A study of neutrinoless double electron capture of ^{40}Ca with AMoRE-I experiment

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TAUP XICHANG

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  - AMoRE phases & Results
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- Summary & Plan

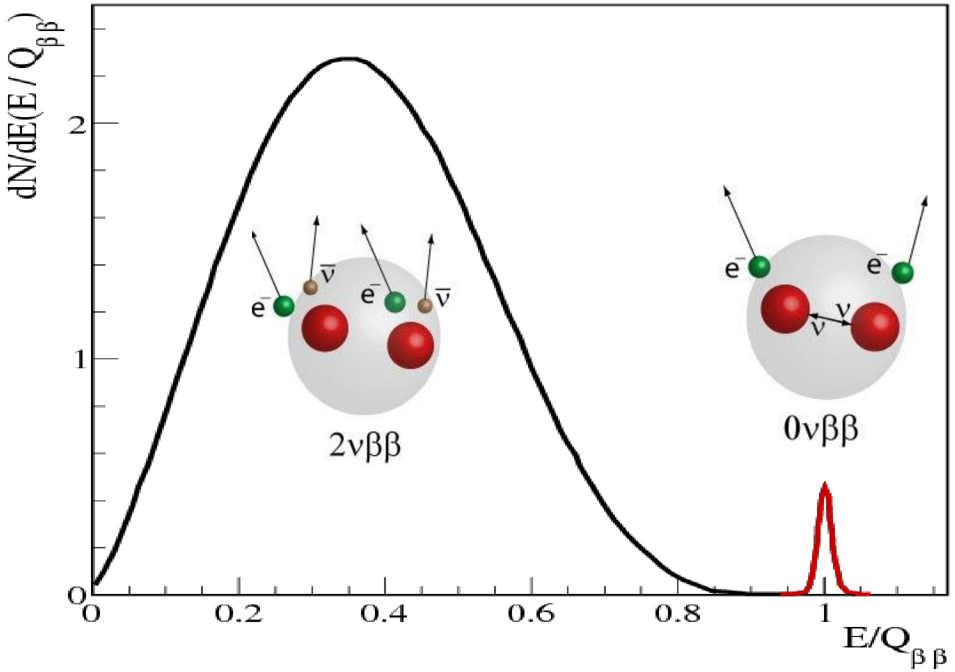
AMoRE : $0\nu\beta\beta$ search using ^{100}Mo

- ❖ Revealing unknown properties of neutrinos
  - Majorana nature of neutrinos
  - Absolute mass scale of neutrinos

- ❖ Lepton number non-conserving process
  - Beyond the standard model
  - Explanation for matter-antimatter asymmetry

^{100}Mo :

- High $Q_{\beta\beta}$ = 3034.5 keV
- High natural abundance : 9.7%
- Scintillation crystals with ^{100}Mo enrichment > 95% ---- $XMoO_4$ where X = Ca, Li_2



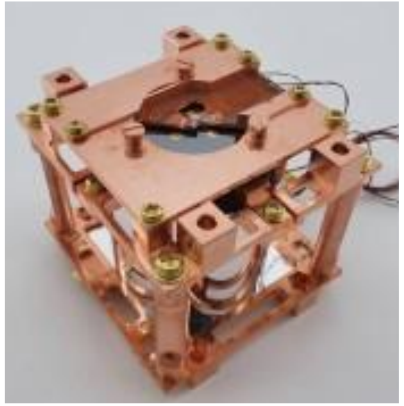
$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$$

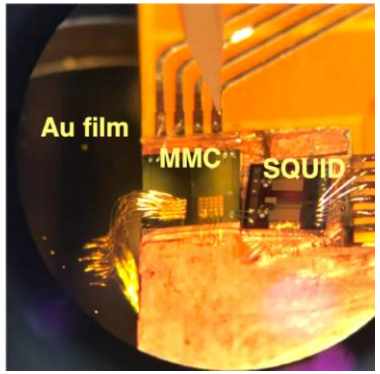
$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

AMoRE detector module

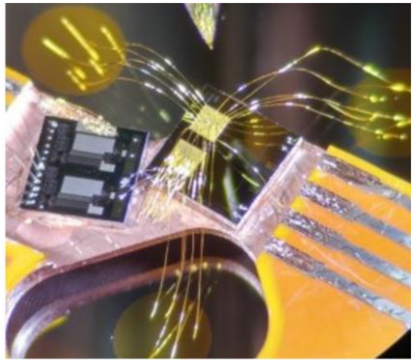
❖ Metallic magnetic calorimeter (MMC) + SQUID

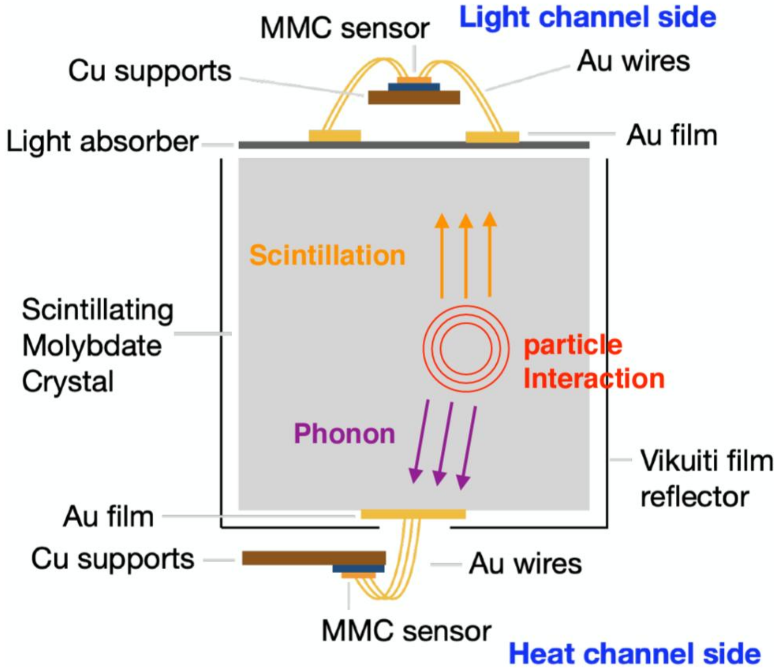
- Fast signal timing: few ms rise-time for phonon at mK
- Good energy resolution ~10 keV @2.6 MeV
- Wide dynamic range
- High linearity

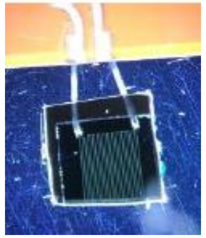


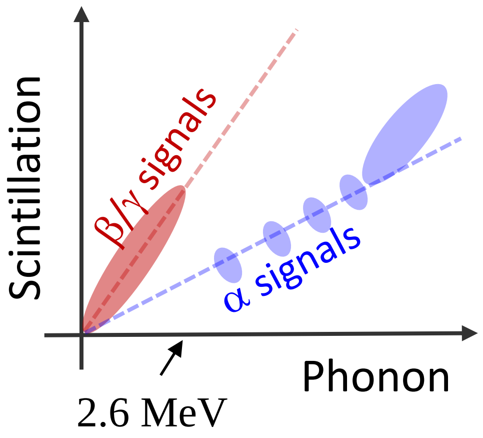


Heat channel


Light channel




Stabilization heater



AMoRE Phases

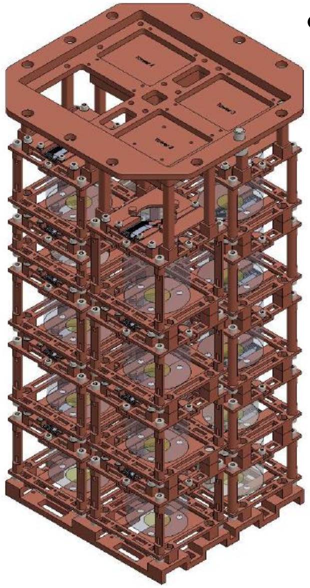
AMoRE-Pilot (2015-2018)	AMoRE-I (2020-2023)	AMoRE-II

AMoRE-Pilot (2015-2018)

- 6 $^{48depl}Ca^{100}MoO_4$ (CMO)
- 1.9 (0.88) kg of CMO (^{100}Mo) Yangyang Underground Lab (Y2L, 700 m depth)
- Live exposure ~0.32 $kg_{^{100}Mo}\cdot yr$
- Background at ROI ~0.5 counts/keV/kg/year (ckky)
- $T^{0\nu}_{1/2} > 3.2 \times 10^{23}$ year (90% C.L.)

Astropart. Phys. 162 102991 (2024)
EPJC 79:791 (2019)

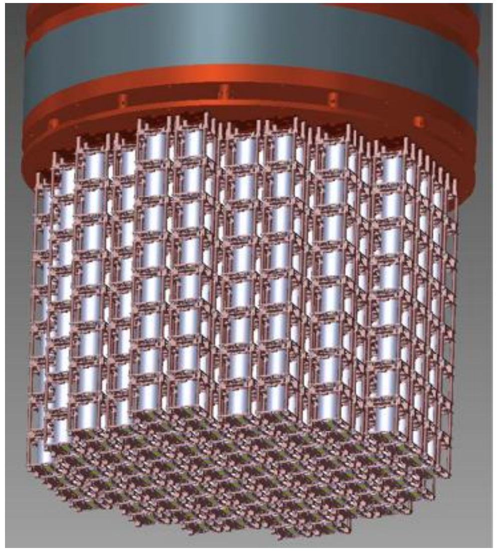
AMoRE-I (2020-2023)



- 13 CMOs + 5 $Li_2{}^{100}MoO_4$
- 6.2 (3.0) kg of CMO + LMO (^{100}Mo), Y2L
- Live exposure:
  - ~4 $kg_{^{100}Mo}\cdot yr$
- Background at ROI ~0.025 ckky
- $T^{0\nu}_{1/2} > 2.9 \times 10^{24}$ year (90% C.L.)
- World's best limit for $0\nu\beta\beta$ of ^{100}Mo

PRL 134 082501 (2025)

AMoRE-II



- 85 kg of ^{100}Mo
- Yemilab, 1000 m depth
- Exposure > 500 $kg_{^{100}Mo}\cdot yr$
- $T^{0\nu}_{1/2} > 4.5 \times 10^{26}$ year

SeungCheon's talk, Monday

Neutrino-less double electron capture ($0\nu2\mathrm{EC}$)

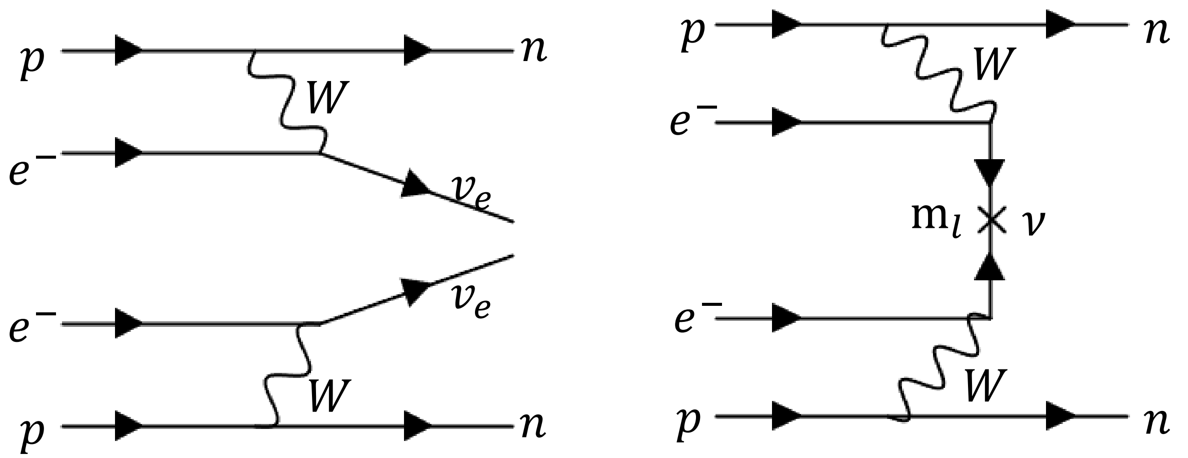
- **Double electron capture** (**2EC**) : rare decay where a nucleus (A, Z) captures two electrons from the inner atomic shells.

- Two modes of the decay: $\mathbf{2\nu2EC}$ & $\mathbf{0\nu2EC}$

  - $\mathbf{2\nu2EC}$: $\mathrm{e_b^-} + \mathrm{e_b^-} + (\mathrm{A,Z}) \rightarrow (\mathrm{A, Z-2})^{**} + 2\nu_e$

  - $2\nu2\mathrm{EC}$ observed for only $^{130}\mathrm{Ba}$ [1], $^{78}\mathrm{Kr}$ [2], and $^{124}\mathrm{Xe}$ [3, 4, 5]

  - $\mathbf{0\nu2EC}$: $\mathrm{e_b^-} + \mathrm{e_b^-} + (\mathrm{A,Z}) \rightarrow (\mathrm{A, Z-2})^{**} + \gamma$
    - $^{40}\mathrm{Ca}$: $\mathrm{e_b^-} + \mathrm{e_b^-} + {}^{40}\mathrm{Ca} \rightarrow {}^{40}\mathrm{Ar} + \mathrm{Q}$ (193.51 keV)



➢ $T_{1/2}^{0\nu2\mathrm{EC}} > \mathbf{10^{21}} - \mathbf{10^{22}}$ **yr** for different experimental techniques. [6]

❑ Motivation of the study

- Understanding the Nature of Neutrino
- Lepton number violation
- Complement to $0\nu\beta\beta$

[1] A. P. Meshik *et al.*, *Phys. Rev. C* 64, 035205 (2001).
[2] Y. M. Gavrilyuk *et al.*, *Phys. Rev. C* 87, 035501 (2013).
[3] E. Aprile *et al.* [XENON Collaboration], *Nature* 568, 532–535 (2019).
[4] J. Aalbers *et al.* [LZ Collaboration], *J. Phys. G* 52, 015103 (2025).
[5] Z. Bo *et al.* [PandaX Collaboration], *arXiv*:2411.14355 [nucl-ex].
[6] K. Blaum *et al.*, *Rev. Mod. Phys.* 92, 045007 (2020).

Data analysis

- The existing AMoRE-I data was for $0\nu\beta\beta$ study of ^{100}Mo with Q-value: 3034.5 KeV

- We are focusing on the 0ν2EC of ^{40}Ca with Q-value: 193.5 keV

- We reprocessed the whole AMoRE-I data with new trigger algorithm (r-value trigger) (See talk by Wootae Kim, Tuesday, Underground Laboratories session)

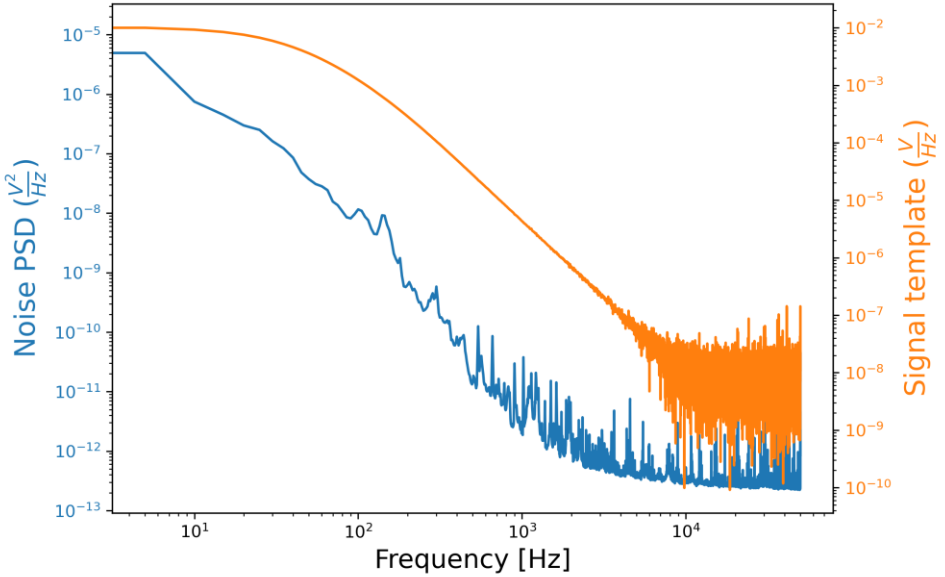
- Re-analyzed the whole data by using optimal filter and different drift correction parameter.

Amplitude estimation: Optimal filter

$$a = \frac{\sum_v S^*(v)A(v)/J(v)}{\sum_v |A(v)|^2/J(v)}$$

Assumptions :

- Signal shape is known
- Noise is stationary

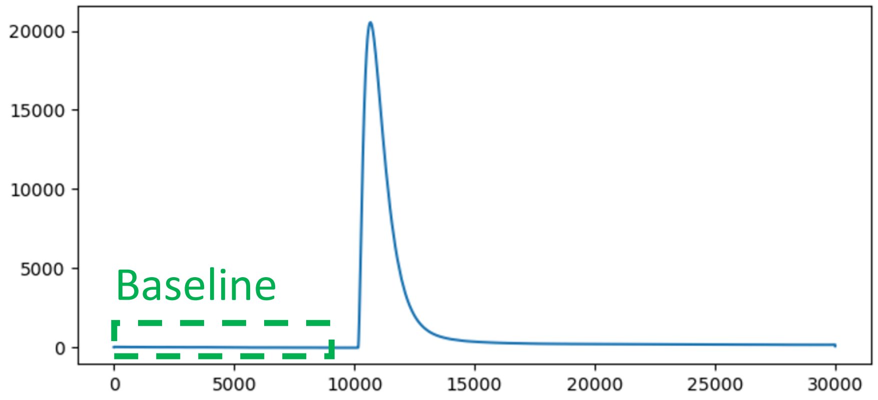


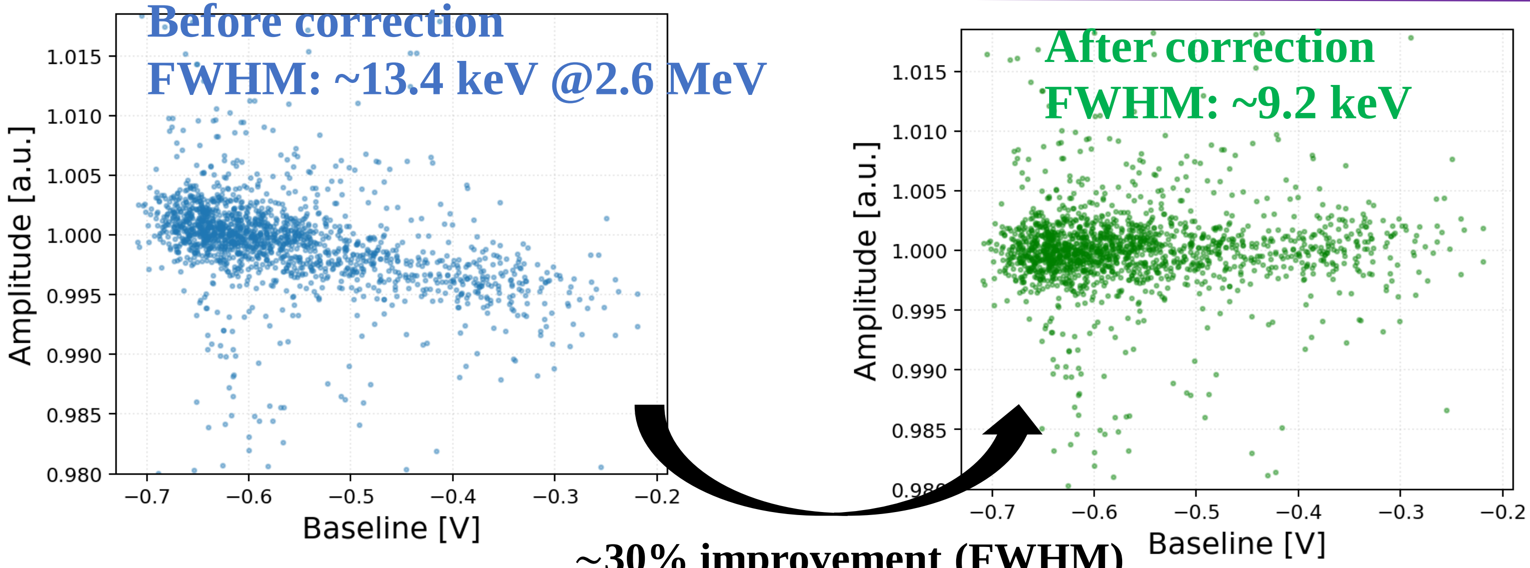
Phys. Rev. D **109**, 043035

S: event signal
A: template signal
J: noise power spectrum density

Drift correction: Baseline

Baseline => Base temperature





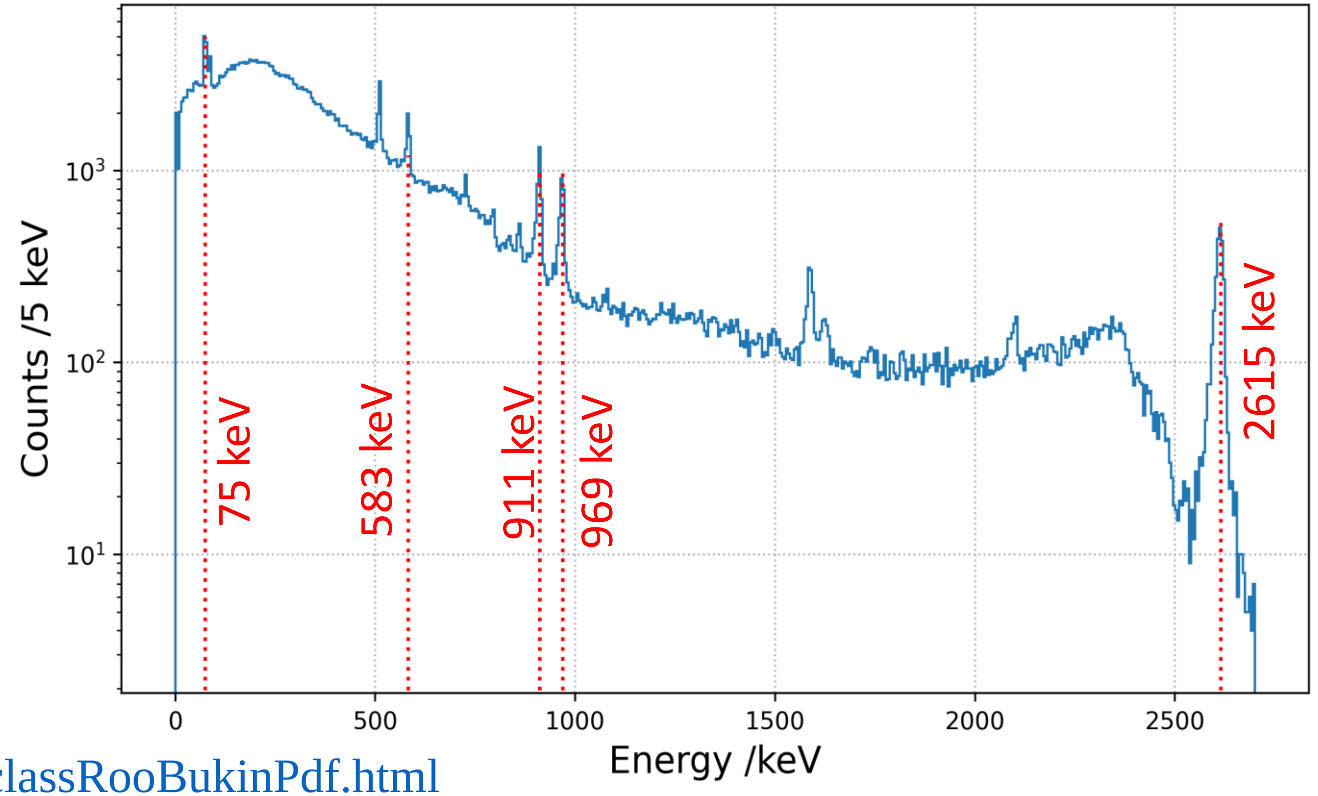
Before correction
FWHM: ~13.4 keV @2.6 MeV

After correction
FWHM: ~9.2 keV

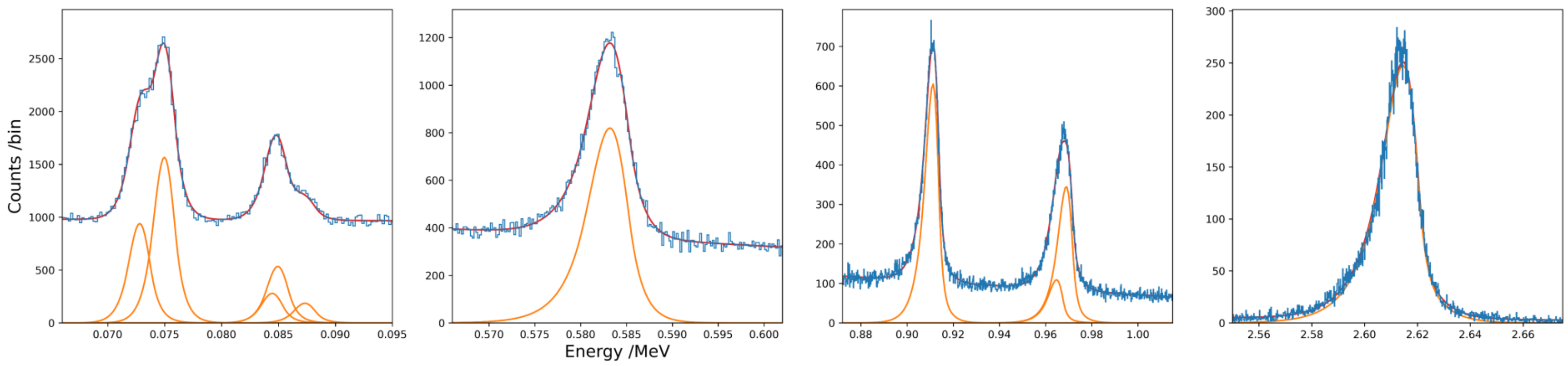
~30% improvement (FWHM)

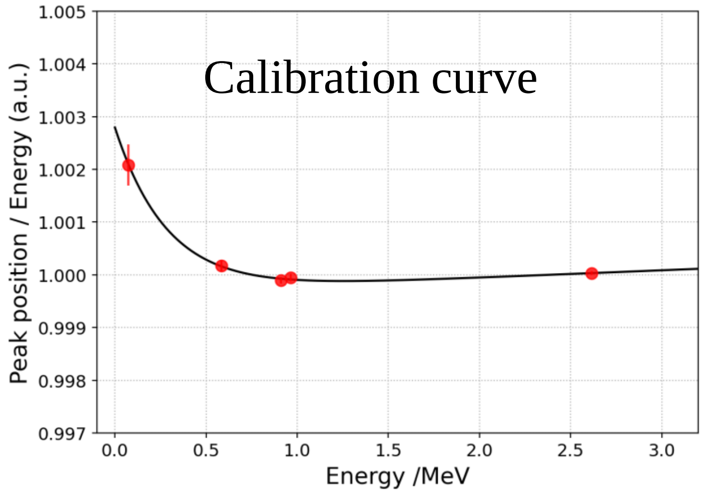
Energy calibration (Preliminary)

- Calibration source: ^{232}Th-rich welding rods
- Calibration function: Linear + exponential function
- Slight non-linearity between signal amplitude and energy.



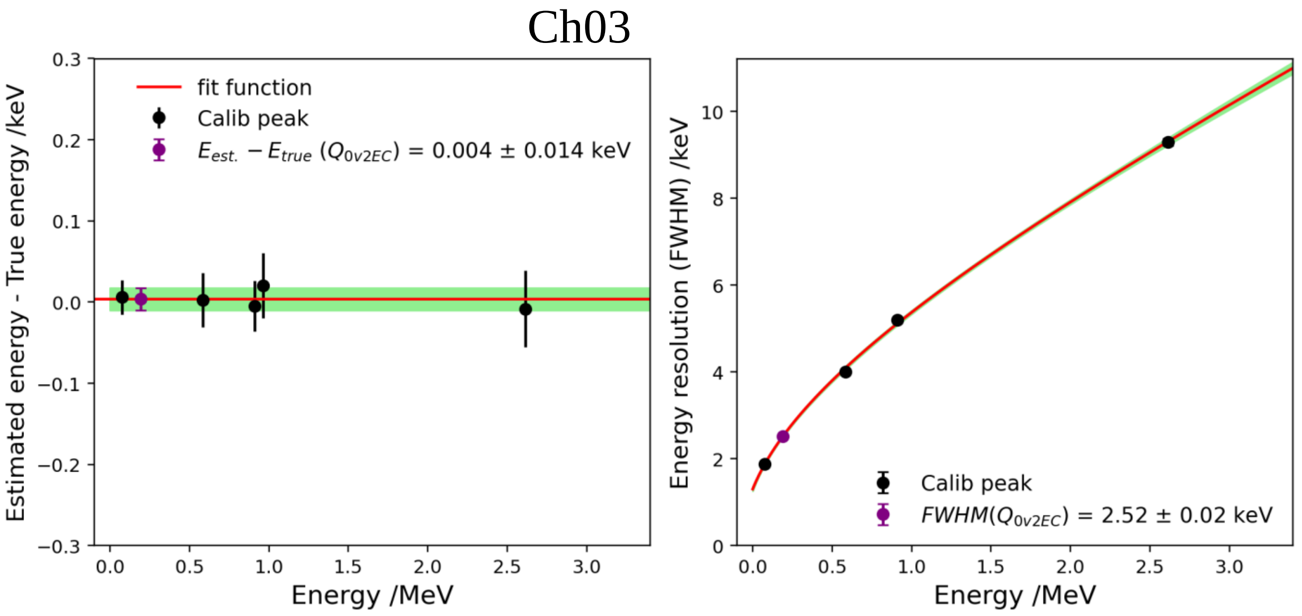
- Bukin function instead of gaussian: better fit to the asymmetry peak shape. https://root.cern.ch/doc/master/classRooBukinPdf.html



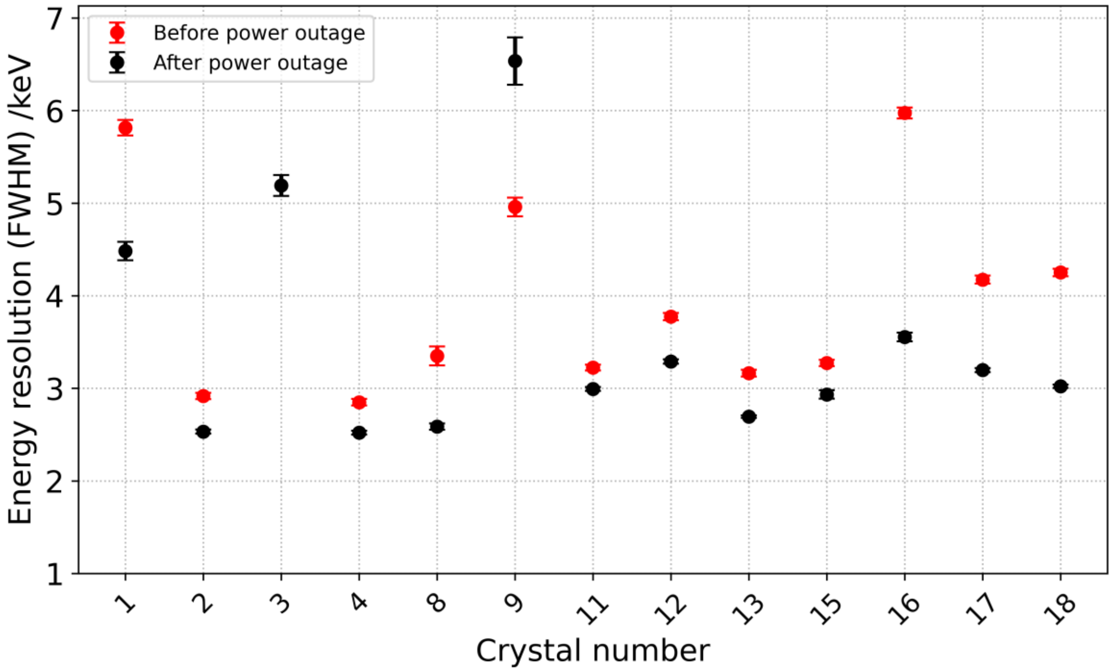


ROI estimation (Preliminary)

- Energy resolution is modeled by using:
  - $\mathrm{FWHM}(E) = (a \times E^2 + b \times E + c)^{\frac{1}{2}}$

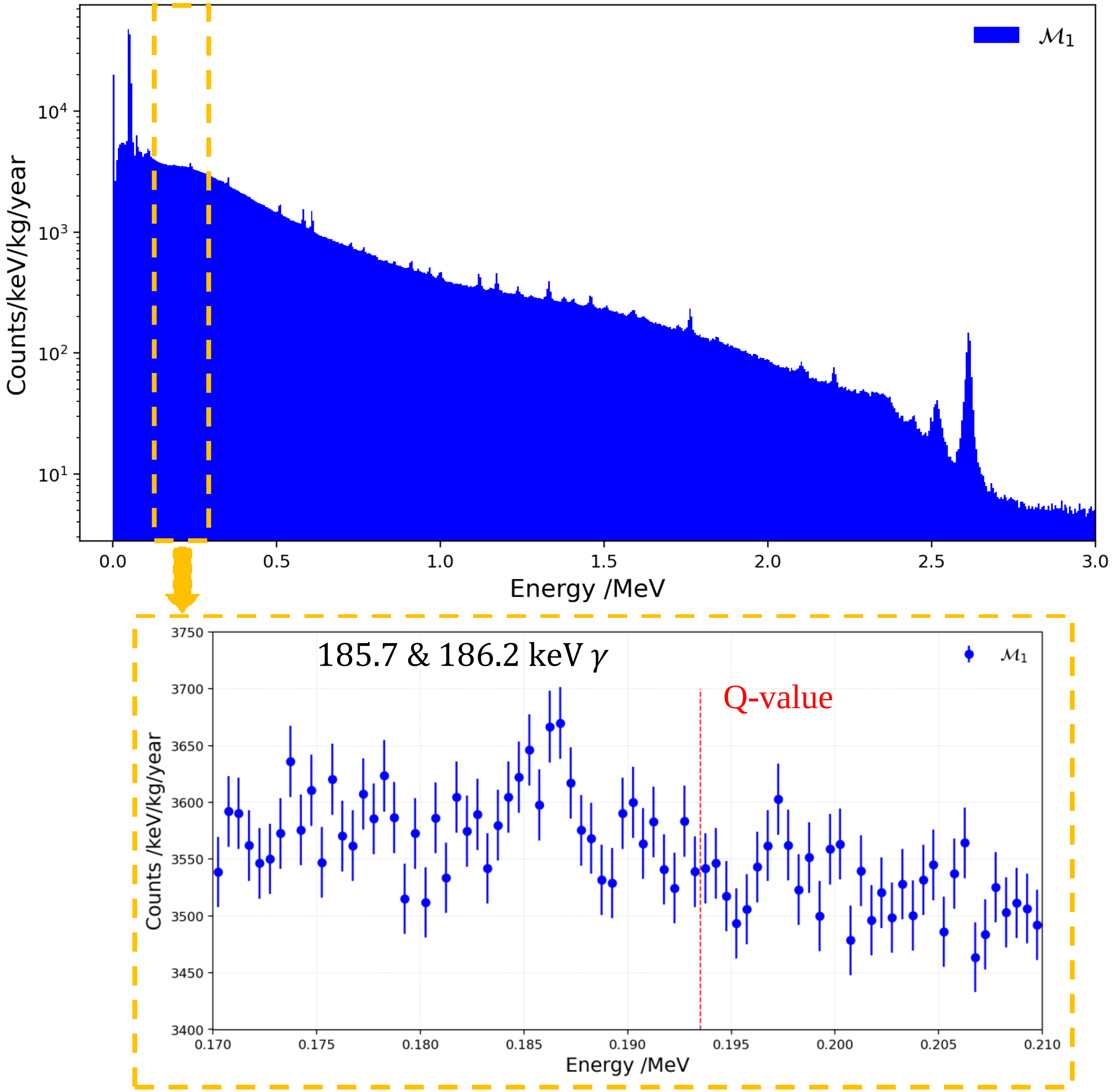


- Each crystal's data is divided into 2 groups (detector performance) :
  - Dec. 2020 – Nov. 2021 (Before power outage)
  - Jan. 2022 – May 2023 (After power outage)
- Energy resolution is improved after power outage.
- Approximately 2.5 ~ 4 keV FWHM is obtained for most of the crystal detectors.



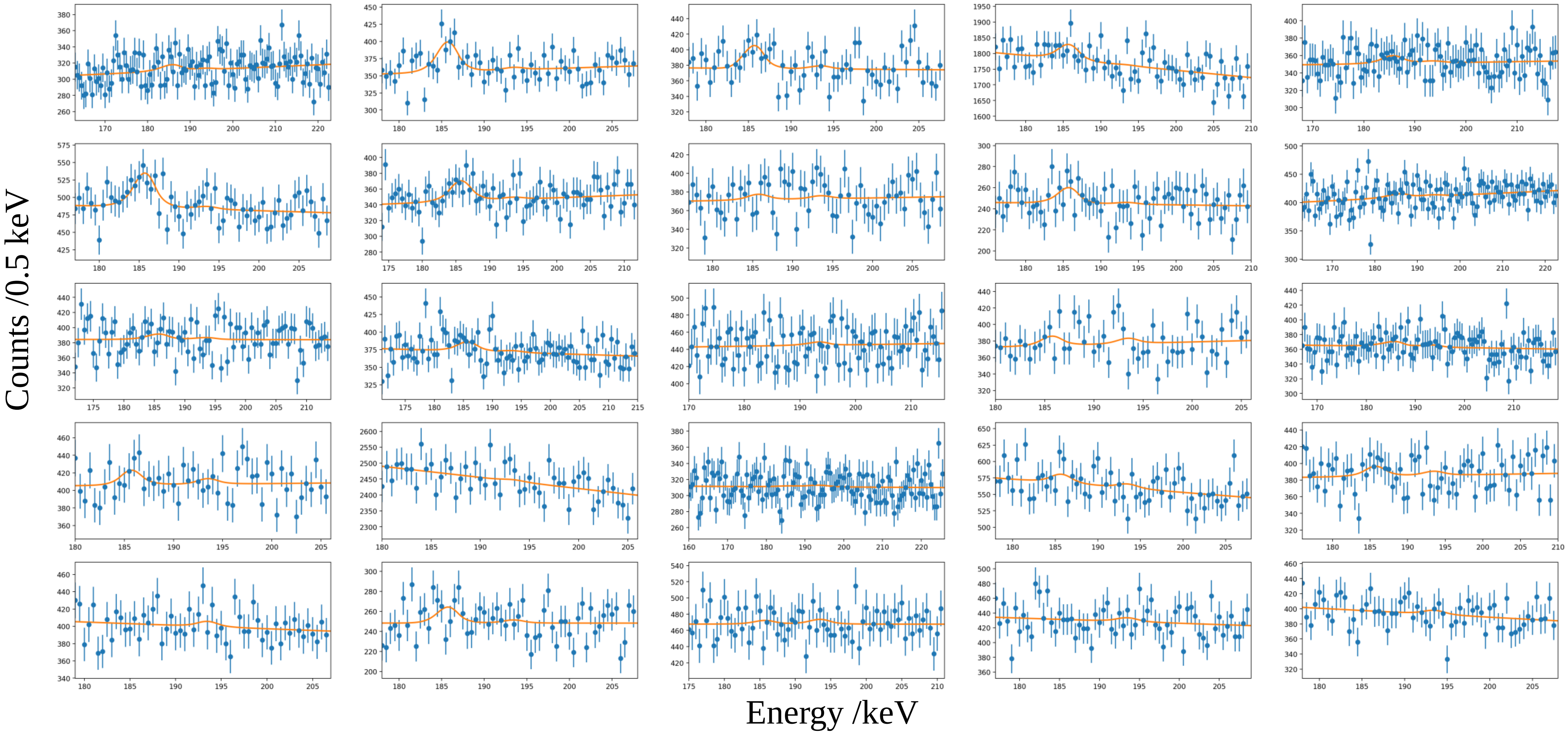
Physics spectrum (Preliminary)

- All 13 CMO crystals
  - Total exposure: 7.35 kg·yr
  - ^{40}Ca exposure: 1.40 kg·yr
- Single hit events are accepted.
- Other Background rejections such as muon veto and ^{212}Bi α tagging is not applied yet.
- Background level: ~3550 counts/keV/kg/year (ckky)



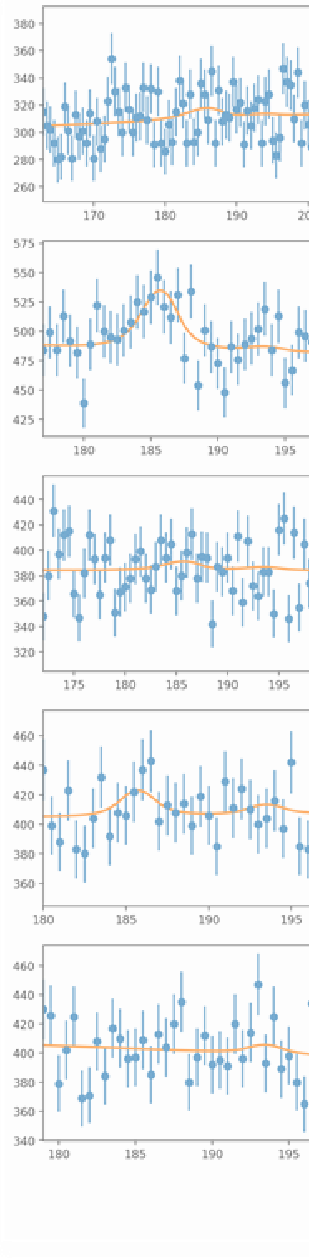
25 datasets (depending on detector performance) are fitted individually and then used for combined half life estimation

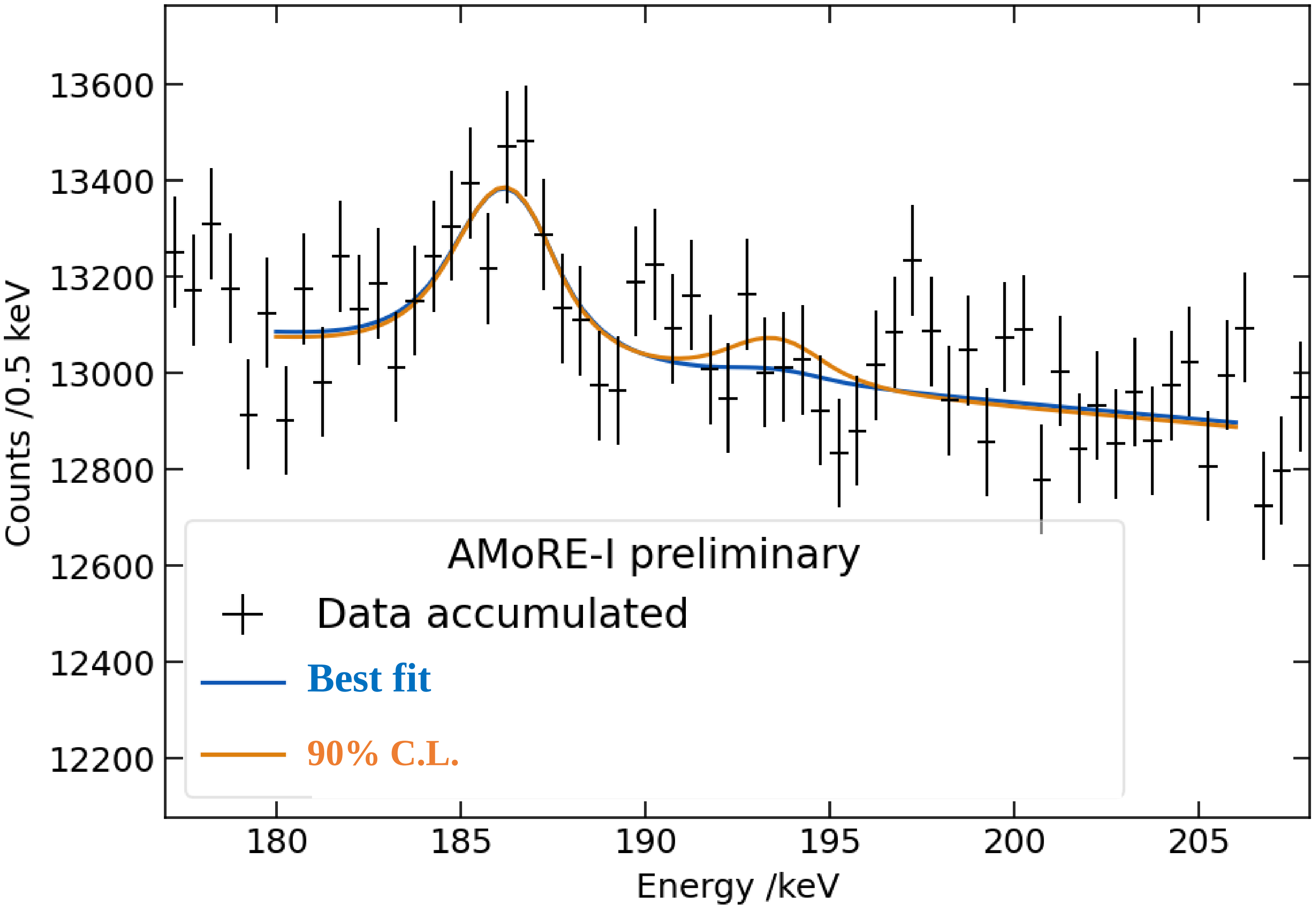
90% C.L.

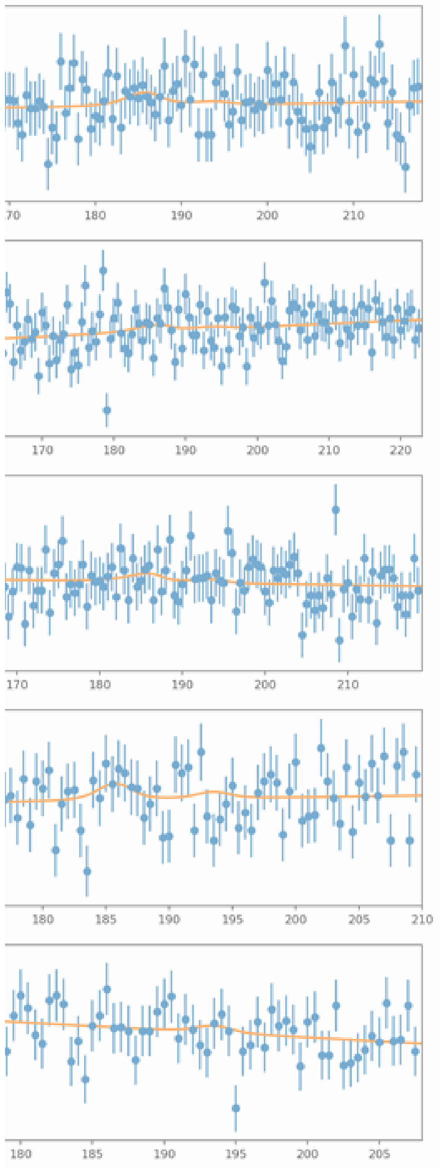


- Fitting model has 3 terms :
  - $^{40}Ca\ 0\nu 2EC$ peak
  - ~ 186 keV, γ & Linear background

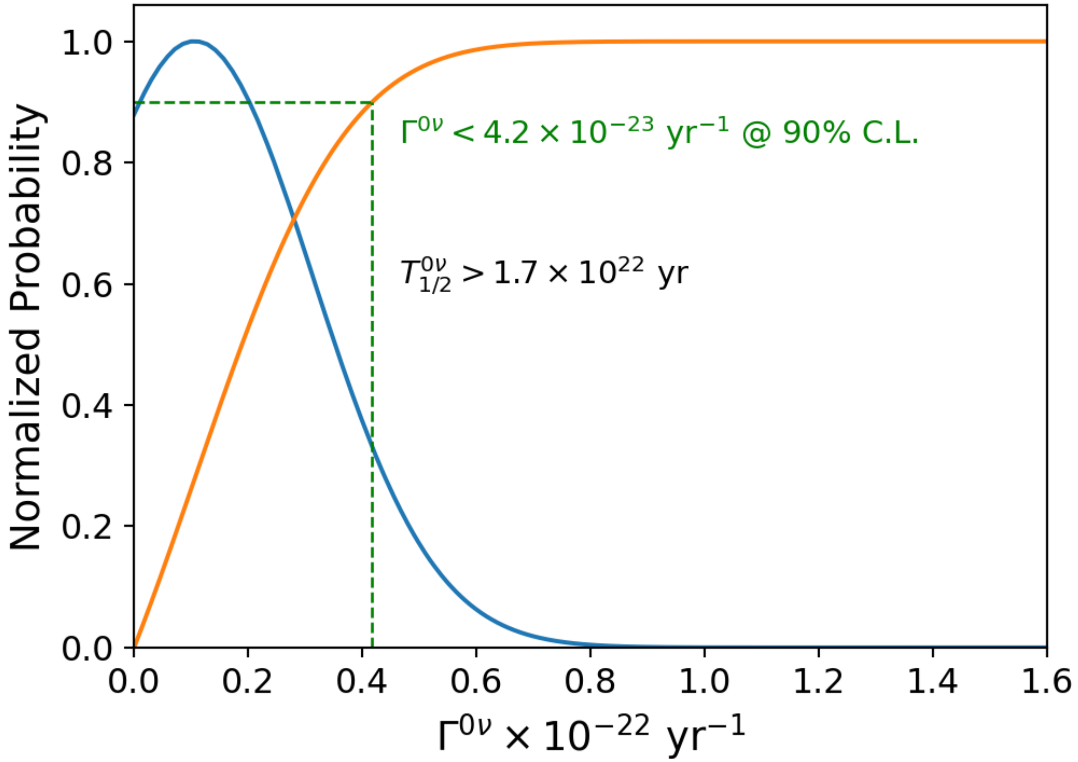
Combining whole dataset

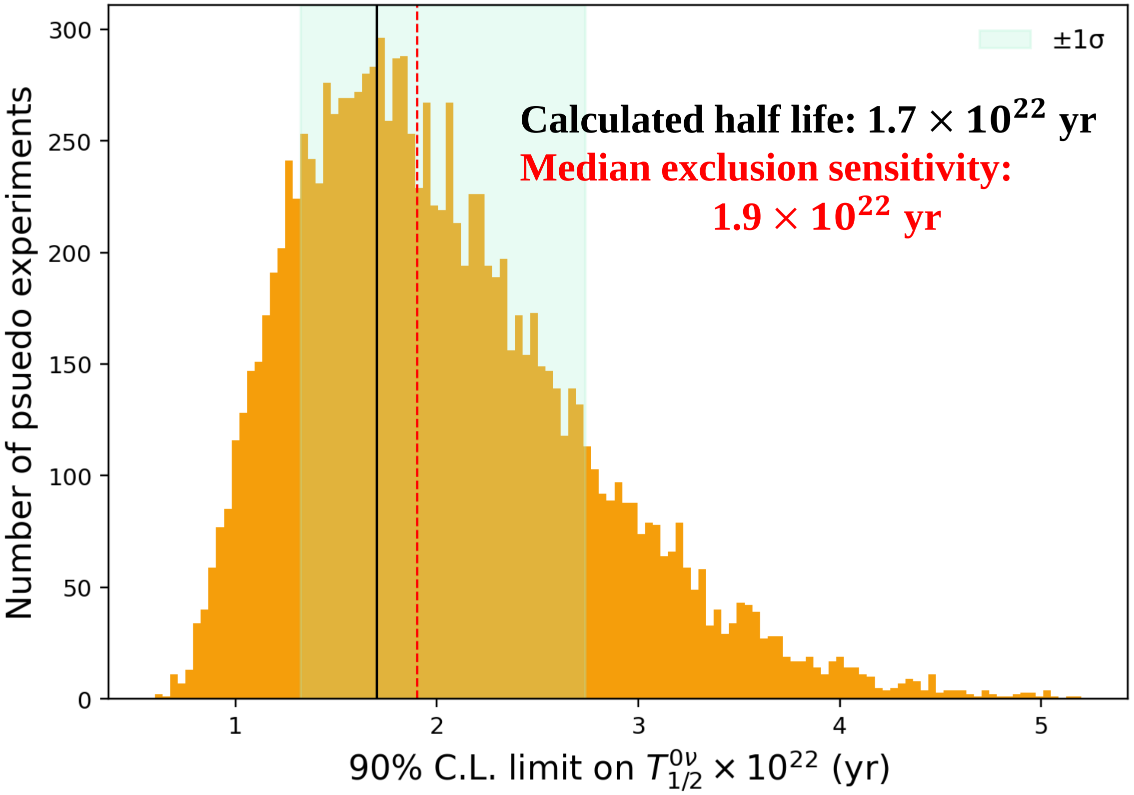






^{40}Ca 0ν2EC limit from AMoRE-I (Preliminary)





- Preparing our own Geant4 simulation tool for obtaining the detection efficiency (ε) for 0ν2EC signature.
  - For now it is taken to be 87.7% (CRESST-II)

J. Phys. G: Nucl. Part. Phys. **43** 095202

- Half life limit: $T^{0\nu}_{1/2} > 1.7 \times 10^{22}$ year at 90% C.L.

  - CRESST-II: $T^{0\nu}_{1/2} > 1.4 \times 10^{22}$ year at 90% C.L.

Summary and plan

- AMoRE-I took a data of ∼29 months
- A thorough study of $0\nu 2EC$ of ^{40}Ca is conducted
- Energy resolution: 2.5 ∼ 4 keV FWHM is obtained for most of the crystal detector at ROI
- Exposure: 7.35 kg·yr total, 1.40 kg·yr of ^{40}Ca
- Half life limit: $T^{0\nu}_{1/2} > 1.7 \times 10^{22}$ year (90% C.L)
- **Next steps:**
  - Detection efficiency for $0\nu 2EC$ signature will be obtained using Geant4 simulation
  - More event selection process with their efficiency will be implemented
- Final result after refined analysis will be reported

Thank you very much for your attention !!!

EXTRA

$$f_{\text{Bukin}}(x;\mu,\sigma,\tau,\rho_1,\rho_2) =$$

https://root.cern.ch/doc/master/classRooBukinPdf.html

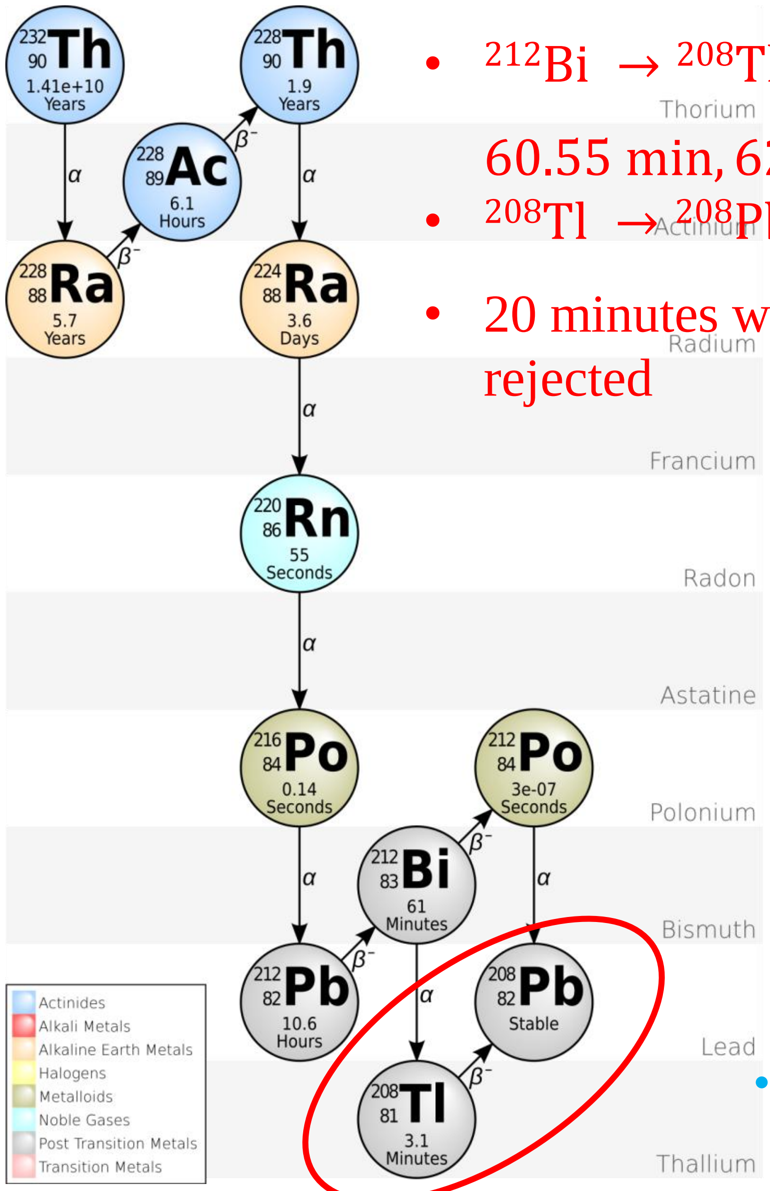
$$A\exp\begin{cases}\left[\frac{\tau\sqrt{\tau^2+1}(x-x_1)\sqrt{2\ln 2}}{\sigma(\sqrt{\tau^2+1}-\tau)^2\ln(\sqrt{\tau^2+1}+\tau)}+\rho_1\left(\frac{x-x_1}{\mu-x_1}\right)^2-\ln 2\right] & \text{if } x<x_1\\ \left[-\ln 2\left[\frac{\ln(1+\frac{2\tau\sqrt{\tau^2+1}(x-\mu)}{\sqrt{2\ln 2}\sigma})}{\ln(1+2\tau(\tau-\sqrt{\tau^2+1}))}\right]^2\right] & \text{if } x_1\le x<x_2\\ \left[-\frac{\tau\sqrt{\tau^2+1}(x-x_2)\sqrt{2\ln 2}}{\sigma(\sqrt{\tau^2+1}+\tau)^2\ln(\sqrt{\tau^2+1}+\tau)}+\rho_2\left(\frac{x-x_2}{\mu-x_2}\right)^2-\ln 2\right] & \text{if } x\ge x_2,\end{cases} \tag{5.4}$$

as

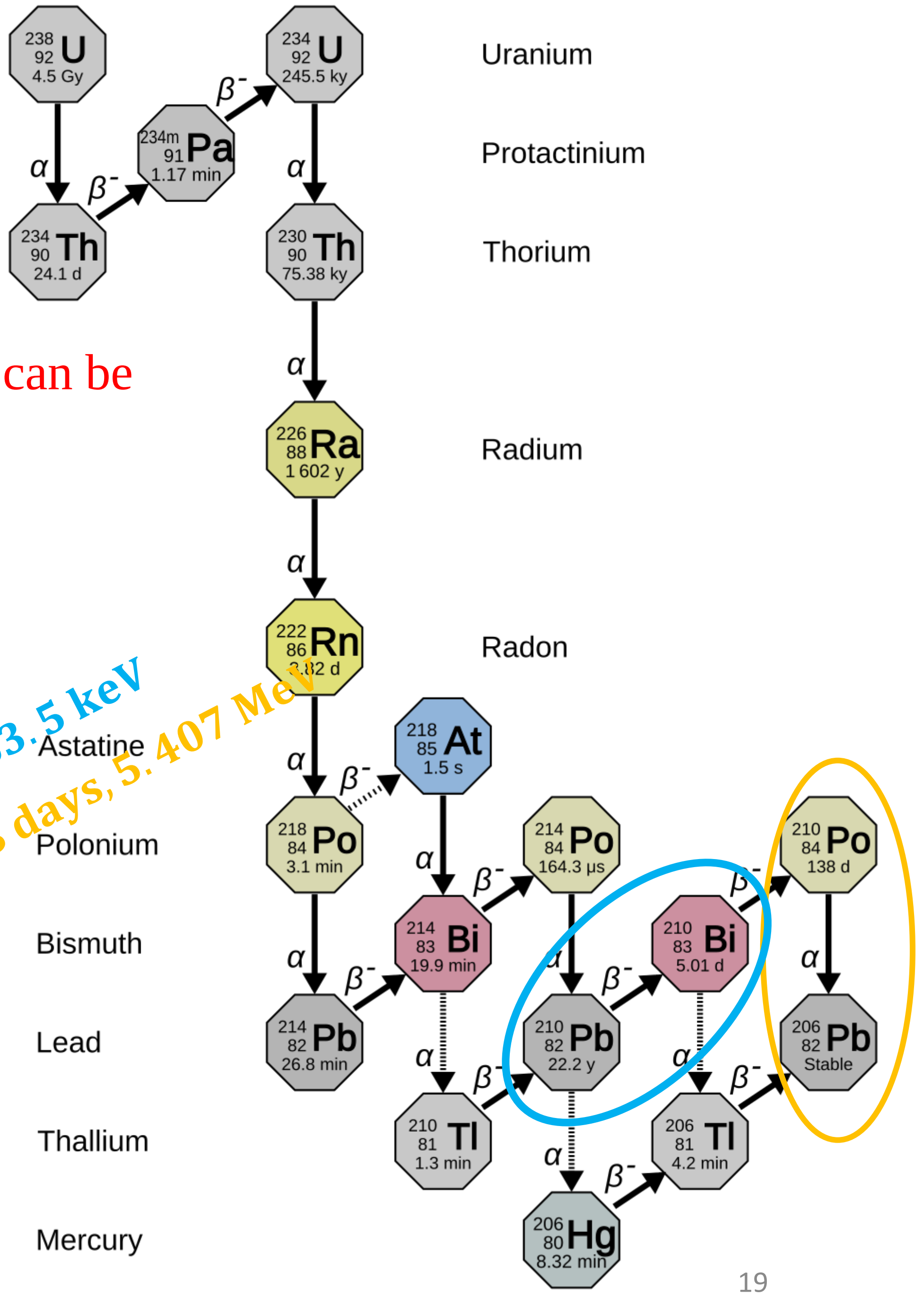
$$x_{1,2}=\mu+\sigma\sqrt{2\ln 2}\left(\frac{\tau}{\sqrt{\tau+1}}\mp 1\right). \tag{5.5}$$

- A: **normalization factor**, μ and σ are the **Gaussian mean** and **standard deviation**. τ, ρ_1 and ρ_2 are the unit less **shape parameters** which describes the **asymmetry of the distribution**.
- For τ **= 0** and $\rho_1 = \rho_2 = -ln2$, **Bukin function** becomes the **same as the Gaussian**.

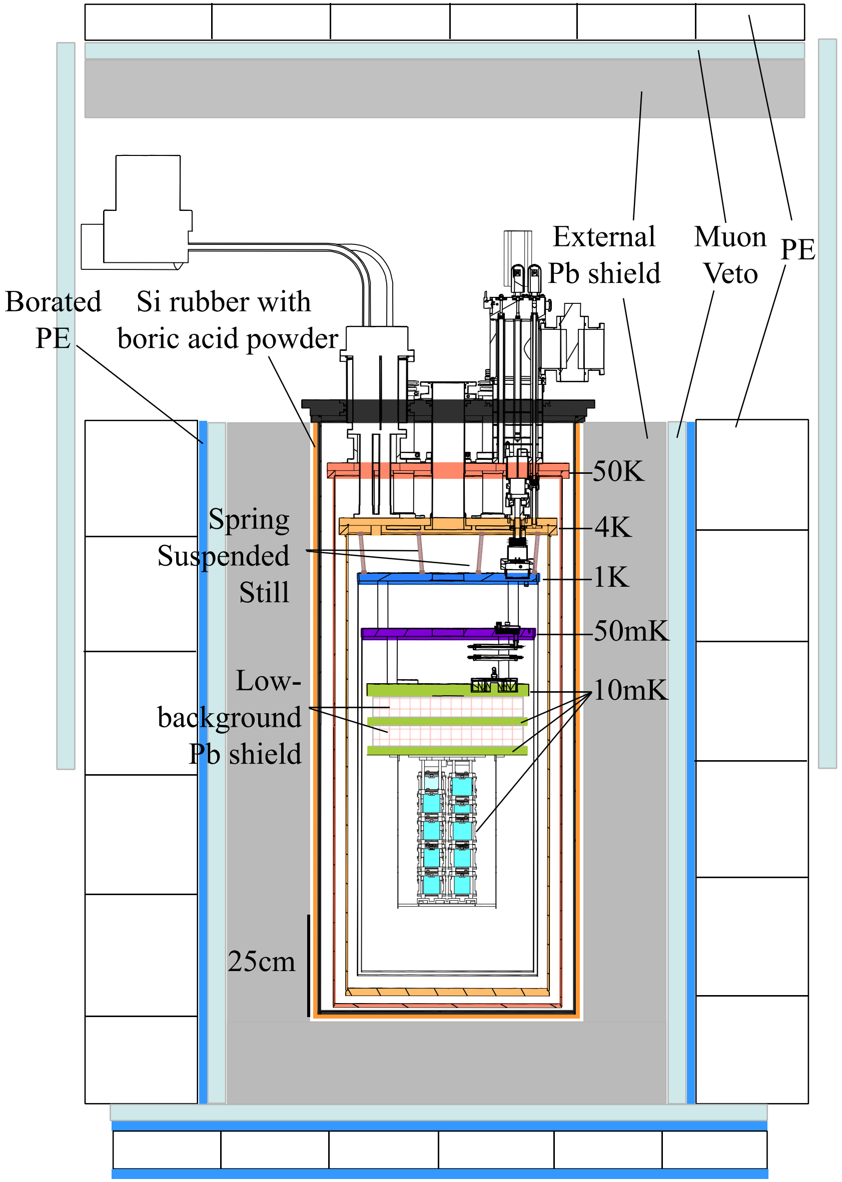
- $^{212}Bi \rightarrow ^{208}Tl$ (α 35.94%): $T_{\frac{1}{2}}$ = 60.55 min, 6207.26 keV
- $^{208}Tl \rightarrow ^{208}Pb$: $T_{\frac{1}{2}}$ = 3.053 min, Q~ 5 MeV.
- 20 minutes window after each ^{212}Bi candidates can be rejected



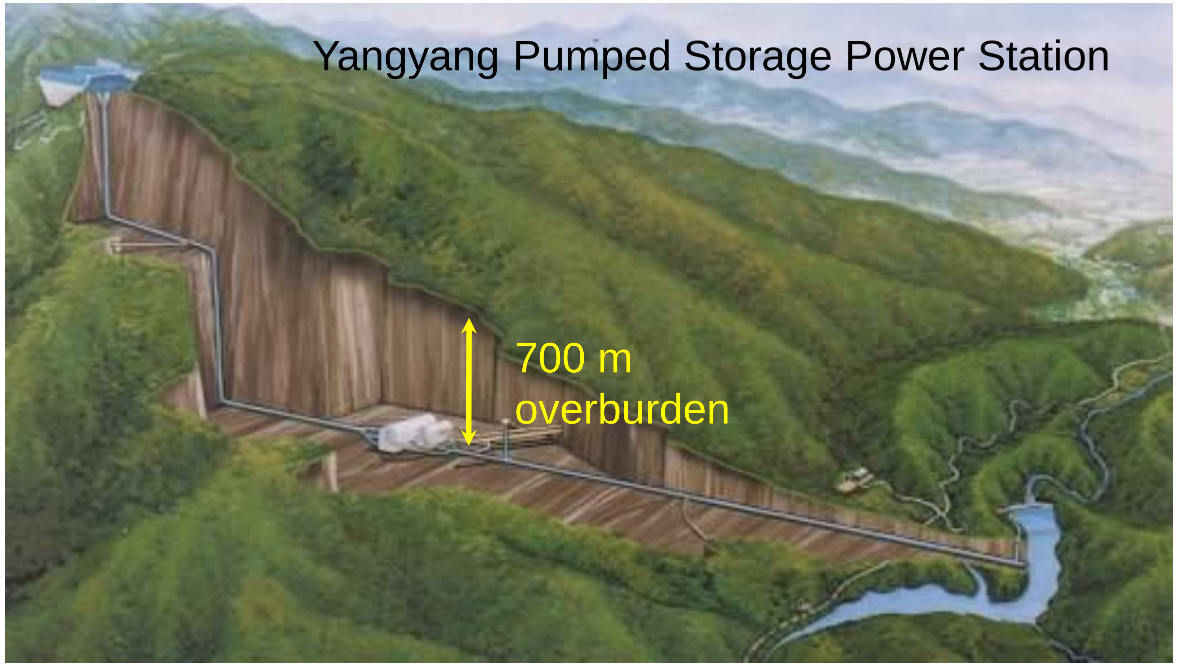
- $^{210}Pb \rightarrow ^{210}Bi$ (β, 100%), $T_{\frac{1}{2}}$: 22 yrs, 63.5 keV
- $^{210}Po \rightarrow ^{206}Pb$ (α, 100%), $T_{\frac{1}{2}}$: 138 days, 5.407 MeV



Cryostat, Shielding & Underground

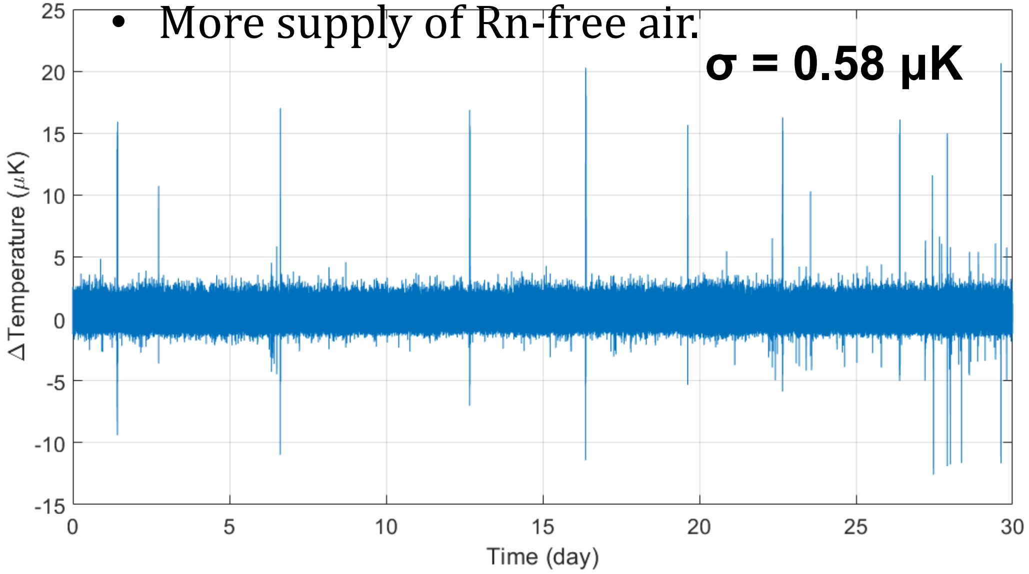


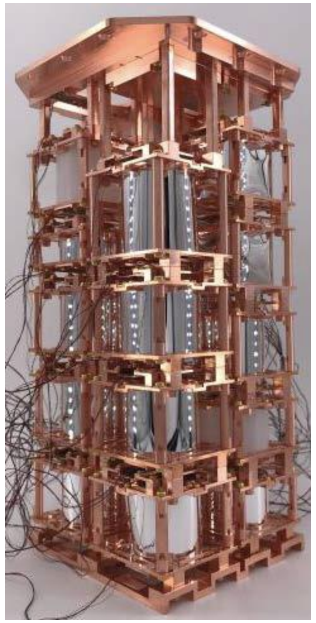
- Cryogen-free dilution refrigerator for AMoRE-pilot (2016~2018) and AMoRE-I.
- ~1 μW cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counters.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.



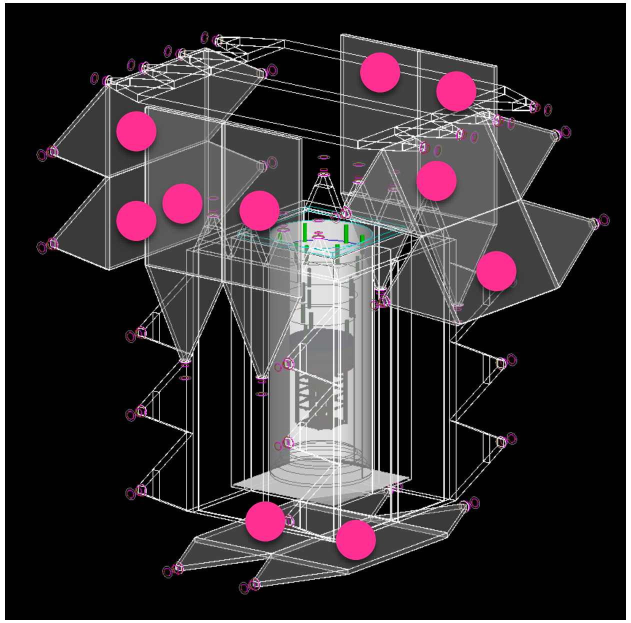
AMoRE-pilot → AMoRE-I

- 6 CMO (1.886 kg) ➔ 13 CMO (4.582 kg) + 5 LMO (1.609 kg)
  - Total crystal mass = 6.193 kg, ^{100}Mo mass = 3.0 kg
- Stabilization heater for all crystals. + 1 additional MMC for temperature regulation
- MMC sensor upgrade: Au:Er ➔ Ag:Er. (~$1/T^2$ heat capacity component associated with nuclear quadrupole moments removed)
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1$ μK.
- Shielding enhancements:
  - Outer Pb: 15 ➔ 20 cm; neutron shields: boric acid silicon + more polyethylene.
  - More muon counter coverage. (~4π)
  - More supply of Rn-free air.

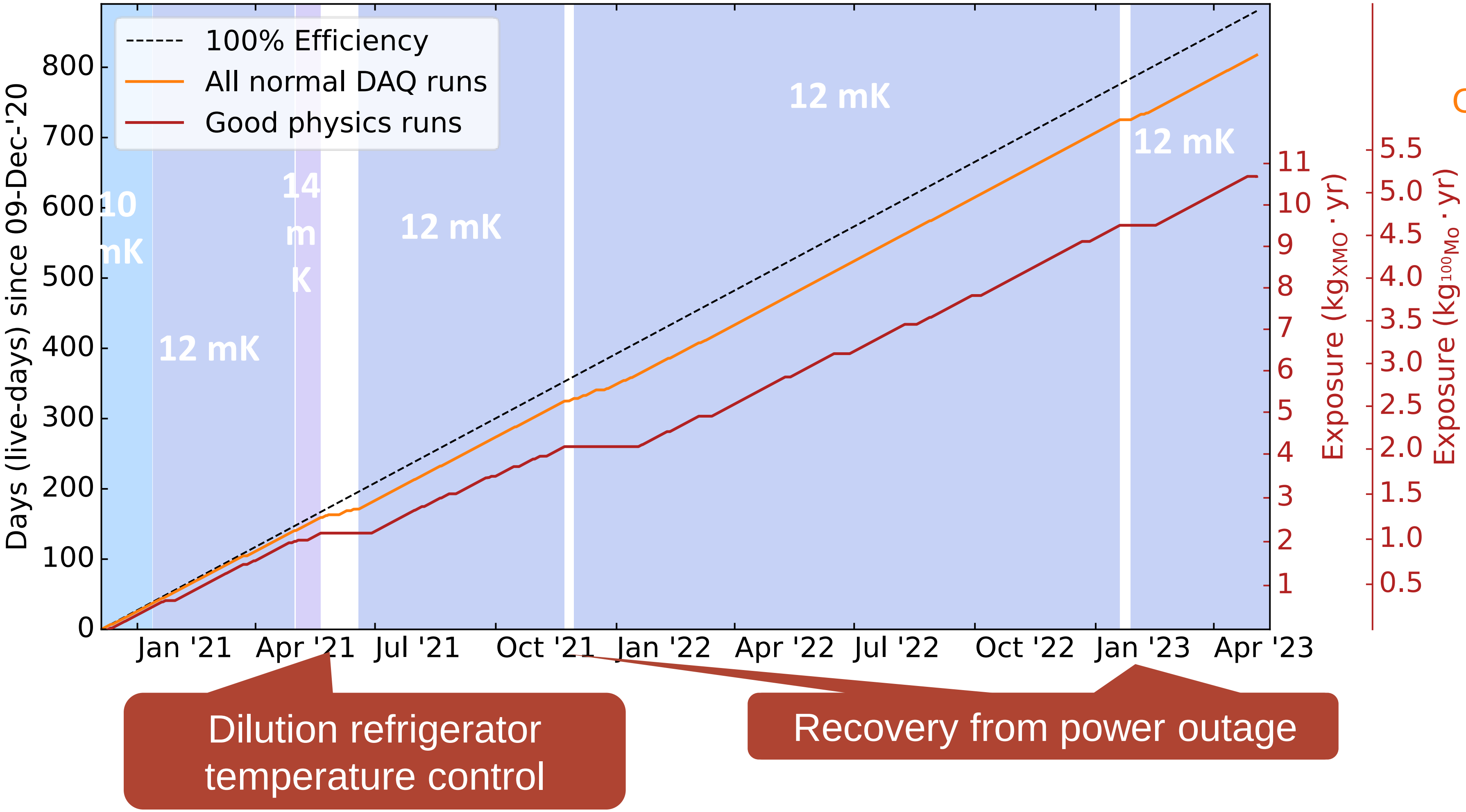


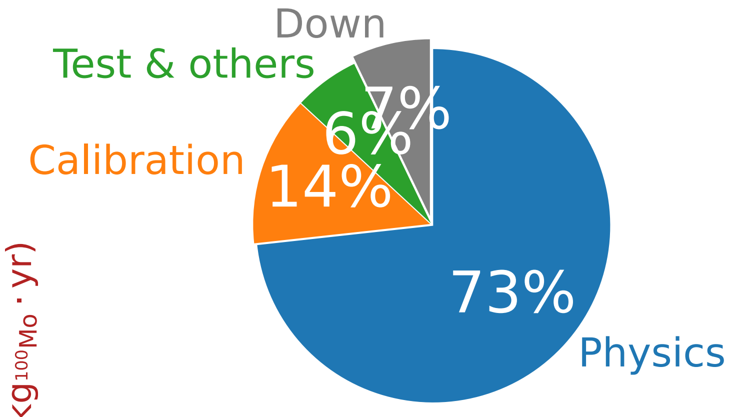


Muon counters

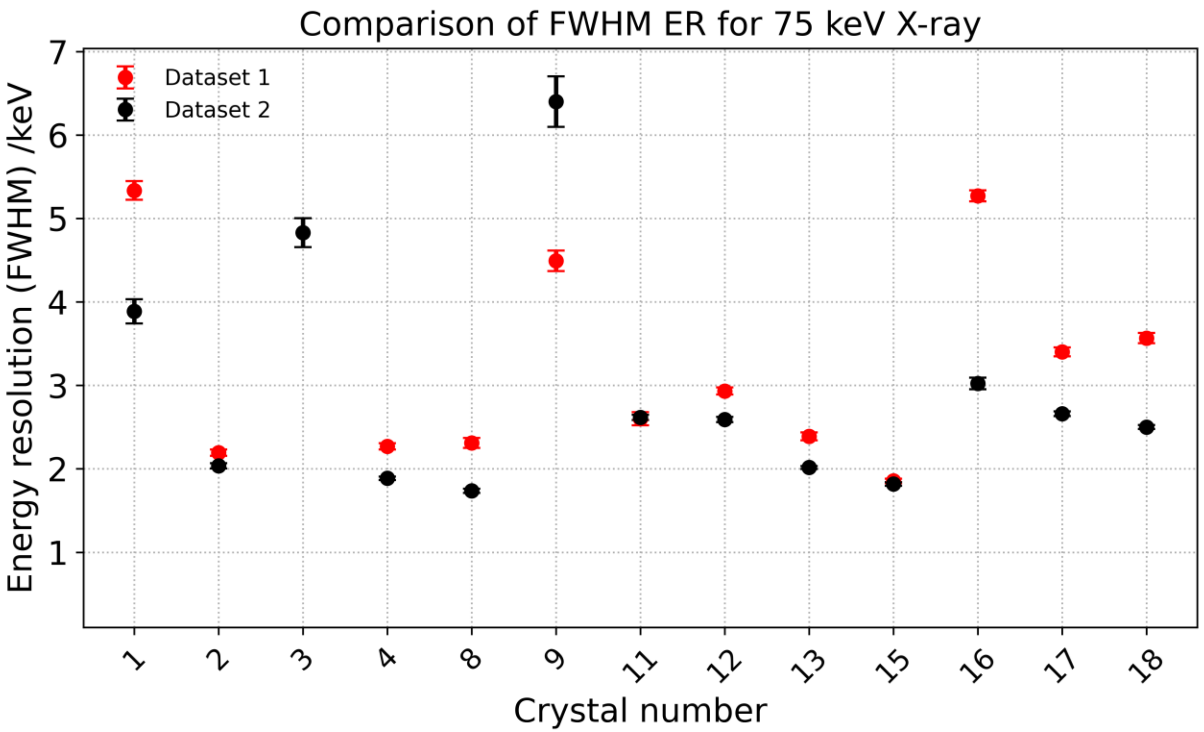


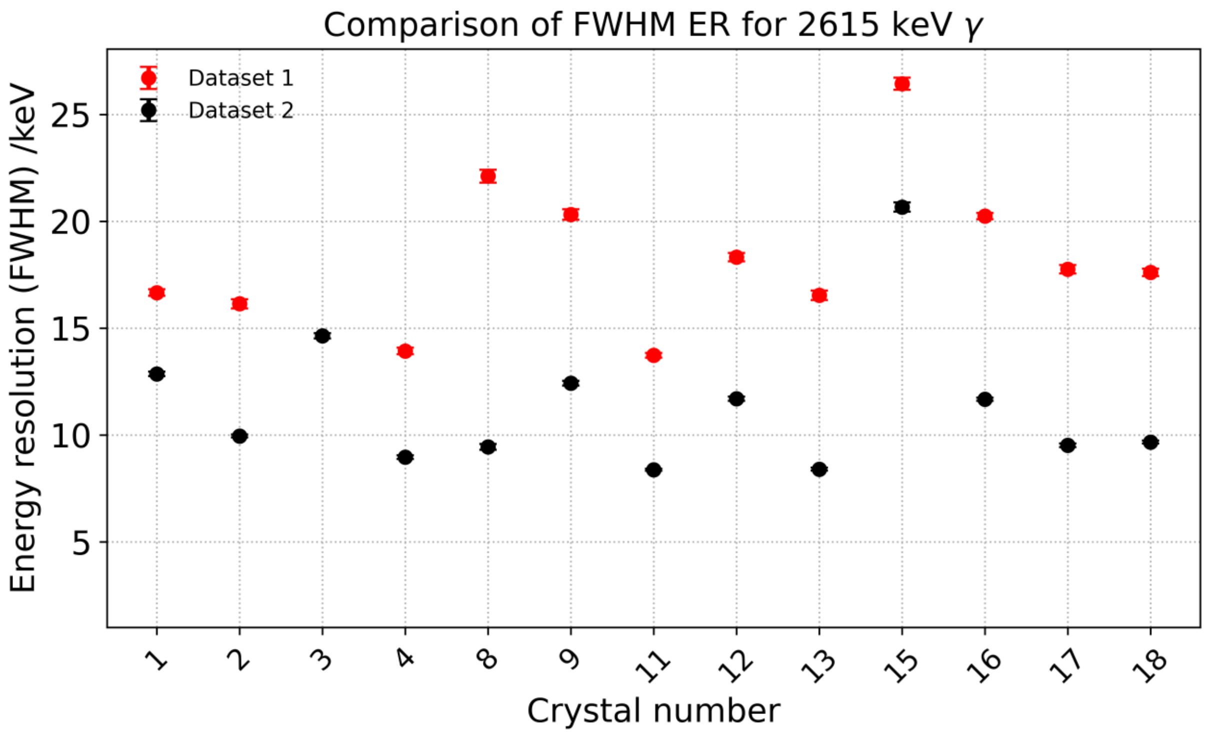
AMoRE-I data taking





12 mK physics data	Exposure ($kg_{XMO}\cdot yr$)
Total	10.16
- Bad channels/runs	8.76
- deadtime & anti-coincidence (= live exposure)	8.02
in ^{100}Mo	3.88 ($kg_{ISO}\cdot yr$)





- Dec. 2020 – Nov. 2021 (Before power outage)
- Jan. 2022 – May 2023 (After power outage)