

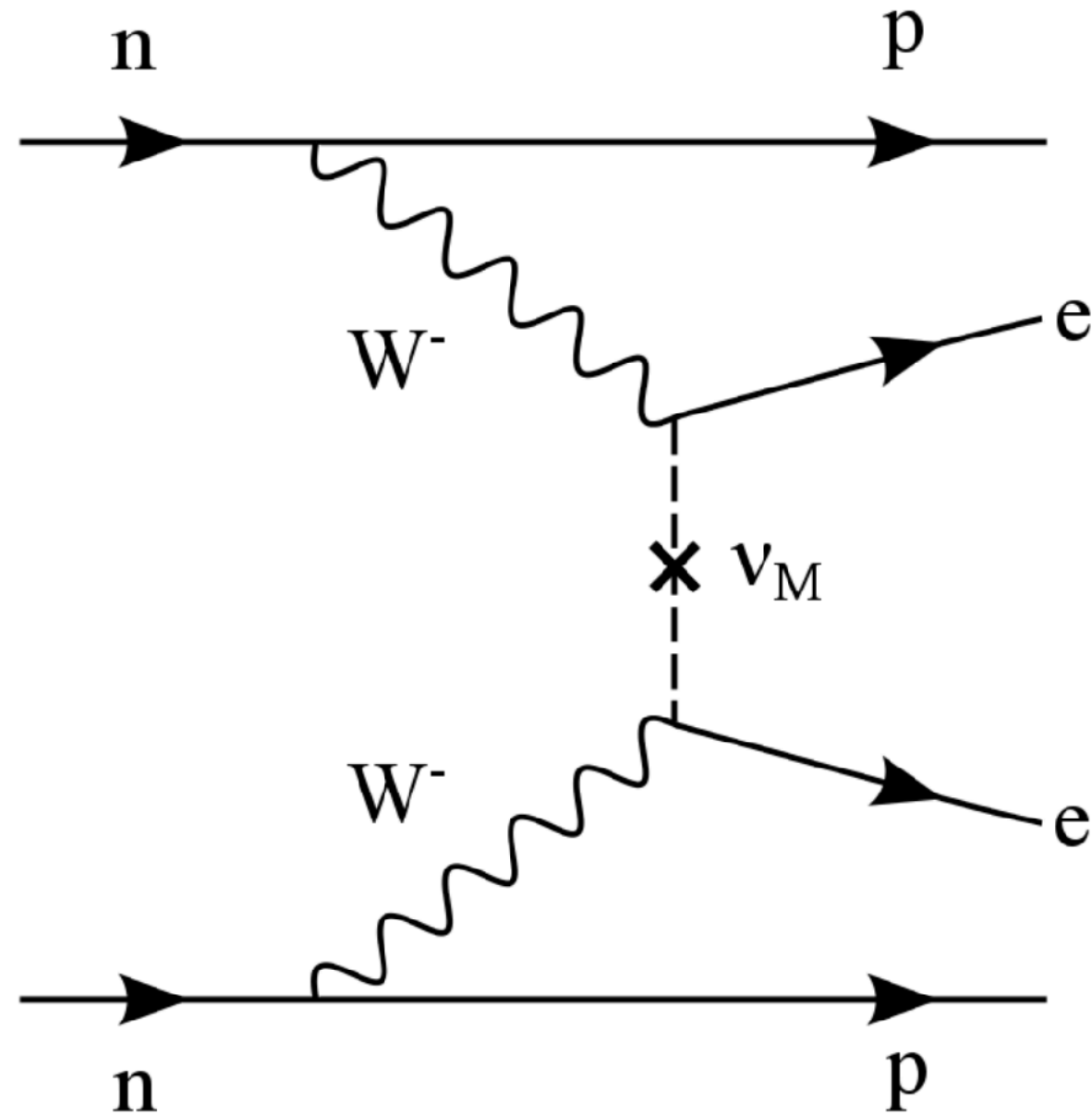
AMoRE

Yoomin Oh / 28—29 Nov @ ANPhA Symposium 2025, Academia Sinica, Taipei



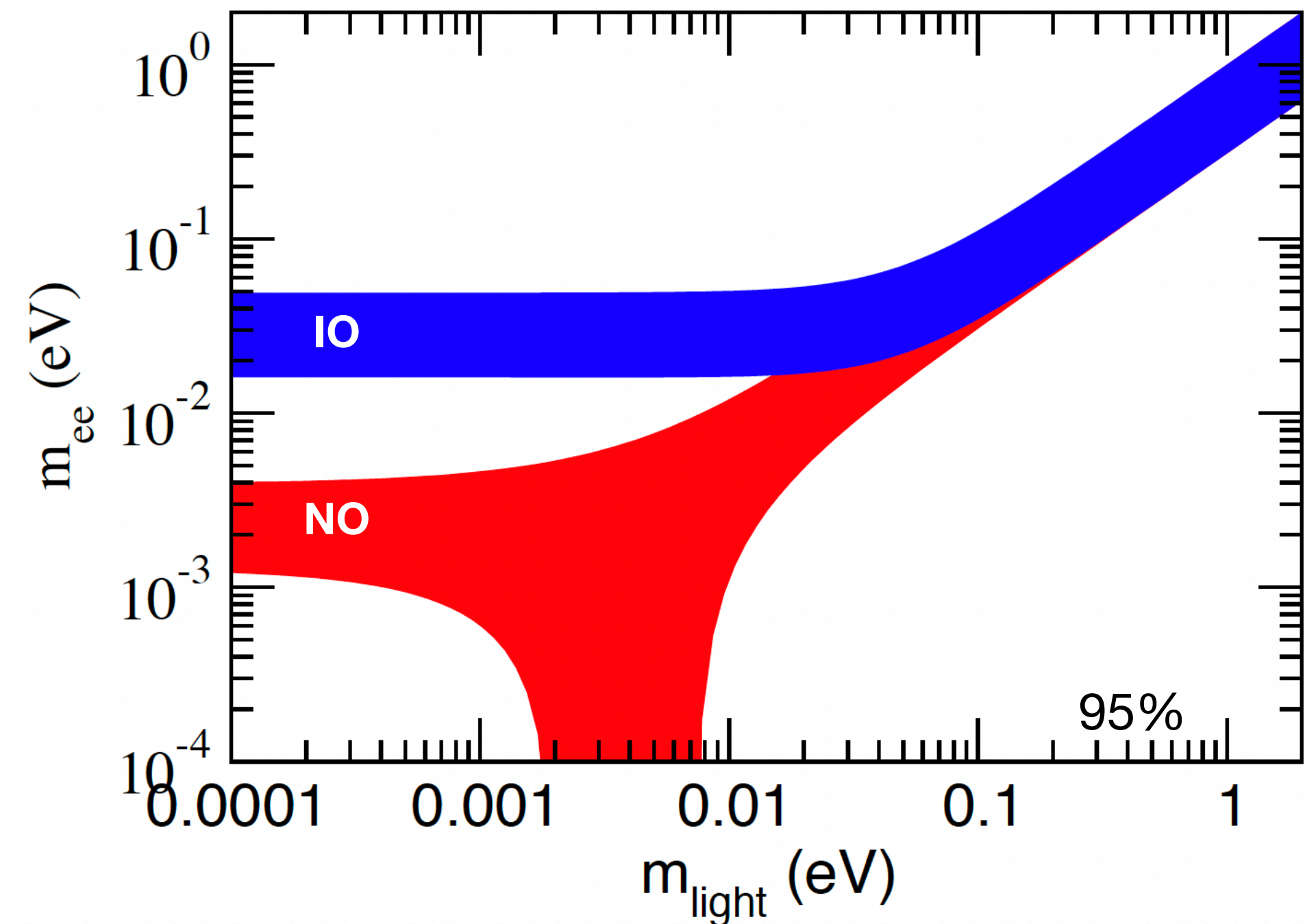
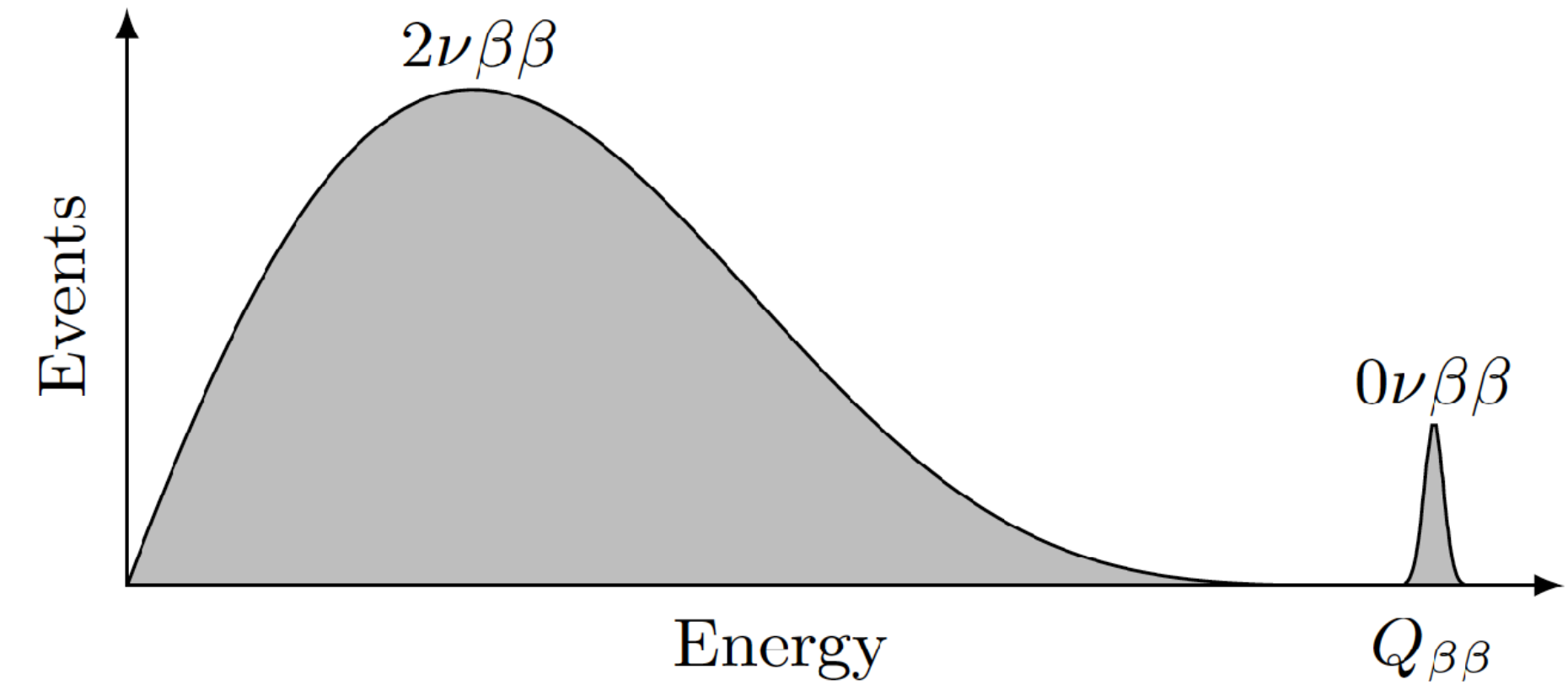
Asian Forum for Accelerators and Detectors (AFAD) 2015 @ NSRRC, Tsinchu

Introduction: $0\nu\beta\beta$ decay, Majorana ν , ν mass



$$\left[T_{1/2}^{0\nu}\right]^{-1} = g_A^4 G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \sum U_{ei}^2 m_i$$



Even-even nuclides for $0\nu\beta\beta$ search

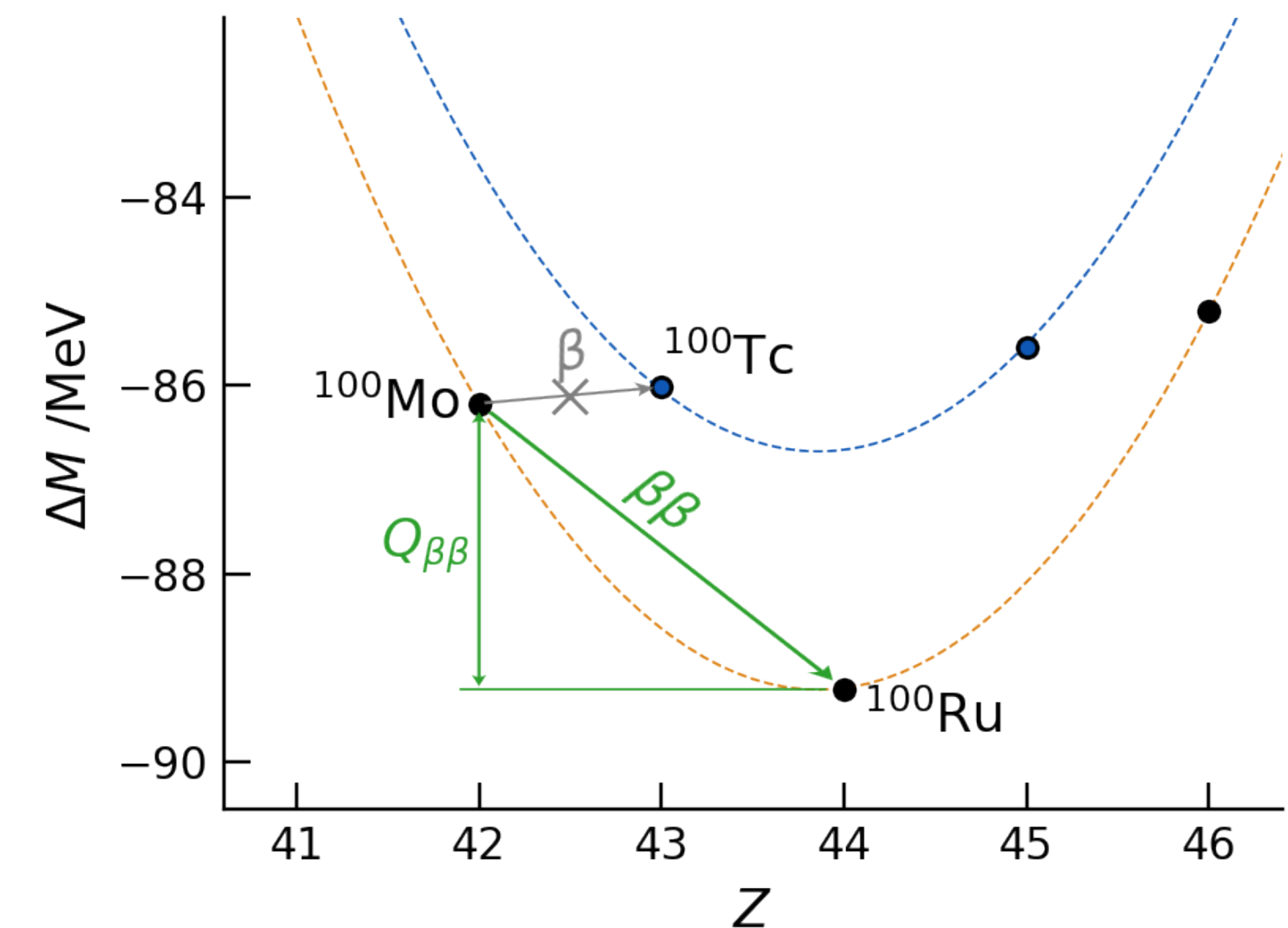
Sticker	$\beta\beta$ isotope	Daughter	$Q_{\beta\beta}$ [keV]	N.A. [%]	$T_{1/2}$ (2ν) [yr]	$T_{1/2}$ (0ν) [yr], 90% C.L. limits	Representative experiments
 	^{48}Ca	Ti	4 268	0.187	6.4E+19	$> 5.8\text{E}+22$	NEMO-3, CANDLES
 	^{76}Ge	Se	2 039	7.75	2.0E+21	$> 1.9\text{E}+26$	GERDA, MAJORANA-DEMON., LEGEND
 	^{82}Se	Kr	2 998	8.82	8.6E+19	$> 4.6\text{E}+24$	NEMO-3, CUPID-0+
	^{96}Zr	Mo	3 356	2.80	2.4E+19	$> 9.2\text{E}+21$	NEMO-3
  	^{100}Mo	Ru	3 034	9.744	7.1E+18	$> 2.9\text{E}+24$	NEMO-3, CUPID, AMoRE
 	^{116}Cd	Sn	2 813	7.512	2.6E+19	$> 2.2\text{E}+23$	NEMO-3, Aurora
  	^{130}Te	Xe	2 528	34.08	7.7E+20	$> 2.2\text{E}+25$	CUORE, SNO+
 	^{136}Xe	Ba	2 458	8.857	2.2E+21	$> 3.8\text{E}+26$	KamLAND-Zen, EXO, XENON
	^{150}Nd	Sm	3 371	5.638	9.3E+18	$> 2.0\text{E}+22$	NEMO-3

-  Larger natural abundance for less effort in enrichment
-  Detector-izability
-  Higher Q-value for less ambient/natural γ background
-  Longer $T_{1/2}^{2\nu}$ for less background

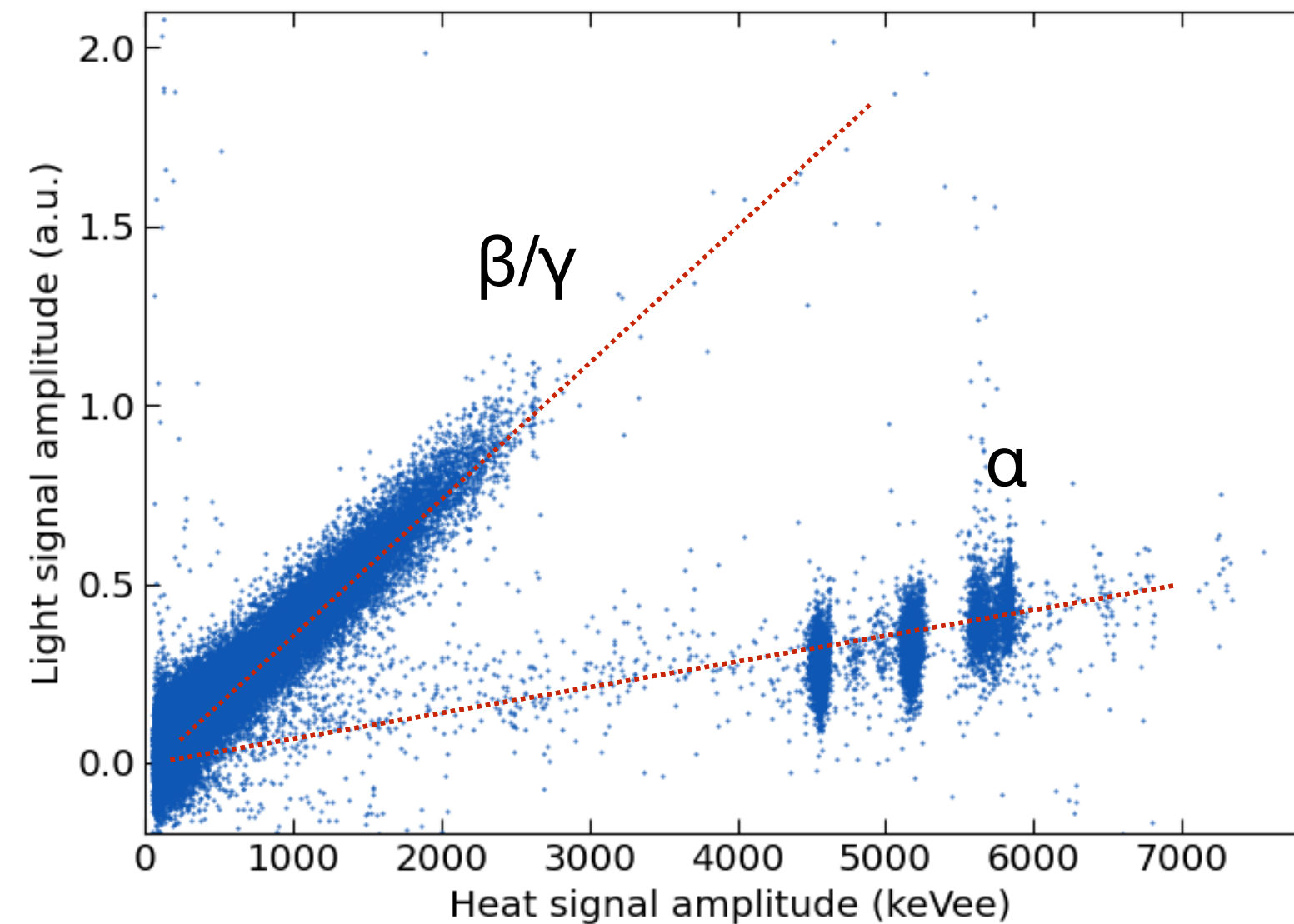
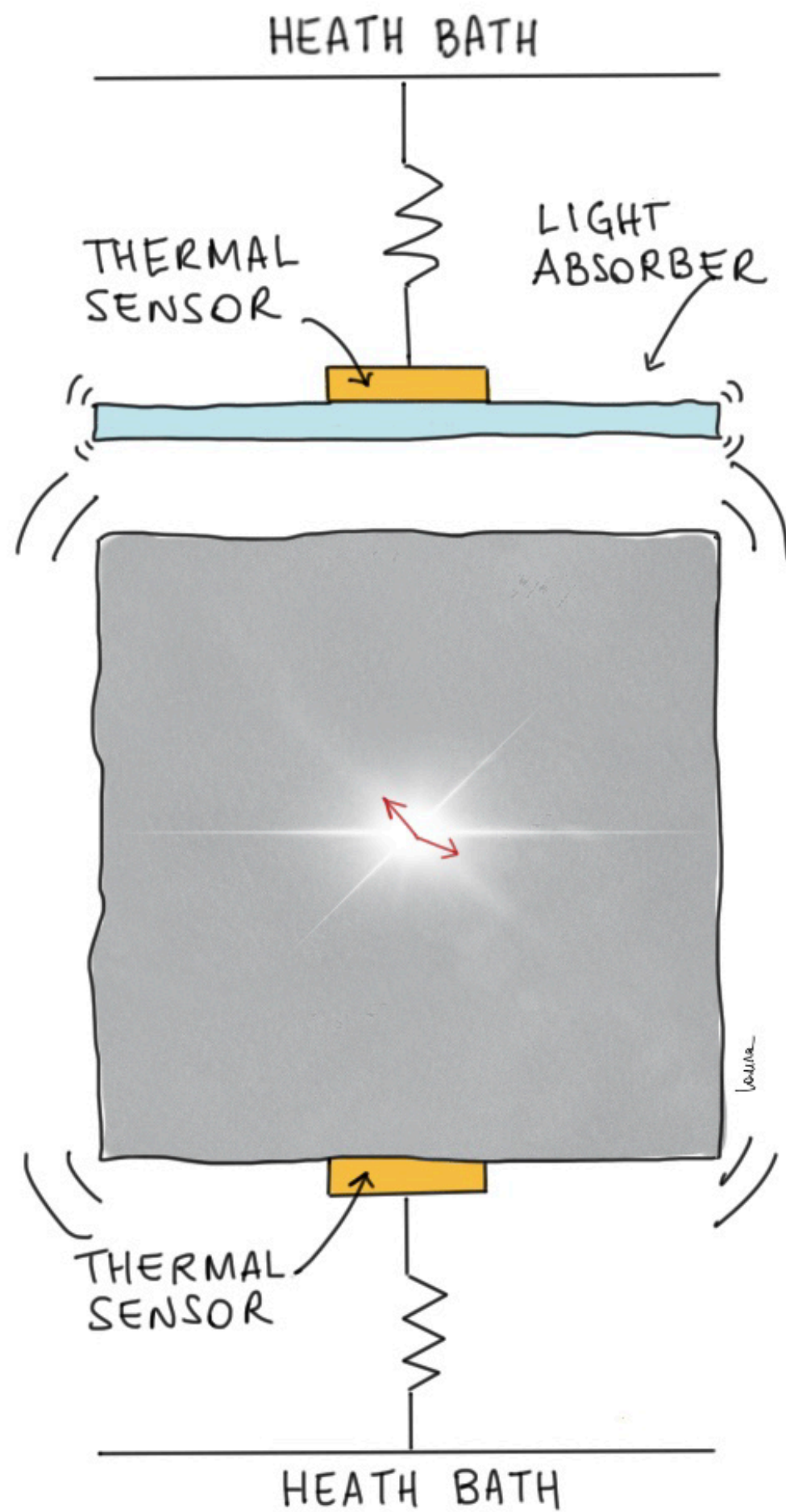
Molybdenum-100

Among $0\nu\beta\beta$ decay candidate isotopes

- $Q = 3034$ keV
- Natural abundance = 9.7%
- $T_{1/2}^{2\nu} = (7.1 \pm 0.1) \times 10^{18}$ yr by CUPID [PRL 131, 162501 (2023)].
- $T_{1/2}^{0\nu} > 2.9 \times 10^{24}$ yr at 90% C.L. by AMoRE-I [PRL 134, 082501 (2025)].
- Shell-model (SM) calculation of the nuclear matrix element (NME) was carried out rather recently [PRC 105, 034312 (2022)], compared to other $\beta\beta$ nuclides.
- Scintillation crystals can be made
 - $X_a\text{Mo}_b\text{O}_c$. — **Li₂MoO₄**, **CaMoO₄**, PbMoO₄, Na₂Mo₂O₇, ...
- Experiments: NEMO-3, CUPID, AMoRE

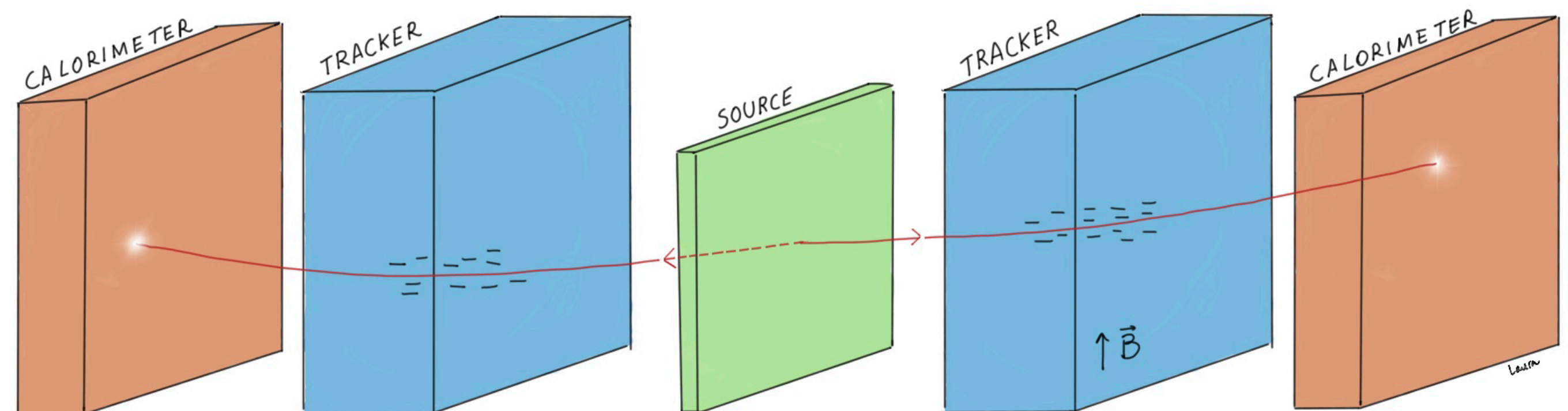


Experiments using ^{100}Mo —AMoRE, CUPID; NEMO-3



AMoRE data example

- Low temperature calorimetry for enhancing energy resolution
- + Scintillation detection for particle identification
 - Discrimination of internal/surface α background
 - Requiring scintillating crystal
- C.f. NEMO-3 (Super-NEMO): tracking calorimeter, various source can be used



Figures $\uparrow \rightarrow$ courtesy of M. Agostini et al,
Rev. Mod. Phys. 95, 025002 (2023)

AMoRE key features

- Scintillation crystals from enriched Mo-100: CaMoO_4 (CMO), Li_2MoO_4 (LMO).
- Metallic magnetic calorimeter (MMC) for low temperature sensor.
- Sensitivity goal for Mo-100 $0\nu\beta\beta$ half-life $\sim 4 \times 10^{26}$ yr, $\langle m_{\beta\beta} \rangle \sim 18\text{--}52$ meV.
 - Energy resolution ~ 10 keV FWHM at $Q_{\beta\beta}=3034$ keV,
 - Background goal at ROI $\sim 10^{-4}$ count/keV/kg/yr (ckky).
- Conducted in 3 phases:
 - AMoRE-pilot: 6 CMO crystals, 1.9 kg.
 - AMoRE-I: 13 CMO + 5 LMO, 6.1 kg in total
 - Data taking completed in Y2L.
 - AMoRE-II: 90 LMO (27 kg) > 360 XMO (157 kg)
 - Being prepared in Yemilab.



Sunkee Kim, Fedor Danevich, Hongjoo Kim, Vasily Kornoukov, and Yeoungduk Kim, from left to right, Photograph taken in 2006, courtesy of Hongjoo.

AMoRE Collaboration

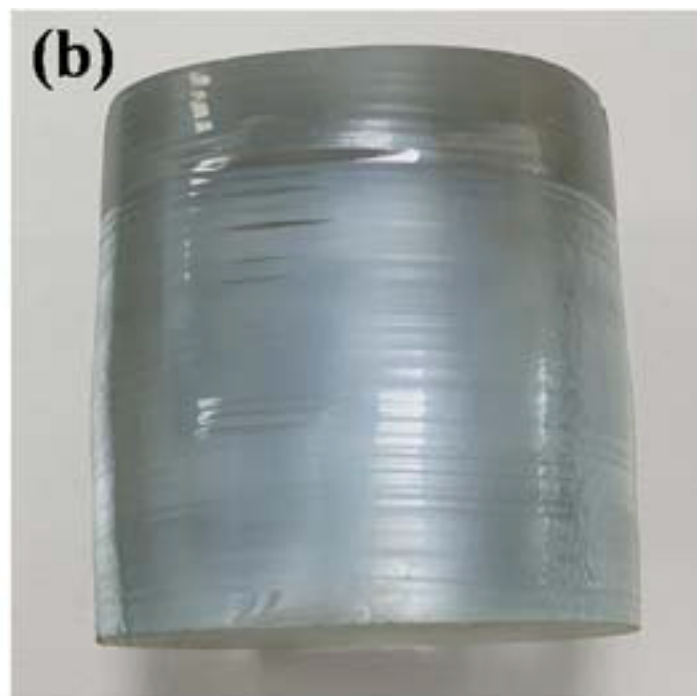
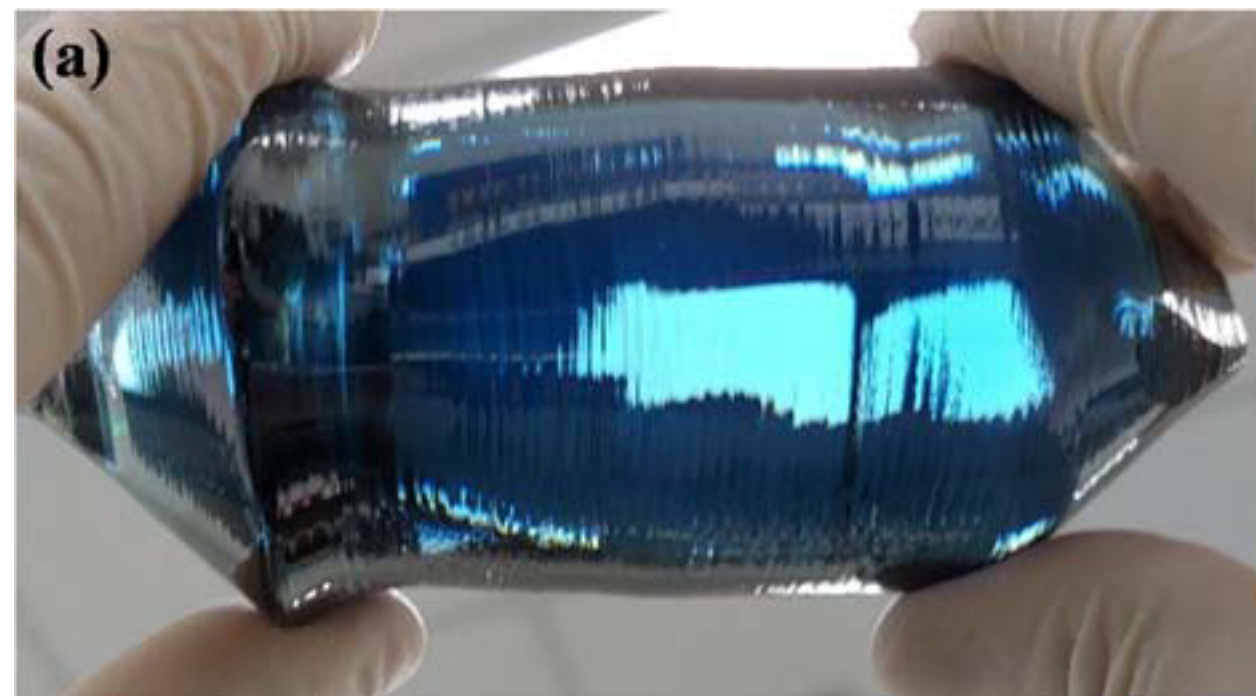
More than 100 members from 27 institutes in 10 (6 Asian) countries



$^{40}\text{Ca}^{100}\text{MoO}_4$ / $\text{Li}_2^{100}\text{MoO}_4$ (CMO/LMO)

Crystals for AMoRE

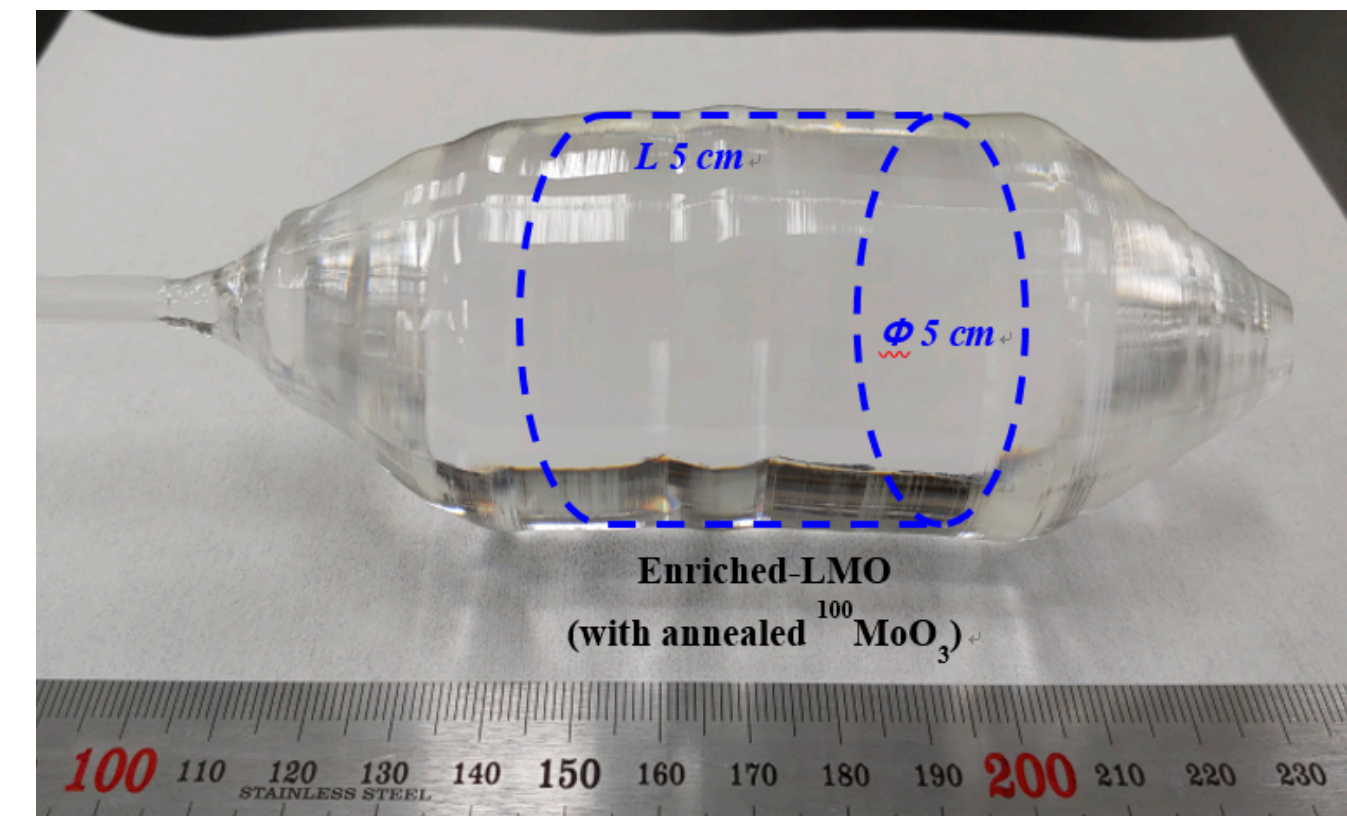
- Produced at NIIC (RUS) and at CUP/IBS.
 - For radio-purification and crystal growth, see:
JINST 15 C07032 & C07035 (2020), Front.in Phys. 12, 1362209 (2024)
- Mo-100 enrichment ~ 95–96%
- Depletion of ^{48}Ca in CMO, to reduce $2\nu\beta\beta$ background
- CMO shows higher light yield (better particle ID), LMO shows less internal radioactivity.



J. Phys. Conf. 1468, 012144 (2020) / TAUP 2019

←CMO

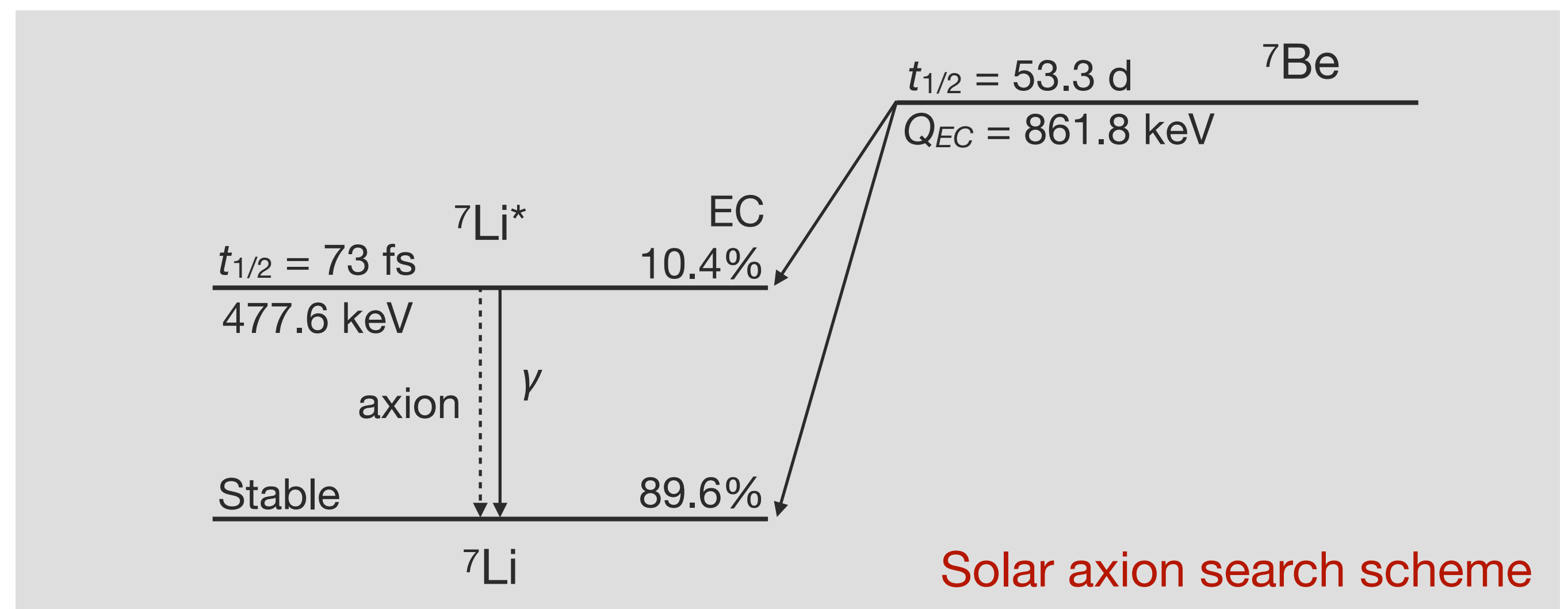
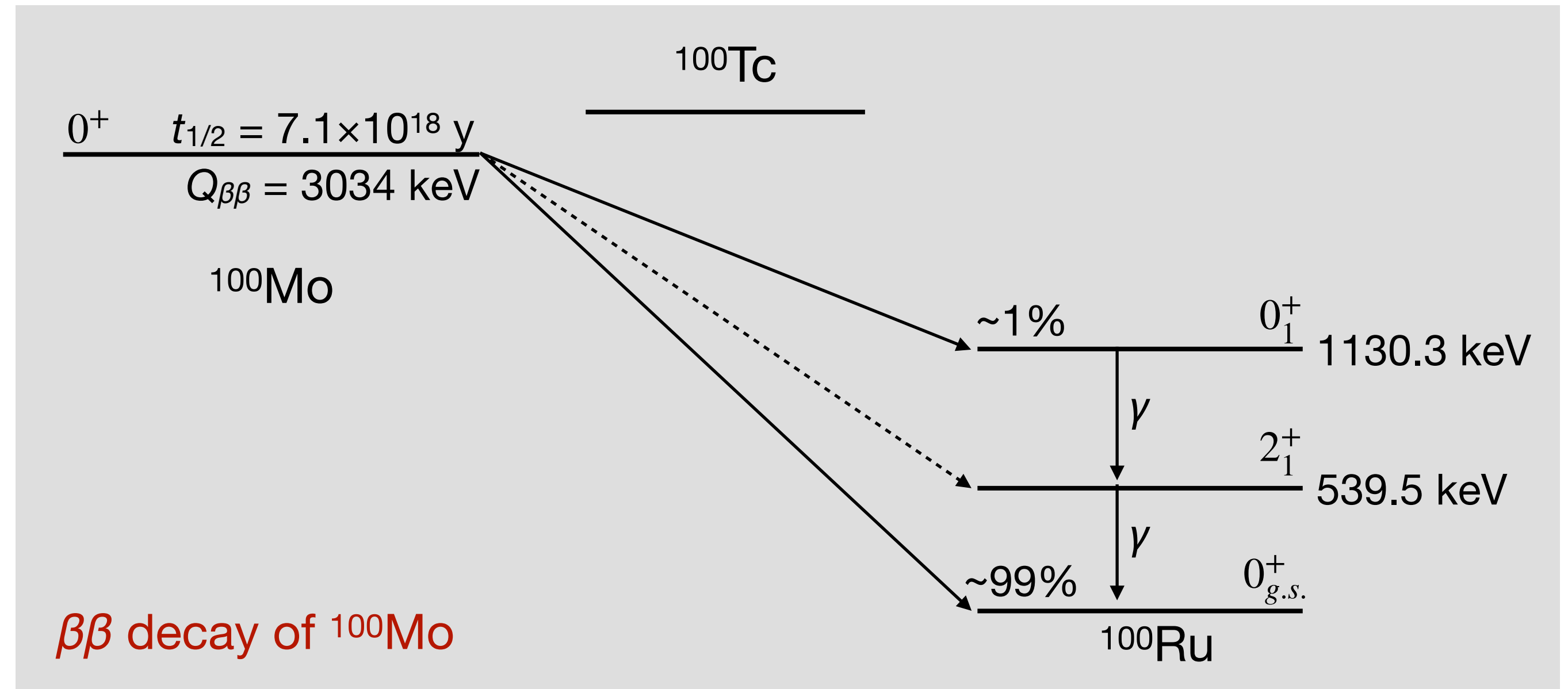
LMO→



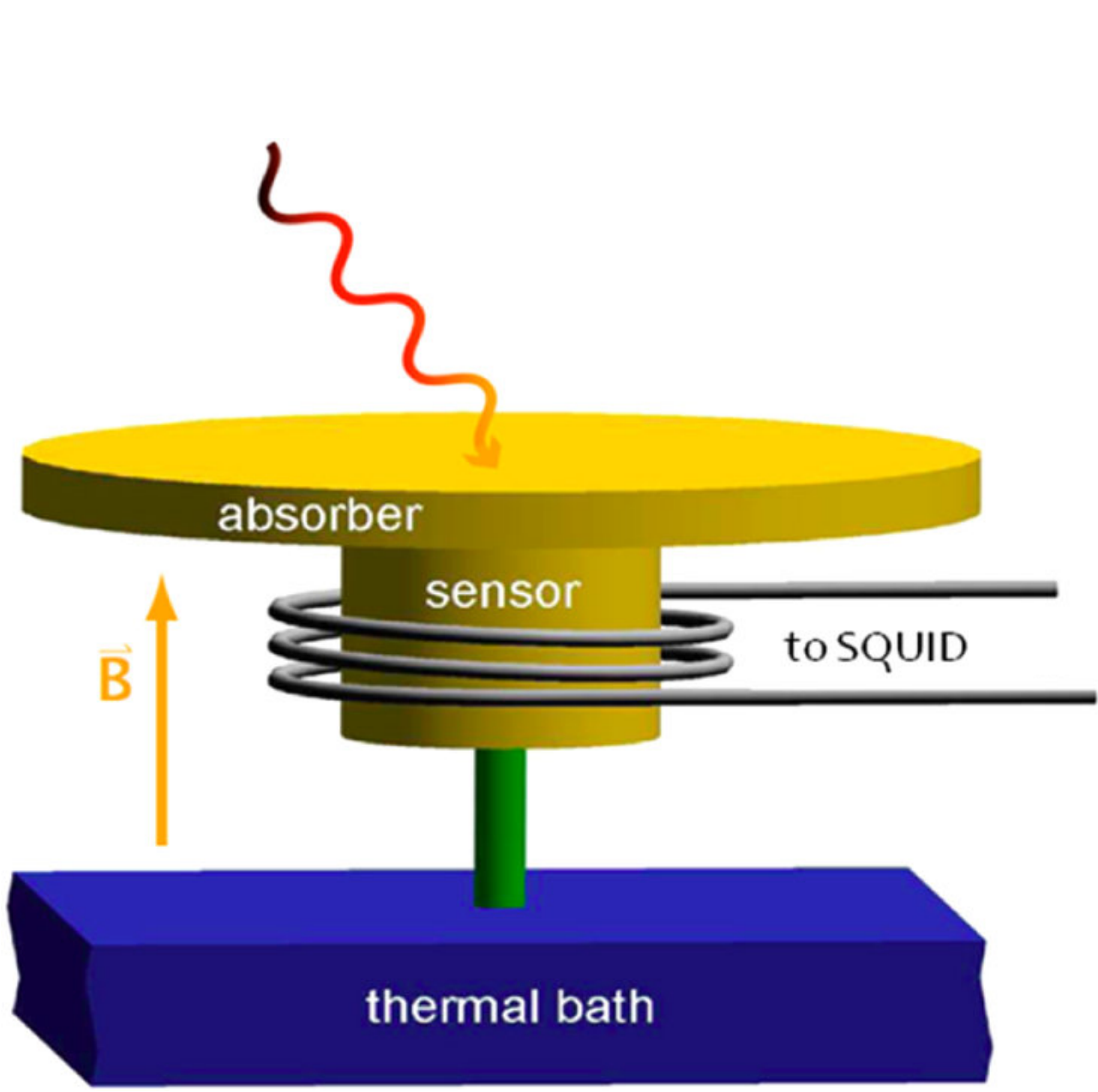
JINST 15, C07035 (2020)

AMoRE physics using CMO/LMO crystals

- $0\nu\beta\beta$
- ^{100}Mo $\beta\beta$ decay to excited state(s) of ^{100}Ru
 - Bosonic neutrino?
- $2(0)\nu 2\text{EC}$ of ^{40}Ca
- Solar axion
- Majoron
- Dark matter

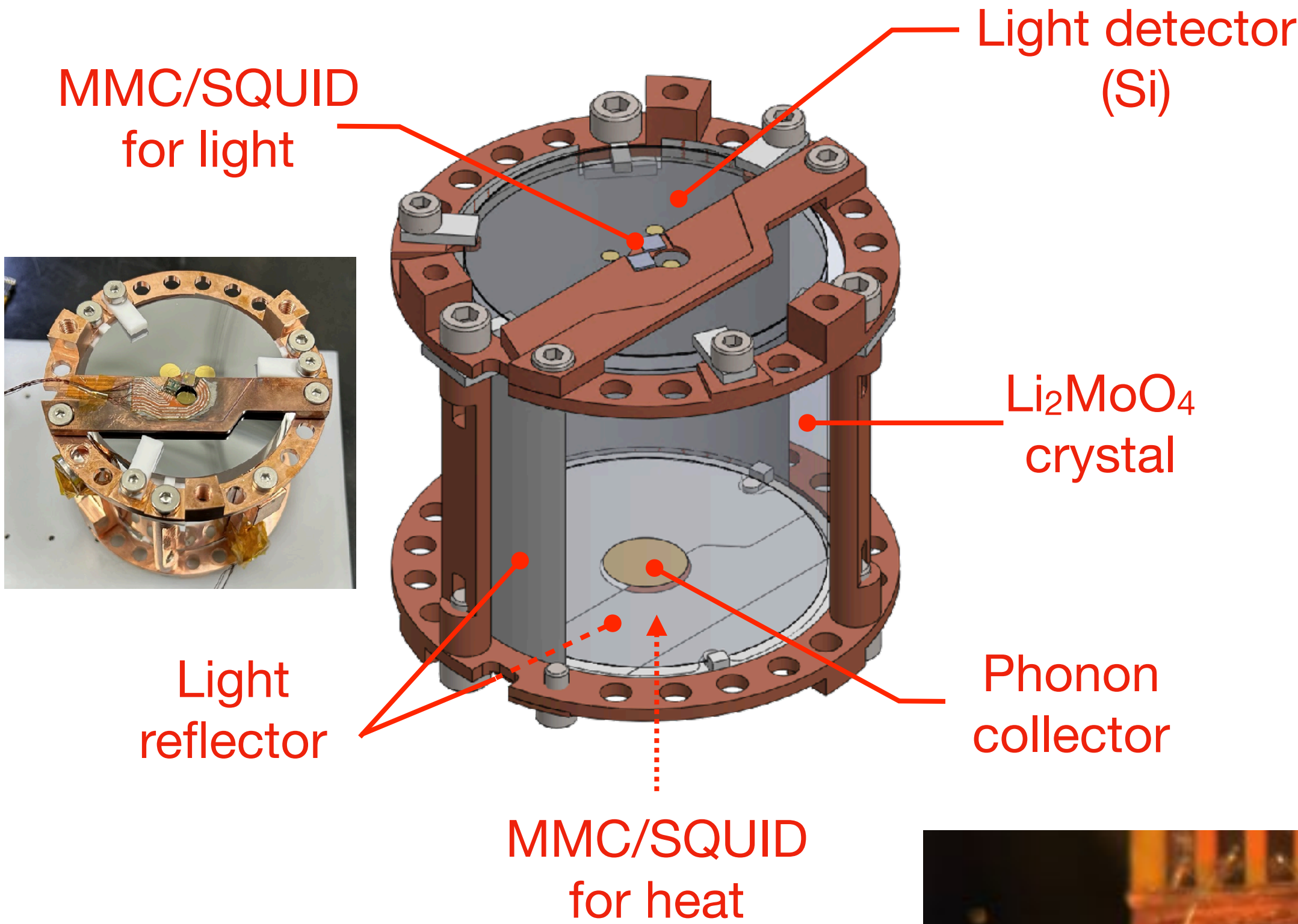


AMoRE detector module

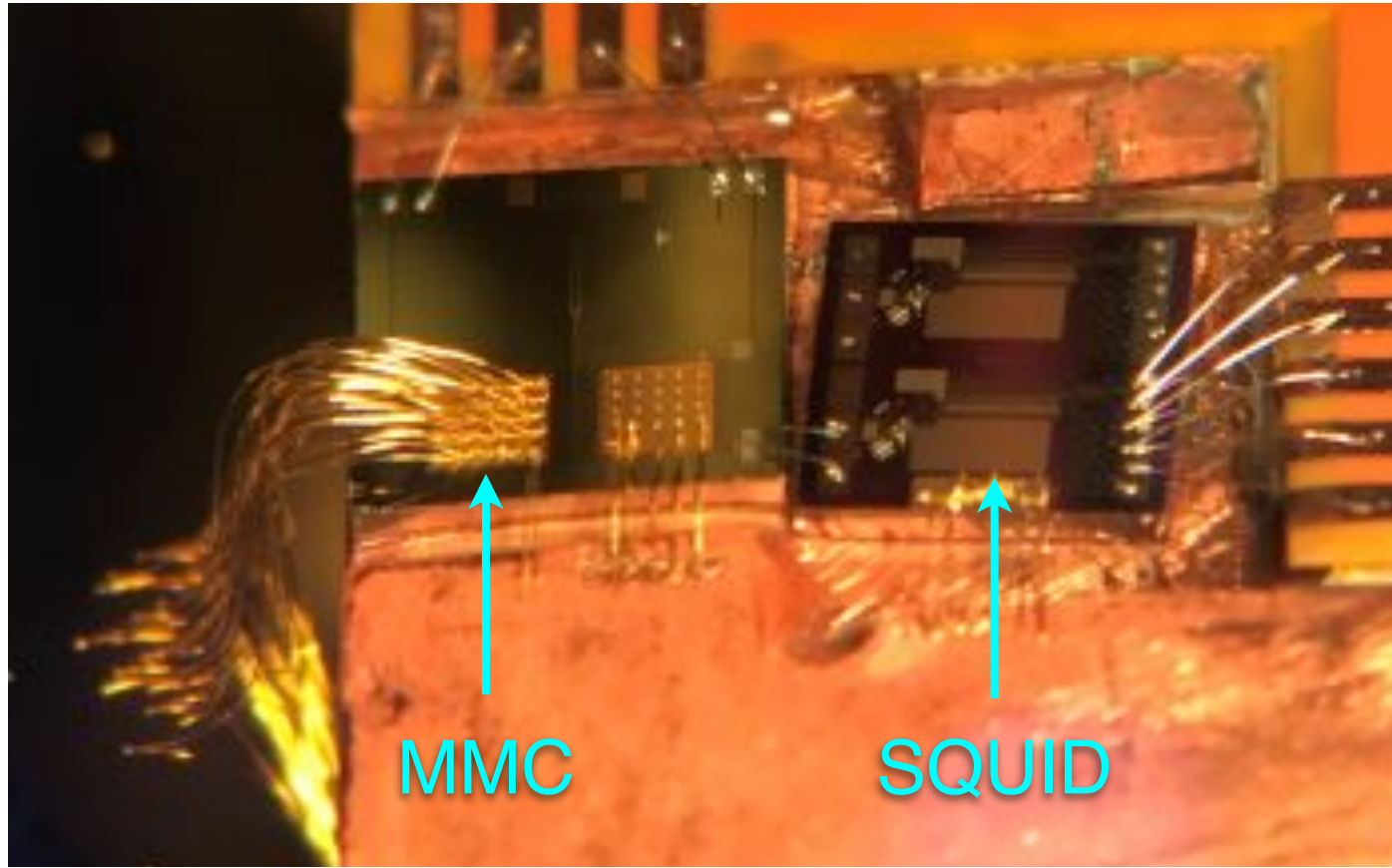


Metallic Magnetic Calorimeter (MMC)
Figure courtesy of D. Hengstler et al (2015)

$$\begin{aligned} \Delta E (\Delta T) \\ \downarrow \\ \Delta M (\text{MMC}) \\ \downarrow \\ \Delta I (\text{SQUID}) \end{aligned}$$

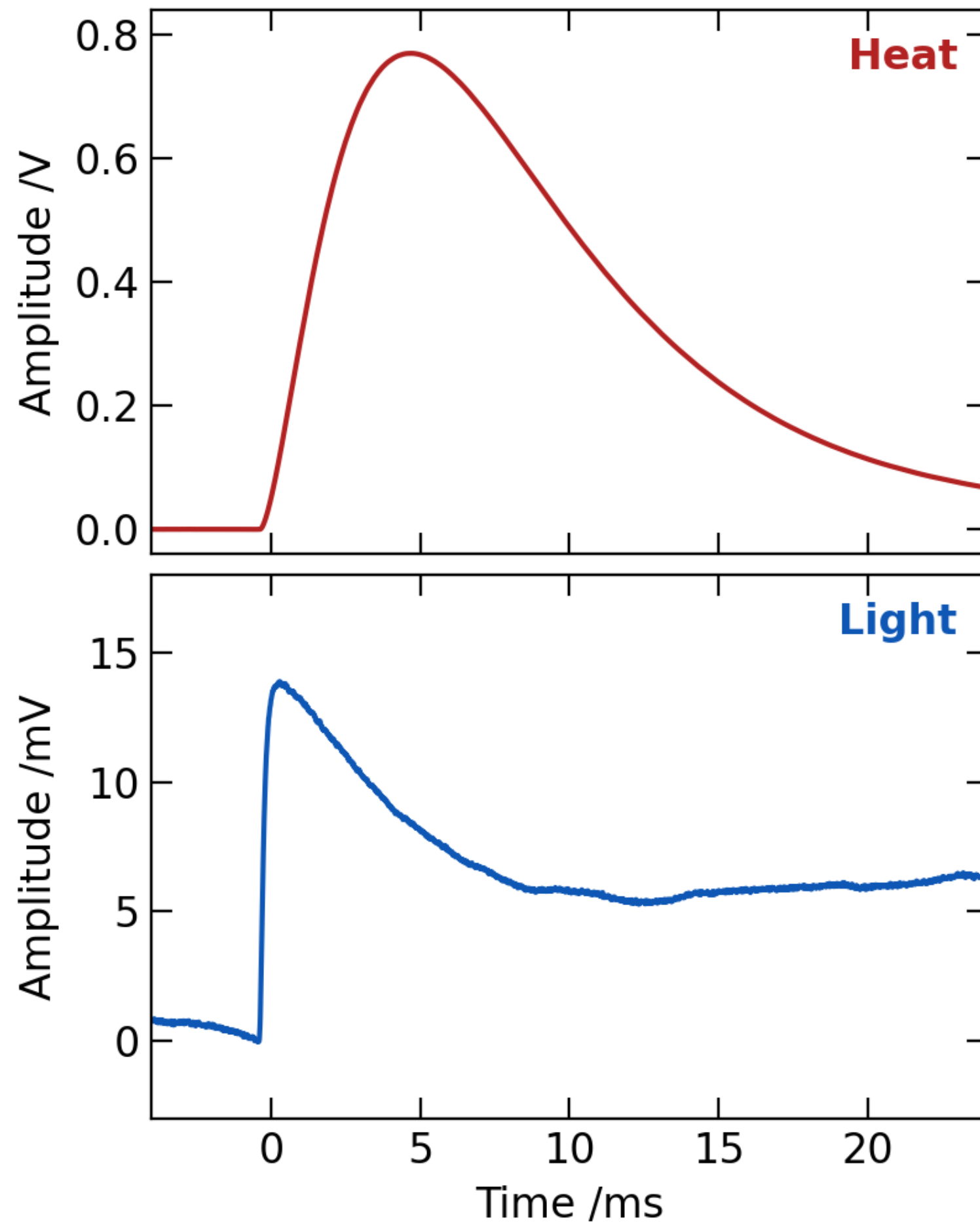


AMoRE-II detector module
Eur. Phys. J. C 85, 172 (2025)



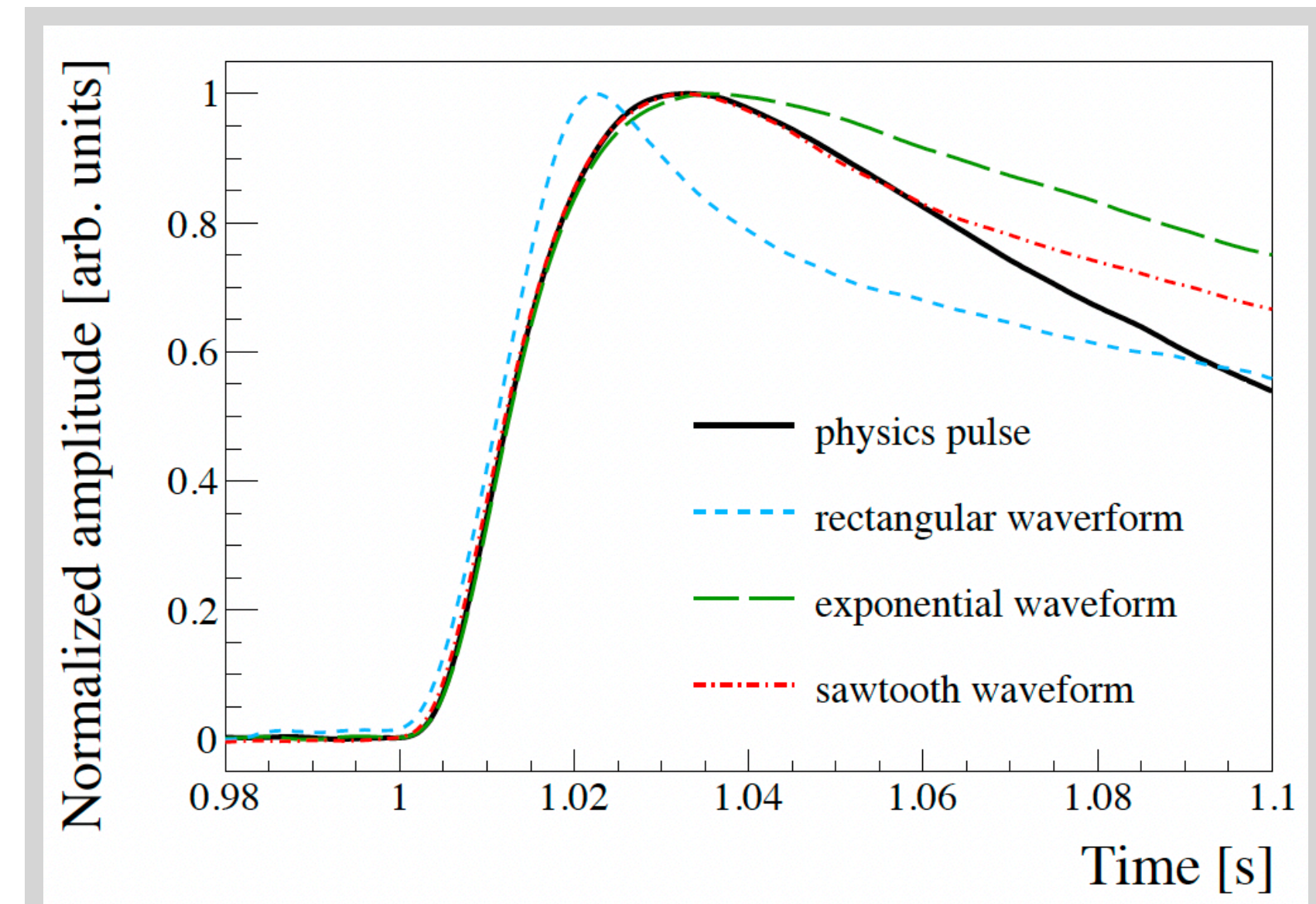
Detector response

Fast signal timing among cryogenic detectors



Averaged 2.6 MeV- γ signals of an LMO detector in AMoRE-I

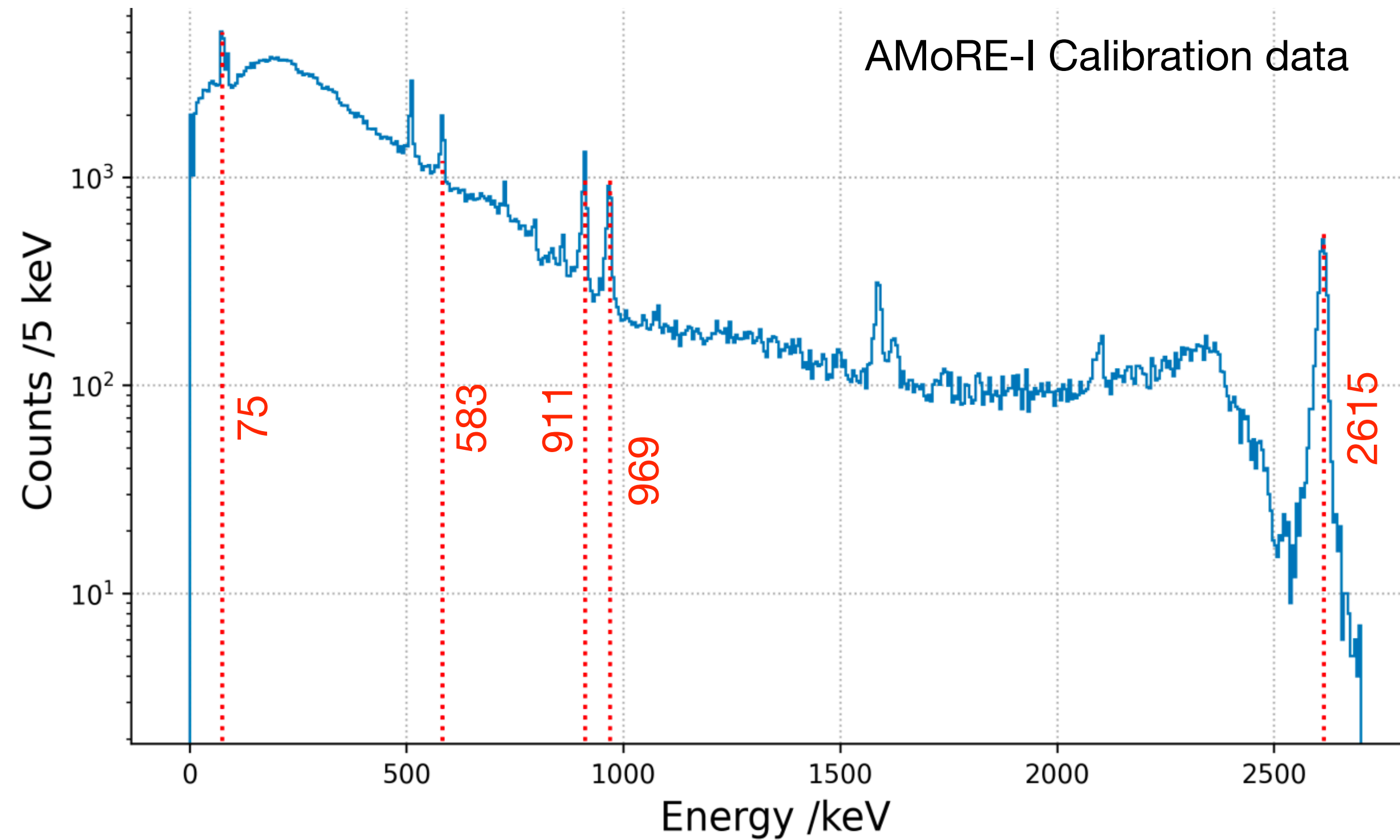
- Signals readout using dedicated ADC (by NOTICE Korea) at 100k sampling/sec, with 18 (16 for AMoRE-II) bit resolution in ± 5 Vpp dynamic range for each channel.
- Heat signal rise-time (10–90%) ~ 1 –5 ms, depending on:
 - Temperature,
 - Crystal surface condition,
 - Thermal connections
- Faster signal timing better for smaller pile-up background.



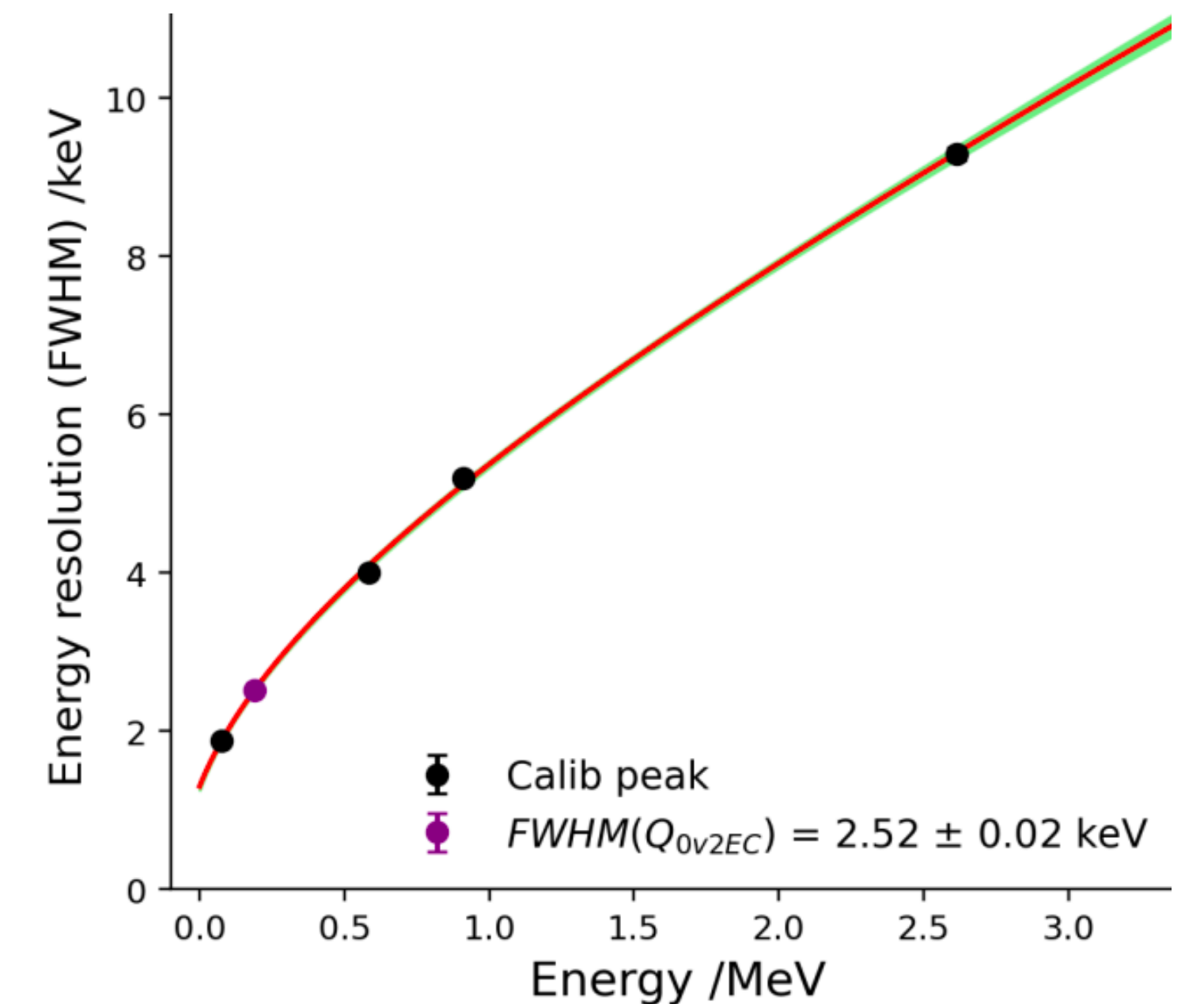
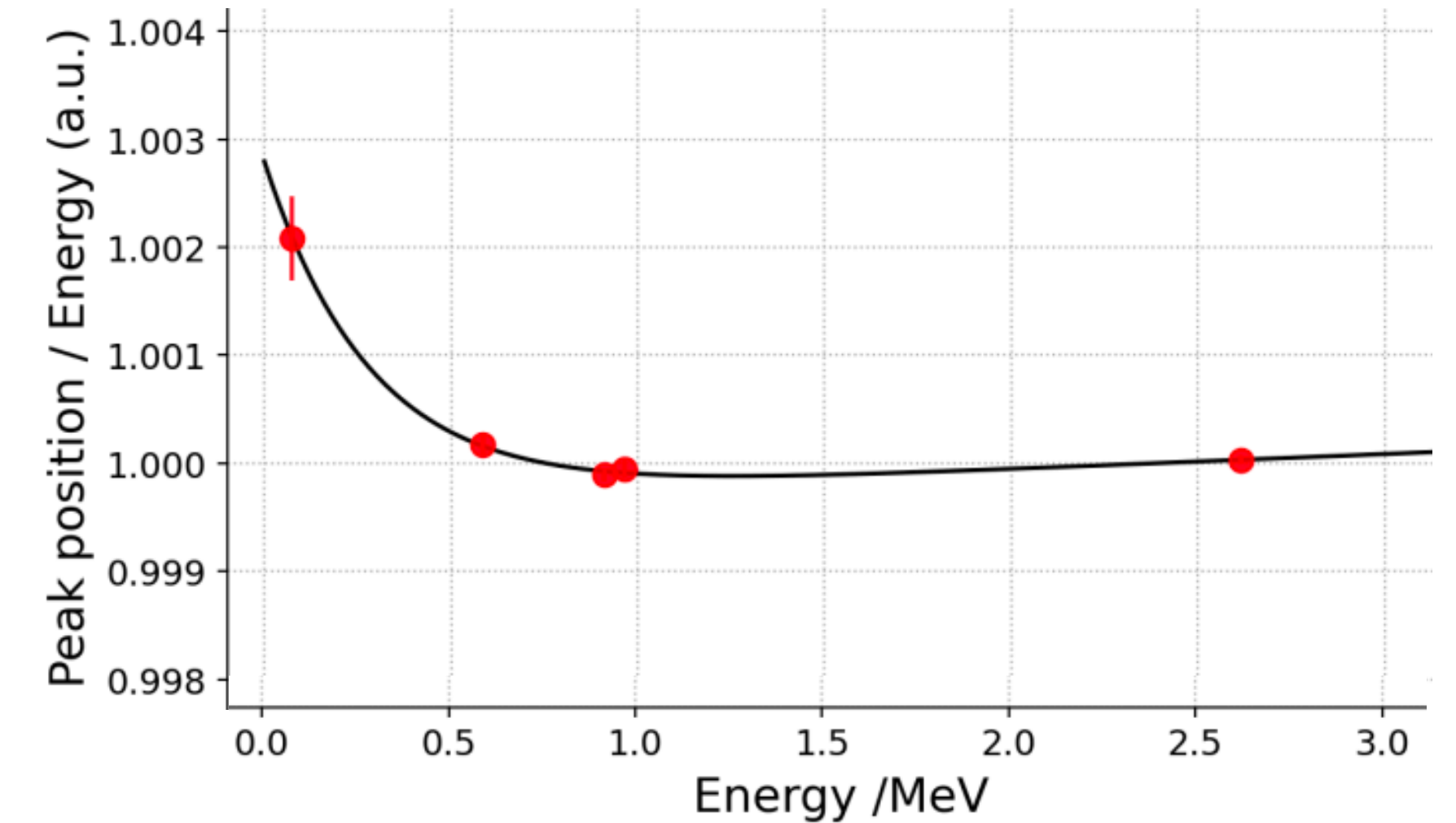
C.f. typical heat signal of CUPID, Phys. Rev. C 104, 015501 (2021)

Detector performances 1. Energy response

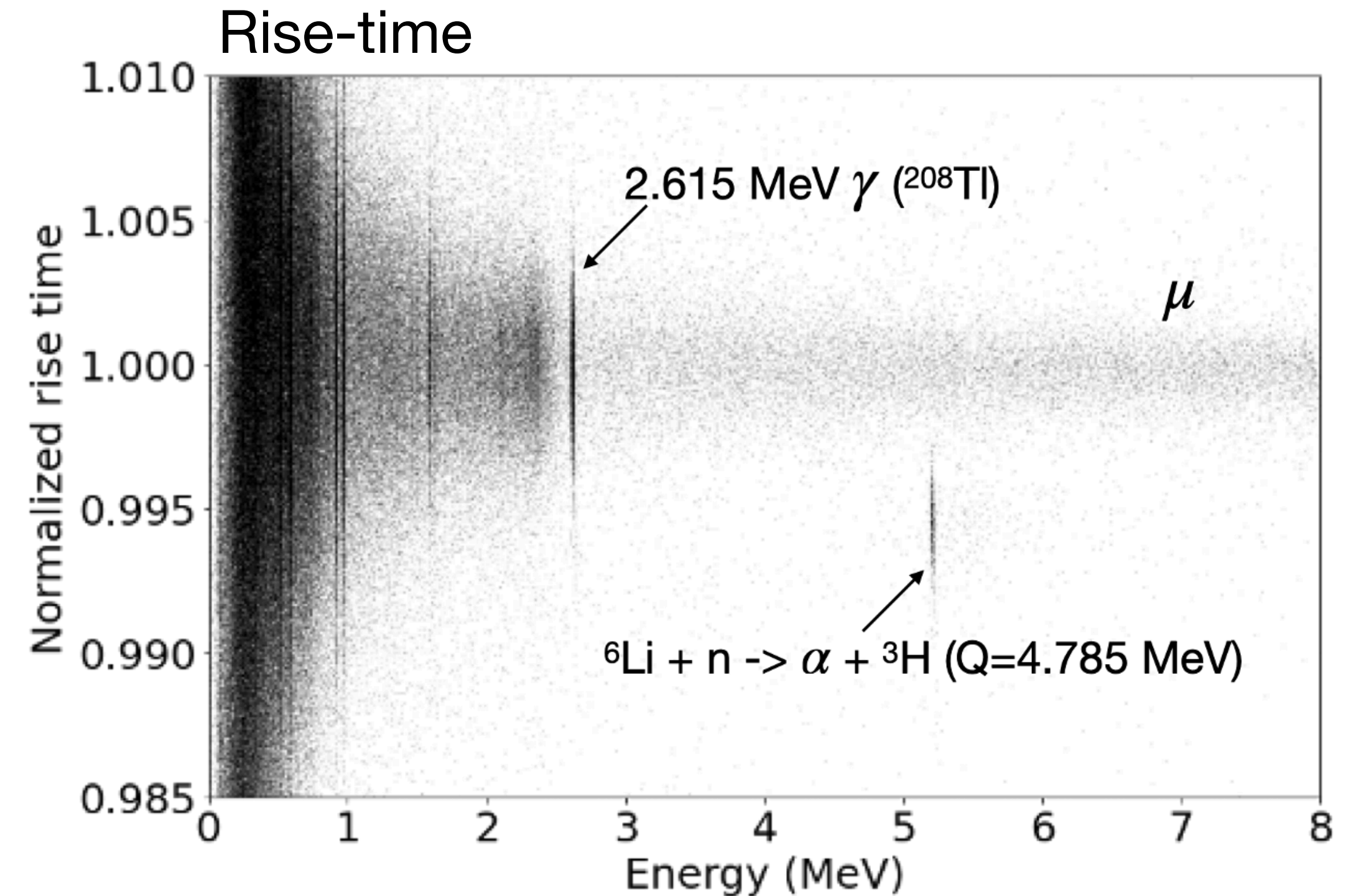
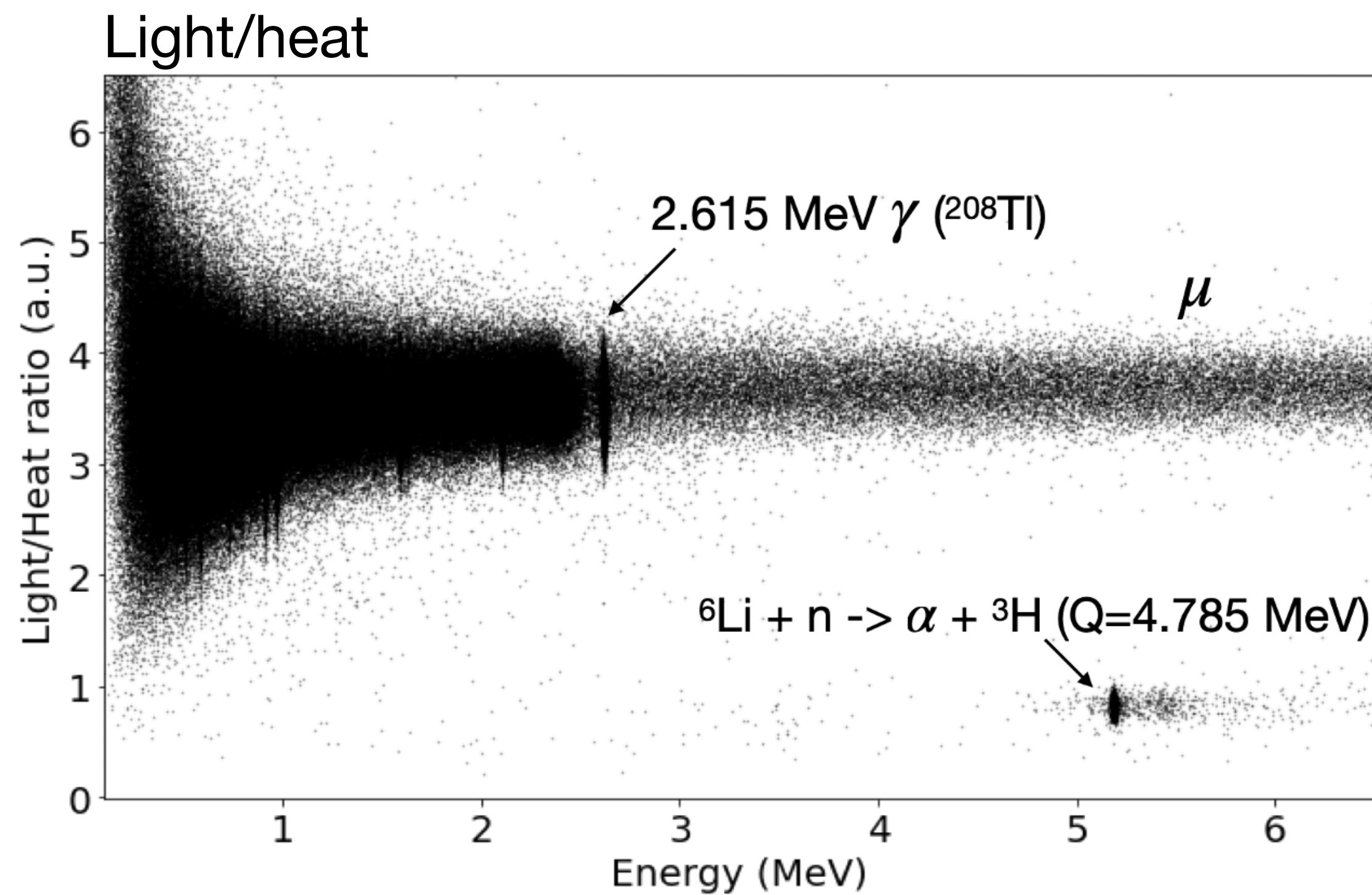
Wide dynamic range, linearity and resolution



- Threshold at 10 keV, saturation at over 10 MeV.
- Signal amplitude $\sim$ energy.
- $\Delta E < \sim 10$ keV FWHM for 2.6 MeV γ .



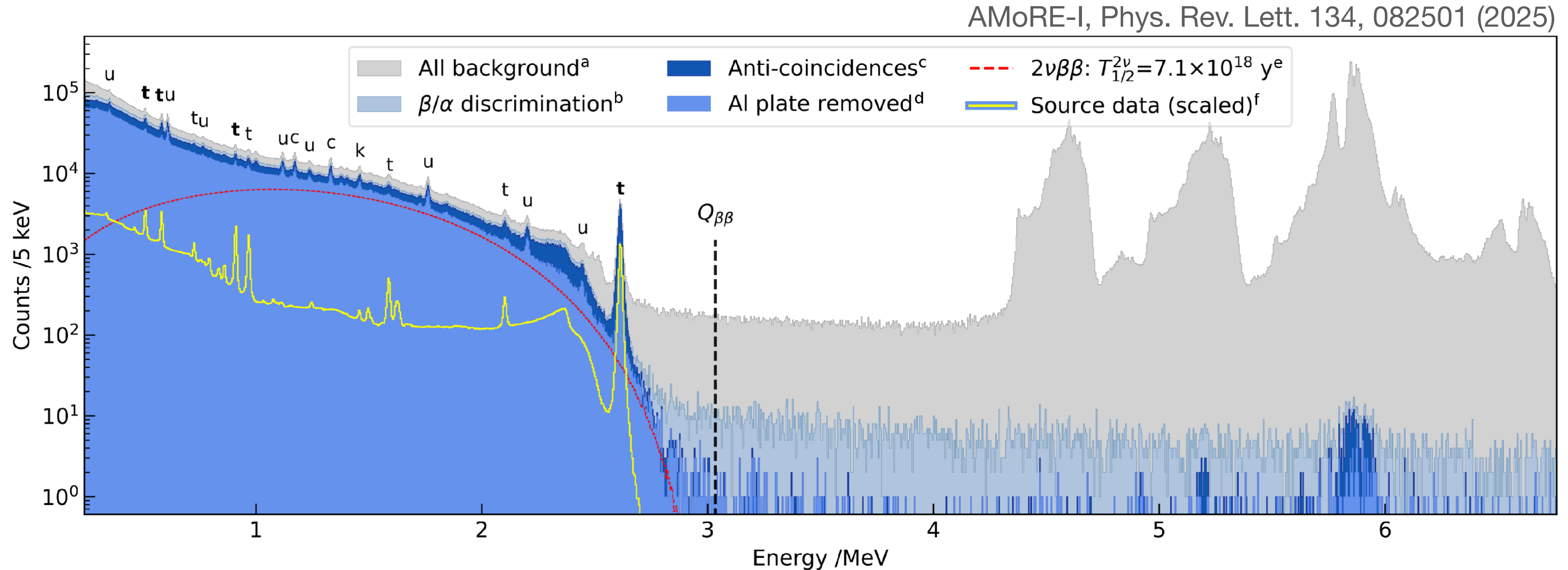
Detector performances 2. Particle identification



R&D data using LMO crystals at surface laboratory
[reference]

- Surface α 's contribute the background at ROI.
- Discrimination utilizing difference in scintillation light quenching.

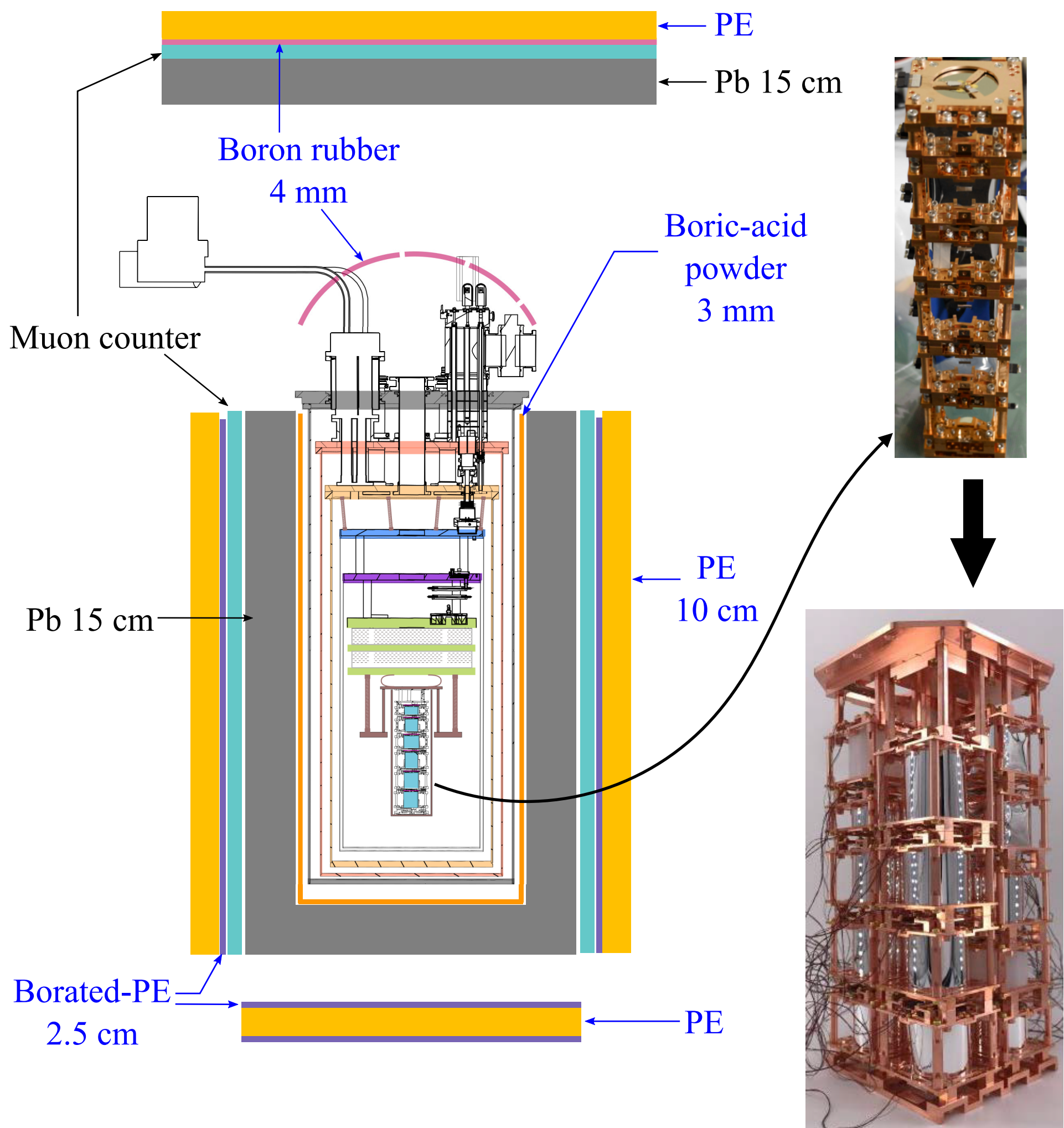
Data analysis and background rejection



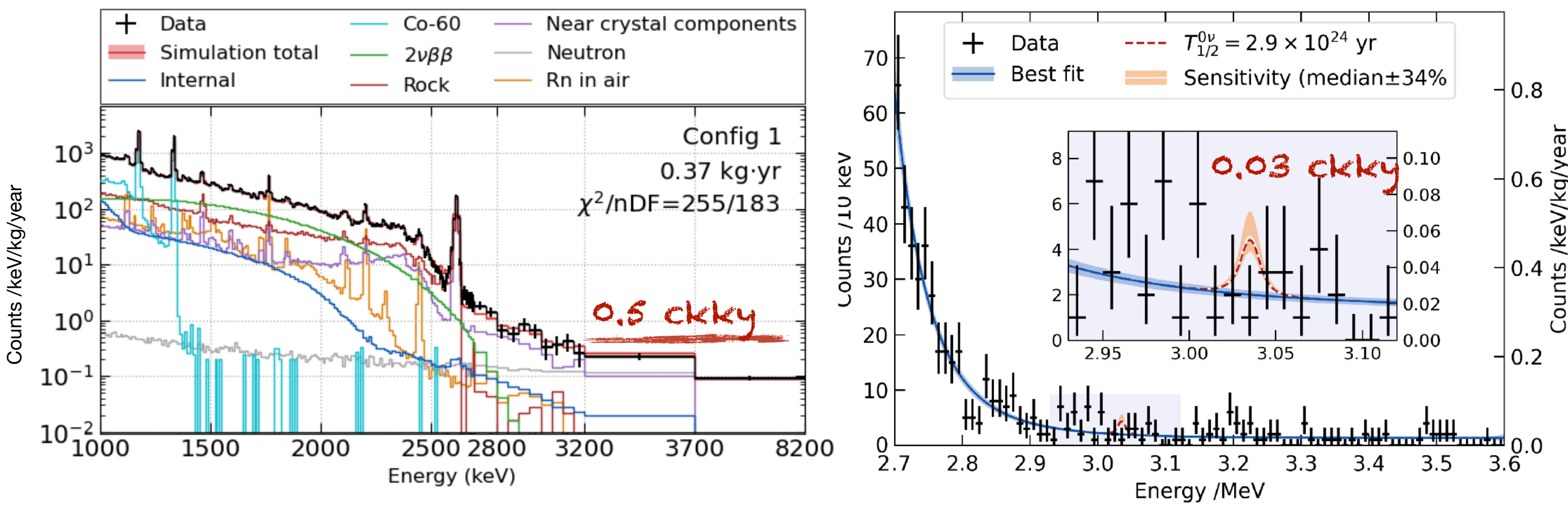
- Energy calibration using external γ source (Th-contained welding rods).
- β/γ , α discrimination: pulse shape (PSD), light/heat ratio.
- Anti-coincidences: between crystals, with muons, or with tagged α 's (^{212}Bi).

AMoRE-pilot (2015–8) and AMoRE-I (2020–23)

at Yangyang Underground Laboratory (Y2L)

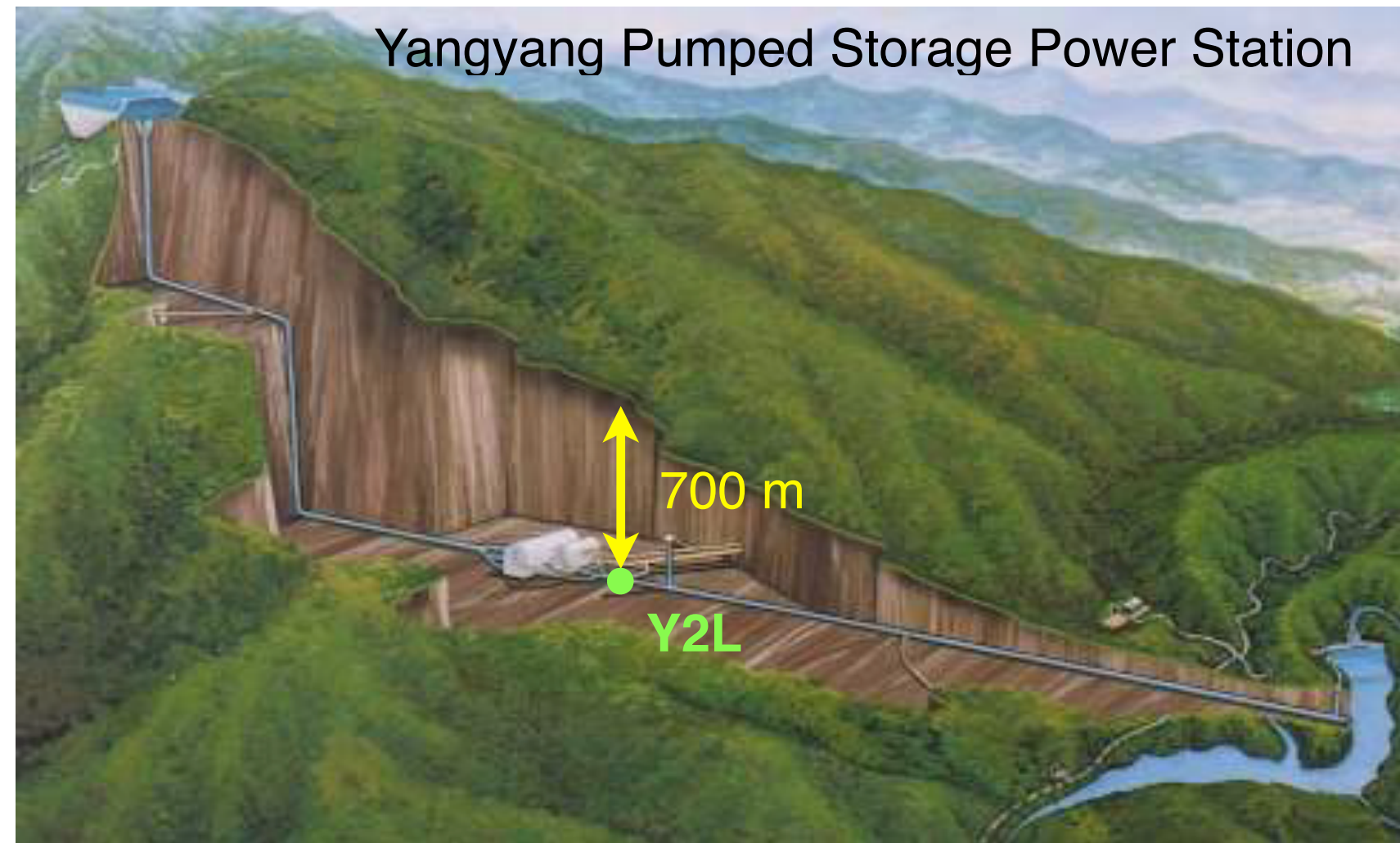


- Detector principle demonstration
- Background source identification, reduction, and realistic modeling.
- Scalability and long-term stable operation.
- Improved experimental sensitivity (AMoRE-I):
 - $T_{1/2}^{0\nu} > 2.9 \times 10^{24}$ yr at 90% C.L.

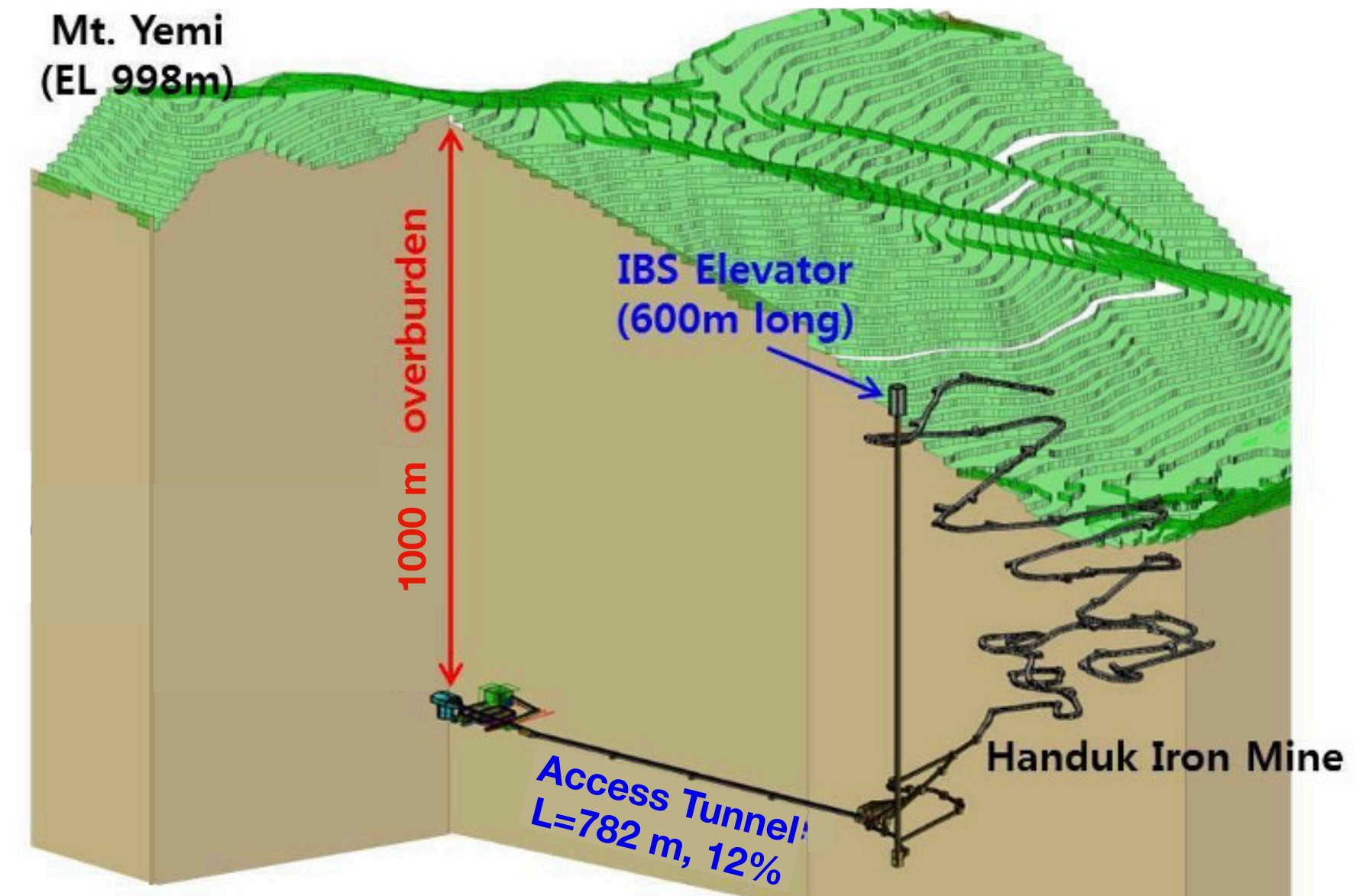


EPJ C 79, 791 (2019), Astropart. Phys. 162, 102991 (2024), PRL 134, 182501 (2025)

From Yangyang (Y2L) and to Yemilab

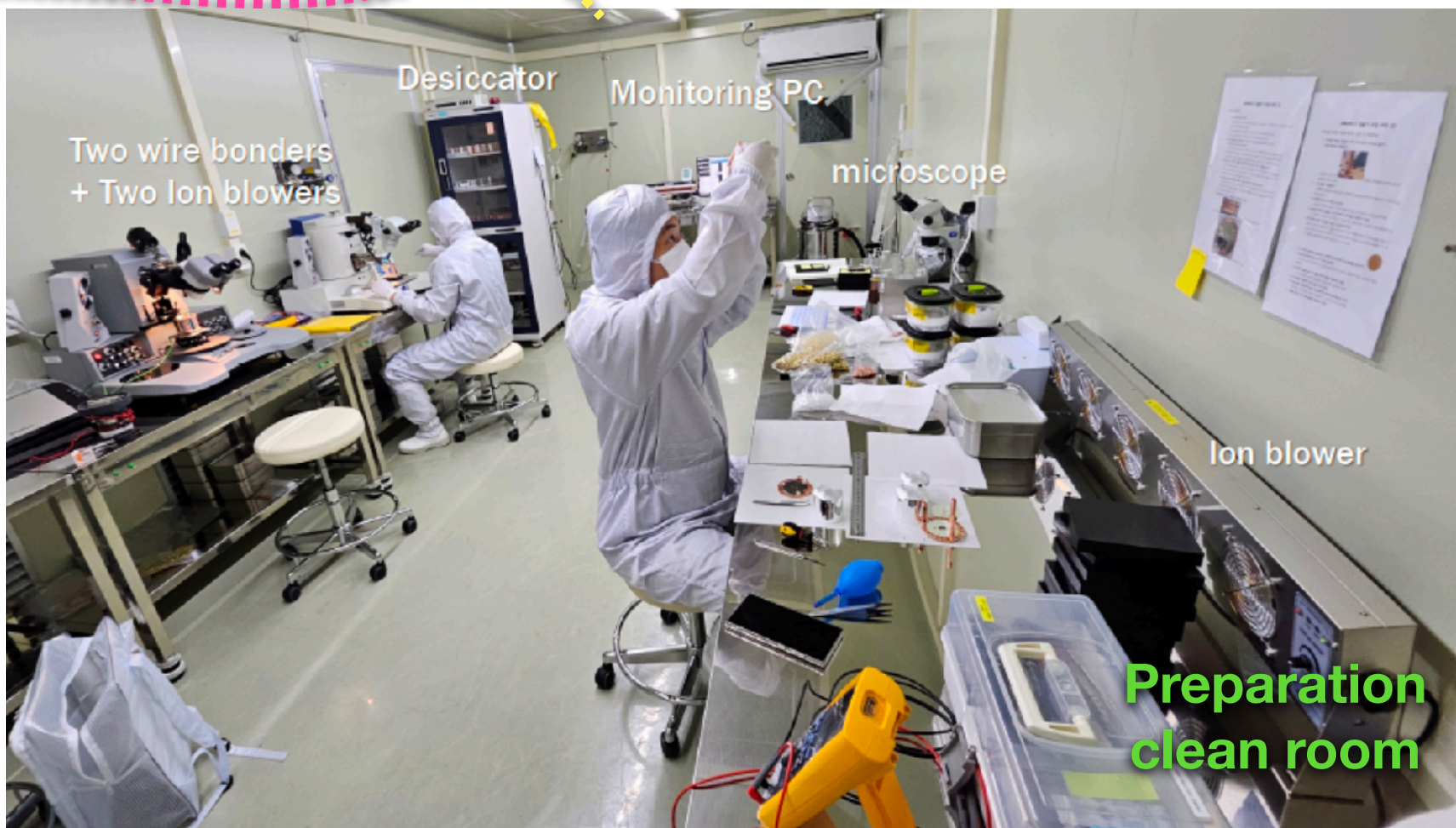
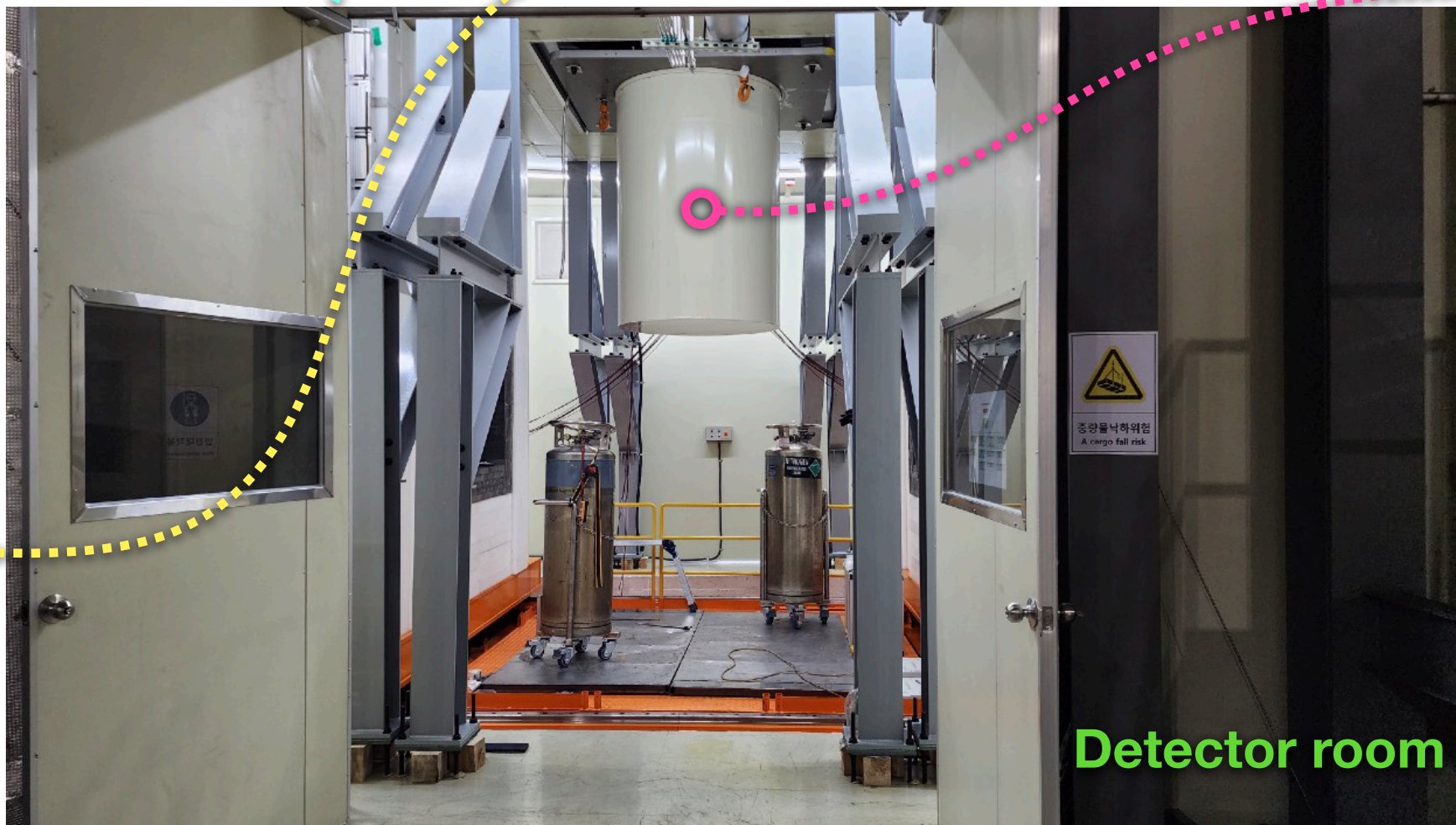


- Operation for 20+ years since 2003.
- By CUP/IBS from 2013.
- Lab area ~ 300 m².
- Access by car using paved road.
- AMoRE-pilot, AMoRE-I, COSINE-100, KIMS...

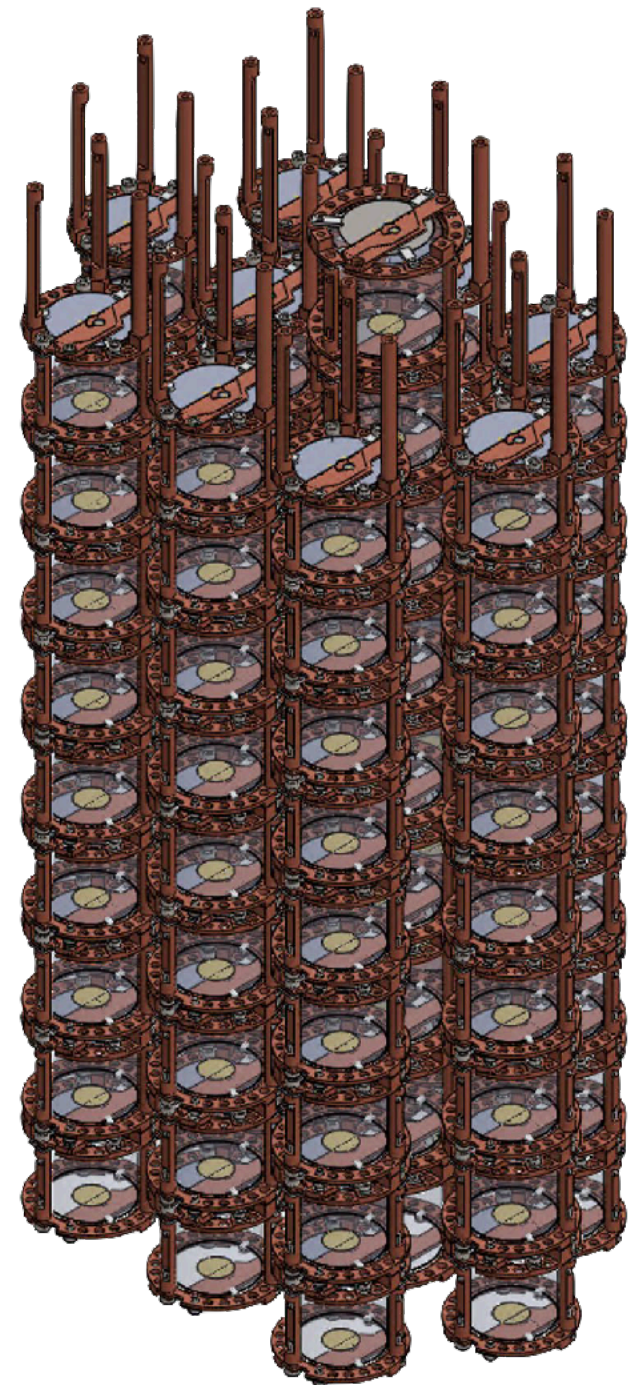
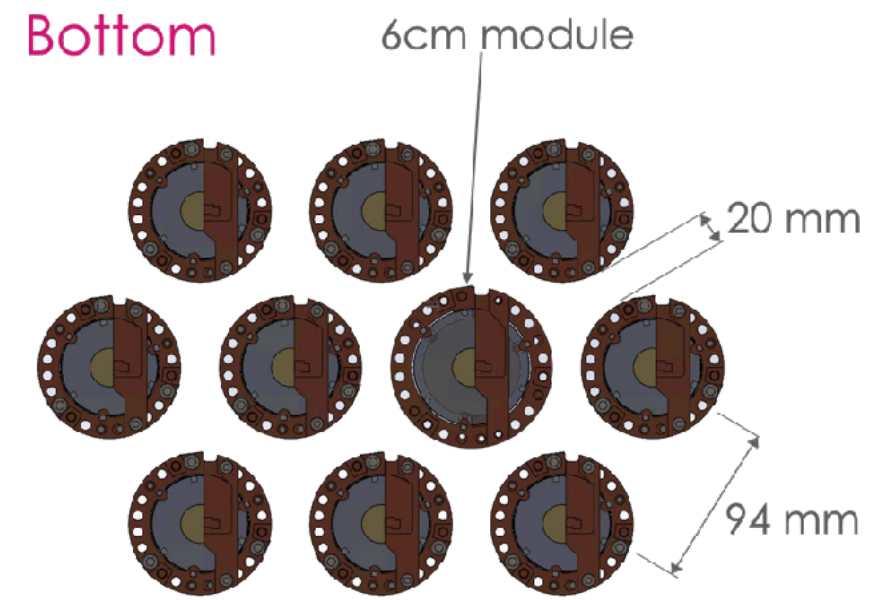


- Operation since October 2022.
- Lab area ~ 3000 m².
- Access using (man-ride elevator) | (unpaved rampway) and paved access tunnel.
- AMoRE-II, COSINE-100U, v-EYE, ...

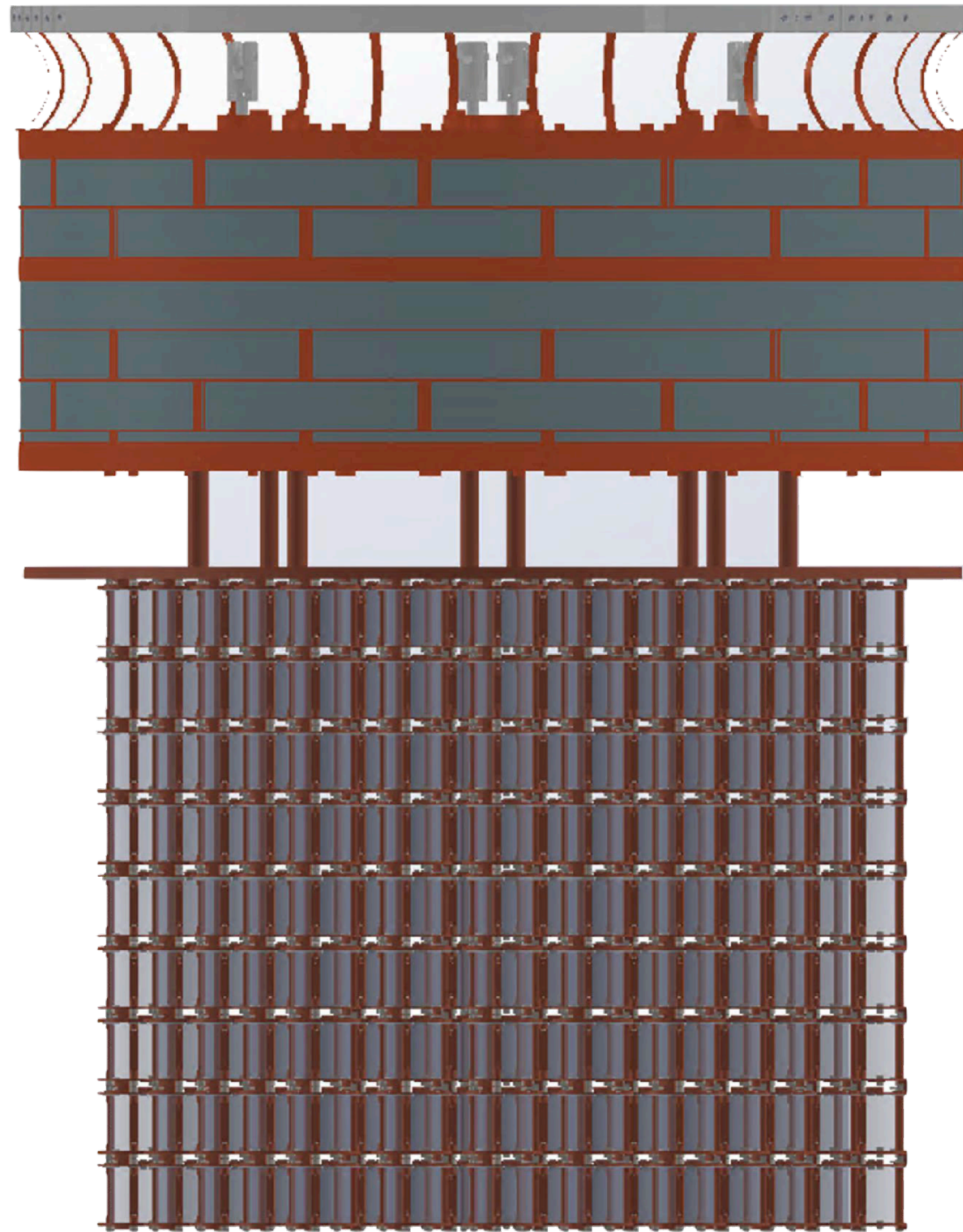
AMoRE-II preparation in Yemilab



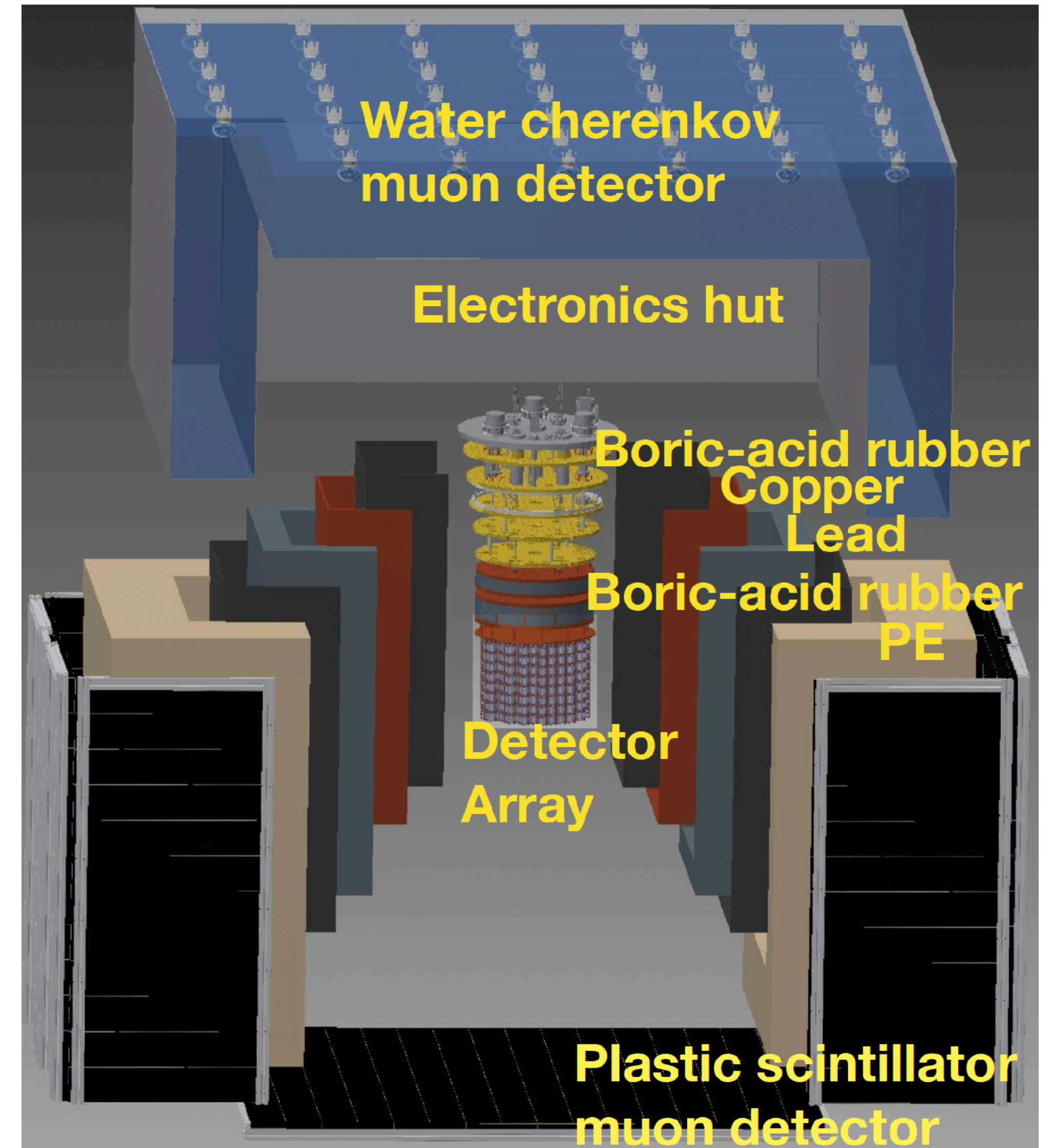
AMoRE-II detector towers and shielding



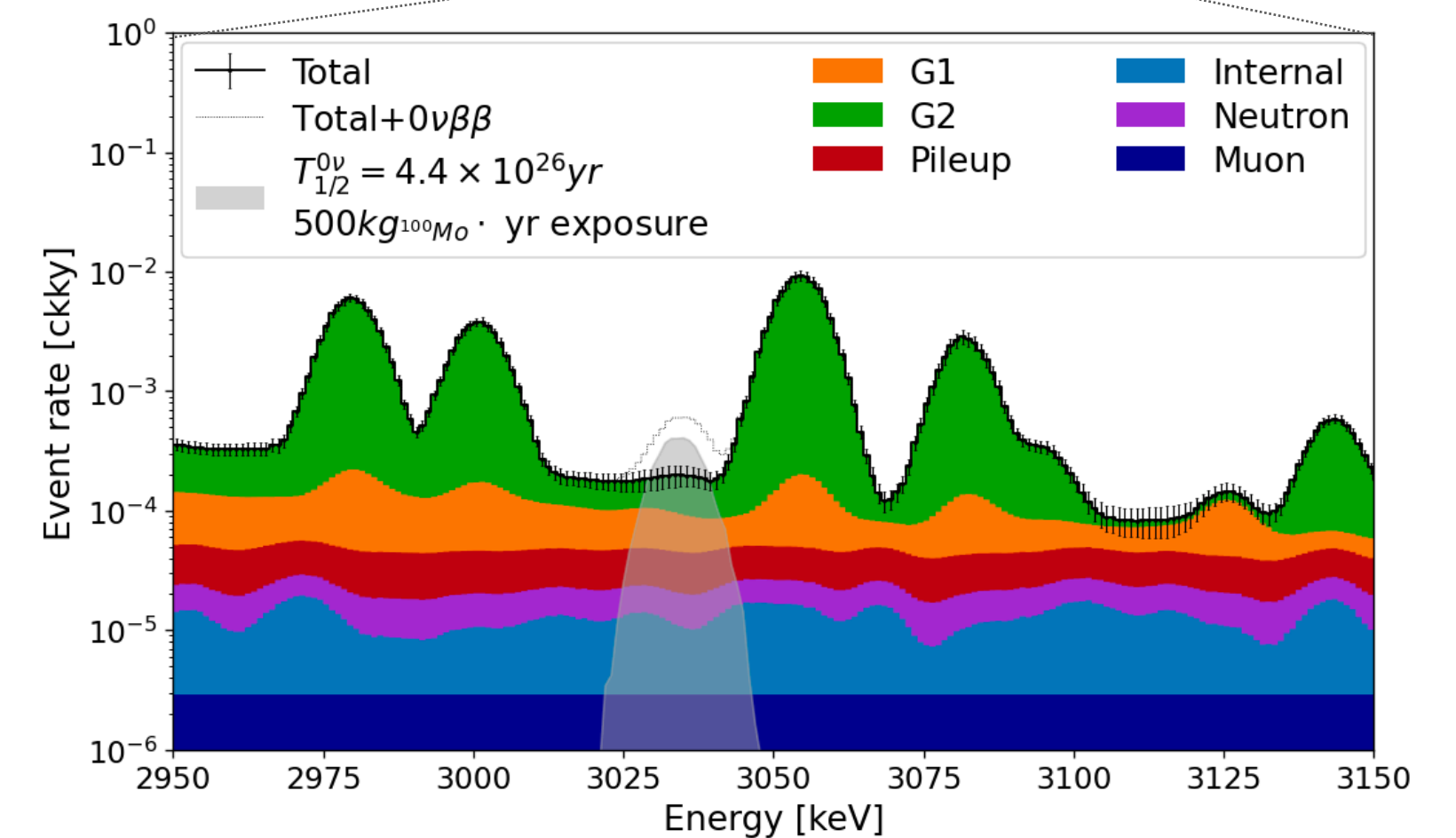
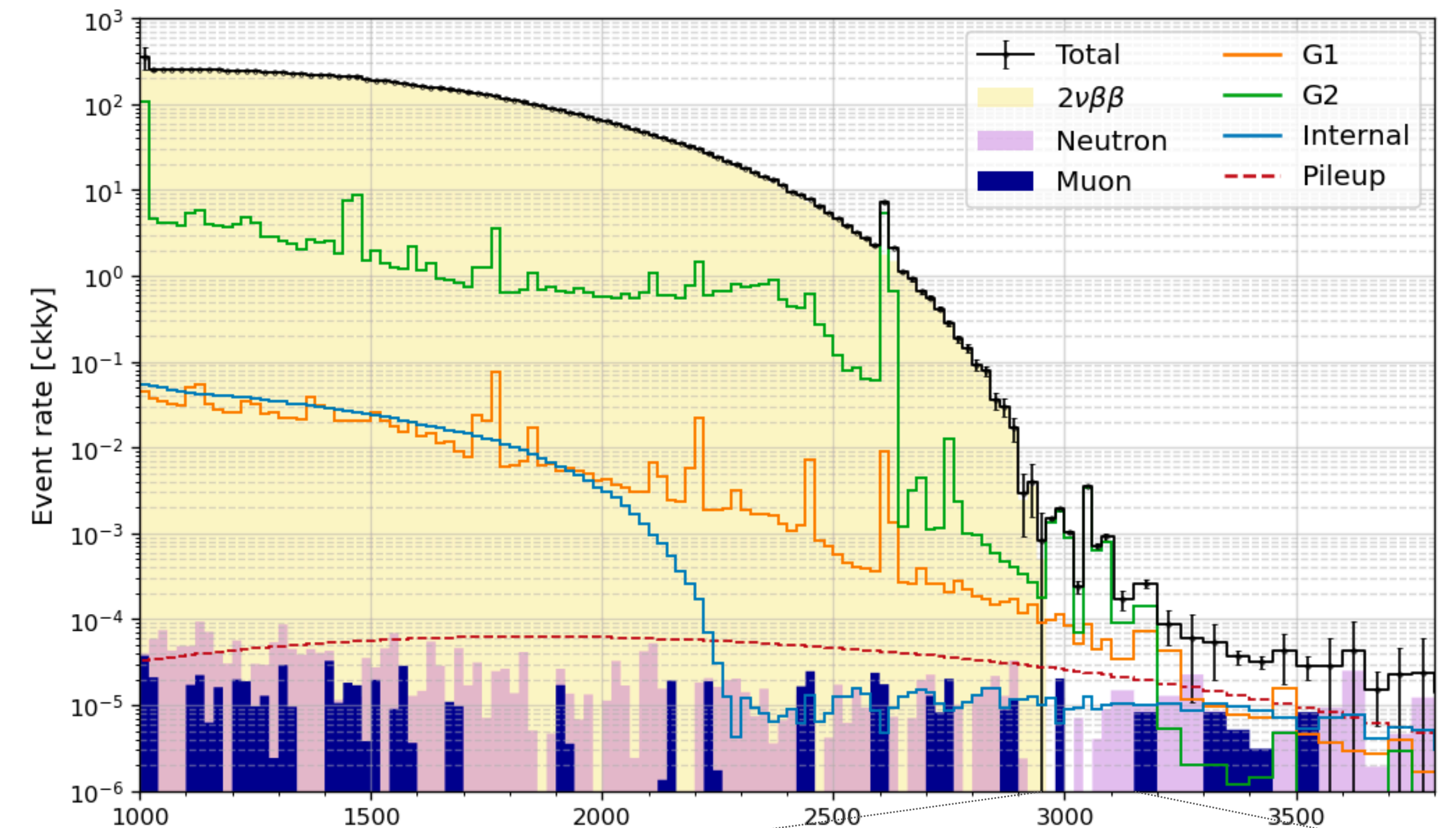
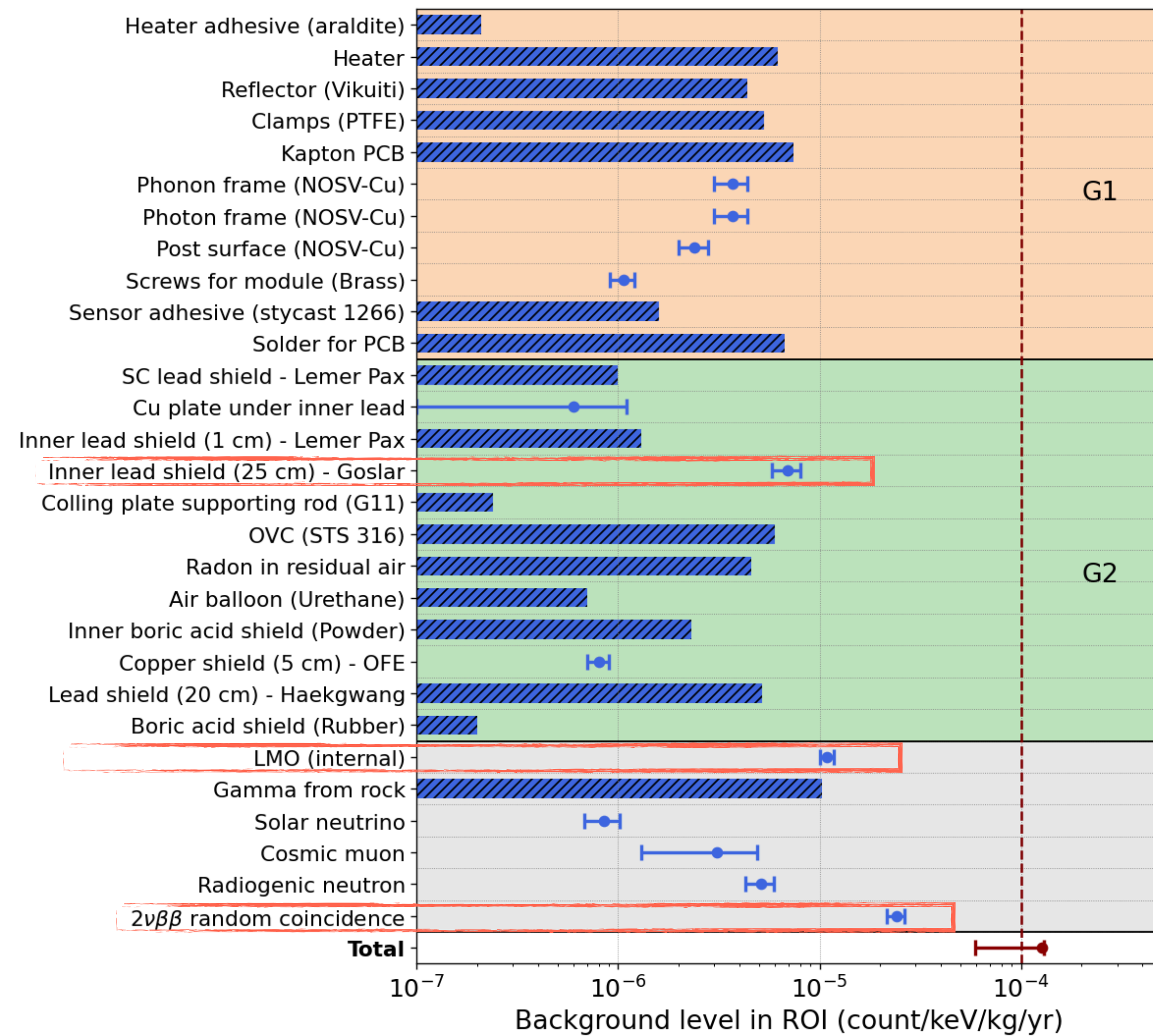
Stage 1:
90 LMO crystals (27 kg)



Stage 2:
360 LMO+CMO crystals (157 kg)

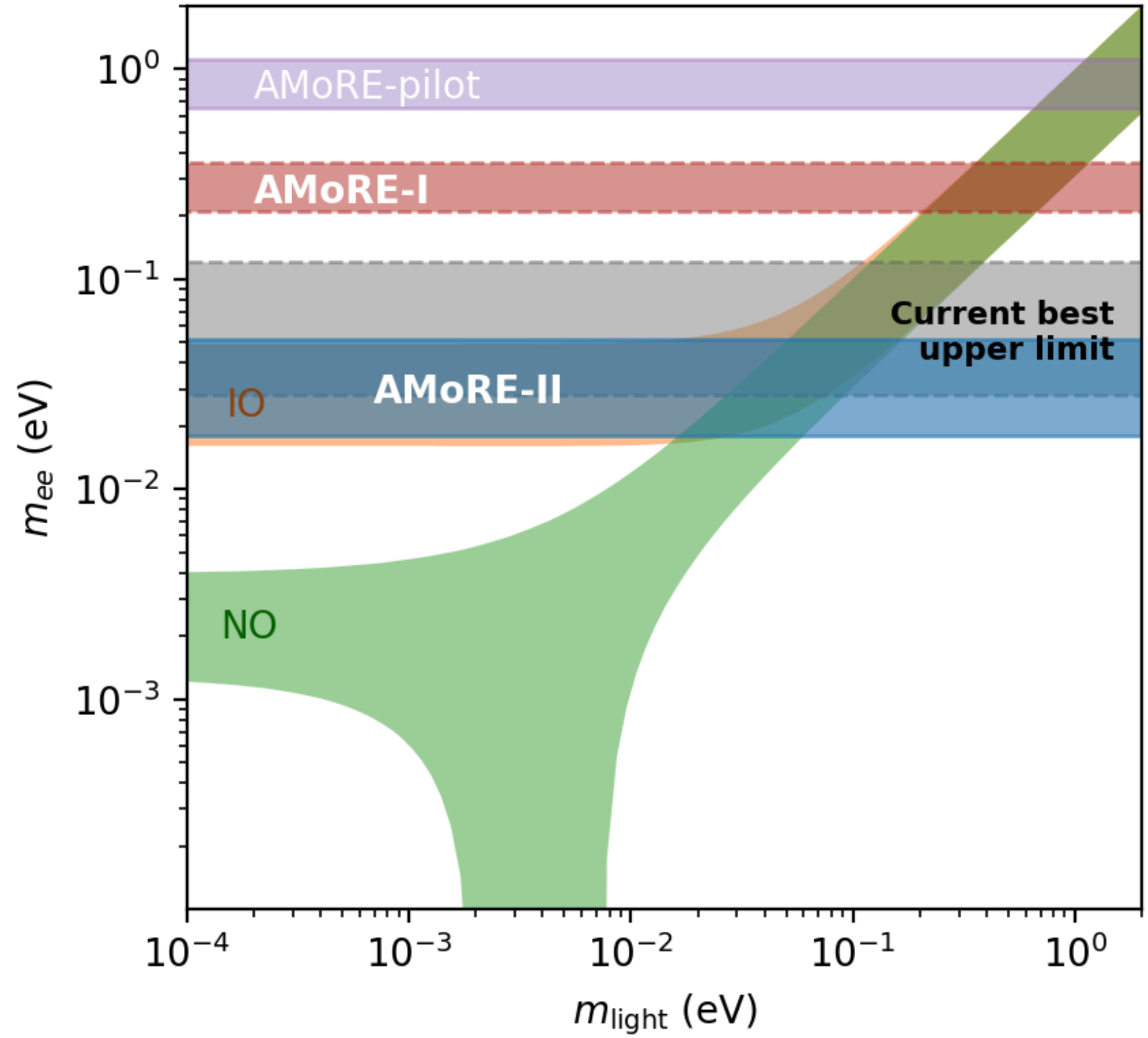
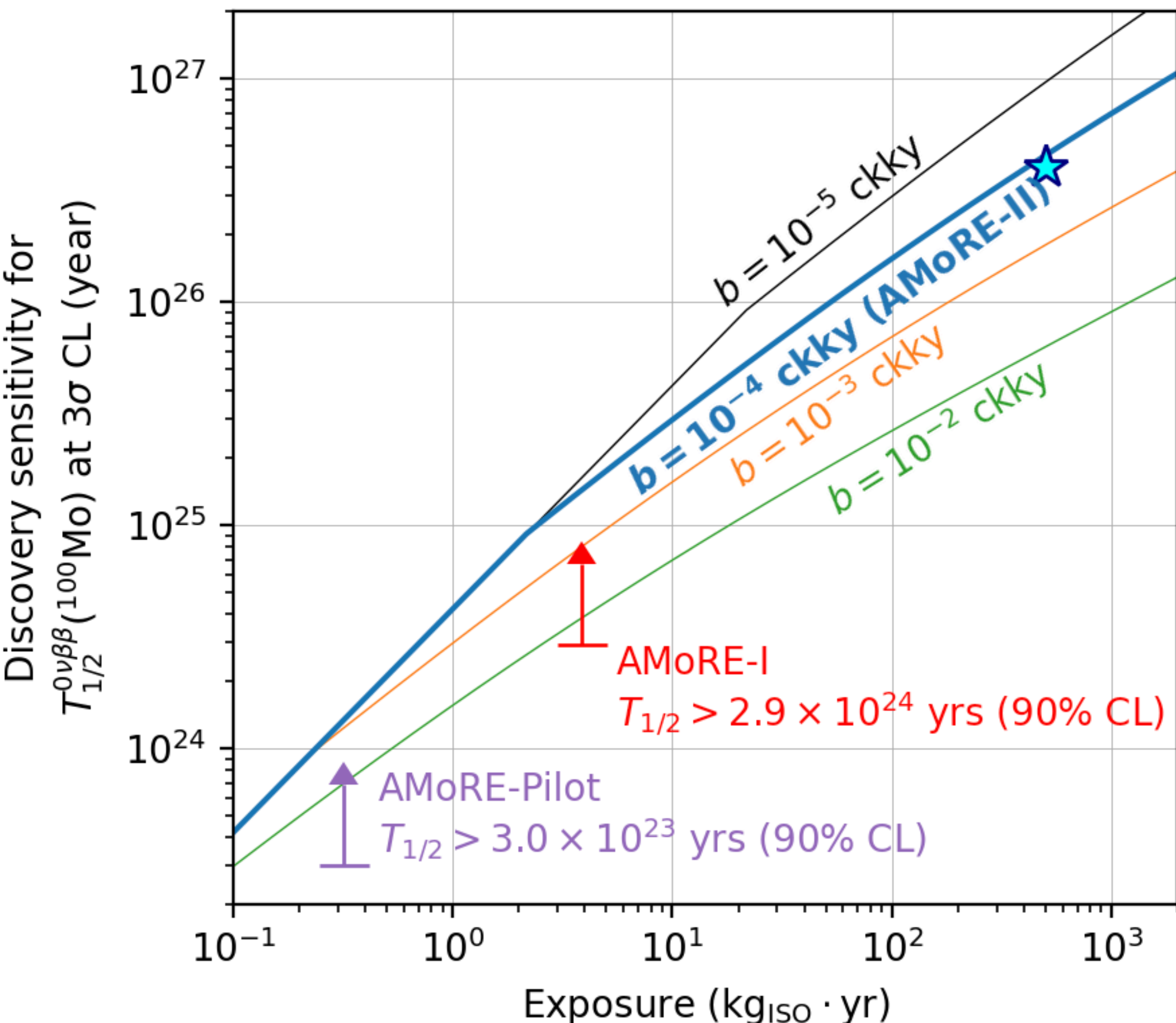


Expected background



Front. Phys. 12, 1362209 (2024), Euro. Phys. J. C85, 9 (2025), TAUP 2025

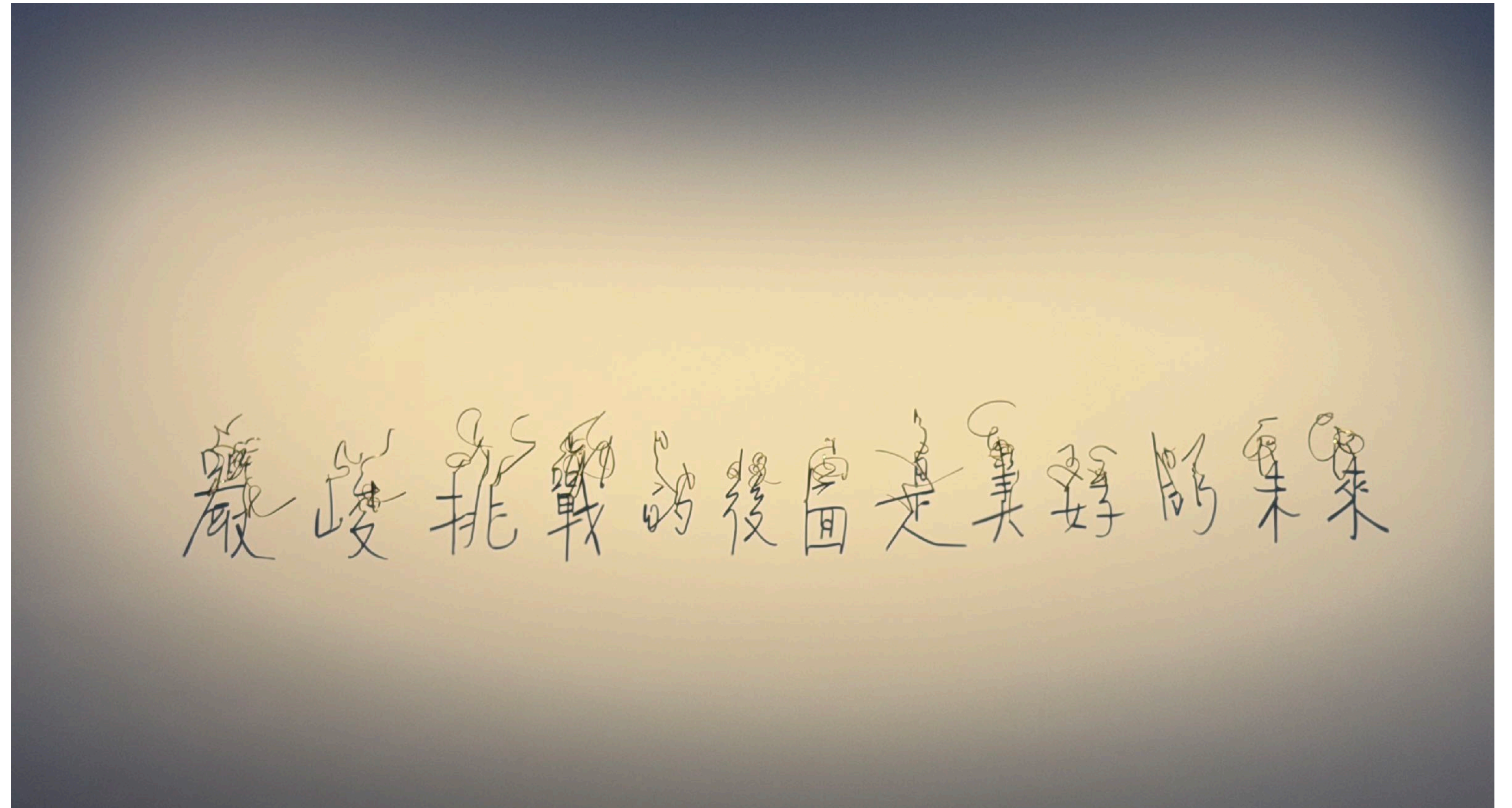
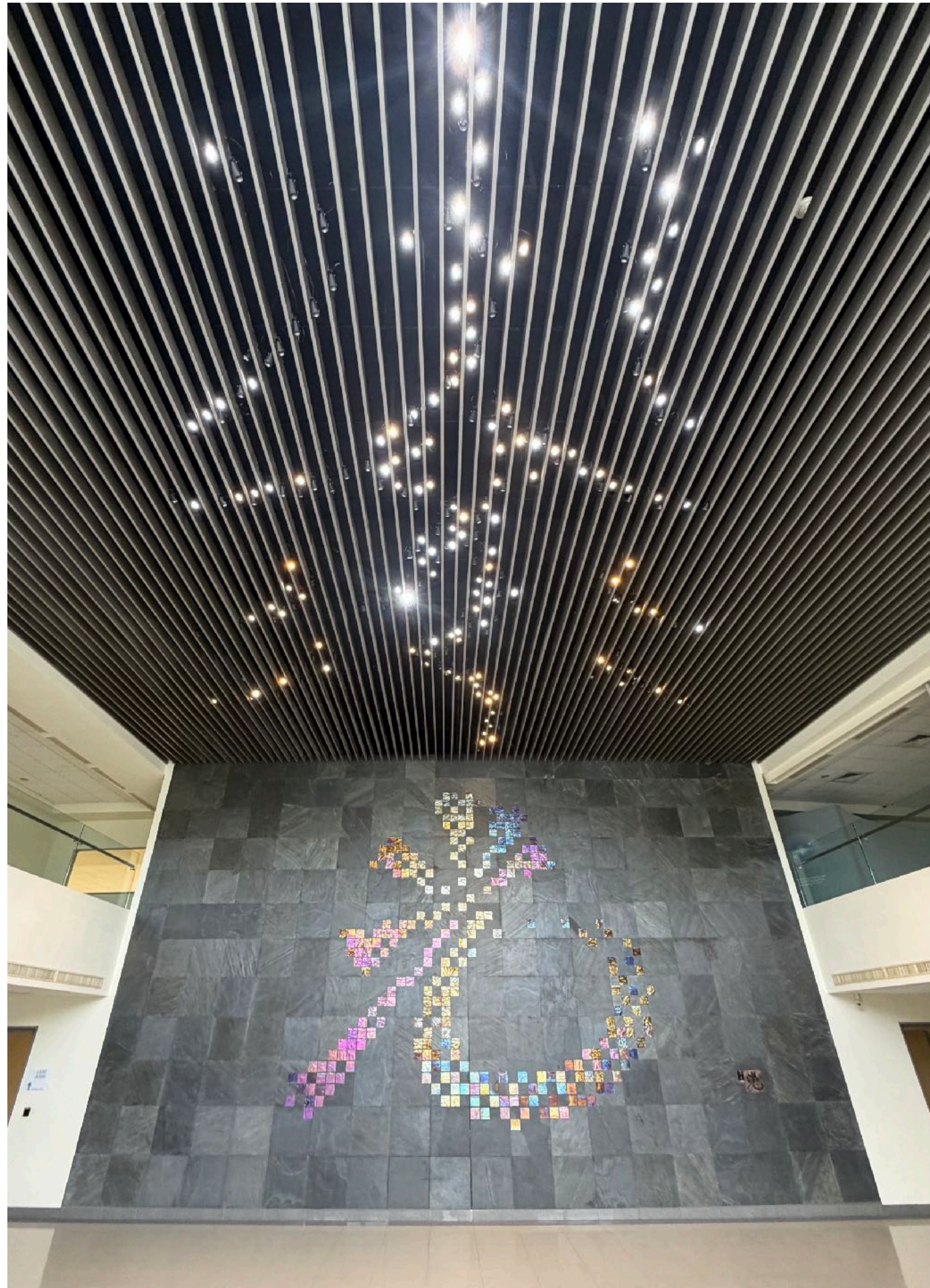
AMoRE-II sensitivity



Summary and closing

- AMoRE for $0\nu\beta\beta$ decay of ^{100}Mo , using scintillation crystals in the cryogenic detector system.
- AMoRE-II aiming at conquering effective Majorana mass at tens of meV range.
 - Cooling test, part cleaning, and sensors test are ongoing.
 - Taking data starts soon.
- Nuclear Matrix Element: hoping to have much improved input from nuclear physics.

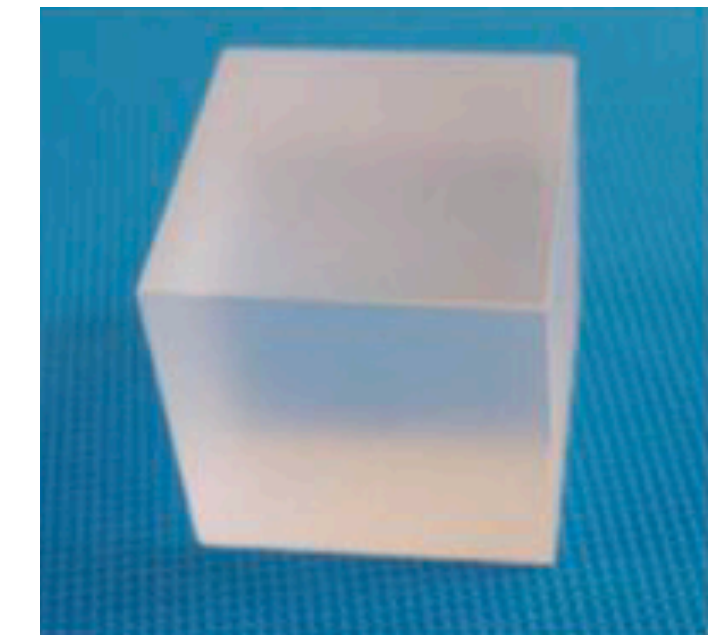
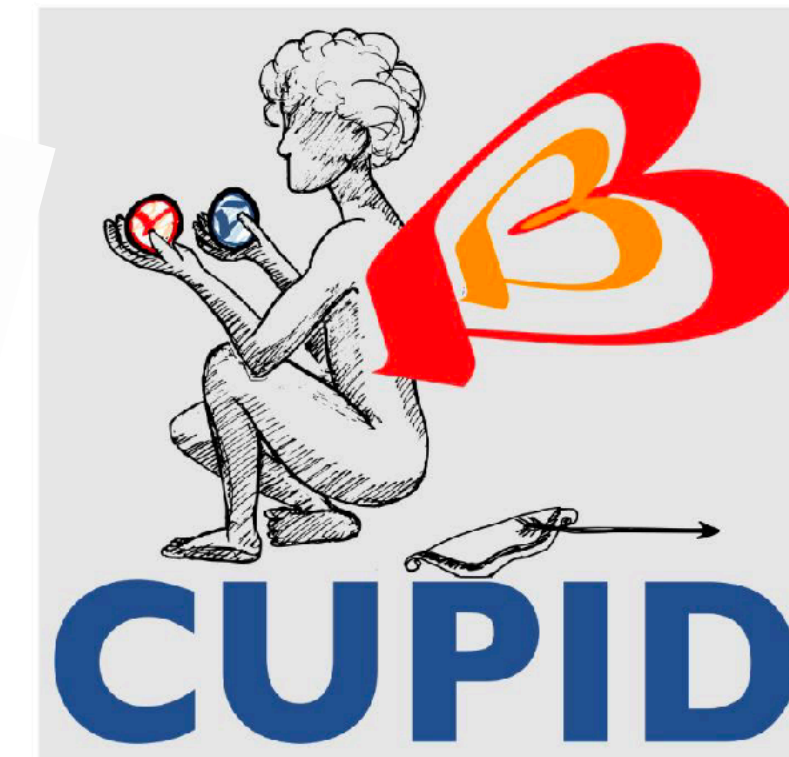
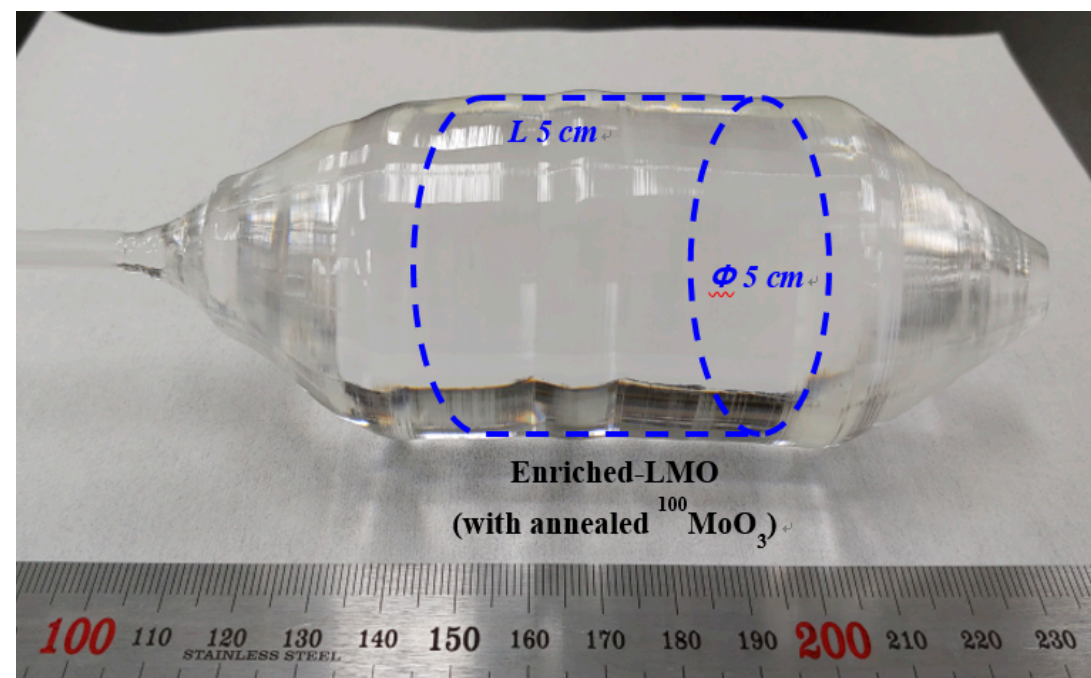
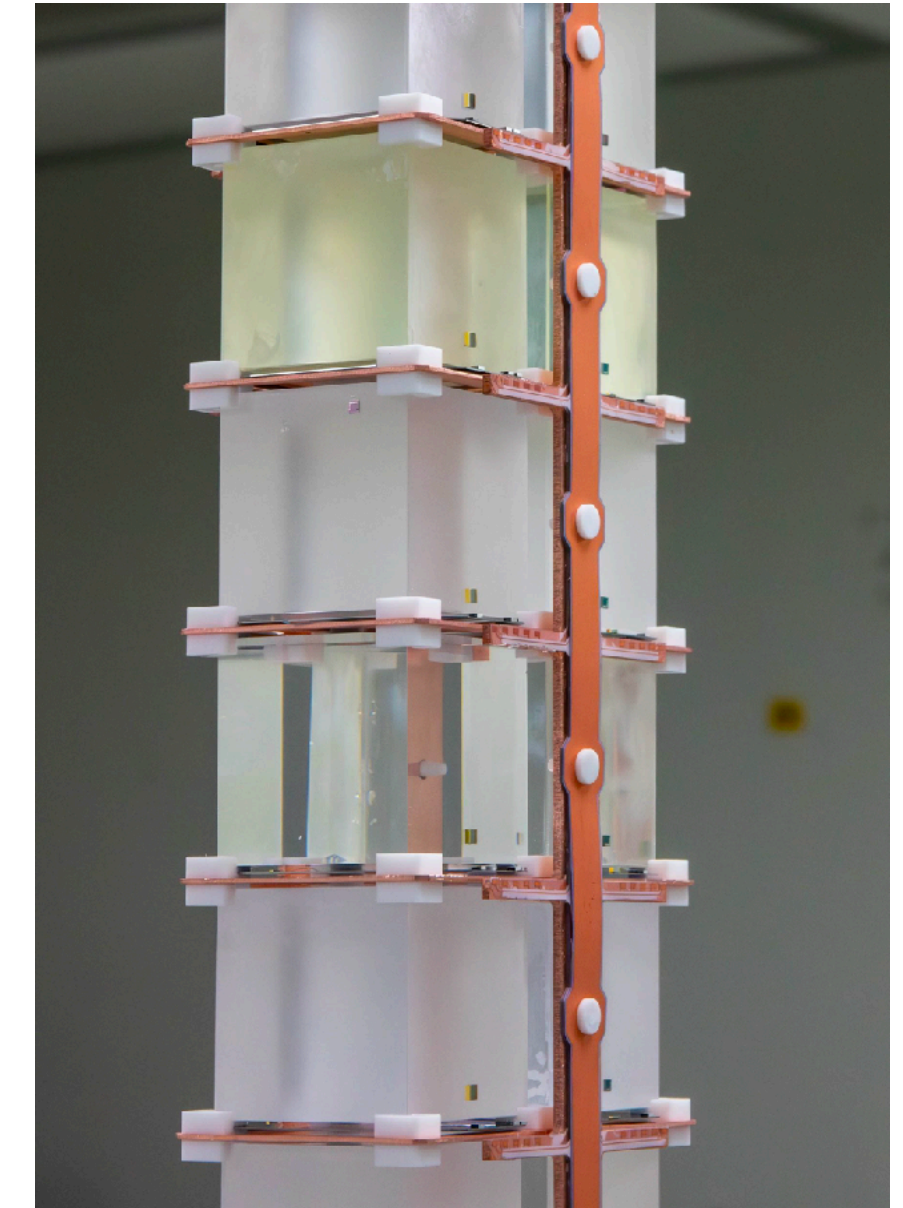
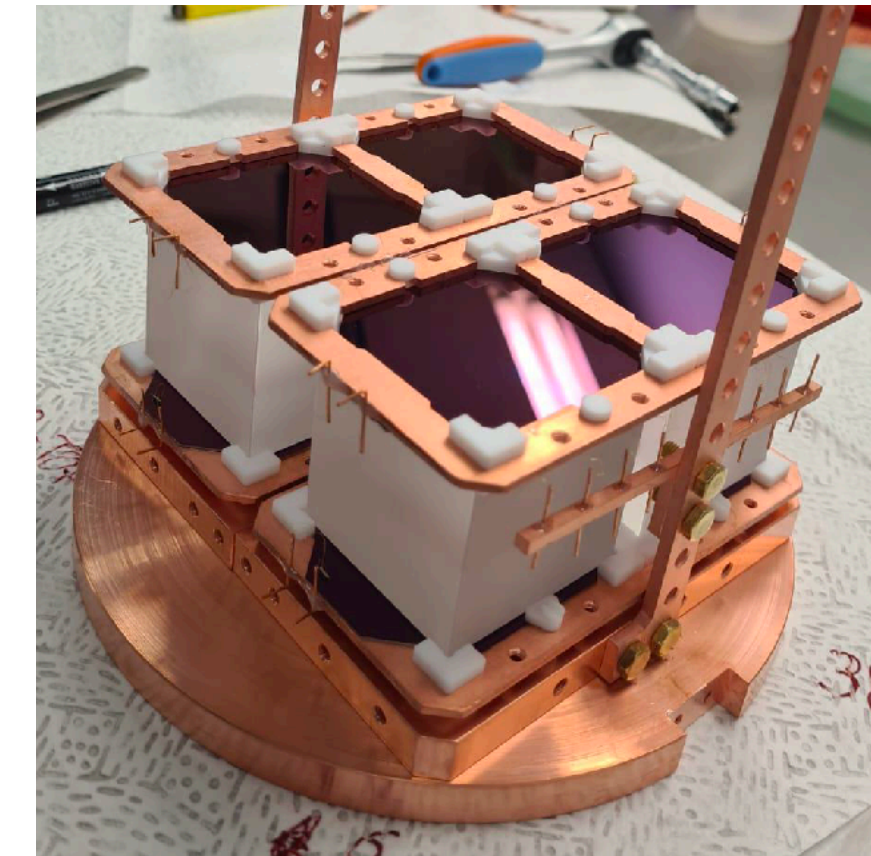
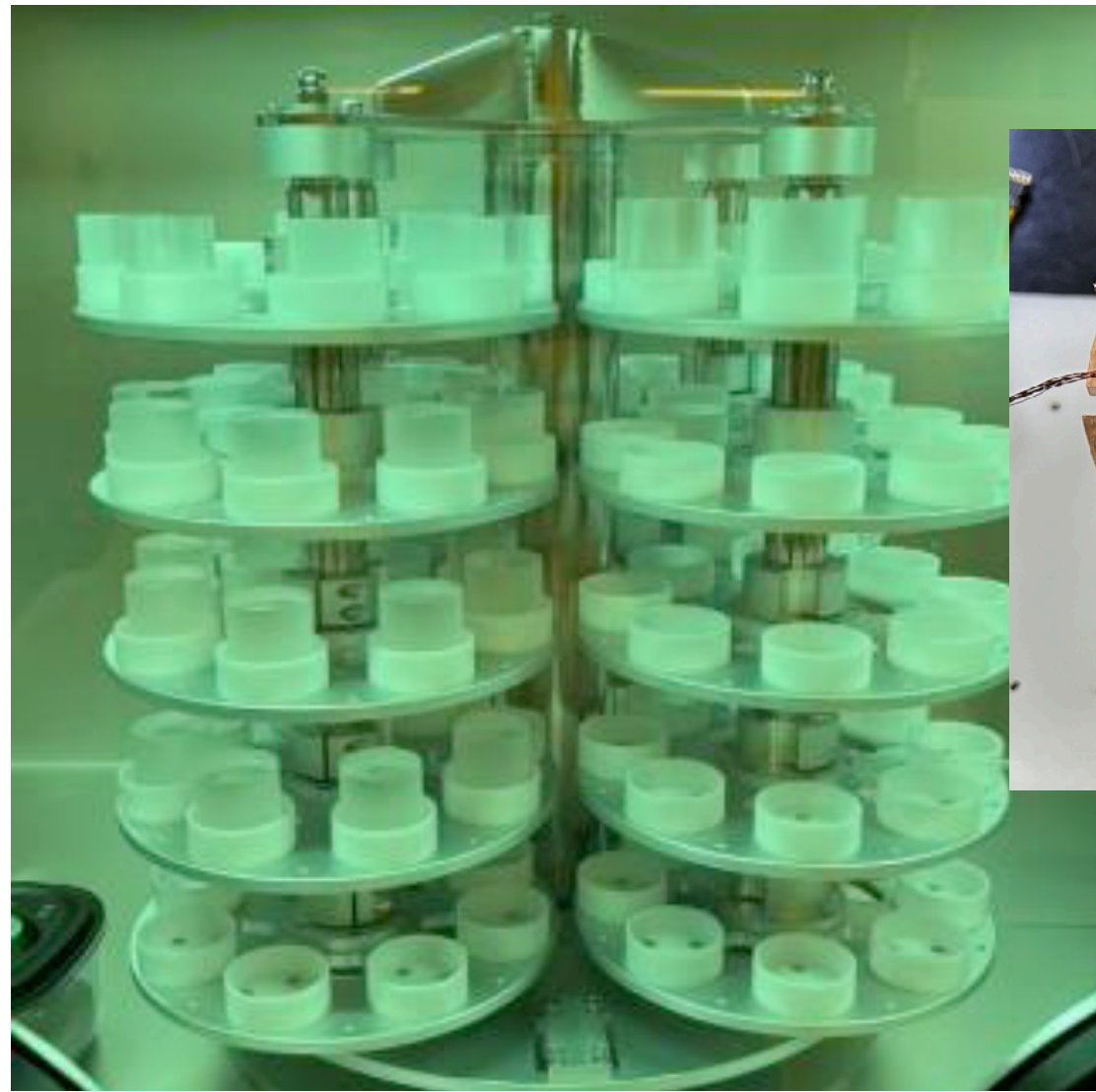




嚴峻挑戰的後面是美好的未來, at TSMC MOI 2025

Backup slides

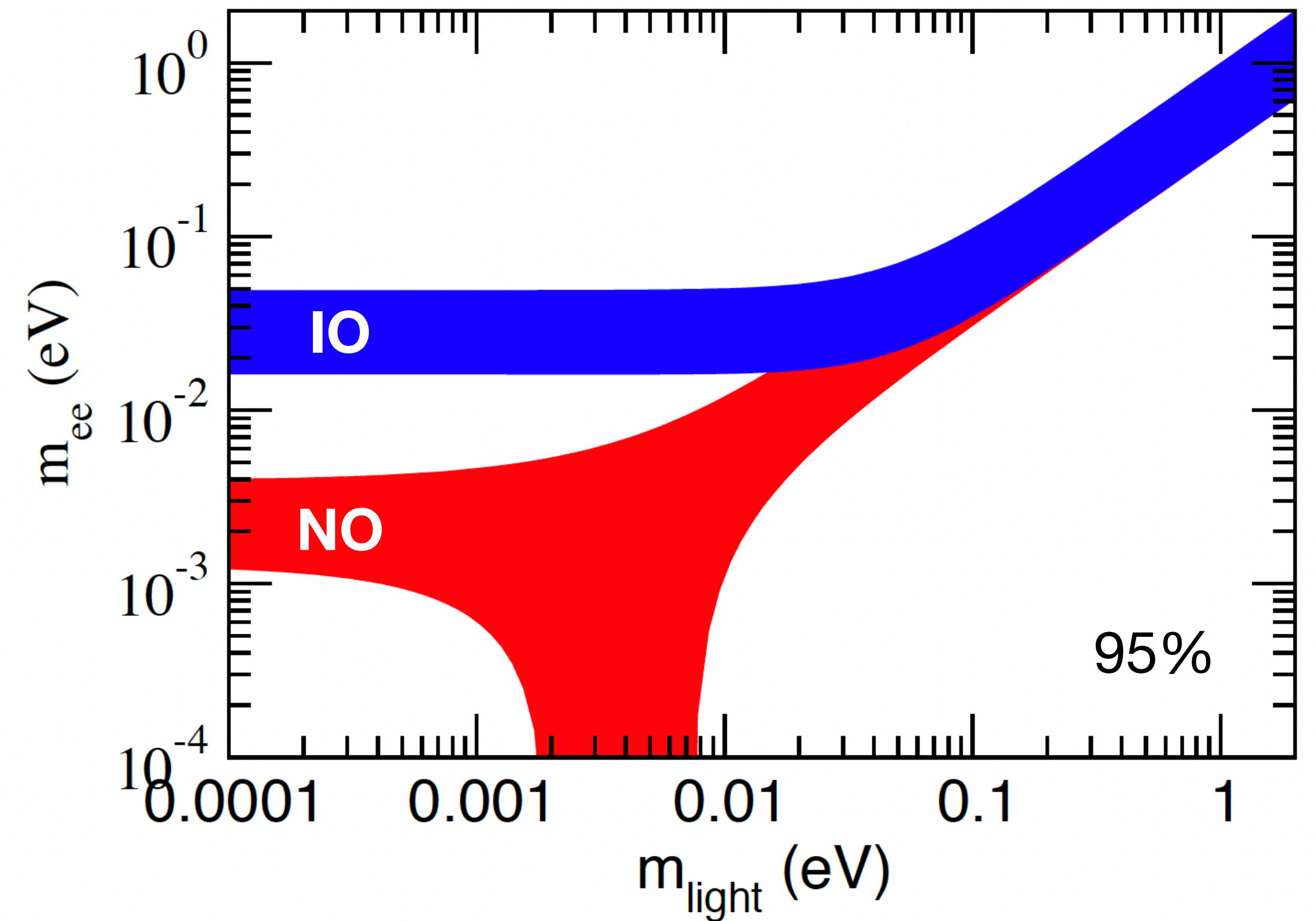
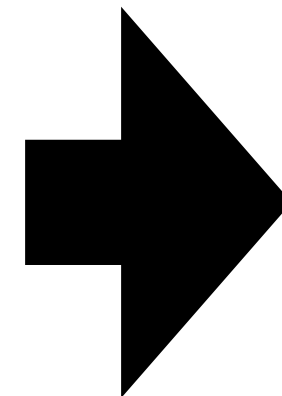
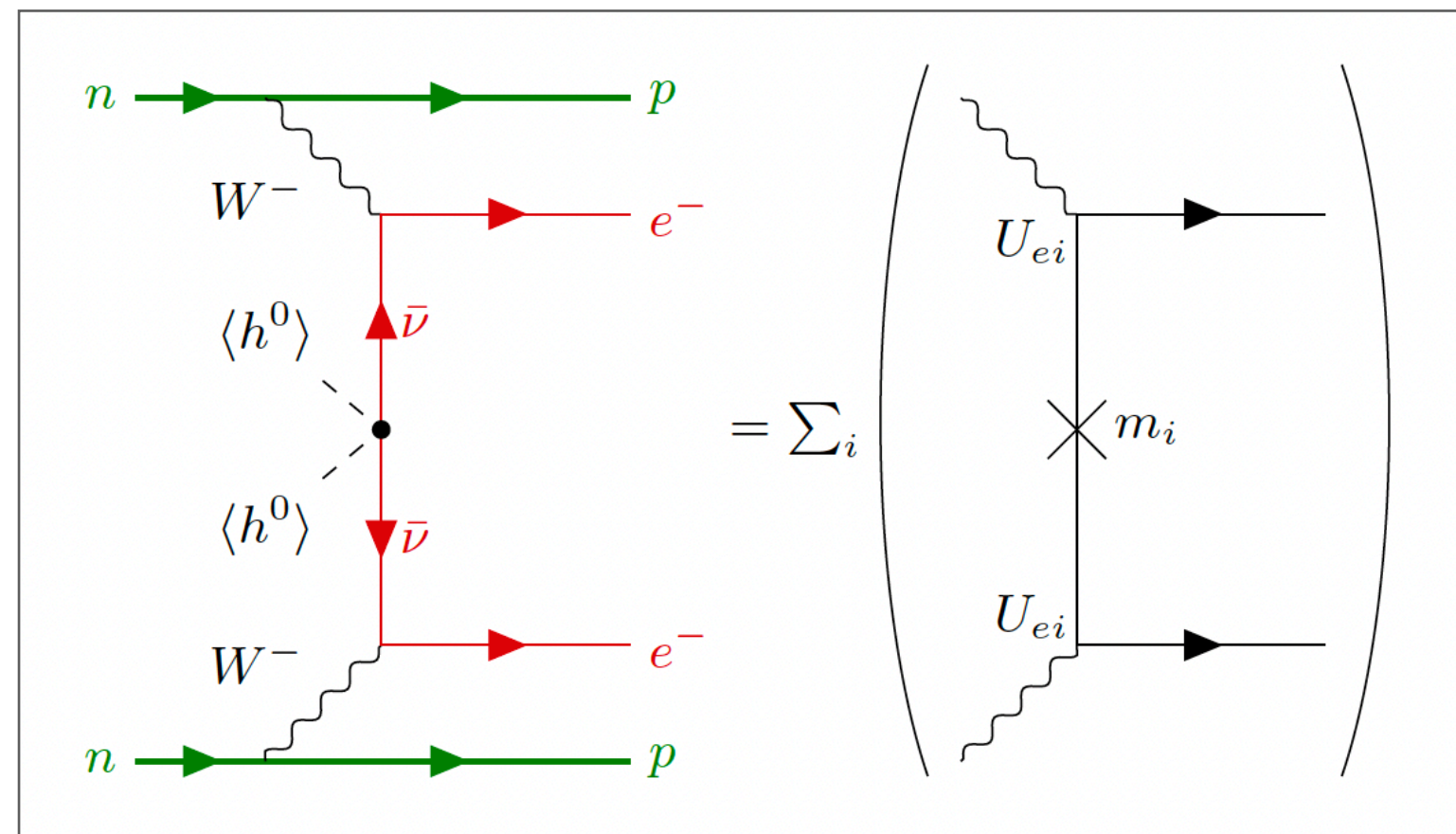
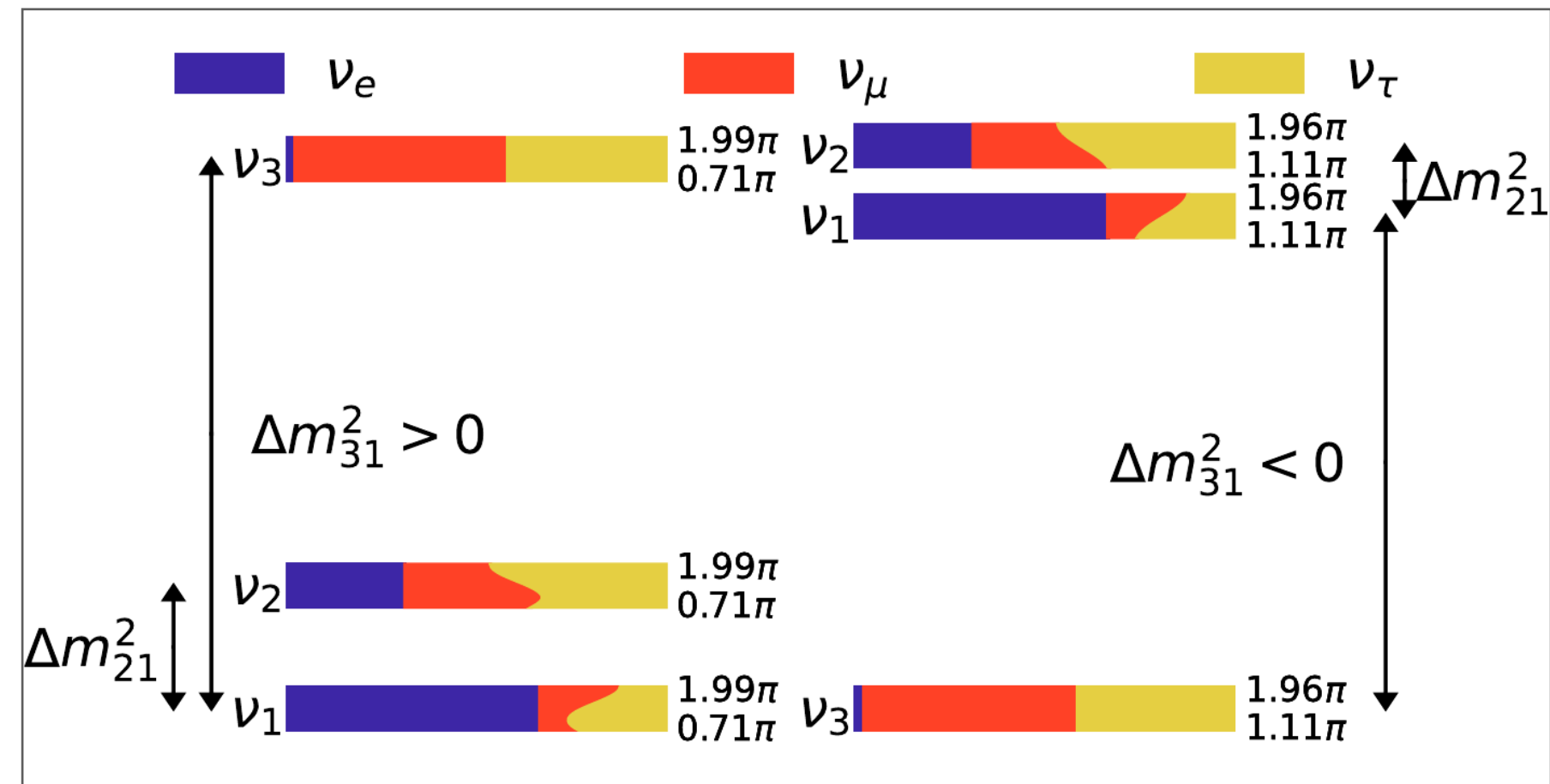
AMoRE and CUPID



- IBS-INFN Global Research Center for neutrinos and dark matter has been established, in October 2015.

Physics of $0\nu\beta\beta$ decay

Majorana particle, and effective Majorana mass



Search for $0\nu\beta\beta$ decay

Experimental sensitivity: function of mass·time exposure and background

- $$N_{\text{signal}} = \varepsilon N_{\text{iso}} \cdot \frac{t}{T_{1/2}^{0\nu}/\ln 2} = \frac{\varepsilon N_A a}{A} \frac{m \cdot t}{\ln 2} g_A^4 G^{0\nu} |M^{0\nu}|^2 m_{\beta\beta}^2$$

ε : detector efficiency, N_{iso} : number of isotope, t : exposure time, N_A : Avogadro number,
 a : isotopic concentration, A : atomic mass of the isotope, m : source mass

- $$N_{\text{obs}} = N_{\text{sig}} + N_{\text{bkg}}$$

- Experimental sensitivity

- Background free (zero background) case:

$$T_{1/2}^{0\nu} \sim \frac{\varepsilon N_A a}{A} m \cdot t$$

- Background becomes large:

$$T_{1/2}^{0\nu} \sim \frac{\varepsilon N_A a}{A} \sqrt{\frac{m \cdot t}{b \cdot \Delta_{\text{ROI}}}}$$

Δ_{ROI} : energy resolution at the energy range of interest (ROI),
 b : number of background events at ROI in a unit energy and mass·time exposure.

