AMoRE-I Analysis Result

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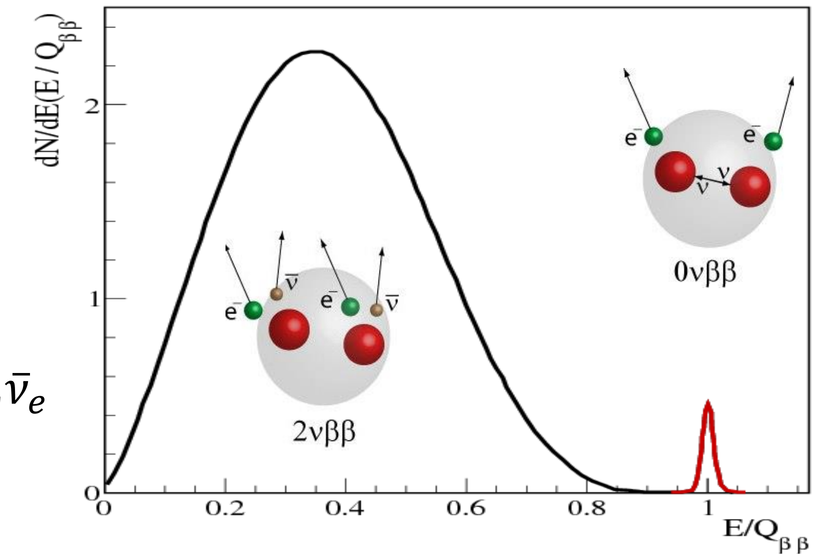
0νββ search using ^{100}Mo

AMoRE:

A search for neutrinoless double beta (0νββ) decay of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.

$2\nu\beta\beta$ decay
- 2nd order beta decay
- Rare nuclear decay
- (>10^{18} years of half life)

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



$0\nu\beta\beta$ decay
- Massive neutrino
- Majorana particle
- Lepton number violation
- Beyond the SM model
- >10^{25} years of half-life

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

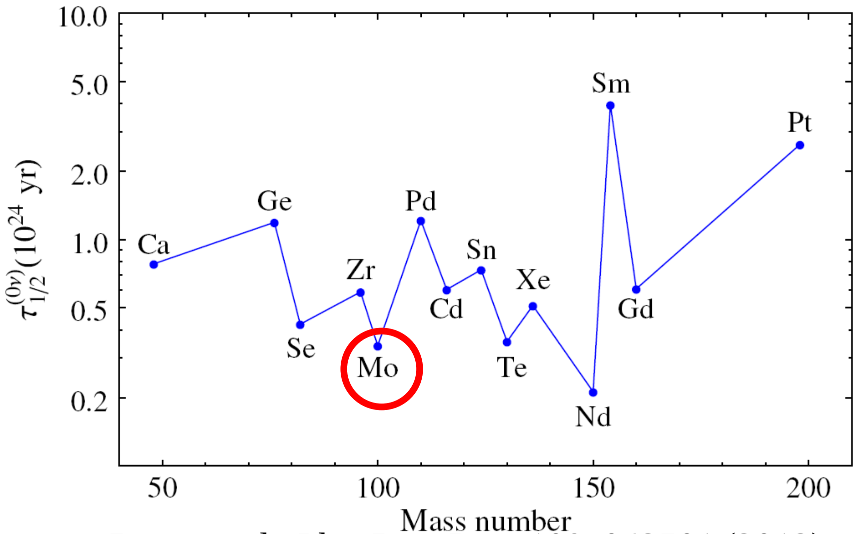
- Neutrinoless double beta decay:
  - Direct measure of Majorana nature of neutrino.
  - Lepton number violation process.
  - Effective neutrino mass.

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

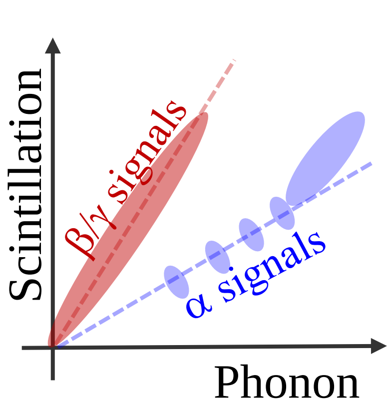
^{100}Mo:

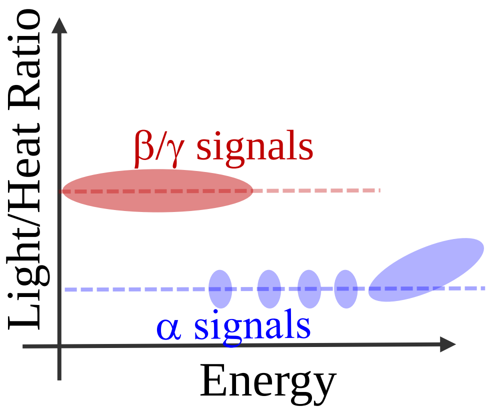
– High $Q_{\beta\beta}$ = 3034 keV
– High natural abundance: 9.7 %
– Scintillation crystals with ^{100}Mo enrichment > 95% —XMo_aO_b (XMO):
  - X=Ca, Li_2, Na_2, Zn, Sr, Pb, …
  - Detection of light/heat signal ➔ rejection of surface-α background.
– Relatively short half life ($0\nu\beta\beta$) in theoretical expectation

ββ-decay nuclei with Q > 2 MeV	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Ru$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Ge$	2.228	5.8
$^{130}Te \rightarrow {}^{130}Xe$	2.528	34.2
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

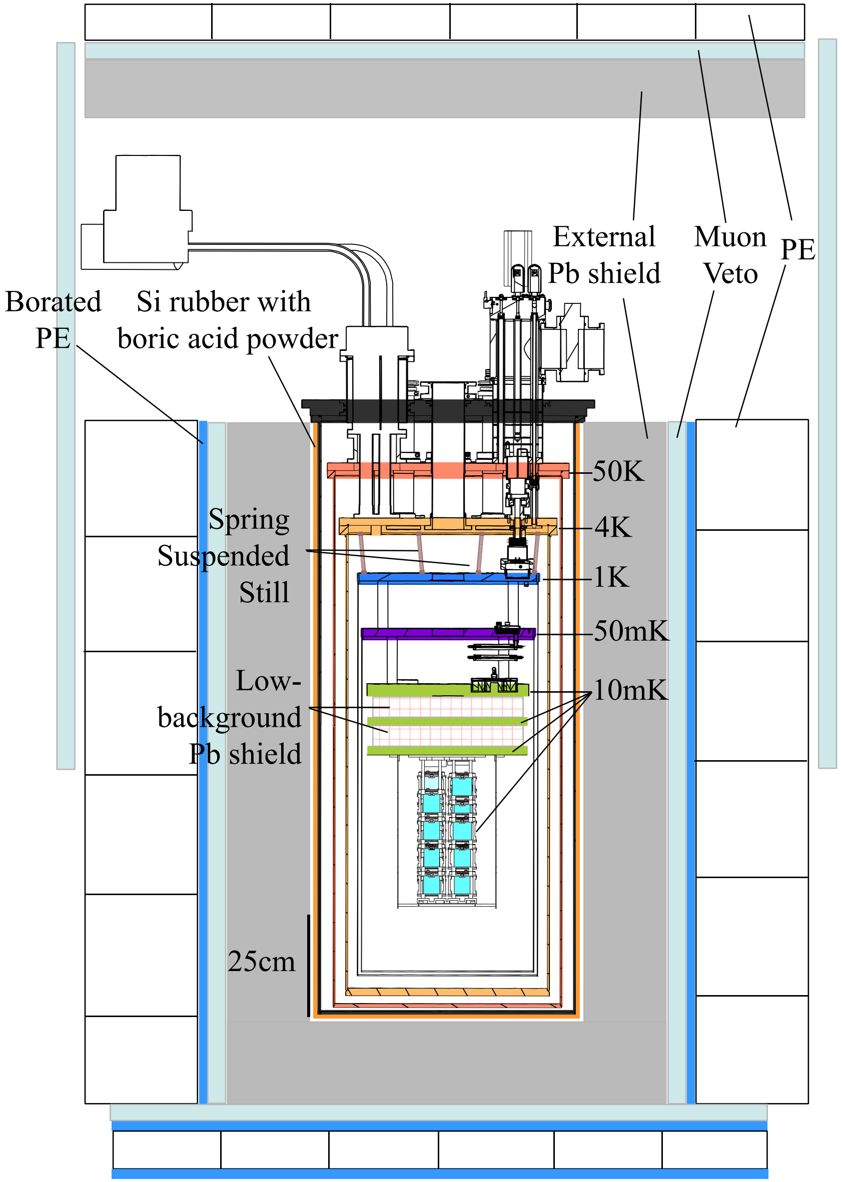


Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

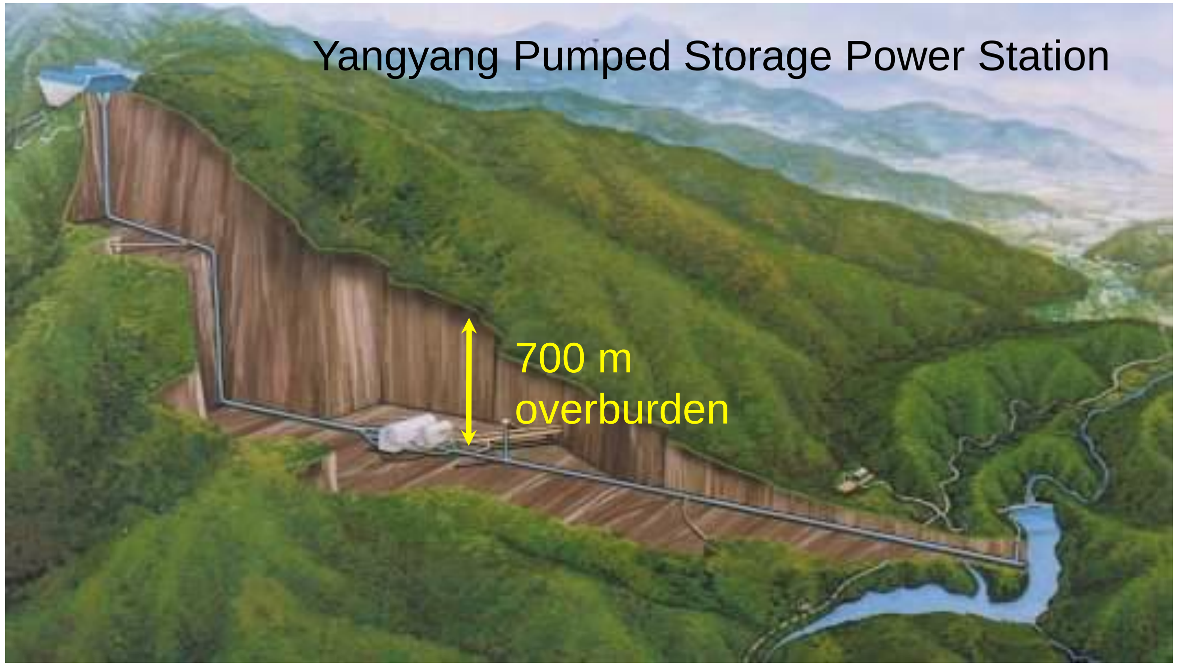




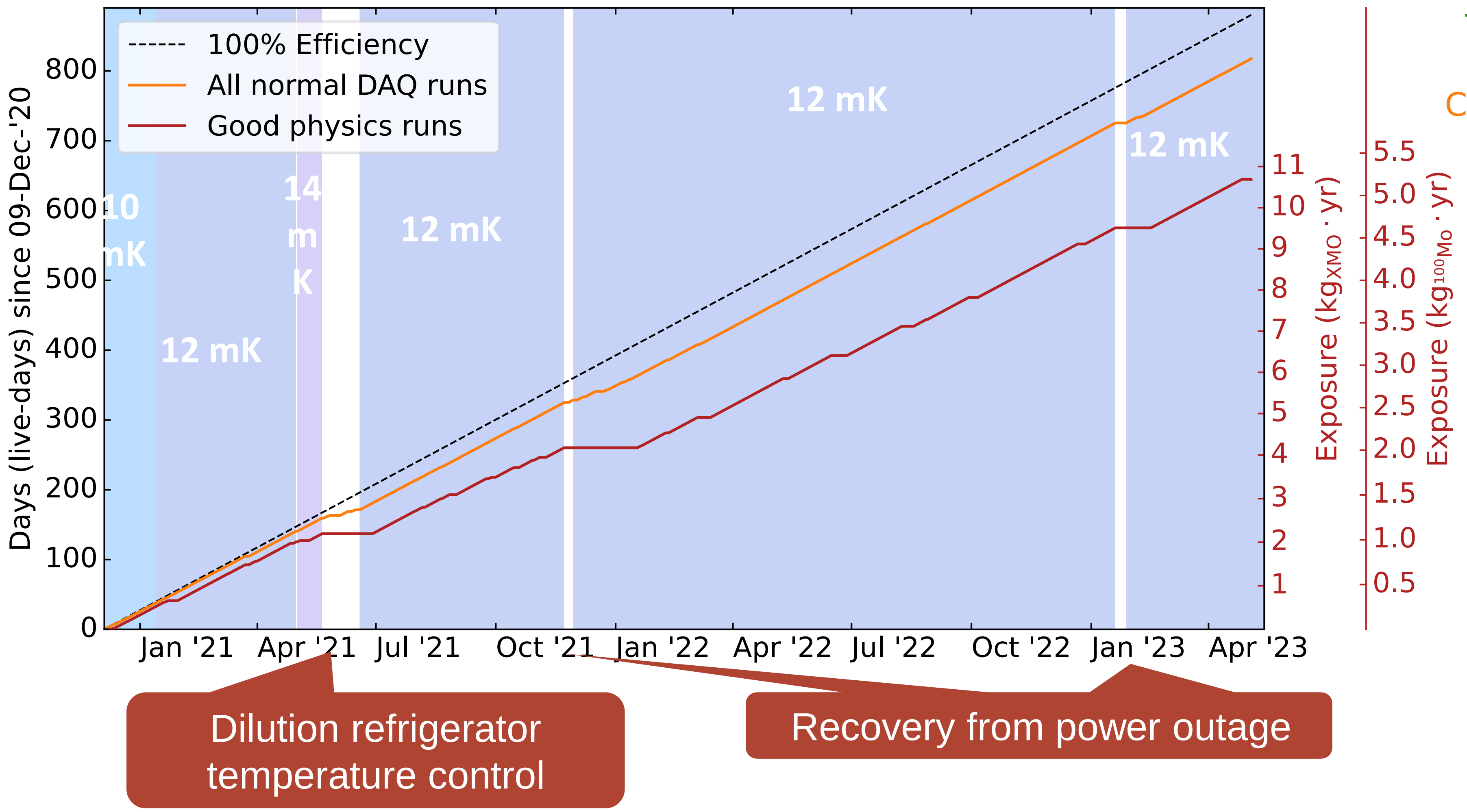
Cryostat, Shielding & Underground

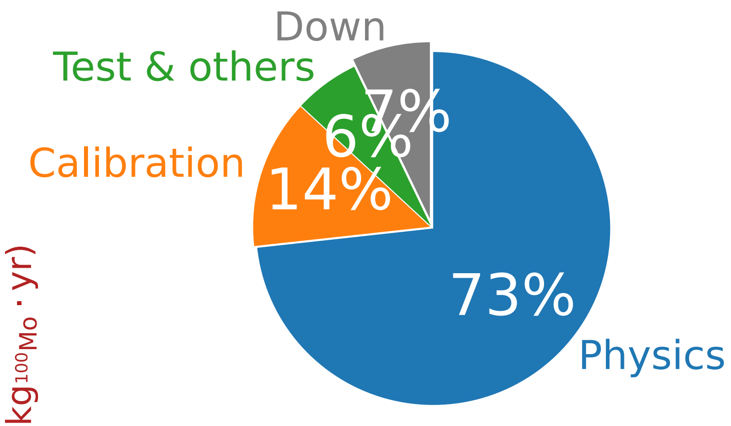


- Cryogen-free dilution refrigerator for AMoRE-pilot (2016~2018) and AMoRE-I.
- ~1 μW cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counters.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.



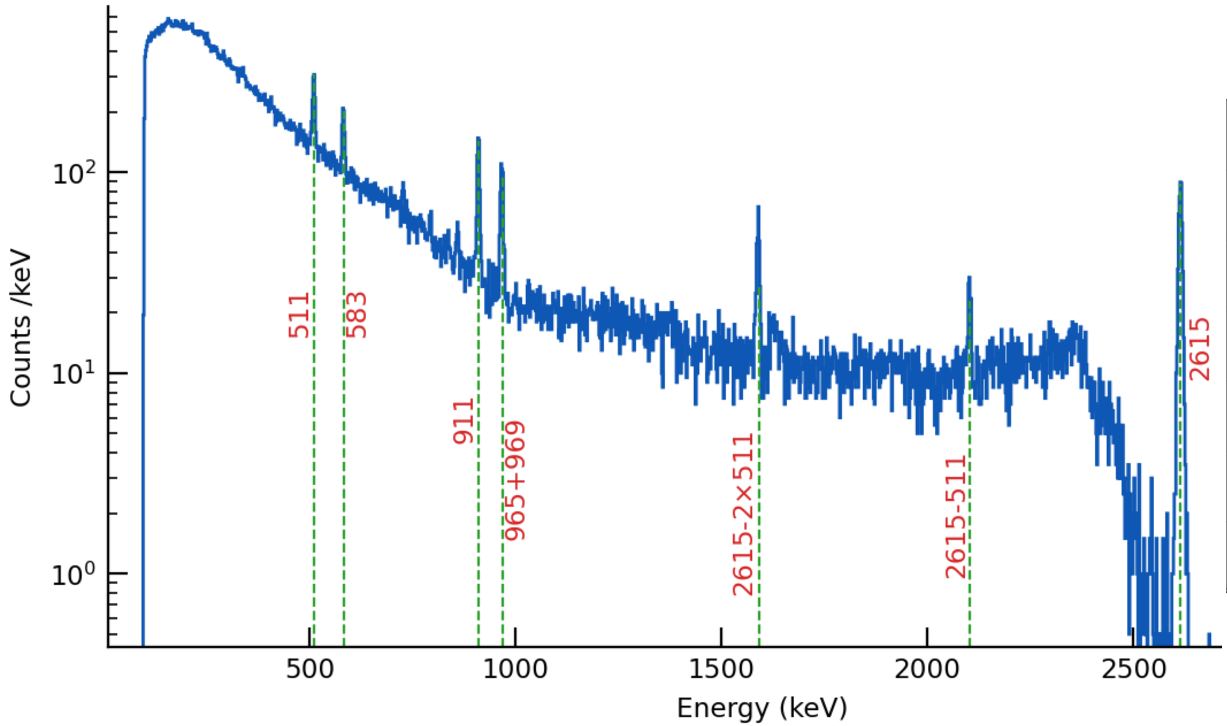
AMoRE-I data taking

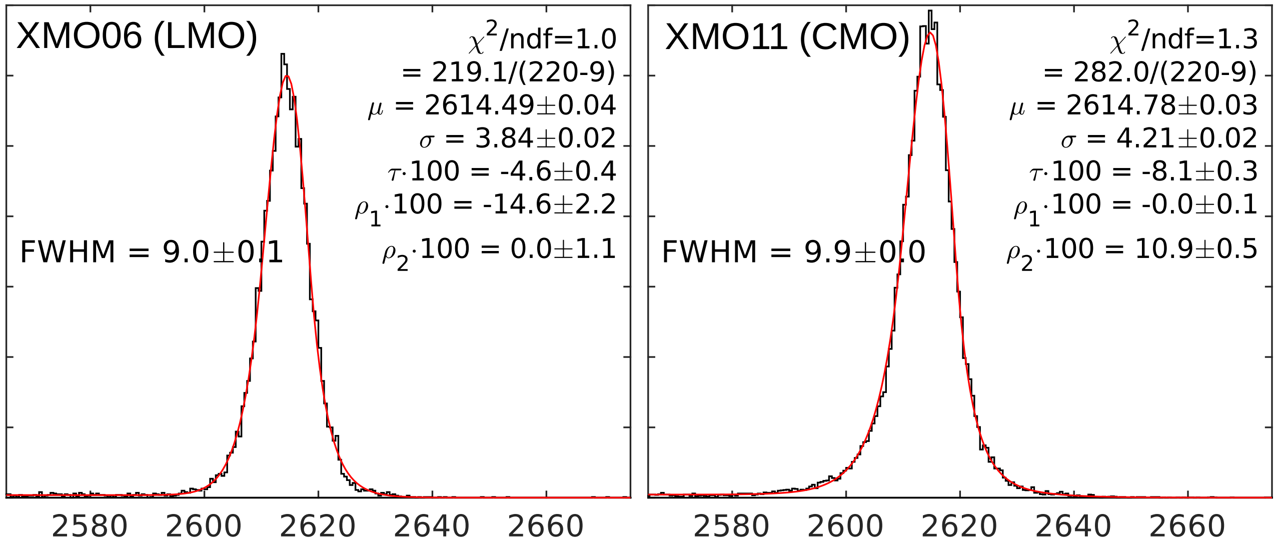


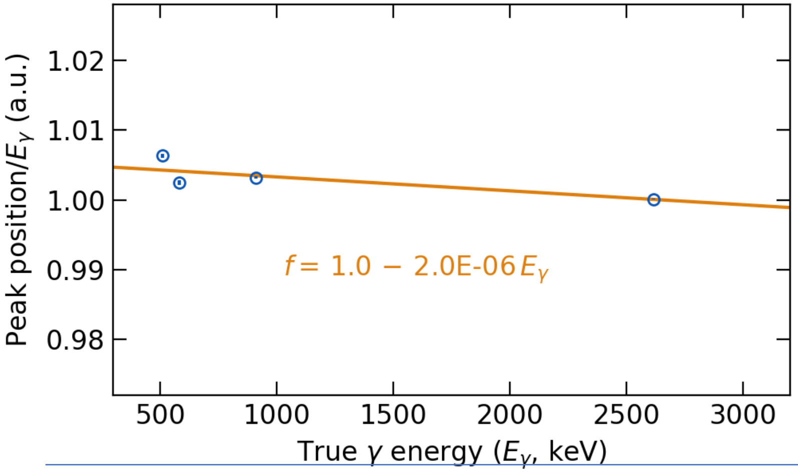


12 mK physics data	Exposure ($kg_{XMO}\cdot yr$)
Total	10.16
- Bad channels/runs	8.76
- deadtime & anti-coincidence (= live exposure)	8.02
in ^{100}Mo	3.88 ($kg_{ISO}\cdot yr$)

Energy Calibration



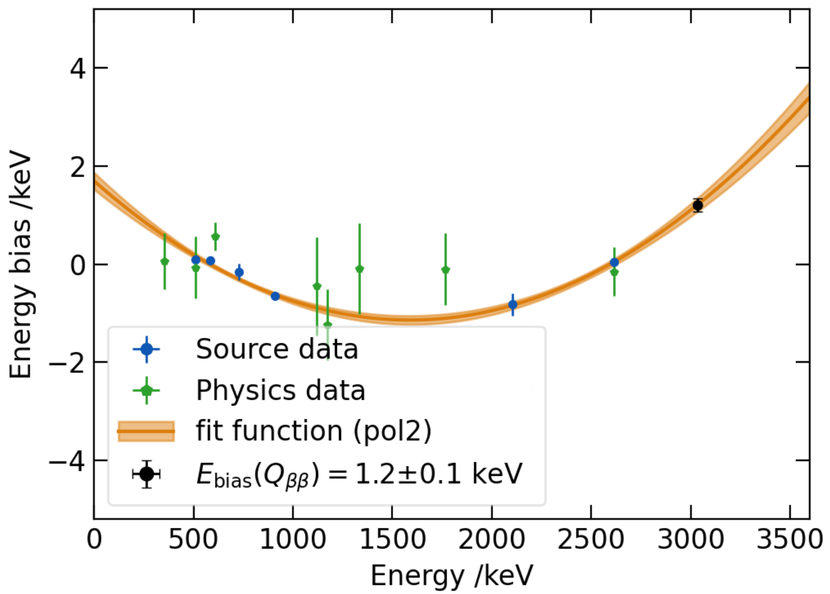


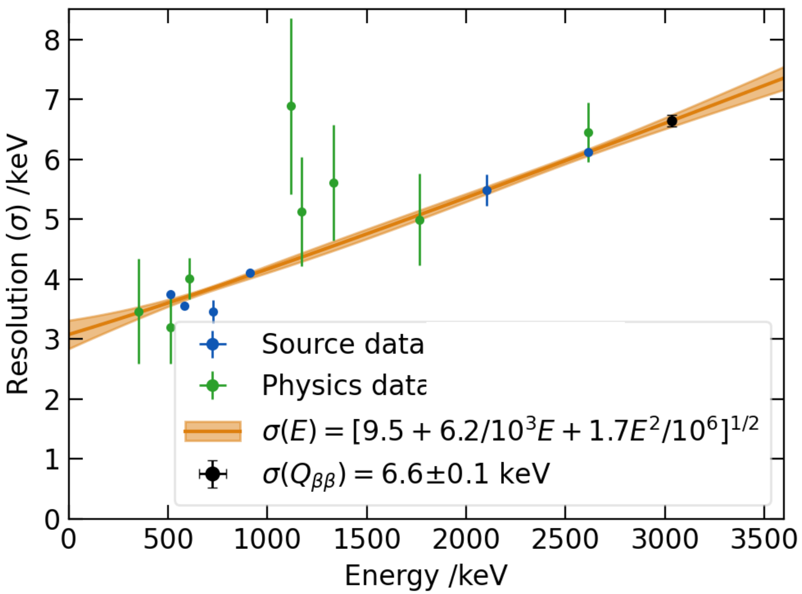


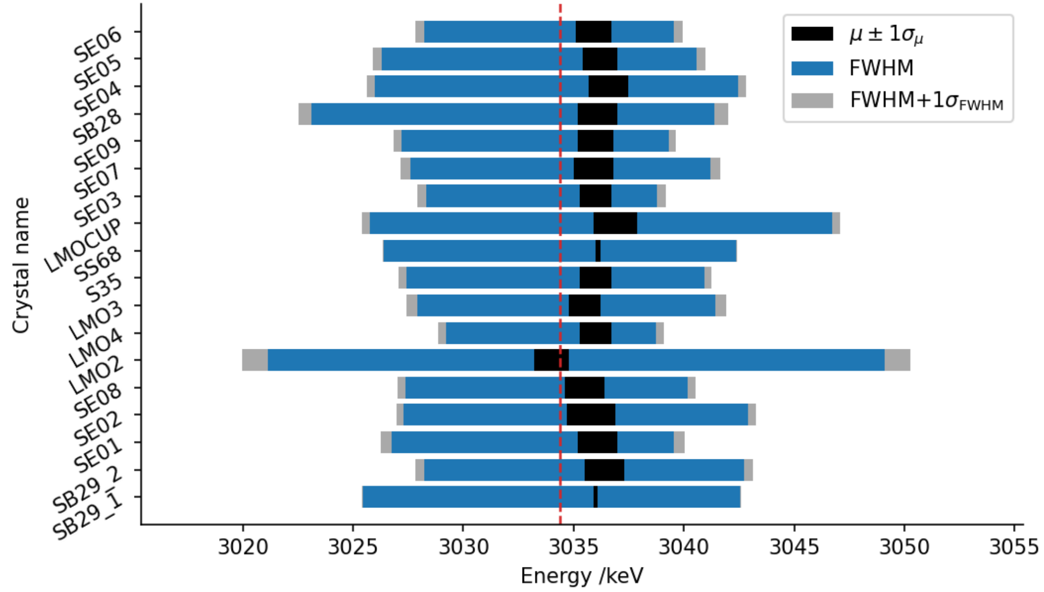
- Calibration source: ^{232}Th-rich welding rods
- Slight non-linearity between signal amplitude and energy.

- Bukin function instead of gaussian/exponentially modified gaussian – better fit to right tails https://root.cern.ch/doc/master/classRooBukinPdf.html

ROI estimation







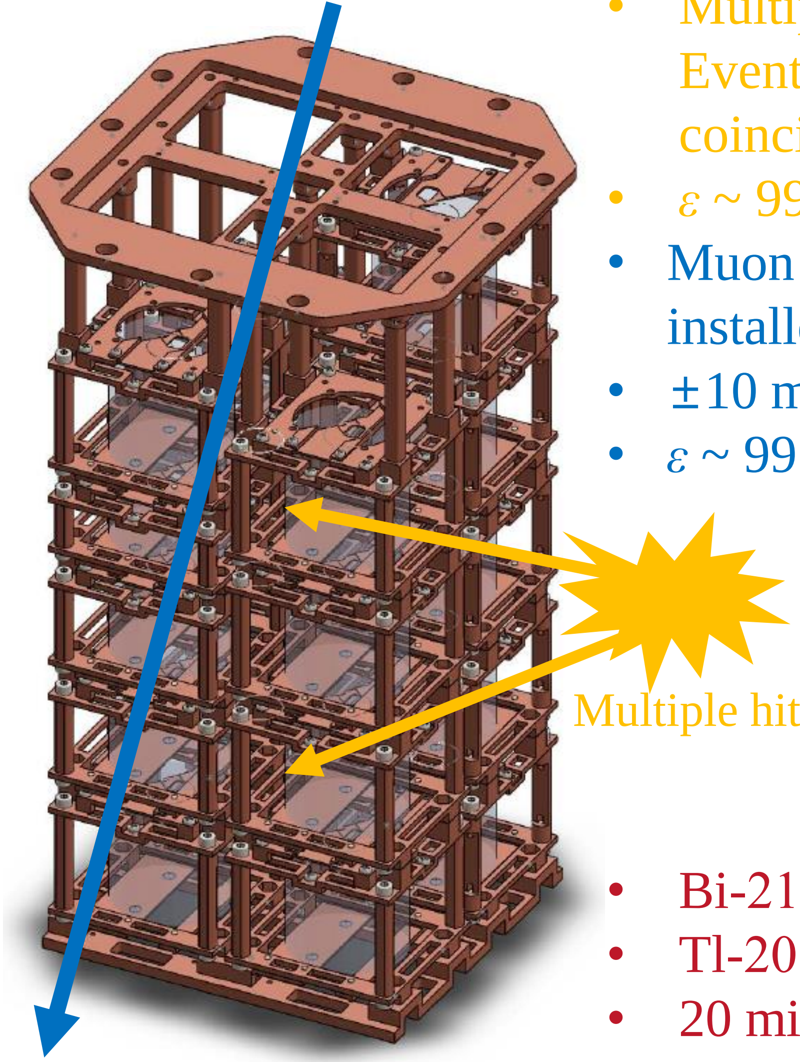
- E_{bias} ~ 2nd polynomial of energy
- $\sigma(E) = \sqrt{b_1 + b_2 E + b_3 E^2}$

(Fittings done only for source data)

$E_{bias}(Q_{\beta\beta})$: -0.4~2.5 keV
FWHM($Q_{\beta\beta}$): 9.5~28.0 keV

Particle Identification

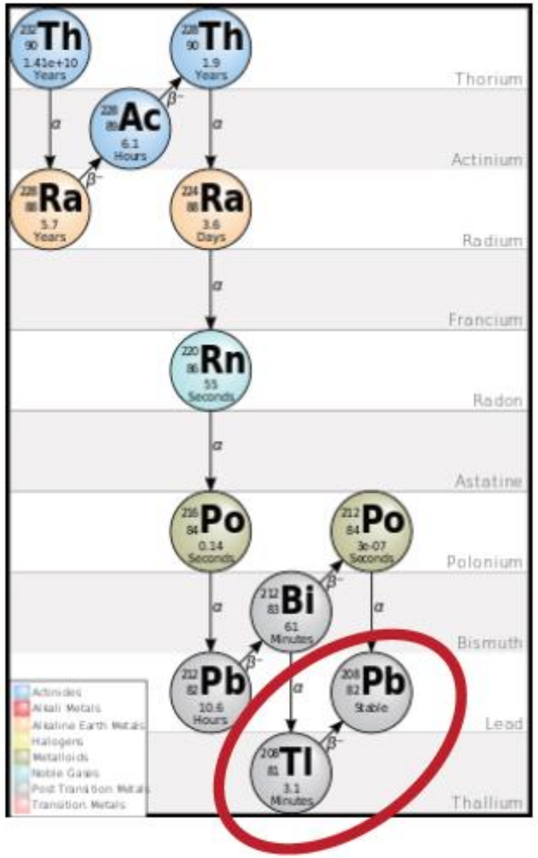
Anti-coincidence



Multiple hit events

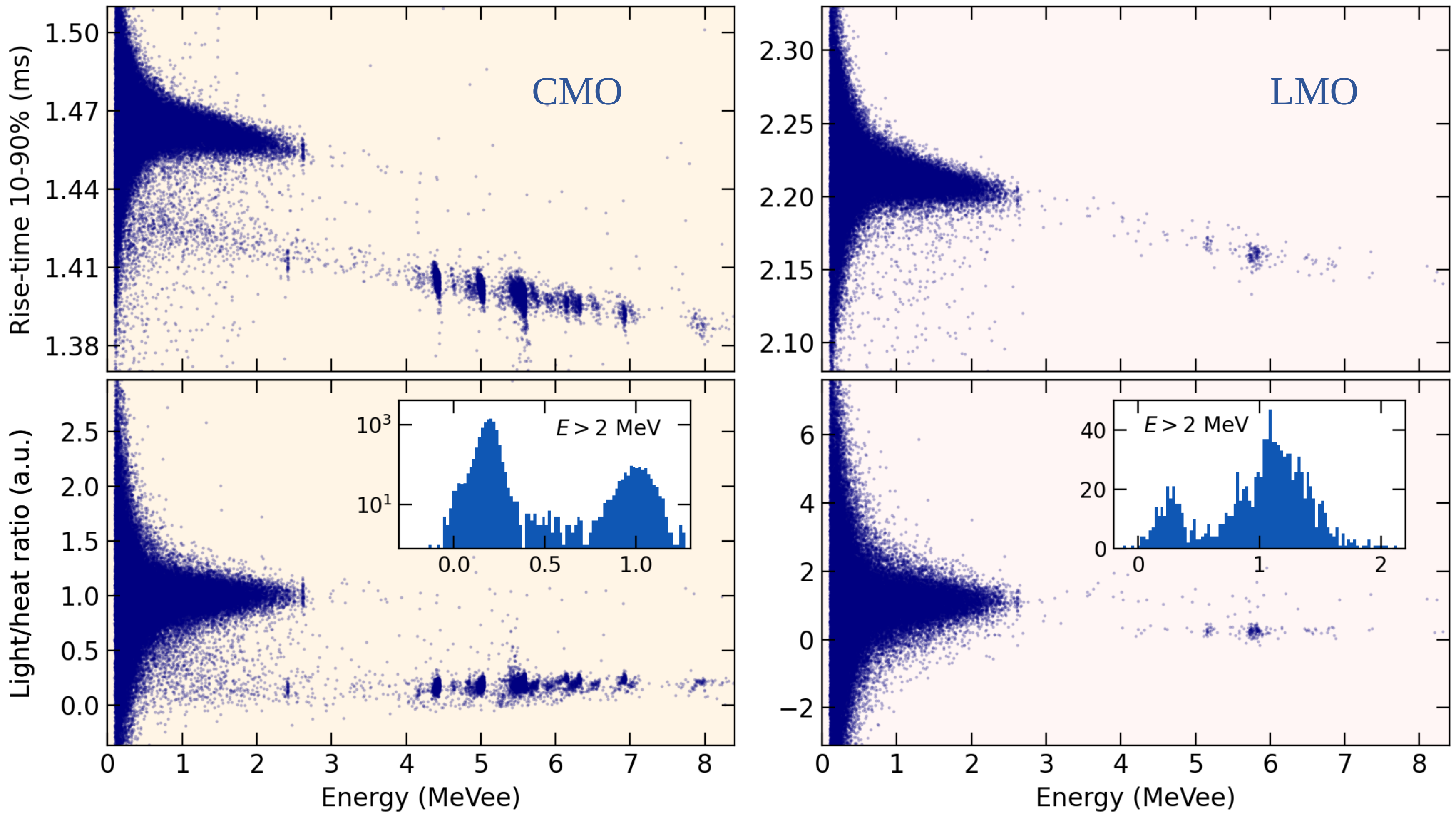
Cosmic ray induced events

- Multiple hits:
  Events within ±2ms time window is thought to be coincidental
- $\varepsilon \sim 99.8\%$
- Muon tagging data from Muon Veto System (MVS) installed outside of the cryostat
- ±10 ms windows are rejected
- $\varepsilon \sim 99.8\%$



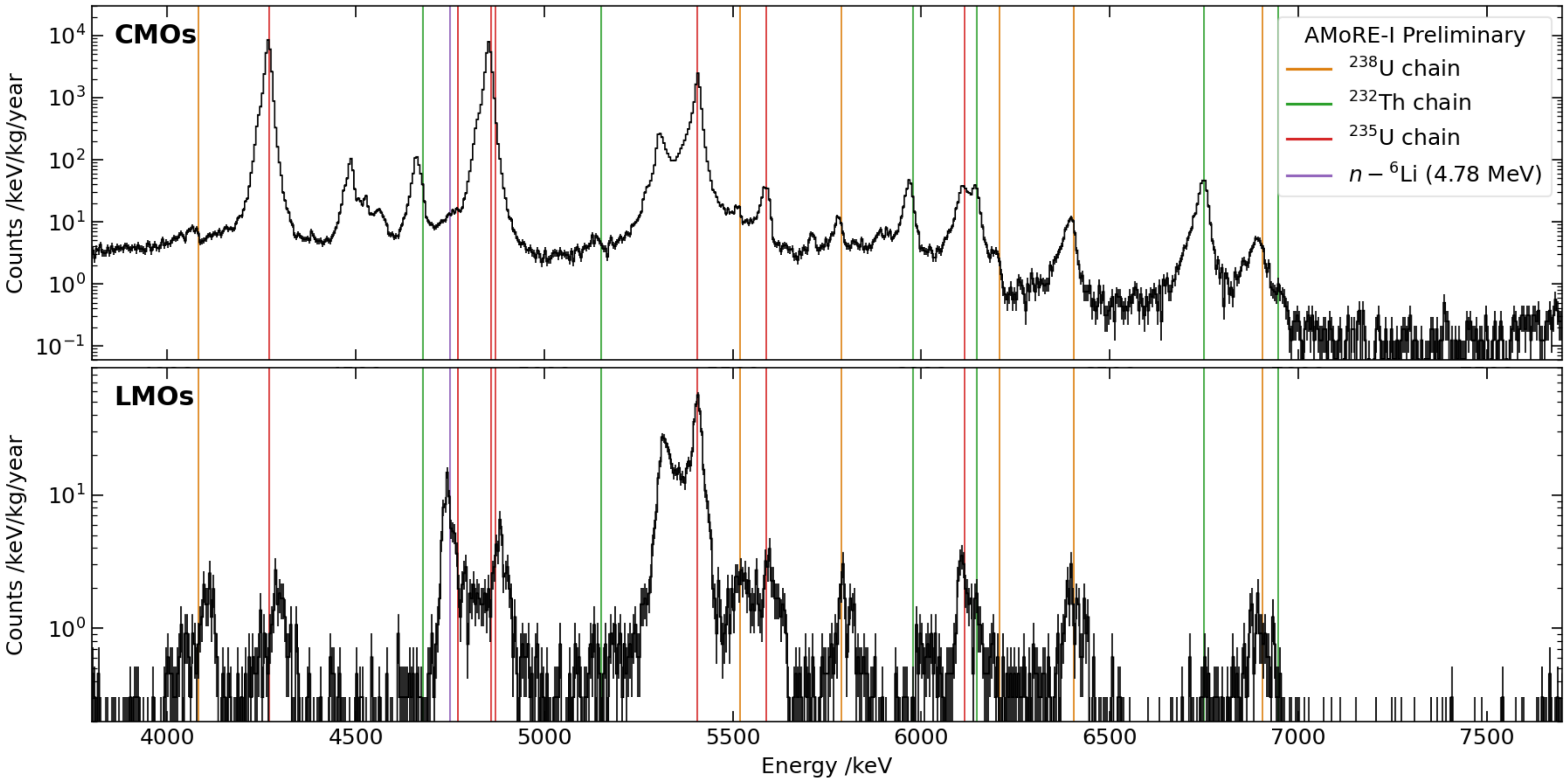
- Bi-212 → Tl-208 (α 35.94%): $T_{1/2}$=60.55 min, 6207.26 keV
- Tl-208 → Pb-208 (β): $T_{1/2}$=3.053 min, Q~5 MeV
- 20 min. window after each Bi-212 candidates are rejected
- $\varepsilon \sim 98\%$ (>99% for many crystals, ~82% for the worst case (SB29))

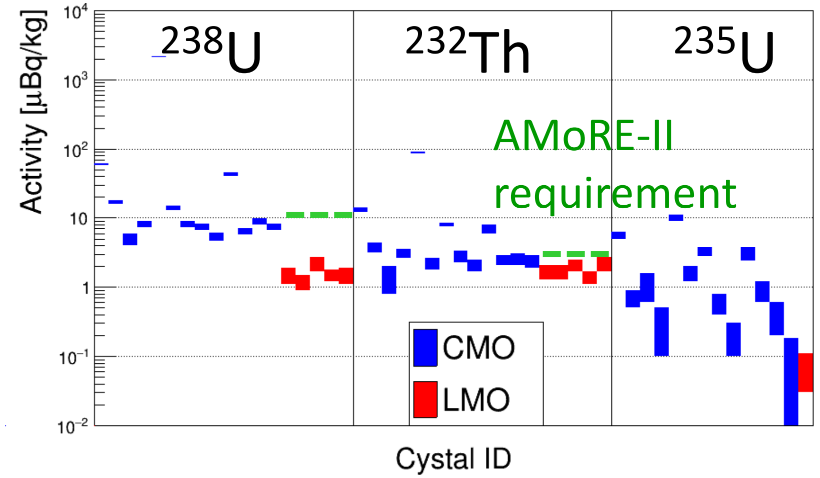
Particle Identification (PaID)



- CMO shows better discrimination power thanks to a higher light yield.
- $\varepsilon_{PaID,ROI}$ – 92.9~99.2 % with ±3 median absolute deviations (MAD) range of PSD & L/H (91.6 % if normally distribution that ±3 MAD (~±2σ) gives 95.70 % C.L.)

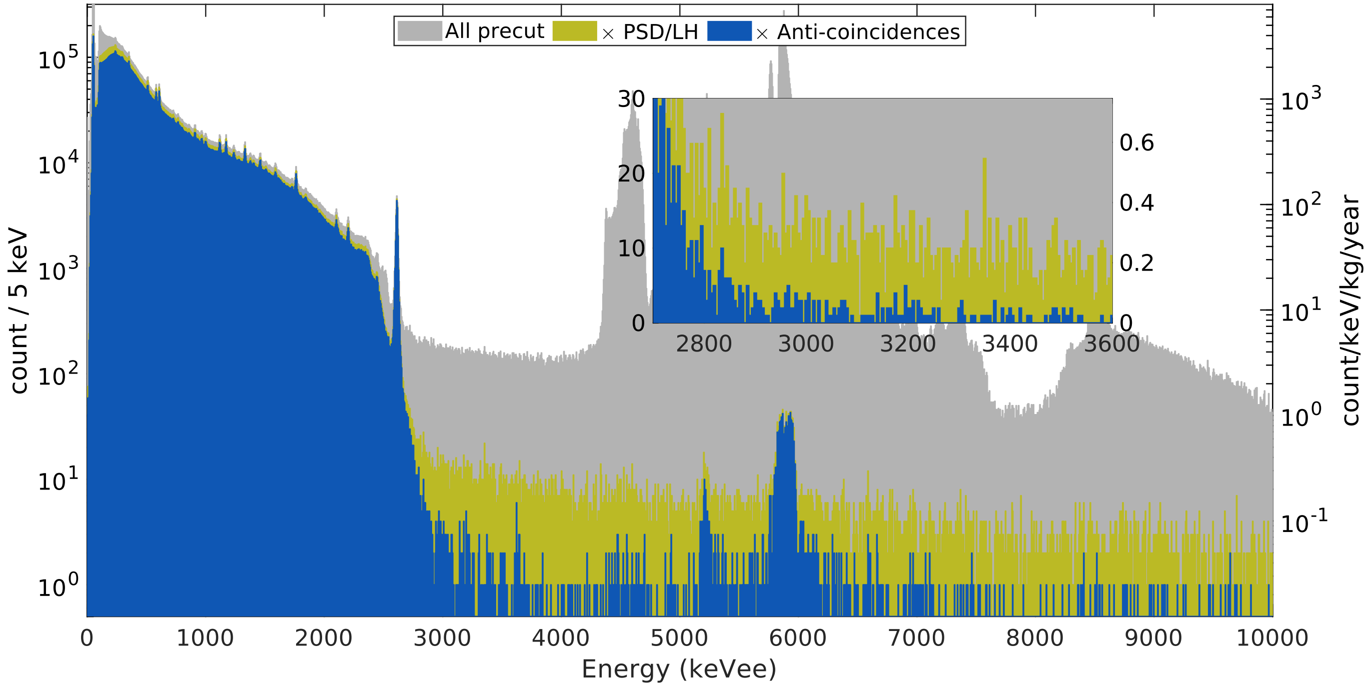
α background

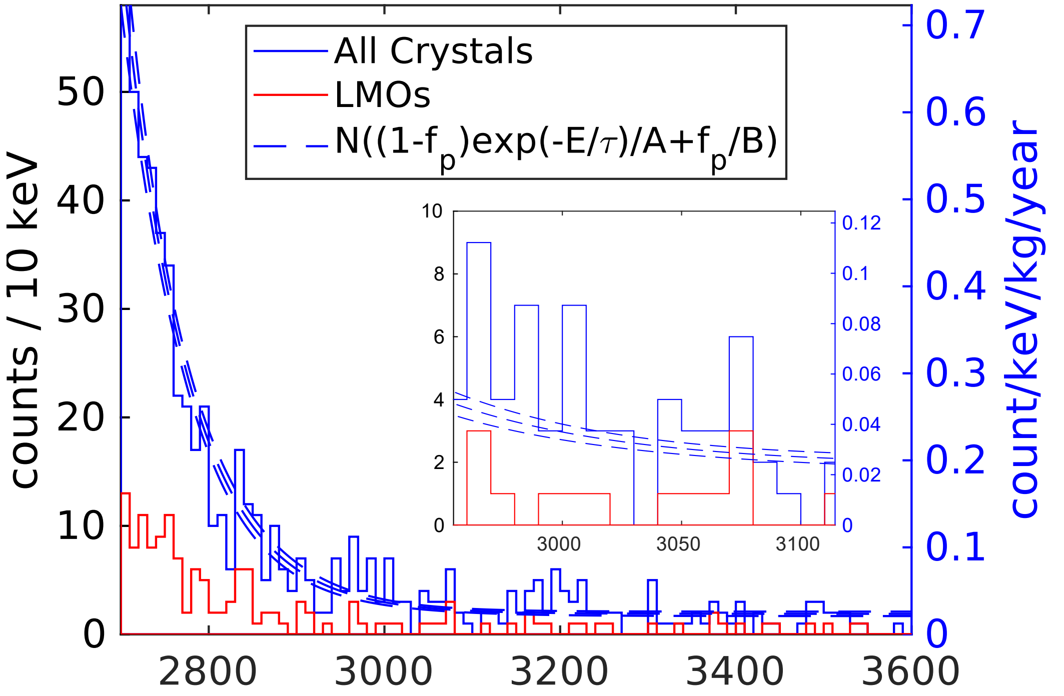




- Overall, the radioactive contamination by U/Th of LMO is measured to be substantially lower than that of CMO.

Physics Spectrum

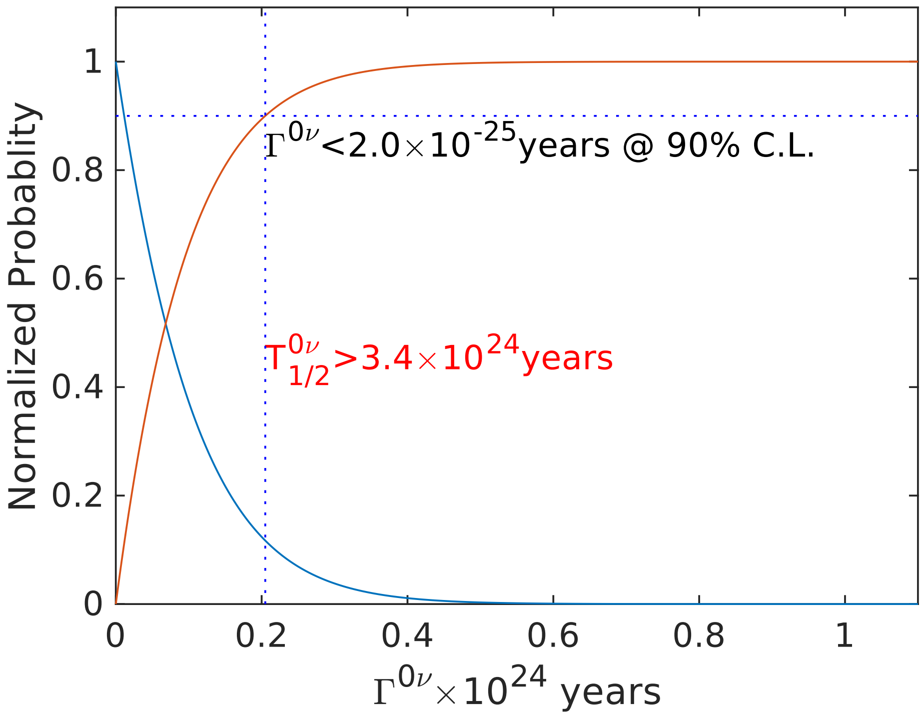




- All crystal excluding one LMO (for very poor β/α discrimination power)
  - 13 CMO + 4 LMO: exposure = 8.02 kg_{XMoO_4} ▪ yr = 3.88 $kg_{^{100}Mo}$ ▪ yr.
- Anti-coincidence cuts reject events:
  - coincident at multiple crystals within 2 ms (ε ~ 99.8%),
  - within 10 ms after a muon counter event (ε ~ 99.8%),
  - within 20 minutes after a ^{212}Bi α-decay event candidate (ε ~ 98%).

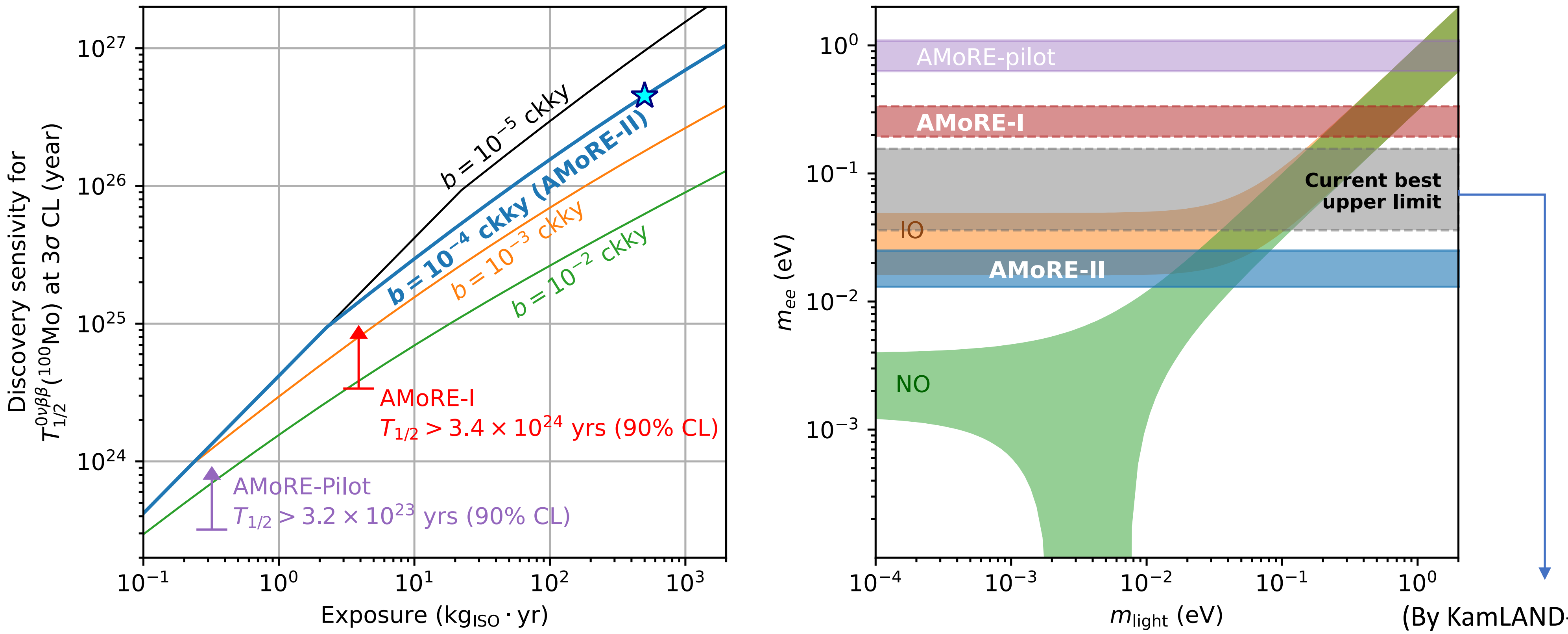
Live exposure	Bkg. @ $Q_{\beta\beta}$ / ckky
Total (8.02 kg_{XMoO_4} yr)	0.032±0.003
CMO (6.19 kg_{XMoO_4} yr)	0.031±0.003
LMO (1.83 kg_{XMoO_4} yr)	0.037±0.006

^{100}Mo 0νββ limit from AMoRE-I



- ROI = $\left|E - Q_{\beta\beta}\right| < 2.5\ \Delta E_{\mathrm{FWHM}}$, $\varepsilon_{\mathrm{containment}}$ ~ 81%.
- Background = 0.032 ± 0.003 counts/keV/kg/year, from ROI side-band.
- Unbinned likelihood for $\Gamma^{0\nu} (= \ln 2\ / T_{1/2})$ for each crystal, with signal shape and background rate constrained from calibration and sideband data, respectively.
- $T^{0\nu}_{1/2} > 3.4 \times 10^{24}$ years at 90% C.L.

Limits & Sensitivities



(By KamLAND-Zen
Phys. Rev. Lett. 130 (2023) 051801)

- AMoRE-II for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years by 100 kg of ^{100}Mo × 5 years running.
- Reduction of background level down below 10^{-4} ckky.

Summary

- AMoRE searches for $0\nu\beta\beta$ using ^{100}Mo based scintillating crystals at the low temperature.

- AMoRE-I took data for 29 months.

- Li_2MoO_4 shows lower discrimination power than $CaMoO_4$ with either PSD parameter or light/heat ratio while the alpha rate is much lower.

- Background rejections such as muon veto, multiple-hit-tagging and alpha(Bi212)-tagging efficiently suppress the background at ROI.

- Result of AMoRE-I:
  - Mass×time live exposure: 8.02 (3.88) kg・yr $XMoO_4$ (^{100}Mo).
  - Background level ~ 0.032 counts/keV/kg/year at $Q_{\beta\beta}$.
  - Resolution: 9.5 – 28.0 keV at $Q_{\beta\beta}$
  - PaID efficiency is better than normally distributed case (>91.6%)
  - Half-life limit: $T^{0\nu}_{1/2} > 3.4 \times 10^{24}$ yr.

Thank you!