AMoRE-II construction status

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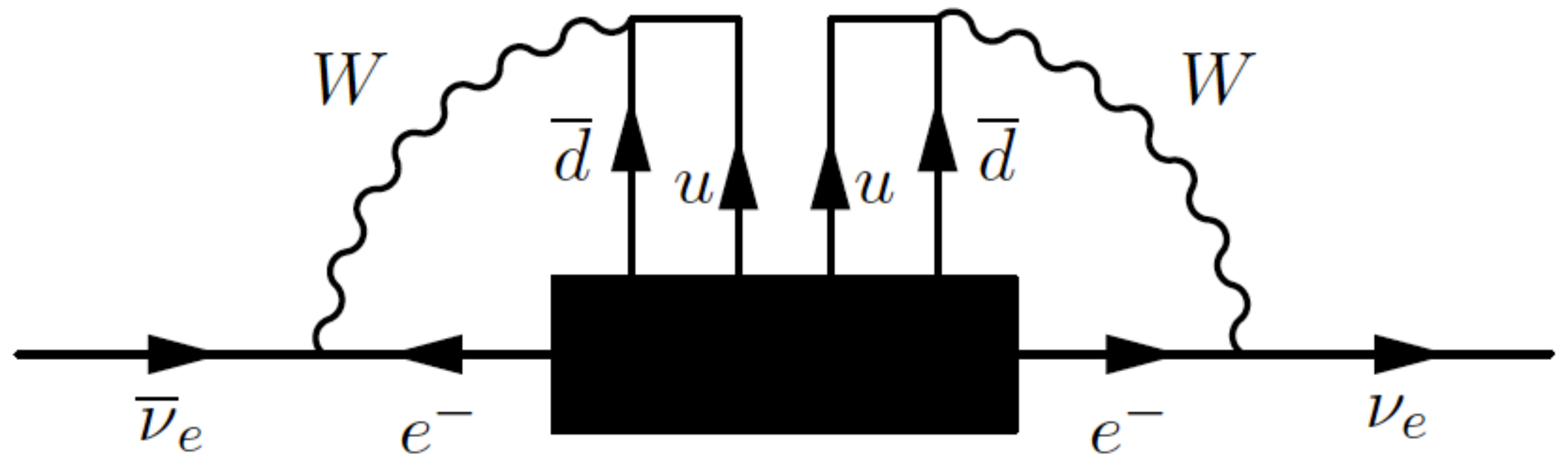
Neutrinoless double beta decay ($0\nu\beta\beta$) ?

Double beta decay:

- Rare nuclear transitions in even-even nuclides (35 nuclides in nature)

- $2\nu\beta\beta$ mode:
  Within Standard Model, $T_{1/2}^{2\nu}$ ~ 10^{18} - 10^{24} years, observed in 11 nuclides, wide spread in $\beta\beta$ spectrum

- $0\nu\beta\beta$ mode:
  $\beta\beta$ carries all the energy, leading to mono-energetic peak
  Lepton number violating process, Beyond Standard Model
  Schechter-Valle theorem: regardless of underlying mechanism, $\nu - \bar{\nu}$ transformation can be constructed !



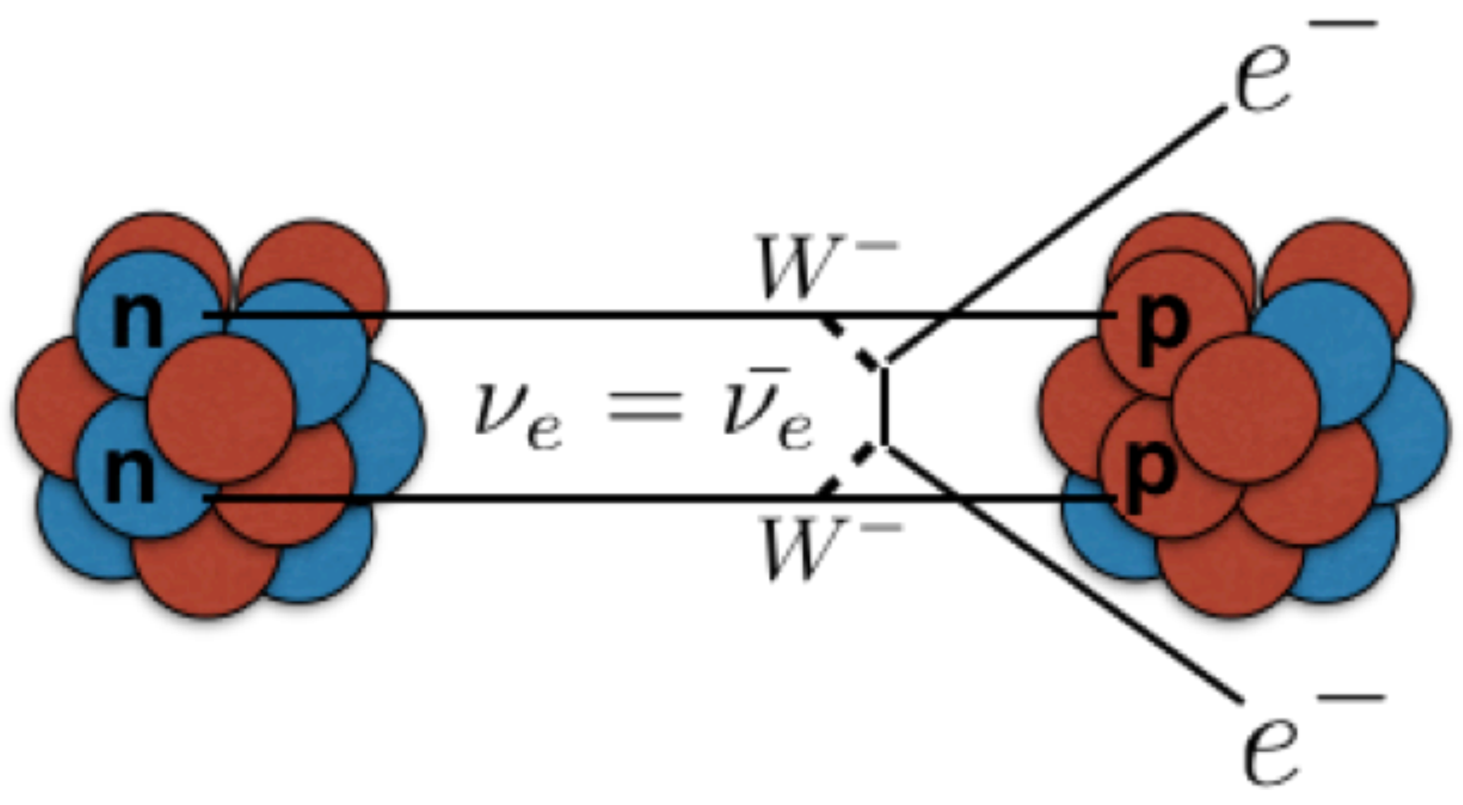
JHEP 2011, 91 (2011)

Clear signature for Majorana nature of neutrinos
Leptogenesis / Baryon asymmetry of the Universe

- Exotic modes: Majorons / sterile neutrinos emission, Lorentz invariance violation …

Neutrinoless double beta decay ($0\nu\beta\beta$) ?

Most popular mechanism for $0\nu\beta\beta$: light Majorana neutrino exchange



Rate: $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 m^2_{\beta\beta}$

Phase space factor

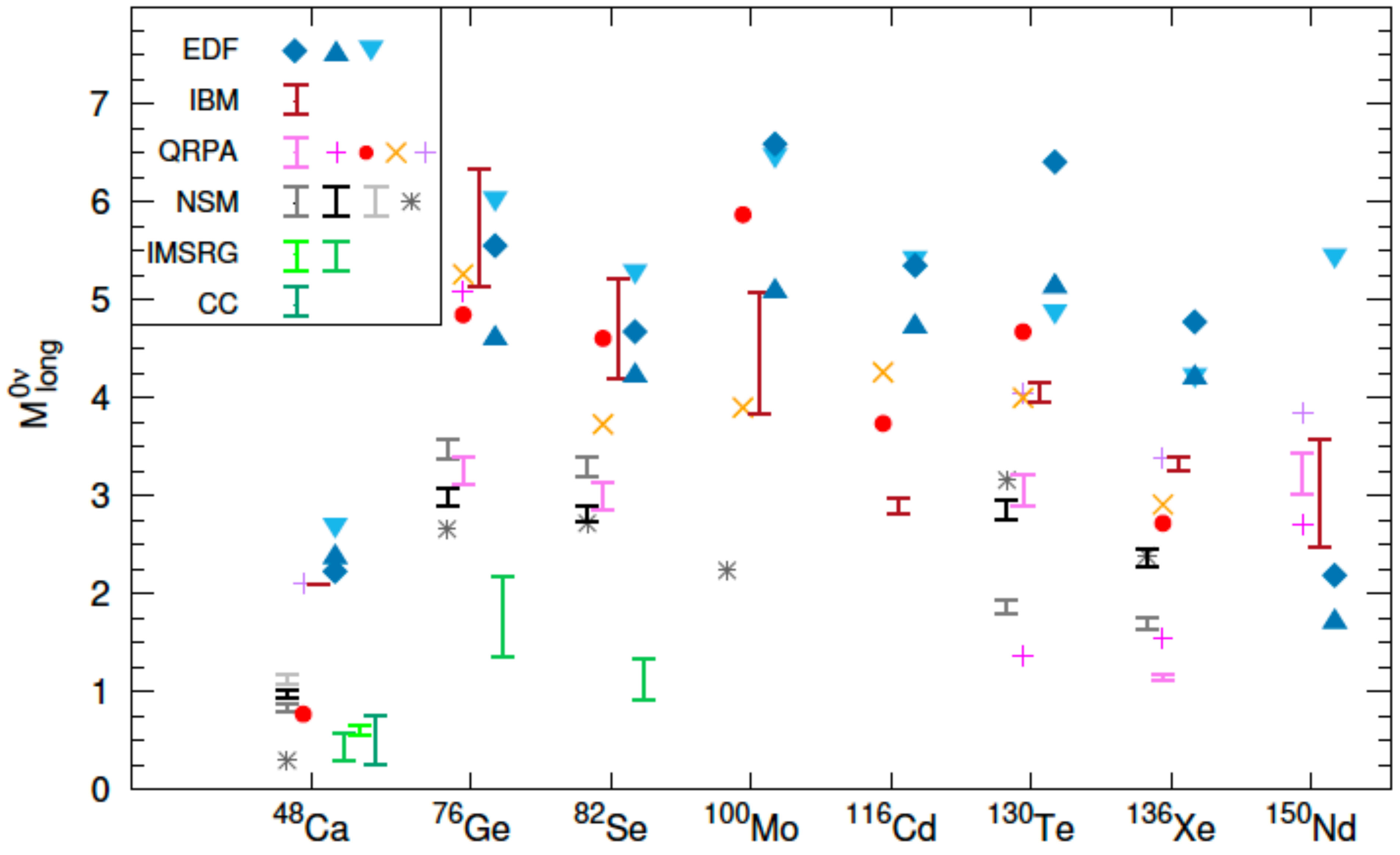
Nuclear matrix element (NME)

Effective Majorana neutrino mass, $m_{\beta\beta} = \Sigma U^2_{ei} m_i$

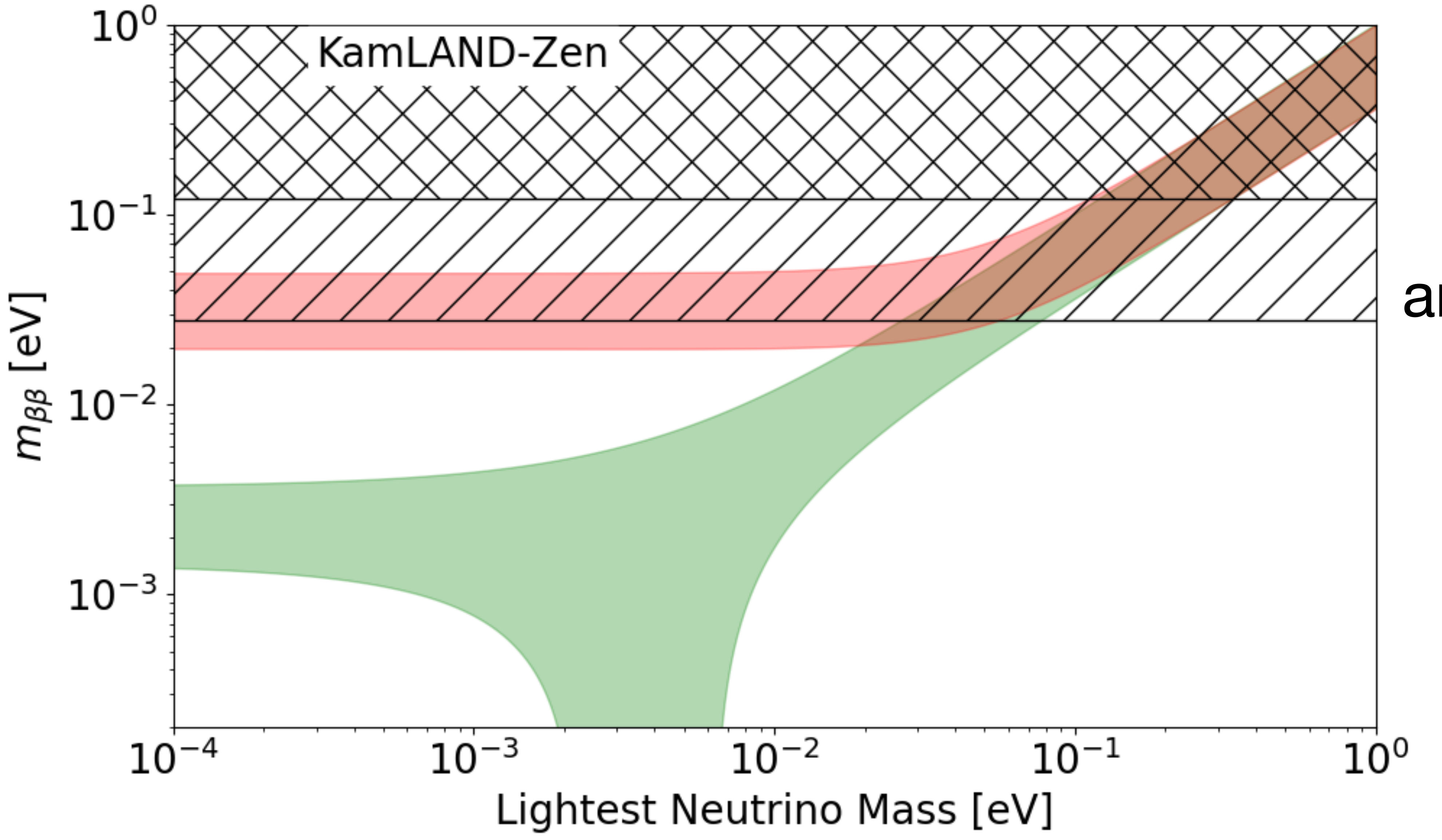
Constraining neutrino mass !

Very rare event rate: $T^{0\nu}_{1/2} > 10^{26}$ years

NME for candidate nuclides



Rev. Mod. Phys. 95, 025002 (2023)



arXiv:2406.11438

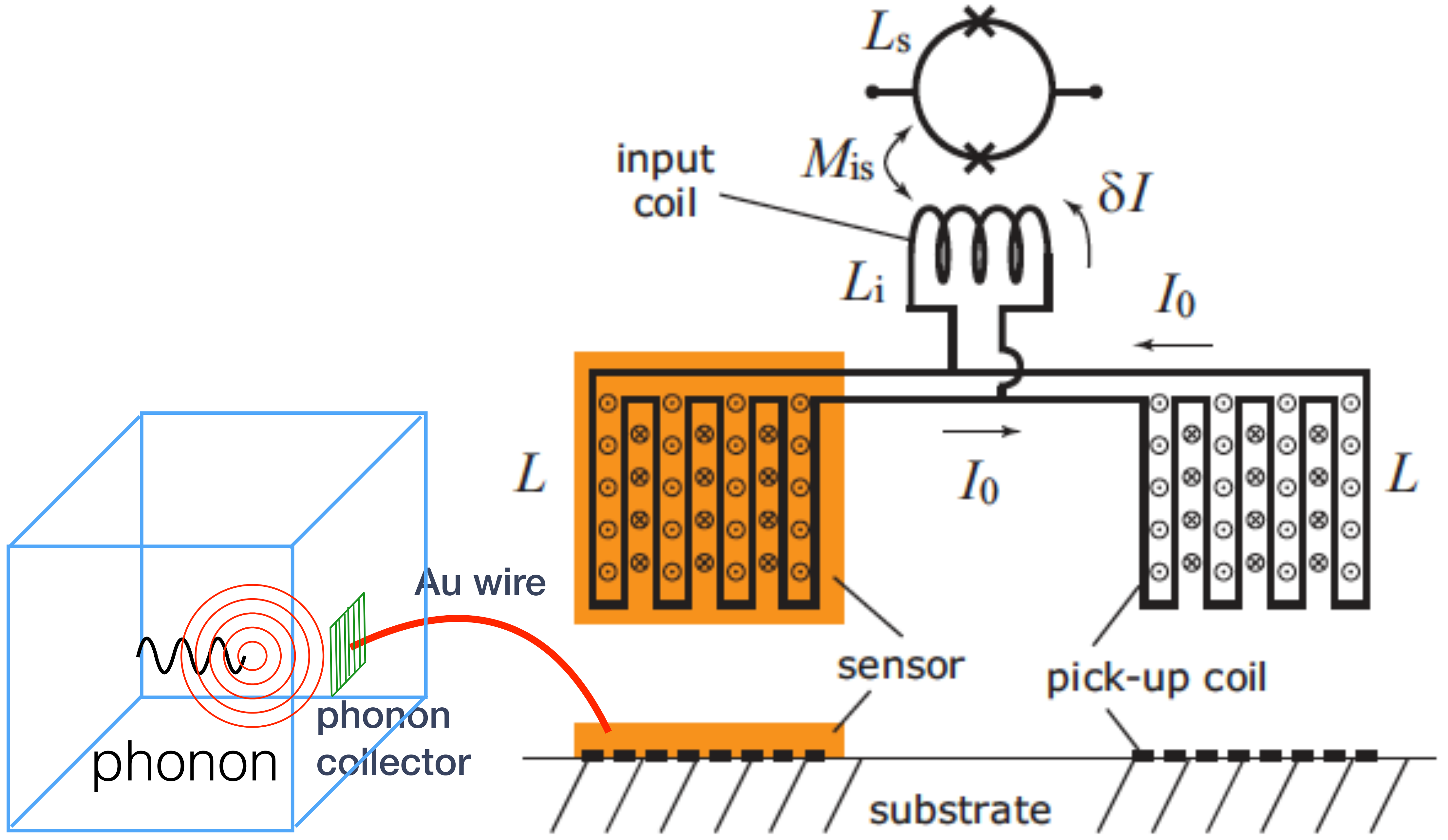
AMoRE experiment

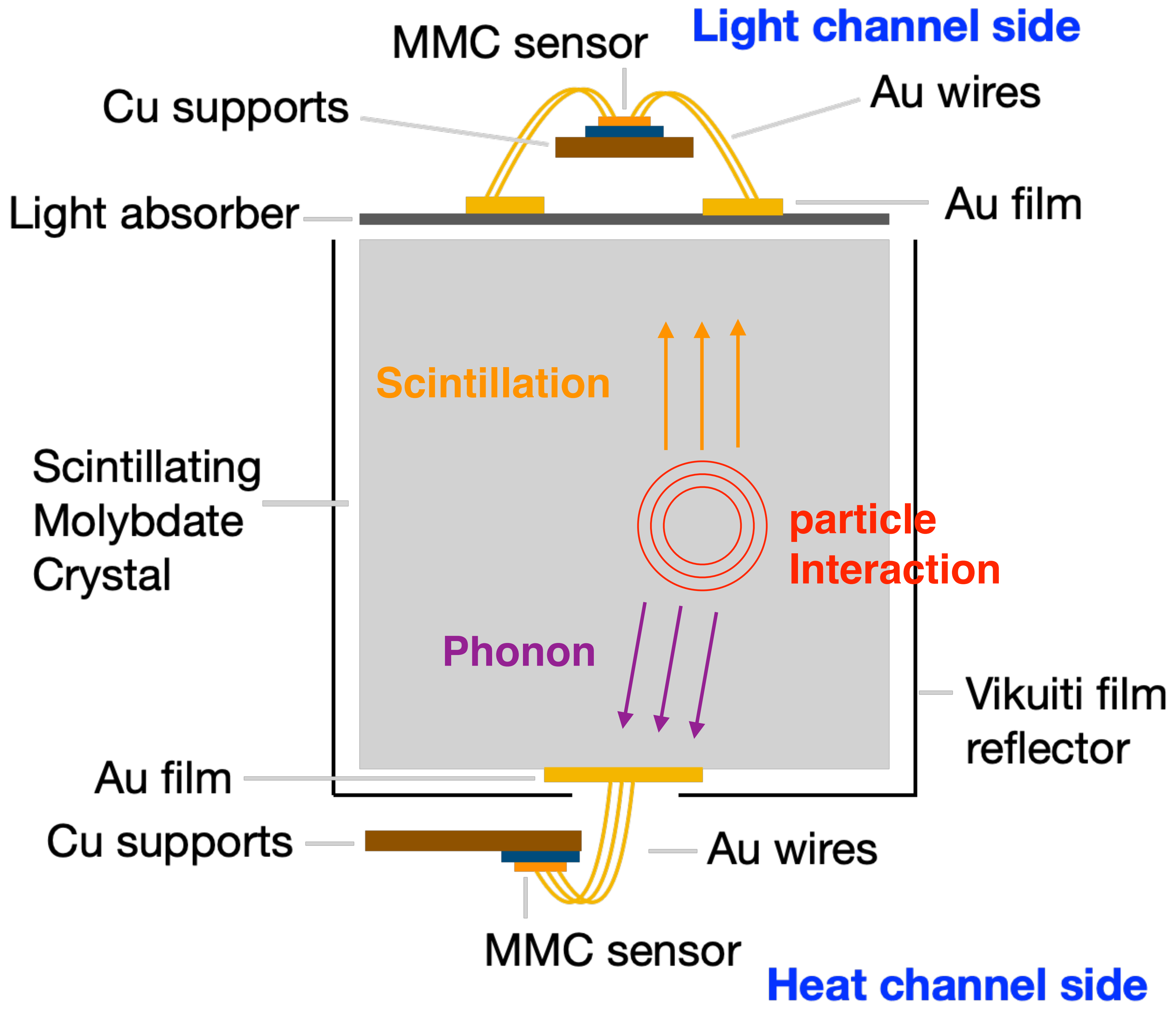
^{100}Mo target material:

- Q-value = 3.034 MeV, natural abundance of 9.7%, relatively high rate

Cryogenic calorimeter with scintillating Mo-containing crystals

- $Ca^{100}MoO_4$, $Li_2{}^{100}MoO_4$ crystals with 95% enrichment of ^{100}Mo
- Detecting energetic phonons and scintillation at ~10 mK
- Metallic magnetic calorimeter (MMC) : Fast response, excellent dynamic range and energy resolution
- Signal: ΔE -> ΔM (MMC) -> ΔI (SQUID)

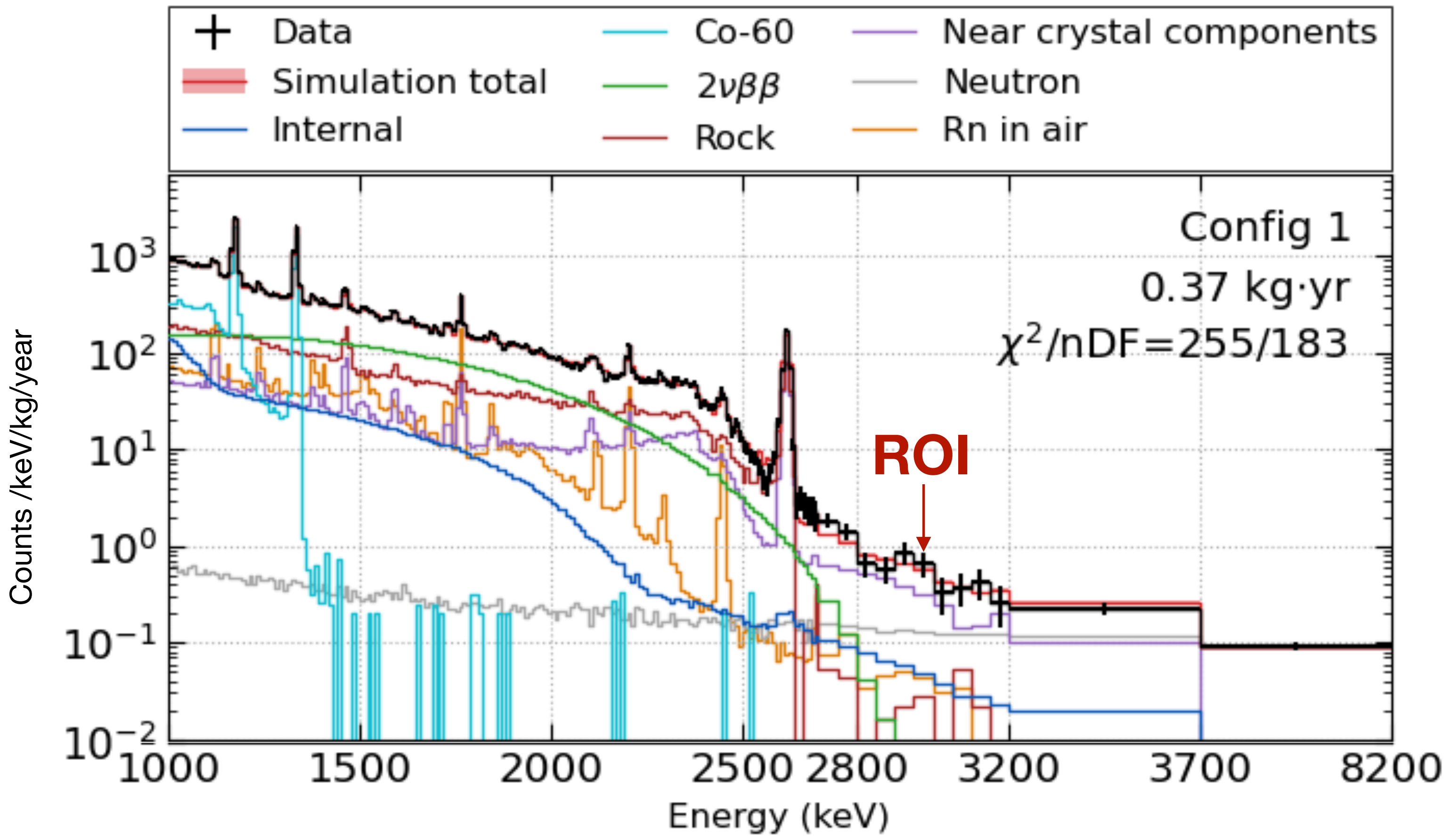




AMoRE experimental campaigns

AMoRE-pilot (2015-2018)

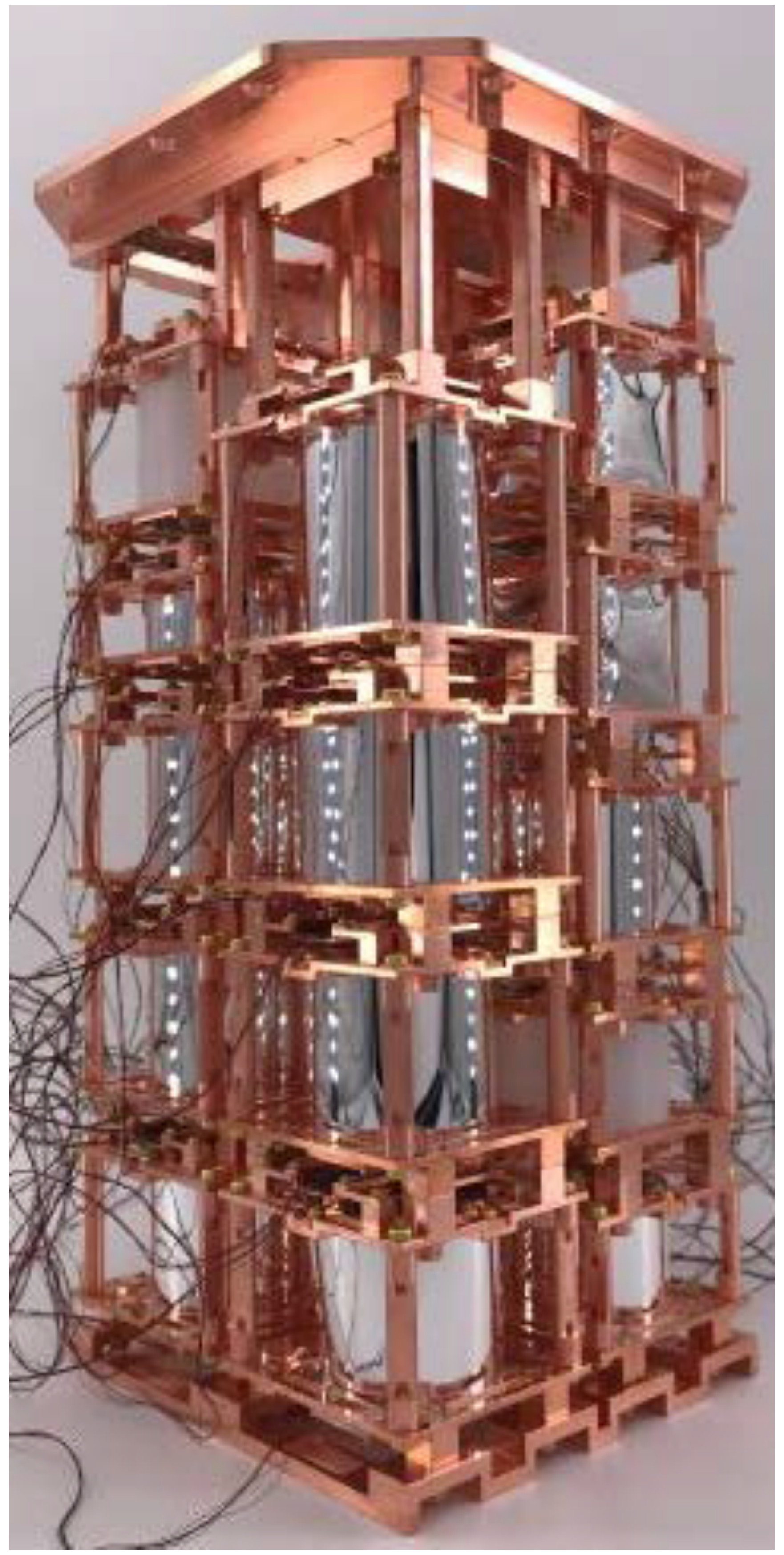
6 $^{48dep}CaMoO_4$ crystals:
1.9 (0.88) kg of CMO (^{100}Mo)
Yangyang Underground Lab
(Y2L, 700 m depth)



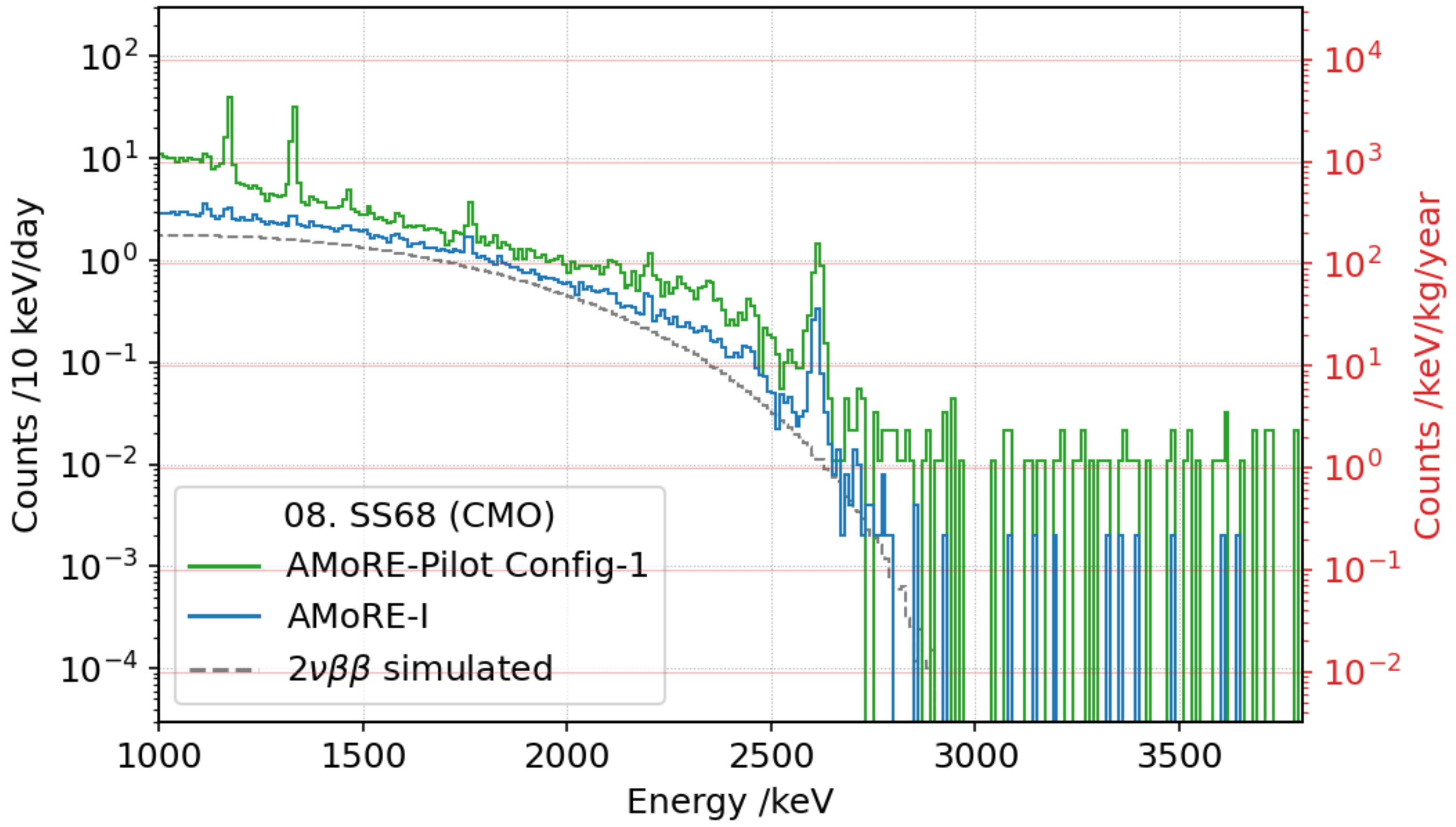
- Live exposure ~ 0.32 $kg_{Mo\text{-}100}$·yr.
- Background at ROI ~0.5 cnts/keV/kg/year.
- $T^{0\nu}_{1/2} > 3.2 \times 10^{23}$ yrs (90% CL)

Astropart. Phys. 162 102991 (2024)
EPJC 79:791 (2019)

AMoRE-I (2020-2023)



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



- Live exposure ~ 4 $kg_{Mo\text{-}100}$·yr.
- Background at ROI~0.025 ckky.
- $T^{0\nu}_{1/2} > 2.9 \times 10^{24}$ yrs (90% CL)
- World best limit for $0\nu\beta\beta$ of ^{100}Mo.

PRL 134 082501 (2025)

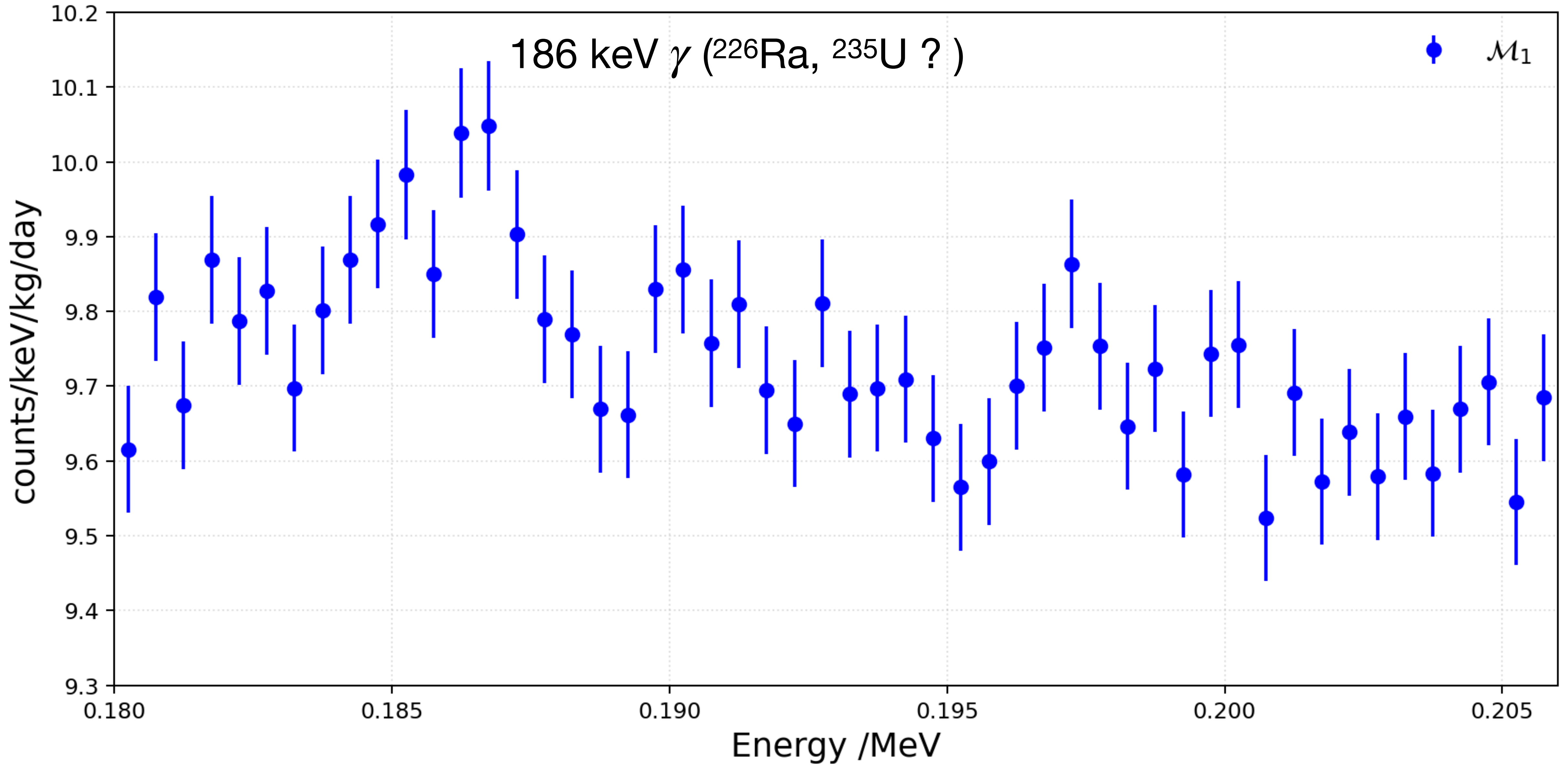
Continuing study with AMoRE-I data

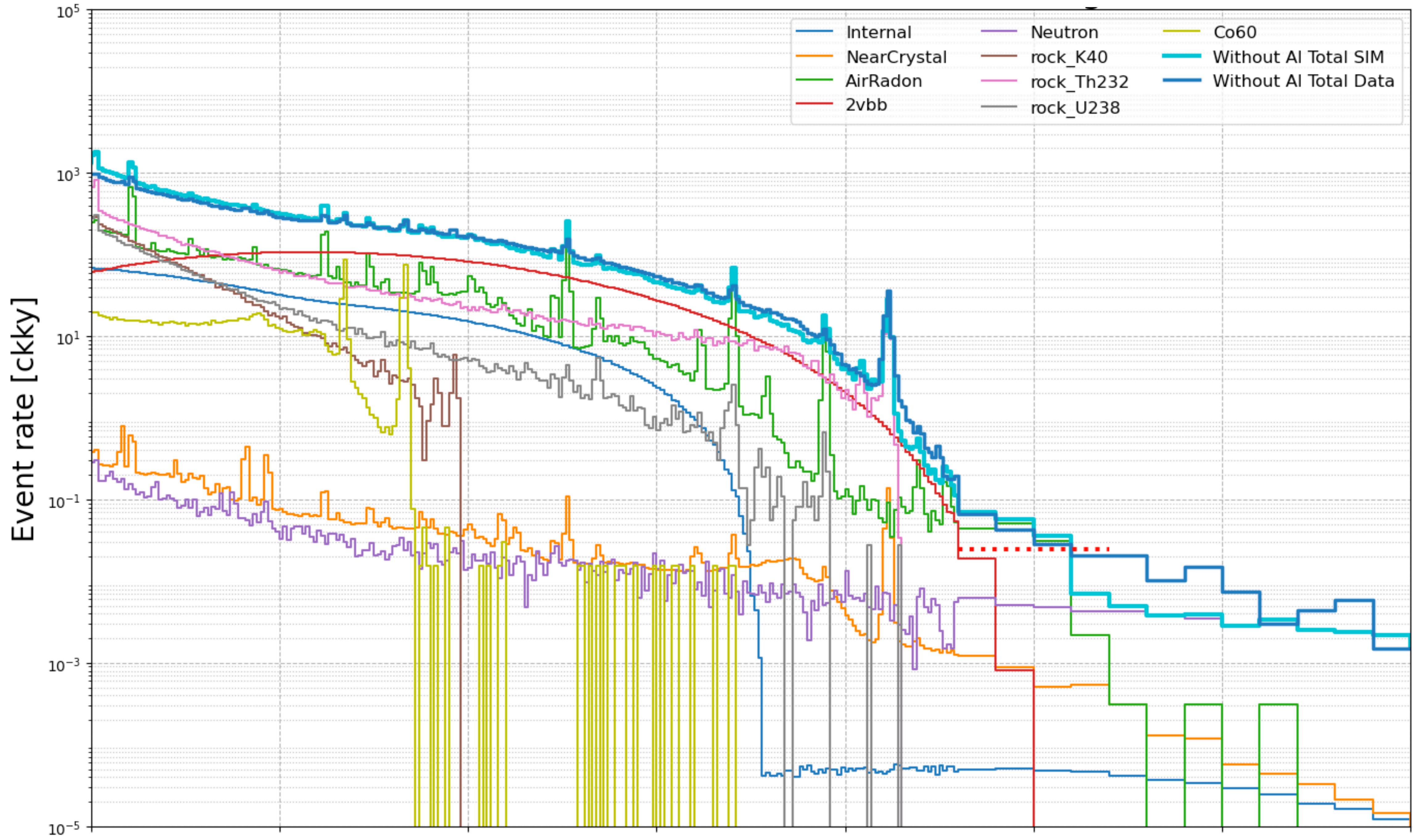
Lowering E threshold with R-value trigger (Wootae Kim's talk)

Improving the energy resolution based on optimal filtering & baseline-dependent drift correction] (Bijaya Sharma's talk)

Searching for $0\nu 2EC$ (193 keV) with 2.5 keV FWHM

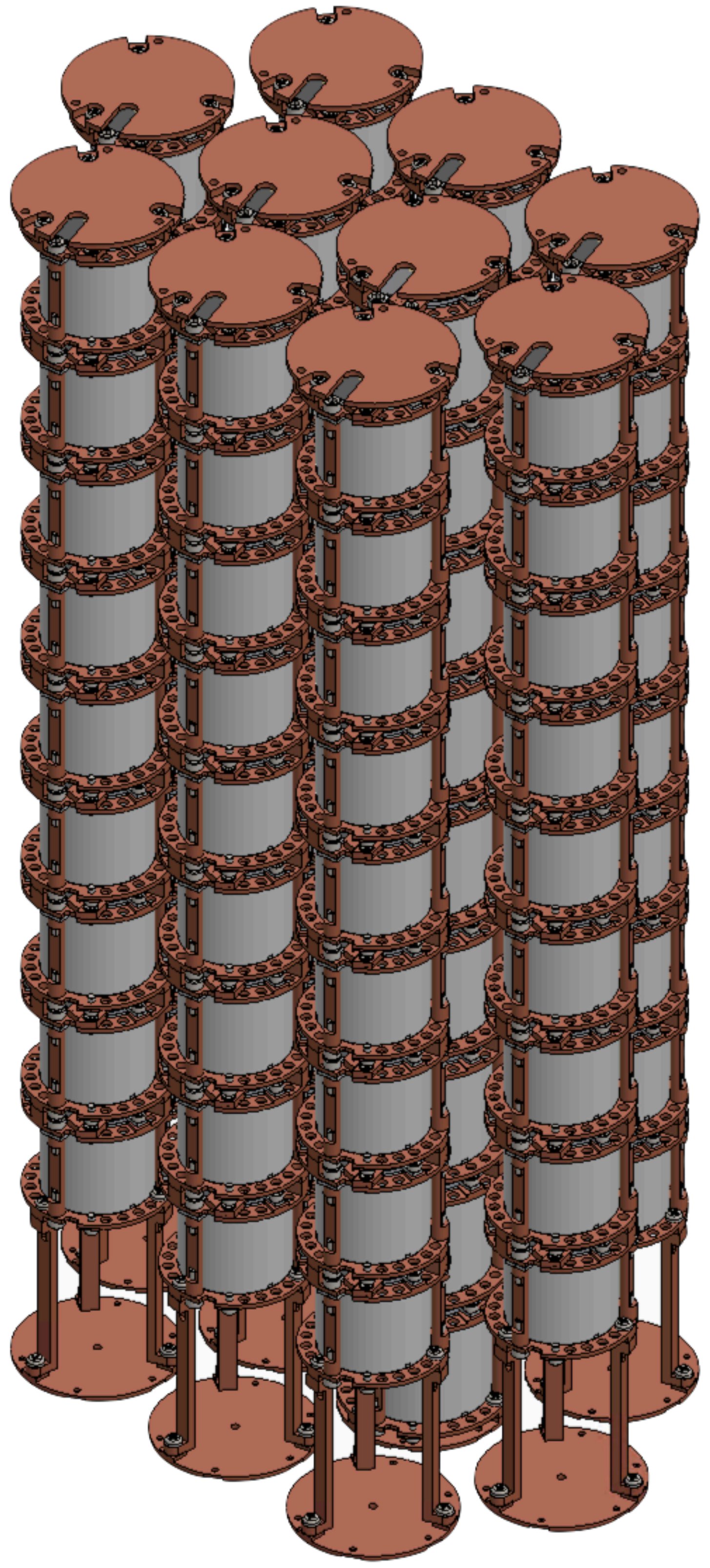
Background modeling with simulation (Binod Bhandari's poster)



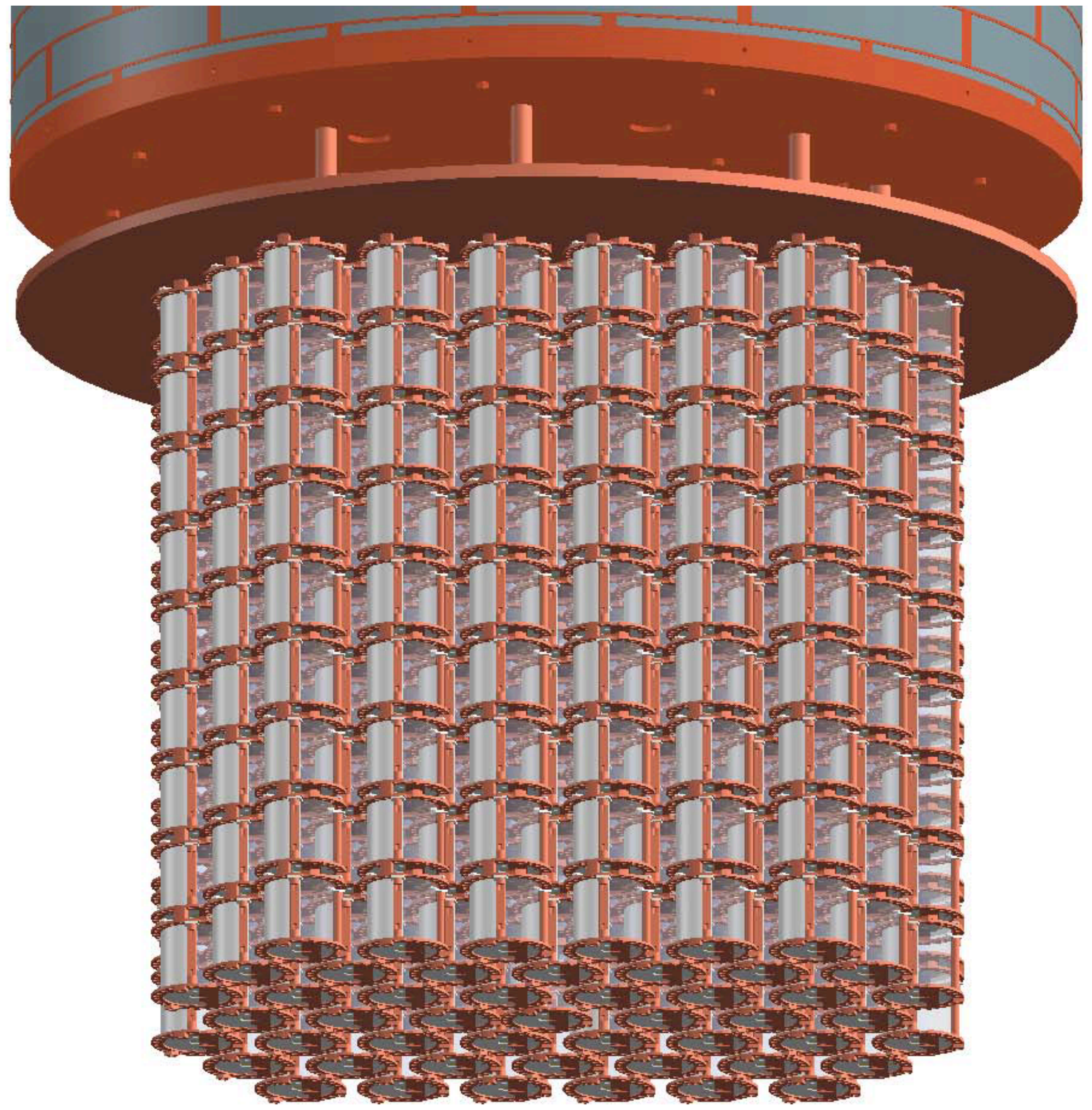


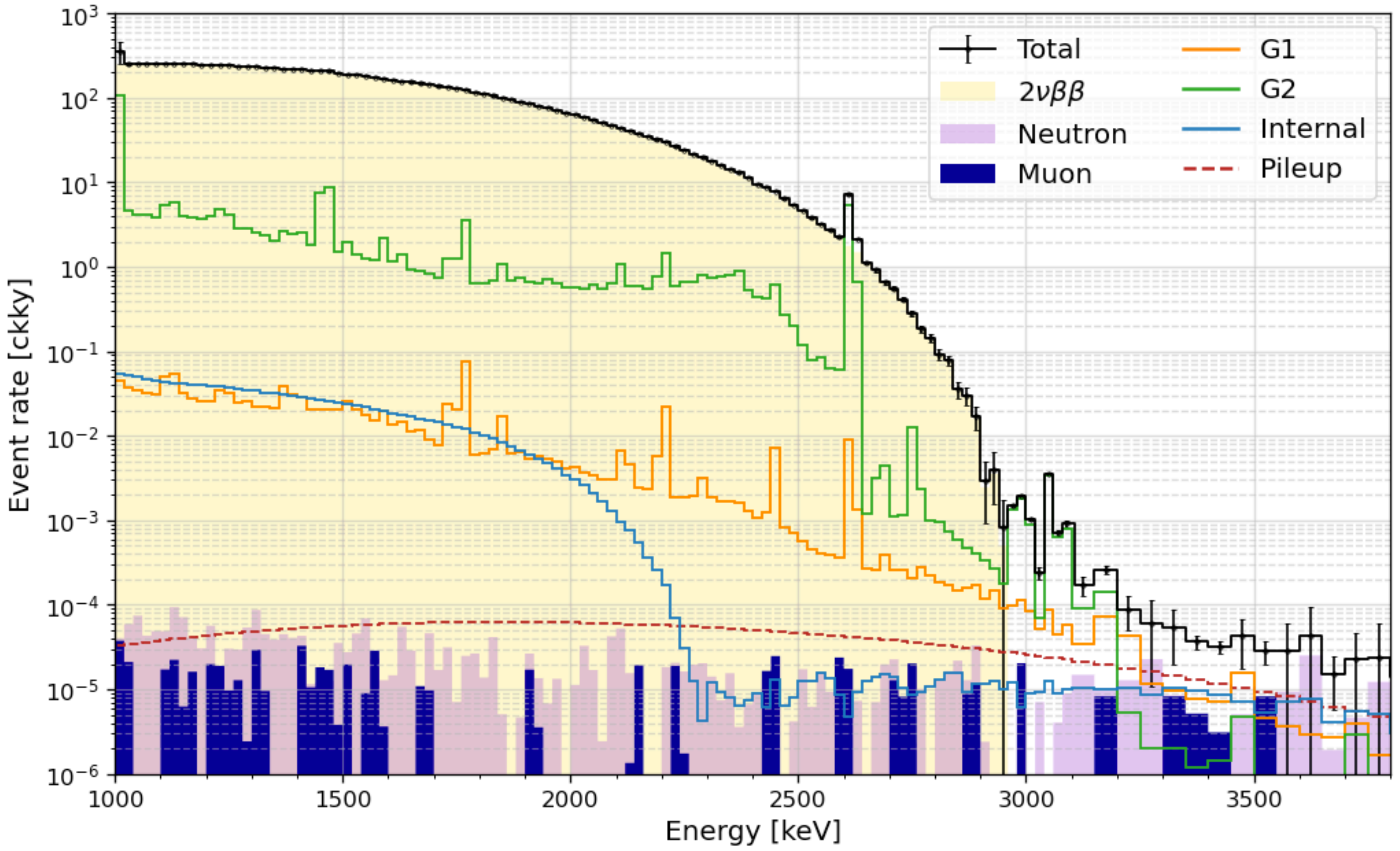
AMoRE-II (2025 -)

Stage 1:
90 LMOs (27 kg)



Stage 2:
360 crystals (157 kg)





- 85 kg of ^{100}Mo
- In Yemilab, 1000 m depth.
- Exposure > 500 $kg_{Mo\text{-}100}$·yr.
- Aiming at ~ zero background event:

  Less than 1cnts / 157 kg / 5 year / 10 keV FWHM@ ROI

  ~ 10^{-4} cnts/kg/keV/year
- Aiming at $T^{0\nu}_{1/2} \sim 4 \times 10^{26}$ yrs

Crystal production

Li_2MoO_4 crystals (^{100}Mo enrichment ~ 96%)

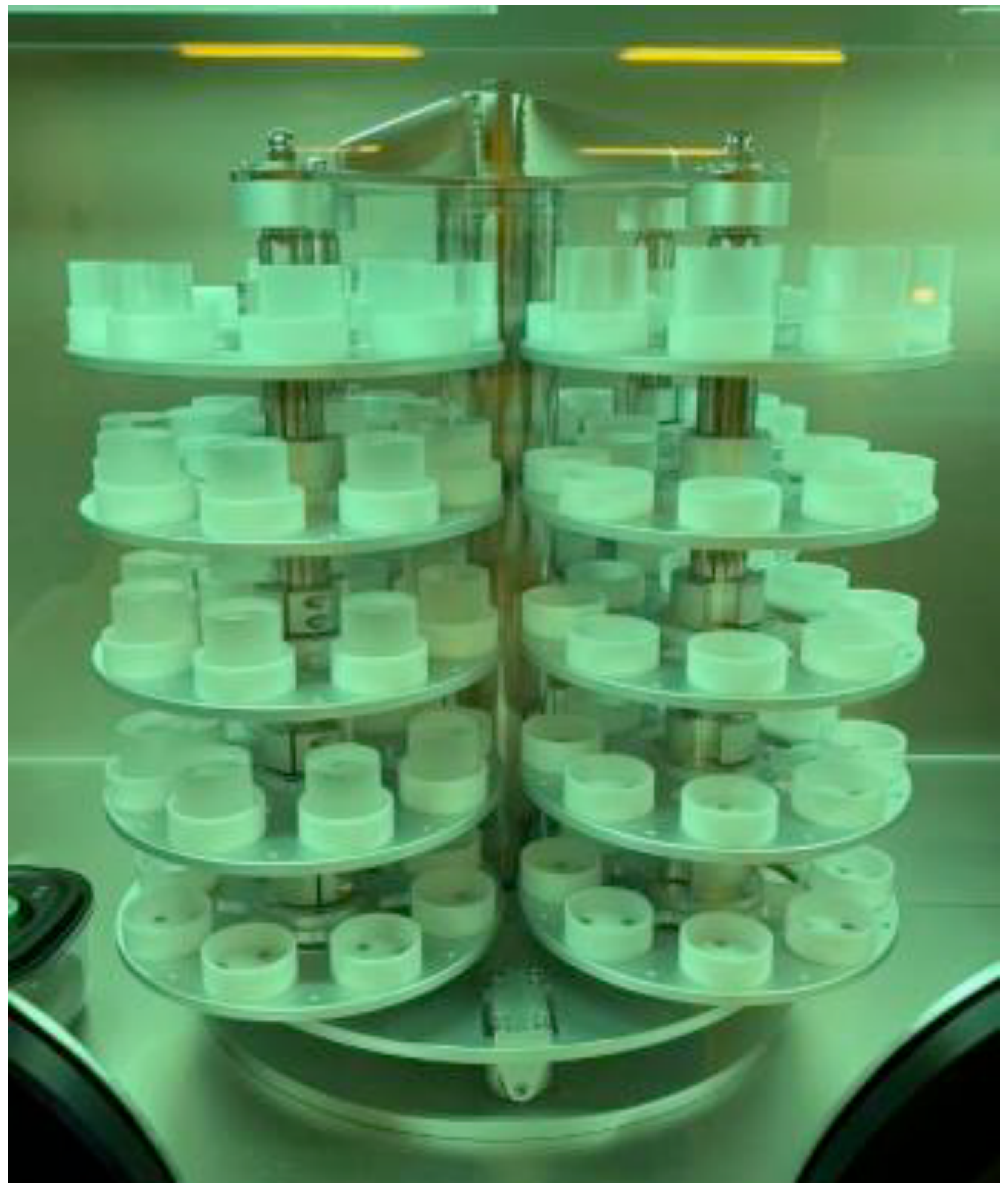
Intensive purification of raw materials

Cylindrical crystals with 5 cm (D) x 5 cm (H) & 6 cm x 6 cm

Manufactured by CUP & NIIC, several years of production

Low background verified

~ 260 crystals (~110 kg) in storage

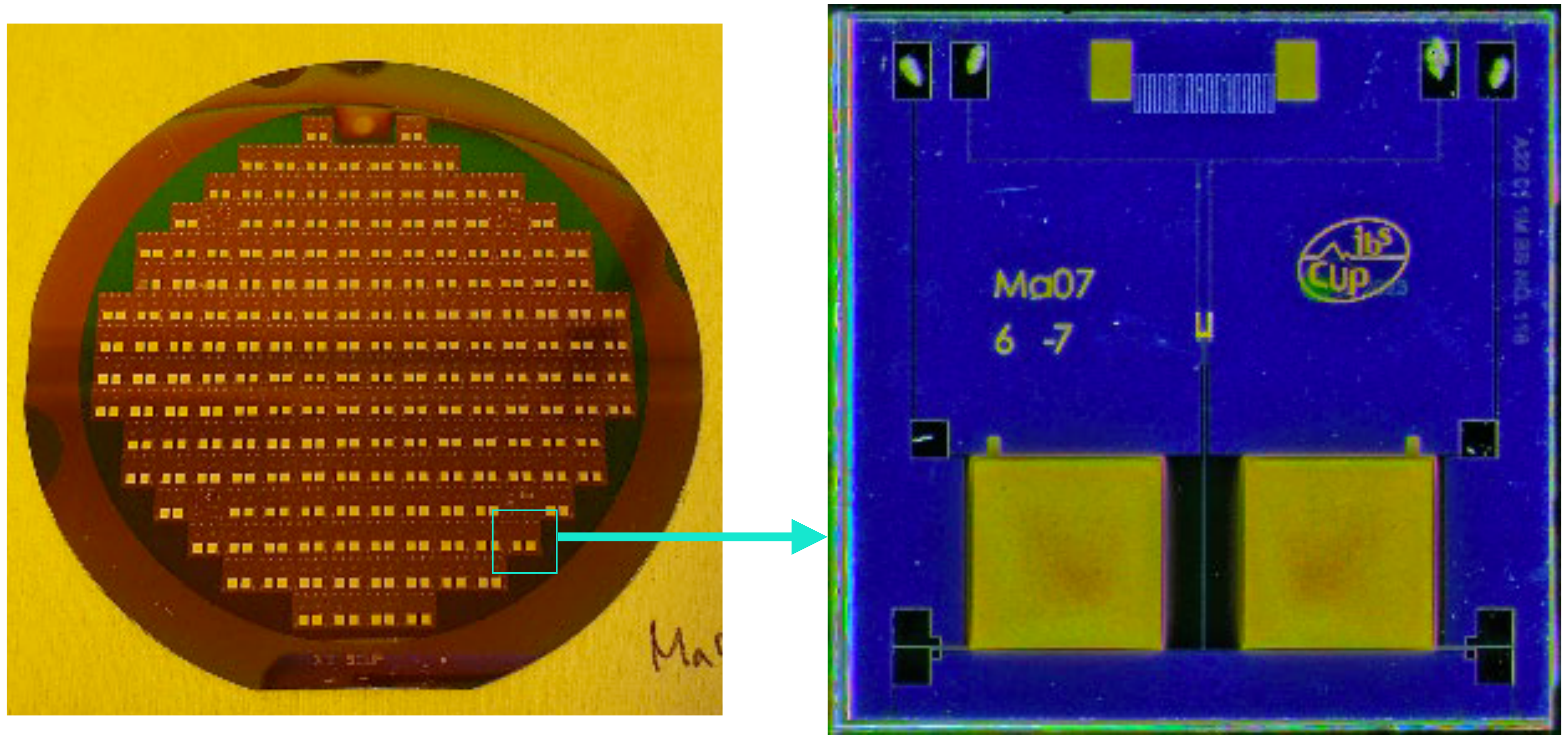


Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)
Crystal	Natural CMO (1902)[a]	CUP	56 (4)	< 5.5	< 5.3	< 39
	Enriched CMO (SE#3)[b]	CUP	< 2.0	< 3.2	< 1.6	< 3.2
	Natural LMO (1602)[a]	CUP	< 3.3	< 2.6	< 1.5	29 (9)
	Natural LMO (1801)[b]	CUP	< 1.2	< 3.2	< 1.3	< 14
	Enriched LMO (1901)[c]	CUP	< 1.5	< 5.7	< 3.4	< 14
	Enriched LMO (2005)[b]	CUP	< 3.5	< 4.1	< 3.6	< 14

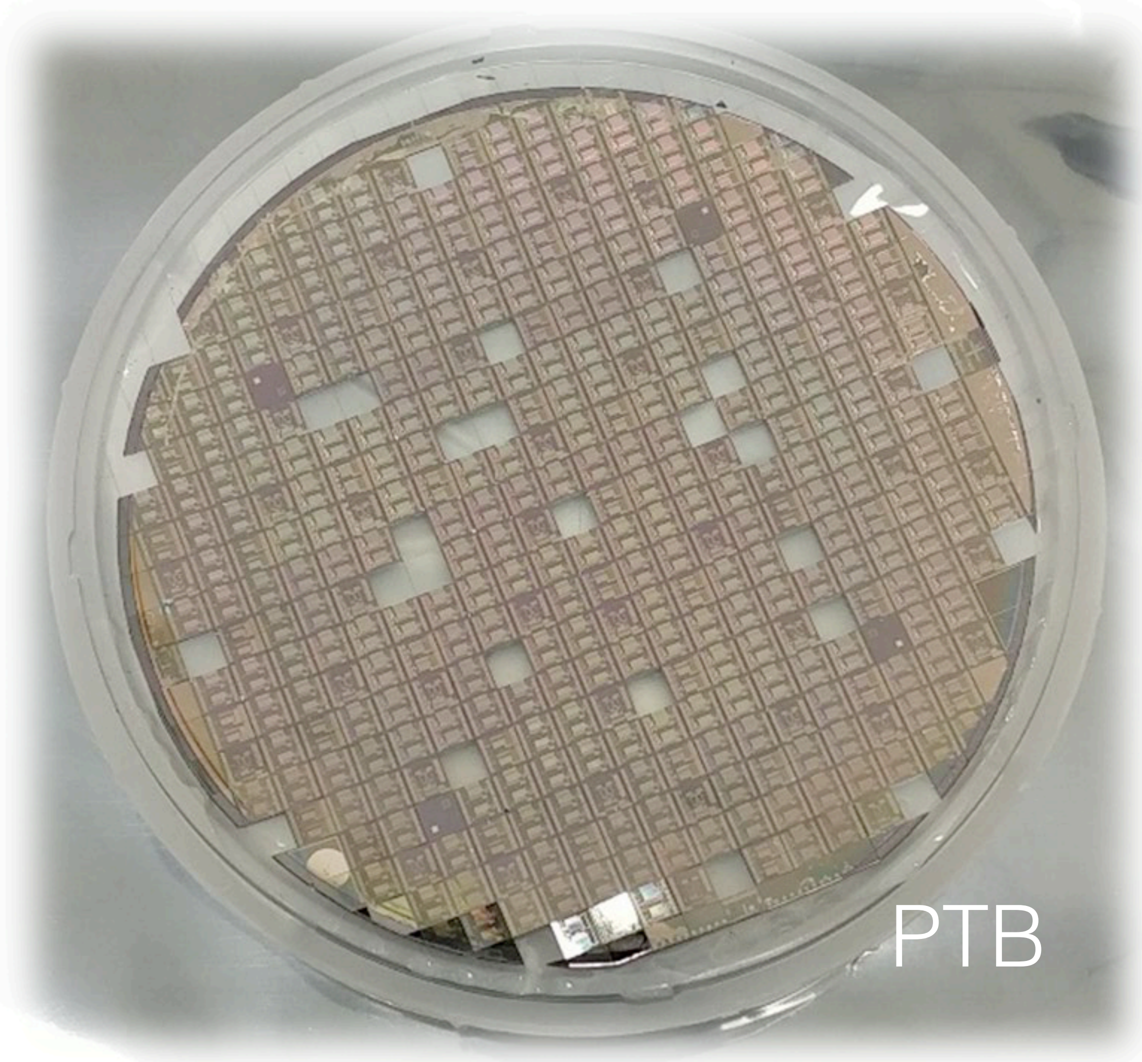
Front. Phys. 12:1362209 (2024)

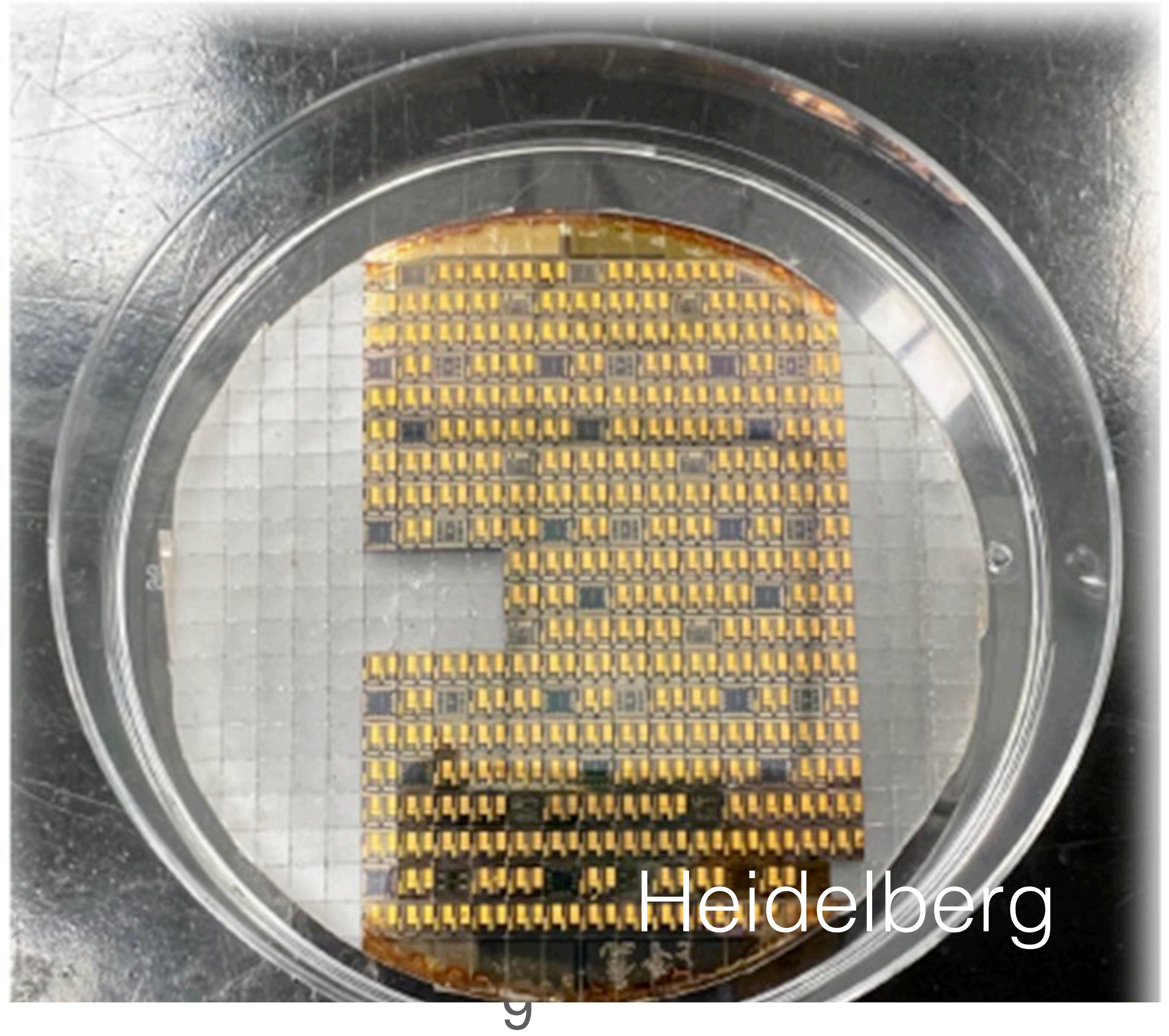
Sensor production

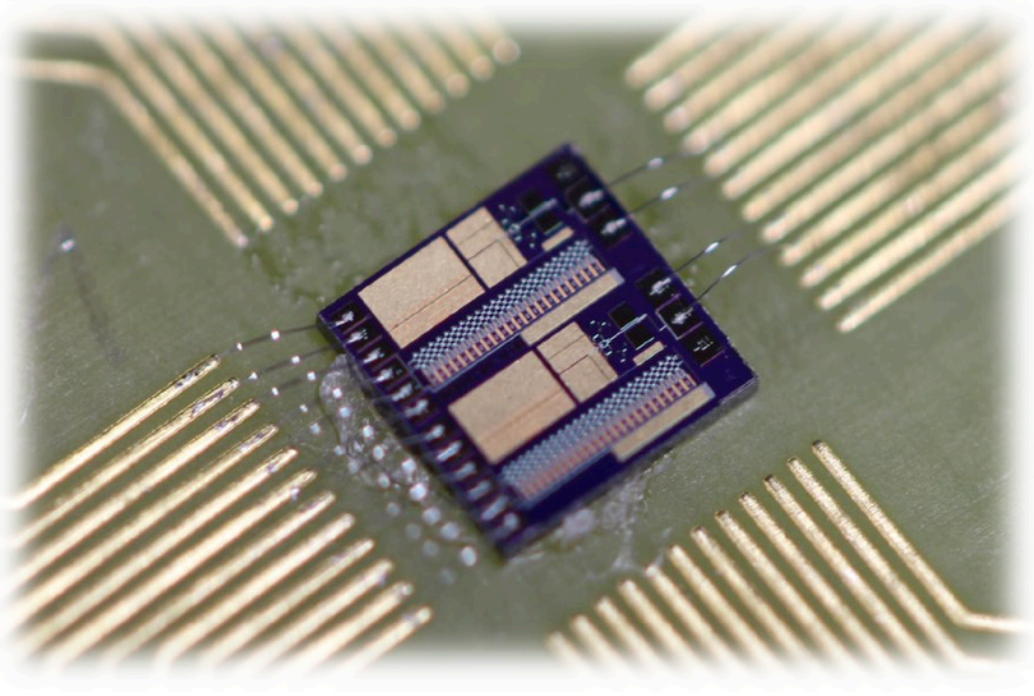
MMC production at CUP & University of Heidelberg



SQUID production at PTB & University of Heidelberg

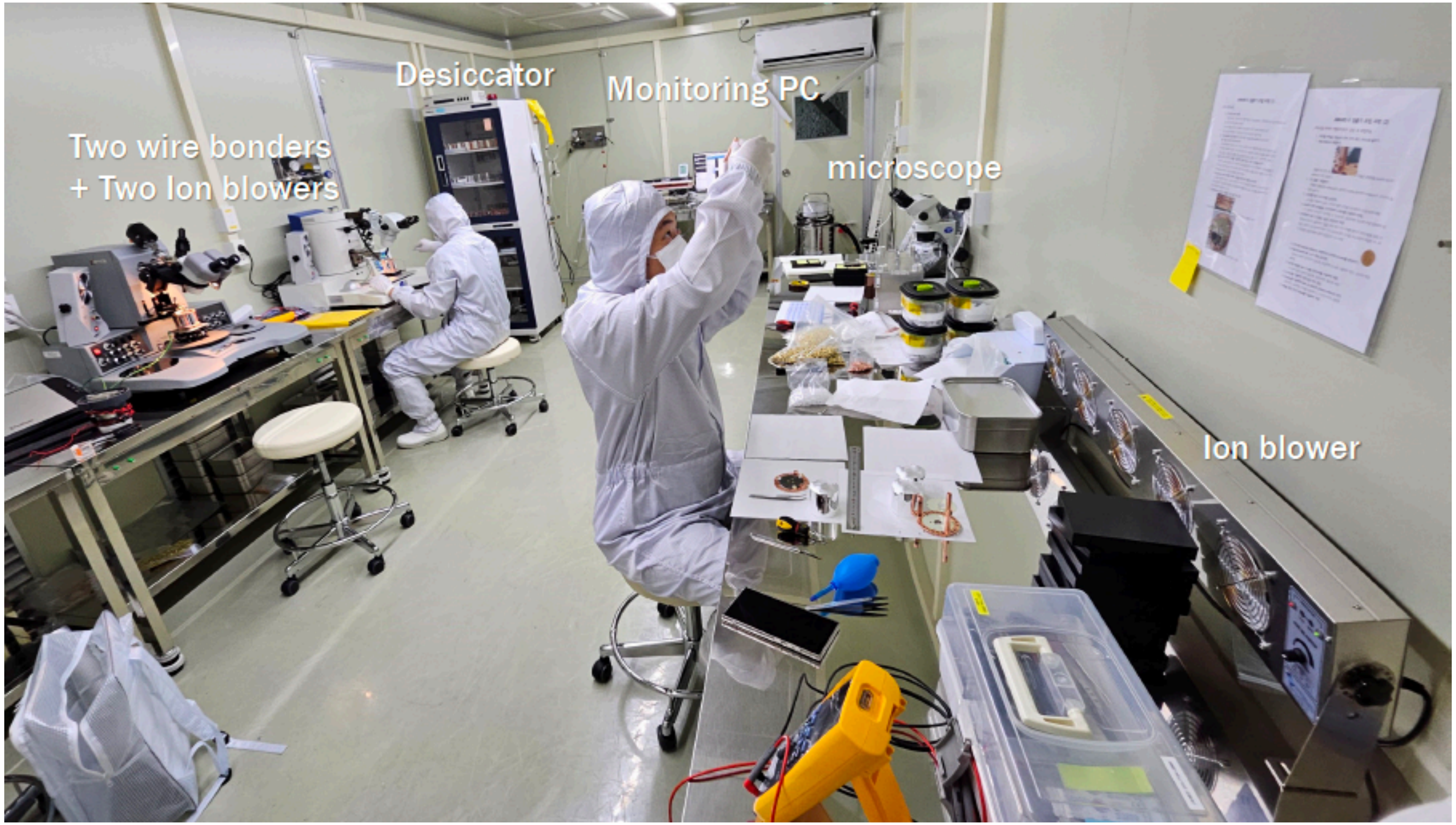






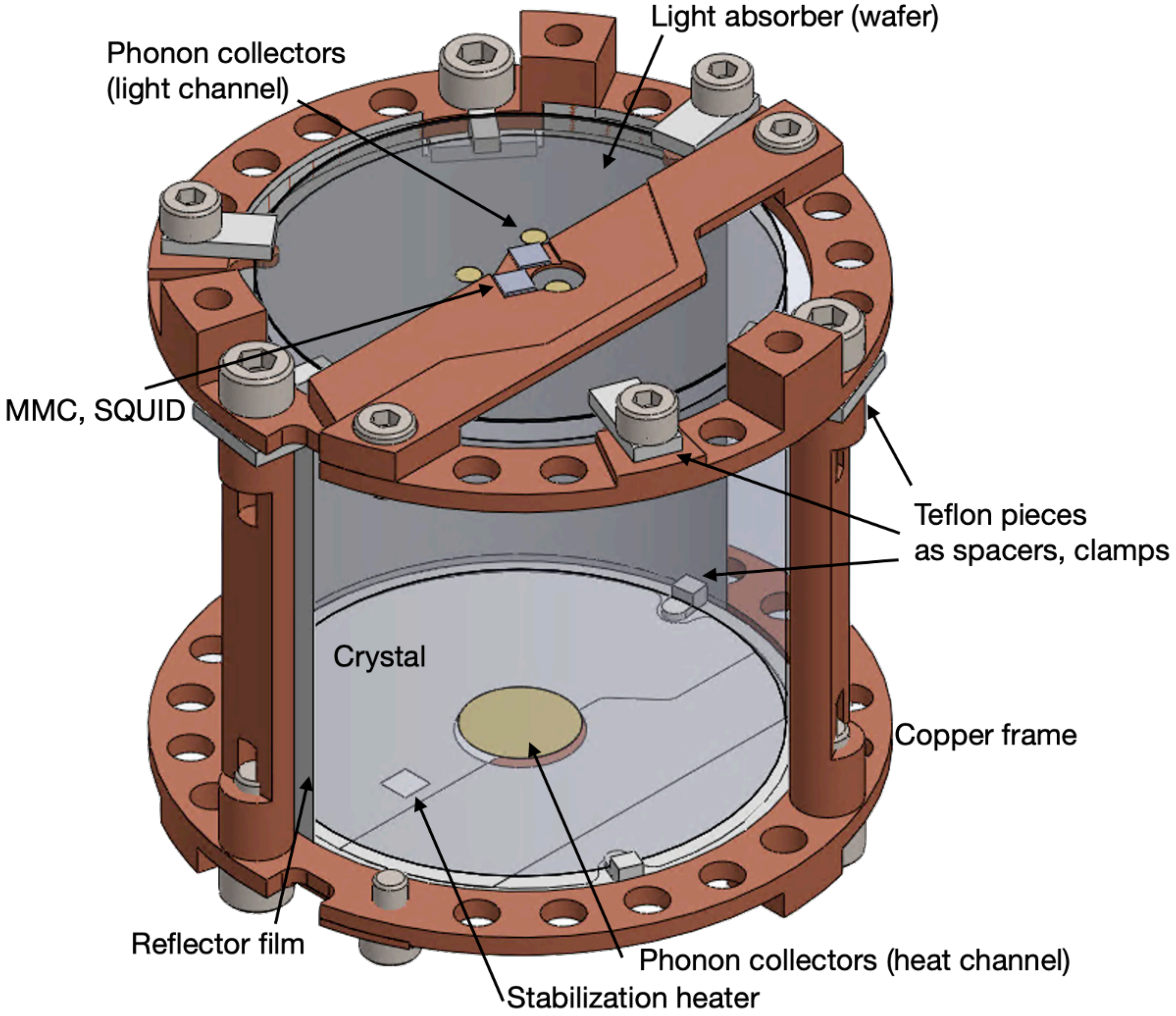
Two stage DC SQUID

Detector module assembly in clean room



Humidity: < 1000 ppm water contents
Rn level: < 0.1Bq/m^3
Dust level: class 100

AMoRE-II detector



Massive crystals:
300 g & 520 g

Very hygroscopic crystal:
handling at < 10% RH at RT

Diffusive surfaces

Phonon collector:
gold w/ Mo adhesion

Ag:Er MMC + 2-stage SQUID

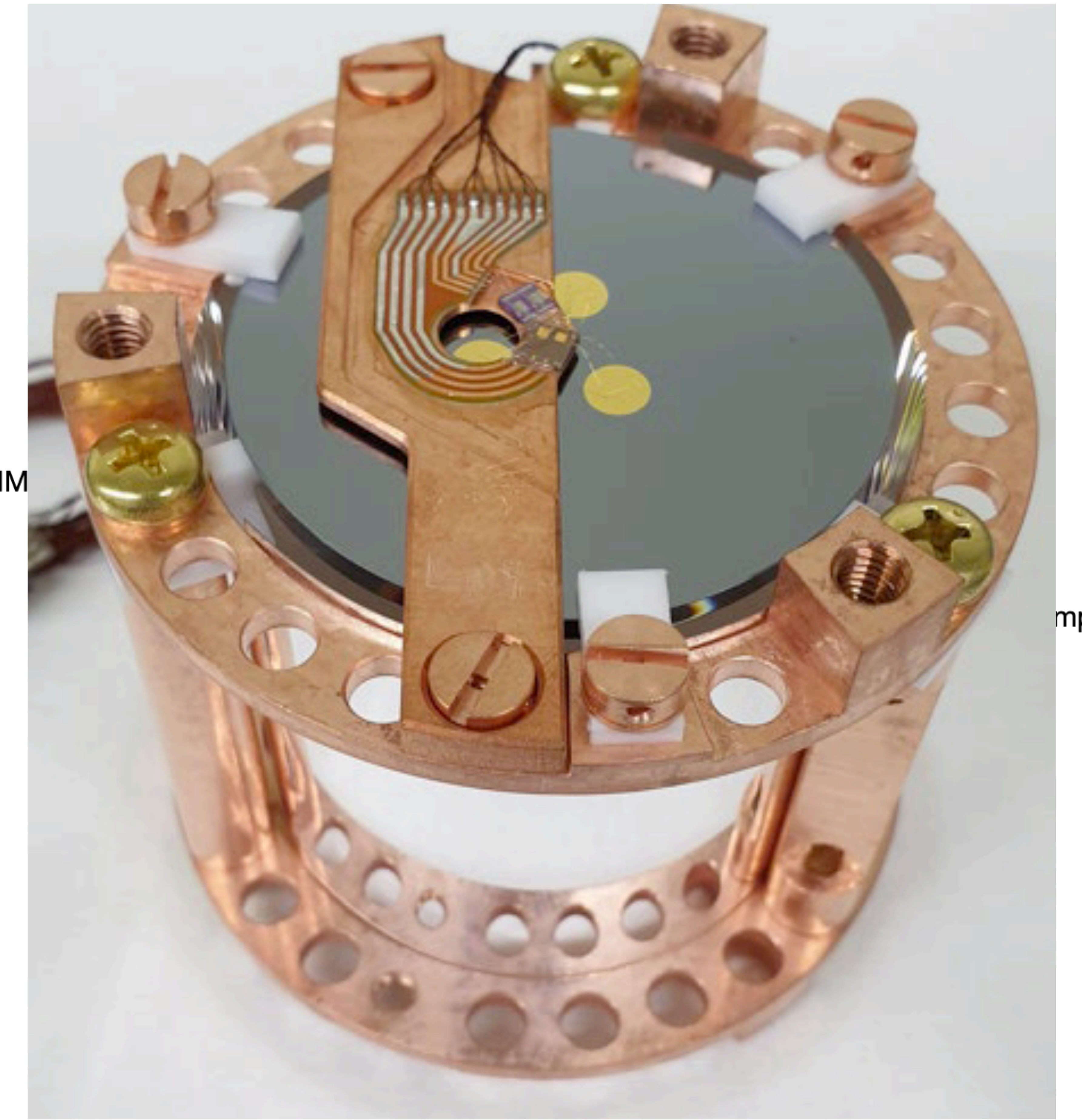
Non-thermal link (optional)

Si-wafer light detector

Si-wafer tightly secured:
vibrationless
closer to the crystal

Efficient stacking

AMoRE-II detector



MM

mps

Massive crystals:
300 g & 520 g

Very hygroscopic crystal:
handling at < 10% RH at RT

Diffusive surfaces

Phonon collector:
gold w/ Mo adhesion

Ag:Er MMC + 2-stage SQUID

Non-thermal link (optional)

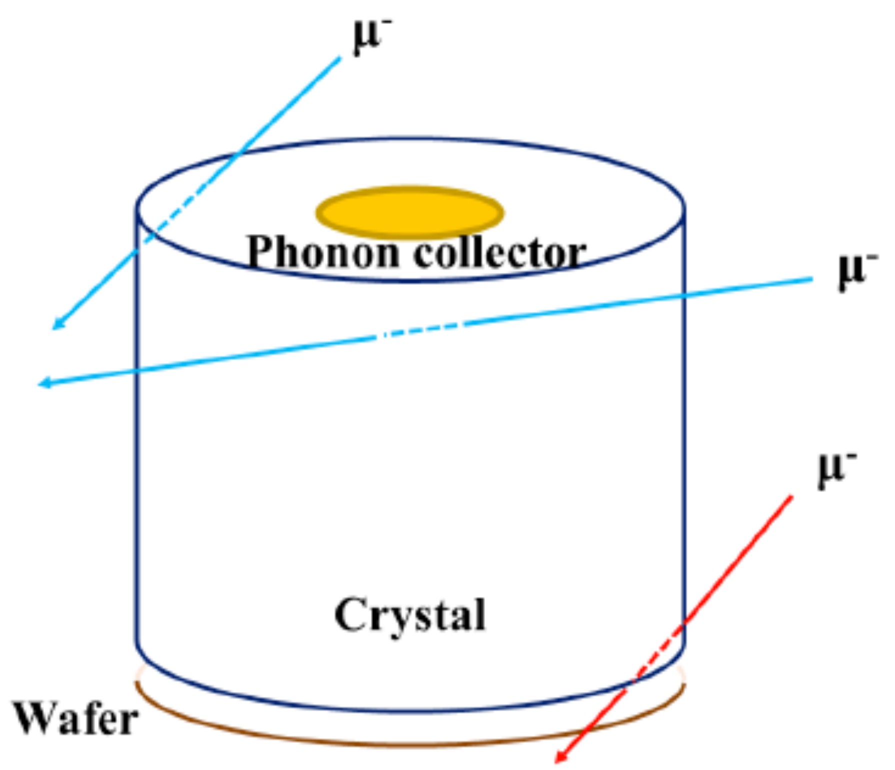
Si-wafer light detector

Si-wafer tightly secured:
vibrationless
closer to the crystal

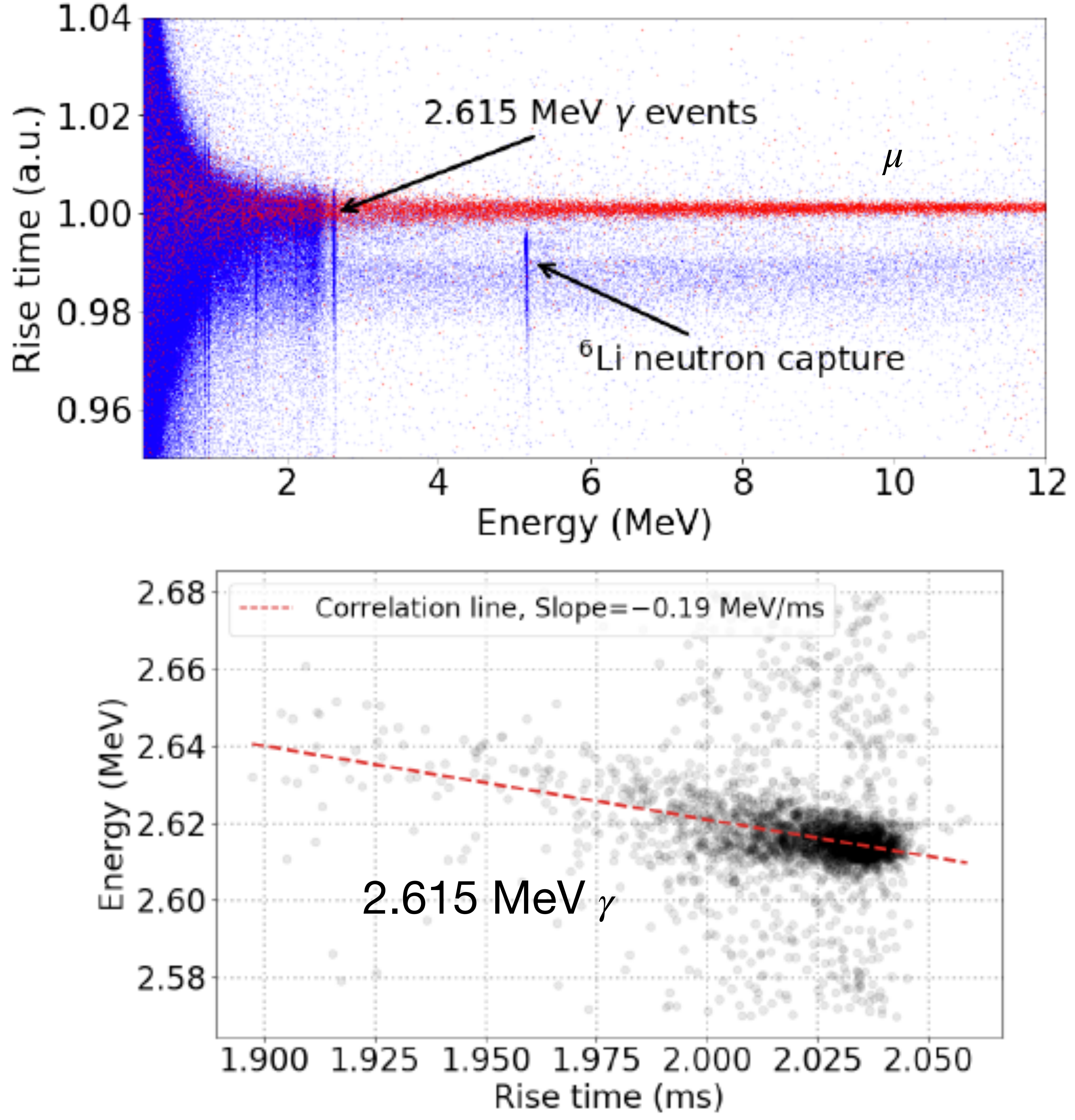
Efficient stacking

AMoRE-II detector

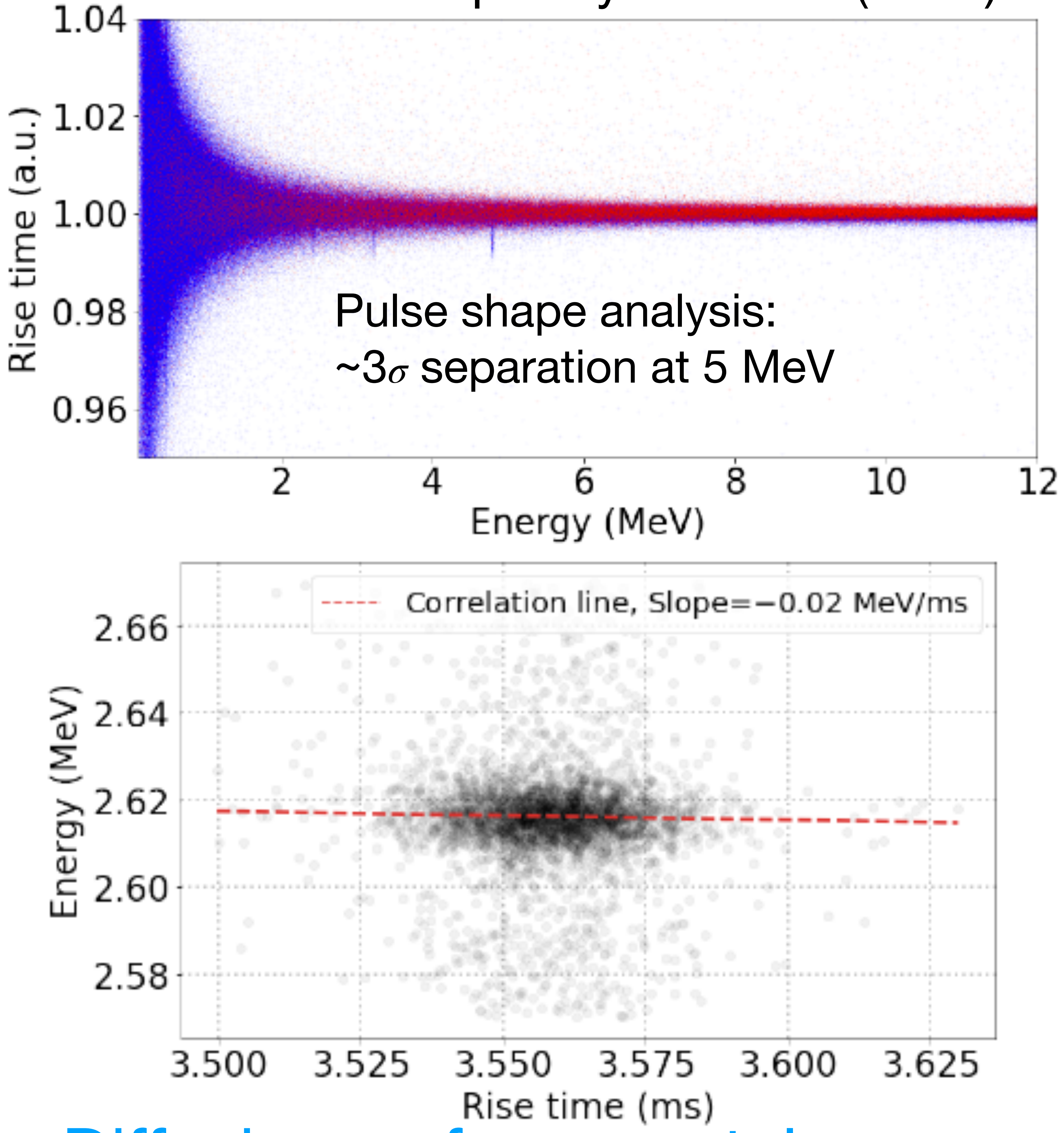
Crystals with diffusive surface:
Slower response, but more consistent behavior
better energy resolution
Demonstrated up to 6 cm x 6 cm, even larger crystals feasible



J. Low Temp. Phys. 218:83 (2024)



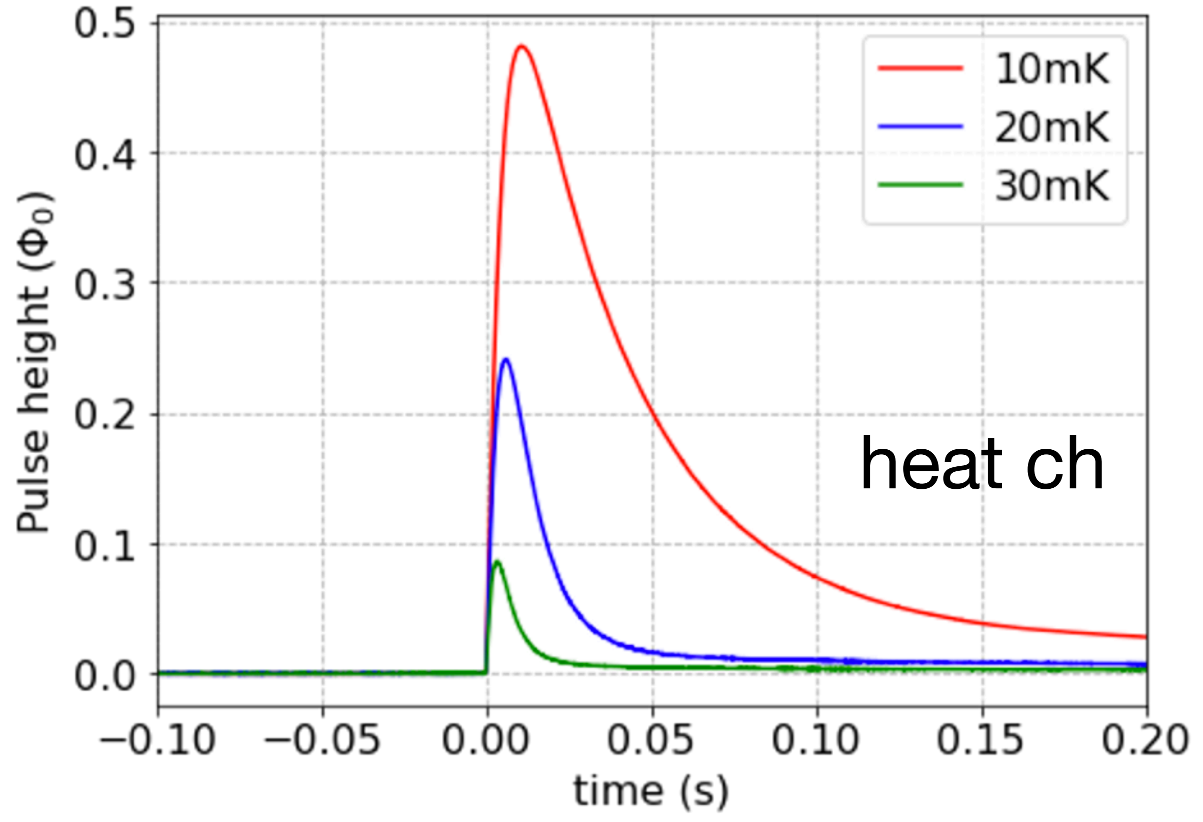
Polished crystal

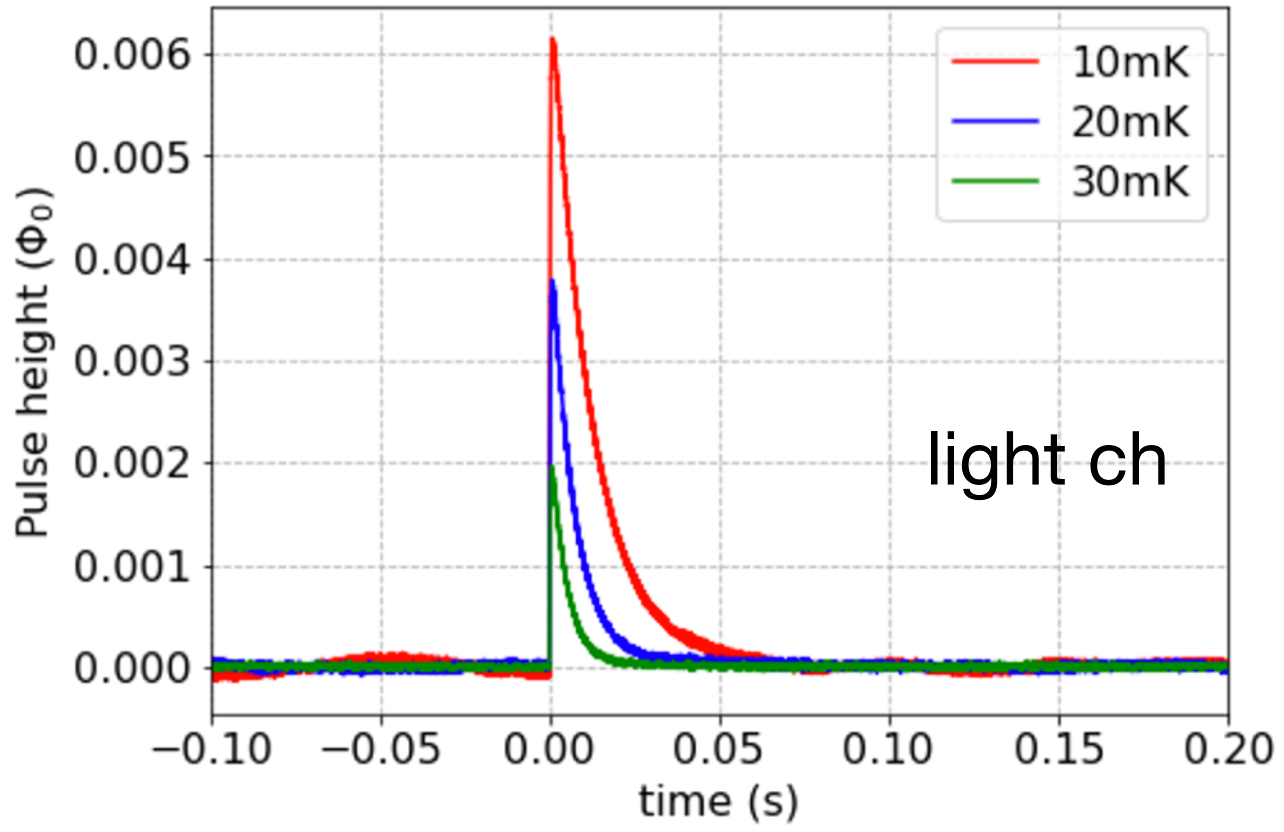


Diffusive surface crystal

AMoRE-II detector

R&D detector performance





At 10 mK,

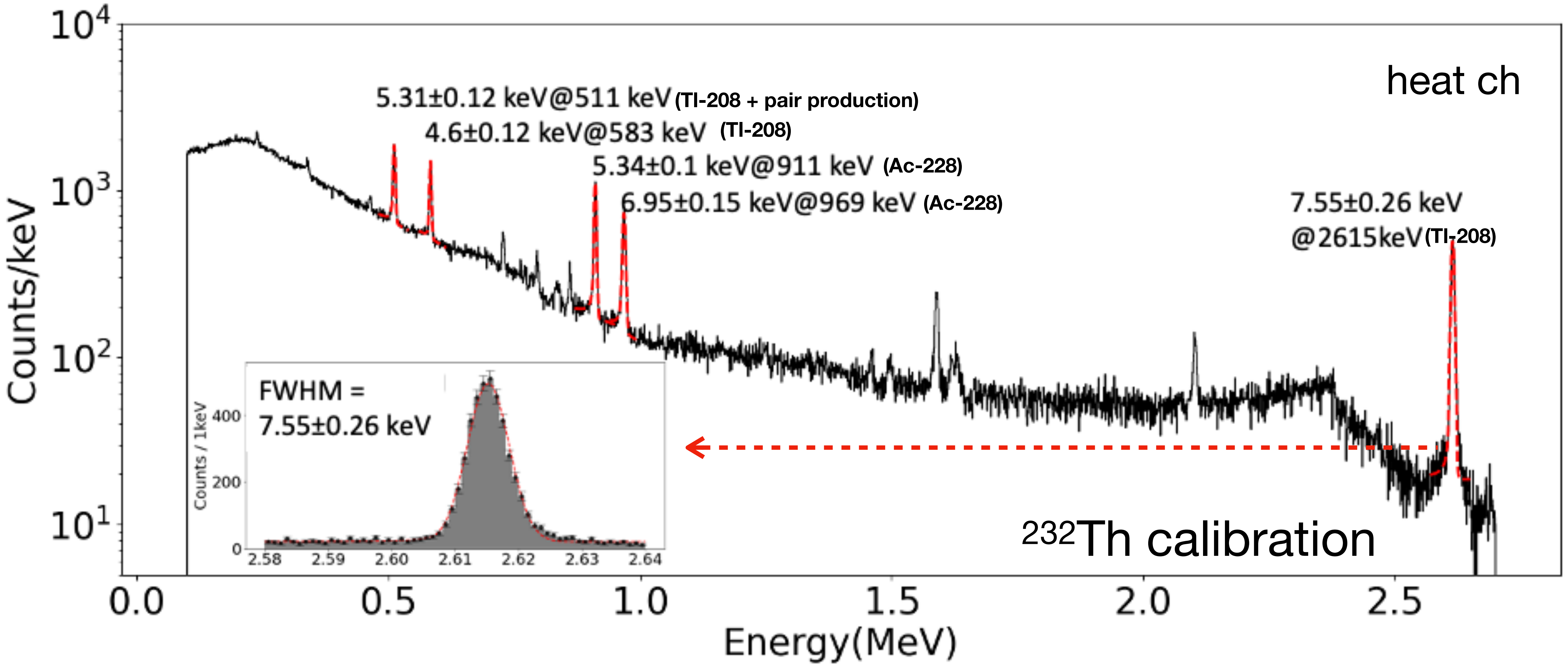
Heat channel: RT = 2 - 5 ms, FWHM@2.6 MeV = 7.6 keV

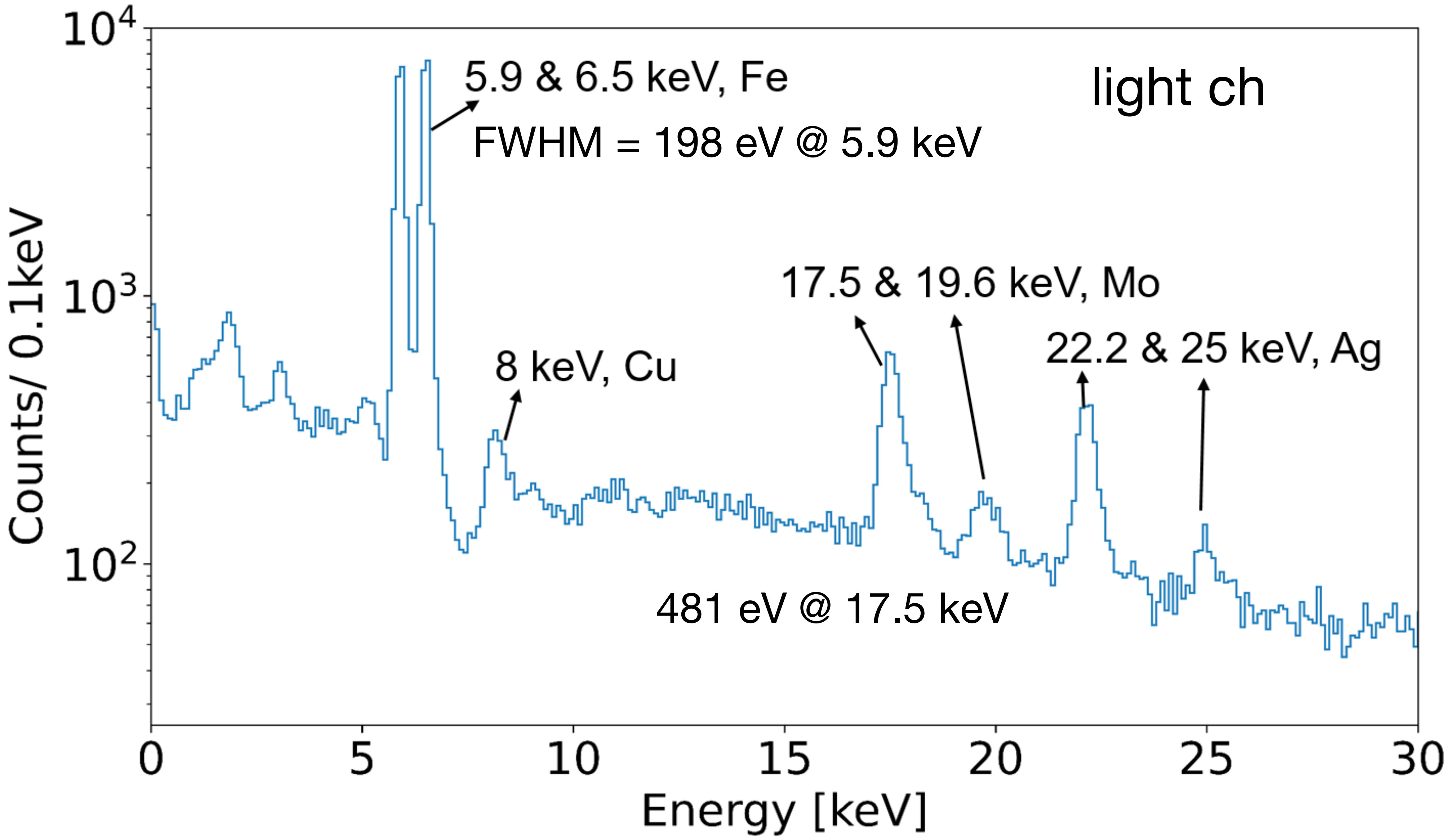
Light channel: RT = 370 - 460 μs,

FWHM@baseline, 5.9 keV = 99, 198 eV

Fast timing useful for pile-up rejection with larger crystal

Good performance in 10 - 30 mK



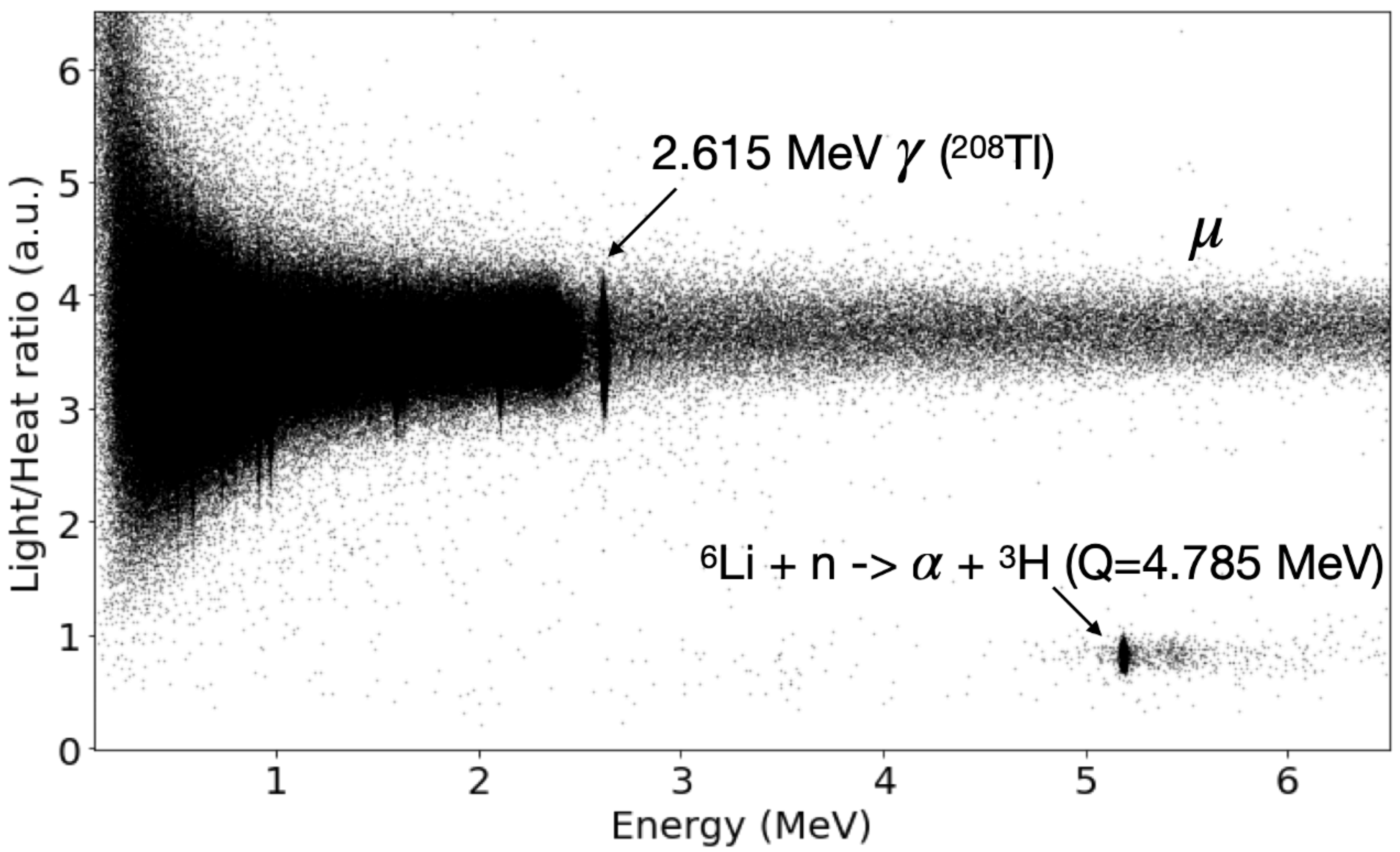


Eur. Phys. J. C. 85:172 (2025)

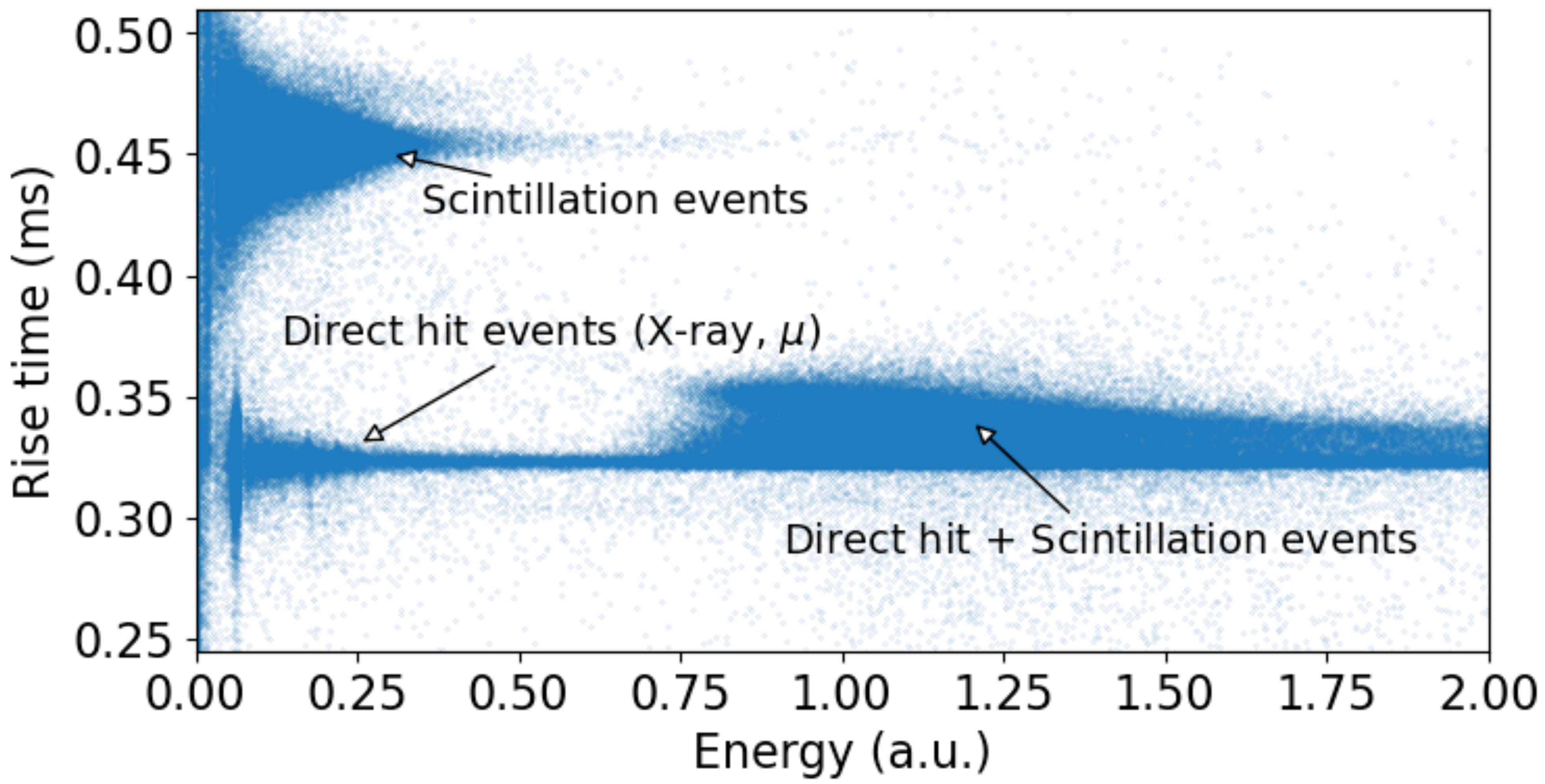
AMoRE-II detector

Particle identification

Crystal absorber



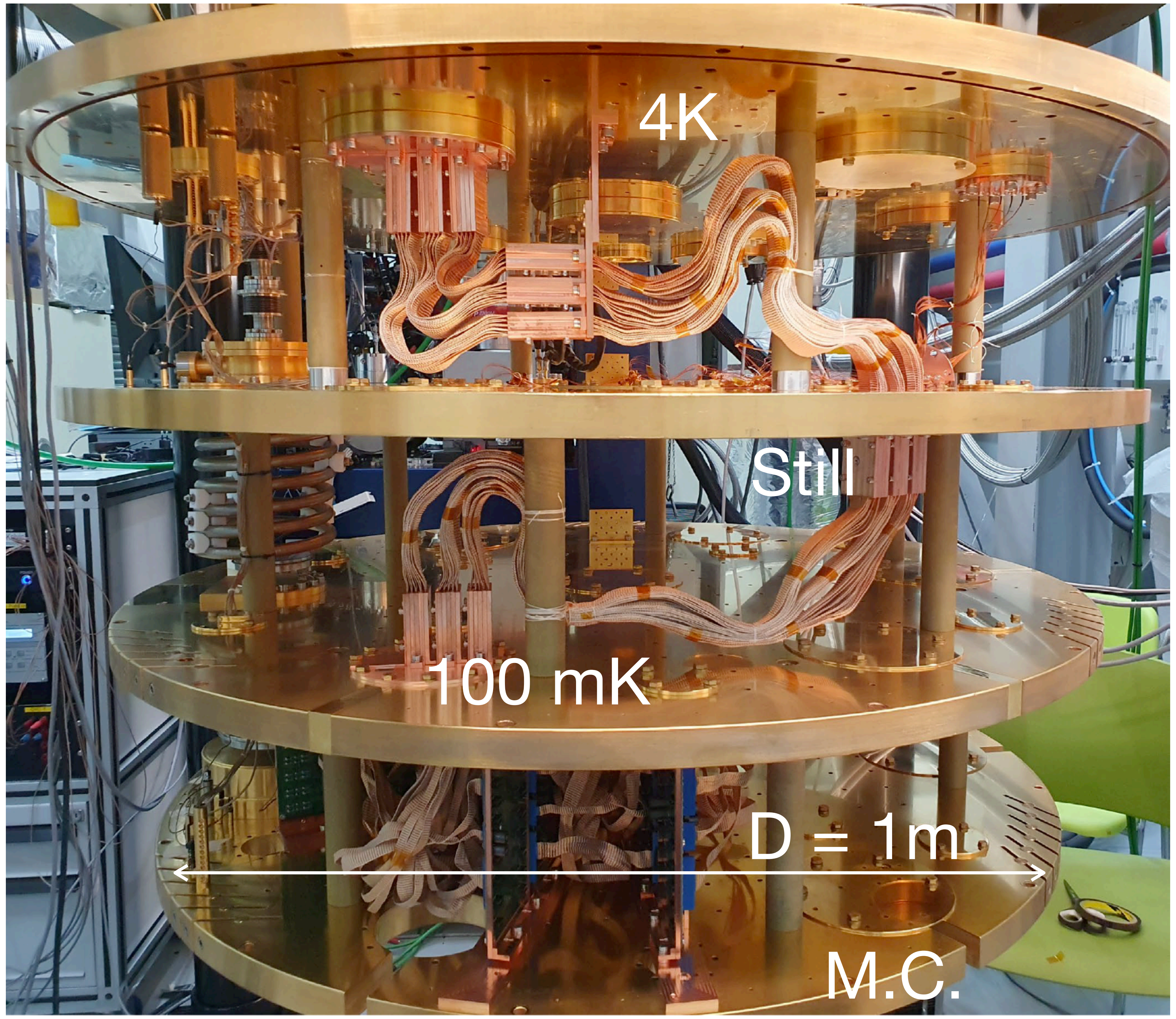
Light absorber (Si)

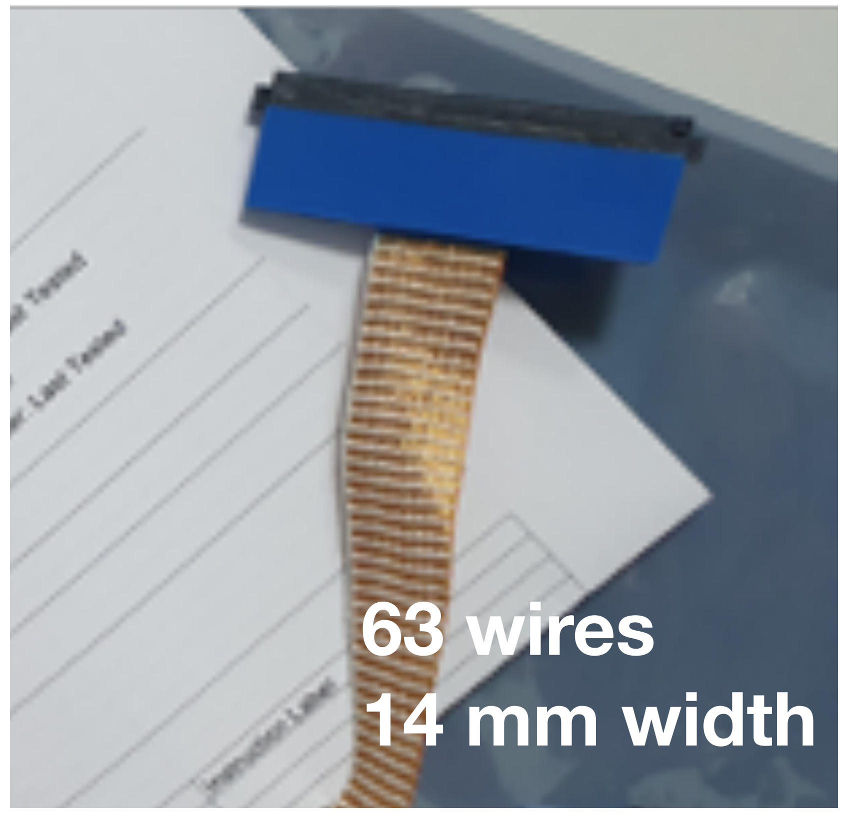


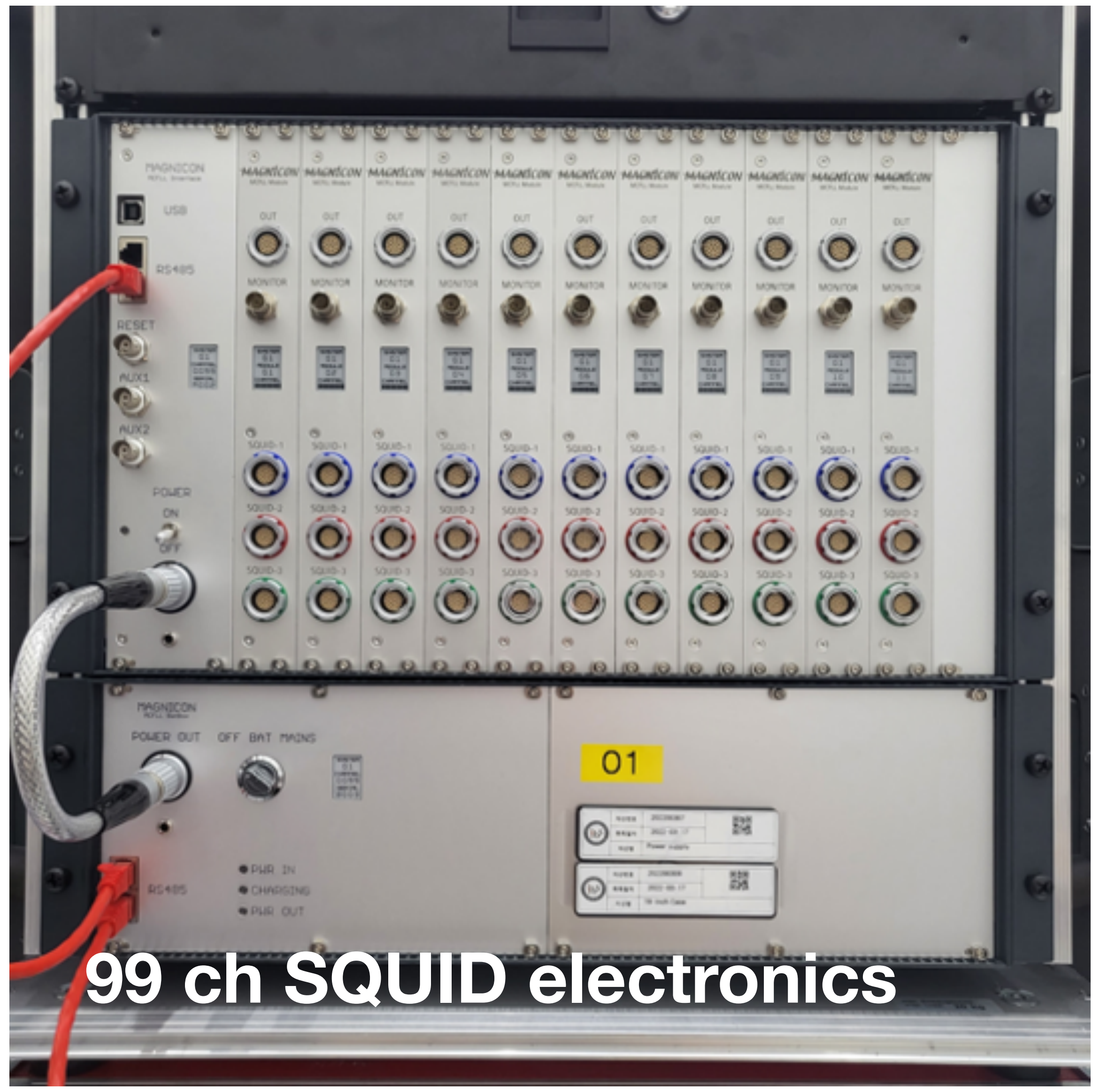
Scinitllation collection = 0.79 - 0.96 keV/MeV
α quenching in scintillation signal ~ 0.25
Clear rejection of α background in the ROI (E = 3.034 MeV)

Overall, promising detector performance for AMoRE-II !!!

AMoRE-II cryostat

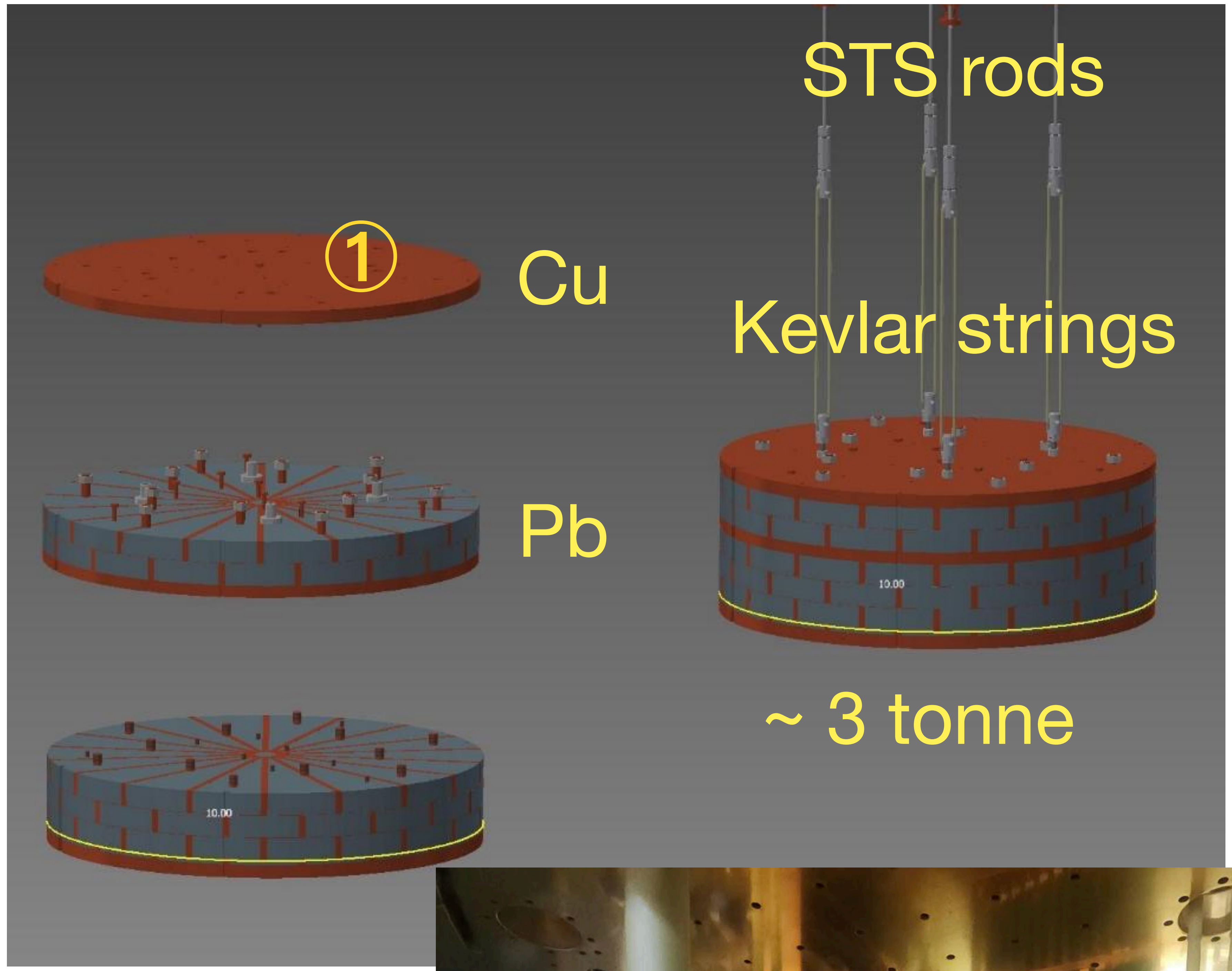


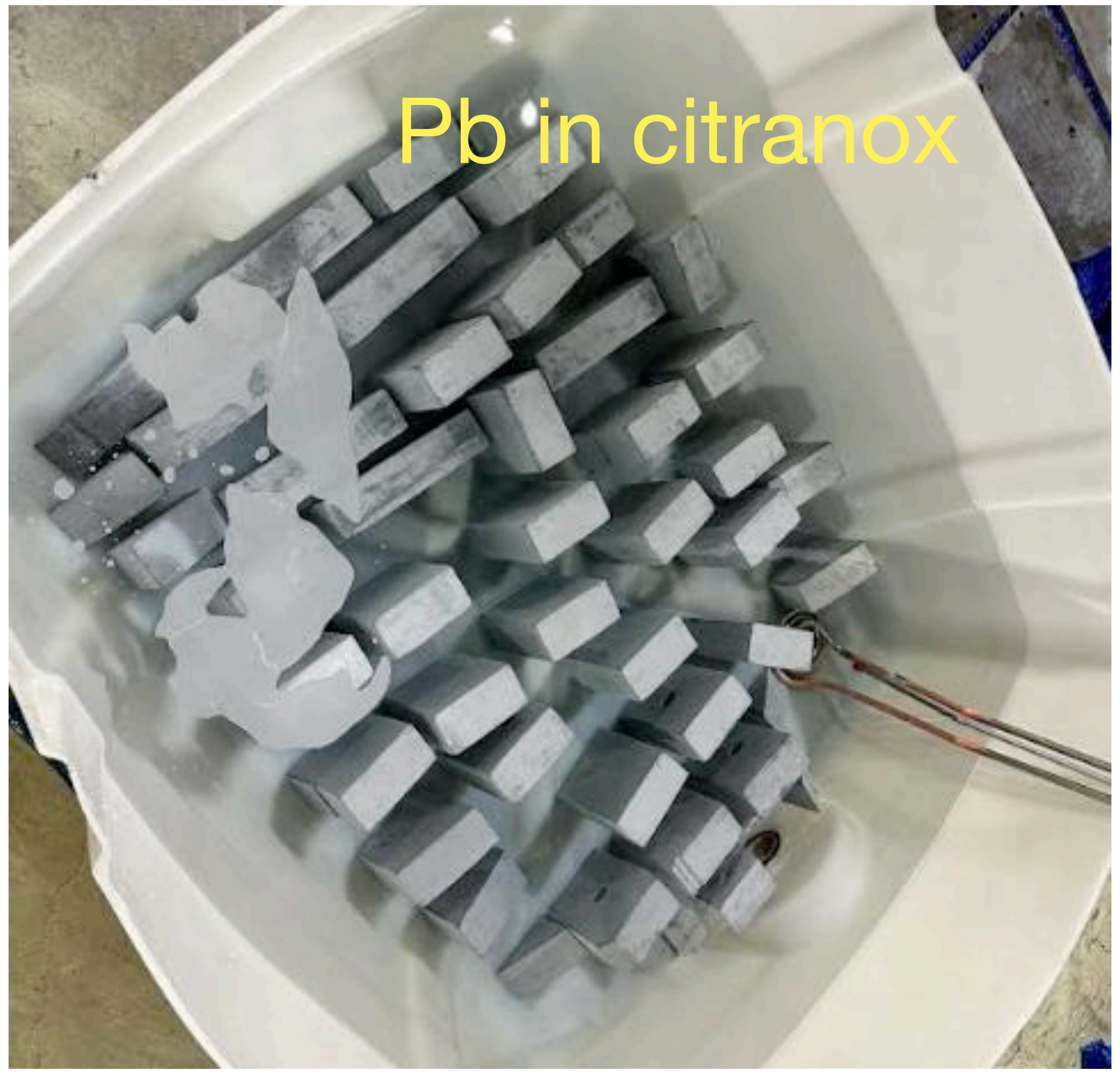


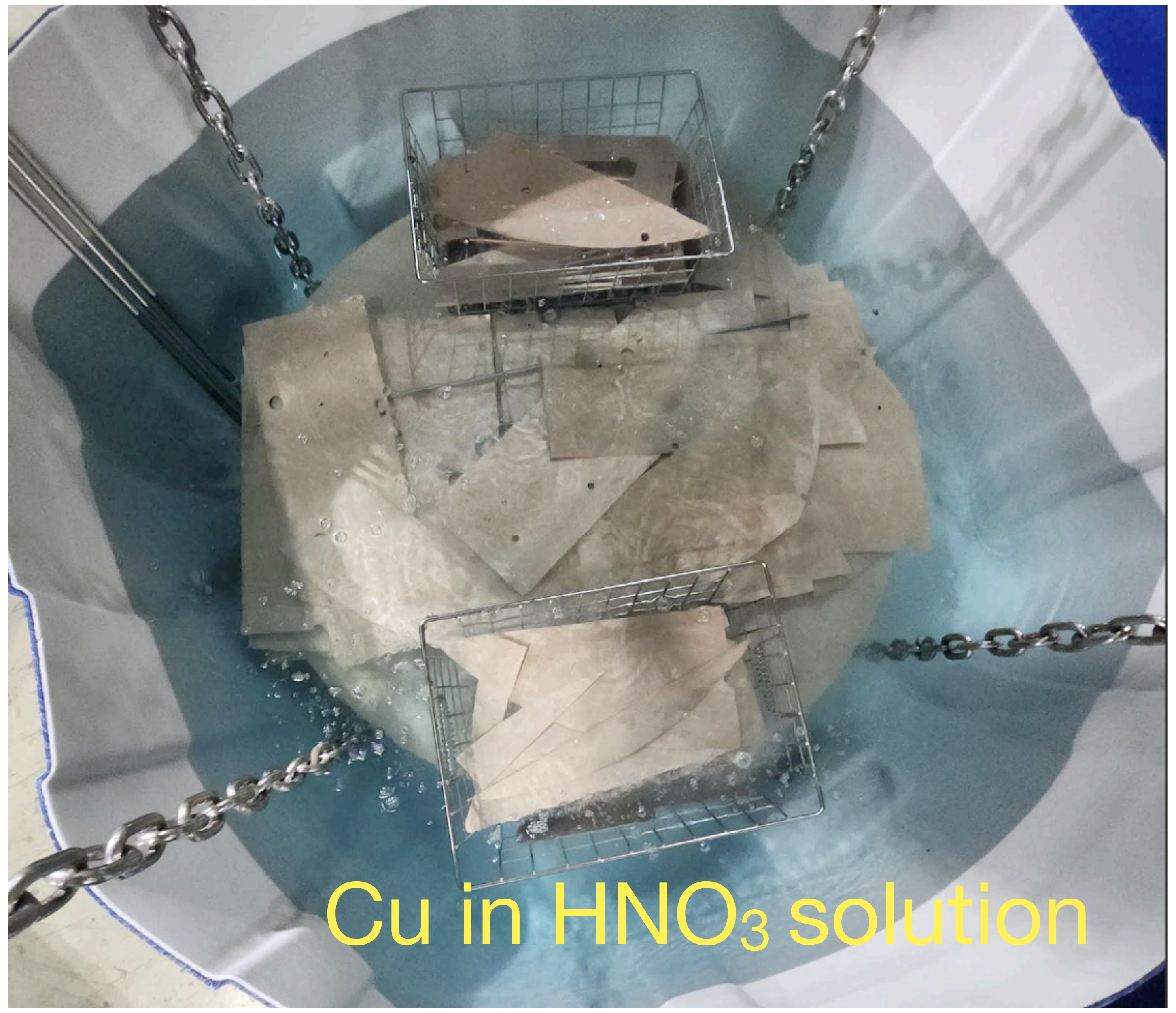


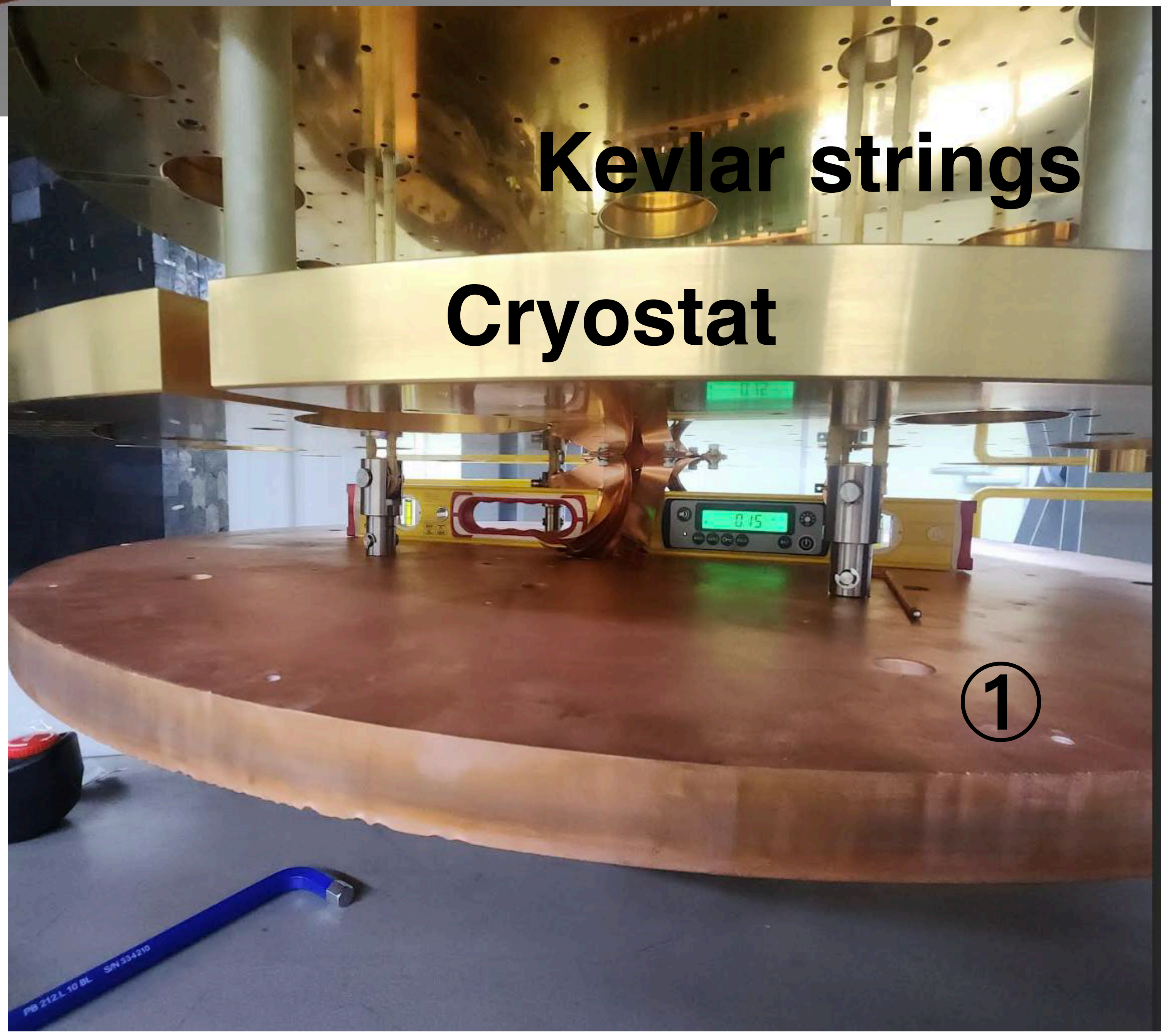
- Large cryogen-free dilution refrigerator with 3 pulse tube refrigerators, cooling power > 5μW@ 10 mK
- Cabling: ~ 8000 wires (~3000 wires installed for stage 1)
  CuNi alloy30 (D=160μm) with NOMAX wire between top plate & MC
- 6.9 mK base temperature reached after 1st stage wiring installation
- Compact SQUID electronics (Magnicon) for large number of SQUID channels
- Accommodating 3.3 tons of setup : detector array + lead shield

Preparation of innermost shielding part



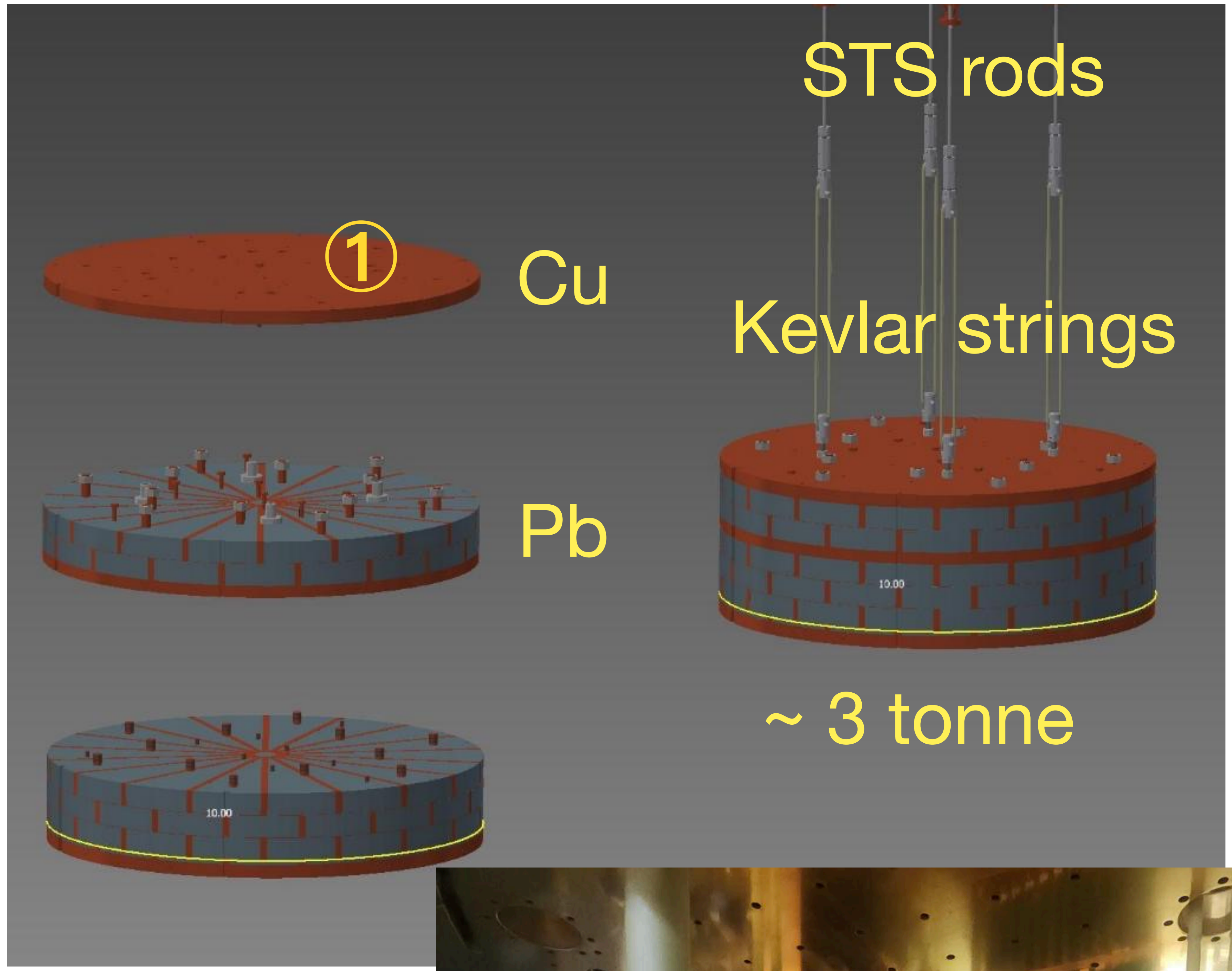


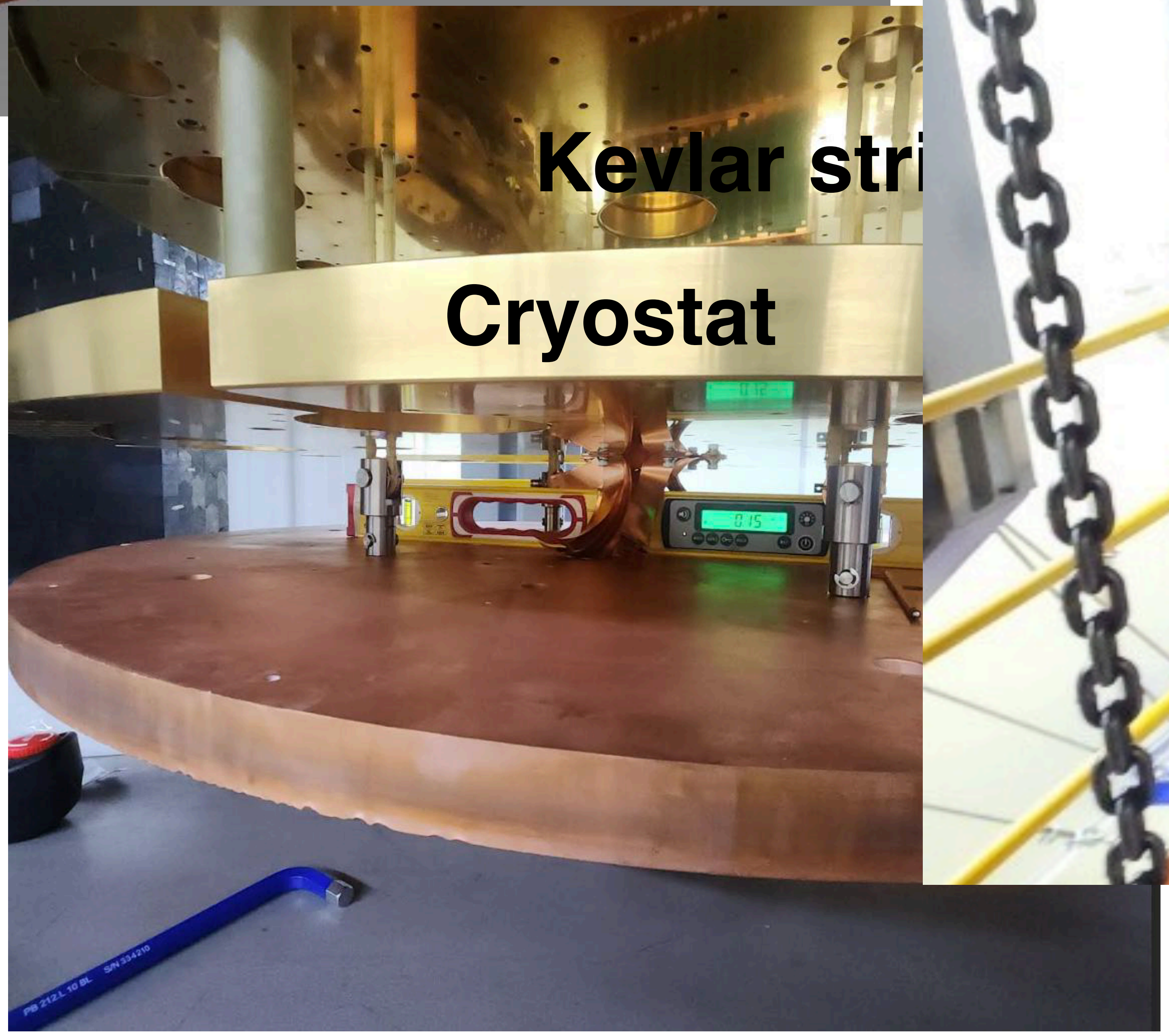




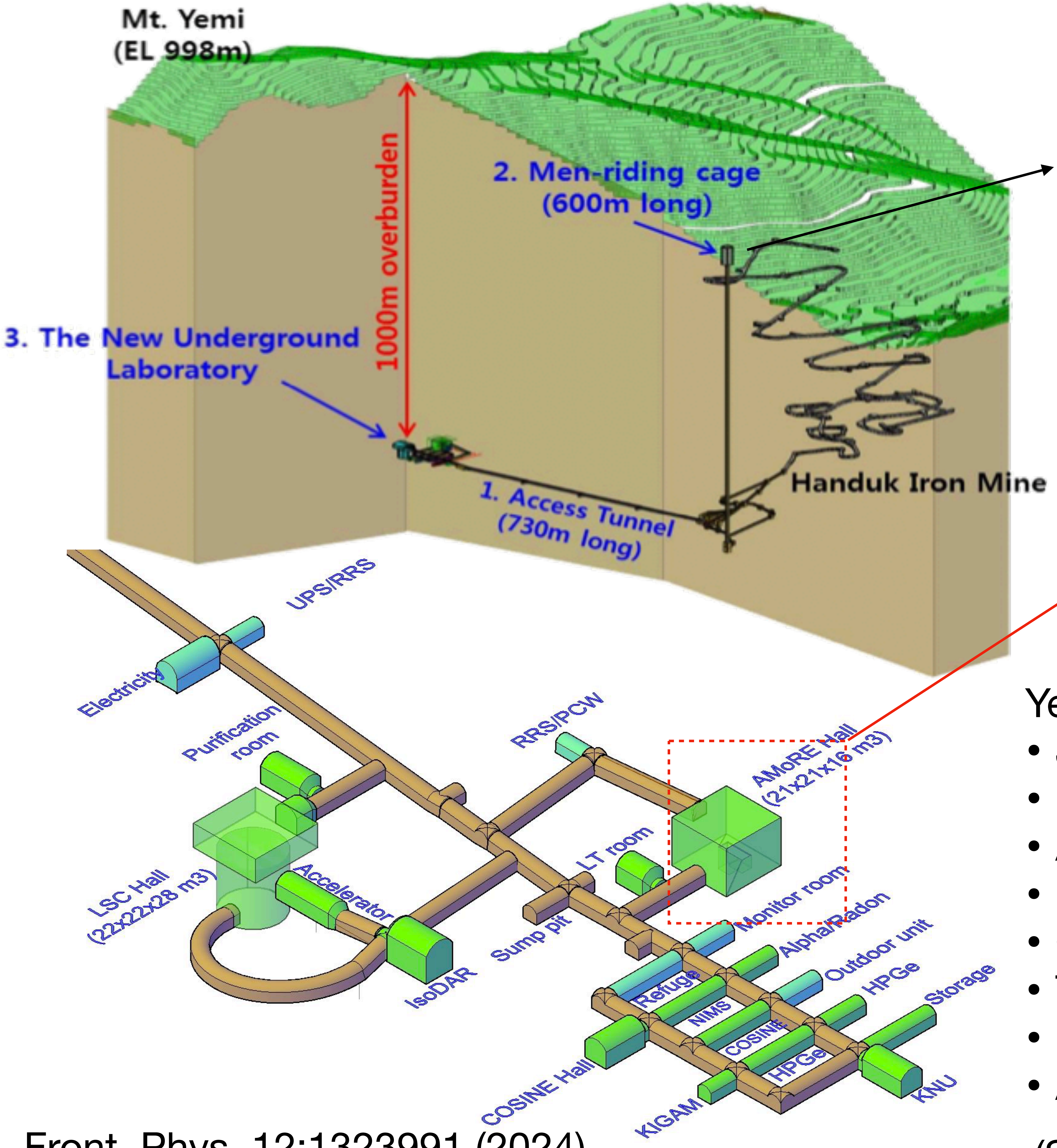
Cu, Pb cleaning:
Degreasing (Kerosene/IPA/Citranox)
Surface etching (Nitric acid)
Passivation (Oxalic acid)

Preparation of innermost shielding part





AMoRE experiment in Yemilab



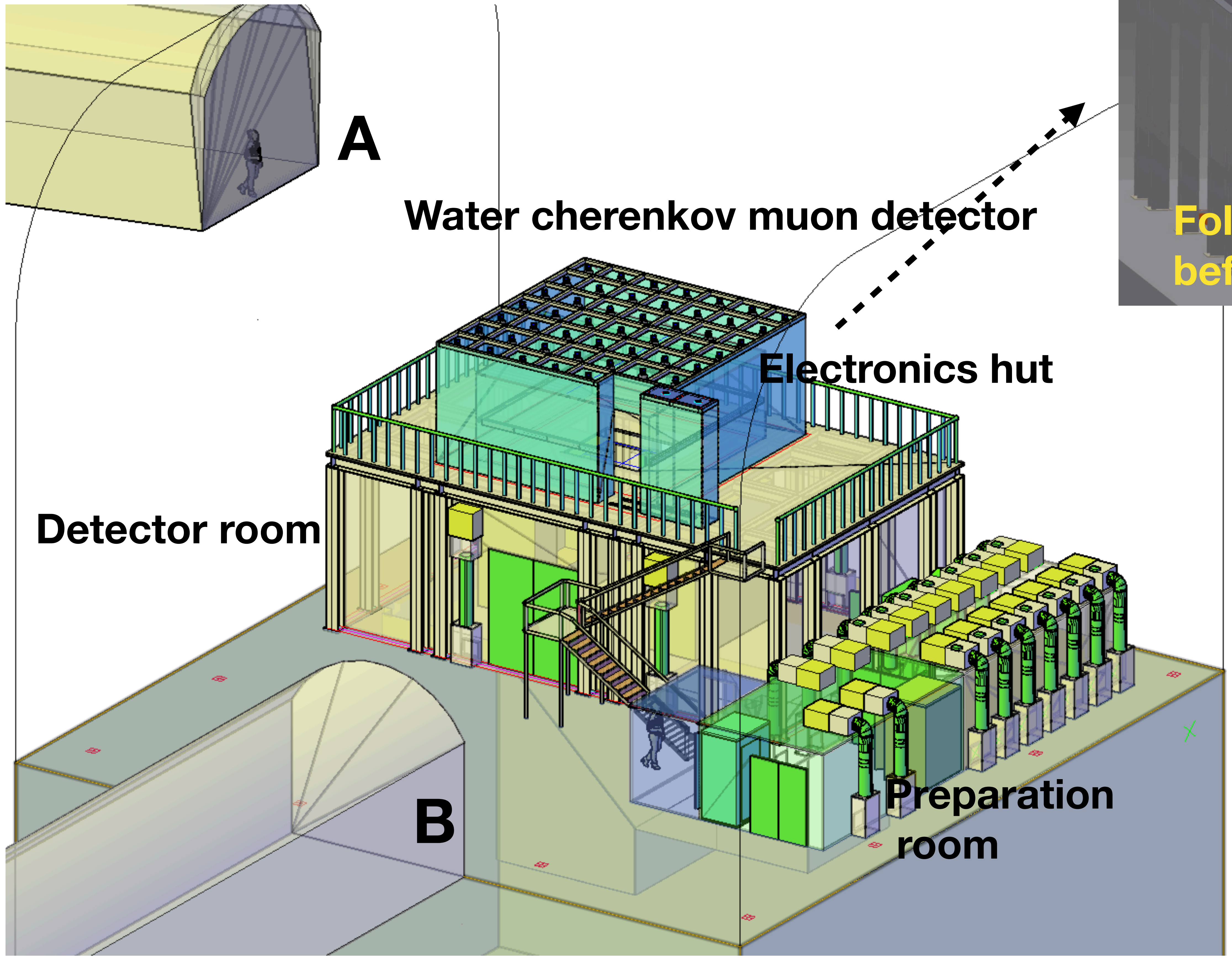
Front. Phys. 12:1323991 (2024)

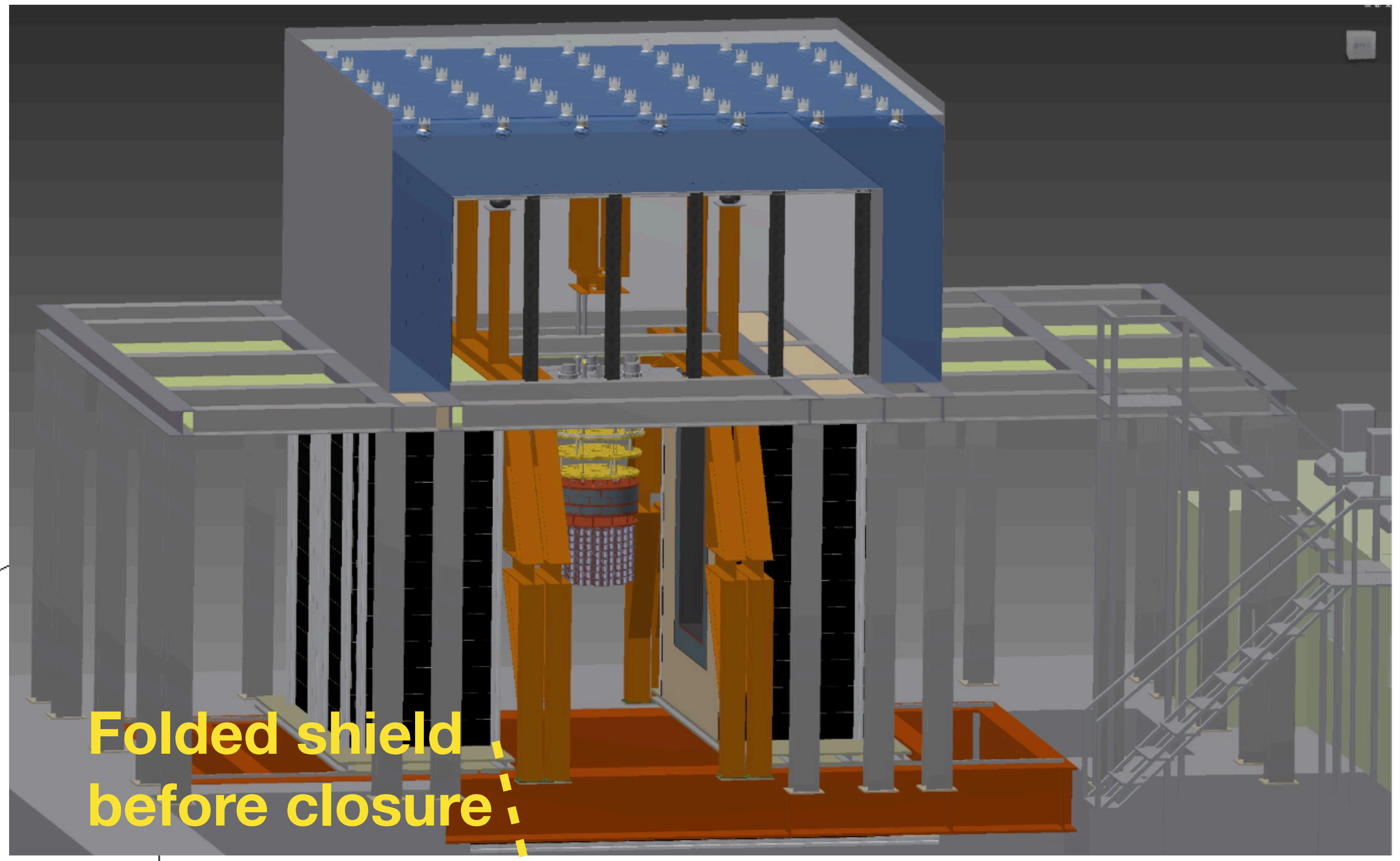
Yemilab:

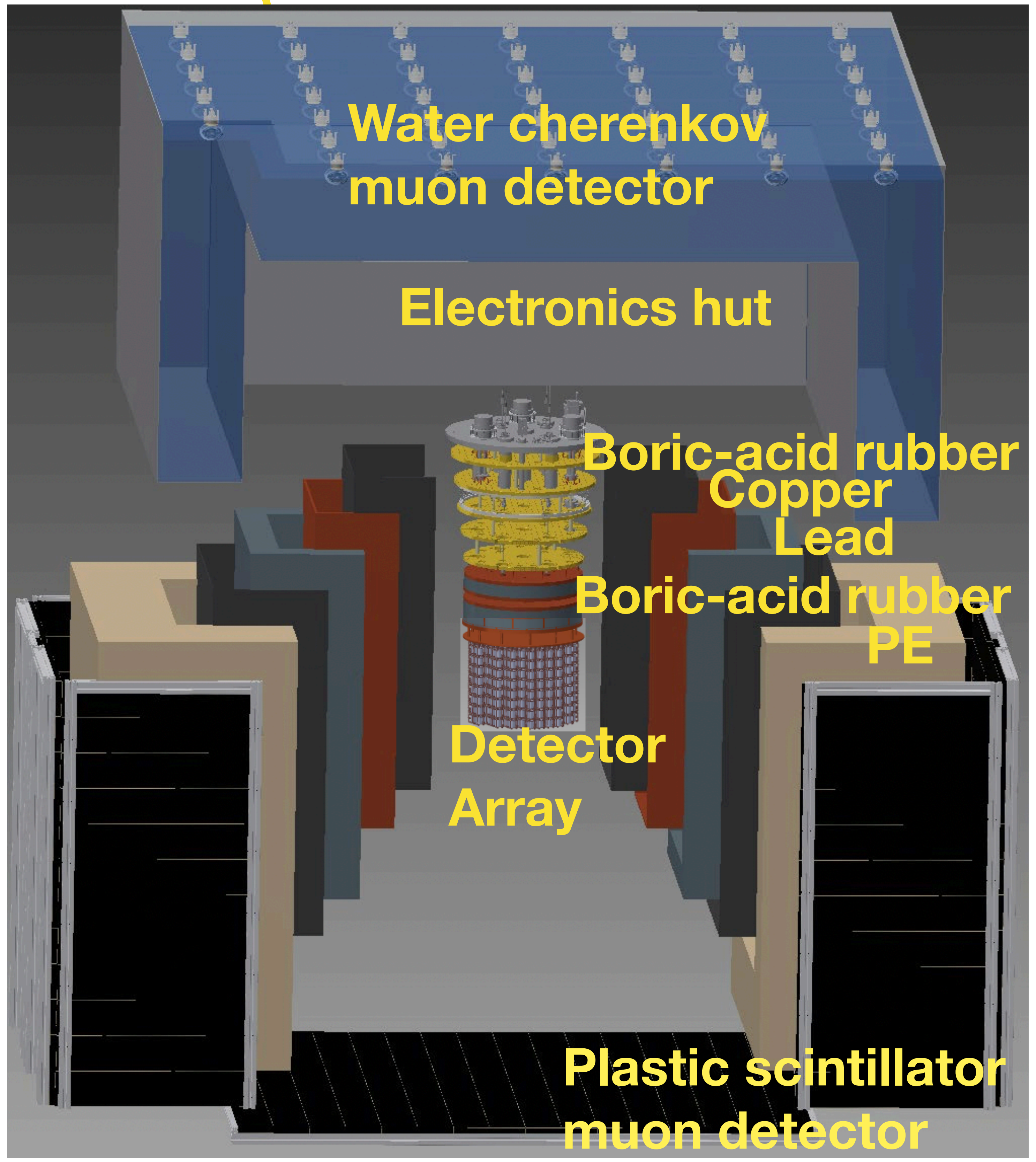
- Jeongseon, South Korea
- 1000 m vertical depth
- Access via elevator & ramp way
- Underground lab for basic sciences
- Opened in Oct, 2022
- Total Area: 3,000 m^2
- Large area & sufficient utilities
- AMoRE-II, COSINE, LSC, Radioassay …

(See Jungho So's talk)

AMoRE Hall in Yemilab







Radon reduction system:
Rn-less (~10Bq/m^3) / Rn-free (< 0.1Bq/m^3) air

Clean room:
Class 100 for Detector & Preparation room

Recent view of AMoRE Hall

Recent view of AMoRE Hall


Recent view of AMoRE Hall
Shield +
Vinyl tent (Rn-free air)

Recent view of AMoRE Hall


Recent view of AMoRE Hall
Room for SQUID electronics,
DAQ, Calibration system
주의

Muon veto detectors in commissioning

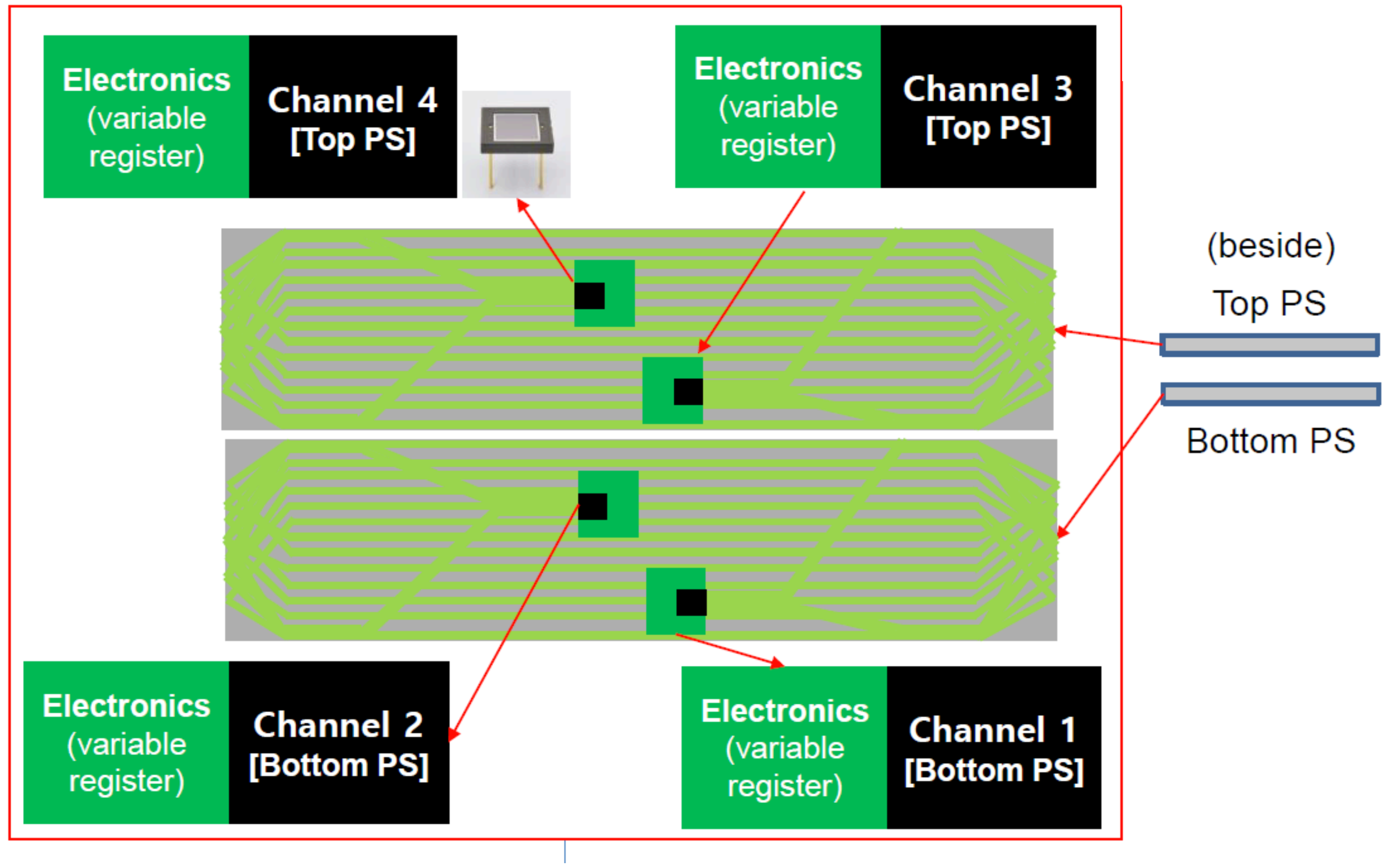
Water Cherenkov muon detector

~60 ton of DI water including water door (electronics hut)
Tyvek reflector inner surface
Instrumented with 48 x PMTs (8 & 10 inch)
Efficient neutron shield

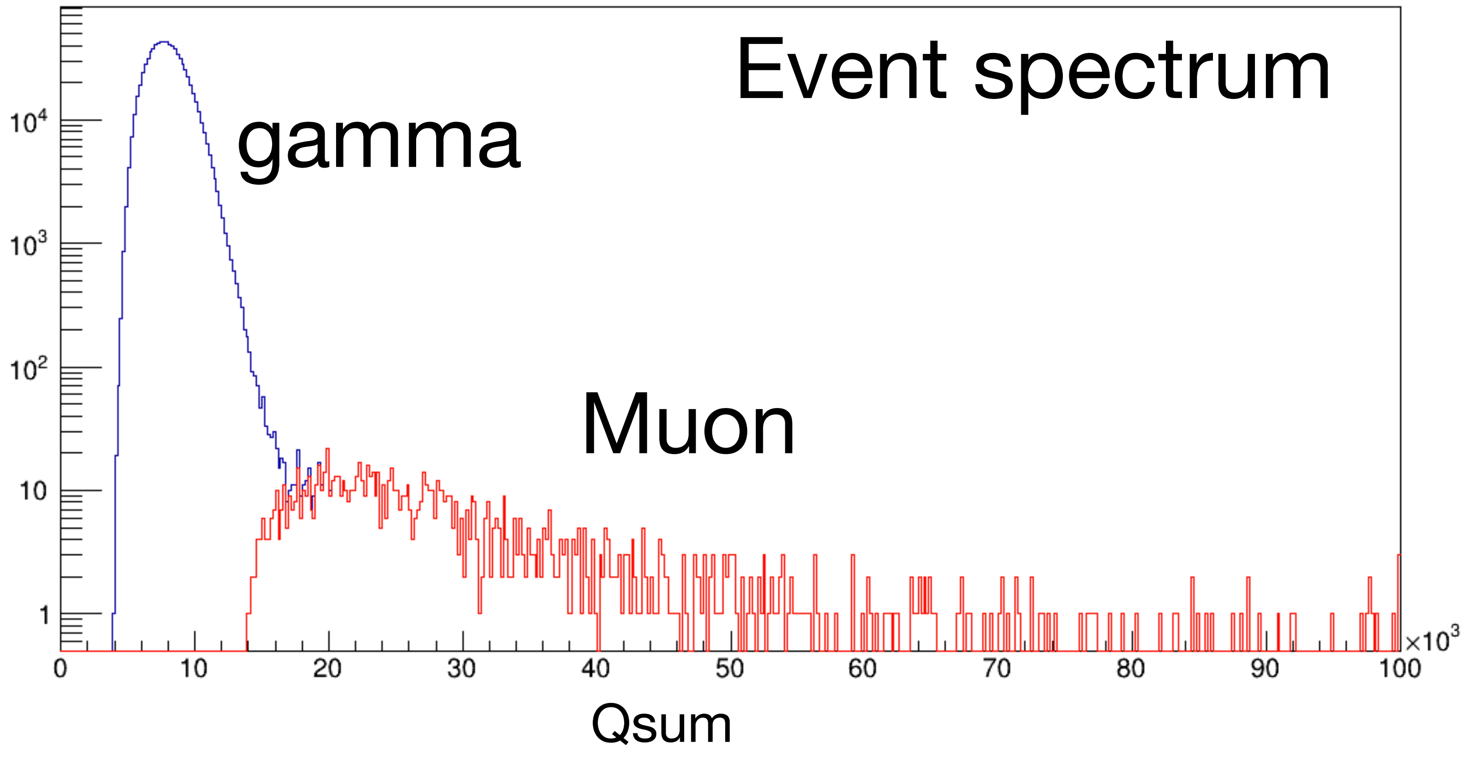
Trigger with 10 PMTs multiplicity:
9.2×10^{-8} muons/cm^2/sec
(79 muons/m^2/day)

Muon veto detectors in commissioning

Plastic scintillator muon detector



Total 130 PSMDs

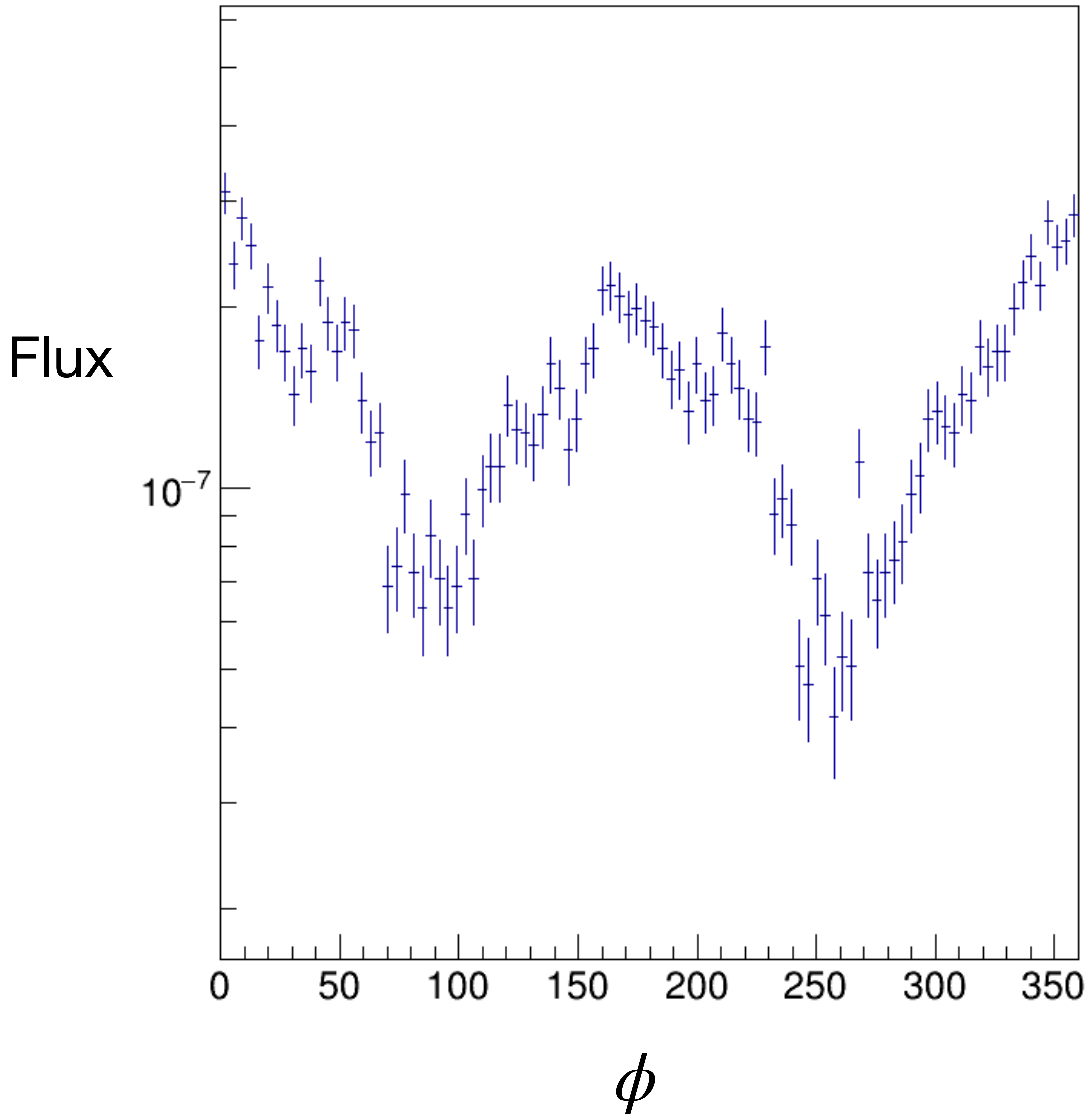


One PSMD:
2 extruded plastic scintillator panels
(30 x 167 x 1.5 cm^3)
+ 32 wavelength-shifting fiber
+ 4 SiPMs, NIMA 1039 167123 (2022)

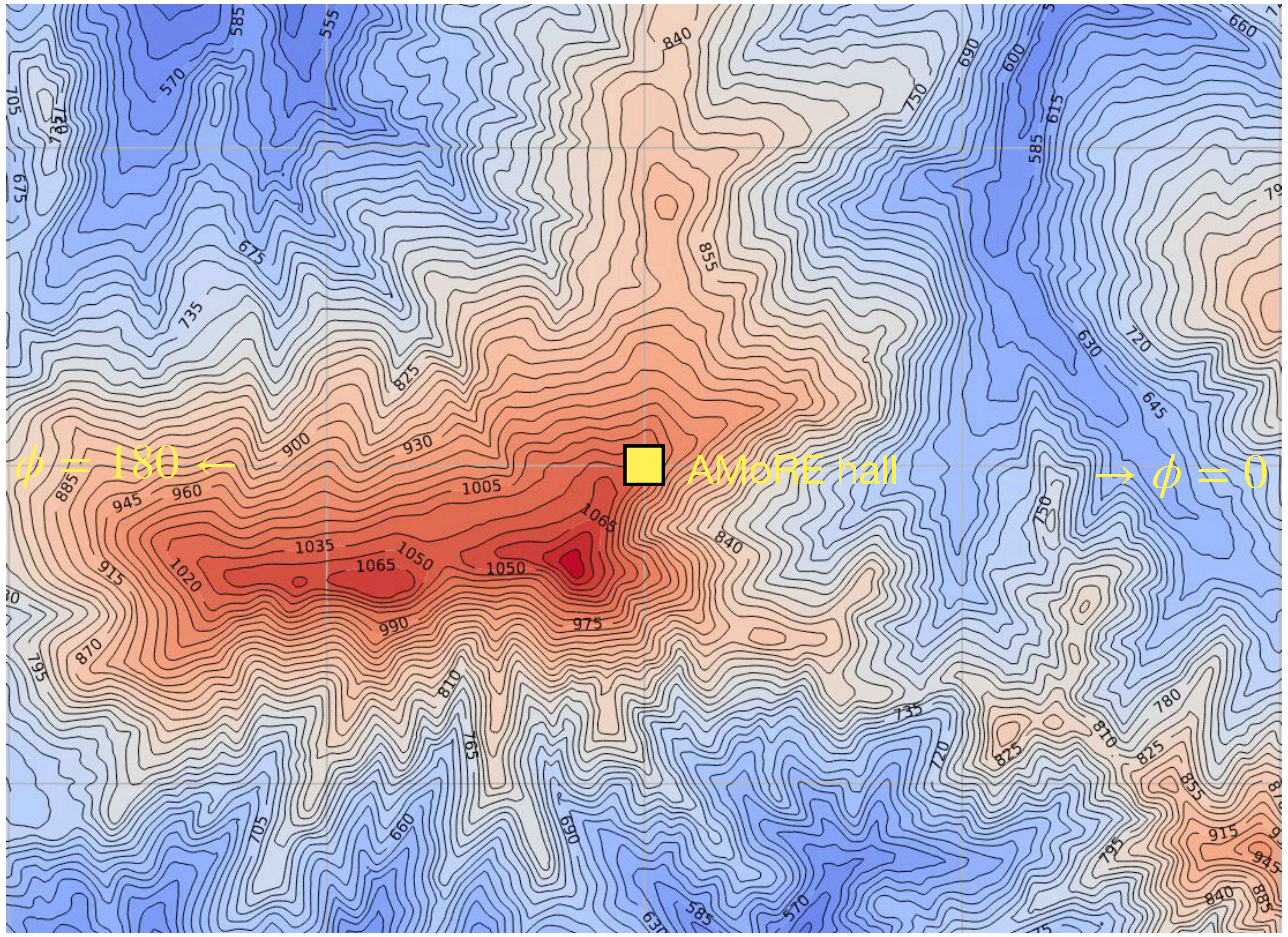
4 SiPM coincidence:
8.6×10^{-8} muons/cm^2/sec

Muon angular distribution with PSMD

Position reconstruction from the signal asymmetry (preliminary)



Yemilab terrain
from National Geographic Information Institute

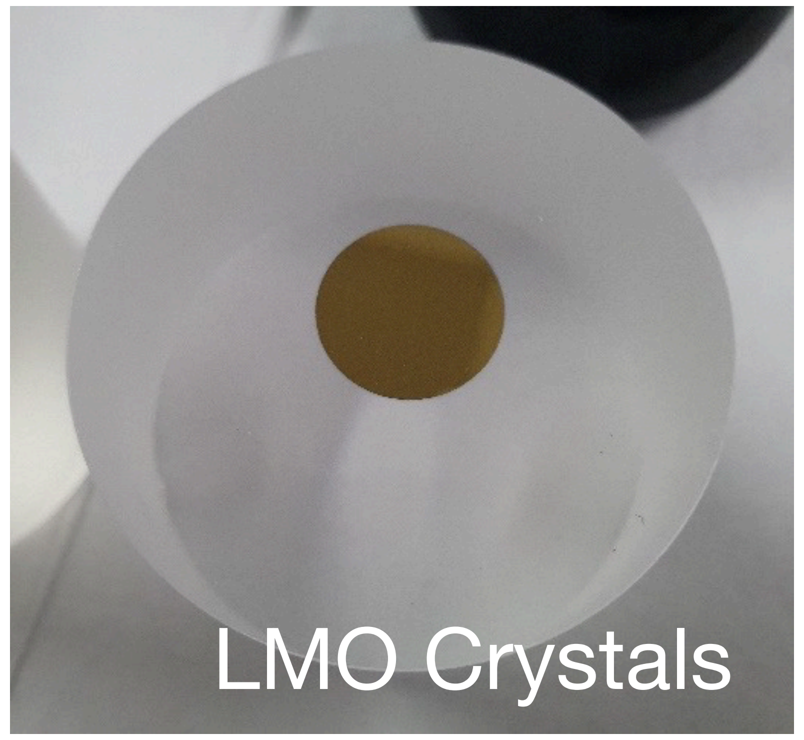


ϕ dependence seems to follow the terrain map

Comparison with simulation underway (MUSIC/MUTE)
(See Jeewon Seo's poster)

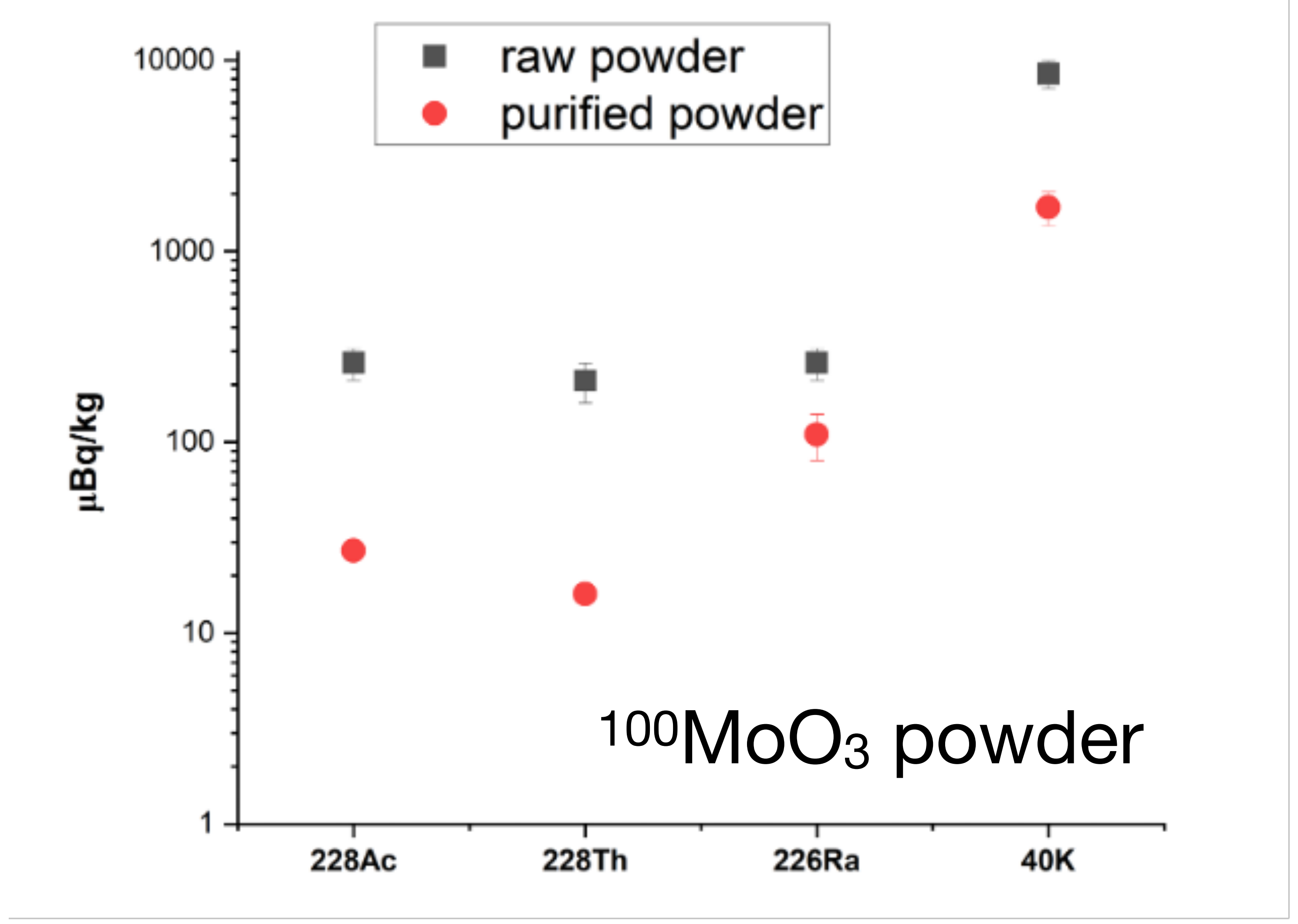
Background control

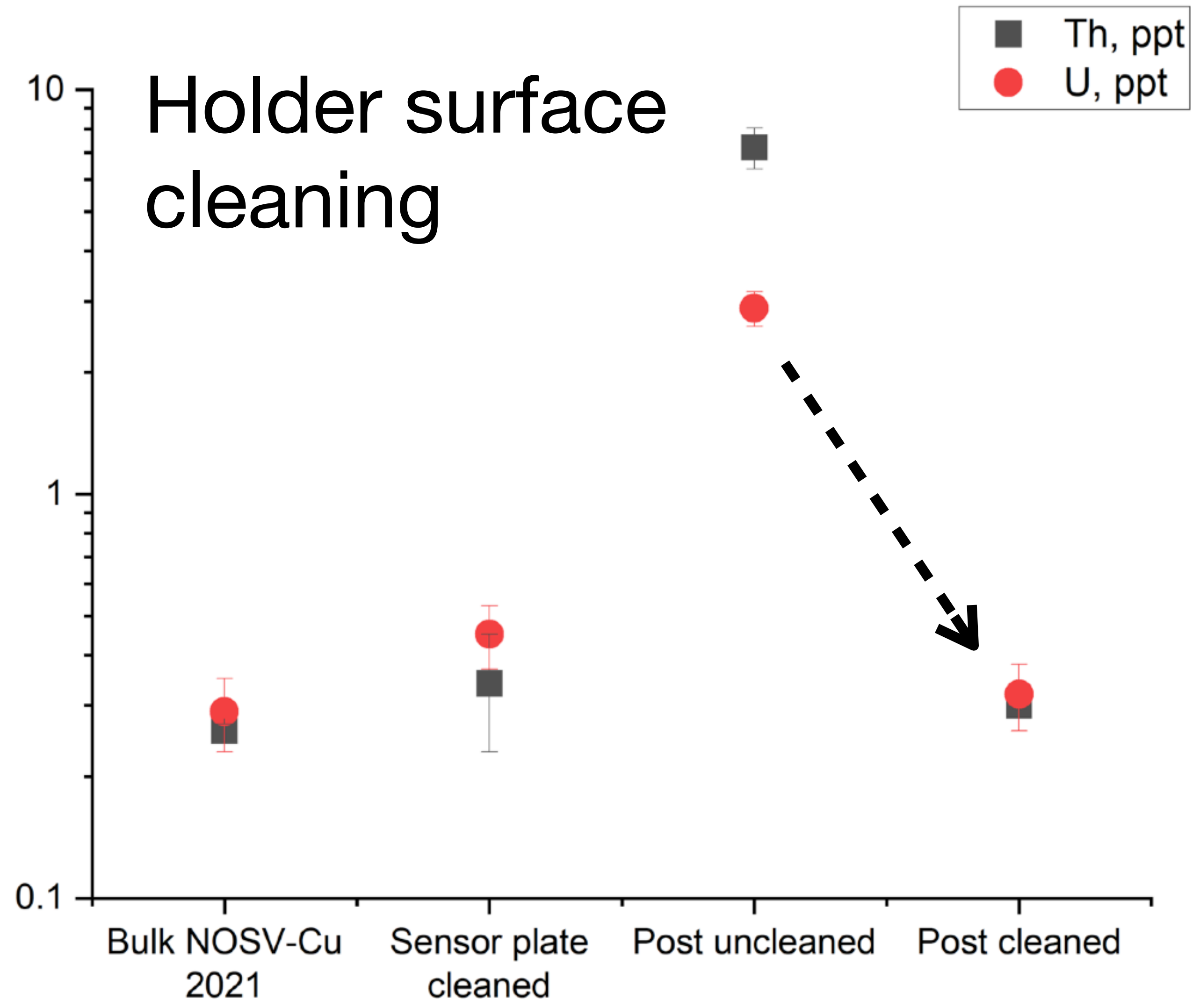
- Target background level at ROI:
  1×10^{-4} cnts/keV/kg/year
- A lot of lessons from AMoRE-Pilot, AMoRE-I:
  Already external source dominant
- Intensive selection/purification/cleaning of materials
- Enhanced radiation shielding:
  Efficient design (neutron inelastic scattering) + pure material for innermost layer
  Rn-less (~10Bq/m³) / Rn-free (< 0.1Bq/m³) air in the experimental hall
  Muon veto with water cherenkov detector + plastic scintillators
  New 1000 m deep underground laboratory



Crystal growing	Crystallization
CUP	Single Convent. Cz.
$Li_2{}^{100}MoO_4$ crystal purity	
K, ppb	<40 - 146
Ba, ppb	<3
Sr, ppt	<50
Pb, ppt	<200
Th, ppt	<6
U, ppt	<6

Front. Phys. 11:1142136 (2023)

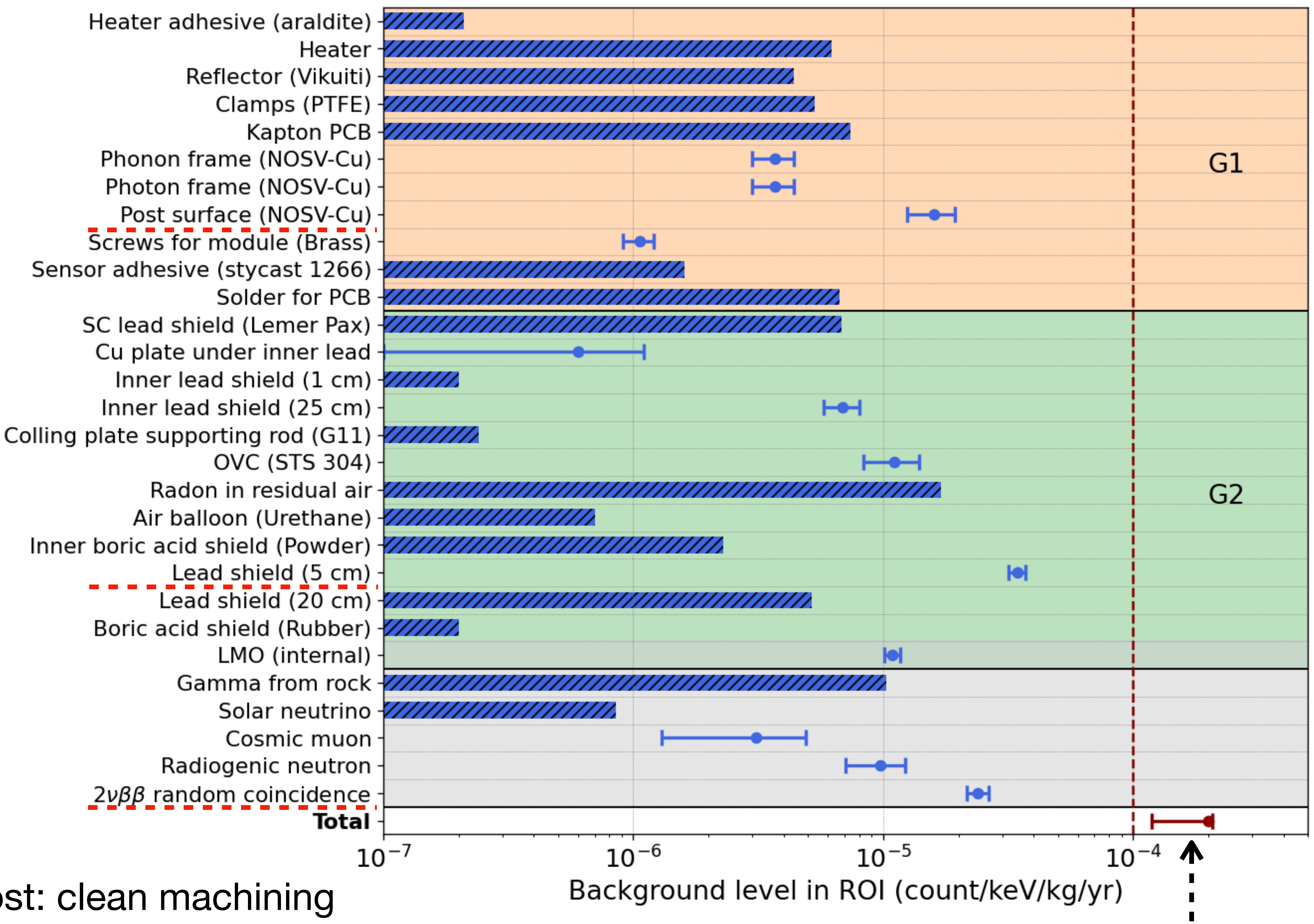




(See talks of Olga Gileva, Eunkyung Lee)

Expected background from simulation

Decomposing background in the ROI



Post: clean machining
Lead: survey of low background lead
$2\nu\beta\beta$ coincidence: inherent background

Eur. Phys. J. C 85:9 (2025)

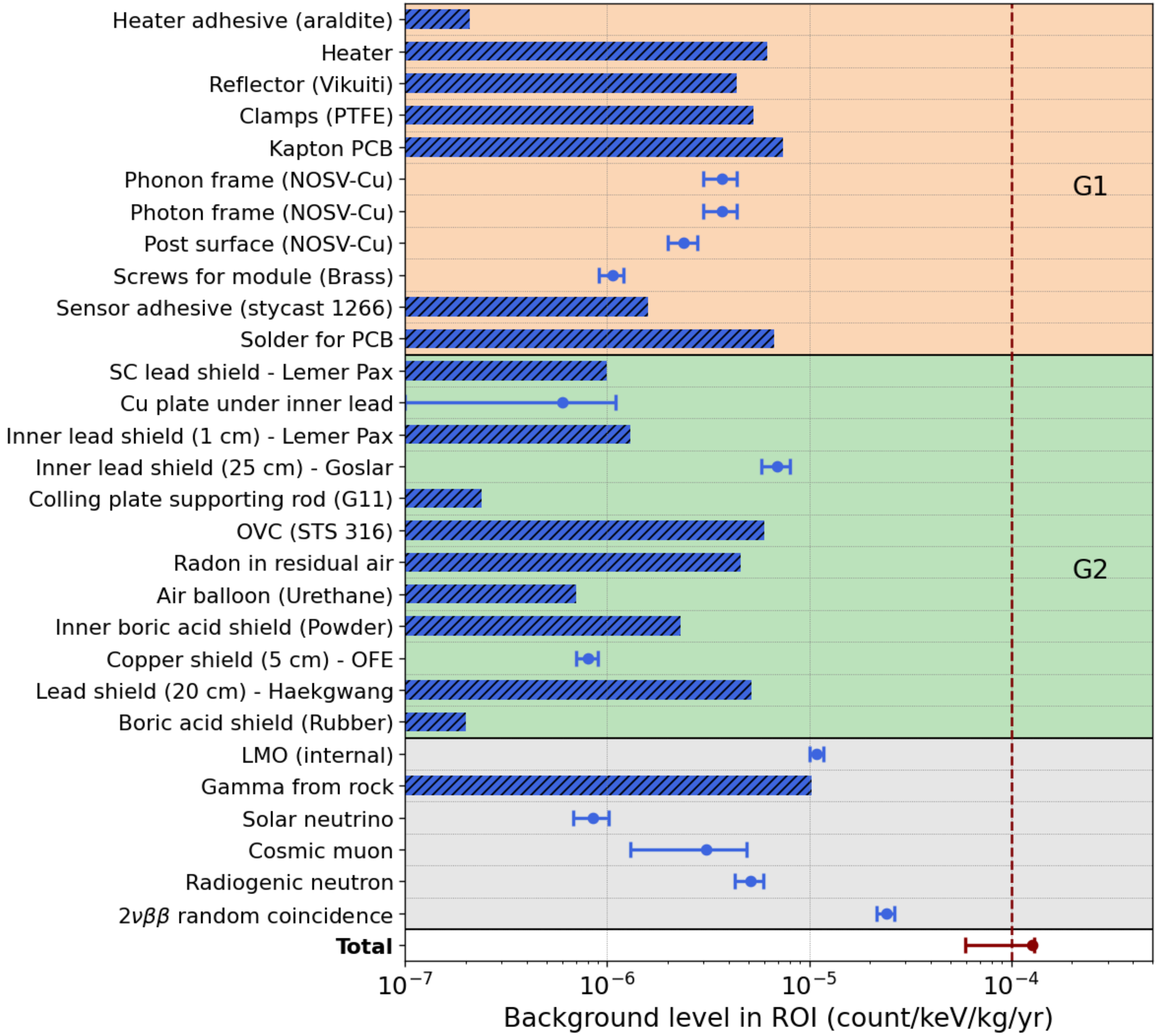
$(1-2)\times 10^{-4}$ cnts/keV/kg/year

Expected background from simulation

New update:
- Cleaner post machining
- Some Pb layer => OFE Cu
- New measurement for inner lead layer

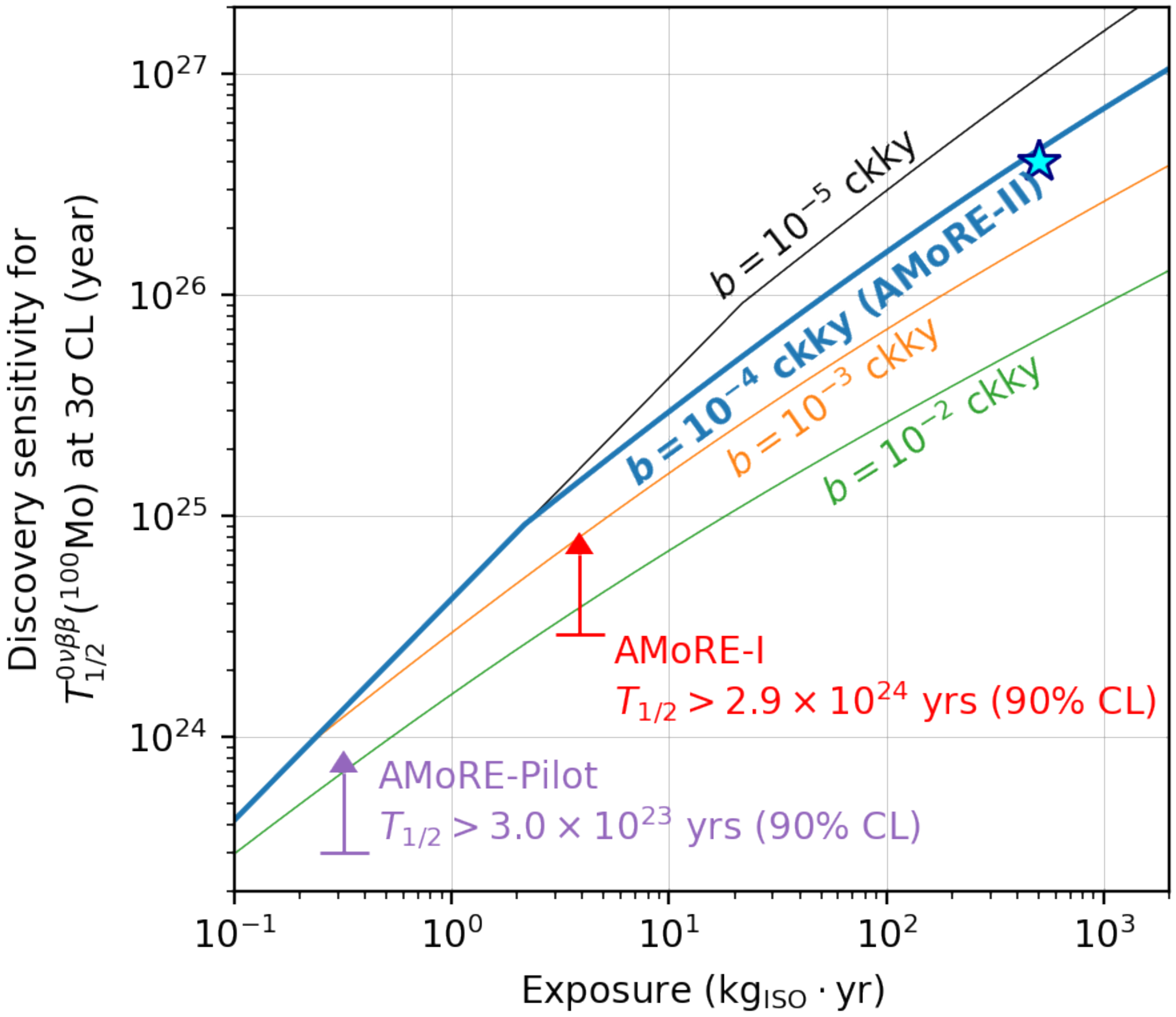
Background $< 10^{-4}$ ckky seems to be reachable.

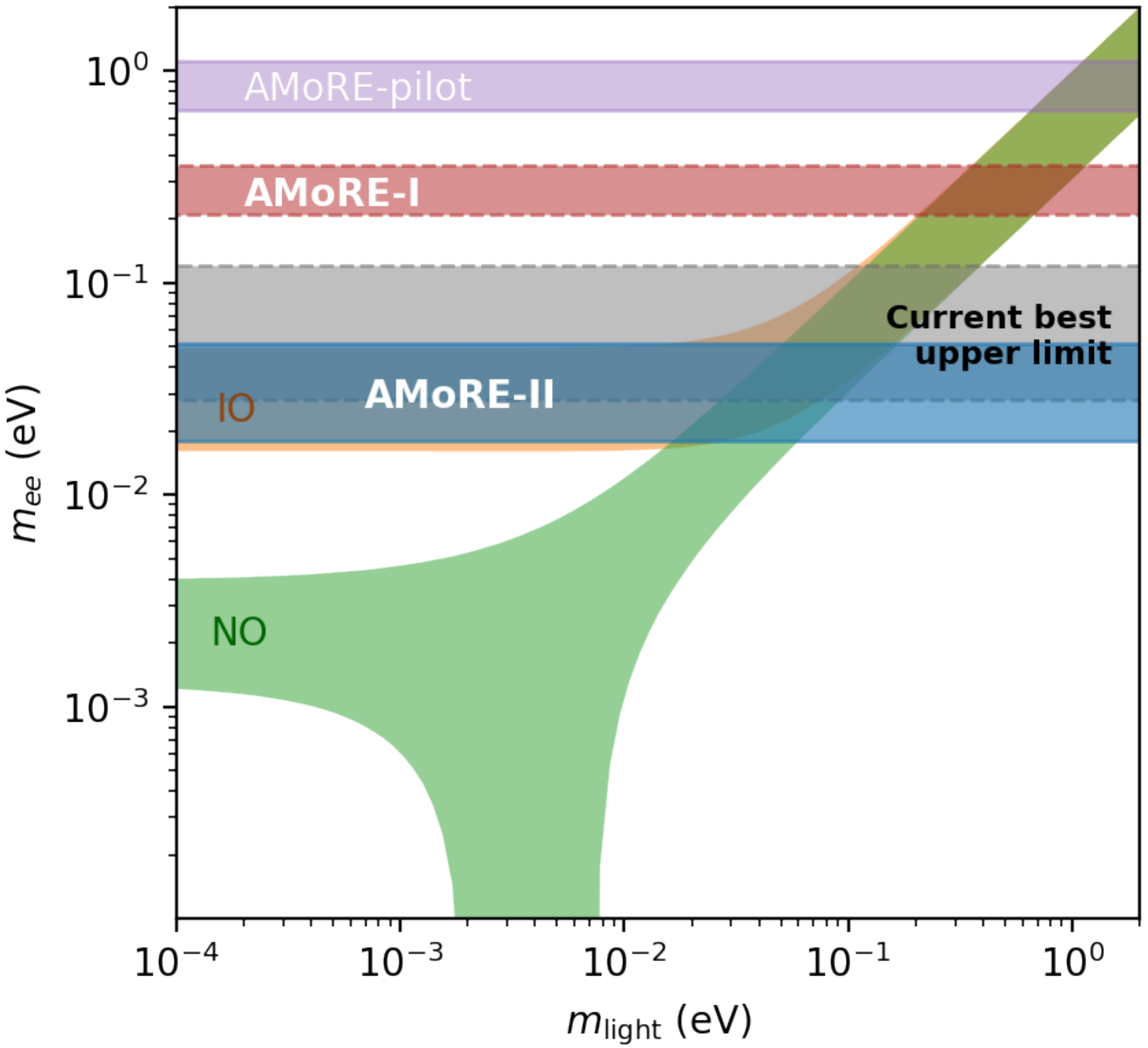
(See Eunju Jeon's talk)



$(0.6 - 1.3) \times 10^{-4}$

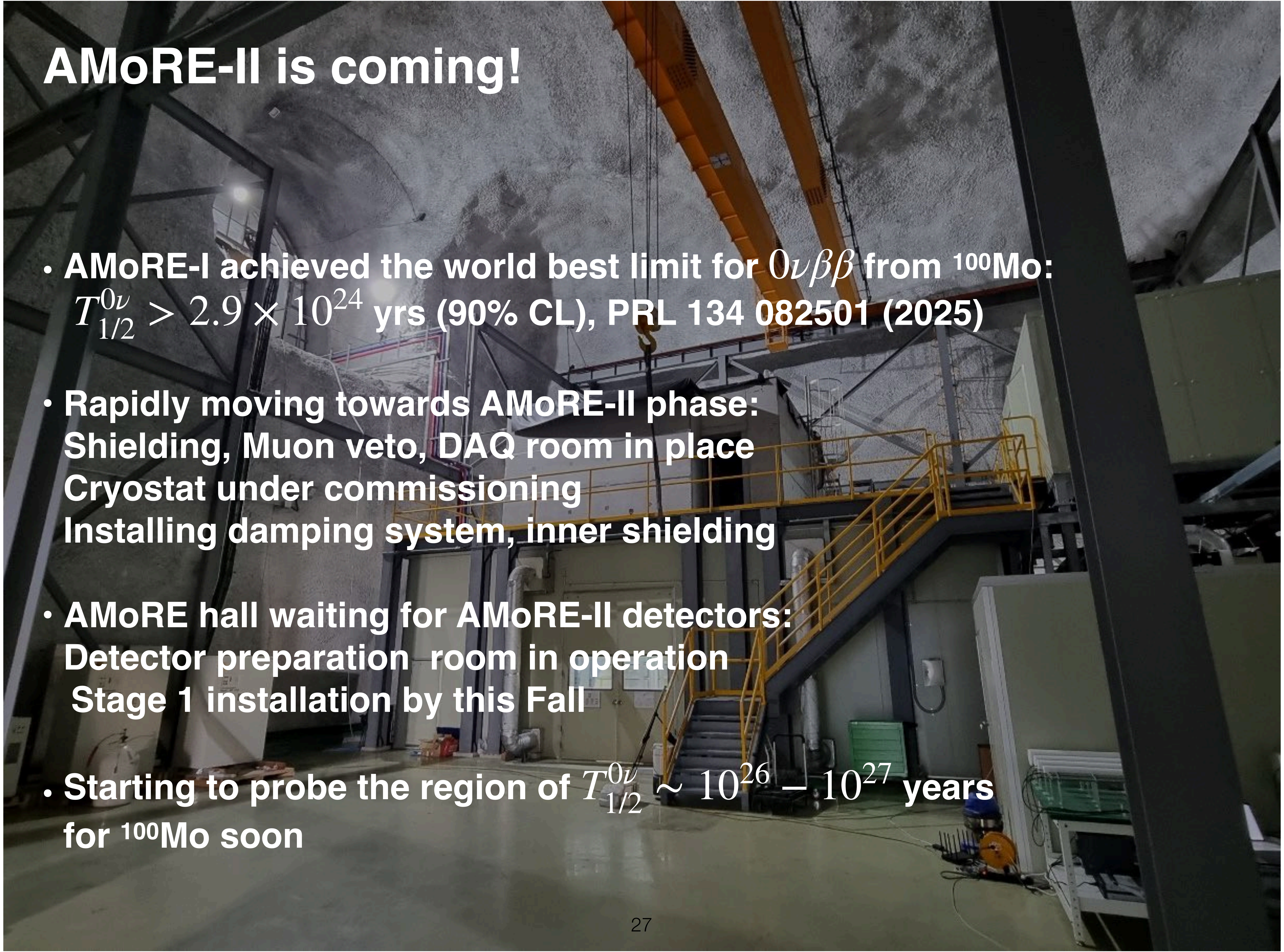
Sensitivity of AMoRE-II





Aiming at $T_{1/2}^{0\nu} \sim 4 \times 10^{26}$ yrs, $\langle m_{\beta\beta} \rangle \sim 18 - 52$ meV

AMoRE-II is coming!



- AMoRE-I achieved the world best limit for $0\nu\beta\beta$ from ^{100}Mo: $T^{0\nu}_{1/2} > 2.9 \times 10^{24}$ yrs (90% CL), PRL 134 082501 (2025)
- Rapidly moving towards AMoRE-II phase:
  Shielding, Muon veto, DAQ room in place
  Cryostat under commissioning
  Installing damping system, inner shielding
- AMoRE hall waiting for AMoRE-II detectors:
  Detector preparation room in operation
  Stage 1 installation by this Fall
- Starting to probe the region of $T^{0\nu}_{1/2} \sim 10^{26} - 10^{27}$ years for ^{100}Mo soon

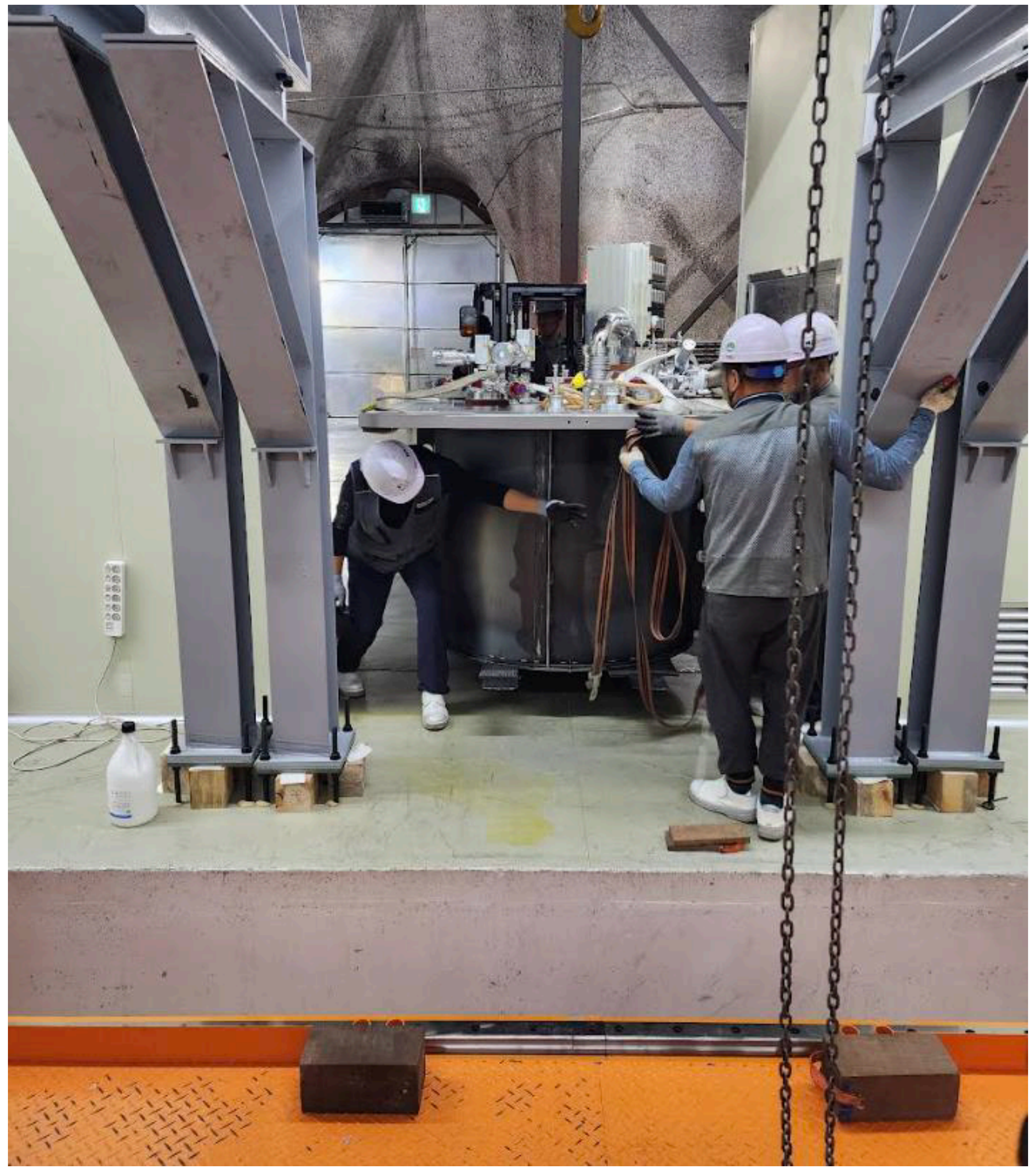
Acknowledgement:
AMoRE collaboration

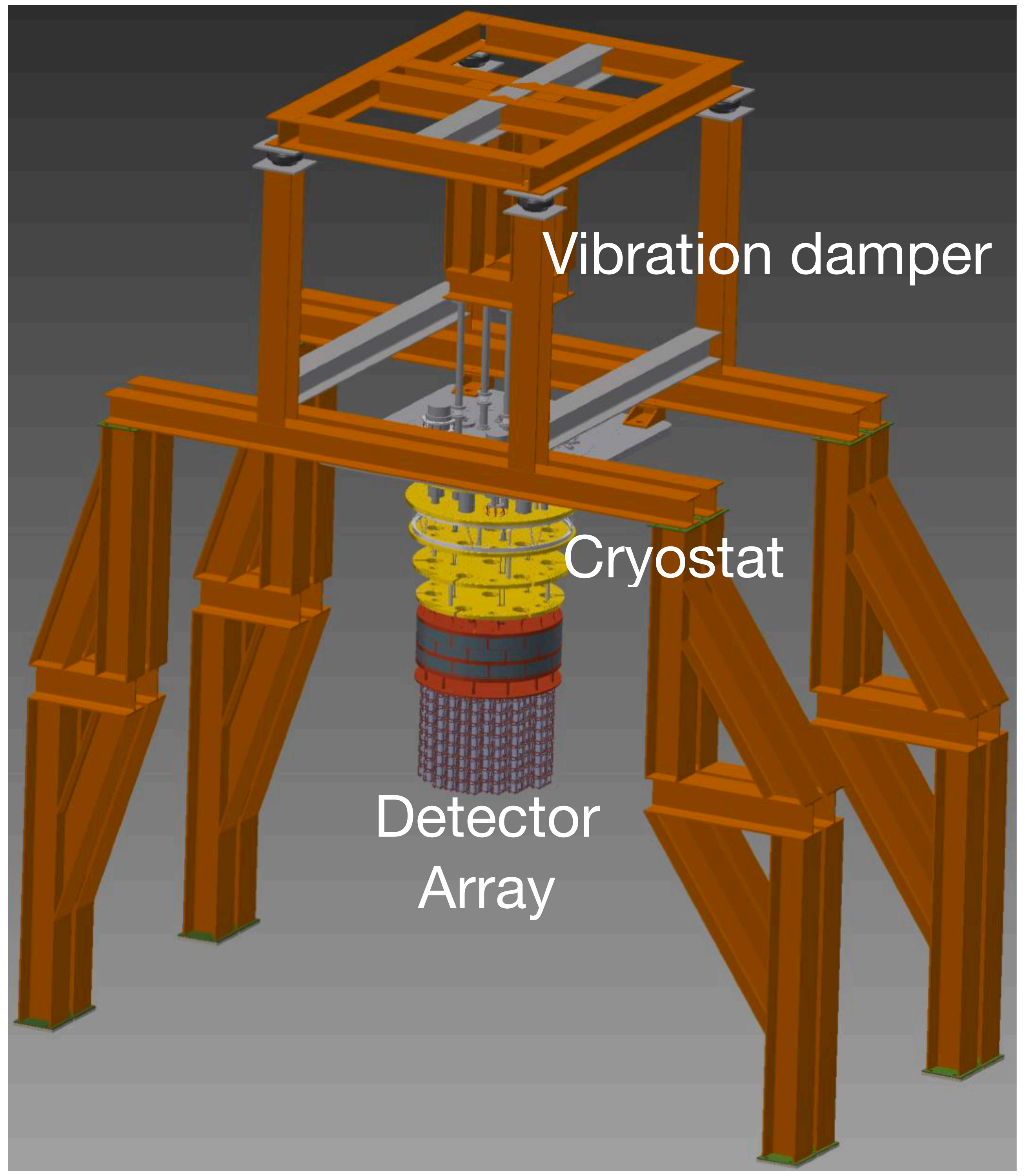
CENTER FOR UNDERGROUND PHYSICS ibs
UST
KRISS
KOREA UNIVERSITY
Lawrence Livermore National Laboratory
PTB
FLORIDA TECH
ИНХ СО РАН
CENS CENTER FOR EXOTIC NUCLEAR STUDIES
SMU
KIT Karlsruher Institut für Technologie

Thank you~!

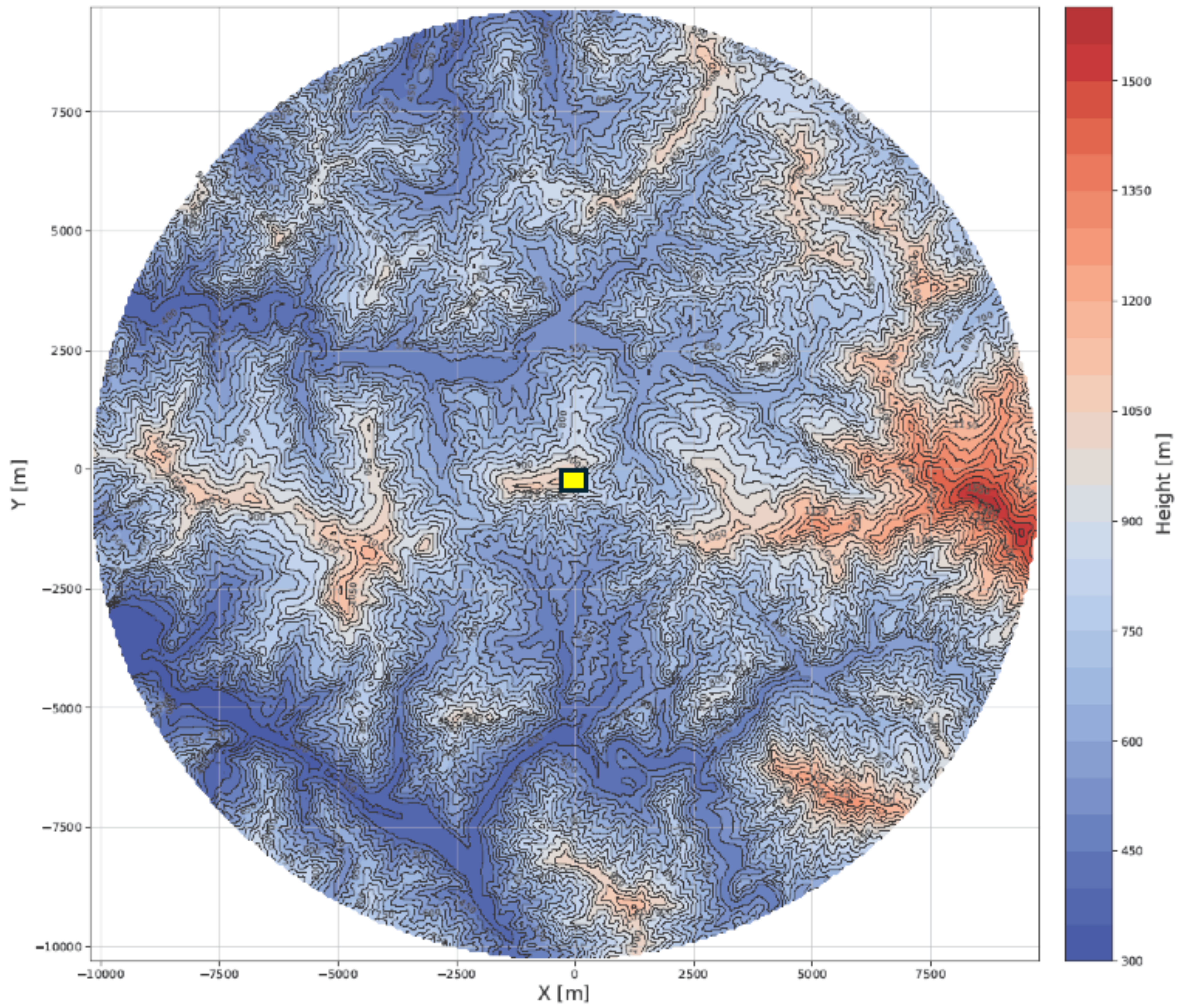
EXTRA

AMoRE-II cryostat settled in Yemilab





Vibration mitigation system:
- Cryostat soft contact with H-beam (anti-vibration pad)
- Soft PTR contact on the fridge (absorbing foam, Cu tapes)
- Internal vibration damper between 4K and still stage
- Kevlar strings suspending detector array in IVC



Yemi Mountain profile