

Result of AMoRE-I

KIM Hanbeom,
On Behalf of the AMoRE Collaboration

TAUP2023, University of Vienna, Austria

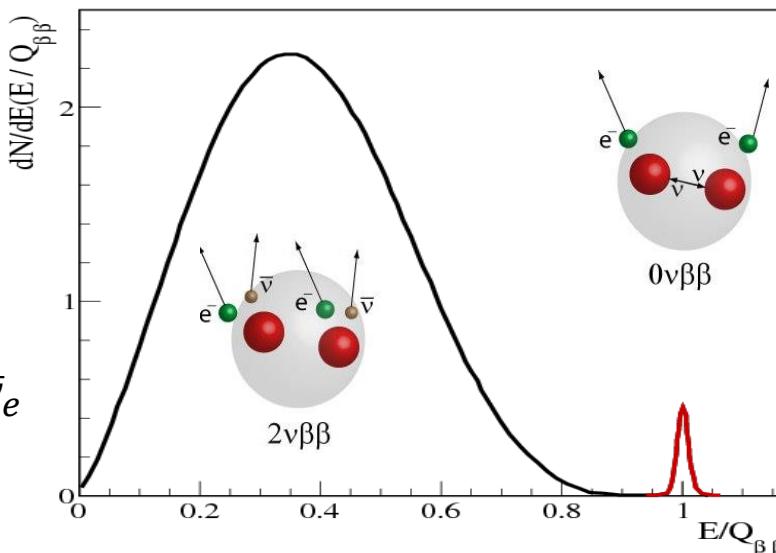
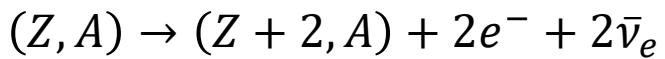
Aug. 28th –Sep.1st, 2023

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

AMoRE:

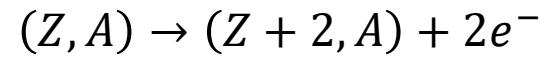
A search for neutrinoless double beta ($0\nu\beta\beta$) decay of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.

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



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

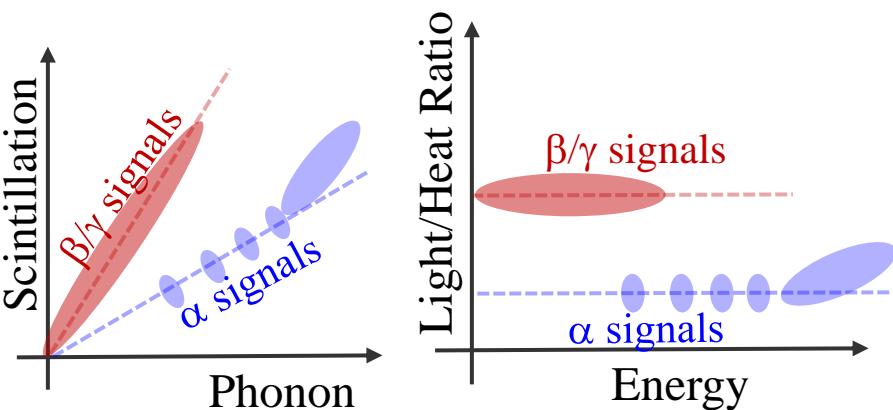
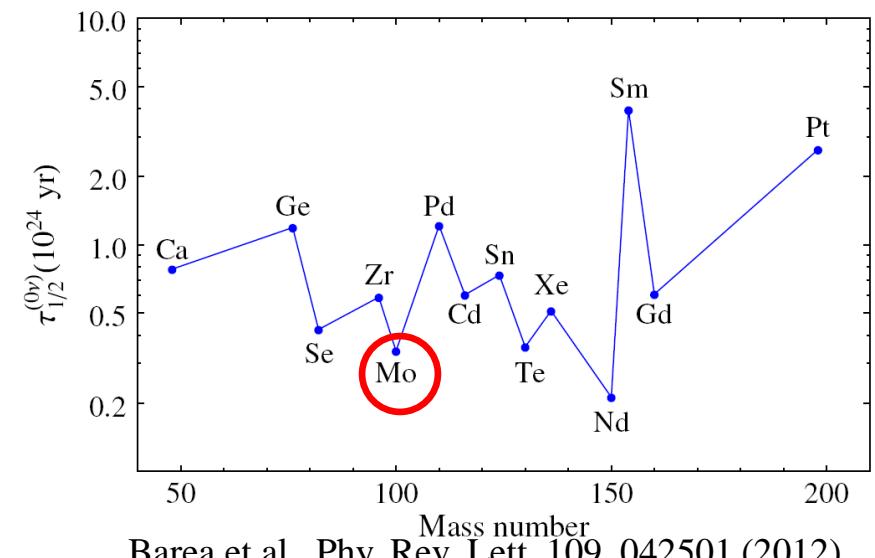
$0\nu\beta\beta$ decay
- Massive neutrino
- Majorana particle
- Lepton number violation
- Beyond the SM model
- $>10^{25}$ years of half-life



0νββ search using ^{100}Mo

^{100}Mo :

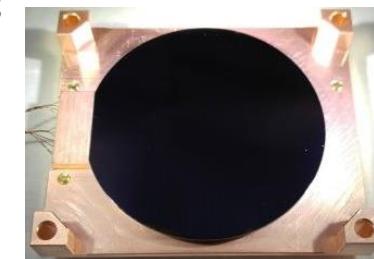
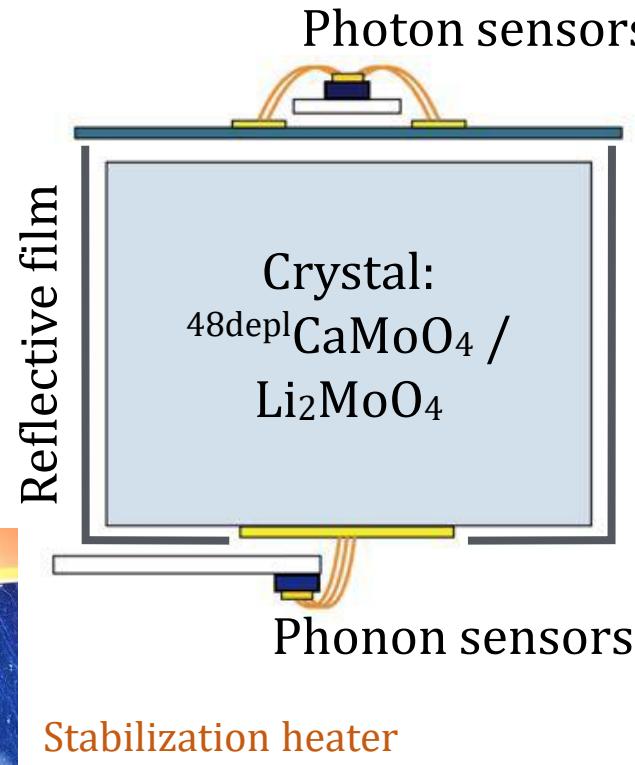
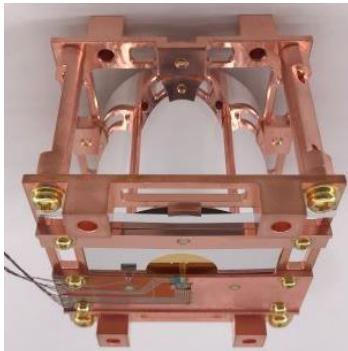
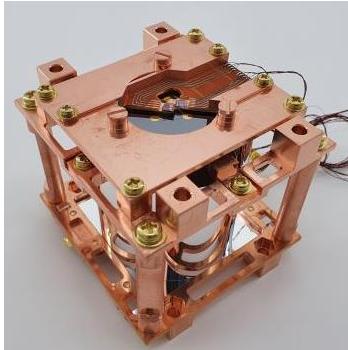
- High $Q_{\beta\beta} = 3034 \text{ keV}$
- High natural abundance: 9.7 %
- Scintillation crystals with ^{100}Mo enrichment > 95% —XMo_aO_b (XMO):
 - X=Ca, Li₂, Na₂, Zn, Sr, Pb, ...
 - Detection of light/heat signal → rejection of surface- α background.
- Relatively short half life (0νββ) in theoretical expectation



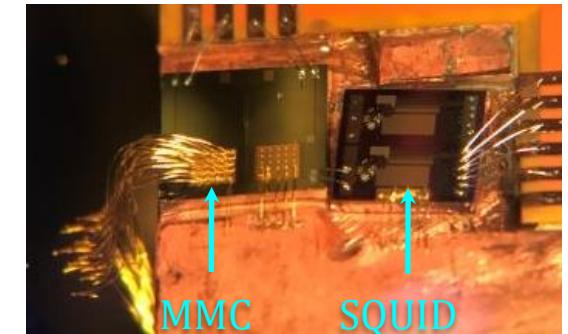
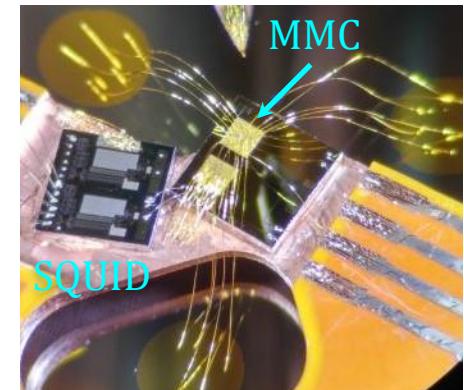
$\beta\beta$ -decay nuclei with $Q > 2 \text{ MeV}$	Q (MeV)	Abund. (%)
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr} \rightarrow ^{96}\text{Ru}$	3.350	2.8
$^{100}\text{Mo}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

Detector Module

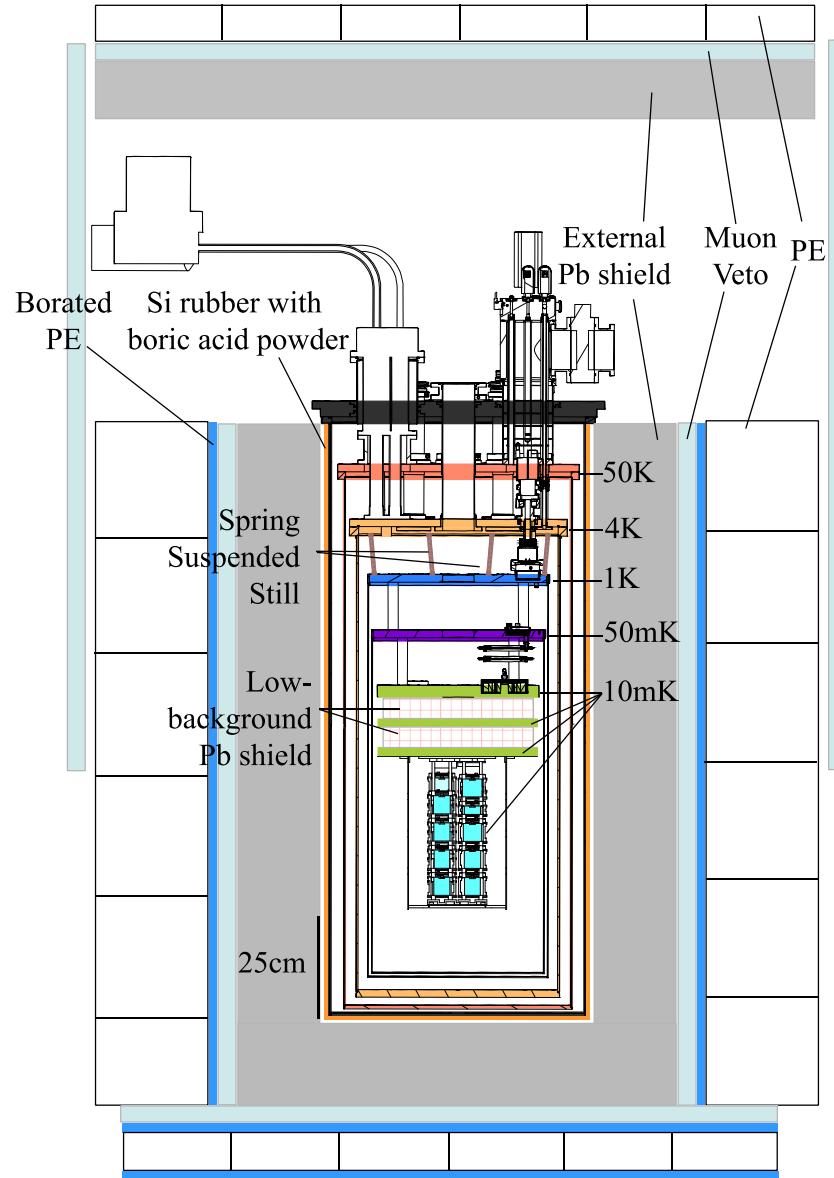
- (Elliptic) cylindrical CMO and LMO crystals, sizes vary $\Phi \geq 4 \text{ cm} / H \lesssim 5 \text{ cm}$.
 - CMO: ^{48}Ca depleted, ^{100}Mo enriched, $Q_{\beta\beta}(^{48}\text{Ca}) = 4271 \text{ keV}$. LMO: ^{100}Mo enriched
- Metallic magnetic calorimeter (MMC) + SQUID:
 - Fast signal timing: a few millisecond rise-time for phonon signals at mK.
 - Low random coincidence background.
 - Energy resolution $\sim 10 \text{ keV FWHM}$ at 2.6 MeV.
 - Wide dynamic range
 - High linearity



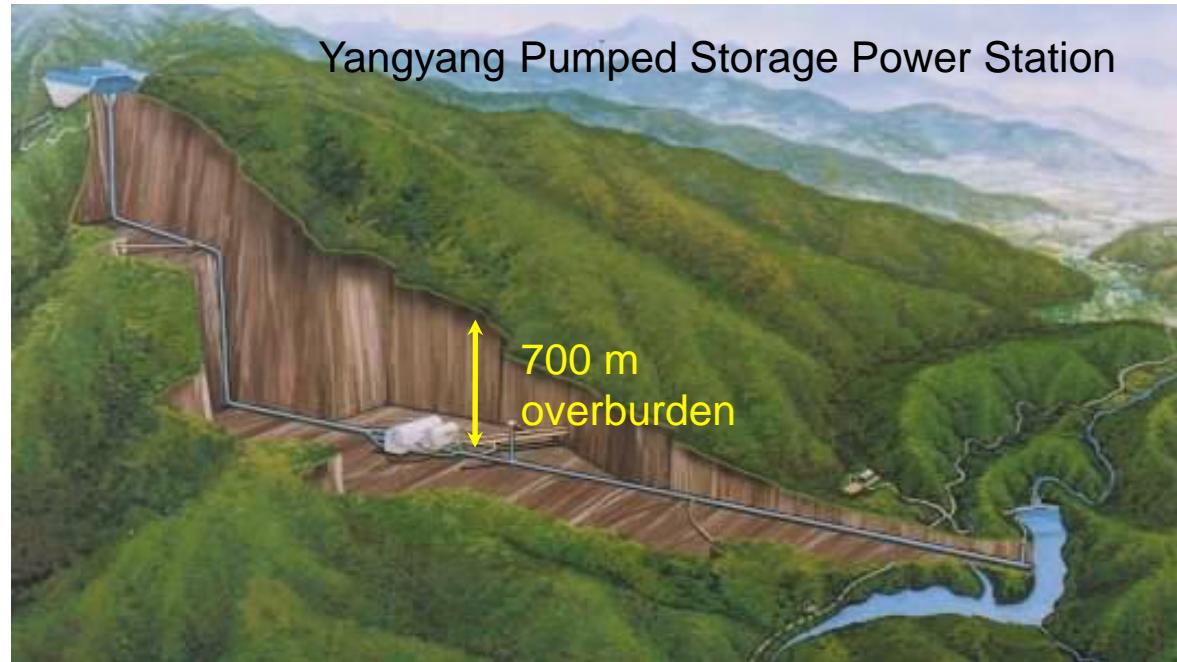
Light absorber
(Ge/Si wafer)



Cryostat, Shielding & Underground

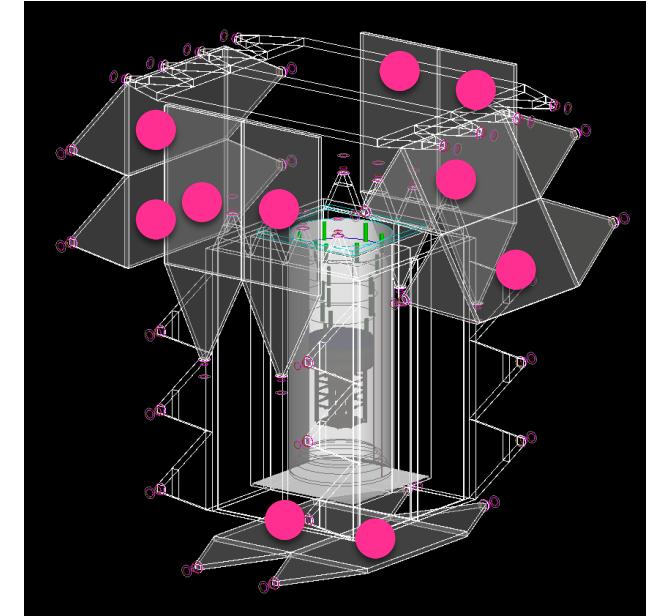
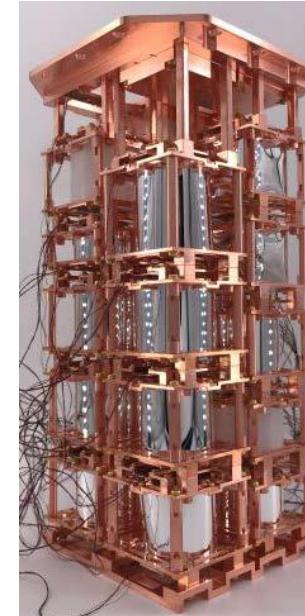
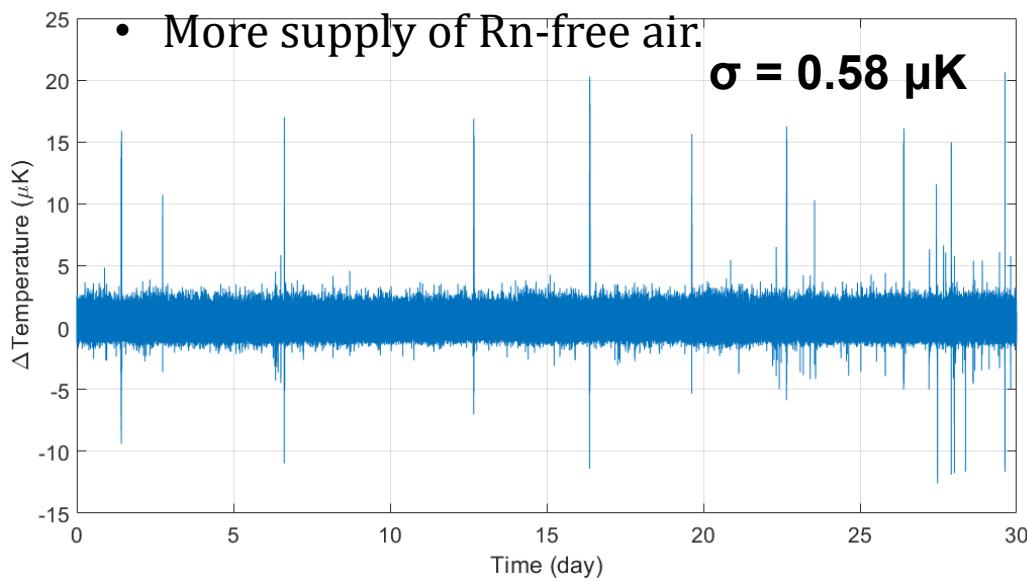


- Cryogen-free dilution refrigerator for AMoRE-pilot (2016~2018) and AMoRE-I.
- $\sim 1 \mu\text{W}$ cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counters.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.



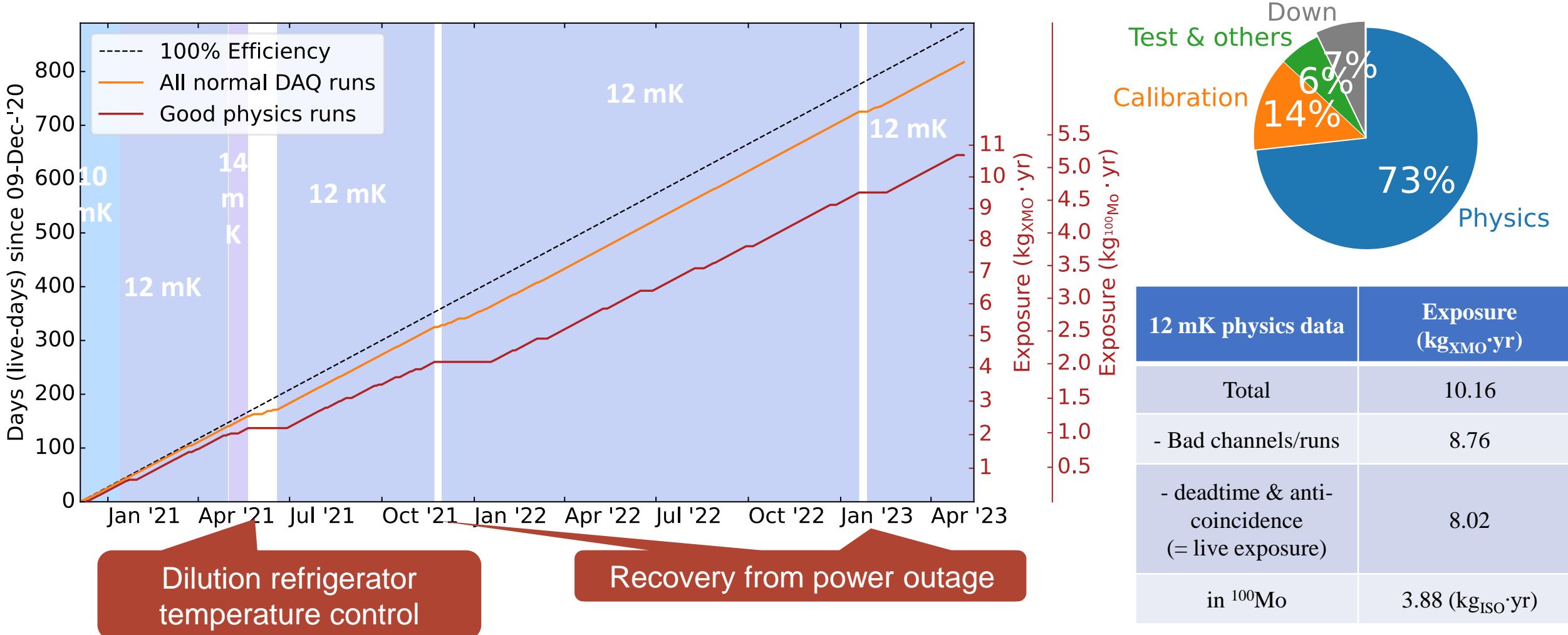
AMoRE-pilot → AMoRE-I

- 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. ($\sim 1/T^2$ heat capacity component associated with nuclear quadrupole moments removed)
- Using same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1 \mu\text{K}$.
- Shielding enhancements:
 - Outer Pb: 15 → 20 cm; neutron shields: boric acid silicon + more polyethylene.
 - More muon counter coverage. ($\sim 4\pi$)
 - More supply of Rn-free air.

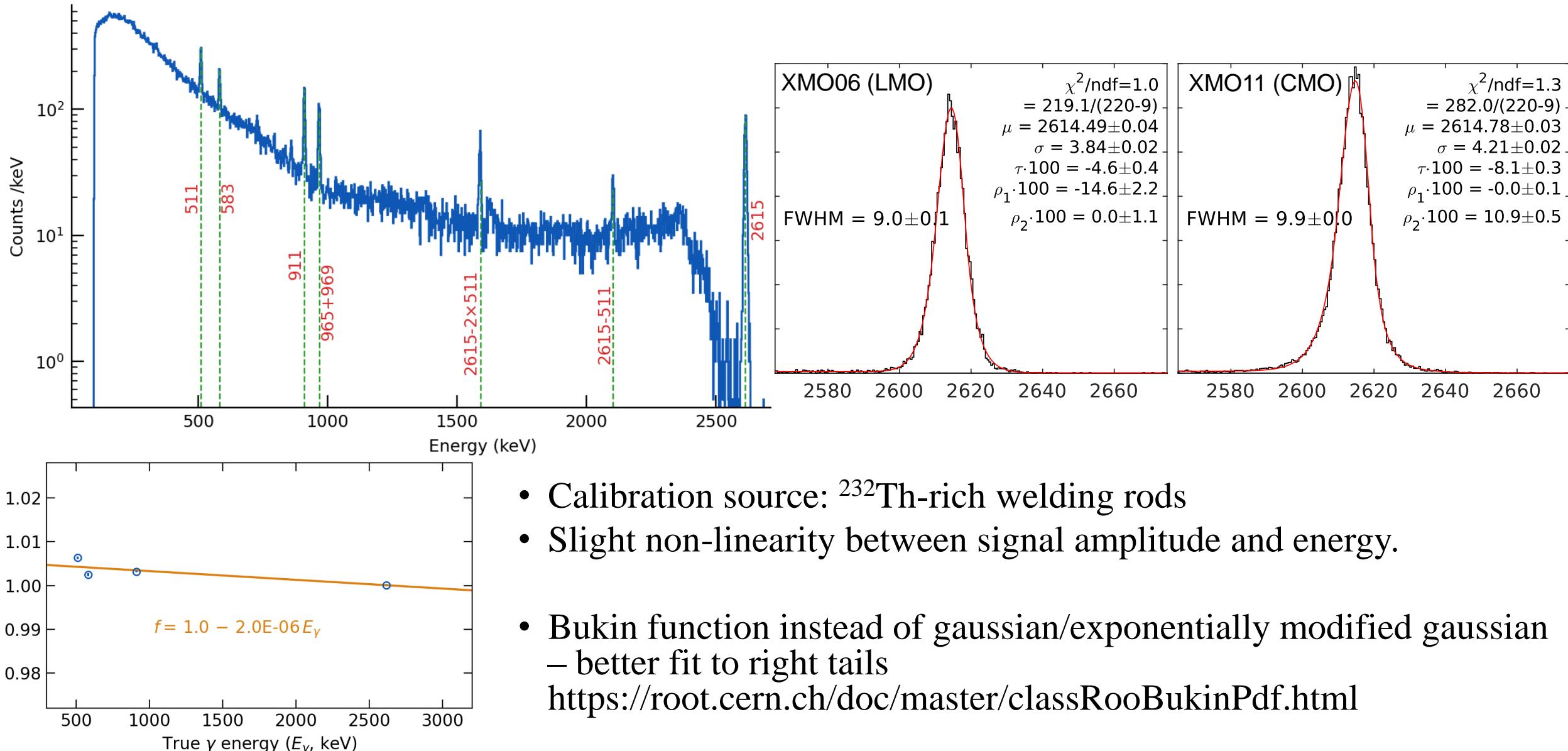


Muon counters

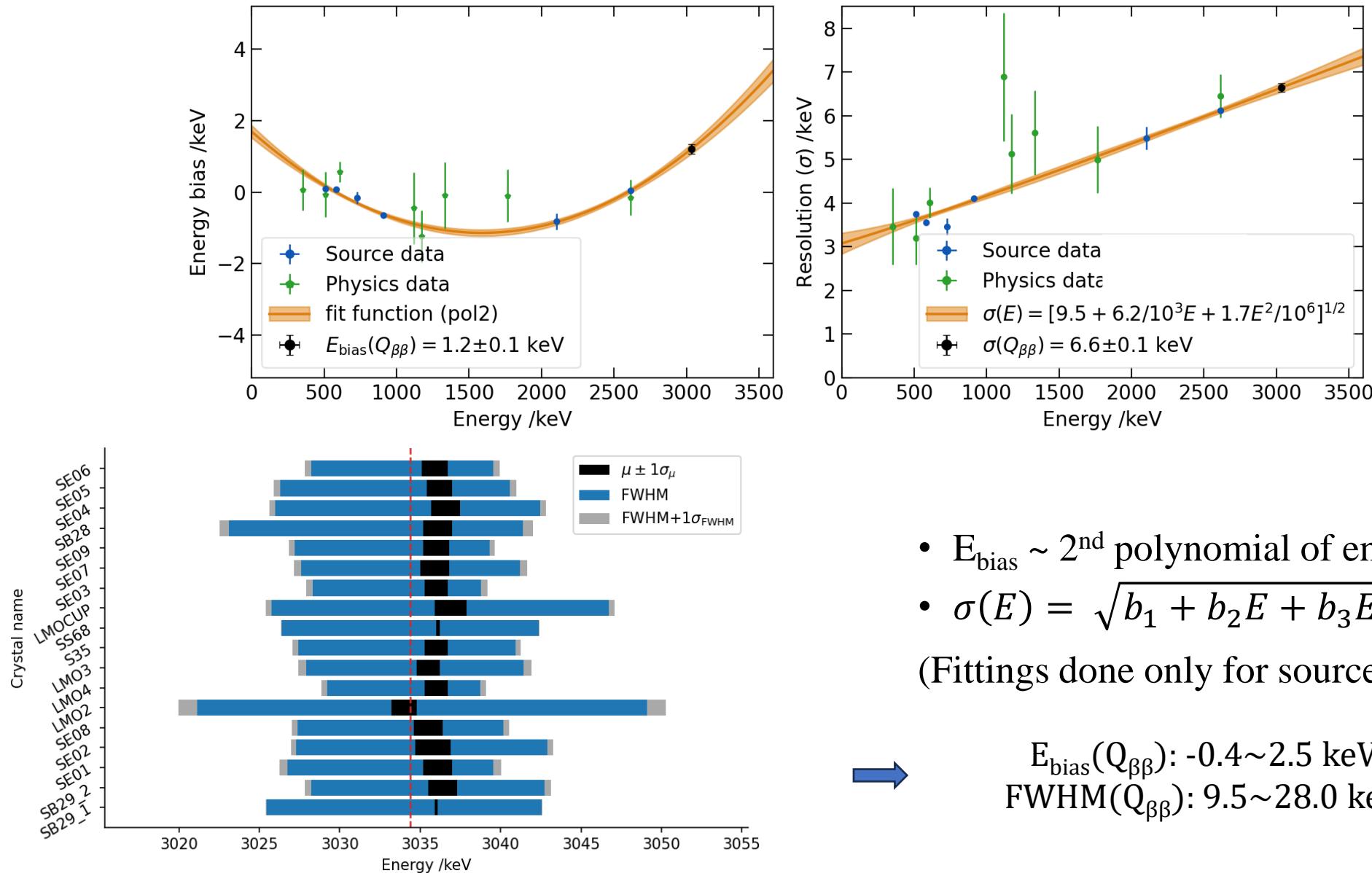
AMoRE-I data taking



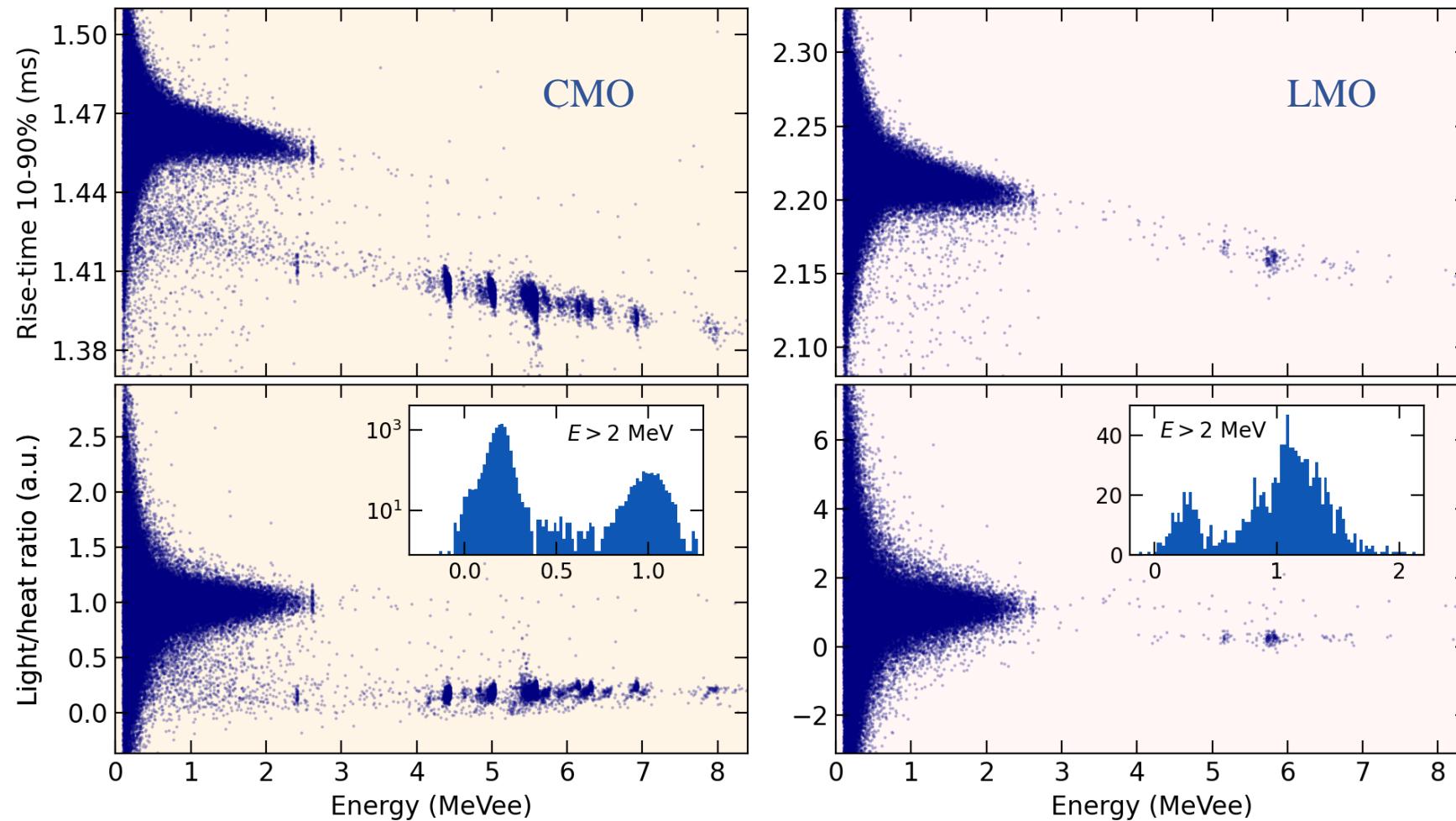
Energy Calibration



ROI estimation

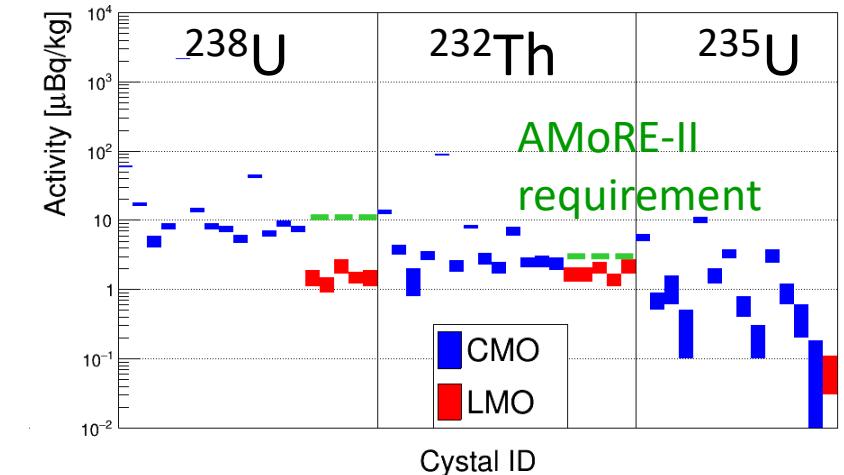
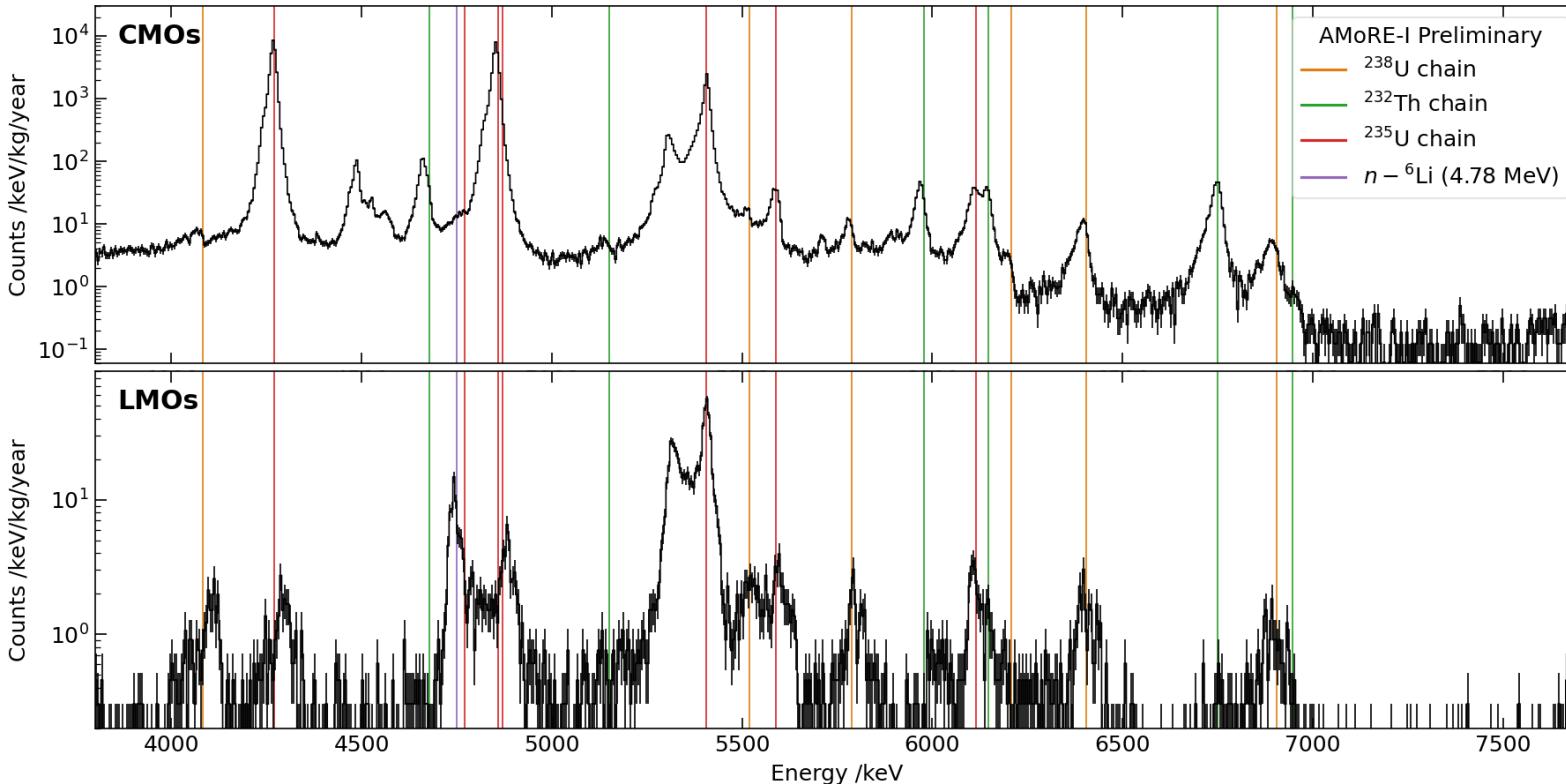


Particle Identification (PaID)



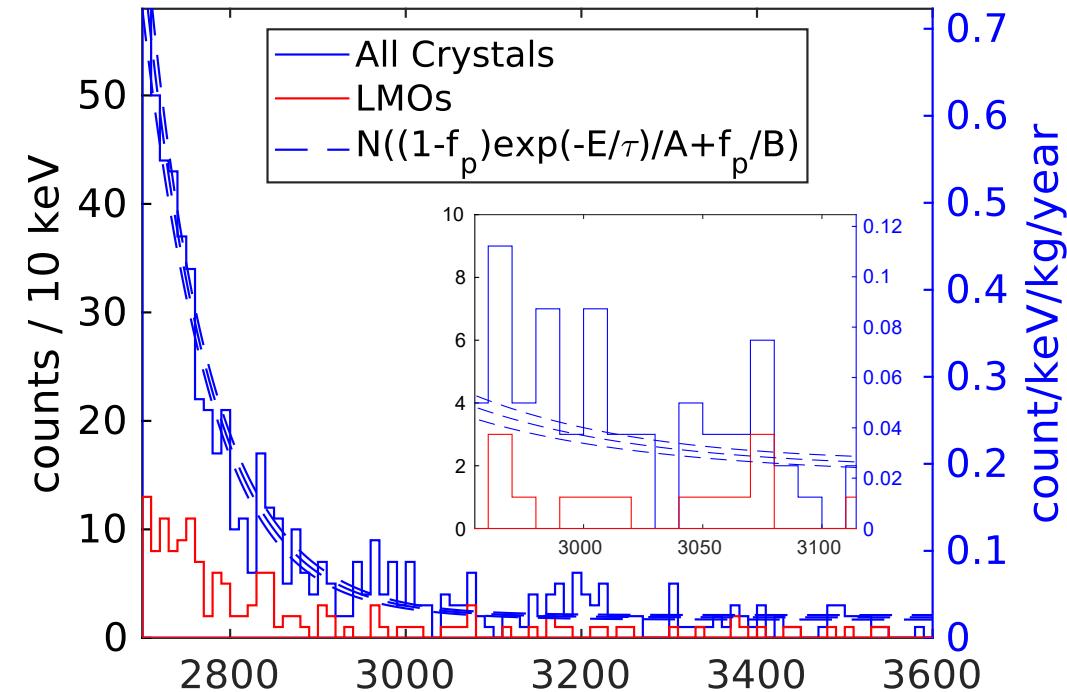
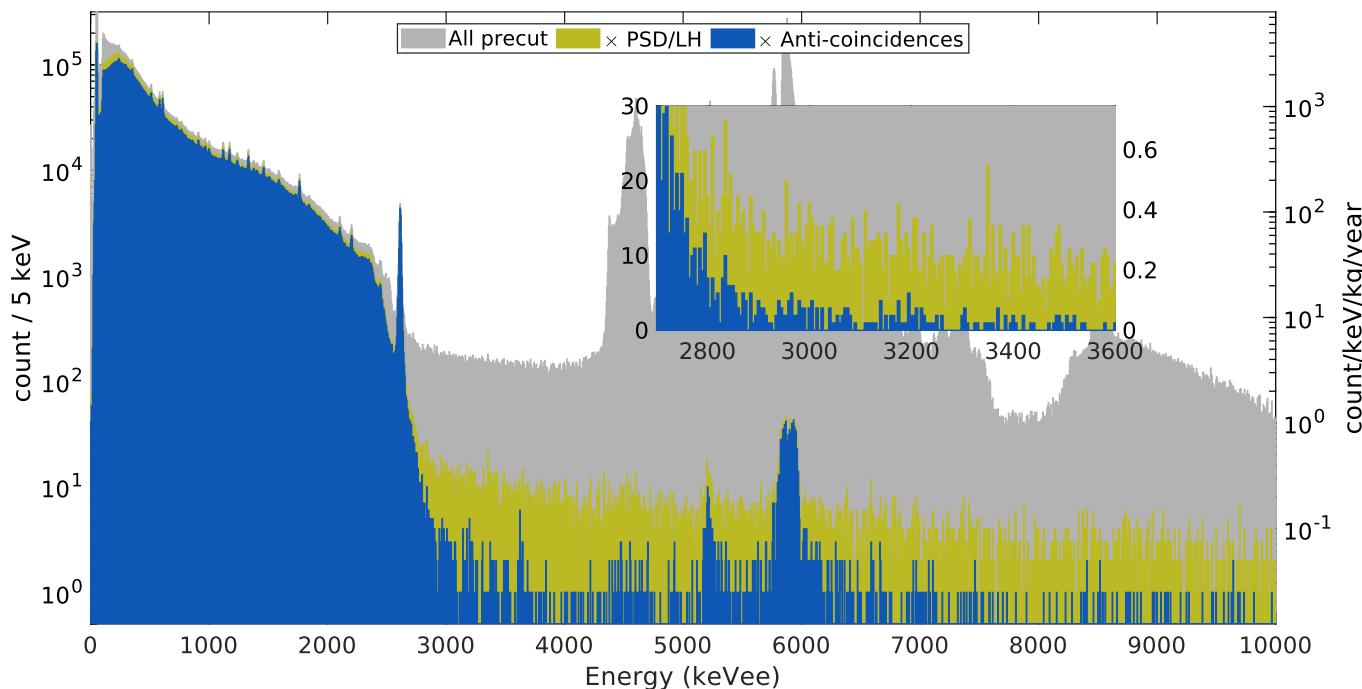
- CMO shows better discrimination power thanks to a higher light yield.
- $\epsilon_{\text{PaID,ROI}} - 92.9\text{--}99.2\%$ with ± 3 median absolute deviations (MAD) range of PSD & L/H (91.6 % if normally distribution that ± 3 MAD ($\sim \pm 2\sigma$) gives 95.70 % C.L.)

α background



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

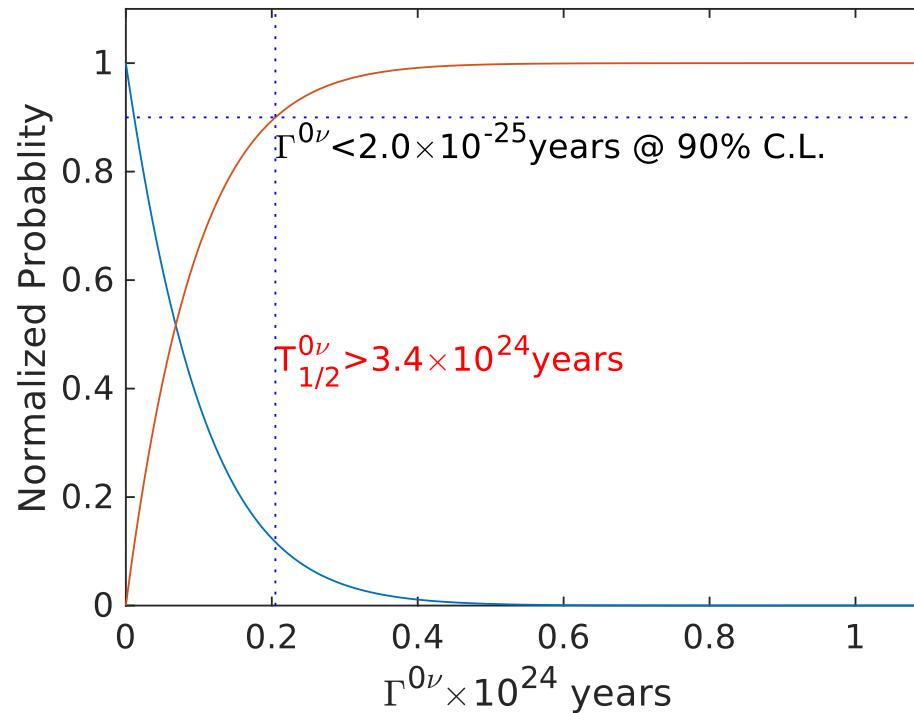
Physics Spectrum



- All crystal excluding one LMO (for very poor β/α discrimination power)
 - 13 CMO + 4 LMO: exposure = $8.02 \text{ kg}_{\text{XMoO}_4} \cdot \text{yr} = 3.88 \text{ kg}^{100\text{Mo}} \cdot \text{yr}$.
- Anti-coincidence cuts reject events:
 - coincident at multiple crystals within 2 ms ($\varepsilon \sim 99.8\%$),
 - within 10 ms after a muon counter event ($\varepsilon \sim 99.8\%$),
 - within 20 minutes after a ^{212}Bi α -decay event candidate ($\varepsilon \sim 98\%$).

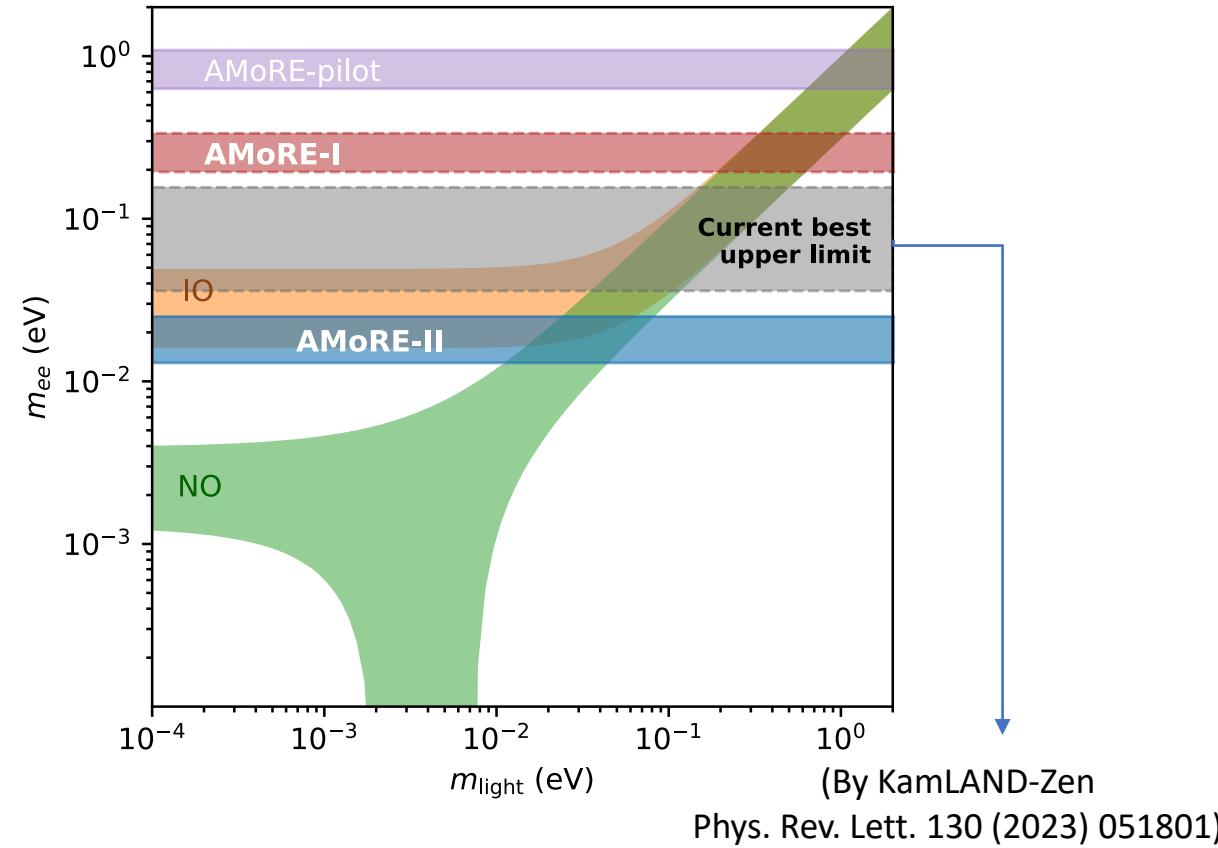
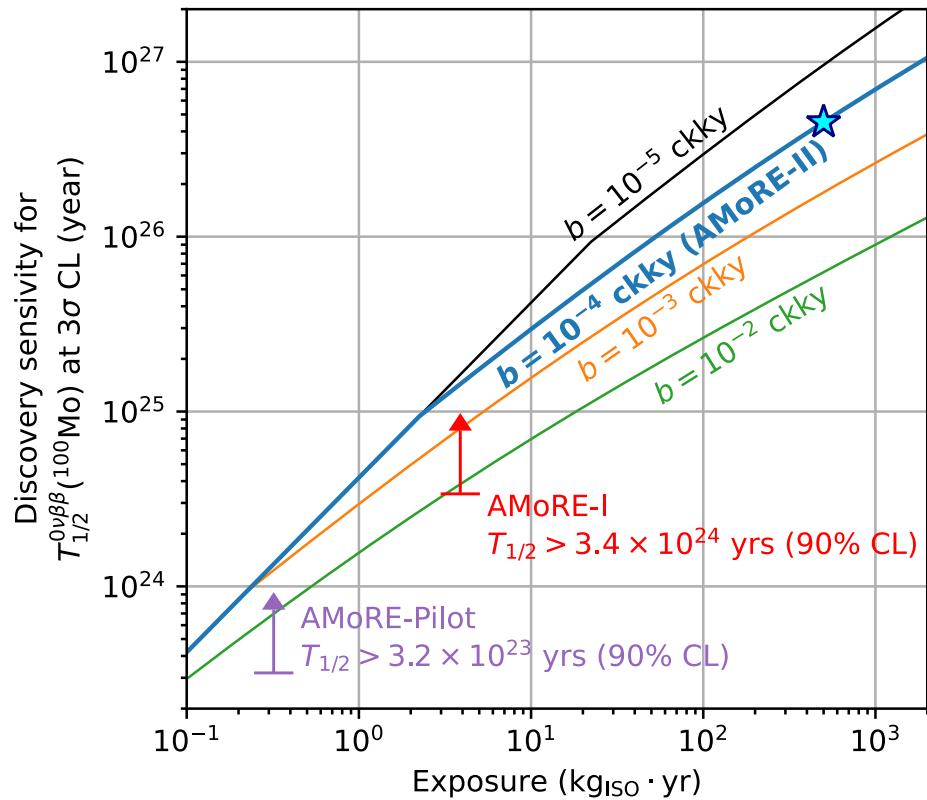
Live exposure	Bkg. @ $Q_{\beta\beta}$ / ckky
Total (8.02 kg _{XMoO₄} yr)	0.032 ± 0.003
CMO (6.19 kg _{XMoO₄} yr)	0.031 ± 0.003
LMO (1.83 kg _{XMoO₄} yr)	0.037 ± 0.006

^{100}Mo $0\nu\beta\beta$ limit from AMoRE-I



- $\text{ROI} = |E - Q_{\beta\beta}| < 2.5 \Delta E_{\text{FWHM}}$, $\varepsilon_{\text{containment}} \sim 81\%$.
- 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.
- $T_{1/2}^{0\nu} > 3.4 \times 10^{24}$ years at 90% C.L.

Limits & Sensitivities



- AMoRE-II for $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years by 100 kg of $^{100}\text{Mo} \times 5$ 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(Bi^{212})-tagging efficiently suppress the background at ROI.
- Result of AMoRE-I:
 - Mass \times time live exposure: 8.02 (3.88) $\text{kg} \cdot \text{yr}$ 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: $T_{1/2}^{0\nu} > 3.4 \times 10^{24}$ yr.

Thank you!