Probing neutrinoless double electron capture in ^{40}Ca with AMoRE

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On behalf of the AMoRE Collaboration

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CENTER FOR UNDERGROUND PHYSICS

Contents

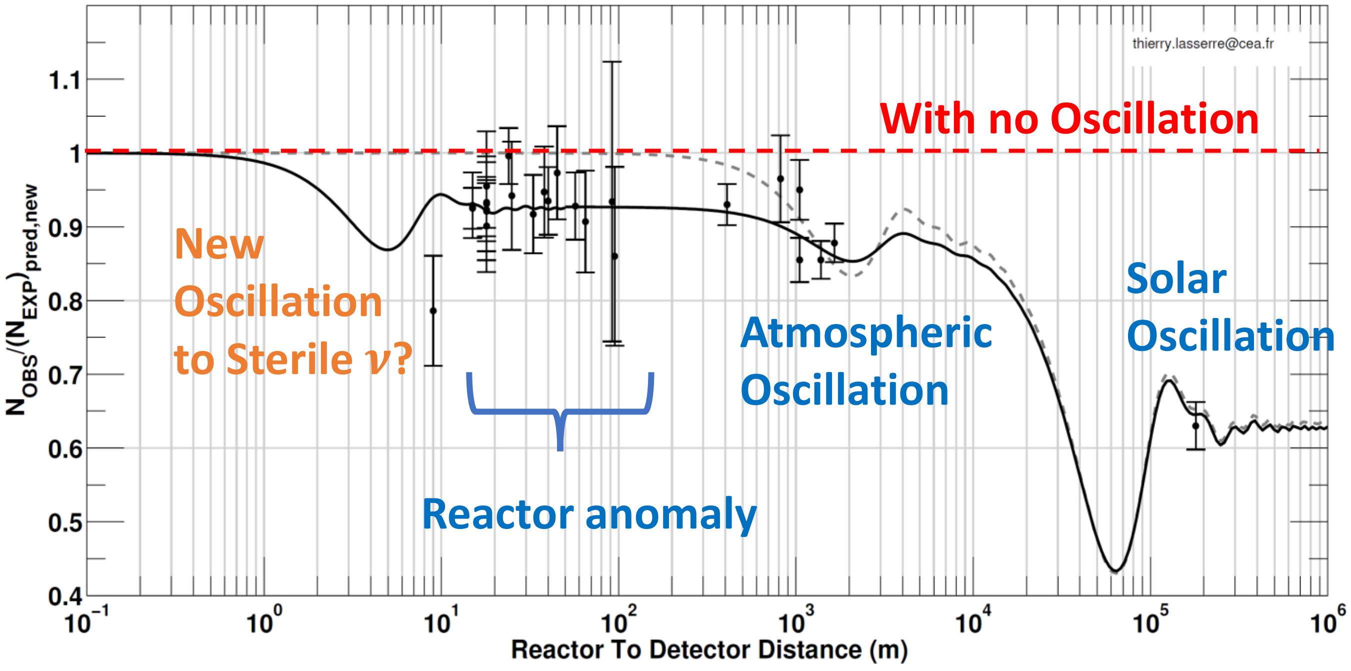
- Questions in neutrino physics
- Double electron capture ($2\nu2EC$ & $0\nu2EC$)
- AMoRE efforts to study $0\nu2EC$ process
- Result & summary

What do we know about neutrinos?

Flavor eigenstates → PMNS matrix → Mass eigenstates

$$|V_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha,i}|V_i\rangle$$

- Known
  - ✓ $\theta_{12}, \theta_{23}, \theta_{13}$, Δm^2_{21} , $|\Delta m^2_{32}|$
- Unknown
  - CP Phase, mass hierarchy, $m_1, m_2, m_3, \alpha_1, \alpha_2$



arXiv:1309.6805v2

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & e^{-i\delta}sin\theta_{13} \\ 0 & 1 & 0 \\ e^{-i\delta}sin\theta_{13} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-\alpha_1} & 0 & 0 \\ 0 & e^{-\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 42^\circ$ by atmospheric neutrinos (1998)

$\theta_{13} \sim 9^\circ$ by reactor neutrinos (2012)

$\theta_{12} \sim 34^\circ$ by solar neutrinos (2001)

Majorana term

How can we understand ν?

- Different experimental approaches answer different fundamental questions about ν's

Questions	Methods/Experiments	Key parameters	Sources
Do neutrinos have mass ?	Oscillations	Δm^2 and θ_{ij}	Accelerators, Reactors, Sun
What is absolute mass?	KATRIN / Cosmology	m_ν (kinematics) / $\sum m_\nu$	^{3}H, CMB
Majorana or Dirac/ absolute mass?	$0\nu\beta\beta$ / 0ν2EC	LNV and $\|m_{\beta\beta}\|$	$\beta\beta$ isotopes; ^{136}Xe, ^{76}Ge, ^{100}Mo, ^{40}Ca etc.
CP violation?	DUNE / T2K	δ_{CP} (CP phase)	Accelerator beams
New physics?	CEνNS / sterile ν	Cross-section / BSM	Spallation sources, Reactors
Astrophysical role?	Supernova / IceCube	Flavor ratios / Energy flux	GRBs, Galactic SN

Double electron capture (2EC)

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

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

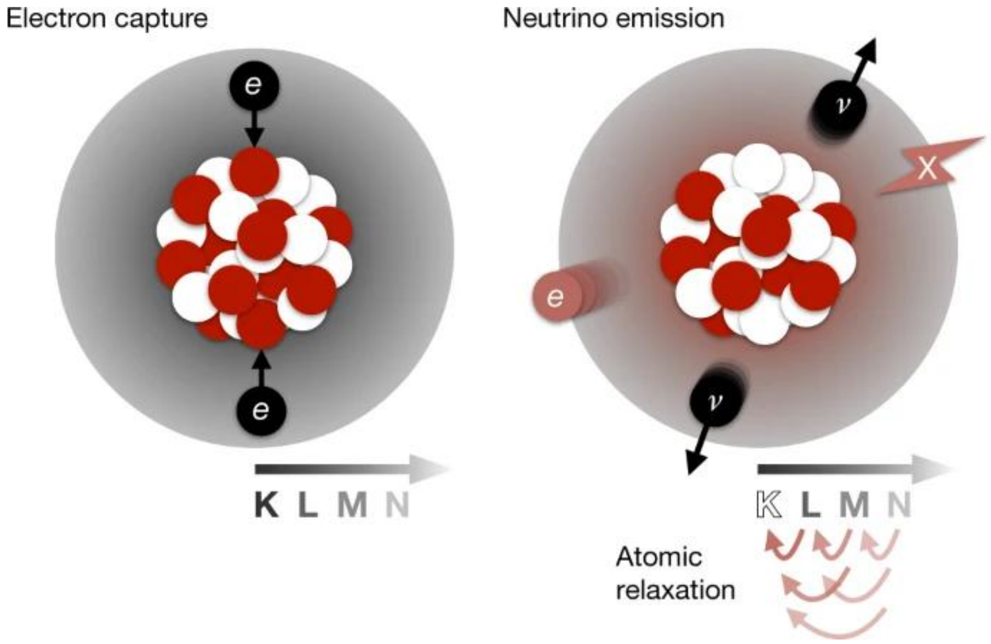
  - $\mathbf{2\nu 2EC}$: $\mathrm{e_b^-} + \mathrm{e_b^-} + (\mathrm{A, Z}) \rightarrow (\mathrm{A, Z-2})^{**} + 2\nu_e$

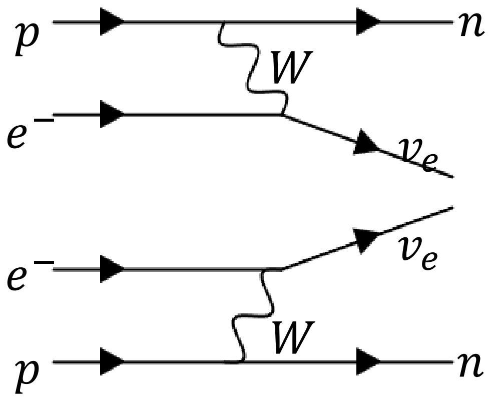
    $$\downarrow$$

    $$(A, Z-2) + \mathrm{X-rays/Auger\ e^-}$$

  - Observed for only ^{130}Ba [1] in geochemical experiment, ^{78}Kr [2] proportional counter, and for ^{124}Xe [3, 4, 5] by XENON1T (First observation with half-life 1.8×10^{22} y), LZ & PandaX Collaboration

  - 34 nuclei undergo 2EC capture.





[1] *Phys. Rev. C* 64, 035205 (2001).
[2] *Phys. Rev. C* 87, 035501 (2013).
[3] XENON Collaboration, *Nature* 568, 532–535 (2019).
[4] LZ Collaboration, *J. Phys. G* 52, 015103 (2025).
[5] PandaX Collaboration, *arXiv*:2411.14355 [nucl-ex].

Neutrinoless double electron capture ($0\nu2EC$)

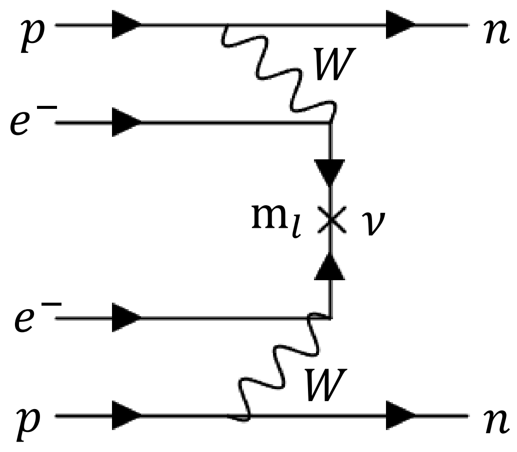
- First discussed by Winter in 1955
- Motivation of study is similar to $0\nu\beta\beta$

- **$0\nu2EC$:** $e_b^- + e_b^- + (A, Z) \rightarrow (A, Z-2)^{**} + \gamma/IC$

- Emission of different particles are considered like e^+e^- pairs, one or two photons, or one IC electron to conserve energy and momentum (T. Doi & A. Kotani, Prog. Theor. Phys. 89, 139 (1993)).

- **Observable energy is *Q*-value** of the decay

- Estimates show that the sensitivity of the $0\nu2EC$ process to the Majorana neutrino mass is many orders of magnitude lower than that of the $0\nu\beta\beta$ decay due to :
  - Phase space suppression
  - Smaller matrix element
  - Lower detection efficiency
  - Lower Q-value than $0\nu\beta\beta$ processes



- The highest up-to-date sensitivity to the $0\nu2EC$ decay is of approximately $T_{\frac{1}{2}} \sim 10^{21} - 10^{22}$ y for different isotopes.

Resonance enhancement of $0\nu 2$EC

- Possible if the energy of the parent $(\mathrm{A, Z})$ and daughter atom $(\mathrm{A, Z}-2)^{**}$ is nearly identical
- Mass degeneracy (Δ) can amplify the transition rate, making $0\nu 2$EC as sensitivity as $0\nu\beta\beta$
- The decay probability is proportional to the Breit-Wigner factor

Rev. Mod. Phys. 92, 045007 (2020)

$$\frac{\Gamma_f}{(\Delta^2 + \frac{\Gamma_f^2}{4})} \qquad \Delta = M_{A,Z} - M^{**}_{A,Z-2}$$

$$\Gamma_f = \text{electromagnetic decay width}$$

$$\textit{for } \Delta \sim 10\ keV, \Gamma_f \sim 10\ eV, \textit{enhances the decay by} \sim 10^6$$

- Degeneracy parameter $\Delta < or \approx \Gamma_f$ gives $T_{\frac{1}{2}}^{0\nu 2EC}$ comparable to $T_{\frac{1}{2}}^{0\nu\beta\beta}$
- Presently, ^{152}Gd is the most favorable case of resonant enhancement, with theoritical half life $\sim 10^{28} - 10^{30}$ y for $\mathrm{m}_{\beta\beta} = 100$ meV)
- Eliseev *et al* (*PRL* ***106****, 052504 (2011)*) found Q-value = 55.70(18) keV with Δ = 0.91(18) keV

EPJC **83**, 1114 (2023)

- Experimental status:
  - First search at Gran Sasso using 198 g Gd_2O_3 (64.8 d, exposure 12.6 kg·d) reported half life of > 4.2×10^{12} y

$0\nu\beta\beta$ / $0\nu 2EC$ search sensitivity

Isotopic concentration (a_{iso}), mass·time exposure ($M\,t$)

$$S = \epsilon\, N_{iso}\, \Gamma^{0\nu}\, t = \epsilon\, \frac{a_{iso}\, N_A\, M\, t \ln 2}{A\, T^{0\nu}_{\frac{1}{2}}}$$

Detection efficiency (ϵ), Decay rate ($\Gamma^{0\nu}$), Half-life ($T^{0\nu}_{\frac{1}{2}}$)

$$B = b\, \Delta E_{ROI}\, Mt$$

Background index (b), Energy resolution at ROI (ΔE_{ROI})

- Background free

$$T_{\frac{1}{2}} \propto \frac{\epsilon\, a_{iso}\, N_A M t}{A}$$

- With Background

$$T_{\frac{1}{2}} \sim \frac{\epsilon\;\, a_{iso}\, N_A}{A} \sqrt{\frac{Mt}{b\, \Delta E_{ROI}}}$$

Searching for these extremely rare processes require :

- Large mass detector
- Long measurement time
- High efficiency
- Low background
- High energy resolution

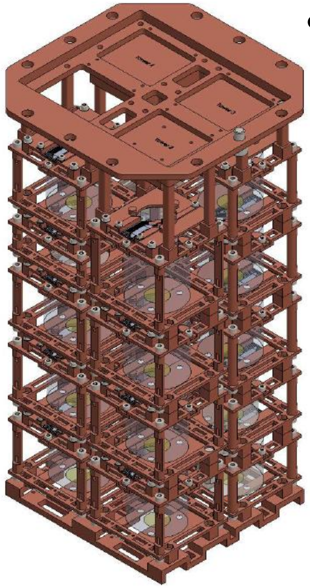
AMoRE Phases

AMoRE-Pilot (2015-2018)

- 6 $^{48deplCa100}MoO_4$ (CMO)
- 1.9 (0.88) kg of CMO (^{100}Mo) Yangyang Underground Lab (Y2L, 700 m depth)
- Live exposure ~0.32 $kg_{100Mo}\cdot yr$
- Background at ROI ~0.5 counts/keV/kg/year (ckky)
- $T^{0\nu}_{1/2} > 3.0 \times 10^{23}$ year (90% C.L.)

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

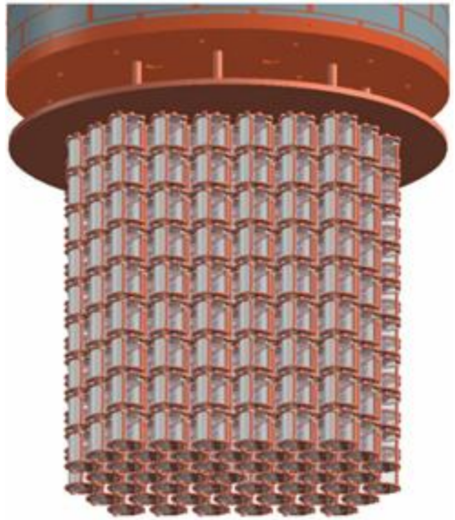
AMoRE-I (2020-2023)



- 13 CMOs + 5 $Li_2{}^{100}MoO_4$
- 6.2 (3.0) kg of CMO + LMO (^{100}Mo), Y2L
- Live exposure:
  - ~4 $kg_{100Mo}\cdot yr$
- 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 $kg_{100Mo}\cdot yr$
- $T^{0\nu}_{1/2} > 4.5 \times 10^{26}$ year

EPJC 85 (1), 9 (2025)

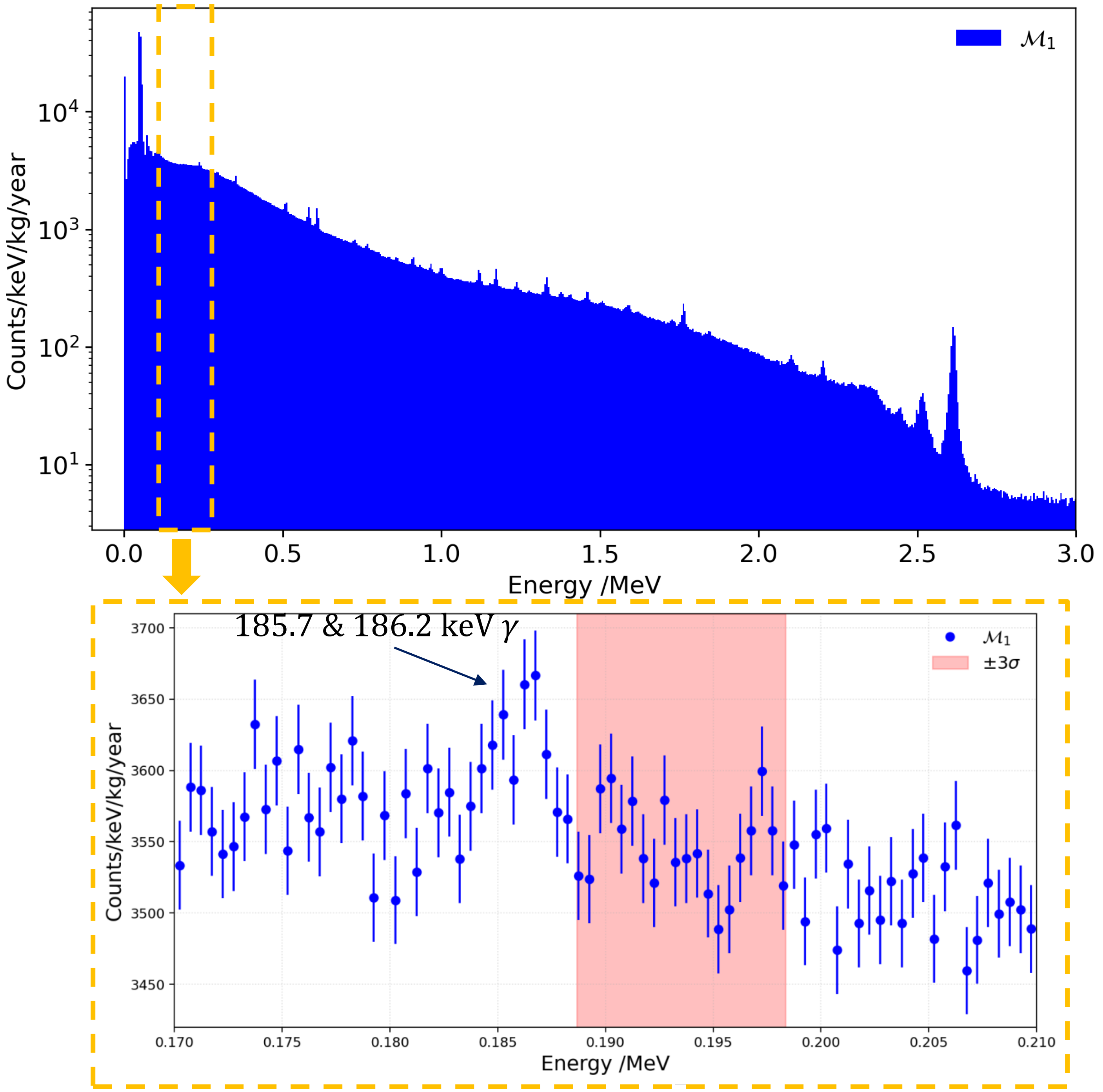
Physics spectrum

^{40}Ca:

- $2\nu 2K$: $2e_b^- + {}^{40}\mathrm{Ca} \rightarrow {}^{40}\mathrm{Ar} + 2\nu_e + 6.4$ keV

− $0\nu 2\mathrm{EC}$: $2e_b^- + {}^{40}\mathrm{Ca} \rightarrow {}^{40}\mathrm{Ar} + Q$ (193.51 keV)

- All 13 CMO crystals
  - Total exposure: 7.32 kg·yr
  - ^{40}Ca exposure: 1.39 kg·yr
- FWHM ER at ROI: 2.5 to 4 keV
- Background level: ~3535 counts/keV/kg/year (ckky)
- Peak ~186 keV is due to ^{235}U (185.7 keV) and ^{226}Ra (186.2 keV)



Detection efficiency

Based on the CRESST study using CAPTURAT, the 2EC capture probabilities in ^{40}Ca is:

- KK capture: 85%
- LL capture: 1%
- KL capture: about 14% (most likely)

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

- Emission of one real photon is forbidden for the $0^+ \rightarrow 0^+$ transition because of the conservation of angular momentum. (DOI & KOTANI, Prog. Theor. Phys. 89, 1, 1993)
- However, we can consider the following scenario.

  - **KK capture**: $e_b^- + e_b^- + (A, Z+2) \rightarrow (A, Z) + (e^-)_{int}$
  - **KL capture**: $e_b^- + e_b^- + (A, Z+2) \rightarrow (A, Z) + \gamma$ or

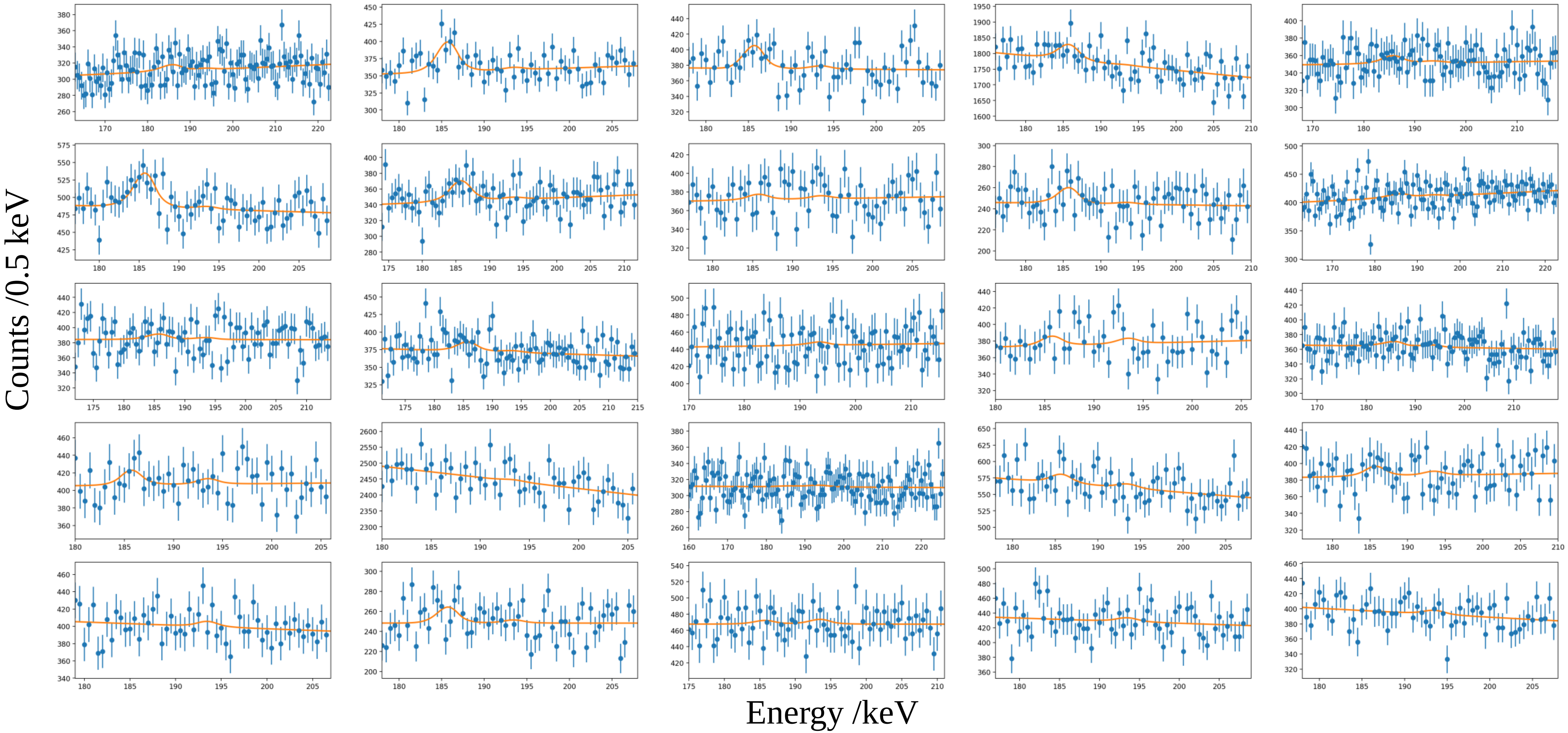
    $e_b^- + e_b^- + (A, Z+2) \rightarrow (A, Z) + (e^-)_{int}$

Weighted detection efficiency

- Considering capture probability and detection efficiency from the simulation
  - Weighted efficiency: $\boldsymbol{\epsilon_{total} = f_{KK} \times eff_{KK} + f_{KL} \times eff_{(KL)_\gamma}}$
  - $\boldsymbol{\epsilon_{total}}$ = 92 to 93% for all CMO crystals

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

90% C.L.

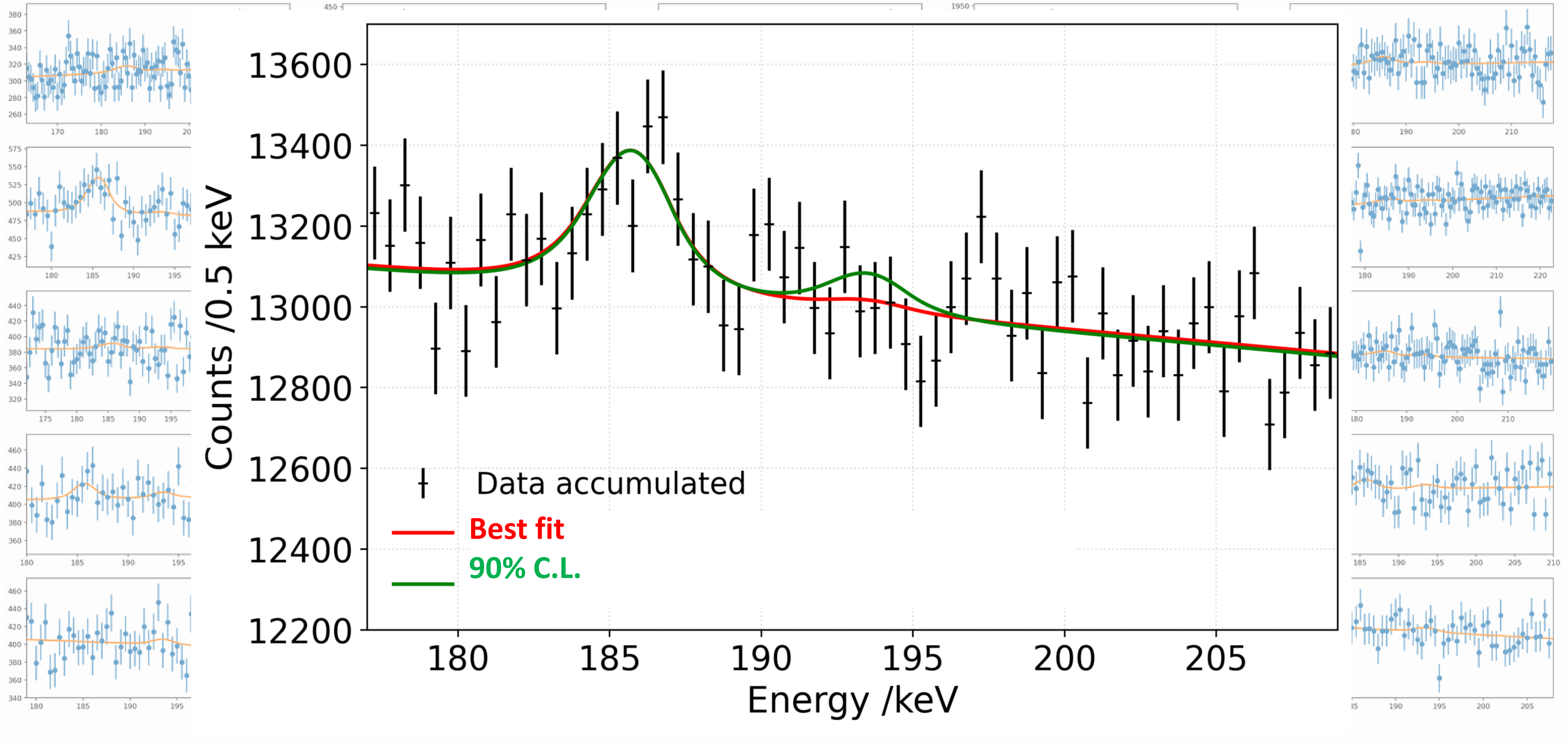


- Fitting model has 3 terms :
  - ^{40}Ca $0\nu 2$EC peak
  - ~186 keV, γ & Linear background

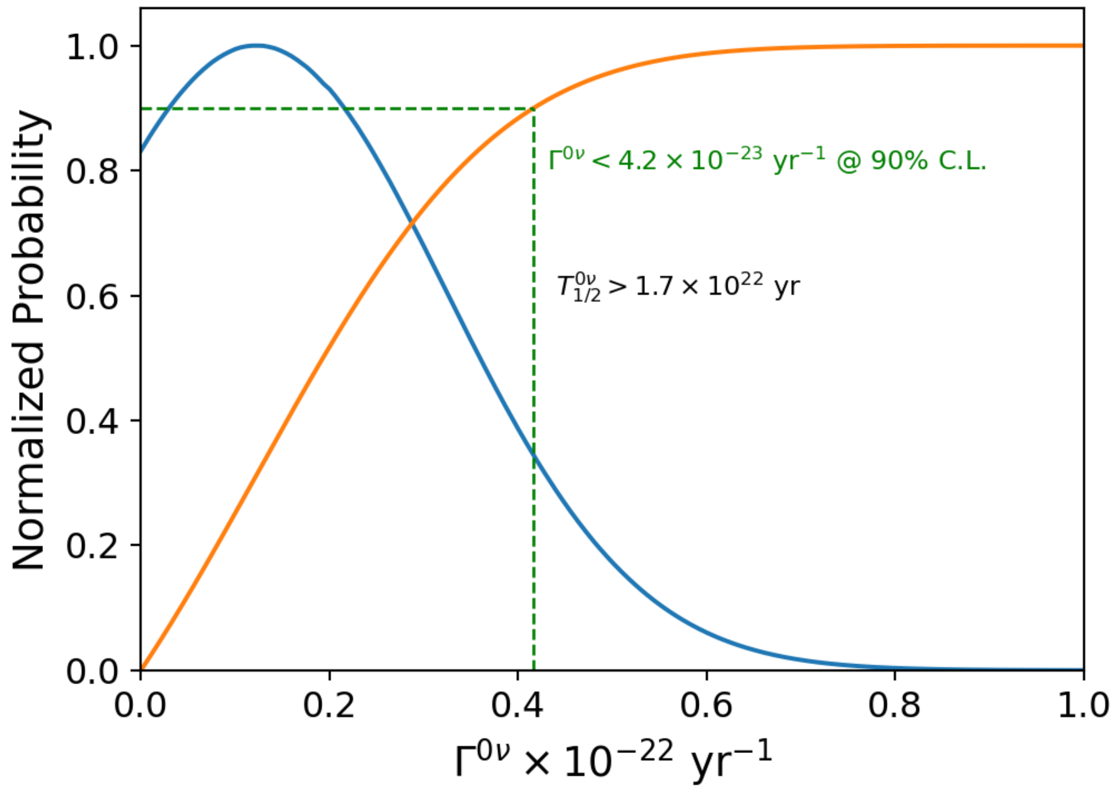
Uncertainty terms

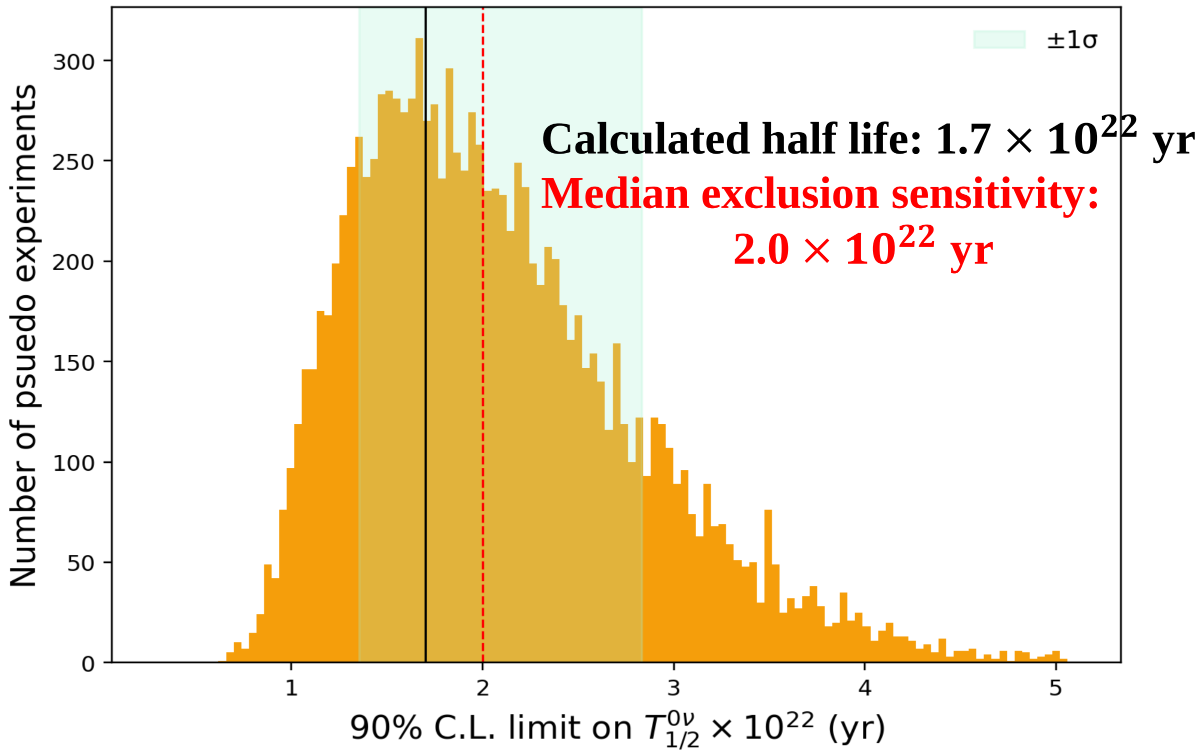
- Systematic uncertainty on Q-value, sigma, detection efficiency, shape parameters etc..
- Trigger efficiency, anti-coincidence & muon veto survival efficiencies are considered

Combining whole datasets



^{40}Ca 0ν2EC limit from AMoRE





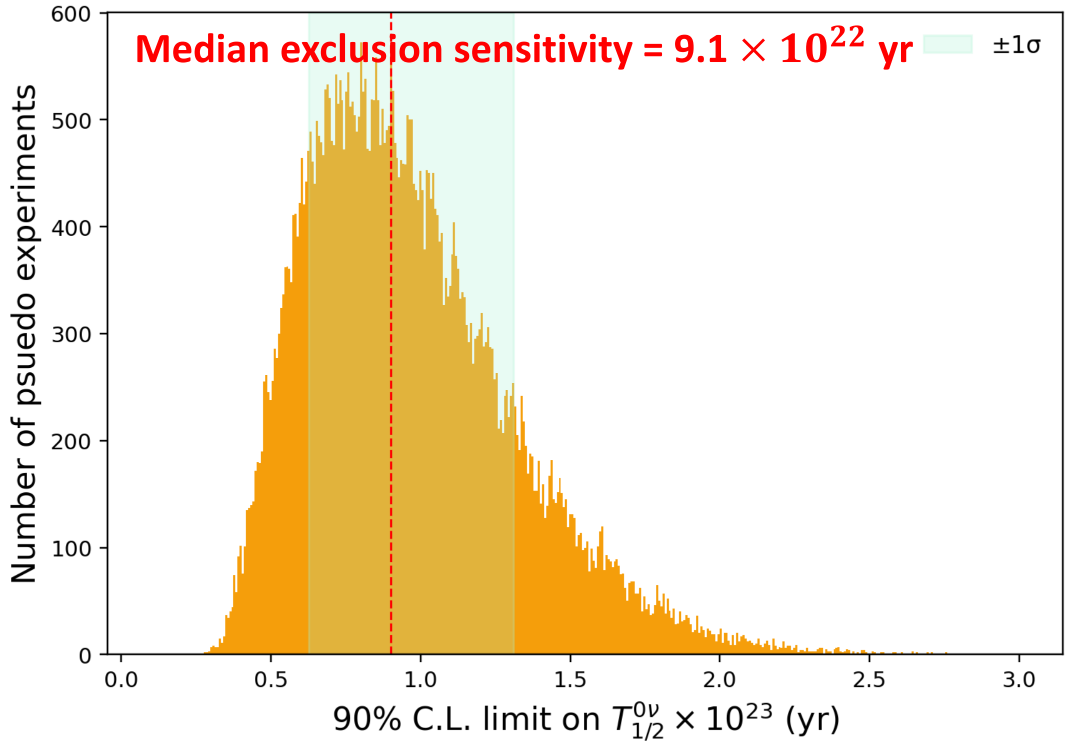
- Half life limit: $T^{0\nu}_{1/2} > 1.7 \times 10^{22}$ year at 90% C.L. [~8 ckkd (BPO, 240 days) & 6 ckkd (APO, 370 days)], ~2.5 keV FWHM, ~7.4 kg·yr)
- CRESST-II: $T^{0\nu}_{1/2} > 1.4 \times 10^{22}$ year at 90% C.L. (~3.8 ckkd, ~1.2 keV FWHM (best case), ~2 kg·yr)

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

40Ca 0ν2EC sensitivity study of AMoRE-II

Assumption for AMoRE-II experiment

- Based on radioassay measurement and background simulation (EPJC 85 (1), 9 (2025)) .
- Energy resolution: 2.54 keV FWHM
- Detector mass: 4.6 kg using same 13 crystals
- Live time: 5 years
- Detection efficiency: 92%



- ❑ Based on peudo-experiments with AMoRE-II background level gives median expected sensitivity of $\mathbf{9.1 \times 10^{22}}$ **yr**
- ❑ About **5 times lower background** and **3 times larger exposure** yield approximately **5 times better sensitivity** than current AMoRE-I result

Summary and Conclusions

- 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: 7.32 kg·yr total, 1.39 kg·yr of ^{40}Ca
- Result:
  - $T^{0\nu}_{1/2} > 1.7 \times 10^{22}$ year (90% C.L) world's best limit for ^{40}Ca
- Sensitivity study of AMoRE-II experiment shows about factor of 5 improvement than current results.
- Results highlights the broader physics potential of the AMoRE program, extending few-keV rare event search to MeV-scale probes of physics BSM.
- We are hopeful to study $2\nu 2K$ (~6.4 keV) study of ^{40}Ca in AMoRE-II experiment

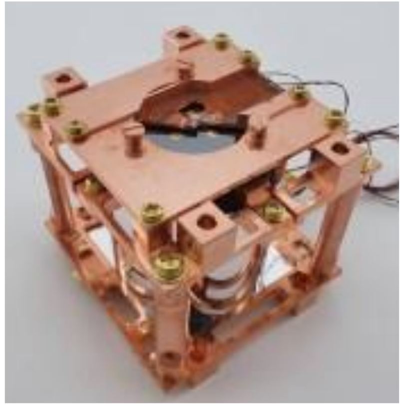
Thank you very much for your attention !!!

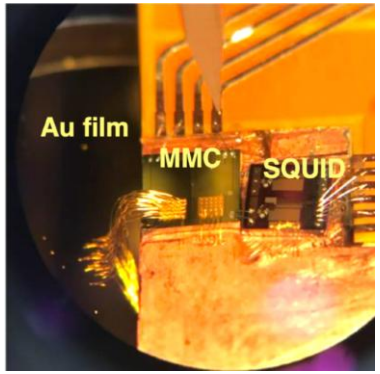
EXTRA

AMoRE Detector module

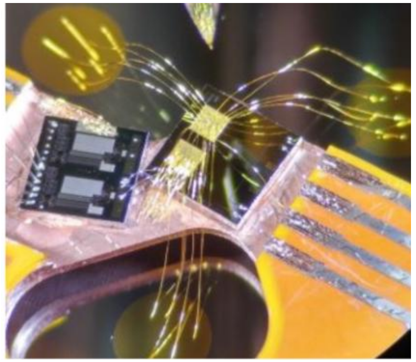
❖ Metallic magnetic calorimeter (MMC)

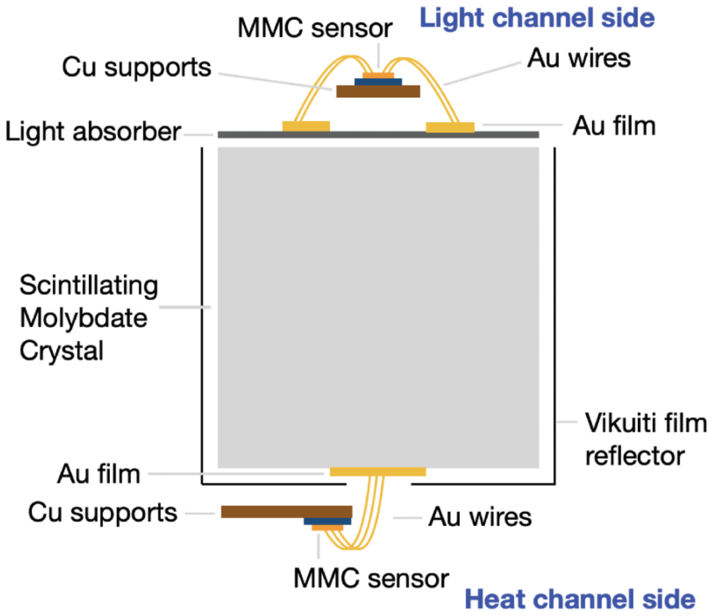
- Fast signal timing: few ms rise-time for phonon at mK
- Good energy resolution ~10 keV @2.6 MeV
- Wide dynamic range
- High linearity

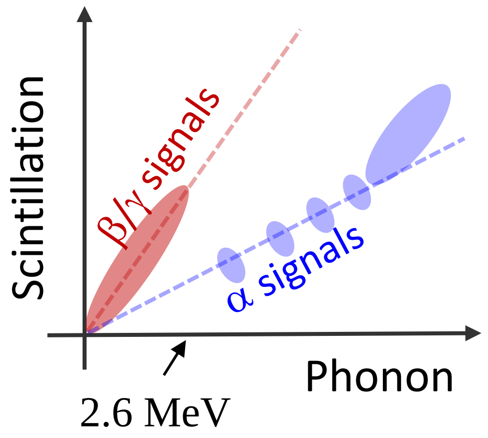




Heat channel


Light channel



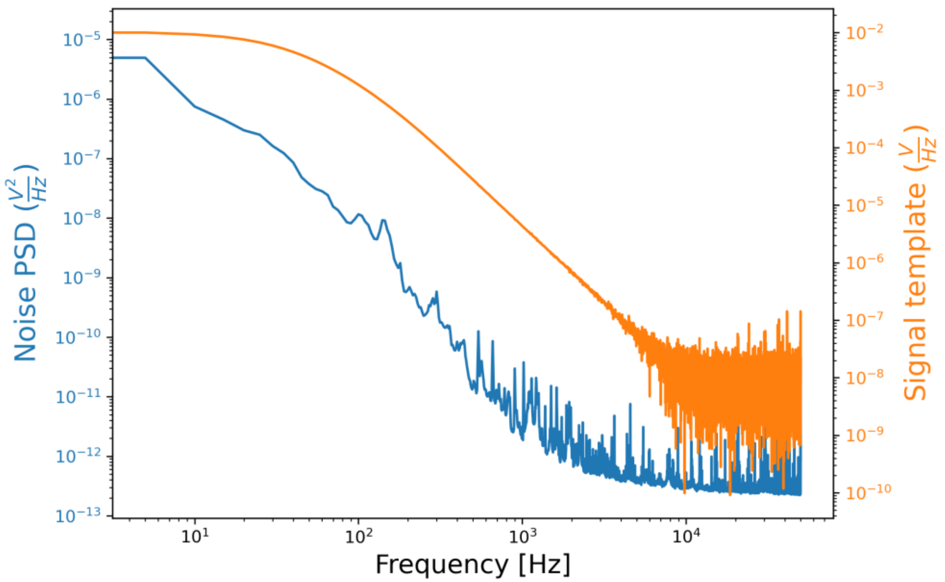


Amplitude estimation: Optimal filter

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

Assumptions :

- Signal shape is known
- Noise is stationary



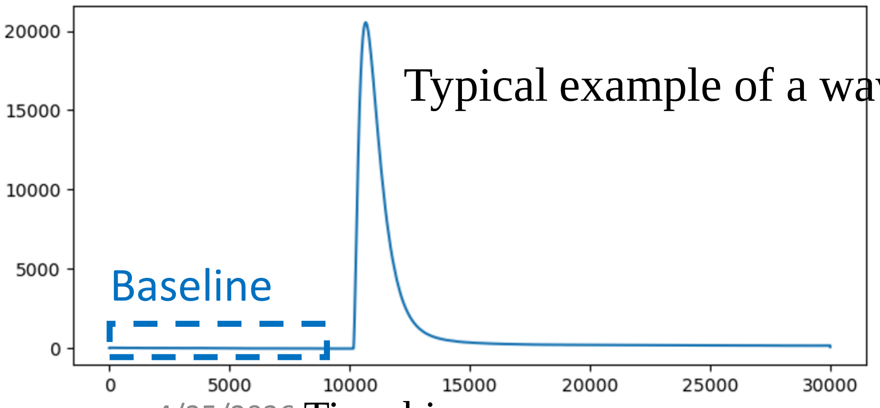
Phys. Rev. D **109**, 043035

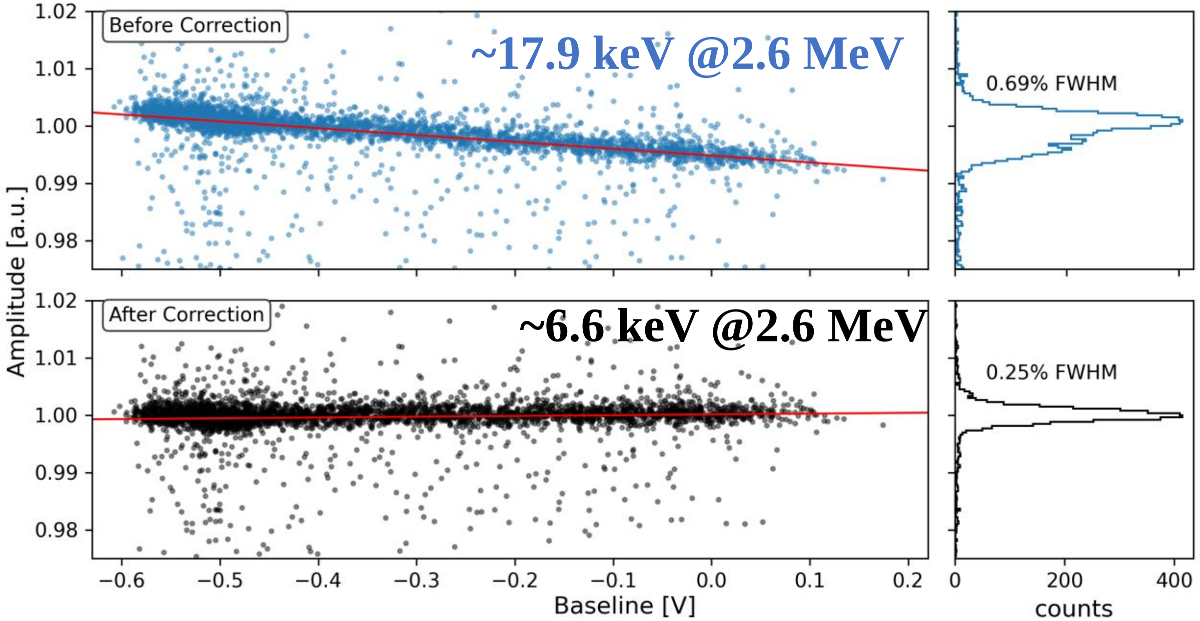
S: event signal
A: template signal
J: noise power spectrum density

Drift correction: Baseline

*FWHM: full width at half maximum

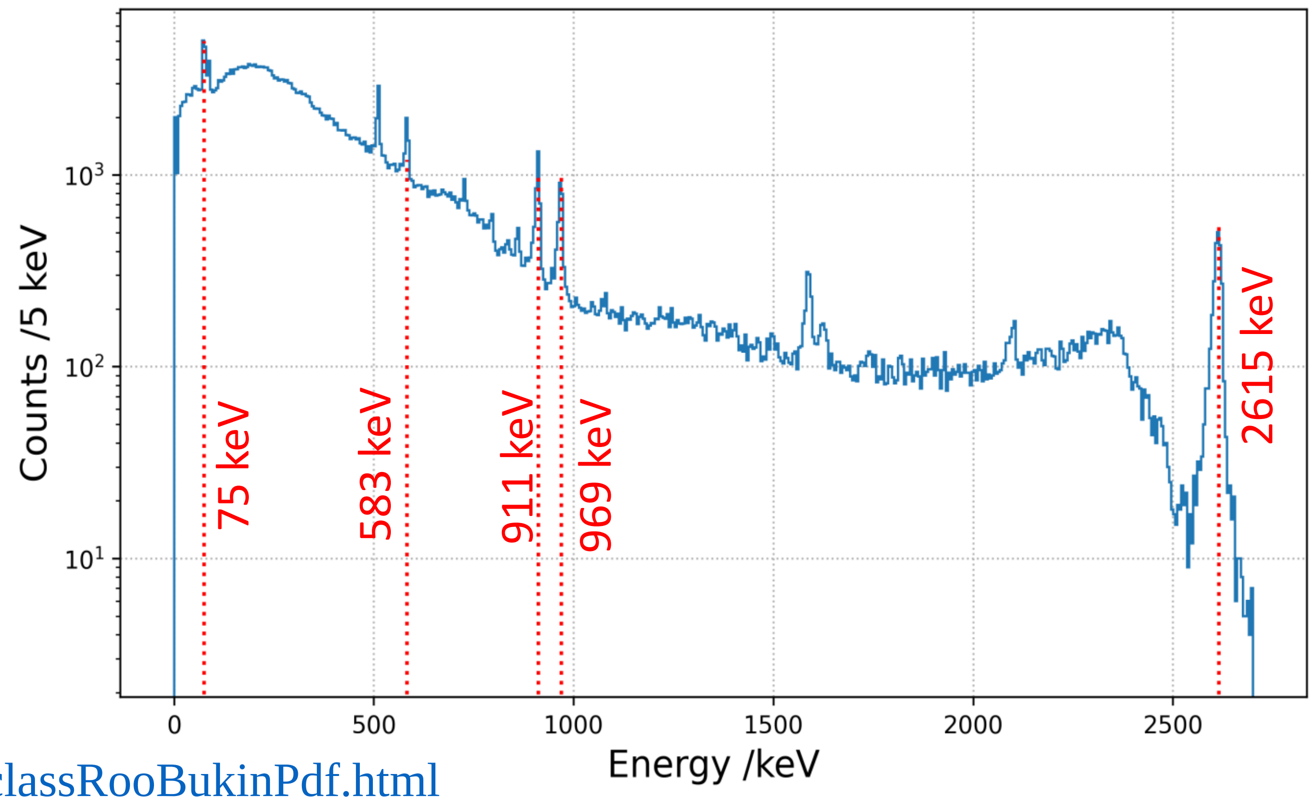
Baseline => Base temperature



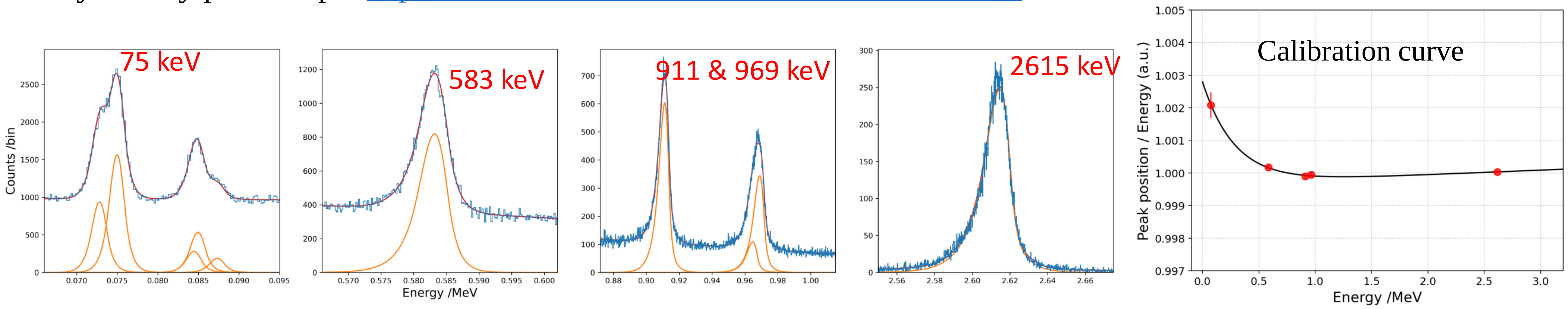


Energy calibration

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

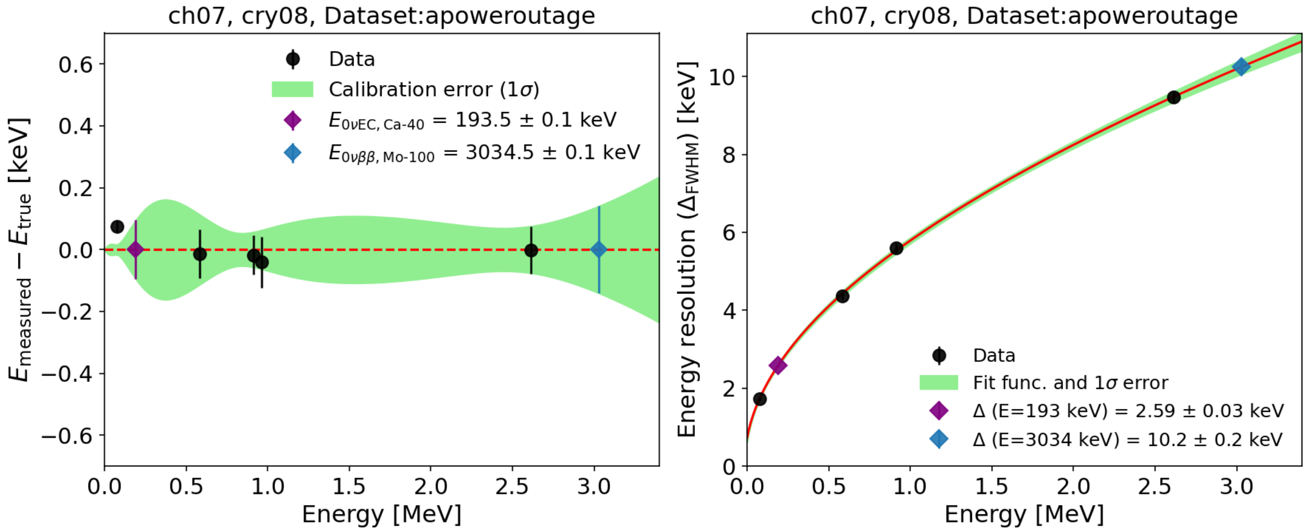


- Bukin function instead of gaussian: better fit to the asymmetry peak shape. https://root.cern.ch/doc/master/classRooBukinPdf.html



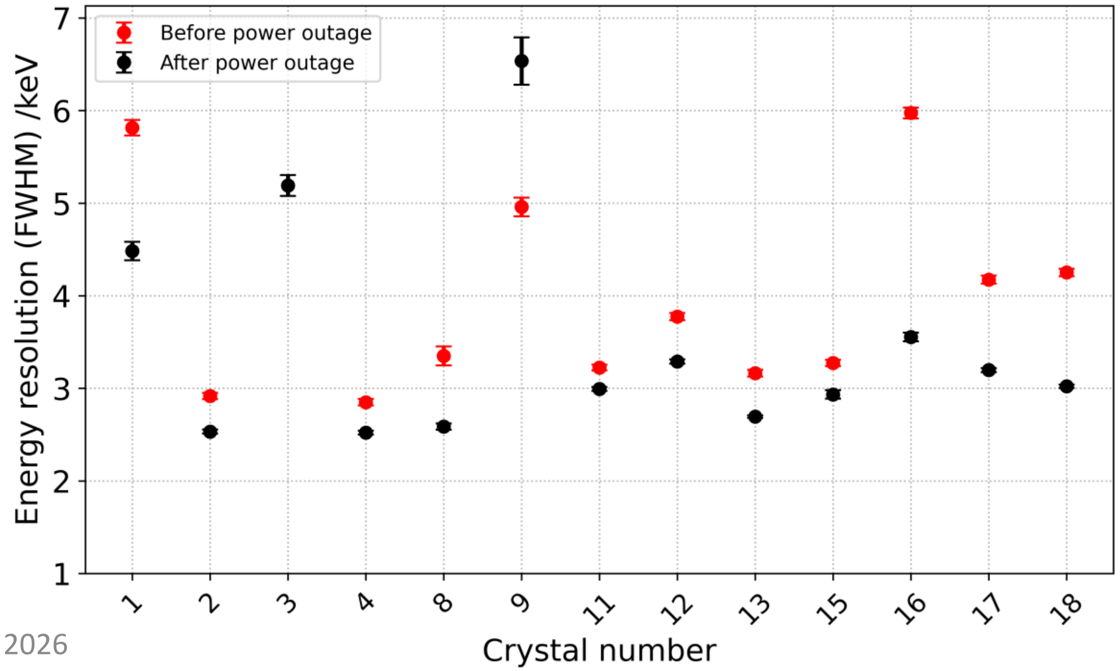
Region of Interest (ROI) estimation

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

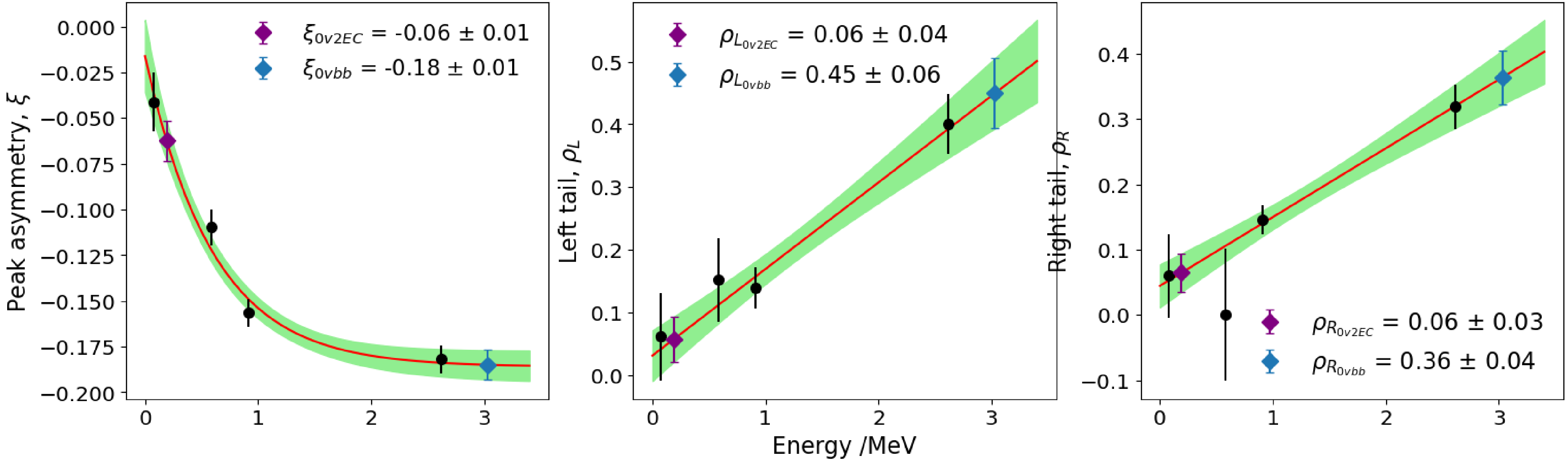


- Each crystal's data is divided into 2 groups (detector performance) :
  - Dec. 2020 – Nov. 2021 (Before power outage)
  - Jan. 2022 – May 2023 (After power outage)
- Energy resolution is improved after power outage.
- Approximately 2.5 ~ 4 keV FWHM is obtained for most of the crystal detectors.

Energy resolution @ ROI



Shape parameters at ROI



- Bukin shape parameters:
  - asymmetry (ξ), left tail (ρ_L) & right tail (ρ_R) are interpolated using exponential and linear function of energy

NDBDecayers

The following known nuclides with A ≤ 260 are theoretically capable of double beta decay, where the red color is the isotopes in which the double beta rate has been measured experimentally, and the black color has yet to be measured experimentally:

^{46}Ca, ^{48}Ca, ^{70}Zn, ^{76}Ge, ^{80}Se, ^{82}Se, ^{86}Kr, ^{94}Zr, ^{96}Zr, ^{98}Mo, ^{100}Mo, ^{104}Ru, ^{110}Pd, ^{114}Cd, ^{116}Cd, ^{122}Sn, ^{124}Sn, ^{128}Te, ^{130}Te, ^{134}Xe, ^{136}Xe, ^{142}Ce, ^{146}Nd, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{160}Gd, ^{170}Er, ^{176}Yb, ^{186}W, ^{192}Os, ^{198}Pt, ^{204}Hg, ^{216}Po, ^{220}Rn, ^{222}Rn, ^{226}Ra, ^{232}Th, ^{238}U, ^{244}Pu, ^{248}Cm, ^{254}Cf, ^{256}Cf, ^{260}Fm

ECEC

The following known nuclides with A ≤ 260 are theoretically capable of double electron capture, where the red color is the isotopes for which the double electron capture rate has been measured, and the black color has not yet been measured experimentally:

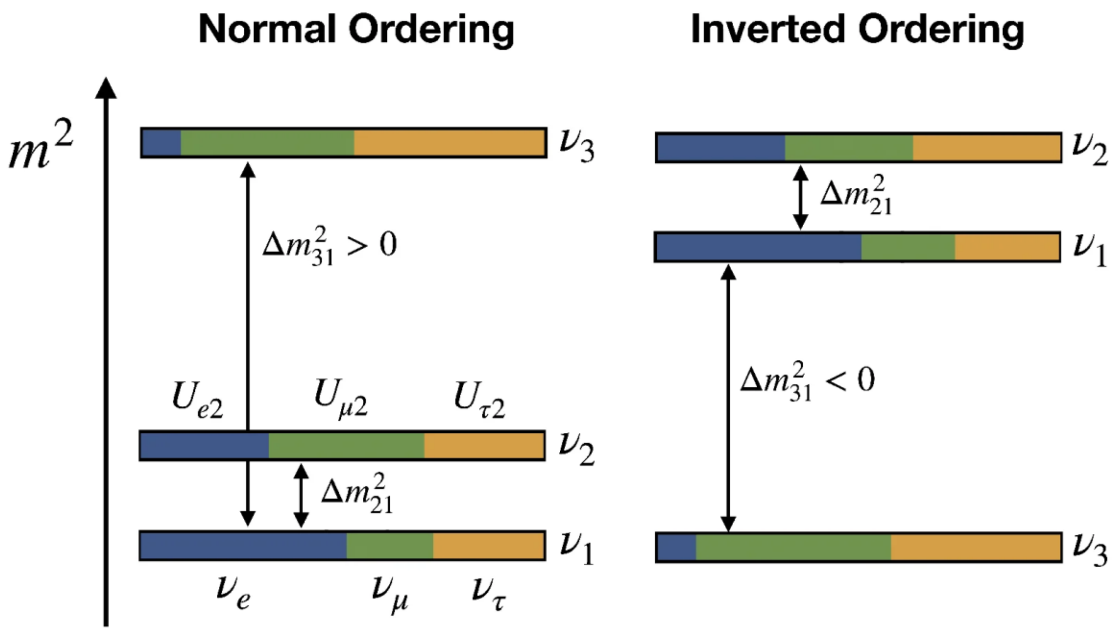
^{36}Ar, ^{40}Ca, ^{50}Cr, ^{54}Fe, ^{58}Ni, ^{64}Zn, ^{74}Se, ^{78}Kr, ^{84}Sr, ^{92}Mo, ^{96}Ru, ^{102}Pd, ^{106}Cd, ^{108}Cd, ^{112}Sn, ^{120}Te, ^{124}Xe, ^{126}Xe, ^{130}Ba, ^{132}Ba, ^{136}Ce, ^{138}Ce, ^{144}Sm, ^{148}Gd, ^{150}Gd, ^{152}Gd, ^{154}Dy, ^{156}Dy, ^{158}Dy, ^{162}Er, ^{164}Er, ^{168}Yb, ^{174}Hf, ^{180}W, ^{184}Os, ^{190}Pt, ^{196}Hg, ^{212}Rn, ^{214}Rn, ^{218}Ra, ^{224}Th, ^{230}U, ^{236}Pu, ^{242}Cm, ^{252}Fm, ^{258}No

Slide courtesy of **Alexander A. Klimenko DLNP, JINR, Feb 24, 2021**

Why $0\nu\beta\beta$ / $0\nu2EC$?

- 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



Phys. Sci. Forum 8, 7 (2023)

Phase factor

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life Measured

Nuclear Matrix Element

Effective 0νββ Neutrino Mass

$$\left|m_{\beta\beta}\right| = \left|\sum_{i=1}^{3} U^2_{ei} m_i\right|$$

TABLE V. Experimental half-life limits of neutrinoless 2EC for transitions to the ground state (denoted as "g.s.") or to the excited level of the daughter nuclide with possible resonant enhancement. The mass differences between the mother and the daughter atoms $Q = M_{A,Z} - M_{A,Z-2}$ are from Wang *et al.* (2017); ι is the isotopic abundance of the nuclide of interest in the natural isotopic compositions of the elements (Meija *et al.*, 2016). To check the resonance enhancement condition, the degeneracy parameter $\Delta = Q - E^* - \epsilon^*_{\alpha\beta}$ is shown, where $E^* = M^*_{A,Z-2} - M_{A,Z-2}$ is the excitation energy of the daughter nuclide and $\epsilon^*_{\alpha\beta} = M^{**}_{A,Z-2} - M^*_{A,Z-2}$ is the excitation energy of the atomic shell with the electron vacancies α and β in the K, L, M, or N orbits. The experimental limits of the $^{54}Fe \rightarrow {}^{54}Cr$ decay are at 68% confidence level (C.L.), and in other cases at 90% C.L. The deexcitation width of the electron shell of the daughter nuclides $\Gamma_f = \Gamma_\alpha + \Gamma_\beta$ [see Campbell and Papp (2001)] is shown in column 6 (orbits are indicated in the brackets). The resonance parameter $R_f = \Gamma_f/(\Delta^2 + \Gamma_f^2/4)$ normalized on the value for the 0ν2EC decay $^{54}Fe \rightarrow {}^{54}Cr$ (g.s. to g.s.) is given in column 7.

Transition Q (keV) ι (%)	Decay channel, level of daughter nuclei (keV)	Δ (keV)	Expt. limit (yr)	Experimental technique (reference)	Γ_f (eV)	R_f
$^{36}Ar \rightarrow {}^{36}S$ 432.59(19) 0.3336(210)	KL, 0^+ g.s.	427.65(19)	$\geq 3.6 \times 10^{21}$	HPGe γ spectrometry (Agostini *et al.*, 2016)	1.04 (KK)	1.2
$^{40}Ca \rightarrow {}^{40}Ar$ 193.51(2) 96.941(156)	2EC, 0^+ g.s.	187.10(2)	$\geq 1.4 \times 10^{22}$	$CaWO_4$ scint. bolometer (Angloher *et al.*, 2016)	1.32 (KK)	8
$^{152}Gd \rightarrow {}^{152}Sm$ 55.69(18) 0.20(3)	All transitions KL, 0^+ g.s.	$(1.1 - 2.1) \pm 0.2$	$\geq 6.0 \times 10^8$ $\geq 6.0 \times 10^8$	Analysis of average parent-daughter abundances (Nozzoli, 2018)	23.1 (KL_1)	4.1×10^6

Benchmark

- An experiment for dark matter direct detection using cryogenic detector.
- Target material : $\boldsymbol{CaWO_4}$ $(\boldsymbol{4\ cm\ \times 4\ cm}), \boldsymbol{300\ g}$
- **2 kg.yr** net exposure

G Angloher *et al* 2016 *J. Phys. G: Nucl. Part. Phys.* **43** 095202

- Background level : ~7 ckkd (at 6.4 keV), ~3.8 ckkd (at 193.5 keV)
- Resolution : 1-sigma resolution is 0.53 keV at 122 keV
- Detection efficiency :
  - $o\nu 2EC$: 0.877, $2\nu 2K$: 1.0
- **AMoRE-I :** exposure : larger by a factor of > 3
  bkg : larger by factor of 1.5
  resolution : worse by a factor of 6

$$2\nu 2K :\ {}^{40}Ca + e_b^- + e_b^- \rightarrow {}^{40}Ar + 2\nu_e + (X - rays\ \&\ A.electrons)$$

$$0\nu 2EC :\ 40Ca + e_b^- + e_b^- \rightarrow {}^{40}Ar + \gamma - rays$$

Isotope	Abundance (%)	Process	Observable energy (keV)	$T_{\frac{1}{2}}^{exp}\ (y)\ (90\%\ CL)$	$T_{\frac{1}{2}}^{th}\ (y)$
^{40}Ca	96.94(16)	$0\nu 2EC$	193.51(2)	$> 1.4 \times 10^{22}$	$--$
		$2\nu 2K$	6.4	$> 9.9 \times 10^{21}$	1.2×10^{33}
^{180}W	0.12(1)	$0\nu 2EC$	143.27(20)	$> 9.4 \times 10^{18}$	$(1.3 - 1.8) \times 10^{31}$
		$2\nu 2K$	130.7	$> 3.1 \times 10^{19}$	$\sim 2.5 \times 10^{28}$

CMO and CaWO4 comparison

Crystal		Molar Mass (g/mol)	Density ρ (g/cm³)
Calcium molybdate	$CaMoO_4$	204	4.34
Lithium molybdate	Li_2MoO_4	178	3.03
Calcium tungstate	$CaWO_4$	288	6.06

Due to the high atomic number of tungsten (Z = 74) and its high density, ZnWO4 is a very efficient gamma-ray absorber. Because of its high effective atomic number, Z^{eff} the photo fraction for gamma-ray absorption is high
Investigation of ZnWO4 and CaMoO4 as target materials for the CRESST-II dark matter search(page 105)

main.pdf

fModuleArray.fCrystalEdep {fModuleArray.fCrystalEdep>0.19}

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

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

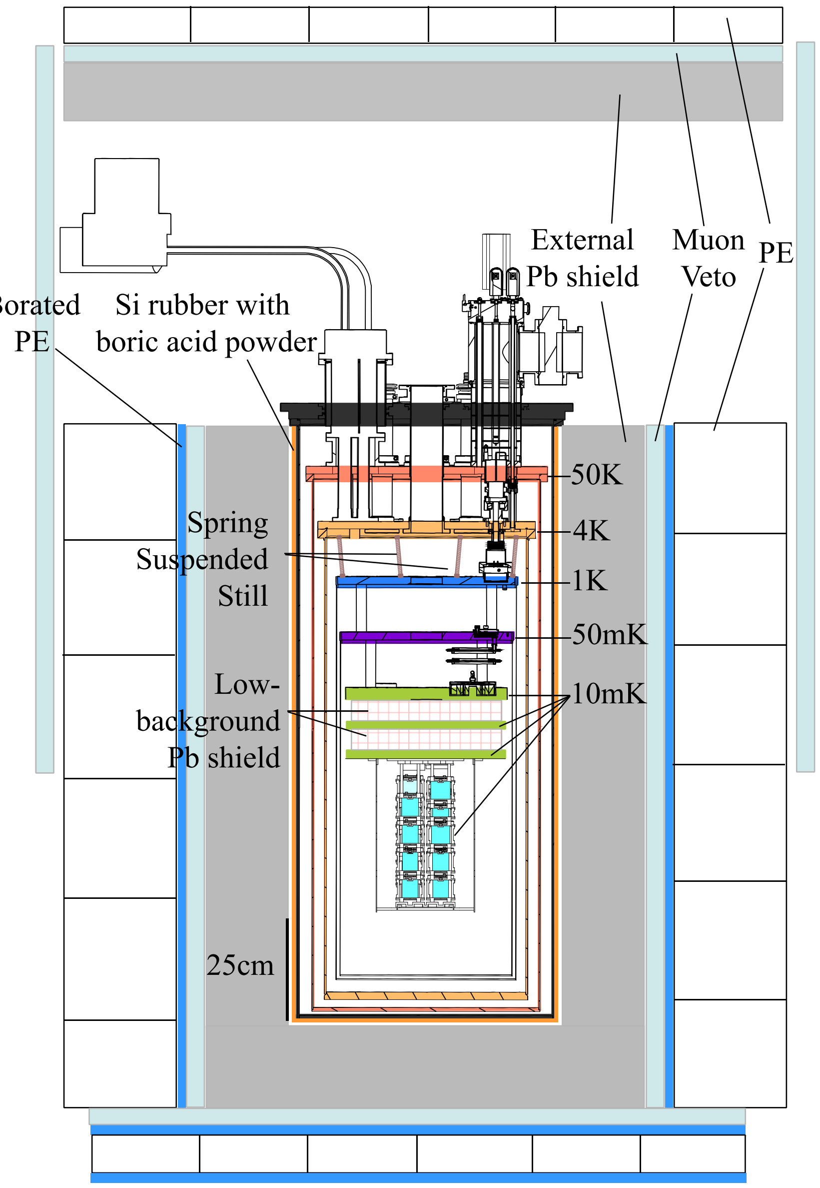
$$A\exp\begin{cases}\left[\dfrac{\tau\sqrt{\tau^2+1}(x-x_1)\sqrt{2\ln 2}}{\sigma(\sqrt{\tau^2+1}-\tau)^2\ln(\sqrt{\tau^2+1}+\tau)}+\rho_1\left(\dfrac{x-x_1}{\mu-x_1}\right)^2-\ln 2\right] & \text{if } x<x_1\\ \left[-\ln 2\left[\dfrac{\ln(1+\frac{2\tau\sqrt{\tau^2+1}(x-\mu)}{\sqrt{2\ln 2}\sigma})}{\ln(1+2\tau(\tau-\sqrt{\tau^2+1}))}\right]^2\right]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

as

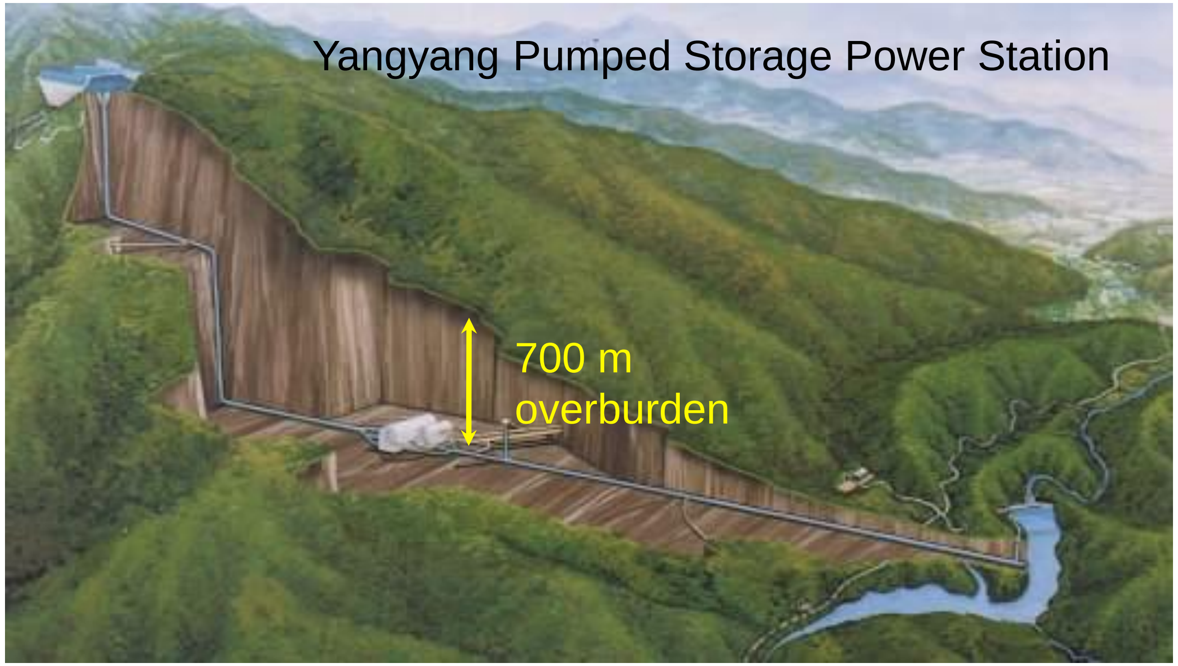
$$x_{1,2} = \mu + \sigma\sqrt{2\ln 2}\left(\frac{\tau}{\sqrt{\tau+1}} \mp 1\right). \tag{5.5}$$

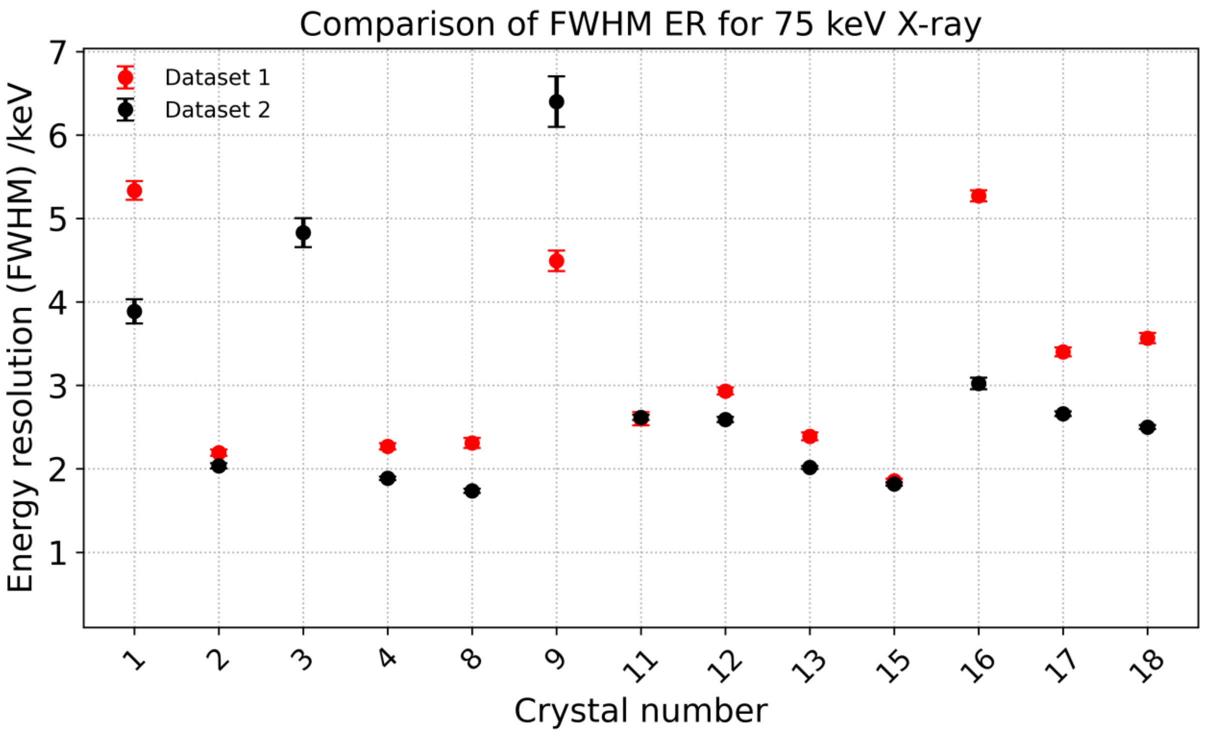
- $\boldsymbol{A}$**: normalization factor**, $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$ are the **Gaussian mean** and **standard deviation**. $\boldsymbol{\tau}$**,** $\boldsymbol{\rho_1}$ and $\boldsymbol{\rho_2}$ are the unit less **shape parameters** which describes the **asymmetry of the distribution**.
- For $\boldsymbol{\tau}$ **= 0** and $\boldsymbol{\rho_1}$ **=** $\boldsymbol{\rho_2}$ **=** $\boldsymbol{-ln2}$, **Bukin function** becomes the **same as the Gaussian**.

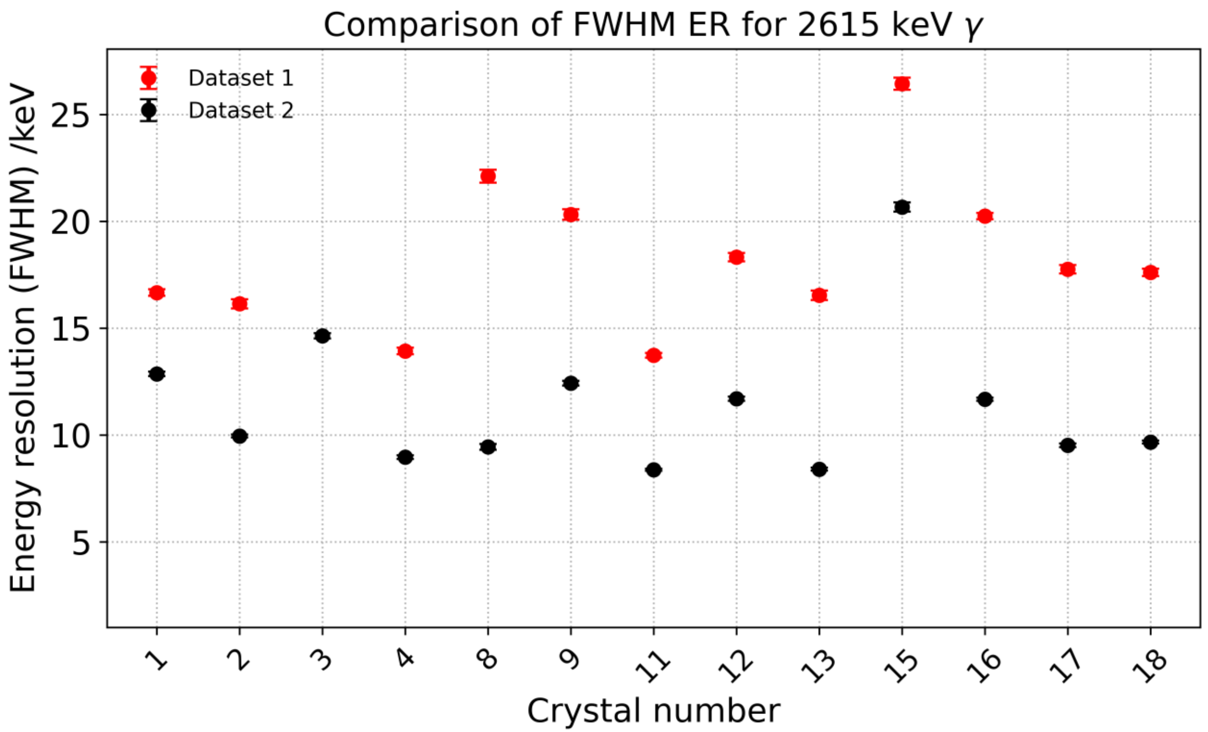
Cryostat, Shielding & Underground



- 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.







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