Probing the nature of neutrinos with cryogenic calorimeters

SeungCheon Kim
Center for Underground Physics (CUP), IBS

NEWS colloquium, RCNP, Osaka University, Sept 2025

OUTLINE

Neutrinos

Neutrinoless double beta decay

AMoRE experiment

- Experimental principle with cryogenic detectors
- Achievement of AMoRE-pilot & AMoRE-I
- Goals of AMoRE-II
- AMoRE-II construction status

Conclusion

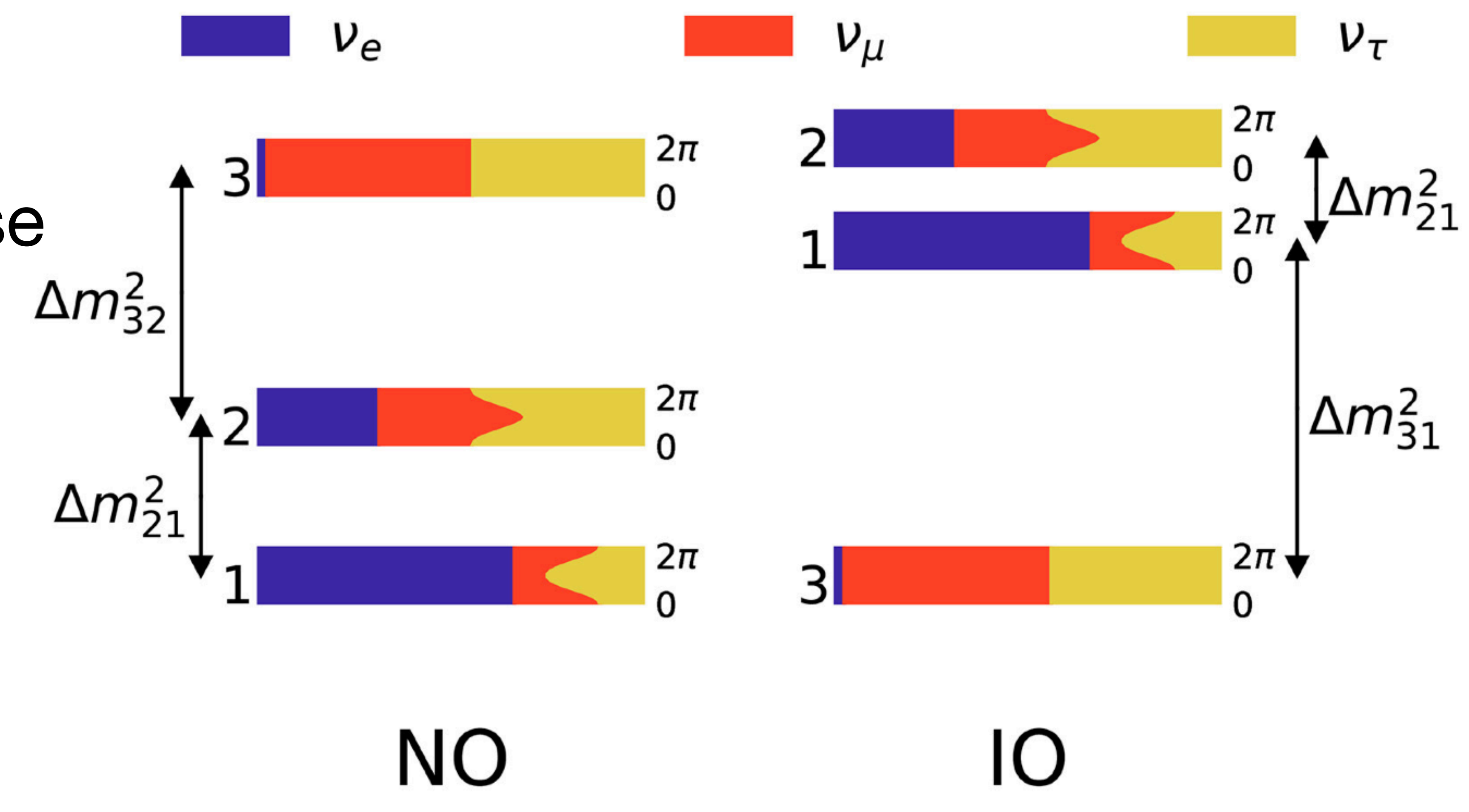
Neutrinos

- Only fermions with no electrical charge
- Precise flavor contents for mass states
- Some burning questions: mass ordering (Normal/Inverse ordering), CP-violating phase
- Very tiny mass
- Stronger constraints from cosmological (DESI) and oscillation experiments

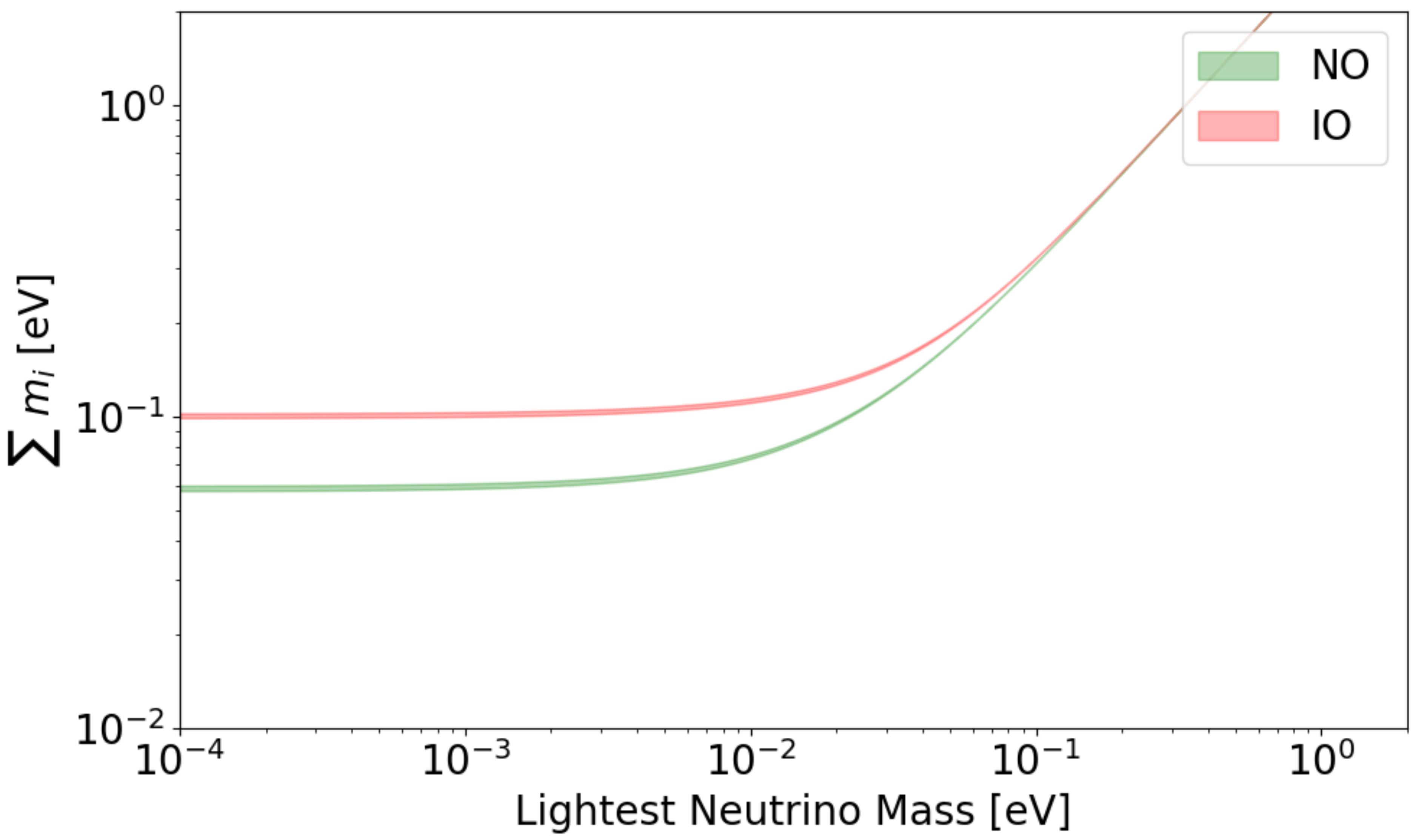
  0.06 (NO) / 0.1 (IO) eV $\lesssim \Sigma m_i \lesssim$ 0.064 (ΛCDM) / 0.16 ($\omega_0\omega_a$CDM) eV
- Another constraints from the beta decay experiment (KATRIN)

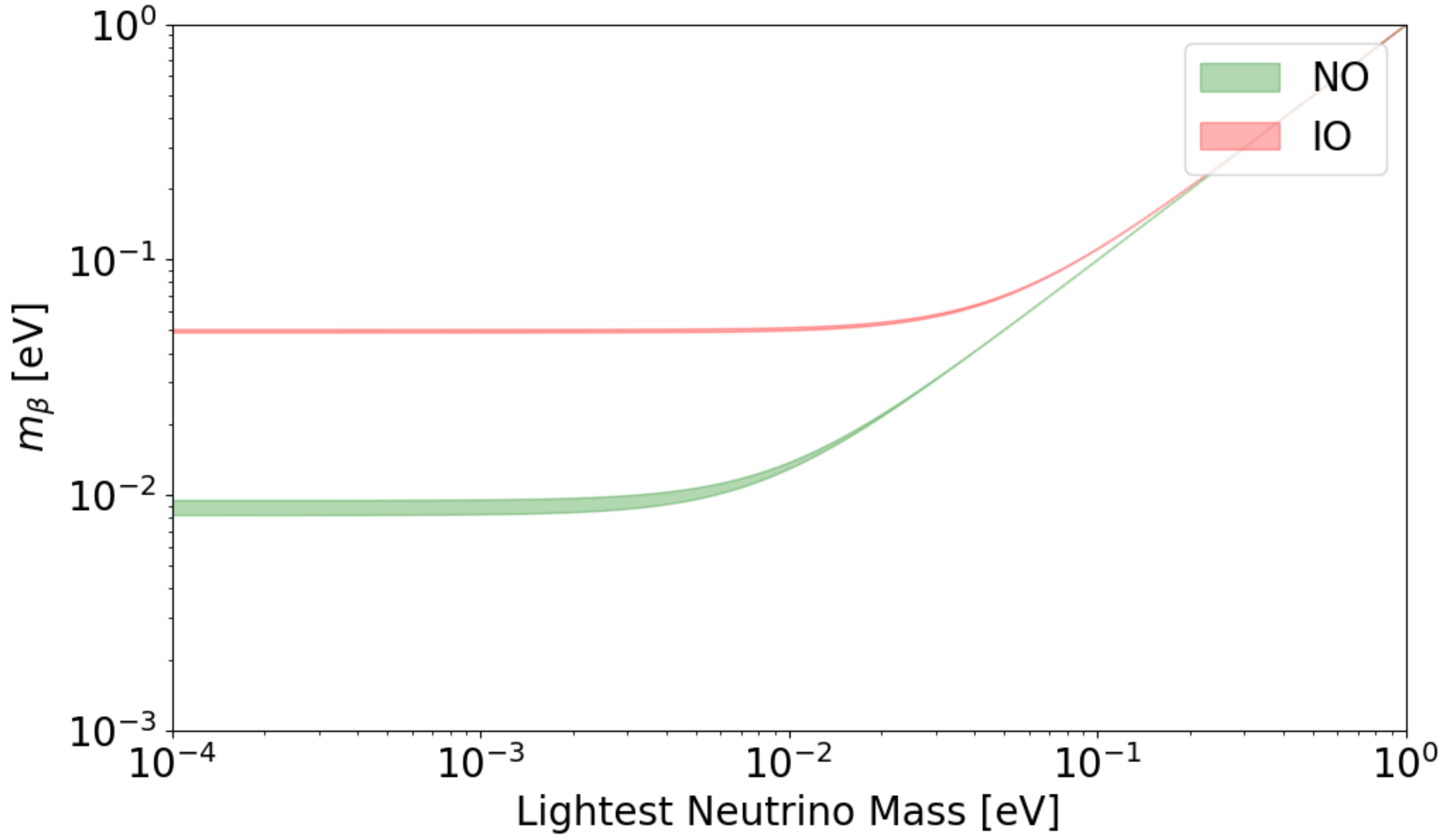
  $m_\beta = \sqrt{\Sigma |U_{ei}|^2 m_i^2}$ < 0.45 eV
- "Simplest" explanation for tiny neutrino mass:

  Seesaw mechanism with Majorana neutrinos ($\nu = \bar{\nu}$)



Front. Astron. Space Sci. 5:36 (2018)



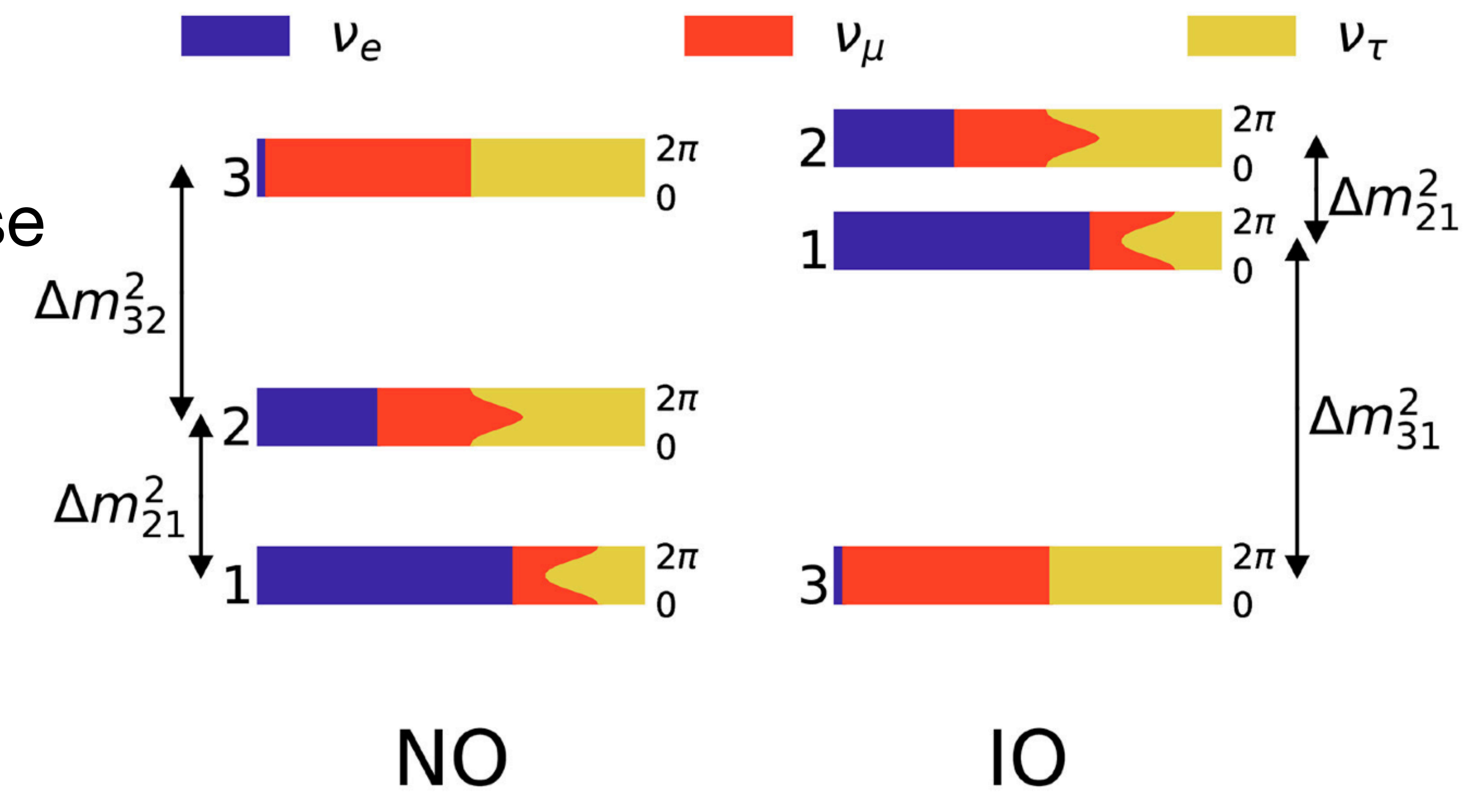


Neutrinos

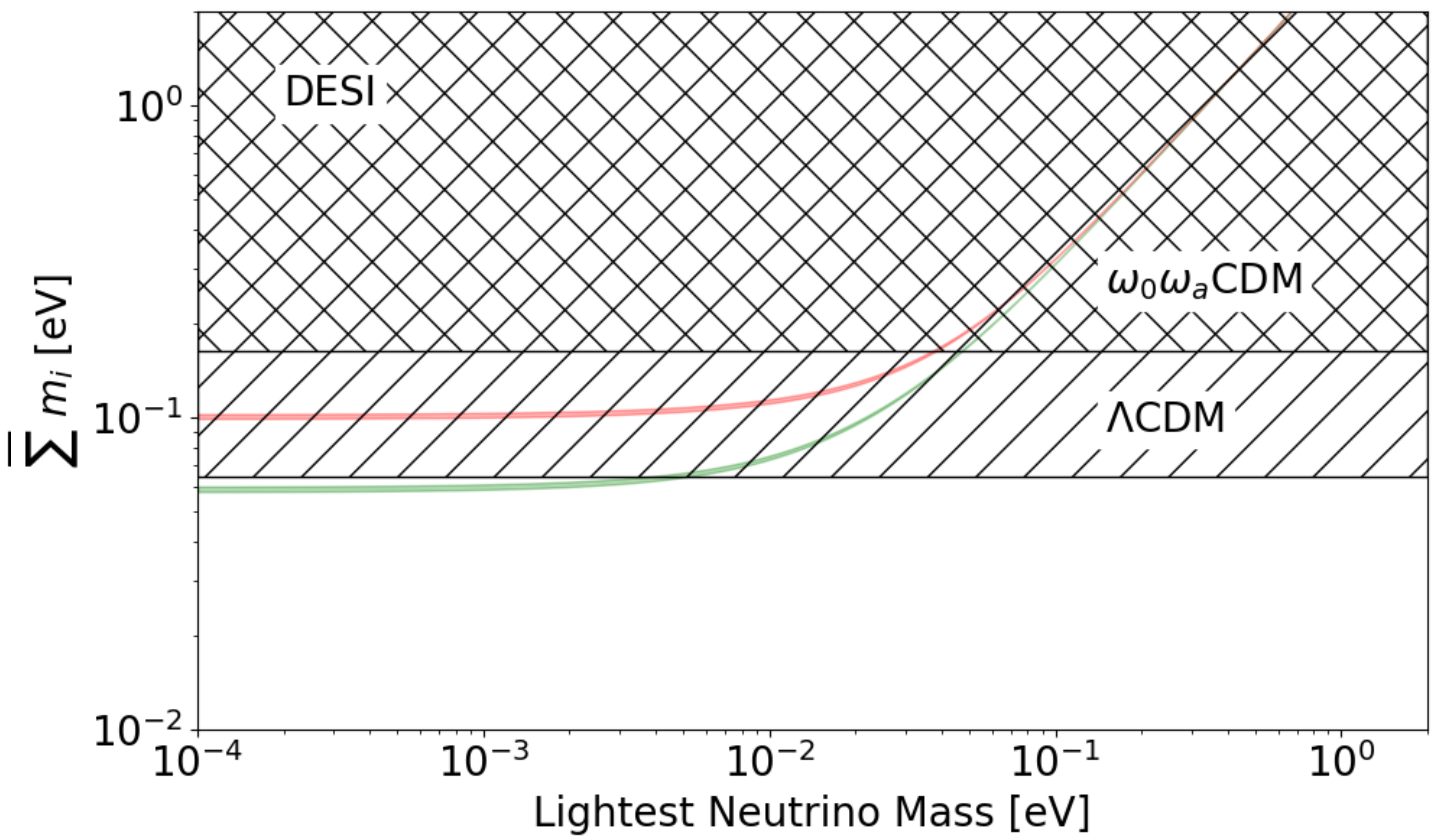
- Only fermions with no electrical charge
- Precise flavor contents for mass states
- Some burning questions: mass ordering (Normal/Inverse ordering), CP-violating phase
- Very tiny mass
- Stronger constraints from cosmological (DESI) and oscillation experiments
  0.06 (NO) / 0.1 (IO) eV $\lesssim \Sigma m_i \lesssim$ 0.064 (ΛCDM) / 0.16 ($\omega_0\omega_a$CDM) eV
- Another constraints from the beta decay experiment (KATRIN)

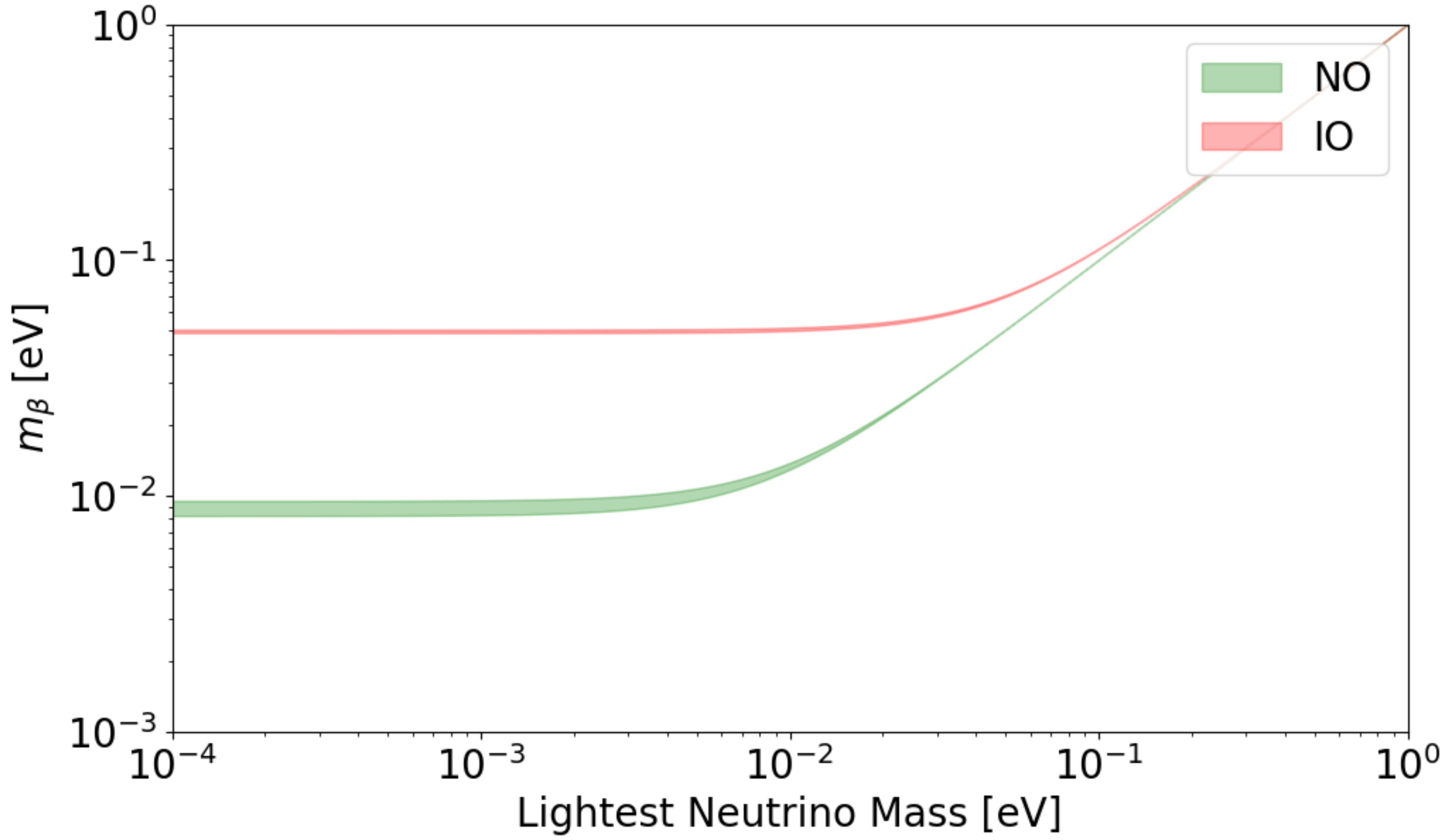
$$m_\beta = \sqrt{\Sigma |U_{ei}|^2 m_i^2} < 0.45 \text{ eV}$$

- "Simplest" explanation for tiny neutrino mass:
  Seesaw mechanism with Majorana neutrinos ($\nu = \bar{\nu}$)



Front. Astron. Space Sci. 5:36 (2018)





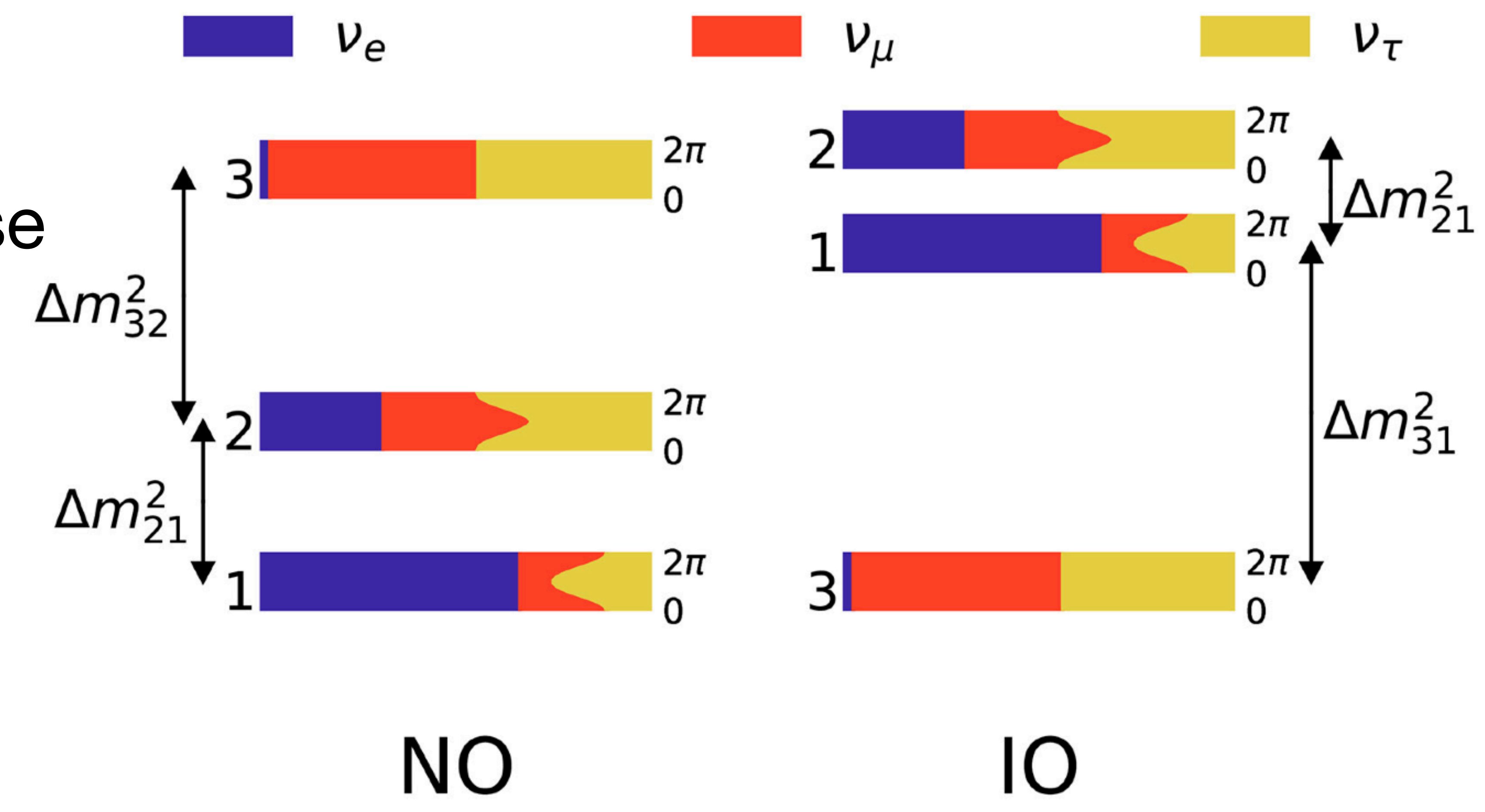
arXiv:2503.14744v2

Neutrinos

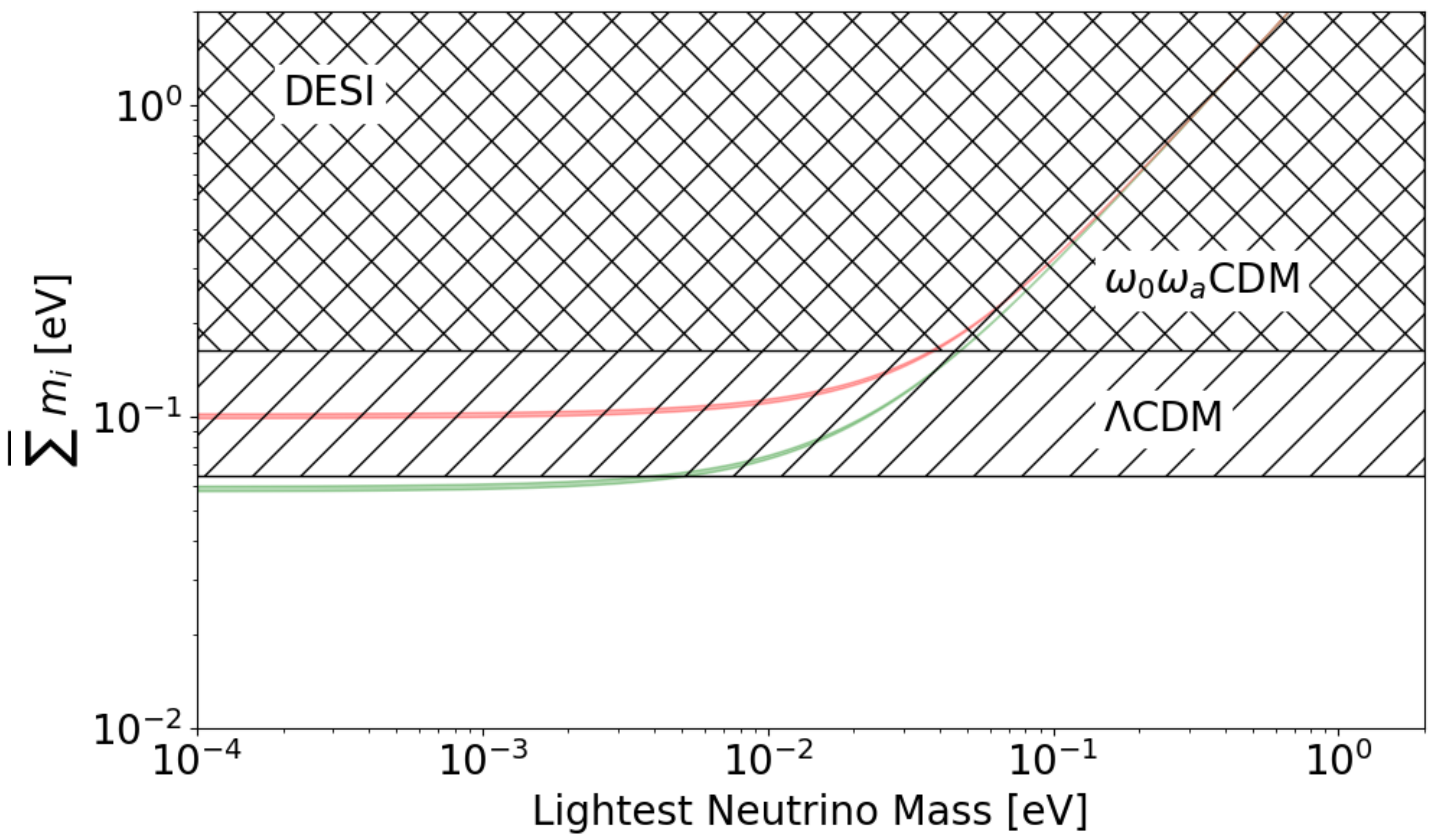
- Only fermions with no electrical charge
- Precise flavor contents for mass states
- Some burning questions: mass ordering (Normal/Inverse ordering), CP-violating phase
- Very tiny mass
- Stronger constraints from cosmological (DESI) and oscillation experiments
  0.06 (NO) / 0.1 (IO) eV $\lesssim \Sigma m_i \lesssim$ 0.064 (ΛCDM) / 0.16 ($\omega_0\omega_a$CDM) eV
- Another constraints from the beta decay experiment (KATRIN)

$$m_\beta = \sqrt{\Sigma |U_{ei}|^2 m_i^2} < 0.45 \text{ eV}$$

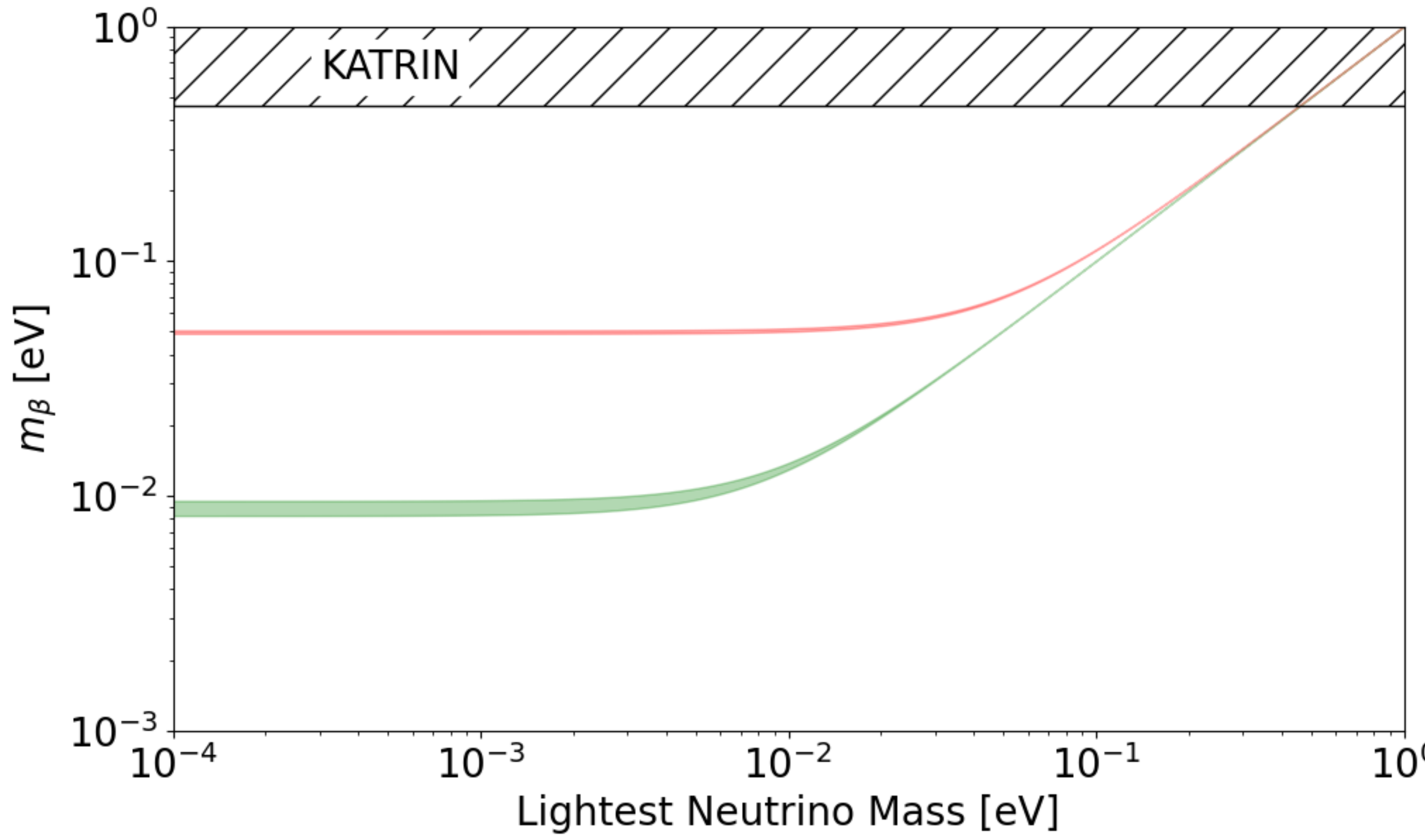
- "Simplest" explanation for tiny neutrino mass:
  Seesaw mechanism with Majorana neutrinos ($\nu = \bar{\nu}$)



Front. Astron. Space Sci. 5:36 (2018)



arXiv:2503.14744v2



Science 388, 180 (2025)

Neutrinos as Majorana fermions?

- Spin 1/2, No electric charge, Non-zero mass, Single handedness (left-handed ν / right-handed $\bar{\nu}$)

- Economical solution for Dirac equation
  Majorana (two chiral states)   vs. Dirac (two chiral states x two antistates)

- No need for sterile neutrinos (ν_R)
  $L^M_{\mathrm{m}} = \frac{1}{2} m^M (\bar{\nu}^c_L \nu_L + \bar{\nu}_L \nu^c_L)$ vs. $L^D_{\mathrm{m}} = -m^D (\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R)$

- No reason for m^D to be small

- Simple understanding of neutrino mass: See-saw mechanism
  $m_1 = \frac{m_D^2}{M_R} \approx m_{\nu_L}$ (LH active neutrino), $m_2 \approx M_R$ (RH sterile neutrino, N_R)
  Lighter m_1 with heavier m_2 ("See-saw")
  It still requires very heavy sterile neutrinos…

- Lepton number violation
  Important ingredient for Letogenesis / Baryon asymmetry
  Lepton asymmetry (ΔL) : $N_R \rightarrow lH$ or $\bar{l}H^\dagger$ in the early Universe with CP-violation & LNV
  Baryon asymmetry (ΔB) : ΔL converted into ΔB, conserving $B - L$

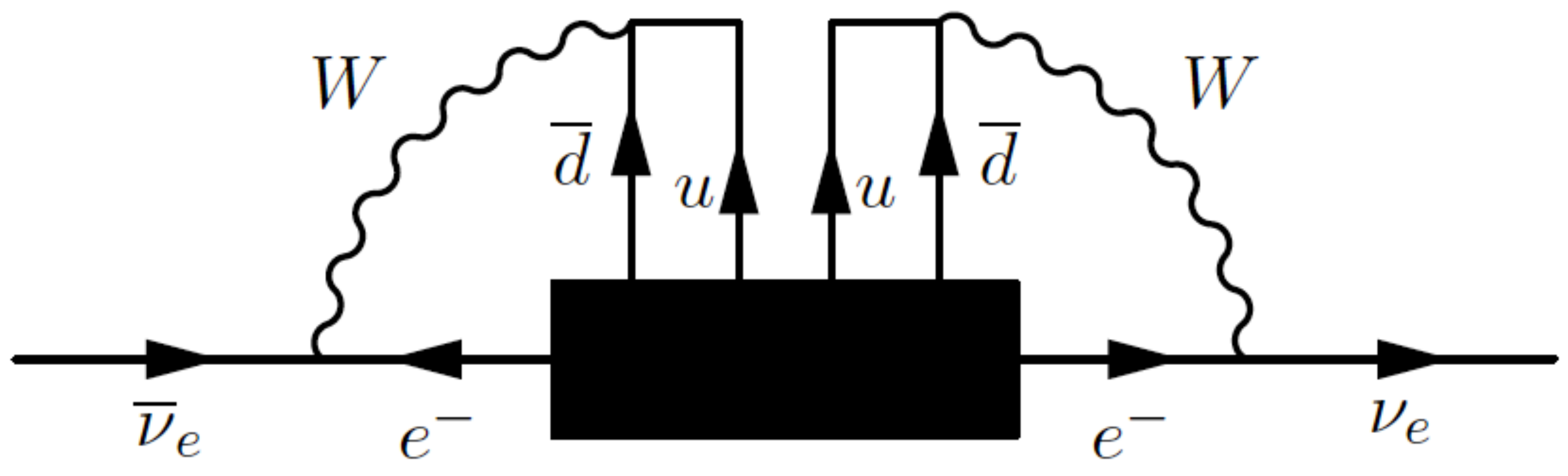
Neutrinoless double beta decay ($0\nu\beta\beta$) ?

Double beta decay:

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

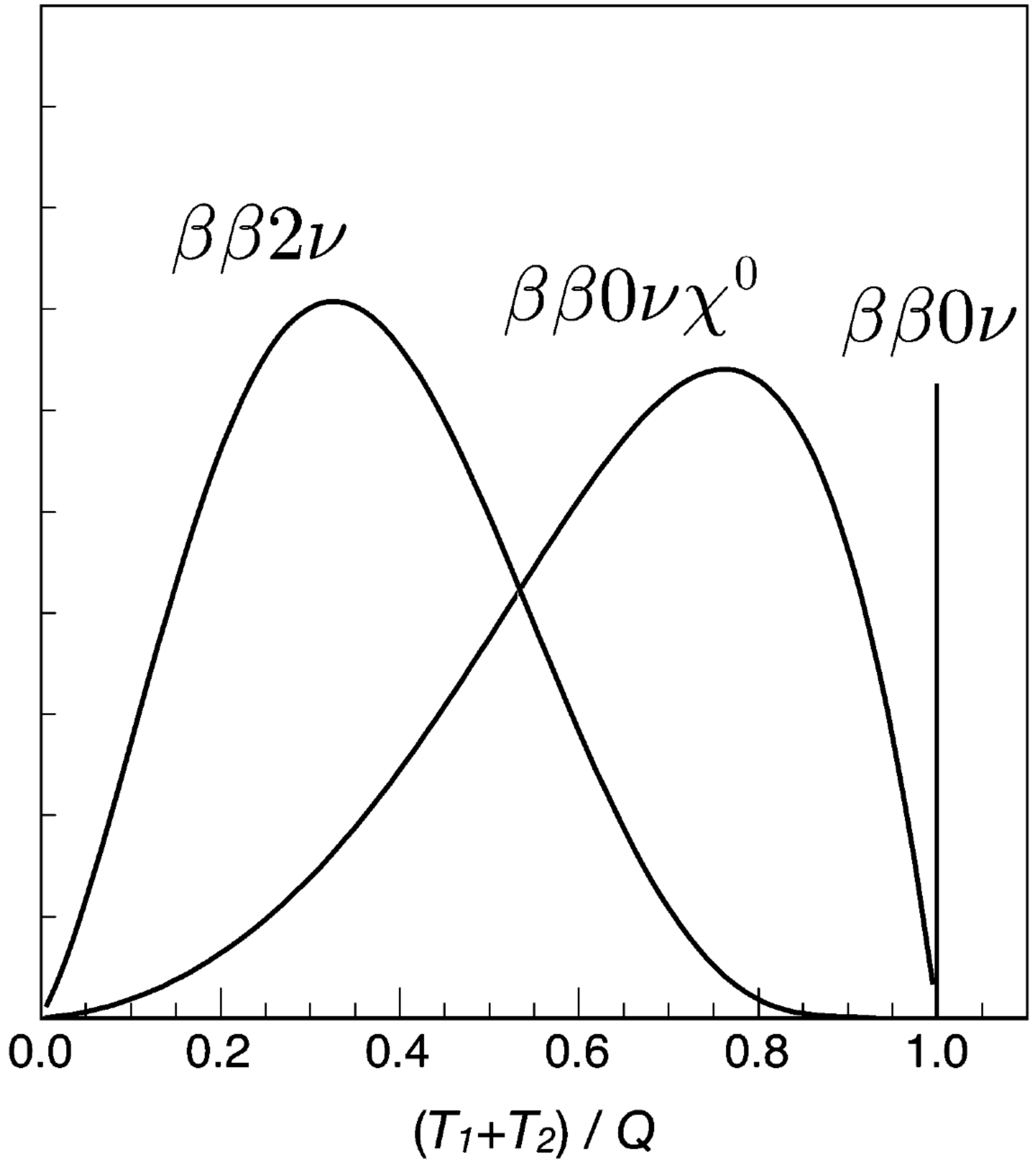
- $2\nu\beta\beta$ mode: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu} + Q_{\beta\beta}$
  Within Standard Model, $T^{2\nu}_{1/2}$ ~ 10^{18} - 10^{24} years, observed in 11 nuclides, wide spread in $\beta\beta$ spectrum

- $0\nu\beta\beta$ mode: $(A, Z) \rightarrow (A, Z+2) + 2e^- + Q_{\beta\beta}$
  $\beta\beta$ 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 !



PRD 25, 2951 (1982)
JHEP 2011, 91 (2011)

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

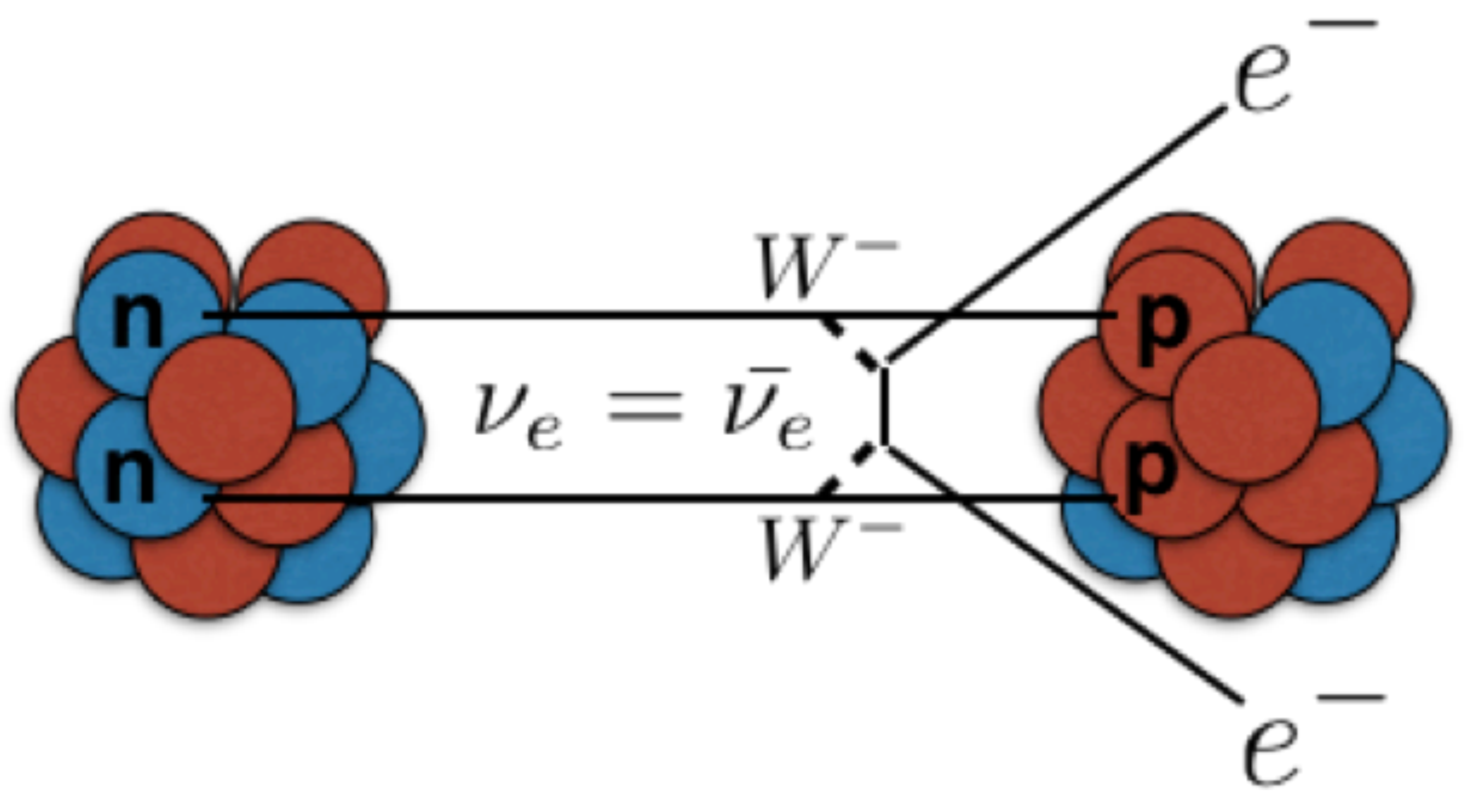


Riv. Nuovo Cim. 35, 29 (2012)

- 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

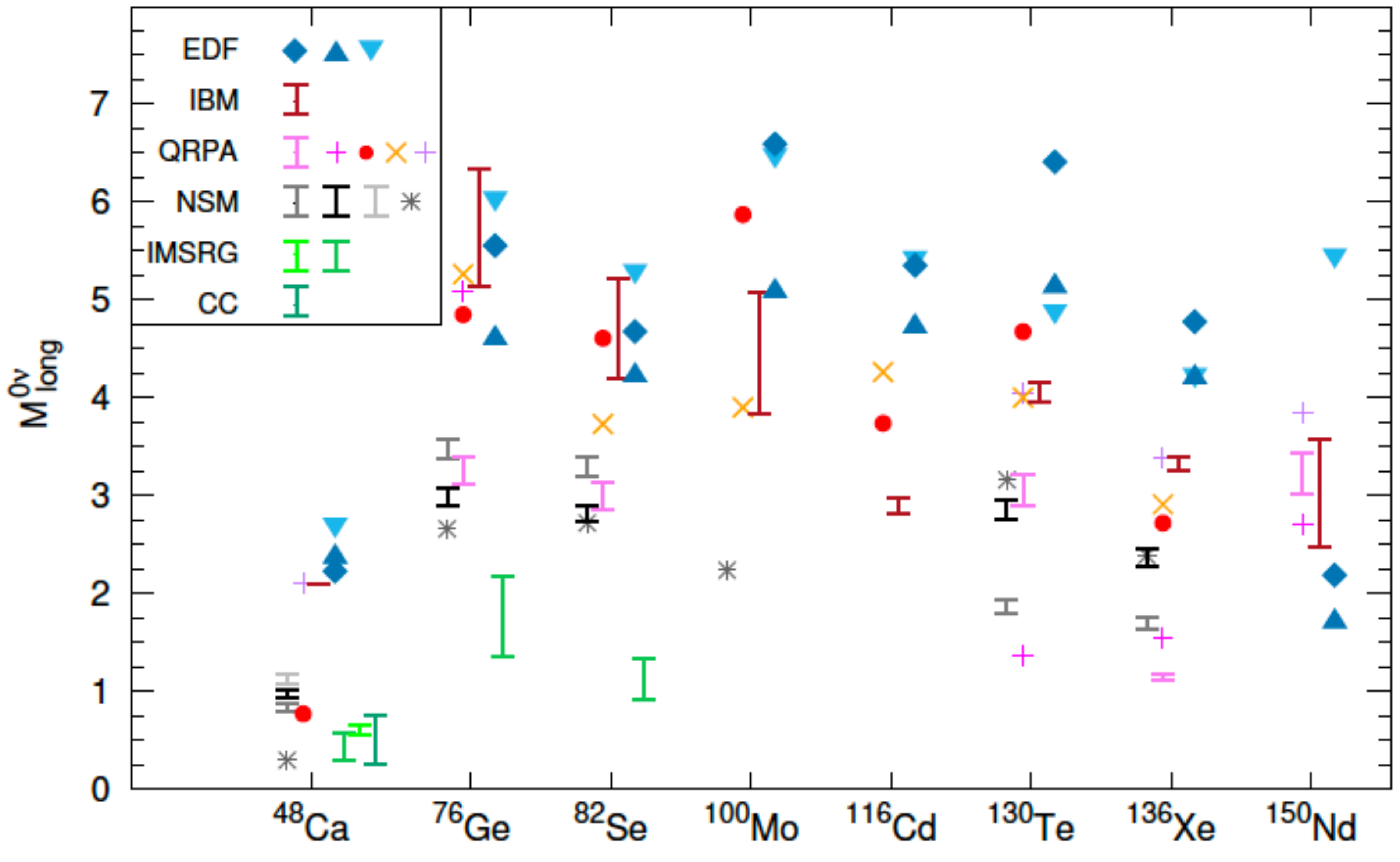
Nuclear matrix element (NME)

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

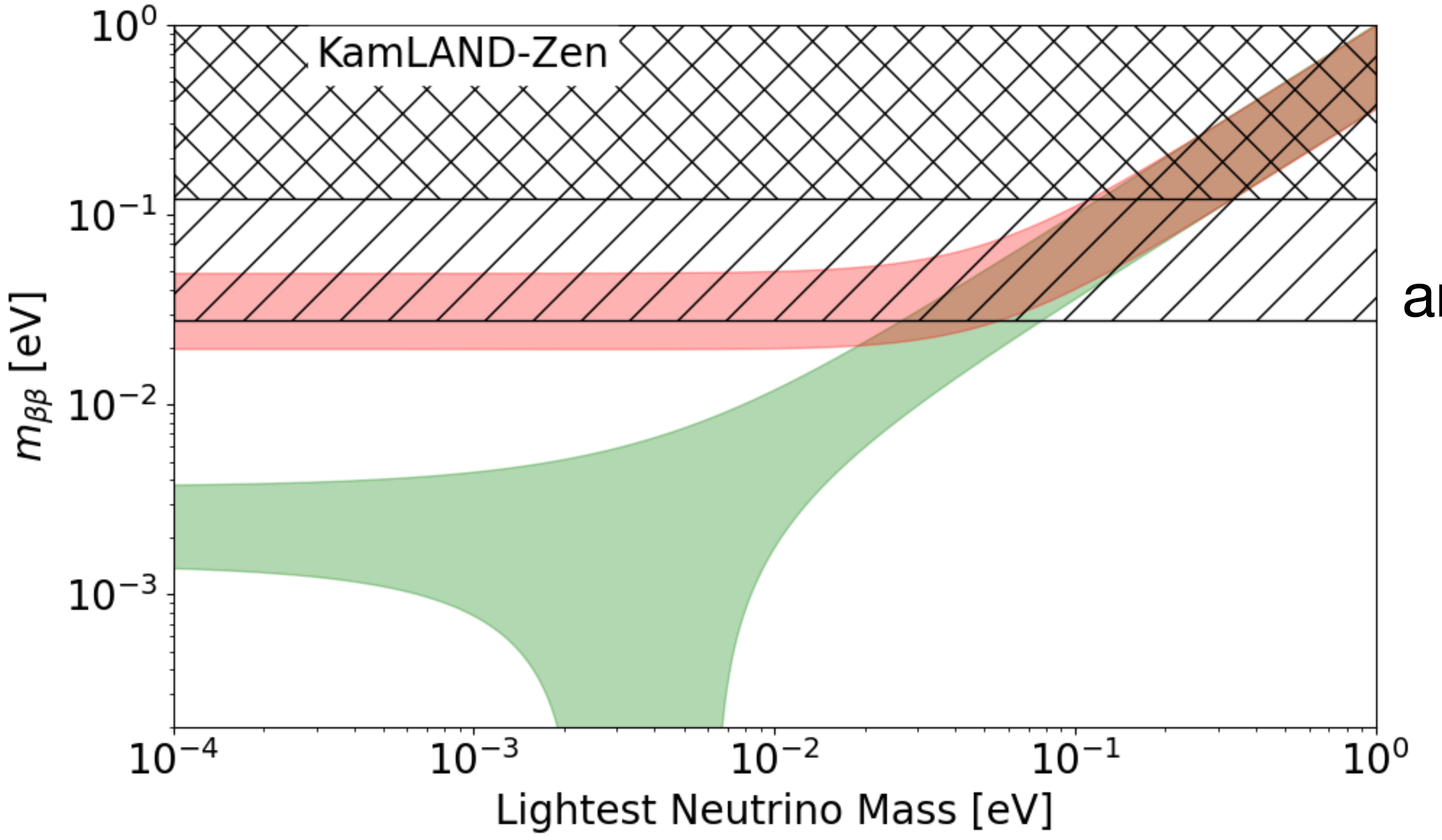
Constraining neutrino mass !

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

Experimental strategy for $0\nu\beta\beta$

Minimal background source

- Thorough material screening, purification, cleaning
- Clean production
- Sufficient radiation shielding
- Underground laboratory

Good detector

- Good energy resolution, detection efficiency
- Extra characteristic signal:
  pulse shape, scintillation, ionization, event topology …
- Fast timing

Large exposure

- Target material with good natural abundance
- Enrichment
- Large target mass: > 100 kg
- Long stable operation

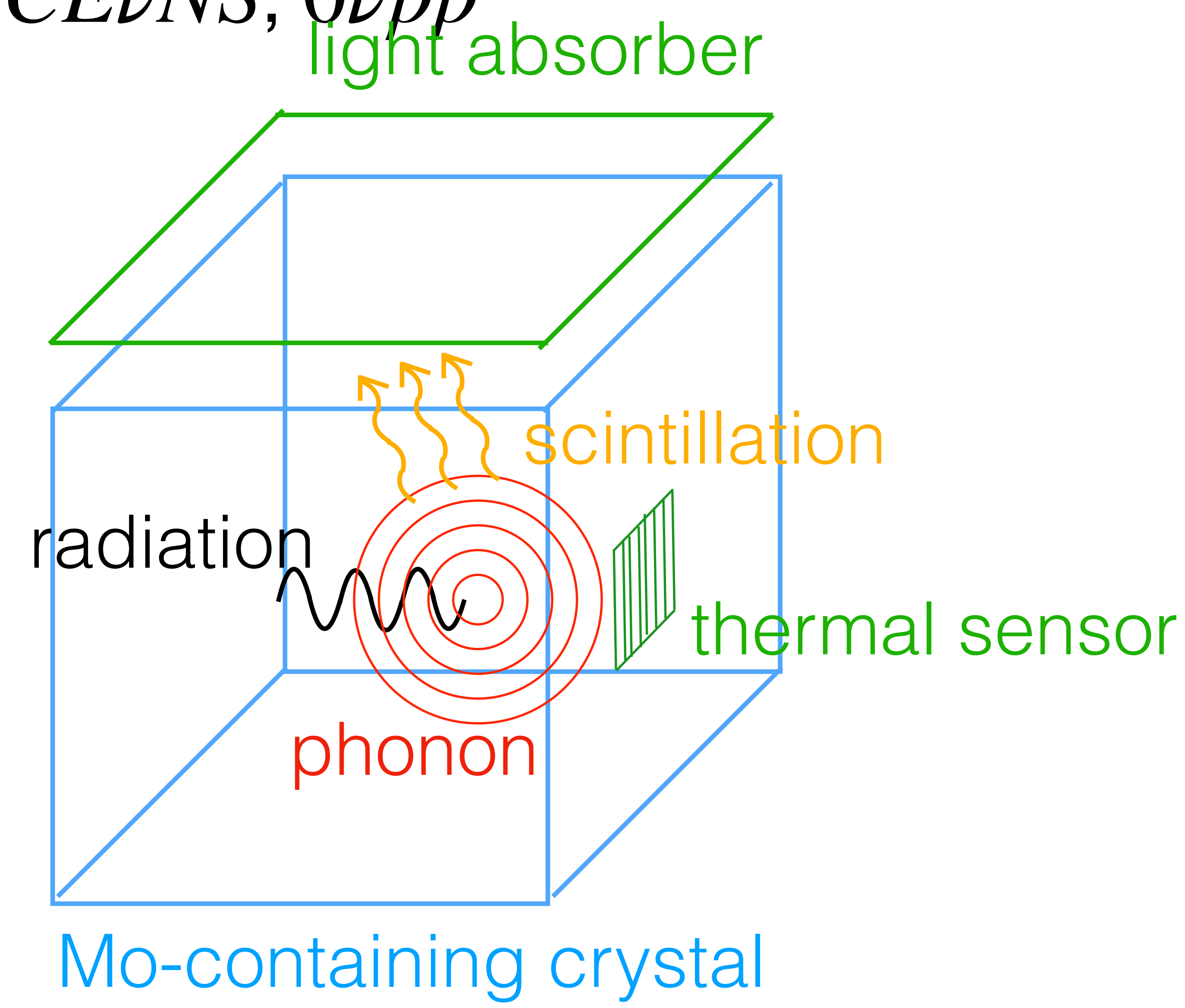
AMoRE experiment

^{100}Mo target material:

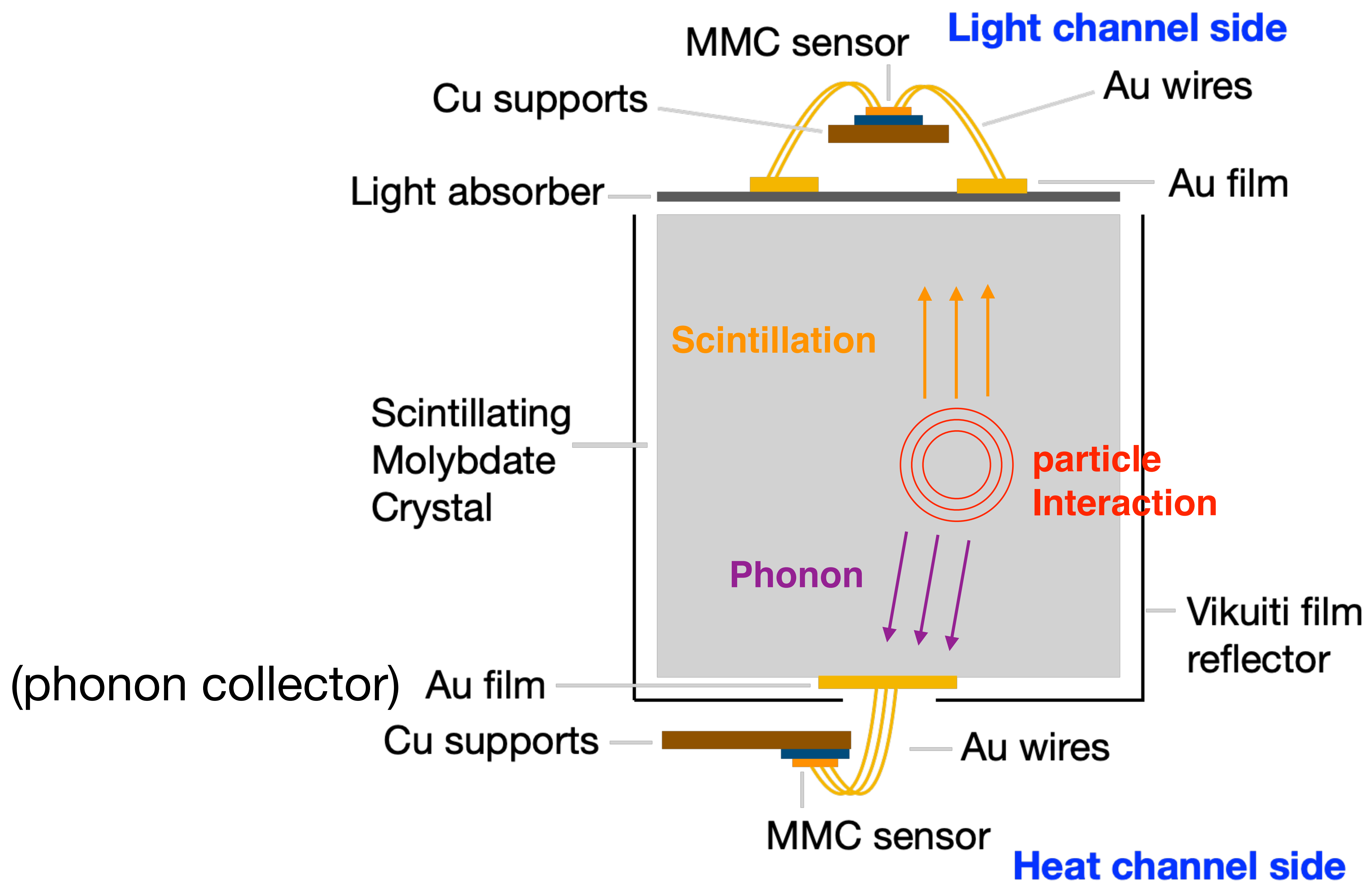
- Q-value = 3.034 MeV, natural abundance of 9.7%, relatively high rate

Cryogenic calorimeter with scintillating Mo-containing crystals

- At low temperature, small heat capacity with sensitive thermal sensor allowing the detection of tiny energy excess from radiation
- Good for low threshold or good energy resolution experiment: dark matter, $CE\nu NS$, $0\nu\beta\beta$
- Detecting energetic phonons and scintillation at ~10 mK
- High energy resolution with metallic magnetic calorimeter (MMC)
- Hybrid scintillation detection for particle identification
- Array of hundreds of detector modules



AMoRE detector



Scintillating molybdate crystal:

- $Ca^{100}MoO_4$ (CMO), $Li_2{}^{100}MoO_4$ (LMO) crystals
- 95% enrichment of ^{100}Mo

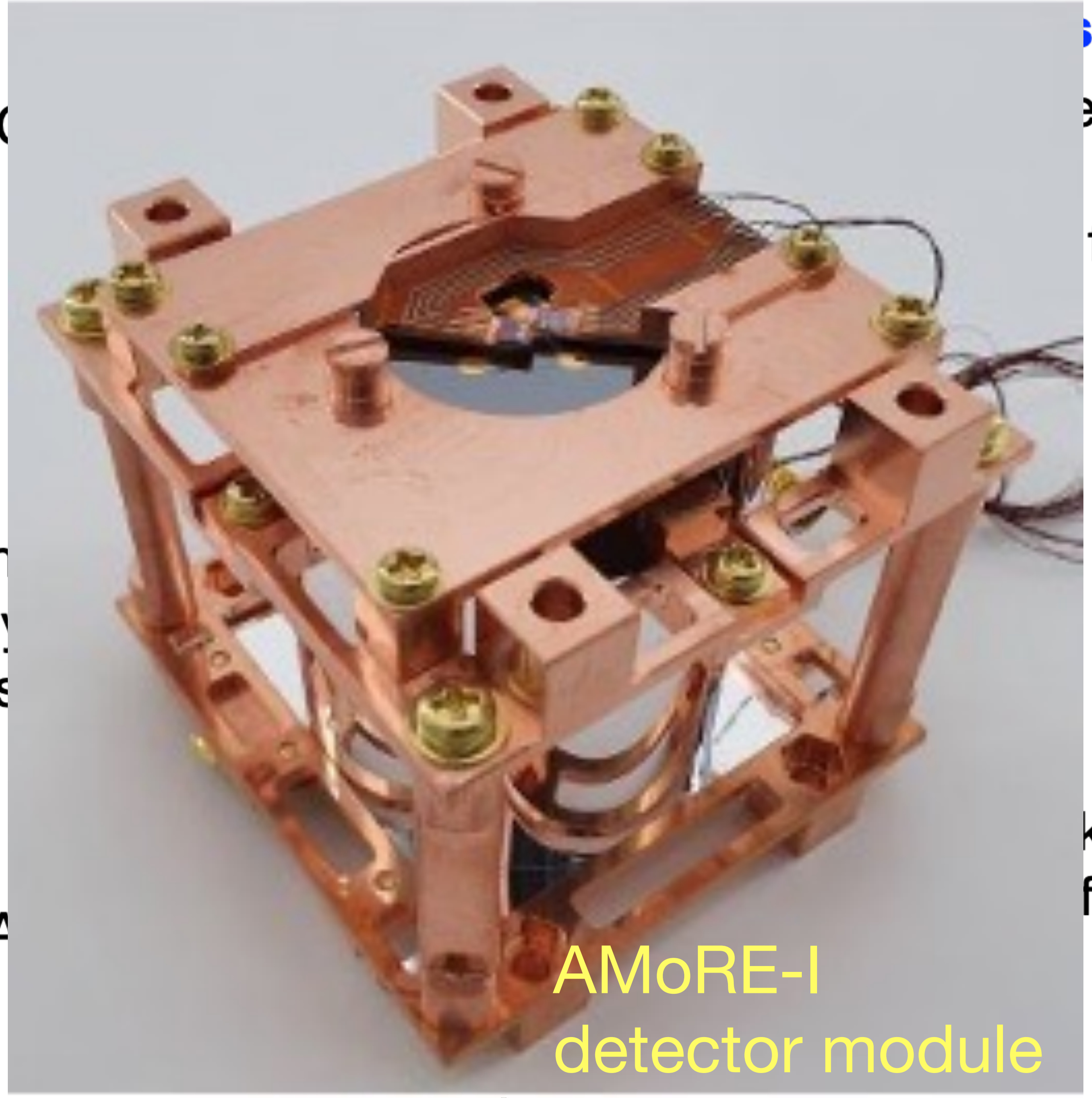
Signals:

ΔE -> phonons -> phonon collector

-> Δmagnetization (MMC) -> ΔI (SQUID)

AMoRE detector

side
es
(
Light
film
Scin
Mol
Crys
kuiti film
flector
(phonon collector) A
Cu



MMC sensor
Heat channel side

Scintillating molybdate crystal:

- $Ca^{100}MoO_4$ (CMO), $Li_2{}^{100}MoO_4$ (LMO) crystals
- 95% enrichment of ^{100}Mo

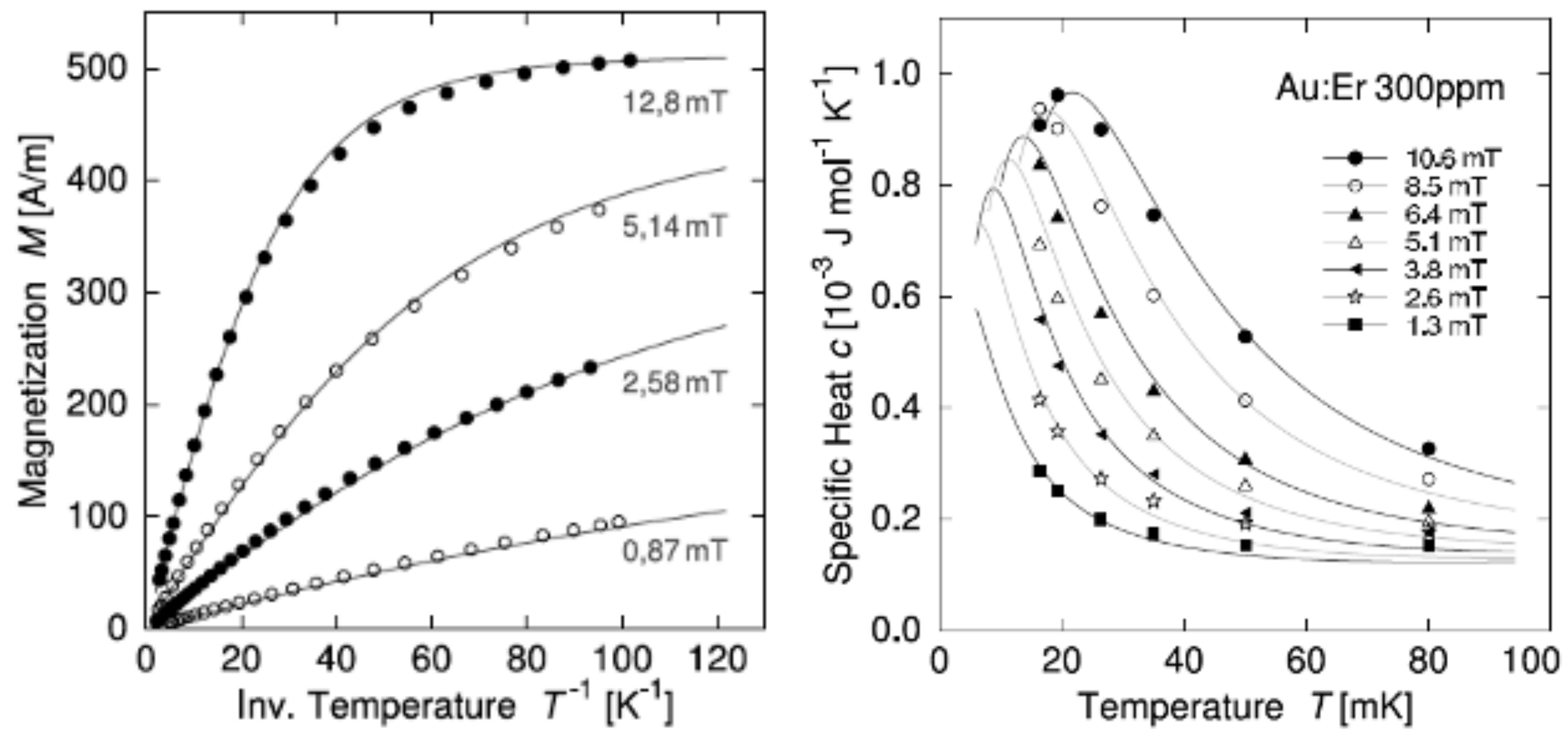
Signals:

ΔE -> phonons -> phonon collector

-> Δmagnetization (MMC) -> ΔI (SQUID)

Metallic magnetic calorimeter (MMC)

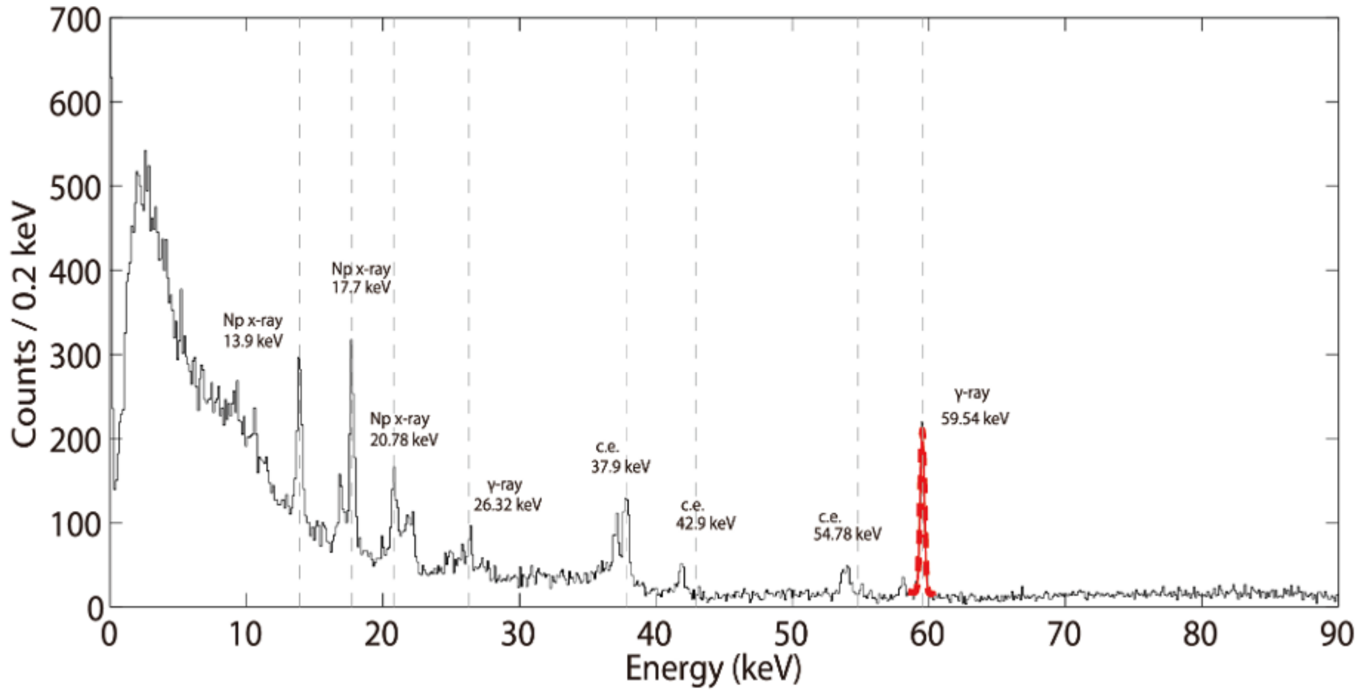
Paramagnetic temperature sensor, $M \sim 1/T$



Metallic Magnetic Calorimeters
A. Fleischmann et al (2005)

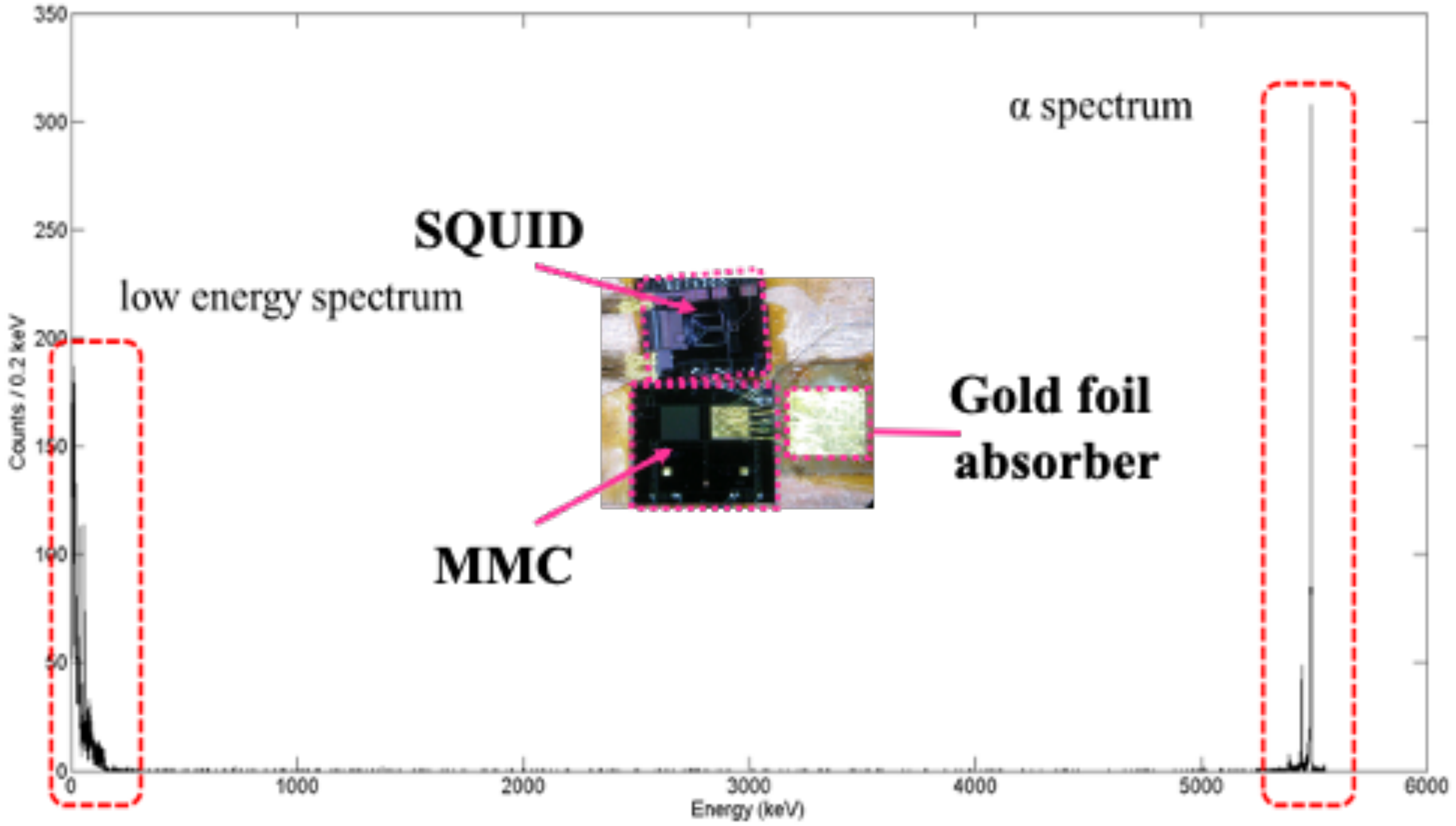
Dilute paramagnetic alloy : Au or Ag + ^{168}Er doping (~ 1000 ppm)

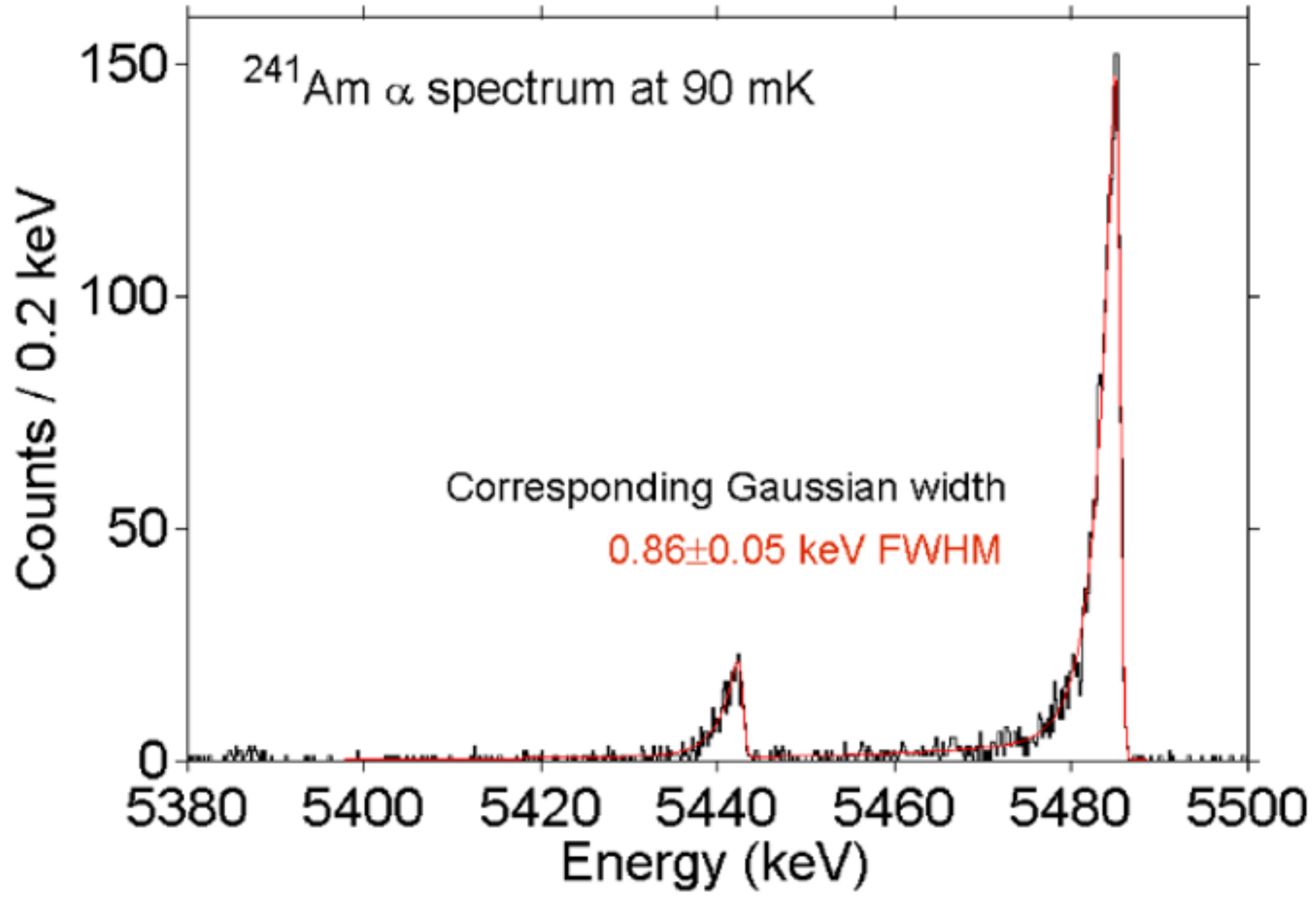
- Fast thermal response
- Choice of small RKKY (interactions between localized spins via electrons)
- Excellent dynamic range and energy resolution
- No bias heating



0.3 keV FWHM for 60 keV γ

Full energy spectrum
from ^{241}Am embedded in gold foil absorber





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

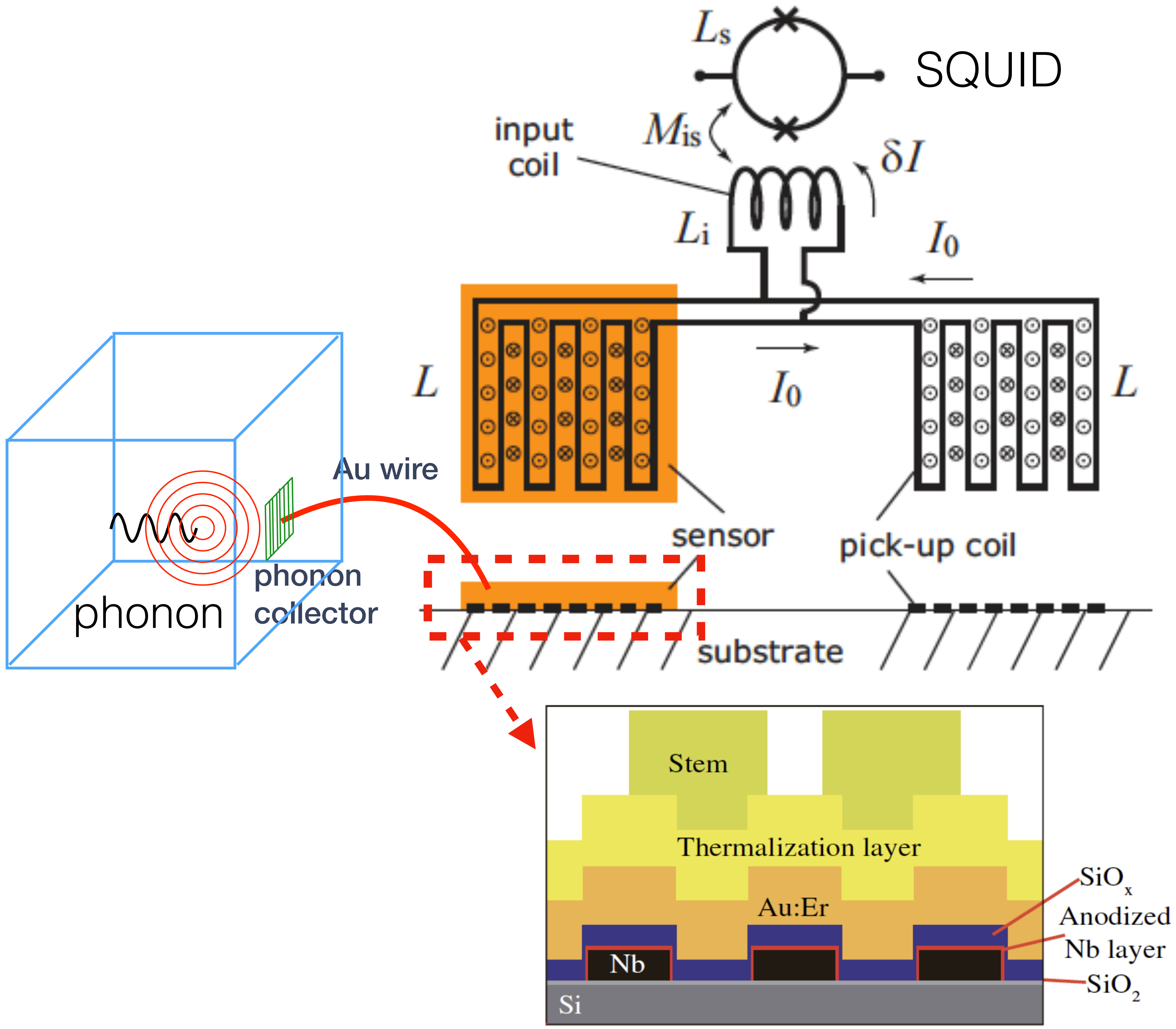
0.9 keV FWHM Gaussian Width@ 5.5 MeV α

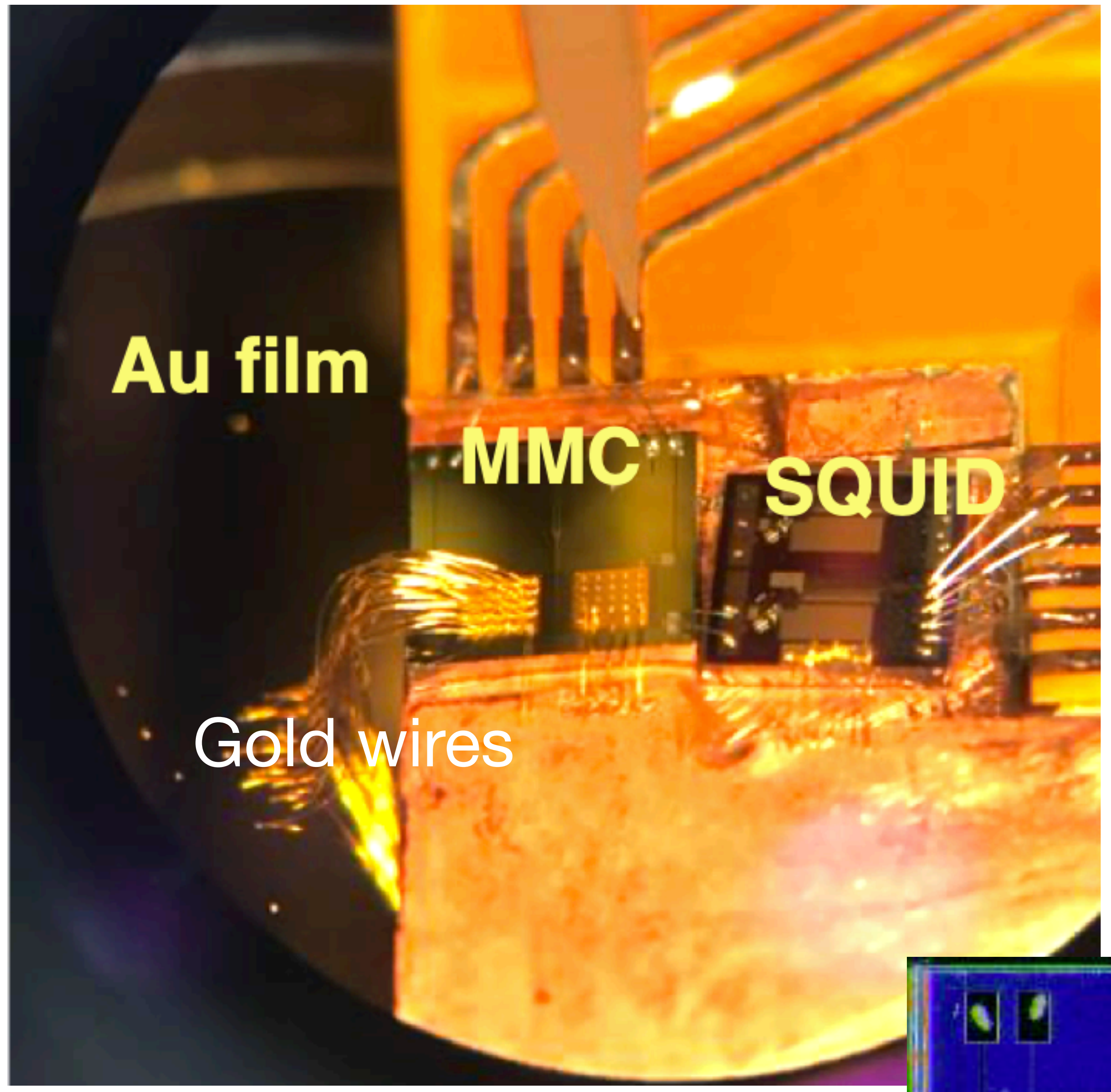
Hanbeom Kim's talk in LTD 2025

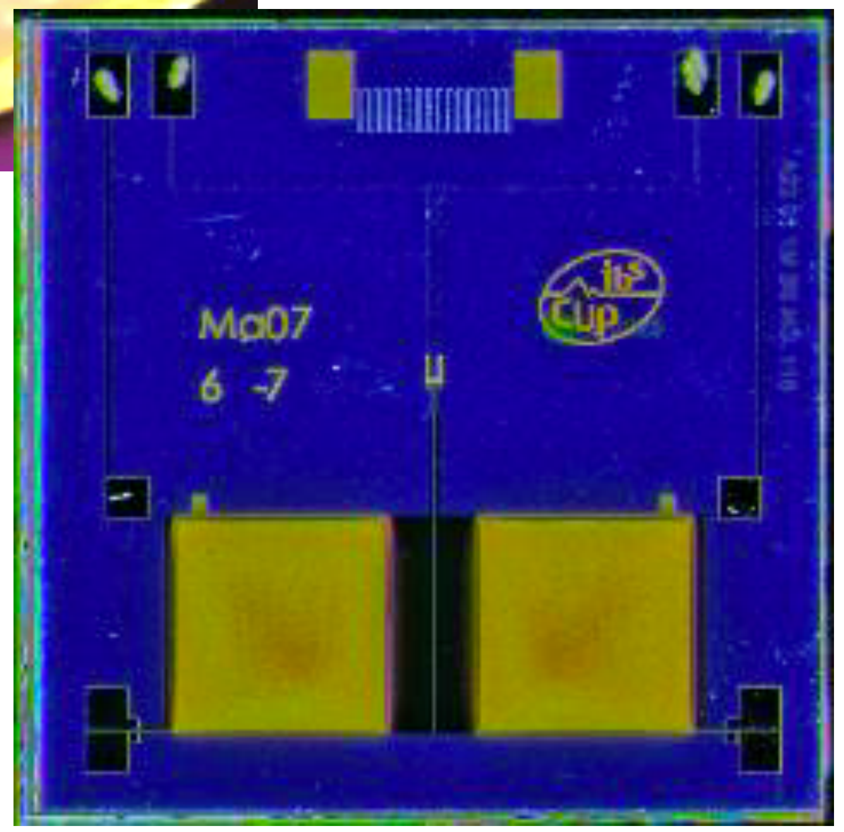
Metallic magnetic calorimeter (MMC)

Micro-fabrication:

- Planar meander-shaped superconducting current loop (Nb): Persistent bias field, ΔM pickups
- Loop + insulation + Ag:Er + gold absorber
- Flux transformer for SQUID readout







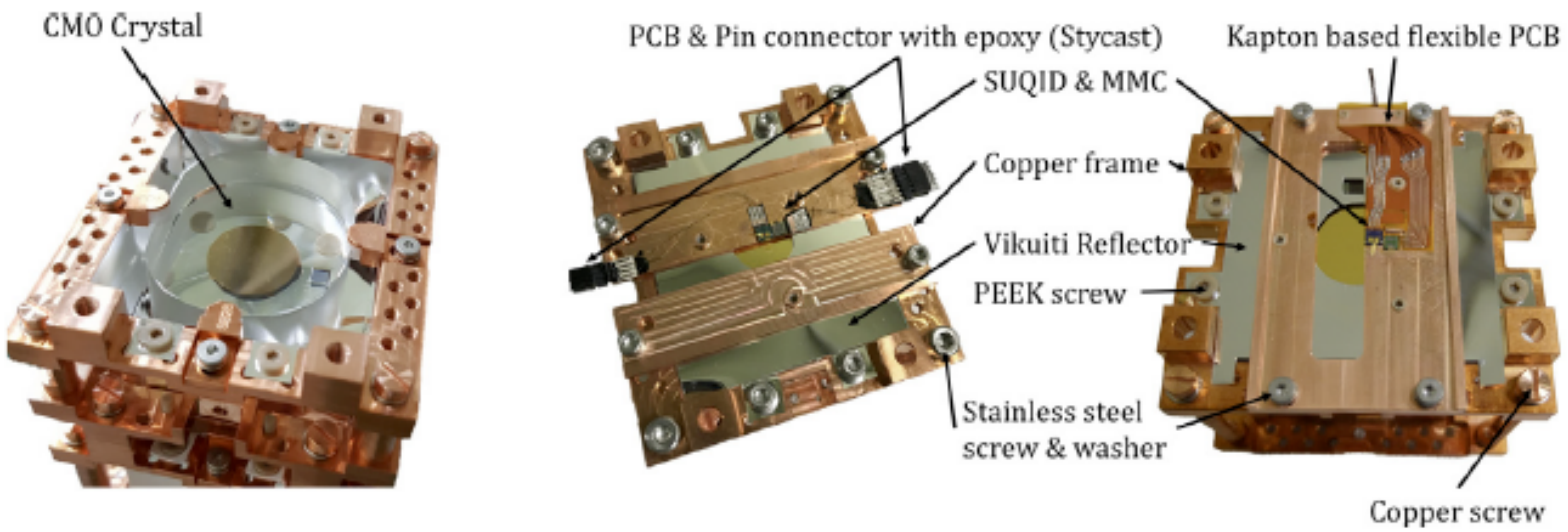
AMoRE-pilot

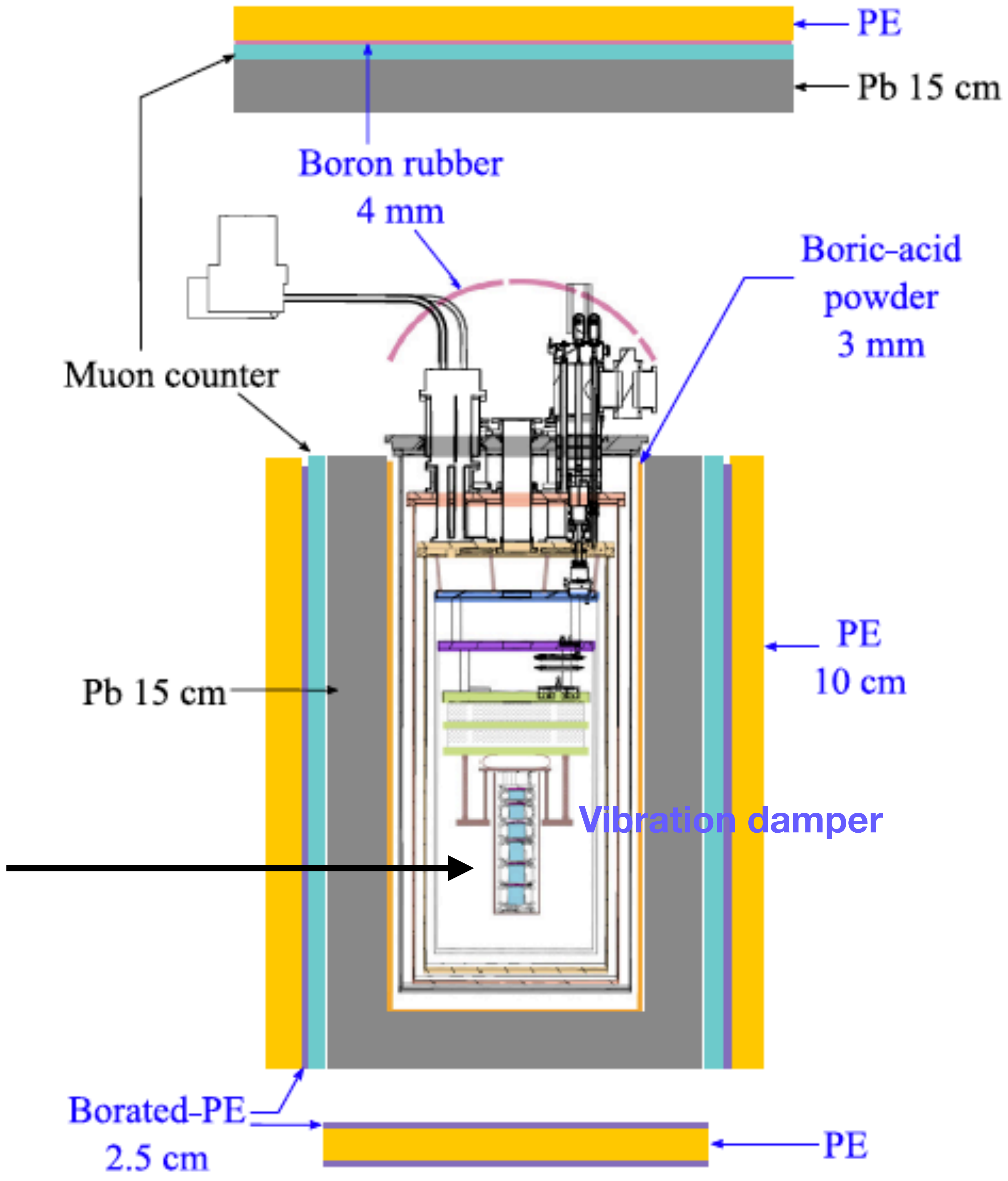
Duration: 2015 - 2018

6 $^{48dep}CaMoO_4$ crystals:
Highest light yield among Mo-containing crystals
95% ^{100}Mo enrichment
1.9 (0.88) kg of CMO (^{100}Mo)

3 configuration run:
Replacing radioactive components
Enhancing neutron shielding

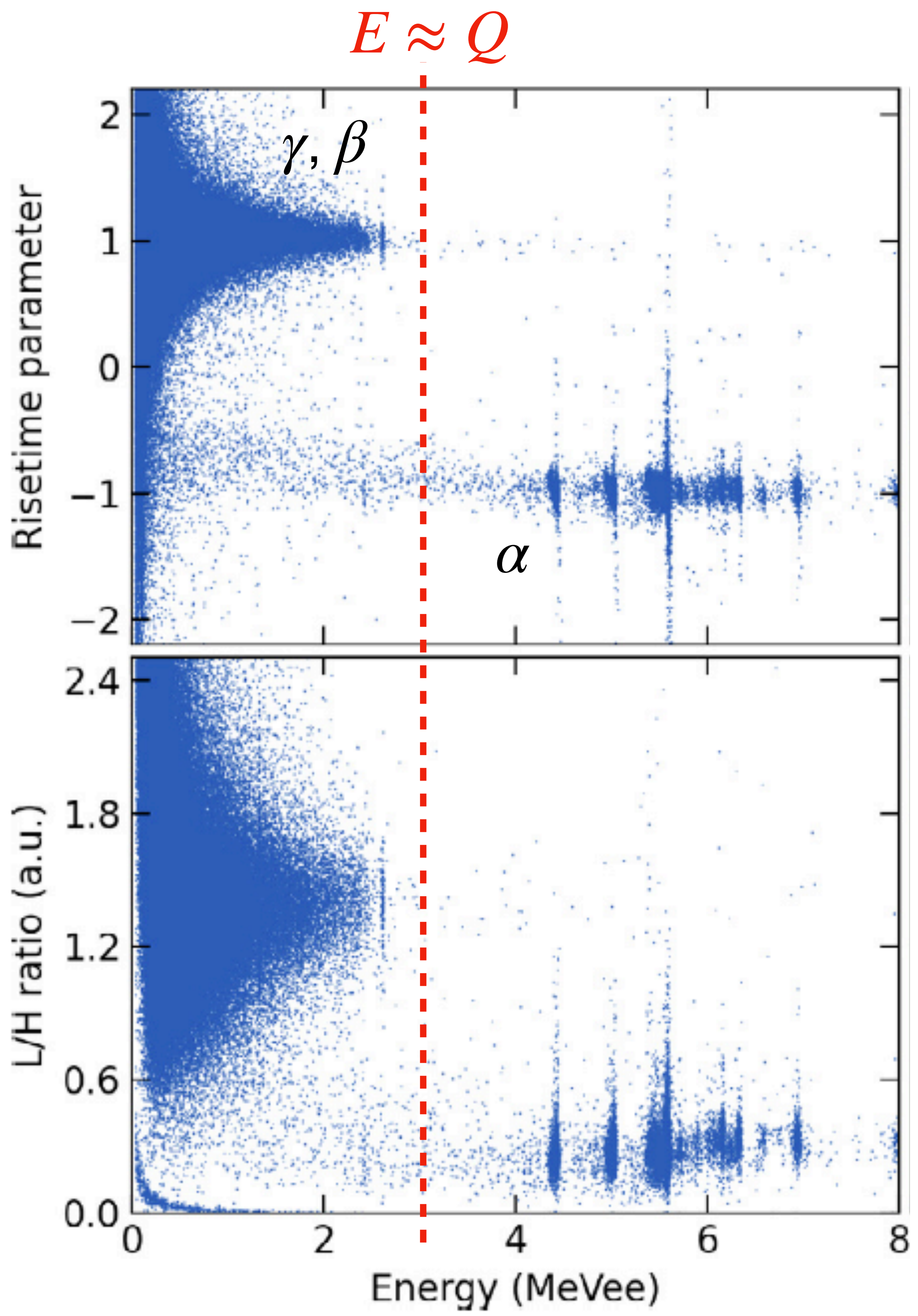
Muon veto with plastic scintillator panels (~91% coverage)



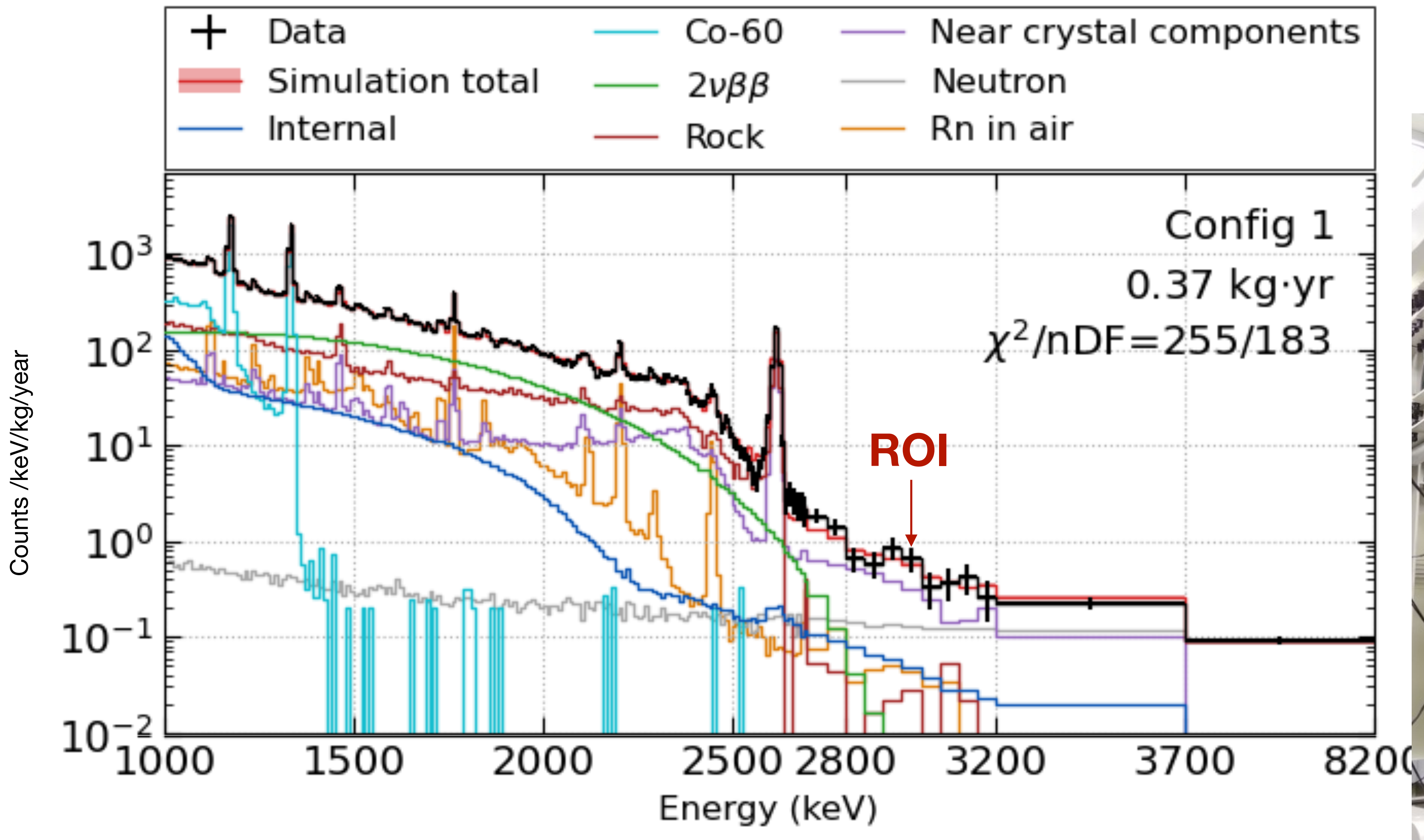


AMoRE-pilot

- Site: Yangyang underground lab (Y2L, 700 m depth)
  Neighbor of KIMS, COSINE DM experiment
- Exposure: ~ 0.32 $kg_{Mo\text{-}100} \cdot yr$
- Background at the ROI (Q = 3.034 MeV): 0.5 cnts/keV/kg/year (ckky)
- Setting the limit for the half-life $T^{0\nu}_{1/2} > 3.2 \times 10^{23}$ yrs (90% CL) for Mo-100
- Demonstration of detector principle and background reduction



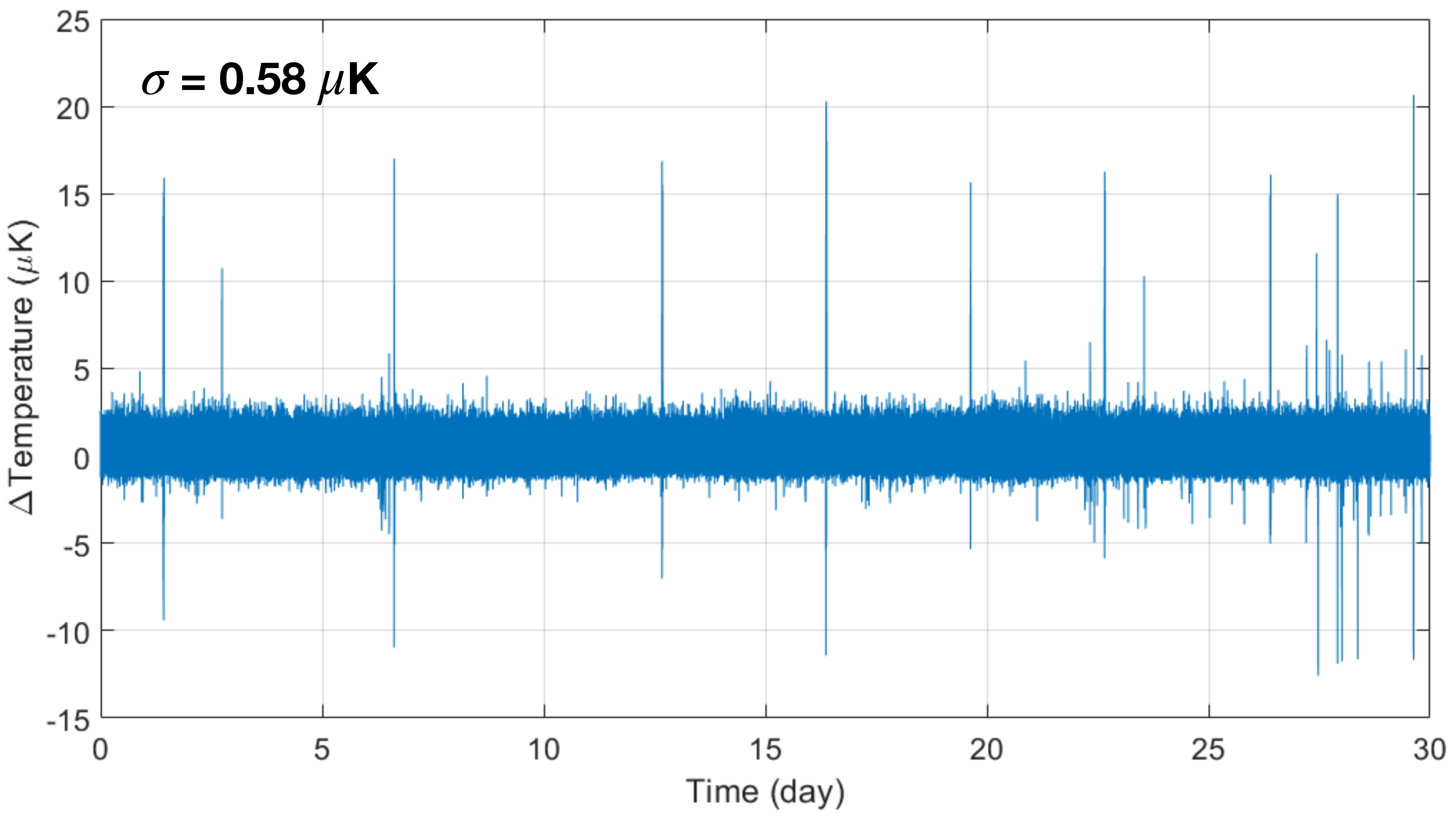
Astropart. Phys. 162 102991 (2024)
EPJC 79:791 (2019)

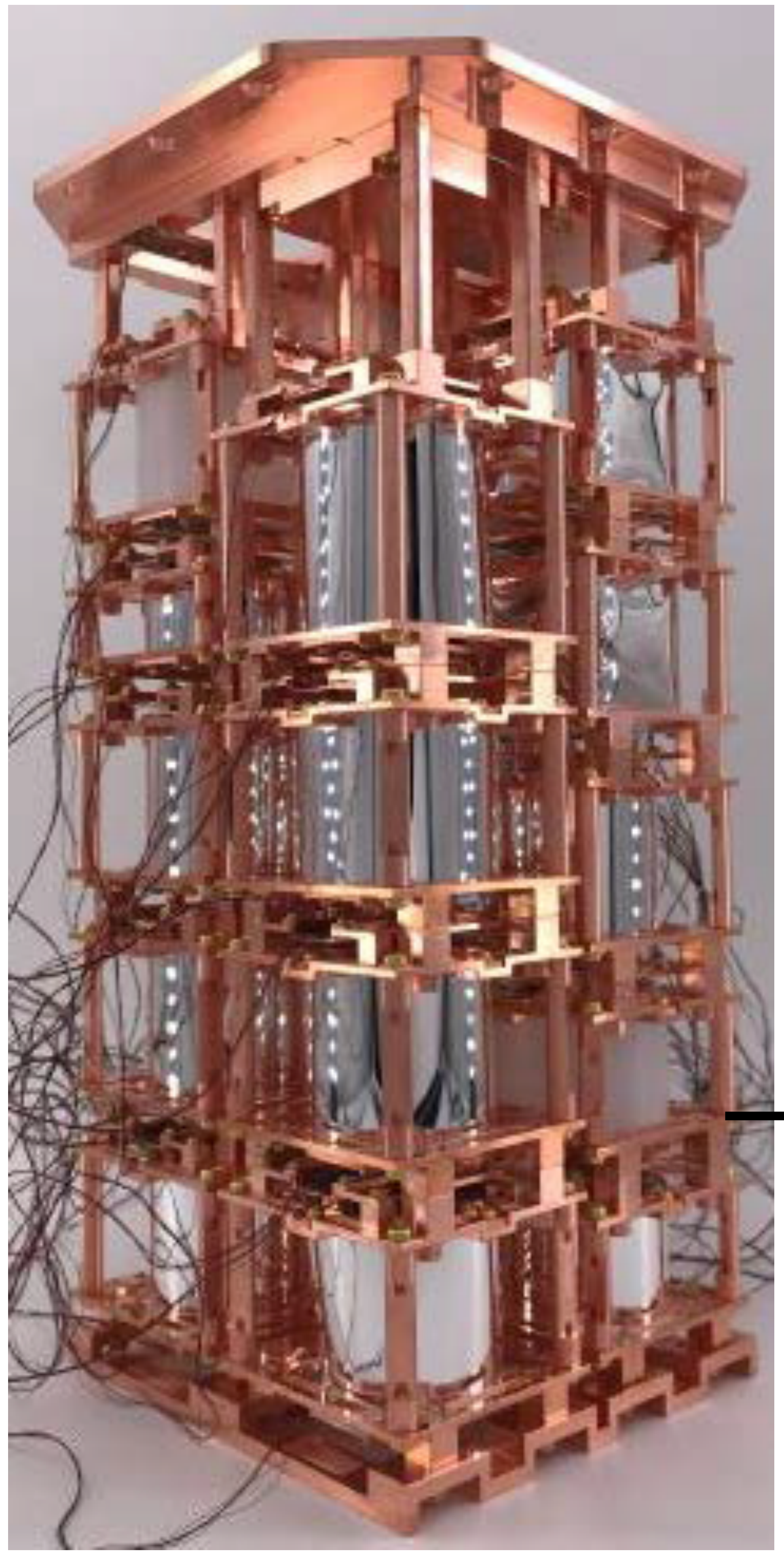


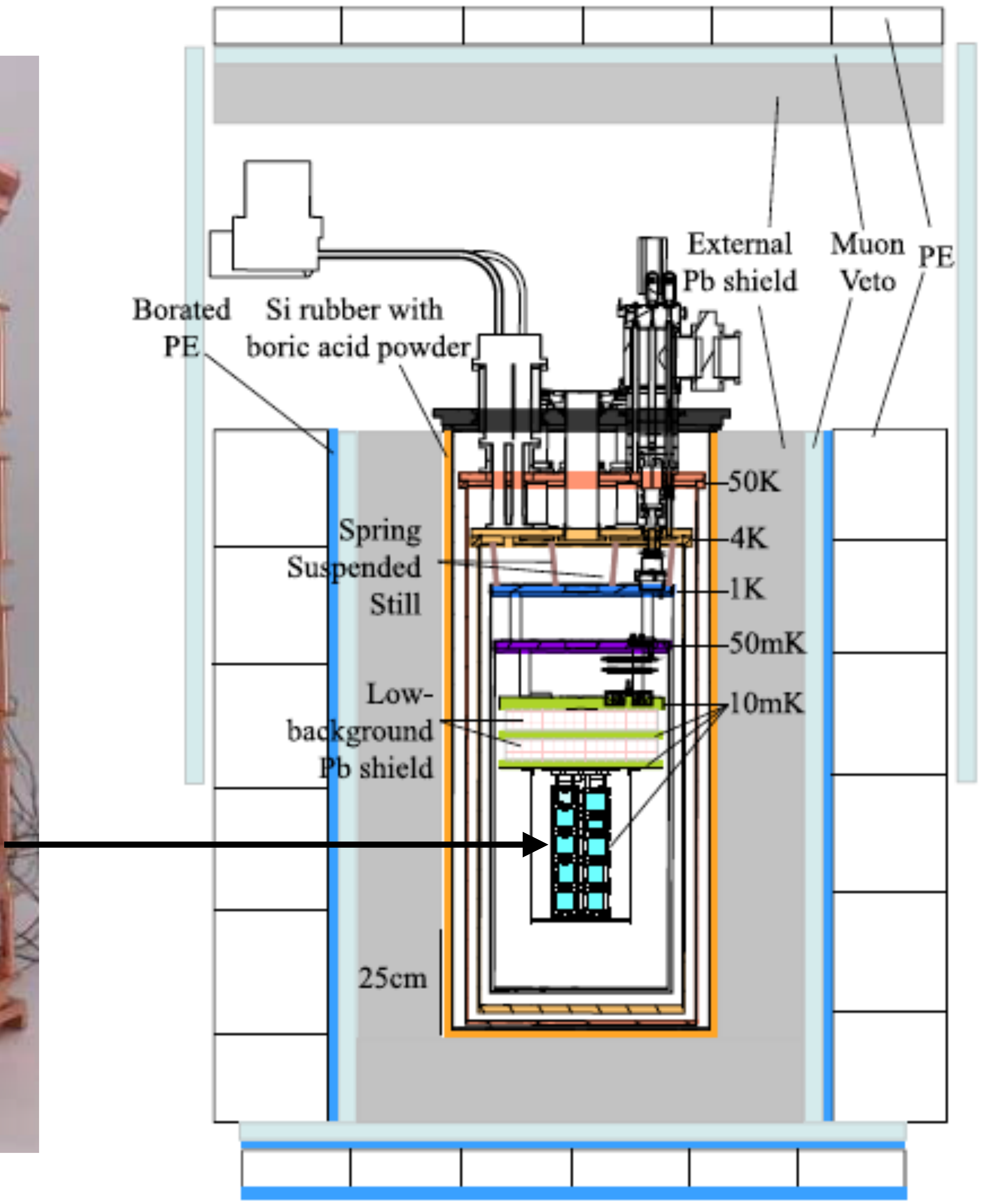
AMoRE-I

Duration: 2020 - 2023

- Same cryostat at Y2L
- 13 $^{48dep}CaMoO_4$ + 5 Li_2MoO_4:
  6.2 (3.0) kg of CMO/LMO (^{100}Mo)
- MMC sensor upgrade: Au:Er -> Ag:Er
- Two stage temperature control: $\Delta T < 1\mu$K at 12 mK
- Shielding enhancement:
  Pb, PE, boric acid silicon, ~ 4π muon veto coverage
- More stable supply of Rn-free air



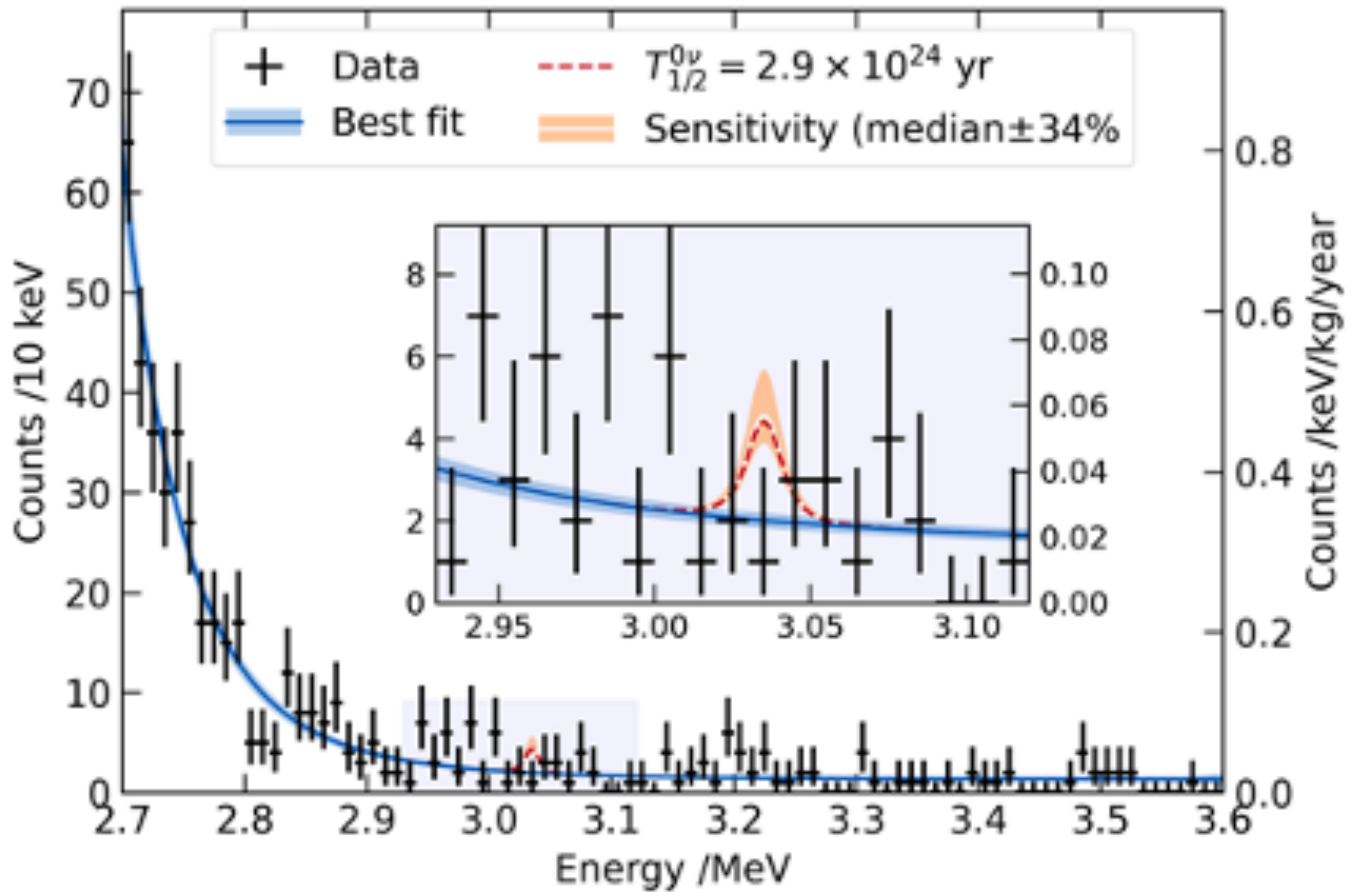




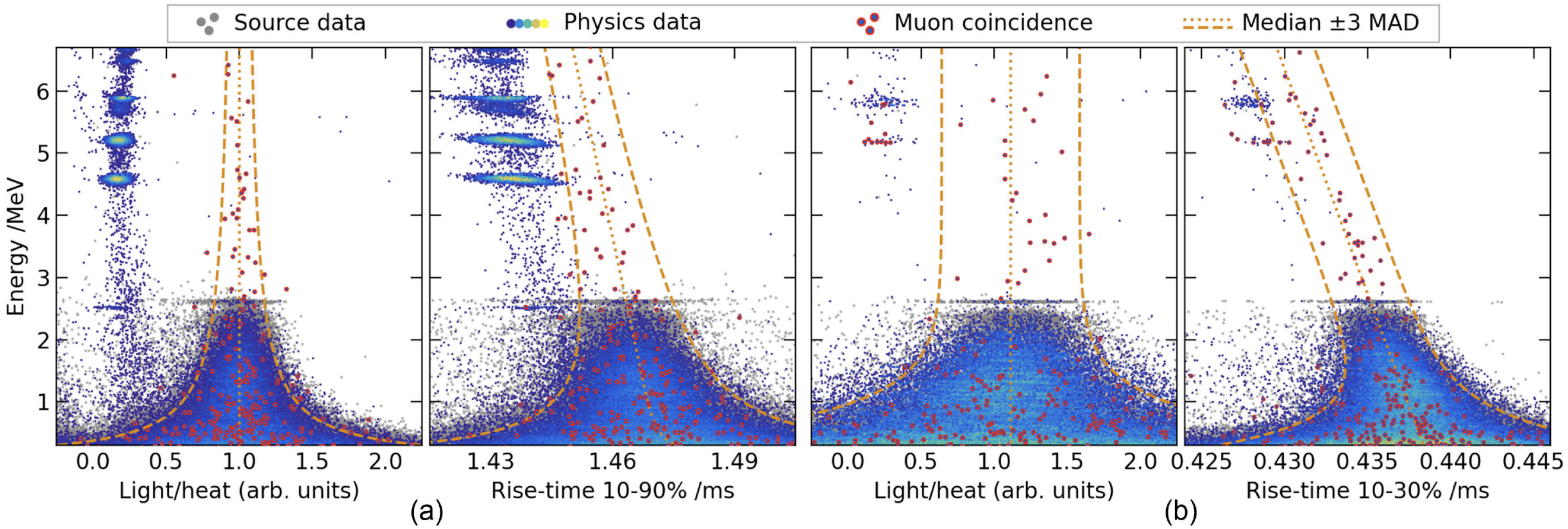
AMoRE-I

Duration: 2020 - 2023

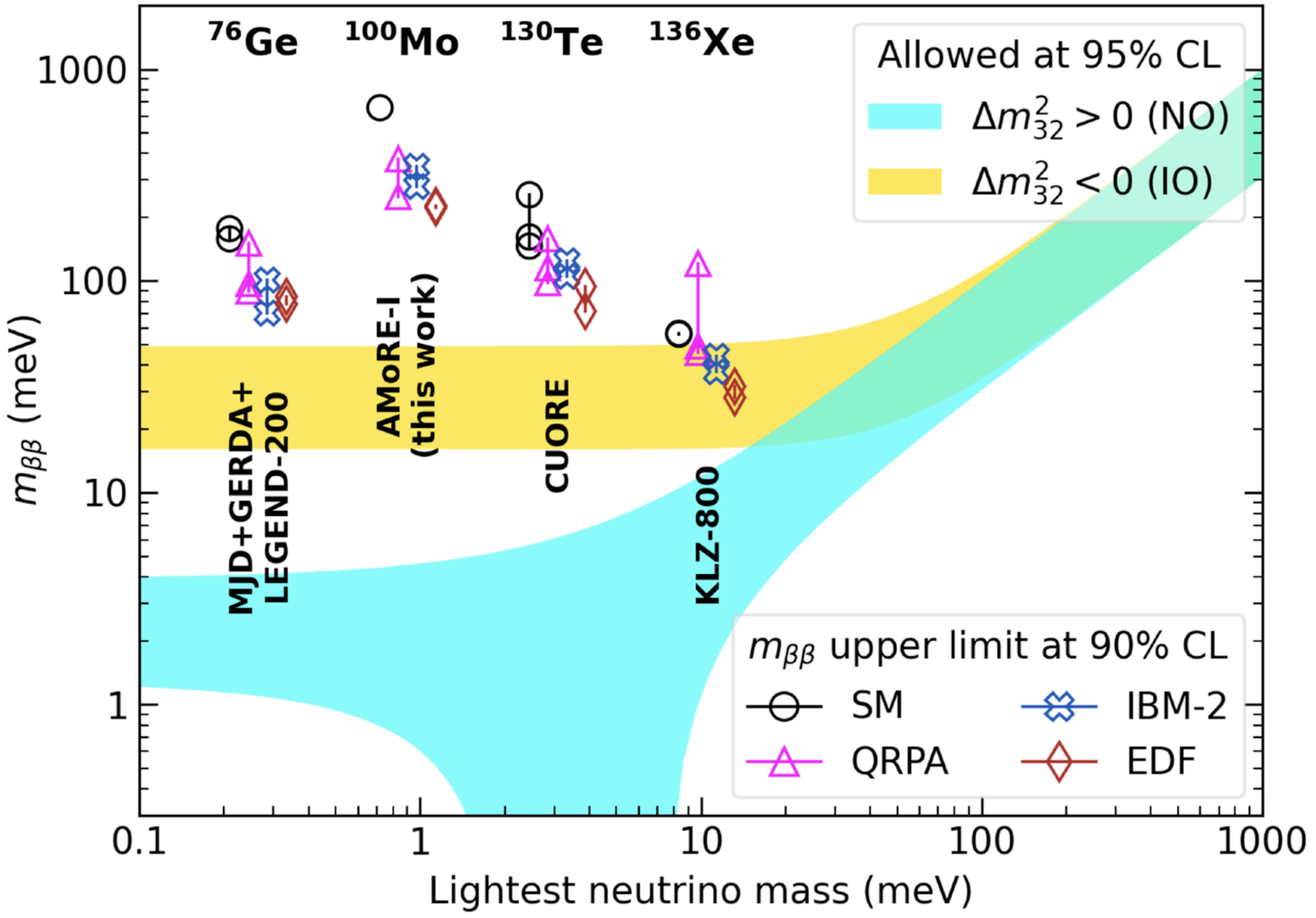
- Exposure: ~ 4 $kg_{Mo\text{-}100}$·yr
- Background: ~0.025 ckky (1/20 of AMoRE-pilot)
  CMO showing high rejection power, but large contamination
  LMO low small
- $T^{0\nu}_{1/2} > 2.9 \times 10^{24}$ yrs (90% CL)
- $m_{\beta\beta} < (210 - 610)$ meV
- World best limit for $0\nu\beta\beta$ of Mo-100



PRL 134 082501 (2025)



CMO LMO



Now, aiming at much higher sensitivity with AMoRE-II

An ambitious scaling-up being pursued !

Goals for AMoRE-II

AMoRE-II wil be built in new underground facility, Yemilab.

Survey of Mo-containing crystals

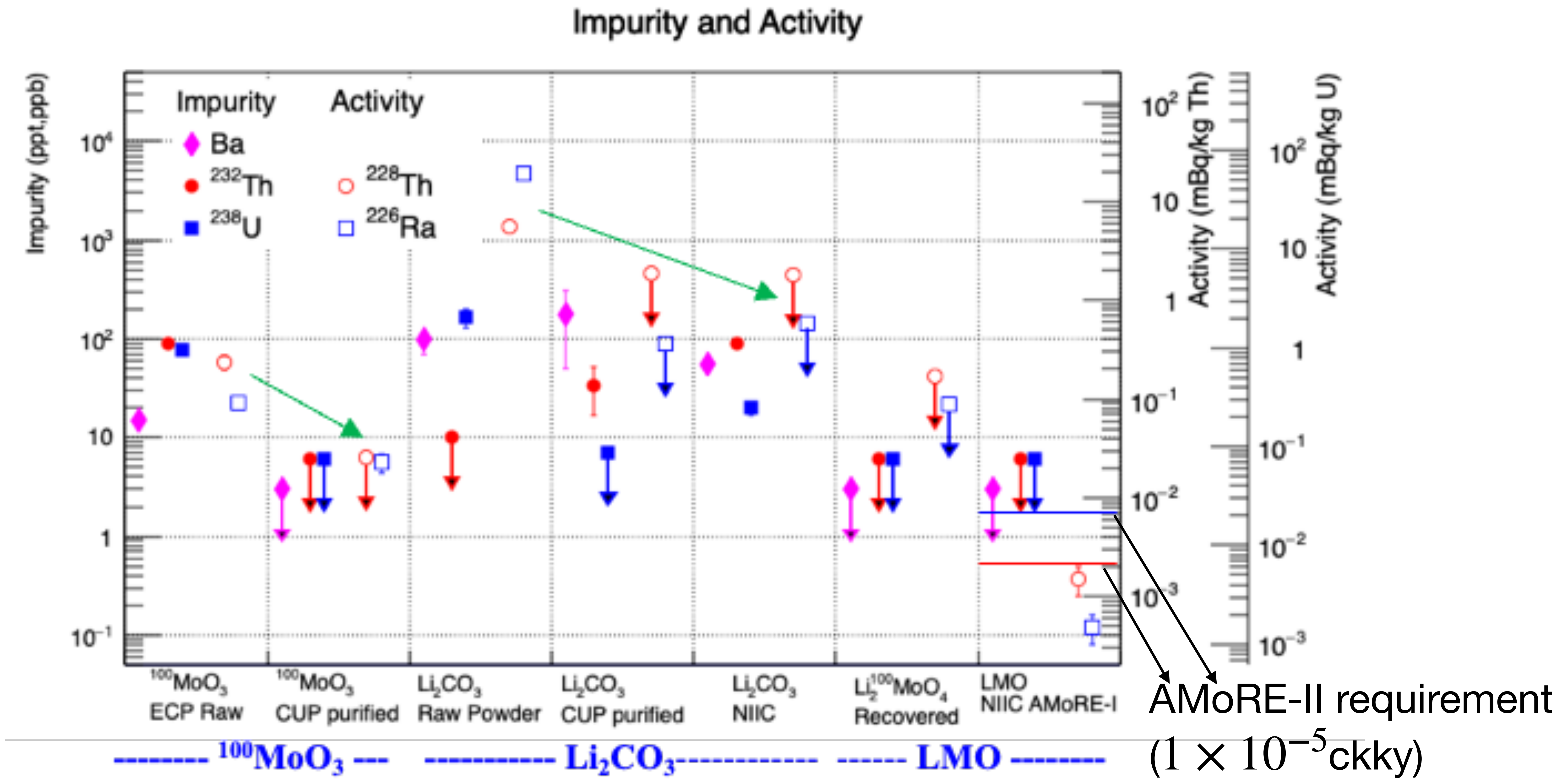
- CMO requires ^{48}Ca depletion and annealing for optical transparency
- LMO has light output smaller than CMO by a factor ~ 8 (Cf. ~ 20 @ 10 K)
- But, discrimination power w/ light detector is similar between these two crystals
- LMO Crystal growing is easier among crystal candidates
- **LMO crystal is chosen for AMoRE-II**

Crystals	Scintillation							Mechanical			Thermal		Comment
	λ_{em} (nm)	Eg (eV)	τ (μs) @10K	τ_f, τ_s (μs) @10mK	A_f/A_s	E scint (Rel.)	Quenching	Dens. (g/cc)	T_M (C)	Mo Fraction	T_D (K)	C (pJ/Kcm^{-3})	
CMO	540	3.78	240	80,4400	0.2	100	0.22	4.32	1445	0.49	446	2.8-3.0	CARAT
NMO	663	3.50	750	60,690	0.3	9	0.06	3.62	687	0.558	332	6.2	NIIC
LMO	535	4.26	23	40,410	1.8	5	0.28	3.03	705	0.562	316	7.5	CUP
PMO	592	3.20	20			105		6.95	1065	0.269			
ZMO	620	4.3				32		4.37	1003	0.436	625		

* CMO(CaMoO4), NMO($Na_2Mo_2O_7$), LMO(Li_2MoO_4), PMO($PbMoO_4$), ZMO($ZnMoO_4$)

Crystal production

Li_2MoO_4 crystals (^{100}Mo enrichment ~ 96%)
Intensive purification of raw material ($^{100}MoO_3$, Li_2CO_3 powders) at CUP & NIIC: ~5 years of work

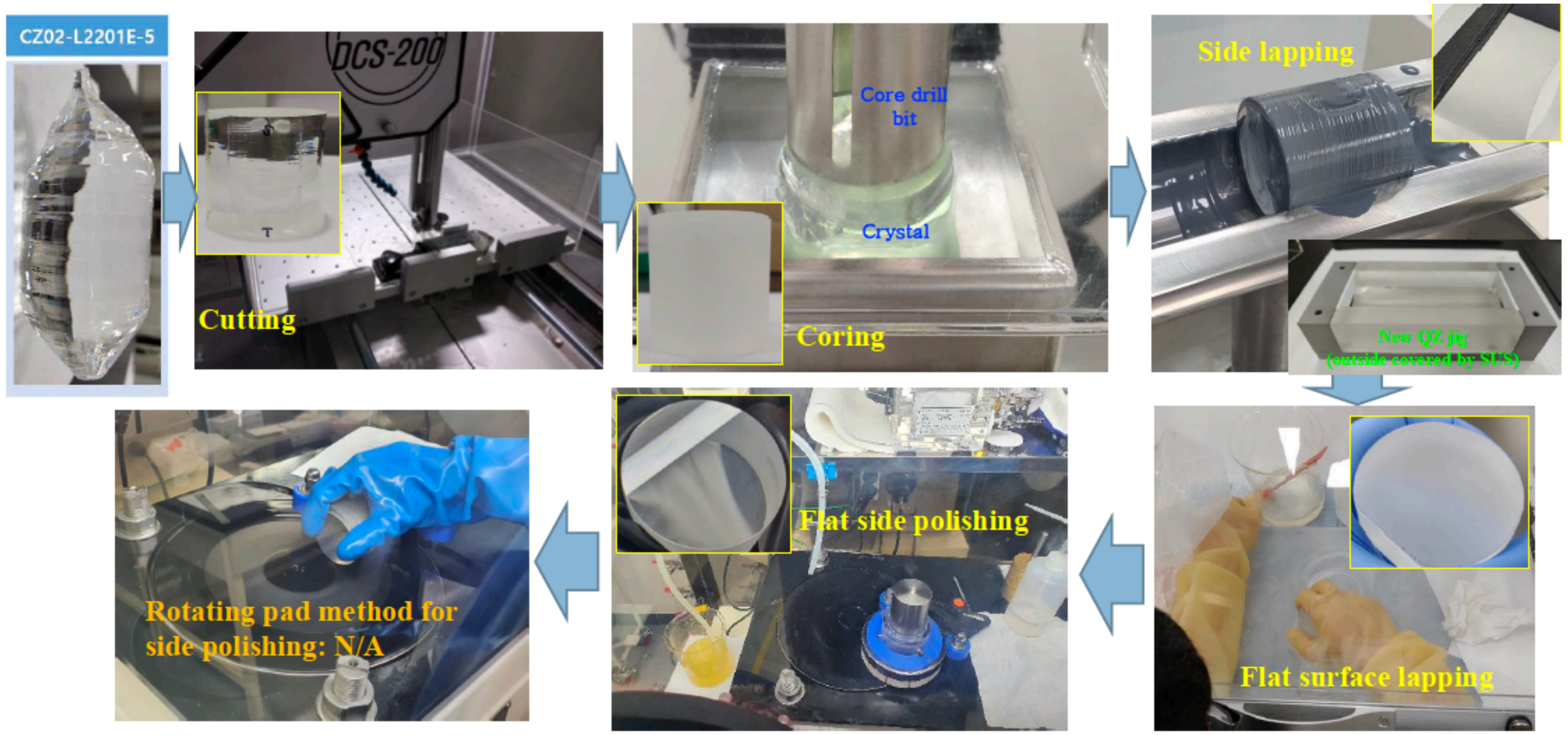


Recyling of crystal melts and wastes is going on

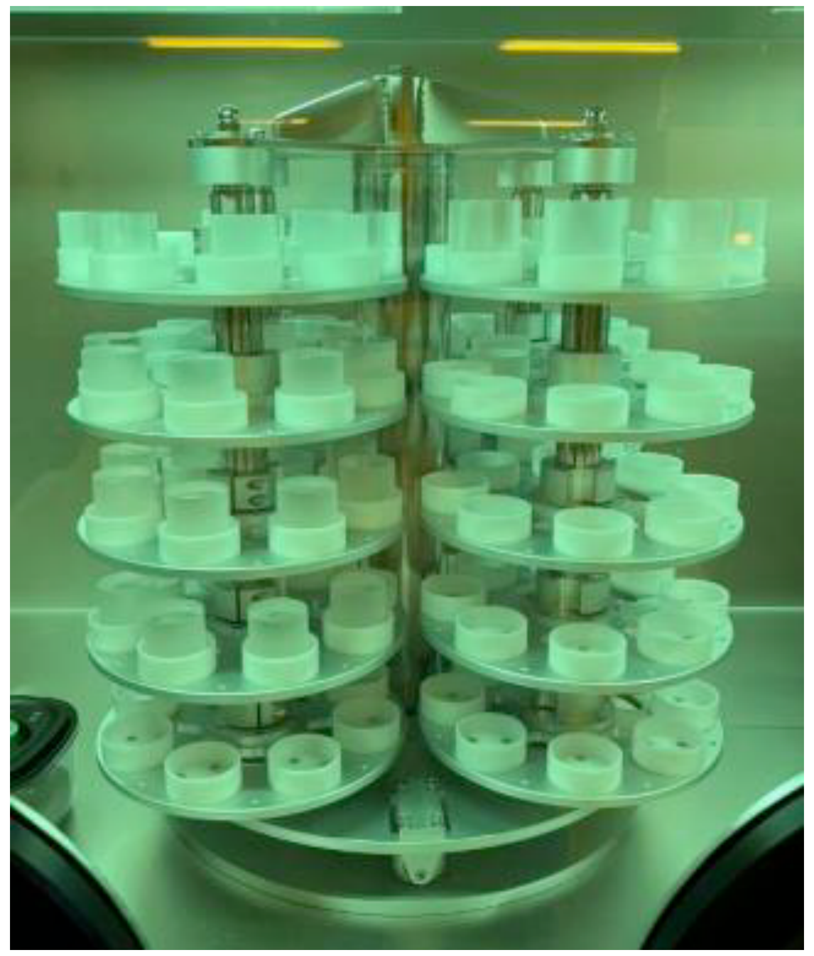
Front. Phys. 11:1142136 (2023)
Front. Phys. 12:1347162 (2024)
Appl. Radiat. Isot. 193, 110654 (2023)

Crystal production

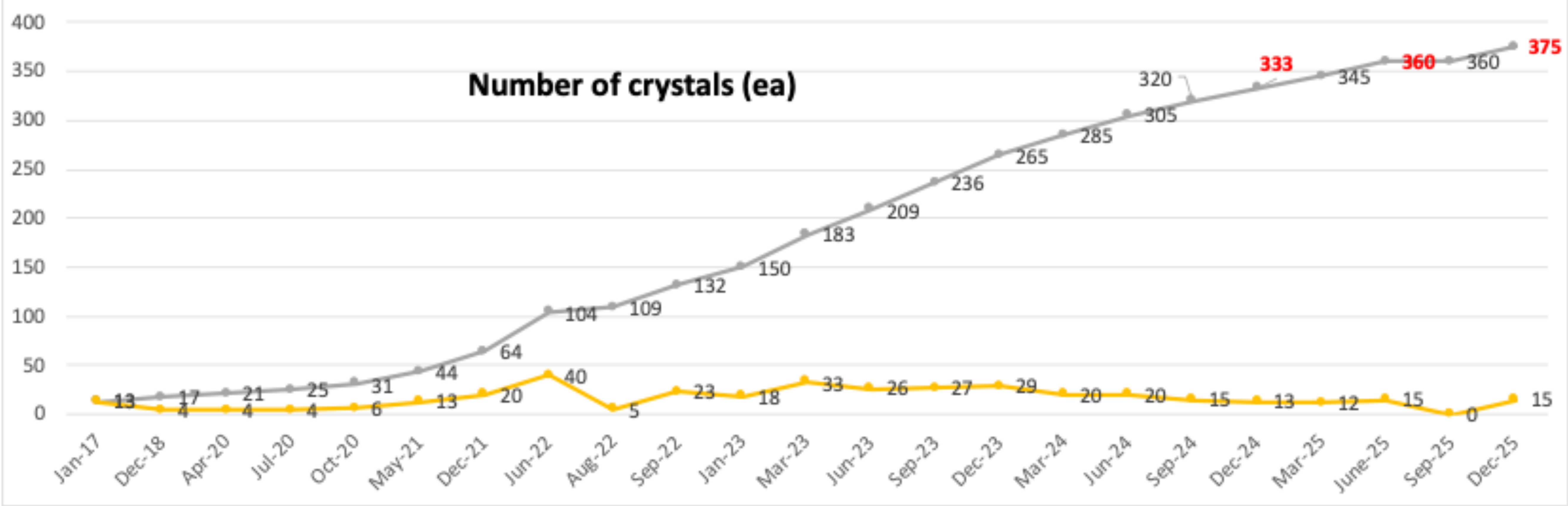
Crystal growing & surface treatment
- CUP (Czochralski) and NIIC (low temp. gradient CZ)
- Protocols for the crystal production established:
  Lapping / polishing for massive crystals: low background abrasives
  LMO is hygroscopic crystal: crystals covered with vacuum oil, stored in dry box
  ~ Half of the crystals polished and the others lapped
- Cylindrical crystals with 5 cm (D) x 5 cm (H) & 6 cm x 6 cm



Crystal production

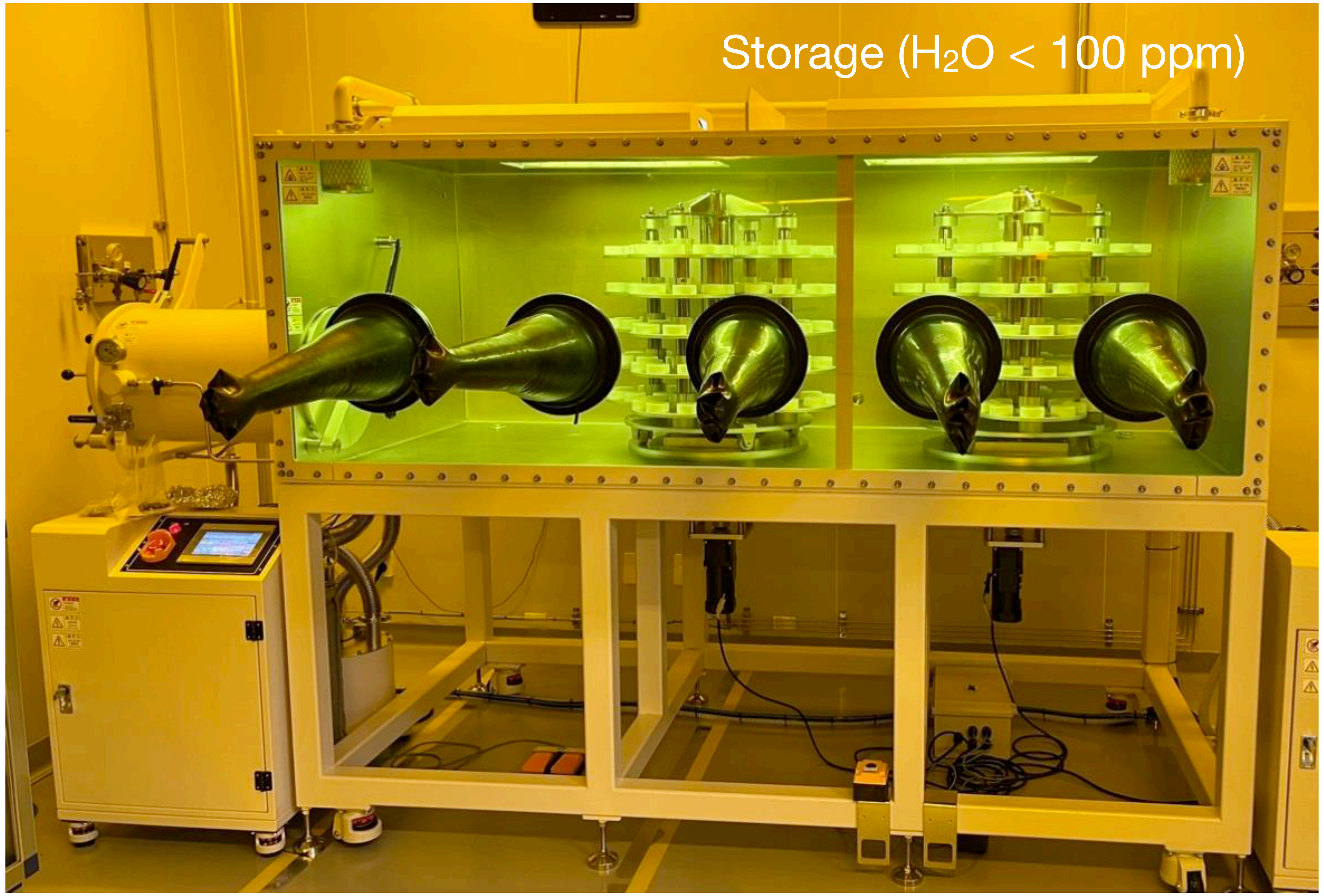


Crystal storage
- Several years of campaign
- ~260 crystals (~110 kg) in storage + ~80 crystals for surface treatment, almost there!
- Low background verified



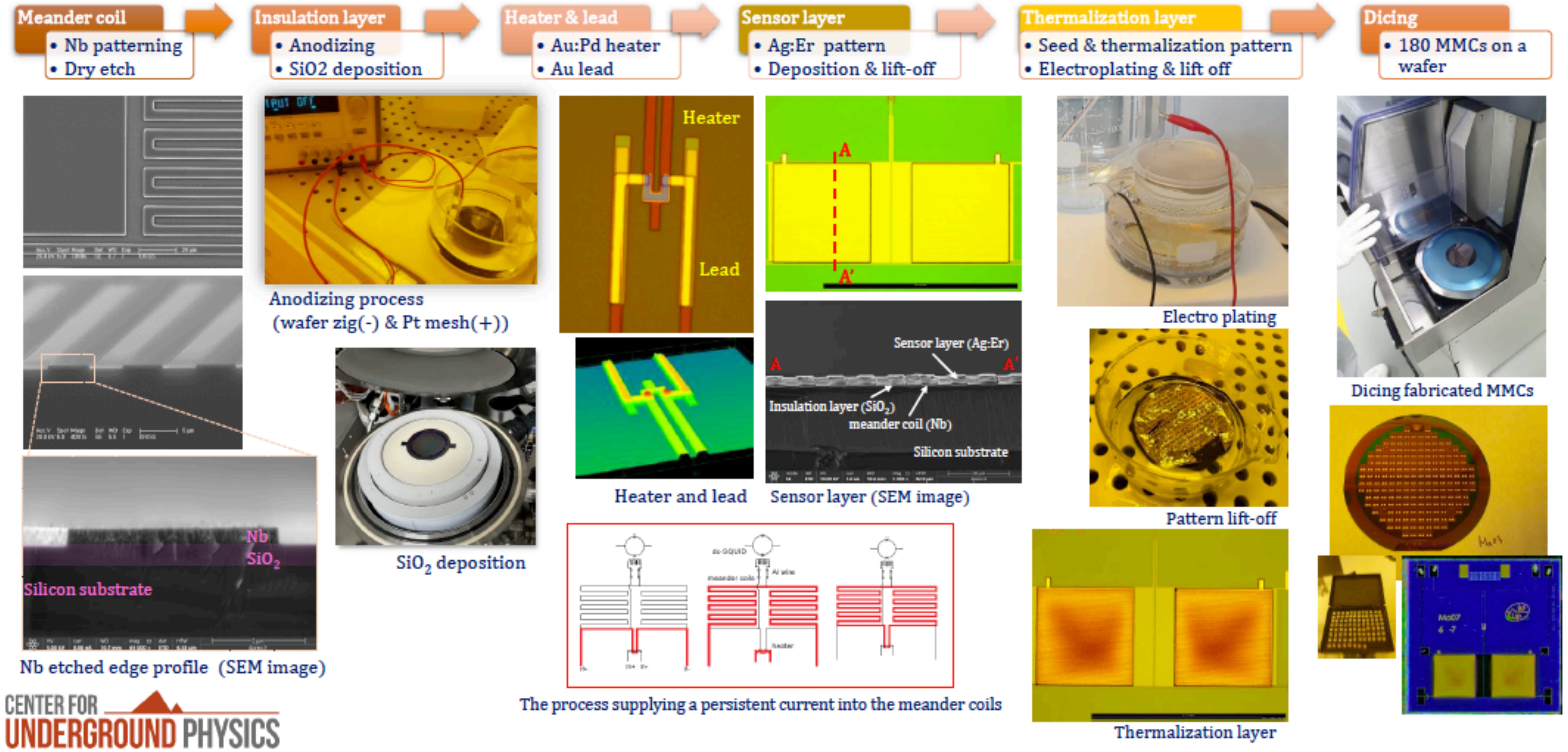
Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)
Crystal	Natural CMO (1902)[a]	CUP	56 (4)	< 5.5	< 5.3	< 39
	Enriched CMO (SE#3)[b]	CUP	< 2.0	< 3.2	< 1.6	< 3.2
	Natural LMO (1602)[a]	CUP	< 3.3	< 2.6	< 1.5	29 (9)
	Natural LMO (1801)[b]	CUP	< 1.2	< 3.2	< 1.3	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

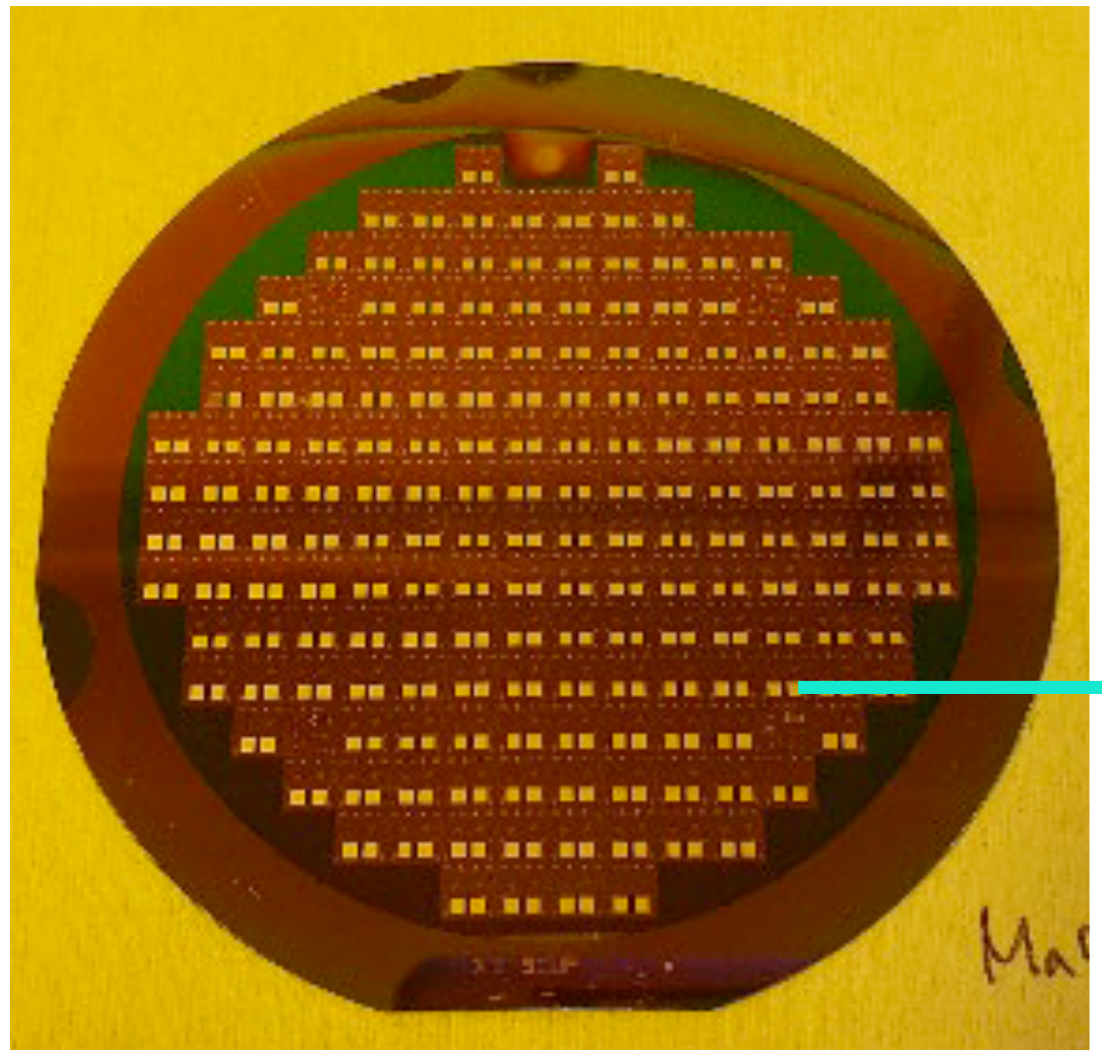
Front. Phys. 12:1362209 (2024)

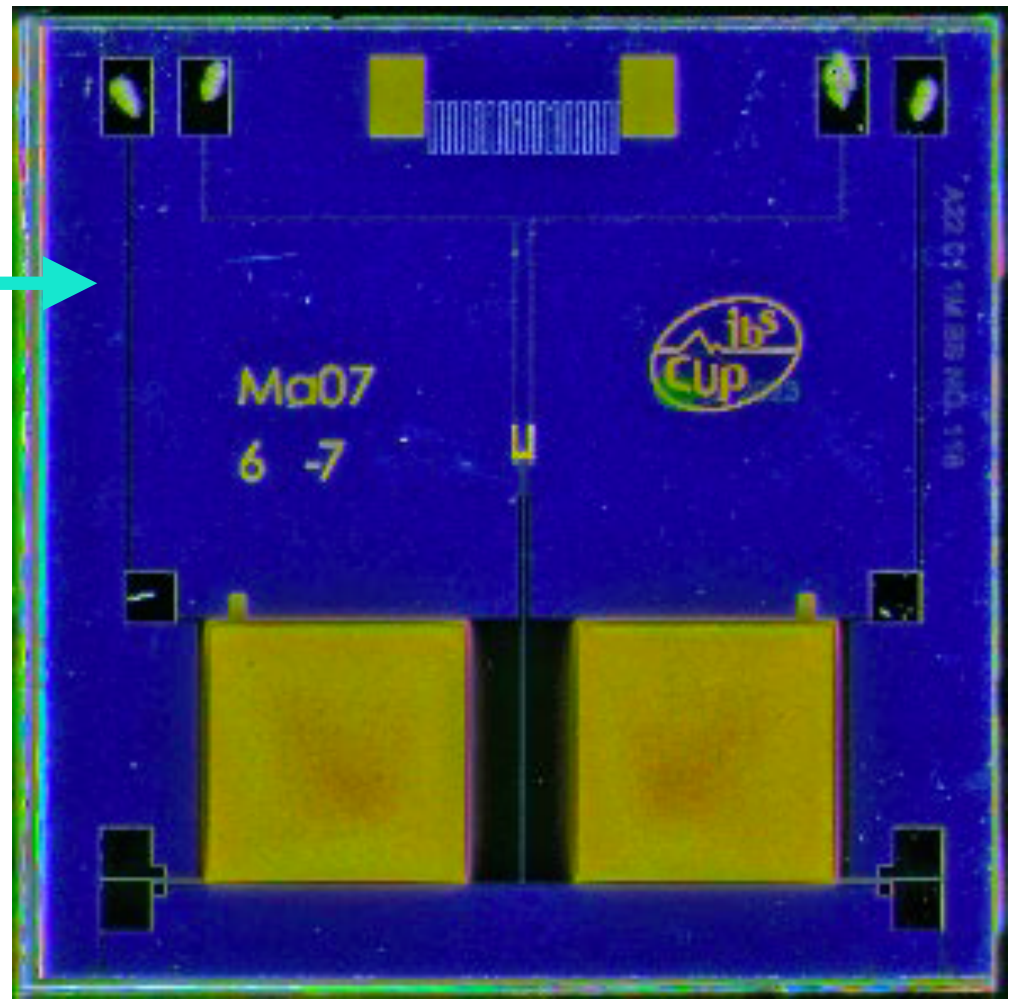


Sensor production

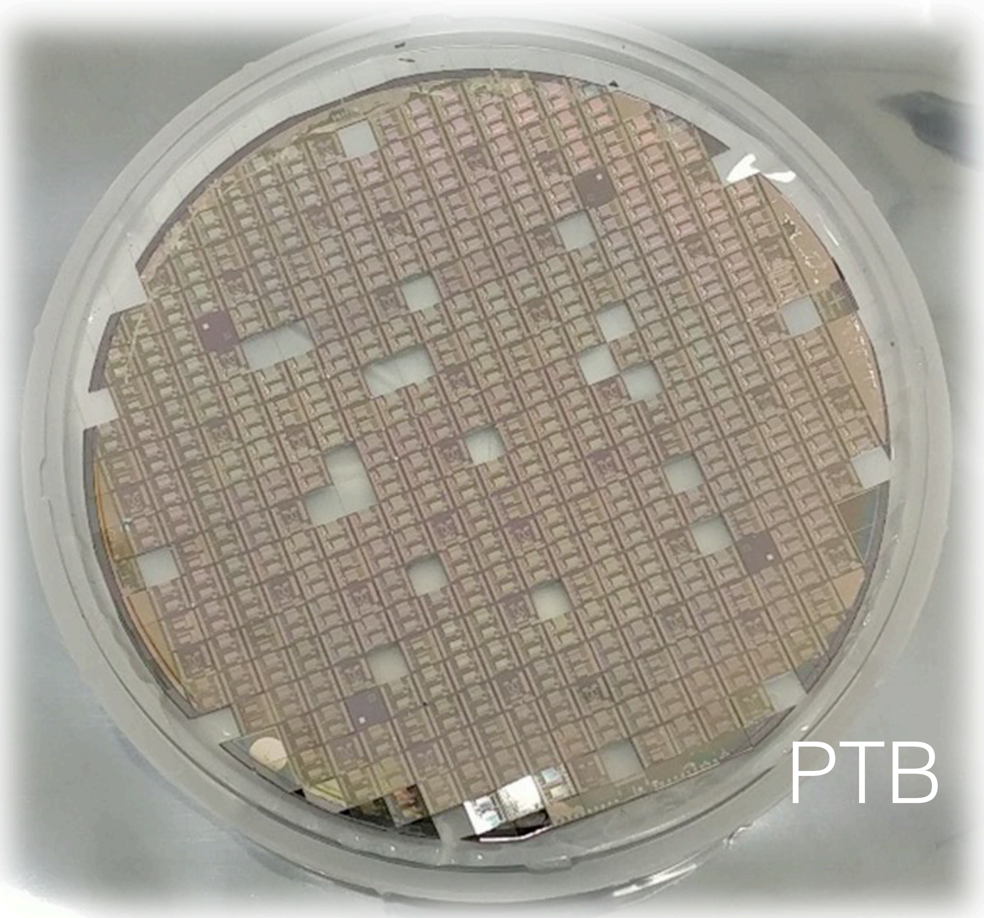
MMC production at CUP & University of Heidelberg



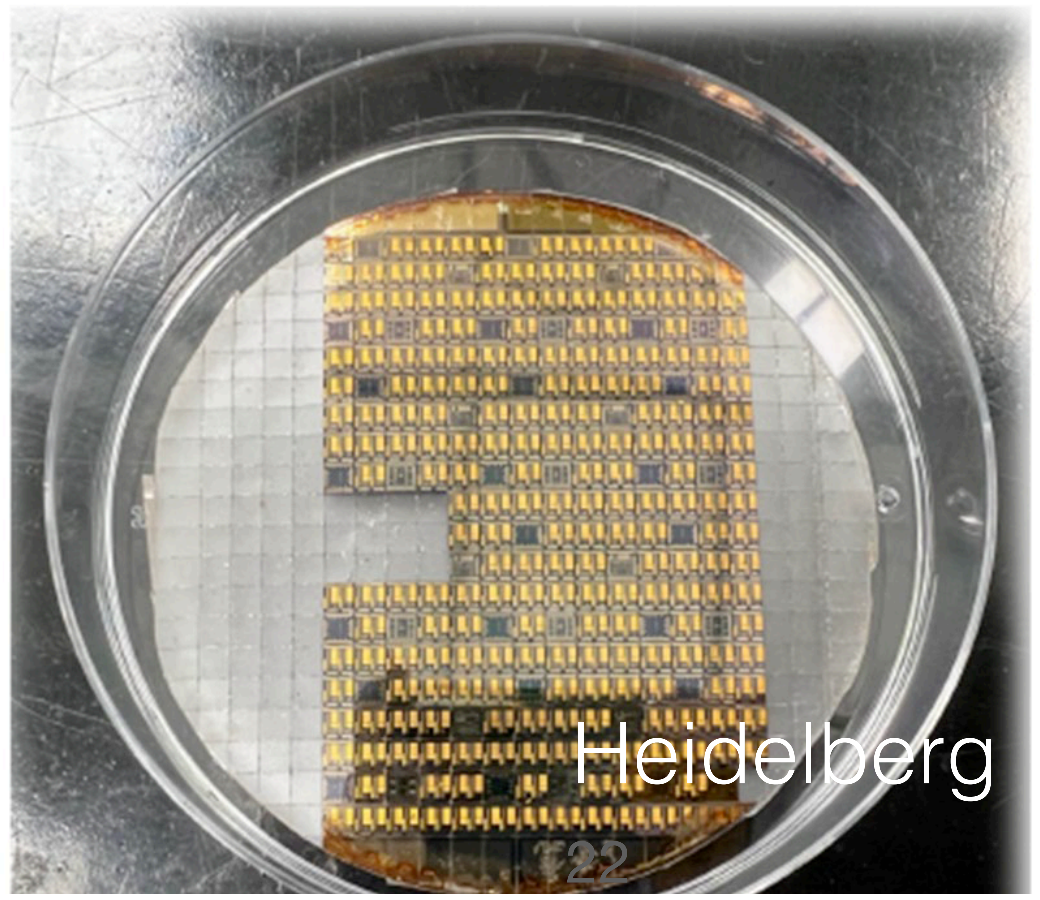




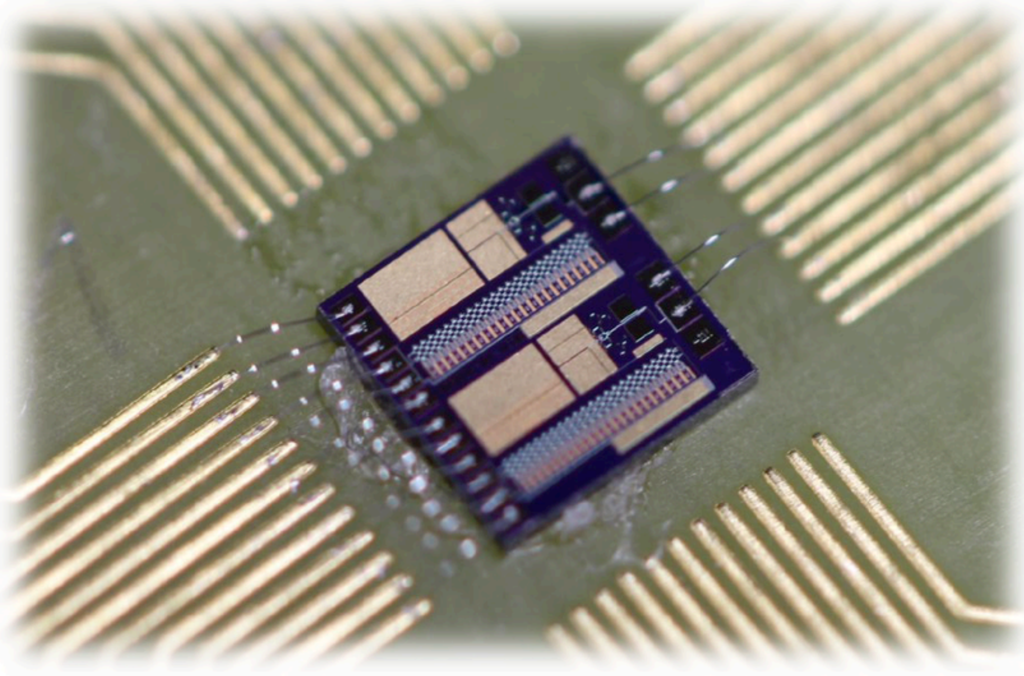
SQUID production at PTB & University of Heidelberg



PTB

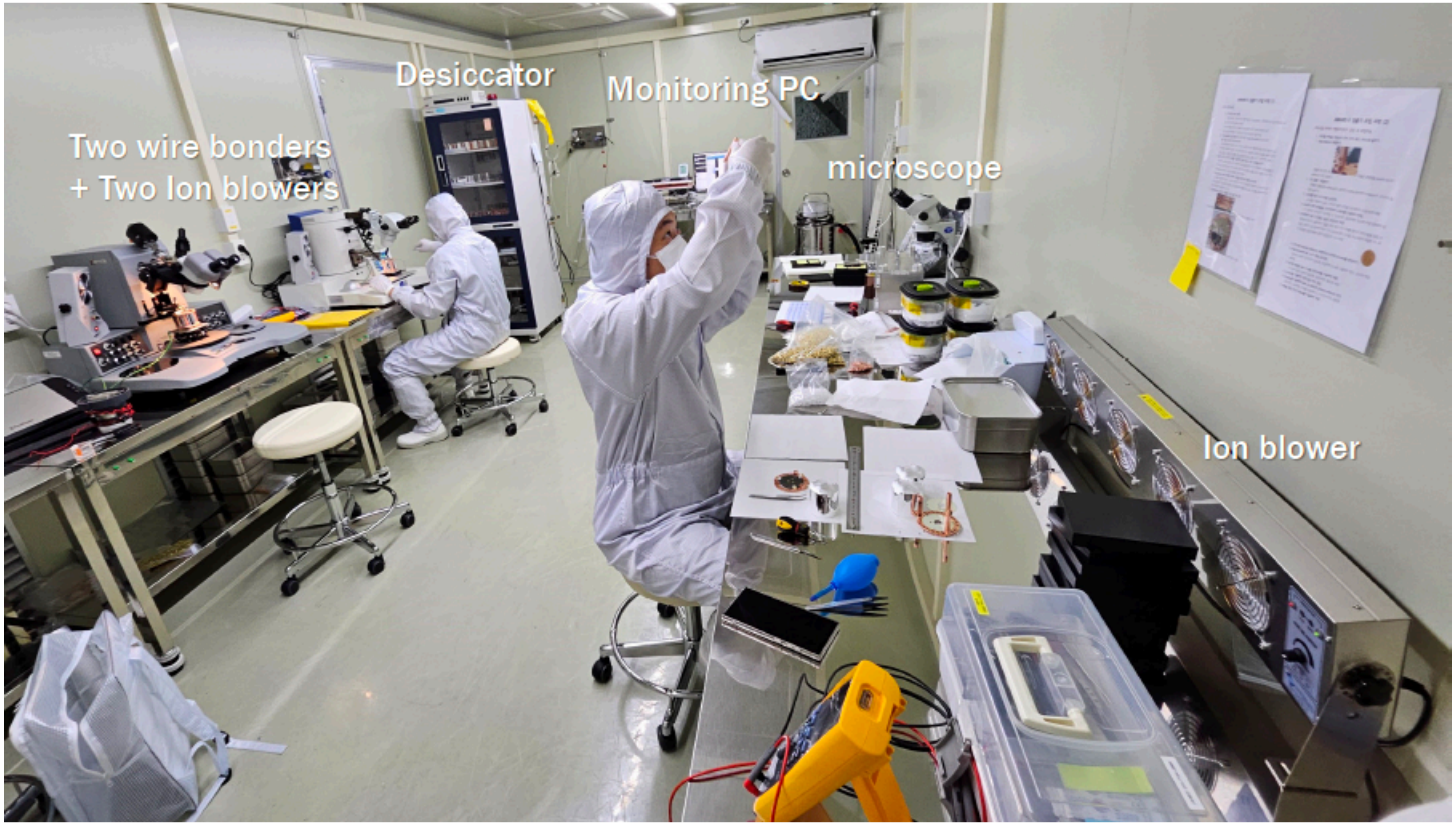


Heidelberg



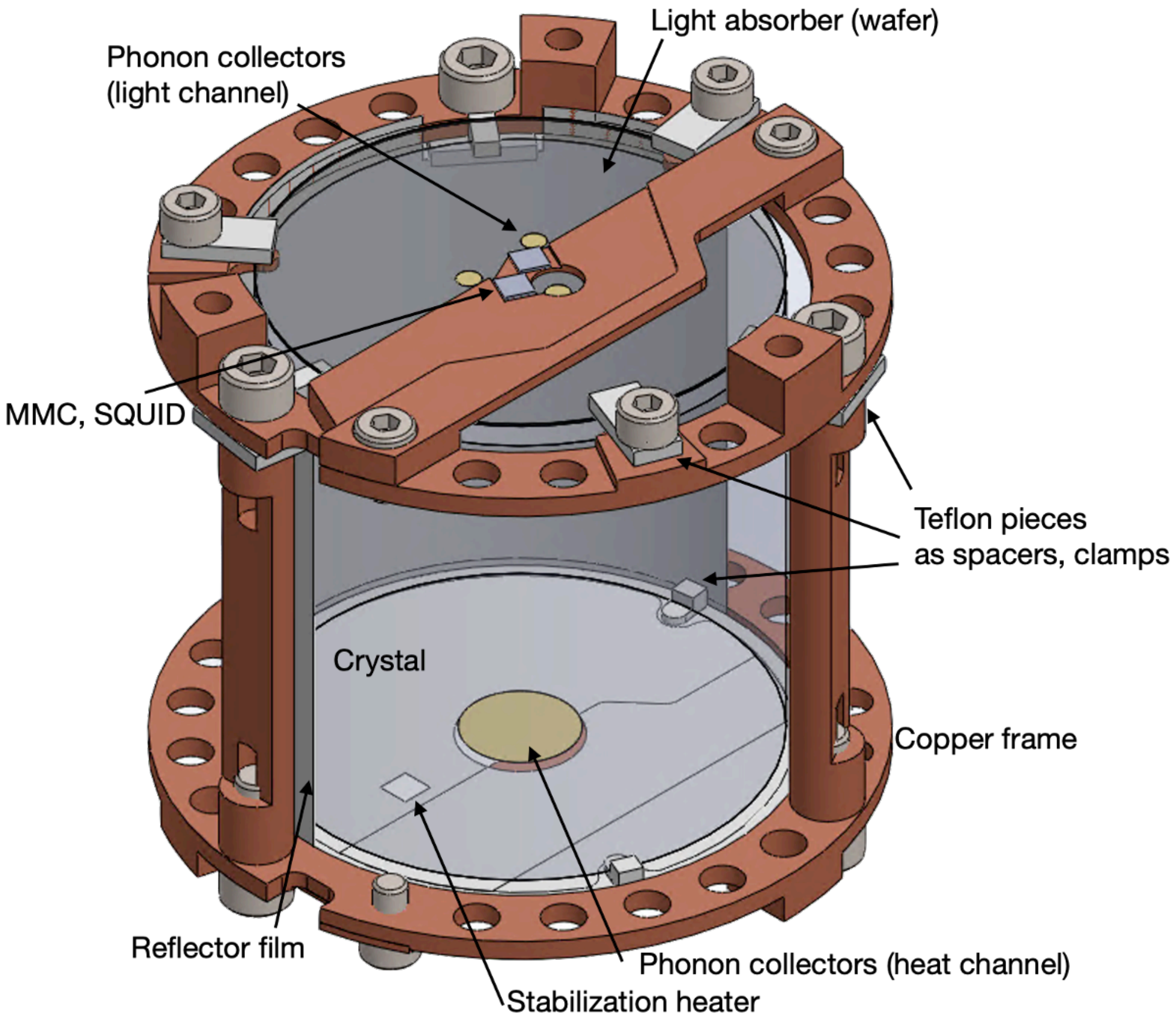
Two stage DC SQUID

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

Reduced material:
Cu, brass screw, teflon, reflective film

Diffusive surfaces

Phonon collector:
gold w/ Mo adhesion

Ag:Er MMC + 2-stage SQUID

Non-thermal link (optional)

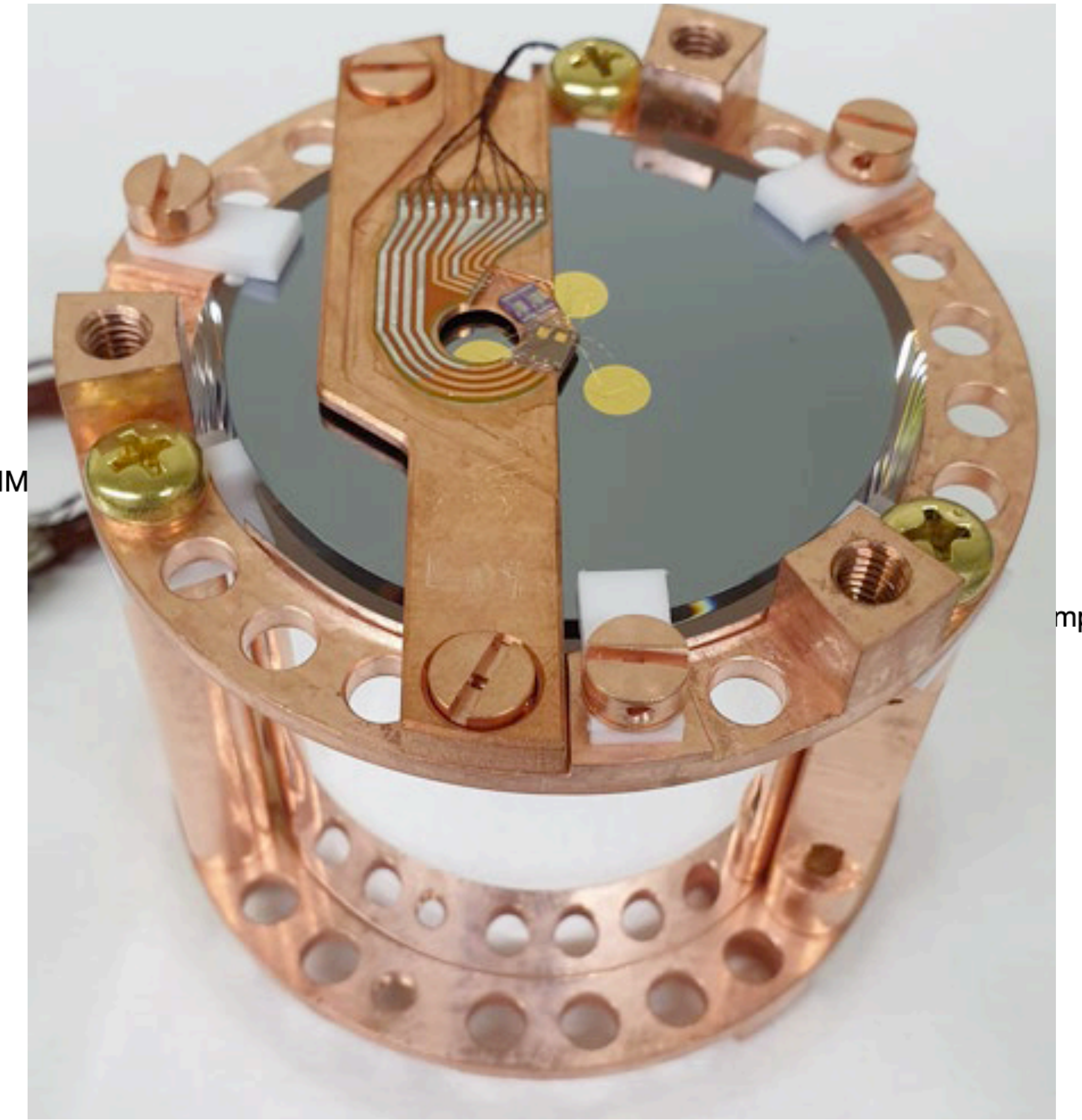
Si-wafer light detector

Si-wafer tightly secured:
vibrationless
closer to the crystal

Efficient stacking

AMoRE-II detector

MM



mps

Massive crystals:
300 g & 520 g

Reduced material:
Cu, brass screw, teflon, reflective film

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

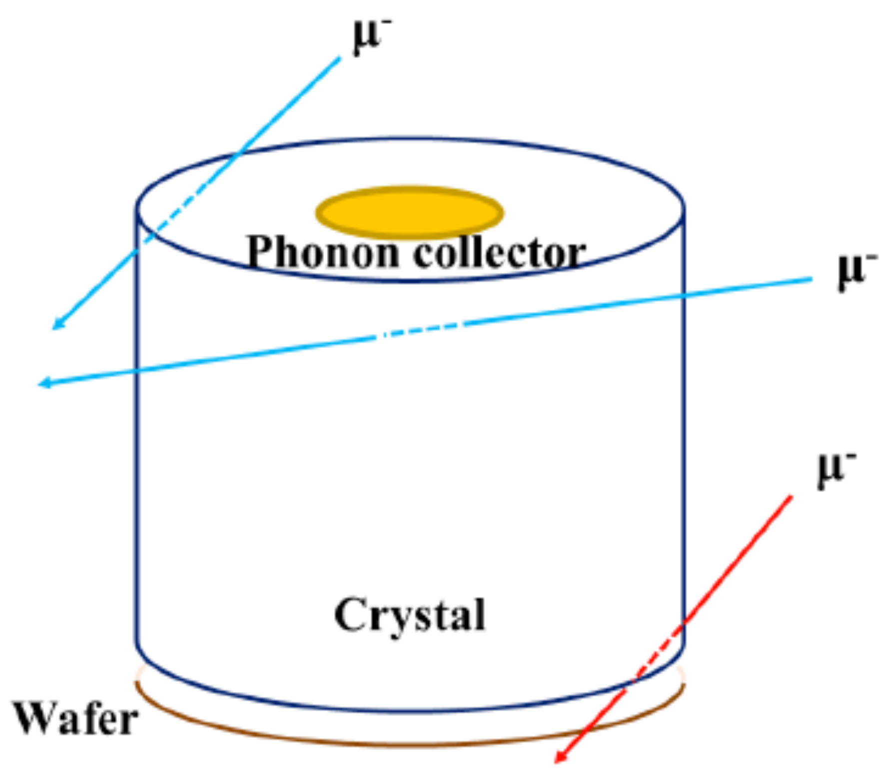
Crystals with diffusive surface:

Slower response, but more consistent behavior

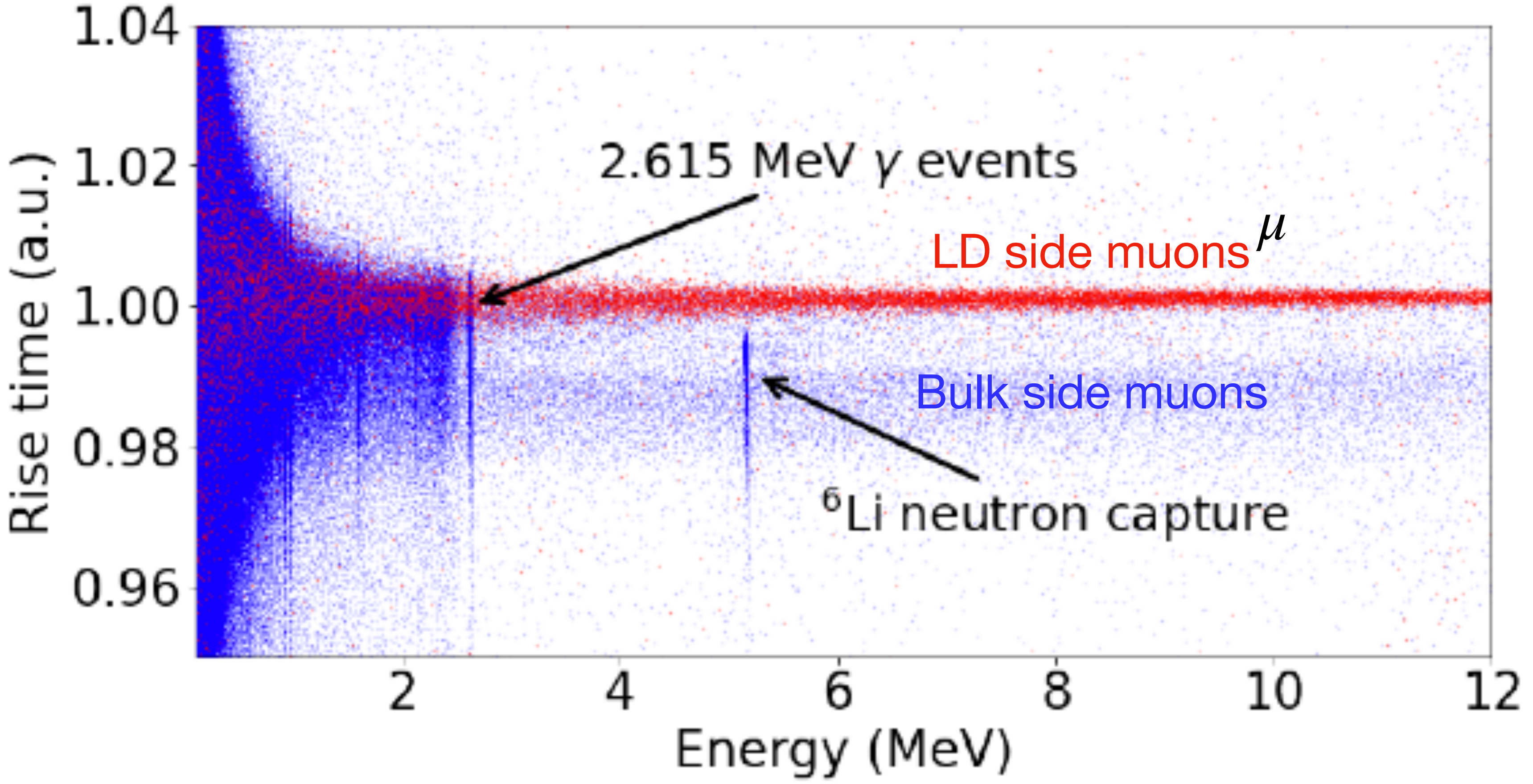
better energy resolution

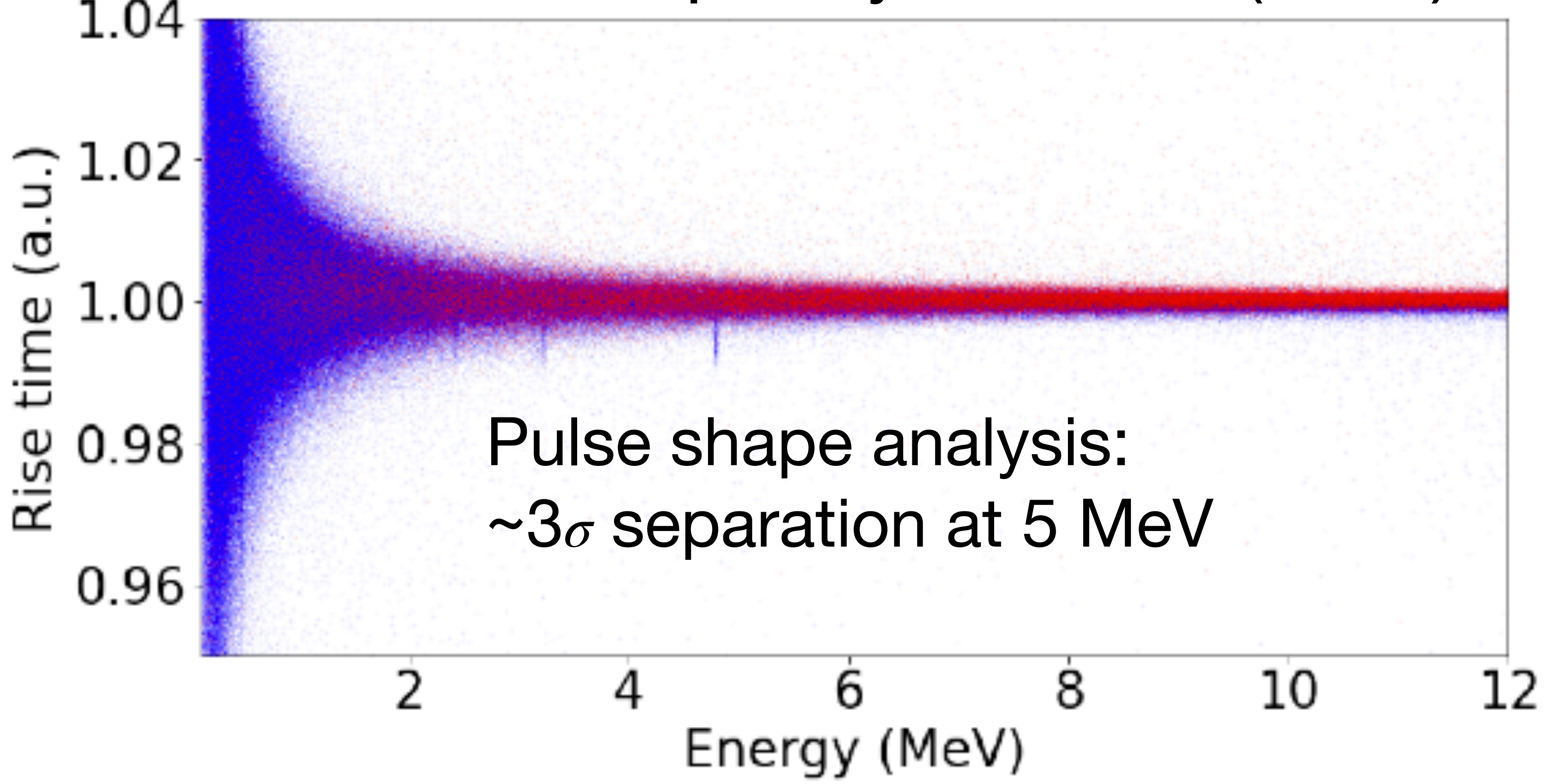
Demonstrated up to 6 cm x 6 cm, even larger crystals feasible

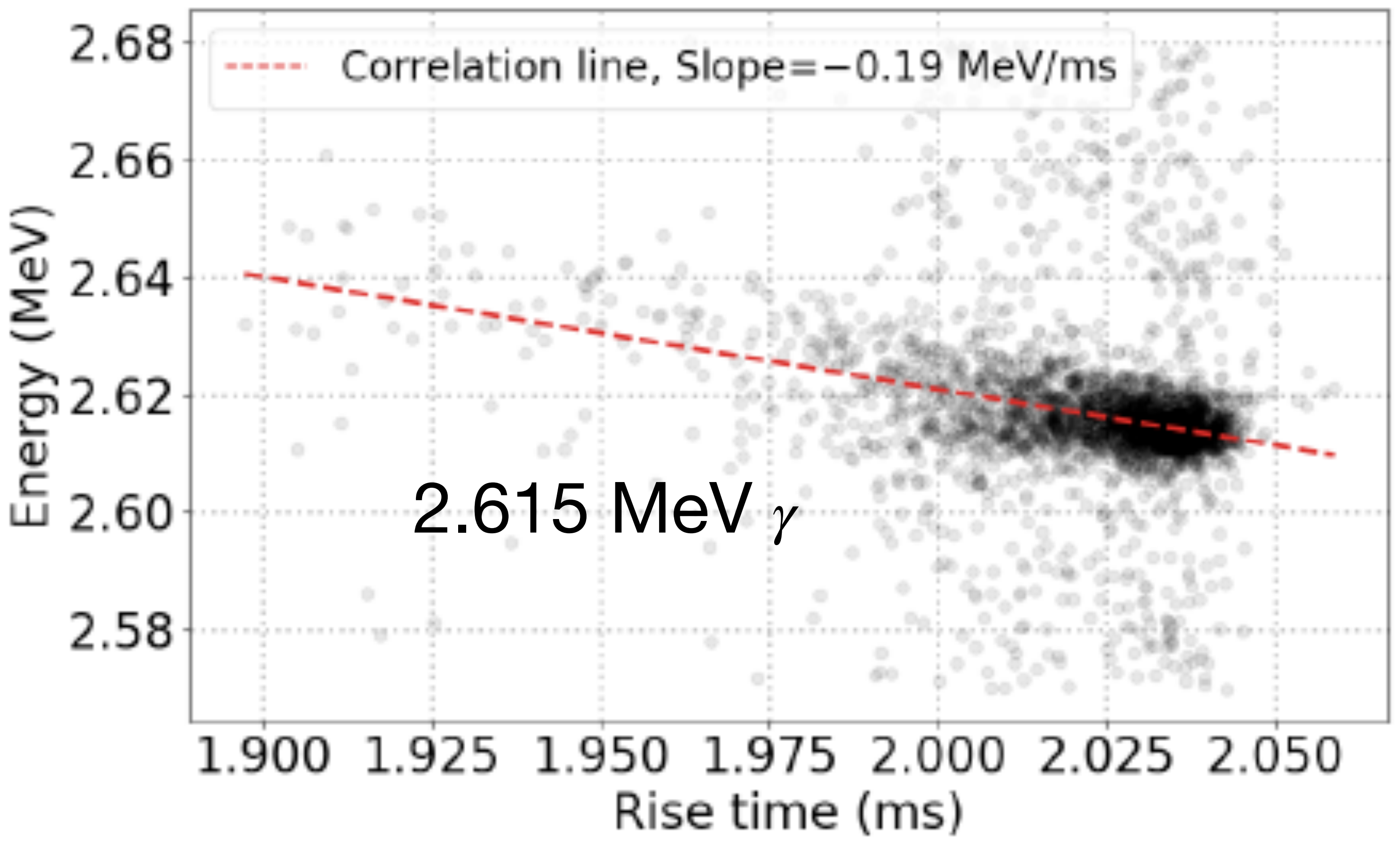
Better for mass production

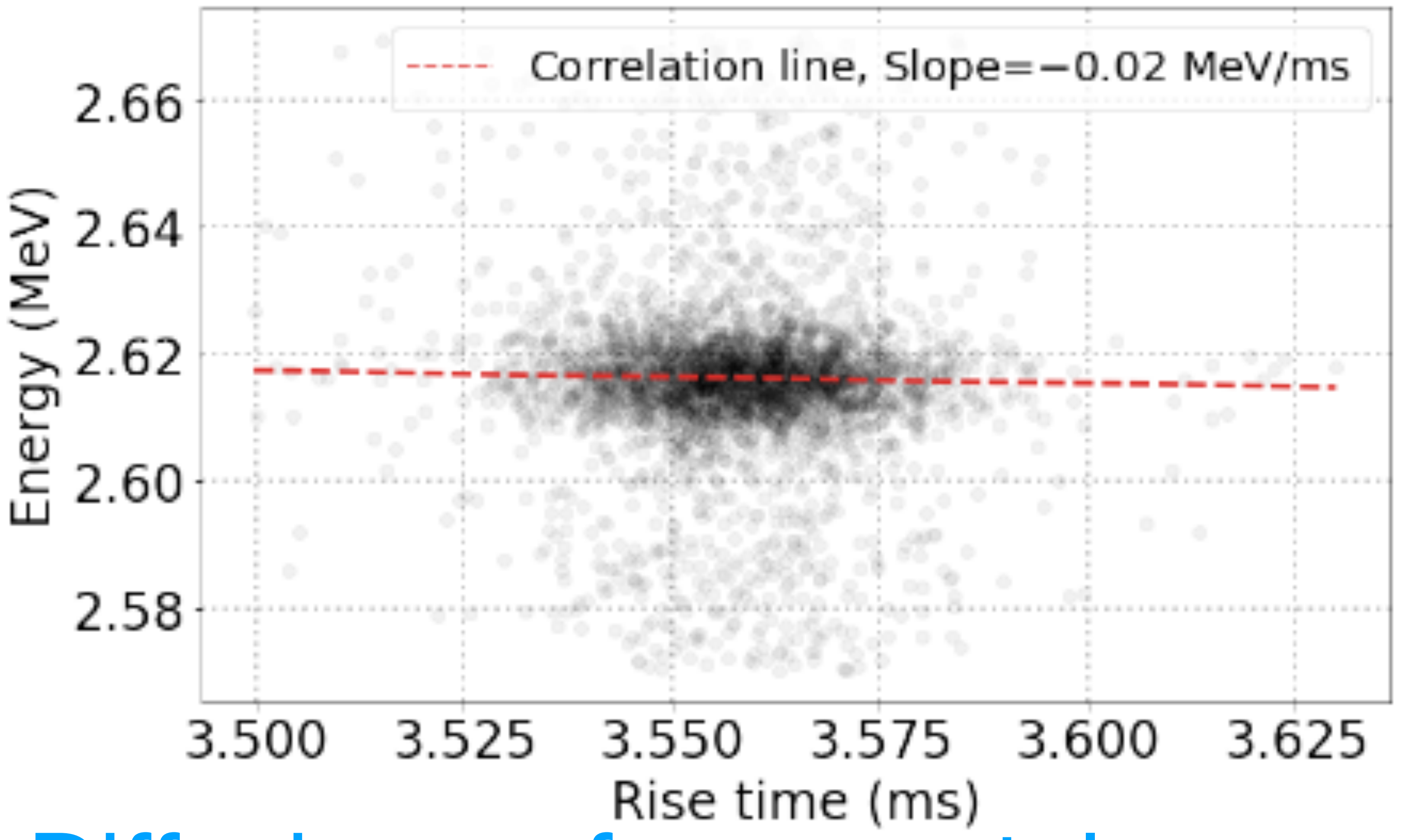


J. Low Temp. Phys. 218:83 (2024)







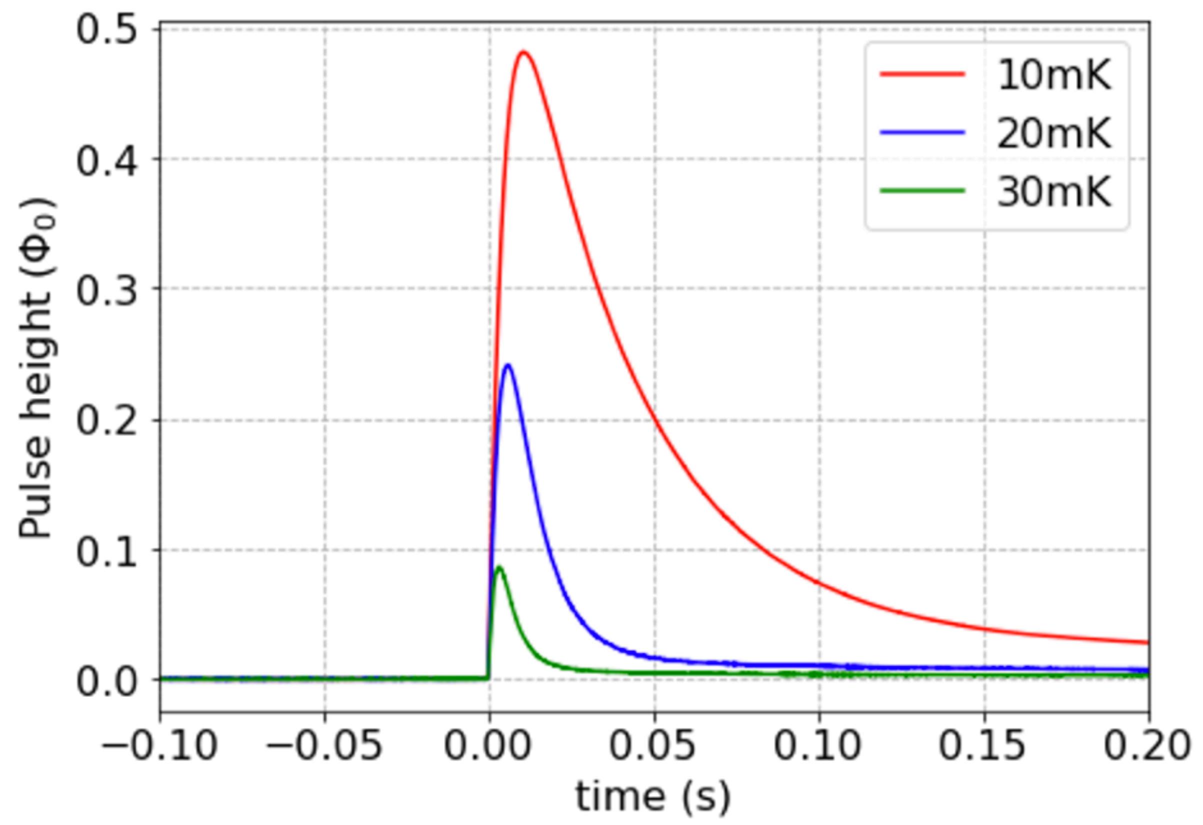


Polished crystal

Diffusive surface crystal

AMoRE-II detector

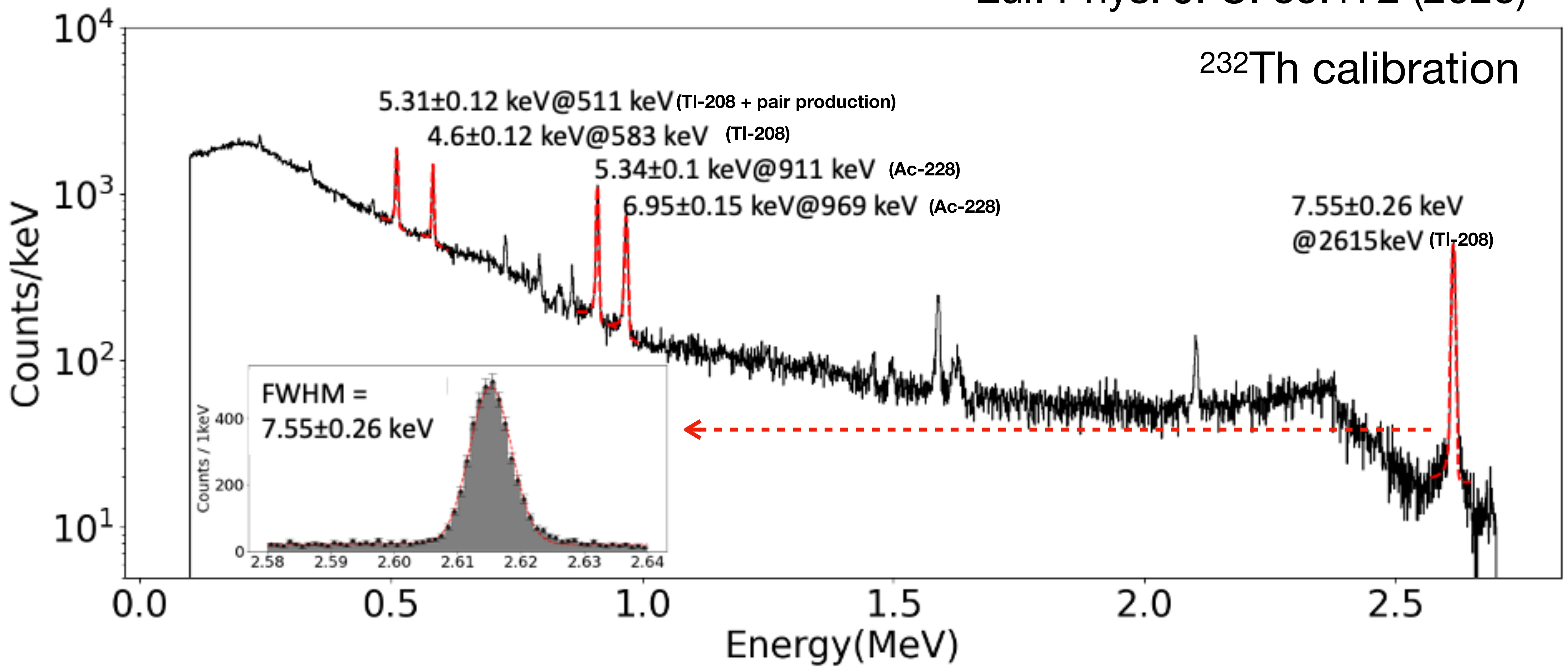
R&D detector performance



At 10 mK,
RT = 2 - 5 ms
FWHM@2.6 MeV = 7.6 - 8.8 keV

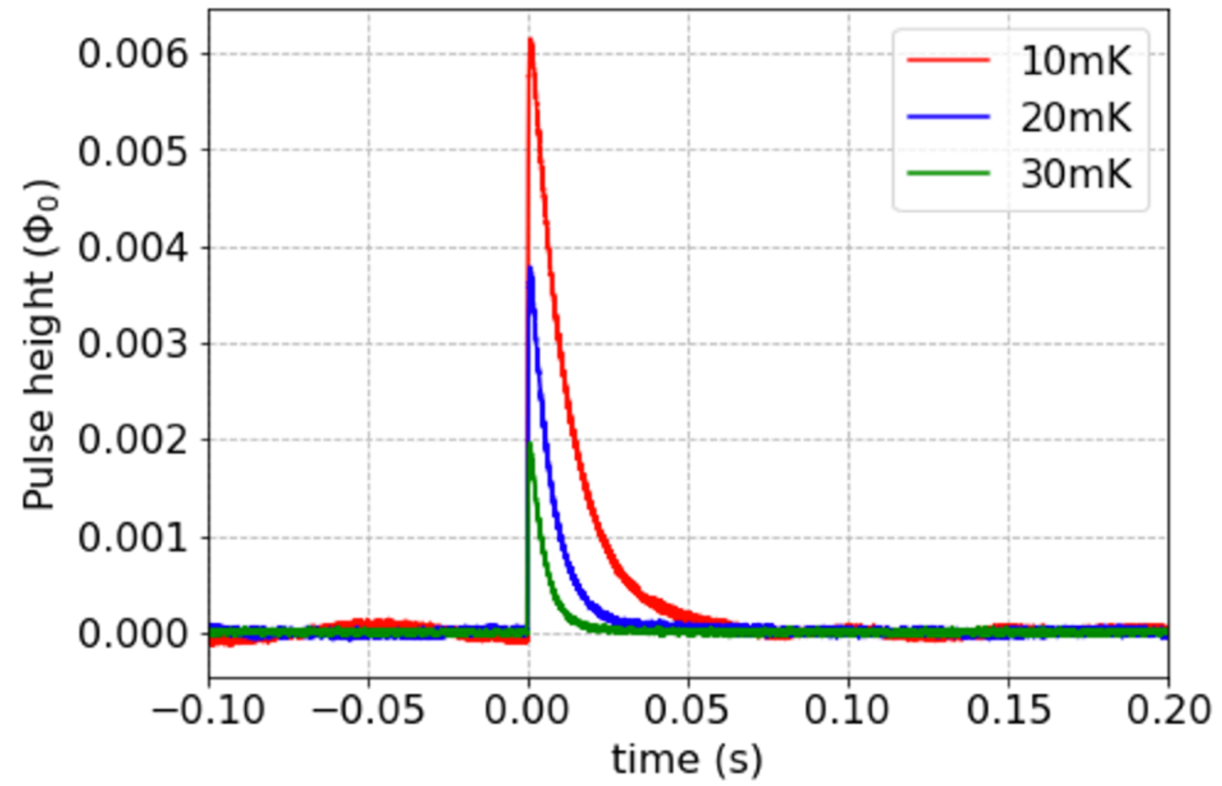
Promising performance at 10 - 30 mK

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



AMoRE-II detector

R&D light channel performance



At 10 mK

RT = 320 μs

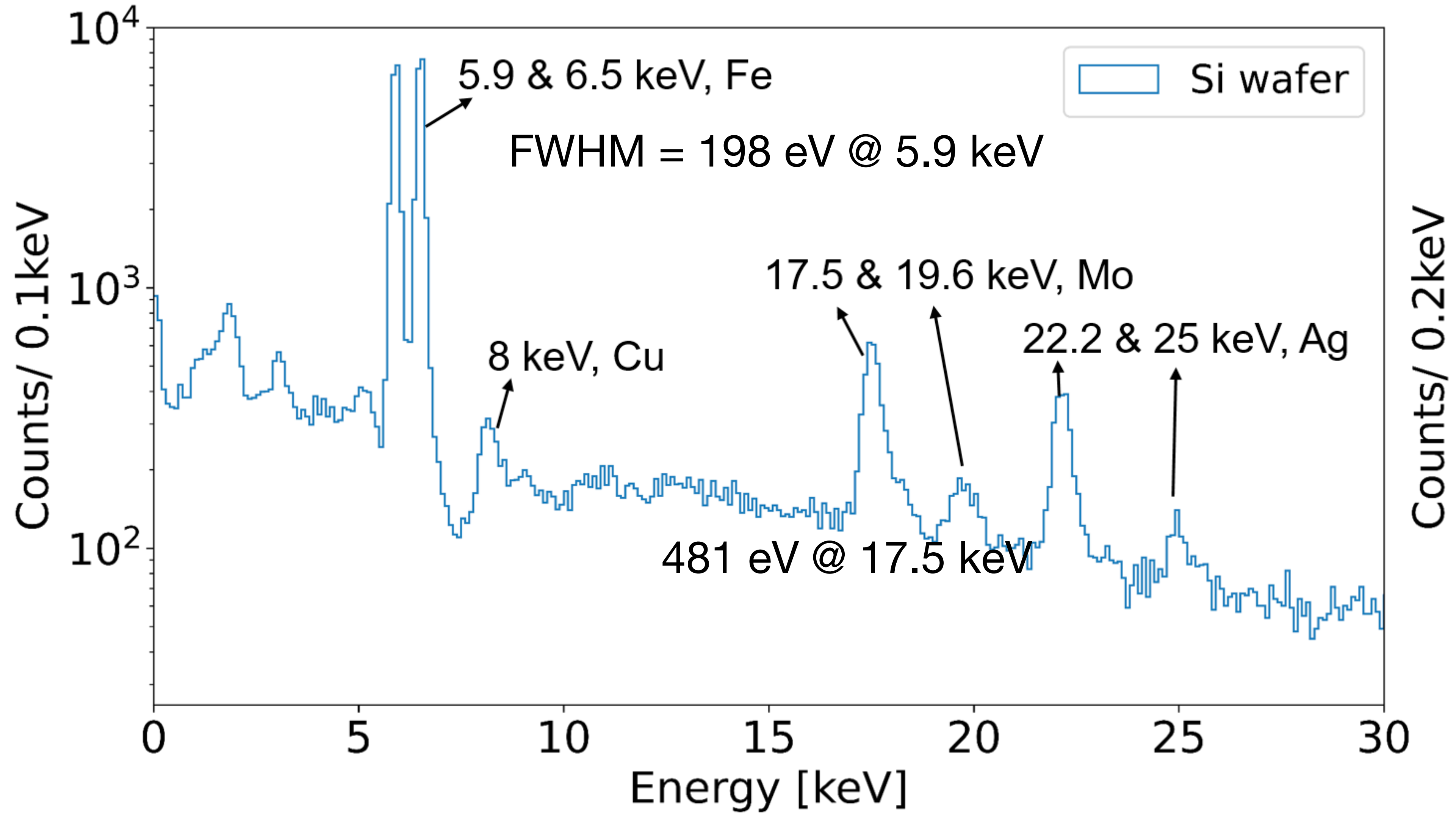
Fast timing useful for pile-up rejection with larger crystal

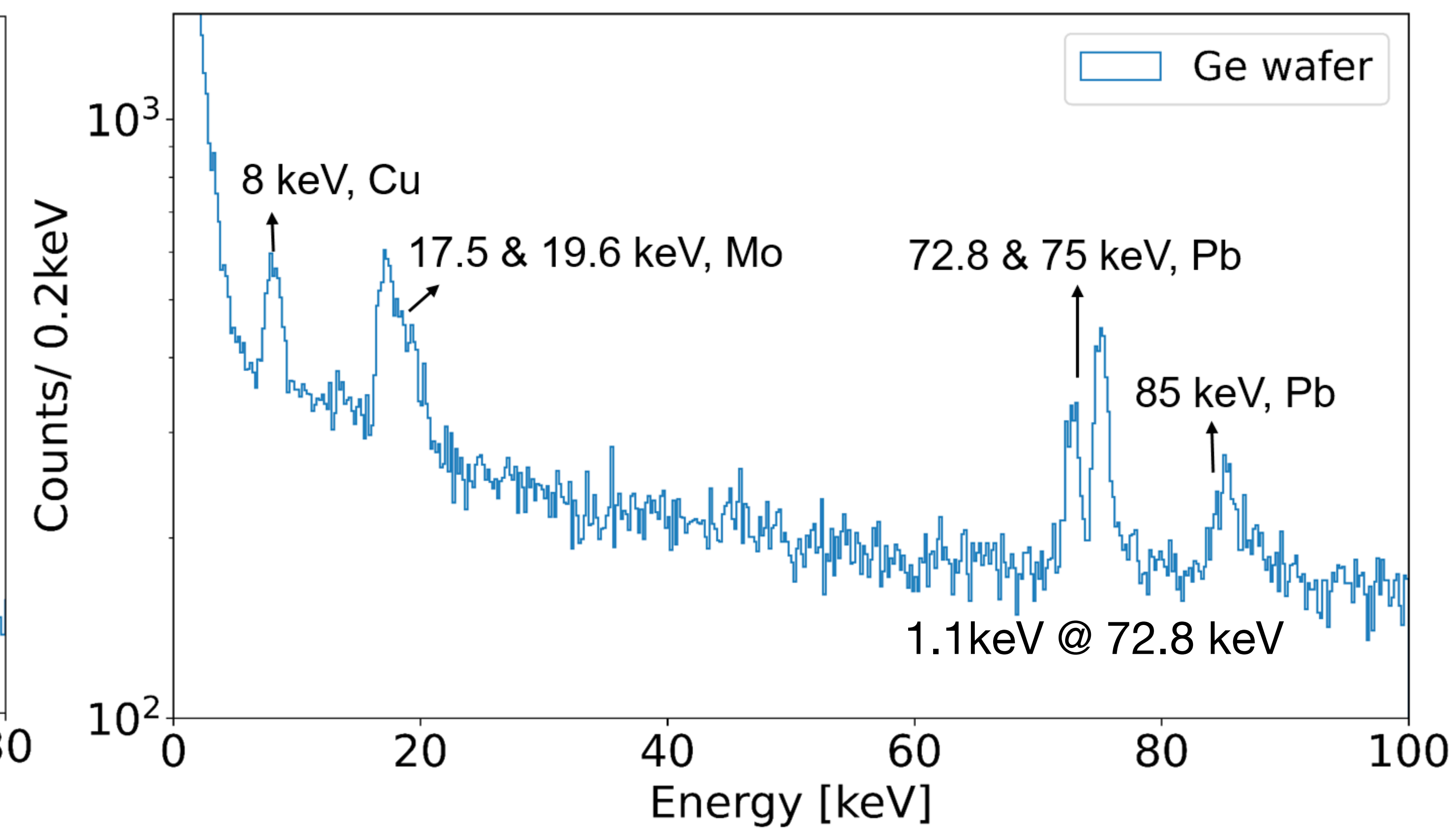
FWHM@5.9 keV = 198 eV

baseline = 99 eV

Scinitllation collection = 0.79 - 0.96 keV/MeV

Light absorber with X-rays



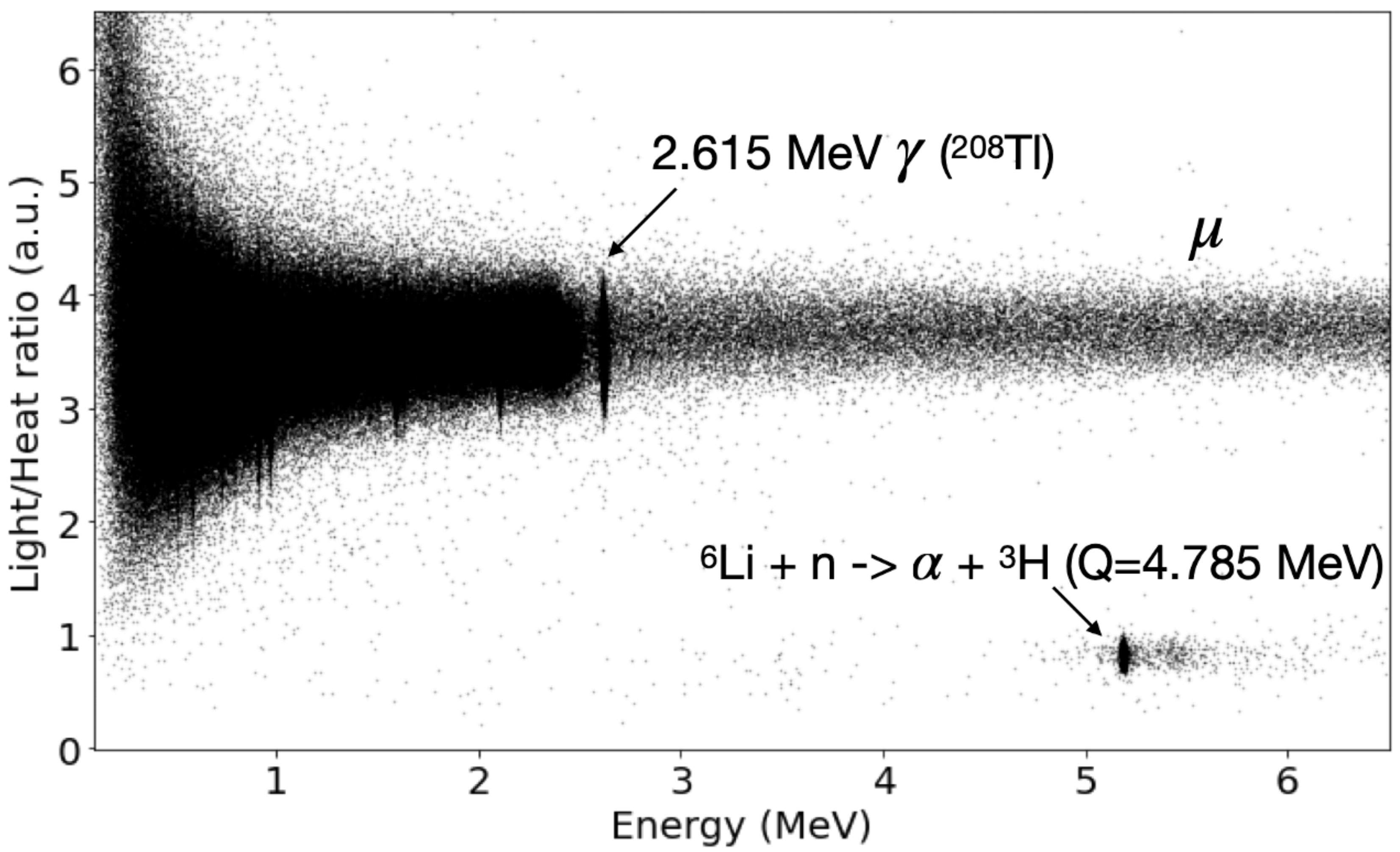


J. Low Temp. Phys. 218:92 (2024)

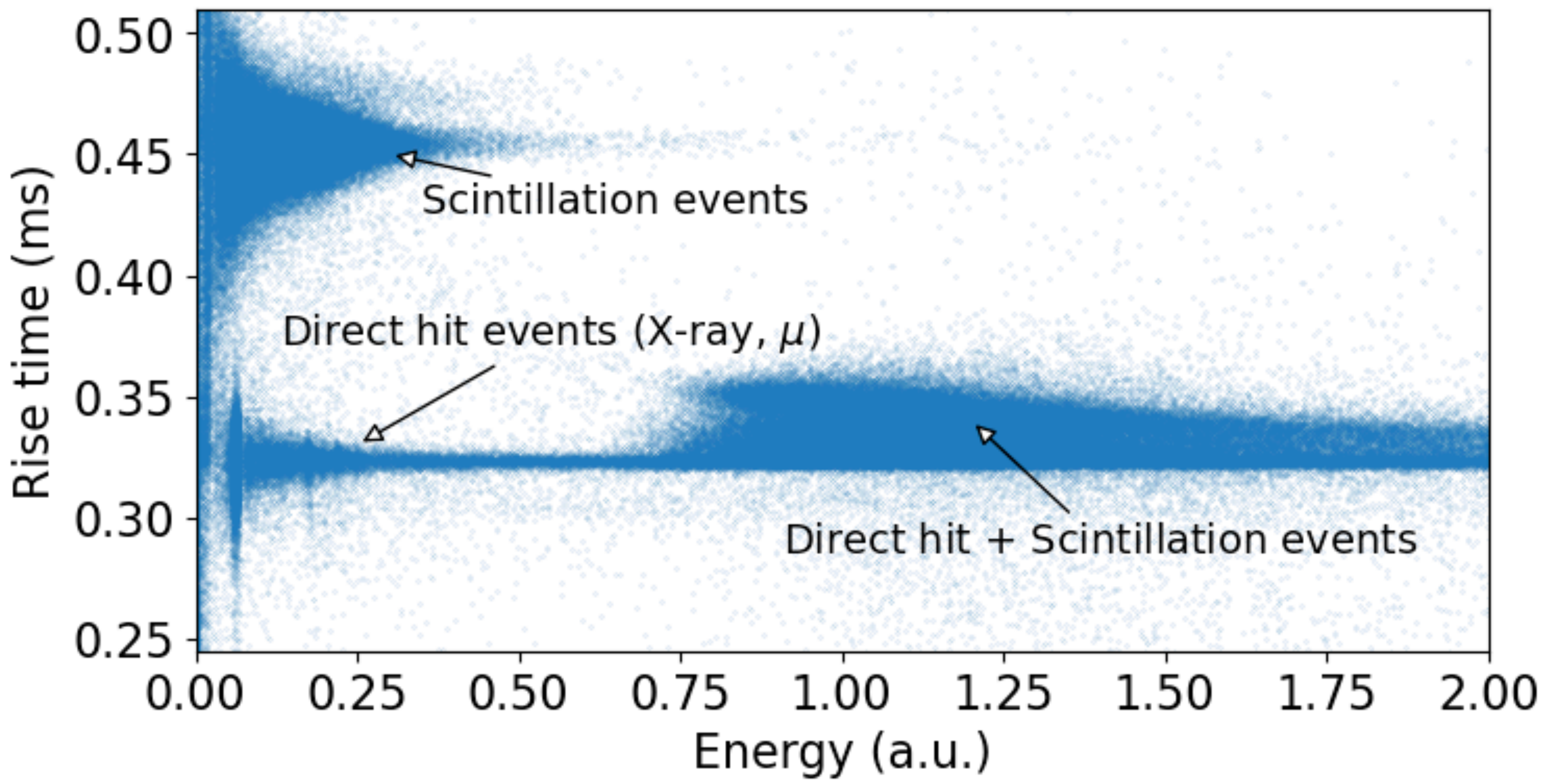
AMoRE-II detector

Particle identification

Crystal absorber



Light absorber (Si)



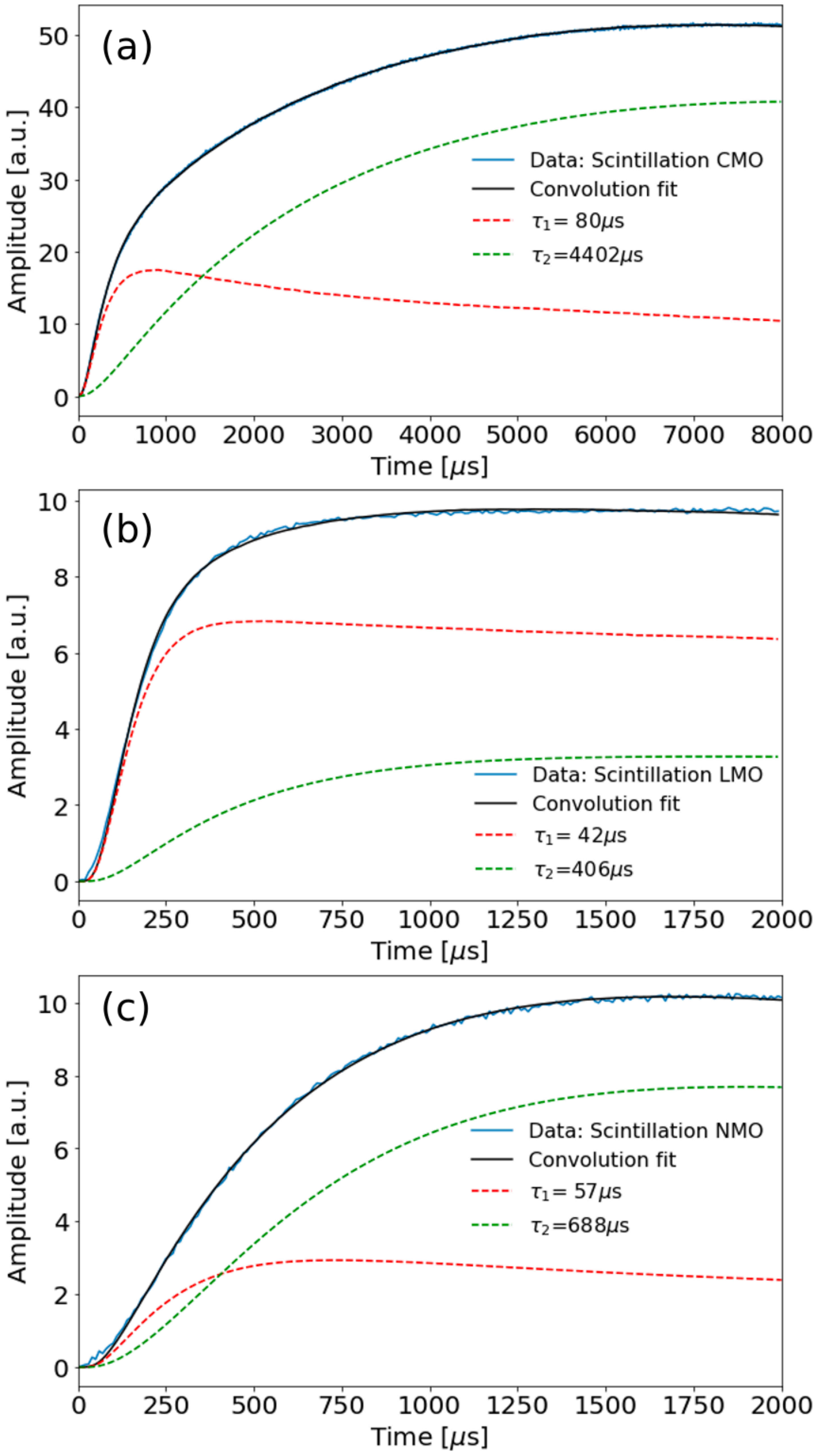
α quenching in scintillation signal ~ 0.25
Clear rejection of α background in the ROI (E = 3.034 MeV)

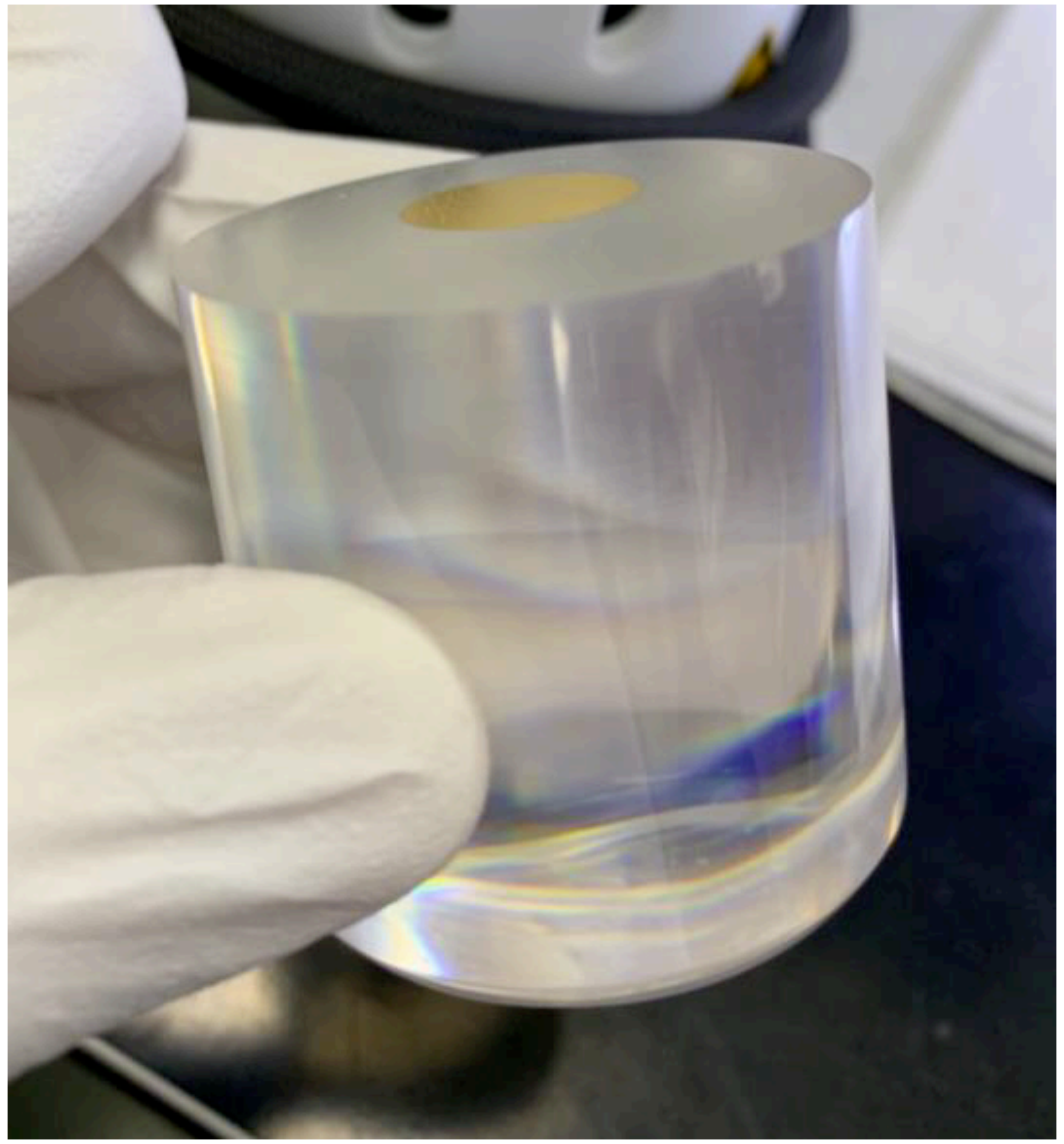
Overall, promising detector performance for AMoRE-II !!!

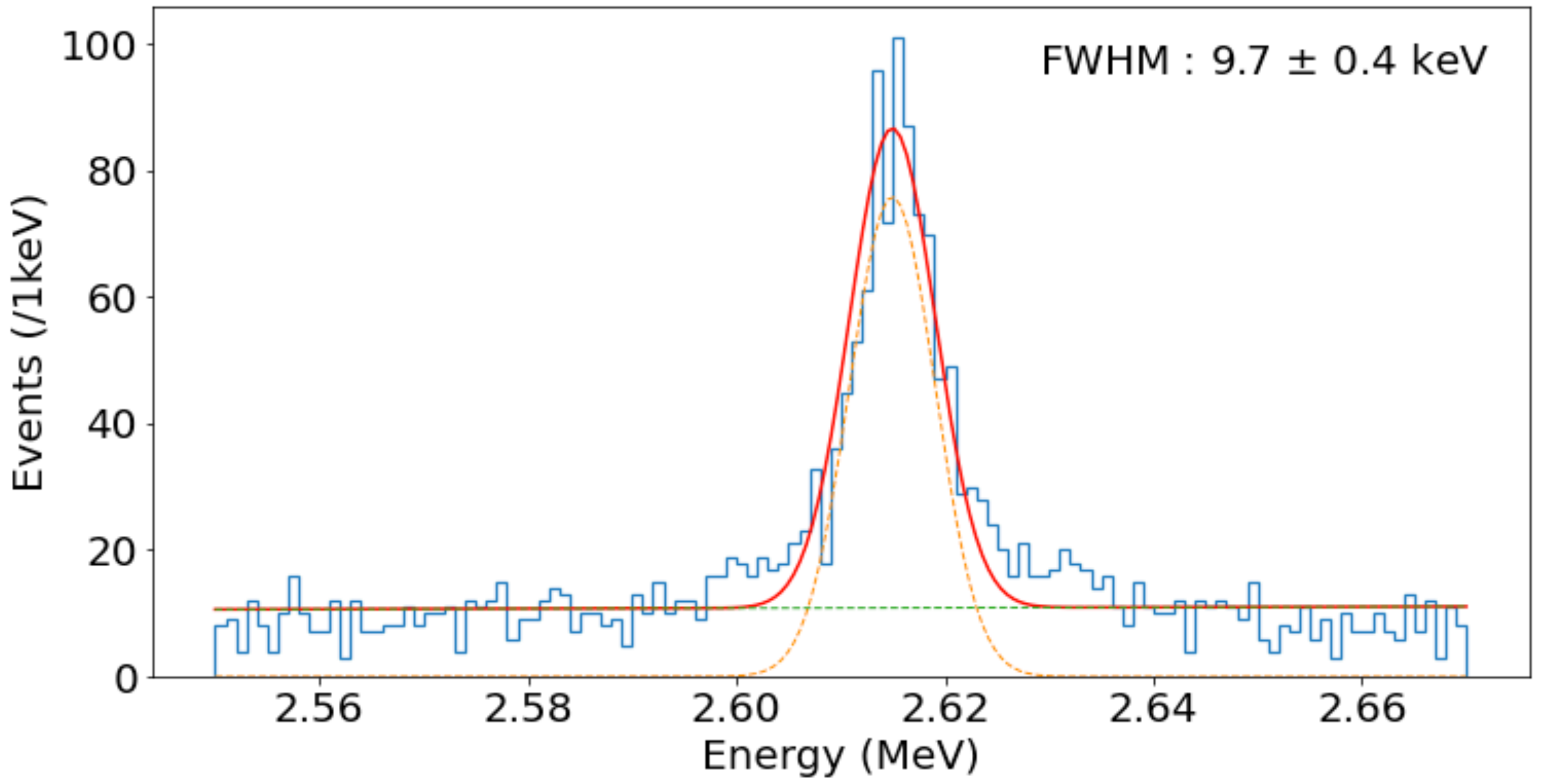
AMoRE-II detector

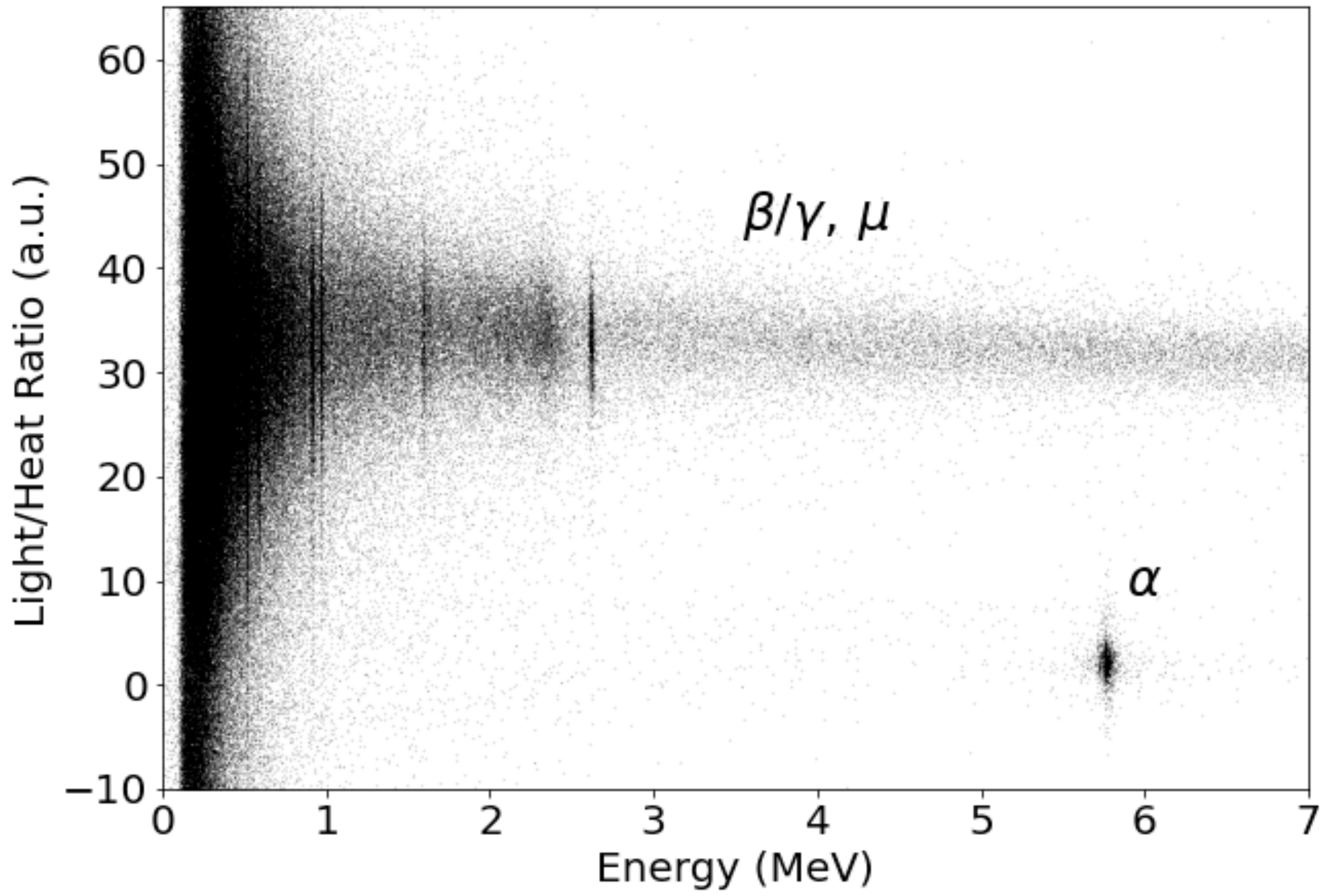
$Na_2Mo_2O_7$ detector R&D

- Cylindrical crystal (4cm (H) x 4cm (D), 178g)
- Good energy resolution and light collection demonstrated at 10 - 20 mK
- Characterization of light signals : time response, light collection, quenching factor
- Difficult to grow large crystal, mass production issue



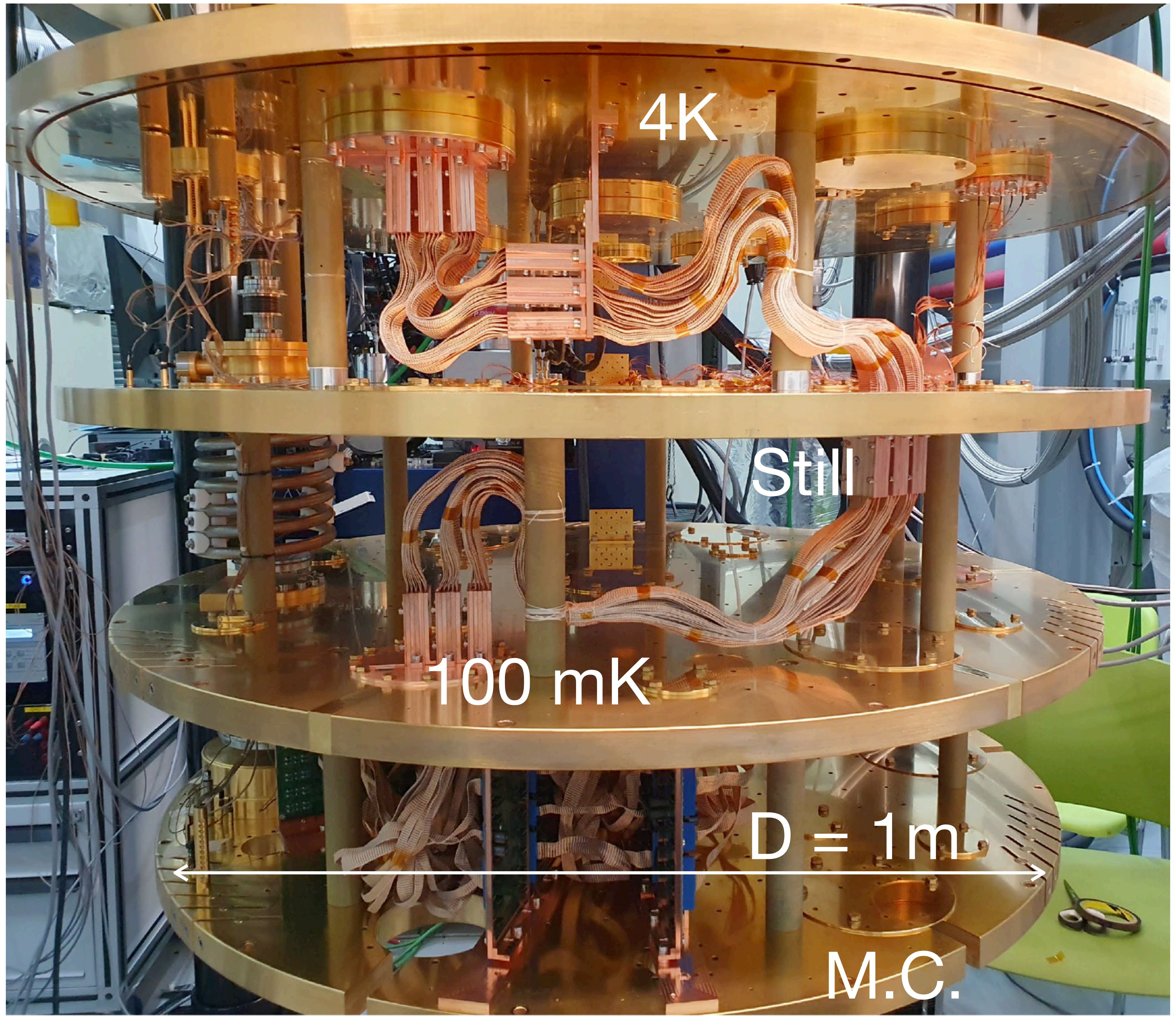


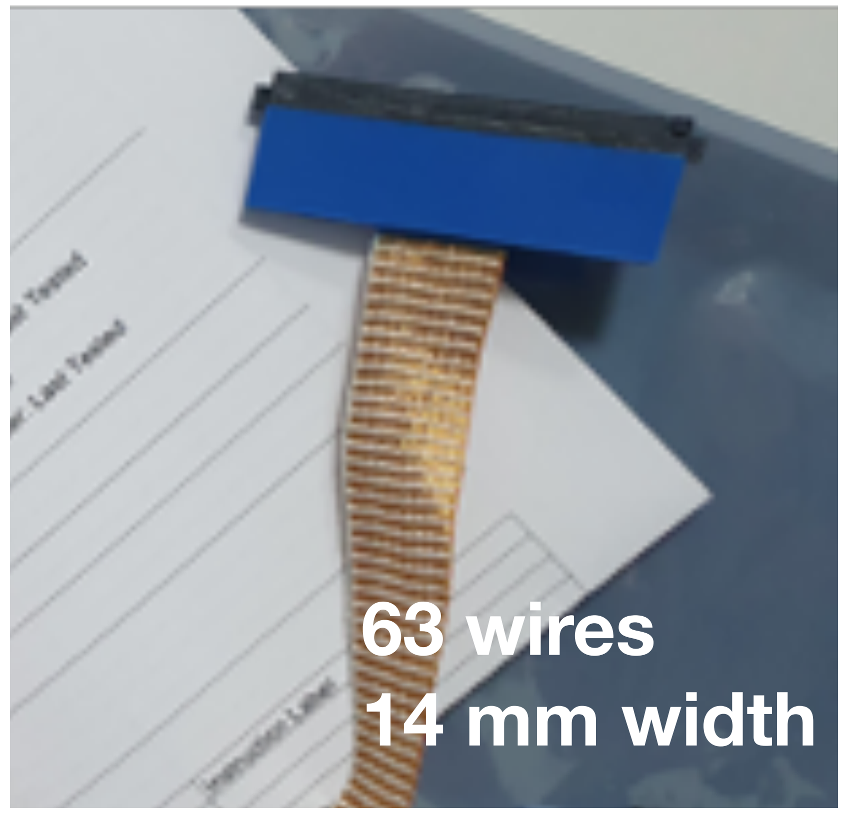


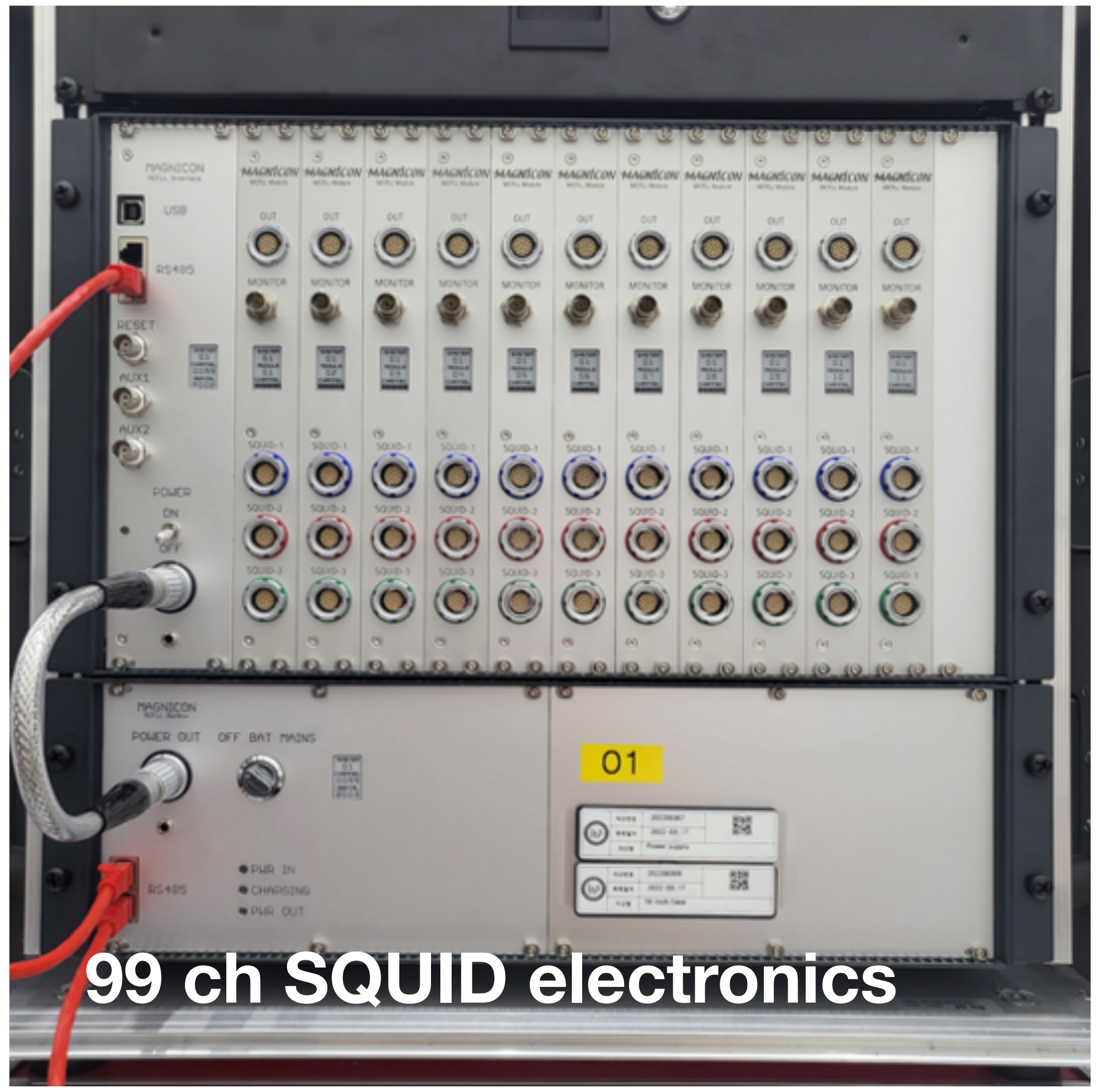


JINST 17 P04004 (2022)
IEEE TNS 70, 1307 (2023)

AMoRE-II cryostat

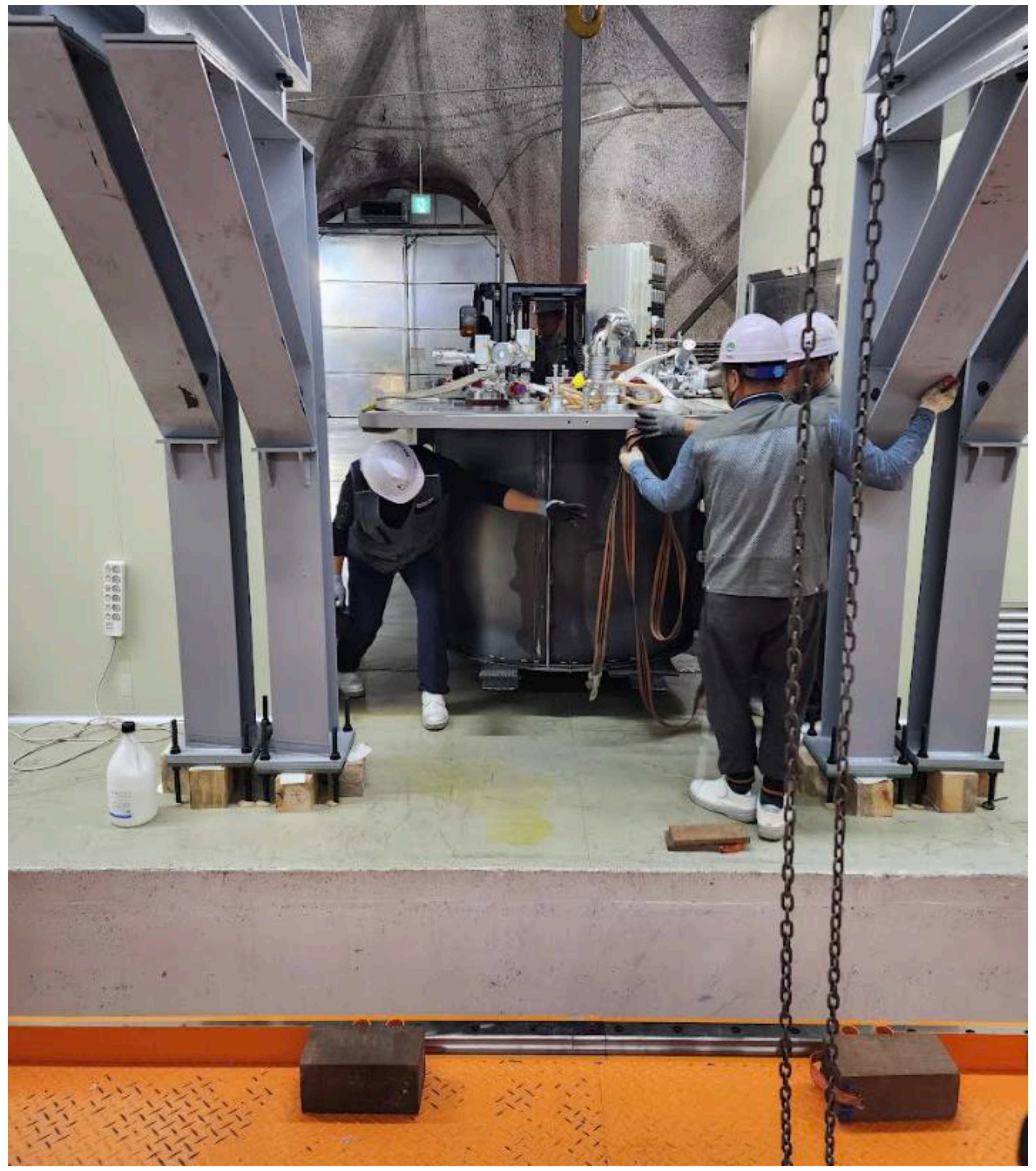


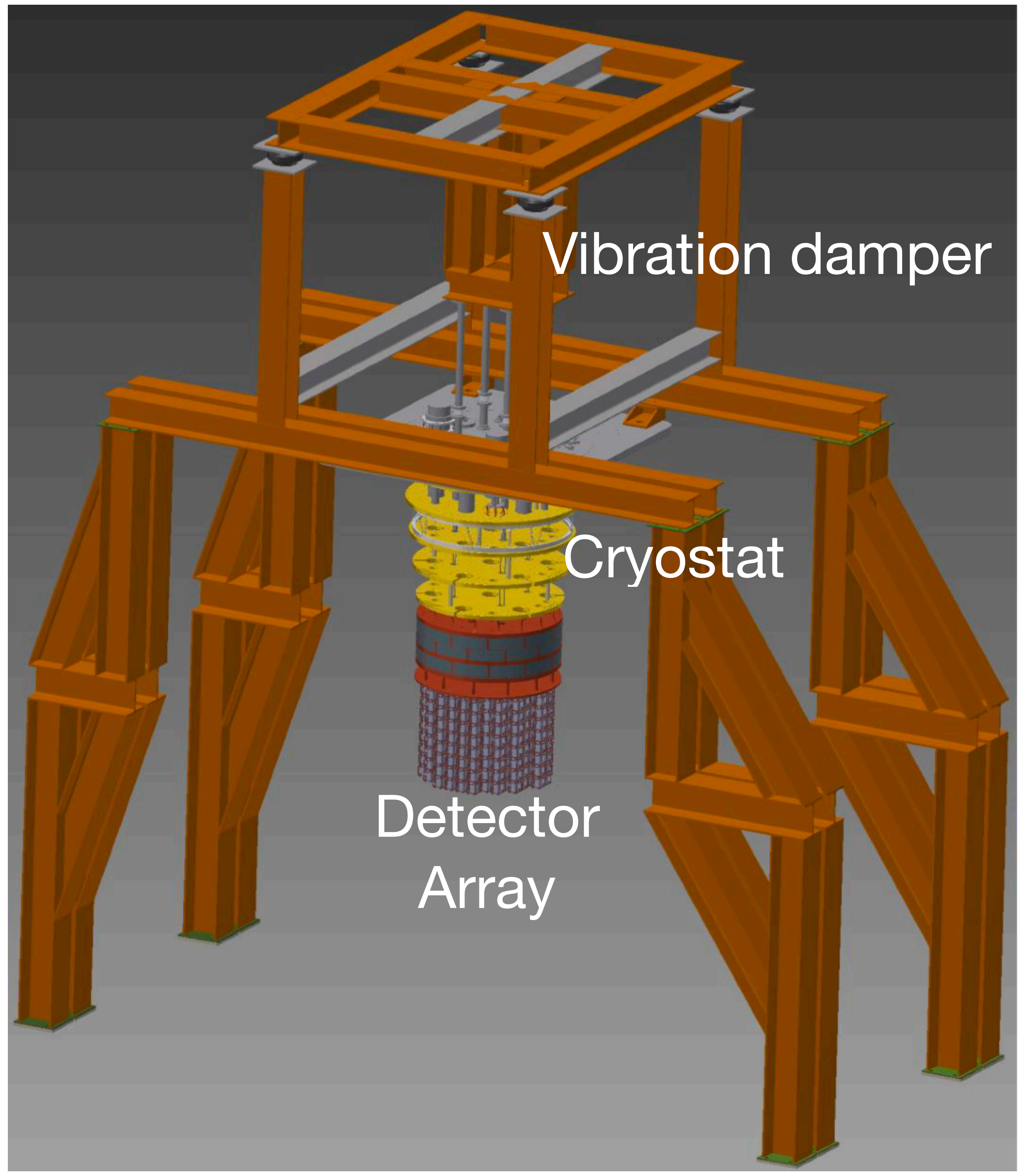




- Large cryogen-free dilution refrigerator with 3 pulse tube refrigerators, cooling power > 5μW@ 10 mK
- Cabling: ~ 8000 wires (~3000 wires installed for stage 1)
  CuNi alloy30 (D=160μm) with NOMAX wire between top plate & MC
- 6.9 mK base temperature reached after 1st stage wiring installation
- Compact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

AMoRE-II cryostat settled in Yemilab

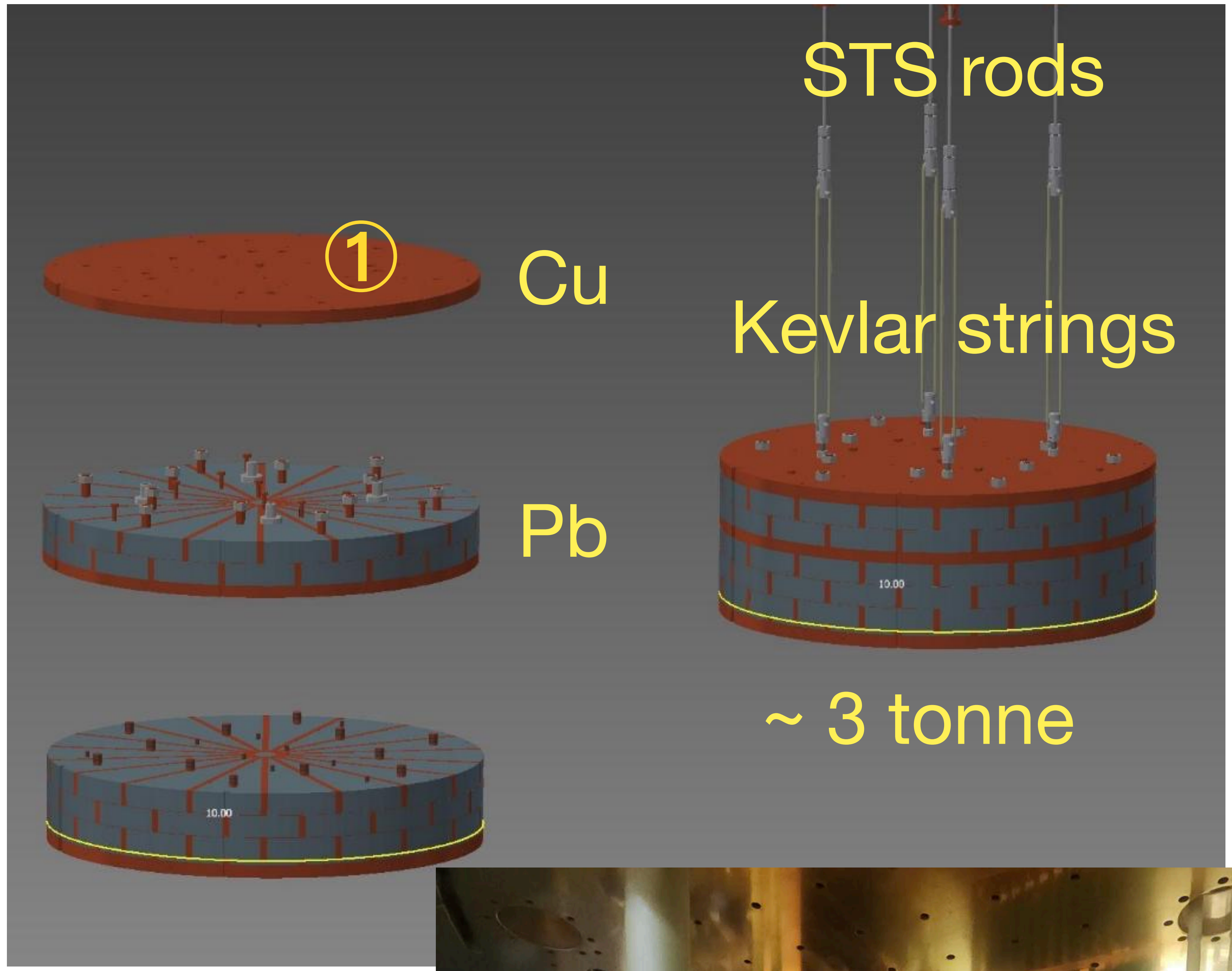


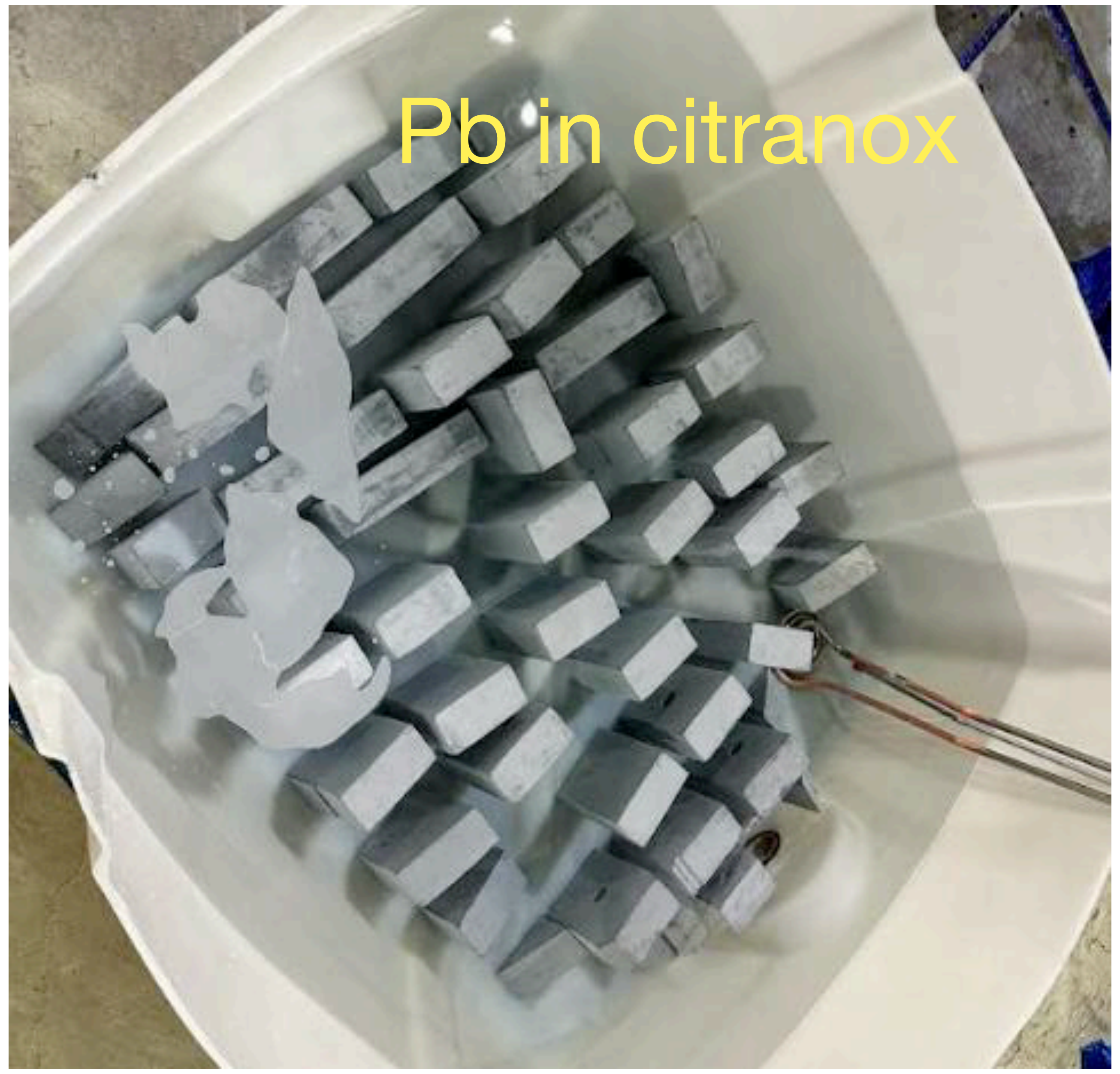


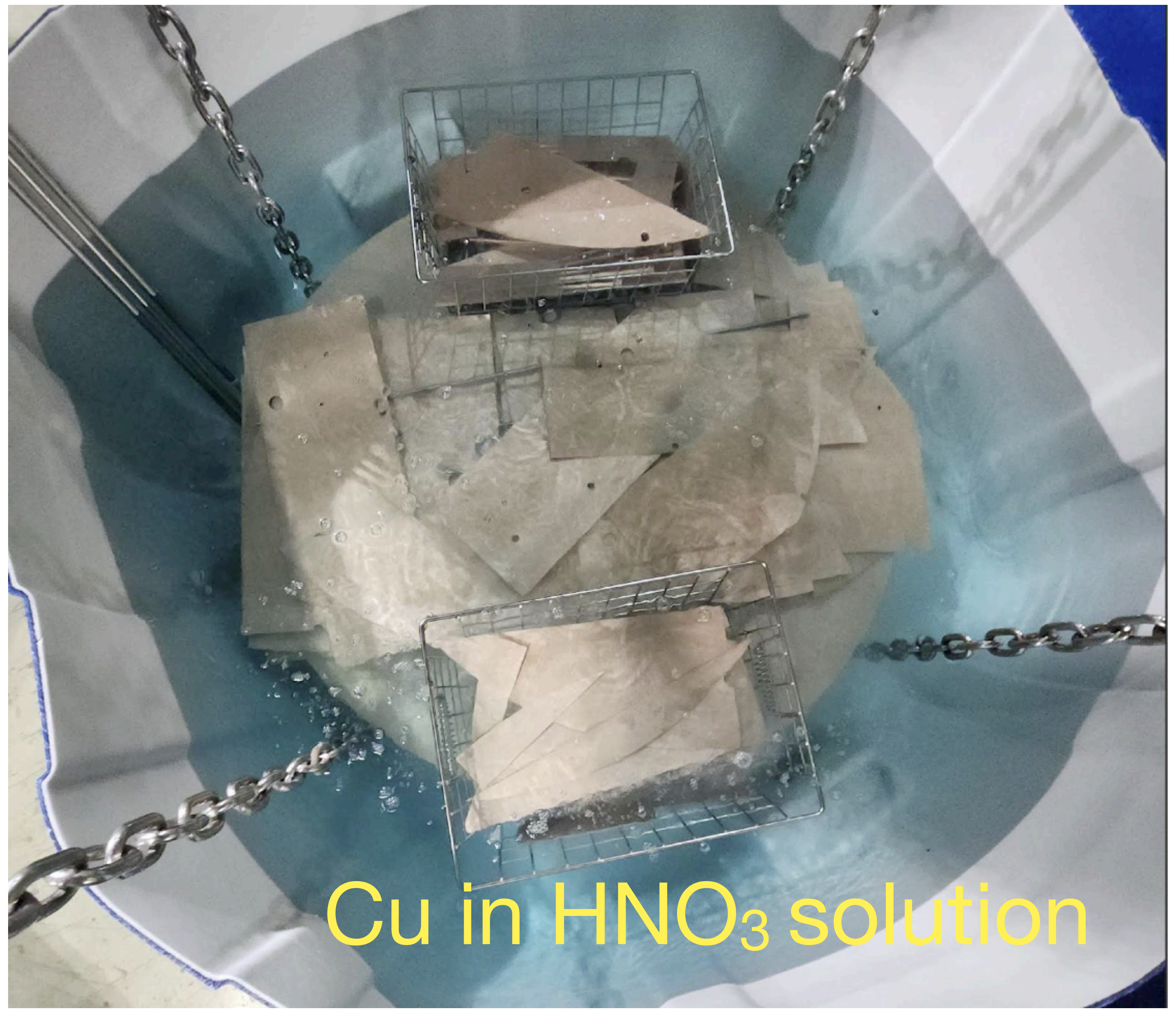
Vibration mitigation system:

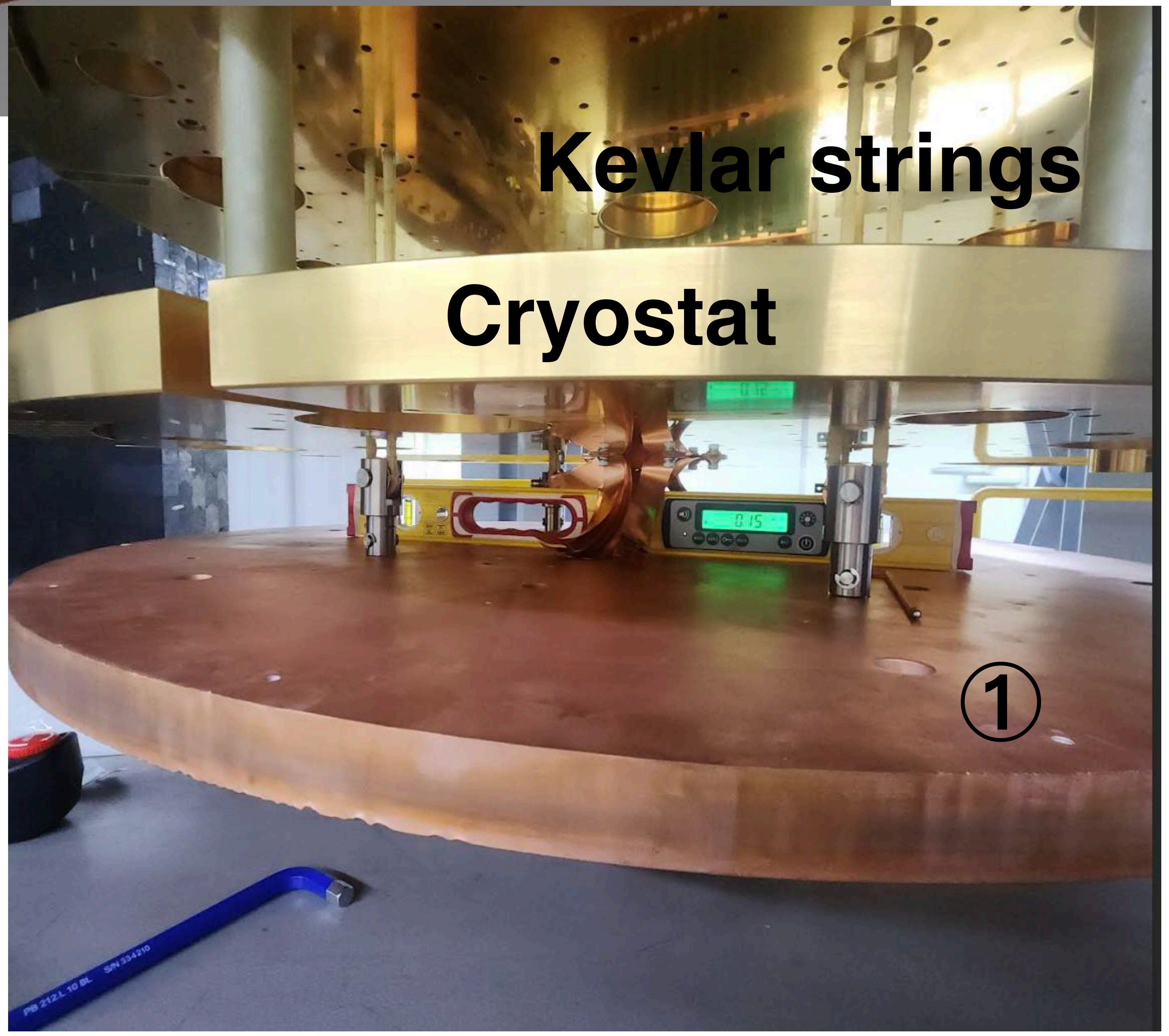
- Cryostat soft contact with H-beam (anti-vibration pad)
- Soft PTR contact on the fridge (absorbing foam, Cu tapes)
- Internal vibration damper between 4K and still stage
- Kevlar strings suspending detector array in IVC

Preparation of innermost shielding part



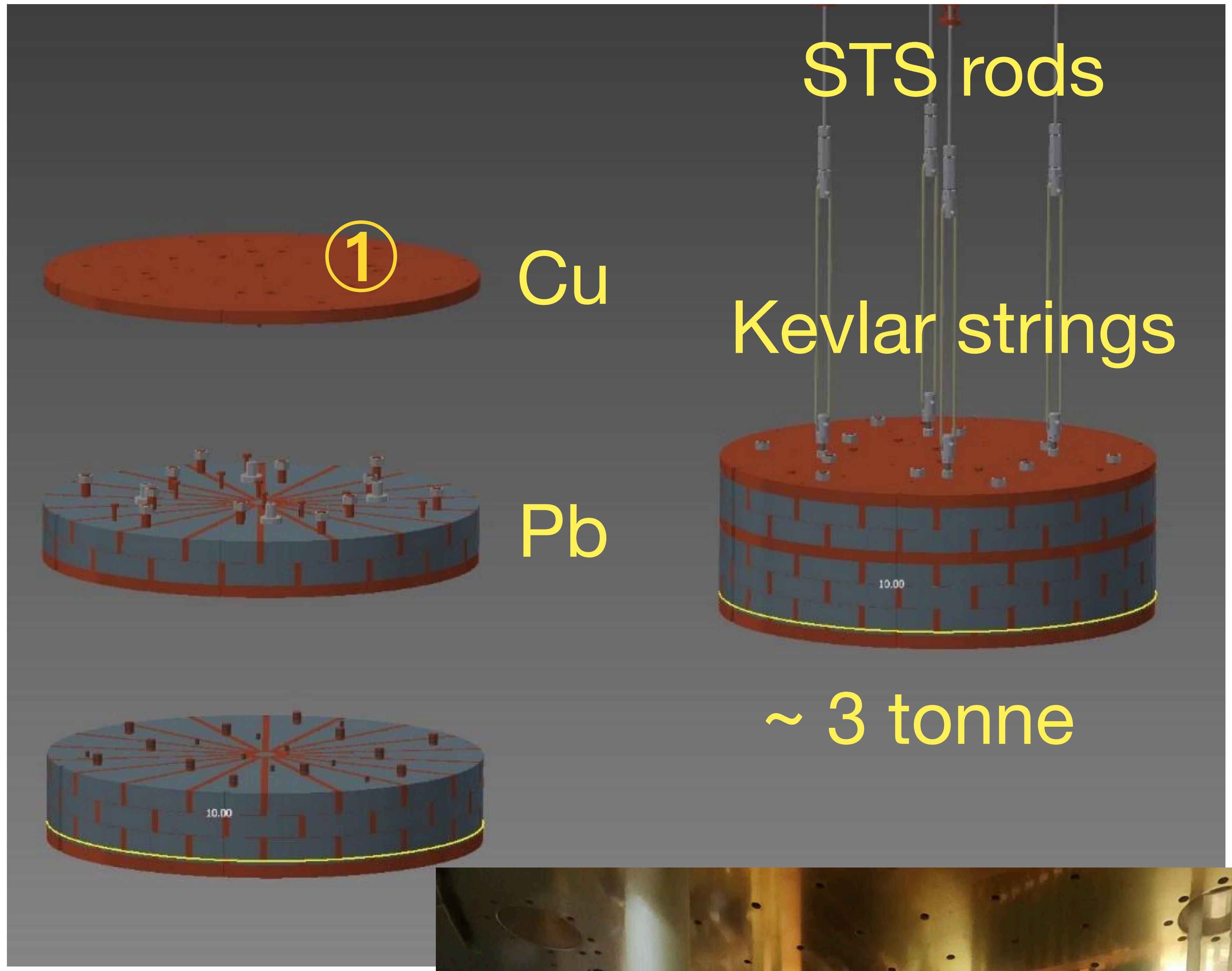


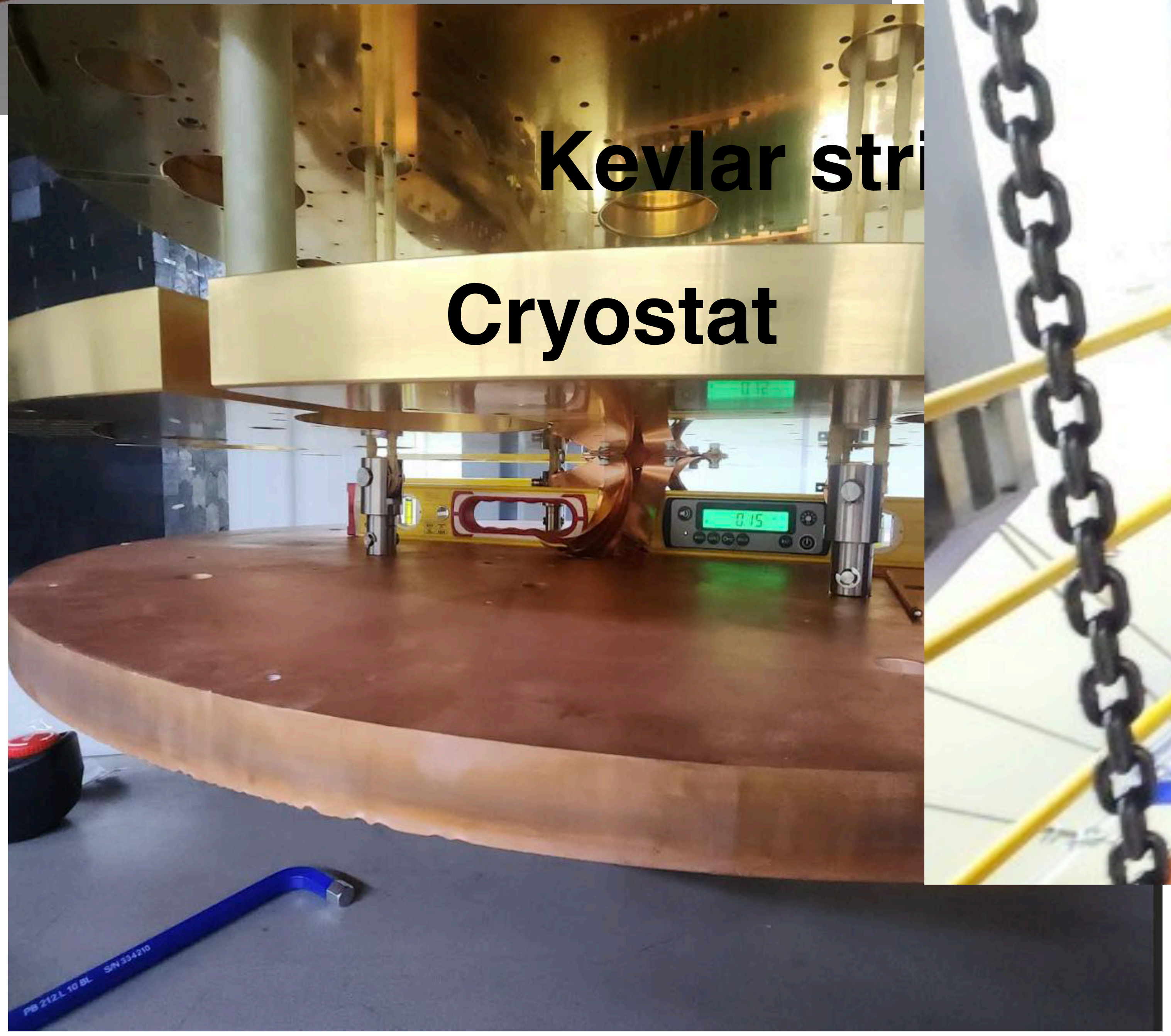




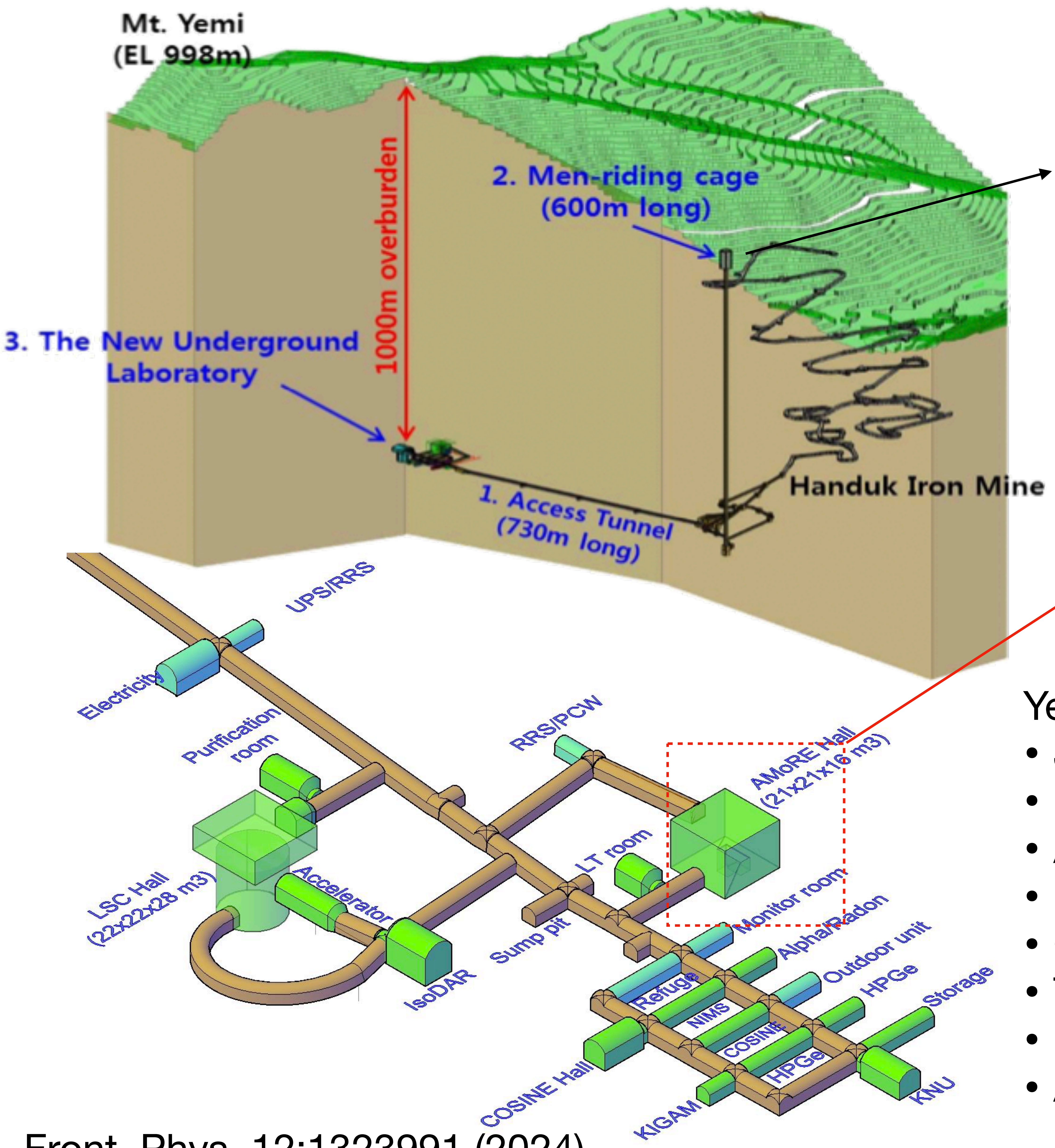
Cu, Pb cleaning:
Degreasing (Kerosene/IPA/Citranox)
Surface etching (Nitric acid)
Passivation (Oxalic acid)

Preparation of innermost shielding part





AMoRE experiment in Yemilab



Yemilab:

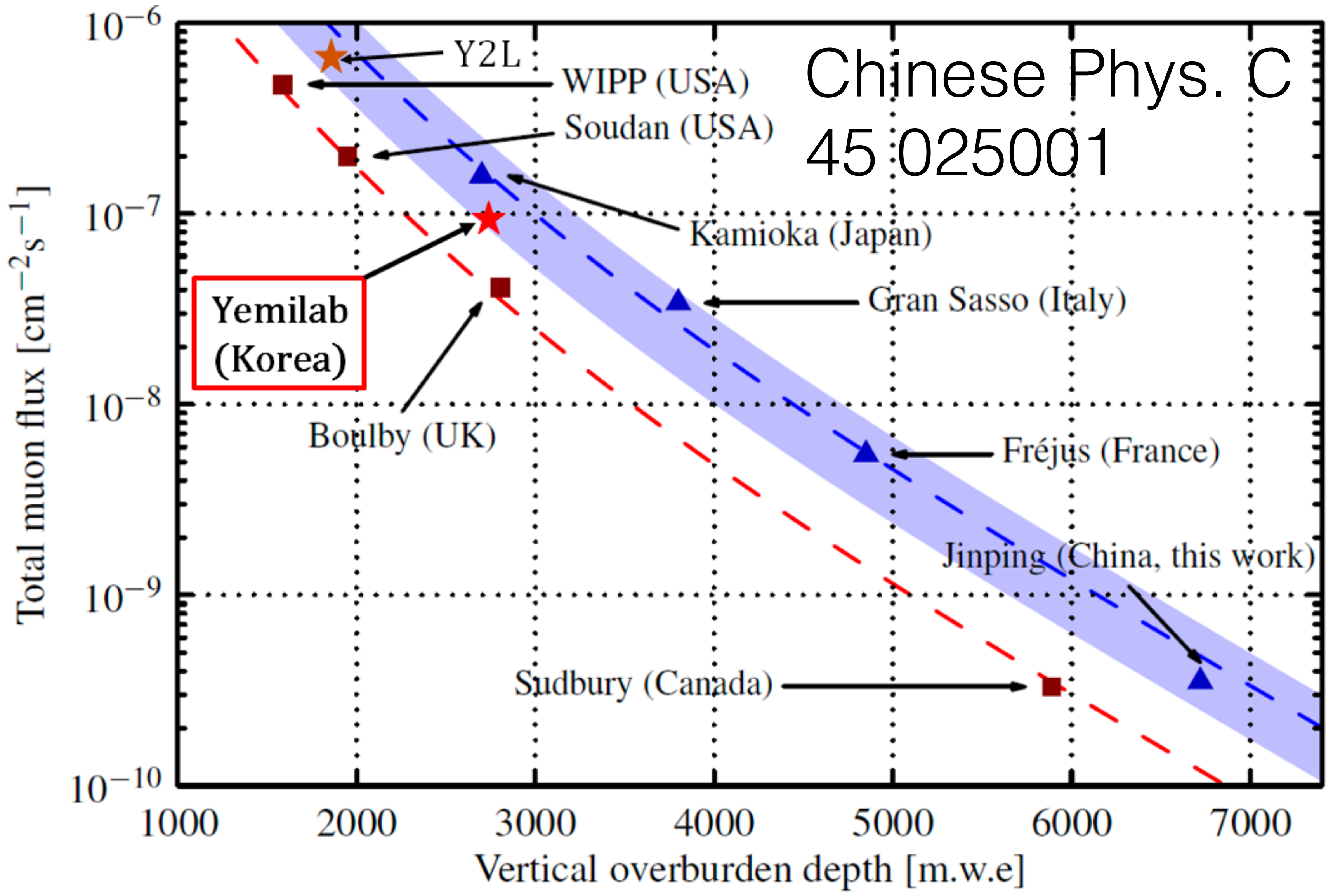
- Jeongseon, South Korea
- 1000 m vertical depth
- Access via elevator & ramp way
- Underground lab for basic sciences
- Opened in Oct, 2022
- Total Area: 3,000 m^2
- Large area & sufficient utilities
- AMoRE-II, COSINE, LSC, Radioassay …

Front. Phys. 12:1323991 (2024)

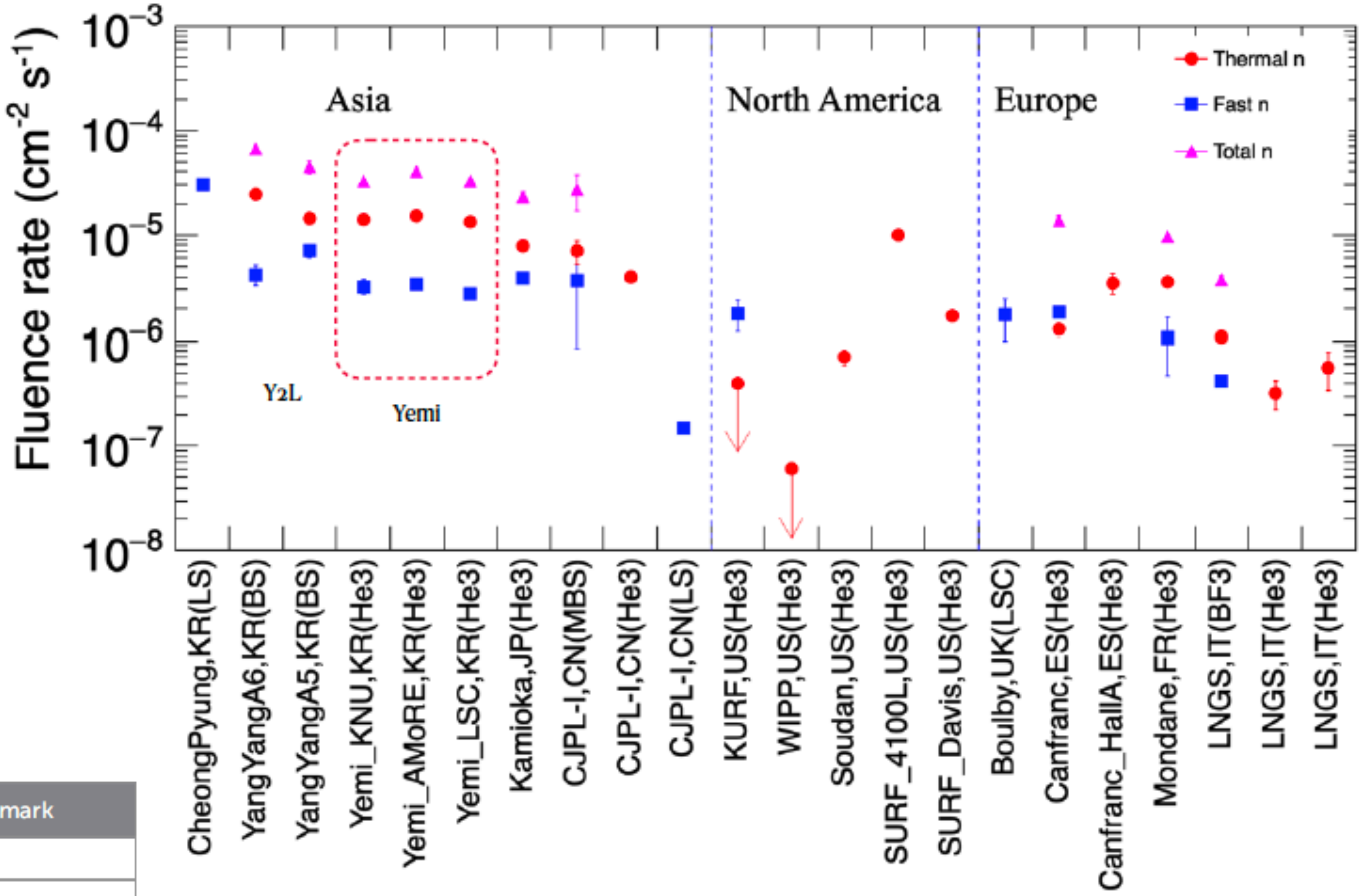
Yemilab survey

Muon flux

Chinese Phys. C 45 025001



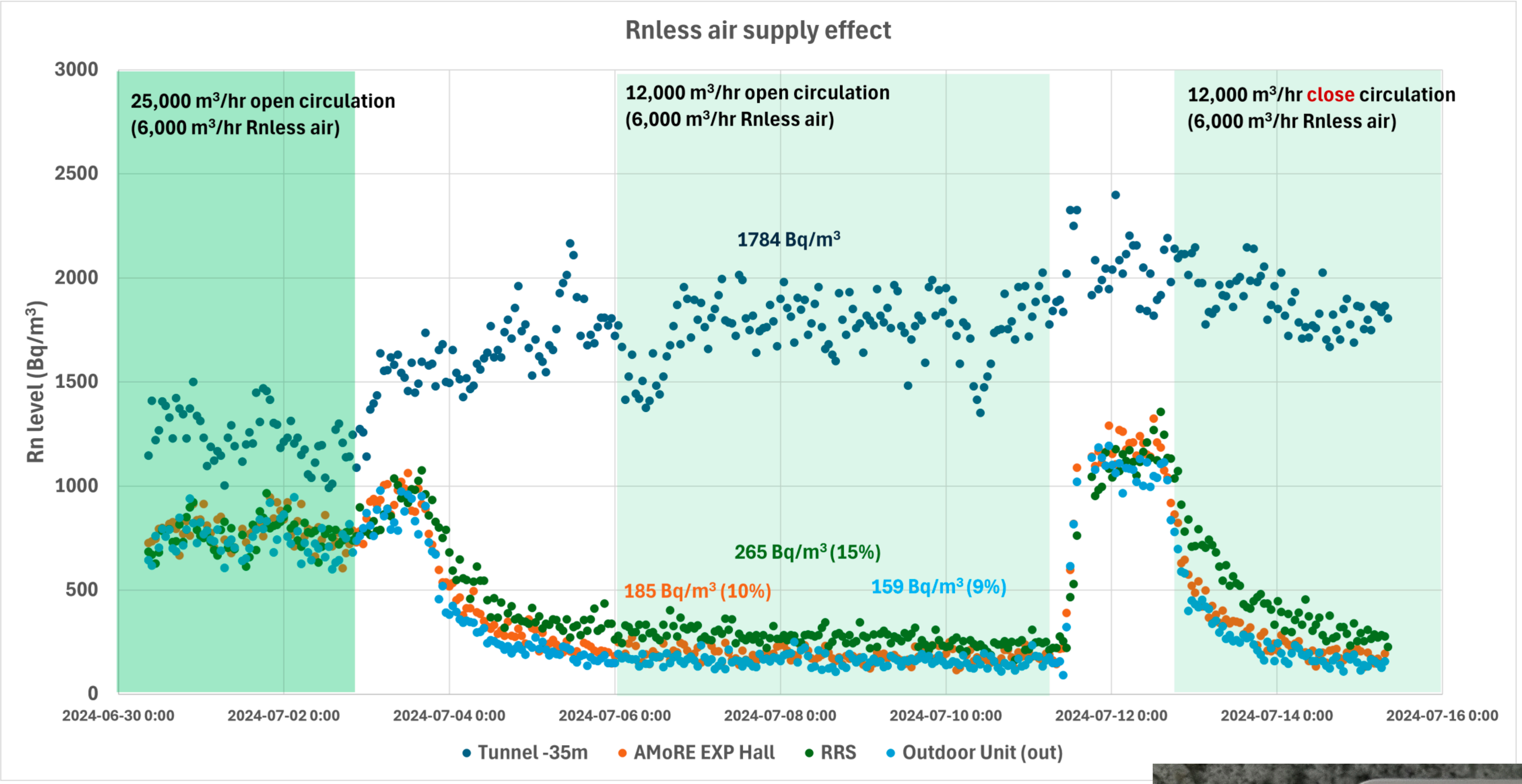
Neutron flux



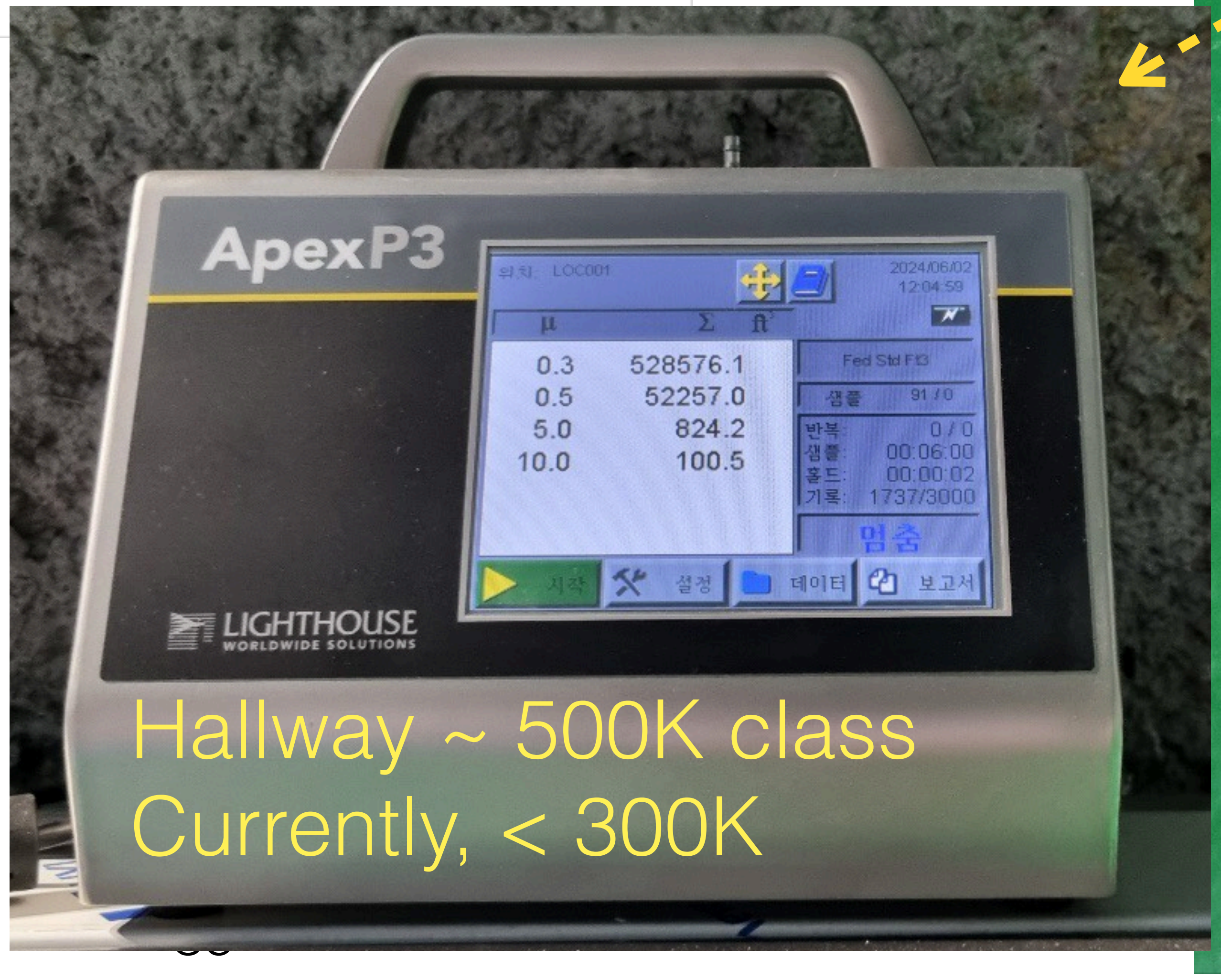
Rock	U (mg/kg)	Th (mg/kg)	K (mg/kg)	Remark
Access tunnel	1.21	9.62	24,267	@ sump pit
AMoRE-Hall	0.84	3.27	11,800	
LSC pit	1.58	7.15	24,600	
Shotcrete	U (mg/kg)	Th (mg/kg)	K (mg/kg)	Mixture Ratio (%)
Sand	1.98	13.05	27,384	49
Gravel	0.72	2.17	1,768	27
Cement	2.10	5.24	6,977	22
Steel fiber	0.22	0.39	610	2
Concrete for expr. room's floor	U (mg/kg)	Th (mg/kg)	K (mg/kg)	Mixture Ratio (%)
Sand	0.50	2.05	4,300	50
Gravel	0.82	1.41	4,900	28
Cement	2.10	5.24	6,977	22

Isotopic composition
of bedrock & construction material

Yemilab survey

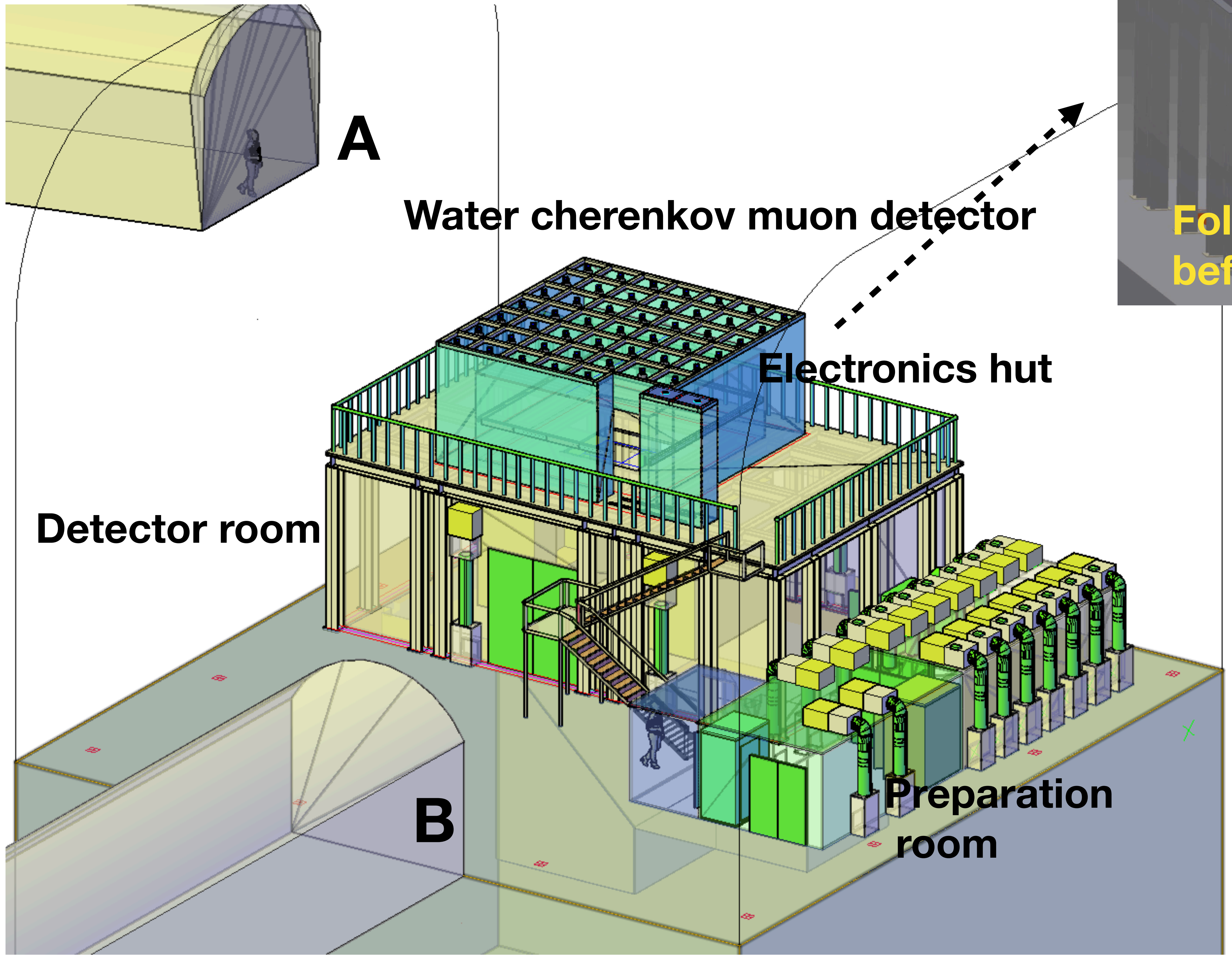


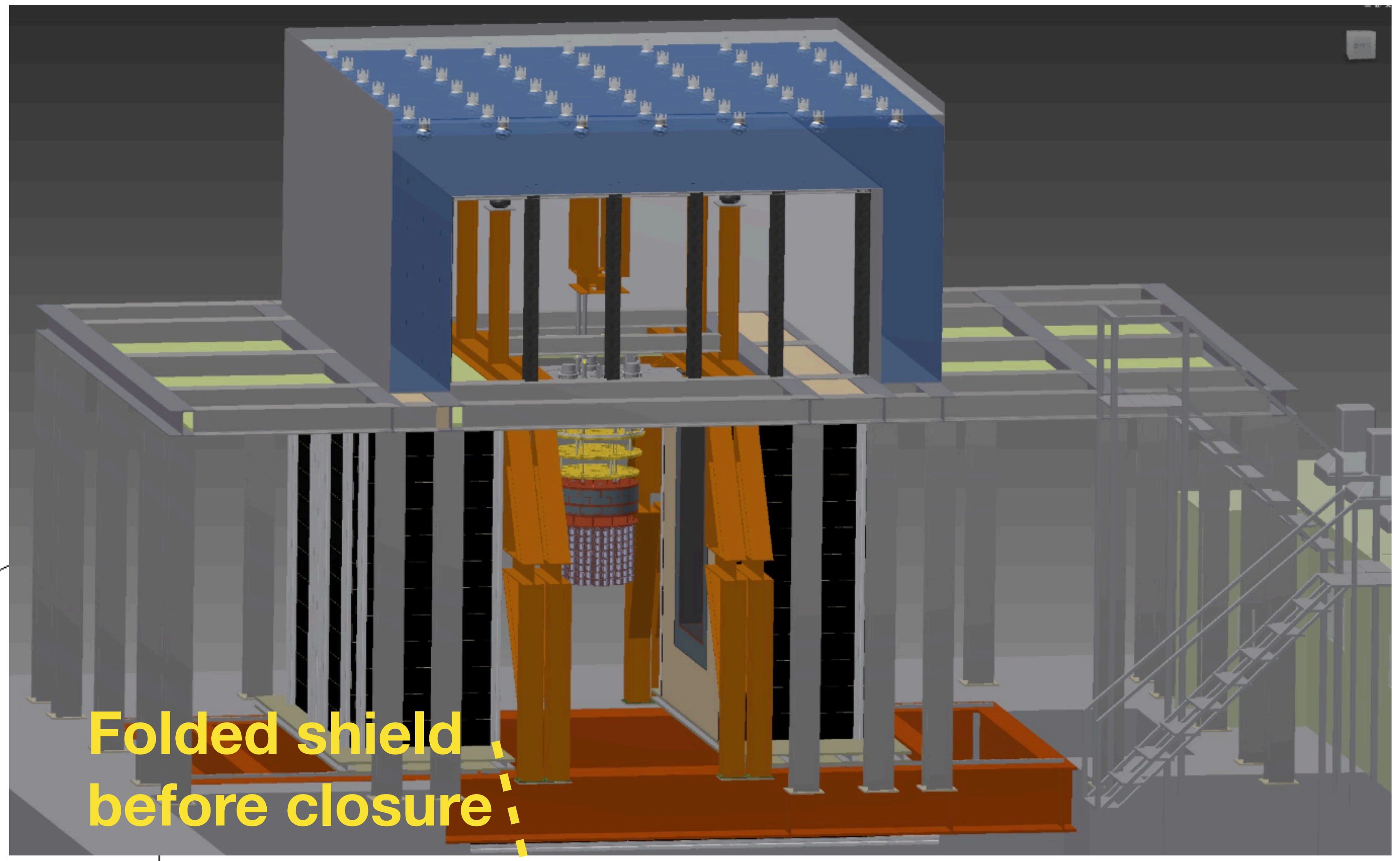
Radon level

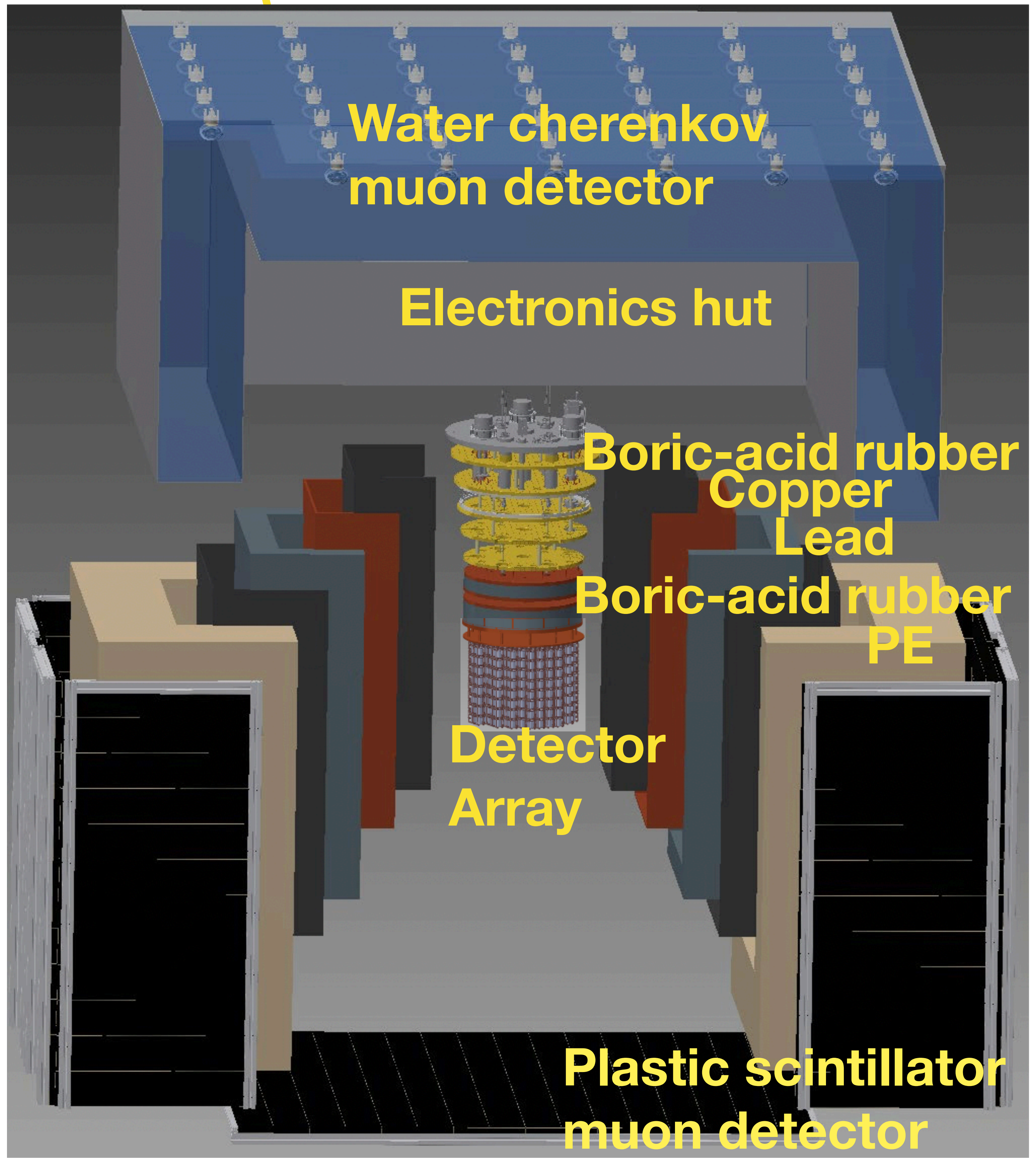


Dust counting

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
주의

Recent view of AMoRE Hall


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


Recent view of AMoRE Hall
주의


Recent view of AMoRE Hall
Water door
(part of
WCMD)

Recent view of AMoRE Hall


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

Muon veto detectors in commissioning

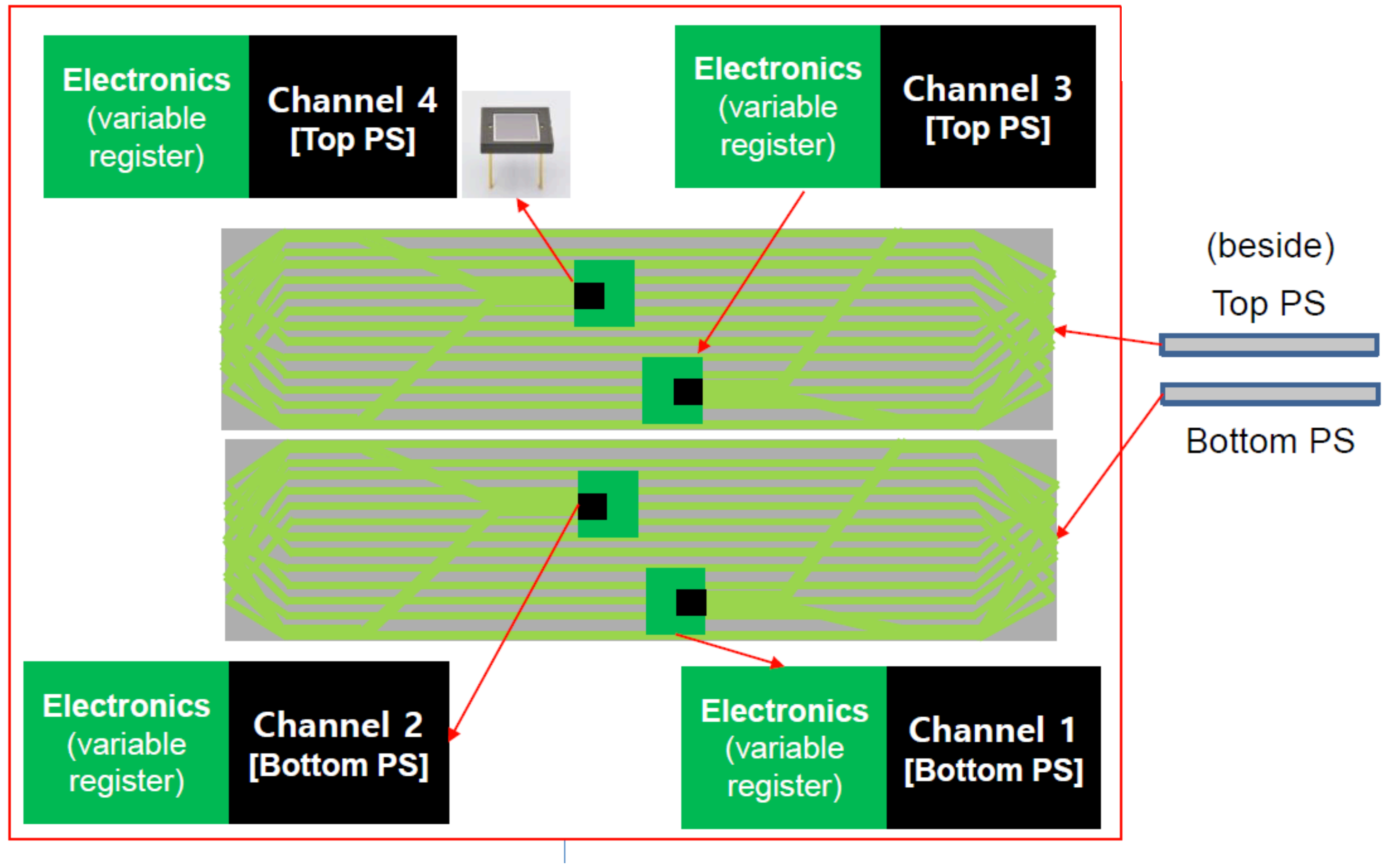
Water Cherenkov muon detector

~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

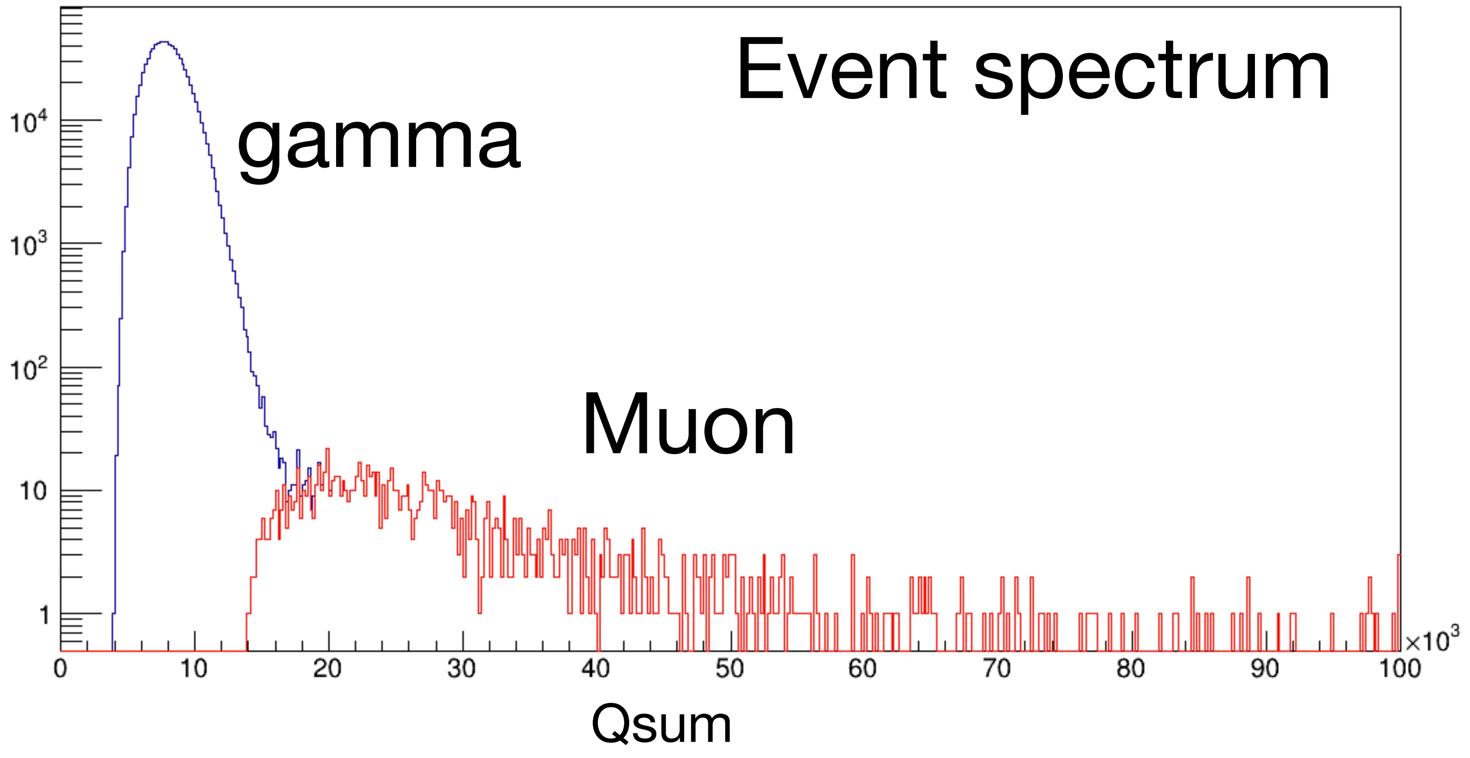
Plastic scintillator muon detector



Total 130 PSMDs

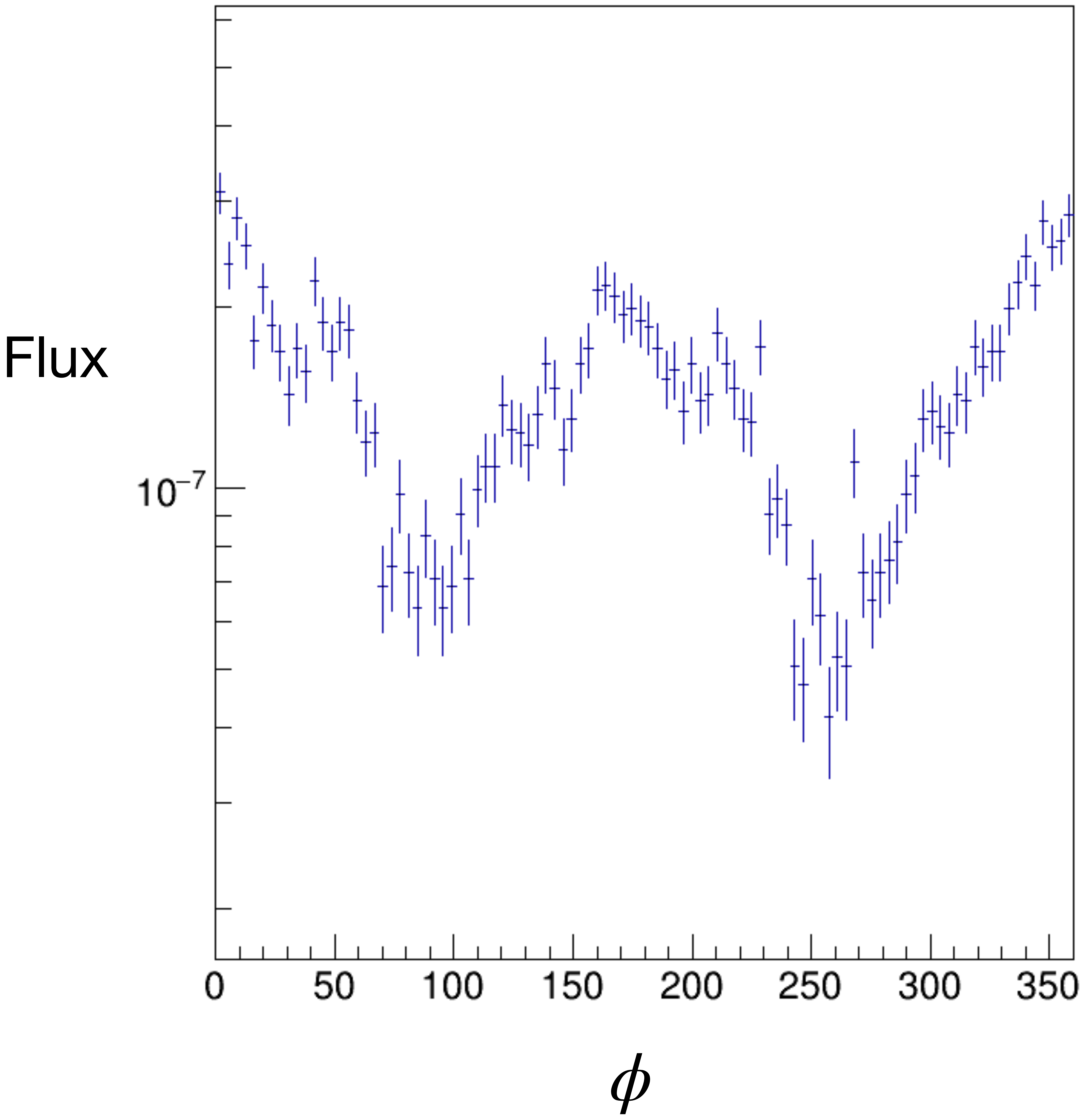
One PSMD:
2 extruded plastic scintillator panels ($30 \times 167 \times 1.5$ cm^3)
+ 32 wavelength-shifting fiber
+ 4 SiPMs, NIMA 1039 167123 (2022)

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

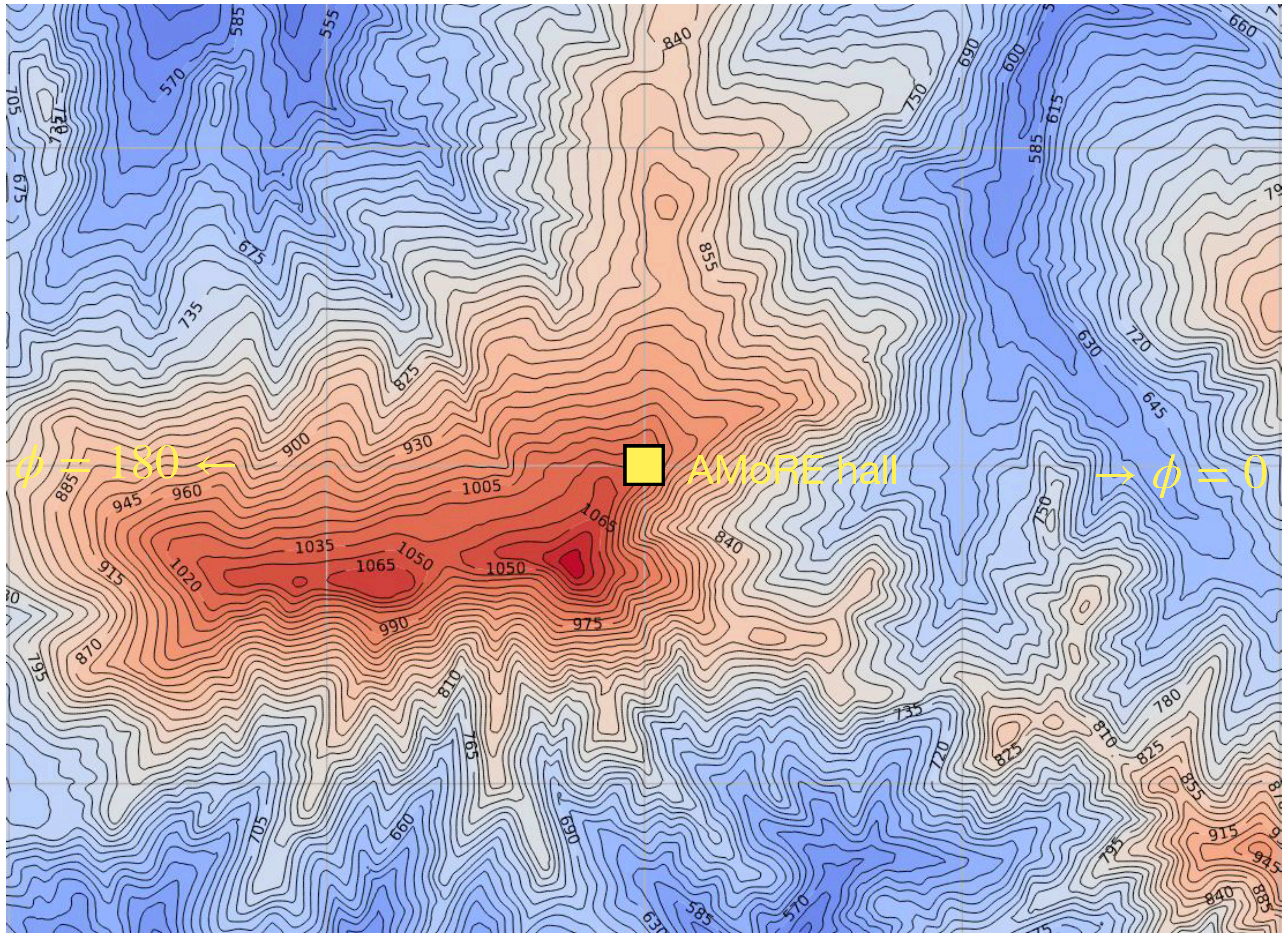


Muon angular distribution with PSMD

Position reconstruction from the signal asymmetry (preliminary)



Yemilab terrain
from National Geographic Information Institute

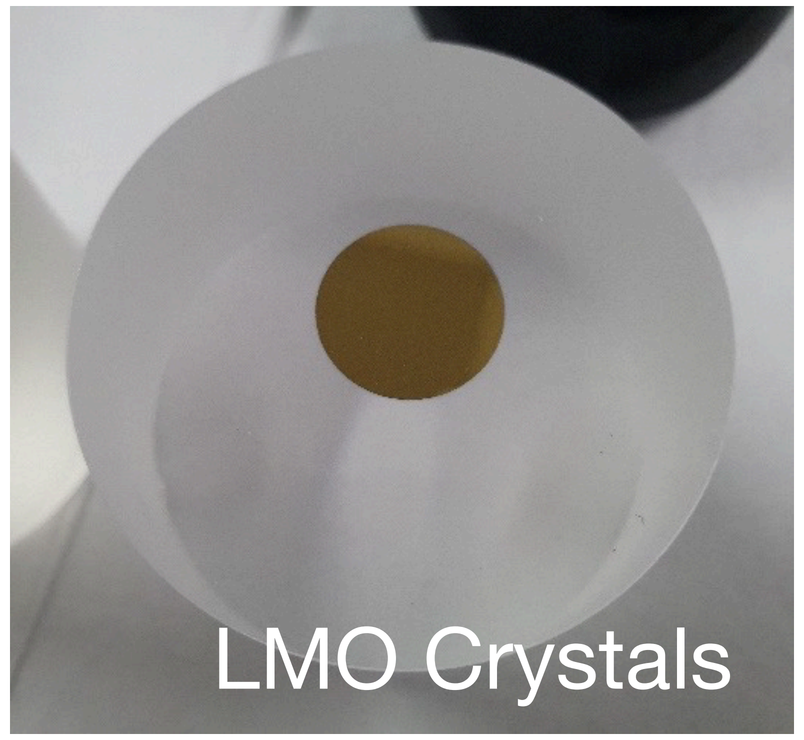


ϕ dependence seems to follow the terrain map

Comparison with simulation underway (MUSIC/MUTE)

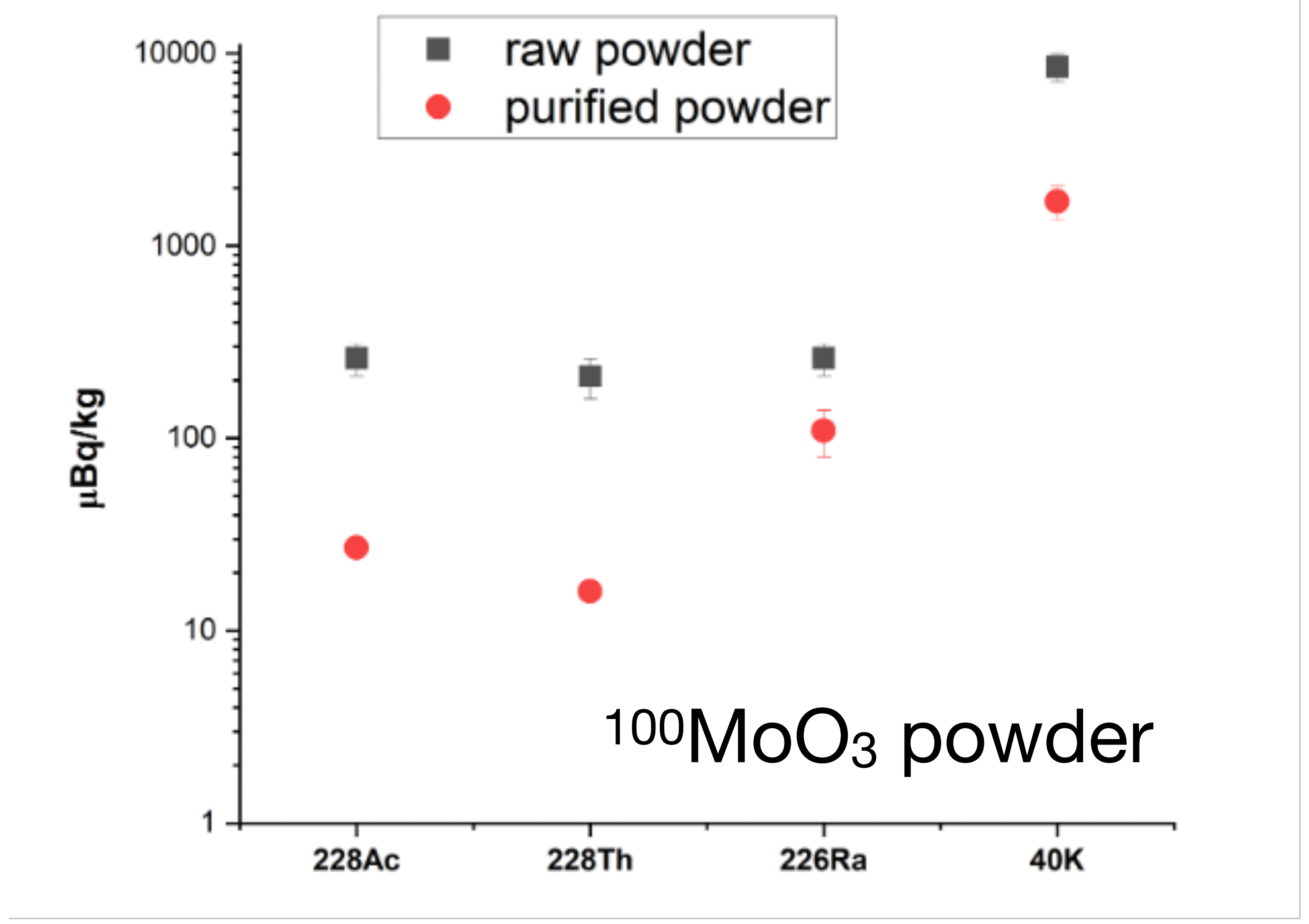
Background control

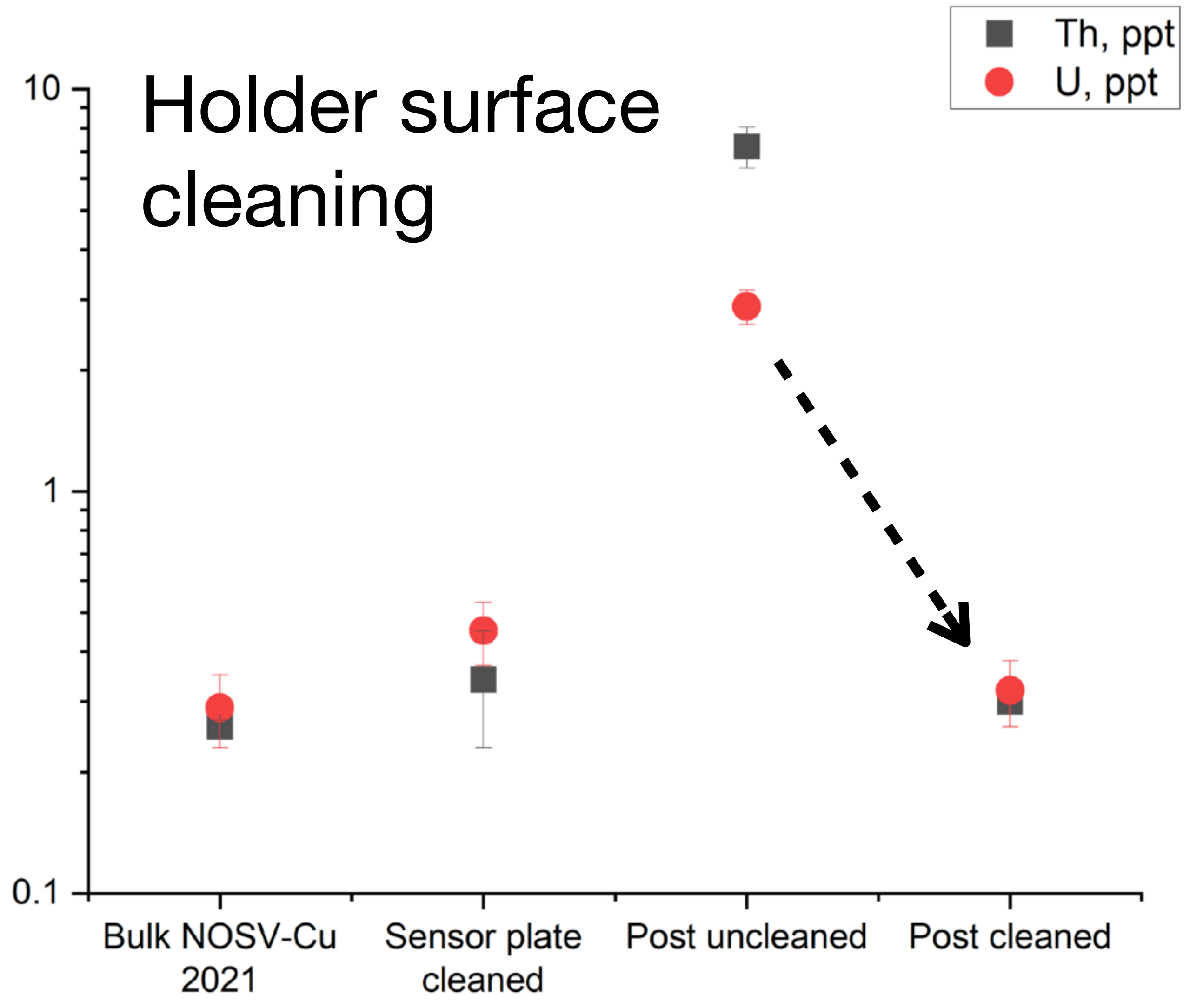
- Target background level at ROI:
  1×10^{-4} cnts/keV/kg/year
- A lot of lessons from AMoRE-pilot, AMoRE-I:
  Already external source dominant
- Intensive selection / purification / cleaning of materials
- Enhanced radiation shielding:
  Efficient design (neutron inelastic scattering) + pure material for innermost layer
  Rn-less (~10Bq/m^3) / Rn-free (< 0.1Bq/m^3) 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)

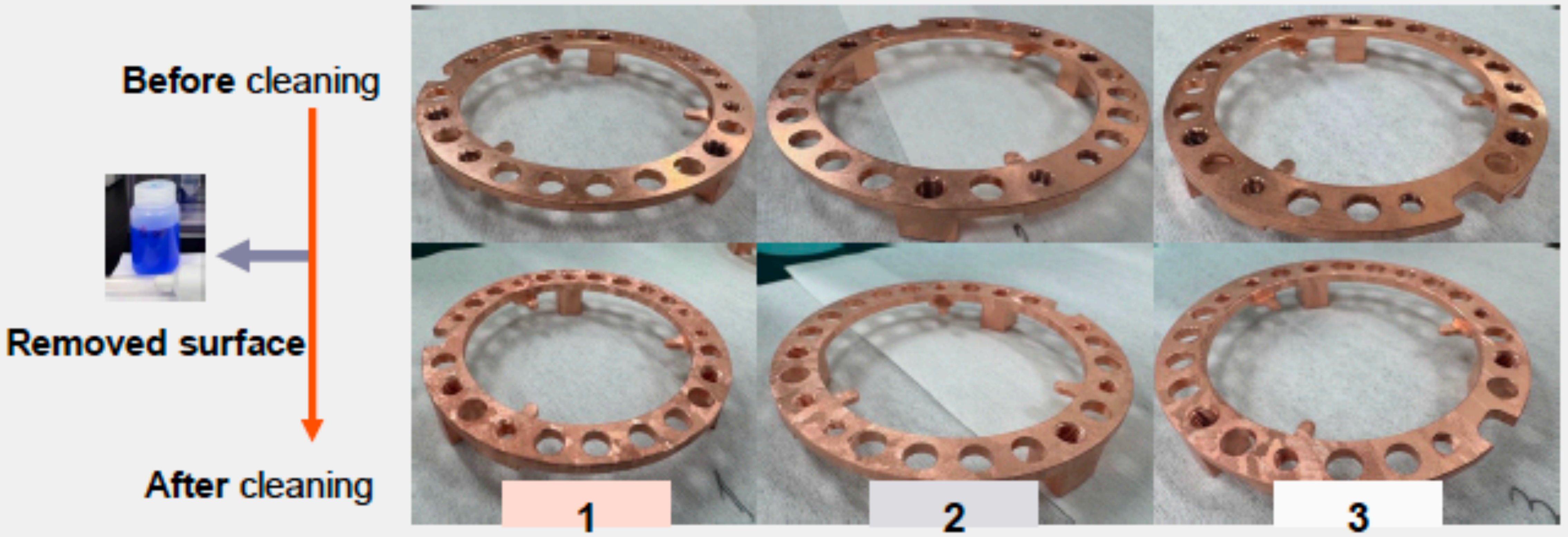




Background control

Cu component (detector parts) cleaning:
- Contamination due to machining
- Measuring the contamination of the removed (etched by HNO_3) surface with ICP-MS
- ~30 μm of the surface to be removed for some components

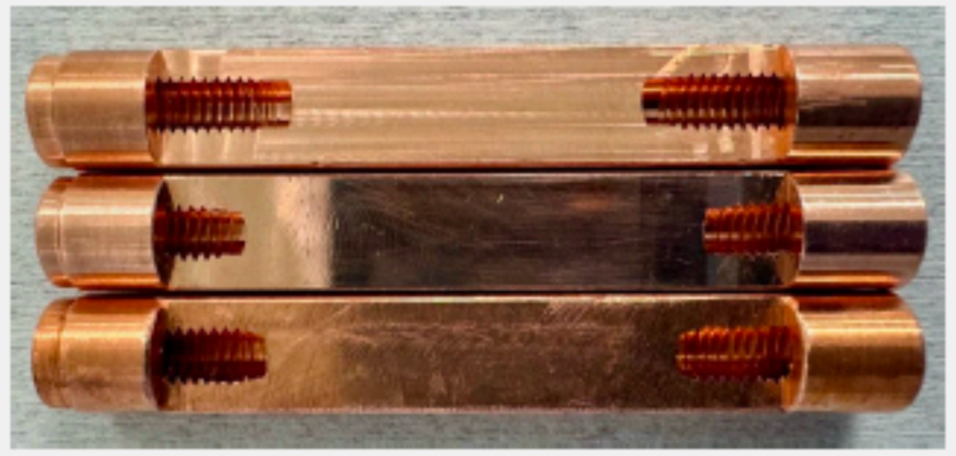
Top/bottom plates



2025 results	1			2			3			NOSV bulk
Thickness, μm	2-4	4-8	8-12	2-5	5-10	10-15	2-5	5-10	10-15	-
Th, pg/g of dissolved surface	521.4	63.5	12.8	50.6	6.0	1.6	19.6	8.0	0.32	0.26 ± 0.01
U, pg/g of dissolved surface	123.2	15.5	5.4	20.4	6.9	2.5	22.0	4.0	8.2	0.29 ± 0.06

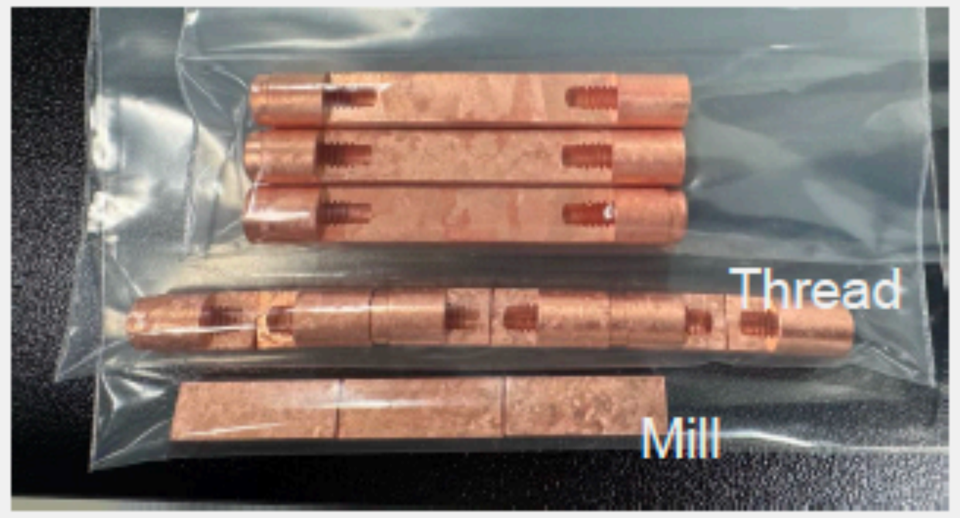
Posts

Selection of the manufacturer



	Th, ppt	U, ppt
NOSV 2021	0.26 ± 0.01	0.29 ± 0.06
After 20 μm surface removal		
Company 1 ES JeongMill	<0.5	0.43 ± 0.09
Company 2 Taeseong Tech	<0.5	0.60 ± 0.09
Company 3 ShinHan TC	77.3 ± 1.8	12.2 ± 0.4

Where is the source of contamination?



	Mill	Thread	NOSV-Cu 2021 bulk
Surface thickness removed, μm	~1	~4	
Th, pg/g of removed surface	80 ± 10	1370 ± 150	**0.26 ± 0.01**
U, pg/g of removed surface	30 ± 5	300 ± 30	**0.29 ± 0.06**

Carefully selected company for post machining

Background control

Relentless radioactivity inspection for all the experimental components

Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)	Detector
Crystal	Natural CMO (1902)[a]	CUP	56 (4)	< 5.5	< 5.3	< 39	CC1
	Enriched CMO (SE#3)[b]	CUP	< 2.0	< 3.2	< 1.6	< 3.2	CC2
	Natural LMO (1602)[a]	CUP	< 3.3	< 2.6	< 1.5	29 (9)	CC1
	Natural LMO (1801)[b]	CUP	< 1.2	< 3.2	< 1.3	< 14	CC1
	Enriched LMO (1901)[c]	CUP	< 1.5	< 5.7	< 3.4	< 14	CC2
	Enriched LMO (2005)[b]	CUP	< 3.5	< 4.1	< 3.6	< 14	CC2
Crystal surface	SiO_2 8 μm	Admatechs	3.5 (6)	< 3.1	1.4 (4)	108 (10)	CC1
	SiO_2 1.5 μm	Admatechs	< 1.7	< 2.3	< 0.90	< 16	CC2
	Diamond, 1 μm	Saint-Gobain	8.2 (12)	64 (5)	54 (3)	34 (7)	CC2
	SiC, 1 μm	Saint-Gobain	193 (10)	95(6)	101 (6)	100 (12)	CC2
	SiC, 3 μm	Saint-Gobain	176 (10)	350 (20)	365 (20)	220 (23)	CC2
	Mineral oil	LUBRIPLATE	< 0.81	< 1.8	< 0.69	< 7.9	CC1
	Polishing pad	Ciegal	< 8.5	< 13	14 (3)	290 (50)	CC1
	Polishing pad	Chem. pol.	840 (45)	55 (10)	71 (7)	480 (60)	CC1
	Gold (4N)	TAEWON	< 5.9	< 6.0	< 11	< 33	CC1
Cu holder	NOSV Cu[d]	Aurubis (2014)	< 0.087	< 0.068	< 0.075	< 1.8	CAGe
	NOSV Cu	Aurubis (2016)	< 0.67	< 0.80	< 0.65	< 3.5	CC1
	Cu post	Aurubis (2021)	< 0.49	< 1.4	< 1.0	< 6.0	CC2
	M3 Brass screws	SANCO	< 0.15	< 0.57	< 0.37	< 2.8	CC2
Reflector	Vikuiti film	3M	0.59 (18)	< 0.93	< 0.64	9.4 (24)	CC1
Sensor assembly	Superconducting wire	Supercon Inc.	< 4.2	< 6.2	< 4.1	< 170	CC1
	Polyimide PCB, HGLS-D211EM	Hanwha L&C	< 1.1	< 13	< 1.1	< 12	CC1
	Pb/Sn solder (2021)	KNU	< 0.88	< 1.2	< 2.2	< 12	CC2
	Pb/Sn solder (2023)	KNU	< 0.56	< 1.1	< 0.83	< 4.1	CC1
	Tin (5N)	Alfa Aesar	1.38 (16)	0.75 (17)	< 0.47	5.1 (8)	CC1
	Tin (6N)	Alfa Aesar	< 0.32	0.83 (24)	< 0.81	< 5.2	CC1
	Stycast 2850	Emerson & Cuming	440 (45)	600 (50)	600 (50)	400 (120)	CC1
	Stycast 1266 resin	Loctite	< 1.1	< 4.2	< 1.2	< 9.9	CC1
	Stycast 1266 hardener	Loctite	< 11	< 12	< 3.1	< 36	CC1
	Solder paste (UP78)	ALPHA	< 2.7	< 3.2	< 1.6	< 29	CC1
	Solder paste	G.F. Thompson Co.	19.4 (12)	7.9 (13)	5.7 (6)	650 (40)	CC2
	Si light detector wafer	IEMT	< 4.1	< 3.2	< 2.0	< 23	CC1
Heater	Araldite AW 106 CI	Huntsman	1.7 (4)	< 1.7	< 1.0	11 (4)	CC2
	Hardener, HV 953 U CI	Huntsman	2.8 (6)	< 2.2	< 1.2	< 8.9	CC2
	Si heat detector wafer	Microchemicals	< 2.0	< 3.0	< 2.0	< 18	CC1

Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)	Detector
Structural materials	OFE Cu	Aurubis (2021)	< 0.64	< 2.1	< 1.5	< 5.4	CC2
	Pb brick	JL Goslar	0.55 (17)	1.21 (28)	0.58 (17)	< 1.2	CAGe
	G11	Leiden	2,700 (200)	930 (110)	906 (66)	9,400 (800)	CC2
	Ultra-low Pb	Lemer Pax	< 3.6	< 2.6	< 2.2	< 16.1	CC1
Fasteners	STS screws M8	Unknown	8.6 (10)	24 (3)	23.1 (17)	18 (6)	CC2
	STS 304 plate	POSCO	1.00 (16)	1.7 (4)	2.36 (22)	7.5 (14)	CC1
Welding materials	Pb/Sn solder (2021)	KNU	< 0.88	< 1.2	< 2.2	< 11	CC2
	TIG Welding rod, ER308L	Hyundai Welding	< 1.1	5.1 (12)	4.2 (8)	< 29	CC1
	Flux core, K-308LT	KISWEL	48,400 (2,400)	15,900 (800)	20,600 (1,000)	129,700 (6,600)	CC1
	STS welded sample	CUP	16.4 (16)	9.6 (18)	12.9 (15)	104 (12)	CC1

Item	Material	Supplier	^{226}Ra (mBq/kg)	^{228}Ac (mBq/kg)	^{228}Th (mBq/kg)	^{40}K (mBq/kg)	Detector
Air balloon	Urethane 0.3 mm	Seokyeong Industry	< 2.2	< 2.5	< 0.86	< 8.9	CC1
	Urethane 0.5 mm	Seokyeong Industry	< 1.2	< 1.9	< 1.4	< 9.7	CC2
Neutron shielding	Boric acid (99.5%)	Fisher Scientific	1.2 (4)	< 2.3	< 0.69	< 9.5	CC2
	Boric Acid (99.5%)	Samchun	10.8 (10)	< 2.8	< 1.8	< 6.5	CC1
	Boric acid (99.99%)	Alpha Aesar	< 0.46	< 1.5	< 0.50	98 (8)	CC1
	Boric acid (99.5%)	Samchun	12.0 (9)	< 1.5	< 0.81	< 9.0	CC2
	Boric acid (99.5%)	Samchun	10.2 (7)	< 1.3	< 0.64	< 11	CC2
	Boric acid (99.5%)	KANTO	< 1.4	< 1.3	< 0.95	< 11	CC2
	Boric Acid (99.5%)	Samchun	< 2.0	< 1.3	< 1.1	< 7.2	CC2
	Silicon	HRS Co.	< 0.57	< 1.4	2.1 (3)	< 4.9	CC1
Outer Lead Shielding	Pb brick	Boliden	0.48 (12)	0.36 (8)	0.45 (11)	1.05 (34)	CAGe
	Pb brick	Haekgwang	0.38(16)	n/a	< 0.25	< 1.5	CAGe
	Ingot Pb	Korea Zinc	0.32 (13)	n/a	0.40 (15)	< 1.3	CAGe
	Pb brick	JL Goslar	0.55 (17)	1.21 (28)	0.58 (17)	< 1.2	CAGe
Boric-acid rubber plate	Borated rubber I	CUP	< 1.9	2.3 (6)	1.2 (3)	< 6.2	CC1
	Borated rubber II	CUP	15.0 (15)	< 1.6	3.2 (8)	< 8.8	CC1

HPGe

ICP-MS / NAA

Item	Material	Supplier	^{238}U (pg/g)	^{232}Th (pg/g)
Reflector	Vikuiti film [22]	3M	< 3.6	< 4.5
Holder	NOSV copper bulk [22]	Aurubis (2014)	1.6 (7)	5.1 (12)
	NOSV-Cu bulk [22]	Aurubis (2016)	0.29 (14)	0.34 (12)
	NOSV-Cu bulk [22]	Aurubis (2021)	0.33 (12)	0.26 (11)
	NOSV-Cu sensor plate[a]	Aurubis (2021)	0.45 (12)	0.33 (12)
	NOSV-Cu post	Aurubis (2021)	0.79 (30)	3.1 (13)
	NOSV-Cu holder (top & bottom)	Aurubis (2021)	0.32 (14)	0.53 (21)
	PTFE, Eriflon plates	Maagtechnic	< 100[b]	< 200[b]
Screw	OFE-Cu bulk [22]	Aurubis (2018)	1.01 (15)	0.98 (10)
	OFE-Cu bulk [22]	Aurubis (2021)	0.83 (11)	0.98 (14)
	OFE-Cu screw machined	Aurubis	1.8 (5)	10.7 (12)
	Brass screw machined	Sanco	0.49 (12)	1.43 (13)
PCB board	Polyimide-based, HGLS-D211EM	Hanwha L&C	890 (90)	< 1.2
Soldering	Tin 6N	Alfa Aesar	< 50	< 50
	Tin 5N	Alfa Aesar	< 50	< 50

Selection of low activity material
process method

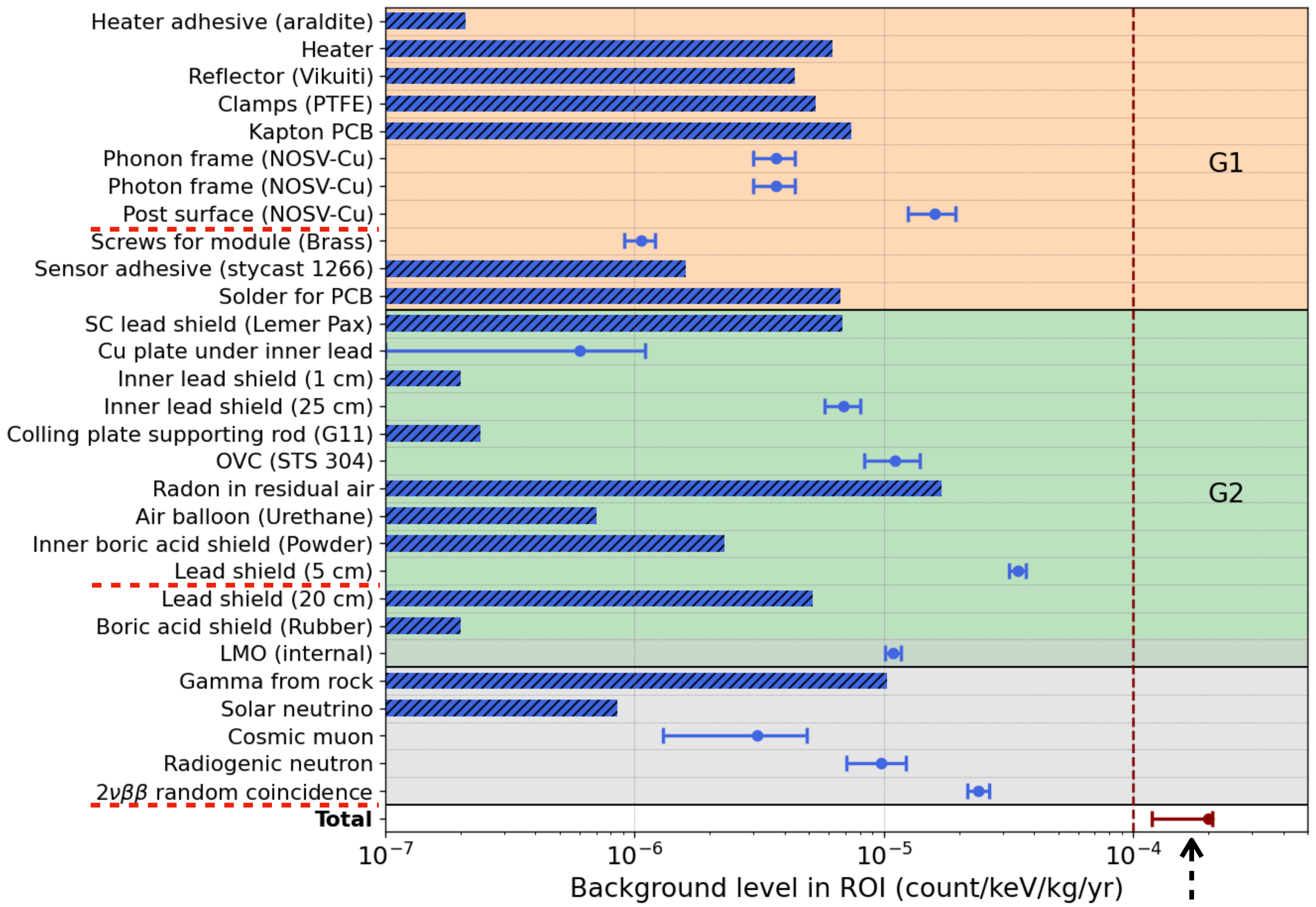
Optimally small amount

Input for the simulation study

Front. Phys. 12:1362209 (2024)

Expected background from simulation

Decomposing background in the ROI



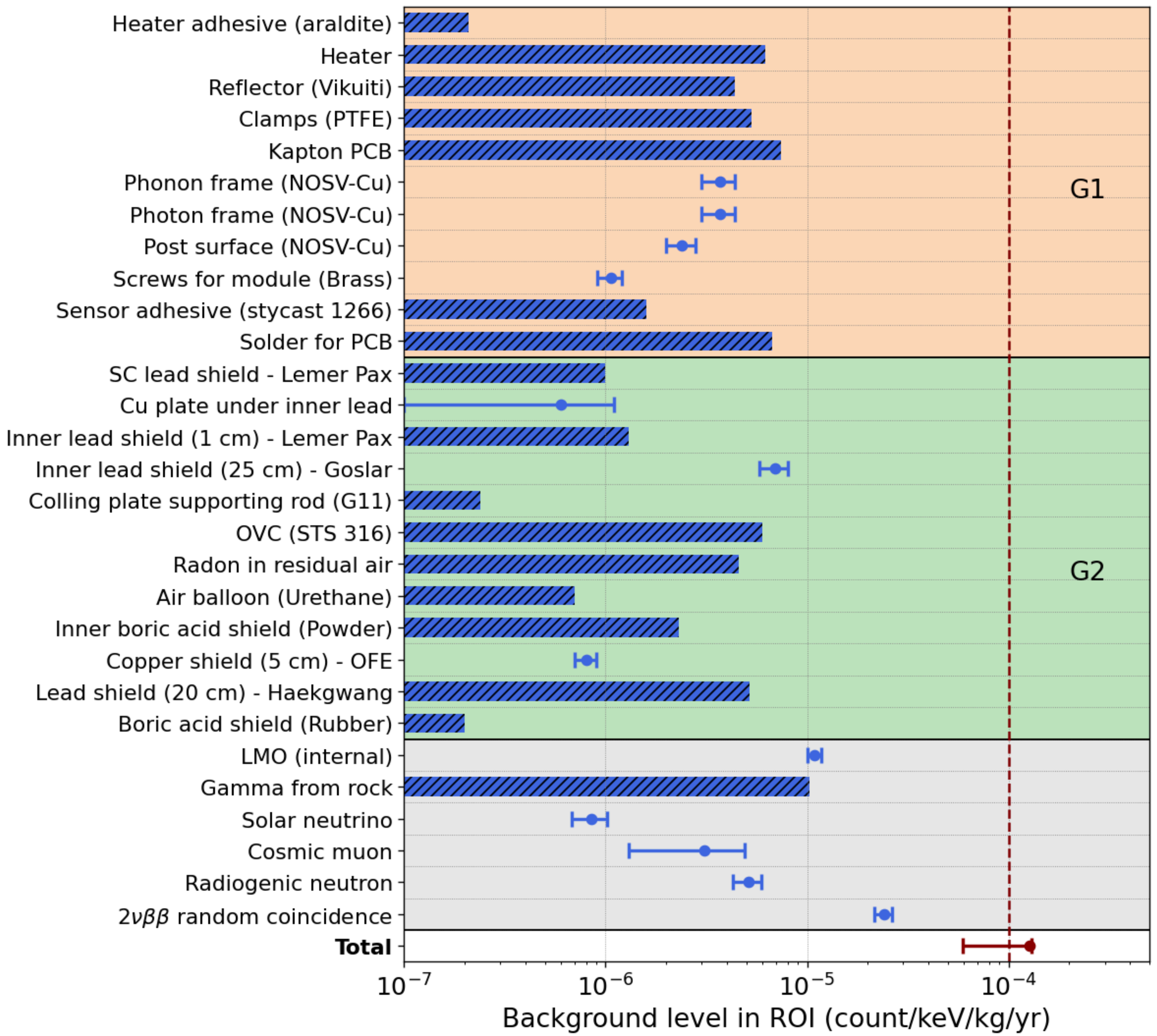
Eur. Phys. J. C 85:9 (2025)

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

Expected background from simulation

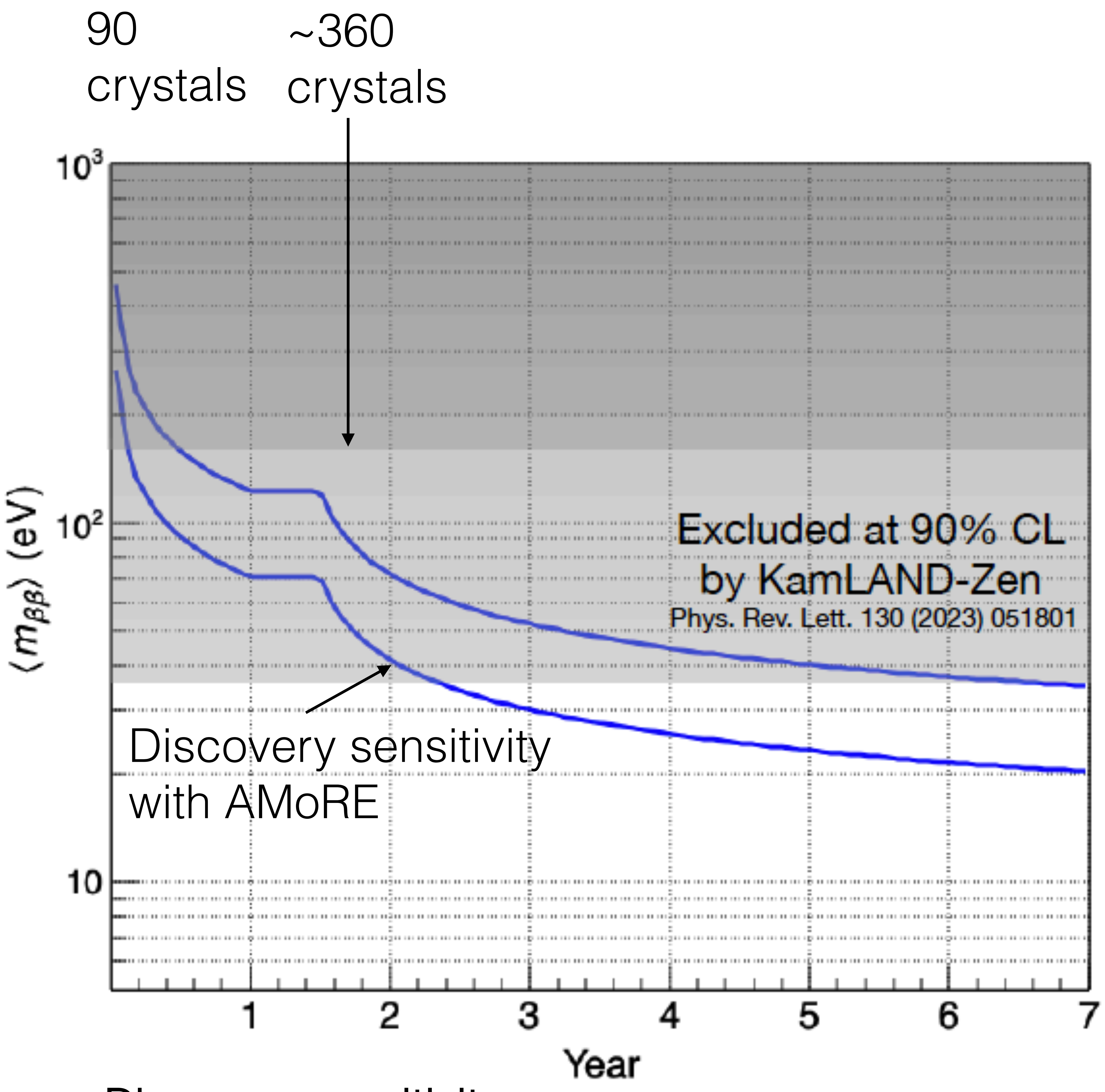
New update:
- Cleaner post machining
- Some Pb layer => OFE Cu
- New measurement for inner lead layer

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



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

Sensitivity of AMoRE-II

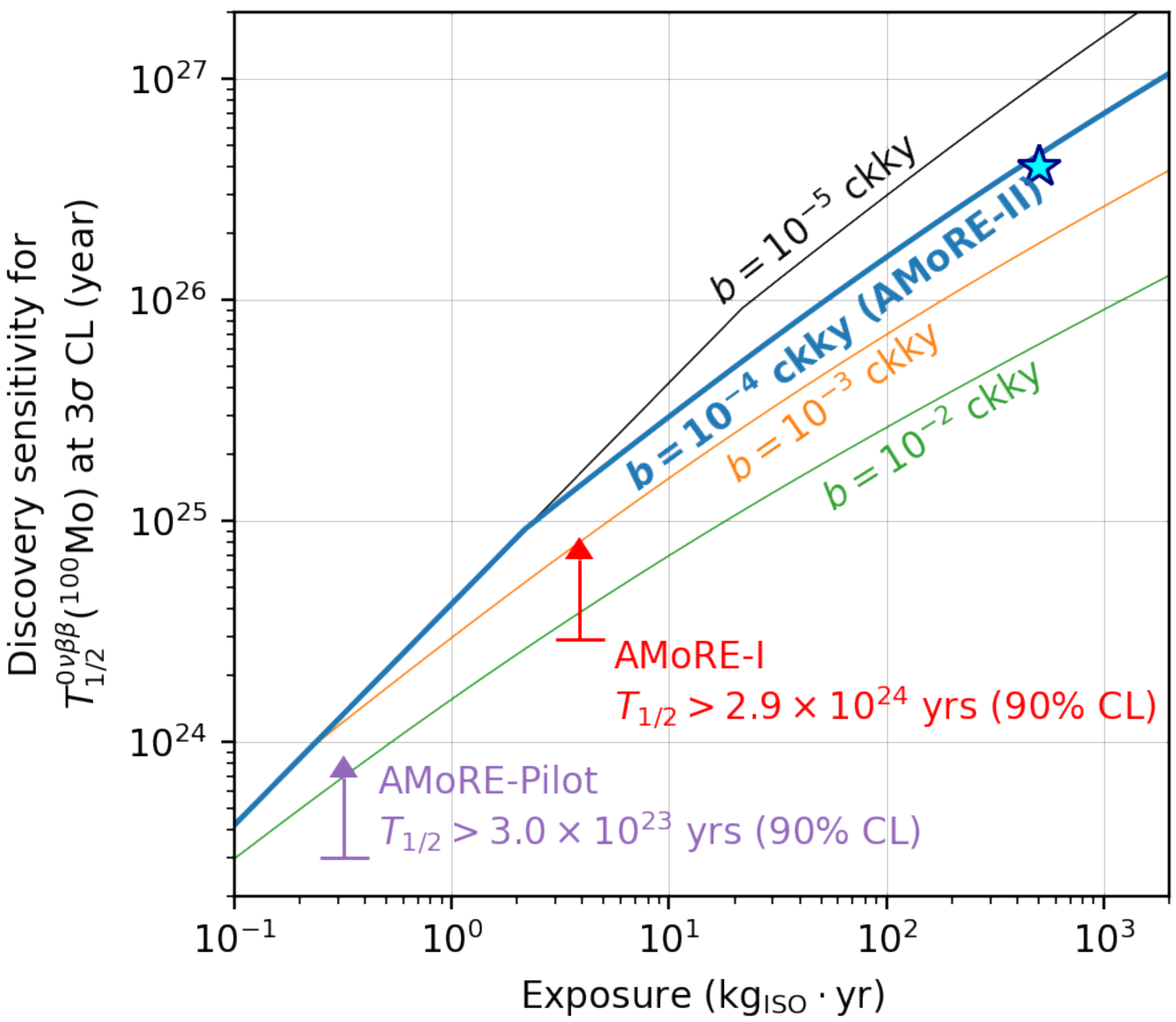


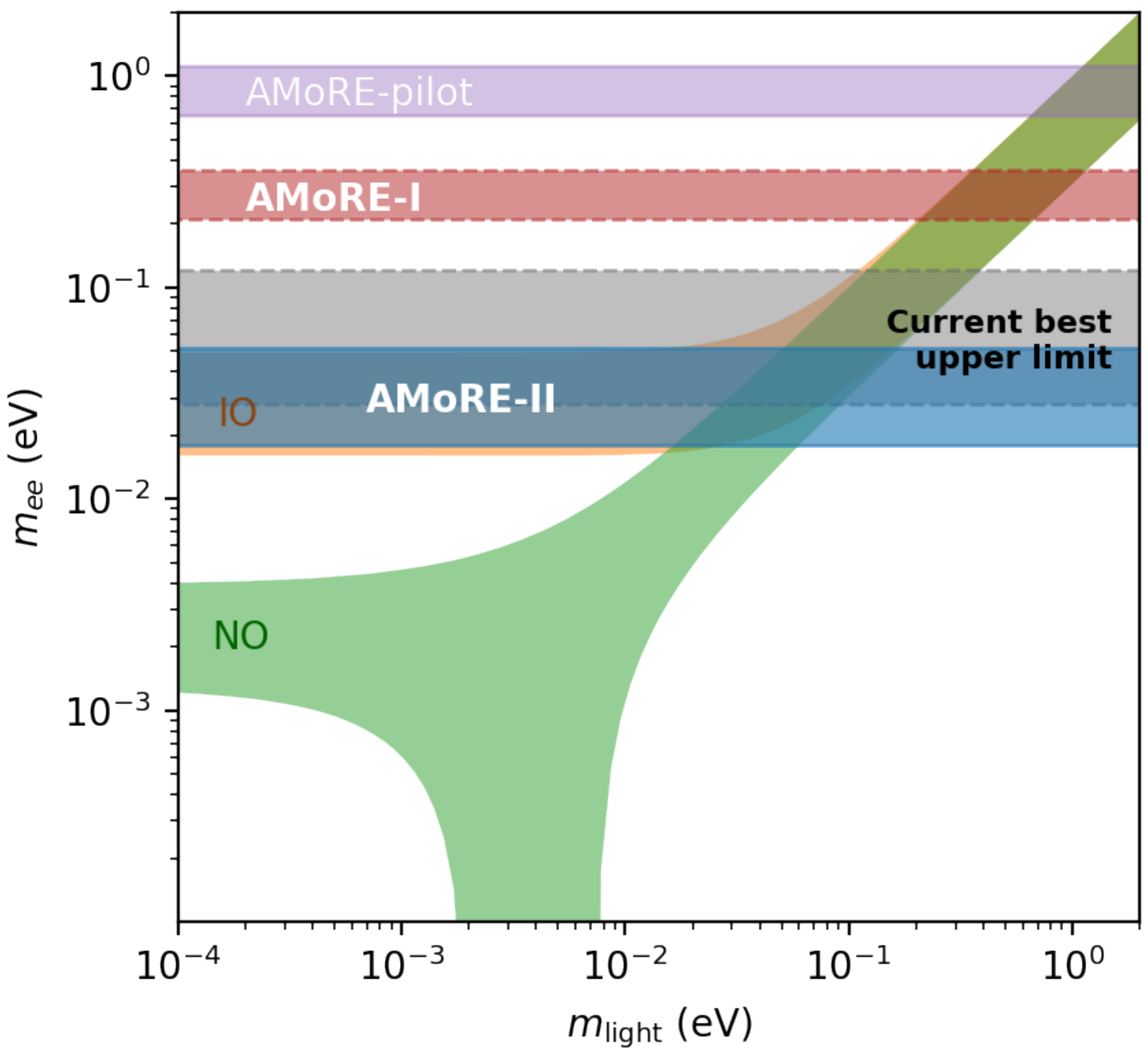
Discovery sensitivity:
50% chance to measure signal 3σ above background

Sensitivity goal:

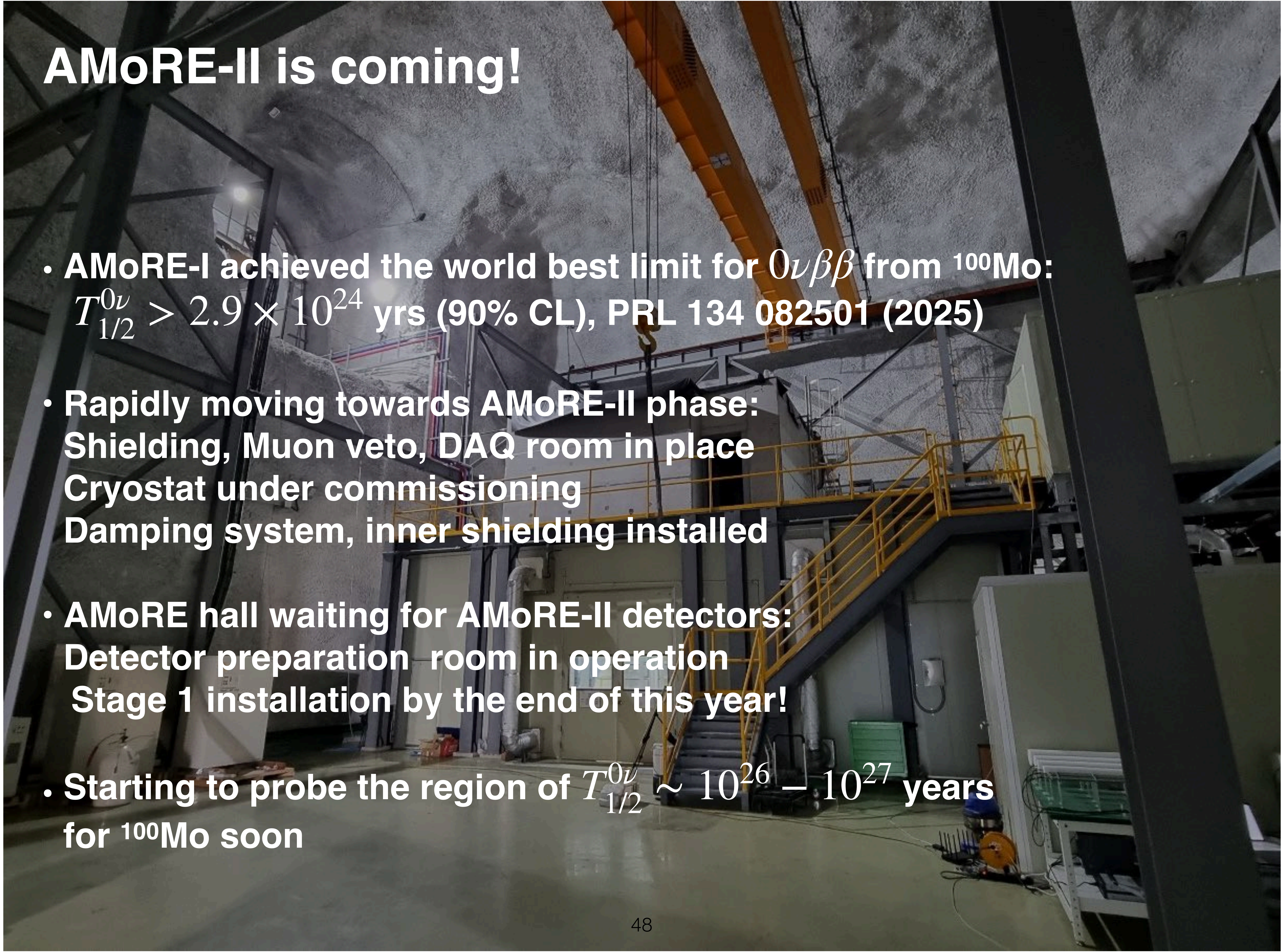
- 90% C.L. exclusion
  $T^{0\nu}_{1/2} \sim 6 \times 10^{26}$ yrs
- 3σ discovery
  $T^{0\nu}_{1/2} \sim 4.5 \times 10^{26}$ yrs
  $m_{\beta\beta}$ ~ 18 - 35 meV

Sensitivity of AMoRE-II





Aiming at $T_{1/2}^{0\nu} \sim 4.5 \times 10^{26}$ yrs, $\langle m_{\beta\beta} \rangle \sim 18 - 52$ meV (depending on NME)



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
  Damping system, inner shielding installed

- AMoRE hall waiting for AMoRE-II detectors:
  Detector preparation room in operation
  Stage 1 installation by the end of this year!

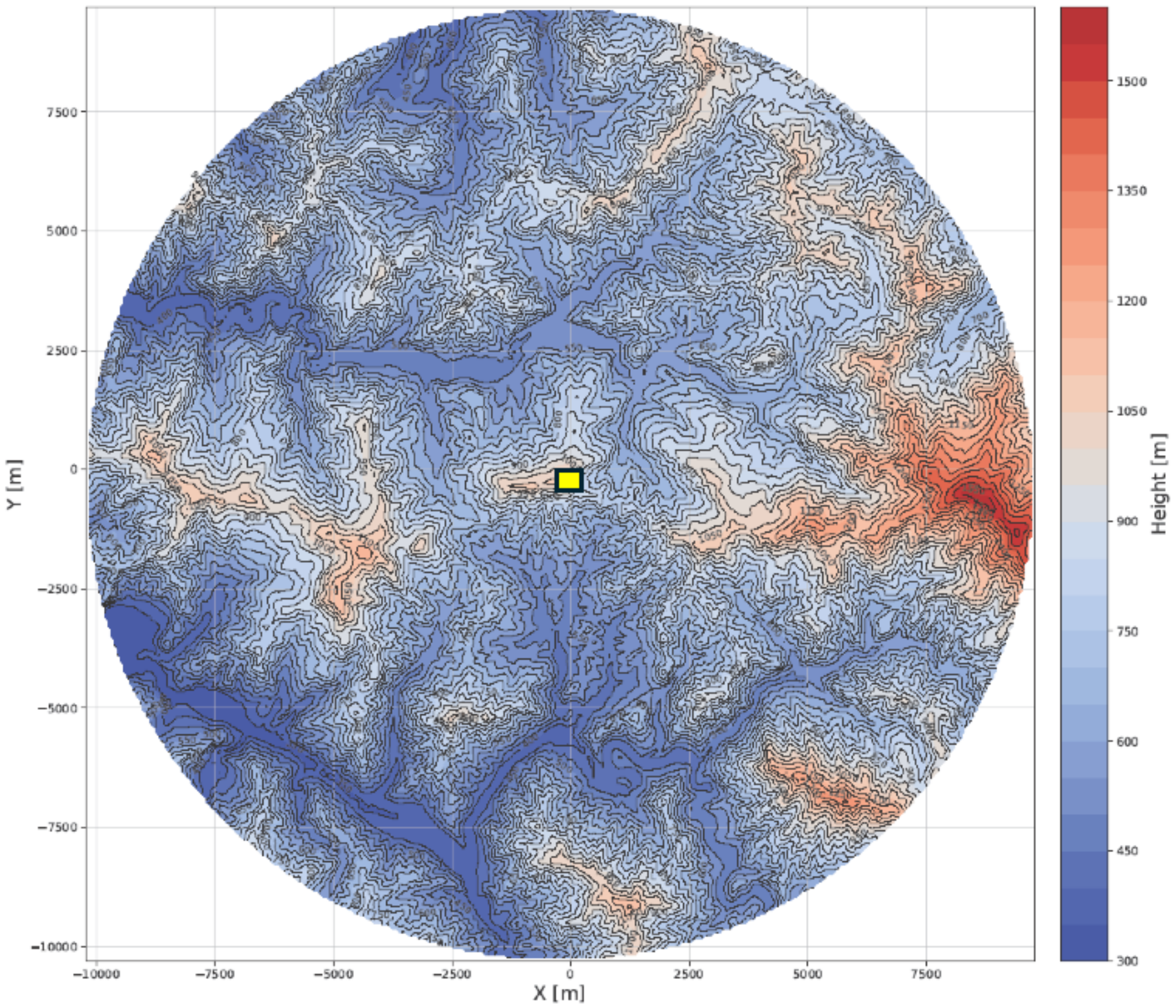
- Starting to probe the region of $T^{0\nu}_{1/2} \sim 10^{26} - 10^{27}$ years for ^{100}Mo soon

Acknowledgement:
AMoRE collaboration

Thank you~!

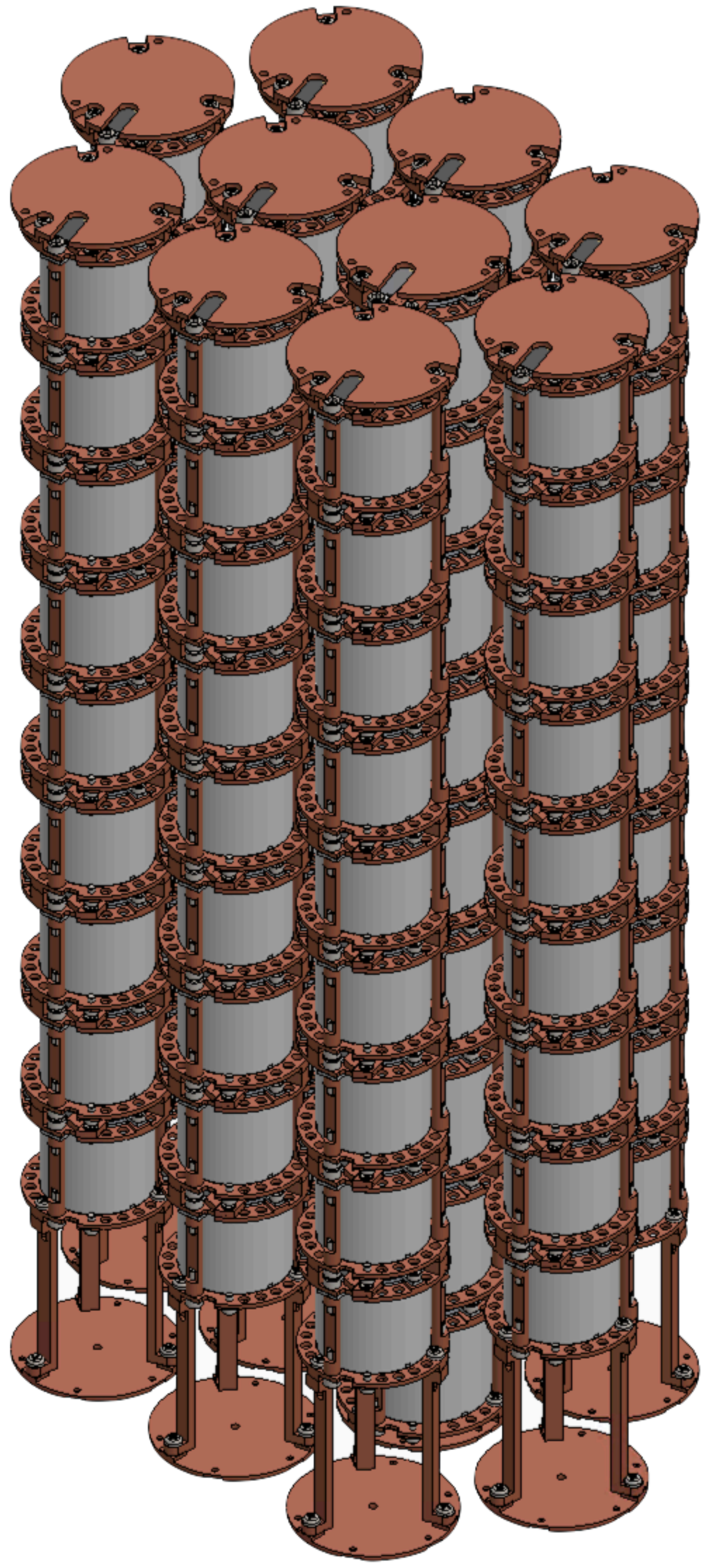
EXTRA

Yemi Mountain profile

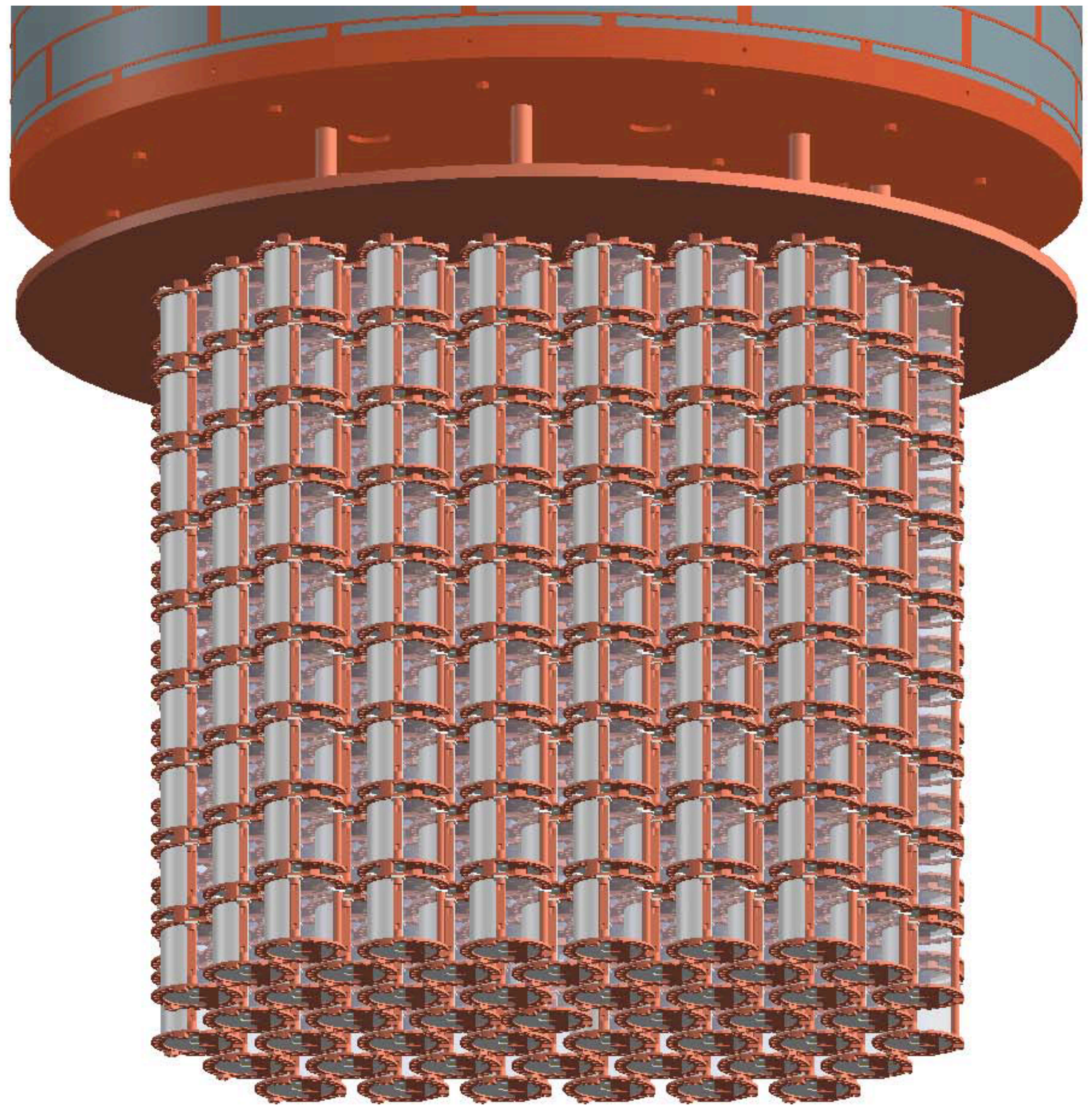


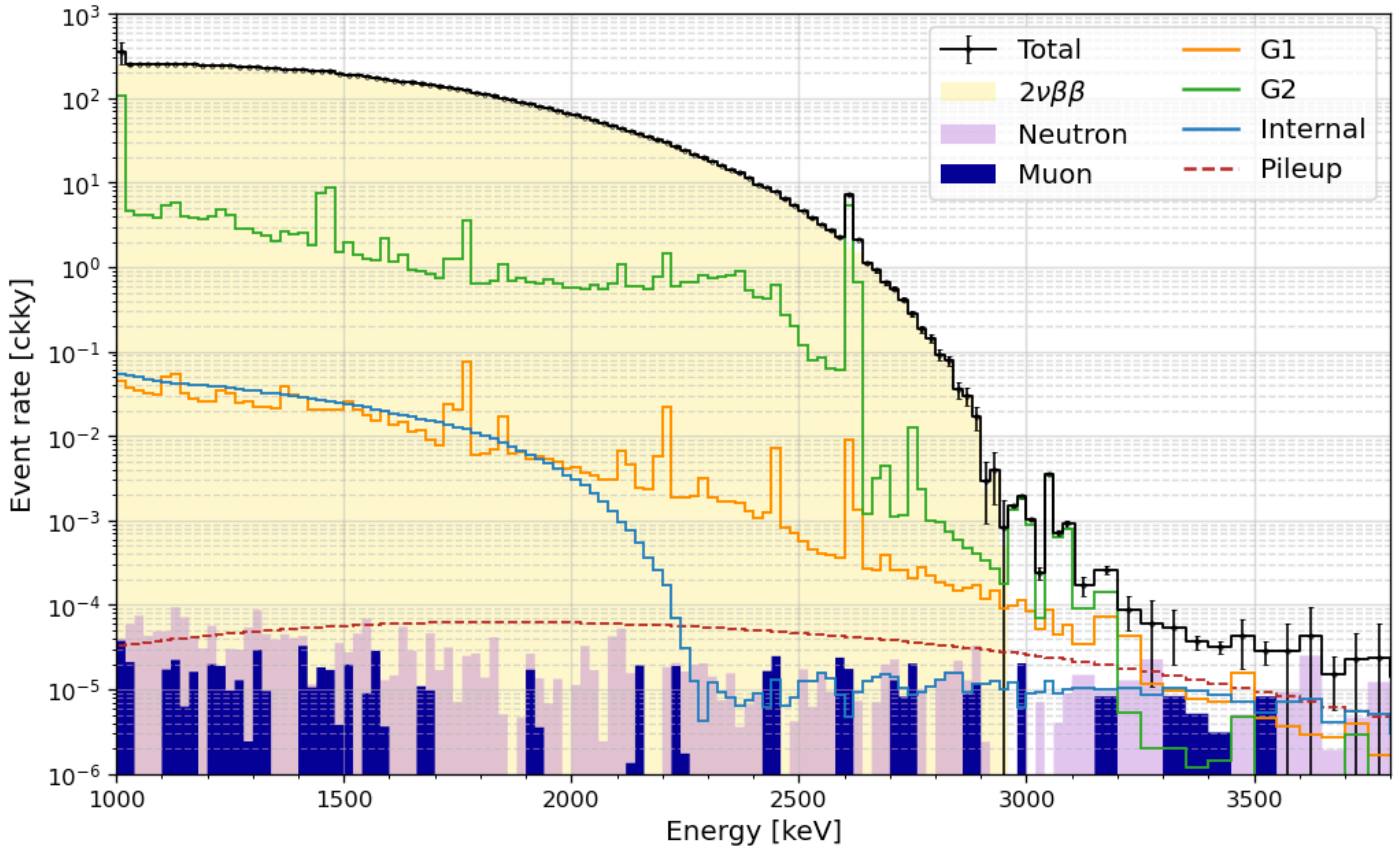
AMoRE-II (2025 -)

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-100}·yr.
- Aiming at ~ zero background event:

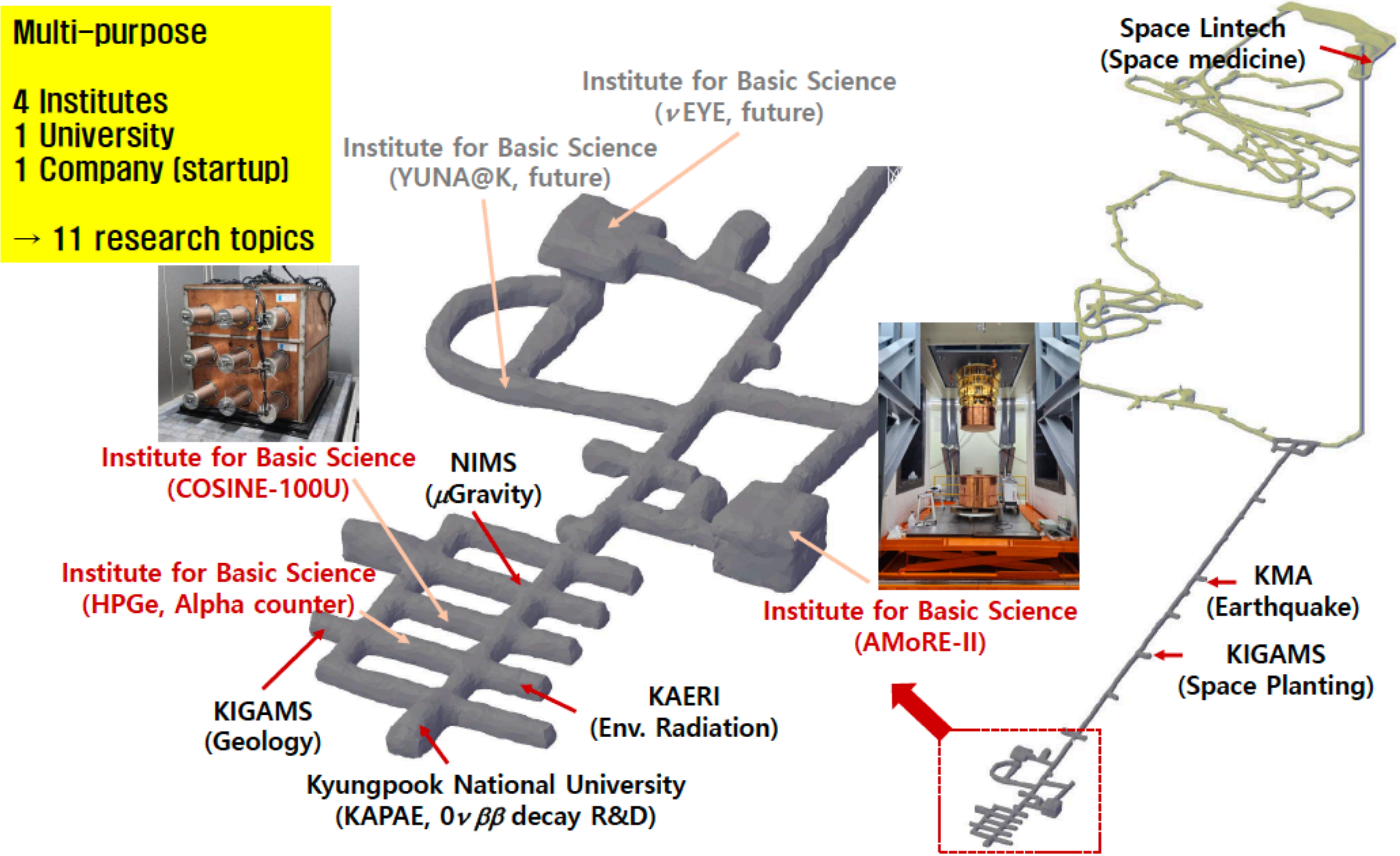
  Less than 1cnts / 157 kg / 5 year / 10 keV FWHM@ ROI

  ~ 10^{-4} cnts/kg/keV/year
- Aiming at $T^{0\nu}_{1/2} \sim 4.5 \times 10^{26}$ yrs

Yemilab survey

The data are from "Snowmass 2021 Underground Facilities and Infrastructure Overview Topical Report" L. Baudis, J. Hall, K.T. Lesko, J.L. Orrell, arXiv:2212.07037

World UL	Depth (mwe)	Expr. Volume (m^3)	Access	Rn conc. (Bq/m^3)	Muon Flux ($/cm^2/s$)	Gamma ($/cm^2/s$)	Th. Neutron ($/m^2/s$)
LNGS (Italia)	3800	180,000	horizontal	20-80	3.4×10^{-8}	0.3	4.6×10^{-6}
SURF (USA)	4300	199,600	vertical & rampway	300	5.3×10^{-9}	1.9	1.7×10^{-6}
SNOLAB (Canada)	6000	37,000	vertical	100	3.1×10^{-10}	?	4.8×10^{-6}
Kamioka (Japan)	2700	338,700	horizontal	64	1.5×10^{-7}	?	1.3×10^{-4}
Yemilab (Korea)	2500	32,000	vertical & rampway	150	1.0×10^{-7}	0.15	1.9×10^{-5}
Boulby (UK)	2850	4,000	vertical	2.5	4.0×10^{-8}	0.13	4.1×10^{-6}


Multi-purpose
4 Institutes
1 University
1 Company (startup)
→ 11 research topics
Institute for Basic Science
(νEYE, future)
Institute for Basic Science
(YUNA@K, future)
Space Lintech
(Space medicine)
Institute for Basic Science
(COSINE-100U)
NIMS
(μGravity)
Institute for Basic Science
(HPGe, Alpha counter)
Institute for Basic Science
(AMoRE-II)
KMA
(Earthquake)
KIGAMS
(Space Planting)
KIGAMS
(Geology)
KAERI
(Env. Radiation)
Kyungpook National University
(KAPAE, 0νββ decay R&D)