Status of Korean underground laboratory and AMoRE experiment

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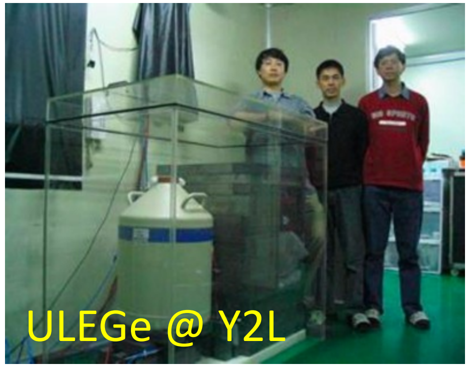
2023. 10. 30.

Chengdu, Symposium on Frontiers of Underground Physics, 2023

China-Korea Collaboration

H. Wong's talk @ 1st Yemilab workshop, 2022

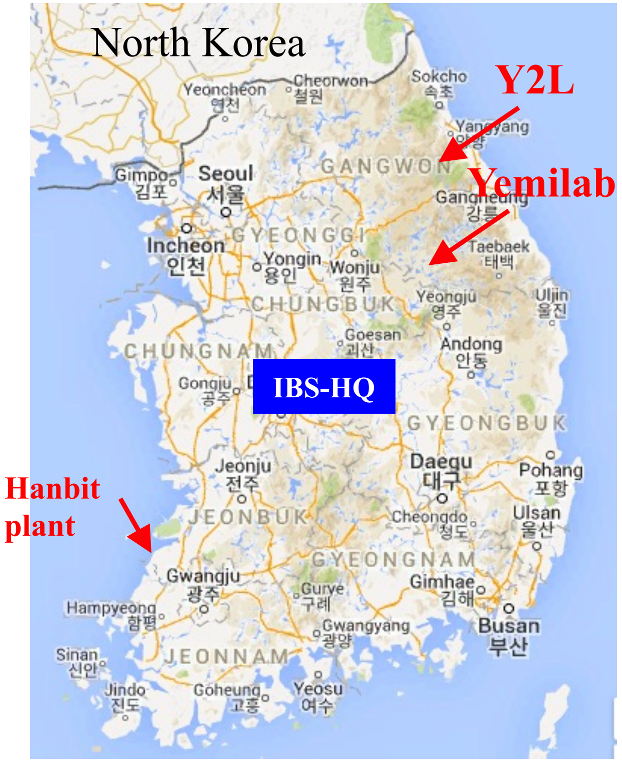
2000: Low background CsI(Tl) techniques brought the teams together. TEXONO-DM joined KIMS and got into DM.
2002~ IHEP and Tsinghua U. group joined KIMS.
2004: TEXONO-DM proposed to bring a 5g ULEGe to Y2L. Start of "Light Dark Matter Searches".



Joint Meeting @ Chengdu , Nov 2010.
Then .. Overnight Train to Xichang for CJPL site visit.

Yemilab, a new underground laboratory

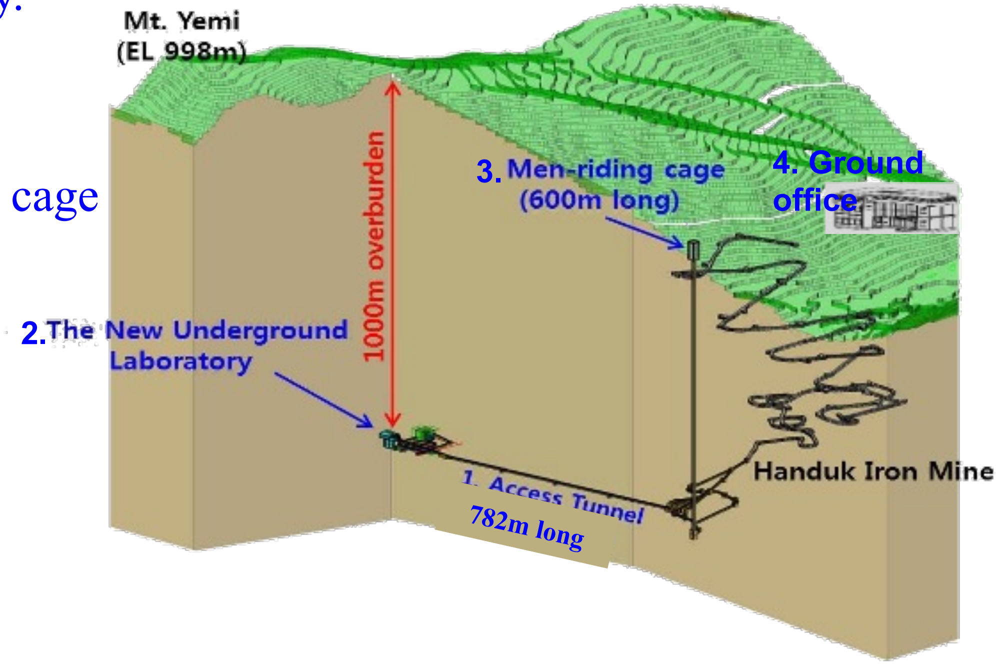
- Y2L was constructed in 2003 to house KIMS dark matter search experiment. (700m deep)
- Yemilab is constructed in 2022. (1000m deep)



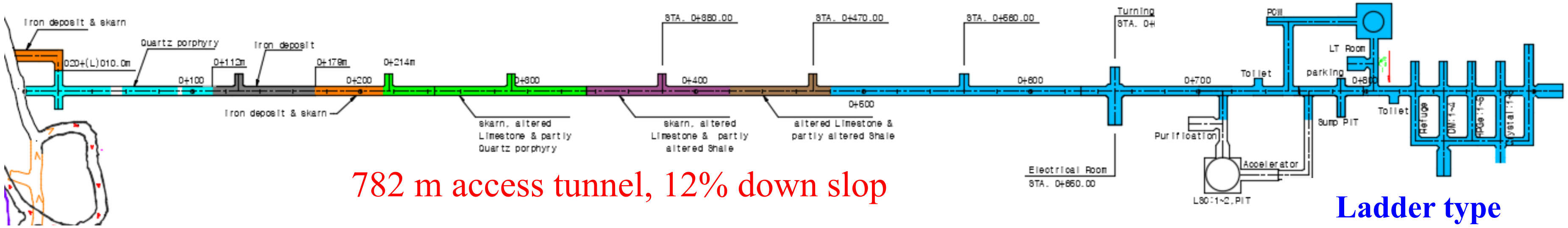
- Lab space > 3000 m^2 , 2.5 MW electricity.
- Rn-free air supplying system,
- Class 100 clean room.
- Two access ways: ramp-way, men-riding cage
- Open to other researchers IBS.

Yemi (禮美)

Etiquette, Beauty

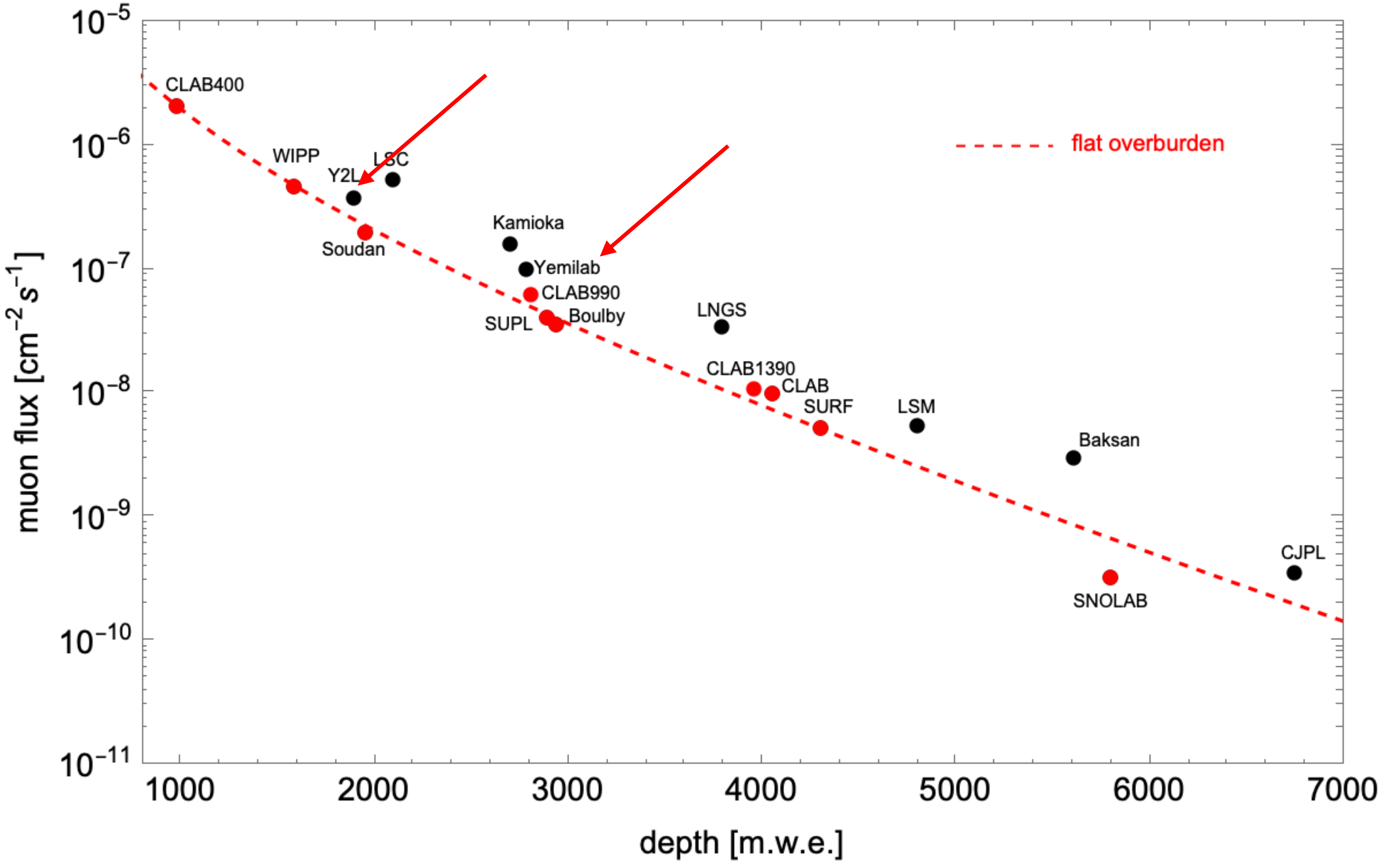


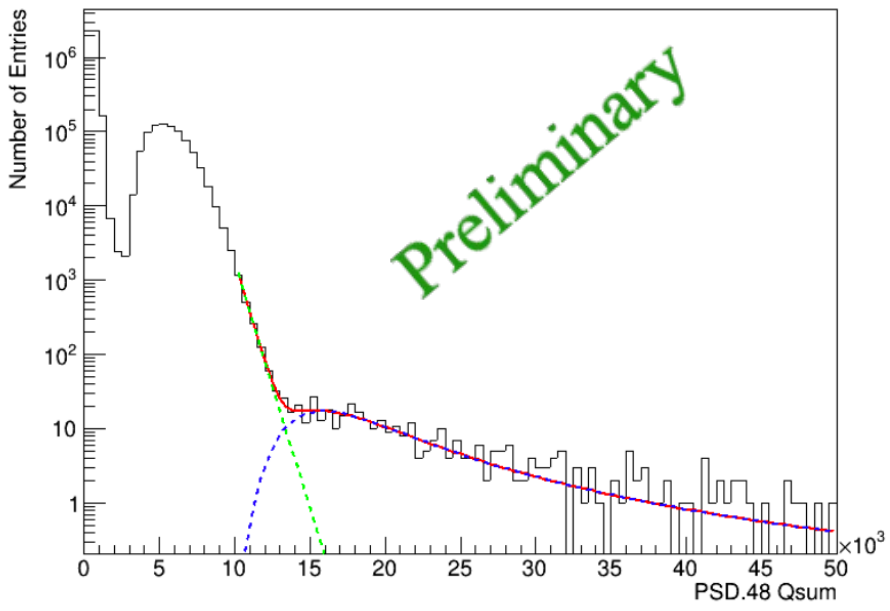
Top view of the Yemilab tunnels



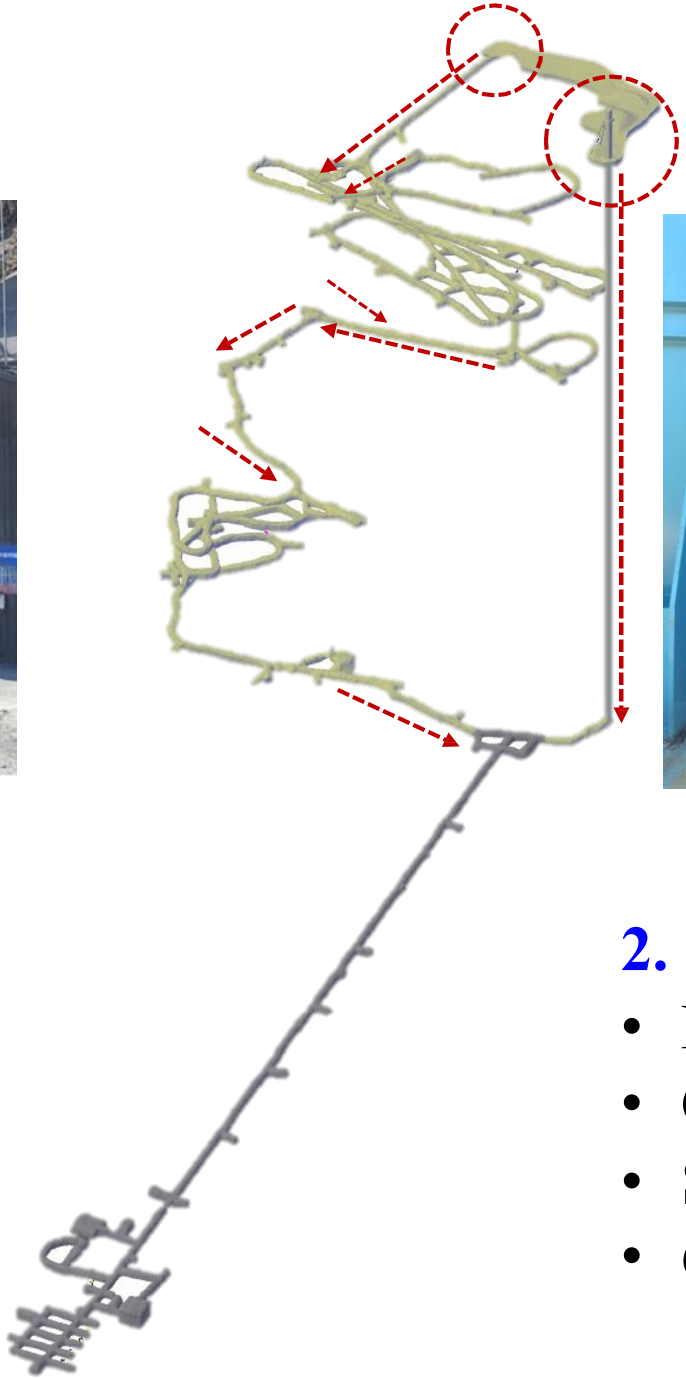
First muon flux measurement @ Yemilab

- The total muon flux is counted all the muons from up towards bottom direction.
- Yemilab has about 1/4 of muons of Y2L.
- Basically, we merge Y2L to Yemilab





Access to Yemilab



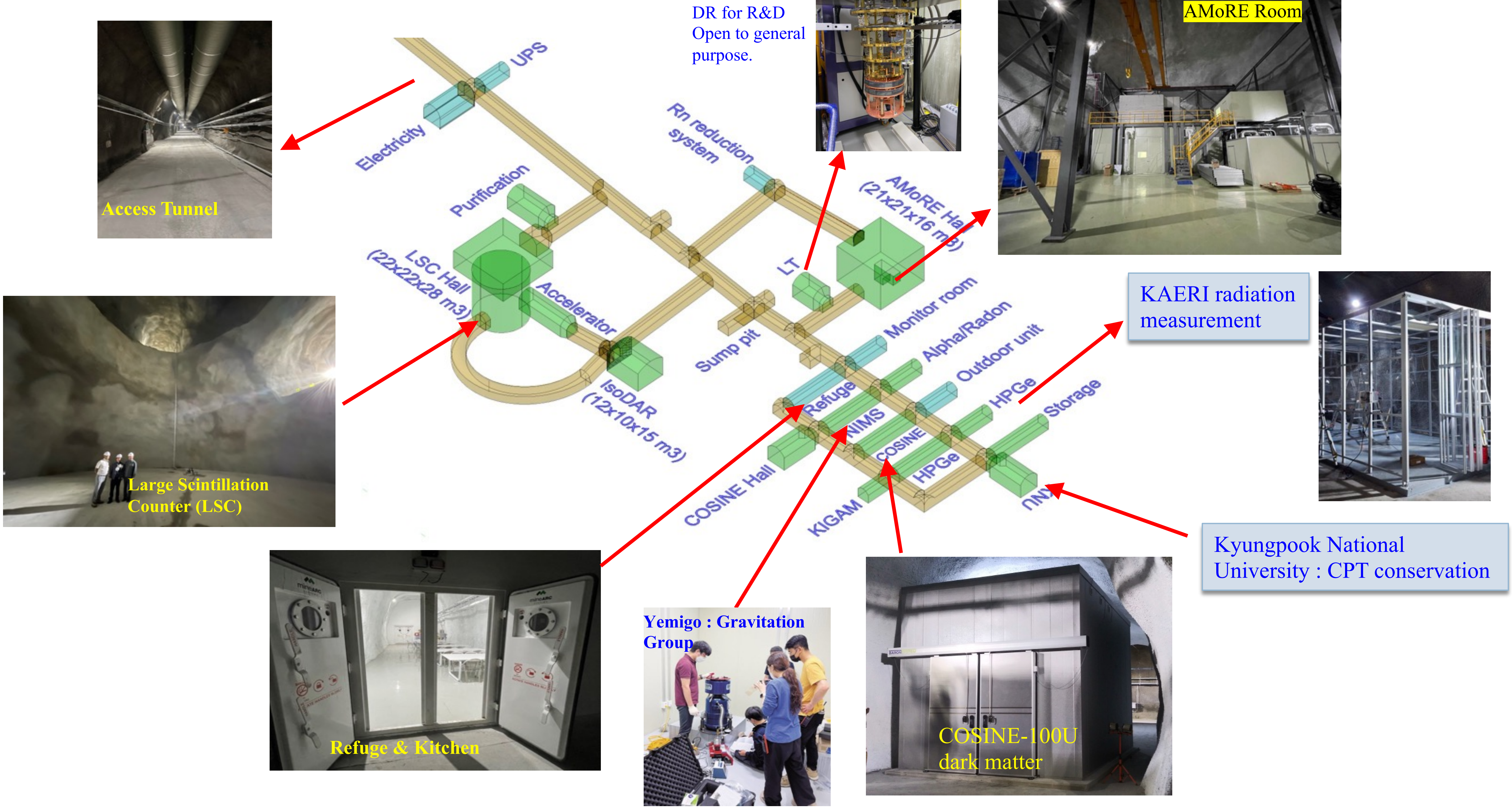
1. Rampway for cargo

- ~ 6 km unpaved road
- 5m × 5m tunnel
- Radio communication

2. Cage for people

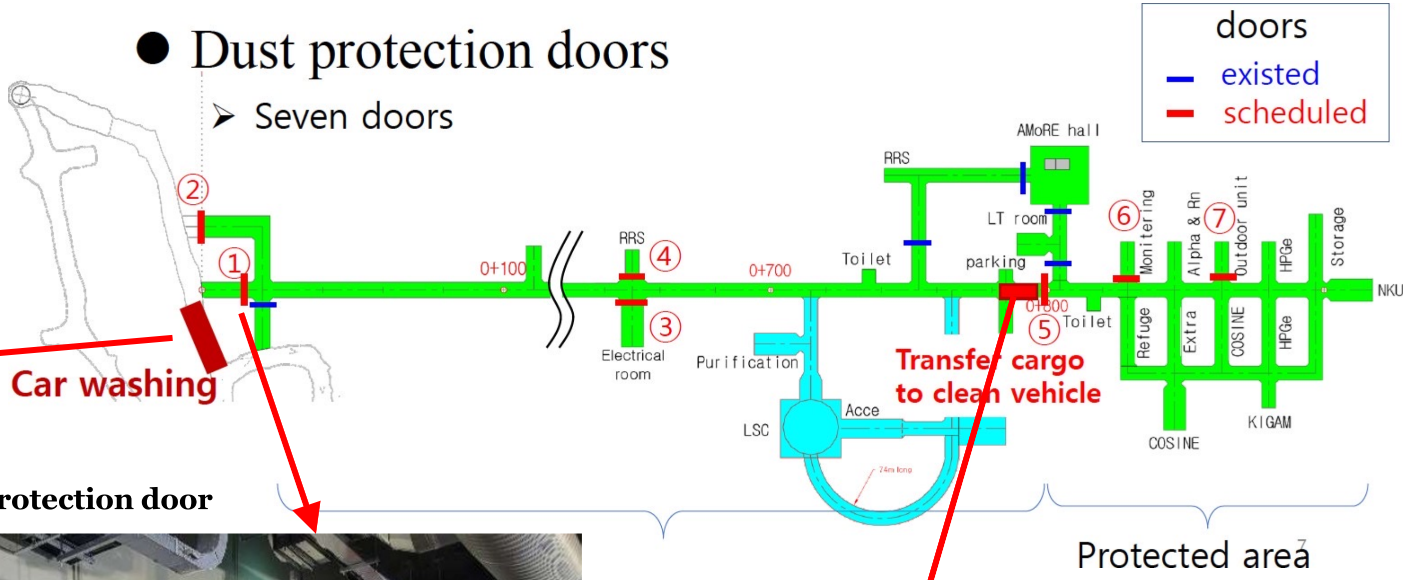
- Manufactured by SIEMAG
- Capacity : ~ 8 people, 1.5 tons
- Speed : 4 m/sec, 2.5 min
- 600m length of shaft

Experimental area of Yemilab

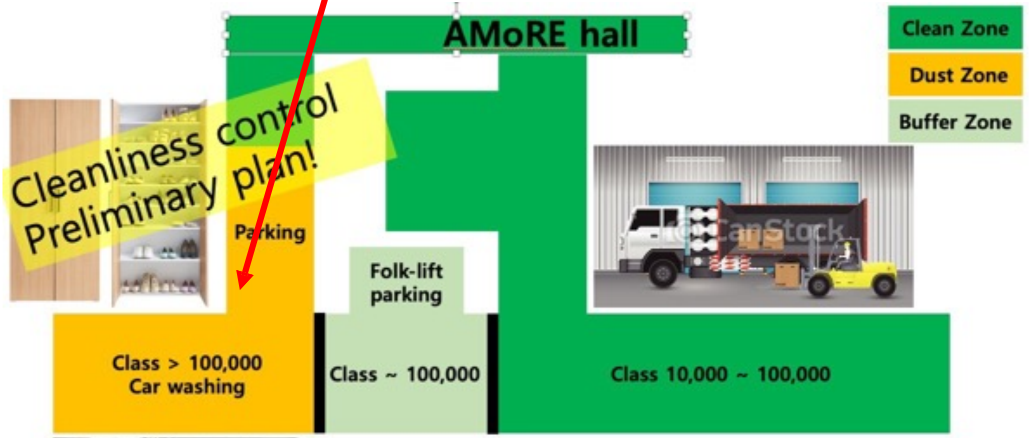


Clean environment concept at Yemilab

- Dust protection doors
  - ➢ Seven doors



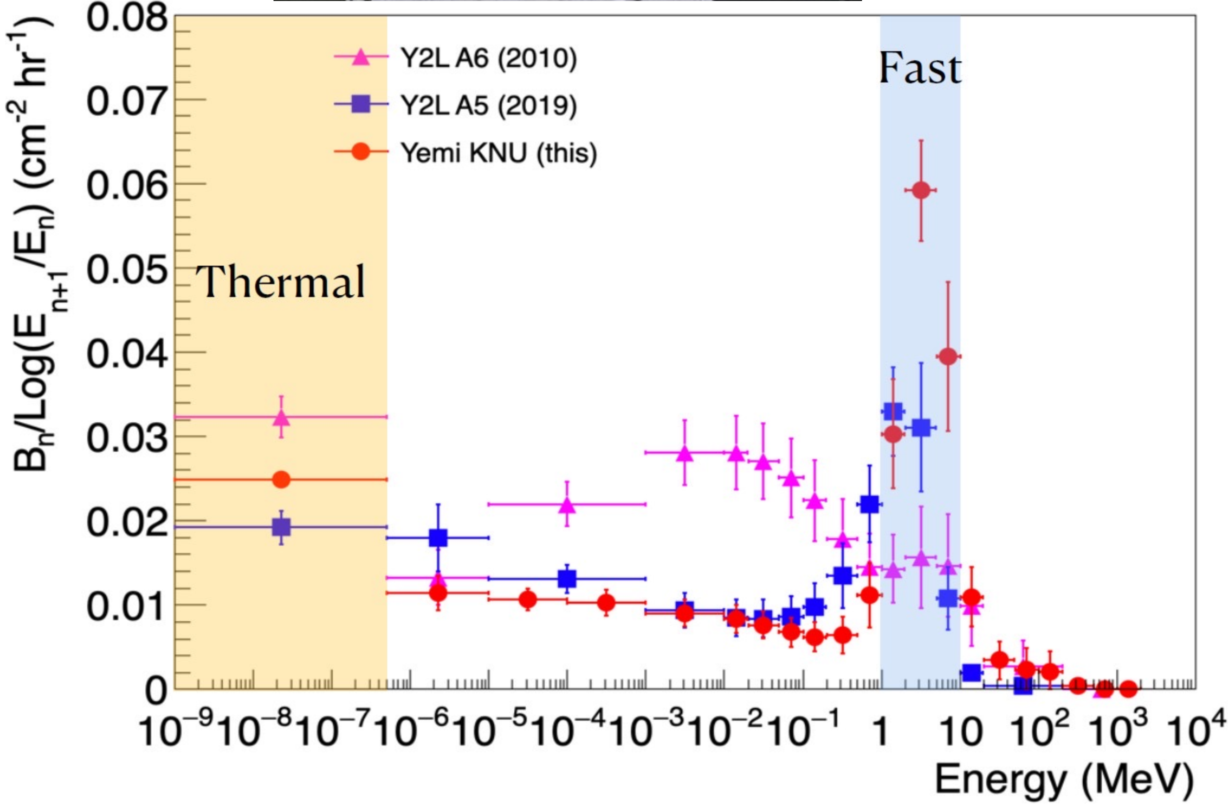
Dust protection door



1. **Safety clothing** change to **lab clothing**
   - **Safety clothing : helmet, safety shoes, long jacket and pants**
   - **Lab clothing : free helmet, lab shoes**
2. **Cargo transferring** by trailer from clean zone

Neutron flux @ Yemilab

Neutron spectrometer
by KRISS
Installed @ KNU room.



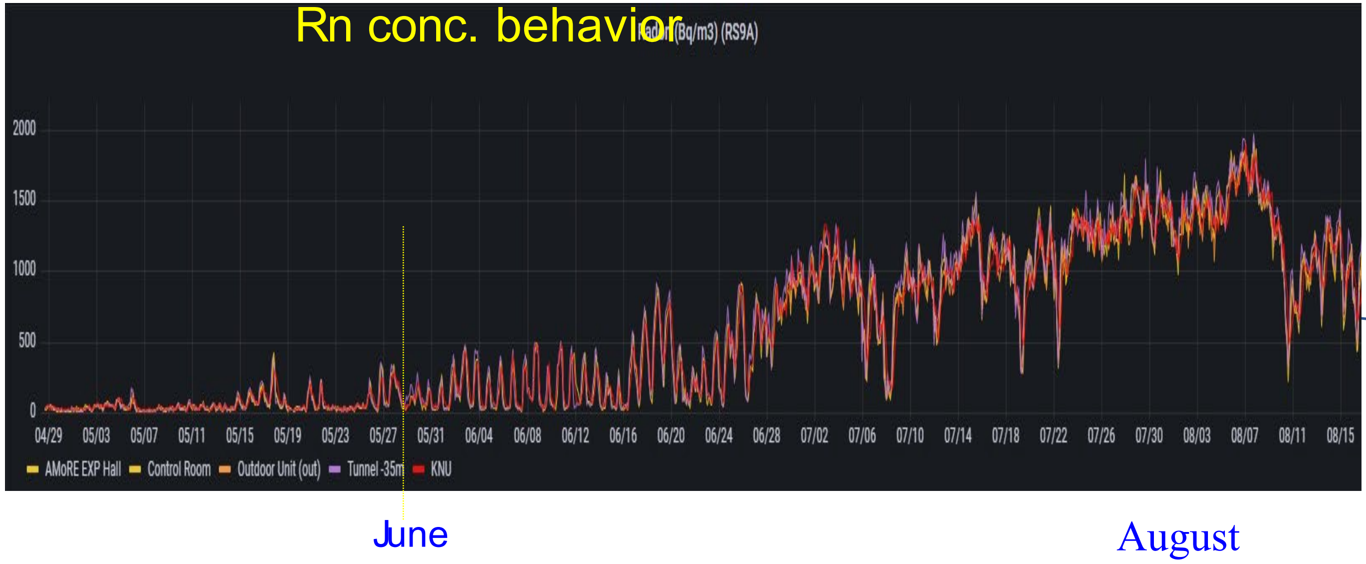
× $10^{-6}/cm_2$ sec	Y2LA6	Y2LA5	Yemilab
Thermal	24.2 ± 1.8	14.4 ± 1.5	**18.6 ± 0.8**
Fast (1~10 MeV)	4.2 ± 0.9	7.1 ± 1.0	**12.4 ± 1.1**
Total	67.2 ± 2.2	44.6 ± 6.6	**49.5 ± 1.8**

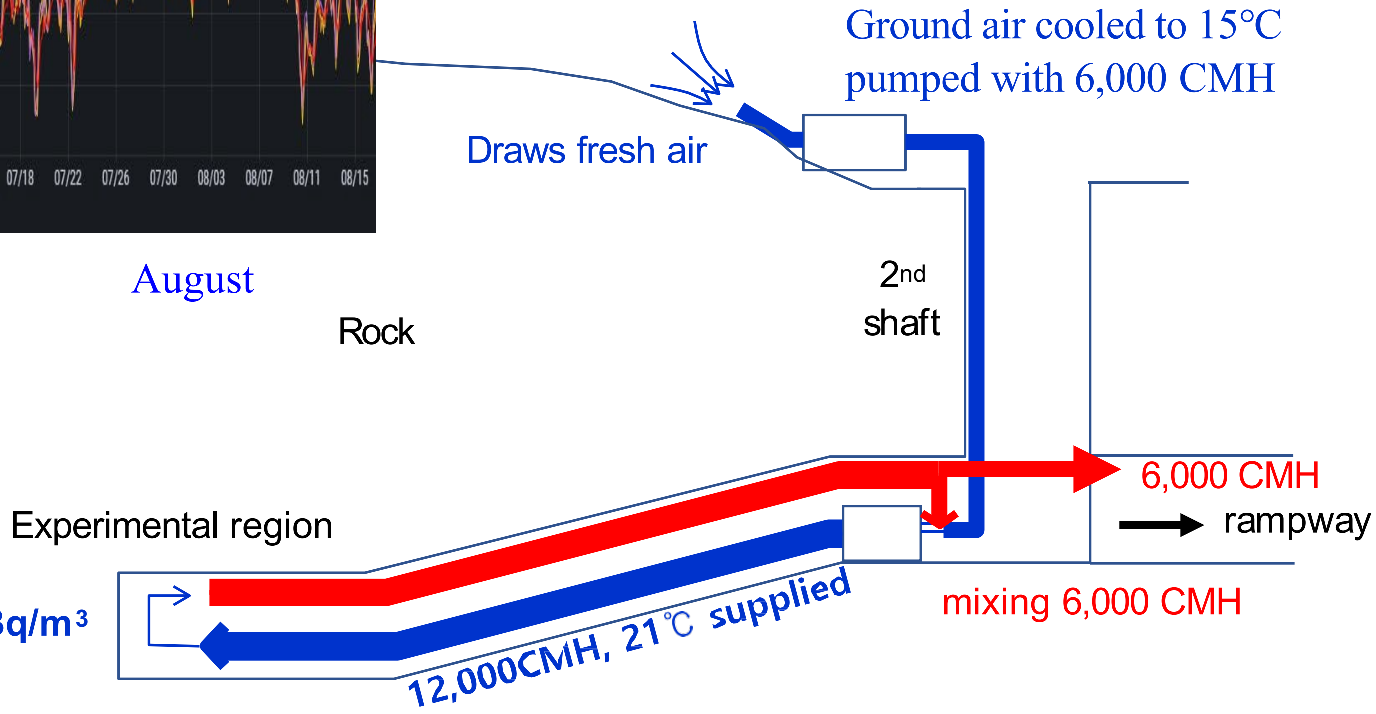
- **Y2L : More moderation by equipment**
- **Yemilab : A few hundreds of tons Shotcrete**
  - ~ 180 tons on AMoRE cavern

- **Non-shotcrete measurement**
- **Si containment in Rock**

Rnless air supply system

- Rn concentration get high in summer due to weak air circulation.
- The installation will be done by end of 2023.
- Rn concentration will be under 150 Bq/m3 even in summer.



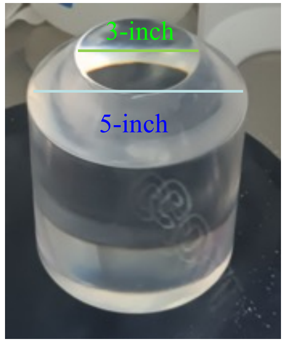


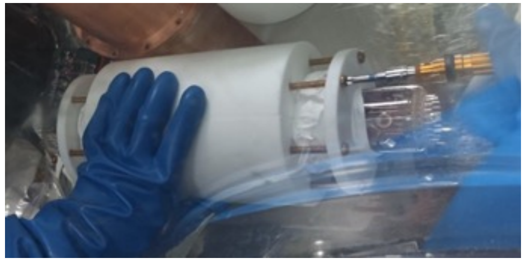
Goal :
- **Under 150Bq/m³**
- **& 25°C**

COSINE-100U, 200 @ Yemilab

COSINE-100 upgrade for high light yield

Polishing





Direct attachment of 3” PMT

NIMA 981 (2020) 164556

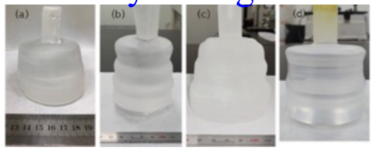
COSINE-100U

21.6 +/- 0.6 NPE/keV

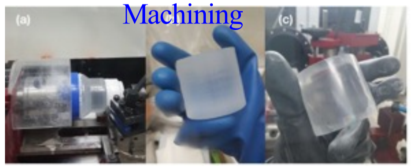
- Moving from Yangyang to Y emilab is ongoing now
- Plan to start COSINE-100U by end of 2023

COSINE-200 with new crystals.

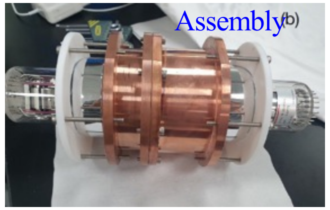
Crystal ingots



Machining



Assembly(b)



Hyun Su Lee,

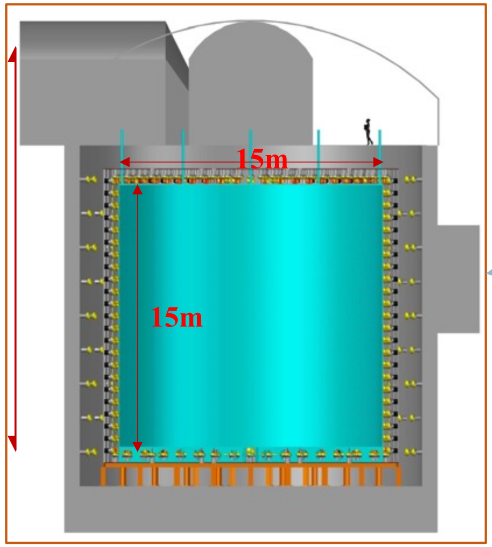
Sterile neutrino searches (Plan)

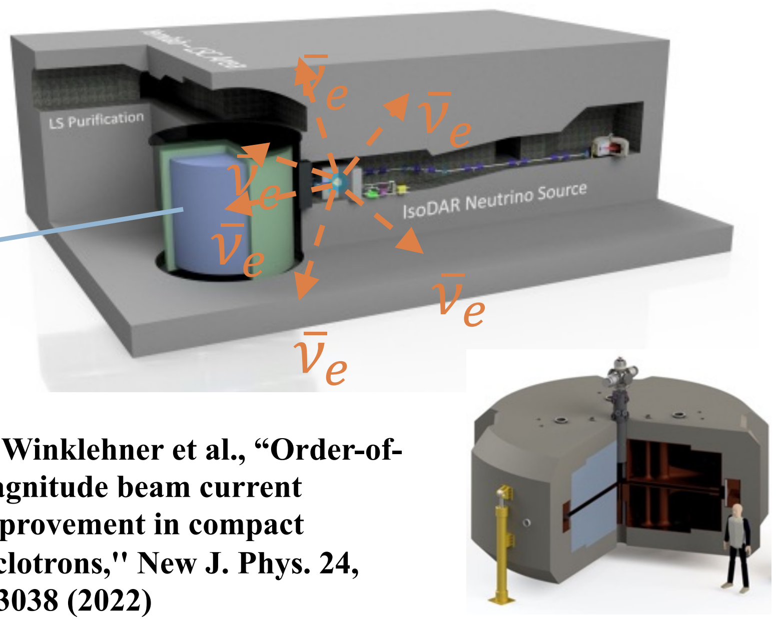
"Neutrino Physics Opportunities with the IsoDAR Source at Yemilab", PRD 105, 052009 (2022)

"IsoDAR@Yemilab: A report on the technology, capabilities, and deployment ", JINST 17, P090429 (2022)

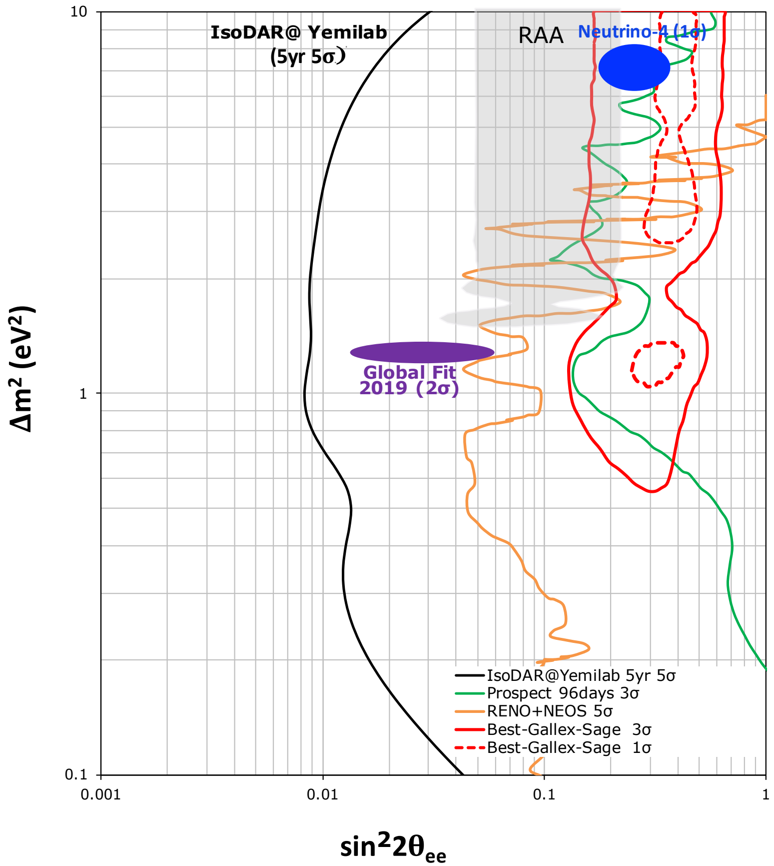
- IBD $\bar{\nu}_e p \rightarrow e^+ n$, short baseline oscillation is searched.
- Assume : $\sigma(E) \sim 6.4\,\%/\sqrt{E(MeV)}$, $\sigma(vertex) = 12cm/\sqrt{E(MeV)}$: reasonable

IsoDAR(isotope decay at rest) uses ^{8}Li Isotope Decay-at-rest





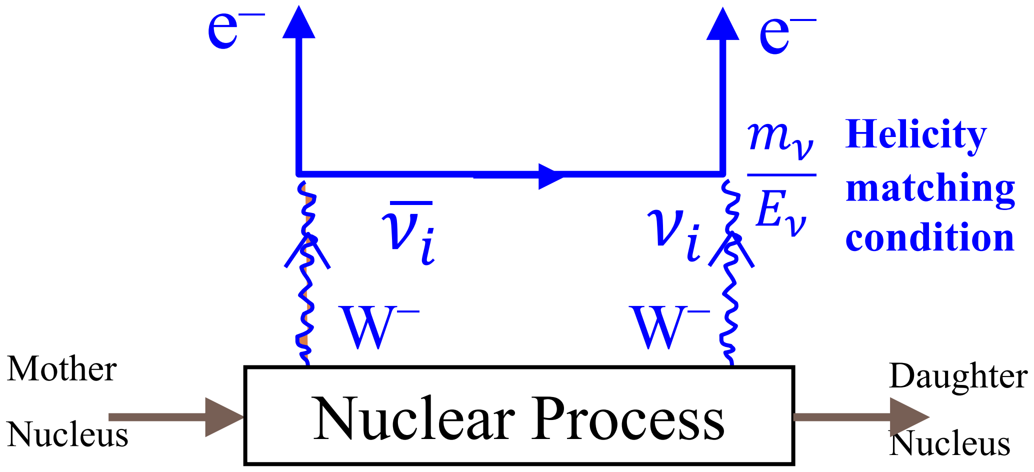
D. Winklehner et al., "Order-of-magnitude beam current improvement in compact cyclotrons," New J. Phys. 24, 023038 (2022)

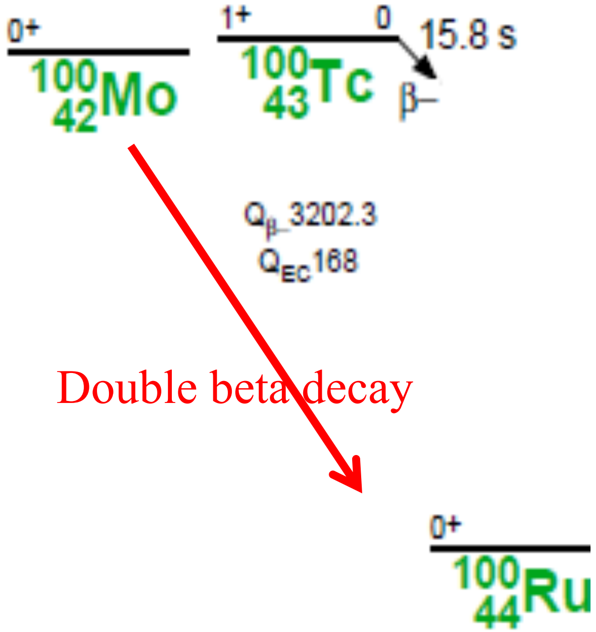


For each event, we measure the energy (E) and vertex(L) of neutrinos. → L/E

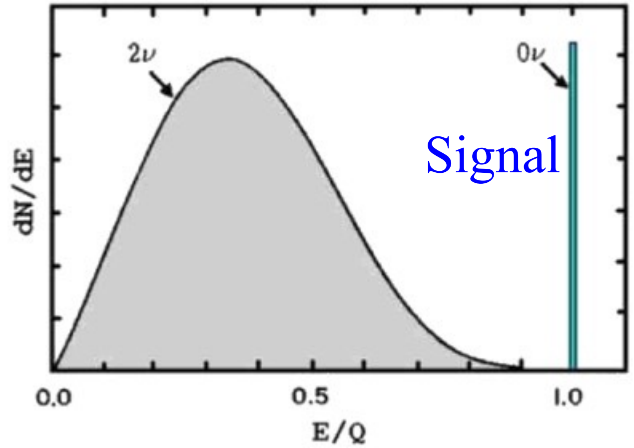
Neutrinoless Double Beta Decay($0\nu\beta\beta$) Search

If $0\nu\beta\beta$ occurs, $\nu = \bar{\nu}$ (Majorana neutrinos)





- 1939, Furry suggested to search $0\nu\beta\beta$ to check Majorana's theory. Furry PR56, 1184(1939)
- In the limit of m→0, it is not possible to distinguish between Dirac and Majorana neutrinos.



Matter creation with NDBD

$0\nu\beta\beta$ half – life is ; $[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} g_A^4 [M^{0\nu}]^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$

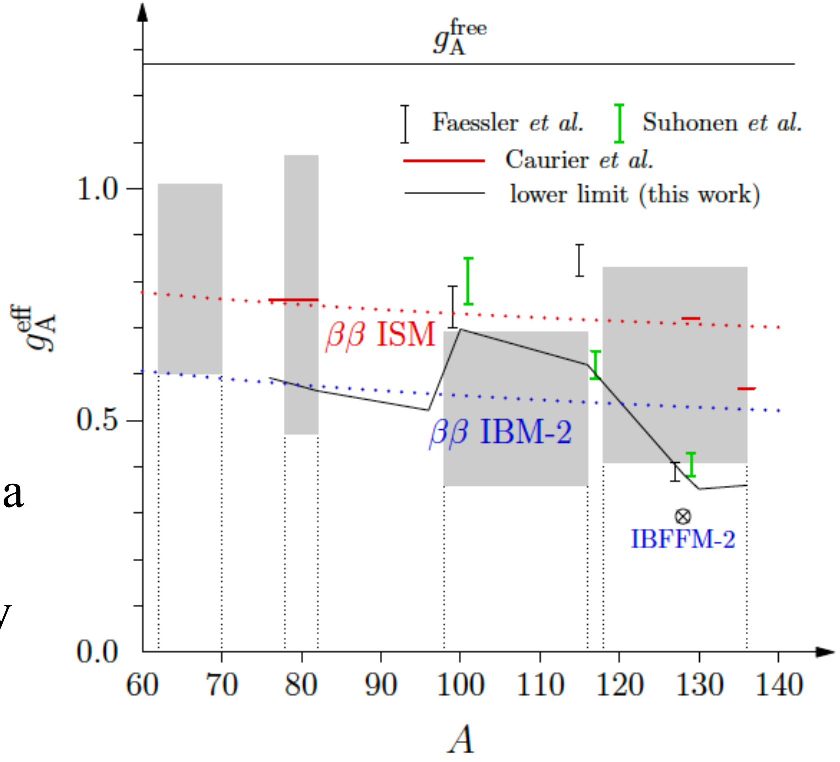
(1) Phase space

$G_{0\nu} \propto Q^5$

(2) Nuclear Matrix Element

$g_A^4 [M^{0\nu}]^2$

g_A **:axial vector coupling constant**

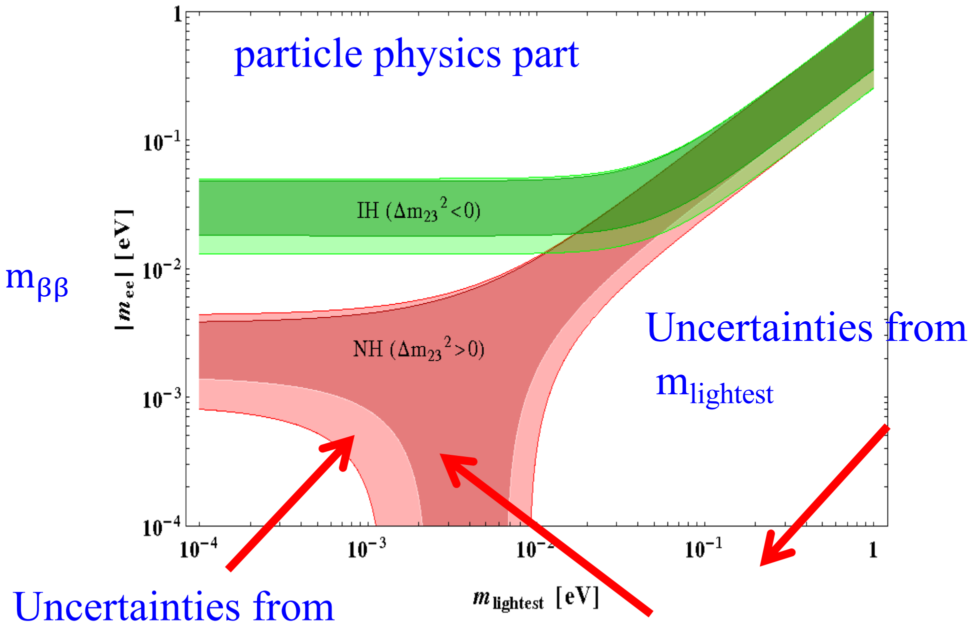


Suhonen, PRC96, 055501 (2017)

Gamow-Teller β decays of a wide range of nuclei (A =62–142) predicted heavily quenched values of g_A.

(3) Effective $0\nu\beta\beta$ neutrino mass (For light neutrino exchange model) is ;

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| = \left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$



AMoRE Collaboration

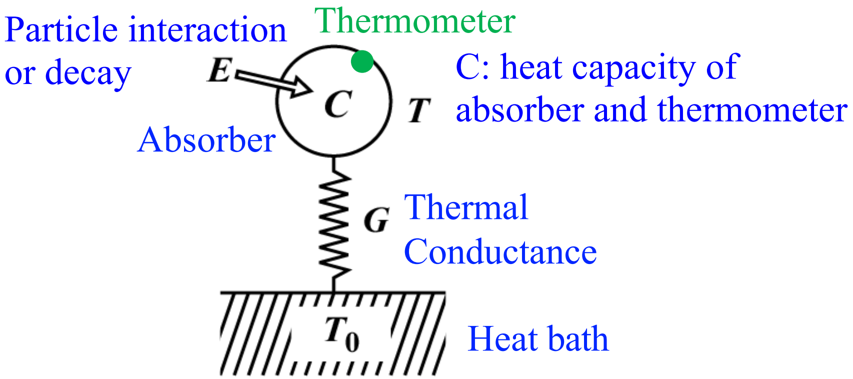
9 Countries, 25 Institutions - Korea, Germany, Ukraine, Russia, China, Thailand, Indonesia, India, Pakistan

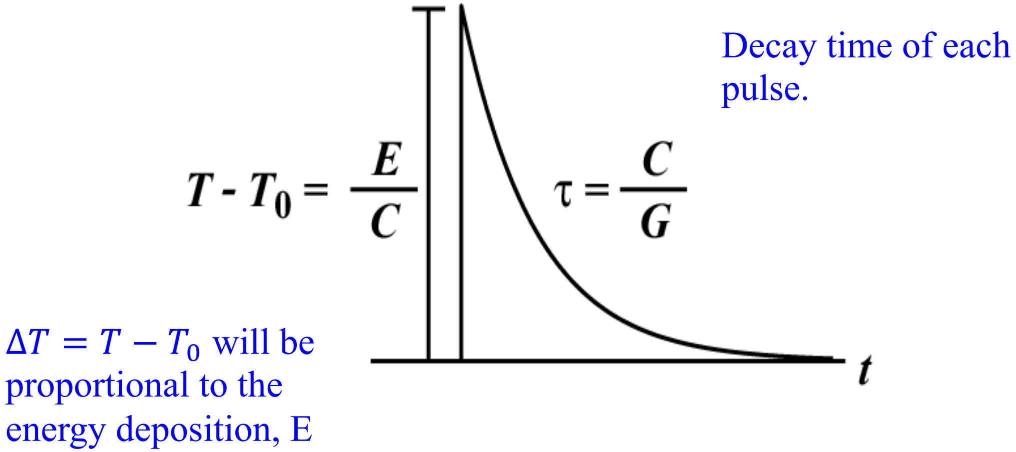
Yue Qian
Tsinghua University

- Lawrence Livermore National Lab. group will join from 2024.

Overview of AMoRE experiment

- AMoRE experiment aim to search $0\nu\beta\beta$ of ^{100}Mo ($Q_{\beta\beta}$□□□□□MeV, Natural abundance : 9.74%) isotopes utilizing scintillating crystal detectors coupled with low temperature magnetic sensors.
- Use Mo-containing scintillating bolometer, $^{40}Ca^{100}MoO_4$(CMO) and $Li_2{}^{100}MoO_4$(LMO) to have energy resolution better than 10 keV (FWHM) at Q-value.

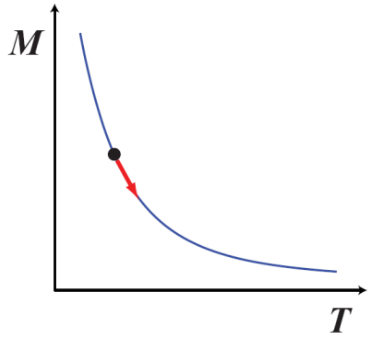




- A few inorganic crystals have Debye temperature(T_D), ~ 300 K. The heat capacity ($C \propto (\frac{T}{T_D})^3$) of such crystals of a few hundred grams are order of 10^{-10}-10^{-9} J/K at 10 mK temperature.
- ~3 MeV signal of neutrinoless double beta decay will increase the temperature of the crystal (absorber) by ~ mK.

Metallic Magnetic Calorimeter (MMC)

- Paramagnetic alloy, Au(Ag):Er (300-1000 ppm), in a magnetic field by persistent current in superconductive (Nb) wire.
- Magnetization (M) variation with temperature read by a SQUID



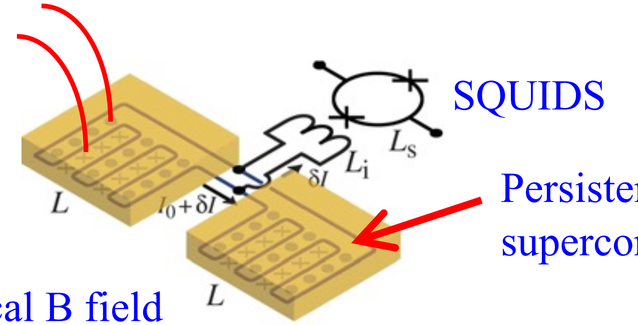
* Erbium (3+), ^{168}Er, in gold has advantages of high spin states and relatively low heat capacity with little nuclear magnetic moments. Using metals (Au or Ag) as host material for paramagnetic Erbium atoms is to make the magnetization change fast.

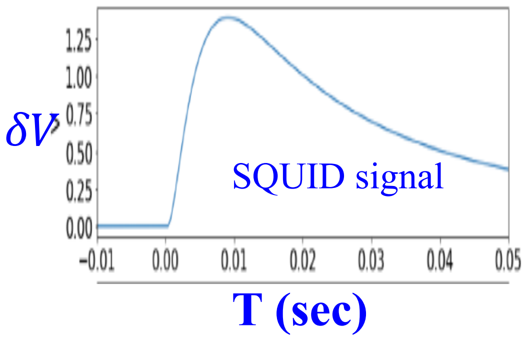
$\delta E \rightarrow \delta M \rightarrow \delta L \rightarrow \delta \Phi_S \rightarrow \delta V$

MMC SQUID

To Au foil on the crystal or light absorber

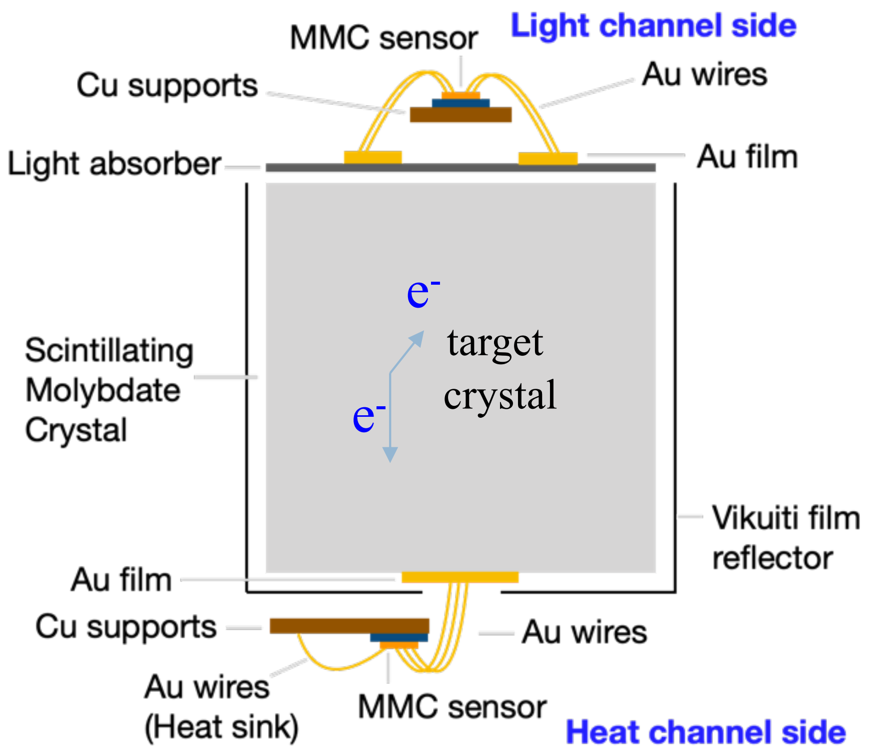
Au(Er) paramagnetic material

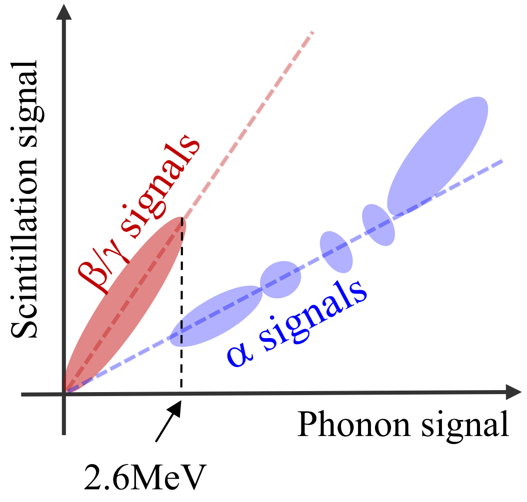




- Pro : High energy resolution, Fast, Large dynamic range, No bias heating
- Con : Complex, More wires & materials needed for SQUIDs and MMCs

Principle of AMoRE detector



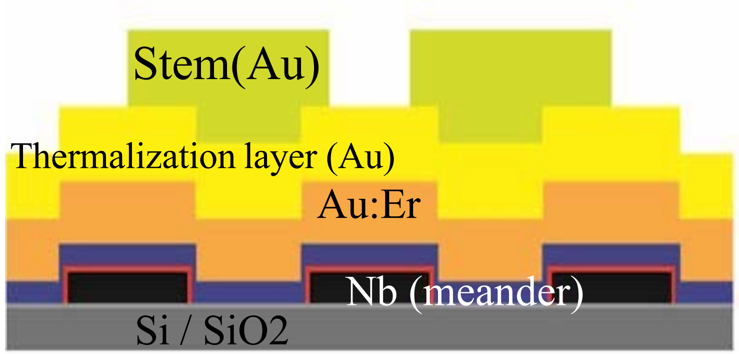


Surface alphas are continuous in energy and can be backgrounds.
Can be rejected by scintillation signal measurement.

- Phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal) to achieve low background level better than 10^{-4} counts/keV/kg/year (ckky).

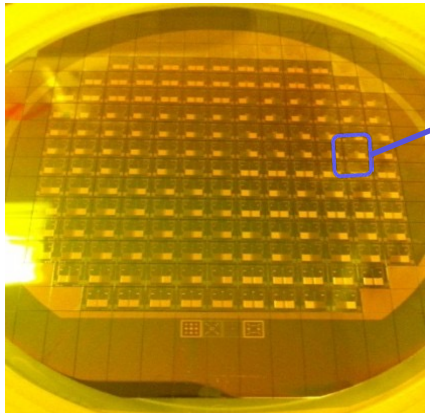
AMoRE detector

- MMC is fabricated at CUP. SQUIDs are made at PTB and Heidelberg University in Germany
- SQUID electronics are purchased from Magnicon company, and digitizers are from NOTICE Korea.

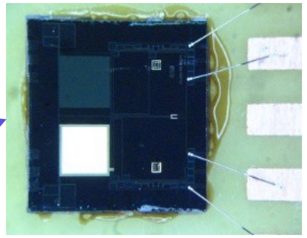


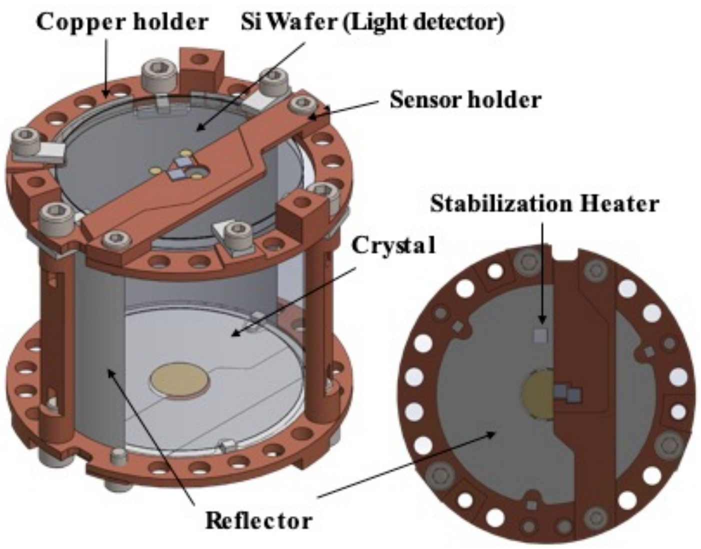
SiO_X(Insulator)

Cross section of MMC



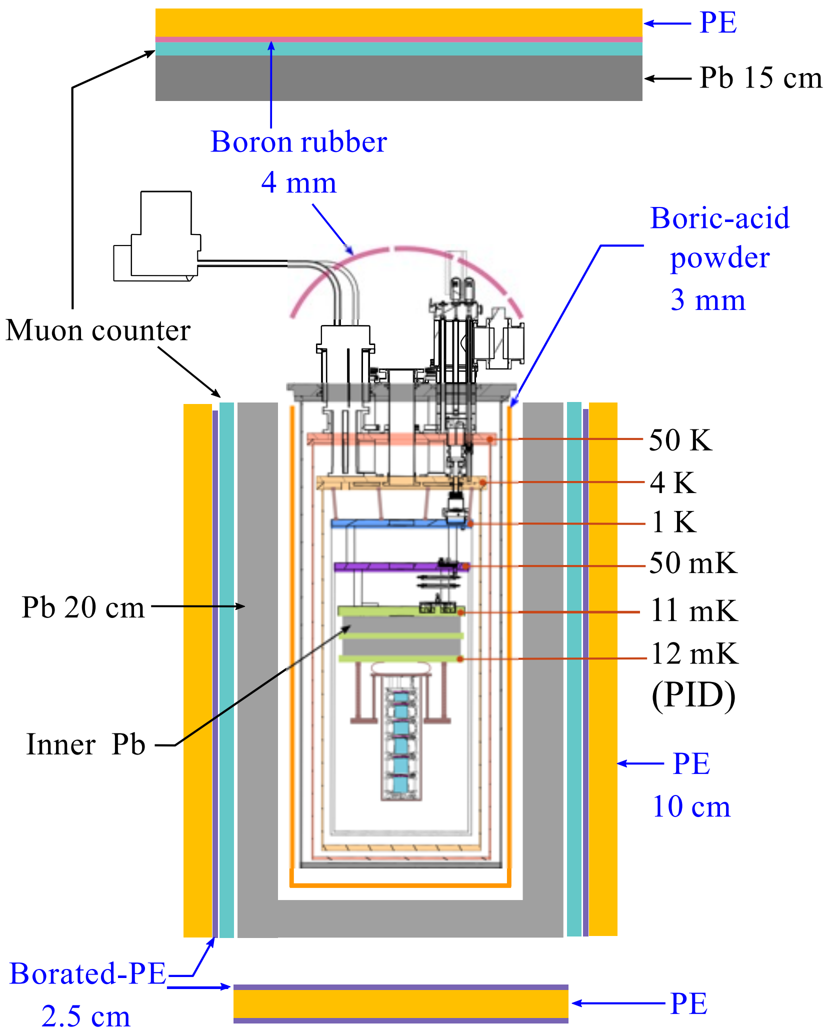
MMCs in a 3inch wafer

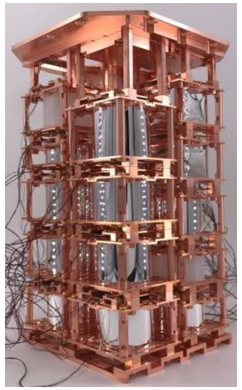


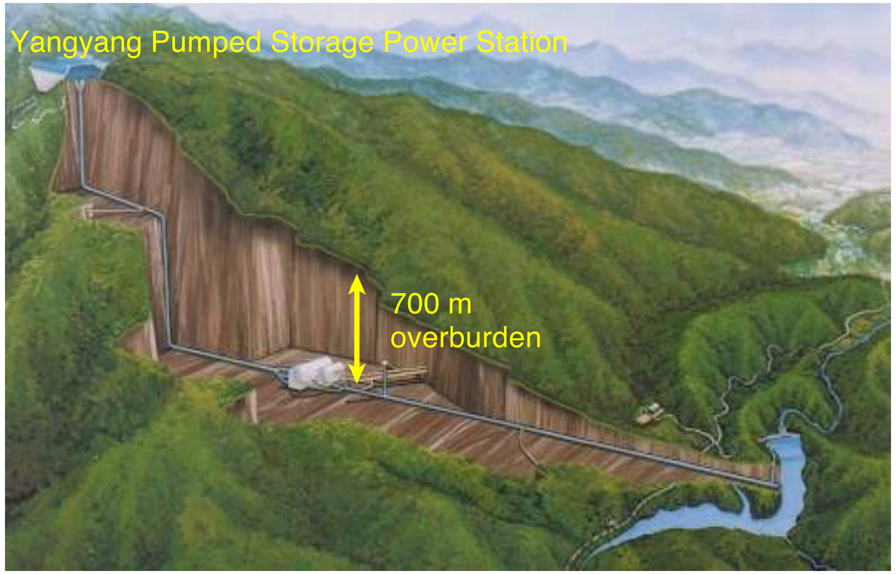


AMoRE-I : (2020.12-2023.5, ~ 900 days)

- To check detector performance & backgrounds.

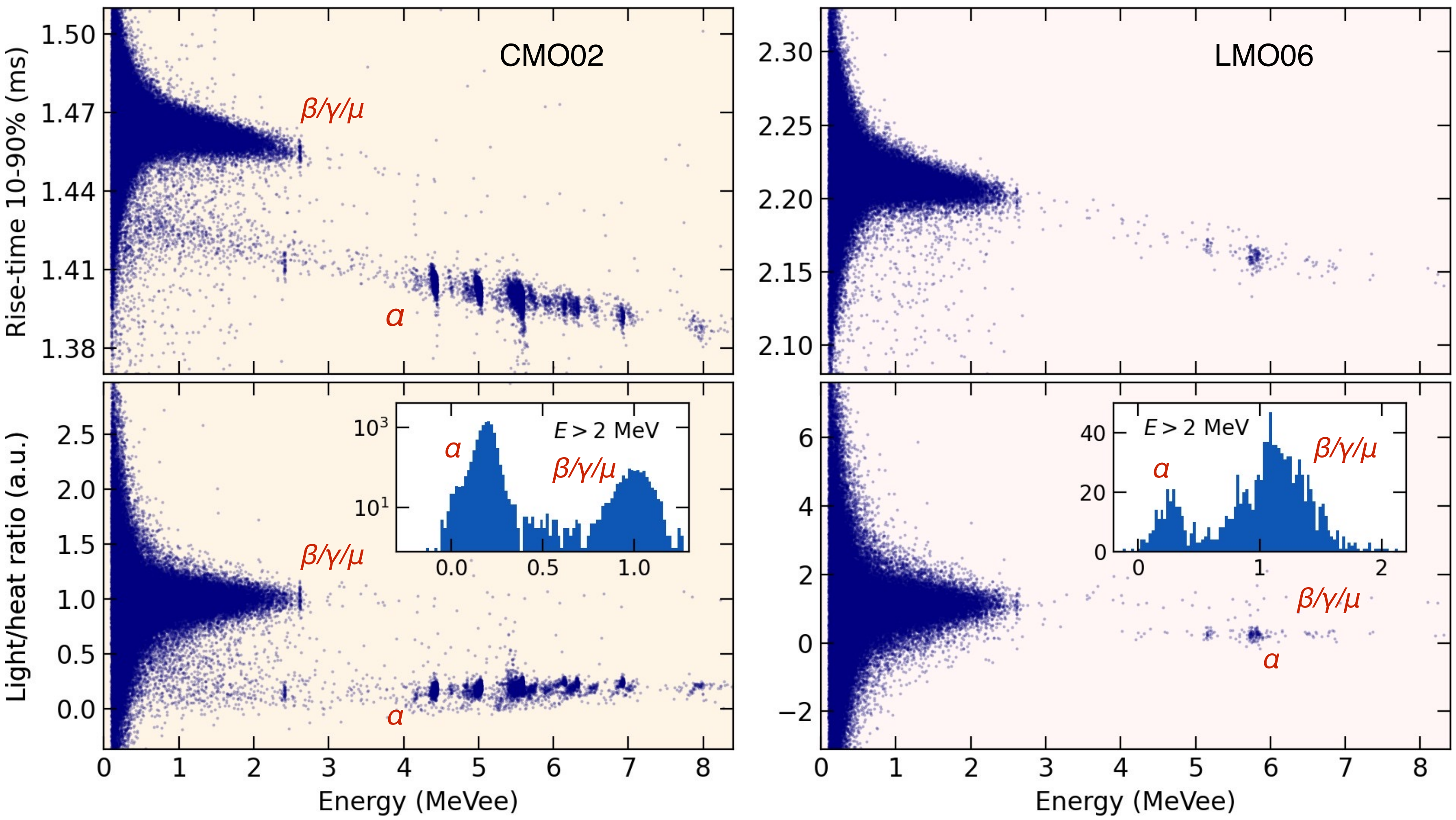






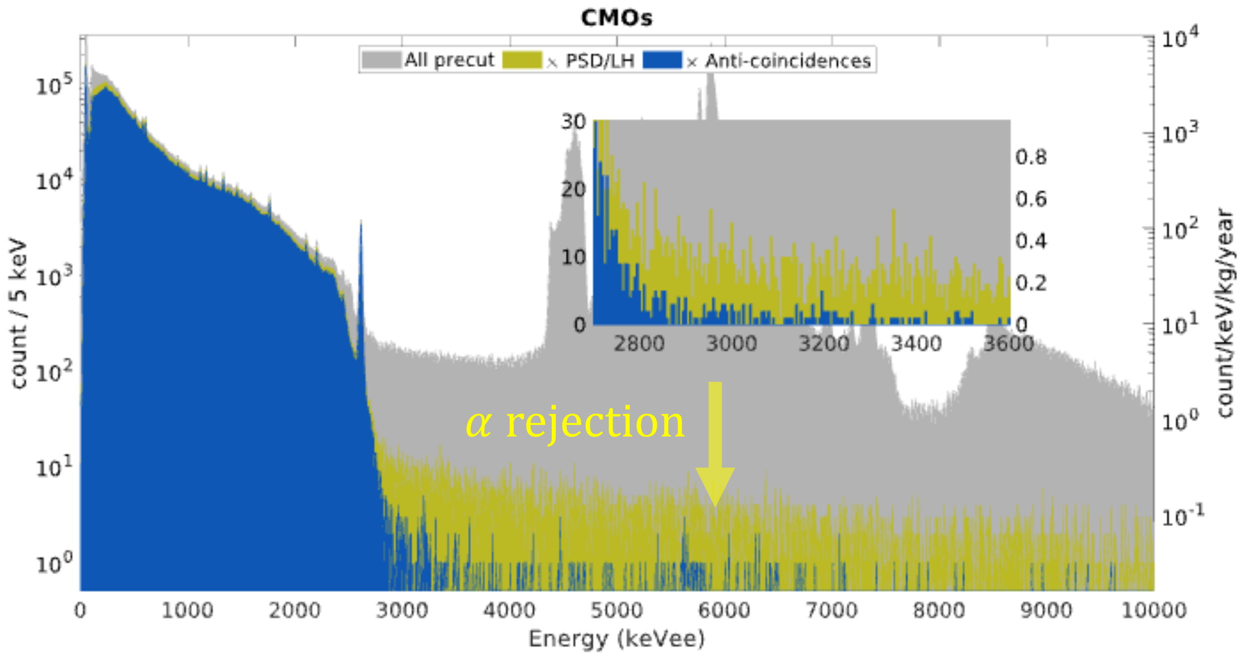
- Run @ Yangyang Underground Laboratory (Y2L)
- Cryogen-free dilution refrigerator @12 mK
- Plastic scintillator muon vetos.
- Detectors: 13 CMO crystals (4.6 kg) and 5 LMO (1.6kg) crystals
- 20cm Pb shielding + neutron shields (boric acid+PE+b.PE)
- Stabilization heater for all crystals.
- MMC-SQUID sensors are stable for more than 3 years.

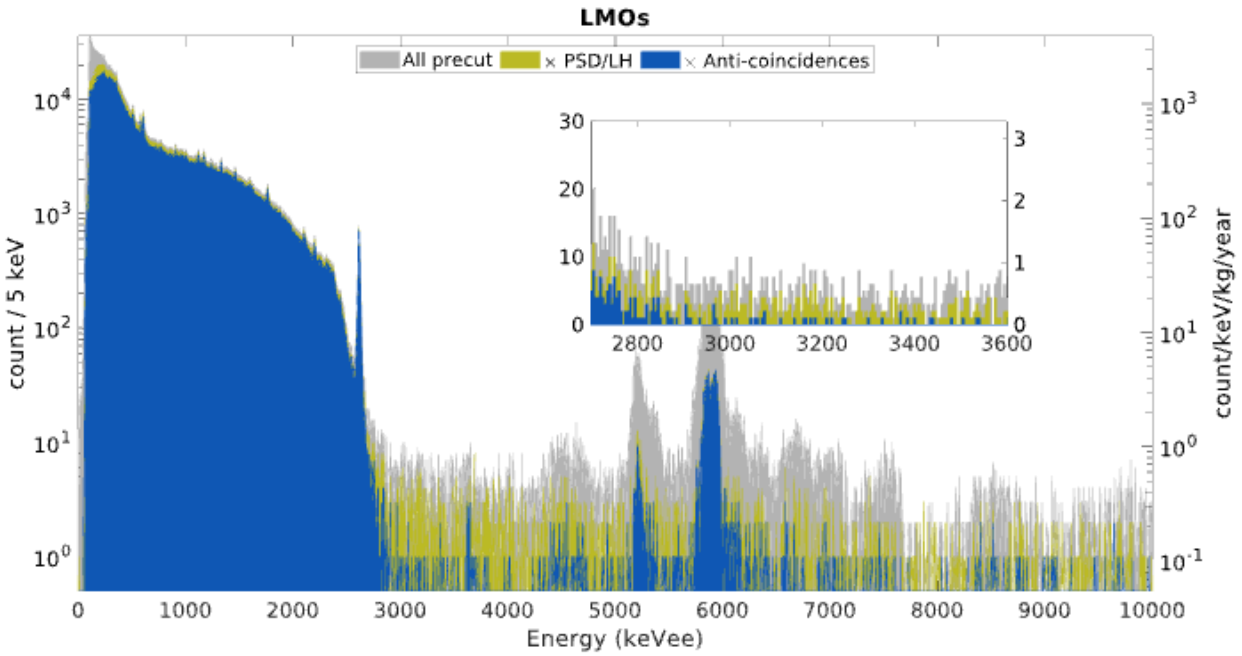
Particle Identifications, CMO and LMO



- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less contamination.

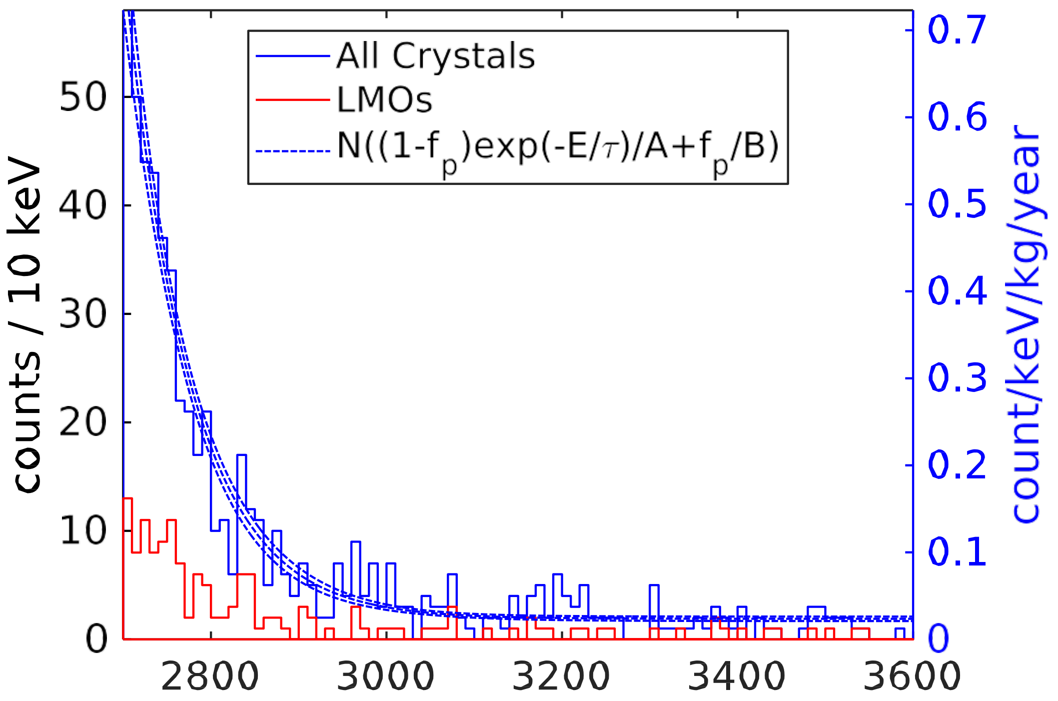
Background spectra after alpha background rejection

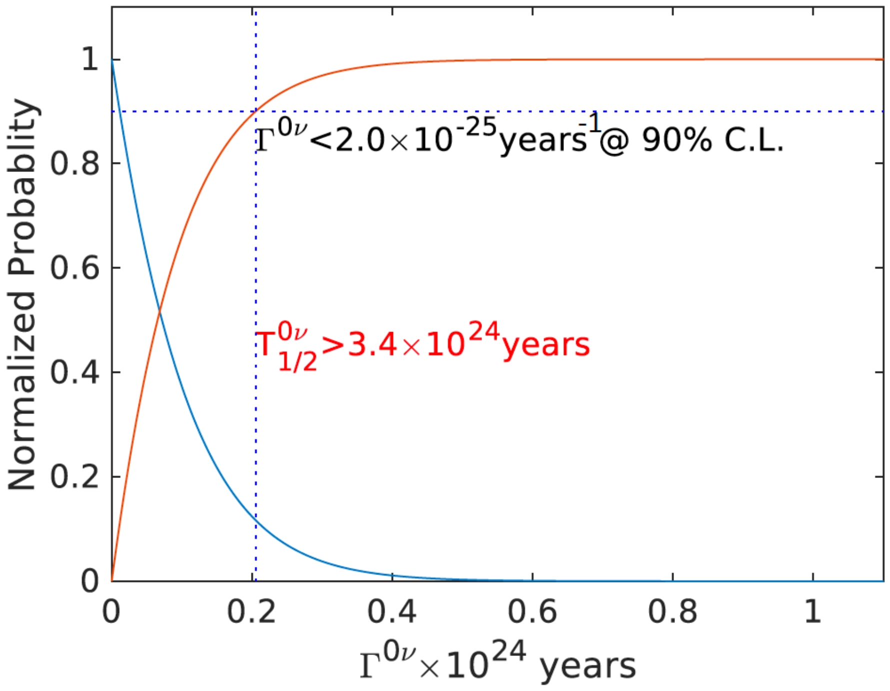




- All crystal excluding one LMO (for very poor β/α discrimination power)
  - 13 CMO + 4 LMO: exposure = 8.02 $kg_{XMoO_4}\cdot yr$ = 3.88 $kg_{^{100}Mo}\cdot yr$.
  - CMO has higher alpha backgrounds and rejection power is high.
  - LMO has lower alpha backgrounds and rejection power is low.
- ~ 3 × CUPID-Mo exposure (1.48 $kg_{Mo\text{-}100}\cdot yr$).
- Cuts to reject backgrounds:
  - Multiplicity=1 (ε ~ 99.8%), $\Delta T(muon) > 10\ ms$ (ε ~ 99.8%), $\Delta T(^{212}Bi\ \alpha) > 20\ min.$ (ε ~ 98%).

Half-life results





- ROI=$|E - Q_{\beta\beta}| < 2.5 * \Delta E_{FWHM}$
- $\varepsilon_{Containment}$~81%
- Background = 0.032 ± 0.003 counts/keV/kg/year @ side-band.
- Unbinned likelihood for $\Gamma^{0\nu}$ for each crystal, with a specific signal shape and background rate constrained from calibration and sideband data, respectively.

Live exposure	Bkg. @ $Q_{\beta\beta}$ / ckky
Total (8.02 kg_{XMoO4} yr)	0.032±0.003
CMO (6.19 kg_{XMoO4} yr)	0.031±0.003
LMO (1.83 kg_{XMoO4} yr)	0.037±0.006

→ $T^{0\nu}_{1/2} > 3.4\times10^{24}$ *years*

Cf. 1.8×10^{24} *years* by CUPID-Mo

Crystal decision for AMoRE-II

- LMO has light output smaller than CMO by a factor ~ 8. (Cf. ~ 20 @ 10 K)
- But, DP w/ light detector is similar between these two crystals.
- Crystal growing is easier for LMO, and ^{48}Ca depletion is necessary for CMO.
- CMO has PSD w/o light detector, ~ DP > 10.
- LMO crystal is chosen for AMoRE-II

Crystals	Scintillation				Mechanical		Thermal		Pro Con
	λ_{em} (nm)	Eg (eV)	τ (μs) @10K	E_{scin} (Rel.)	Dens. (g/cc)	Mo Fraction	T_D (K)	T_M (C)	
CMO (CARAT)	540	3.78[1]	240	100	4.32	0.49	446	1445	High light out High melt T, difficult growing, high bkg, 48Ca
NMO-I (NIIC)	663	3.50	750	9	3.62	0.558	332	687	Cleavage plane
LMO (CUP)	535	4.26.[2]	23	5	3.03	0.562	316	705	Low melt. T, easy growing, low bkg, high T_D Low light, hygroscopic,
$PbMoO_4$	592	3.20[4]	20	105	6.95	0.269		1065	High light out,Low Mo fraction, higher bkg

- Enriched LMO crystals are grown at Center for Underground Physics (CUP) and NIIC

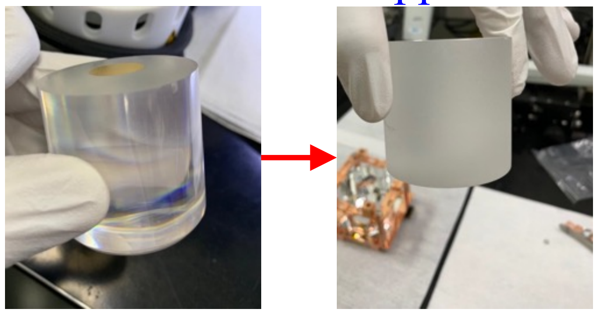
Improvements of LMO crystals

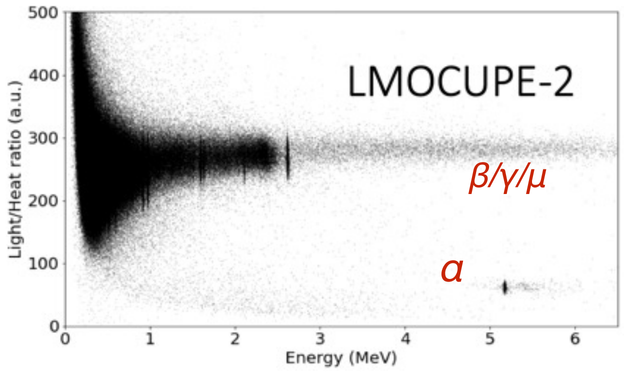
- Recently, we improved the detector performance.

JINST 17, p07034(2022)

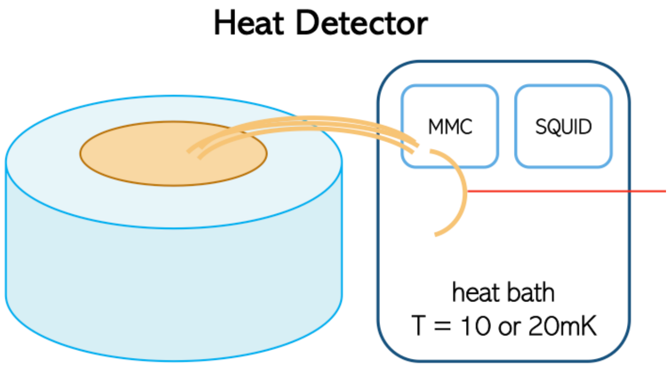
(1) Polishing vs lapping(roughening)

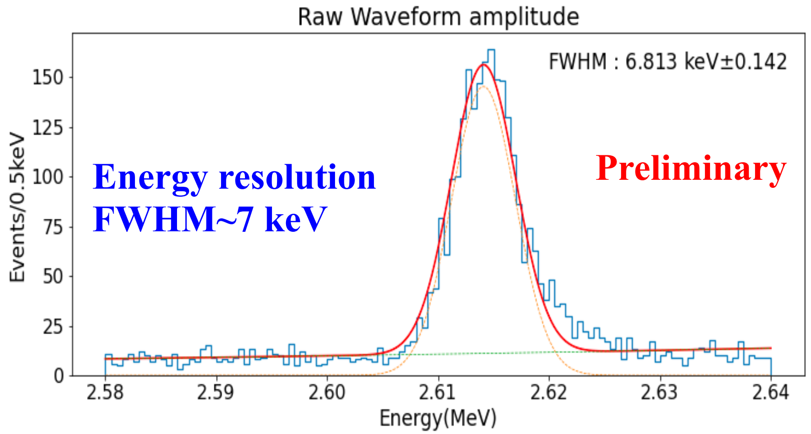
Polished surface   Lapped surface



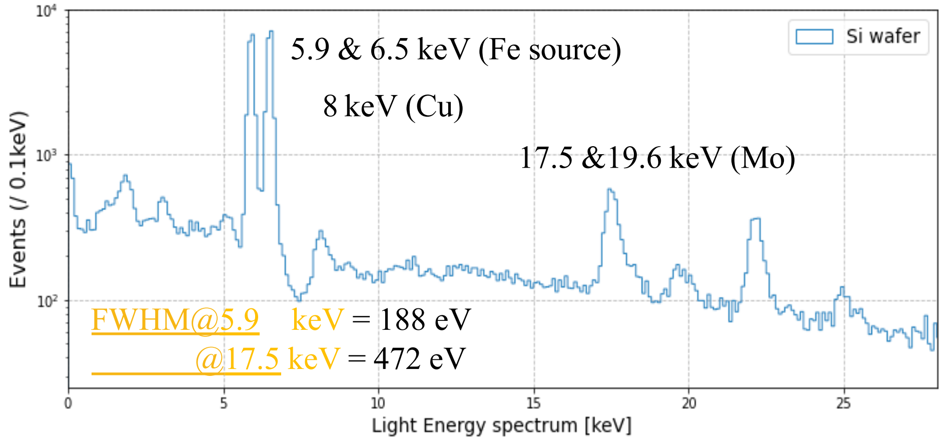


(2) w/o thermal link to heat bath





(3) Si wafer for light detector



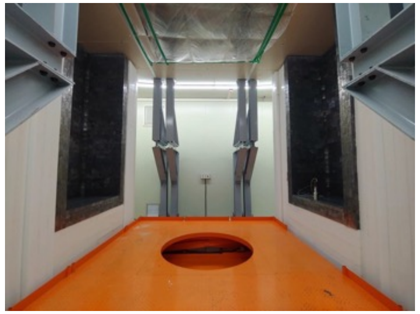
Lapping and thermal link removal :

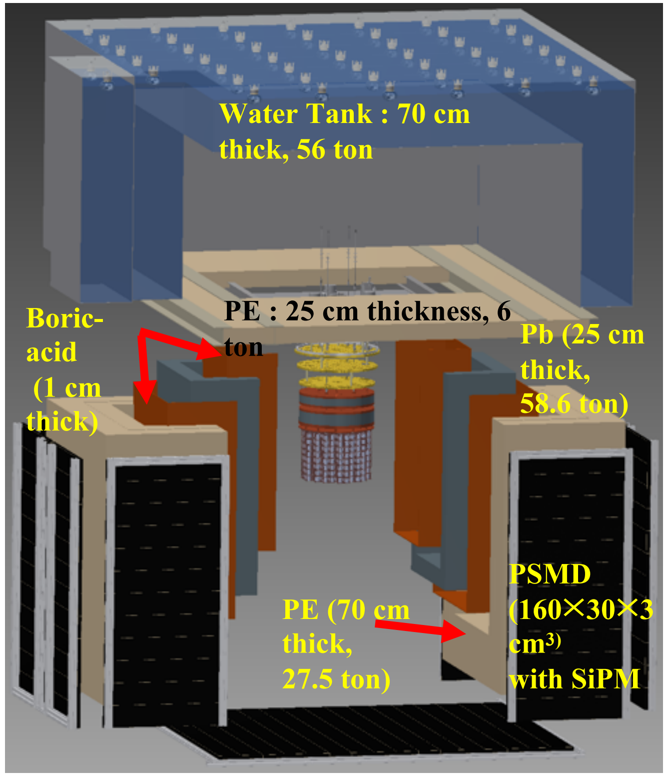
- Better energy resolution ~ 7 keV FWHM.
- Better PID → DP factor > 10.
- Signal slower, rising time 3.2 ms → 4.8 ms.

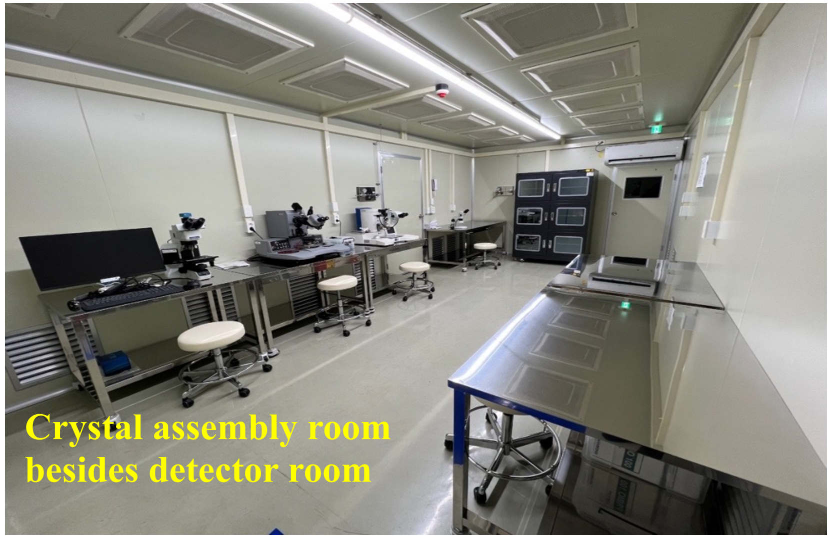
Now, AMoRE's energy resolution is close to CUPID-Mo in the test setup, still keeping the faster rise time.

AMoRE-II @ Yemilab

- 100 kg of ^{100}Mo @ Yemilab for 5 years
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 400 crystals)
- DR inside heavy shielding with Pb, PE, and water.
- Muon detectors installed.
  - 132 Plastic Scintillator Muon Detectors (PSMD)
  - Water Cherenkov Muon Detector(WCMD) with 48 PMTs, 70 cm thick water.







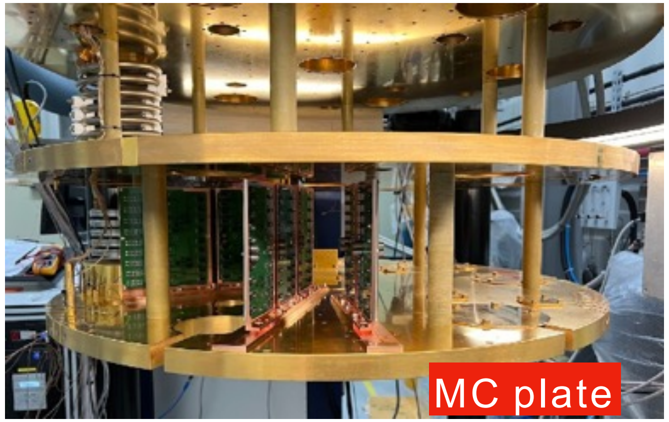
Crystals are assembled in copper holder and tower

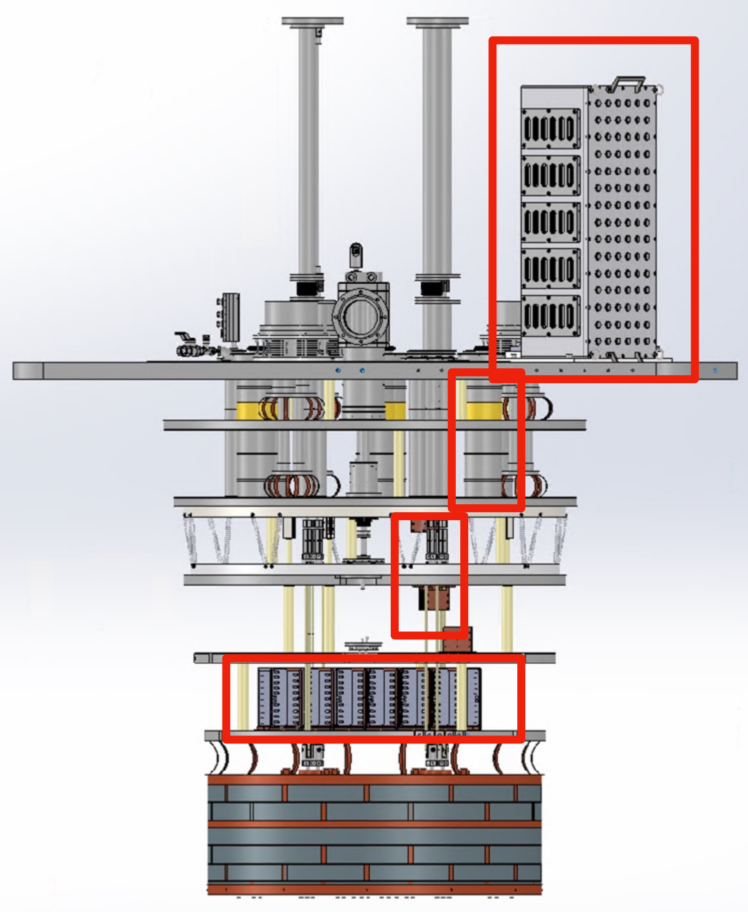
- **Class 100**
- **Humidity<1%**
- **Rn < 200mBq/m³**

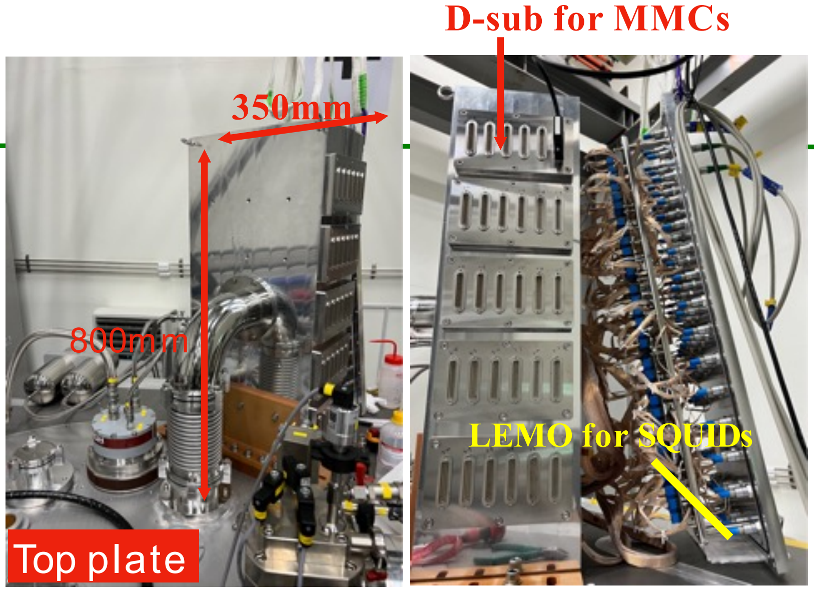
Vacuum Feedthrough & Wiring

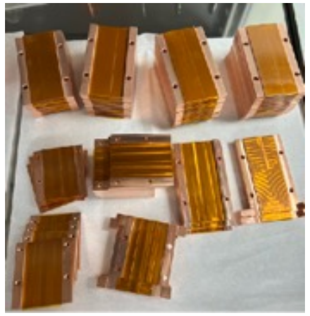
- Installed 270 SQUID & MMC channels for stage-1.

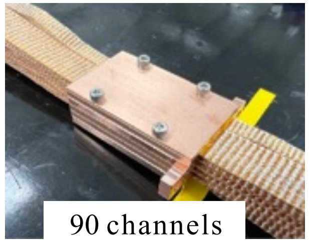
- **PCBs for MMC & Stabilization's filter circuits.**
- **ribbon wires ←→ detector wires.**



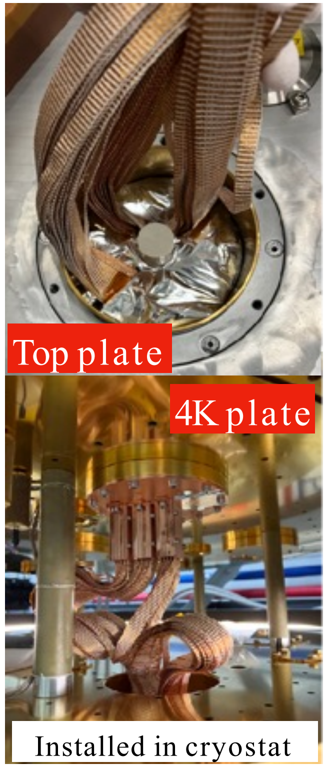








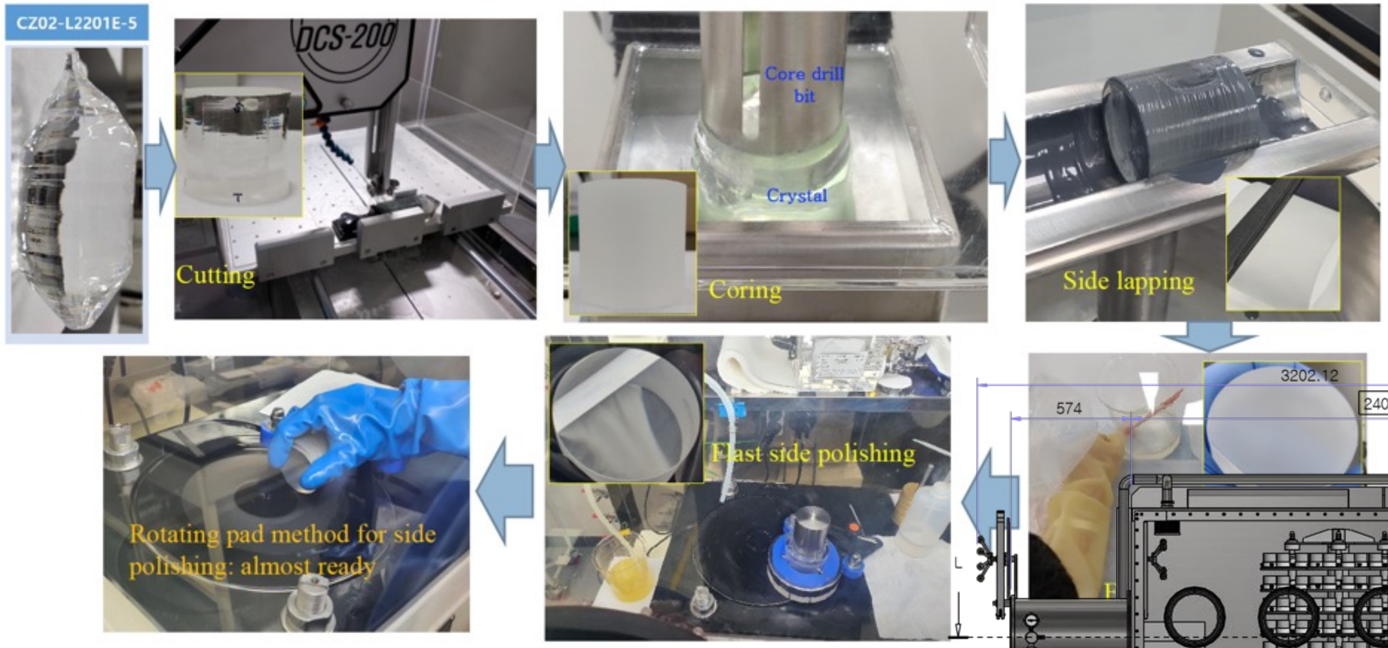
50K anchoring part with ribbon cable

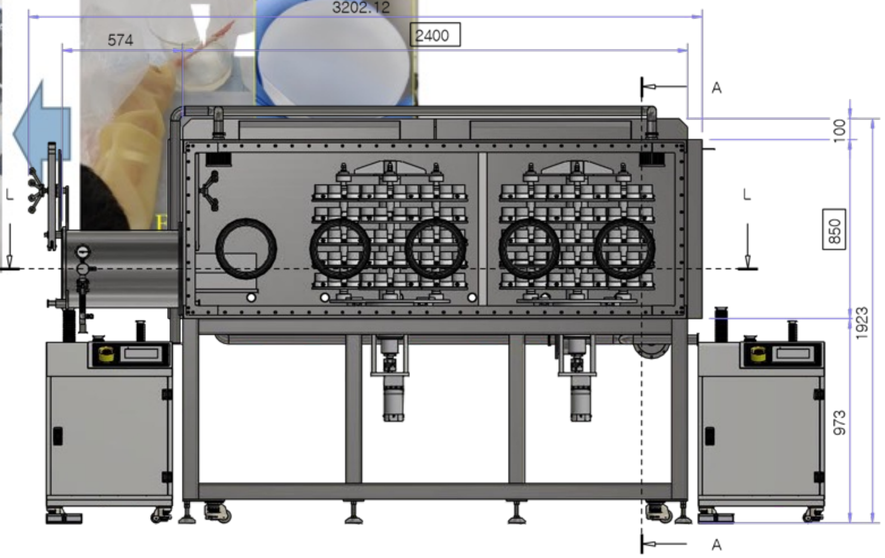


- Each bundle consists 90 channels of MMCs and SQUIDs

Crystal growing

- 120 kg of enriched MoO_3 powder is purificed in wet chemistry.
- Crystals are grown at both CUP (Chochralski) and NIIC (Low temp. gradient).
- Growing speed get slower due to the recycling necessary.

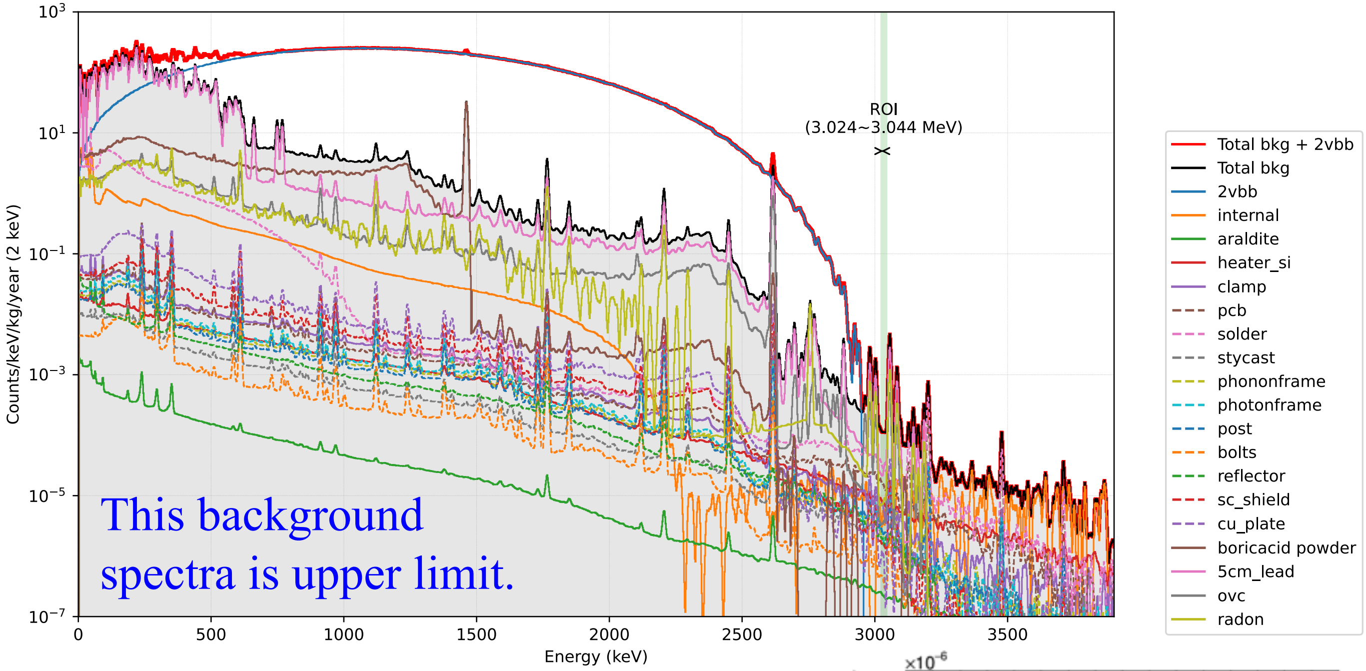




- Dry box for crystal storage

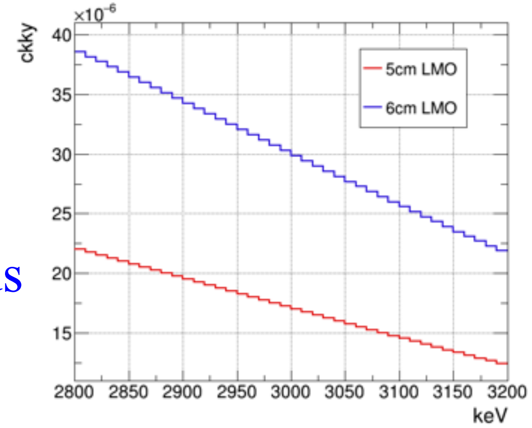
Backgrounds of AMoRE-II

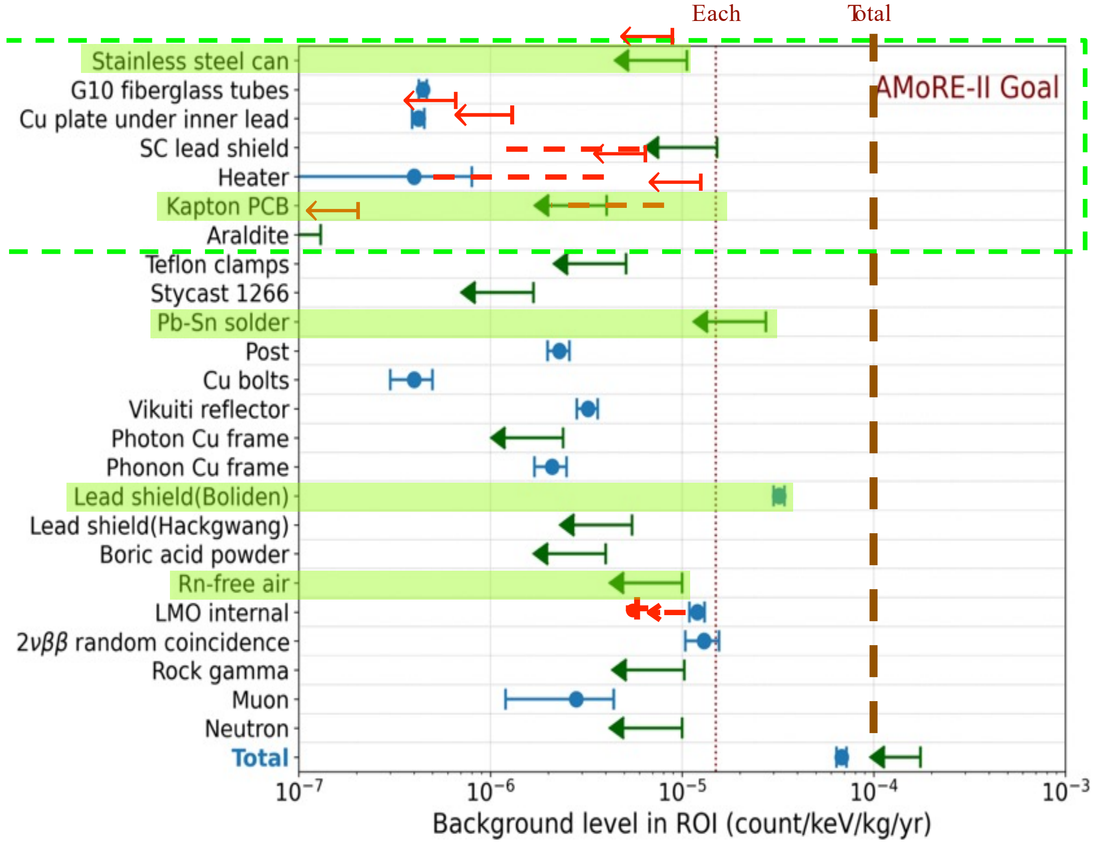
- The total backgrounds estimated are satisfactory for AMoRE-II requirements.
- Current limit is due to the finite contamination of ^{214}Bi in outside Pb shielding and will replace with Pb bricks (10 tons) less contaminated for the inner 5 cm layer.



This background spectra is upper limit.

Pile-up backgrounds



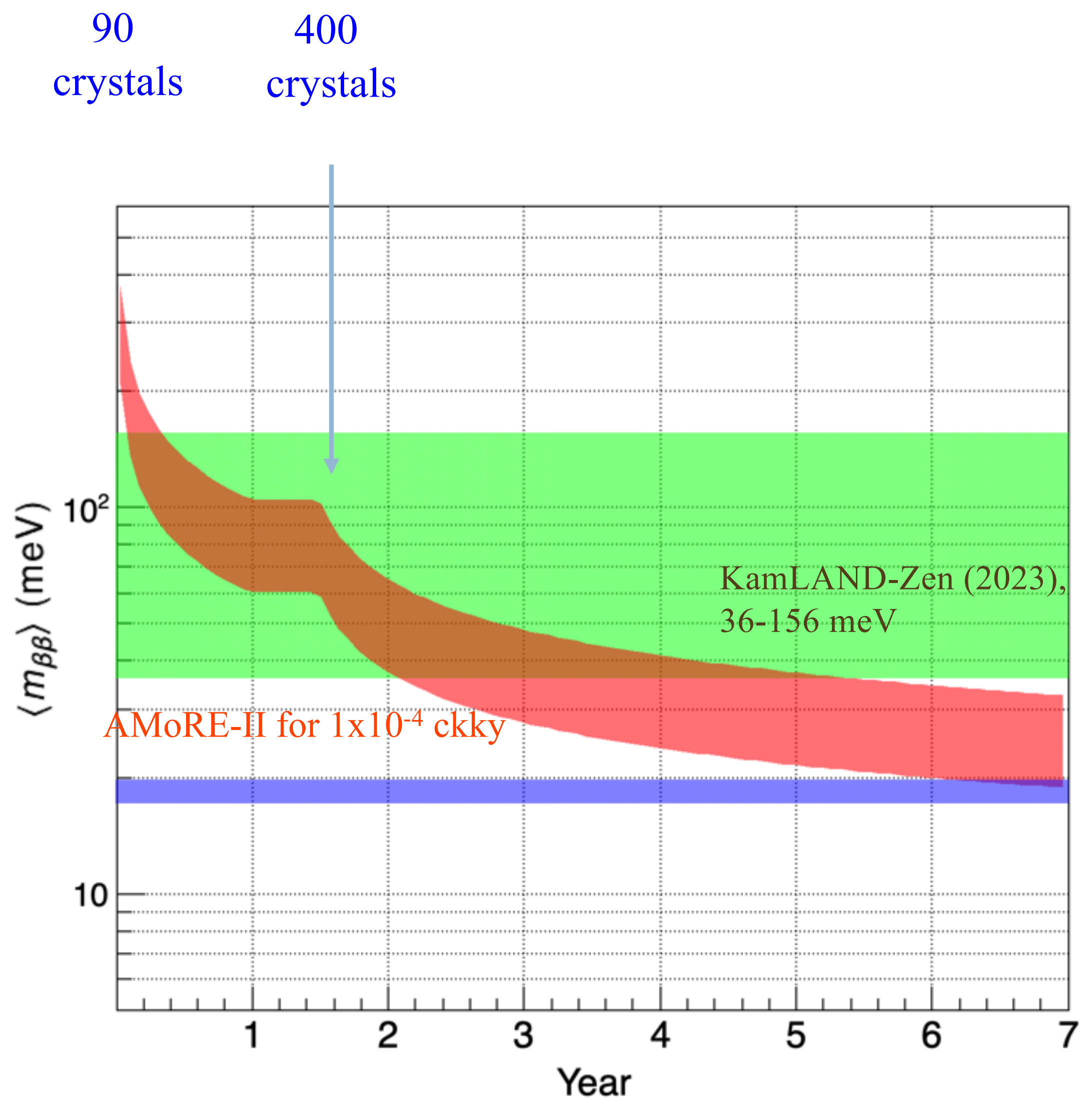


Sensitivity of AMoRE-II

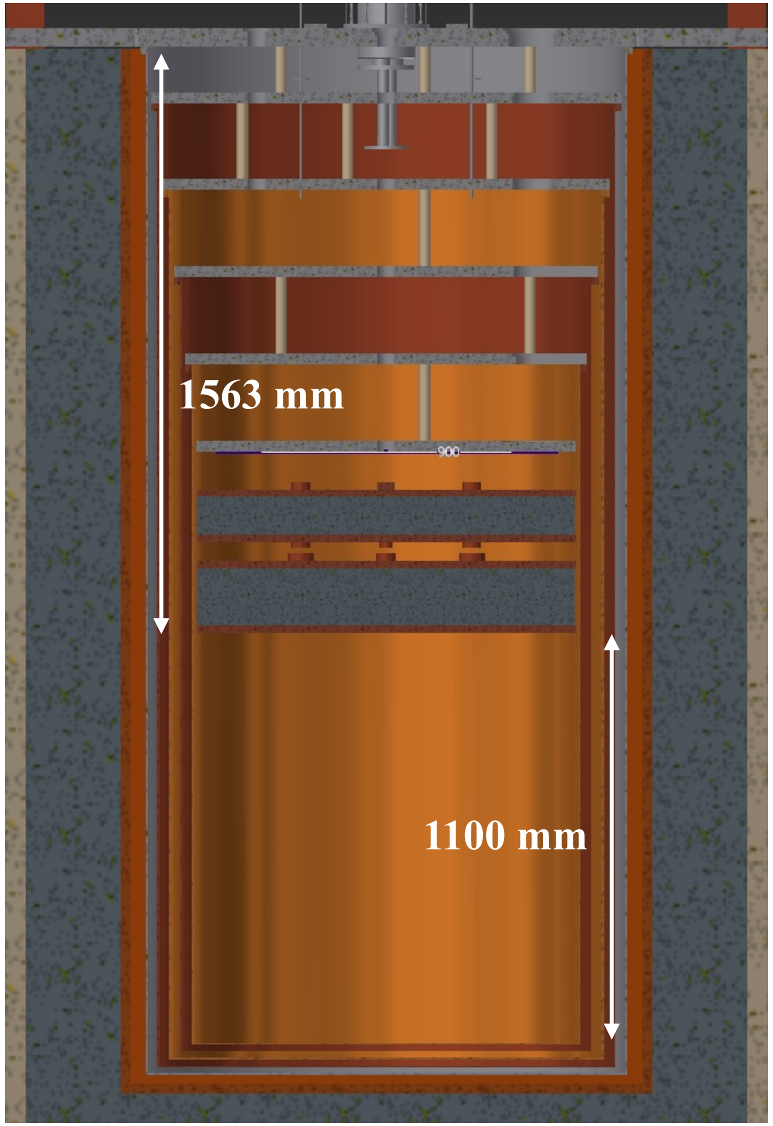
Discovery sensitivity :

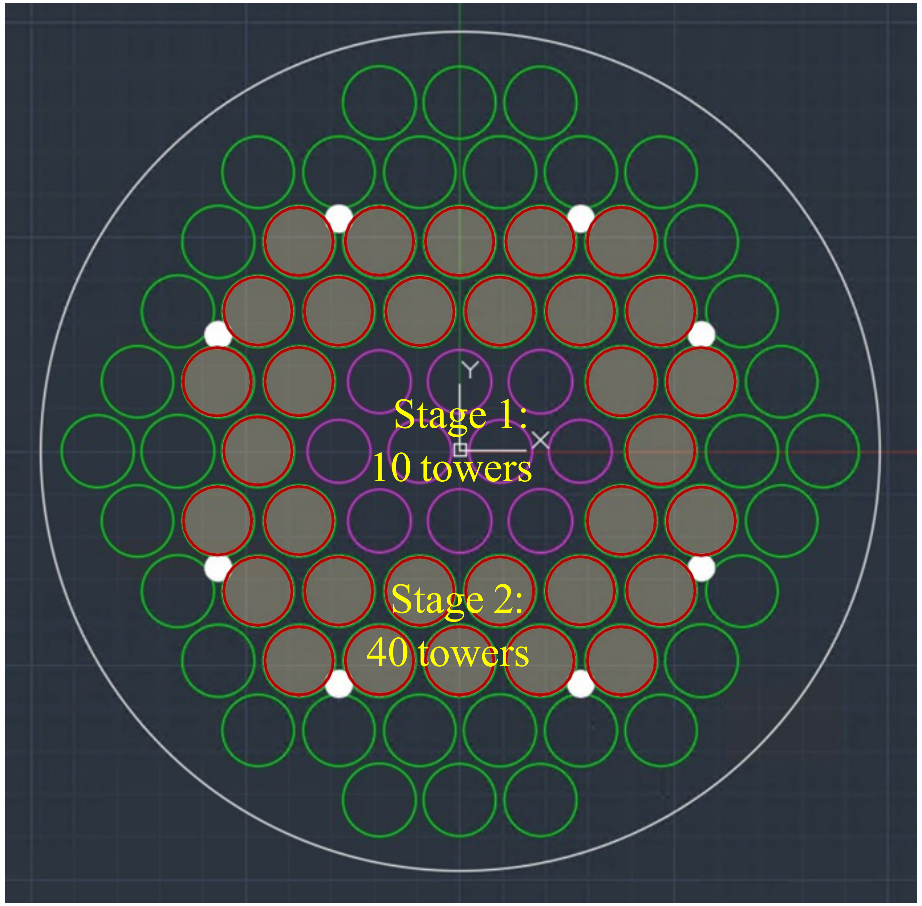
The half-life for which an experiment has a 50% chance to measure a signal above background with a significance of at least 3 sigma (99.7%).

We have grown 250 crystals. (Oct, '23)



Beyond AMoRE-II

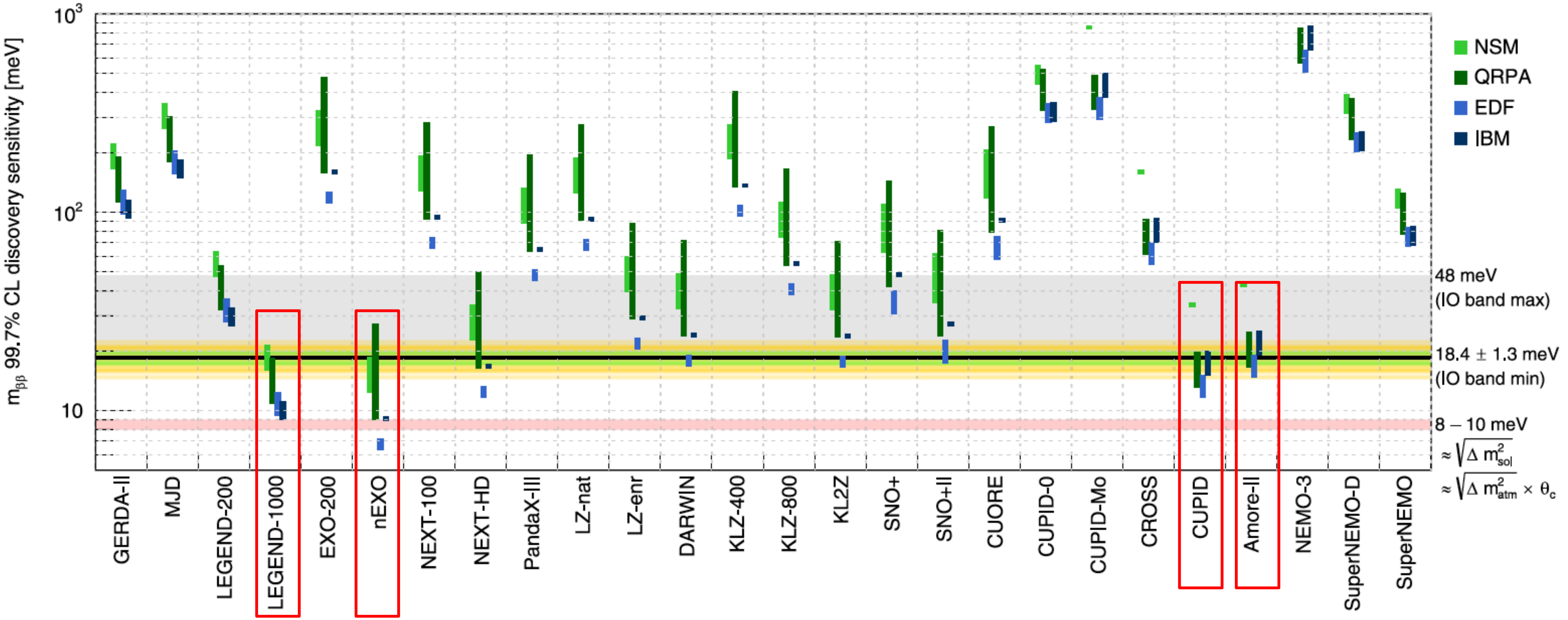




Maximum capacity of current Cryostat:
~ 900 crystals. (~200 kg ^{100}Mo isotopes)

Persepectives

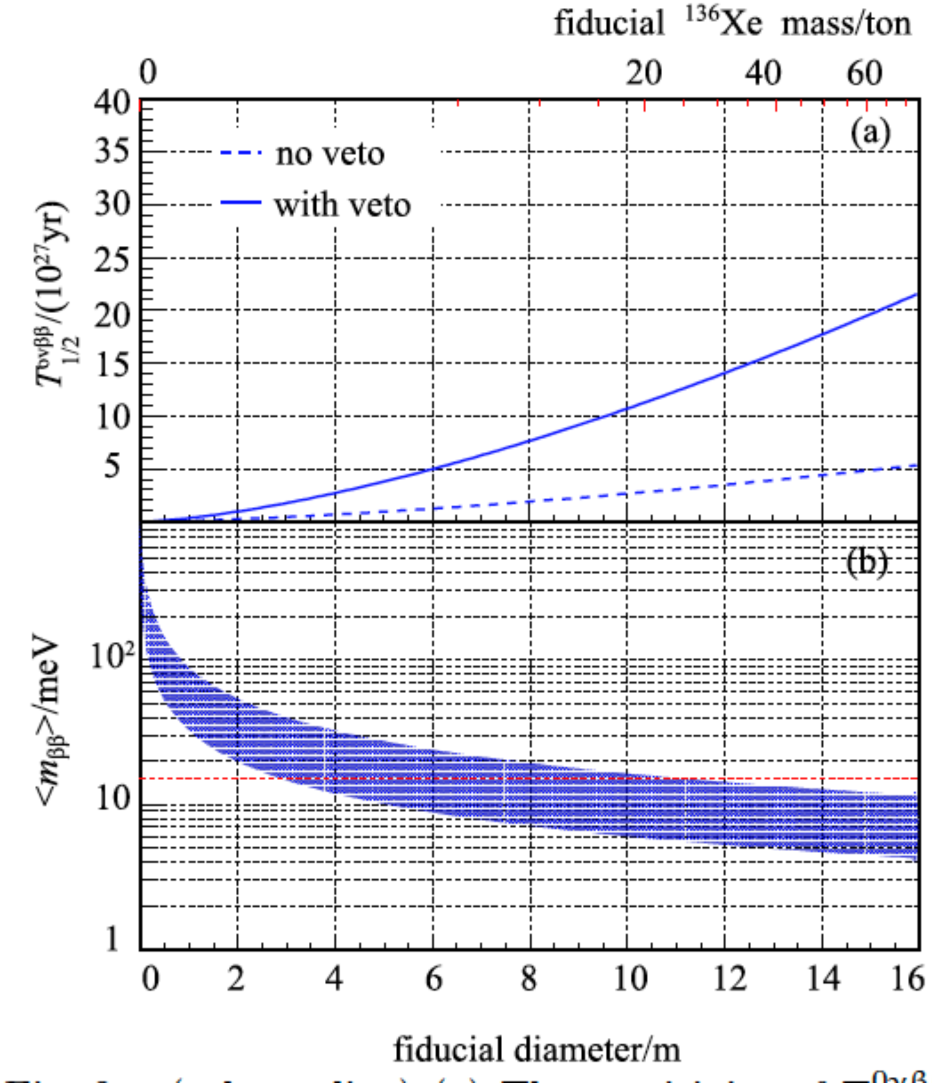
"Toward the discovery of matter creation with neutrinoless ββ decay", Agostini et al., RMP95, 025002 (2023)



- It will be real challenge to go below the IO (18.4 meV) mass region. Ton scale detector with lower background level. At least, we should study the feasibility of reaching to ~ 8 meV mass region.

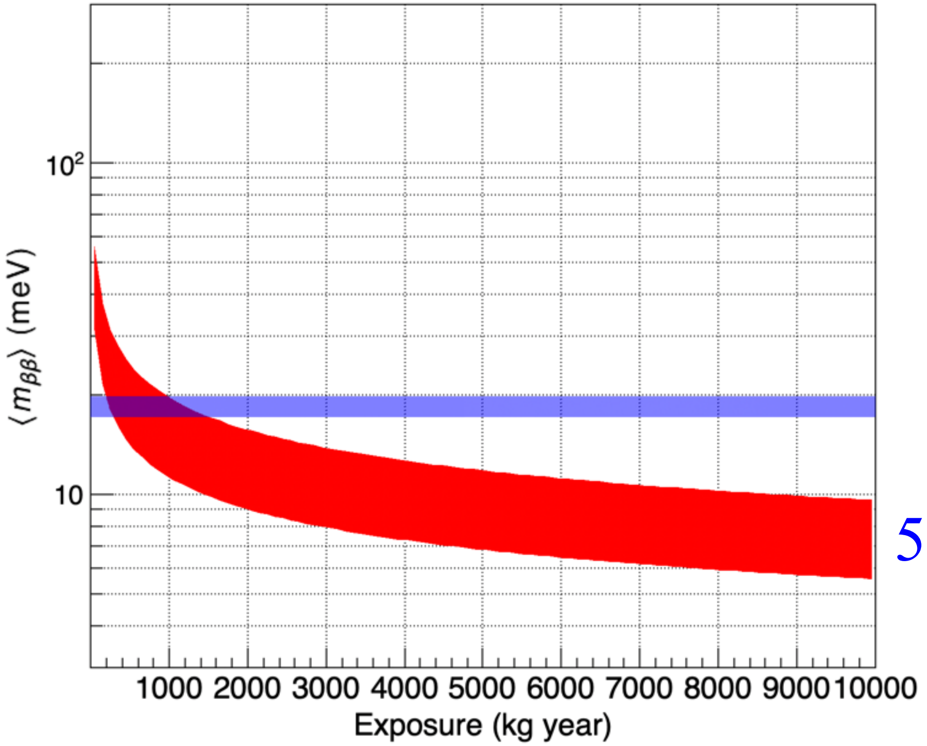
Jump to reach ~ 8 meV

JUNO-Xe, Similar to THEIA-Xe, Theia-Te
5 years run → 300 ton year exposure



5-12 meV

^{100}Mo, Bkg $=2\times10^{-5}$ ckky



5.5-10 meV

Need international collaborative work to achieve the backgrounds and energy resolution etc.

BSM with $2\nu\beta\beta$

"Probing Beyond the Standard Model Physics with Double-beta Decays", E. Bossio et al., arXiv:2304.07198

- New particles
  - Bosons : Majoron
  - Fermions : Sterile neutrino
- Violation of fundamental symmetries
  - Lorentz violation
  - Violation of Pauli Exclusion Principle
- Non standard interactions
  - Right-handed current
  - Neutrino self-interaction

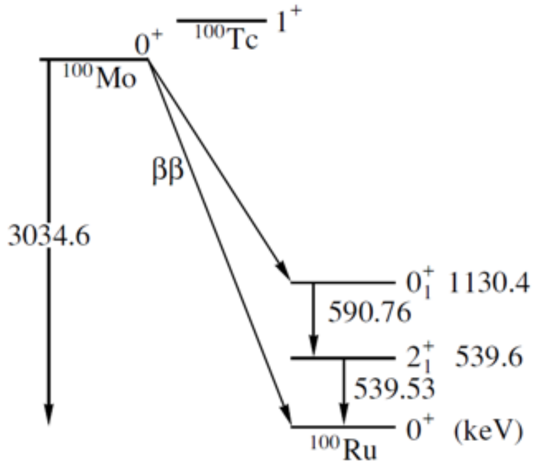
- No correlation between the BSM decay and the SM 2ndbd.
- BSM decays affects the total decay rates of SM 2ndbd.
- BSM alter the prediction of 2ndbd.

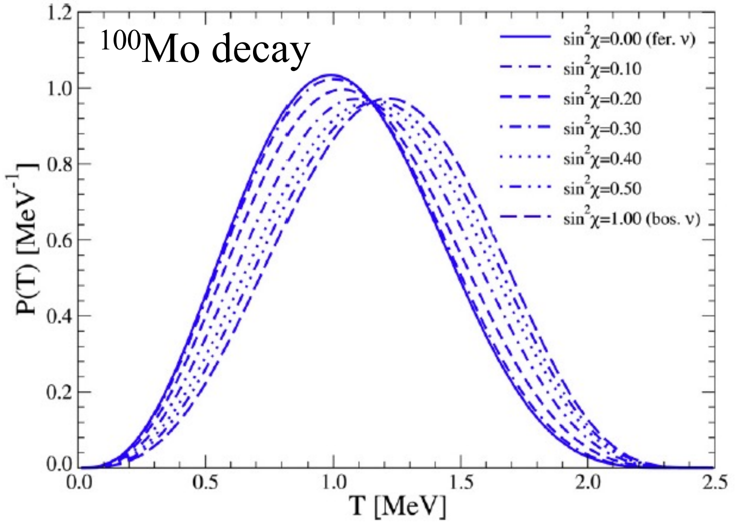
2^+ state in ^{100}Mo decay

- Barabash and Smirnov et al., "Statistics of neutrinos and the double beta decay" PLB 783 (2012) 90

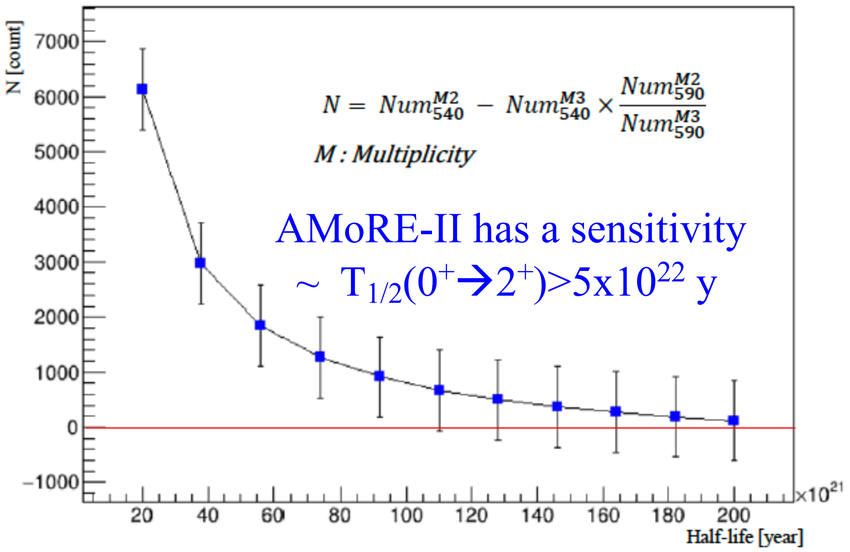
"Neutrinos can have substantially different properties from those of the charged leptons. Violation of the Pauli principle may occur in a hidden sector of theory."

- Double beta decays to excited states can be sensitive to a Bosonic contribution to the neutrino wave function. The predictions are ;
  - $T_{1/2} \sim 2.4\text{x}10^{22}$ yr, for Bosonic neutrinos
  - $T_{1/2} \sim 1.7\text{x}10^{23}$ yr for Fermionic neutrinos .
  - The current limit $T_{1/2} > 4.4\text{x}10^{21}$ yr





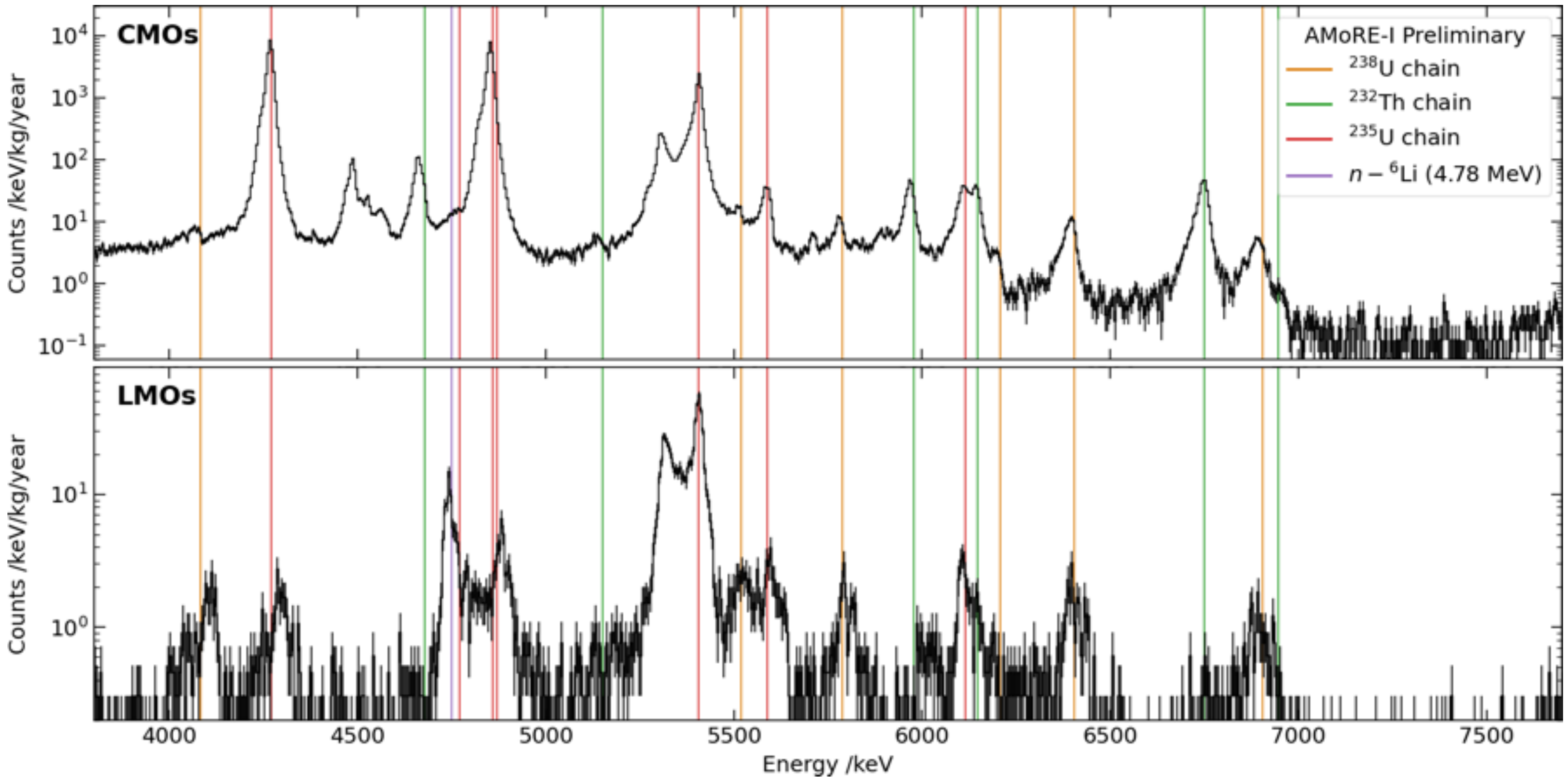
2νββ energy spectrum
Distortion for 2^+ state decay

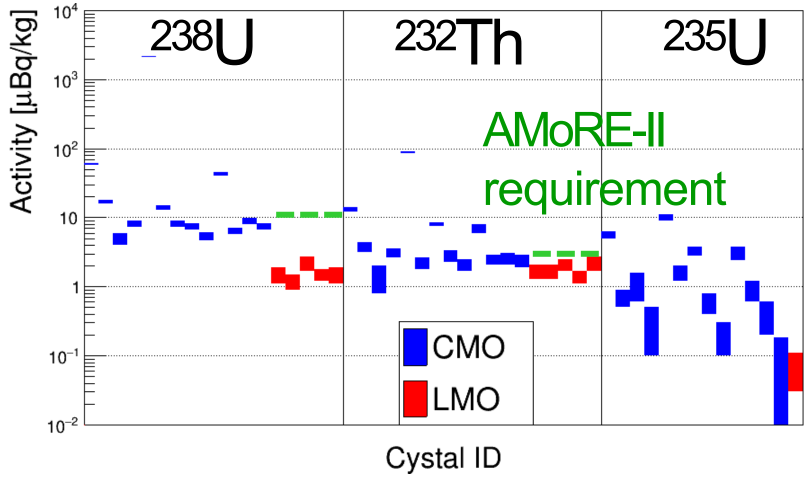


Summary

- Yemilab is constructed for dark matter and NDBD. Many projects are under preparation.
- Neutrinoless DBD experiments are progressing towards > Ton scale experiment. Multiple Isotopes should be pursued. AMoRE-II experiment aims to be sensitive ~ 5×10^{26} years range for ^{100}Mo isotope and could expand to 200 kg of isotope mass scale.
- AMoRE-II is open for collaboration !

α background

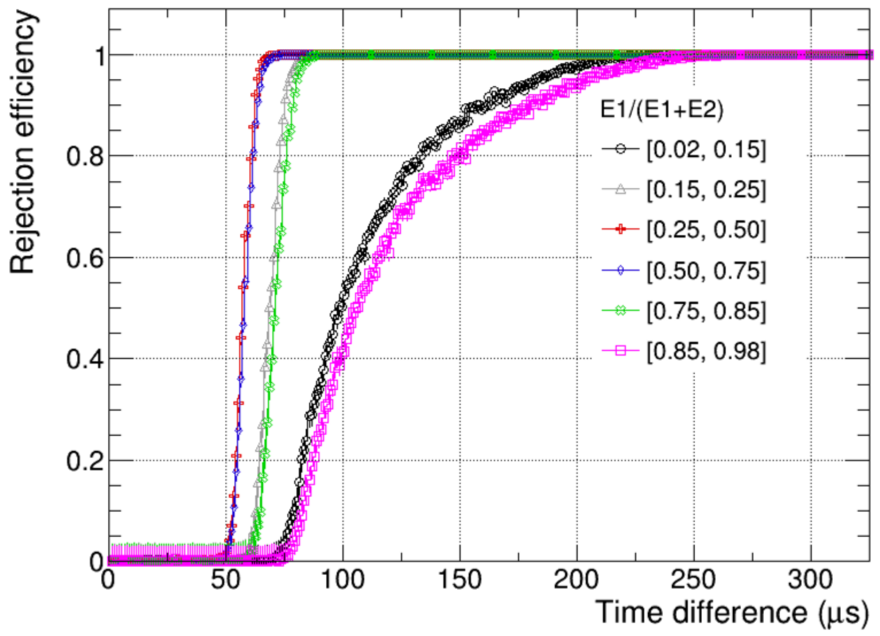


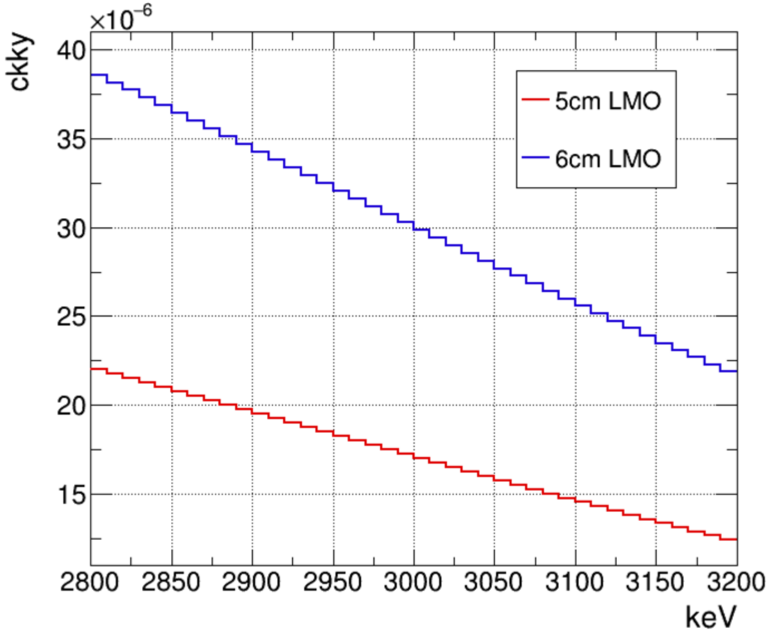


- Overall, the radioactive contamination by U/Th of LMO is measured to be s ubstantially lower than that of CMO.

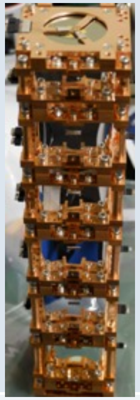
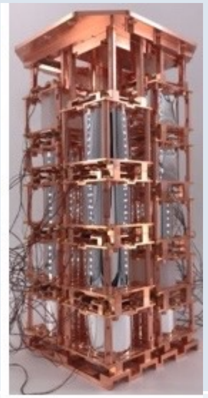
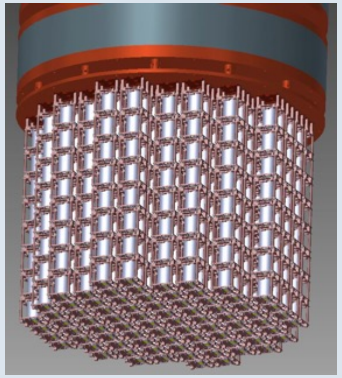
Pileup background estimation

- A realistic estimation assuming real spectra and noise data from AMoRE-pilot
- Crystal size is important – pile up event rate is proportional to square of single rates.
- 6cm crystal is acceptable.





Plan of AMoRE Project

Phases	AMoRE-Pilot	AMoRE-I	AMoRE-II
Detector Setup (Not in scale)			
Crystals	$^{40}Ca^{100}MoO_4$ (CMO)	$(^{40}Ca,Li_2)^{100}MoO_4$	$Li_2{}^{100}MoO_4$ (LMO)
Crystal # & Mass	6, 1.9kg	18, 6.2kg	596, 178kg
Backgrounds (**ckky**)	$\sim 10^{-1}$	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$\sim 3.0\text{x}10^{23}$	$\sim 7.0\text{x}10^{24}$	$\sim 8.0\text{x}10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	17-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2023	Yemilab / 2024-2029

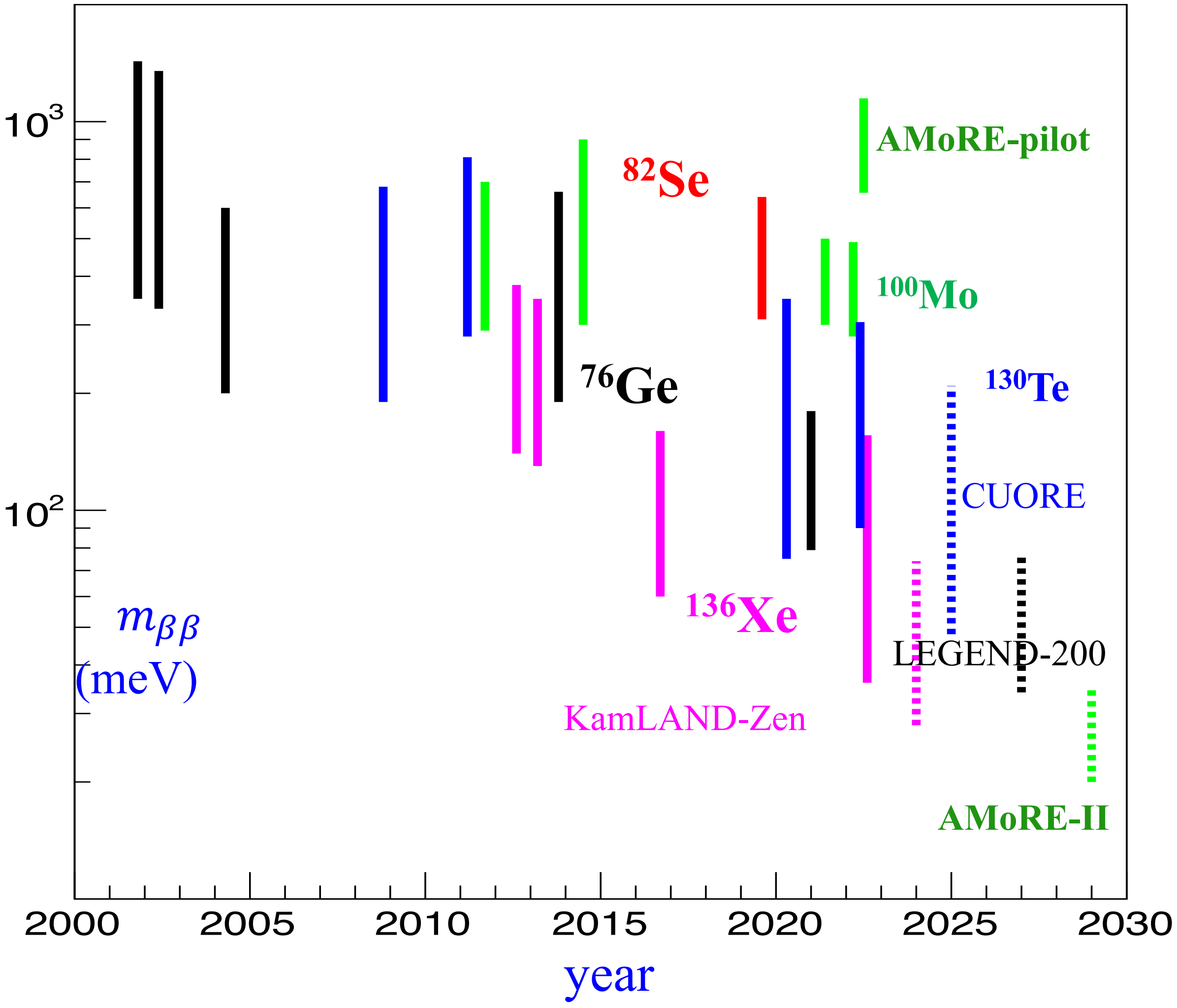
Background Unit :
ckky=counts/(keV kg year)

AMoRE Collaboration : 9 Countries, 25 Institutions.

Korea, Germany, Ukraine, Russia, Thailand, Indonesia, China, India, Pakistan.

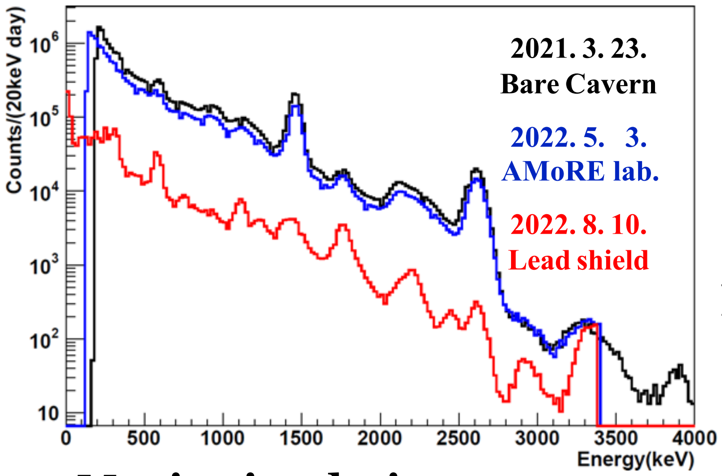
Recent Limits & Persepectives

- AMoRE-II will have an exposure more than 100 times larger than any ^{100}Mo experiment in a few years.



Environmental measurement and monitoring

Gamma background with NaI(Tl)



ICP-MS/HPGe measurements of rock and dust samples

	238U	232Th	40K
Rock (lab)	10.4Bq/kg	13.3Bq/kg	366Bq/kg
Dust (cage)	24.6Bq/kg	15.2Bq/kg	226Bq/kg
Dust (lab)	25.0Bq/kg	23.1Bq/kg	407Bq/kg

Neutron and muon flux measurements are ongoing

Monitoring device

Temperature & Humidity

Radon

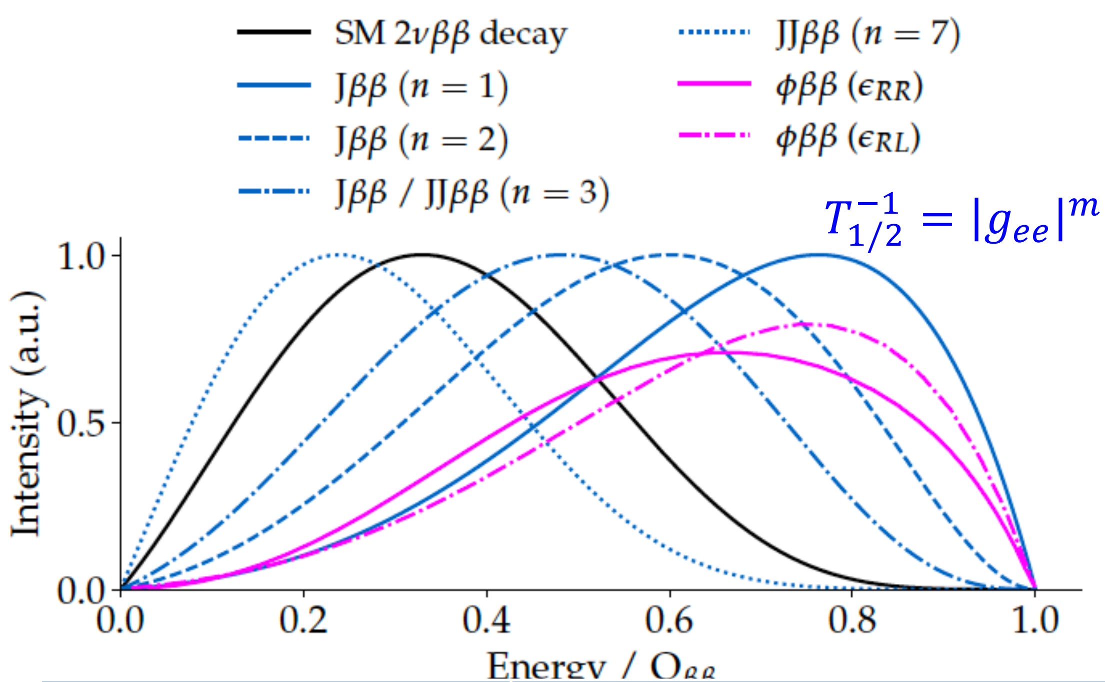
Dust level

CO, CO2, and O2

Online monitoring

Majoron with $2\nu\beta\beta$

Mojorons are Goldstone boson from the violation of lepton number conservation.
Several Majoron emitting mode of $2\nu\beta\beta$ decay.



$T_{1/2}^{-1} = |g_{ee}|^m G |M|^2$

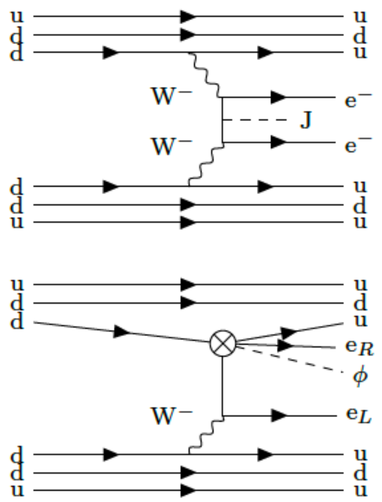


Figure 4. (Top) Feynman diagram for the double-β decay with the emission of a Majoron in classical models. (Bottom) Feynman diagram for the emission of a Majoron-like particle ϕ through an effective dimension-seven operator containing right-handed currents in double-β decay (adapted from [66]).

	Half-life limits (x10^{23} years)				
	n=1	n=2	n=3	n=7	Reference
KAMLAND-ZEN (^{136}Xe)	26	10	4.5	0.11	
GERDA(^{76}Ge)	6.4	2.9	1.2	1.0	
CUPID-0 (^{82}Se)	1.2	0.38	0.14	0.022	
EXO-200(^{136}Xe)	43	15	6.3	0.51	PRD 104, 112002

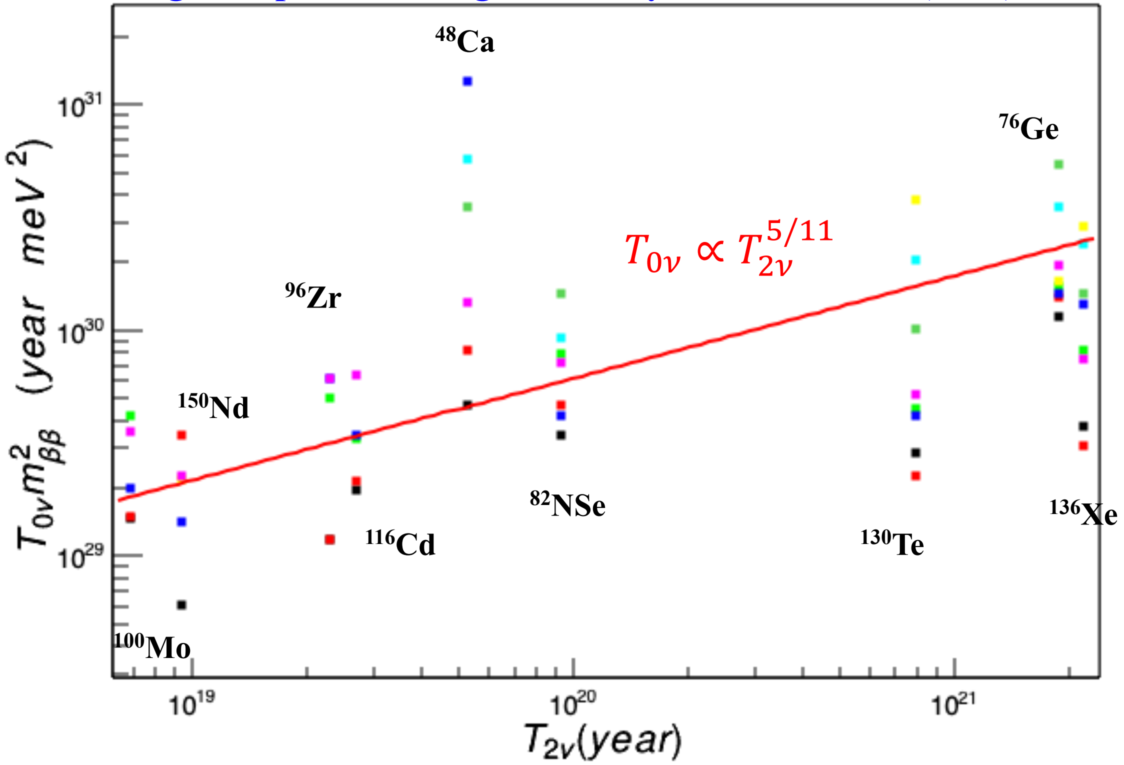
$0\nu\beta\beta$ vs $2\nu\beta\beta$ T(1/2)

- **A correlation between $2\nu\beta\beta$ half-life(measured) vs $0\nu\beta\beta$** half-life (calculated)
- It is important to run multiple isotopes since the real mechanism can be understood with a comparison between multiple isotope data.

$G_{0\nu} \propto Q^5, \; G_{2\nu} \propto Q^{11}.$ H. Ejiri's comment

- ^{100}Mo has shortest 2νββ half-life.

Engel, Reports on Progress in Physics, 80, 046301 (2017)



- ^{100}Mo has ~ 500 times shorter lifetime than ^{76}Ge and ^{136}Xe.

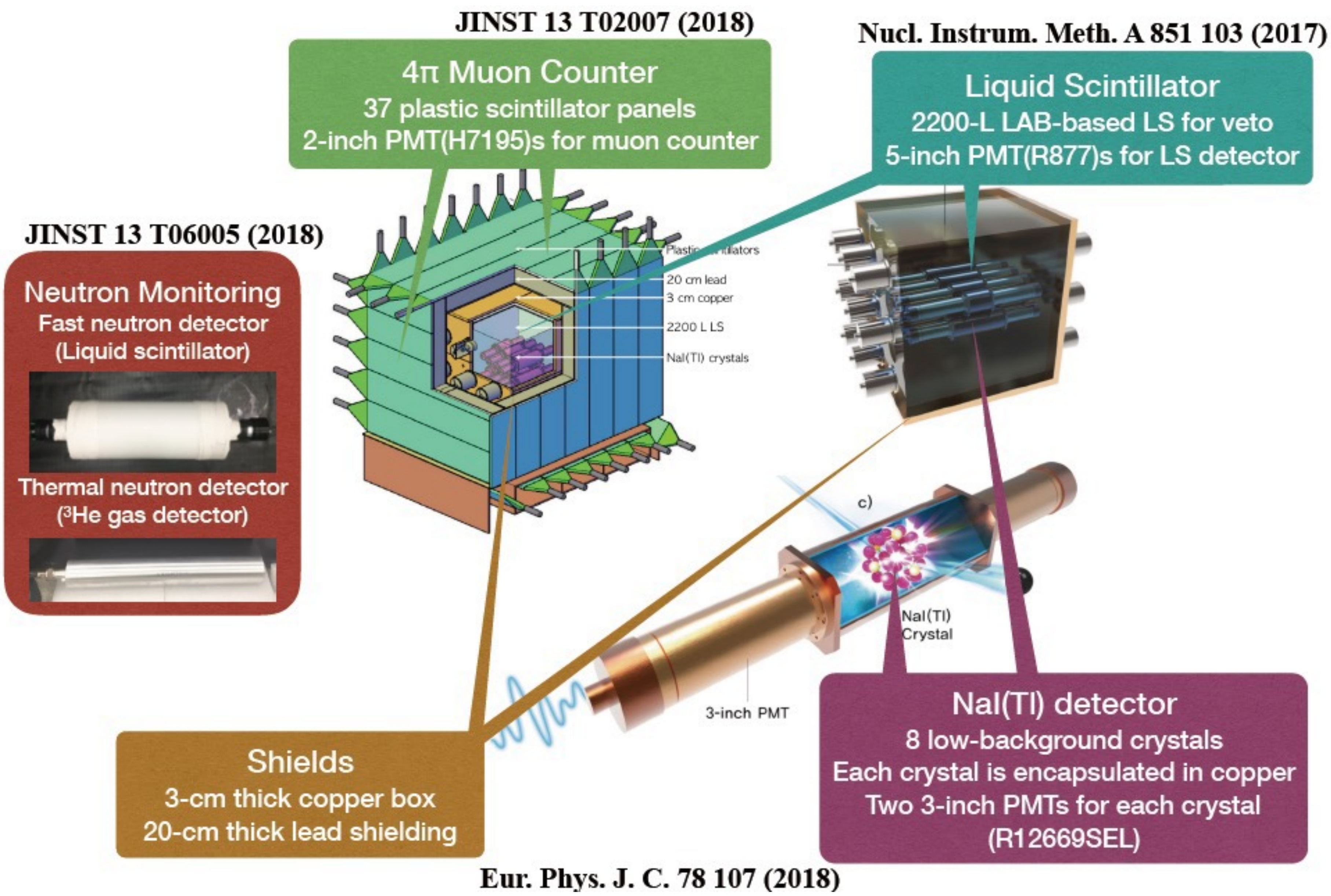
Current best results for $0\nu\beta\beta$

2023. 2. 12

Nucl.	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T^{0\nu}_{1/2}$ (10^{24} Y)	M (meV)	Ref.
^{48}Ca	4270.0	0.187	0.53(0.1)	CANDLES	> 0.058	<3100-15400	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	18.8(0.8)	GERDA-II	>180	<79-180	PRL125, 252502 (2020)
^{82}Se	2997.9	9.2	0.93(0.05)	CUPID-0	> 4.6	<263-545	PRL129, 111801 (2022)
^{100}Mo	3034.4	9.6	0.0688(0.0025)	CUPID-Mo	>1.8	<280-490	EPJC82, 1033 (2022)
^{116}Cd	2813.4	7.6	0.269(0.009)	AURORA	> 0.22	<1000-1700	PRD 98 092007 (2018)
^{130}Te	2527.5	34.5	7.91(0.21)	CUORE	> 22	<90-305	Nature 605, 53 (2020)
^{136}Xe	2458.0	8.9	21.8(0.5)	KamLAND-Zen	> 230	<36-156	PRL130, 051801 (2023)
^{150}Nd	3371.4	5.6	0.0934(0.0065)	NEMO-3	> 0.02	<1.6-5.3	PRD 94 072003 (2016)

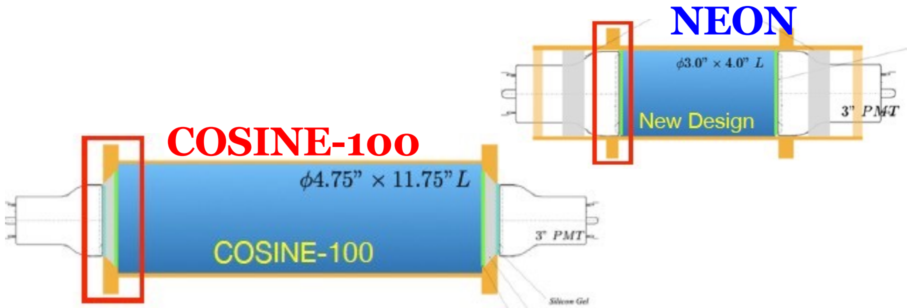
Bolometer, Scintillation, Ionization

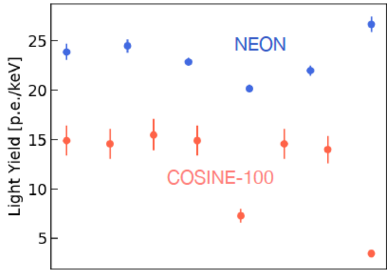
COSINE-100 detector



COSINE-100U (upgrade) @ Yemilab

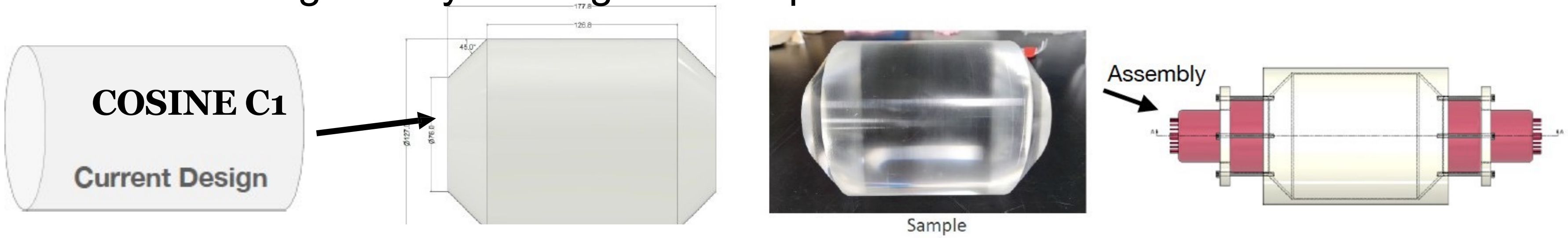
- Novel technique of crystal encapsulation (applied to NEON)



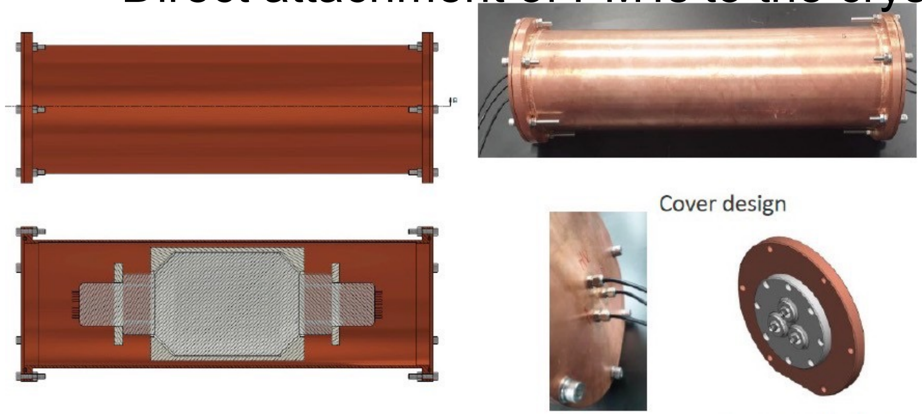


NIMA 981, 164556 (2020)

Machining the crystal edges to couple with 3" PMTs



Direct attachment of PMTs to the crystal

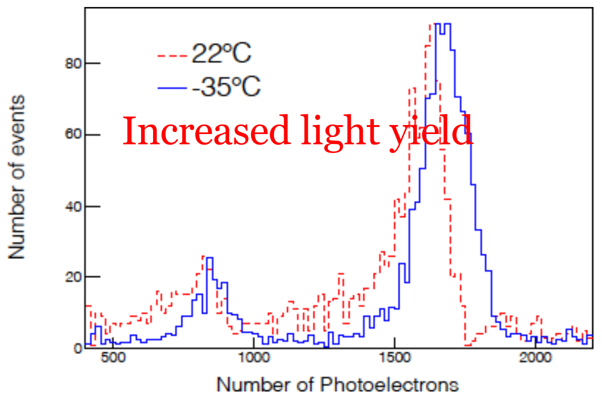


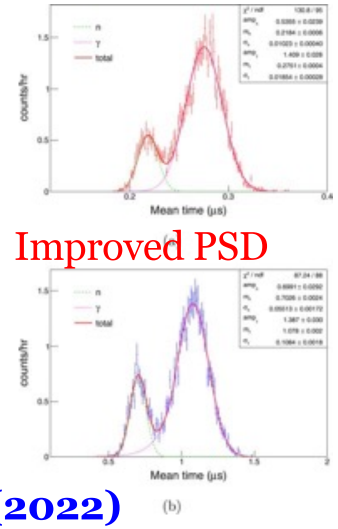
Increased light yield above 20 photoelectrons/keV expected

Similar design was applied to NEON experiment and proved the long-term stability

-35^{o}C operation @ Yemilab

-35^{o}C operation



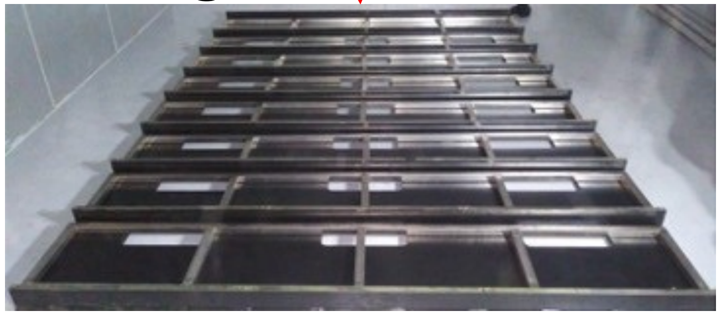


Astropart. Phys. 141, 102709 (2022)

- 5% gamma light yield increase
- 10% alpha quenching increase
  - Will measure nuclear recoil quenching
- Pulse shape discrimination is significantly improved

Warehouse freezer at Yemilab

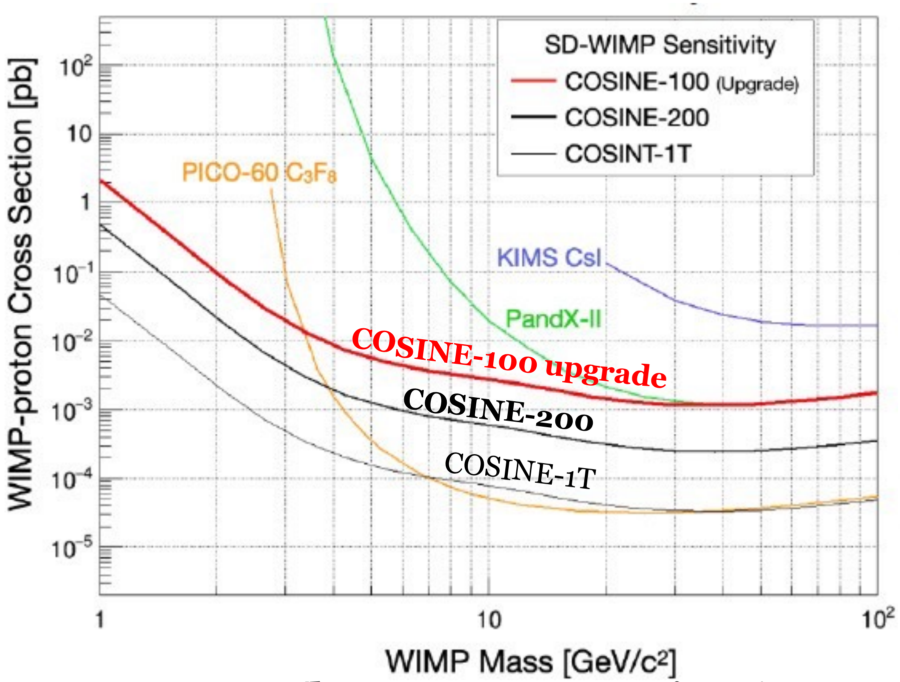
Shielding base for muon detector



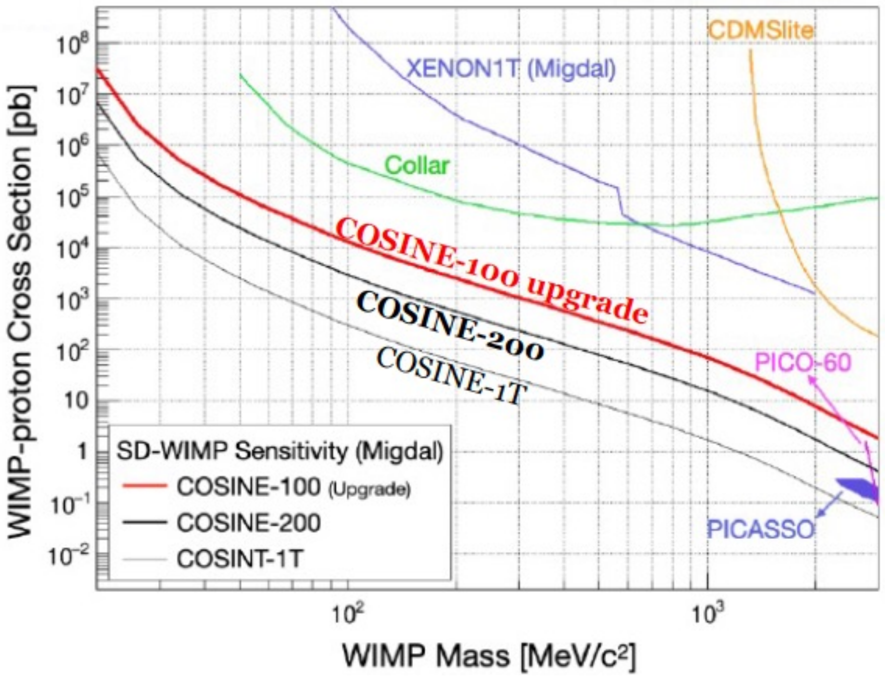
To start COSINE-100U at Yemilab October/2023

COSINE-100U sensitivities @ Yemilab

WIMP-proton spin-dependent



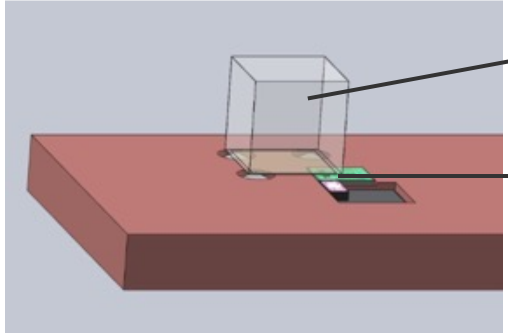
Low mass search with Migdal



22 NPE/keV, 1 year operation (100% efficiency), 5 NPE threshold

- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test for the COSINE-200 & 1T experiments

Low Mass DM search @ CUP

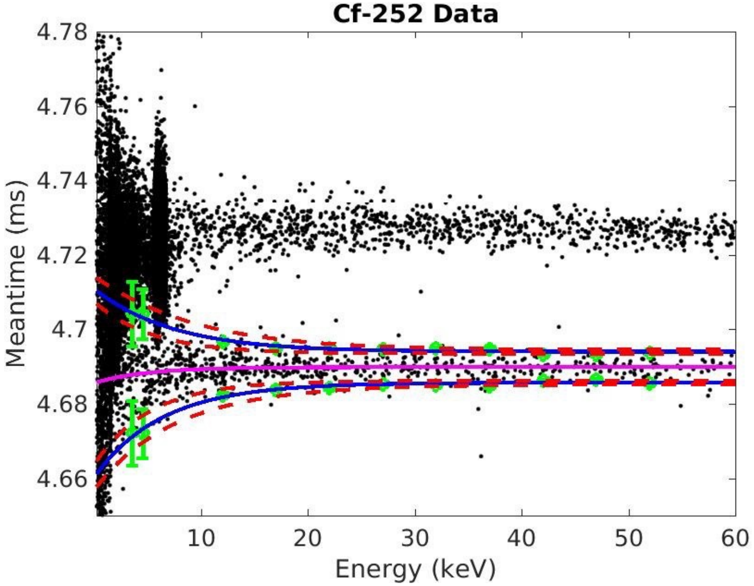


Many choices: **LiF, CaF$_2$, Sapphire(Al_2O_3)**(SD)
$CaMoO_4$, Diamond (SI)

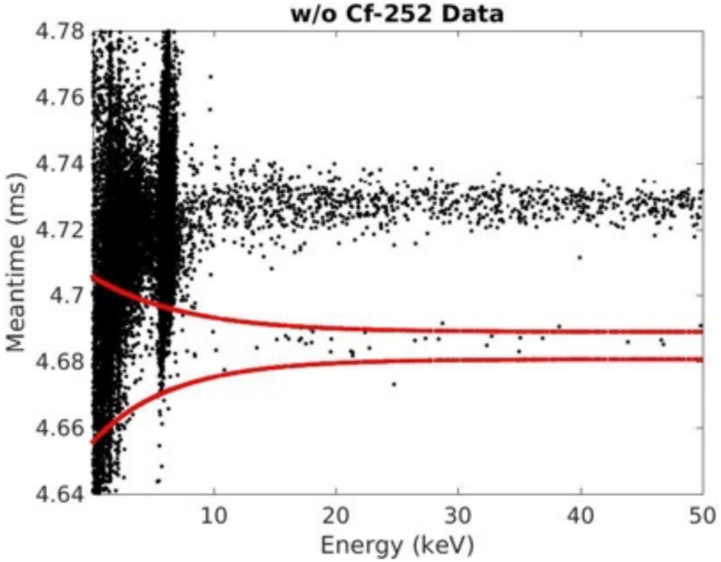
MMC

First trial with CaF_2 ($5 \times 5 \times 5$ mm^3, 0.4g) 30 mK at ground laboratory. ${}^{19}_{9}F$ is proton spin isotope.

w/ neutron source

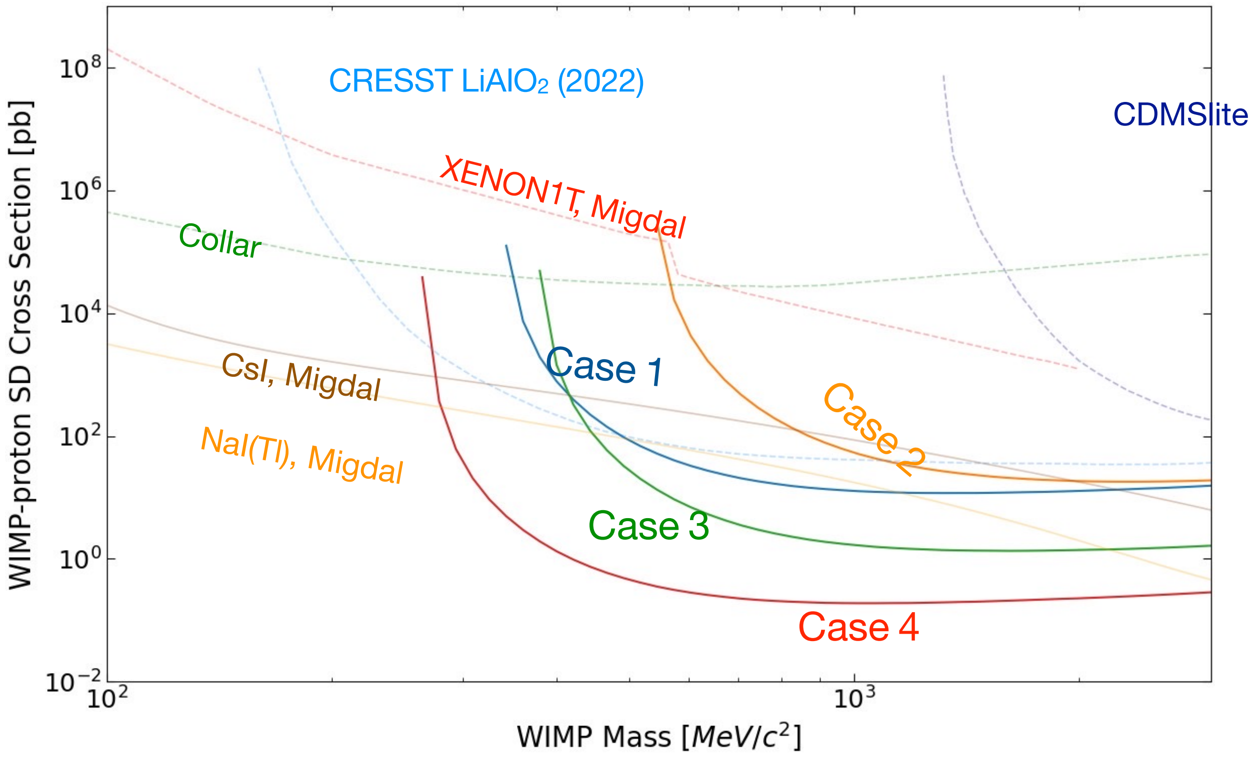


w/o neutron source



- It is promising to see good PSD even w/o light detector.
- Preliminary energy threshold ~ 50 eV.
- Will test various crystals for optimization, and further @ underground

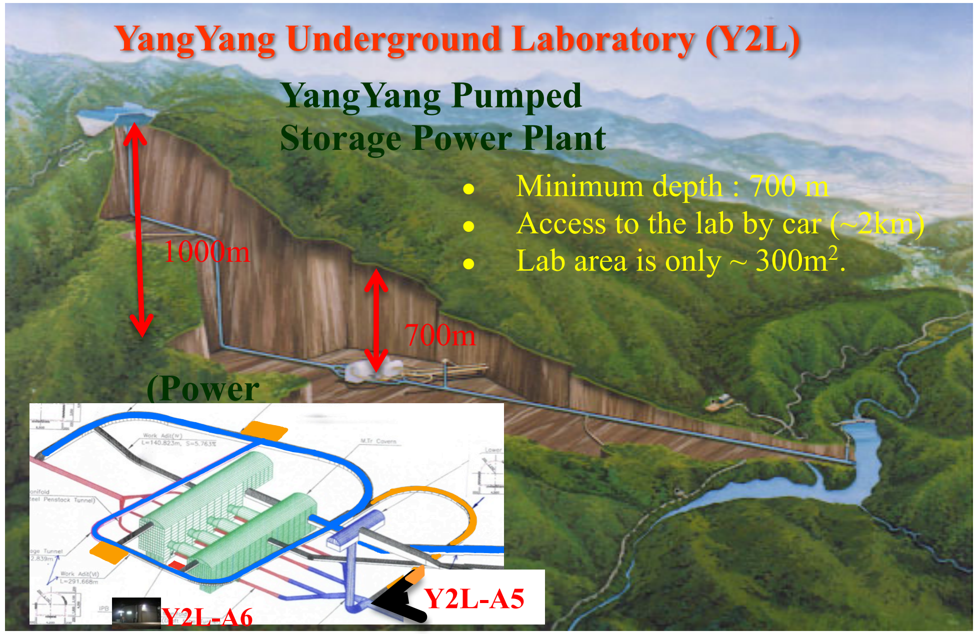
Sensitivity with CaF2 crystal @ Yemilab



CaF_2	Exposure	Threshold	Background
Case 1	0.4 kg·day	80 eV	40k dru
Case 2	0.1 kg·day	200 eV	10k dru
Case 3	1 kg·day	100 eV	1000 dru
Case 4	3 kg·day	50 eV	100 dru

PSD with light detector has a threshold ~ 1 keV, so low mass dark matter search will be done w/o light detector.

Y2L

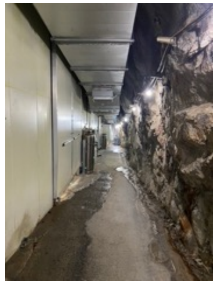


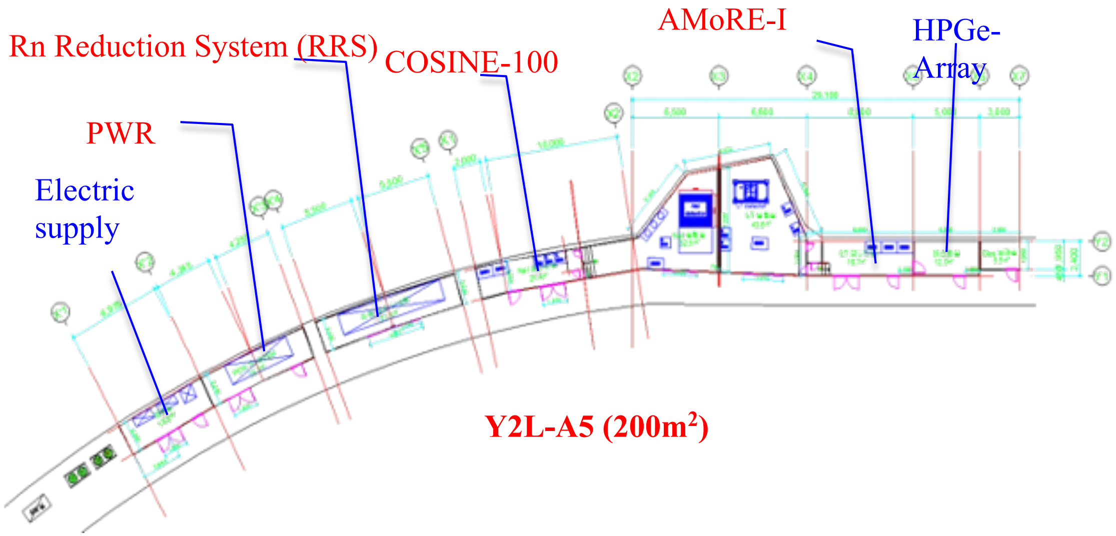
- Y2L began in 2003 with KIMS experiment.
- CUP began in 2013.
- 2023 is 20th of Y2L and 10th of CUP.

Y2L-A5 is built by CUP in 2015.

COSINE-100 (2016-2023.2) → Yemilab for tests of general purpose

AMoRE-I(2019-2023.5) → Yemilab for other rare decay searches.

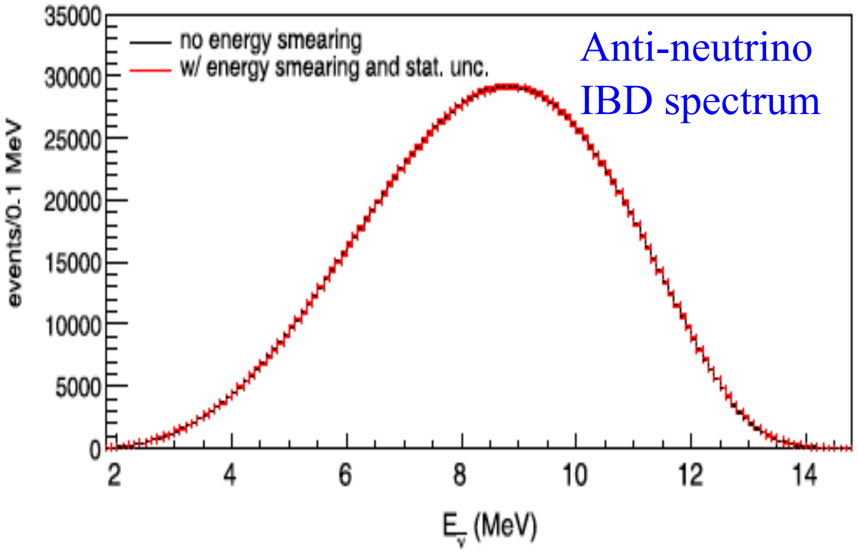




Sterile neutrino searches.

"Neutrino Physics Opportunities with the IsoDAR Source at Yemilab", PRD 105, 052009 (2022)

- IBD $\overline{\nu}_e p \rightarrow e^+ n$, short baseline oscillation is searched.
- Assume : $\sigma(E) \sim 6.4\,\% / \sqrt{E(MeV)}$, $\sigma(vertex) = 12cm/\sqrt{E(MeV)}$: reasonable

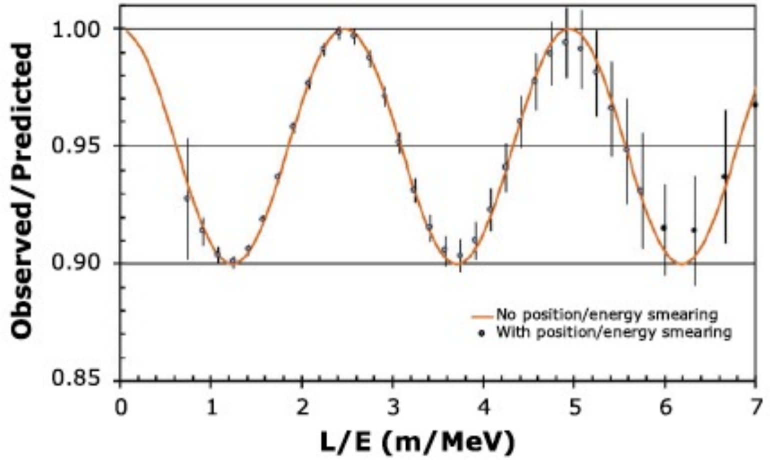


Runtime	5 calendar years
IsoDAR duty factor	80%
Livetime	4 years
Protons on target/year	$1.97 \cdot 10^{24}$
^{8}Li/proton ($\bar{\nu}_e$/proton)	0.0146
$\bar{\nu}_e$ in 4 years livetime	$1.15 \cdot 10^{23}$
IsoDAR@Yemilab mid-baseline	17 m
IsoDAR@Yemilab depth	985 m (2700 m.w.e.)

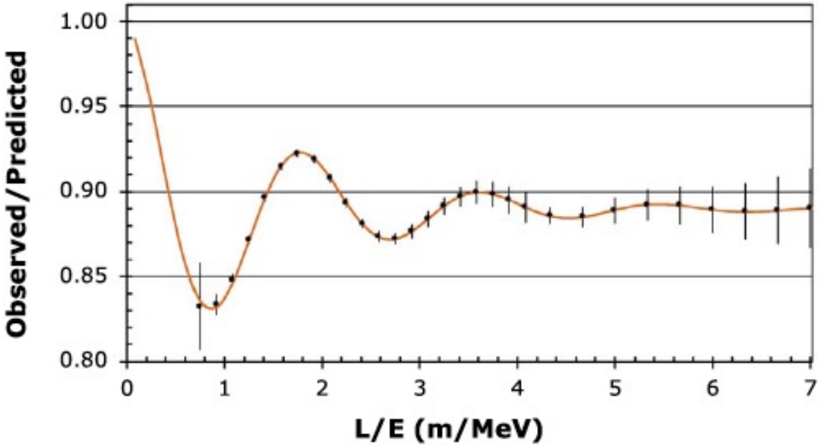
For each event, we measure the energy (E) and vertex(L) of neutrinos. → L/E

Sterile neutrino searches.

$(3+1)$: $\Delta m^2 = 1\ eV^2$, $\sin^2 2\theta = 0.1$



$(3+1+decay)$:
$\Delta m^2 = 1.35\ eV^2$, $\sin^2 2\theta = 0.214, \tau = 4.5 eV^{-1}$



5σ sensitivity with 5 year run

Cover most of the confusing parameter spaces.