AMoRE 0νββ Experiment

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AMoRE Collaboration

AMoRE: **A**dvanced **Mo**-based **R**are process **E**xperiment

28 institutes, >100 collaborators

AMoRE Introduction

^{100}Mo

- ✓ Q = 3034 keV > ^{208}Tl line (2615 keV)
- ✓ Natural abundance : 9.7%
- ✓ $T_{1/2}$ (2ν) = 7.1 × 10^{18} y: the largest ββ decay rate

$^{40}Ca^{100}MoO_4$: enriched ^{100}Mo and depleted ^{48}Ca

: Selected for a pilot and AMoRE-1'

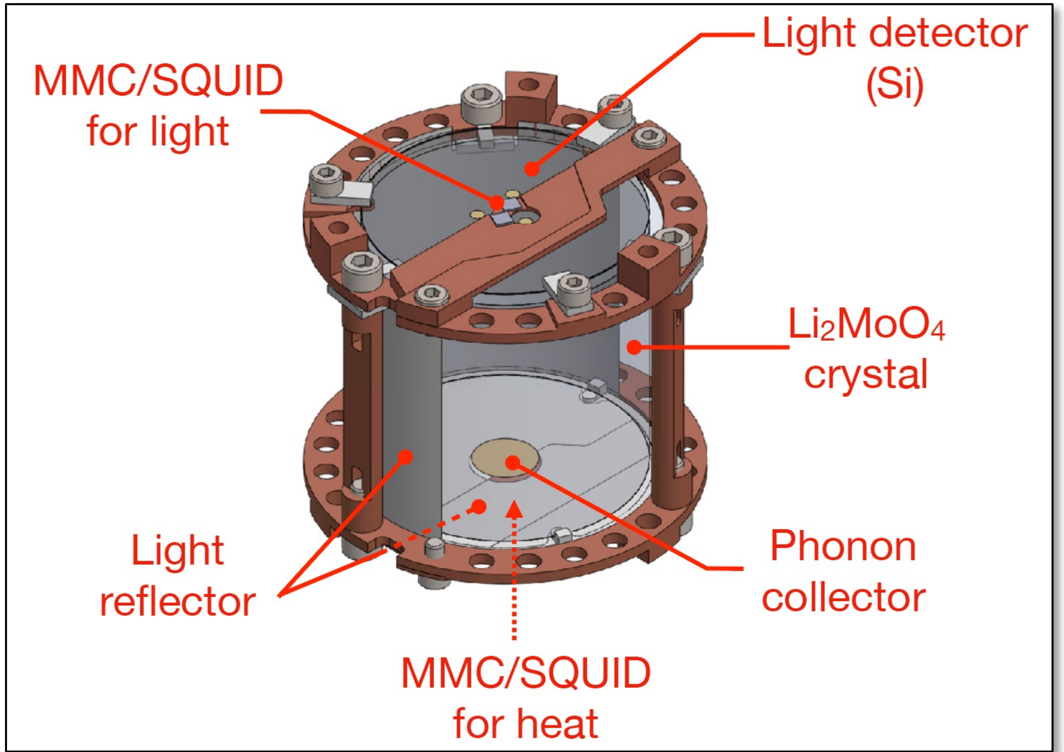
: High T_D = 446 K, Large scintlation yield

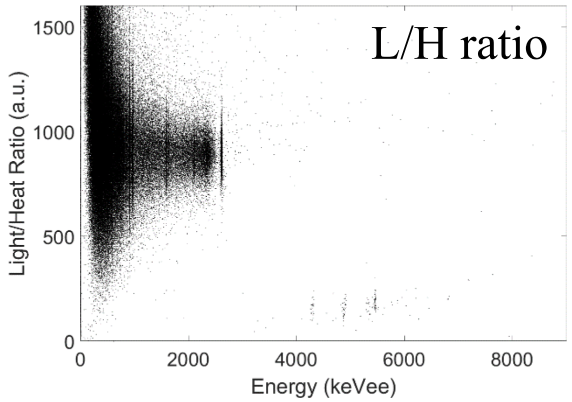
$Li_2{}^{100}MoO_4$: Selected for AMoRE-II

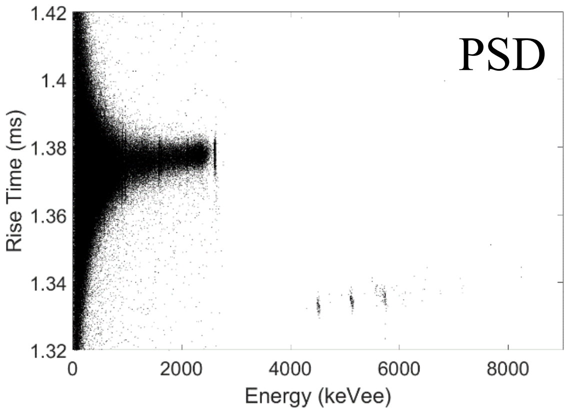
: Moderate: T_D = 316 K

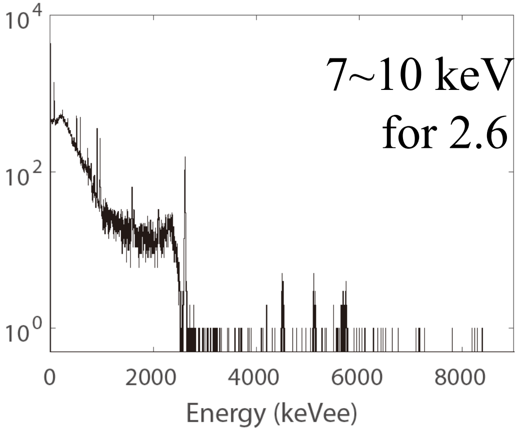
: Hygroscopic, Low scintlation yield

MMC for heat and light detection







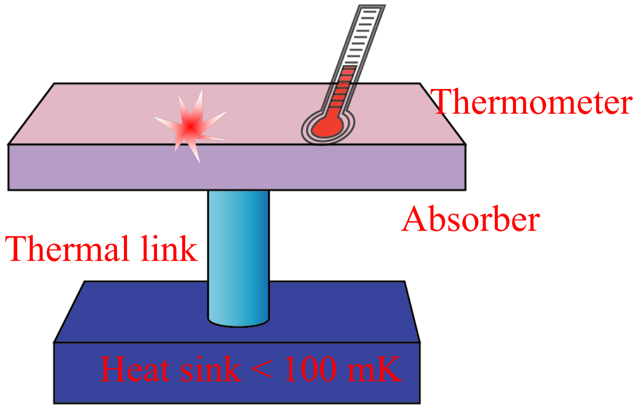


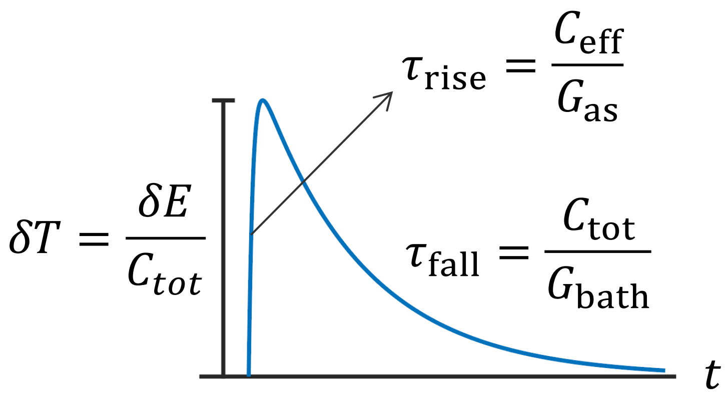
7~10 keV FWHM for 2.6 MeV

Low Temperature Thermal Calorimeters

"Thermal calorimetric measurement of heat signals at mK temperatures"

Energy absorption ➔ Temperature



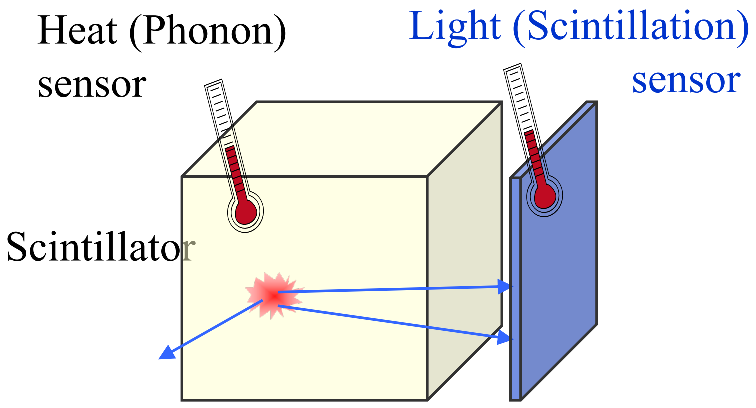


Choice of thermometers for 0νββ searches

- **Thermistors (NTD Ge)** CUORE, CUPID
- **MMC (Metallic Magnetic Calorimeter)** AMoRE CANDLES-LT
- TES (Transition Edge Sensor) Light detector, mutli-phonons
- KID (Kinetic Inductance Device) CALDER
- etc.

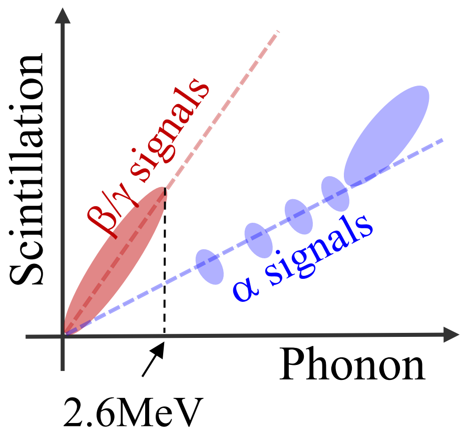
Simultaneous phonon-scintillation detection for 0νββ searches

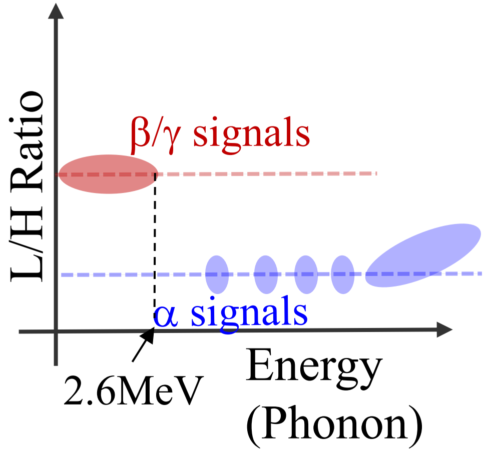
✓ Scintillating crystal as target material



Li_2MoO_4 $CaMoO_4$
$CdWO_4$ ZnSe, CaF_2 etc.

Scintillating crystal ➔
Active bkg. Rejection
using **L/H ratio and PSD**

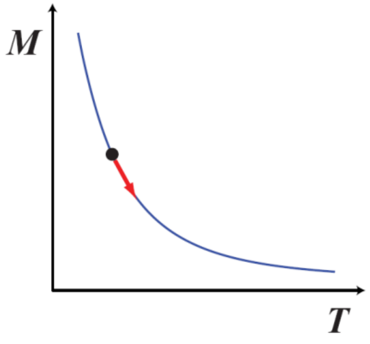




Magnetic microcalorimeter (MMC)

(Metallic Magnetic Calorimeter)

- Paramagnetic alloy in a magnetic field
  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)
  → Magnetization variation with temperature
- Readout: SQUID
- High resolution + High linearity + Wide dynamic range + Absorber friendly + No bias heating + Relatively fast + MUX
- More wires & materials needed for SQUIDs and MMCs



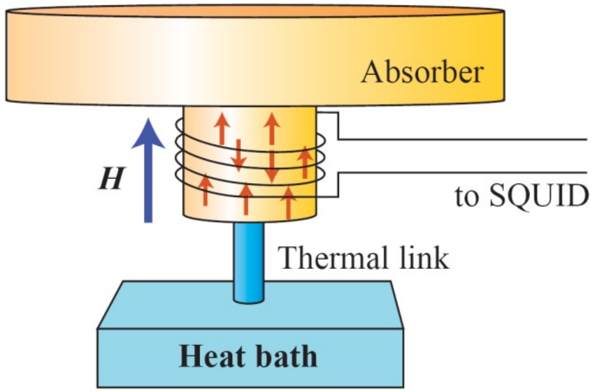
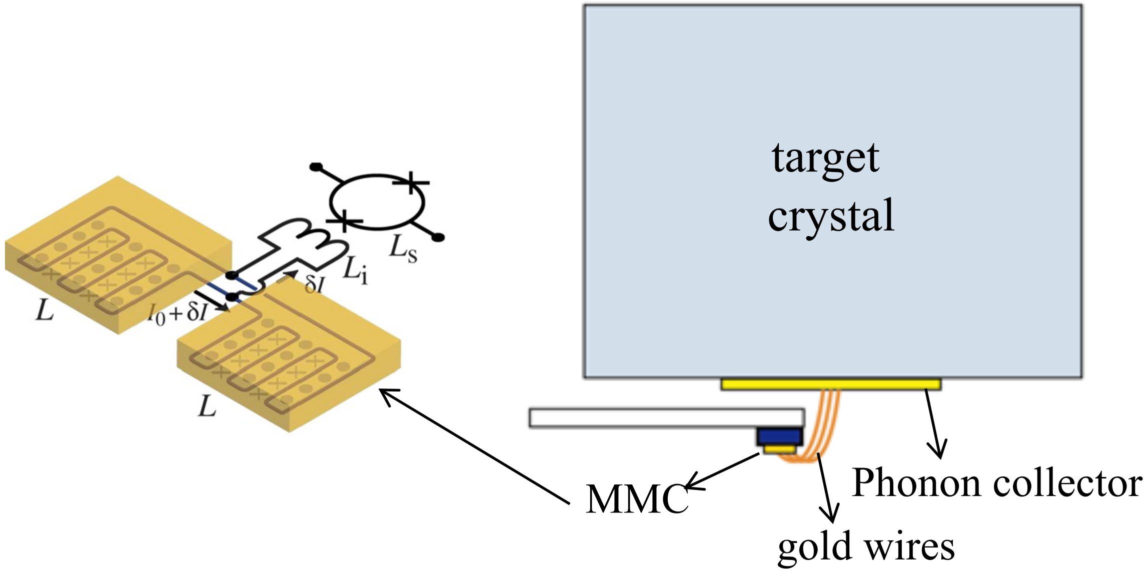
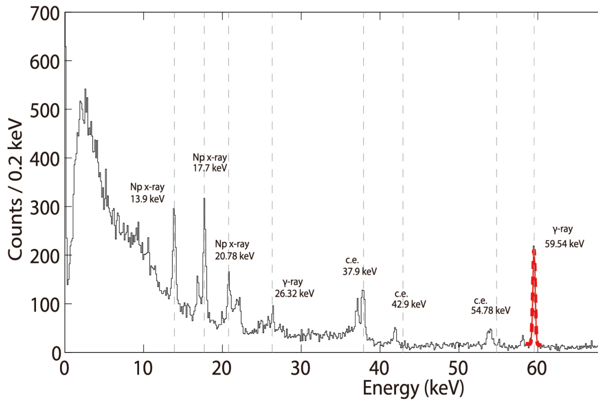


fig. from SY Oh et al SuST 2017

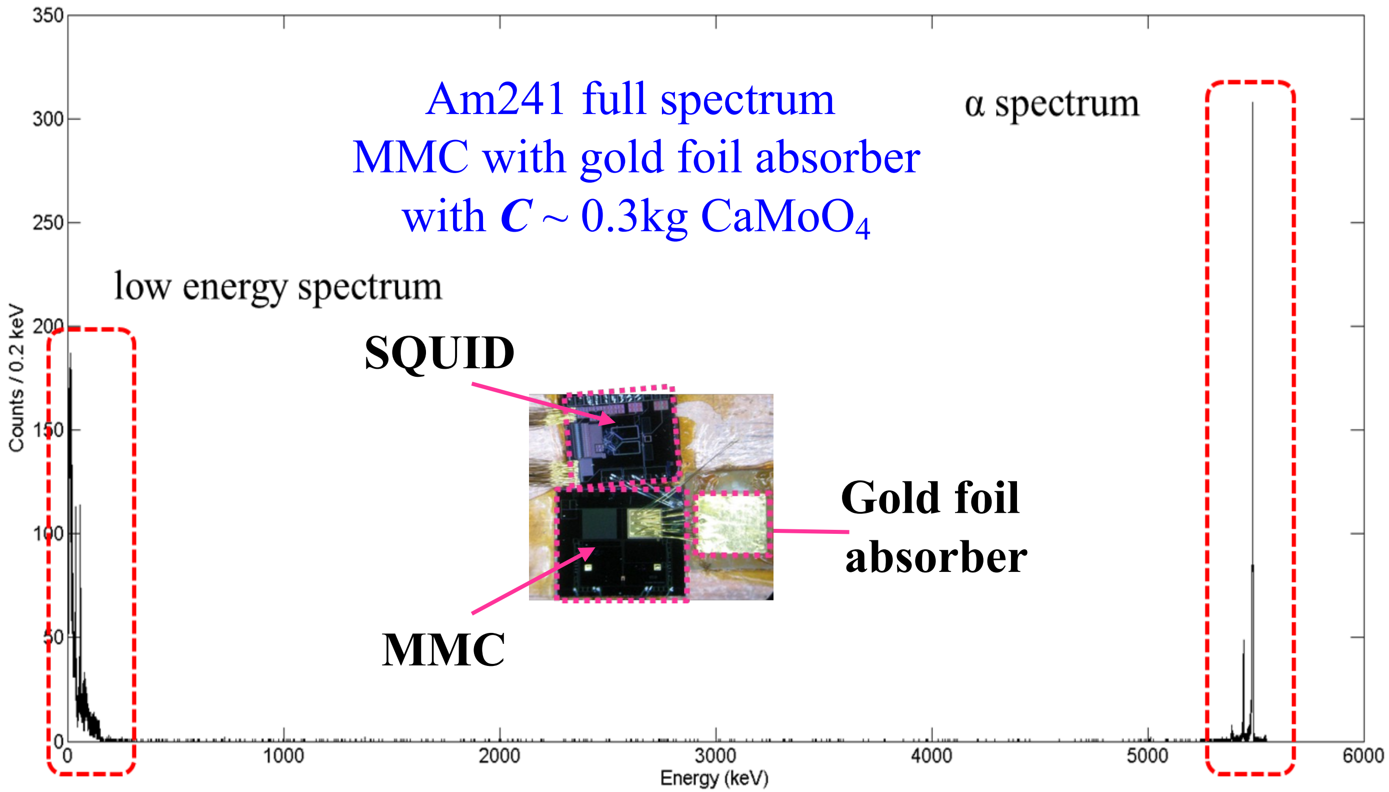


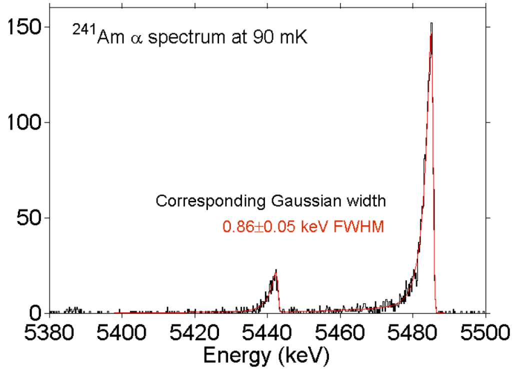
MMC performance in a wide energy region

"Superior dynamic range with high resolution"



0.3 keV FWHM for 60keV γ

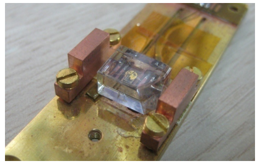




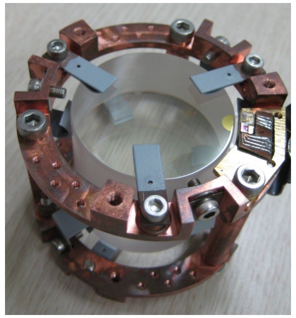
$$\frac{\delta E_{rms}}{E} = 1/15{,}000$$

0.9 keV FWHM Gaussian width for 5.5MeV α

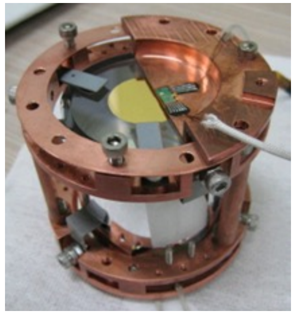
AMoRE Detector Progress



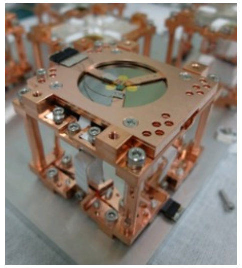
CMO (4g)
+MMC
(2010)



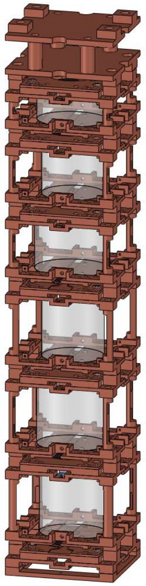
216 g CMO
2011



Phonon collector
(high resolution)
2012

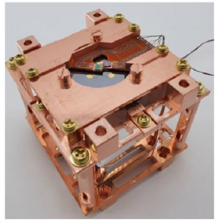


Single module
Heat+Light
2014

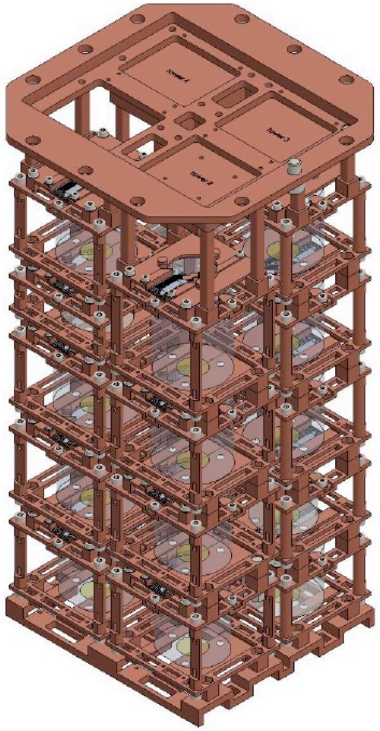


AMoRE-Pilot
Ended 2018

Underground Exp.



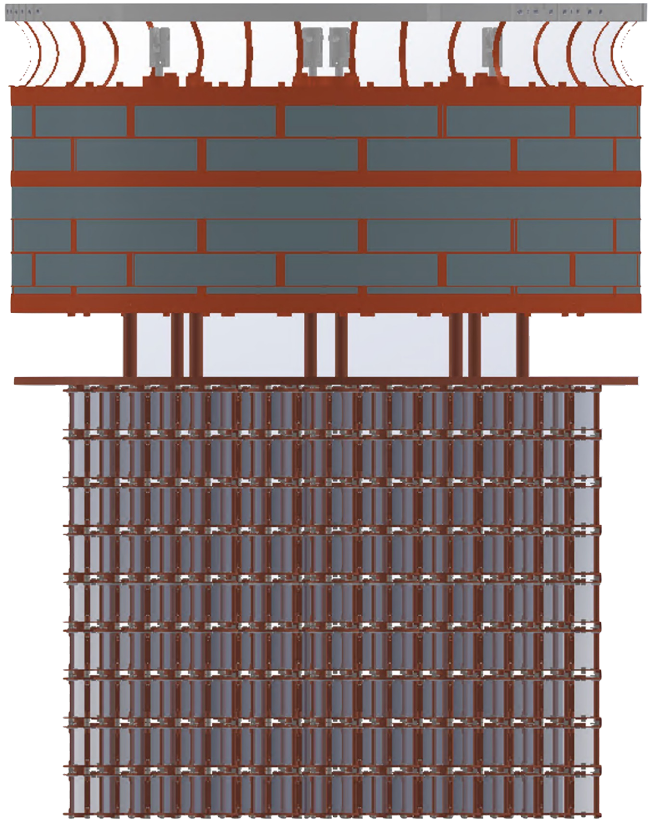
13 CMOs
+ 5 LMOs



Ended 2023

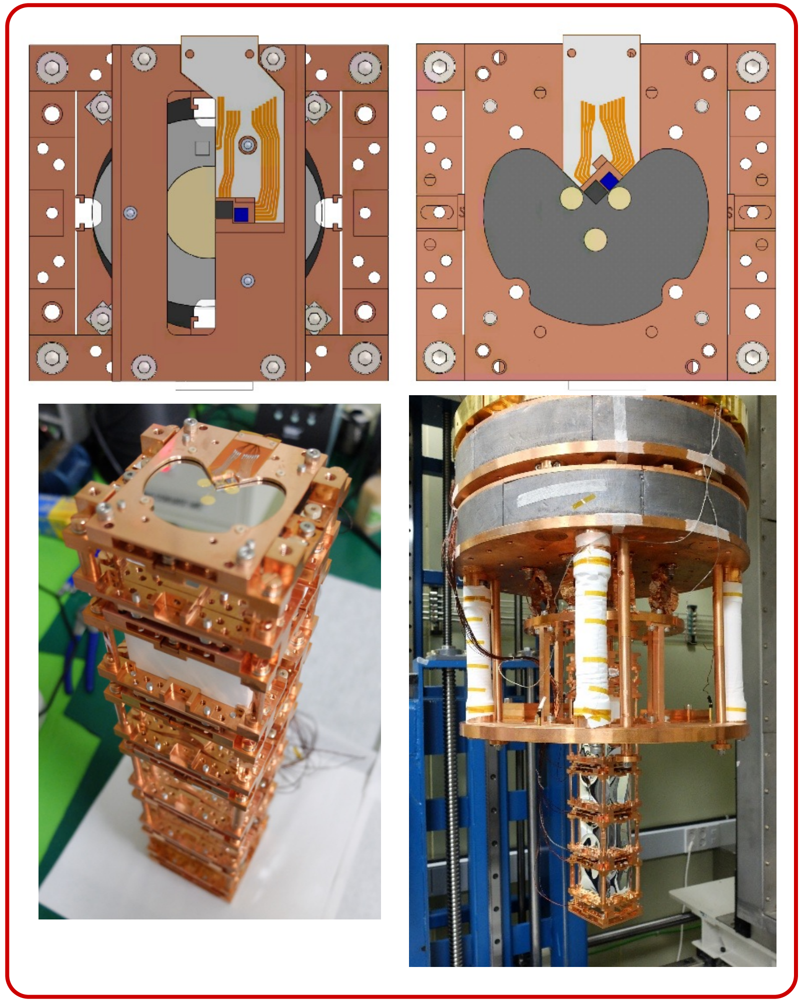
AMoRE-I

To begin 2024

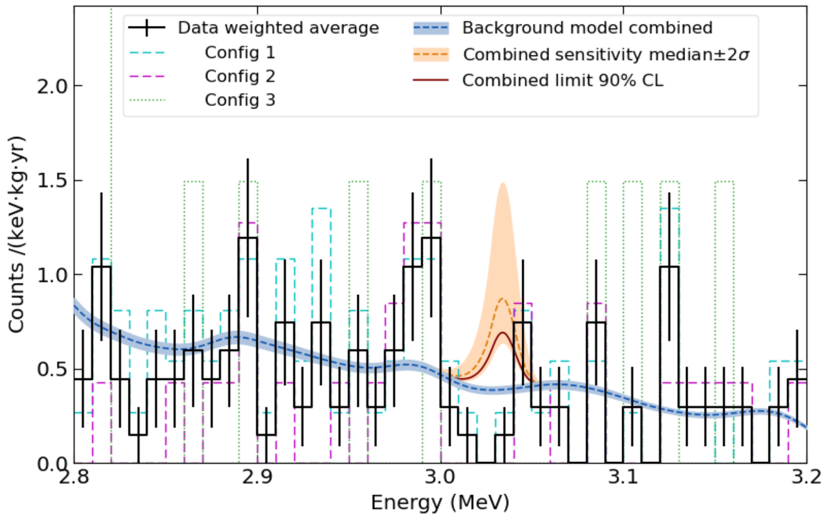


AMoRE-II
Being prepared

AMoRE Pilot result



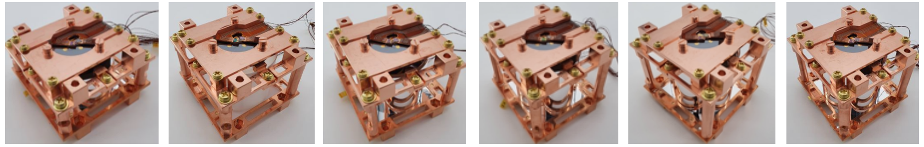
- $^{48depl}Ca^{100}MoO_4$: 6 crystals 1.9 kg (0.9kg ^{100}Mo)
- Proof of the AMoRE detection principle
- Understanding of the background components & their reductions
- Background level of ~0.5 ckky at 2.8-3.2 MeV
  - n-induced γ, Internal bkg, rock/air-radon γ
  - Internal background— arXiv:2107.07704
- $T_{1/2}$ (0ν) > 3.2×10^{23} years at 90% CL.



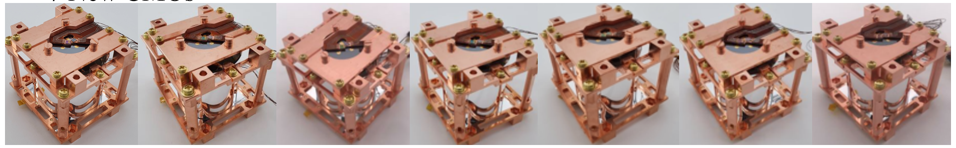
AMoRE Pilot → AMoRE-I

- 18 crystals: 13 $^{48depl}Ca^{100}MoO_4$ (4.58 kg) + 5 $Li_2{}^{100}MoO_4$ (1.61 kg)
- Total crystal mass 6.19 kg (3.0 kg ^{100}Mo)
- MMC sensor: Au:Er ➔ Ag:Er
- Using 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 supply of Rn-free air.

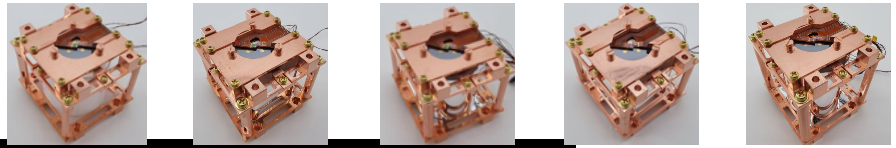
6 Pilot CMOs

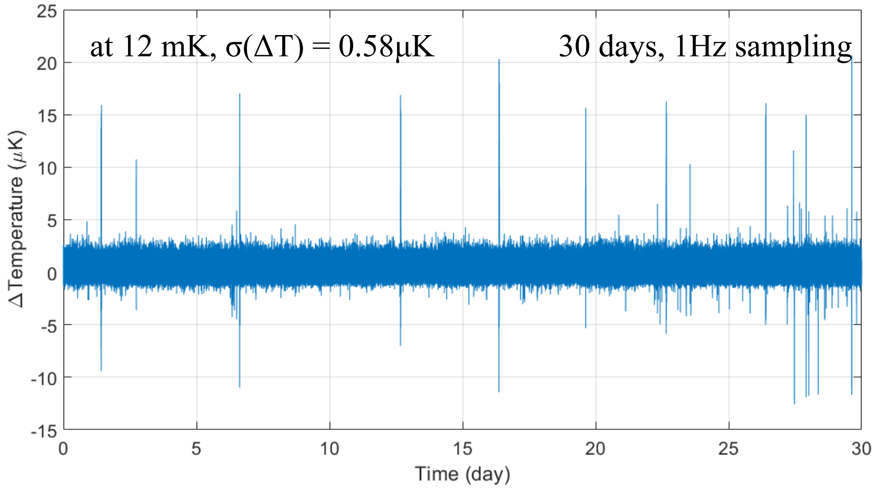


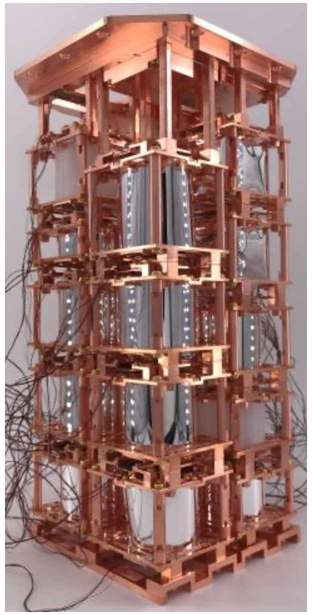
7 New CMOs

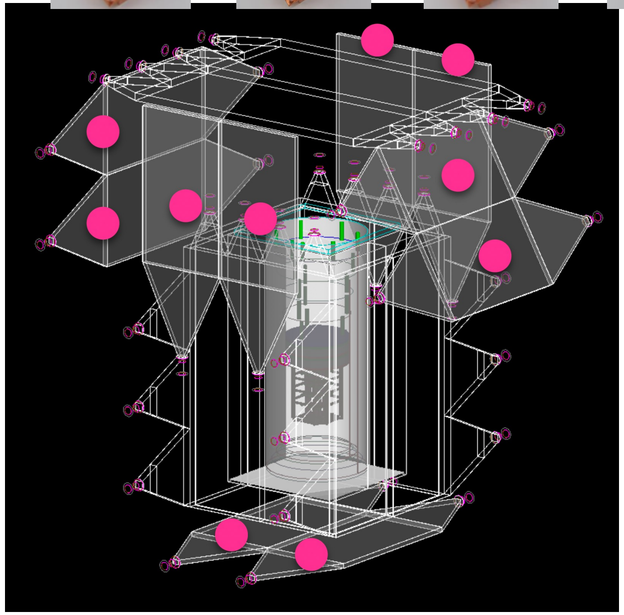


5 New LMOs

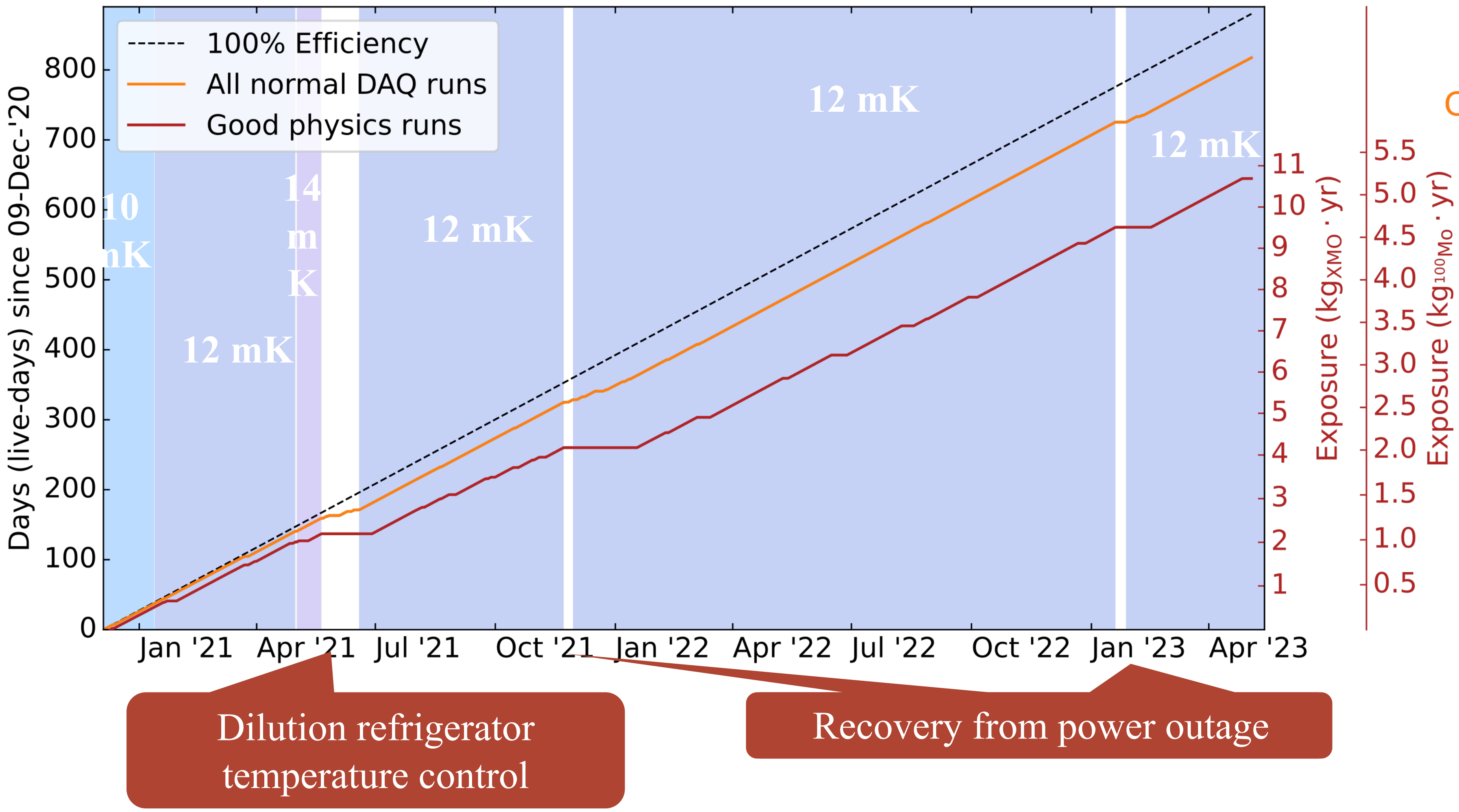


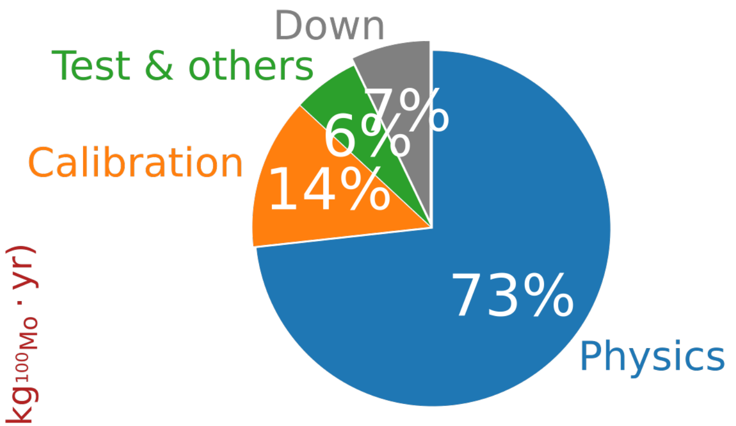






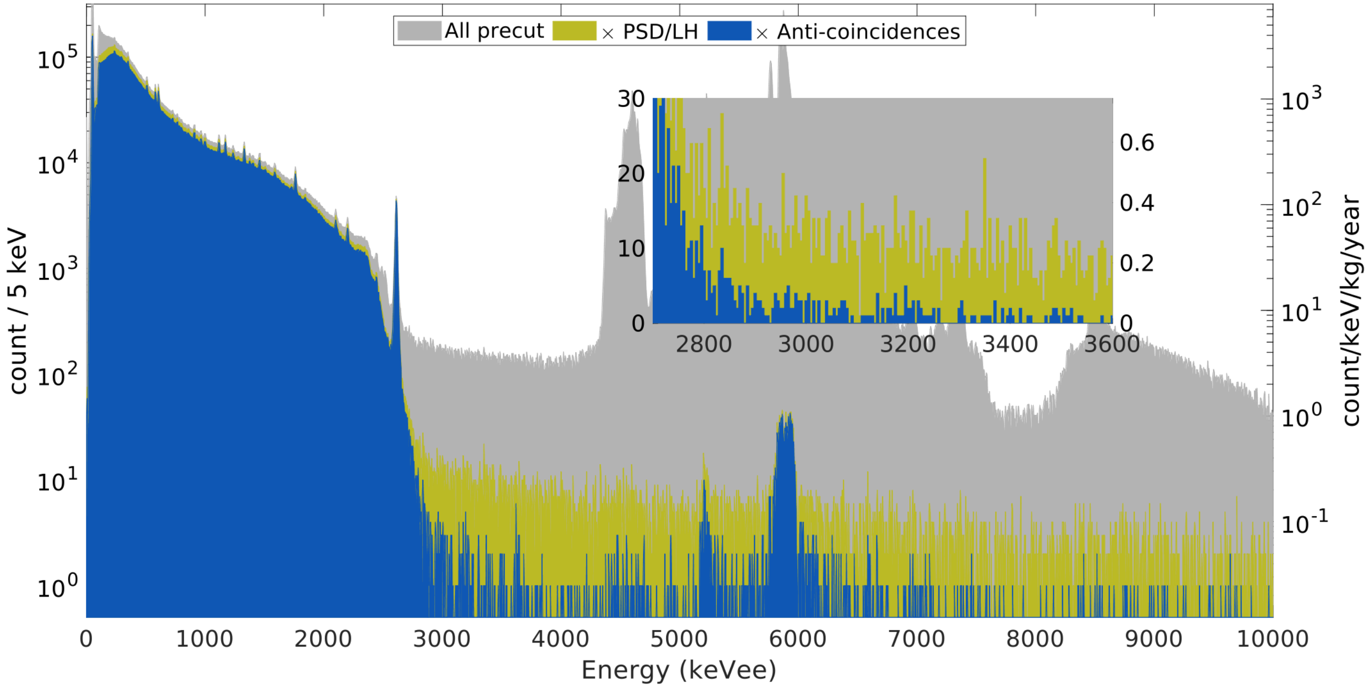
AMoRE-I (Preliminary) Results

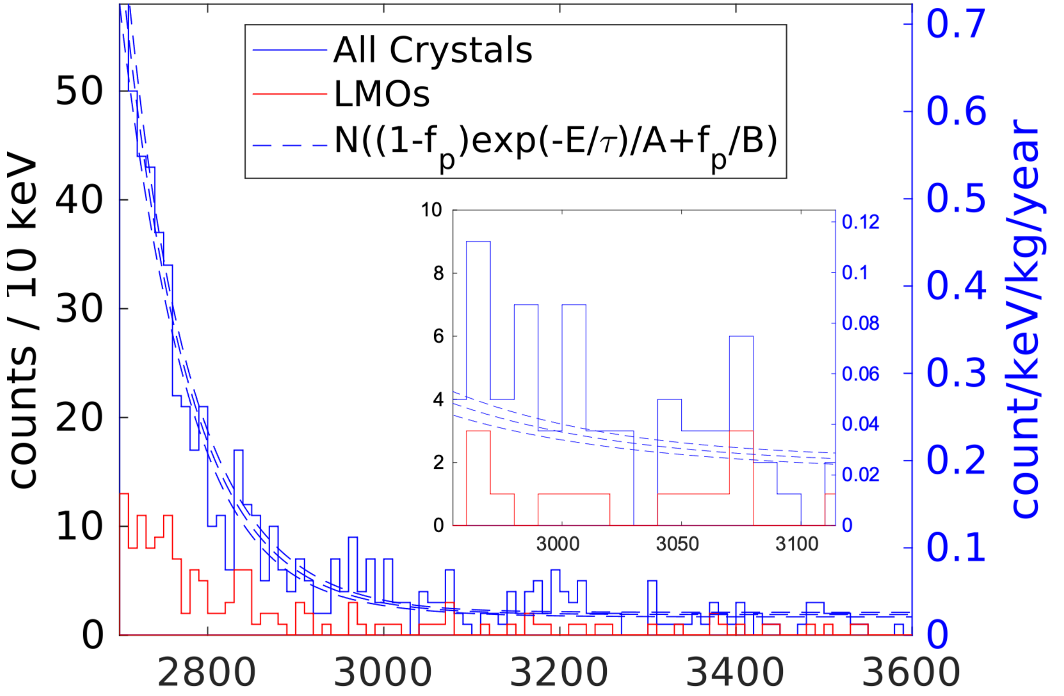




12 mK physics data	Exposure ($kg_{XMO} \cdot yr$)
Total	10.16
- Bad channels/runs	8.76
- deadtime & anti-coincidence (= live exposure)	8.02
in ^{100}Mo	3.88 ($kg_{ISO} \cdot yr$)

AMoRE-I backgrounds (Preliminary)

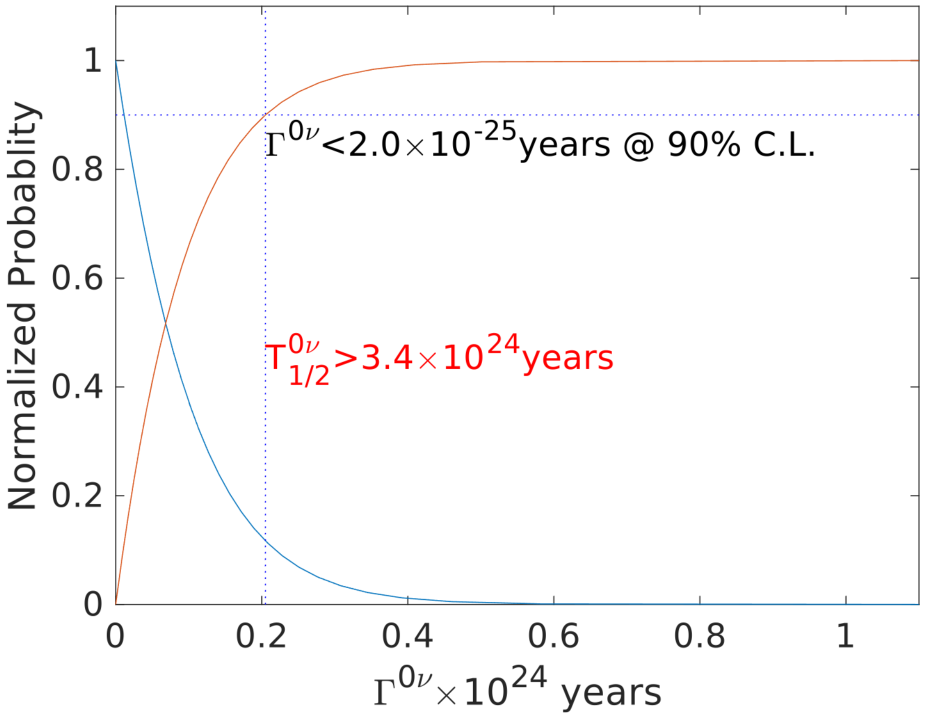




- All crystal excluding one LMO (for very poor β/α discrimination power)
  - 13 CMO + 4 LMO: exposure = 8.02 kg_{XMoO_4}·yr = 3.88 $kg_{^{100}Mo}$·yr.
- Anti-coincidence cuts reject events:
  - coincident at multiple crystals within 2 ms ($\varepsilon \sim 99.8\%$),
  - within 10 ms after a muon counter 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_{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

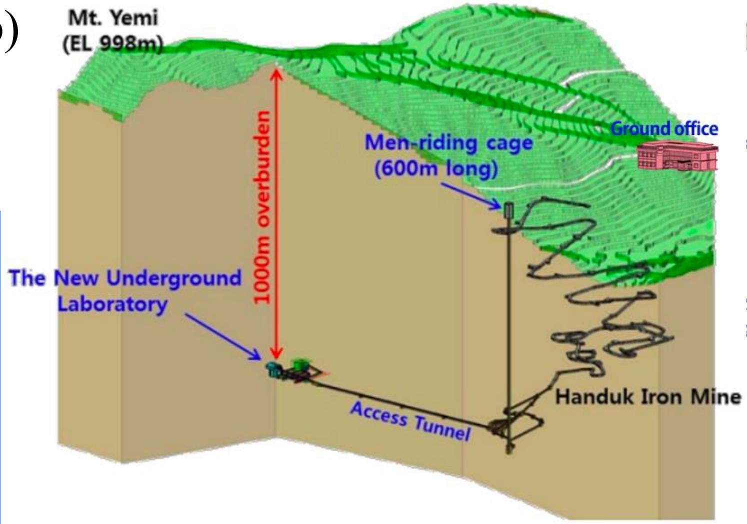


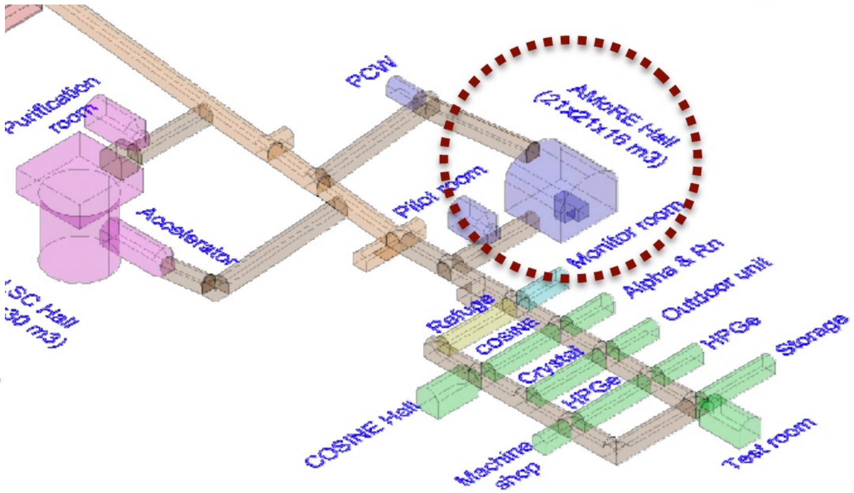
- ROI = $|E - Q_{\beta\beta}| < 2.5\ \Delta E_{\mathrm{FWHM}}$, $\varepsilon_{\mathrm{containment}} \sim 81\%$.
- Background = 0.032 ± 0.003 counts/keV/kg/year, from ROI side-band.
- Unbinned likelihood for $\Gamma^{0\nu} (= \ln 2 / T_{1/2})$ for each crystal, with signal shape and background rate constrained from calibration and sideband data, respectively.
- $\boldsymbol{T^{0\nu}_{1/2} > 3.4 \times 10^{24}}$ **years at 90% C.L. for Mo-100**

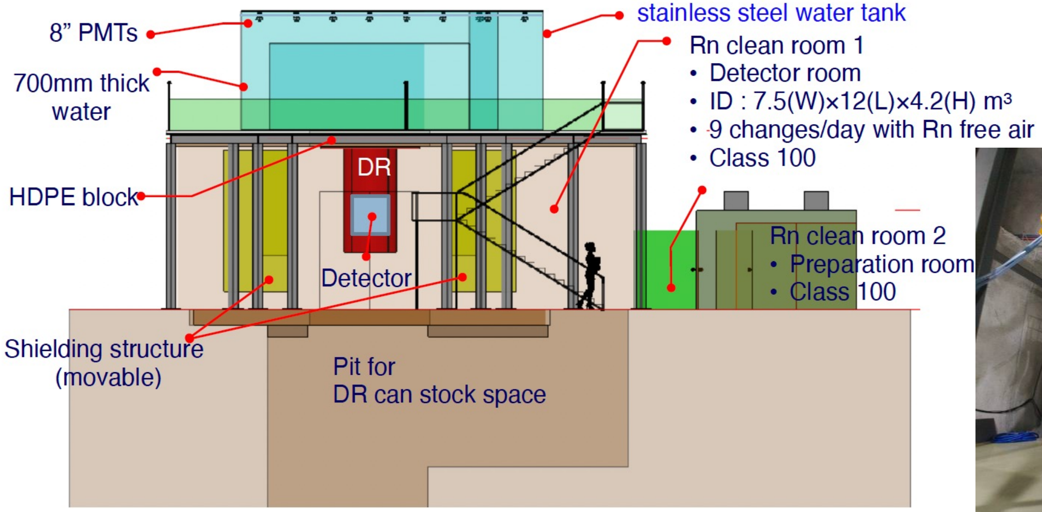
Yong-Hamb Kim

AMoRE-II in preparation at Yemilab

- In a new underground lab (Yemilab)
- With new cryostat and new shields



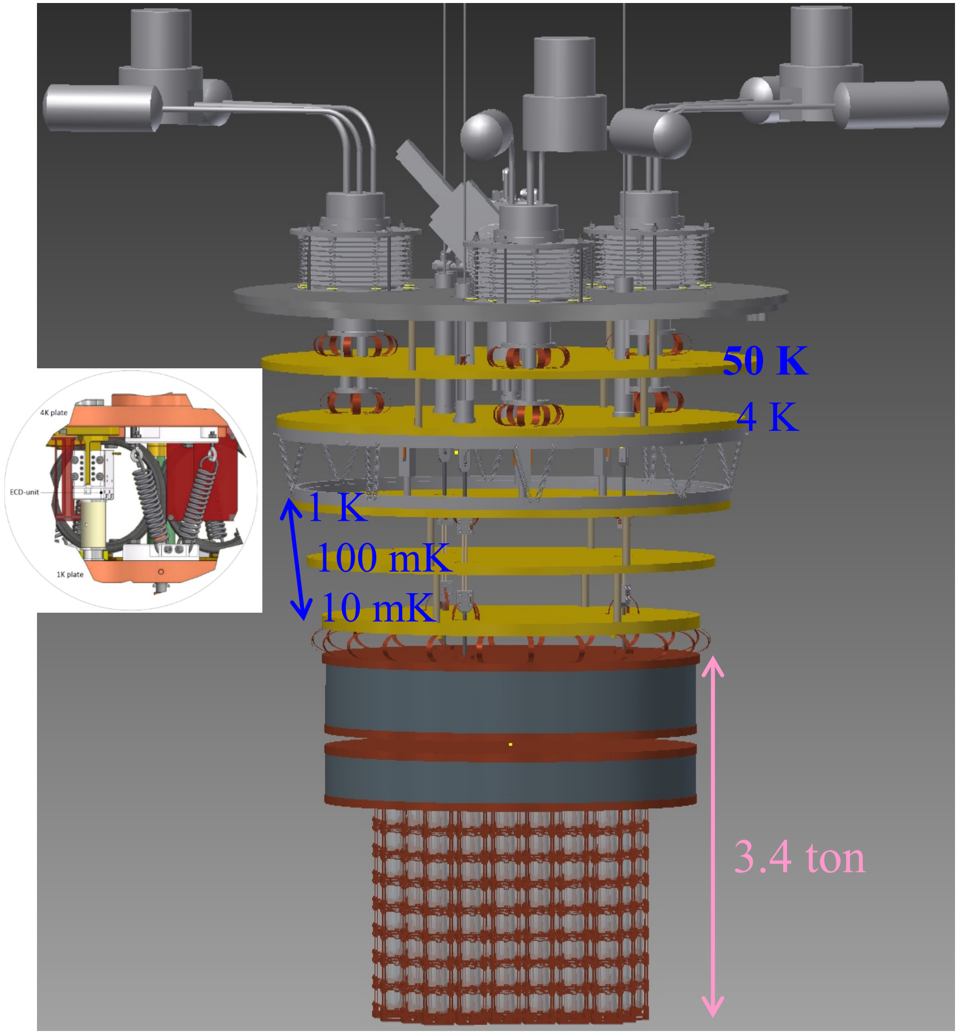


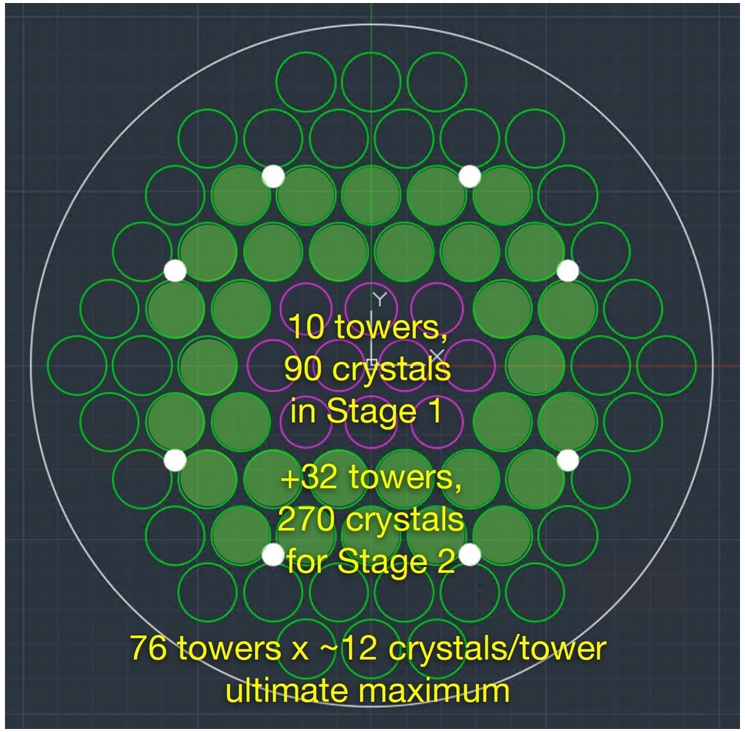


AMoRE-II Cryogenics

- Three PTRs (PT420 RM)
- Dilution refrigerator
    - 6 mK base temperature w.o. wirings
    - 7 uW at 10 mK

- Spring Suspended Still with Eddy Current Damper
- Independent holding structure for detector tower

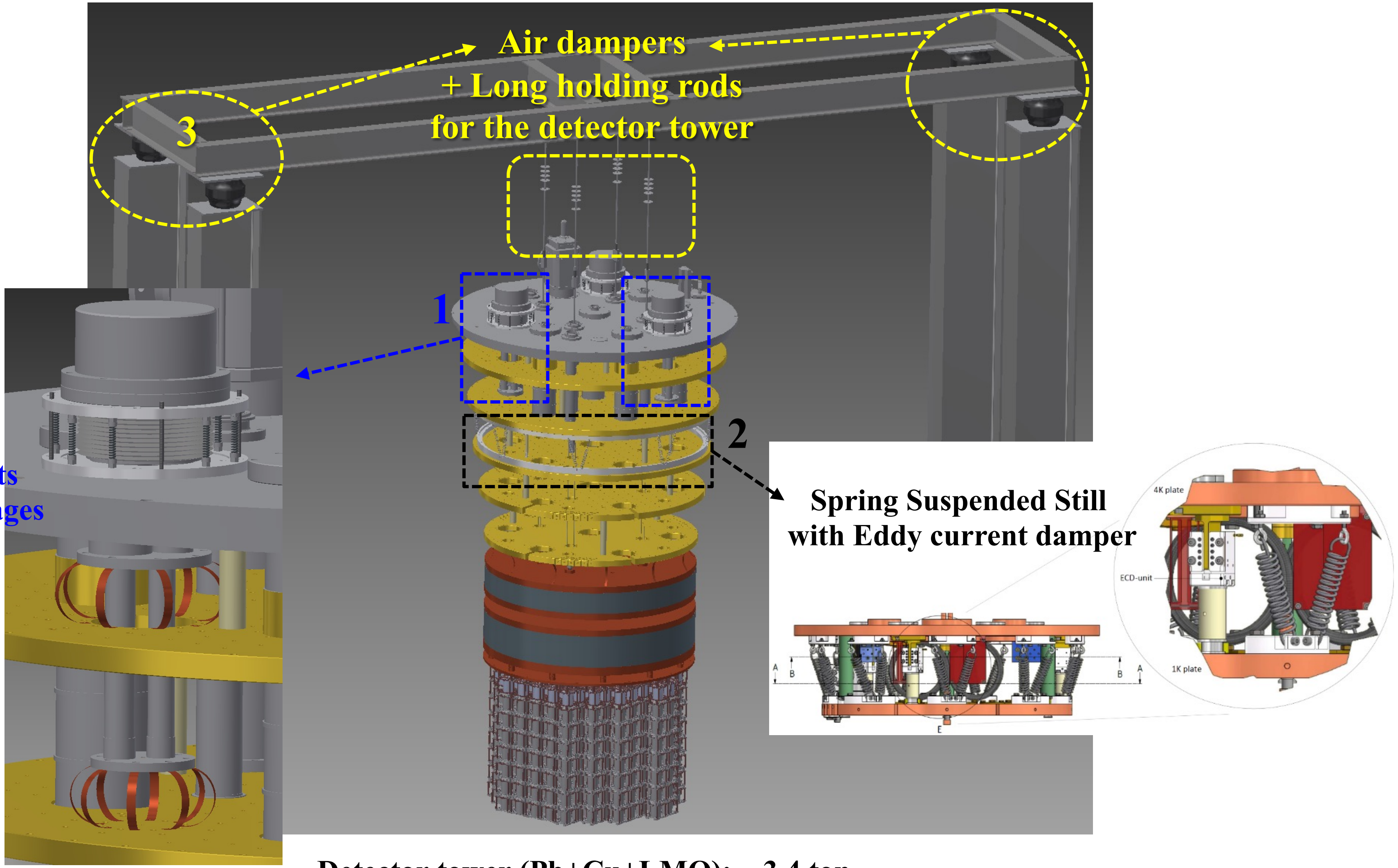




1st Stage: 9×10 Modules
~ 24 kg crystal mass

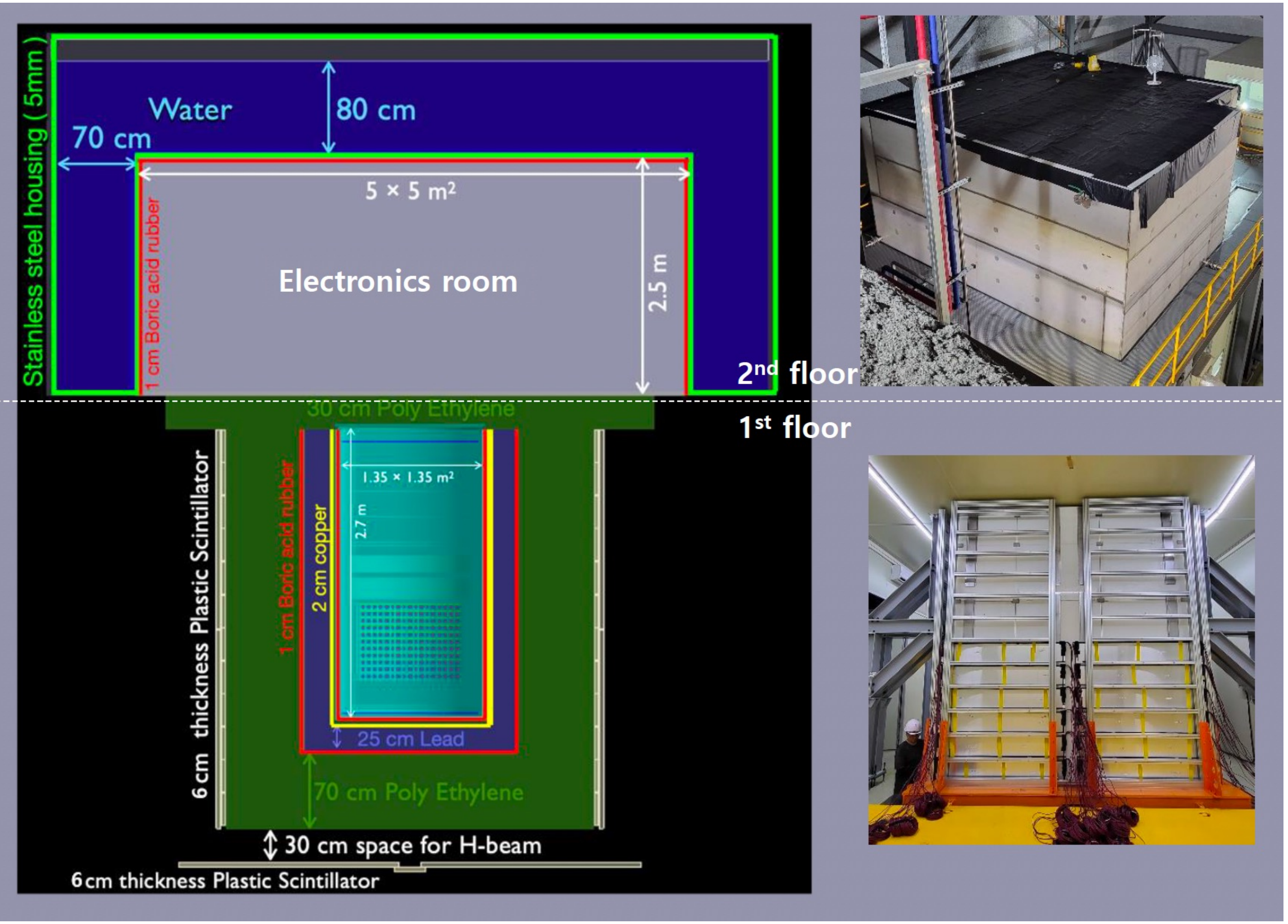
2nd Stage: +9×32 Modules
~ 160 kg crystal mass

Vibration damping systems



Detector tower (Pb+Cu+LMO): ~ 3.4 ton
Independent support of Kevlar strings + STS rods from room temp.
Cooling method: IVC exchange gas + soft copper foils

AMoRE-II Shielding



- Pb 26 cm over the crystal towers, below the mixing chamber plate in IVC.
- Bottom: boric acid rubber 1 cm < Cu 2 cm
  < Pb 25 cm < boric acid rubber 1 cm
  < polyethylene 70 cm
  < Plastic scint. μ-counter
- Top: boric acid rubber 1 cm
  < water Cherenkov μ-counter 70-80 cm.
- Muon rate ~ 10^{-7} cm^{-2} s^{-1}.
- Radon-free air supply.

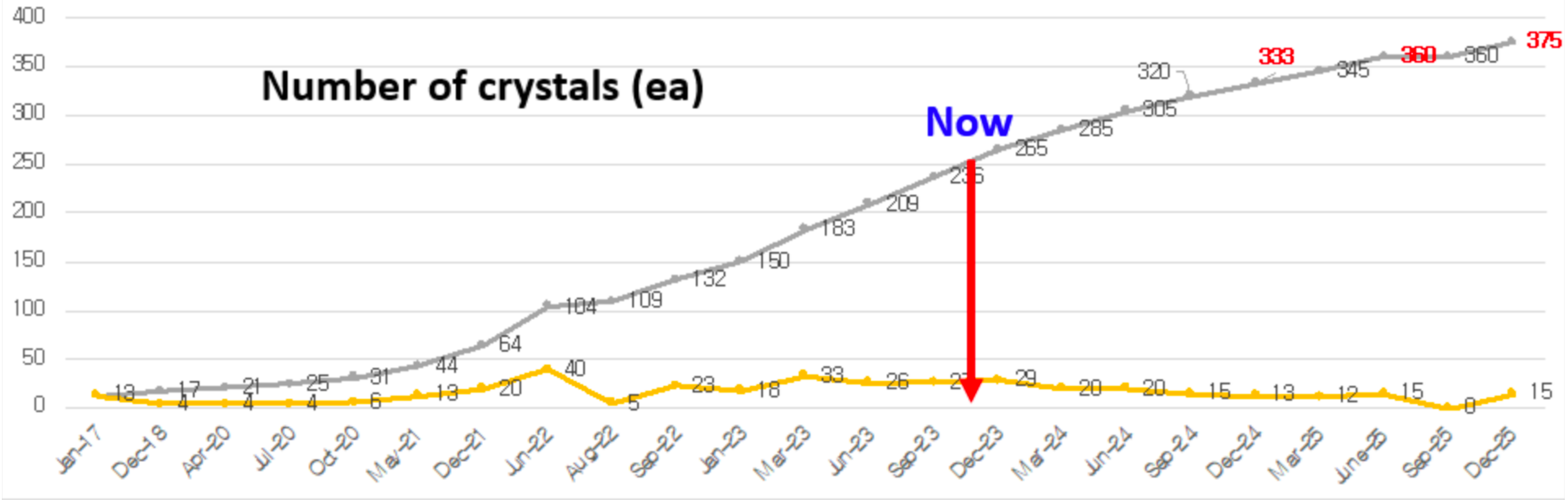
Crystal preparation

- Mo-100 enrichment = 95%.
- Purification of MoO3 and Li_2CO_3 powder at CUP.
- Crystals produced at CUP/IBS and NIIC

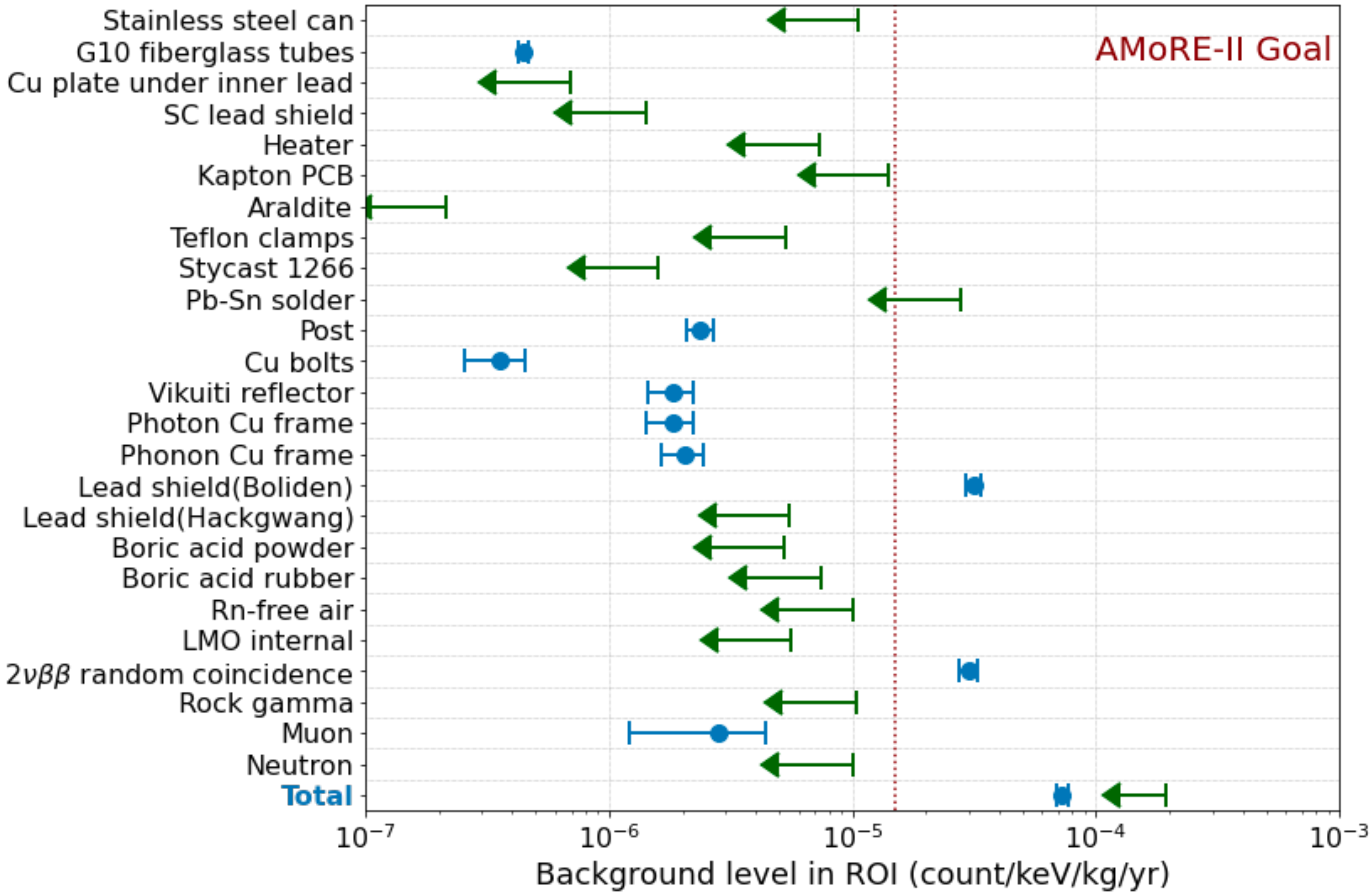
- ~ 360 ea (~ 157 kg) of crystals (including AMoRE-I CMOs) will be ready by mid-2025.

MoO_3 powder \ Activity (μBq/kg)	Raw	Purified
Ac-228	260 ± 50	< 27
Th-228	210 ± 50	< 16
Ra-226	260 ± 50	110 ± 30
K-40	8500 ± 1400	1700 ± 340

Yeon H., et al. Front. Phys. 11, 1142136 (2023)



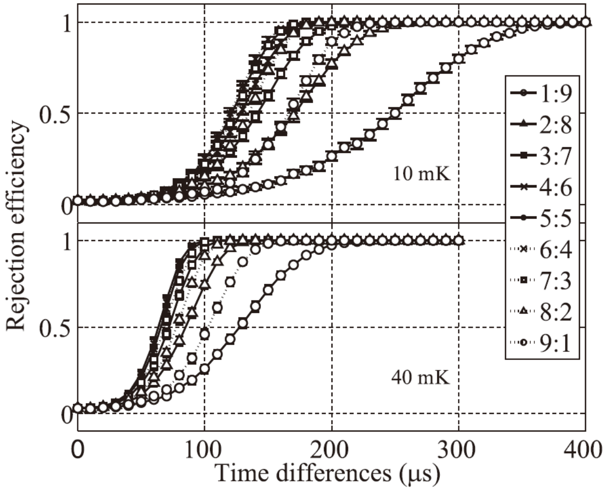
AMoRE-II Background budgets



Unresolved pileups of ^{100}Mo 2νββ signals

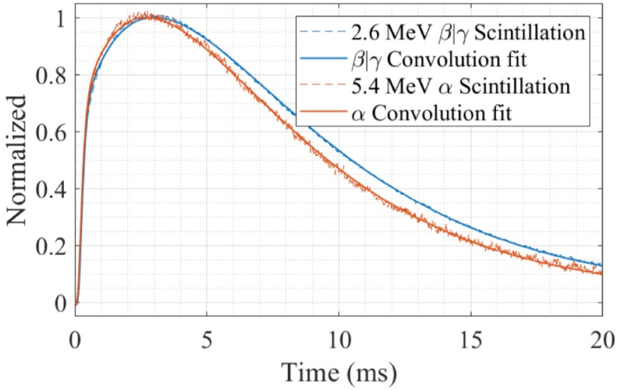
- 1 kg ^{100}Mo → ~20 mBq of 2νββ $T_{1/2}$ (2νββ ^{100}Mo): ~7.1×10^{18} year
- Timing resolution for pileup rejection:
  : ~ 40 μs for 10^{-5} ckky in a Ø50×50 LMO (in most conservative way)
  : ~ 100 μs goal for AMoRE-II

With heat-signal rise-time only.
120 μs at 10 mK, 60 μs at 40 mK



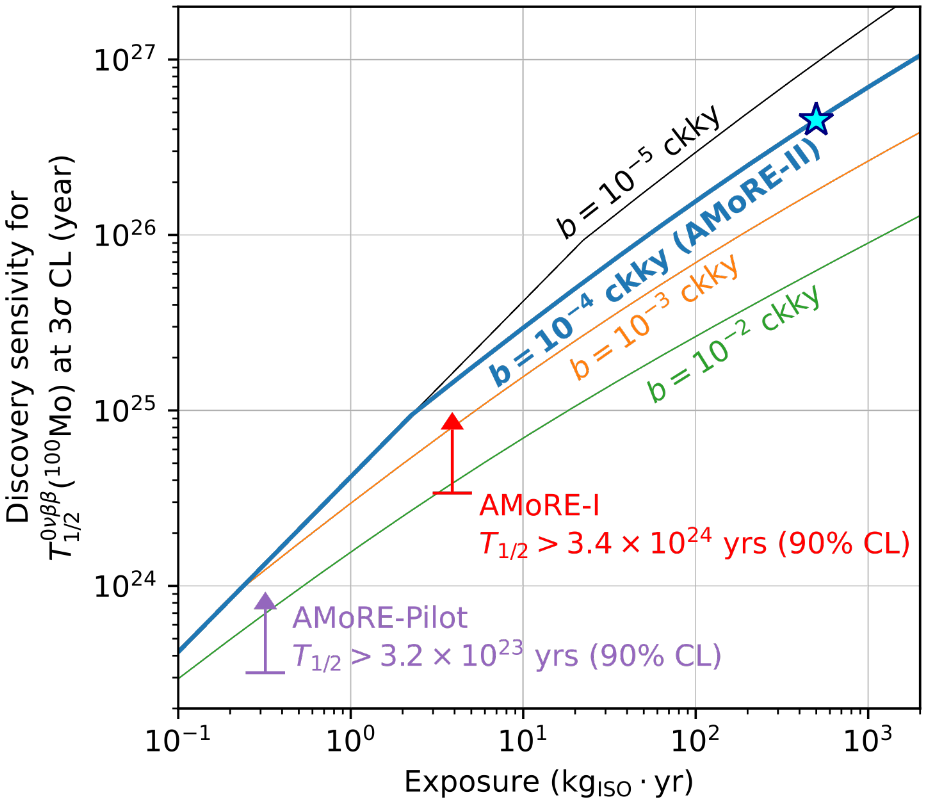
Astroparticle Phys. 91:105 (2017)

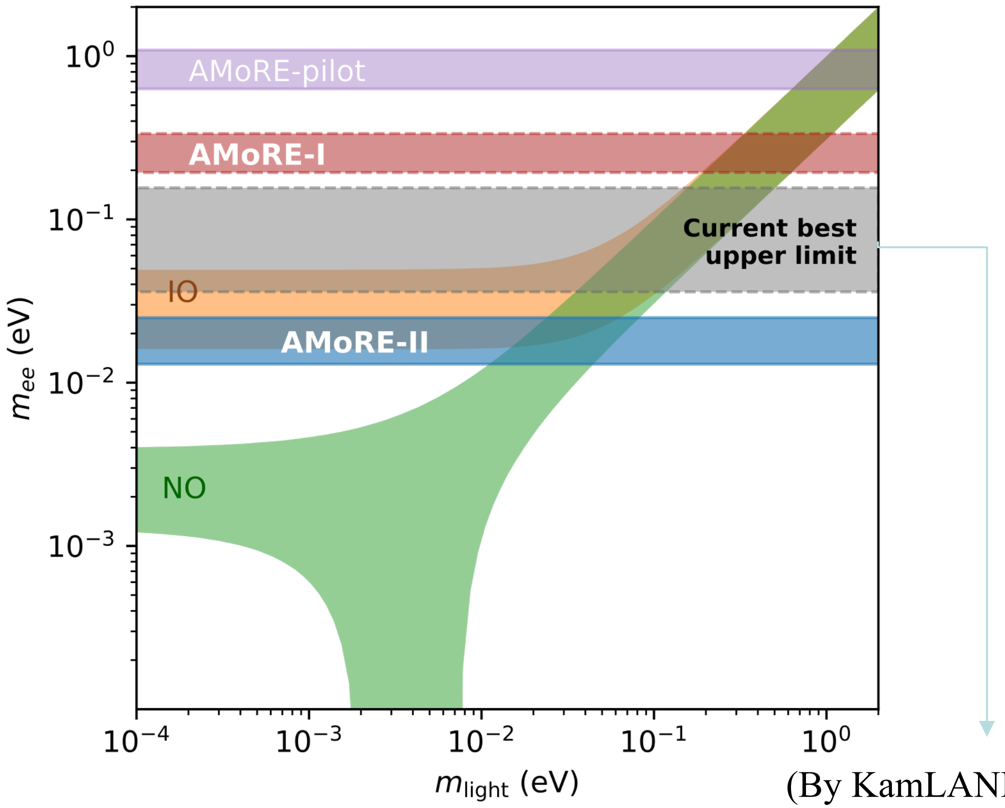
Light signals: $\tau_{rise,\ fast}$ ~ 200 μs
→ ~ 100 μs rejection possibility



- Likelihood pileup rejections or machine learning should be implemented.

AMoRE-II goals





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

- AMoRE-II for $T > \sim 5 \times 10^{26}$ years by 100 kg of ^{100}Mo × 5 years running.
- Reduction of background level down below 10^{-4} ckky.

R&D challenges

(for future projects)

SWOT for LT Detectors in 0νββ search

Strengths
- ✓ High energy resolution
- ✓ Particle ID
- ✓ Proven technology

Weaknesses
- ✓ Surface effect
- ✓ Unresolved pileups
- ✓ Bkg from copper
- ✓ Number of channels

Opportunities
- ✓ Use of Cherenkov light
- ✓ New crystal targets
- ✓ Single-site selection
- ✓ Multiplexing
- ✓ **Possible collaboration**

Threats
- ✓ Isotope production
- ✓ Crystal growing
- ✓ Purification

→

AMoRE-II
is secure from these.

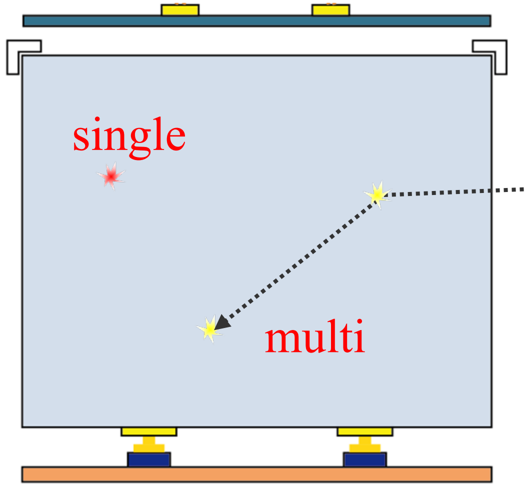
Any project after AMoRE-II
is NOT.

Technical tasks and challenges for future ^{100}Mo projects

- ✓ Unresolved pileups for Mo-100.
- ✓ Single-site event selection.
- ✓ Resolve position dependence for fast sensors.
- ✓ Multiplexing capability.

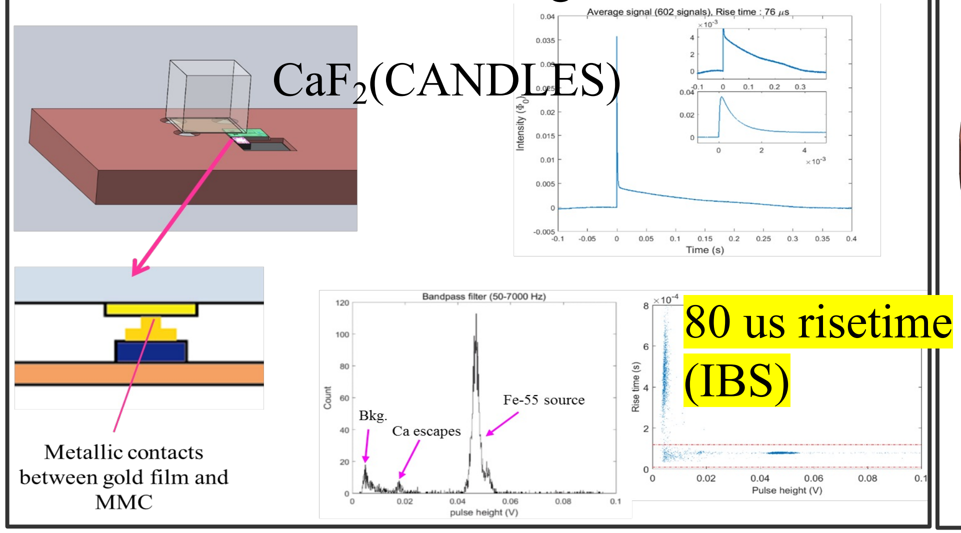
R&D proposal to multi-site event rejection

fast light signals

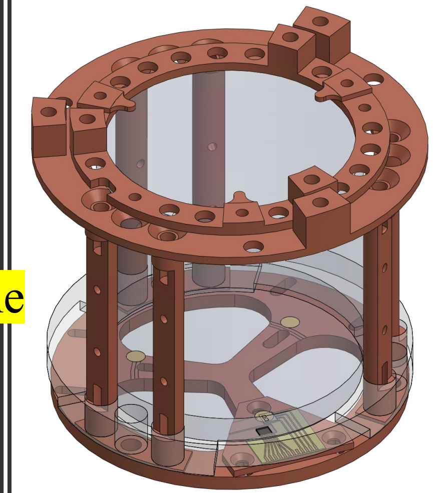


fast phonon signals

R&D result for fast heat signals



Drawing for Ø7cm×7cm (IBS)

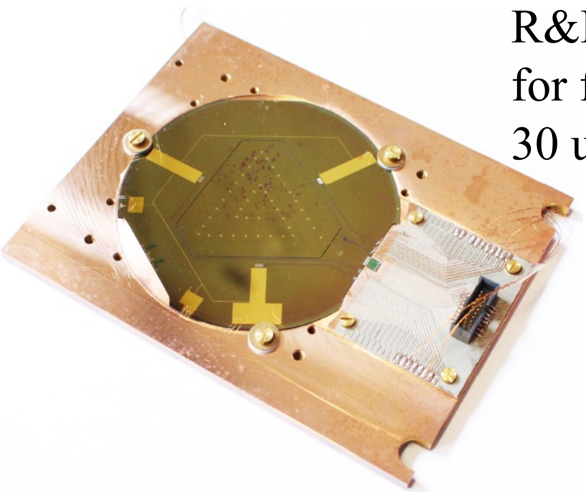


3 Heat + 1 Light

Easy to replace the target crystals

Li_2MoO_4
CaF_2
TeO_2
Etc

- Fast heat & light signals.
- Finite phonon speed: ~10^5 cm/s
- Correlated PSD can be studied.



R&D setup (Heidelberg)
for fast phonon-photon signals:
30 us rise time

Stay tuned for AMoRE