TIPP 2023
4 - 8 SEPTEMBER 2023
CTICC CAPE TOWN SOUTH AFRICA

CENTER FOR UNDERGROUND PHYSICS

Neutrinoless double beta decay search with the AMoRE-II experiment

SeungCheon Kim
(Center for Underground Physics (CUP), IBS)
sckim@ibs.re.kr

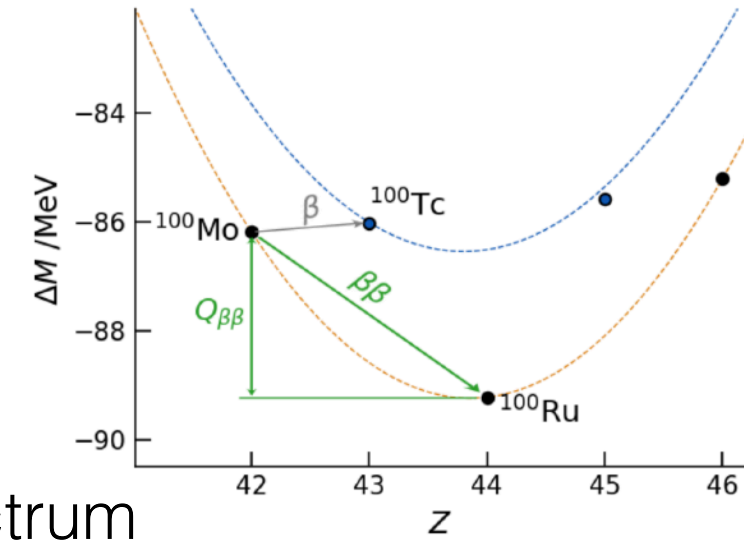
On behalf of the AMoRE collaboration

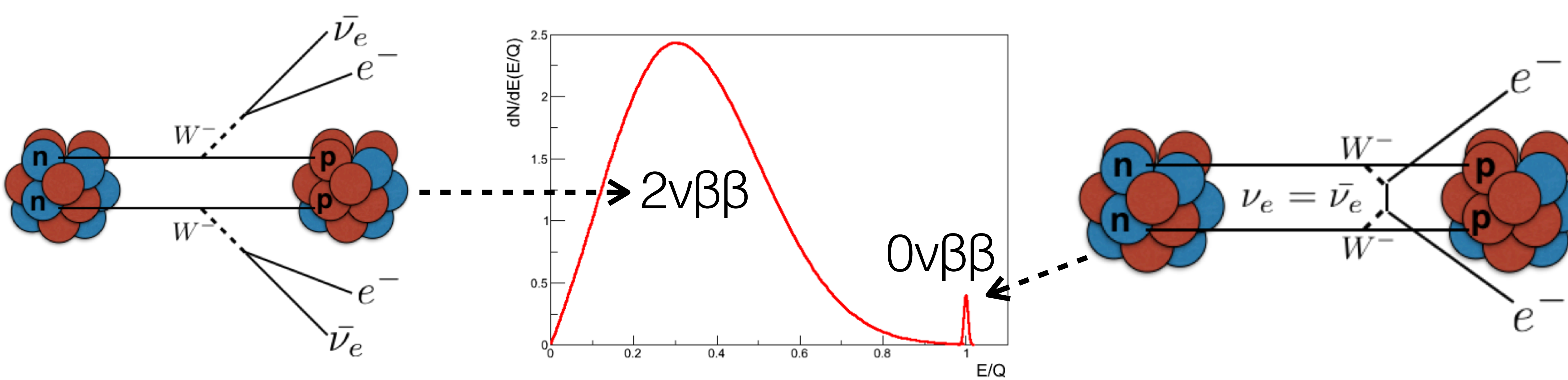
TIPP 2023 (7Sep2023)

AMoRE

Searching for neutrinoless ββ decay of ^{100}Mo with cryogenic calorimeters

- Some even-even nuclei more tightly bound than their odd-odd neighbors
  Single β forbidden but ββ allowed
- Two modes: 2vββ (T~10^{18}-10^{24} yrs), 0vββ (T>10^{26} yrs)
- Probing Majorana nature of neutrinos
- Lepton number violating process: $(A, Z) \rightarrow (A, Z+2) + 2e^- + Q_{\beta\beta}$
  Beyond Standard Model, Lepton / Baryon asymmetry
- Absolute neutrino mass scale
- New physic search with the precision measurement of ββ spectrum
- ^{100}Mo nuclide:
  high Q-value = 3.034 MeV (ROI), relatively high natural abundance = 9.7%
  relatively high decay rate expected

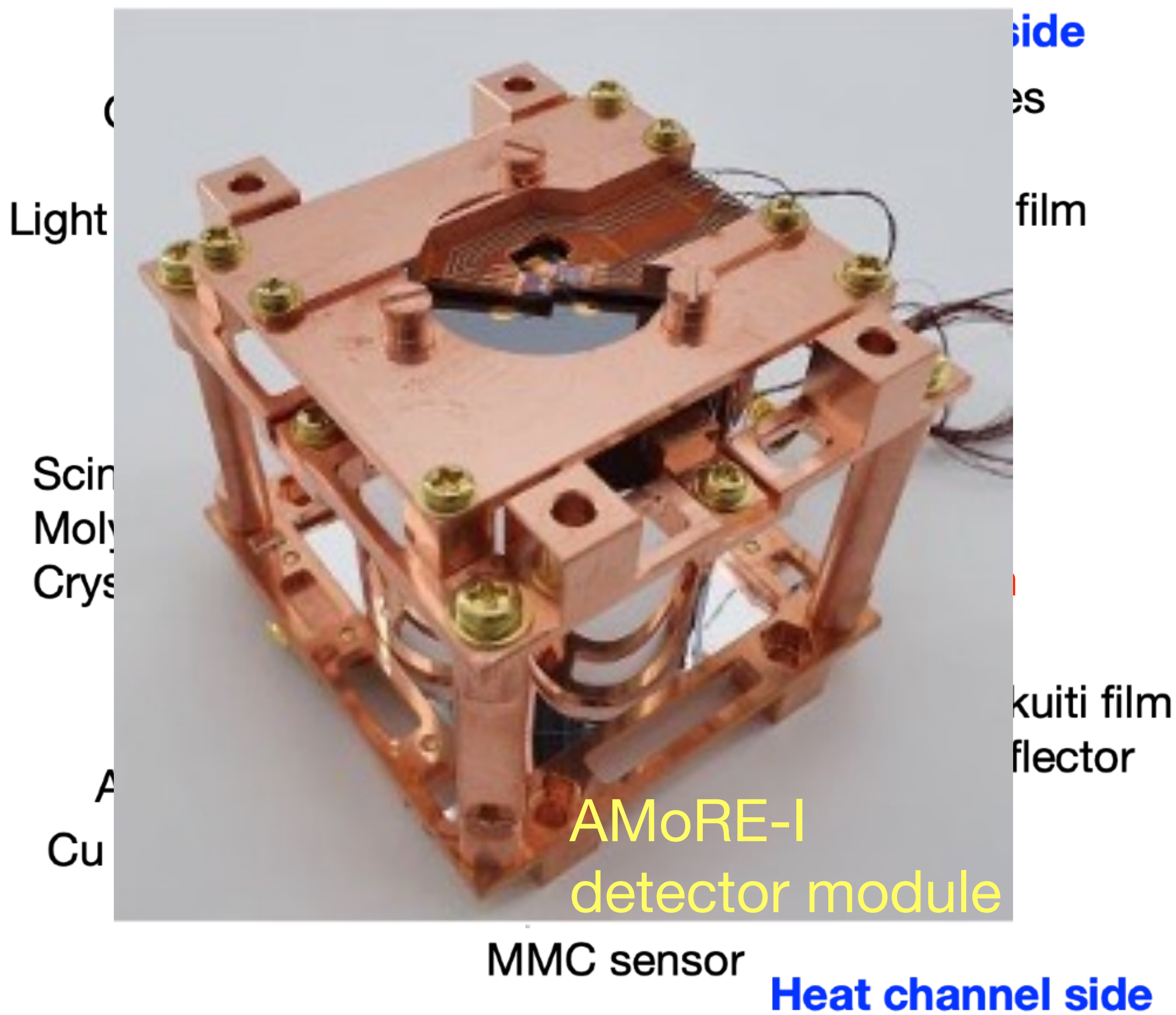




Rev. Mod.Phys. 95, 025002

AMoRE detector

measuring ββ energy in scintillating molybdate crystal with MMC



Signals:

- Operating at 10~20 mK
- Phonons / scintillation detection
- molybdate crystals / light absorber

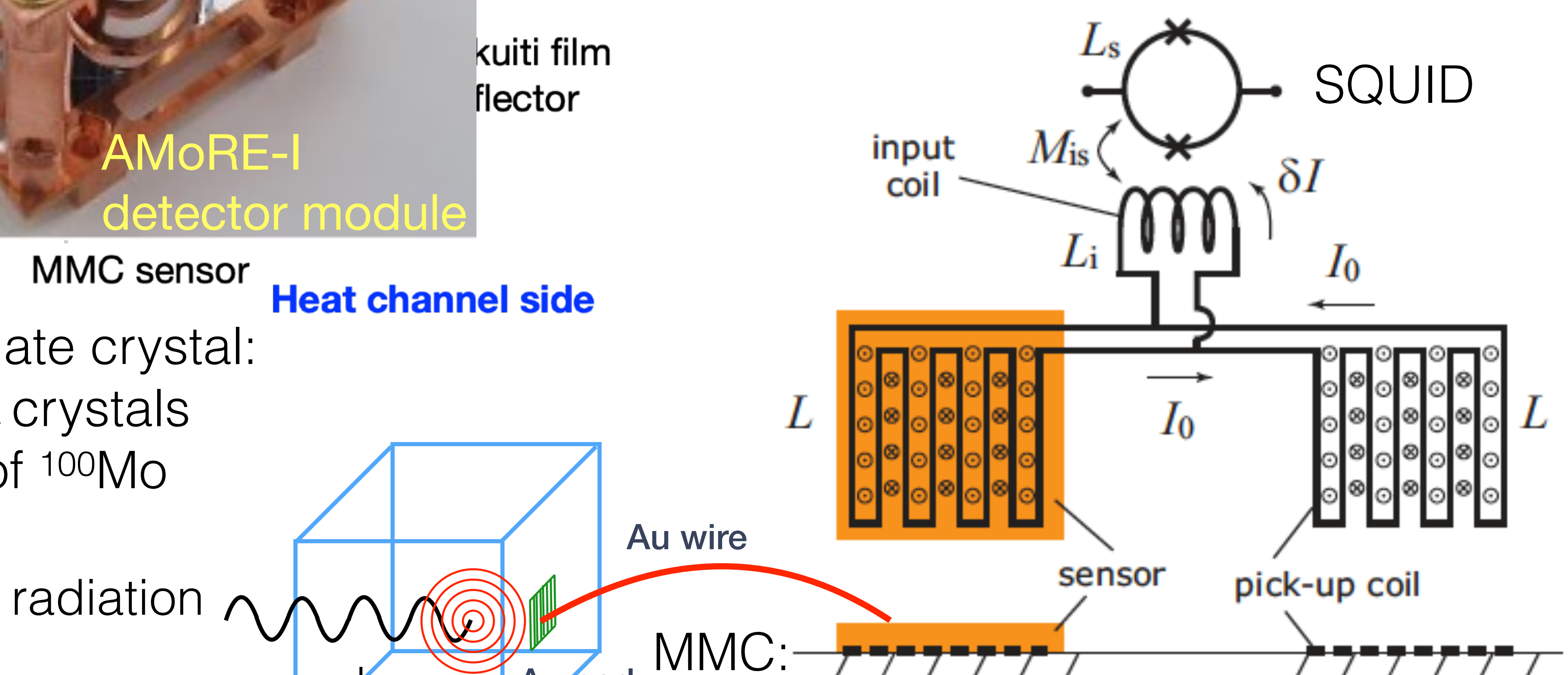
=> heating gold film (“phonon collector”)

=> heating metallic magnetic calorimeter (MMC)

=> **ΔM** (MMC) => **ΔI** (SQUID)

Scintillating molybdate crystal:

- Mainly $Li_2{}^{100}MoO_4$ crystals
- 95% enrichment of ^{100}Mo



MMC:
Au:Er, Ag:Er
(^{168}Er concentration ~ hundreds ppm)

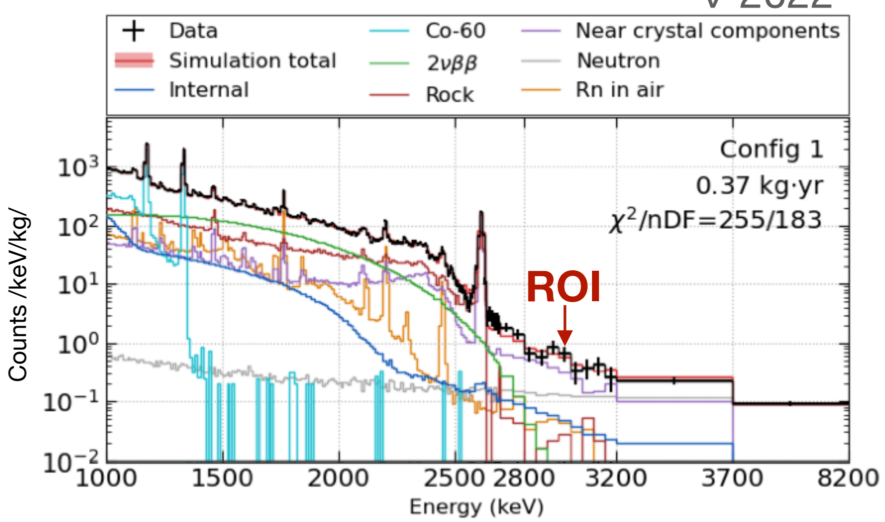
AMoRE experimental campaigns

AMoRE-pilot

2015-2018

6 $^{48dep}CaMoO_4$ crystals:
1.9 (0.88) kg of CMO (^{100}Mo)
Yangyang Underground Lab
(Y2L, 700 m depth)

v-2022



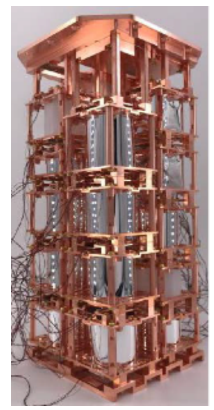
- Live exposure ~ 0.32 kg_{Mo-100}·yr.
- Background at ROI
  ~0.5 cnts/keV/kg/year.
- $T^{0\nu}_{1/2} > 3.2 \times 10^{23}$ years at 90% CL.

×12

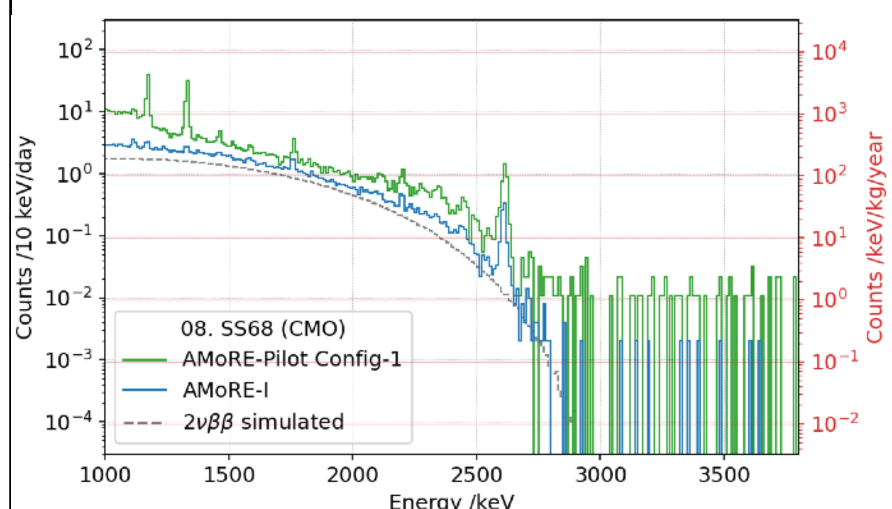
×1/15

AMoRE-I

2020-2023



13 CMOs
+ 5 Li_2MoO_4 crystals :
6.2 (3.0) kg of XMO (^{100}Mo)
Y2L



- Live exposure ~ 4 kg_{Mo-100}·yr.
- Background at ROI~0.03 ckky.

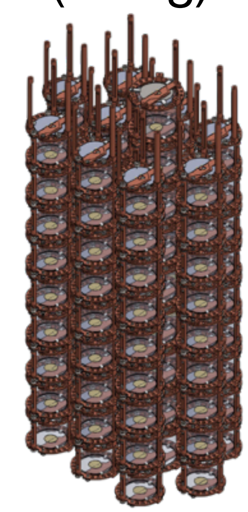
×120

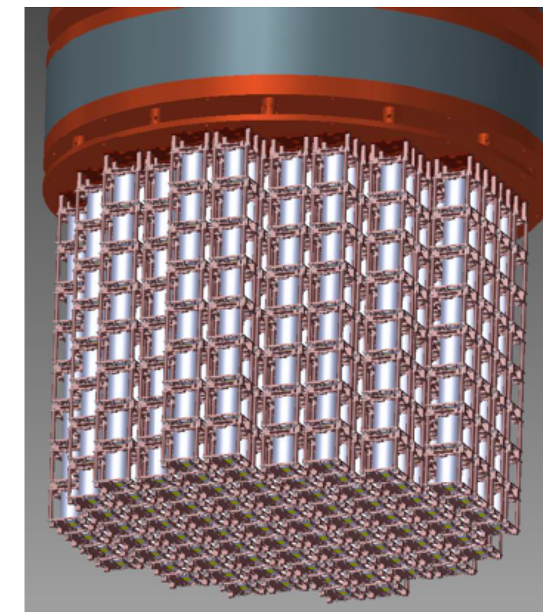
×1/200

AMoRE-II

2024-

Stage 1:
90 LMOs
(27 kg)

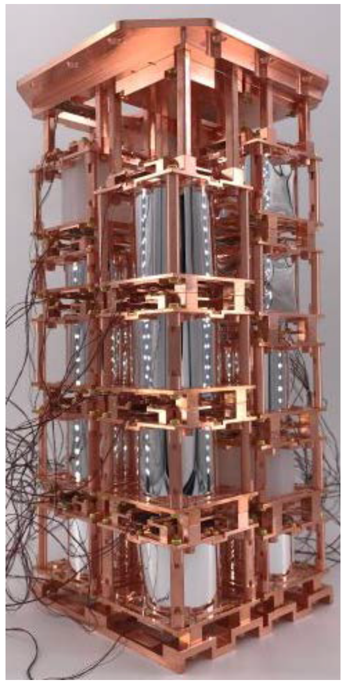




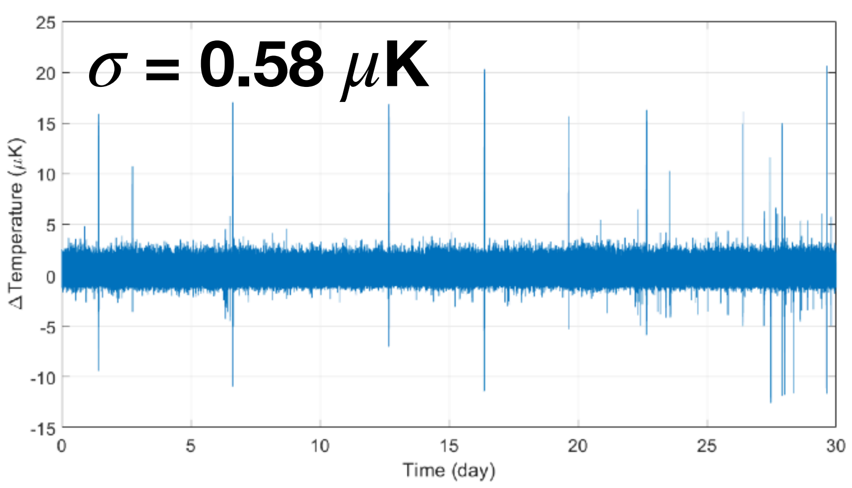
Stage 2:
360 crystals (157 kg)

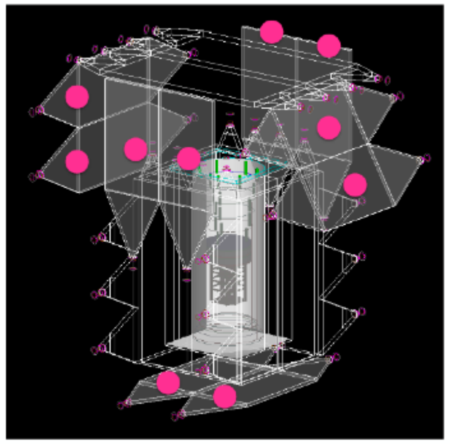
- ~ 100 kg of ^{100}Mo
- In Yemilab, 1000 m depth.
- Exposure > 500 kg_{Mo-100}·yr.
- Background at ROI~10^{-4} ckky.

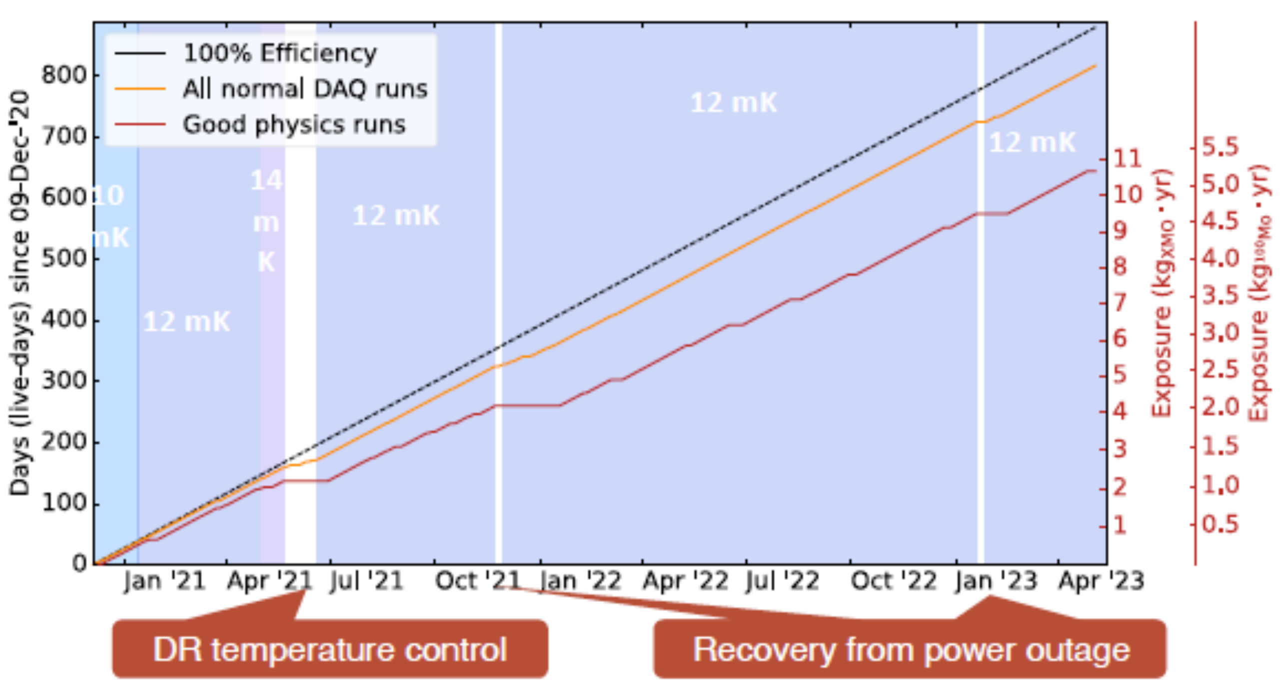
AMoRE-I data taking just completed last May!



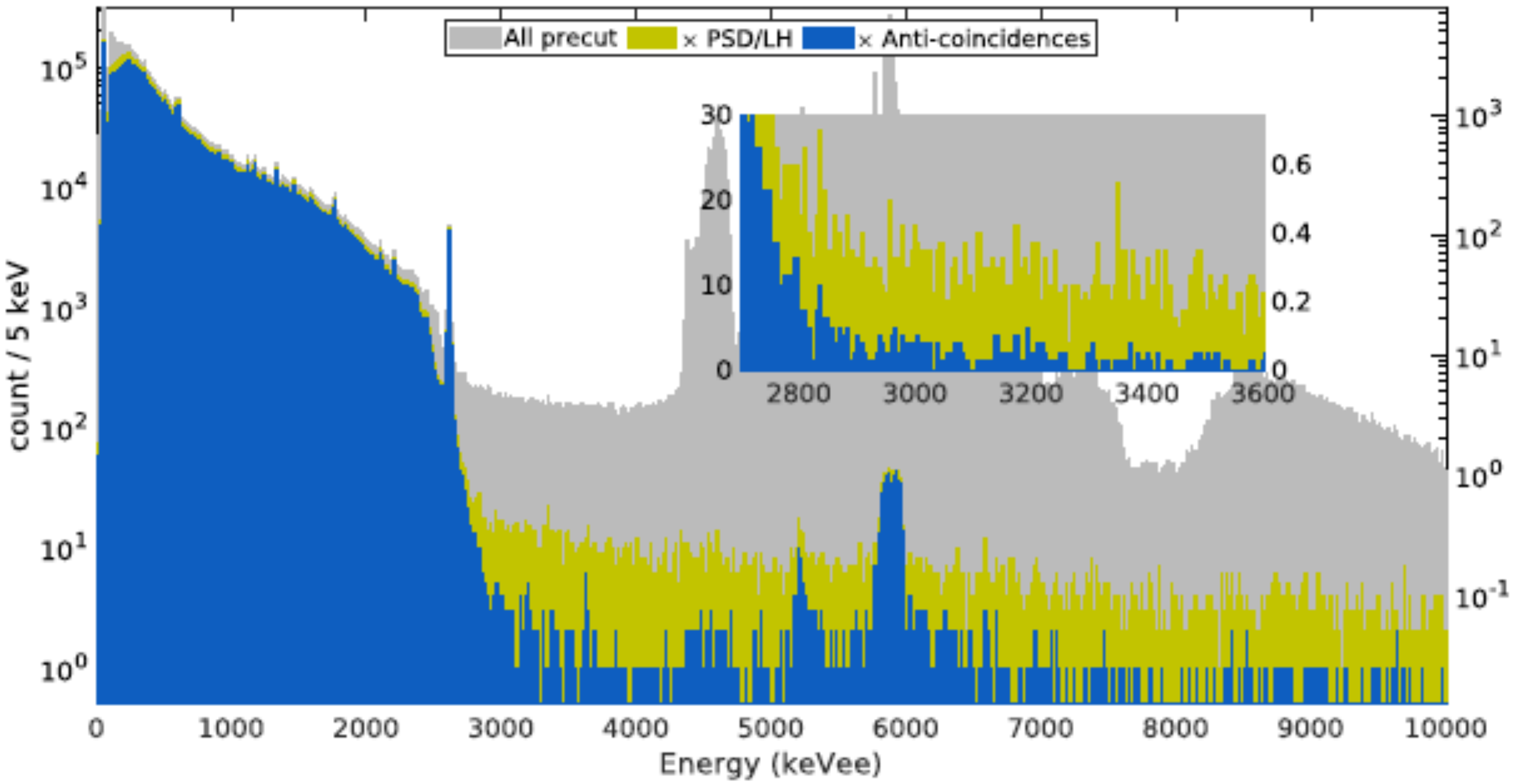
- Data taking for 29 months
- Compared to AMoRE-pilot:
  - Same cryogen free dilution refrigerator at Y2L
  - More stable detector operation with two-stage temperature control
  - Enhanced shielding:
    enhancement in Pb, boron, PE, μ-veto coverage, Rn-free air supply
- Exposure: 8.02 $kg_{XMO}\cdot yr$ = 3.88 $kg_{Mo\text{-}100}\cdot yr$
- Anti-coincidence:
  coincidence at multiple crystals within 2 ms, 10 ms after muon veto signal
  20 mins after ^{212}Bi α candidates
- α rejection in ROI: light/heat ratio, PSD
- Energy resolution in ROI: 9.5 - 28.0 keV FWHM



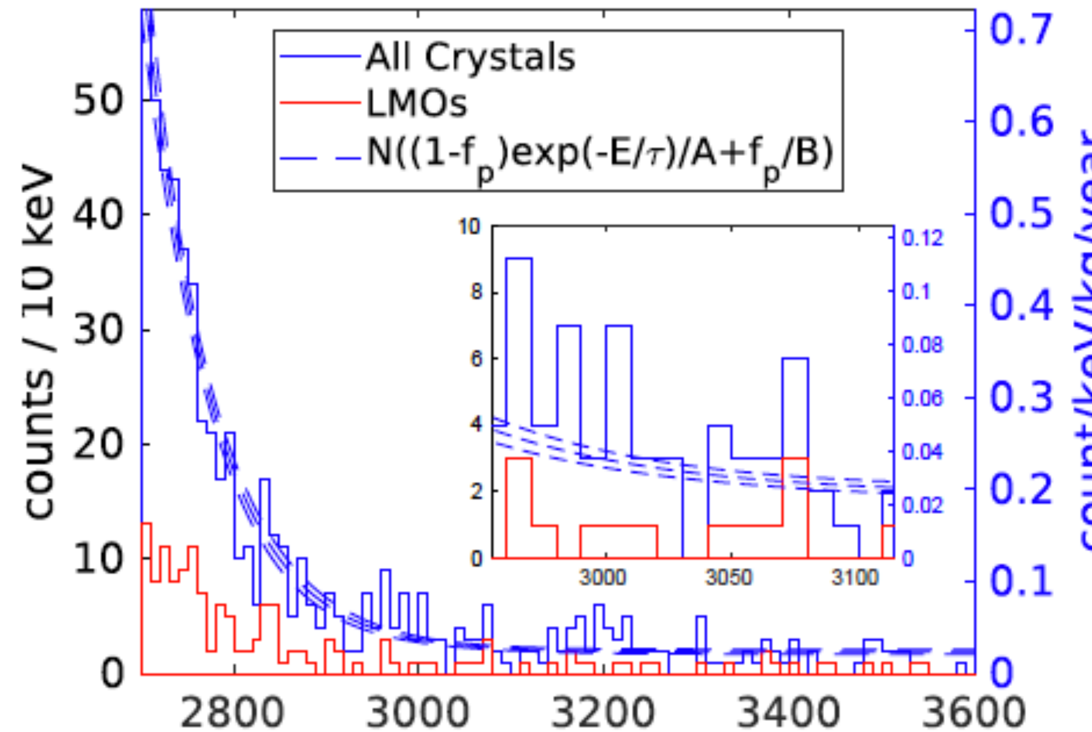


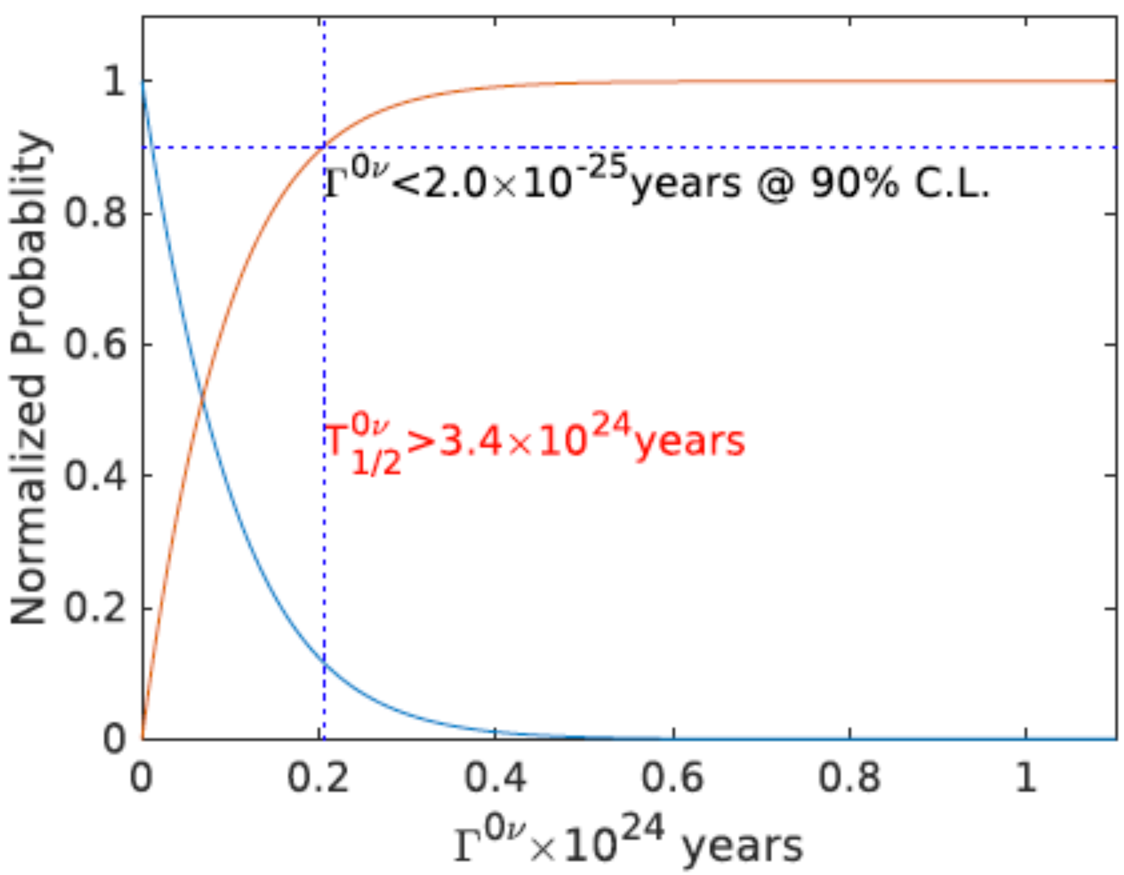


AMoRE-I results



Q = 3.034 MeV





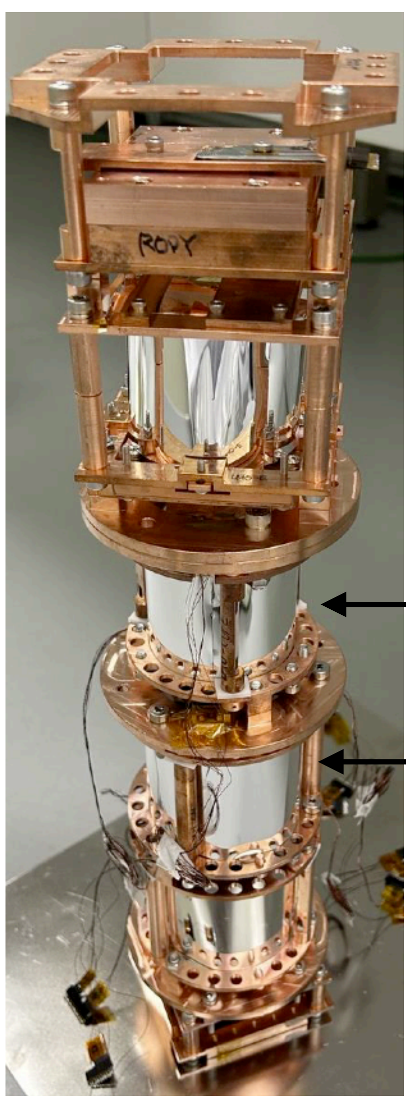
- ROI = $|E - Q| < 2.5 \times \Delta E_{\mathrm{FWHM}}$
- Background = 0.032 ± 0.003 cnts/keV/kg/year from ROI side-band
- Unbinned likelihood for $\Gamma^{0\nu}$ for each crystal with signal shape (Bukin) and background rate constrained from calibration and sideband data
- No significant observation of the signal
- $T^{0\nu}_{1/2} > 3.4 \times 10^{24}$ years at 90% C.L.
- World best limit for $0\nu\beta\beta$ of ^{100}Mo

AMoRE-II is coming!

- Intensive detector R&D
- Detector production
- Preparation of the cryostat system
- Building the experimental hall
- Building the detector housing with shield and muon veto
- Simulation study of the expected background

Detector R&D efforts

- Cryogenic calorimeter with Li_2MoO_4 (LMO) crystal using MMC readout
  - humidity exposure, crystal size, surface treatment, thermal link, AMoRE-II holder
- Test results with AMoRE-II holder at cryogen-free DR
  - Large individual detector mass: 300 & 516 g
  - Energy resolution: FWHM@2.6MeV = 7-9 keV at 10 mK
  - Alpha particle discrimination with light signal: α rejection by more than 10σ
  - Rise time of event signal : ~ 5ms (10 mK), ~3ms (20 mK)
  - Pile-up background (ROI) < 3×10^{-5} cnts/keV/kg/year



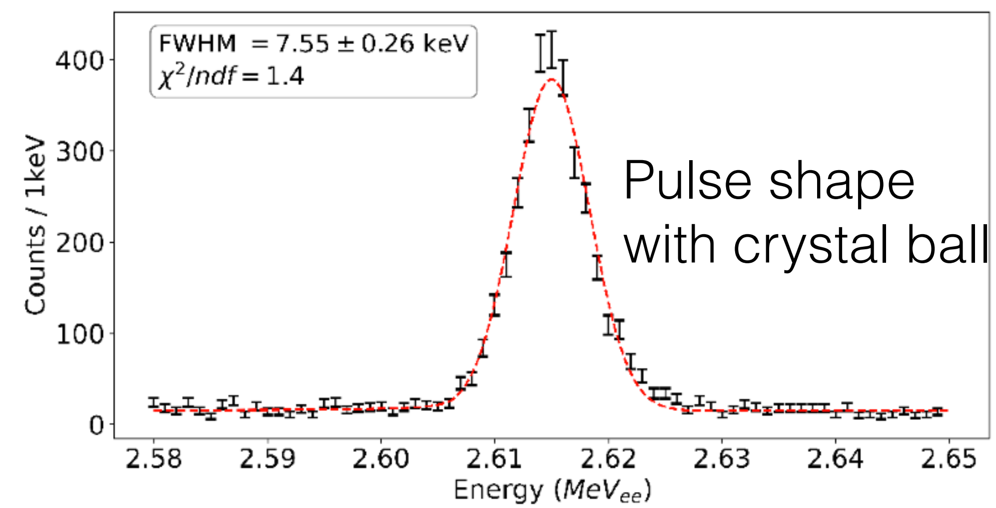
R&D detector tower

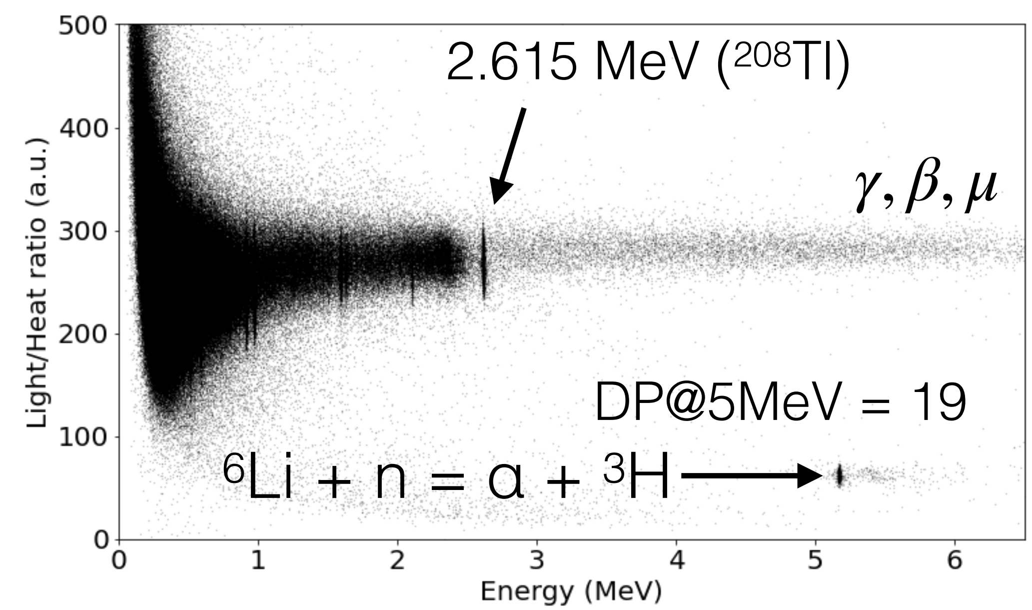
AMoRE-II type detectors

Det with D=5cm/H=5cm
crystal (300g)

Det with D=6cm/H=6cm
crystal (516g)

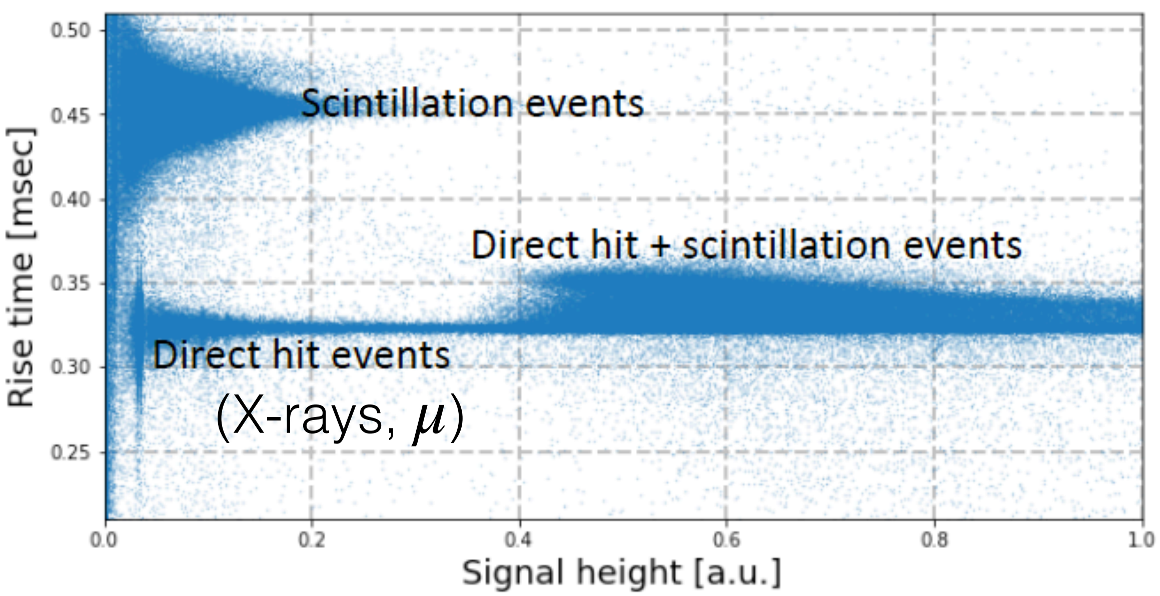
JINST 17 P07034 (2022)
JLTP 209:299 (2022)

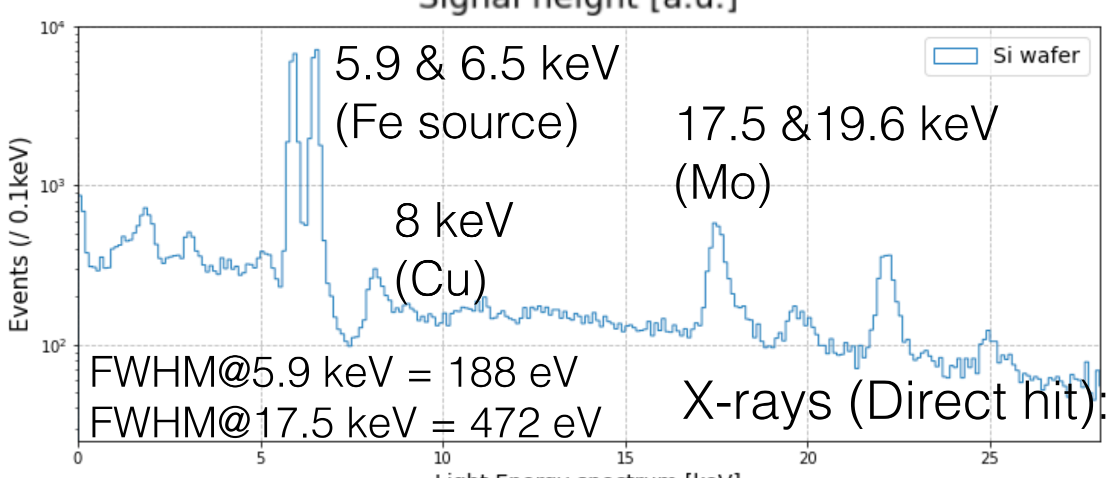




Detector R&D efforts

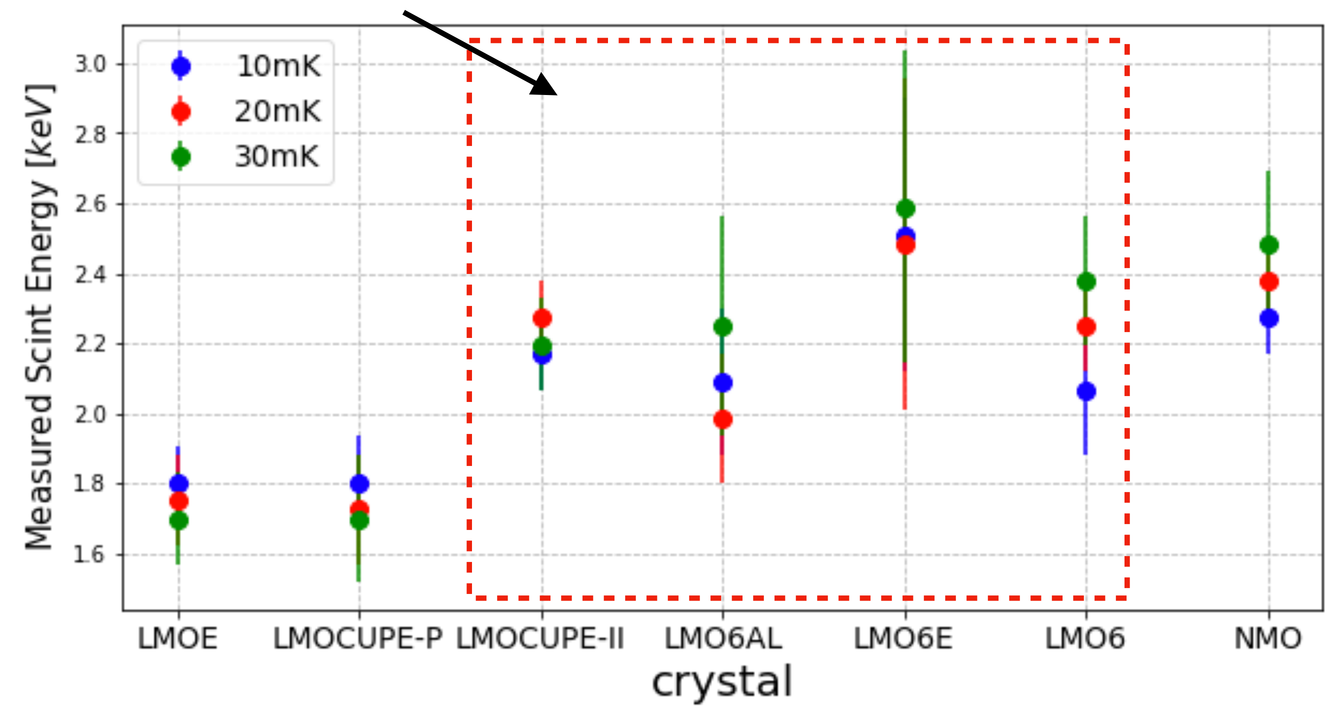
- Improving the light detector performance
- Some highlights for the AMoRE-II light detectors tested at CR-DR
  - Baseline design: Si wafer (D = 5, 6 cm, t = 280, 350 μm) with SiO_2 coating with MMC readout
  - Baseline energy resolution: FWHM = ~100 eV at 10 mK
  - Clear separation of X-rays and scintillation lights
  - Scintillation light measurement : 0.8 - 0.95 keV/MeV
  - Clear separation of alpha signals with light/heat ratio
  - Rise time of the event signal : 300 - 600 μs at 10 mK





X-rays (Direct hit): useful for calibration

Scintillation measurement:
2-2.6 keV for 2.6 MeV with AMoRE-II holders

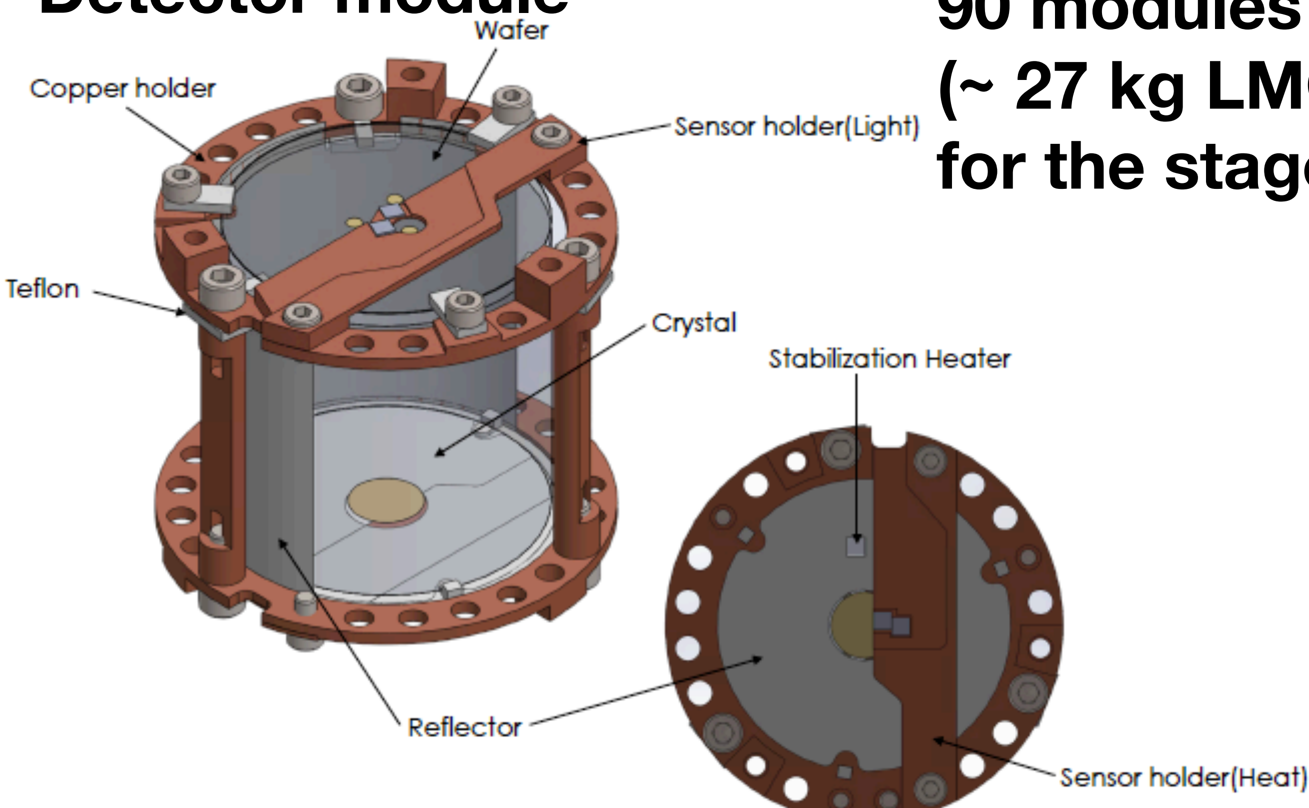


IEEE TNS 2023.3267387
IEEE TASC 2023.3263333

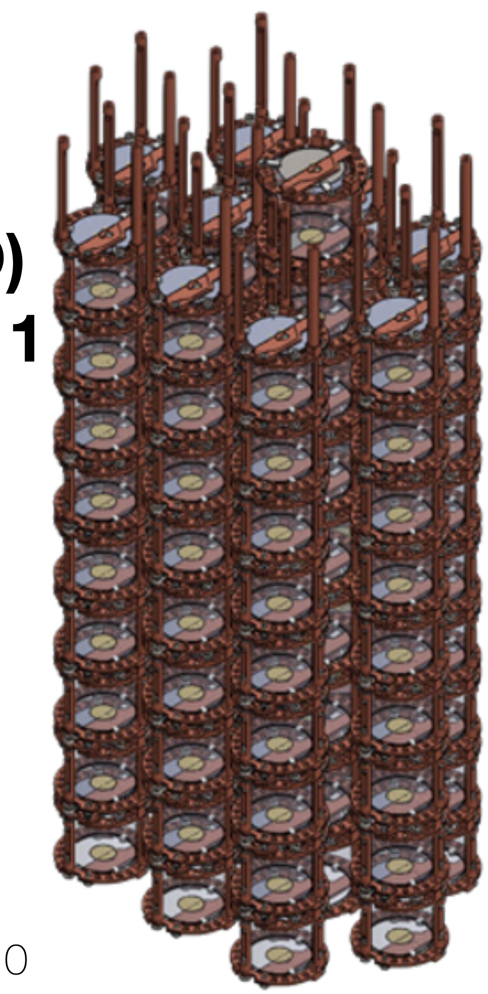
AMoRE-II detector production

- Detector parts:
  mixture of cylindrical crystals, 5 cm (D) x 5 cm (H) & 6 x 6
  MMC (Ag:Er) by CUP (IBS) & Heidelberg Univ.
  Two-stage DC SQUID by PTB & Heidelberg Univ.
  NOSV Cu frame
- Detector assembly in low humidity and radon-free environment
- Building in two stages
  Stage 1: 90 modules in 2024
  Stage 2: 360 modules in 2025

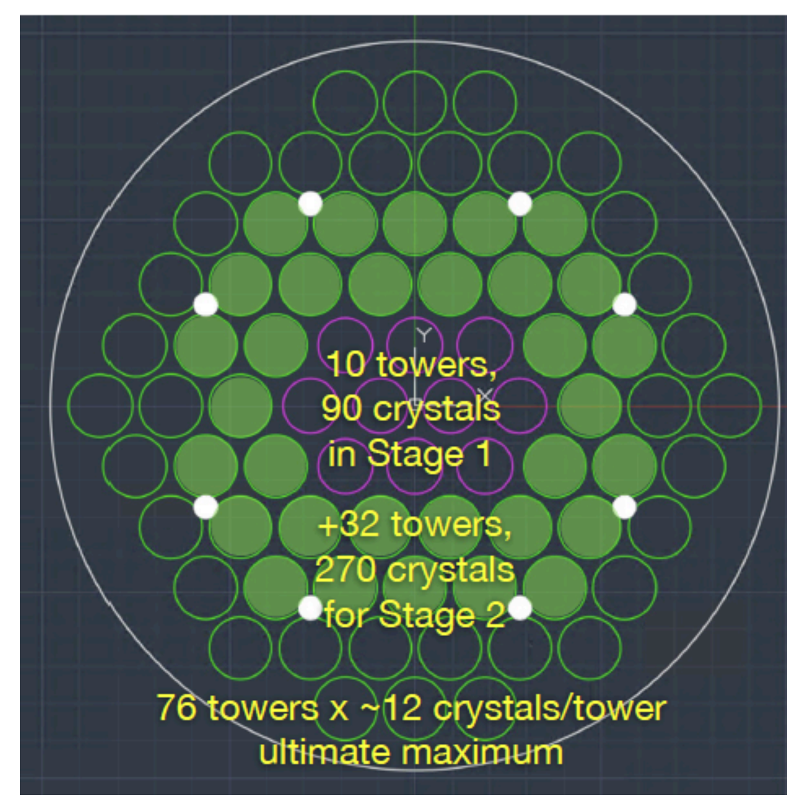
Detector module



90 modules (~ 27 kg LMO) for the stage 1



157 kg for stage 2

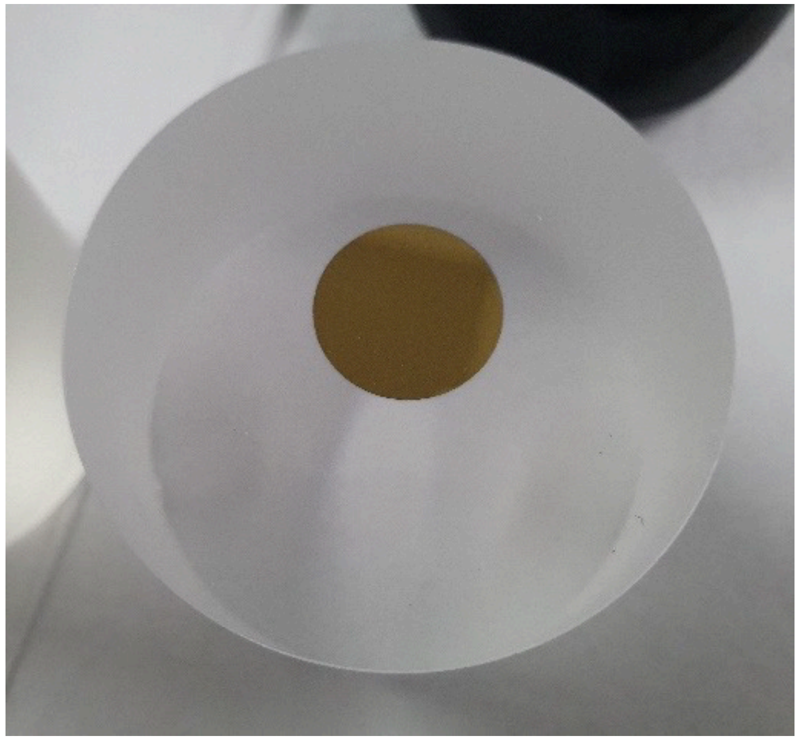


Crystal production

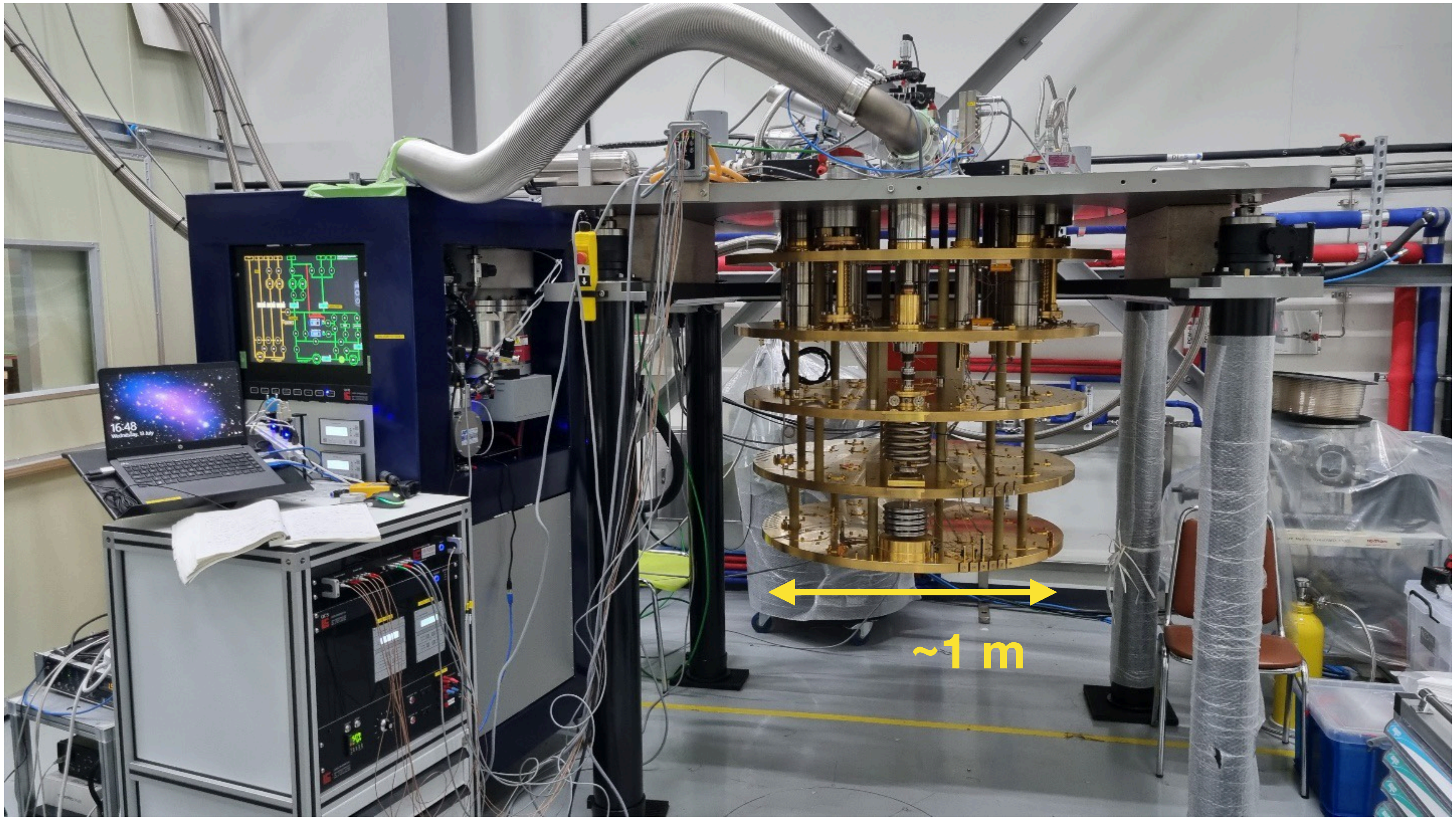
- Li_2MoO_4 : easy crystal growing, low background, but hygroscopic surface
- 120 kg of ^{100}Mo as $^{100}MoO_3$ powder in storage
- Powder ($^{100}MoO_3$, Li_2CO_3) purification at CUP
- Crystal growing in NIIC & CUP
- Low background level demonstrated with the powder and crystals
- Crystals for stage 1 complete, full production through 2025
- Vacuum sealed packaging, very low humidity for crystal storage in fab process
- Proper cleaning necessary for phonon collector deposition

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

Front. Phys. 11, 1142136 (2023)

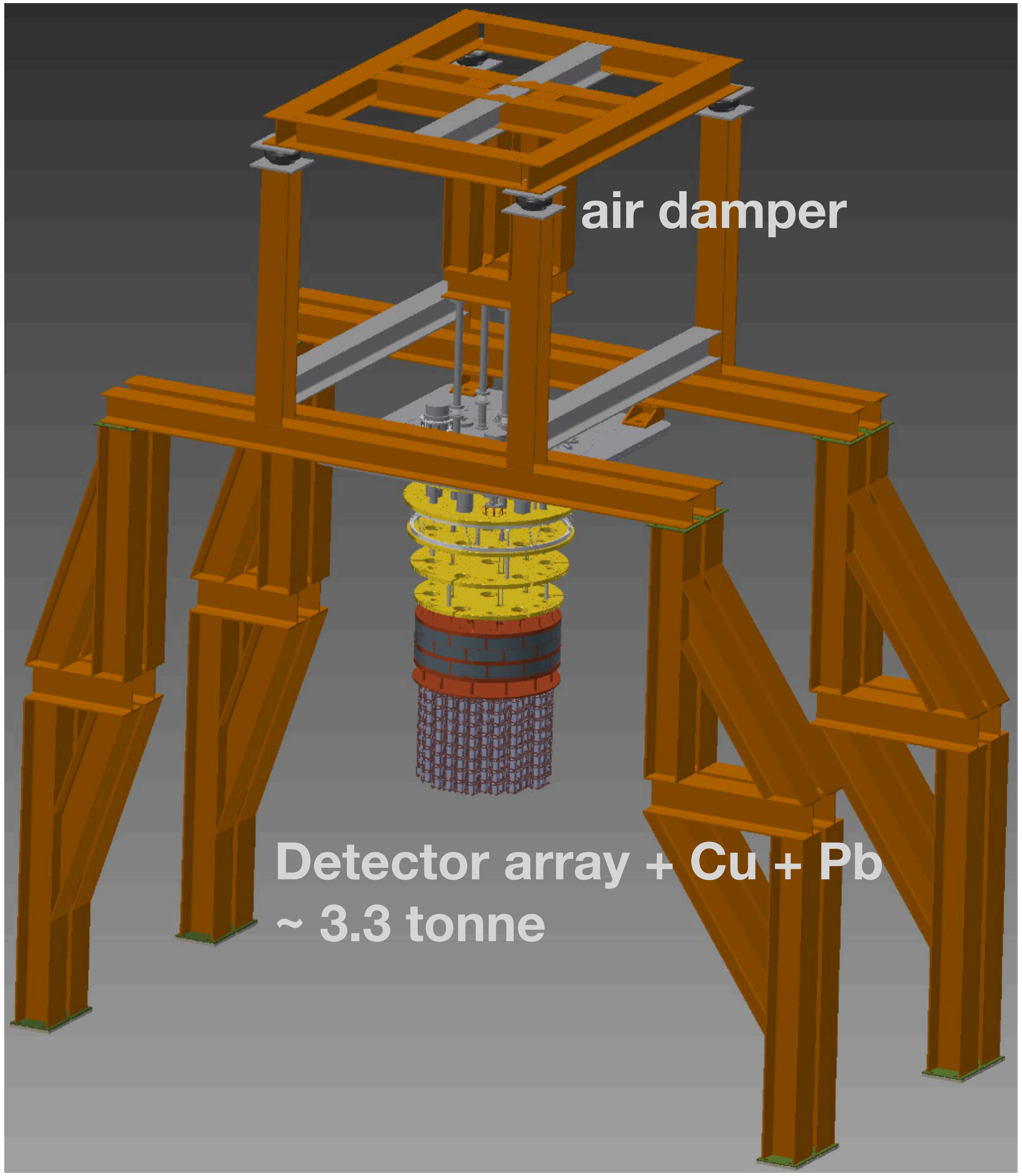


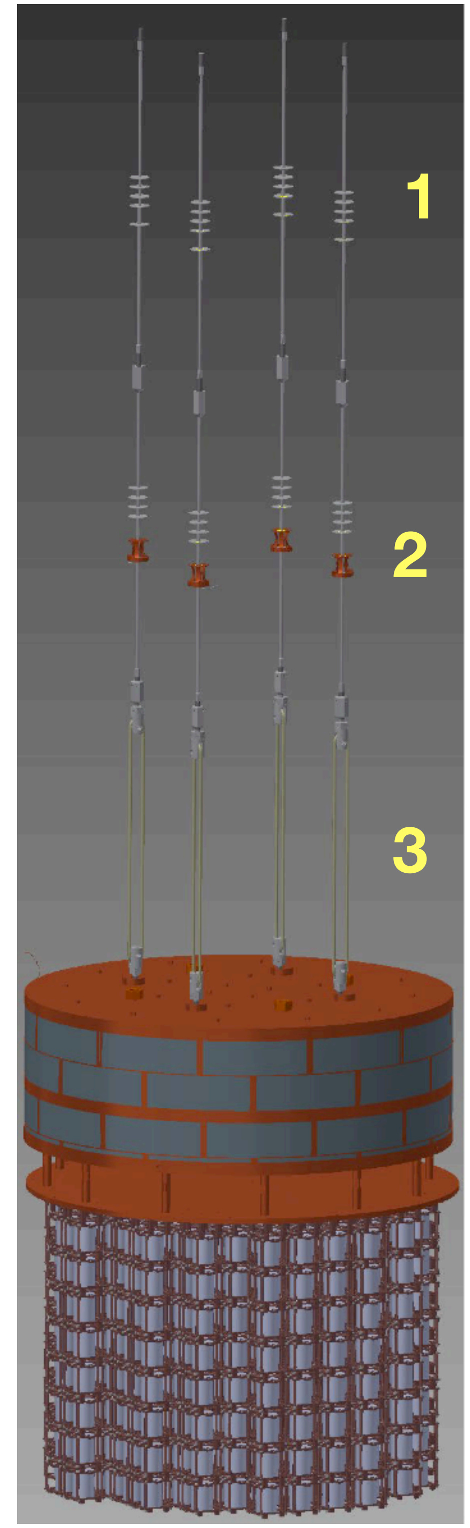
AMoRE-II cryostat



- Cryogen-free dilution refrigerator with 3 PTR by Leiden cryogenics
- Cooling power: 1mW@100 mK, 7μW@ 10 mK
- Base temperature: 5.3 mK
- Commissioning and wiring underway
- Vacuum and thermal shield cans with low radioactive material almost complete

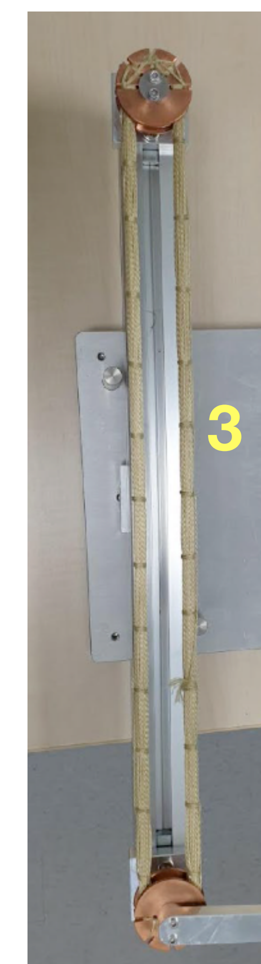
AMoRE-II cryostat vibration damping





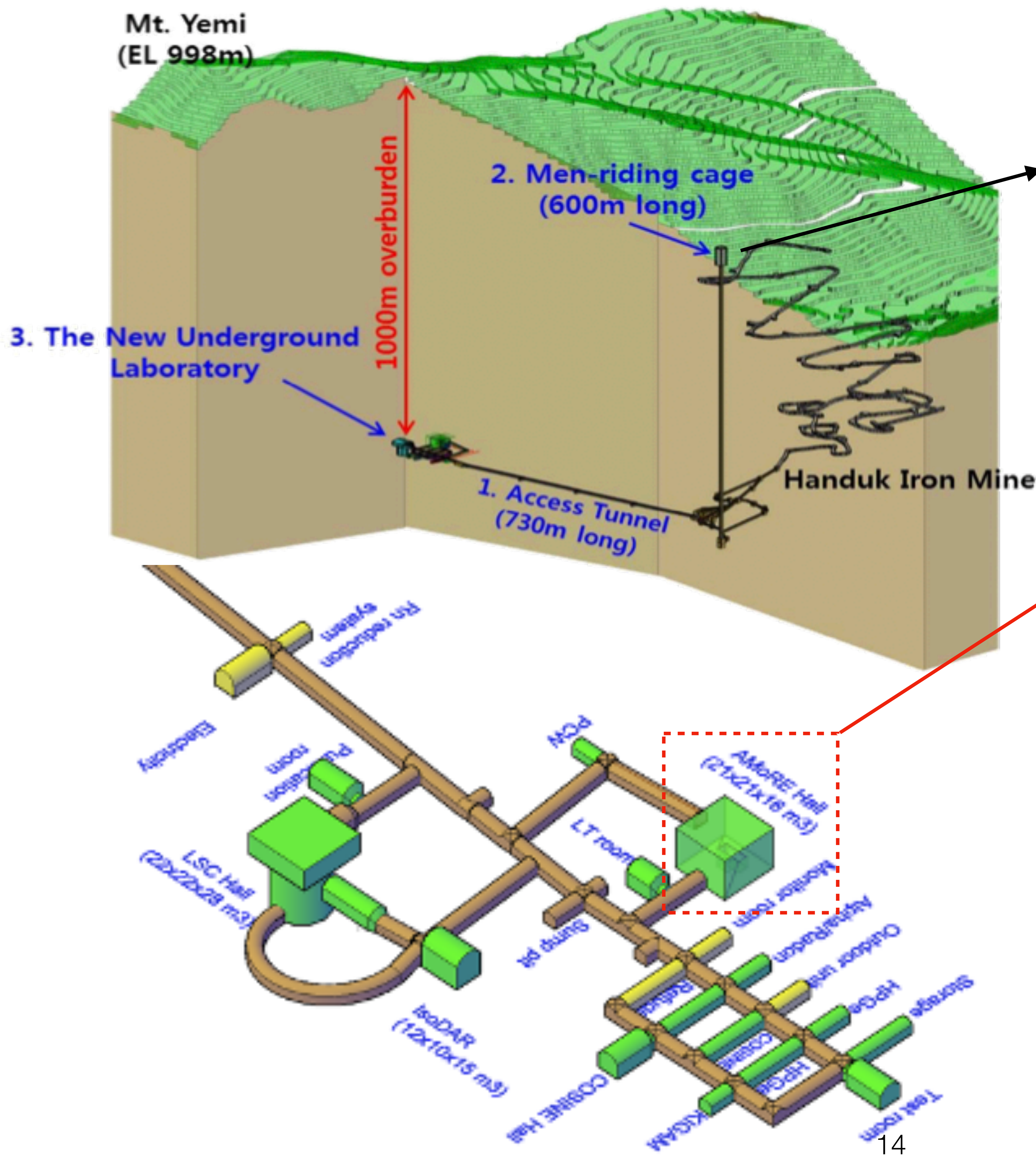
Suspending
the detector array
with 4 strings in IVC

Each string:
STS rod
(durable up to 3.8 ton)
+ kevlar wire system
(2.4 ton)



Other vibration reduction efforts:
Soften PTR contact on the fridge (absorbing foam, Cu tapes)
Internal vibration damper between 4K & still stage

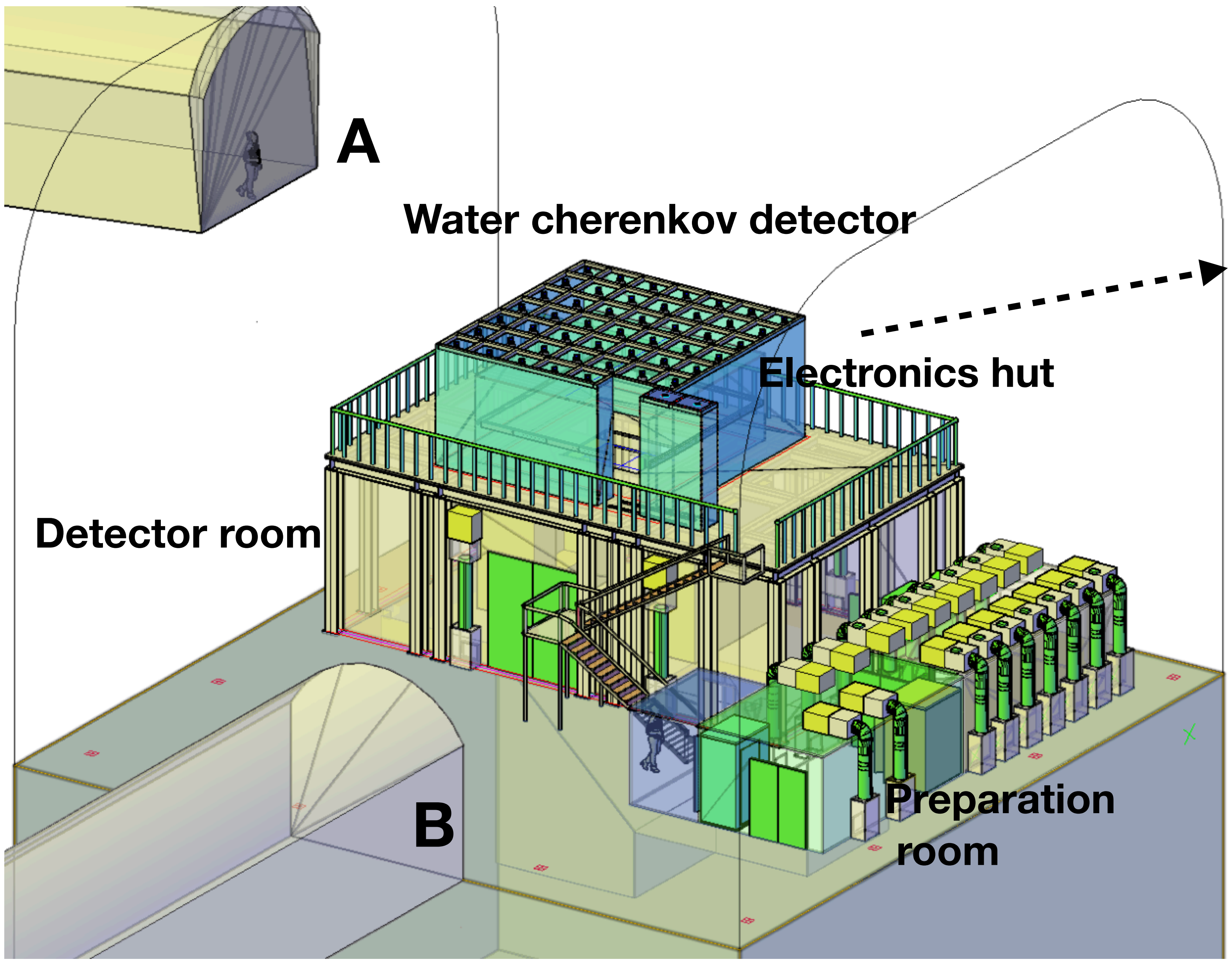
Experimental site: Yemilab



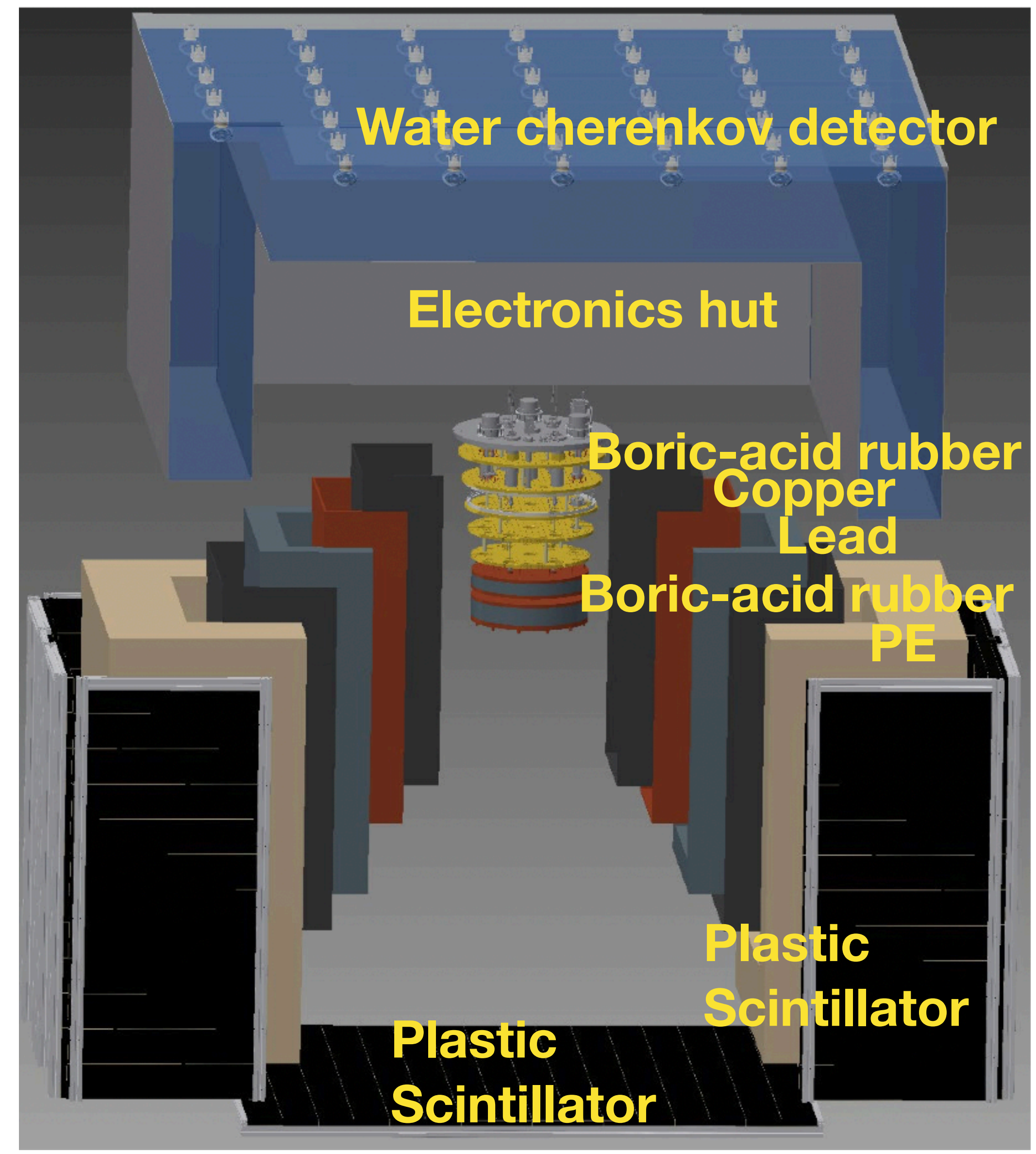
Jeongseon, South Korea
1000 m vertical depth
Underground lab for basic sciences
Opened in Oct, 2022

Total Area: 2600 m^2
Sufficient area for new large scale experiments: AMoRE, COSINE, LSC

AMoRE Hall in Yemilab



Radon-free air supply
Clean room
(detector preparation in class 100)



Shield structure

Muon veto detectors in commissioning

Water Cherenkov detector

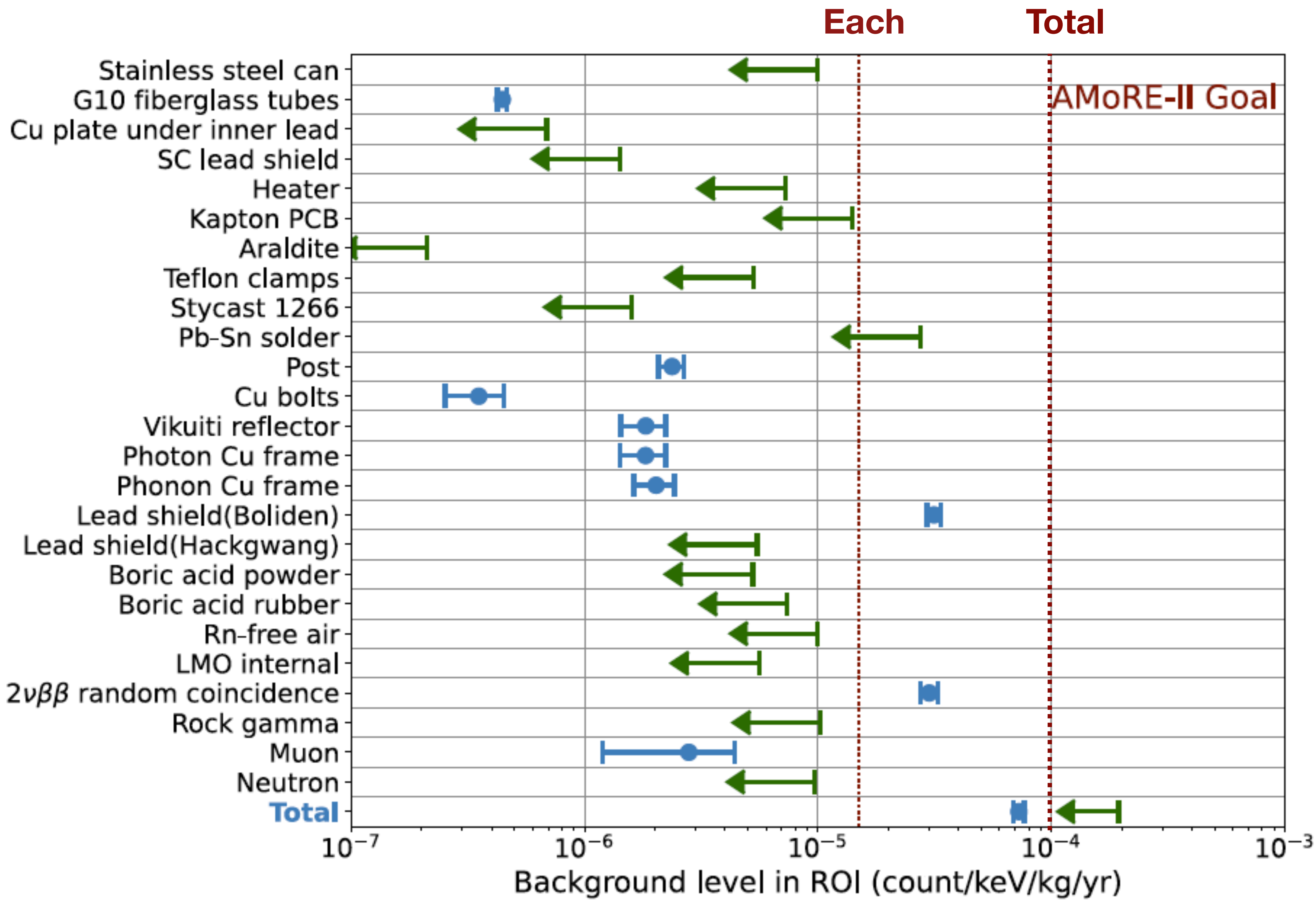
~60 ton of water
Testing DI water / 4-MU loaded water
Installed with 49 x PMTs (8 & 10 inch)
Good neutron shield

Plastic scintillator

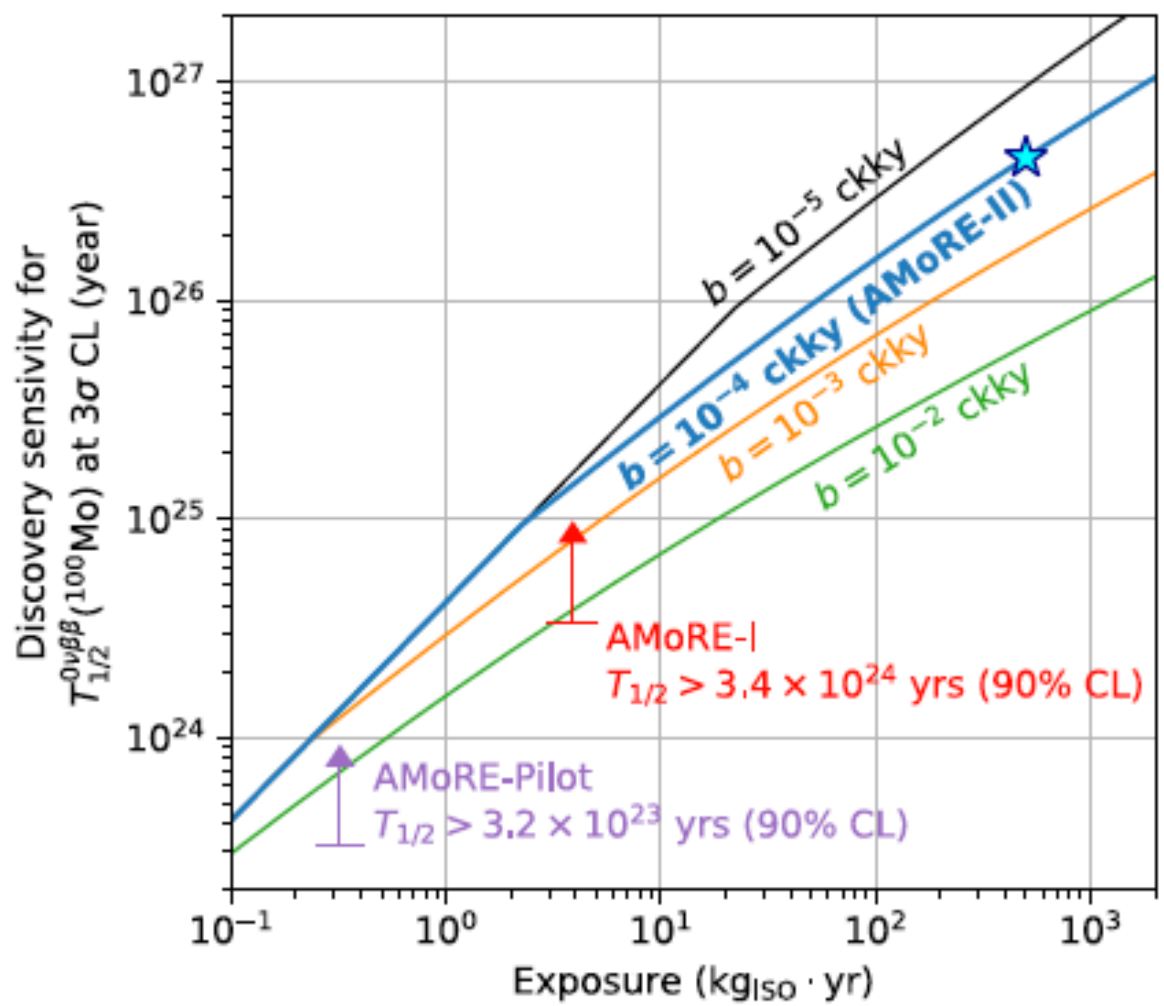
One PS box:
2 plastic scintillator panels
+ wavelength-shifting fiber + 4 SiPMs
Total 136 boxes
muon flux measurement ≃ 10^{-7} $cm^{-2}s^{-1}$

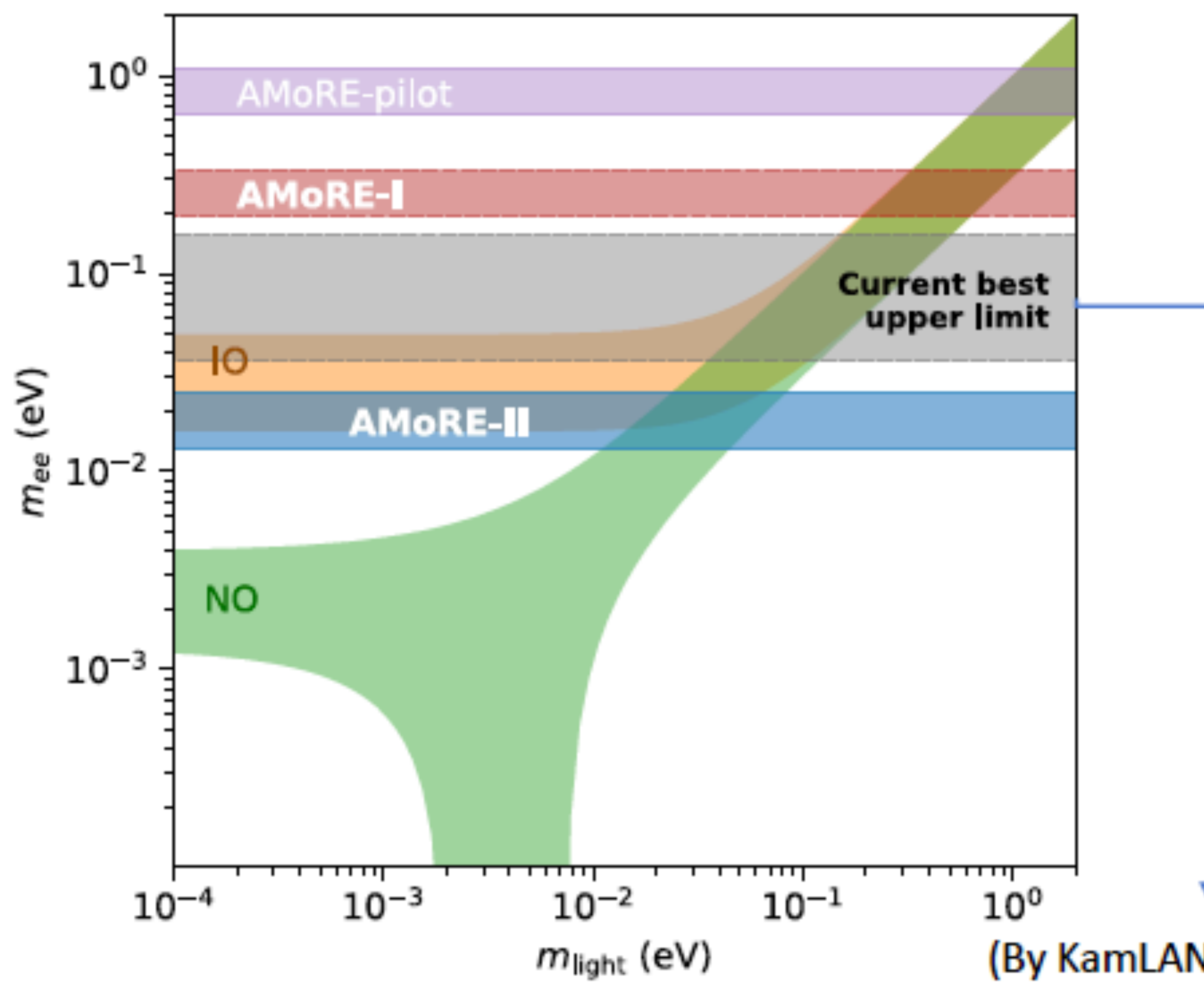
Recent view of AMoRE Hall

Expected background level



AMoRE-II prospects





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

- $T^{0\nu}_{1/2} \sim 4 \times 10^{26}$ years (3σ discovery) with background of 10^{-4} cnts/keV/kg/year
  5 years after full detector array installation

- $\langle m_{\beta\beta} \rangle \sim 20 - 35$ meV

Conclusion

- AMoRE-I data taking completed in last May
  - $T^{0\nu}_{1/2}$ > 3.4 x 10^{24} years at 90% C.L.
  - World best limit for $0\nu\beta\beta$ of ^{100}Mo

- Gearing up for the AMoRE-II experiments with 100 kg of ^{100}Mo isotopes
  - Improved detector performance in heat & light channel signals
  - Detector production underway
  - Cryostat system under preparation
  - New experimental hall ready in Yemilab
  - Shielding installed and muon veto under commissioning
  - Background reduction campaigns with rigorous radioassay and simulation: ~10^{-4} cnts/keV/kg/year achievable
  - AMoRE-II is happening!
    Stage 1: 90 detector modules in 2024
    Stage 2: Full detector array in 2025
    Aiming at $T^{0\nu}_{1/2}$ ~ 4 x 10^{26} yr (3σ discovery potential) in 5 year operation

And others…

Acknowledgement: AMoRE collaboration

Extra

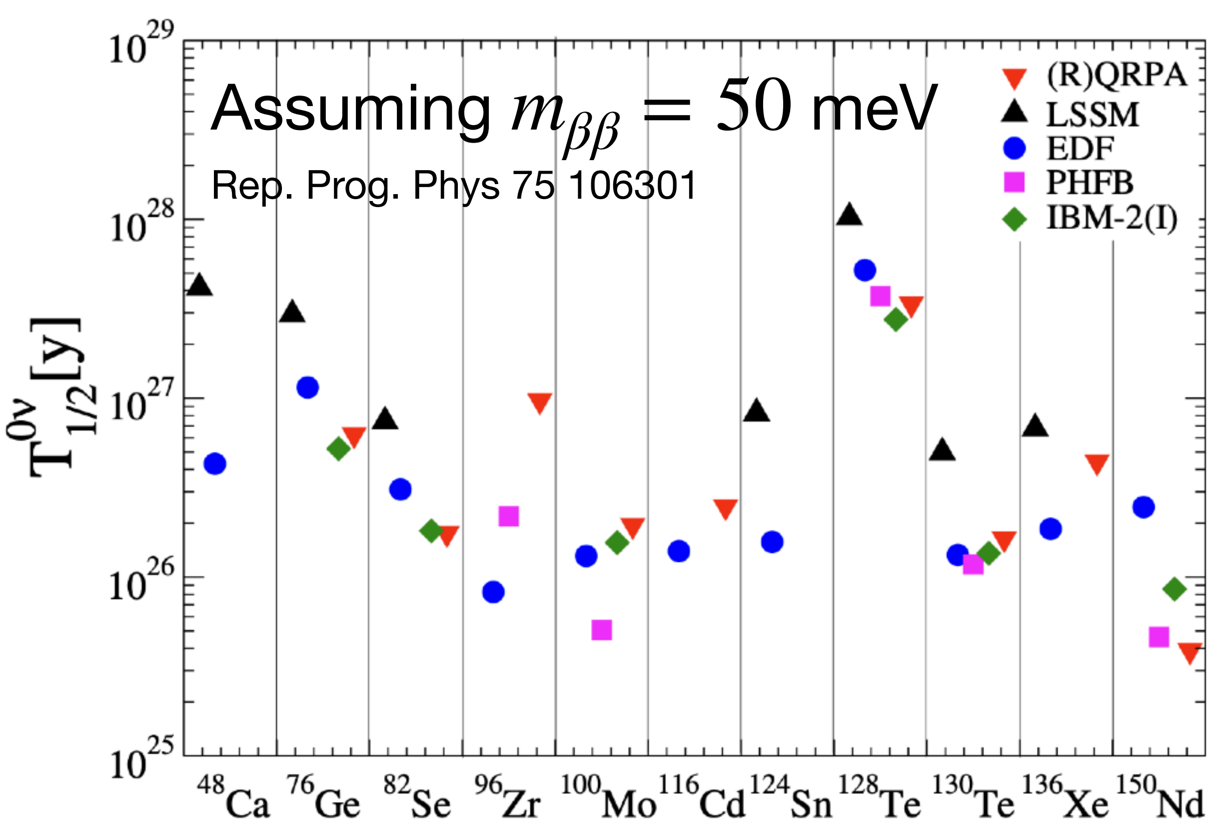
Where $0\nu\beta\beta$ happens?

Rev. Mod.Phys. 95, 025002

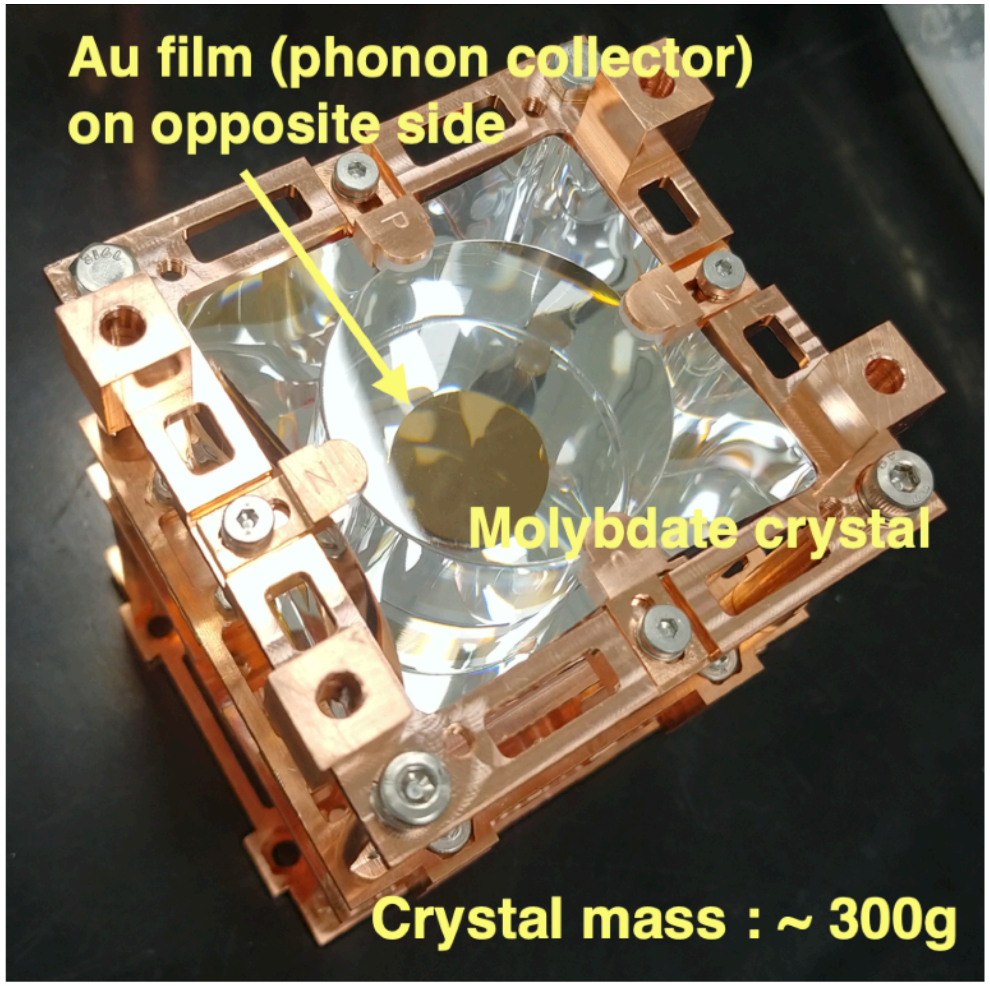
Isotope	Daughter	$Q_{\beta\beta}$[a] [keV]	f_{nat}[b] [%]	f_{enr}[c] [%]	$T_{1/2}^{2\nu\beta\beta}$[d] [yr]	$T_{1/2}^{0\nu\beta\beta}$[e] [yr]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16	$(6.4^{+0.7}_{-0.6}(\text{stat})^{+1.2}_{-0.9}(\text{syst})) \cdot 10^{19}$	$> 5.8 \cdot 10^{22}$
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92	$(1.926 \pm 94) \cdot 10^{21}$	$> 1.8 \cdot 10^{26}$
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3	$(8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})) \cdot 10^{19}$	$> 3.5 \cdot 10^{24}$
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86	$(2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst})) \cdot 10^{19}$	$> 9.2 \cdot 10^{21}$
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5	$(7.12^{+0.18}_{-0.14}(\text{stat}) \pm 0.10(\text{syst})) \cdot 10^{18}$	$> 1.5 \cdot 10^{24}$
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82	$(2.63^{+0.11}_{-0.12}) \cdot 10^{19}$	$> 2.2 \cdot 10^{23}$
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92	$(7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst})) \cdot 10^{20}$	$> 2.2 \cdot 10^{25}$
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90	$(2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})) \cdot 10^{21}$	$> 1.1 \cdot 10^{26}$
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91	$(9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})) \cdot 10^{18}$	$> 2.0 \cdot 10^{22}$

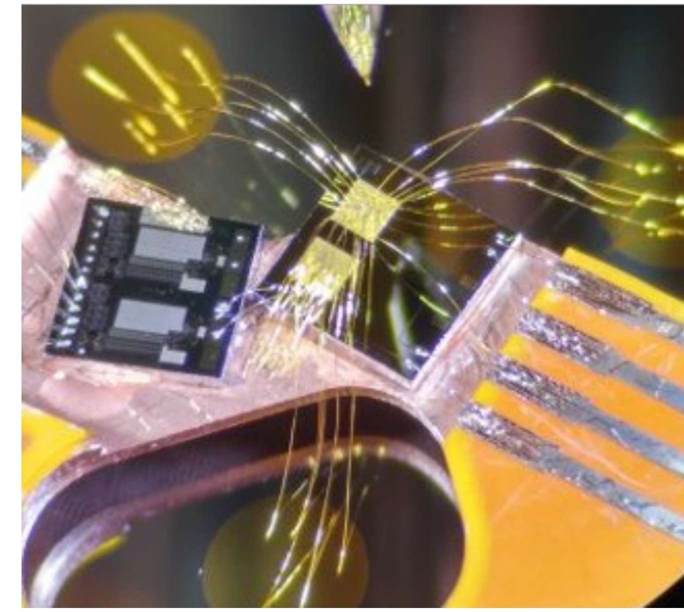
AMoRE's choice, ^{100}Mo:

- high Q > 2.6 MeV,
  ROI in the region of low natural background
- Relatively high natural abundance
- Relatively high decay rate expected

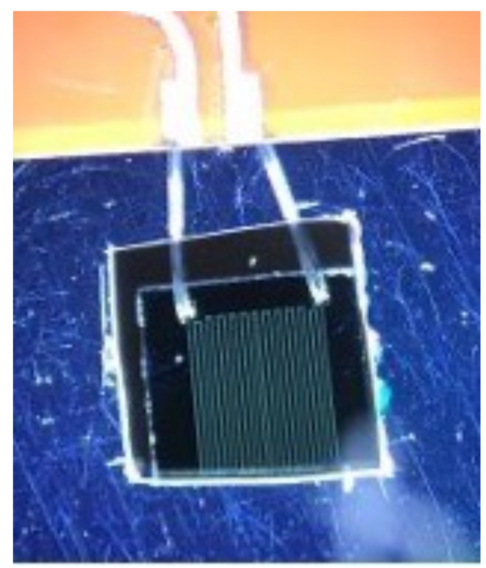


AMoRE detector

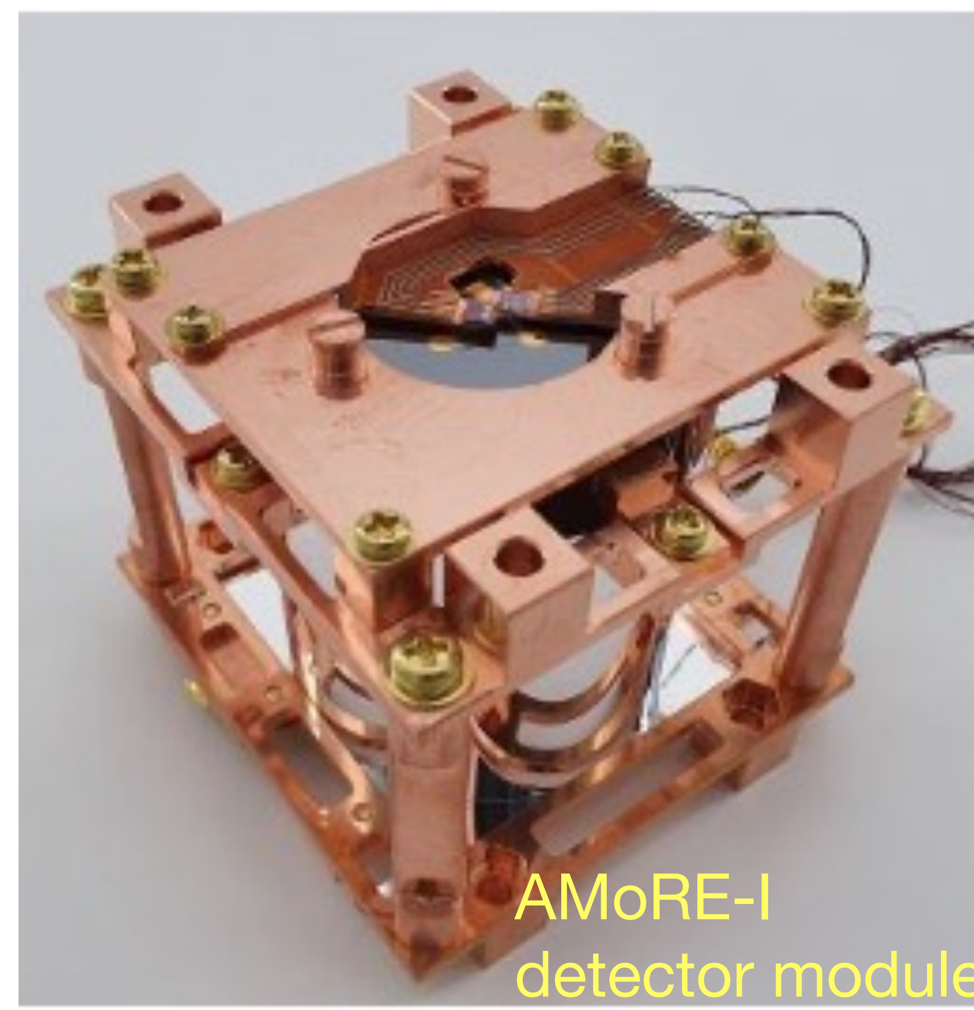


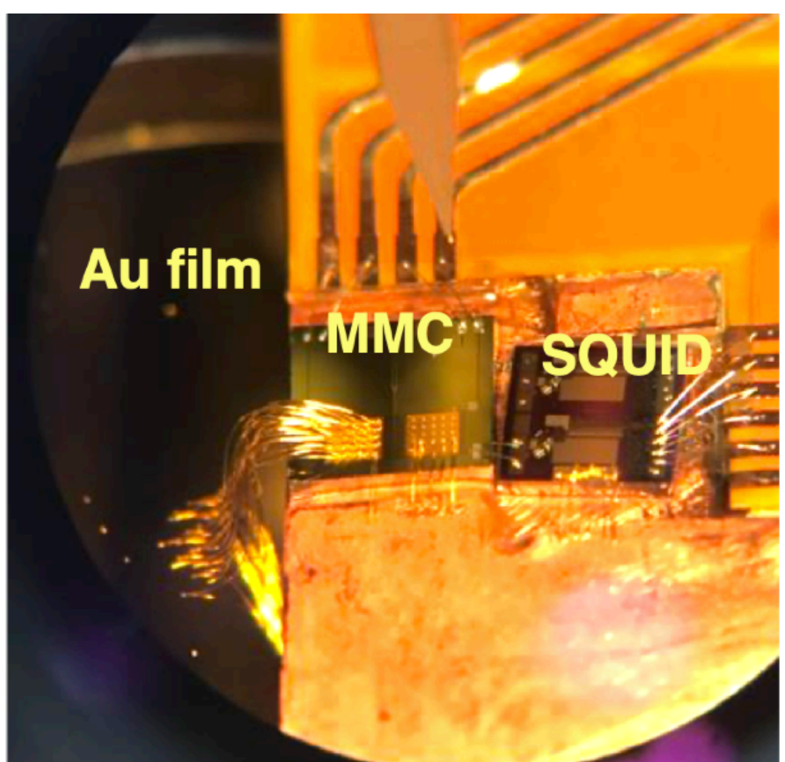


Light channel



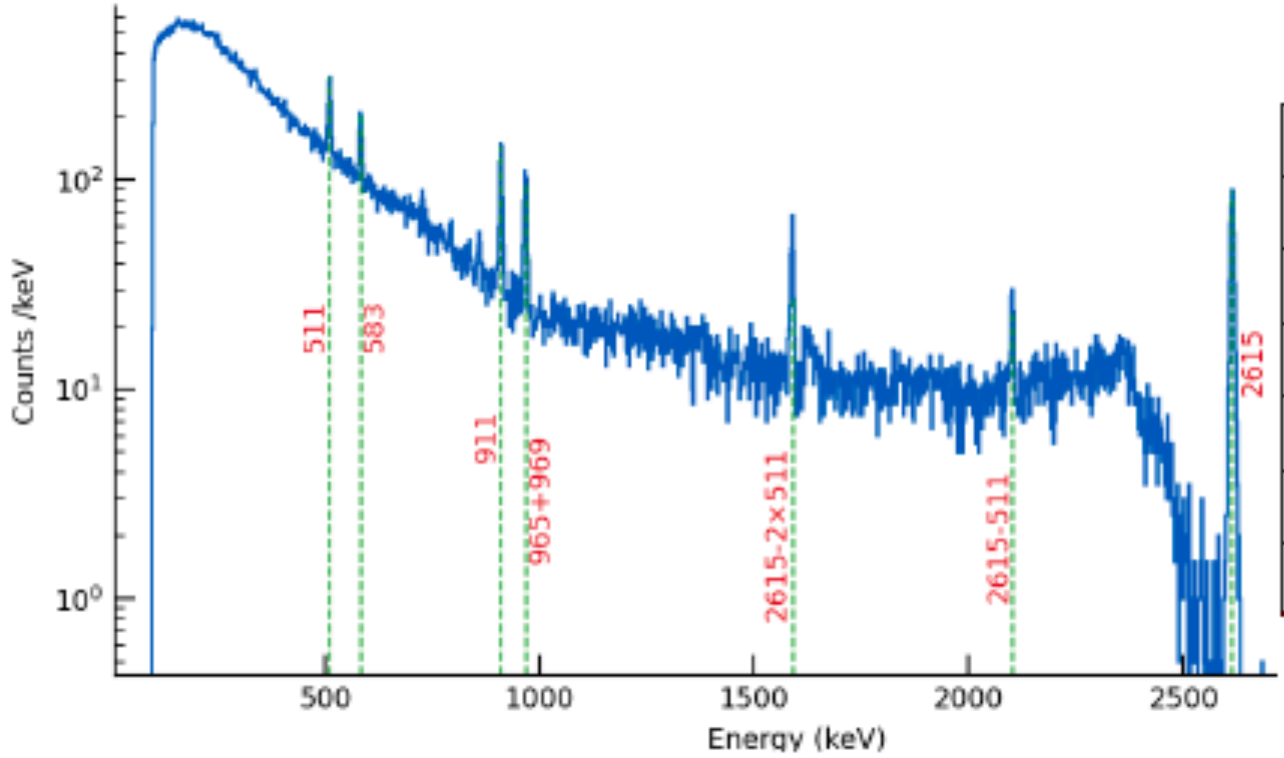
Stabilization heater

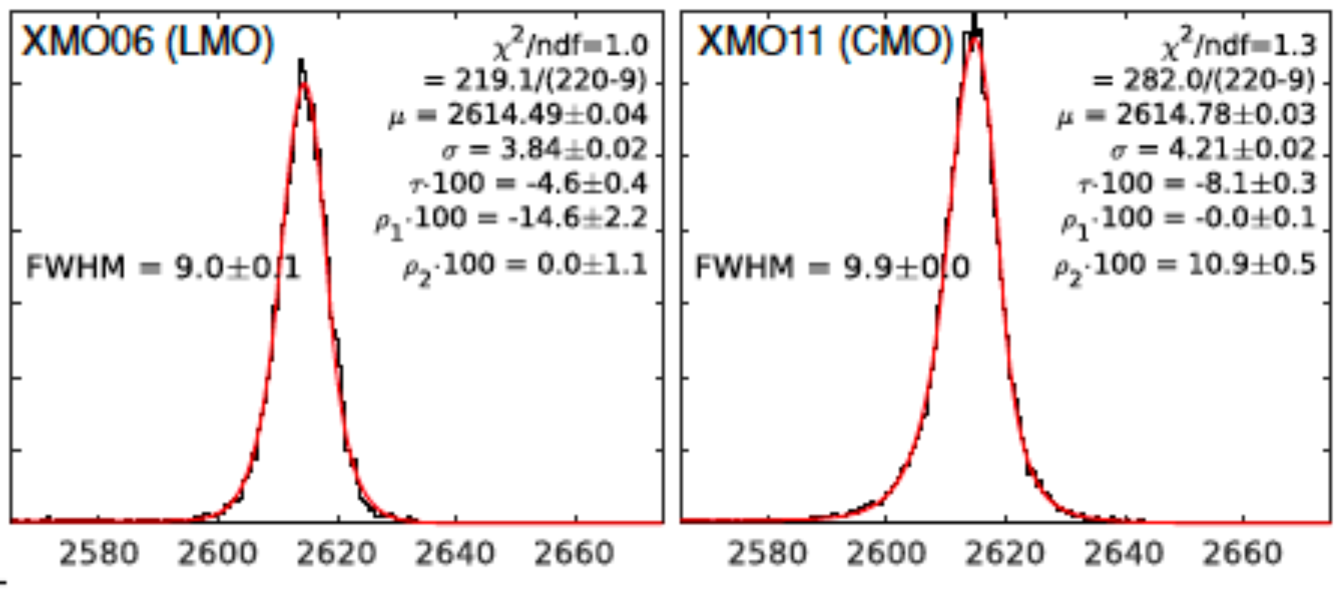


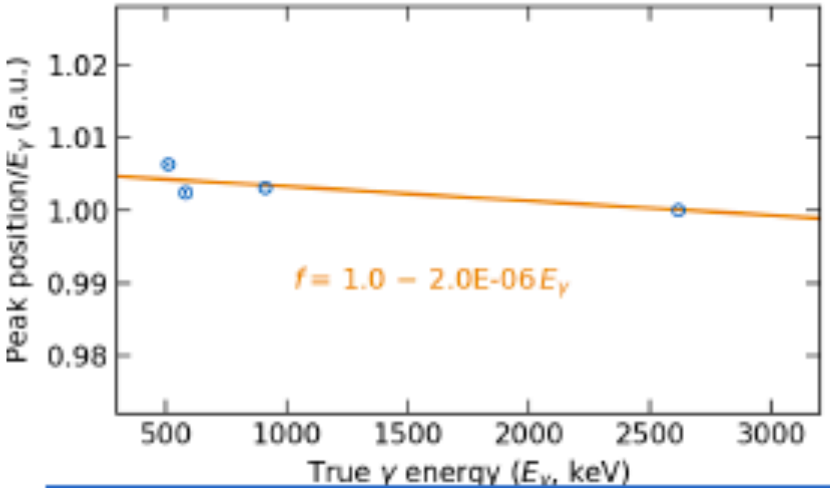


Heat channel

Energy Calibration



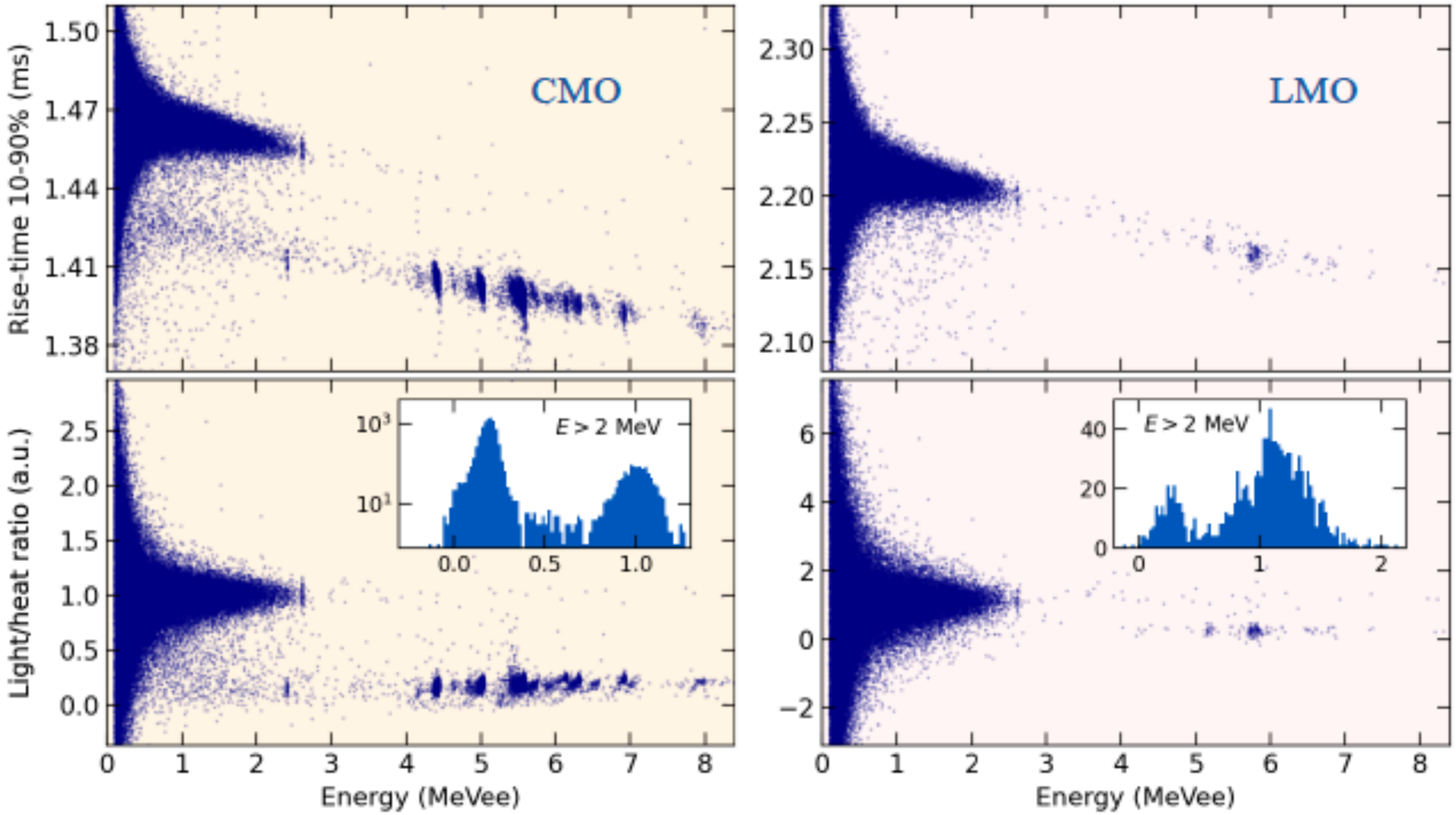




- Calibration source: ^{232}Th-rich welding rods
- Slight non-linearity between signal amplitude and energy.

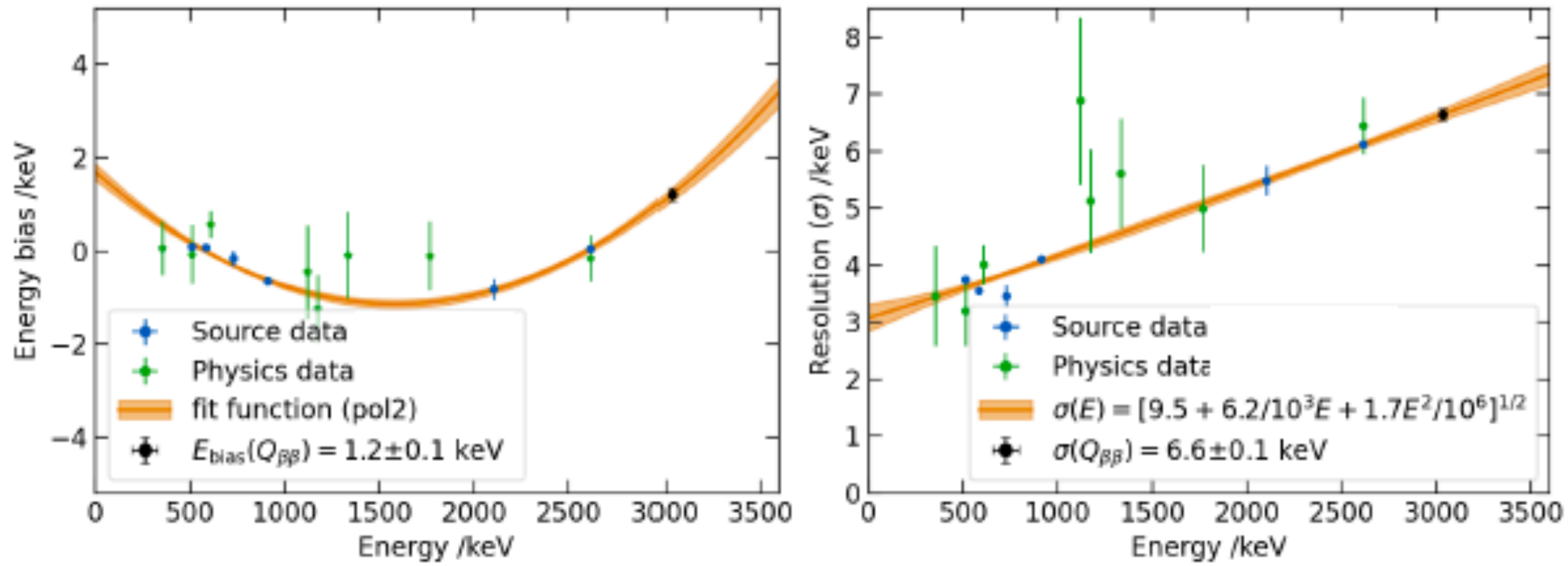
- Bukin function instead of gaussian/exponentially modified gaussian – better fit to right tails https://root.cern.ch/doc/master/classRooBukinPdf.html

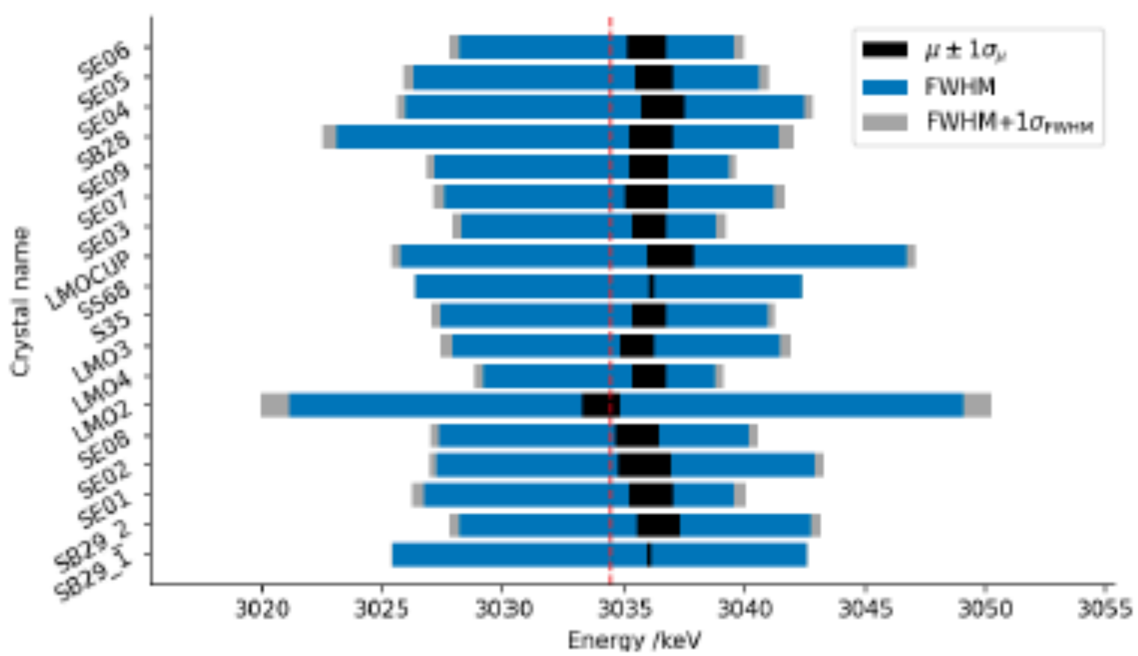
Particle Identification (PaID)



- 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.)

ROI estimation





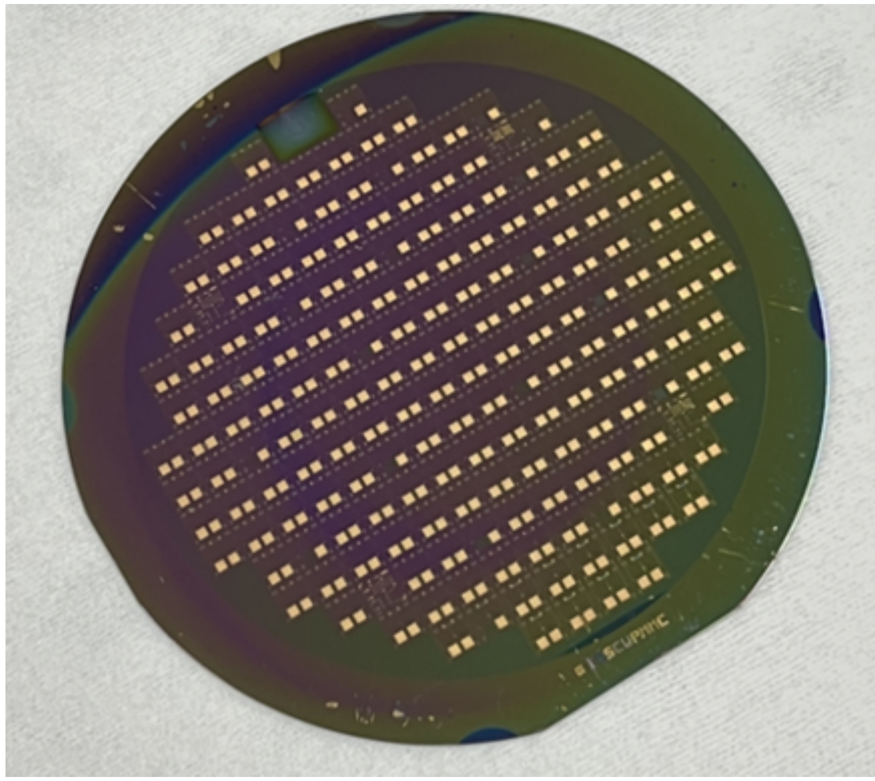
- E_{bias} ~ 2^{nd} polynomial of energy
- $\sigma(E) = \sqrt{b_1 + b_2 E + b_3 E^2}$

(Fittings done only for source data)

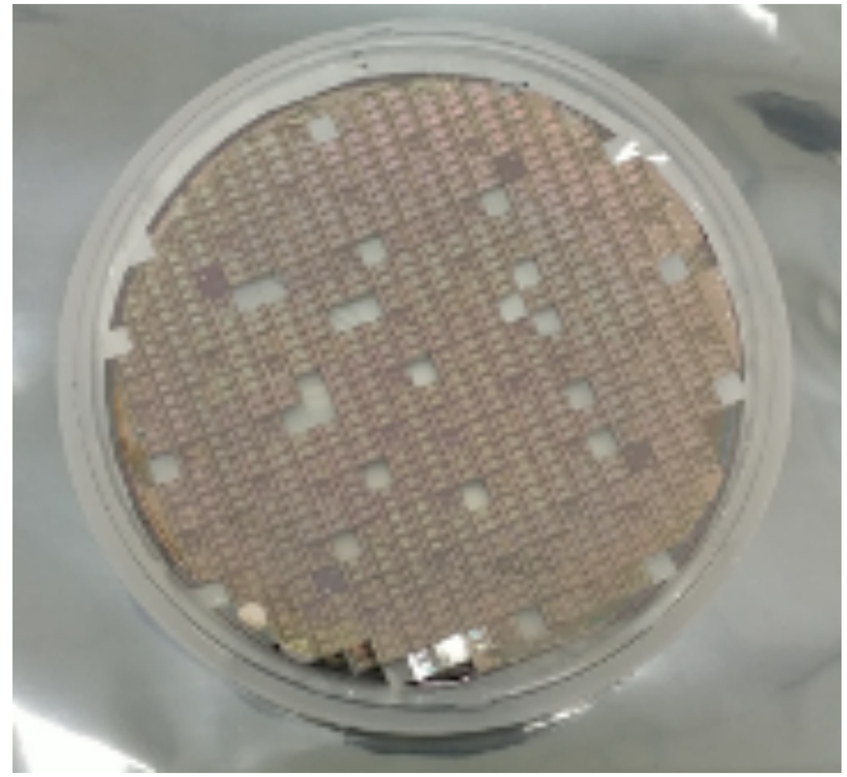
$E_{bias}(Q_{\beta\beta})$: -0.4~2.5 keV
$FWHM(Q_{\beta\beta})$: 9.5~28.0 keV

Detector fabrication on-going

Fabrication of MMC

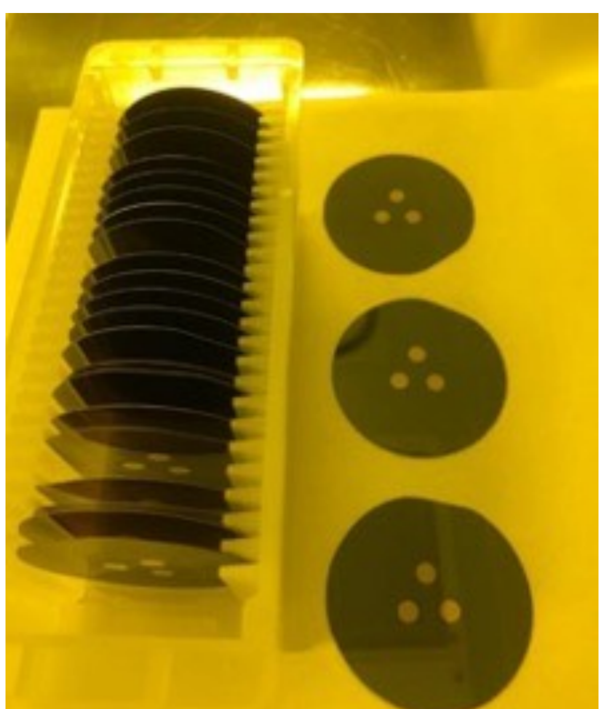


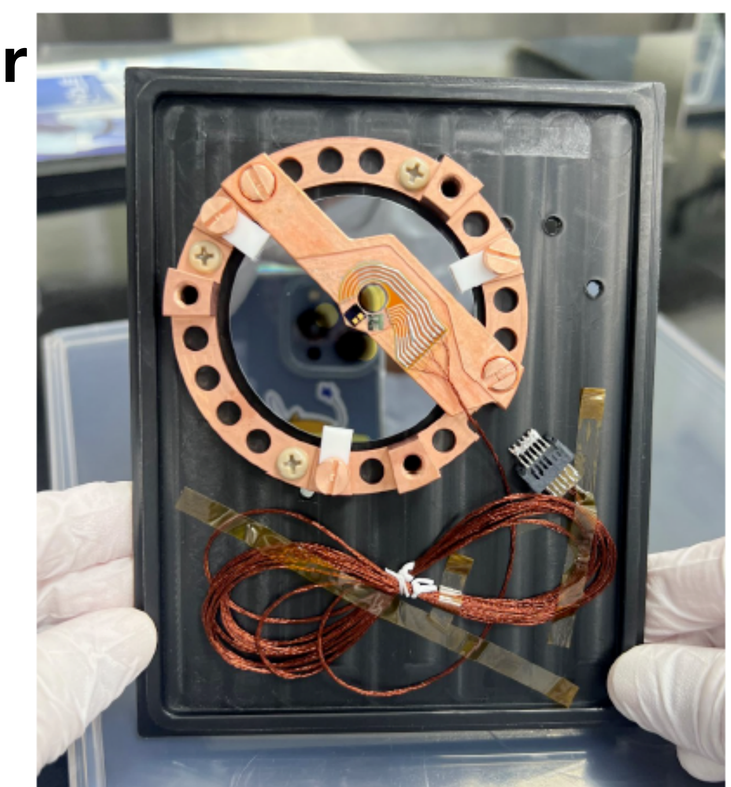
Fabrication of SQUID



Intensive sensor tests underway

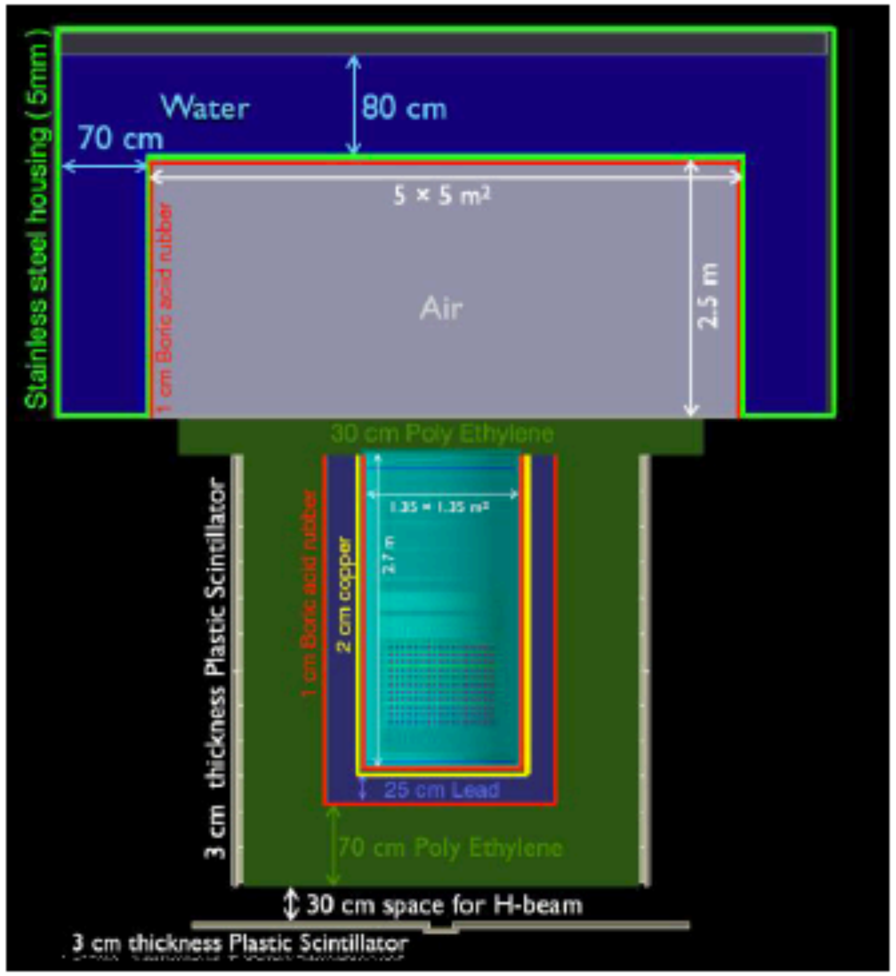
Detector absorber + phonon collector



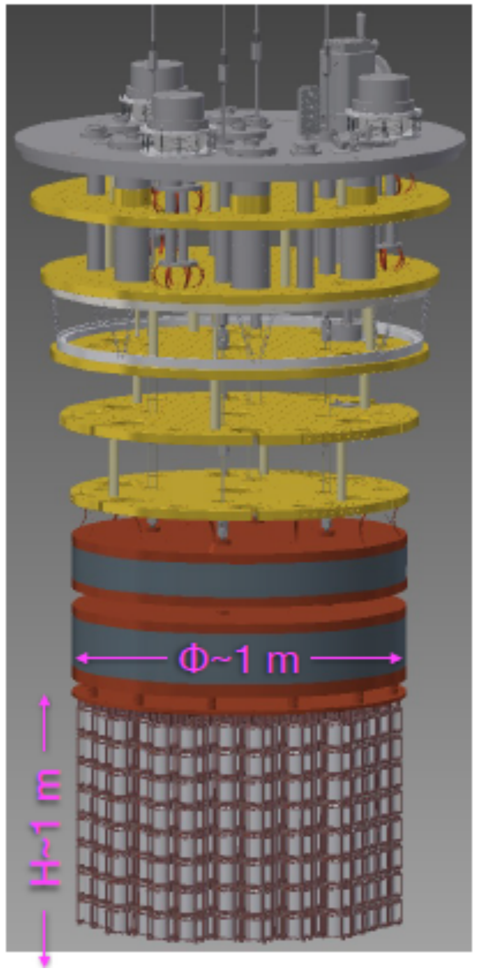


Fabrication of light detector

Heat detector (Crystal) Production will follow soon!



- 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 acide rubber 1 cm < water cherenkov μ-counter 70-80 cm.
- Muon rate $\simeq 10^{-7}$ cm^{-2} s^{-1}.
- Radon-free air supply.



Expected background level

***b*~10-4 ckky, *ΔE*=10 keV FWHM**