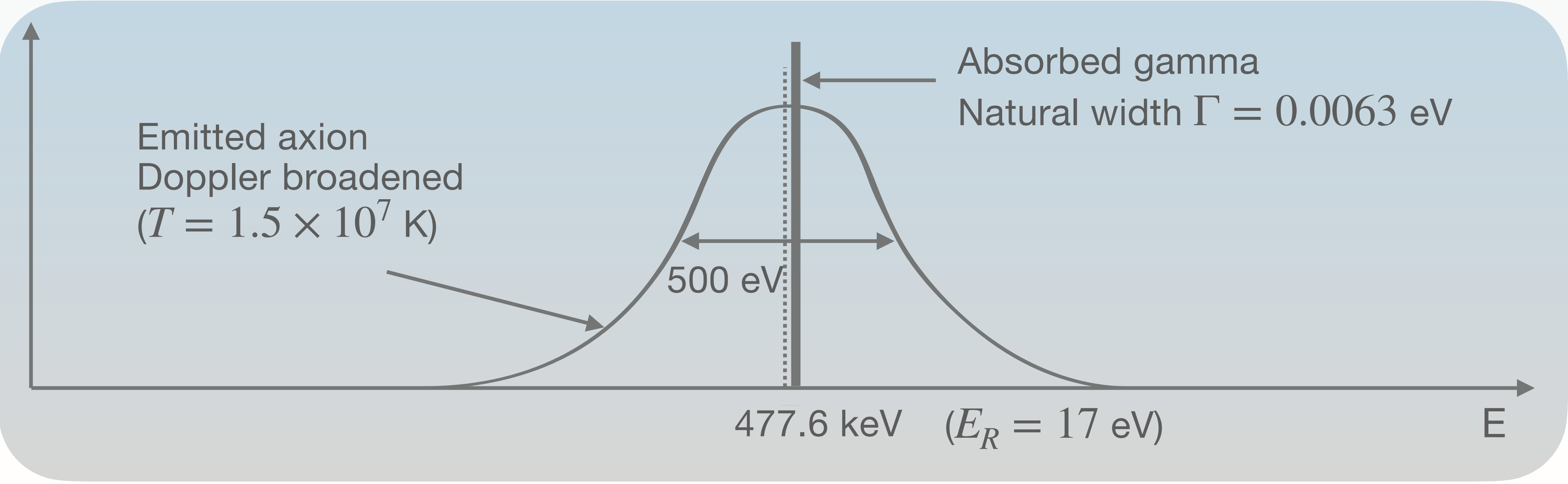


Motivation for solar axion search

Solar core

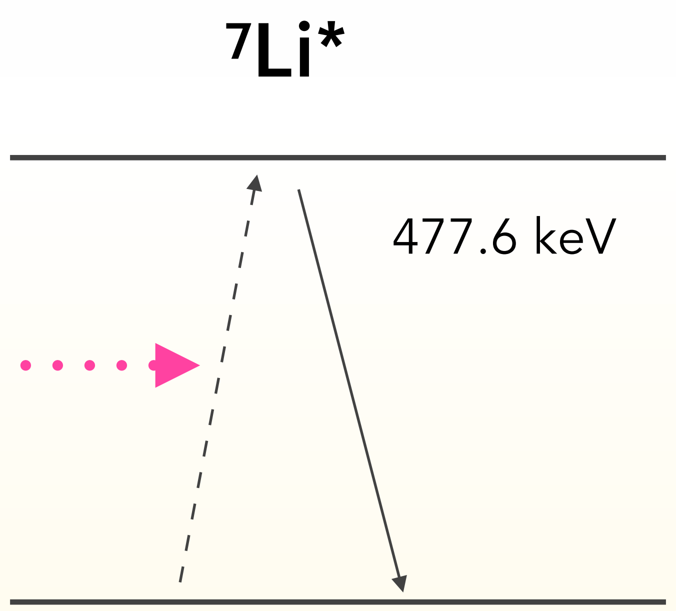


Axion resonant absorption to ^{7}Li



Axion

Earth laboratory



The number of axion absorption event

$$N_{abs} = 1.74 \times 10^{-45} \cdot N_7 \cdot t \cdot m_a^4$$

The number of signals on the detector

$$S = \varepsilon \cdot N_{abs}$$

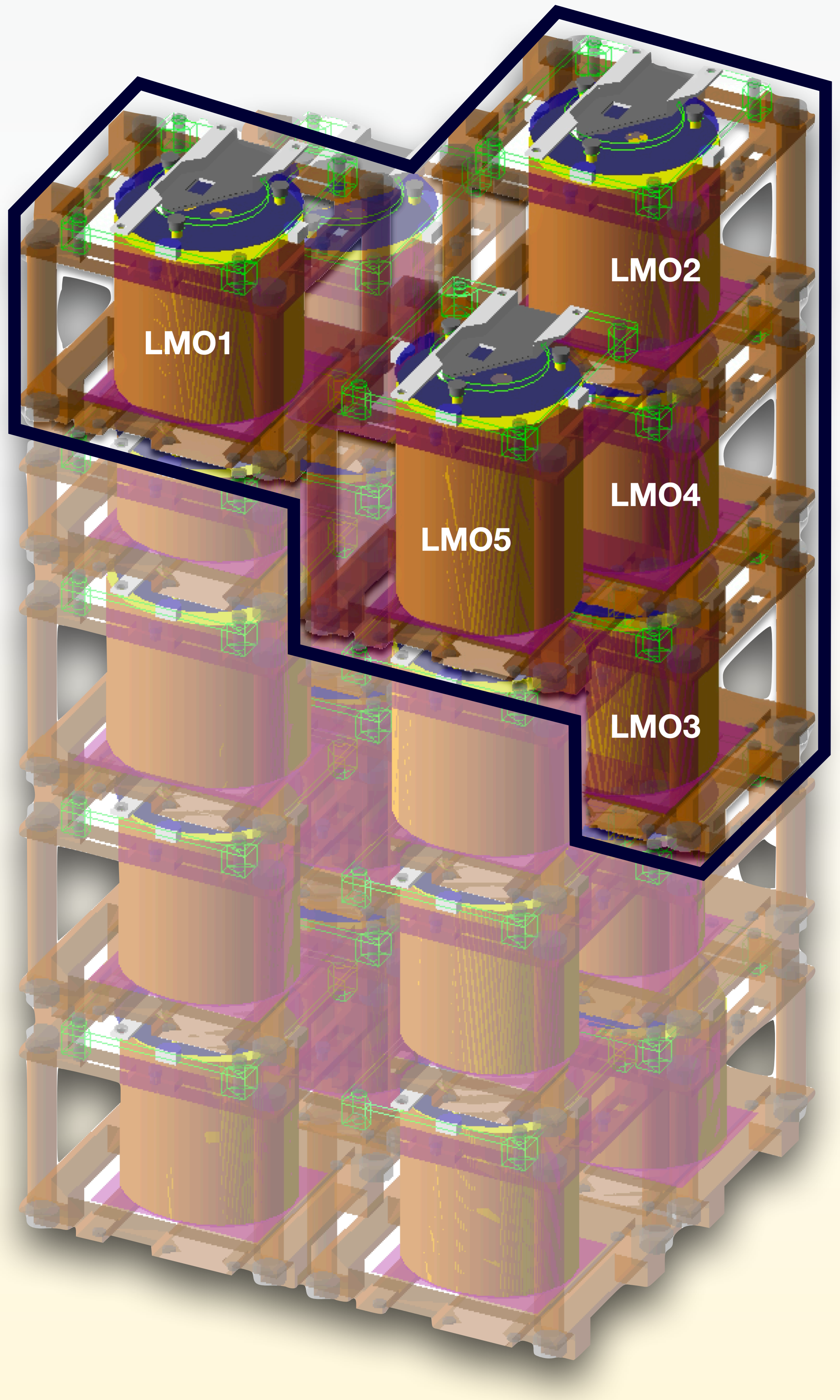
$$m_a = 1.55 \times 10^{11} \times \left(\frac{S}{\varepsilon N_7 t}\right)^{\frac{1}{4}} \text{ eV}$$

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.

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

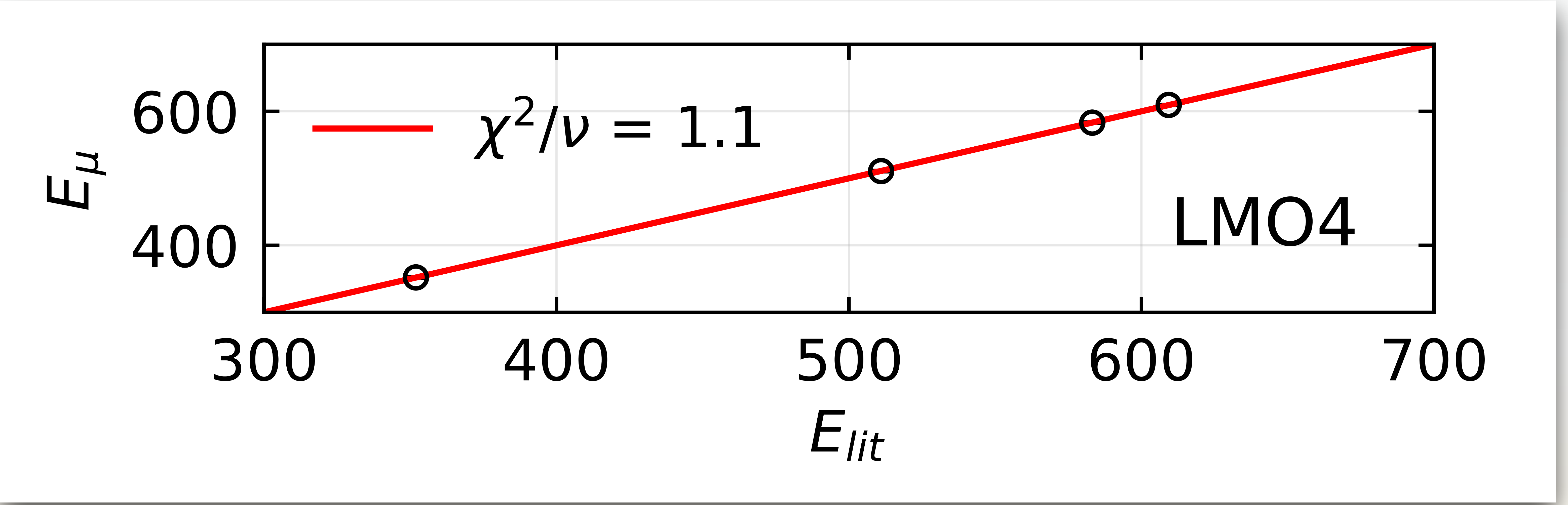
Solar axion search with AMoRE-I



- Full peak detection efficiency for the 5 crystals
  - Obtained by Geant4 simulation (v10.7)
  - 14.19%
- The measurement time: 333 days
- Our system has 50 ms dead-time for each event.

Crystal	Mass (g)	N_7 (× 10^{24})	Exposure (× 10^{24} · Li · day)
LMO1	300	1.92	606.72
LMO2	312	2.00	632.00
LMO3	312	2.00	632.00
LMO4	308	1.97	622.52
LMO5	378	2.42	764.72
Total	**1610**	**10.31**	**3257.96**

Energy calibration and events selection

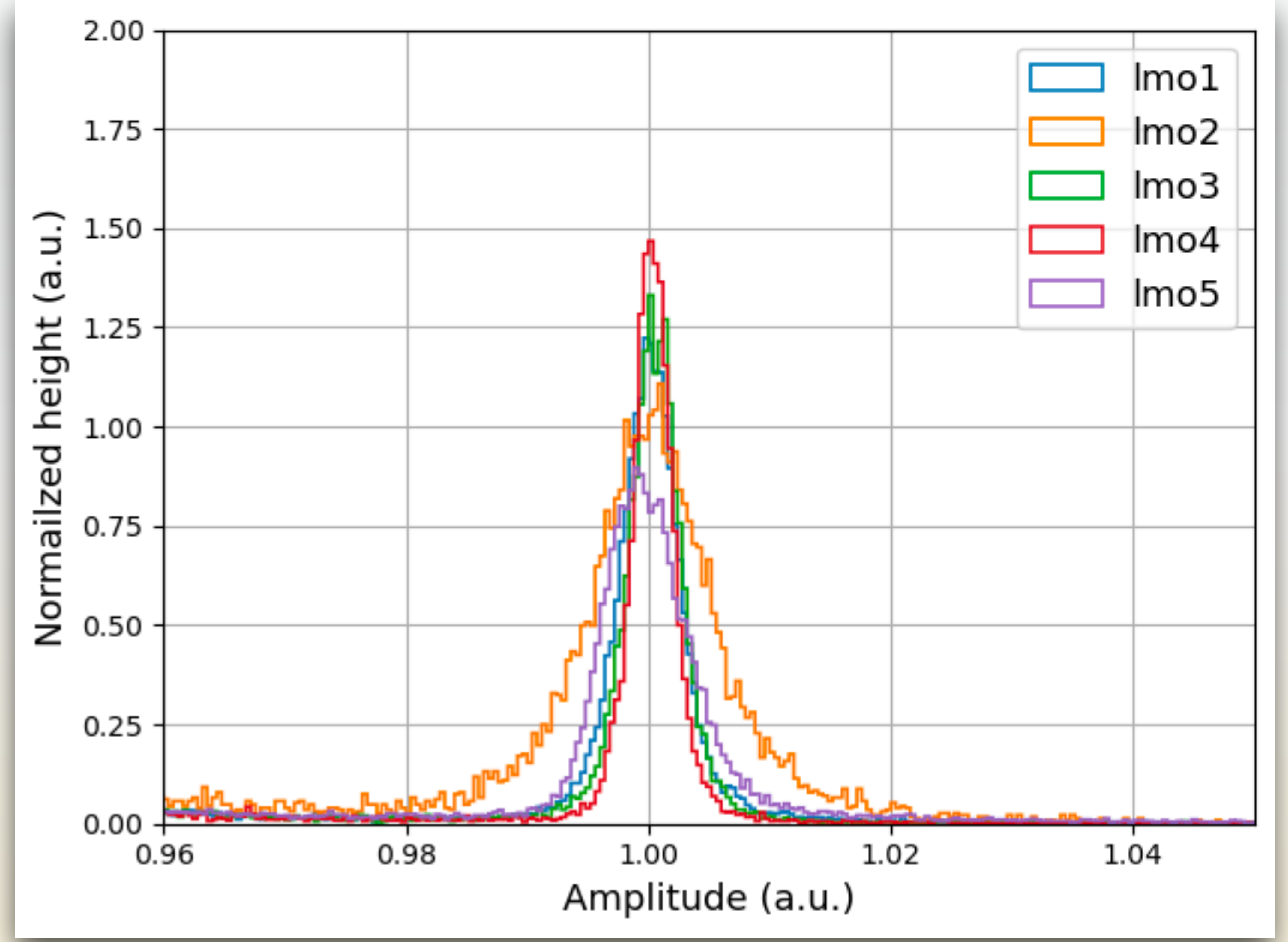


Cut	Efficiency at 478 ± 10 keV (%)
LH ratio	96.00 ± 0.11
Rising time	97.93 ± 0.10
Muon veto	99.78 ± 0.11
Total	**93.22 ± 0.11**

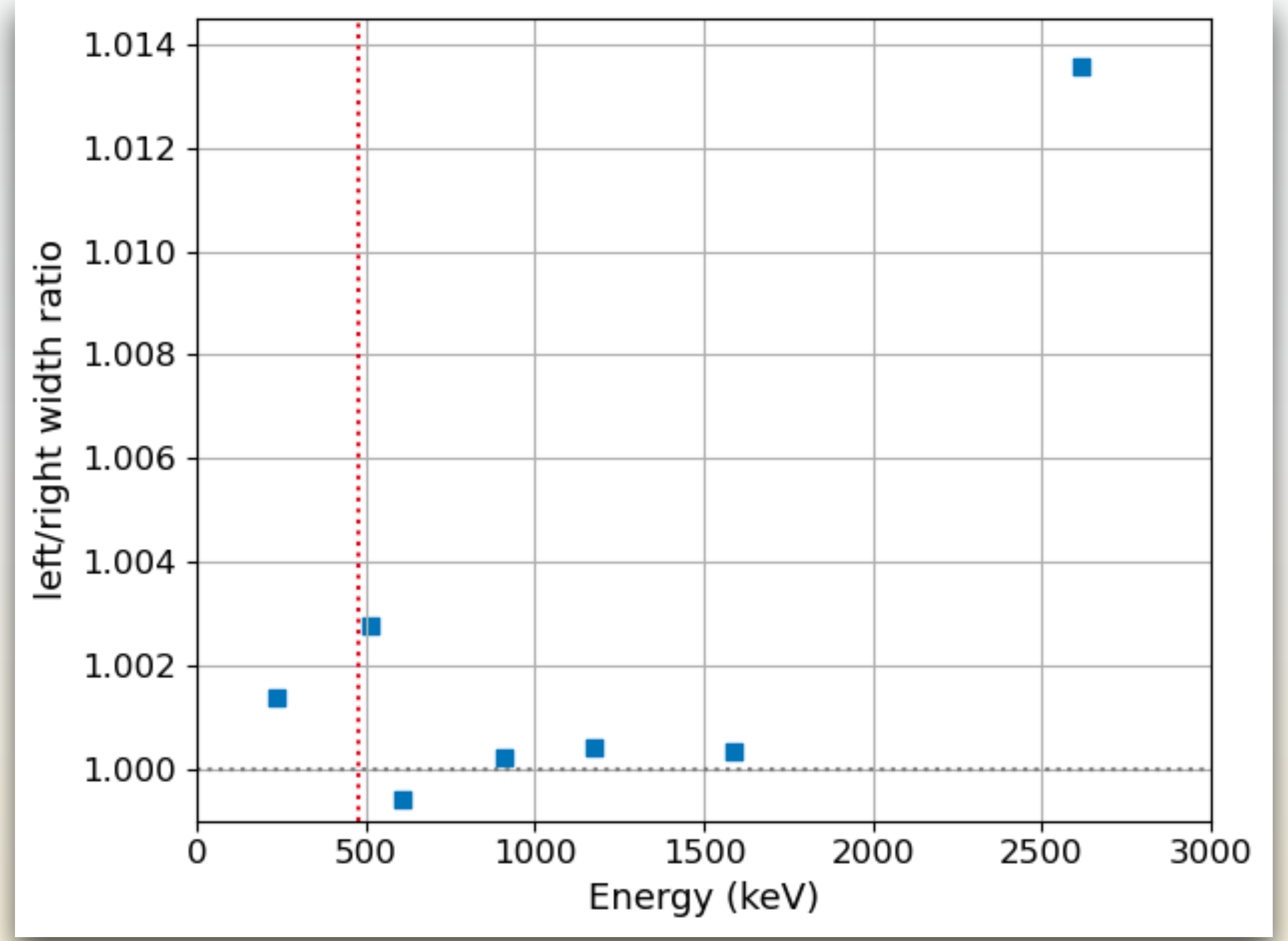
- Literature energy: 351.9, 511, 583.2, 609.2, 1120.3, 1173.2, 1332, 2614.5 keV
- The mean energy (μ) obtained after Gaussian + background fitting for each crystal
- μ as a function of literature energy was fitted with $p_0x+p_1x^2$

Signal shape

The shape of the 2.6 MeV energy peak



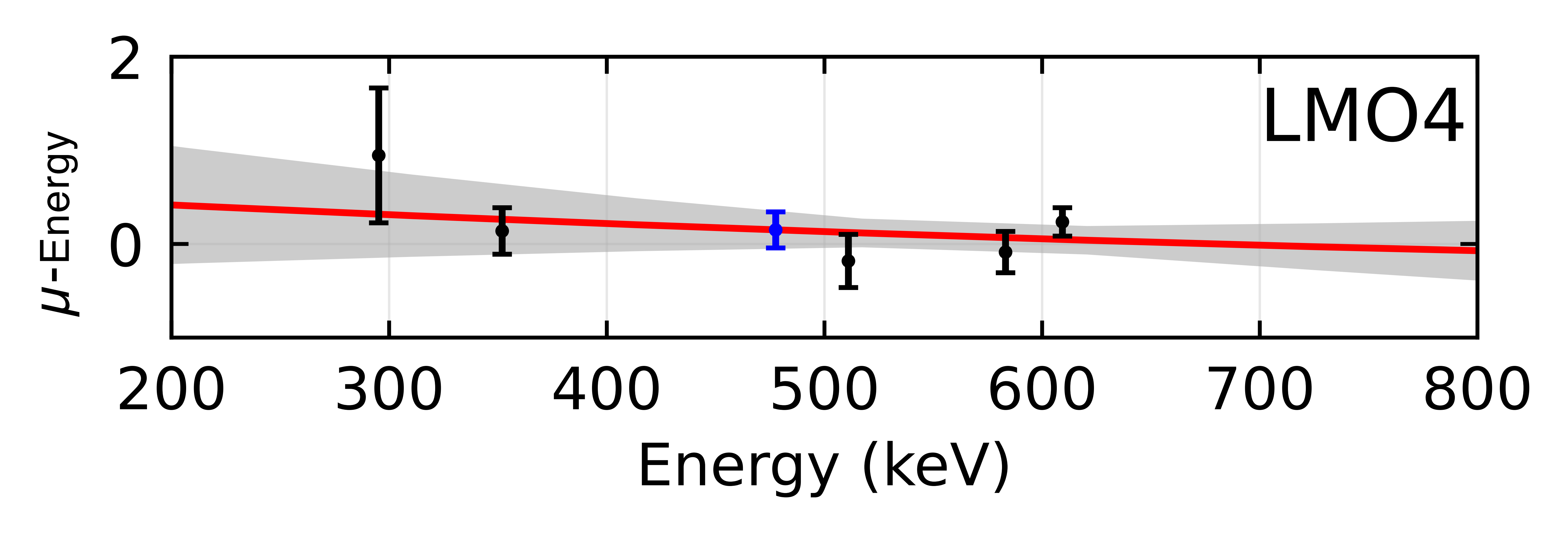
The ratio of left and right width of the peak



- 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 calibration

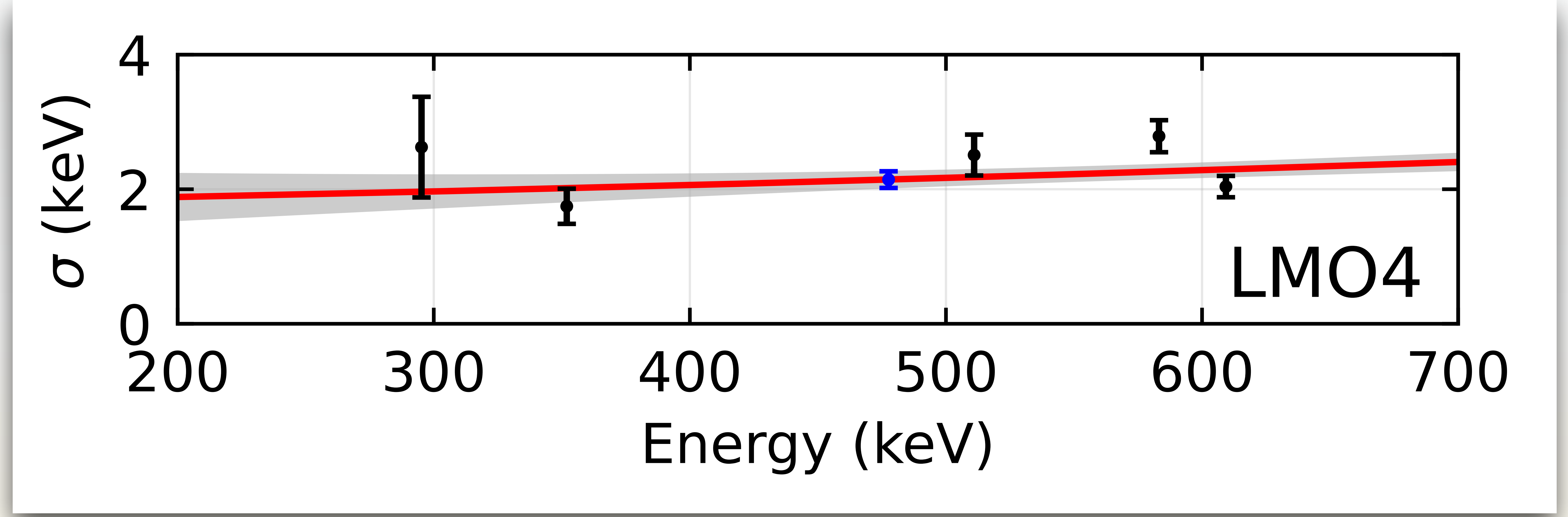


- Second-order polynomial fit on the difference between the fitting result and literature energy as a function of energy.
- The uncertainty band is a sum of the uncertainty from changing the fitting function.

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

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	Sigma	
	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

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

The number of parameters = 41

i = crystal id

j = data point

k = systematic source

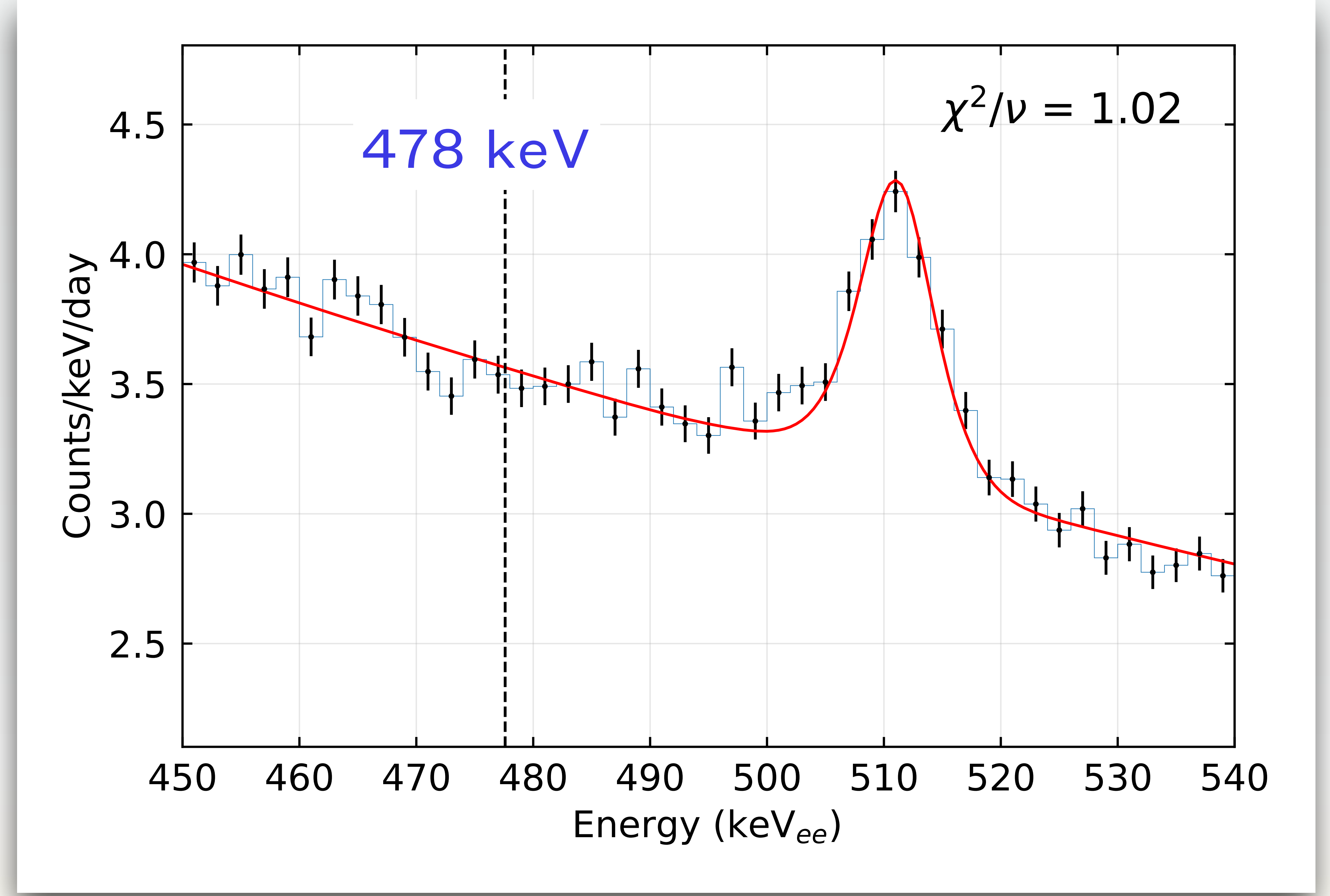
p = parameter

y = data

$f(x)$ = fitting model

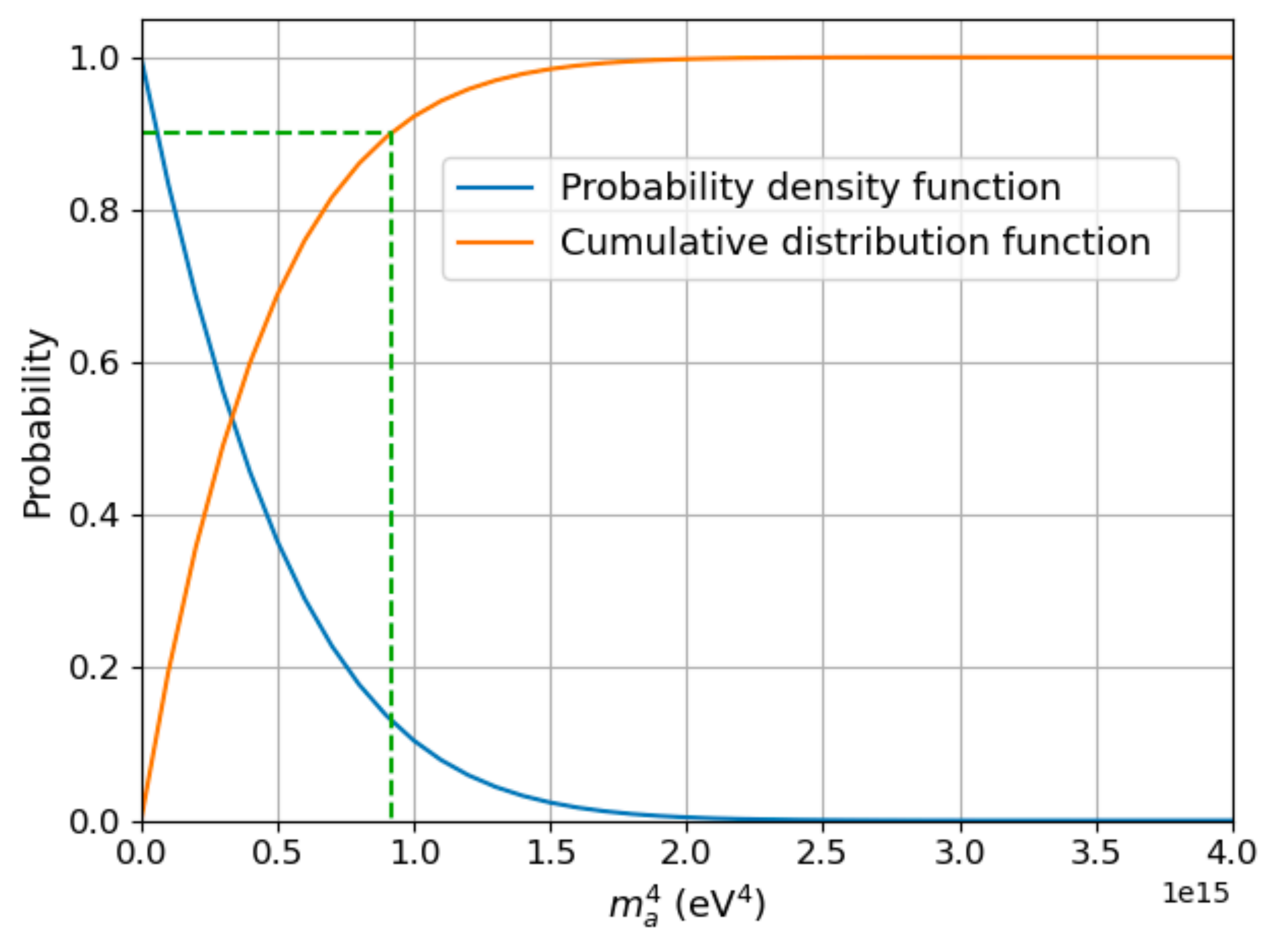
a = central value of the systematic source

Δa = systematic uncertainty



$$f_i(x_{ij}) = \underbrace{\mathbf{Ap_0}\frac{1}{\sqrt{2\pi p_{2_i}}} exp\left[-\left(\frac{x_{ij} - p_{1_i}}{\sqrt{2}p_{2_i}}\right)^2\right]}_{\text{Gaussian for 478 keV}} + \underbrace{p_{3_i} exp\left[-\frac{x_{ij} - p_{4_j}}{p_{5_j}}\right]}_{\text{exponential background}} \underbrace{+ p_{6_i}\frac{1}{\sqrt{2\pi p_{8_i}}} exp\left[-\left(\frac{x_{ij} - p_{7_i}}{\sqrt{2}p_{8_i}}\right)^2\right]}_{\text{Gaussian for 511 keV}}$$

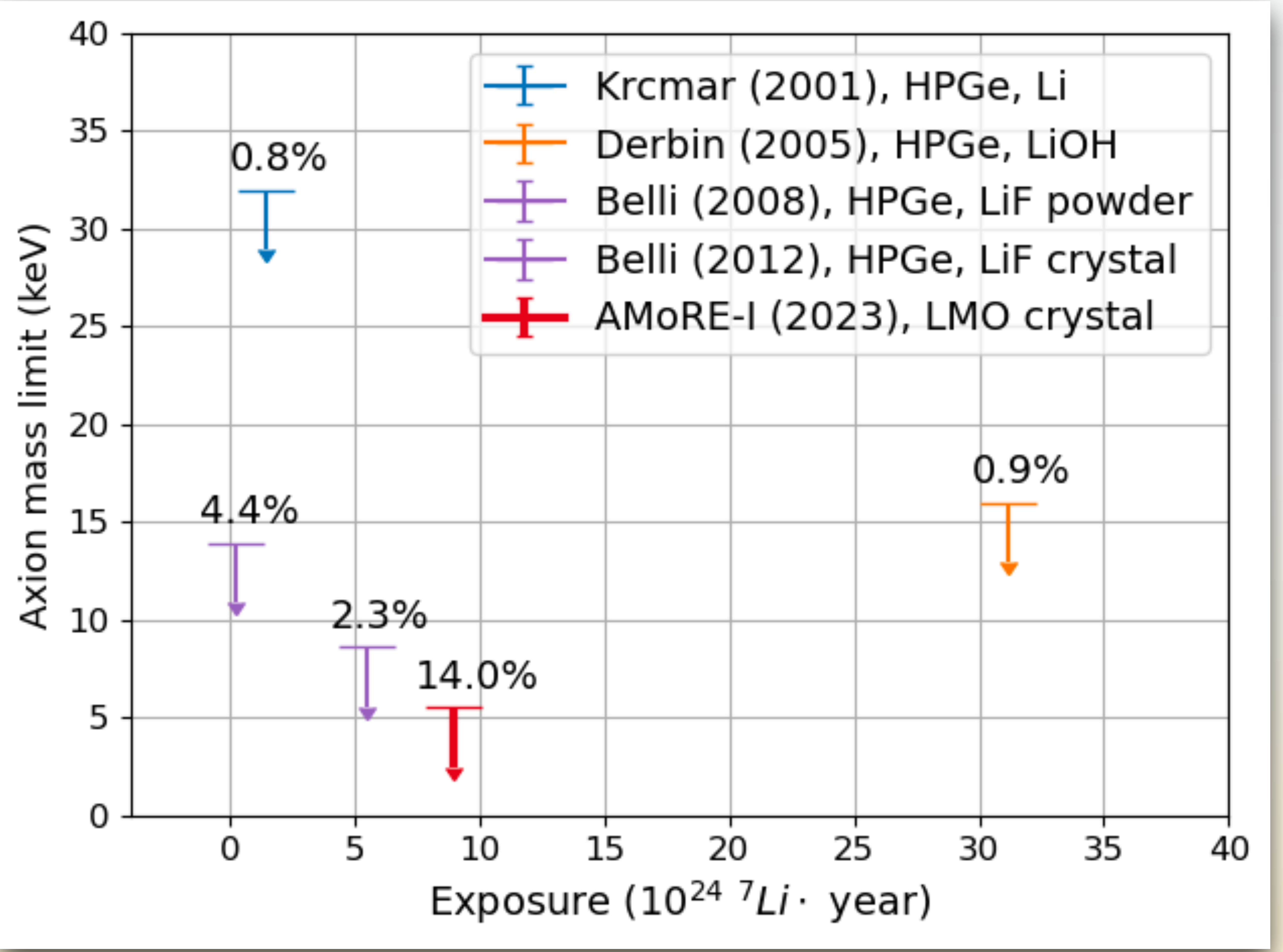
Axion mass limit



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

$m_a < 5.5$ keV at 90% C.L.

Summary



	AMoRE-I	AMoRE-II
Crystal size	Ø 50 mm × 50 mm	Ø 50 mm × 50 mm Ø 60 mm × 60 mm
Total mass	1.6 kg	180 kg
NLi7	1.13 × 1025	1.28 × 1027
Efficiency (%)	14.19	21.83
Axion mass (keV)	< 5.5	~ 2

Thank you

Calculation of the solar axion absorption rate

The rate of the absorption of solar axions per ^{7}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

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

Axion resonance absorption cross-section

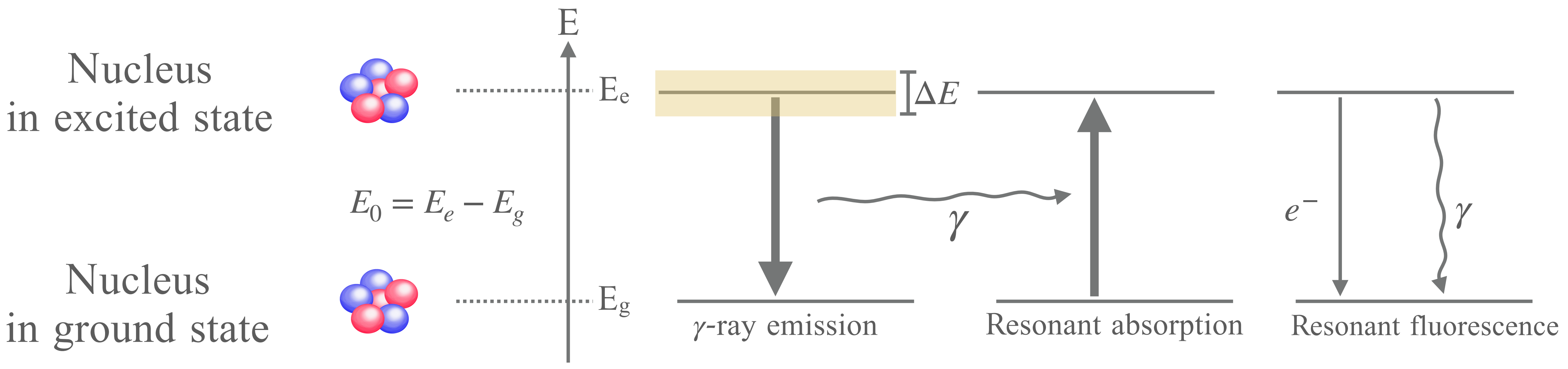
$$\sigma(E_a) = \sqrt{\pi}\sigma_{0\gamma}\frac{\Gamma_a}{\Gamma_\gamma}exp\left[-\frac{4(E_a - E_\gamma)^2}{\Gamma^2}\right]$$

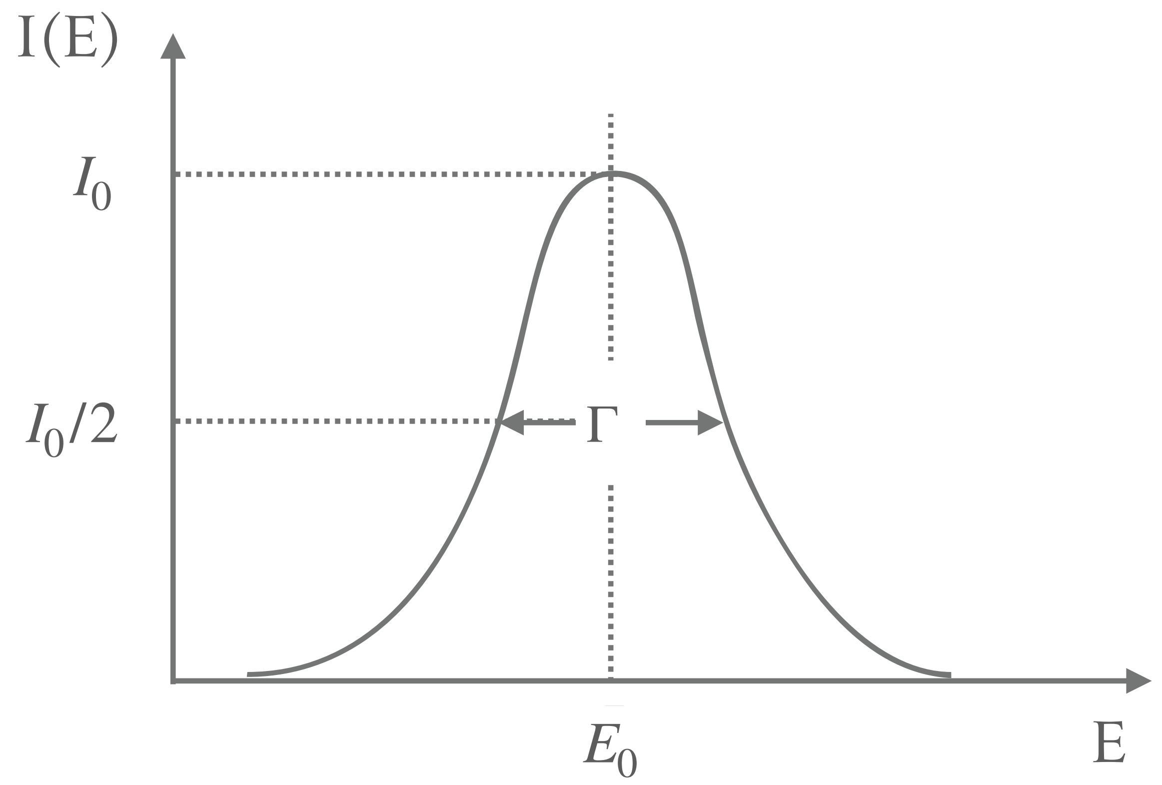
Probability of axionic emission

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

$R_\odot$: solar radius, $d\Phi_\nu^{Be}$: fraction of the $\nu_{^7Be}$ 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}Li nucleus
electron conversion factor $\alpha \approx 0$

Explain for resonant absorption (1/2)





$\Delta E \Delta t \geq \hbar$: Heisenberg uncertainty relation

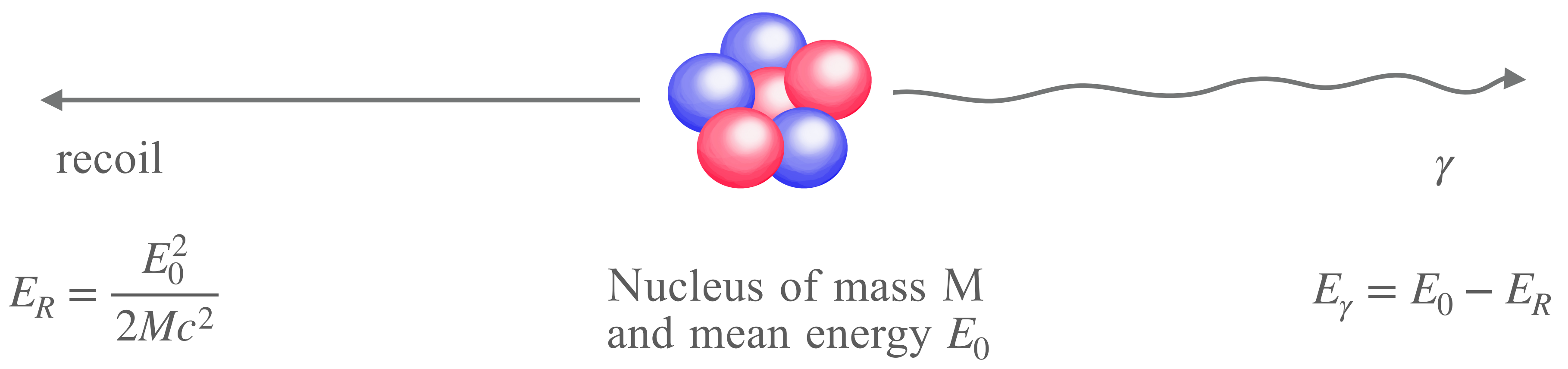
→ Natural width $\Gamma = \hbar/\tau$ (where, $\Delta E = \Gamma, \Delta t \approx \tau$)

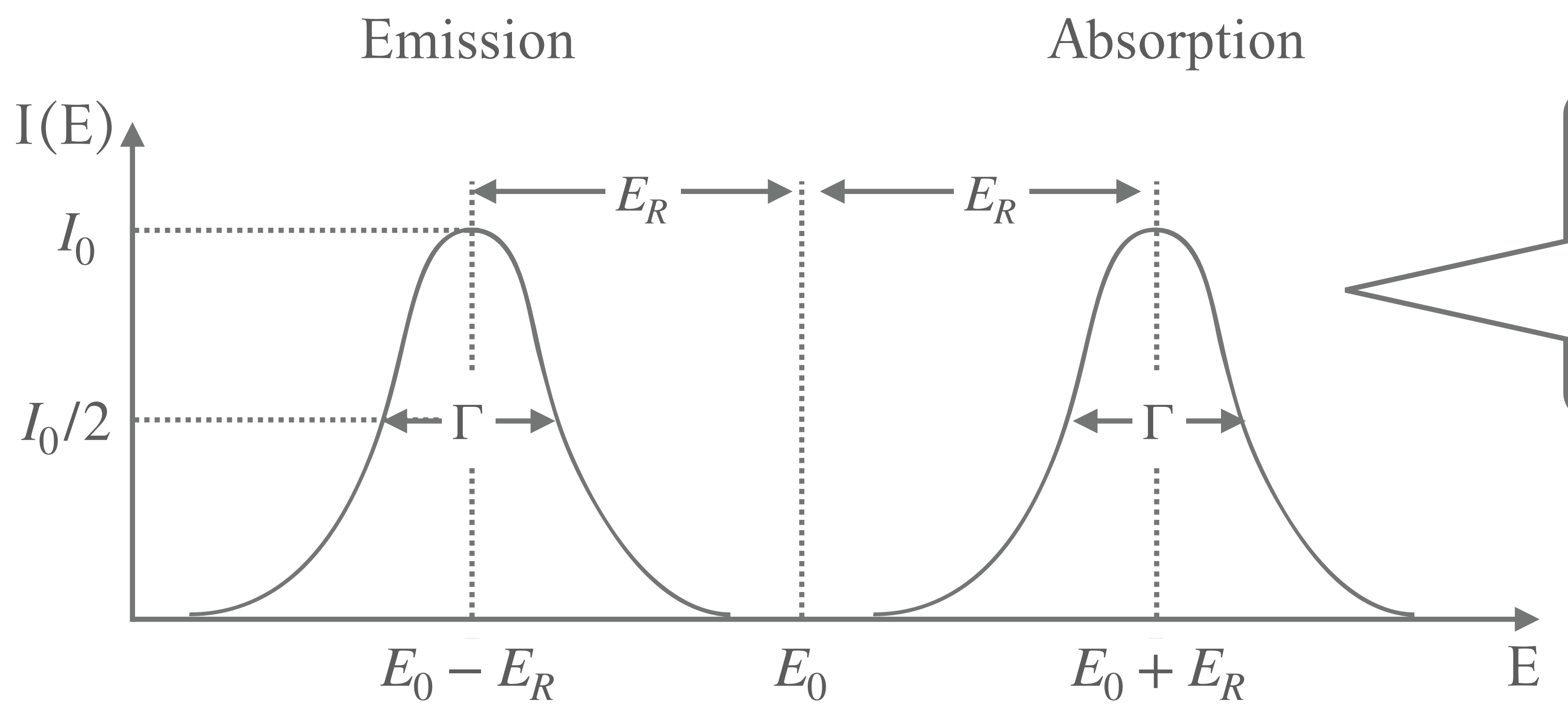
The probability of resonance absorption

$$I(E) \sim \frac{\Gamma/2\pi}{(E - E_0)^2 + (\Gamma/2)^2}$$: Breit-Wigner distribution

The resonance absorption cross section

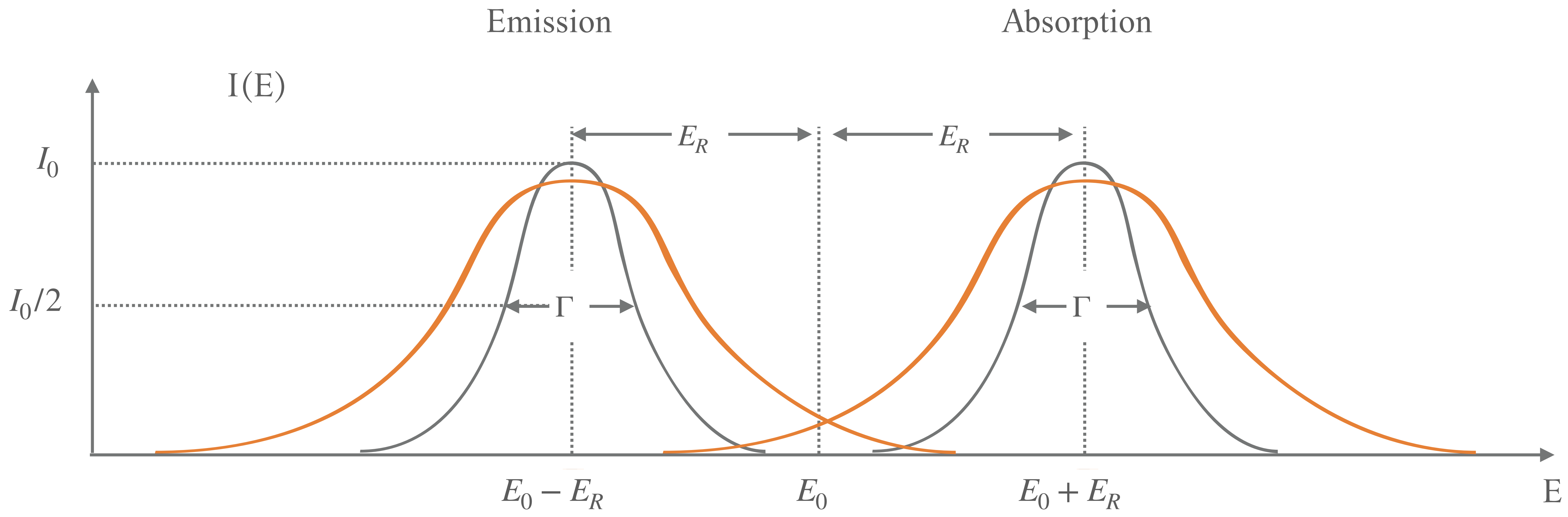
$$\sigma(E) = \frac{\sigma_0 \Gamma_i \Gamma_f}{\Gamma^2 + 4(E - E_0)^2} \quad \text{where } \sigma_0 = \frac{\lambda^2}{2\pi}\frac{2I_e + 1}{2I_g + 1}\frac{1}{\alpha + 1}$$





When the two transition lines are overlapped, nuclear resonance absorption is possible.

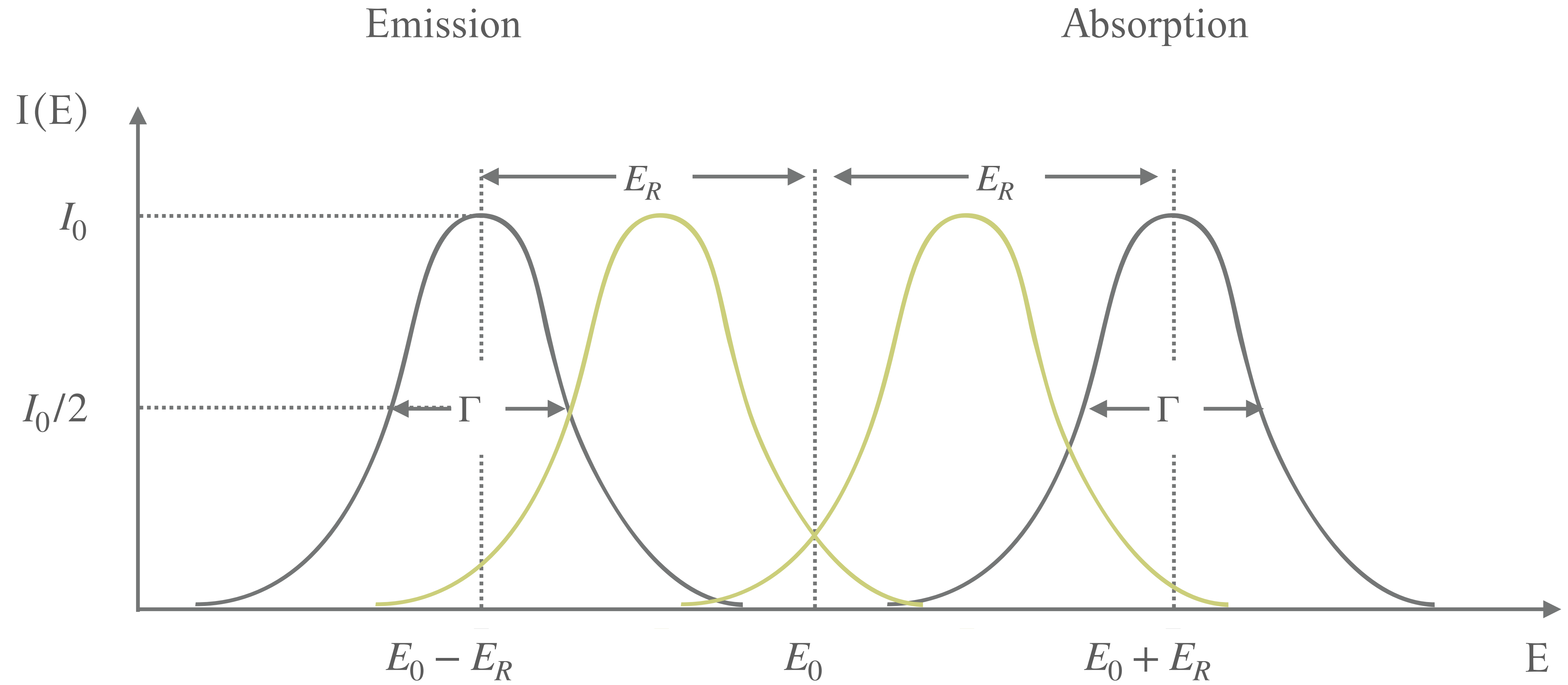
Explain for resonant absorption (2/2)



Doppler (thermal) broadening

$$\sigma_E = E_\gamma \sqrt{\frac{kT}{M}}$$

The probability of resonance absorption
is given by the convolution of
the Breit-Wigner and the Gaussian distribution



Crystal → recoil-free fraction
(Lamb-Mössbauer factor)

$$f = exp[-\frac{E_R}{k\Theta_D}(\frac{3}{2} + \frac{\pi^2 T^2}{\Theta_D^2})] \text{ for } T \ll \Theta_D$$

$$f = exp(-\frac{6E_R T}{k\Theta_D^2}) \text{ for } T > \Theta_D$$

Θ_D: Debye temperature