Status of the AMoRE experiment

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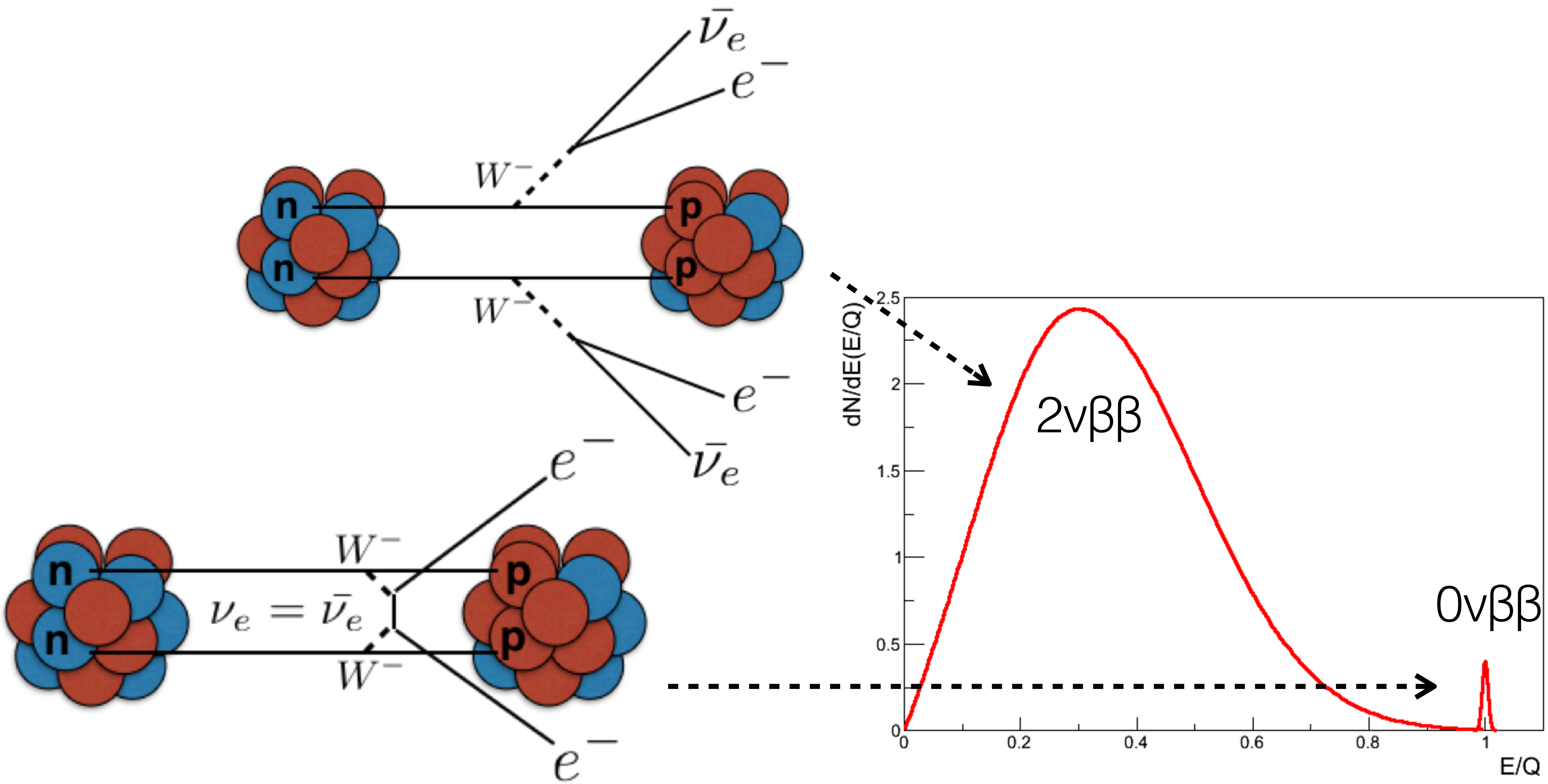
On behalf of the AMoRE collaboration

18th Rencontres du Vietnam, Neutrino physics
ICISE, July 2022

Neutrinoless double beta decay (0vββ) ?

Double β decay
=> In some even-even nuclei, single β decay forbidden
But, double β decays may be allowed
=> Two modes : 2vββ (T~10^{18}-10^{24} yrs), 0vββ (T>10^{26} yrs)



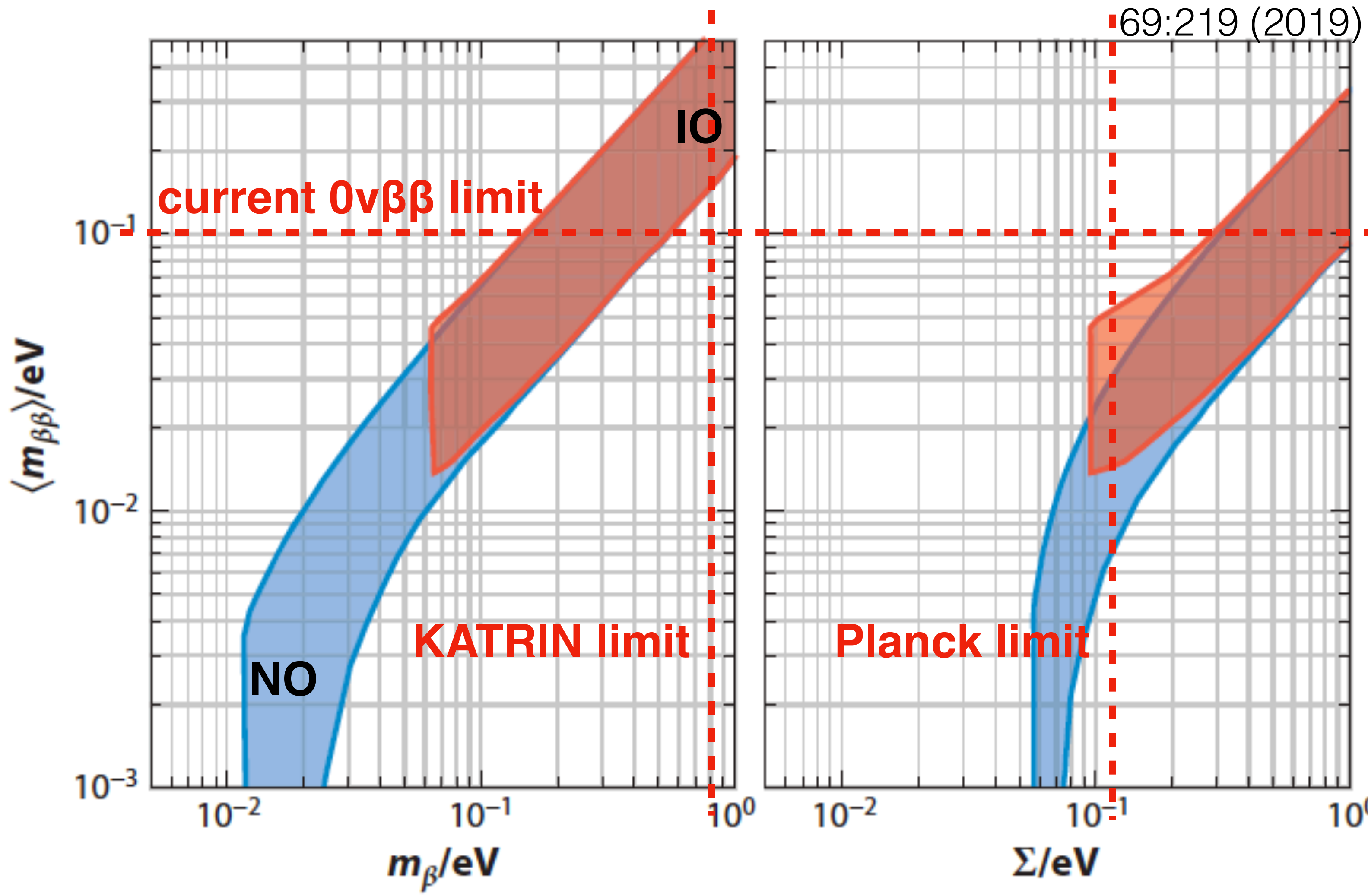
Why 0νββ ?

Lepton number non-conserving process
=> Process beyond the standard model
=> Leptogenesis / Baryon asymmetry

Revealing unknown properties of neutrinos
=> Unambiguous signature for Majorana nature of neutrinos
=> Absolute Neutrino mass

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Annu.Rev.Nucl.Part.Sci 69:219 (2019)



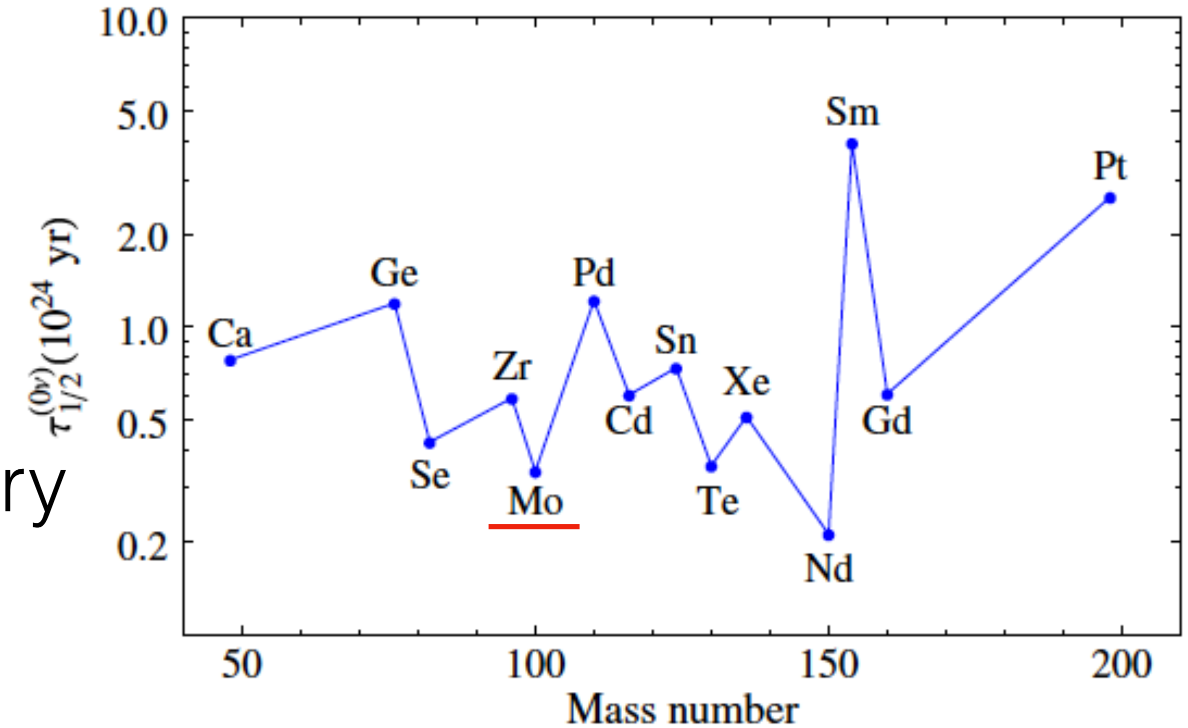
Direct mass measurement

CMB

AMoRE experiment

0νββ source : ^{100}Mo isotope

=> relatively high Q-value: 3034 keV
shorter half-life expected
=> high natural abundance of 9.7 %
=> Nuclide with long DBD search history

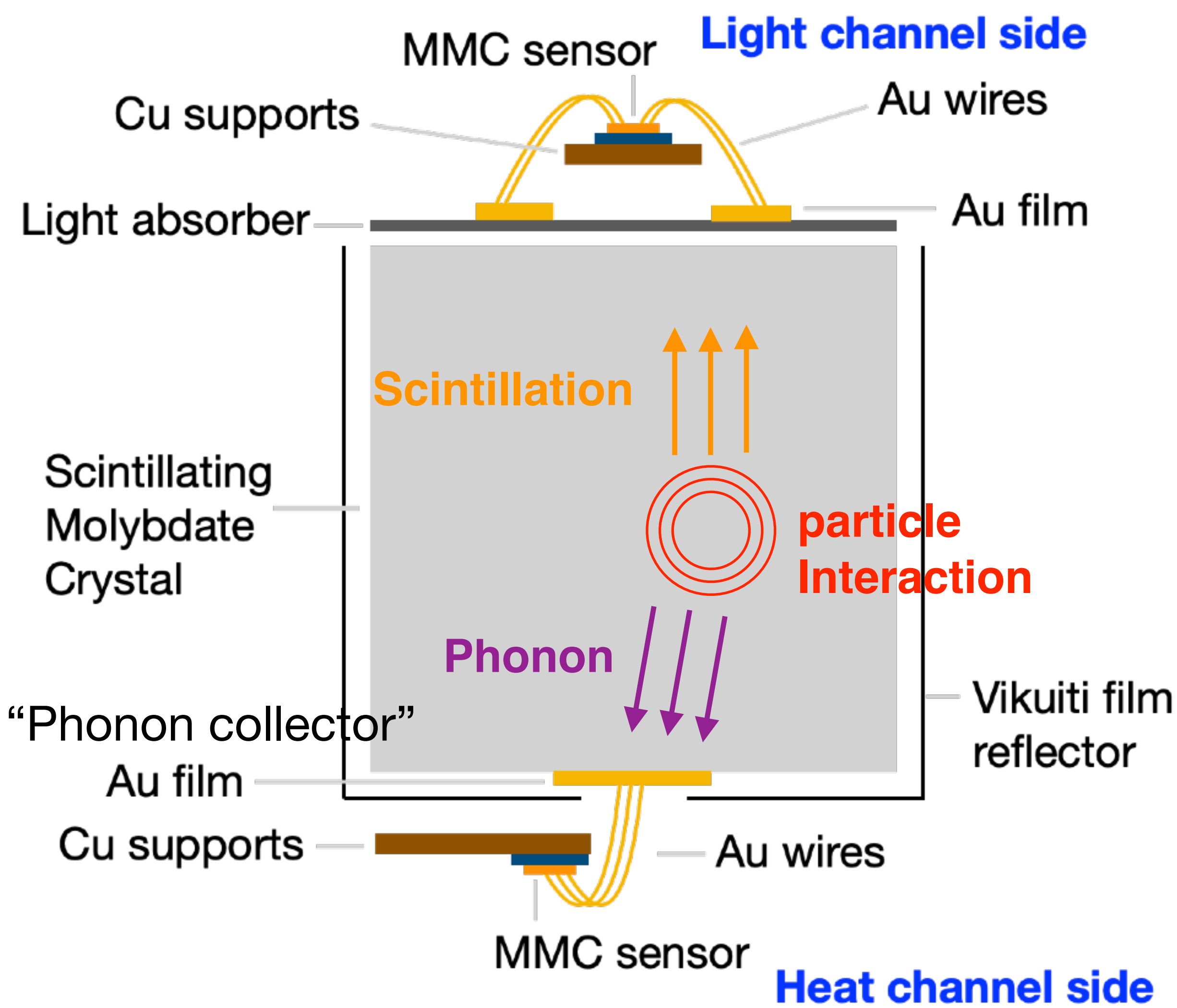


PRL 109 042501 (2012)

Detector : cryogenic calorimeter with scintillating molybdate crystal

=> Cryogenic calorimeter with massive crystal absorber:
Detector absorber equals source
Heat signal, high energy resolution ($\sigma/E \lesssim$ 0.2% at 2.6MeV)
=> Scintillating crystal:
Light signal depending on the particle type
Different pulse shape in heat signal as well
Rejection of alpha signals in ROI

Principle of AMoRE detector



MMC (Metallic Magnetic Calorimeter)

=> Paramagnetic material

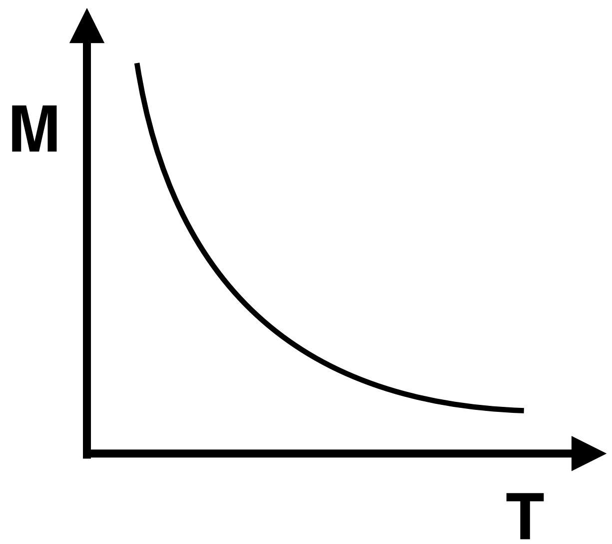
Metallic host (Au or Ag) + Magnetic ions (Er)

=> Magnetization (**M**) very sensitive to **T**

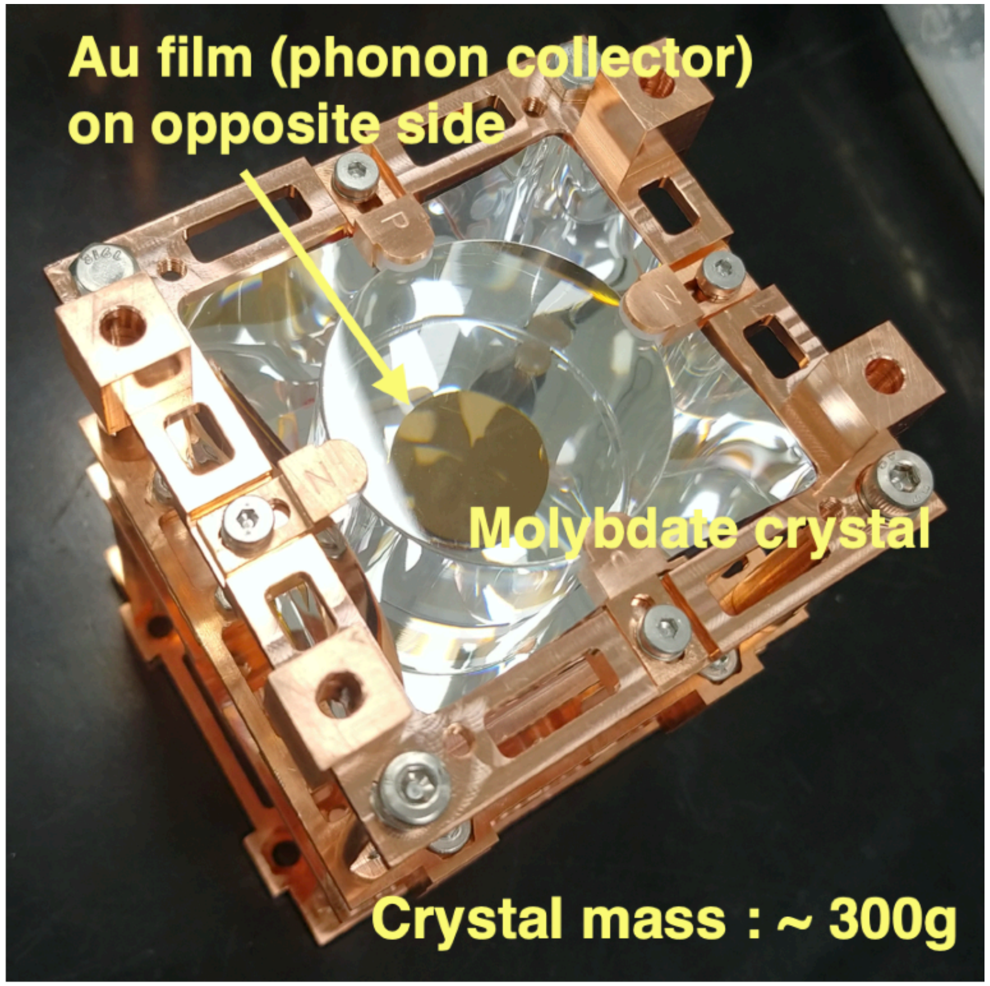
=> MMC implemented with superconducting current (**I**) loop to provide B-field

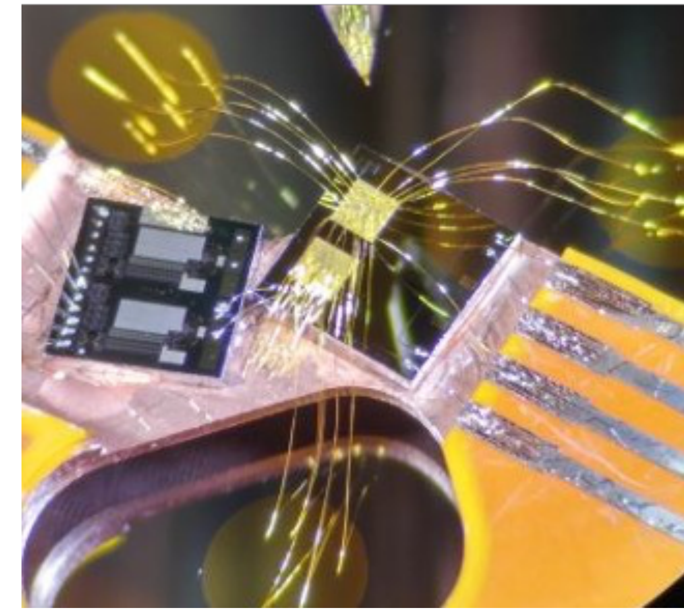
=> Δ**I** induced by Δ**M** as a function of Δ**T**

=> SQUID measures Δ**I** as signal

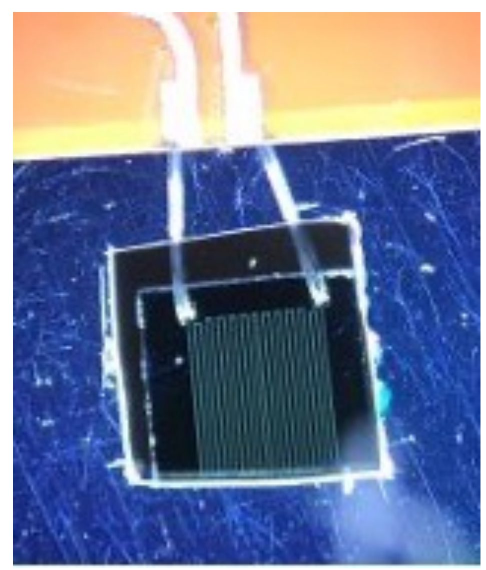


AMoRE detector

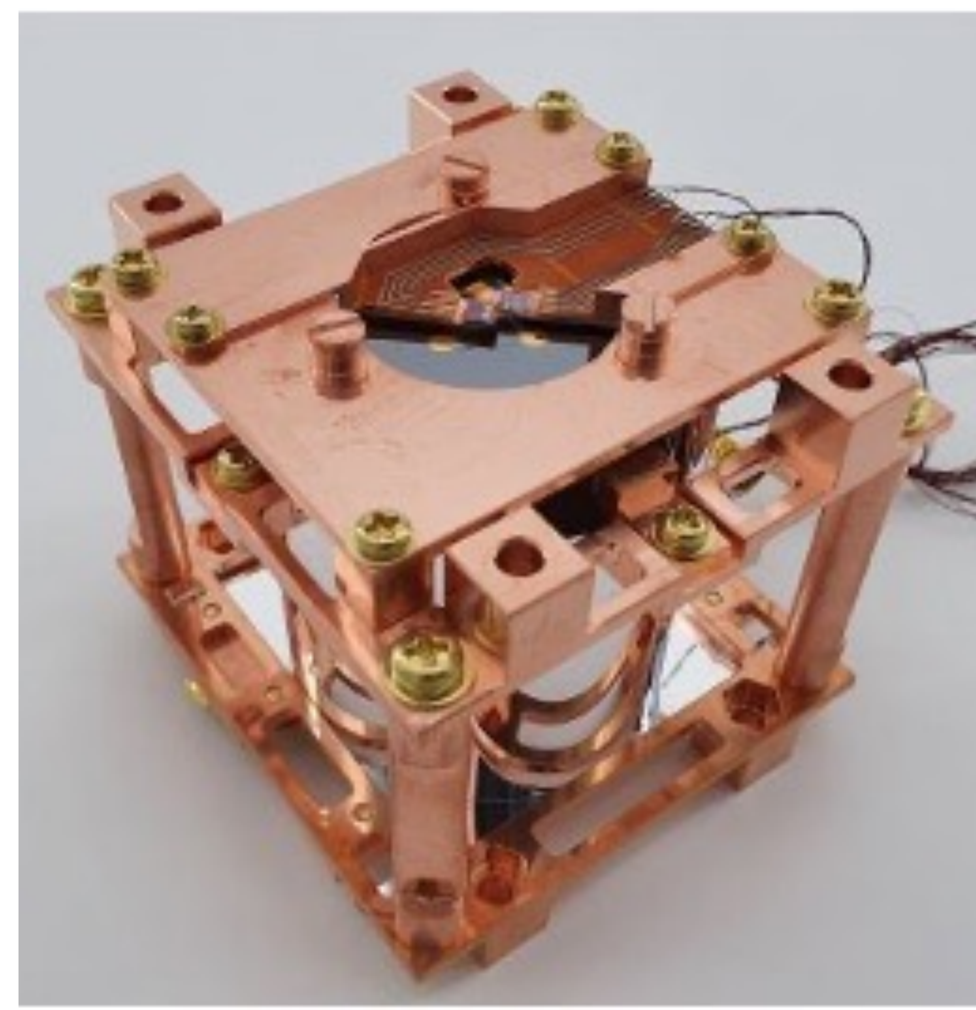


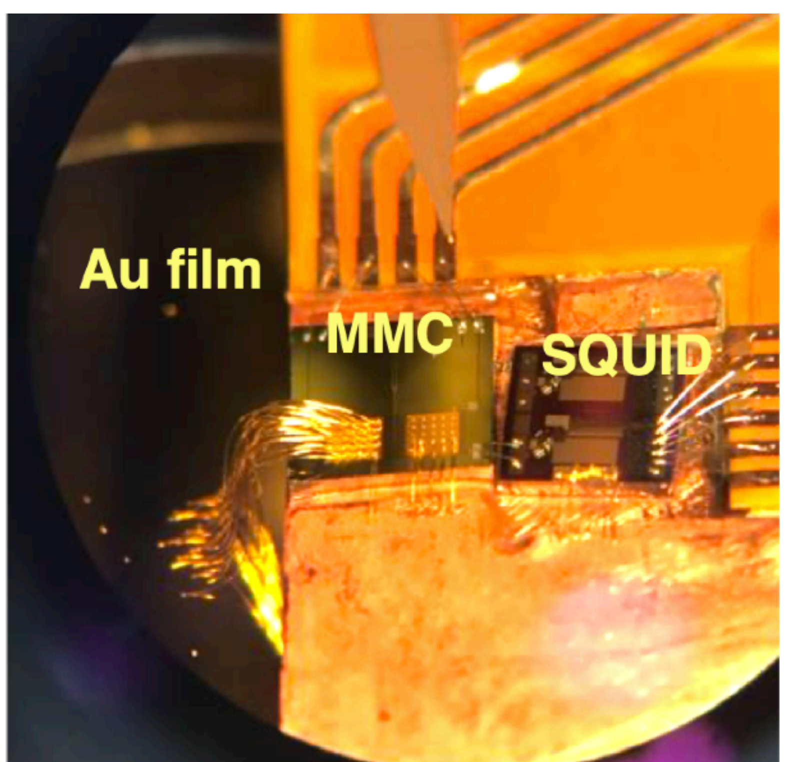


Light channel



Stabilization heater





Heat channel

Scintillating Molybdate crystals

Early option: calcium molybdate crystal ($CaMoO_4$), "CMO"
=> Highest light output molybdate
=> Easy crystal handling
=> Good energy resolution / Particle identification demonstrated
=> Annealing necessary for the optical quality
=> ^{48}Ca depletion required
=> high radioactive contamination (chemical affinity of Ca & Ra)

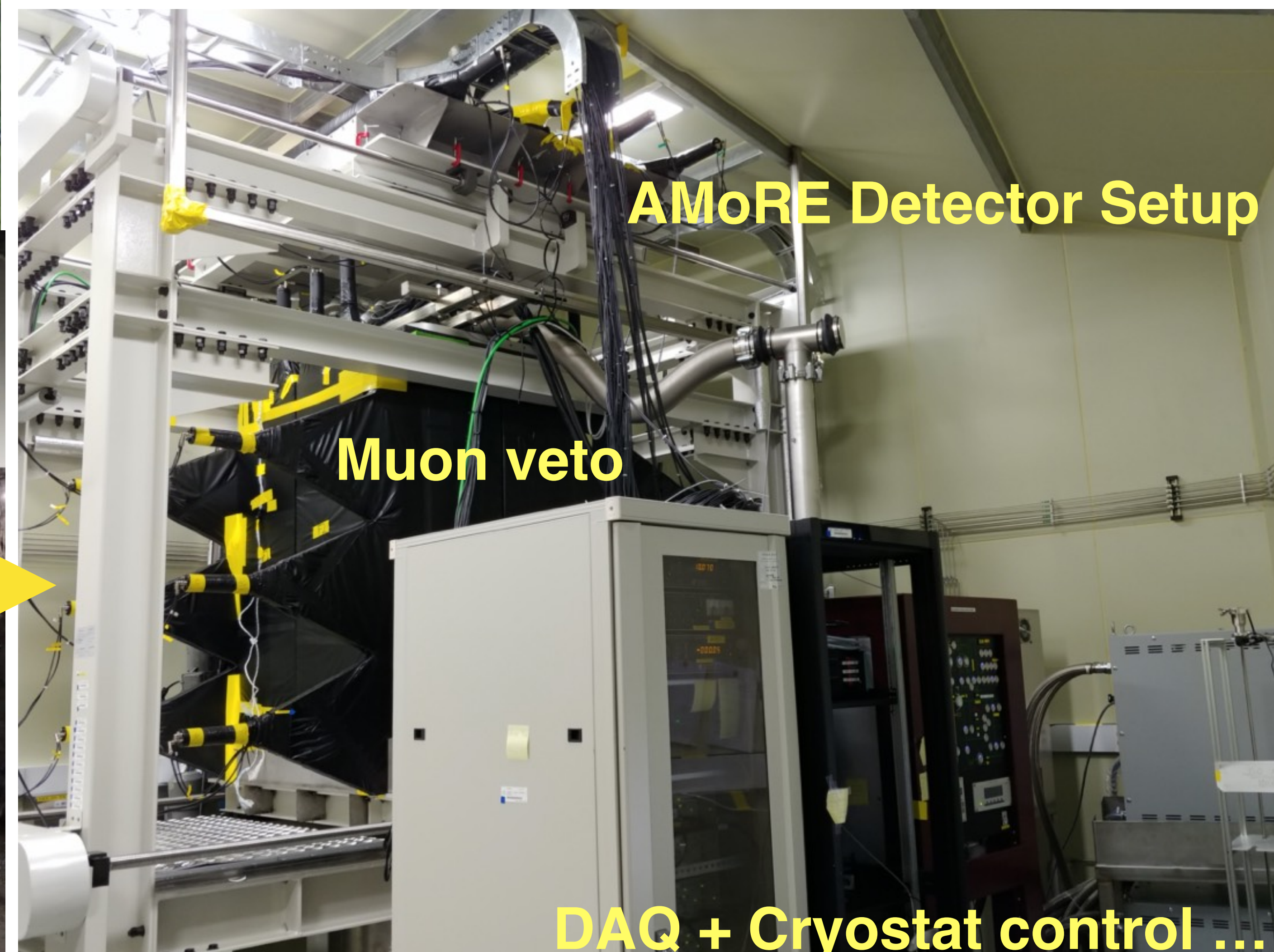
Final option: Lithium molybdate crystal (Li_2MoO_4), "LMO"
=> High molybdenum content
=> Simple crystal growth: low melting point, no need of annealing
=> Low radioactive contamination
=> Good energy resolution / Particle identification demonstrated
=> Small light output
=> Hygroscopic surface, some difficulties with detector handling

Experimental site: Yangyang (Y2L) underground lab

700 m minimum vertical depth (2000 m w.e.)

Radon free air supplied

Neighbor of COSINE dark matter search experiment



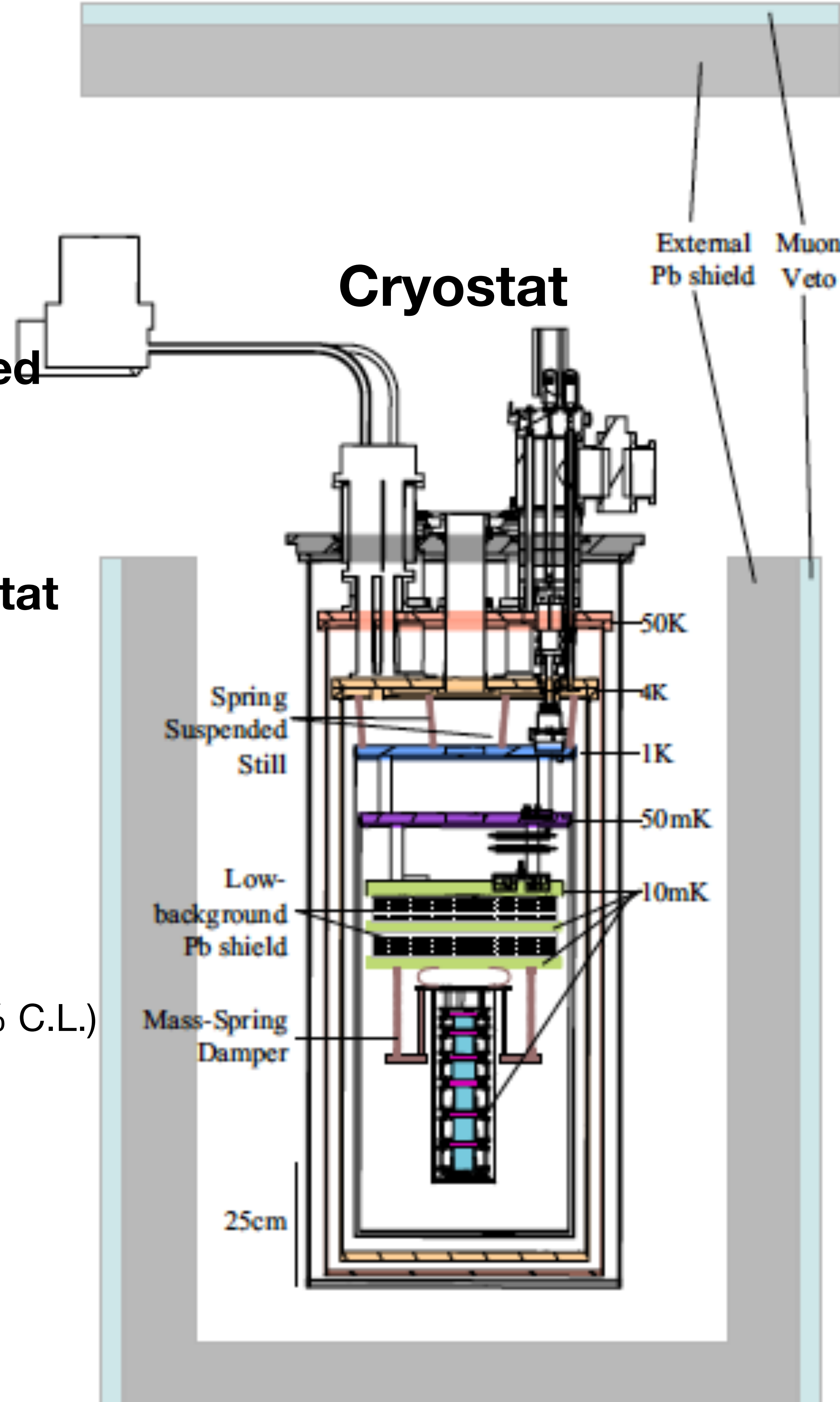
AMoRE pilot

Period: 2015 - 2018
6 CMO (FOMOS)
^{48}Ca depleted, ^{100}Mo enriched
Total mass: 1.9 kg

Cryogen-free DR:10-20 mK
Vibration damping for cryostat

First results (2019):
0.3 kg yr exposure
BKG at ROI ~ 0.55 ckky
$T^{0\nu}_{1/2} > 9.5 \times 10^{22} \mathrm{yrs}$ (90% C.L.)

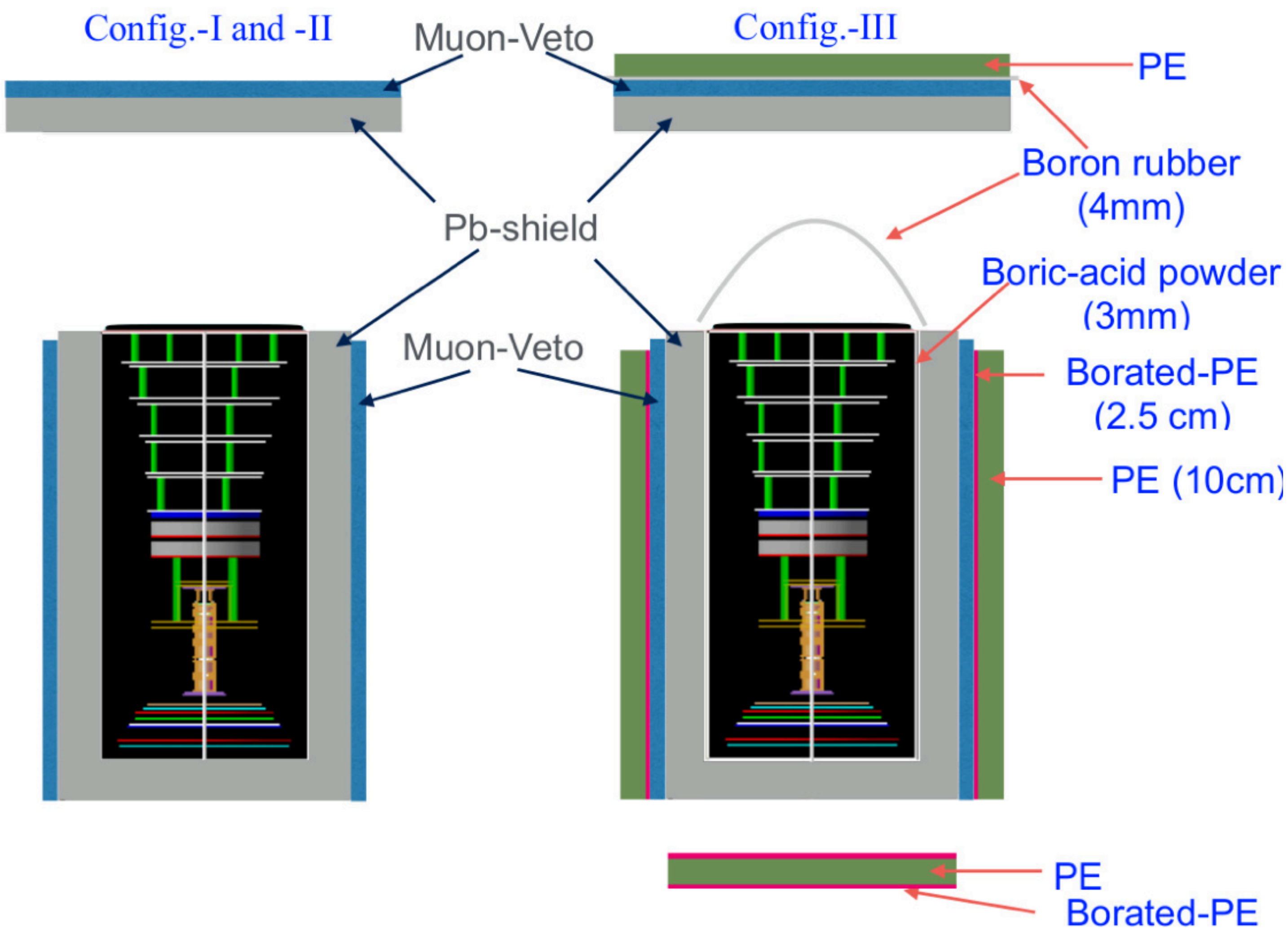
Demonstration of detectors for 0νββ search

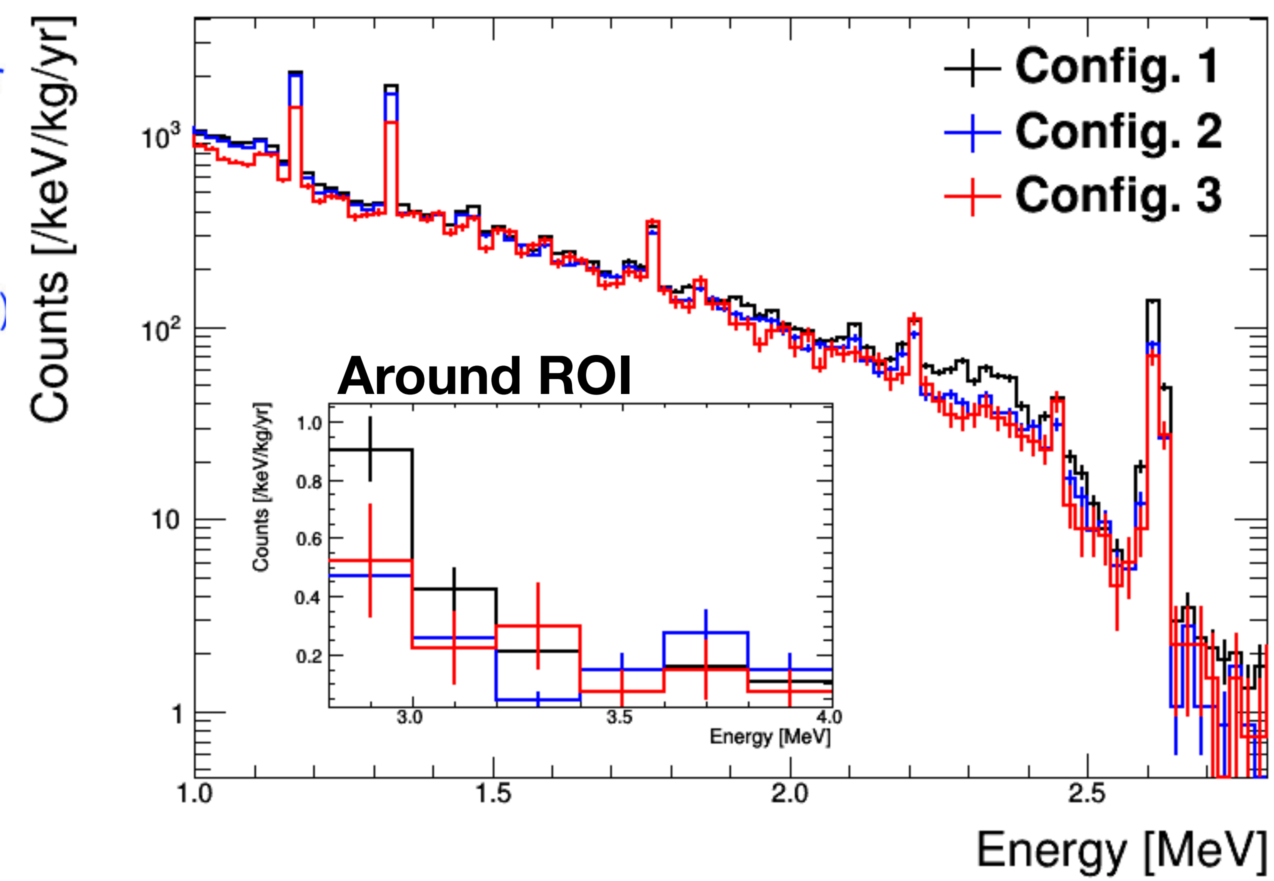


*** ckky = cnts/kg/keV/yr**

AMoRE pilot

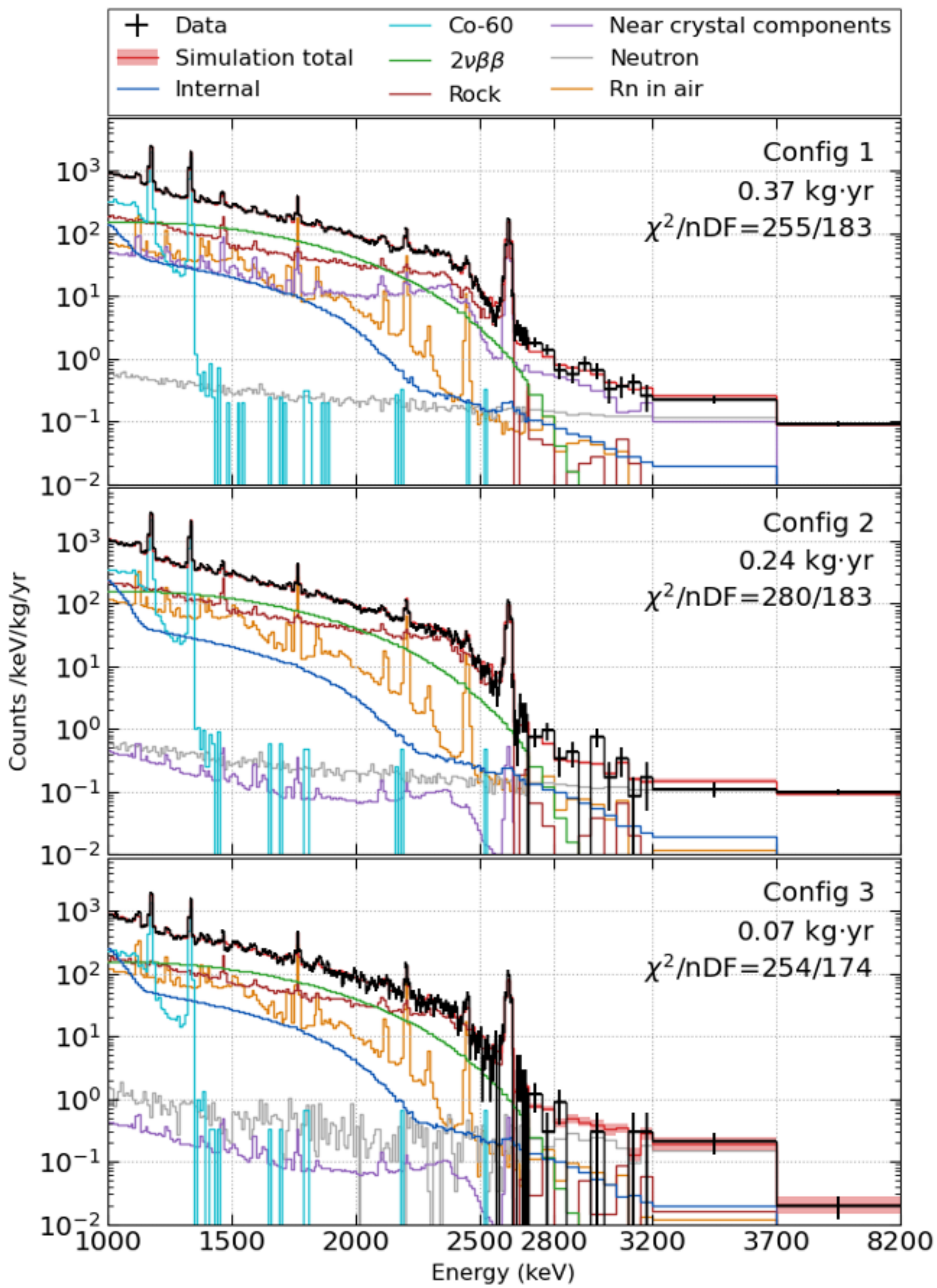
A lot of learnings about the background control





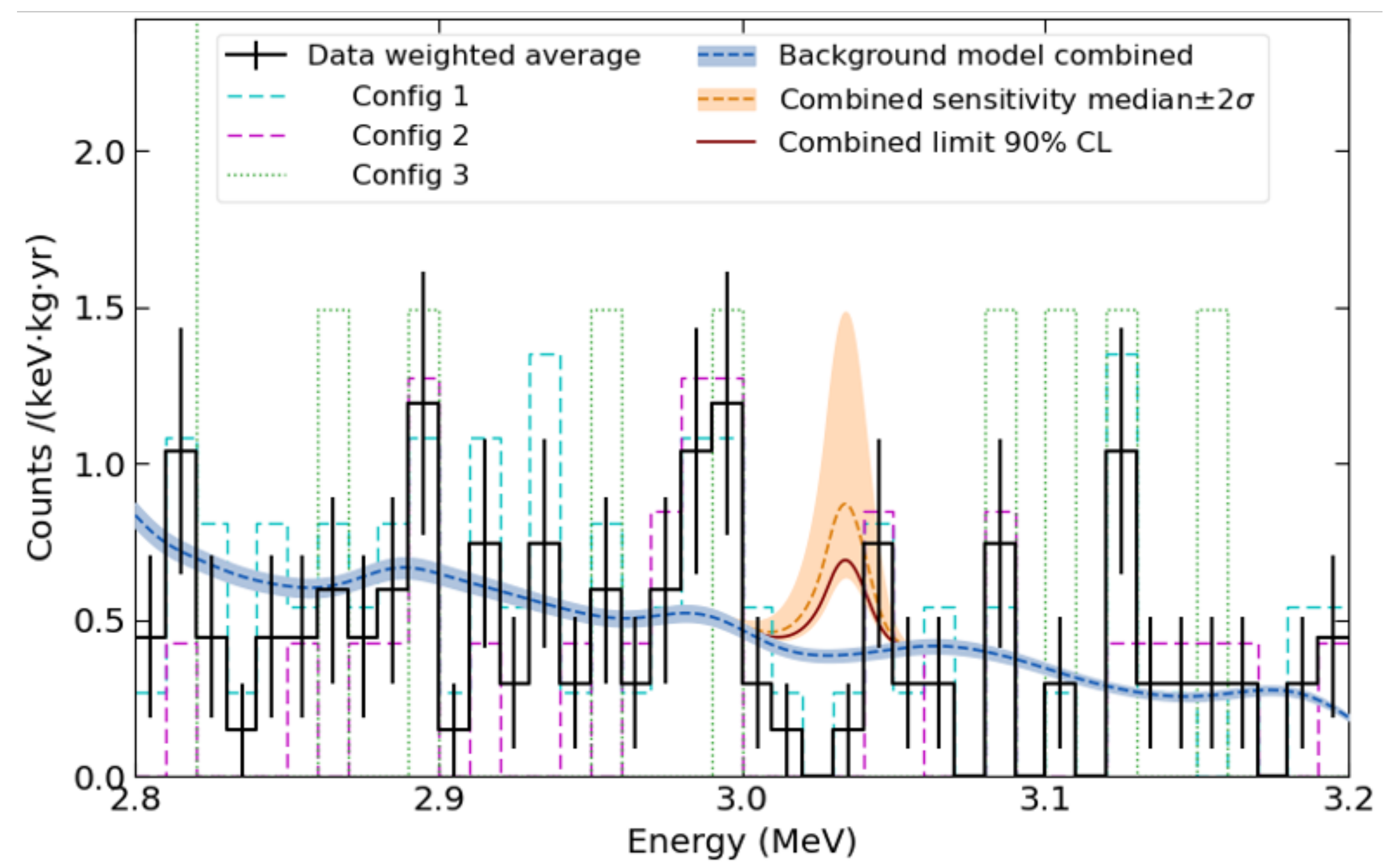
Config. 2 : Removing "hot" radioactive components (epoxy, pin connector, holder…)
Config. 3 : Neutron shielding

AMoRE pilot final results



BKG ~ 0.5 ckky at 2.8 - 3.2 MeV
=> neutron-induced γ
crystals' internal contamination
rock/air-radon γ

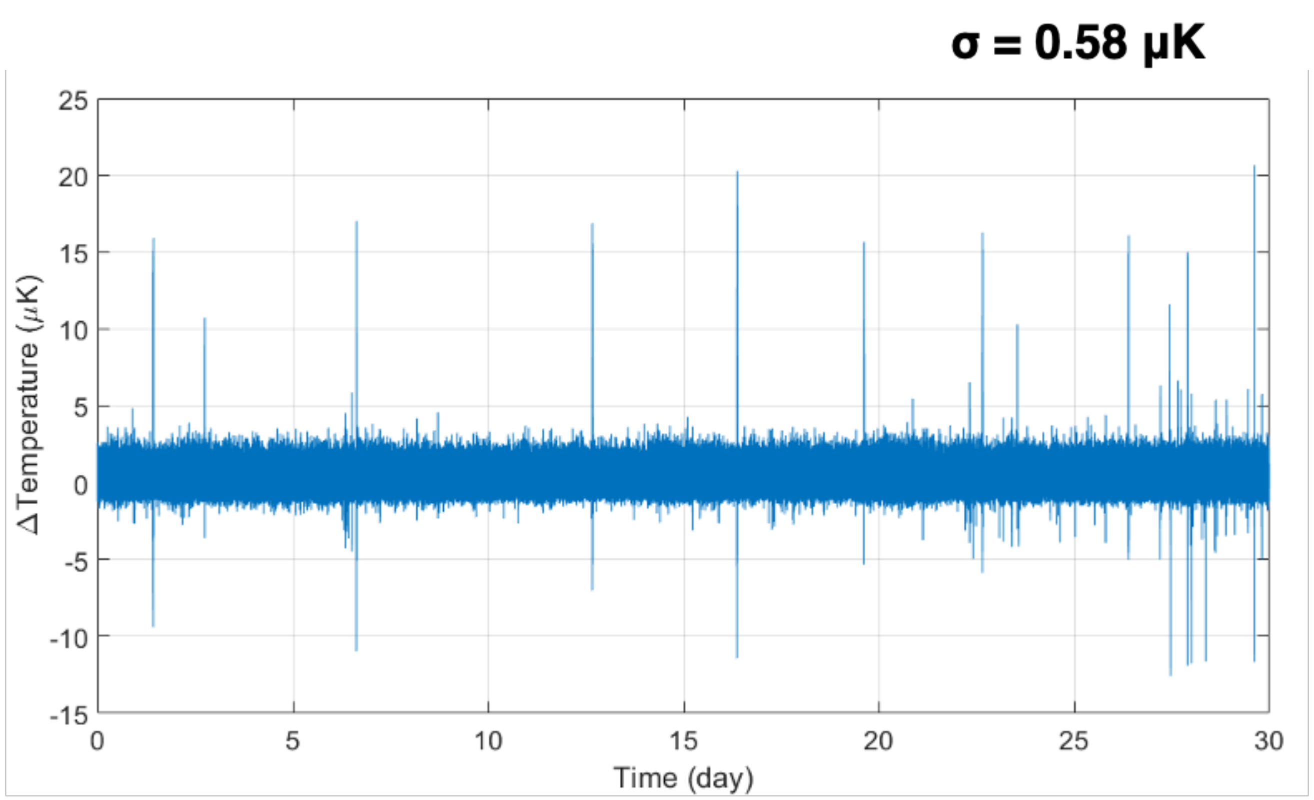
$$T^{0\nu}_{1/2} > 3.4 \times 10^{23}\text{yrs} \quad \text{(90\% C.L.)}$$

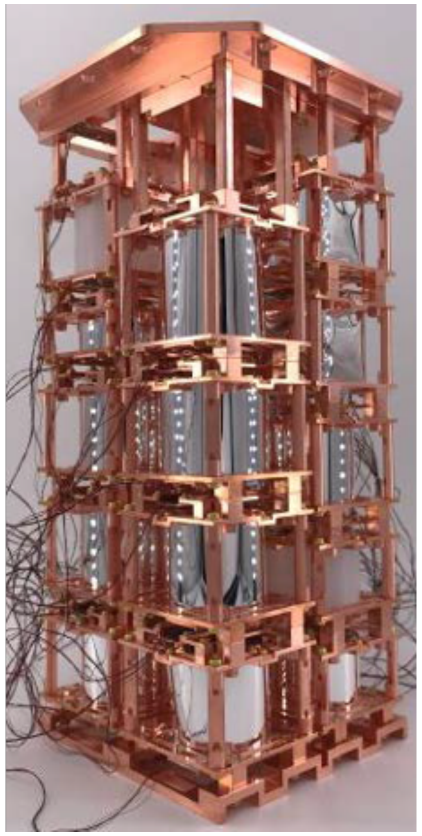


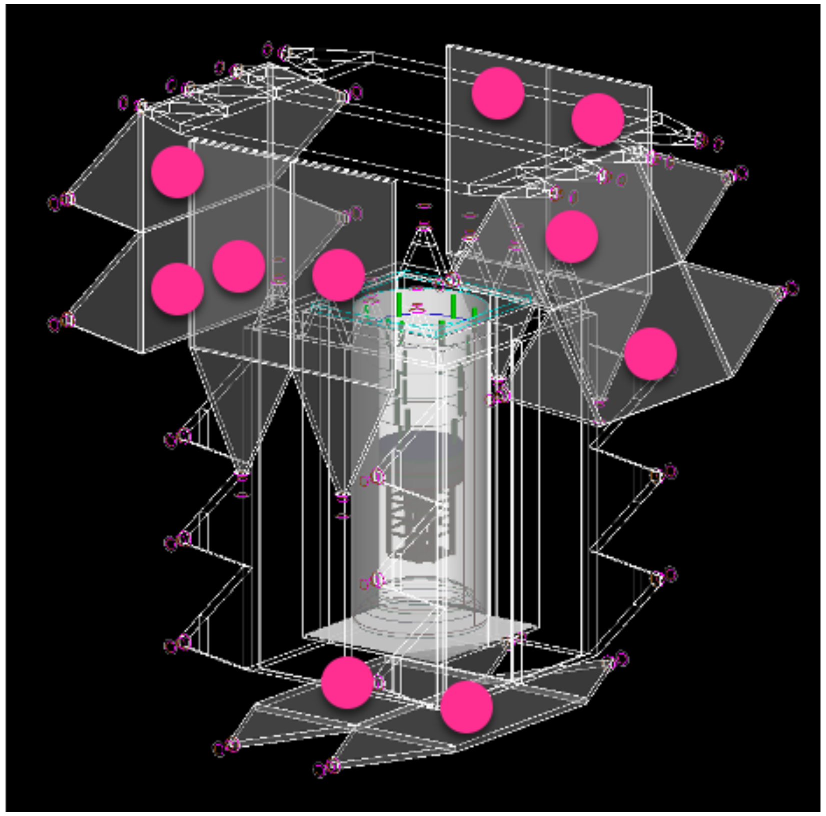
From AMoRE pilot to AMoRE-I

6 CMO (1.89 kg) => 13 CMO (4.58 kg) + 5 LMO (1.61 kg)
total crystal mass = 6.19 kg, ^{100}Mo mass = 3.0 kg
Stabilization heaters for all crystals
MMC sensor: Au:Er => Ag:Er
Same cryostat + two stage temperature control: $\langle \Delta T \rangle < 1\ \mu K$

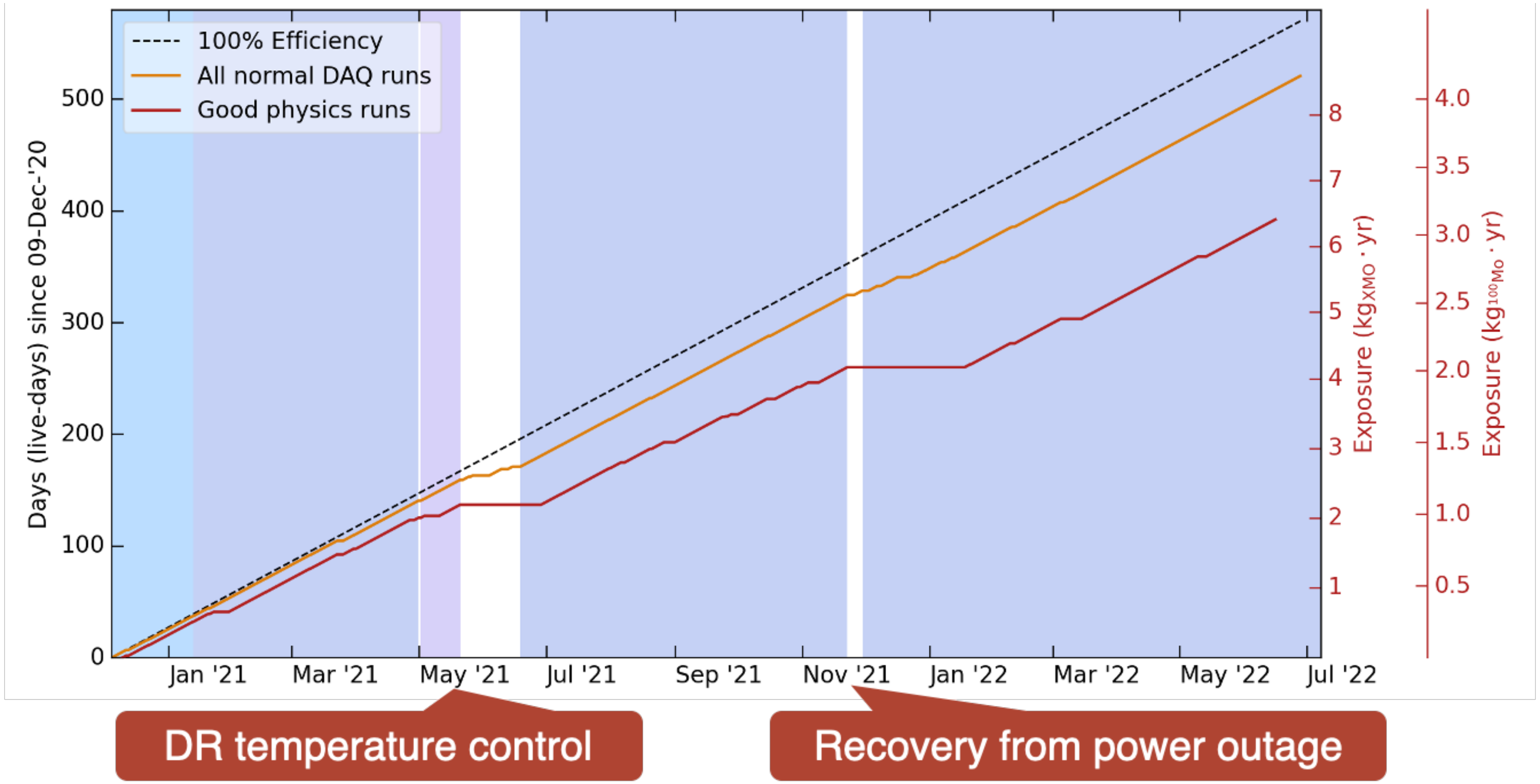
Shielding enhancements:
Outer Pb: 15 => 20 cm; neutron shields: boric acid silicon + more PE/B-PE
More muon counter coverage, More stable supply of Rn-free air

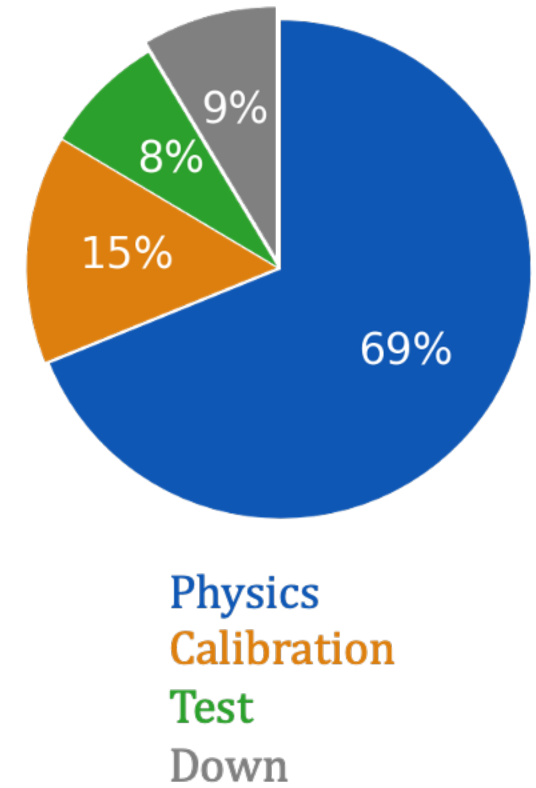






AMoRE-I data taking

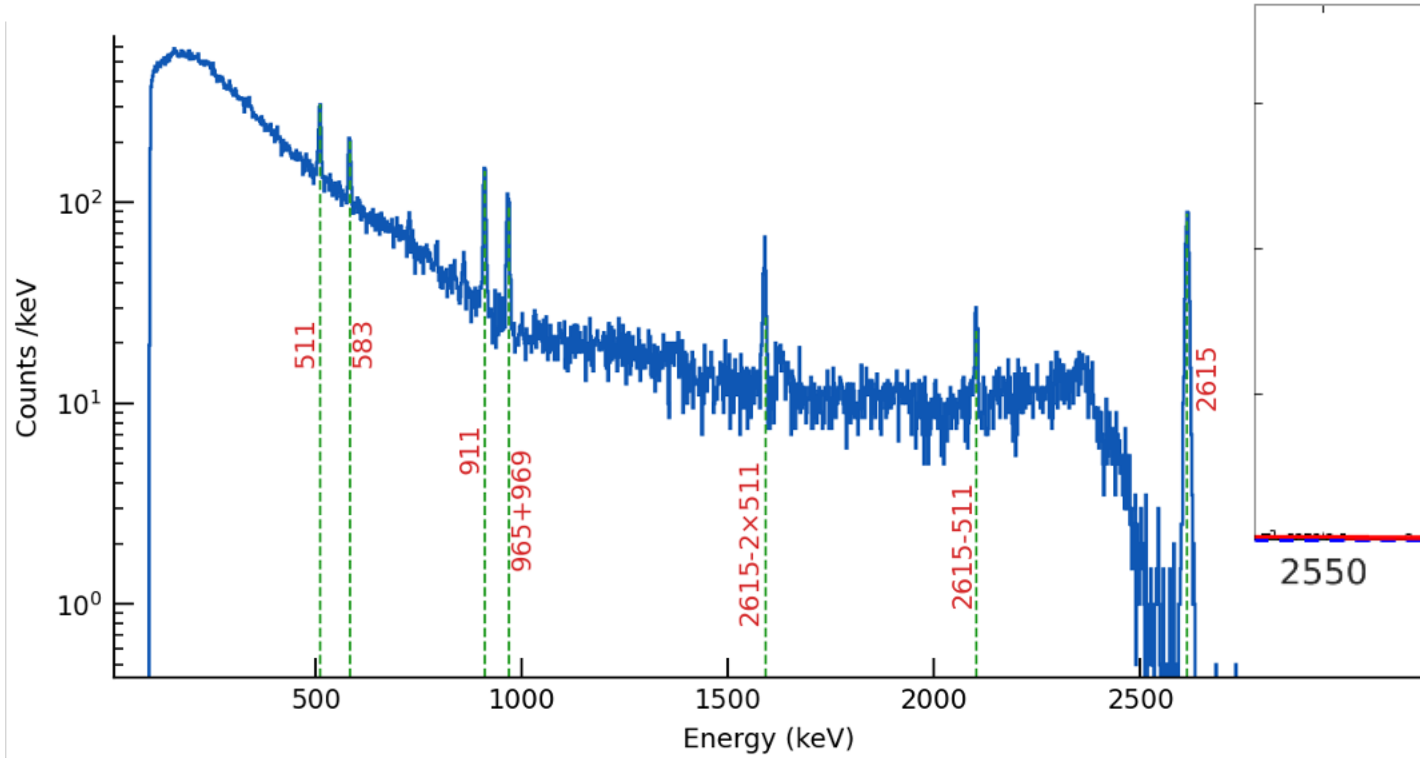


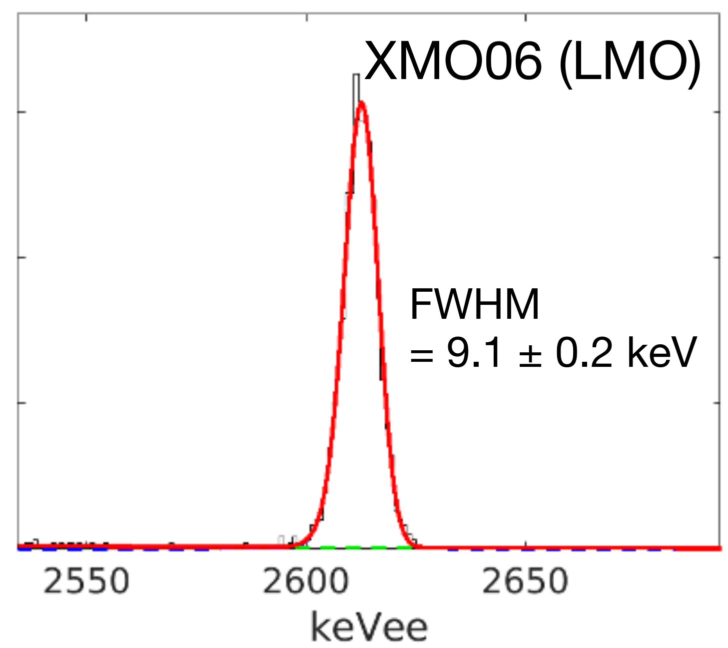


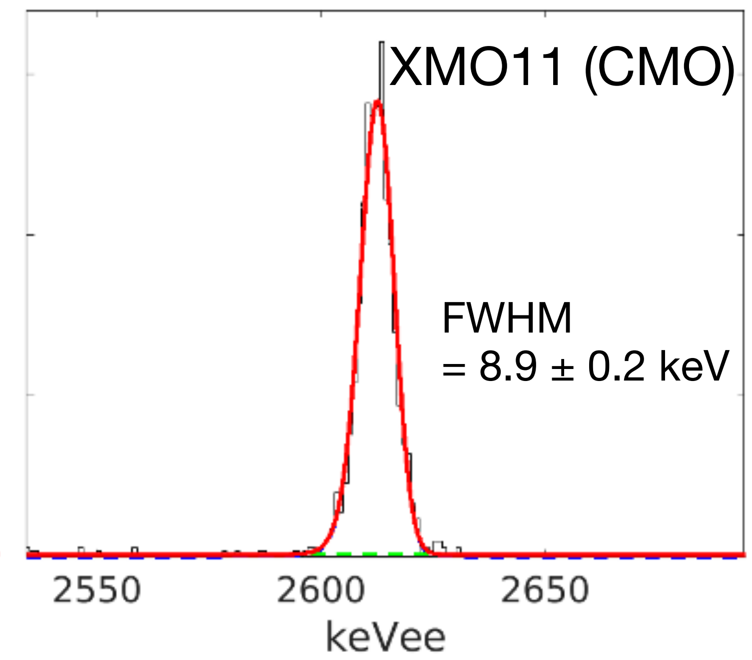
Data taking until the end of 2022 (at least)

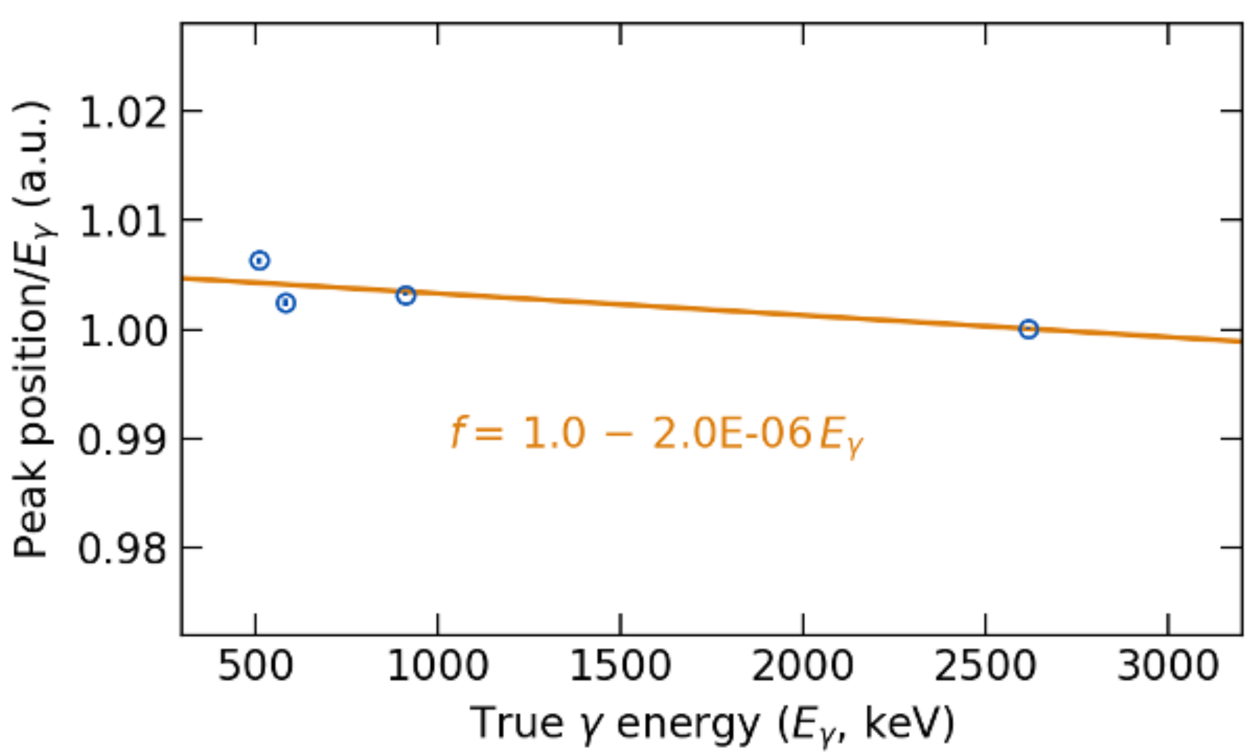
4.68 kg · year crystal (2.24 kg · year ^{100}Mo) exposure is presented here

Energy calibration







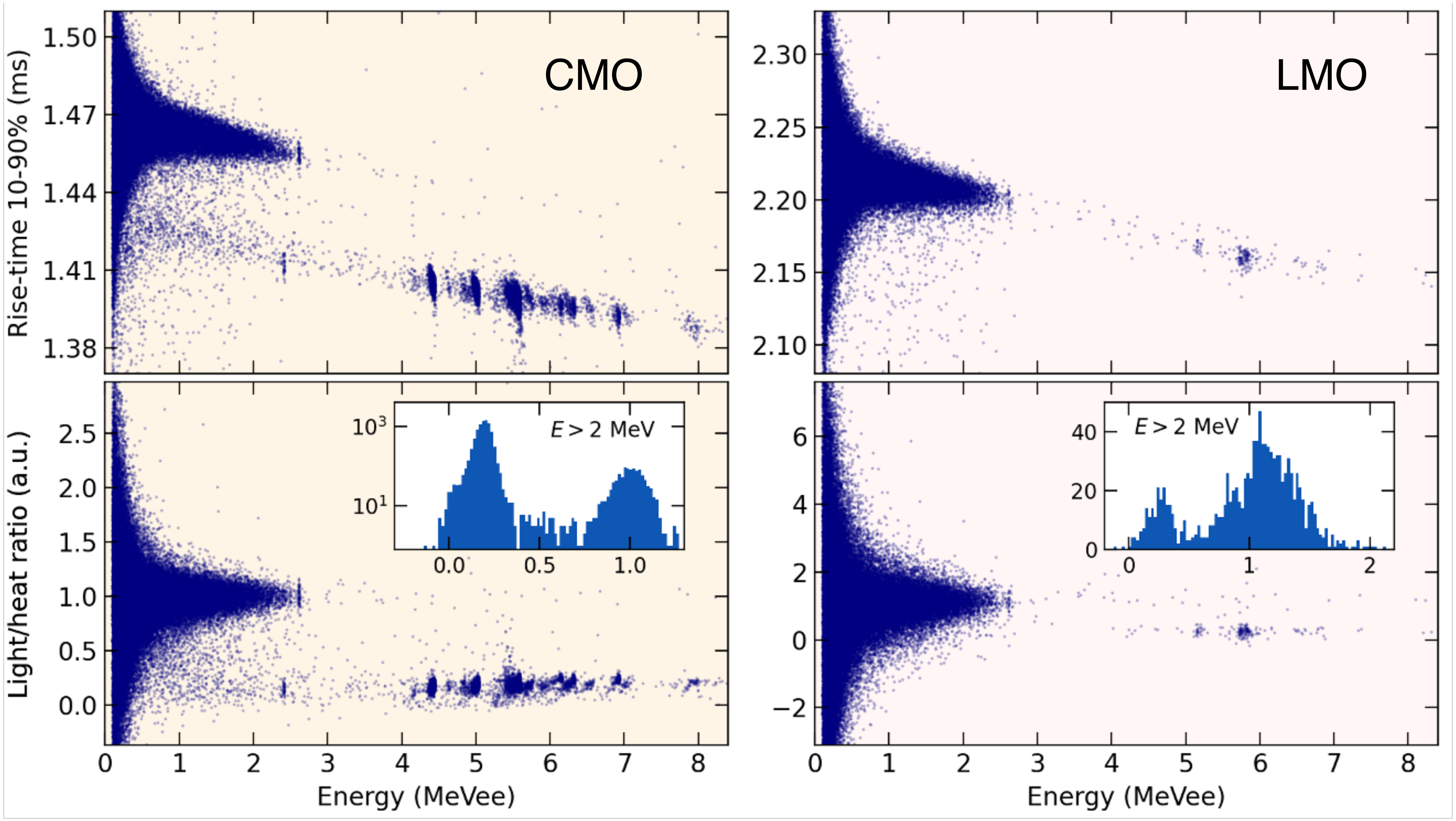


Calibration source: ^{232}Th-rich welding rods just outside OVC

Slight non-linearity between signal amplitude and energy

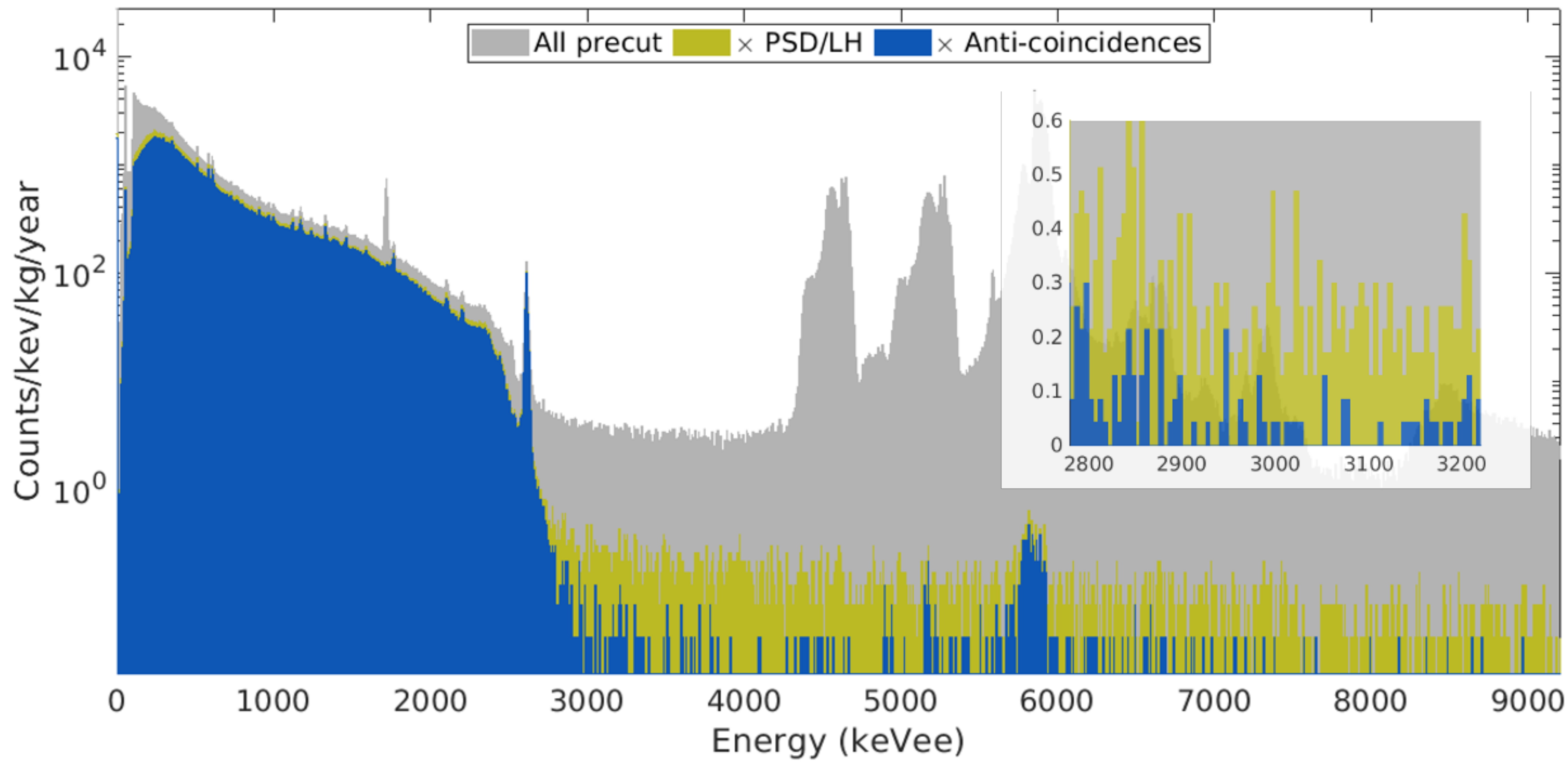
Energy resolution:
=> [8.9-32.7] keV FWHM at 2615 keV,
=> ~15 keV in average

Particle identifications, CMO and LMO



CMO shows better discrimination power: light yield CMO > LMO
LMO has much less α contamination

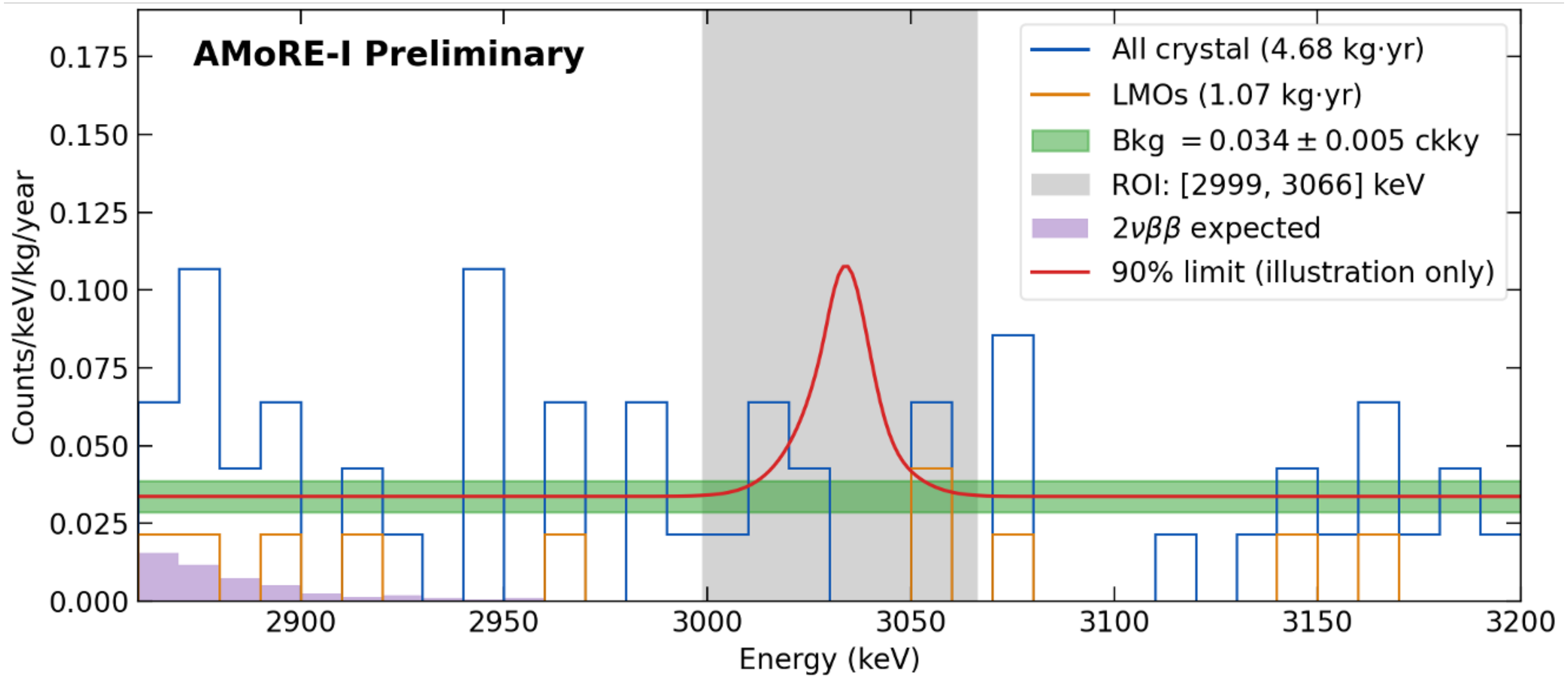
Background Spectrum



All crystal excluding 1 LMO for very poor *β/α* discrimination power:
=> 13 CMO + 4 LMO: exposure = 4.68 kg$_{(crystal)}$ · yr = 2.24 kg$_{(^{100}Mo)}$ · yr

Anti-coincidence cuts reject events:
=> coincident at multiple crystals within 2 ms (*ε* ~ 99%),
=> within 10 ms after a muon counter event (*ε* ~ 99.7%),
=> within 20 minutes after a ^{212}Bi *α*-decay event candidates (*ε* ~ 98%)

Preliminary 0νββ limit from AMoRE-I

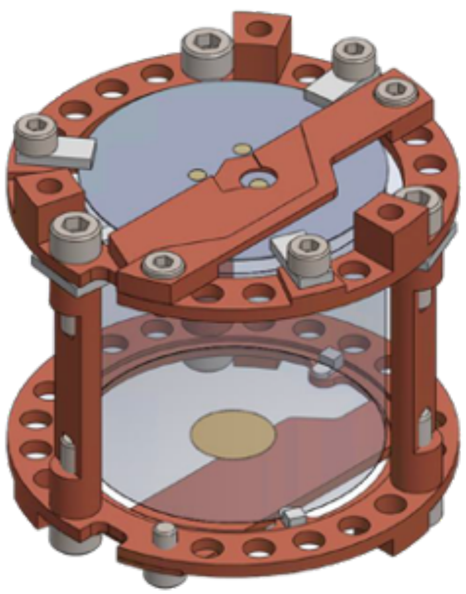


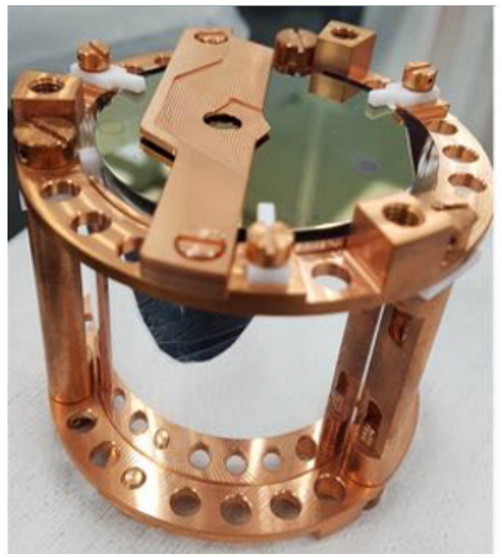
ROI to contain most (> 99%) of the 0νββ signal peak, $\varepsilon_{\text{containment}}$ ~ 81%.
Background = 0.034 ± 0.005 cnts/keV/kg/year, from ROI side-band

Combining the result of counting analysis at ROI, with a flat background constraint from the side-band events for each crystal

$T^{0\nu}_{1/2} > 1.05 \times 10^{24}$ yrs at 90% C.L. for ^{100}Mo

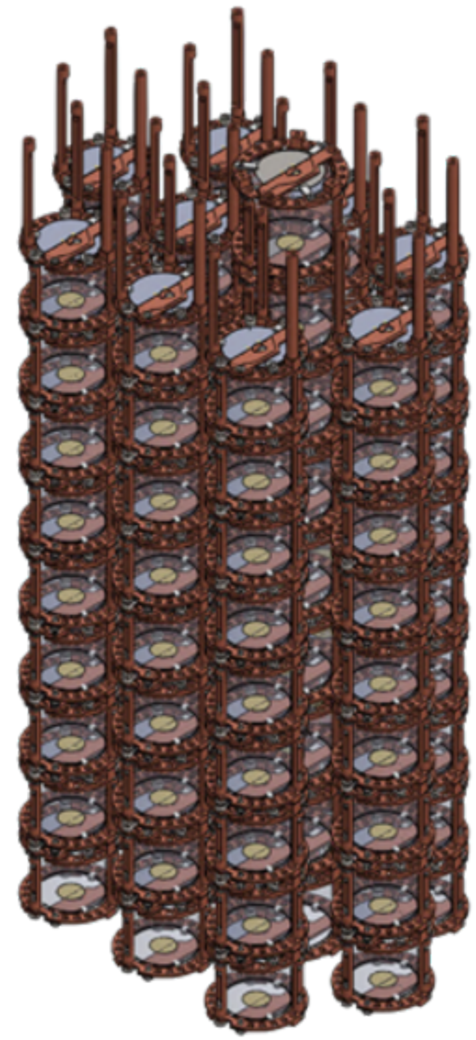
Moving toward AMoRE-II



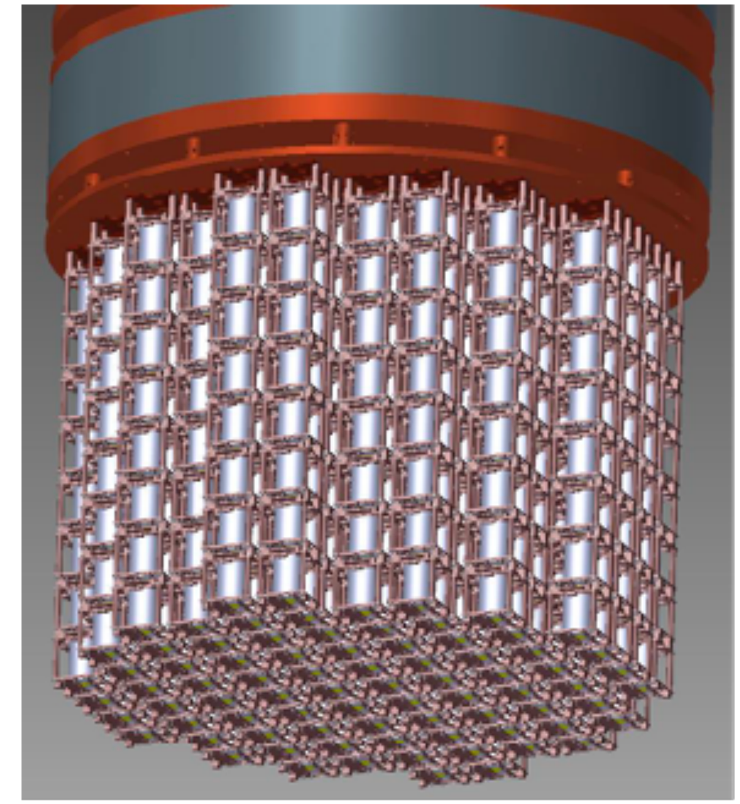


AMoRE-II Detector module

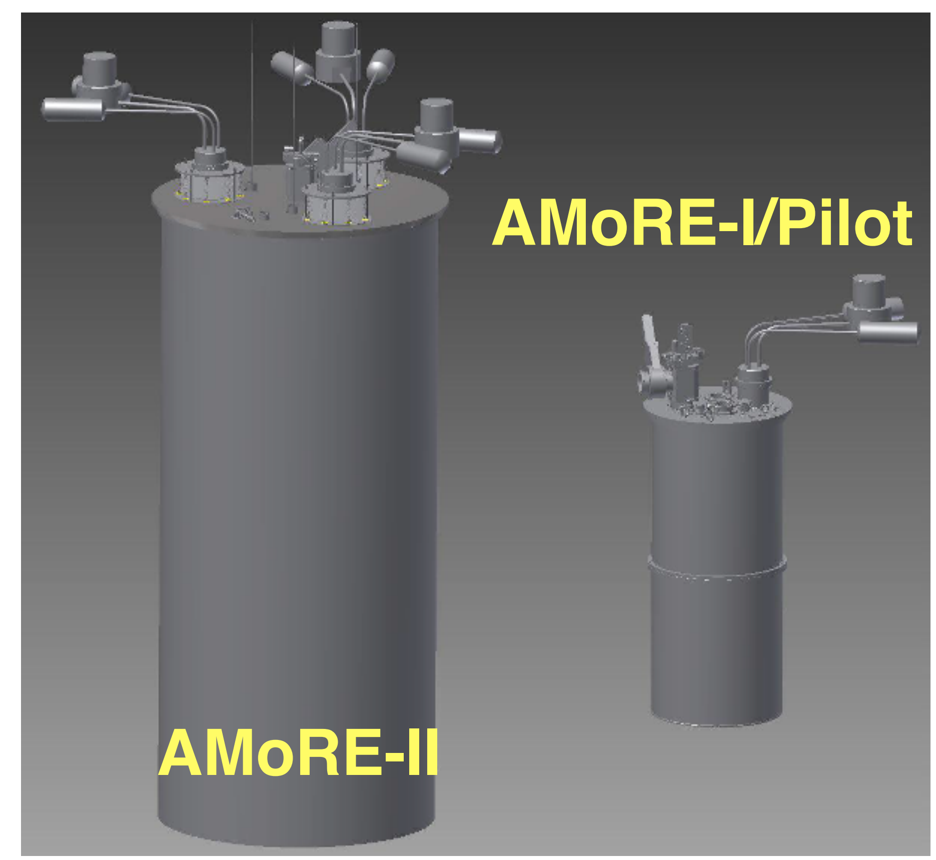
Mixture of two LMO crystals:
6 cm (D) x 6 cm (H), ~515 g
5 cm (D) x 5 cm (H), ~300 g



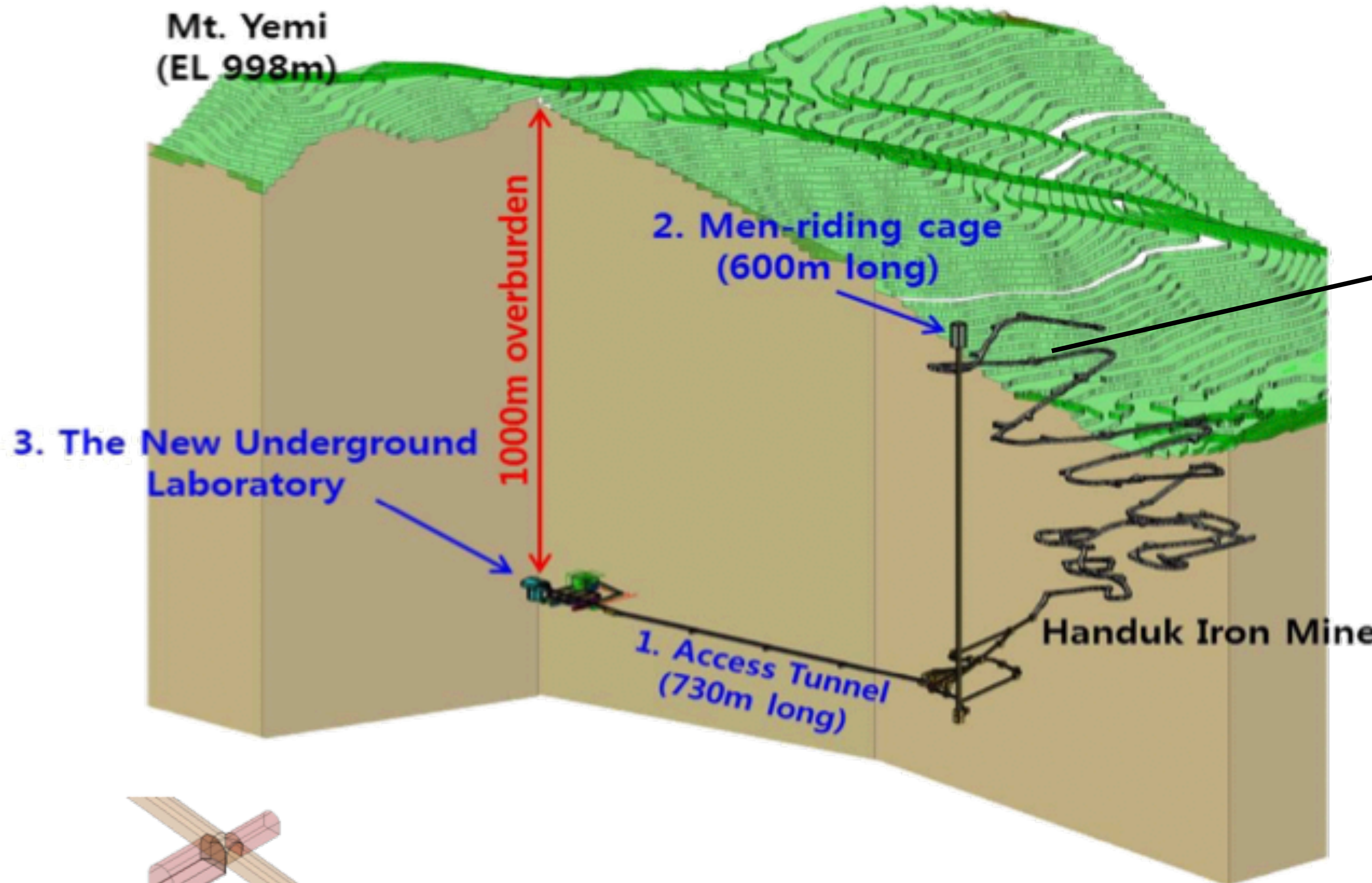
90 modules (~ 27 kg LMO)
for the first stage

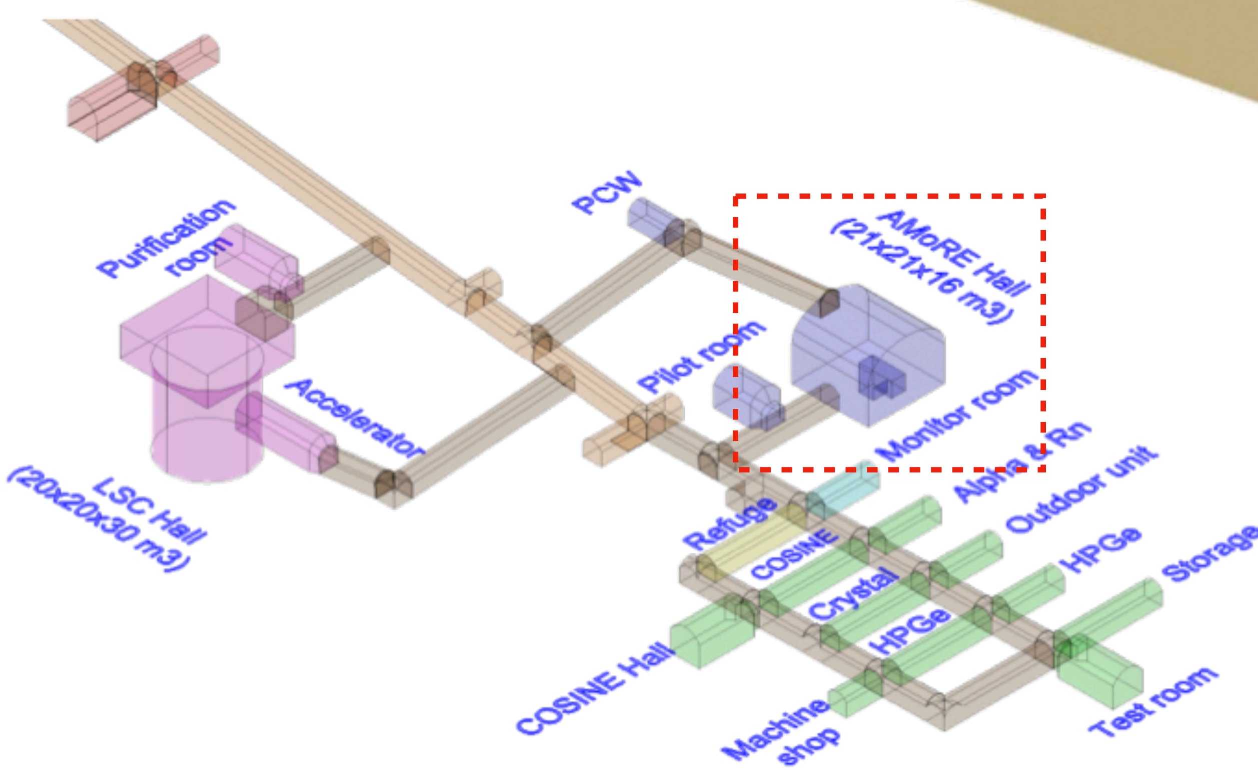


178 kg LMO at final
100 kg of ^{100}Mo



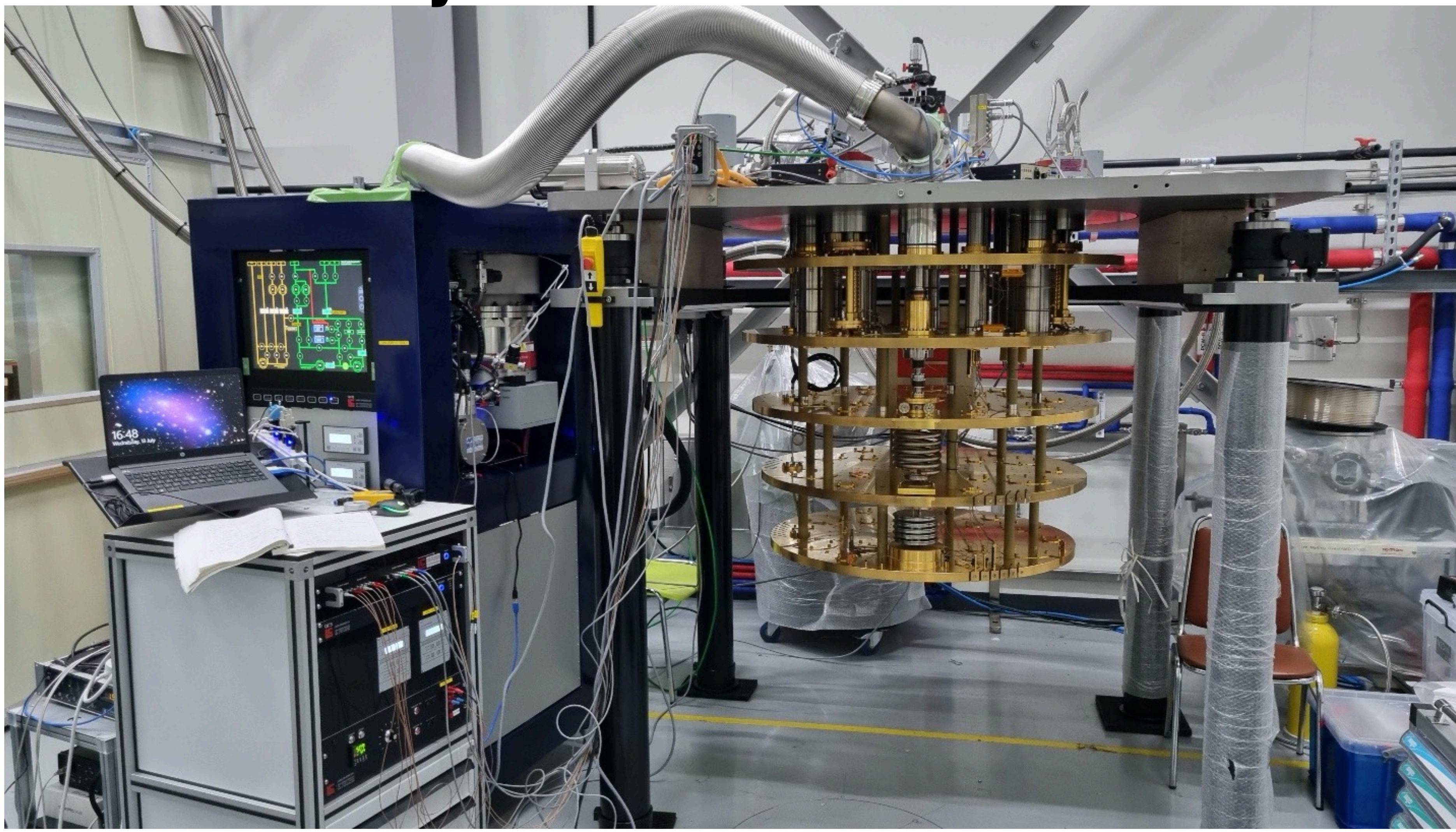
Yemilab

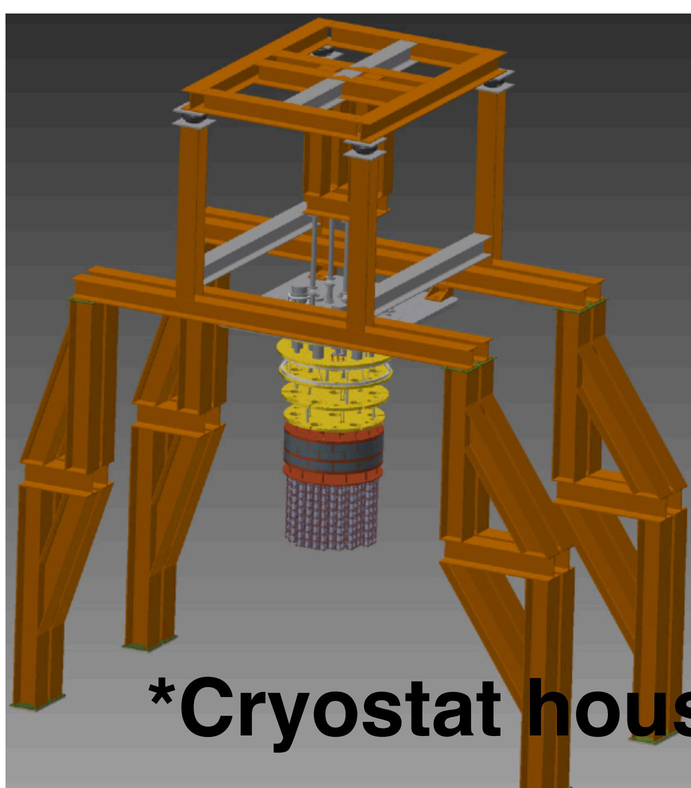




Jeongseon, Korea
1000 m vertical depth
Underground lab with 2600 m^2
Open in October this year!

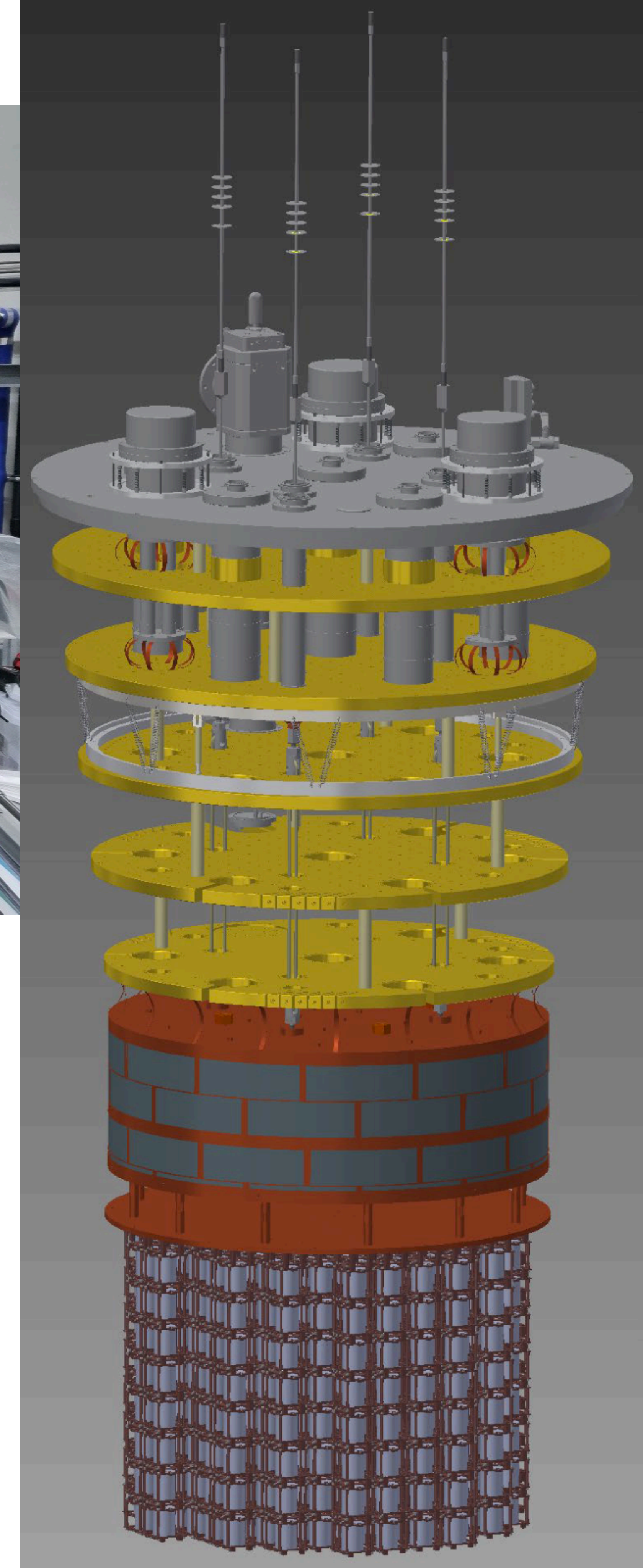
AMoRE-II cryostat



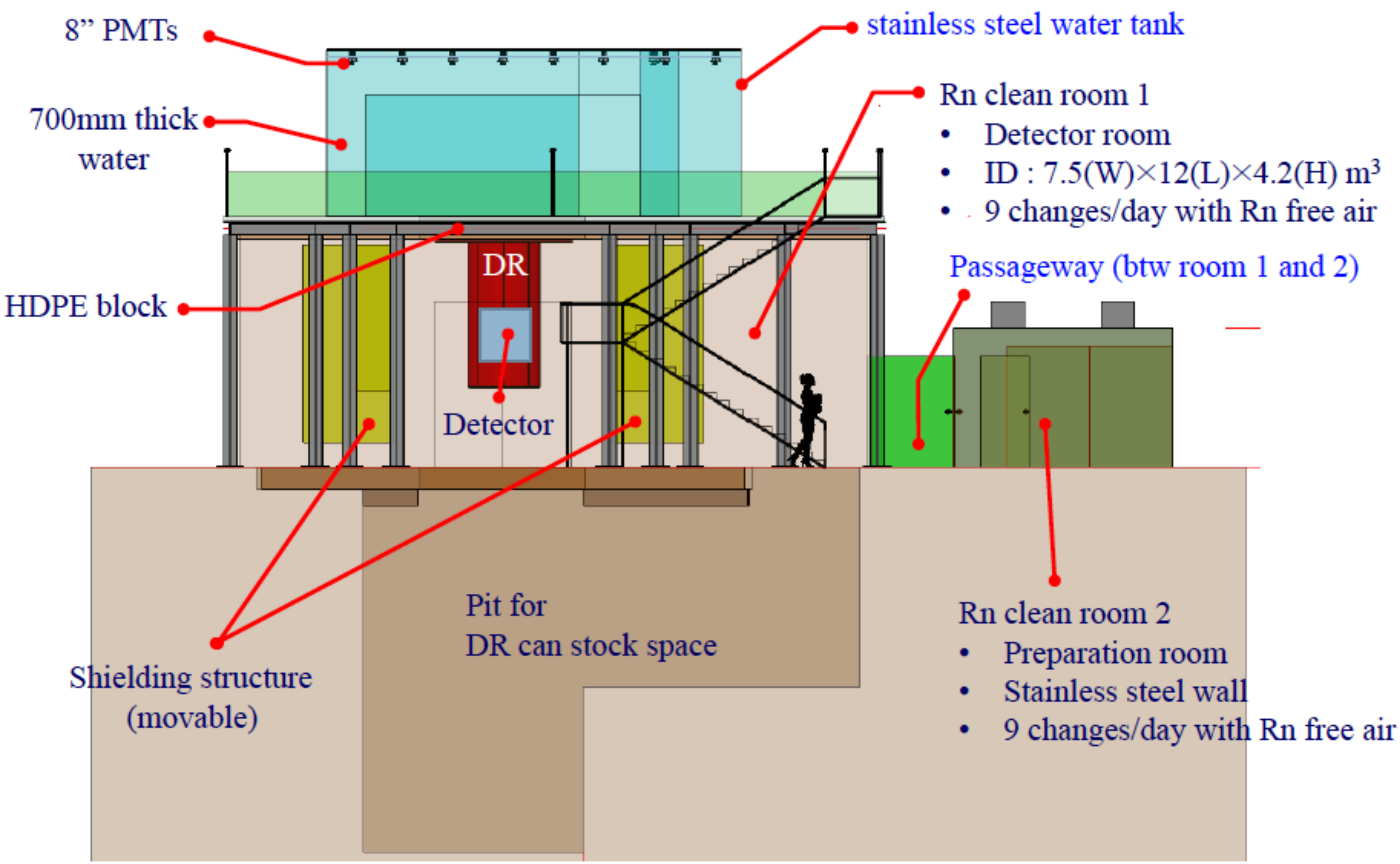


New vibration damping
=> Hanging by Kevlar wire system
=> suspending ~3.4 tonne

*Cryostat housing not drawn



Detector room



Current view of AMoRE Hall

Dust proof door
Radon free air to the detector room during the assembly work
Cleanness: Hall (100 k), Detector room(10 k), Preparation room(100)

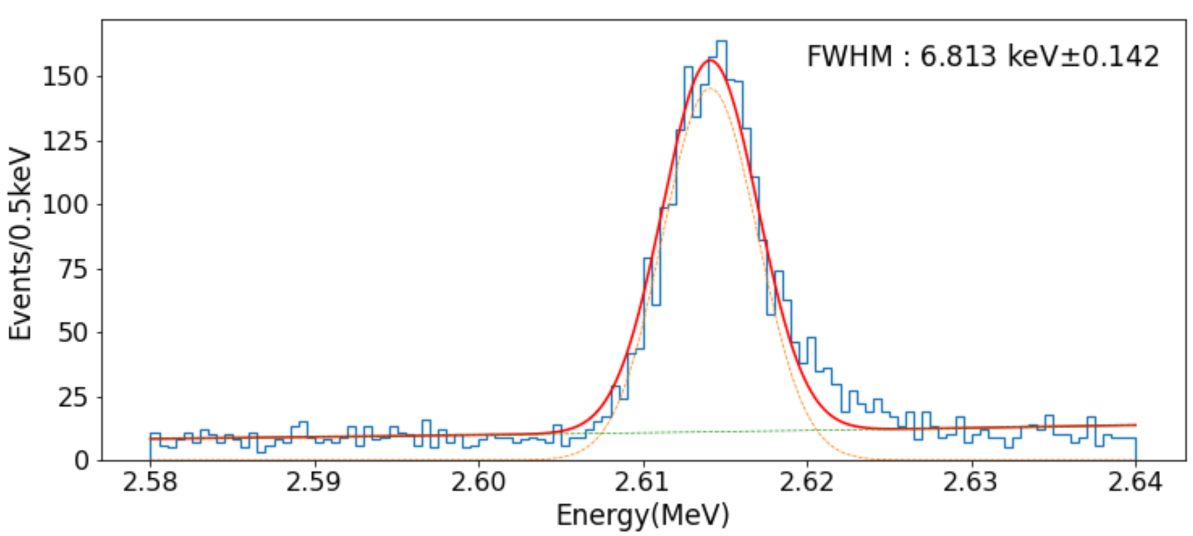
Detector R&D for AMoRE-II

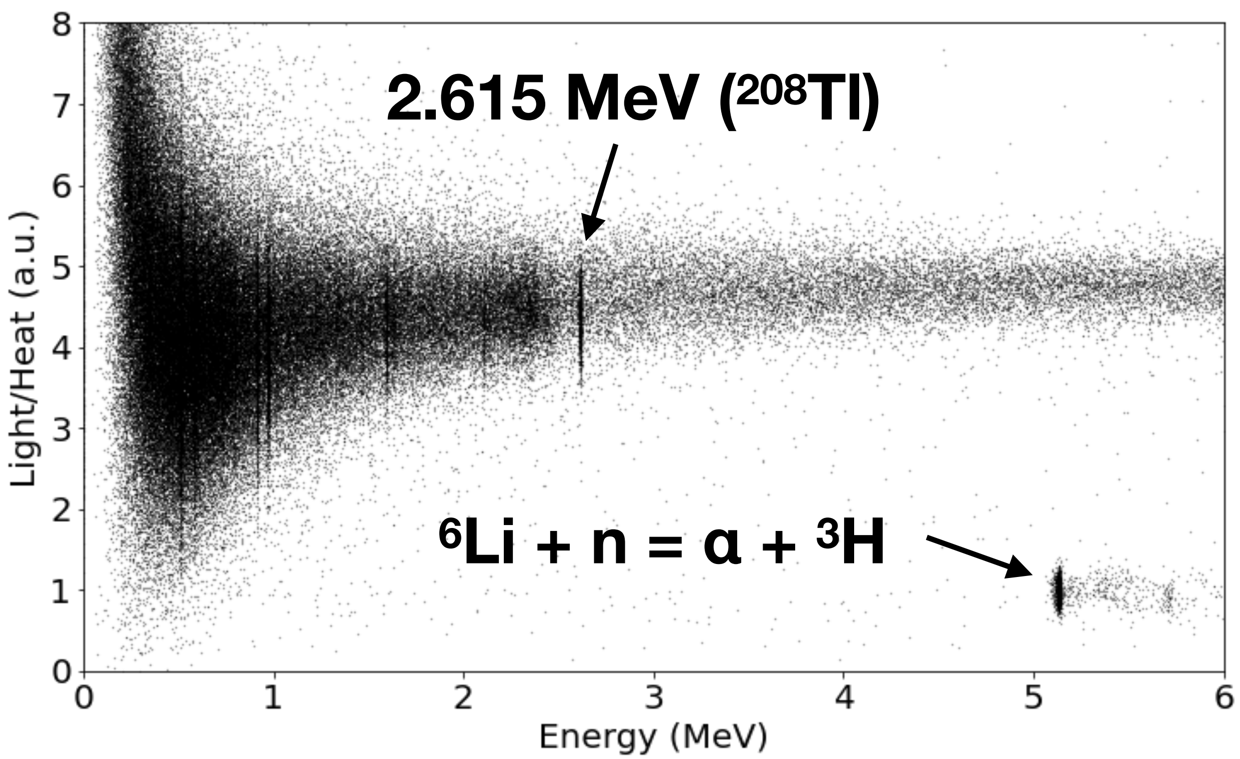
Optimization: better performance, preparation (a lot of detectors in time)

LMO with various experimental conditions:
humidity, large crystal, surface treatment, thermal connection …

Recently, demonstrated the improvement of the detector performance:
=> FWHM = 6-7 keV at 2.6 MeV with a crystal of 516 g
=> DP = 14 at 5-6 MeV by light/heat ratio (~10 at ROI)

To appear in JINST

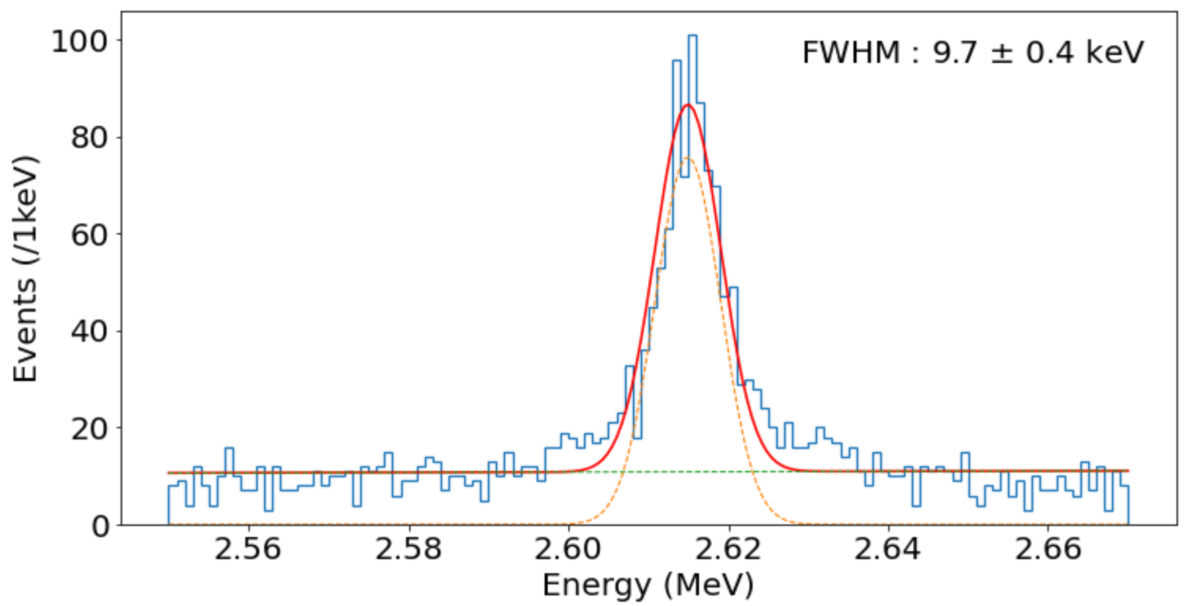


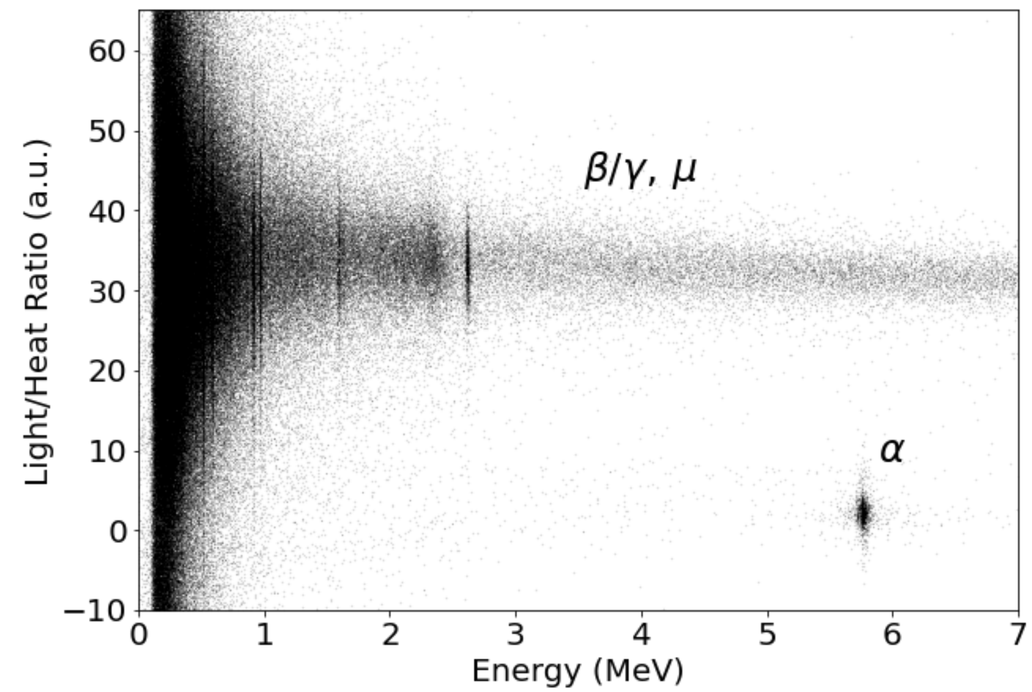


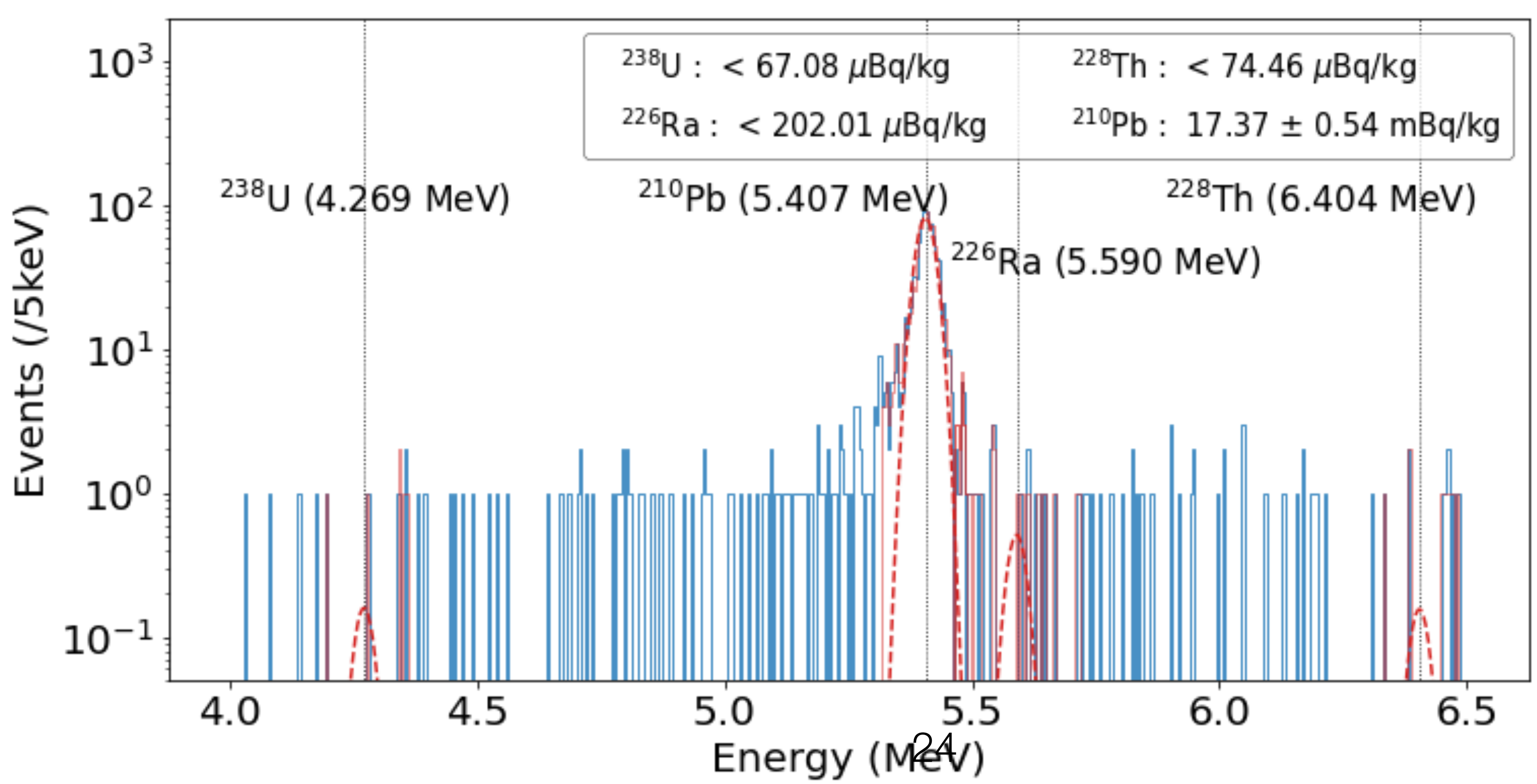
Detector R&D for AMoRE-II

Massive (178 g) sodium molybdate ($Na_2Mo_2O_7$, NIIC) crystal

FWHM@2.6MeV: 9.7 keV, DP = 12.4 at 5 - 6 MeV

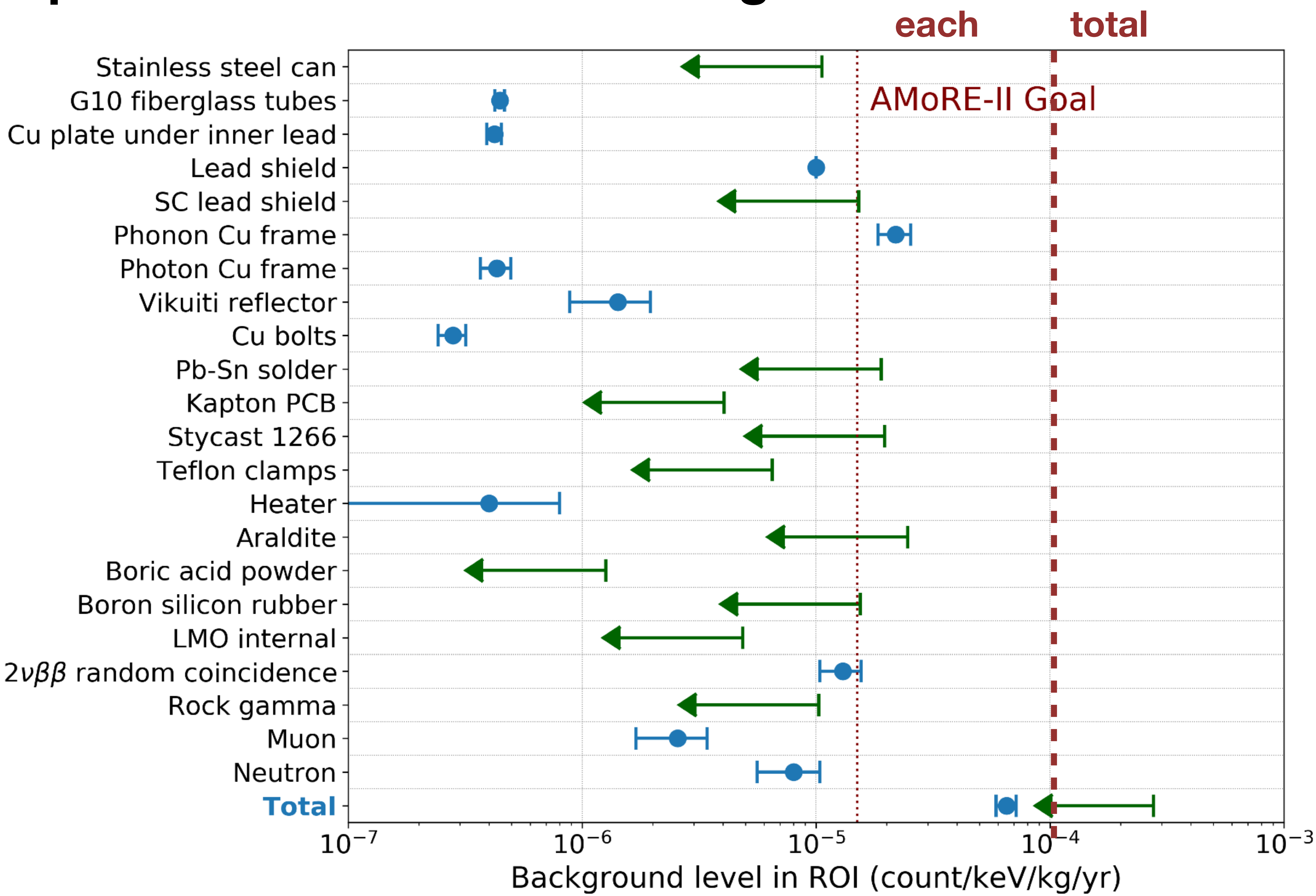






JINST 17 P04004

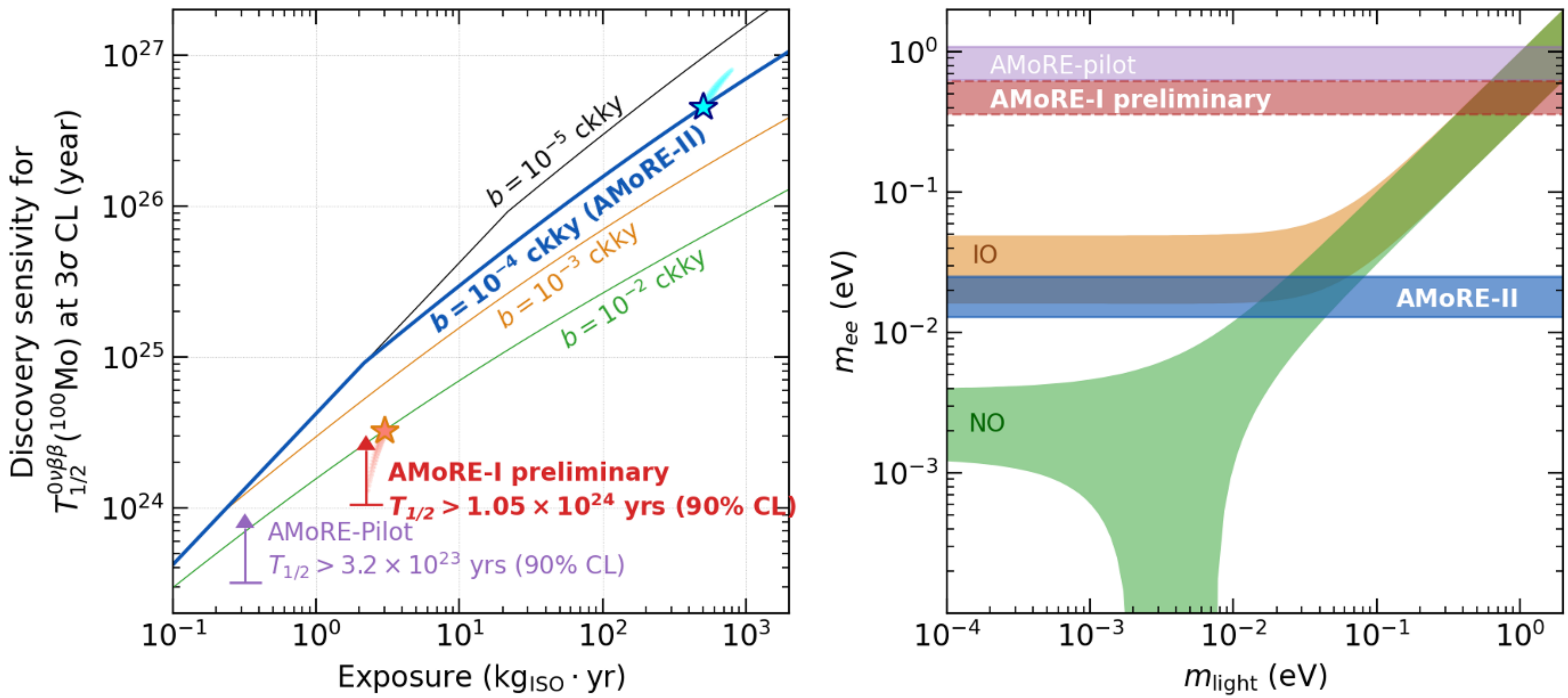
Expectation of AMoRE-II Backgrounds



Other effects:

Solar neutrino capture and subsequent decay (^{100}Mo->^{100}Tc -> Decay: 8.5 x 10^{-7} ckky)

Limits & Sensitivities



Final results of AMoRE-I with doubled data

AMoRE-II with 100 kg of ^{100}Mo × 5 years operation

Reduction of background level down to 10^{-4} ckky

$$T_{1/2}^{0\nu} >\sim 5 \times 10^{26} \text{ yrs}$$

Conclusion

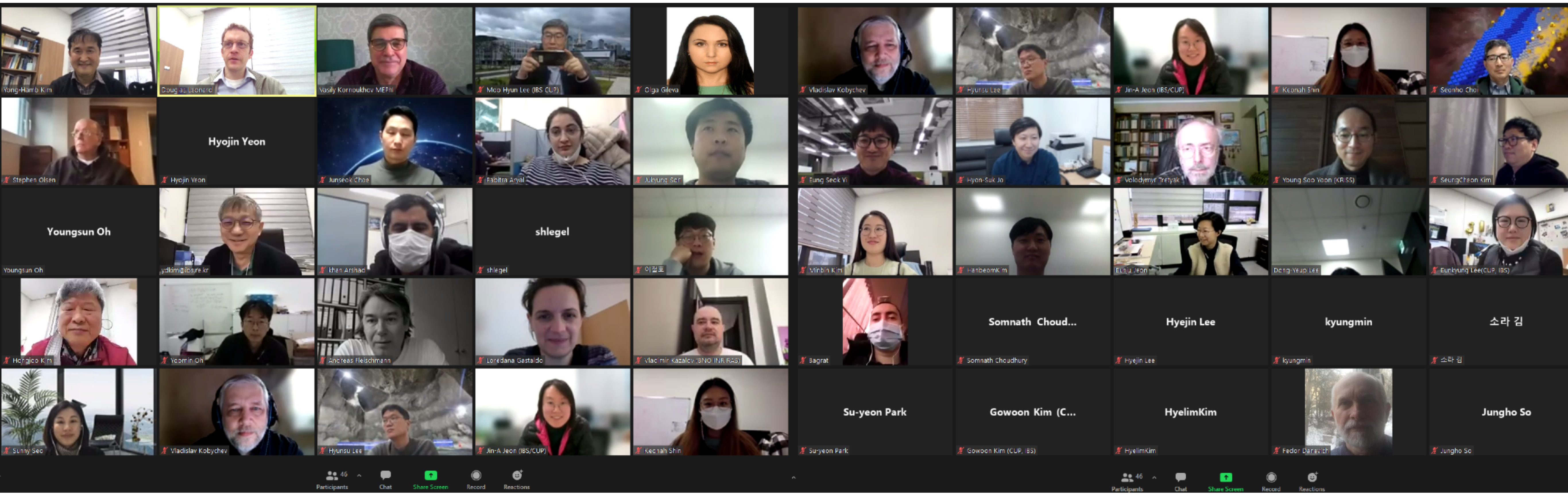
Search for 0vββ from ^{100}Mo using CMO/LMO crystals

Cryogenic calorimeter with simultaneous light & heat detection using MMC

Preliminary result of AMoRE-I at its mid-point:
=> Mass × time exposure: 4.68 (2.24) kg · yr by crystal mass (^{100}Mo)
=> Background level ~ 0.03 cnts/keV/kg/year at 2860-3200 keV
=> $\mathbf{T^{0\nu}_{1/2} > 1.05 \times 10^{24} yrs}$
=> AMoRE-I data taking will continue at least until the end of 2022

Preparing for AMoRE-II with 100 kg of ^{100}Mo
=> Build in two stages, the first stage starts at the end of this year
=> R&D improvement: FWHM@2.6MeV < 7 keV, DP@5-6MeV = 14
=> New experimental hall at Yemilab, more strict background control
=> Aiming at $\mathbf{T^{0\nu}_{1/2} >\sim 5 \times 10^{26} yrs}$ **in 5 year operation**

Acknowledgement :
AMoRE collaboration



~107 members, 25 institutes, 9 countries