Perspectives for Center for Underground Physics

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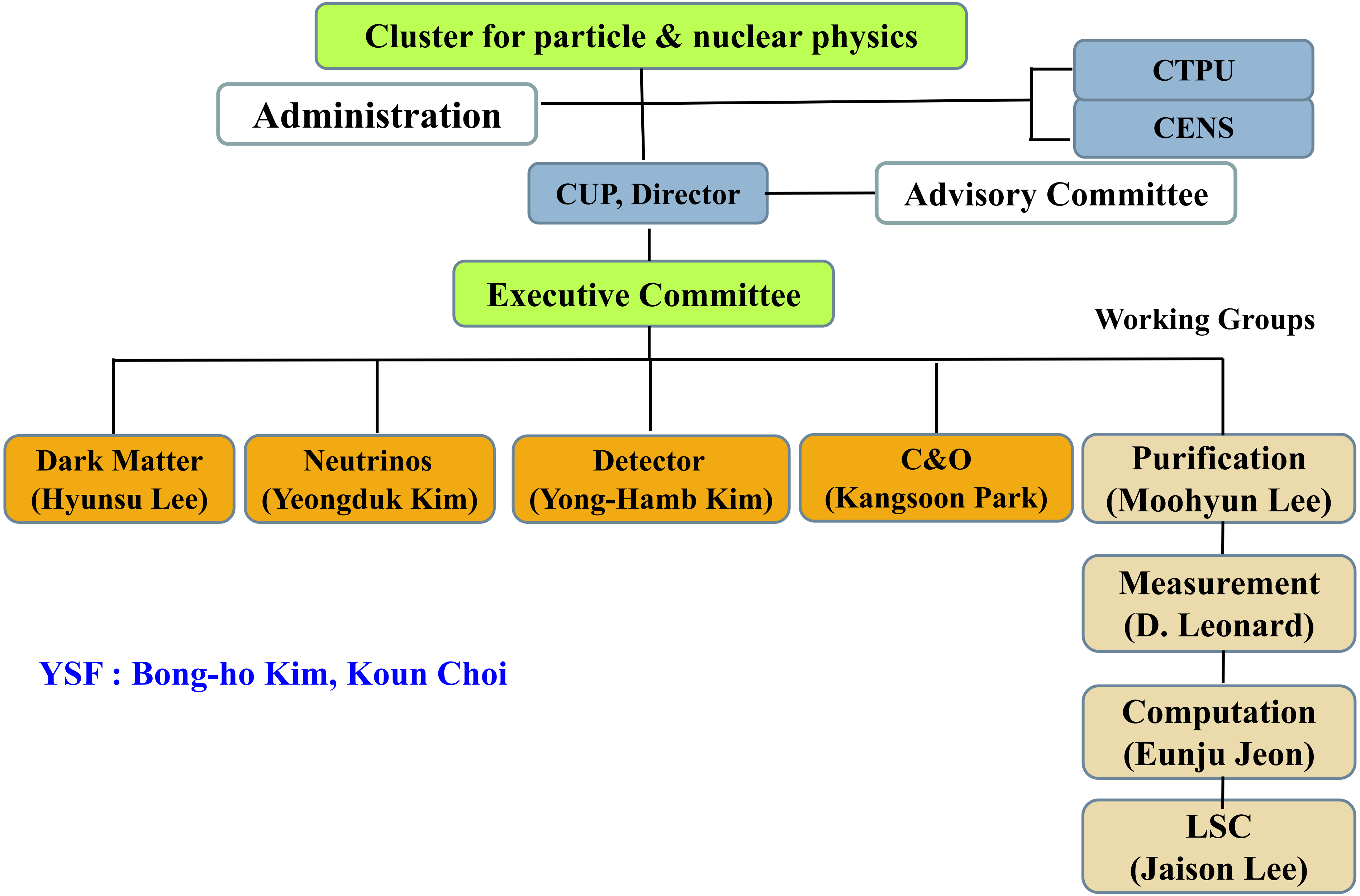
Center for Underground Physics
Institute for Basic Science

2024. 1. 17.

Yeosu, Workshop on Dark Universe, Yonsei University

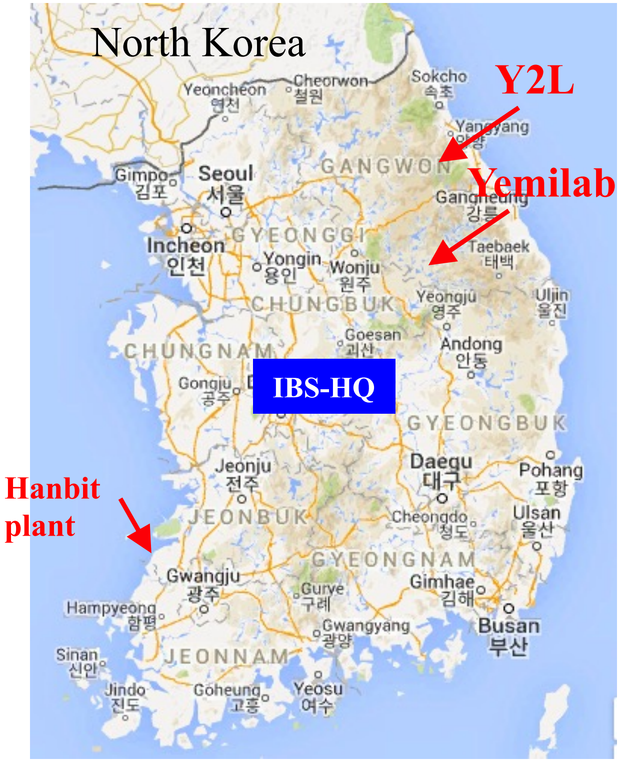
Organization of CUP



YSF : Bong-ho Kim, Koun Choi

Yemilab, a new underground laboratory

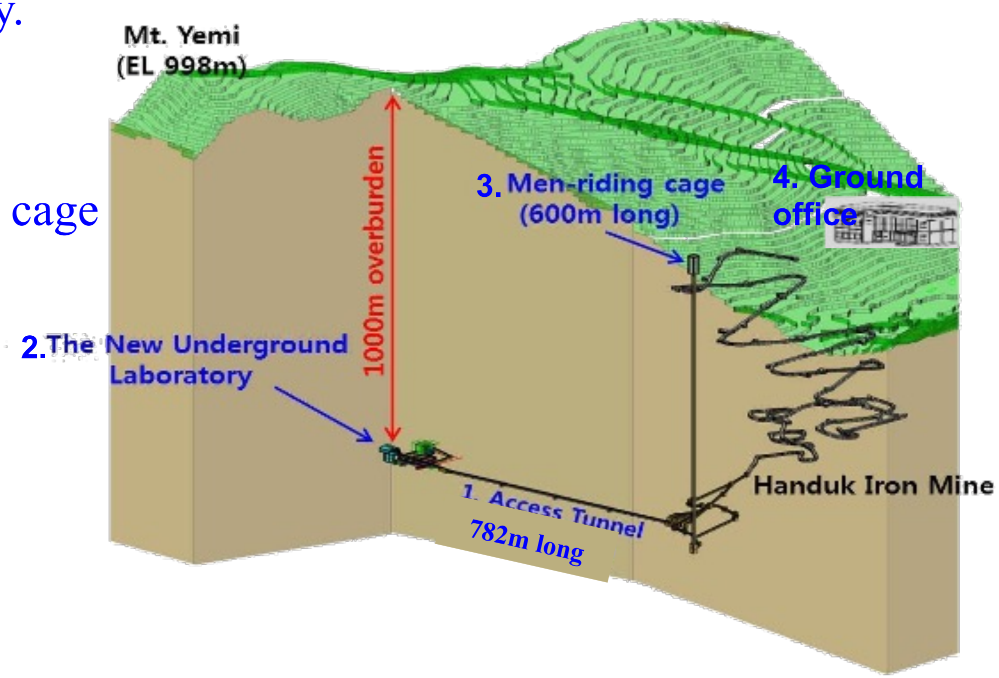
- Y2L was constructed in 2003 to house KIMS dark matter search experiment. (700m deep)
- Yemilab is constructed in 2022. (1000m deep)



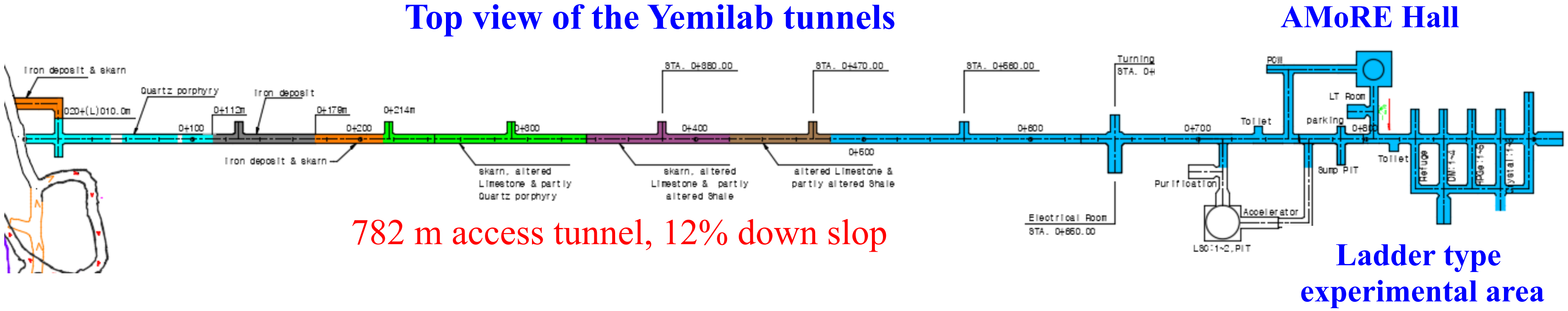
- Lab space > 3000 m^2 , 2.5 MW electricity.
- Rn-free air supplying system,
- Class 100 clean room.
- Two access ways: ramp-way, men-riding cage
- Open to other researchers IBS.

Yemi (禮美)

Etiquette, Beauty



Top view of the Yemilab tunnels

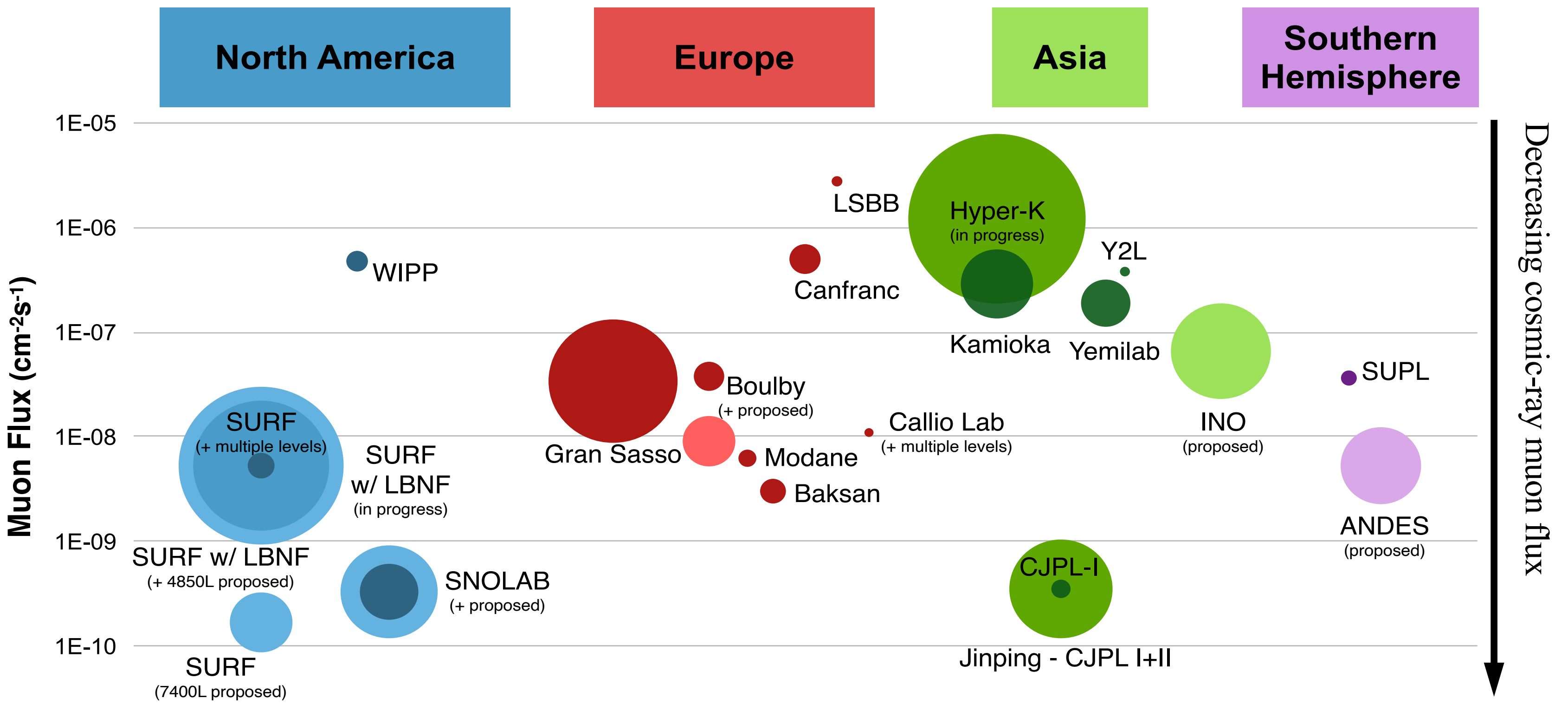


782 m access tunnel, 12% down slop

Underground Research Facility

Worldwide Underground Facilities

From Jaret Heise's plot

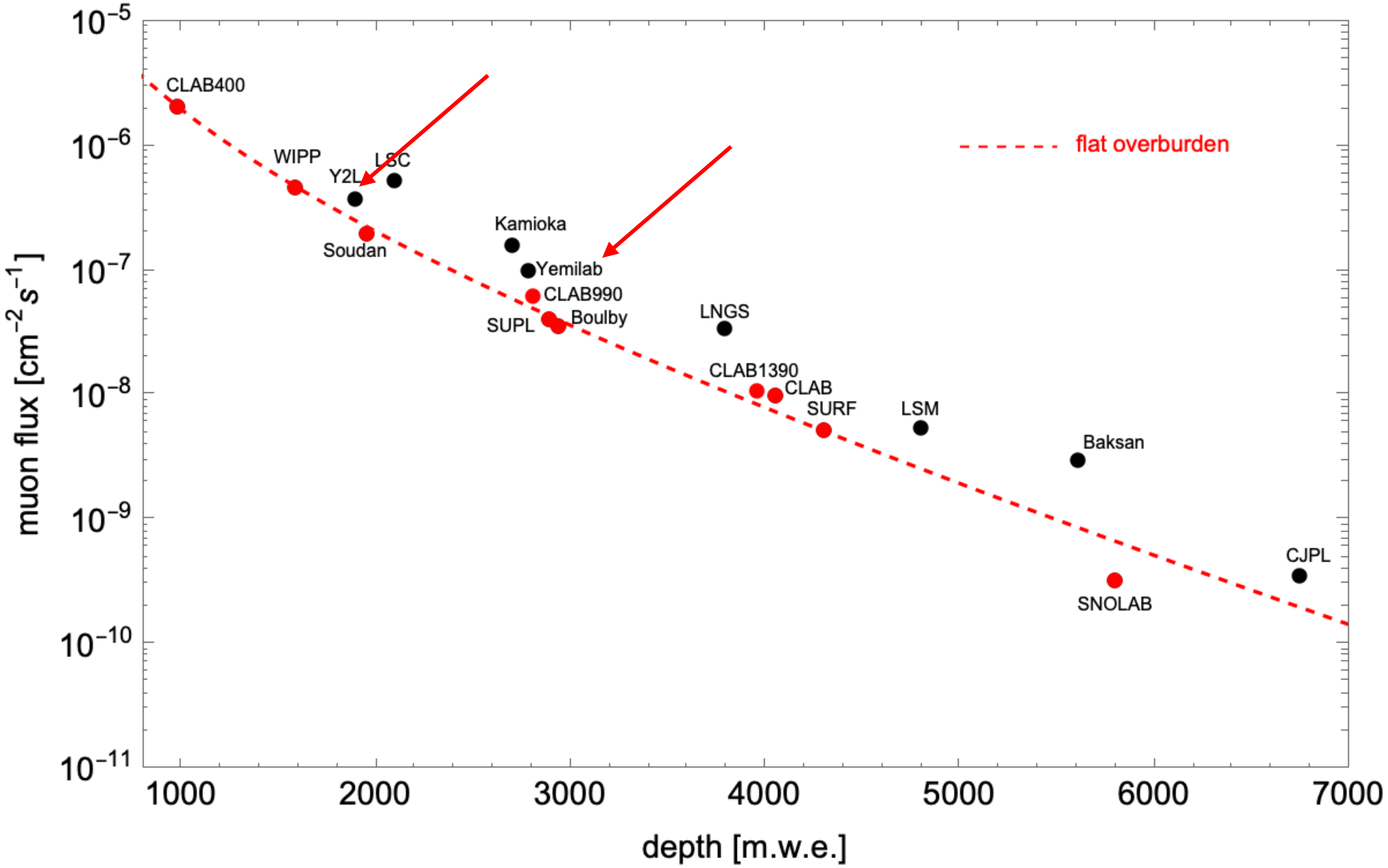


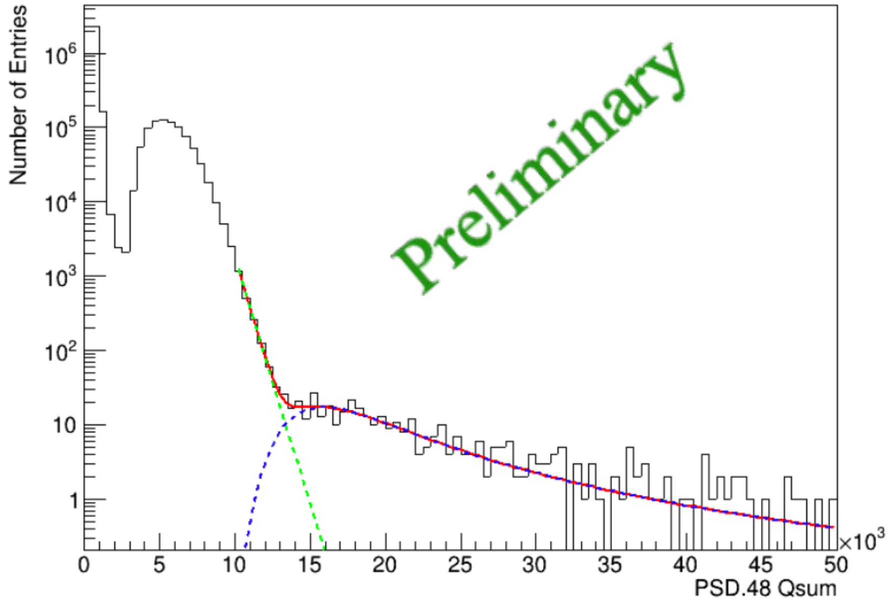
Note: Circles represent volume of science space

- For last years, 5 new underground laboratories are completed or under construction in Asia.
- CJPL-II, HK, JUNO, Yemilab, SUPL

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





What’s updated on Yemilab in 2023.

Most of facilities are done

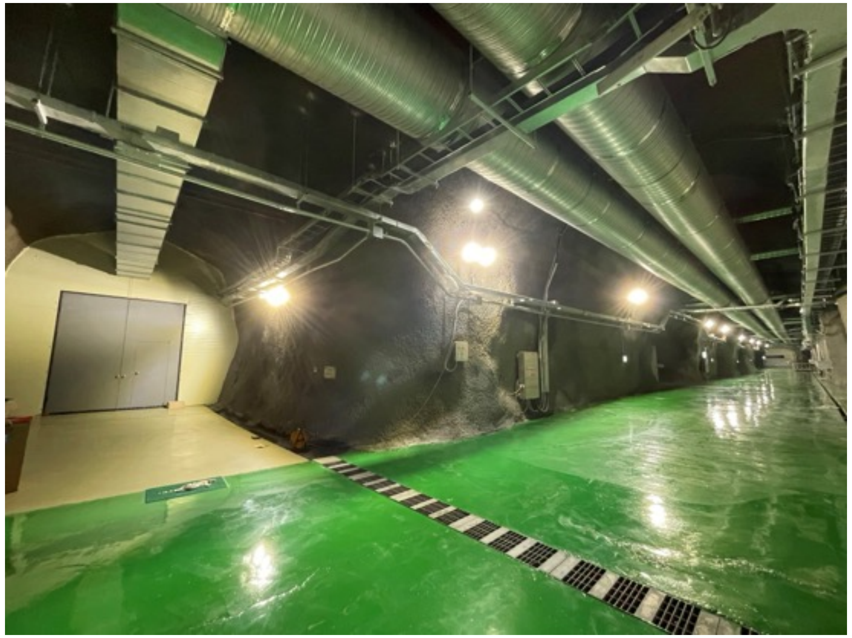
- Electricity : power cable line completed for 2,500kW
- Dust-proof doors, painting expr. wall, epoxying floor etc…
- Rn-less air supply system to reduce underground Rn level less than 150Bq/m^3

AMoRE-II preparation

- Moving Dilution Refrigerator from Deajeon(HQ)
- Commissioning starts late 2024

Y2L move to Yemilab (2023 ~ early 2025)

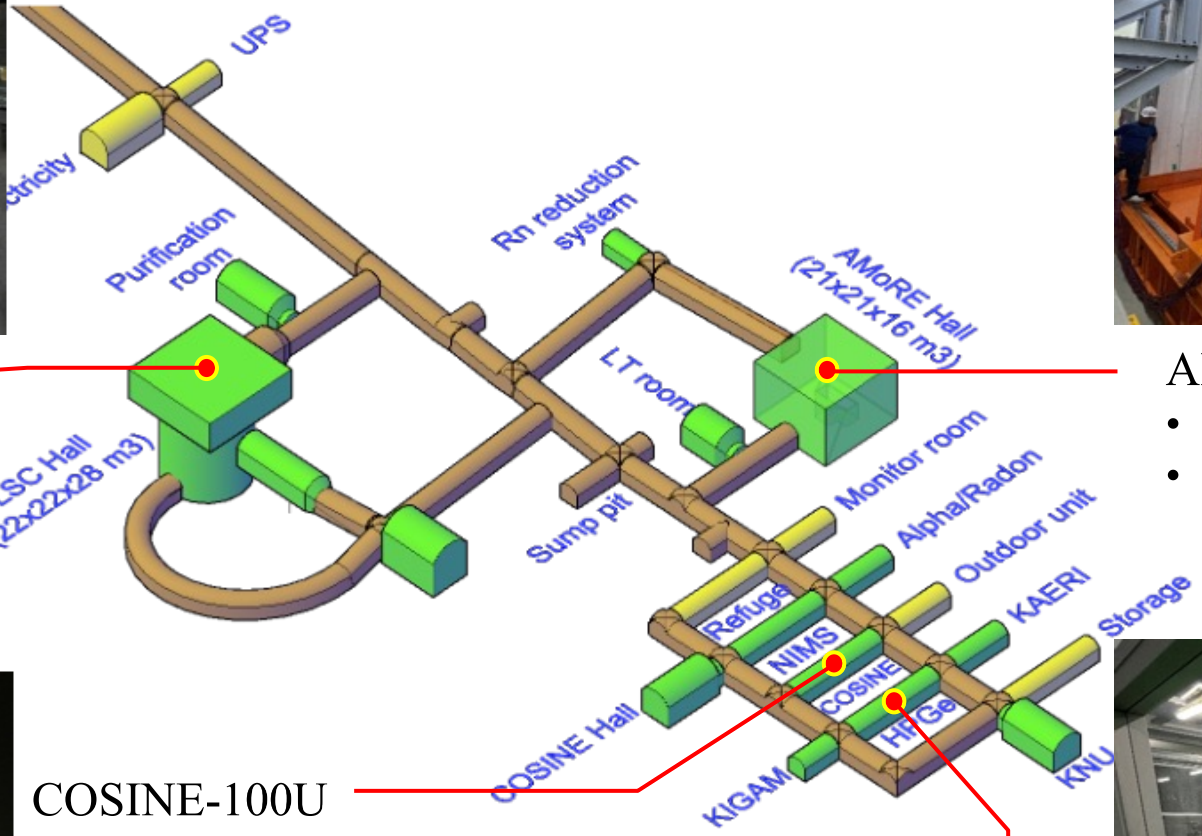
- COSINE-100U
- AMoRE-1
- HPGes’
- And so on…



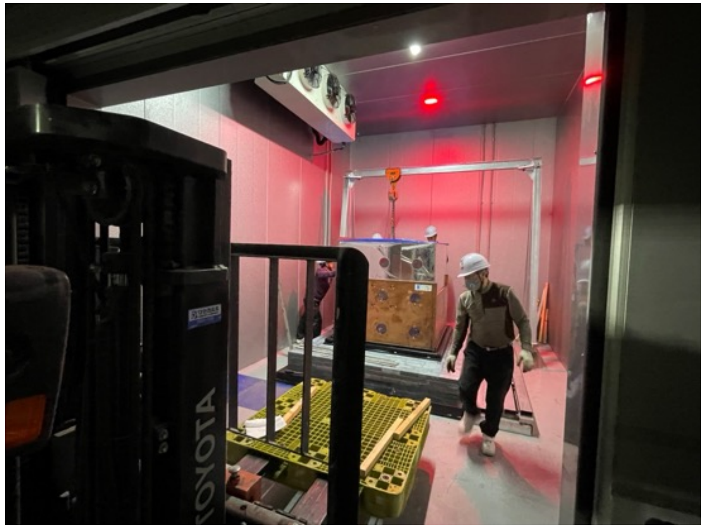
Rn-less air supply system

Experimental area of Yemilab

LSC Hall 10-ton crane
- Completion June 2023



AMoRE-II
- Shield structure done
- Late 2024, commissioning



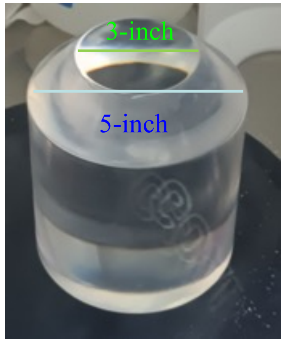
COSINE-100U
- -30℃ low-temp. room
- Moving Y2L detector to the room
- Early 2024, commissioning

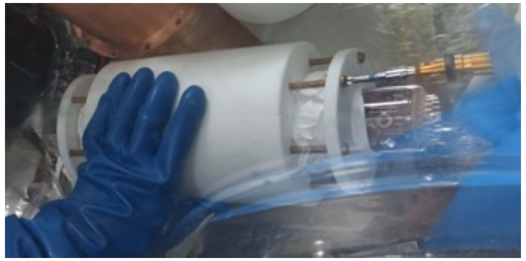
HPGe
- Moving from Y2L
- Feb. 2024, start

COSINE-100U, 200 @ Yemilab

COSINE-100 upgrade for high light yield

Polishing





Direct attachment of 3” PMT

NIMA 981 (2020) 164556

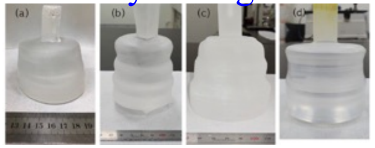
COSINE-100U

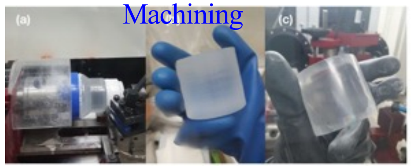
21.6 +/- 0.6 NPE/keV

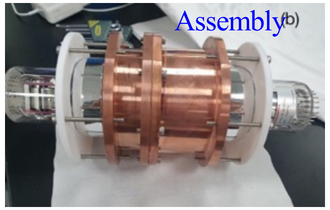
- Moving from Yangyang to Yemilab is ongoing now
- Plan to start COSINE-100U by end of 2023

COSINE-200 with new crystals.

Crystal ingots

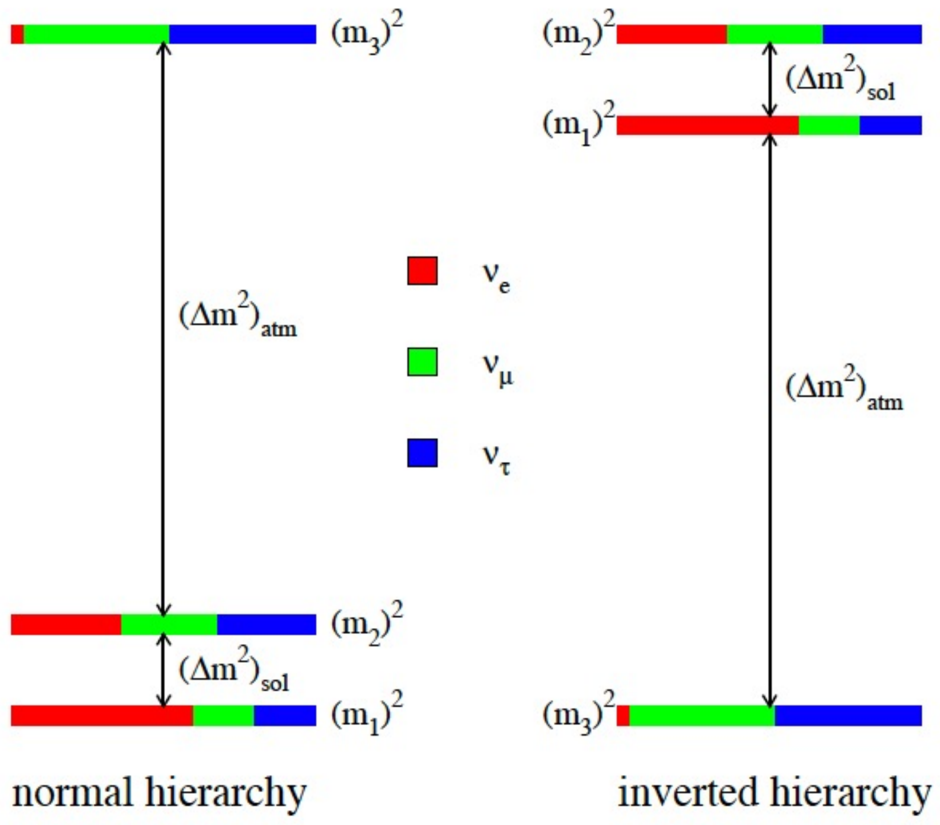






Missing Oscillation Parameters: Are We There Yet? (NO!)

Gouvea TAUP 2023



- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

Neutrino mass

http://www.nu-fit.org

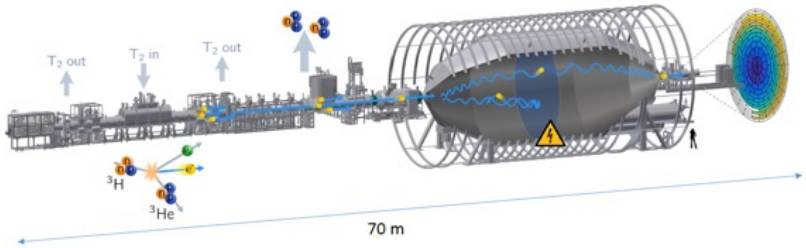
Cosmology can set the total mass of neutrinos from neutrino dark matter fraction.

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93.14\, h^2\ \mathrm{eV}}$$

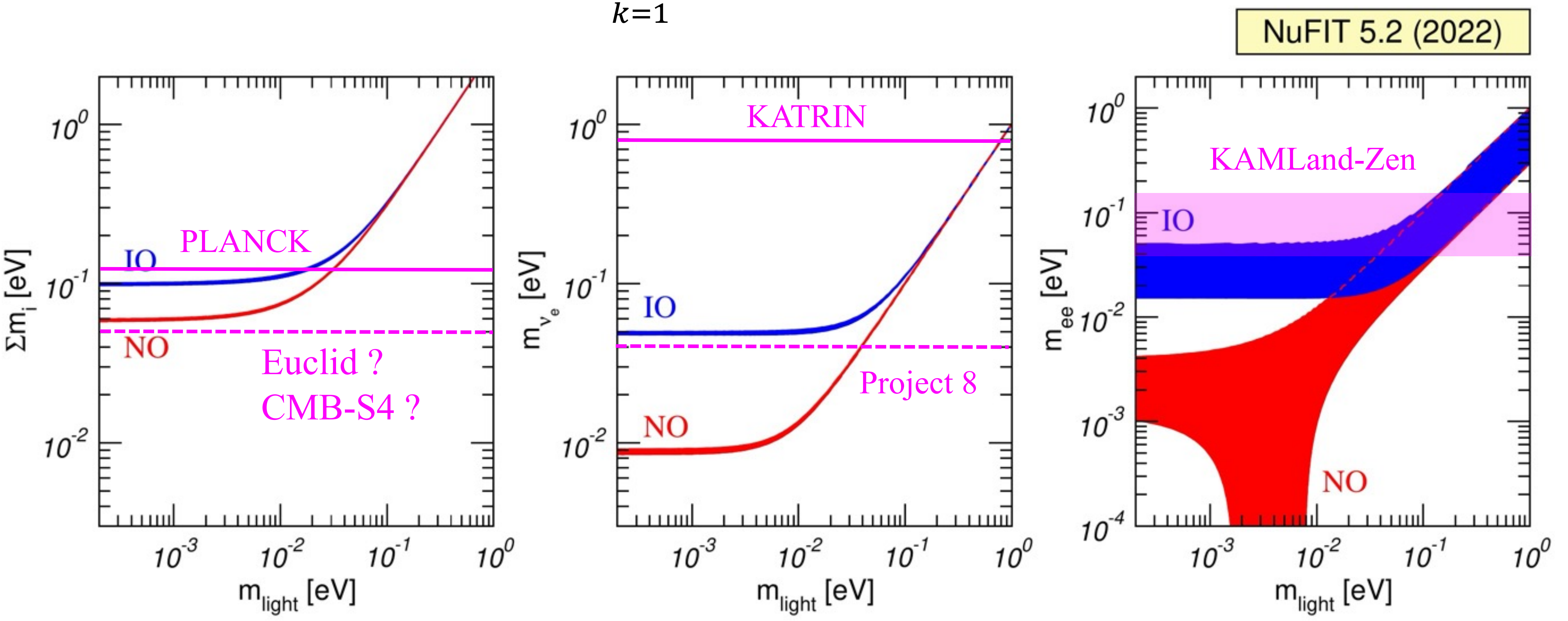
- Beta decay end point.
- KATRIN will finally reach 0.3 eV
- PROJECT8 down to 40 meV

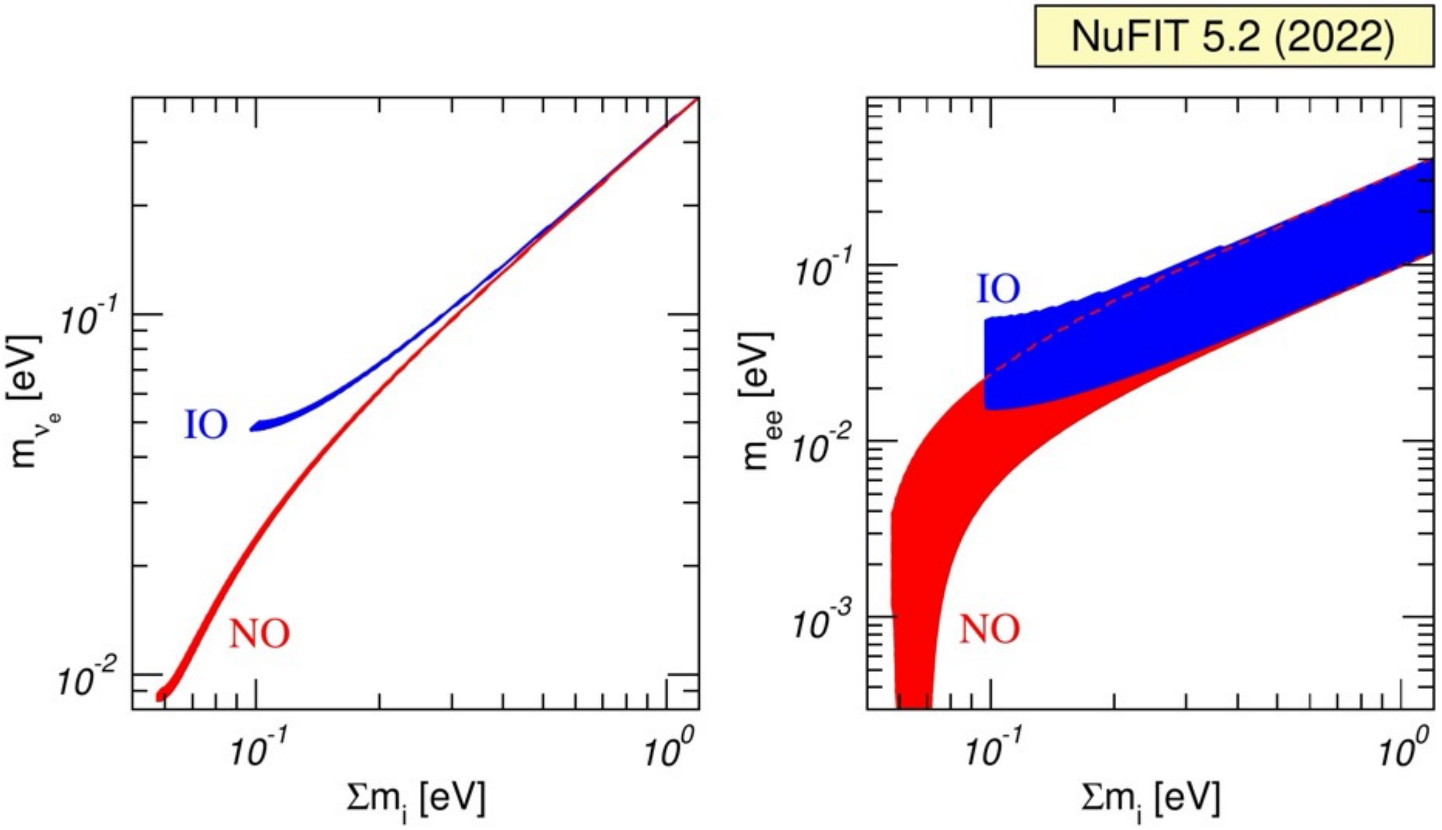
$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

KATRIN



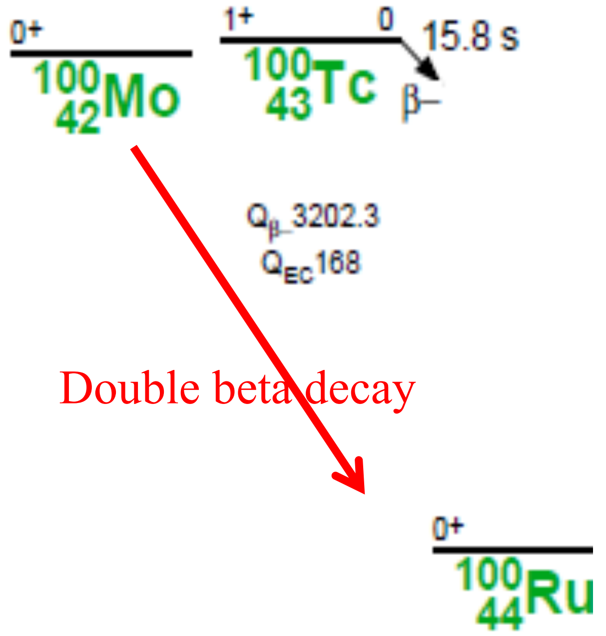
Euclid



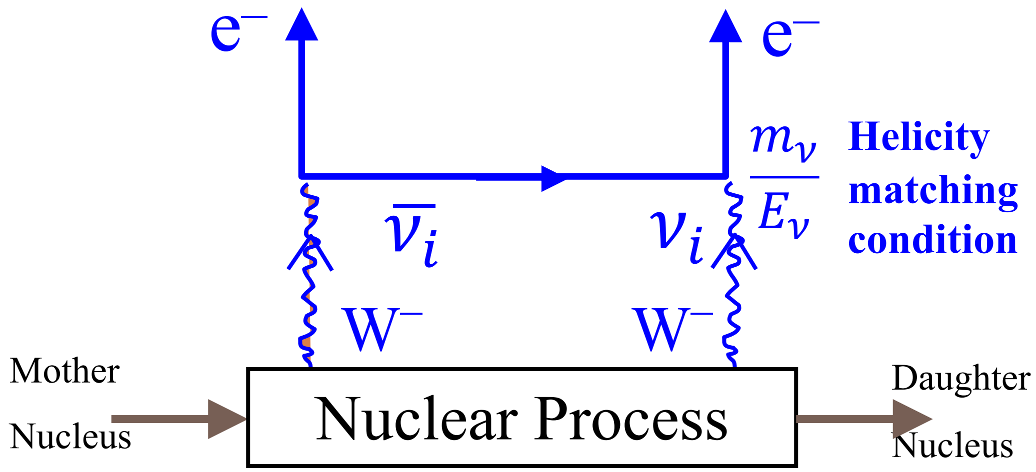

NuFIT 5.2 (2022)
m_{ν_e} [eV]
10^{-1}
10^{-2}
IO
NO
10^{-1}
10^{0}
Σm_i [eV]
m_{ee} [eV]
10^{-1}
10^{-2}
10^{-3}
IO
NO
10^{-1}
10^{0}
Σm_i [eV]

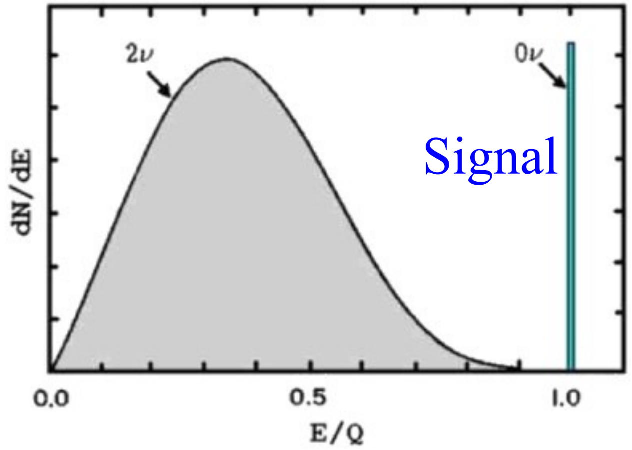
Neutrinoless Double Beta Decay($0\nu\beta\beta$) Search

Why are the neutrino mass so small compared to other fermions ?
- Neutrinos may be Majorana particles and by seesaw mechanism.



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.

Decay rate of 0νββ

With various Lepton # violation mechanism, $0\nu\beta\beta$ half – life can be written generally ;

$$[T^{0\nu}_{1/2}]^{-1} = \sum_i G_i g_i^4 |M_i|^2 f_i(\Lambda) + interferences.$$

where $f_i(\Lambda)$: a dimensionless function encompassing BSM physics

For light neutrino exchange model ;

(1) Phase space

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

(2) Nuclear Matrix Element

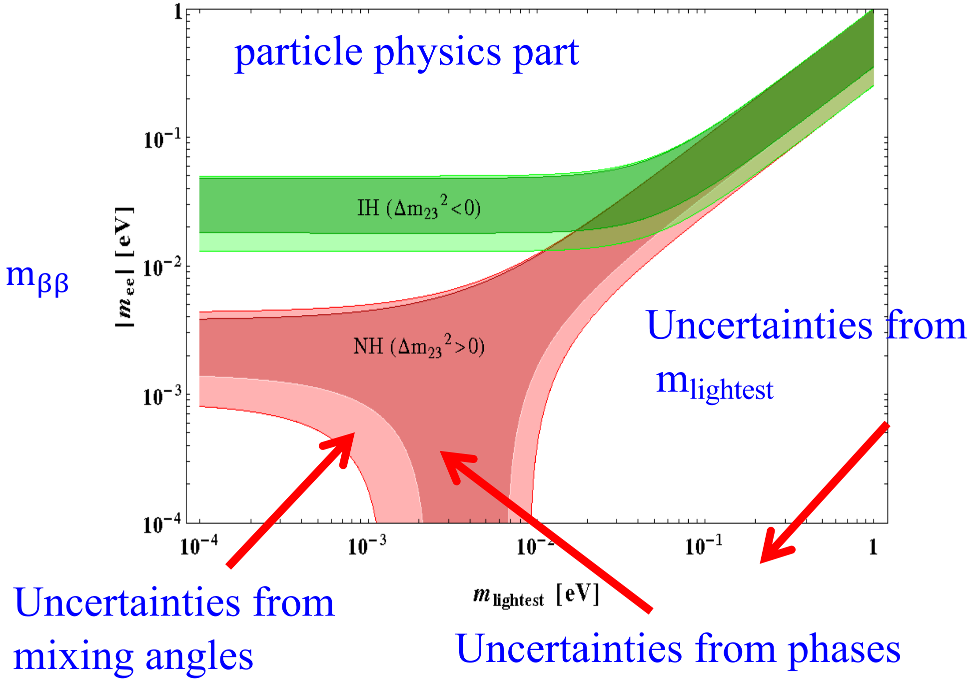
$g_A^4[M^{0\nu}]^2$

g_A :axial vector coupling constant

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

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| =$$

$$|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3|$$

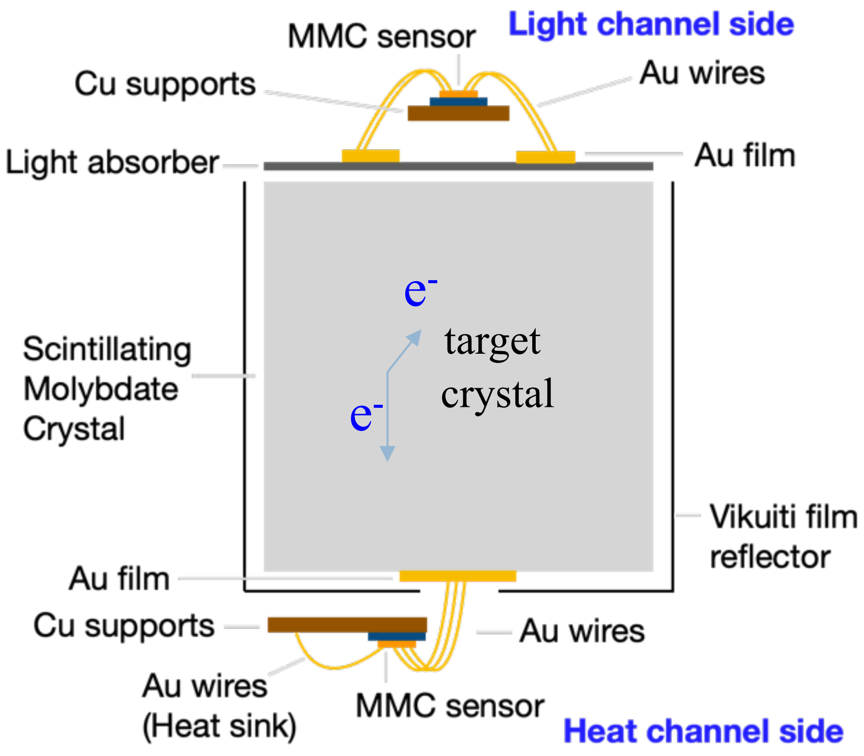


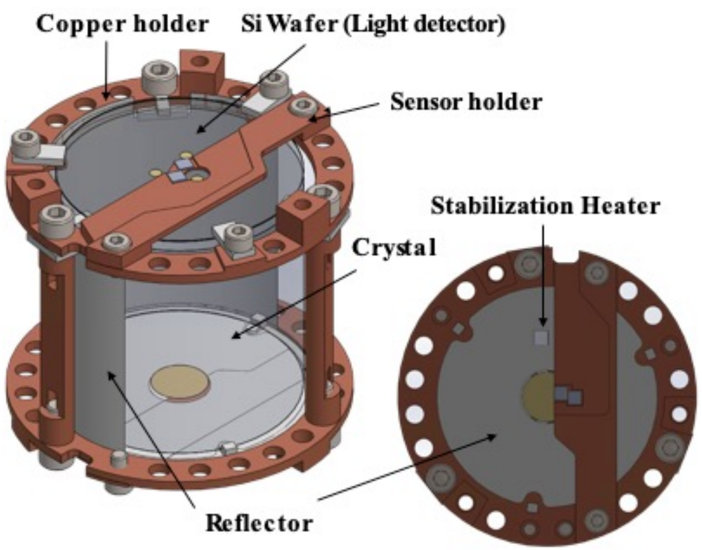
AMoRE Collaboration

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

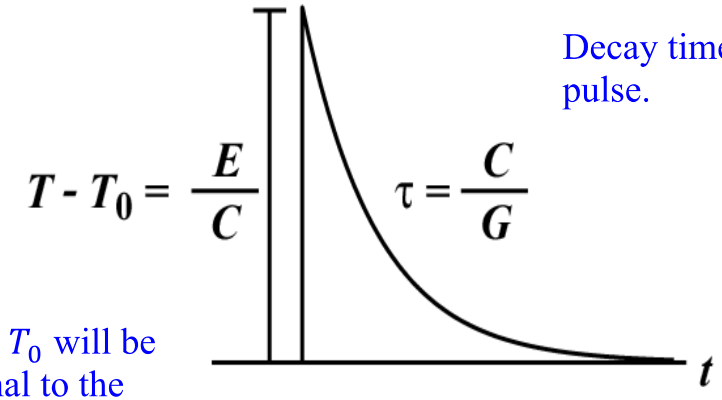
- Lawrence Livermore National Lab. group will join from 2024.

Principle of AMoRE detector



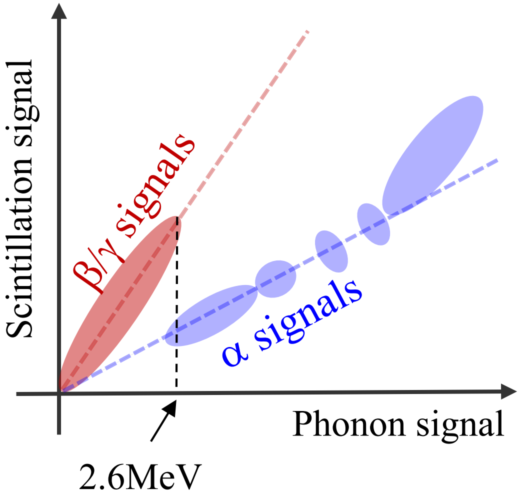


Surface alphas are continuous in energy and can be rejected by scintillation measurement with MMC+SQUID sensors.

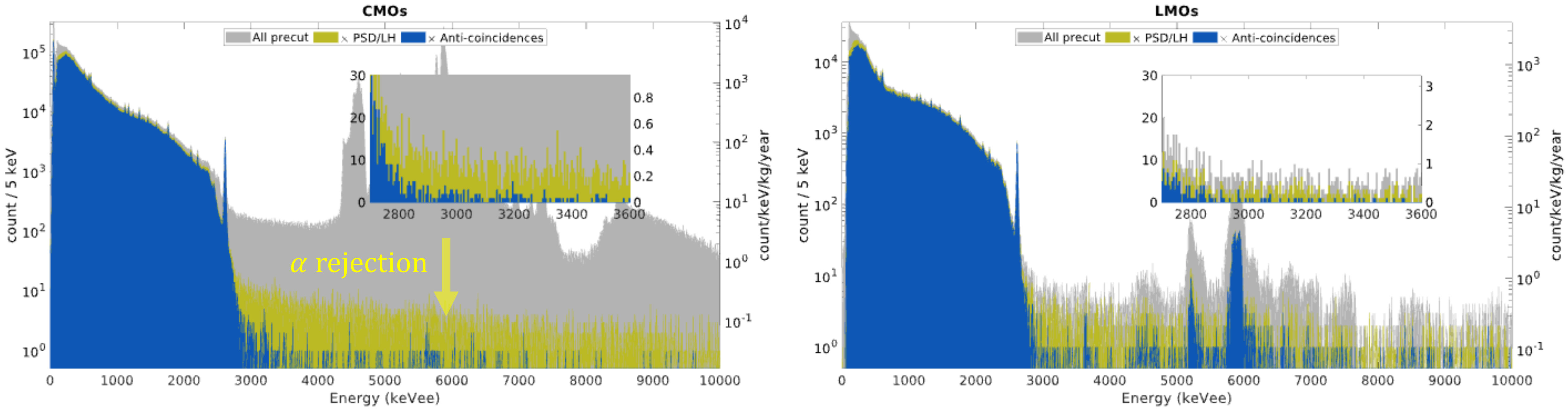


Decay time of each pulse.

$\Delta T = T - T_0$ will be proportional to the energy deposition, E

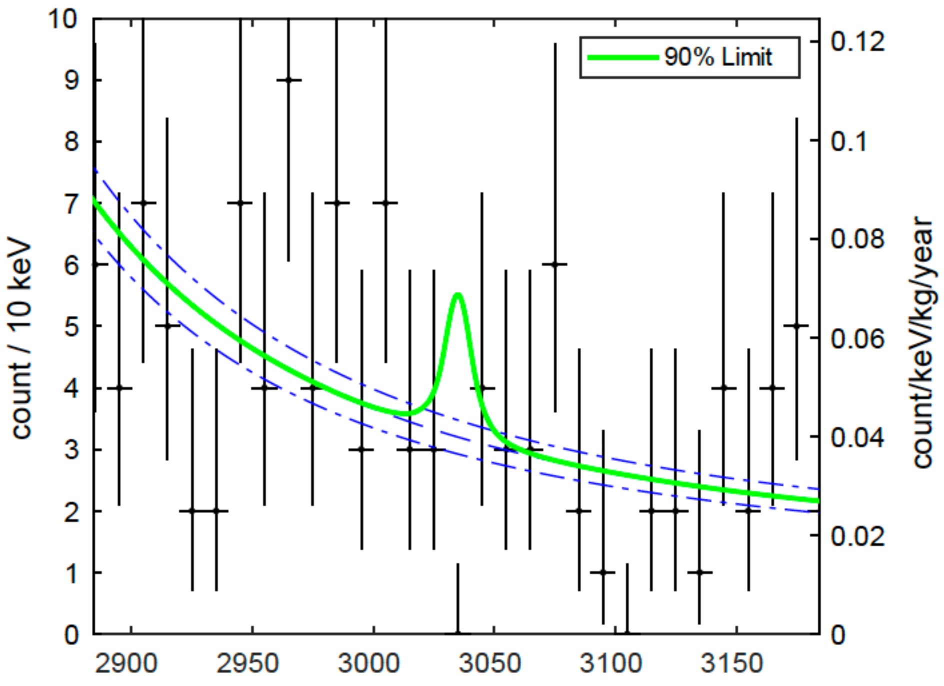


Background spectra after alpha background rejection



- 17 crystals excluding one LMO (for very poor β/α discrimination power)
  - 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 $kg_{Mo\text{-}100}\cdot yr$).

$0\nu\beta\beta$ Half-life results



Background Unit :
ckky counts/keV/kg/year.

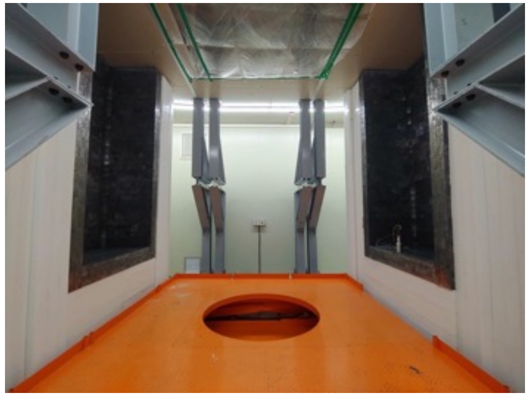
Live exposure	Bkg. @ $Q_{\beta\beta}$ / ckky
Total (8.02 kg_{XMoO_4} yr)	0.032±0.003
CMO (6.19 kg_{XMoO_4} yr)	0.031±0.003
LMO (1.83 kg_{XMoO_4} yr)	0.037±0.006

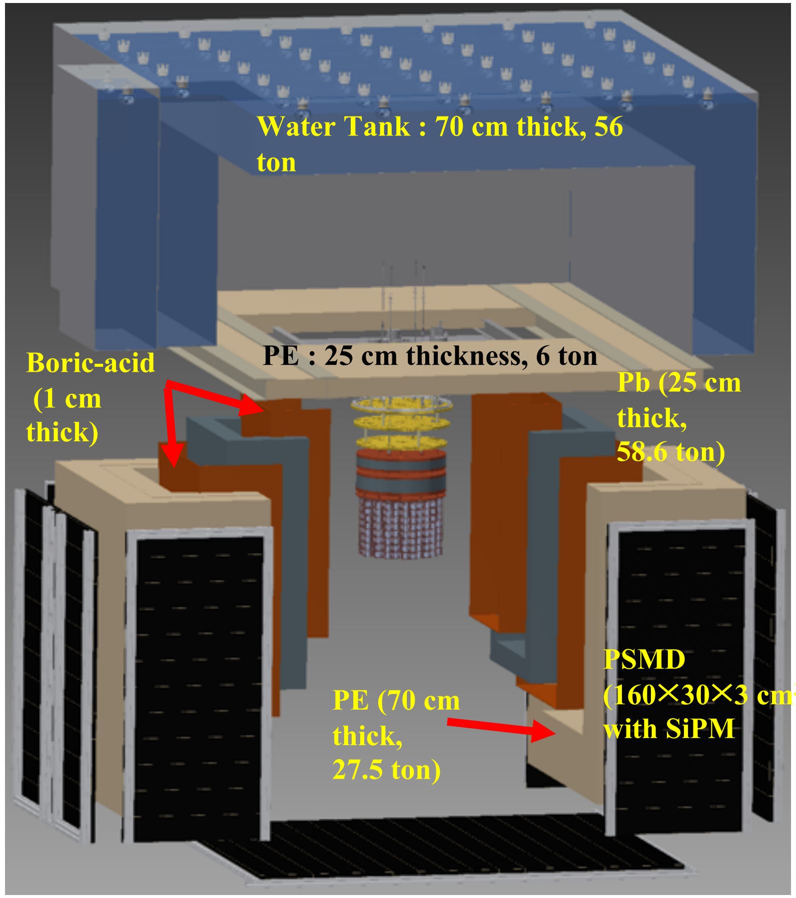
→ $T^{0\nu}_{1/2} > 3.4\times10^{24}$ *years*

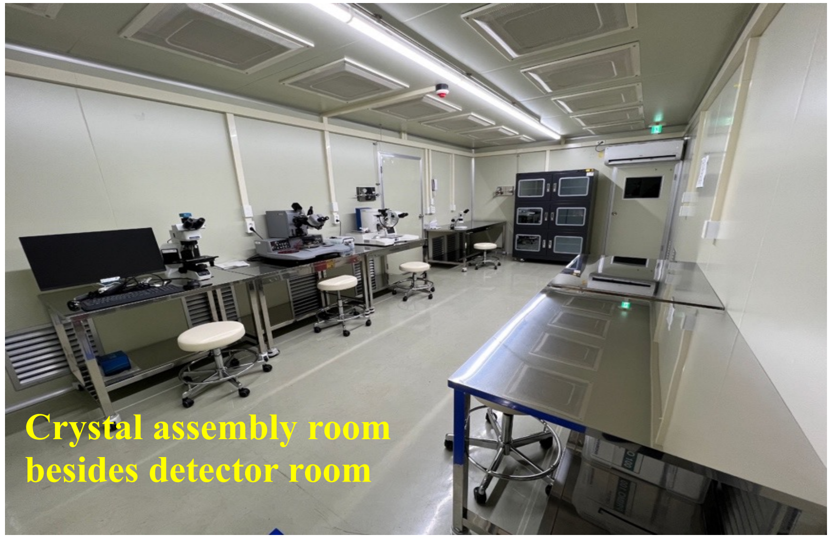
Cf. Current best limit 1.8×10^{24} *years* by CUPID-Mo

- ROI=$|E - Q_{\beta\beta}| < 2.5 * \Delta E_{FWHM}$
- Unbinned likelihood for $\Gamma^{0\nu}$ for each crystal, with background rate constrained from sideband data, respectively.

AMoRE-II installation







Crystals are assembled in copper holder and tower

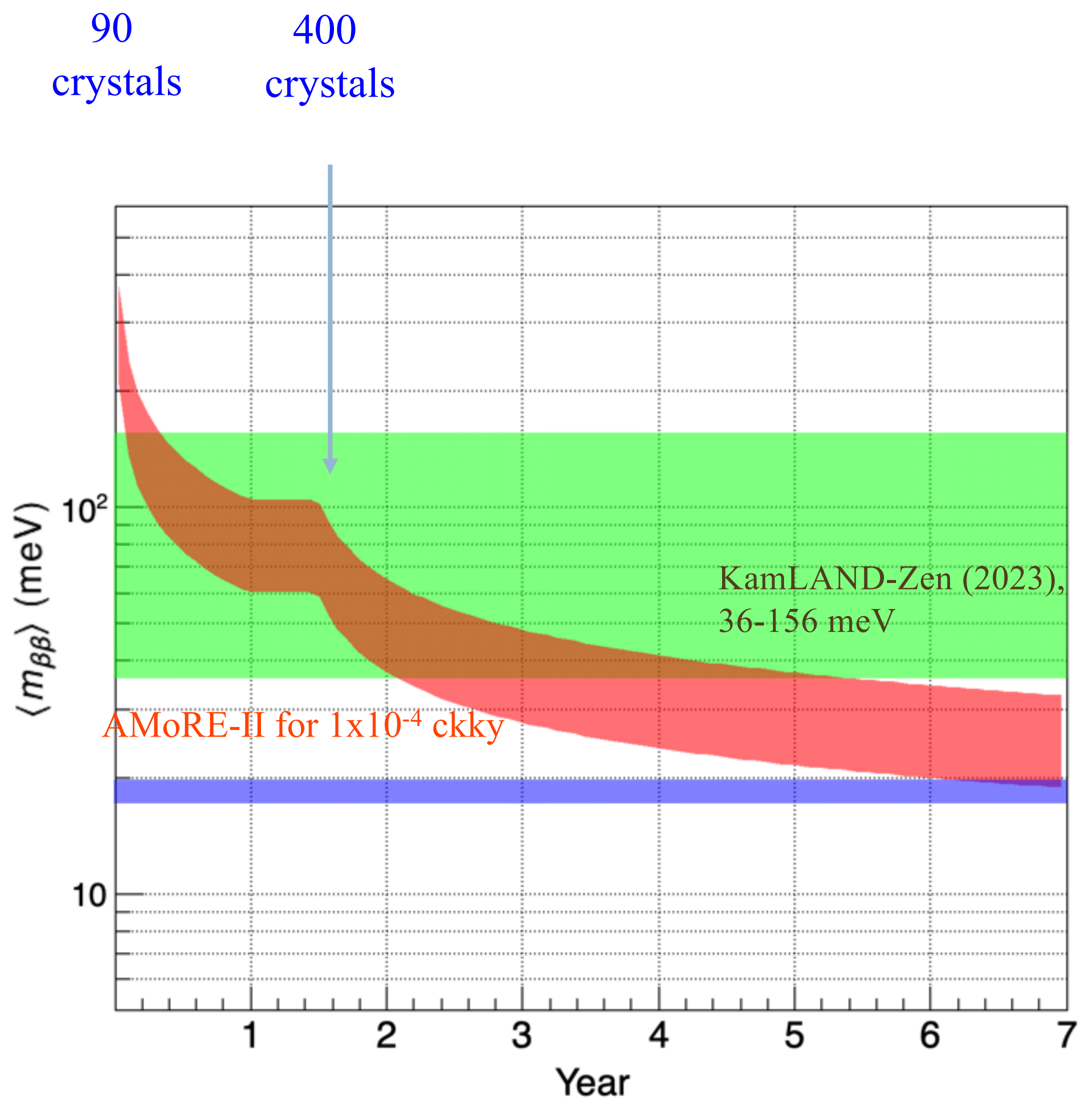
- **Class 100**
- **Humidity<1%**
- **Rn < 200mBq/m^3**

Sensitivity of AMoRE-II

Discovery sensitivity :

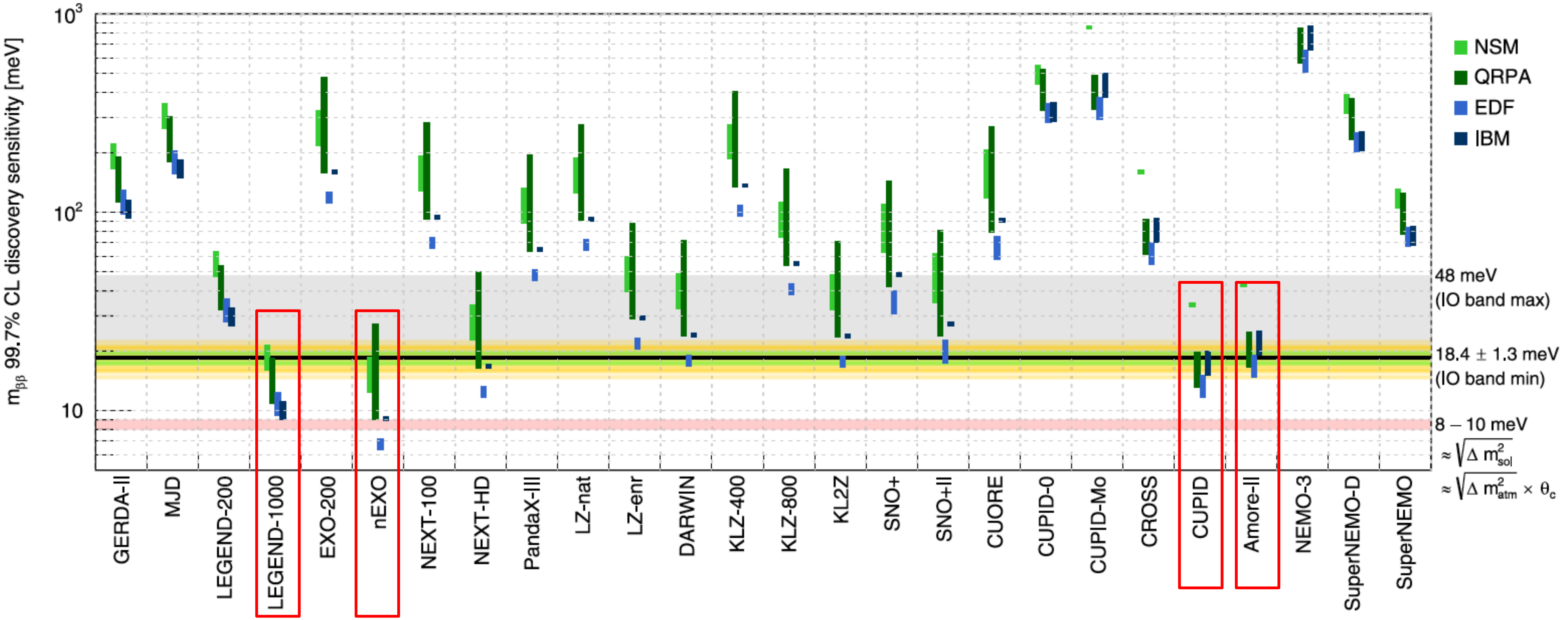
The half-life for which an experiment has a 50% chance to measure a signal above background with a significance of at least 3 sigma (99.7%).

We have grown ~270 crystals. (Dec, ‘23)



Persepectives

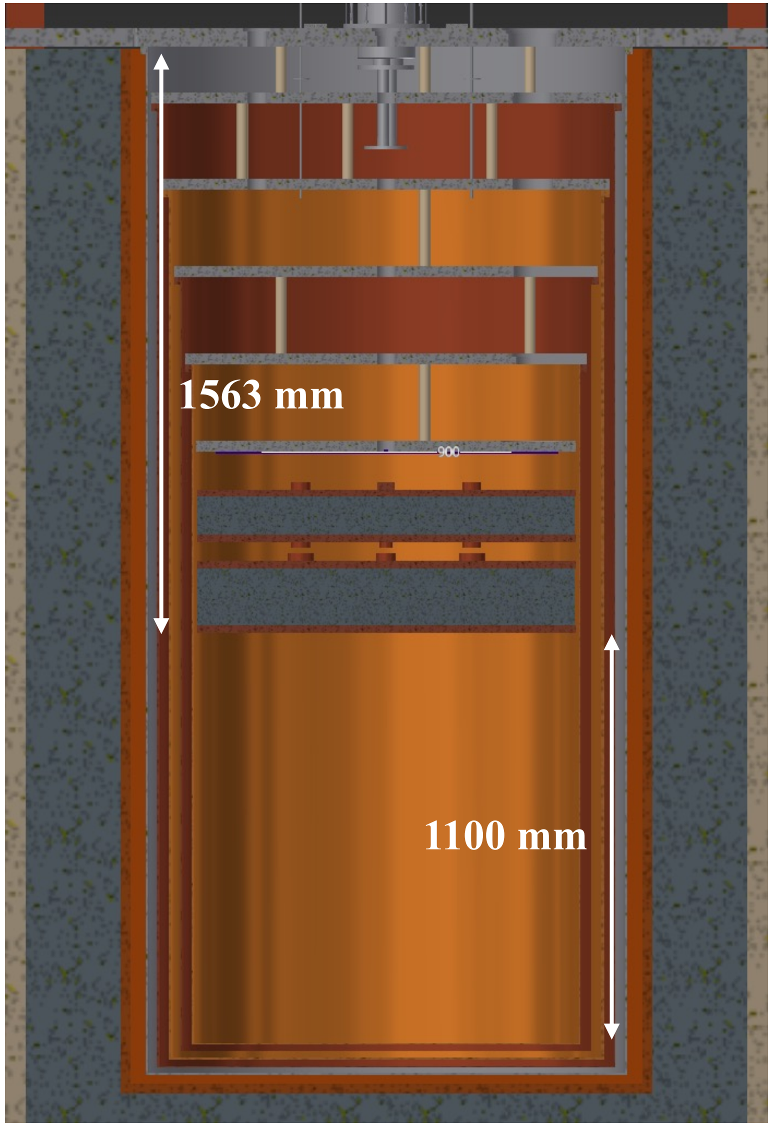
"Toward the discovery of matter creation with neutrinoless ββ decay", Agostini et al., RMP95, 025002 (2023)

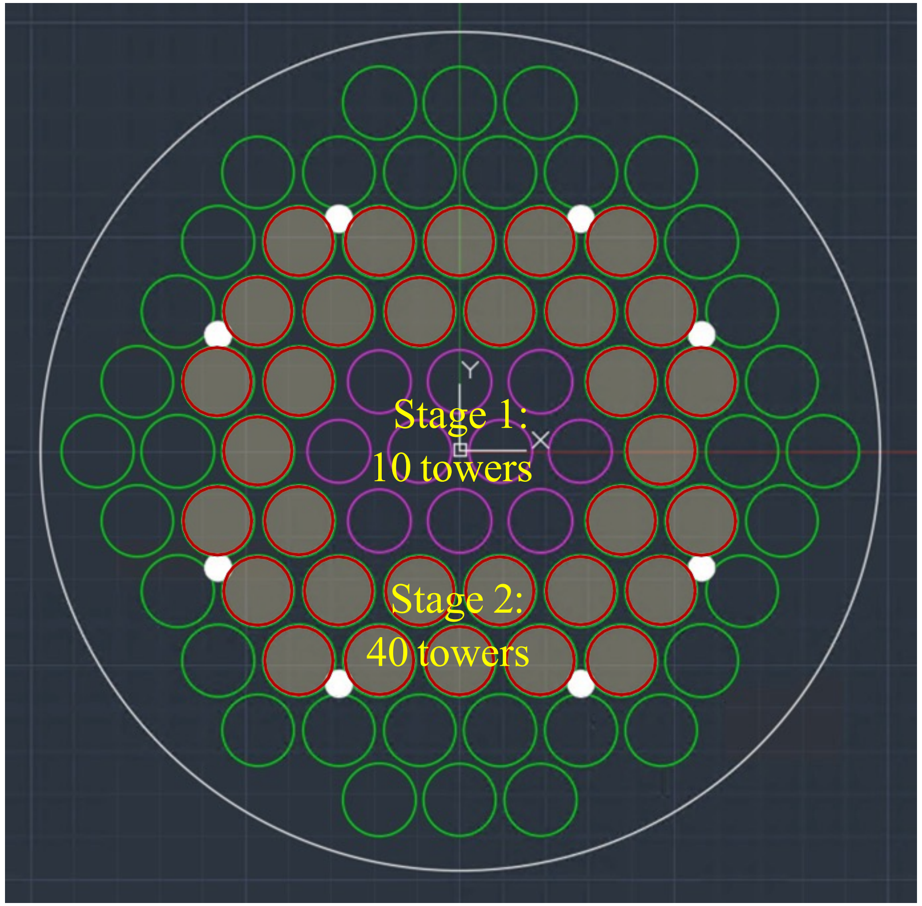


- It will be a real challenge to go below the IO (18.4 meV) mass region.
- Ton scale detector with lower background level.

$$\sqrt{(7.41\times10^{-5}eV^2)} = 8.6\, meV$$

Beyond AMoRE-II



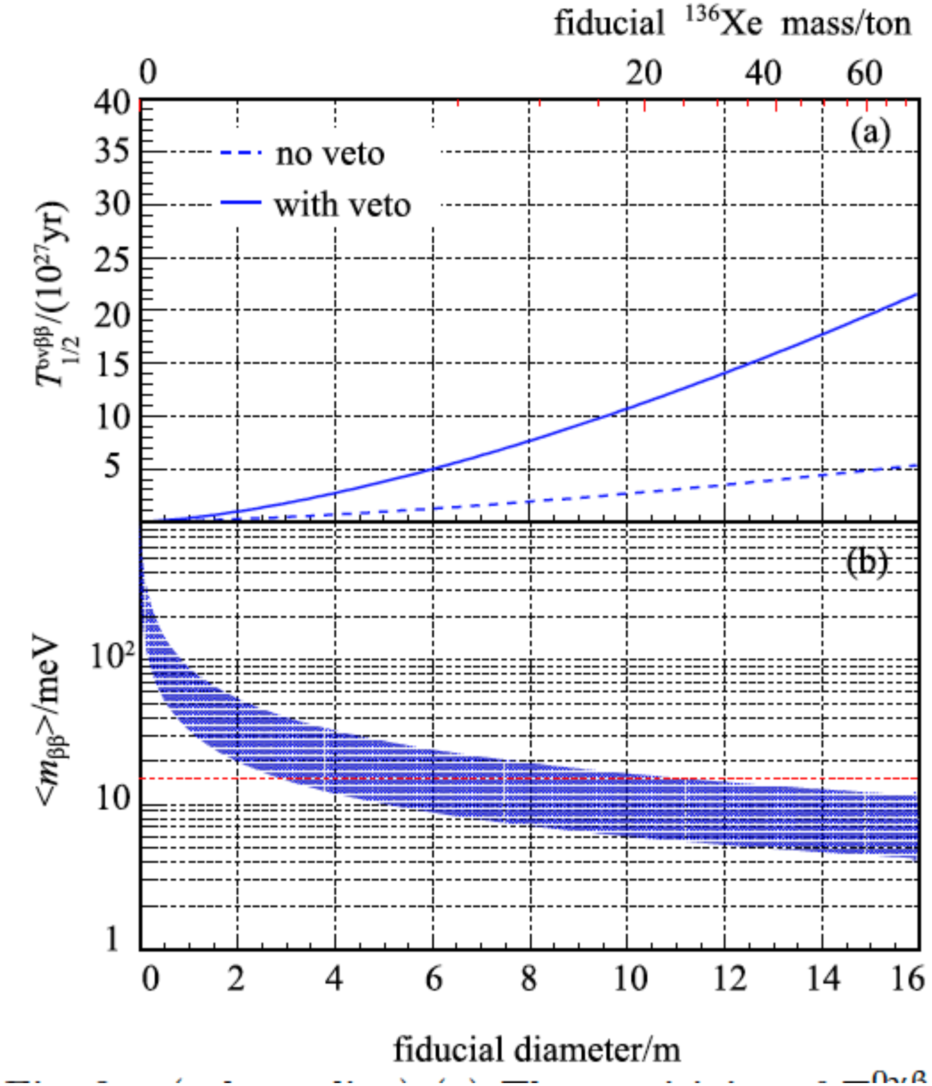


Maximum capacity of current Cryostat:
~ 900 crystals. (~200 kg ^{100}Mo isotopes)

Jump to reach ~ 8 meV

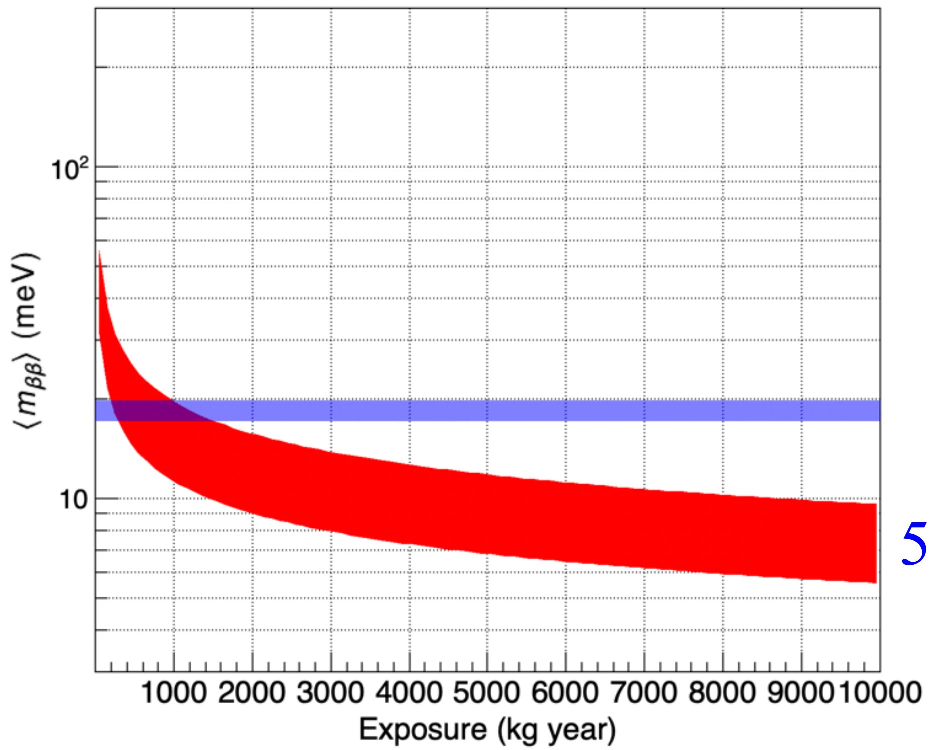
JUNO-Xe, Similar to THEIA-Xe, Theia-Te

5 years run → 300 ton year exposure



5-12 meV

^{100}Mo, Bkg =2x10^{-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

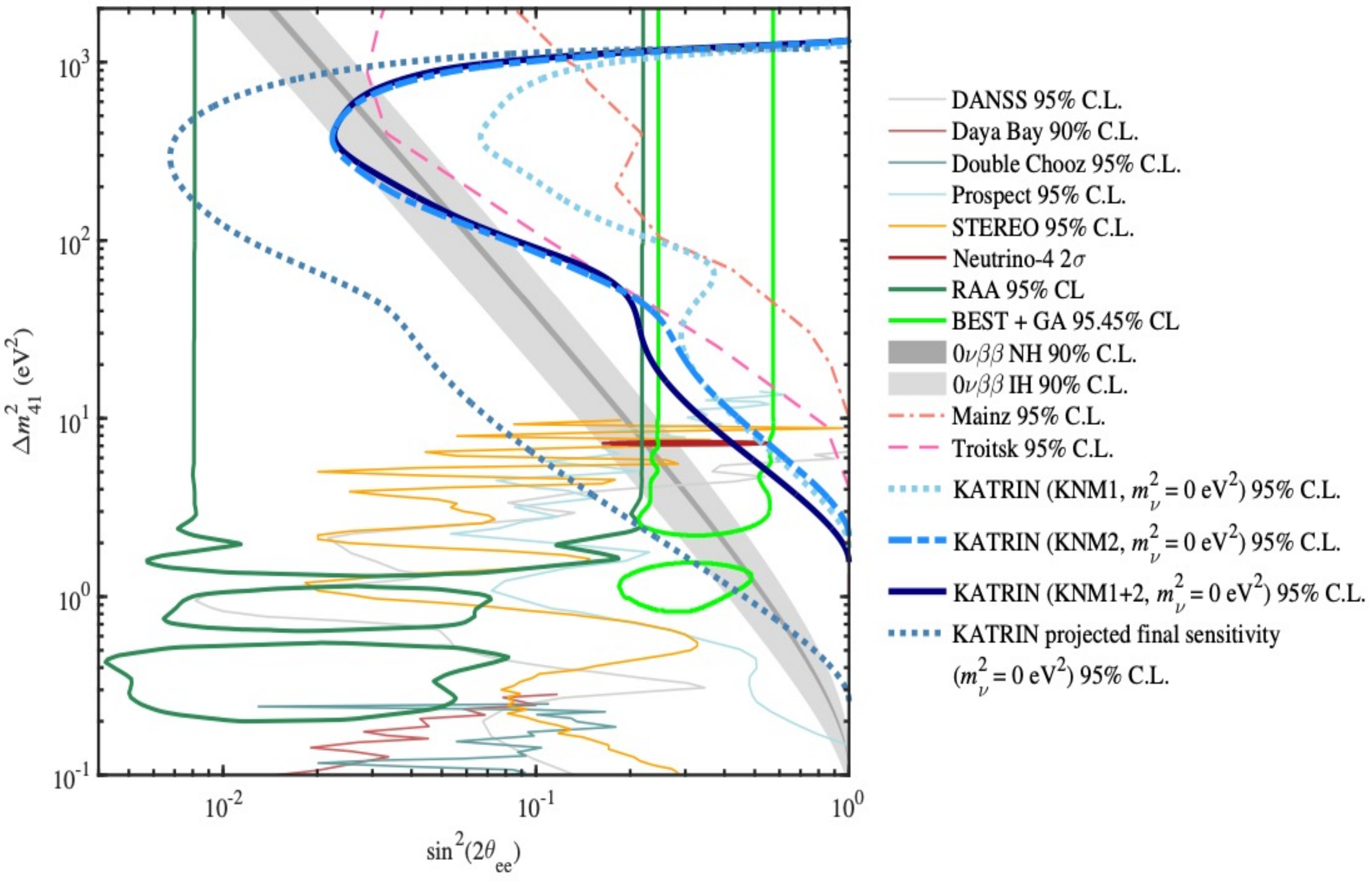
- New particles
  - Bosons : Majoron
  - Fermions : Sterile neutrino
- Violation of fundamental symmetries
  - Lorentz violation
  - Violation of Pauli Exclusion Principle
- Non standard interactions
  - Right-handed current
  - Neutrino self-interaction

- 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.

Sterile neutrino ?

- Sterile neutrinos with a mass different from 3 active neutrinos may exist.
- They should be right-handed neutrinos to be sterile.
- LSND, MINIBOONE, BEST, Neutrino-4 experiments hint light (~ eV) sterile neutrinos with large mixing angle.

- NEOS gave null results.
- RAA is most likely resolved.



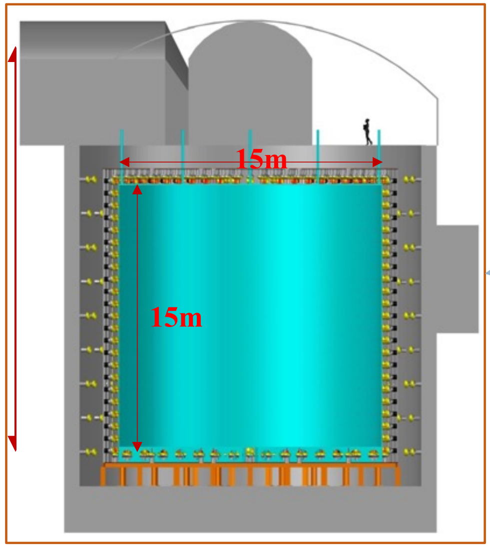
Sterile neutrino searches

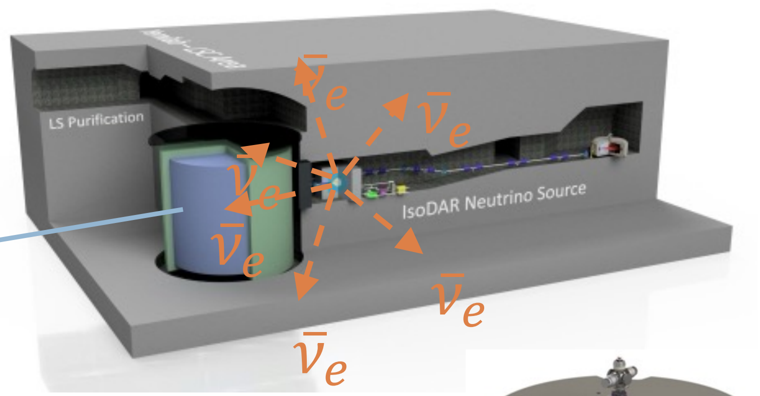
"Neutrino Physics Opportunities with the IsoDAR Source at Yemilab", PRD 105, 052009 (2022)

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

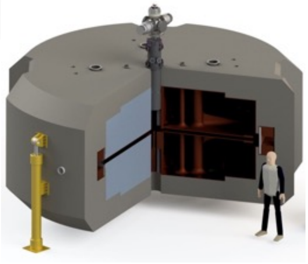
- IBD $\bar{\nu}_e p \rightarrow e^+ n$, short baseline oscillation is searched.
- Assume : $\sigma(E) \sim 6.4\,\%/\sqrt{E(MeV)}$, $\sigma(vertex) = 12cm/\sqrt{E(MeV)}$: reasonable

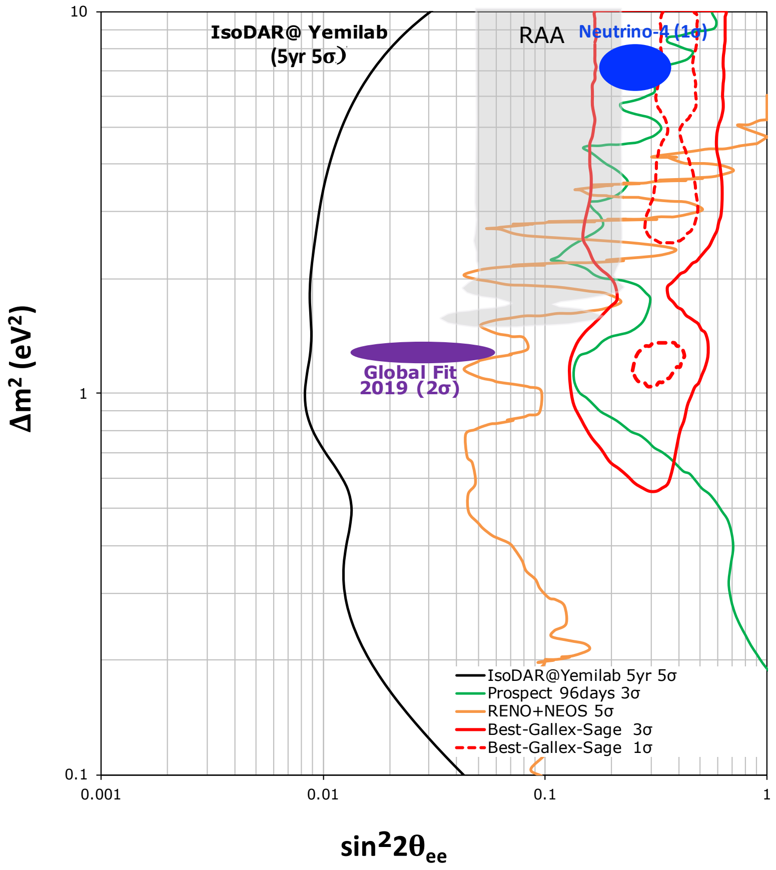
IsoDAR(isotope decay at rest) uses ^{8}Li Isotope Decay-at-rest





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



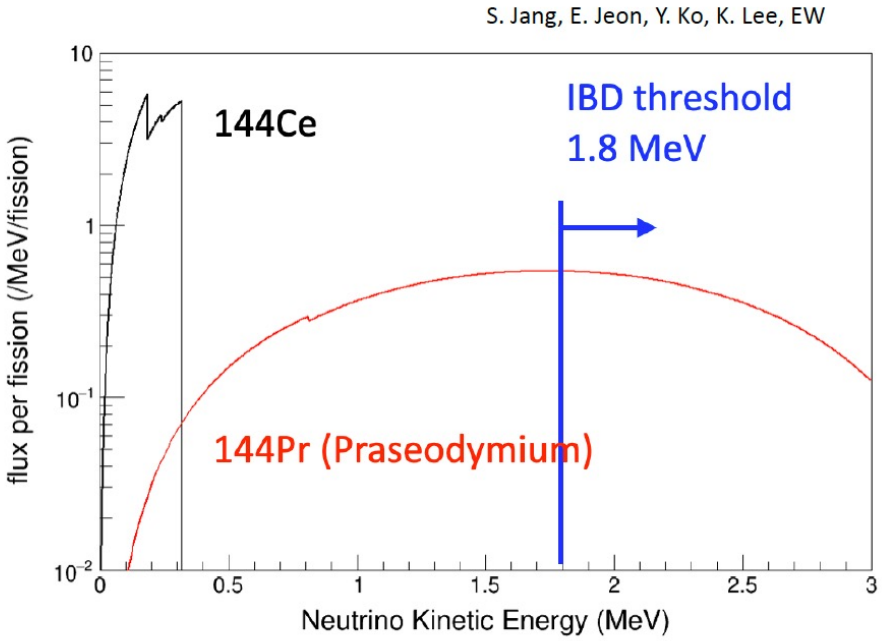


For each event, we measure the energy (E) and vertex(L) of neutrinos. → L/E

E. Won (Korea University) presentation at Y2L workshop

Sterile Neutrino Search @ Yemilab

- 2 ktons of LS.
- 144Ce with the activity of 100 kCi is assumed. ($\overline{\nu}_e$ source):
  - One year data taking, 70% efficiency assumed.
- Detection: Inverse beta decay ($\overline{\nu}_e + p \rightarrow e^+ + n$).
- We look at 3+1 model.



Expected sensitivity (likelihood):

$$\mathscr{L}(\Theta\,|\,\mathbf{n}) = \Pi_{i=1}^{N} \frac{m_i^{n_i} e^{-m_i}}{n_i!}$$

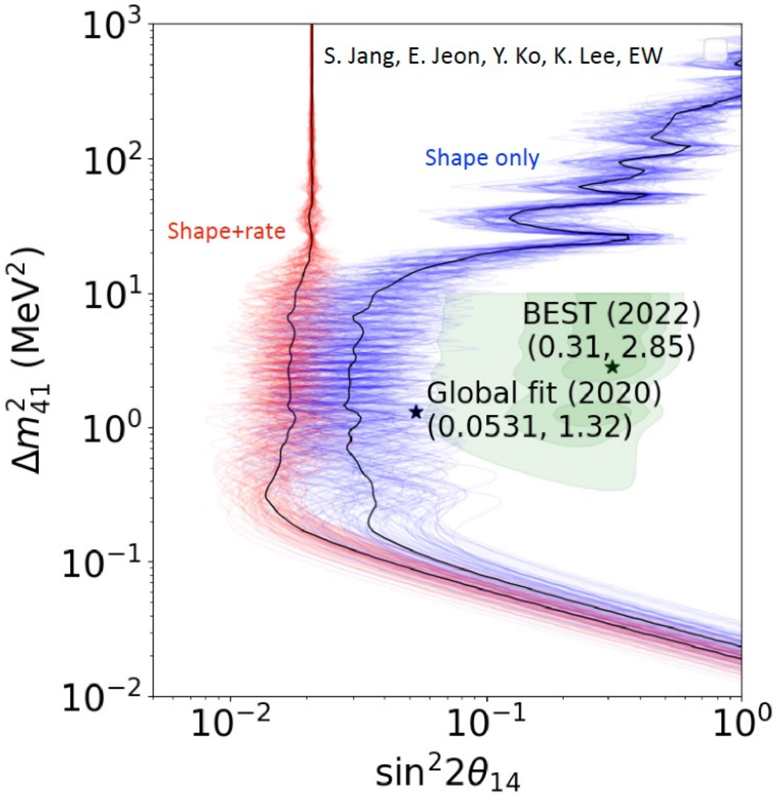
Θ : parameters in the model.

$\mathbf{n}$: binned data (here binning in distance/energy, or L/E).

N : number of bins.

m_i : expected number of events from the model in i-th bin.

n_i : observed number of events in the i-th bin.

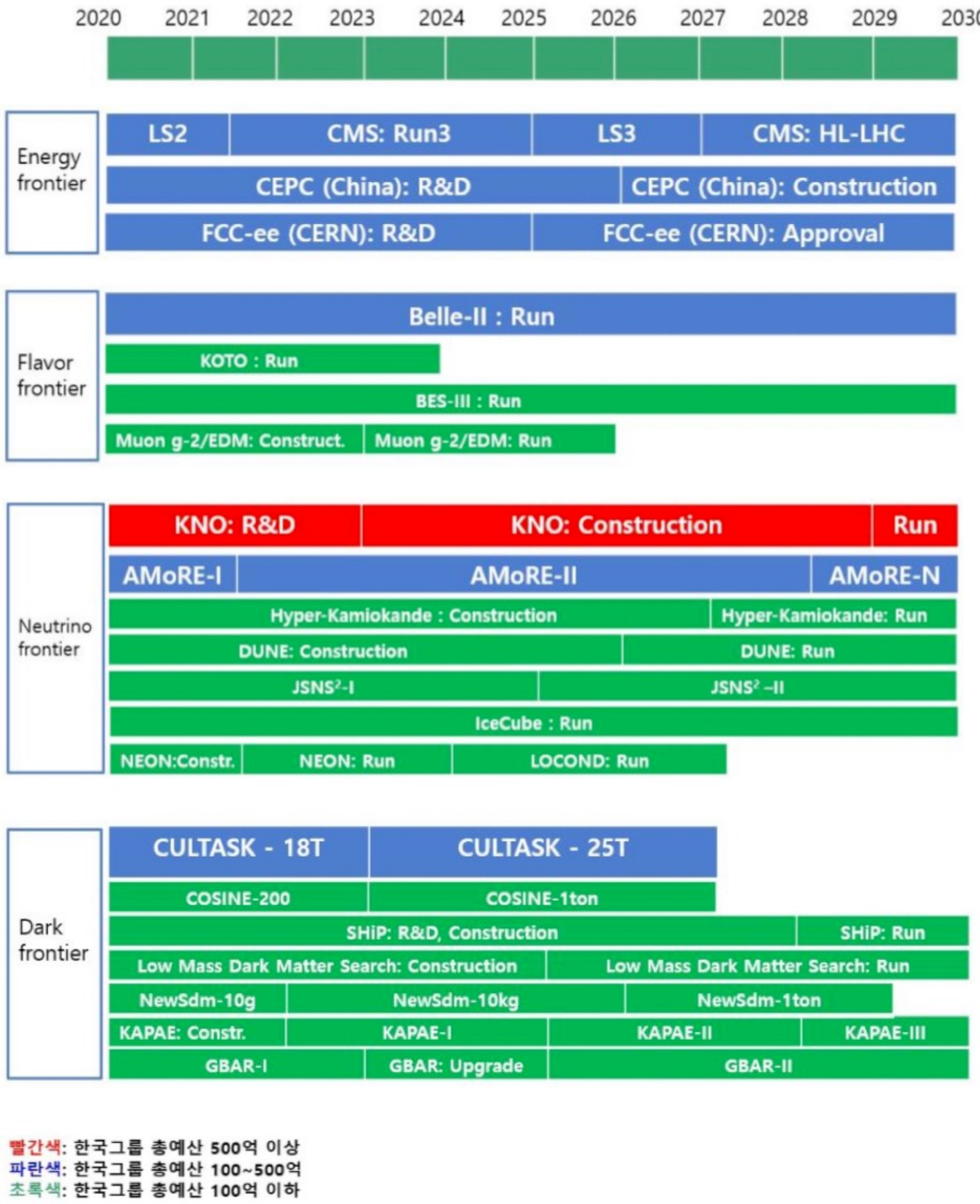


Idea for development of Korean particle physics

- Organizer asked me to say about it.
- I looked at P5 report published last year, and try to say about the direction.

- Decipher the Quantum Realm
  - Elucidate the Mysteries of Neutrinos
  - Reveal the Secrets of the Higgs Boson
- Illuminate the Hidden Universe
  - Determine the Nature of Dark Matter
  - Understand What Drives the Cosmic Evolution
- Explore New Paradigms in Physics
  - Search for Direct Evidence of New Particles
  - Pursue Quantum Imprints of New Phenomena

Current and Major Initiative



We continue to finish current major initiatives, domestic and international. These are flagship experiments, well defined and organized.

- International Collaboration
  - CMS
  - BELL-II
  - DUNE
  - Hyper-Kamiokande
  - ICE-CUBE
  - JSNS2
  - SHIP
- National(Domestic) Projects
  - AMoRE
  - COSINE-100U, 200
  - CAPP Axion search
  - **KNO**
  - **IsoDAR@Yemilab**

Agile initiatives : Small scale project

- Since we don’t have strong candidates for dark matter and dark sector, we have to try many different probes.
- We should check the ideas quickly and have more communication about the ideas.

Good examples are;

- NEOS
- NEON
- RENE
- keV sterile neutrino searches
- CPT violation
- KAPAE
- Low Mass DM using bolometer
- Graphene based DM search

- Yemilab & Detector Lab of HEP @ RAON can be the Hub.

Utilizing Future Facilities

- International
  - XLZD (next generation liquid Xenon detector)
  - FCC-ee, CEPC

- Domestic
  - KNO
  - Multi-ton DBD experiment (Mo or Te ?)
  - “Institute for Particle Physics”

- We should keep proposing the future program with a clear vision.
- Try to write proposals for communication.

Summary

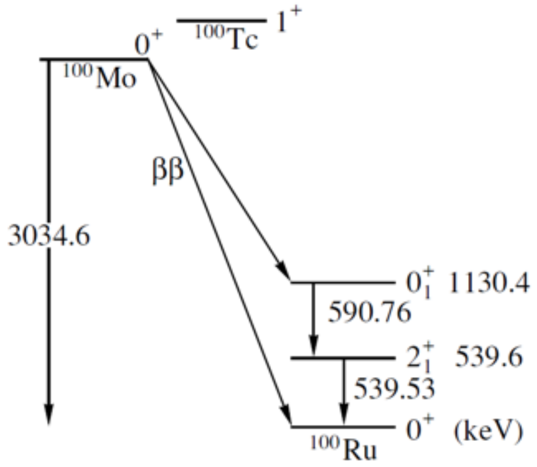
- Yemilab is constructed for searches of dark matter, NDBD, and BSM physics. Many projects are under preparation.
- Neutrinoless DBD experiments are progressing towards > Ton scale experiment. Multiple Isotopes should be pursued. AMoRE-II experiment aims to be sensitive ~ $5x10^{26}$ years range for ^{100}Mo isotope and could expand to 200 kg of isotope mass scale.
- Sterile neutrino search could be done with neutrino sources.

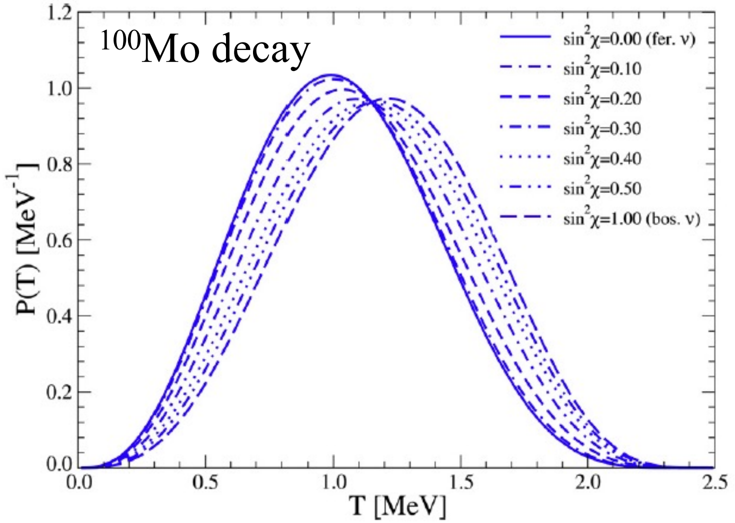
2^+ state in ^{100}Mo decay

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

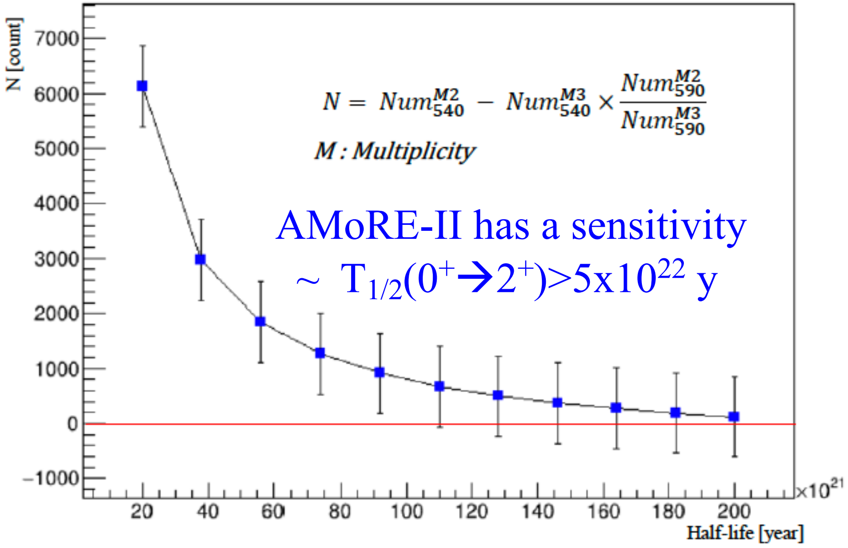
"Neutrinos can have substantially different properties from those of the charged leptons. Violation of the Pauli principle may occur in a hidden sector of theory."

- Double beta decays to excited states can be sensitive to a Bosonic contribution to the neutrino wave function. The predictions are ;
  - $T_{1/2} \sim 2.4\times10^{22}$ yr, for Bosonic neutrinos
  - $T_{1/2} \sim 1.7\times10^{23}$ yr for Fermionic neutrinos .
  - The current limit $T_{1/2} > 4.4\times10^{21}$ yr



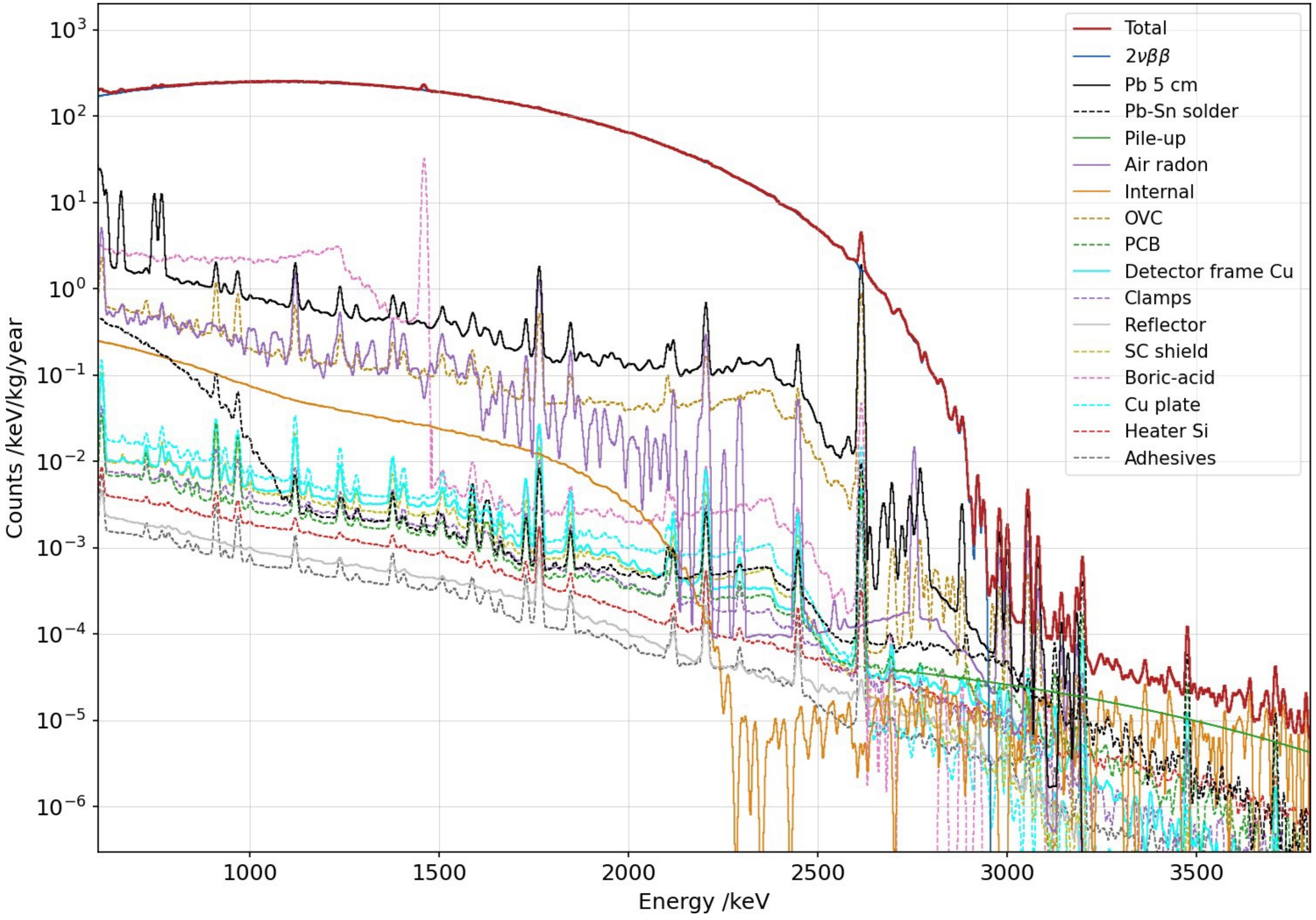


2νββ energy spectrum
Distortion for 2^+ state decay



Background estimation

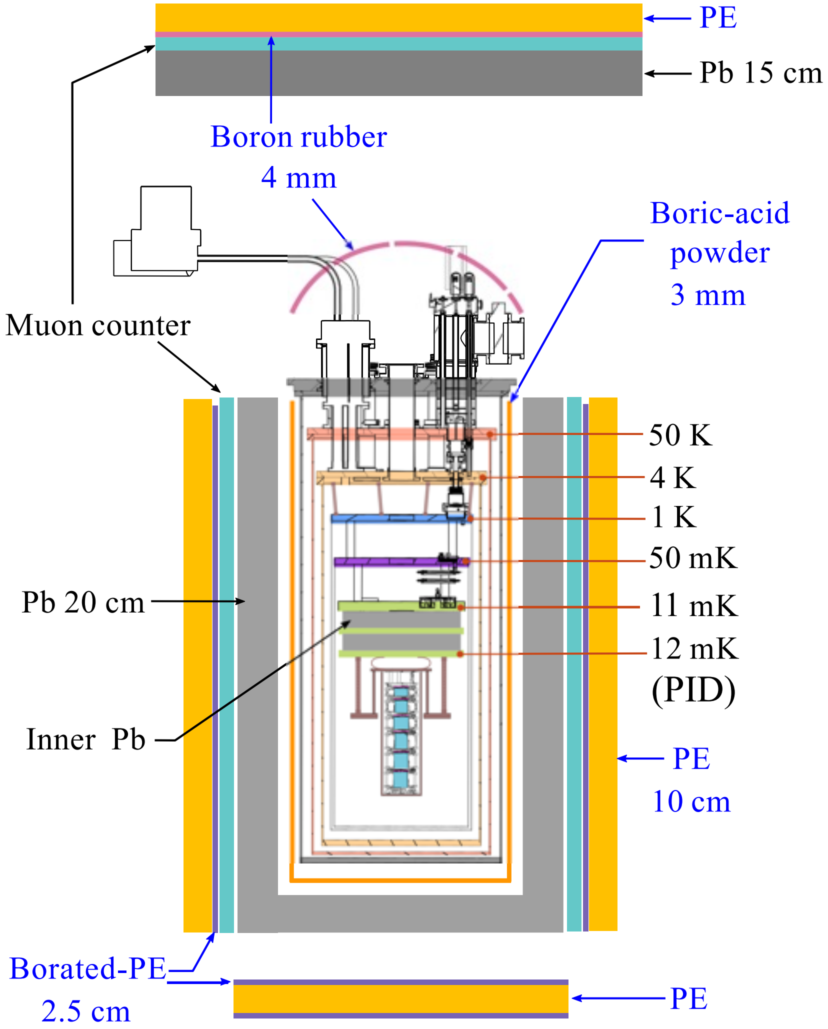
Source material	U-238 mBq/kg	Th-232 mBq/kg	Other mBq/kg	method
LMO internal	< 3.1E-3	< 1.9E-3	<1.8E-3 (^{235}U)	AMoRE-I
Vikuiti	4.2(37)E-2	1.3(9)E-3		ICP-MS
Araldite	2.21(75)	< 1.10		HPGe
Stycast	< 3.27	< 1.64		HPGe
Pb-Sn solder	< 0.88	< 2.19		HPGe
PTFE	< 0.12	< 0.04		ICP-MS
Kapton PCB	< 0.93	<0.93		HPGe
Cu (2022 NOSV)	3.5(7)E-3	1.10(4)E-3		ICP-MS
Heater Si	4.13	2.04		HPGe
Cu plate	< 1.24E-2	< 4.1E-3		ICP-MS
Si rubber	< 0.57	2.07(34)	4.90 (^{40}K)	HPGe
Boric acid	< 0.46	< 0.50	98(8) (^{40}K)	HPGe
Pb (Boliden)	0.44(8)	0.21(7)	12E+3 (^{210}Pb)	HPGe
Pb	0.76(21)	< 0.38	180E+3 (^{210}Pb)	ICP-MS
Rock	10.4E+3			ICP-MS

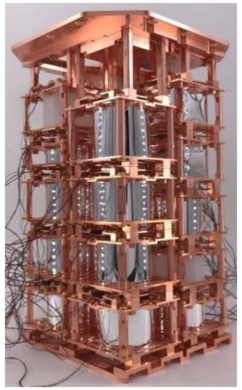


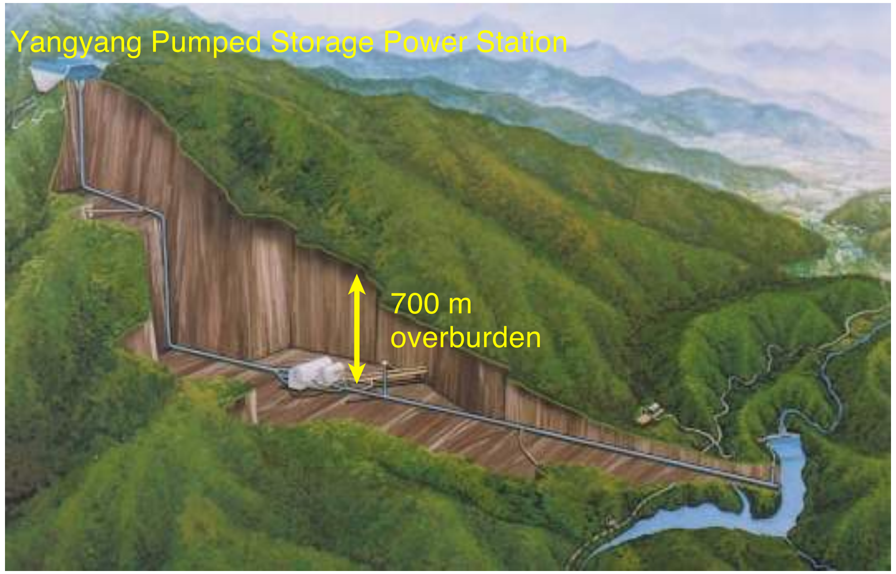
- Muon rate ~ 8.2E-8 μ/cm²/s; neutron rate ~ 7.1E-6 n/cm²/s.
- Rn-222 in air < 0.29(6) Bq/m³; OVC < 0.375 mBq/kg.
- Crystal and detector frame surface radioactivity to be controlled.

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 (1.6 kg) crystals
- 20cm Pb shielding + neutron shields (boric acid+PE+b.PE)

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

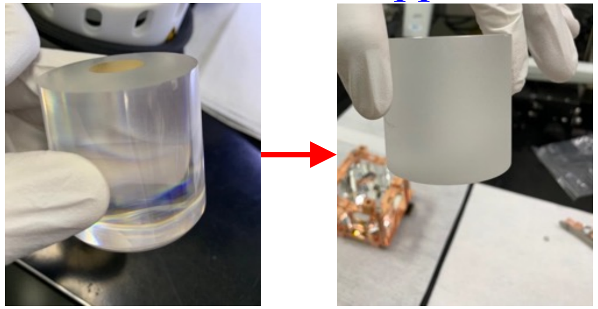
Improvements of LMO crystals

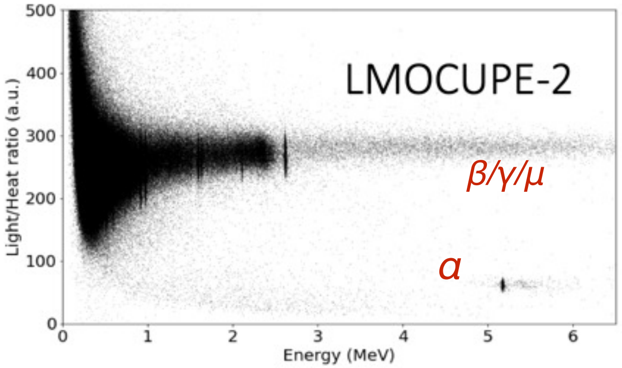
- Recently, we improved the detector performance.

JINST 17, p07034(2022)

(1) Polishing vs lapping(roughening)

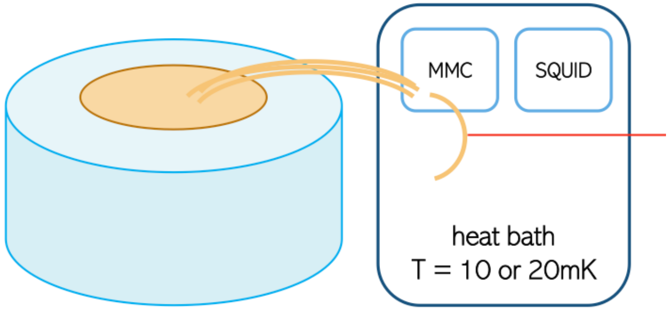
Polished surface Lapped surface

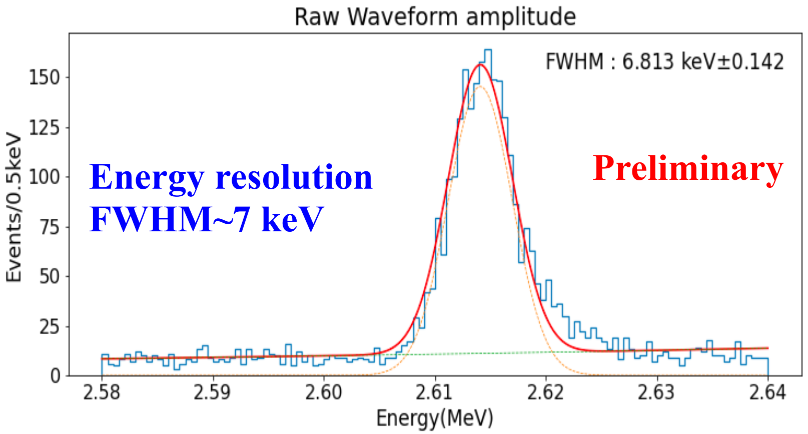




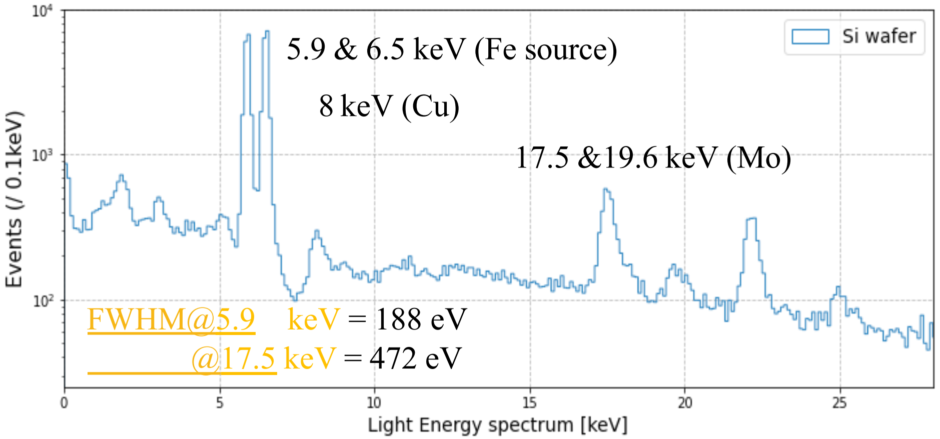
(2) w/o thermal link to heat bath

Heat Detector





(3) Si wafer for light detector

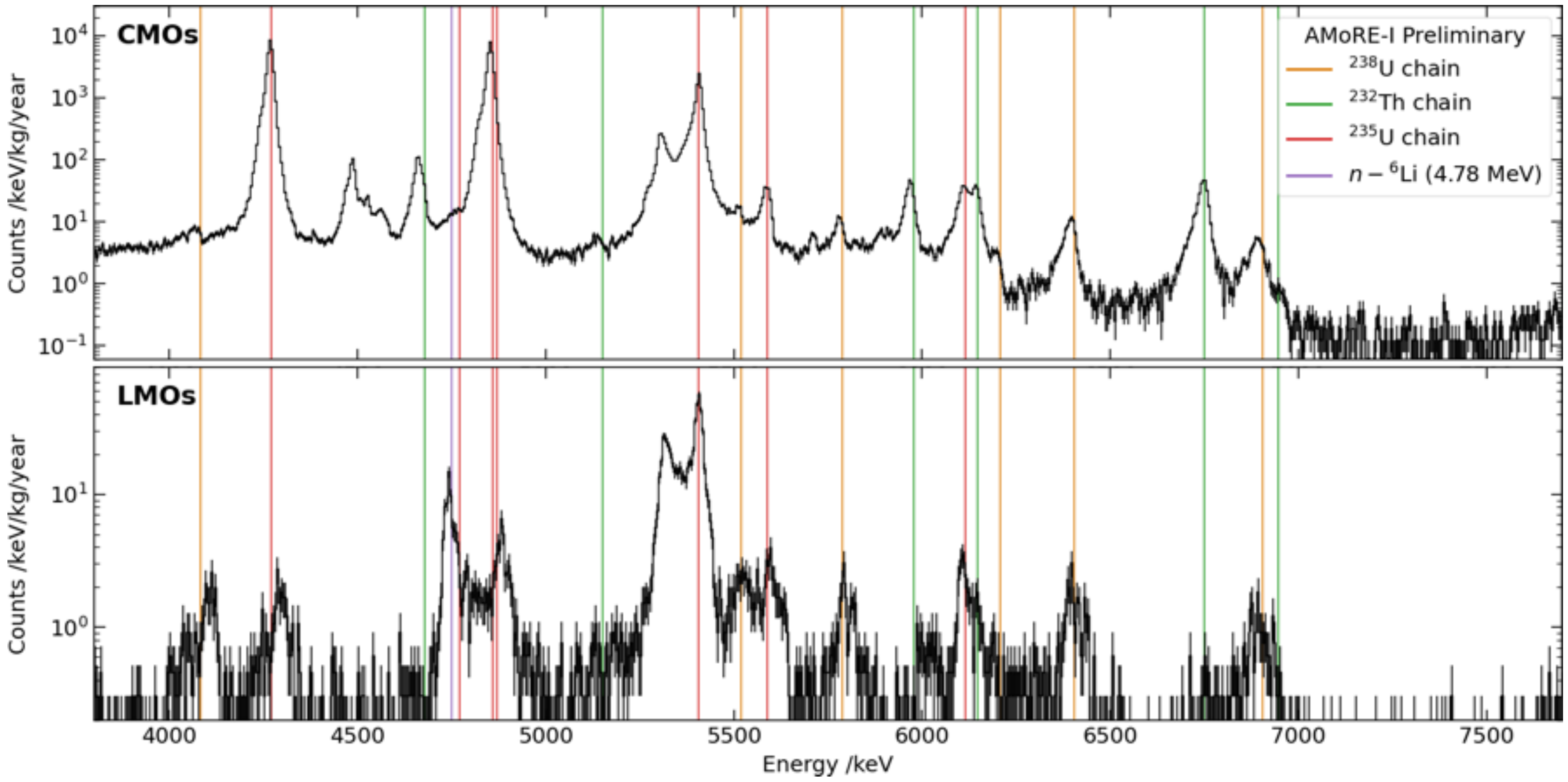


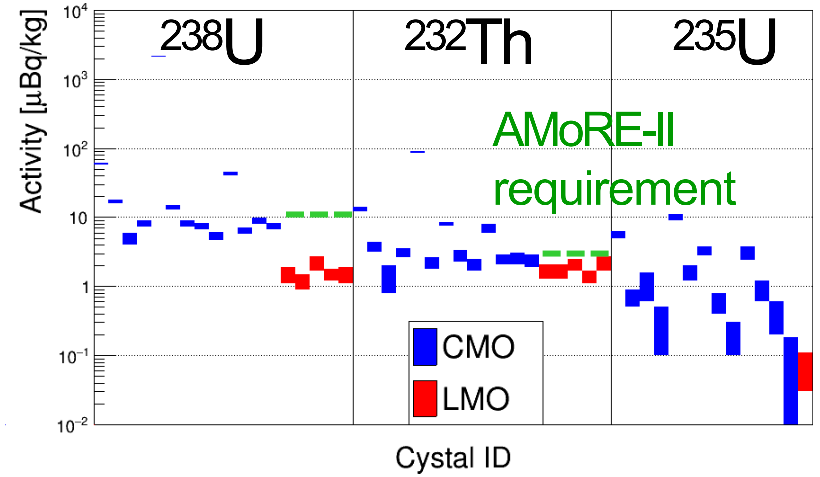
Lapping and thermal link removal :

- 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.

α background

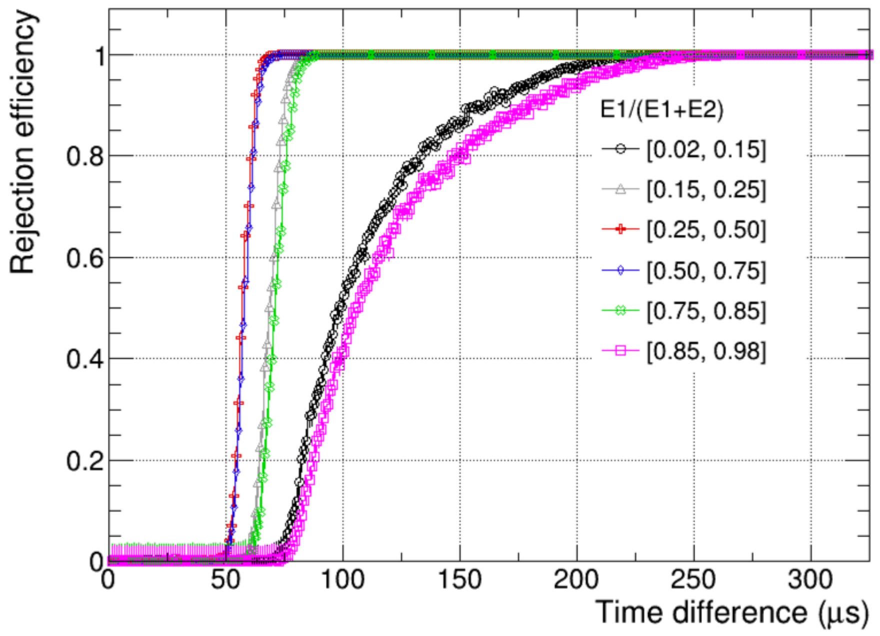


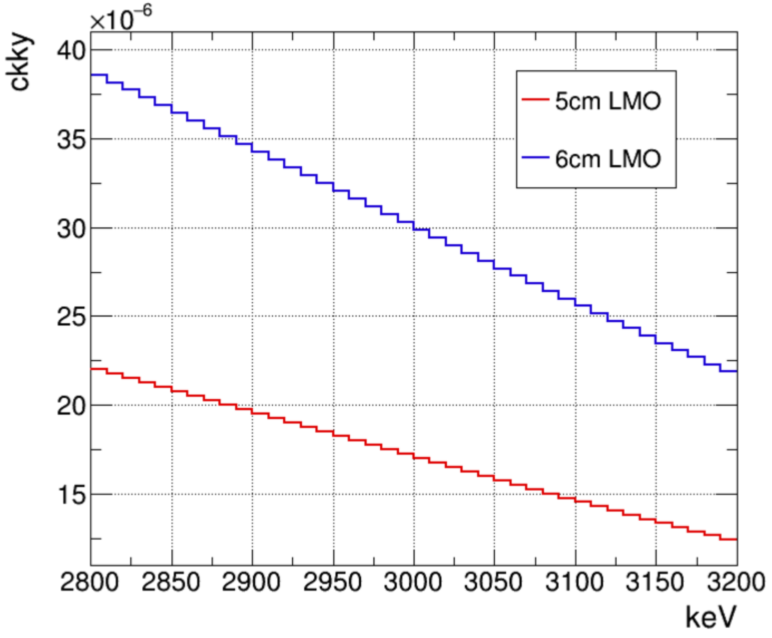


- Overall, the radioactive contamination by U/Th of LMO is measured to be s ubstantially lower than that of CMO.

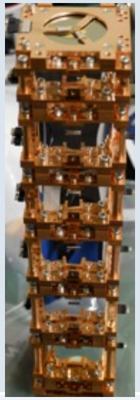
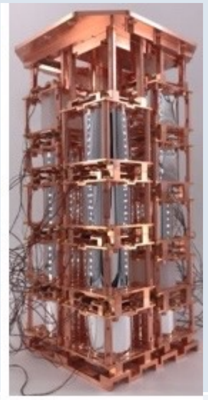
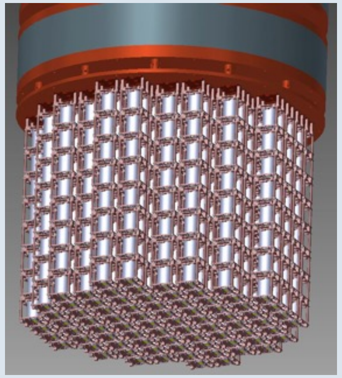
Pileup background estimation

- 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)	$\sim 3.0 \times 10^{23}$	$\sim 7.0 \times 10^{24}$	$\sim 8.0 \times 10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	17-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2023	Yemilab / 2024-2029

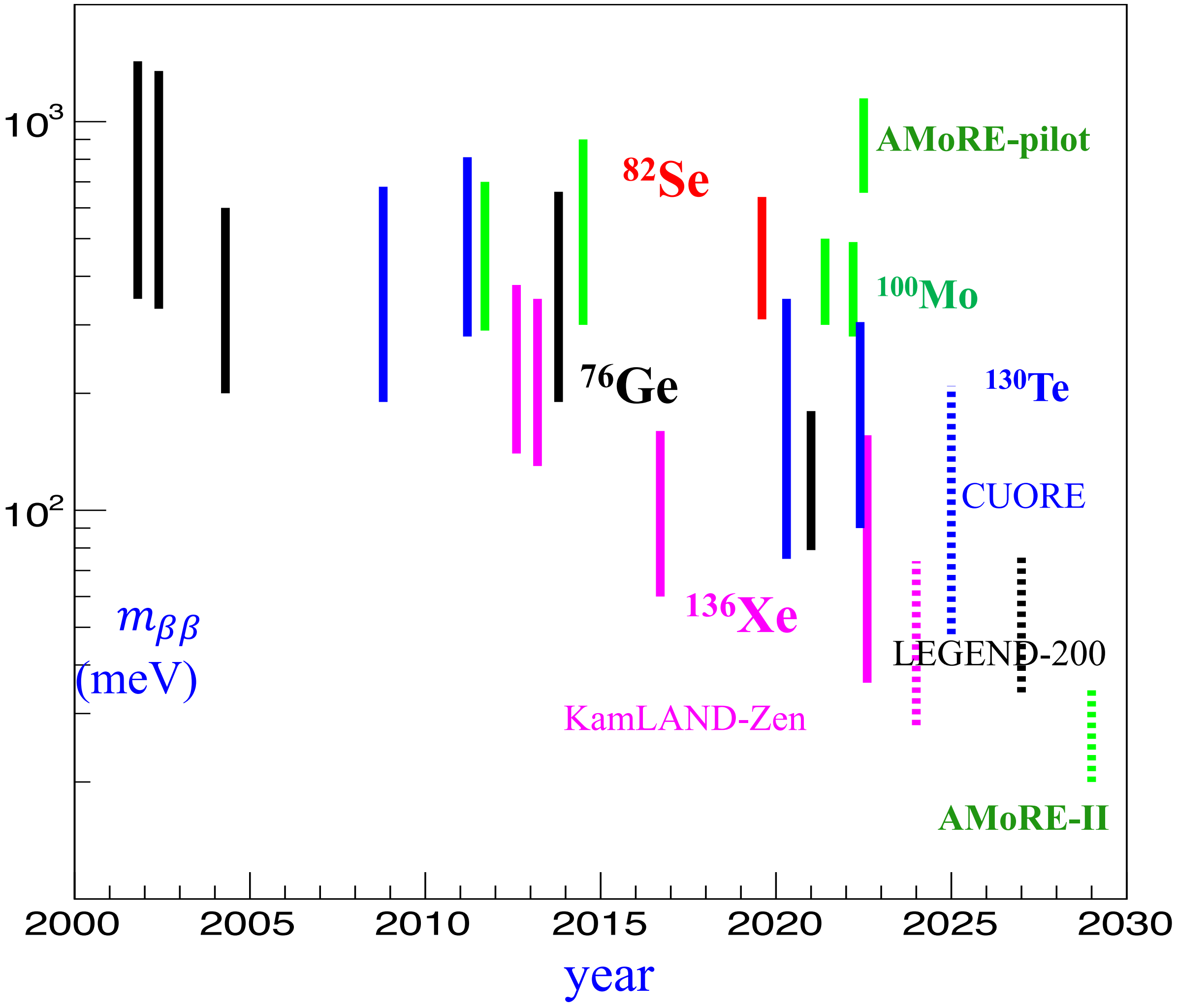
Background Unit :
ckky=counts/(keV kg year)

AMoRE Collaboration : 9 Countries, 25 Institutions.

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

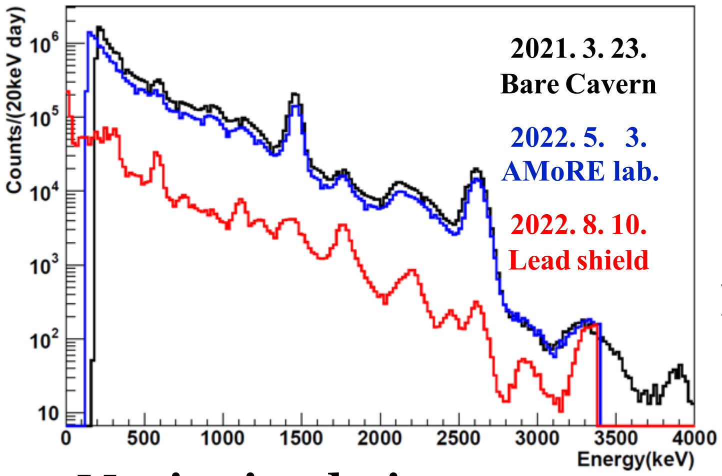
Recent Limits & Persepectives

- 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

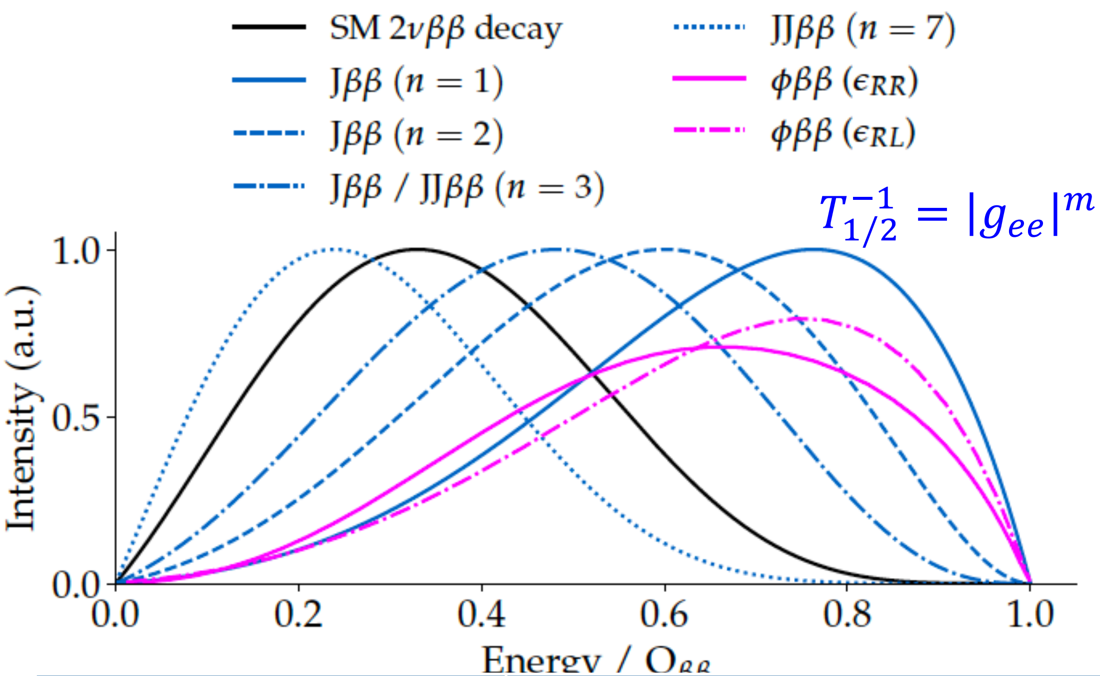
Dust level

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.



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

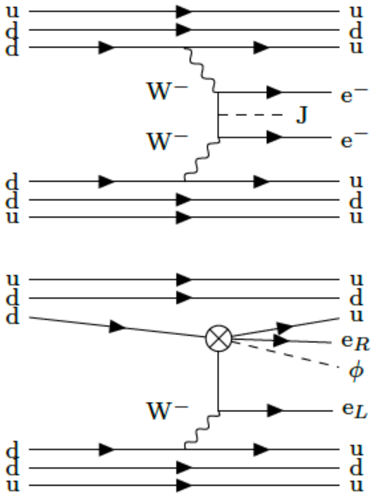


Figure 4. (Top) Feynman diagram for the double-β decay with the emission of a Majoron in classical models. (Bottom) Feynman diagram for the emission of a Majoron-like particle ϕ through an effective dimension-seven operator containing right-handed currents in double-β decay (adapted from [66]).

	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

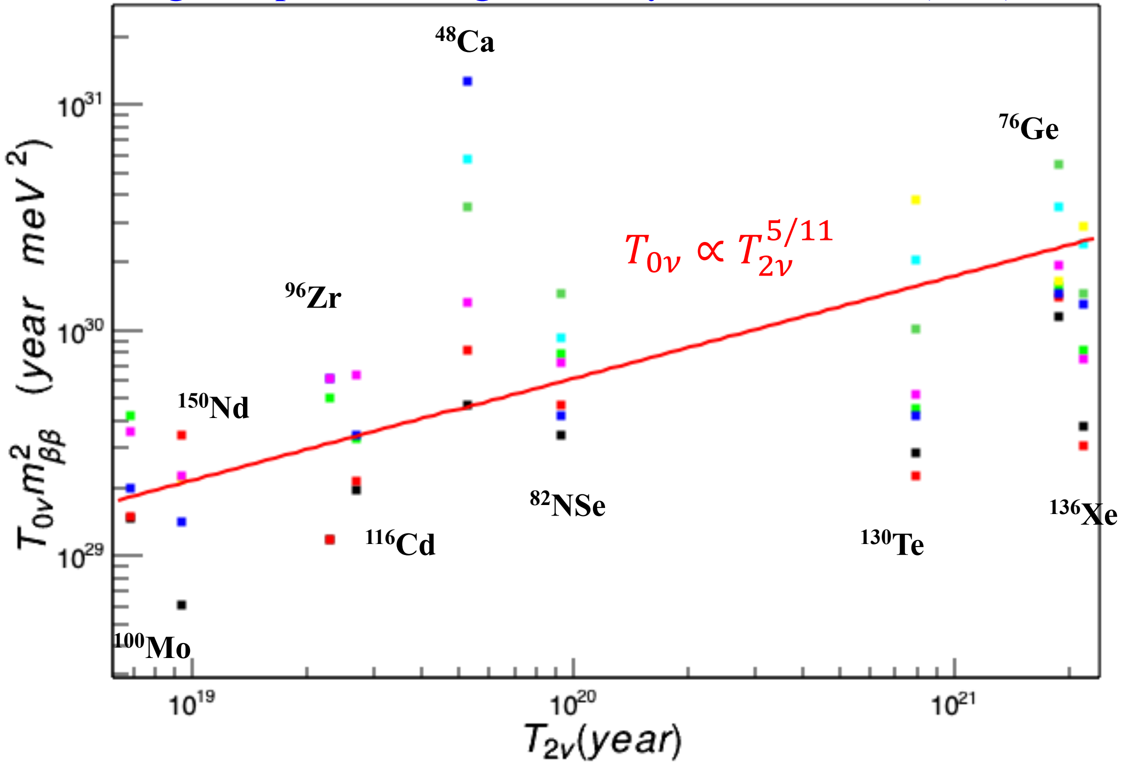
$0\nu\beta\beta$ vs $2\nu\beta\beta$ T(1/2)

- **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 $2\nu\beta\beta$ half-life.

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



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

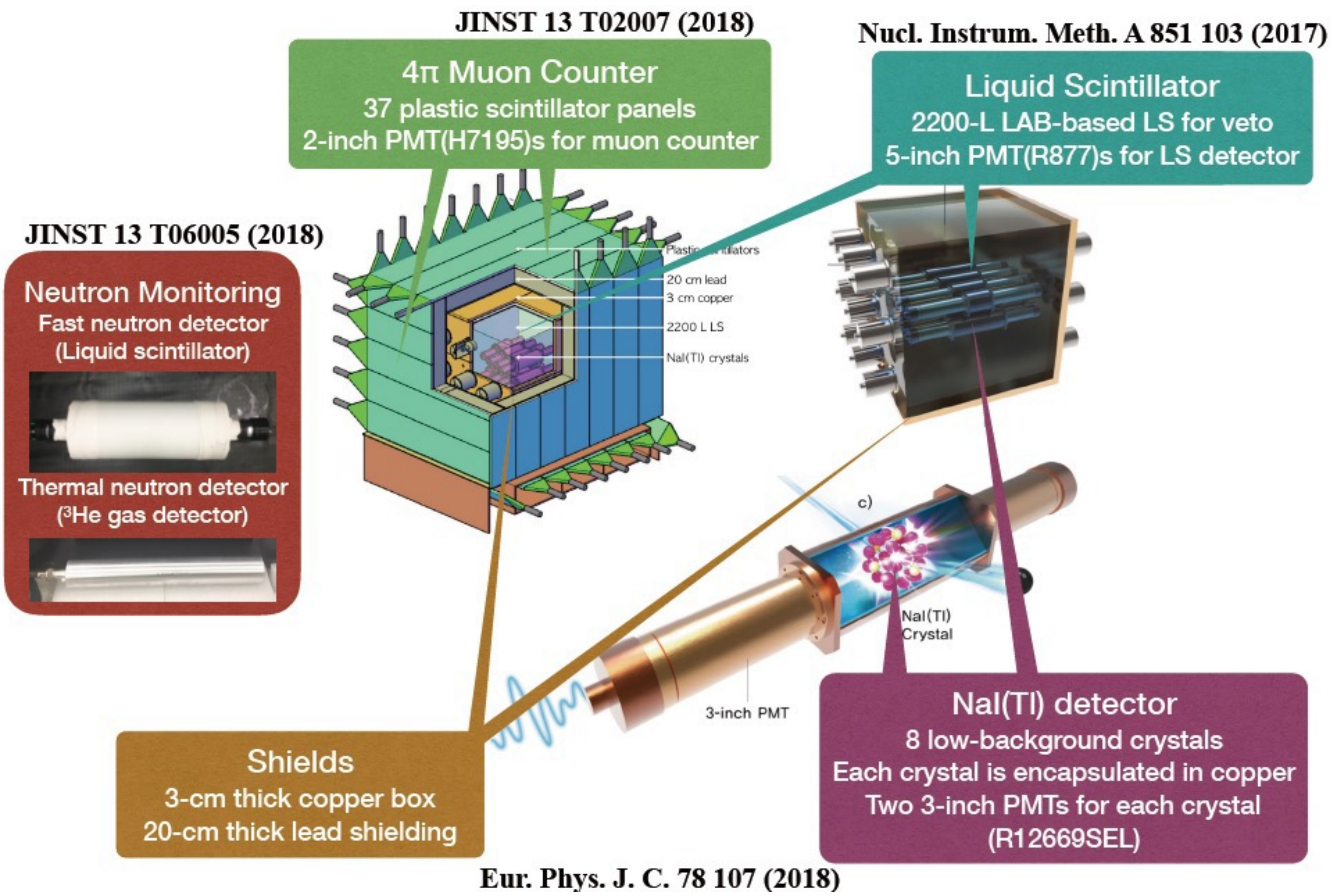
Current best results for $0\nu\beta\beta$

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)

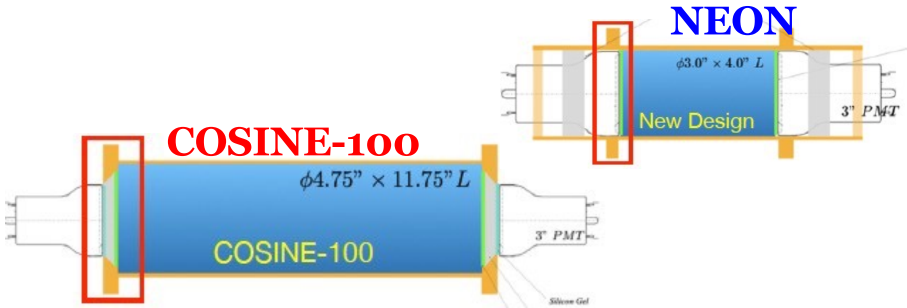
Bolometer, Scintillation, Ionization

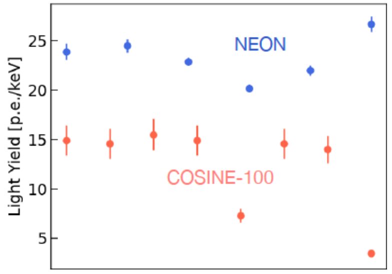
COSINE-100 detector



COSINE-100U (upgrade) @ Yemilab

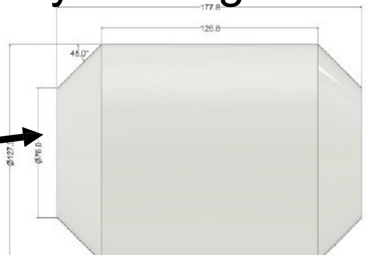
- Novel technique of crystal encapsulation (applied to NEON)

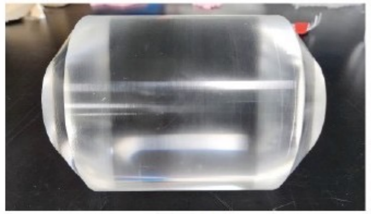




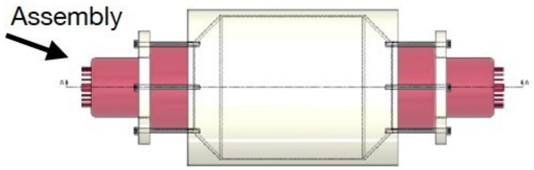
NIMA 981, 164556 (2020)

Machining the crystal edges to couple with 3" PMTs

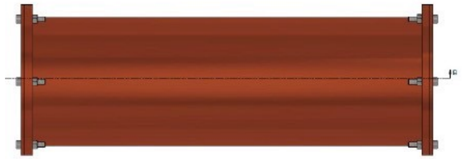


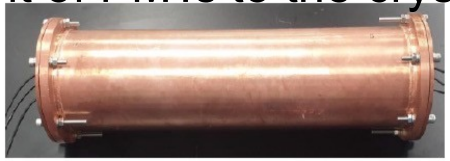


Sample

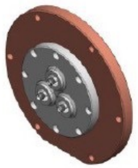


Direct attachment of PMTs to the crystal





Cover design

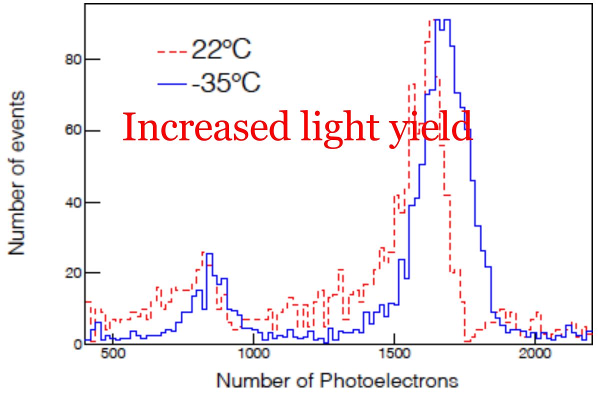


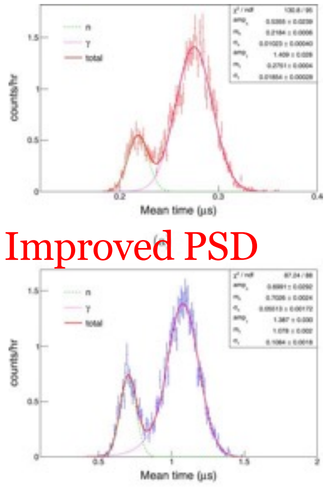
Increased light yield above 20 photoelectrons/keV expected

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

-35°C operation @ Yemilab

-35°C operation





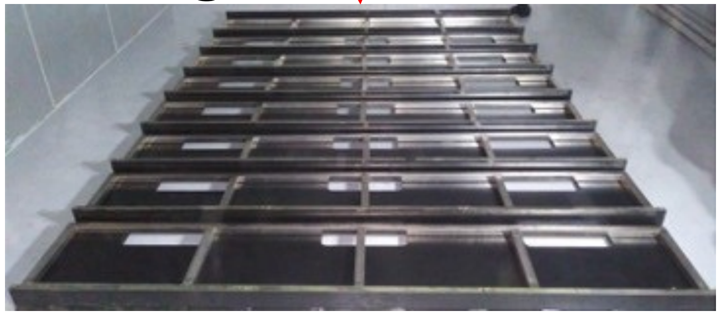
Astropart. Phys. 141, 102709 (2022)

(b)

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

Warehouse freezer at Yemilab

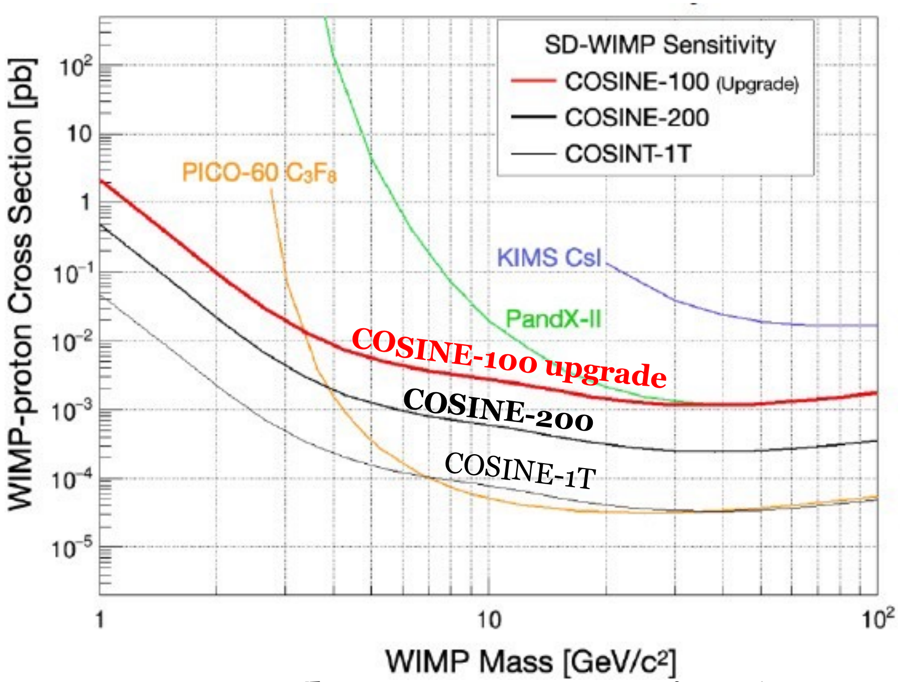
Shielding base for muon detector



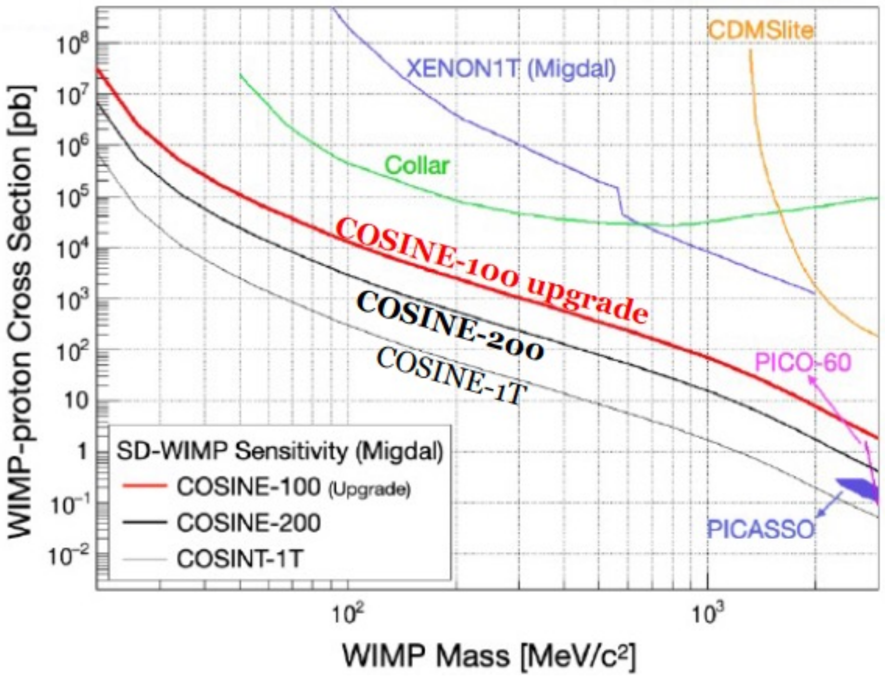
To start COSINE-100U at Yemilab October/2023

COSINE-100U sensitivities @ Yemilab

WIMP-proton spin-dependent



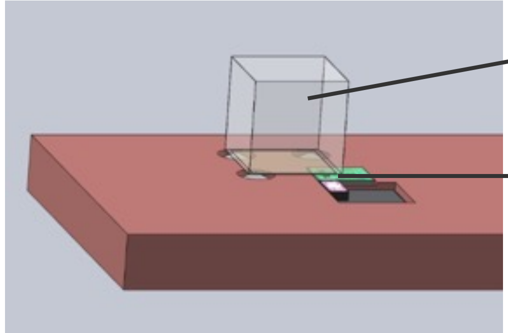
Low mass search with Migdal



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

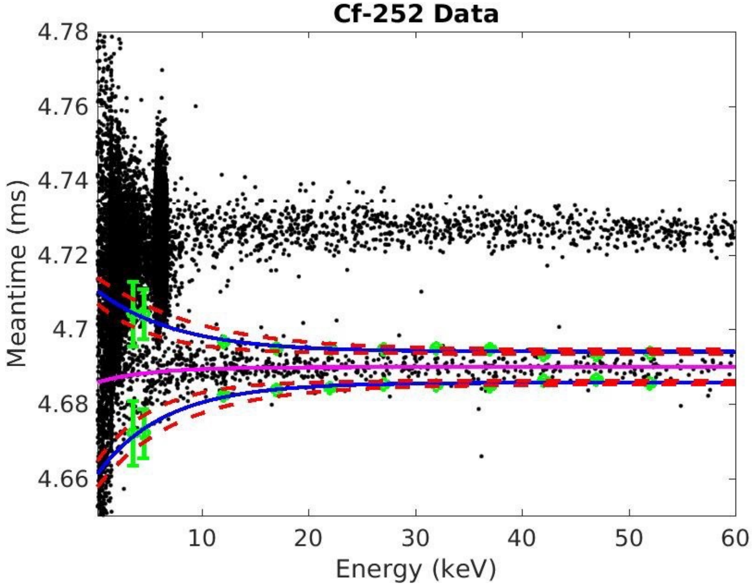


Many choices: **LiF, CaF$_2$, Sapphire(Al_2O_3)**(SD)
$CaMoO_4$, Diamond (SI)

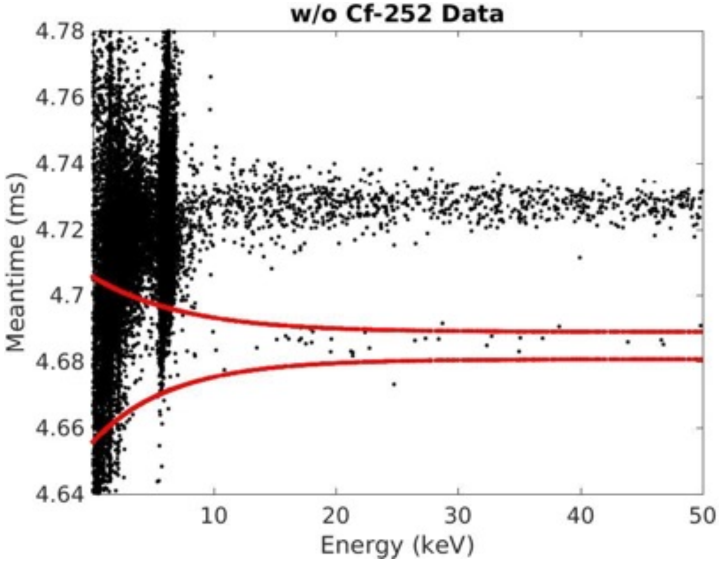
MMC

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

w/ neutron source

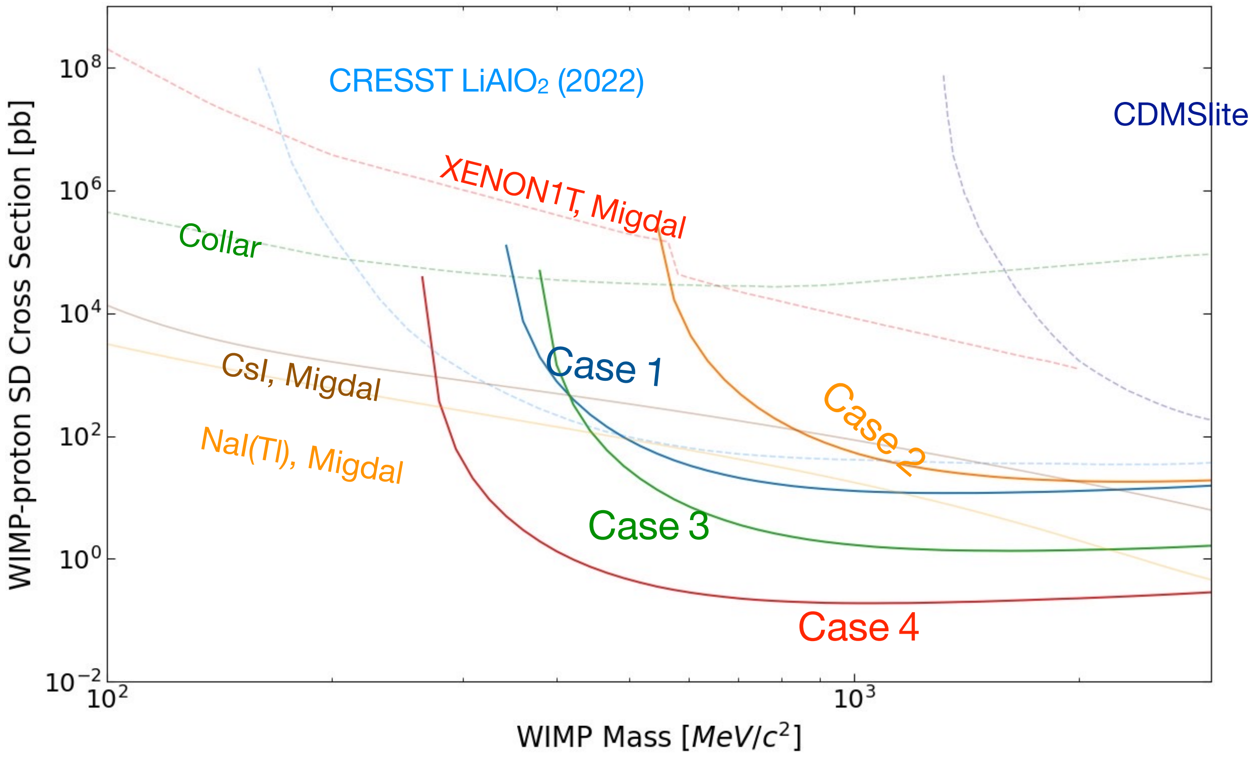


w/o neutron source



- 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

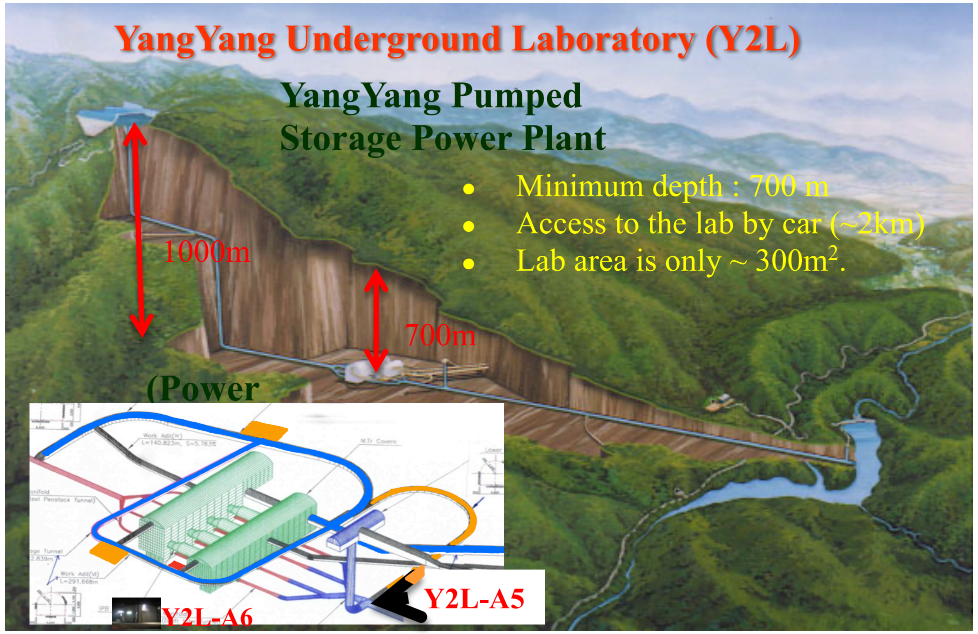
Sensitivity with CaF2 crystal @ Yemilab



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

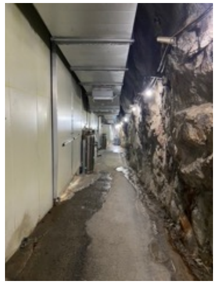


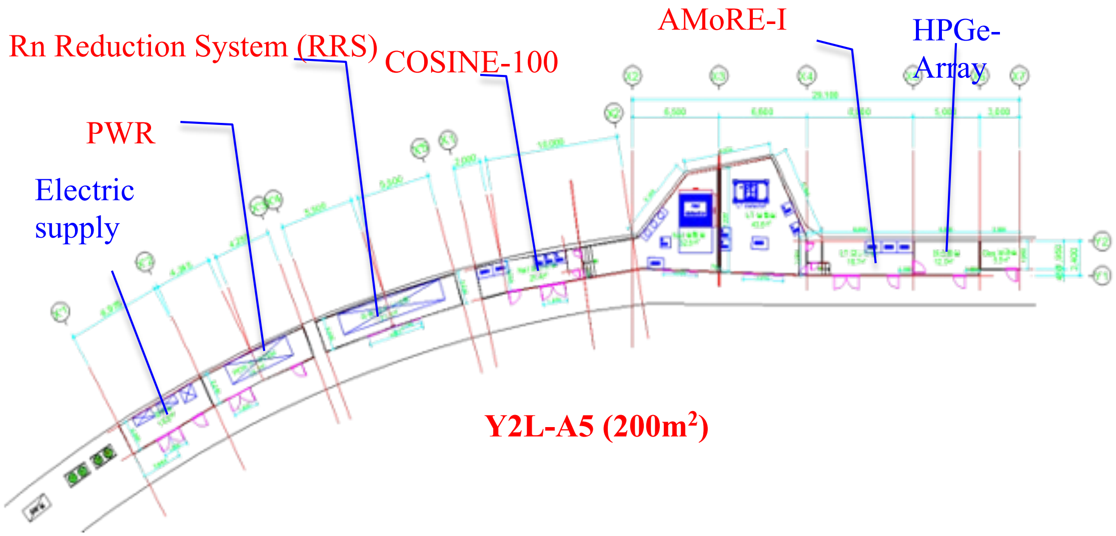
- Y2L began in 2003 with KIMS experiment.
- CUP began in 2013.
- 2023 is 20th of Y2L and 10th of CUP.

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.

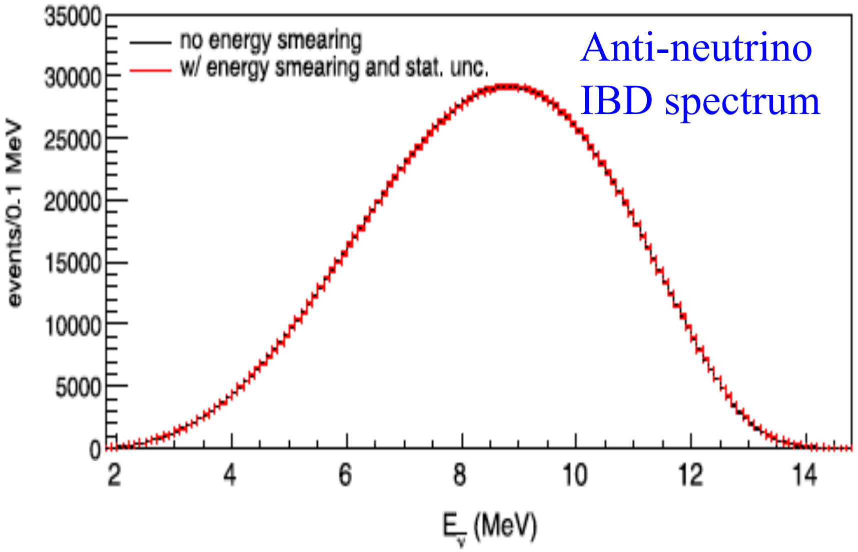




Sterile neutrino searches.

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

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

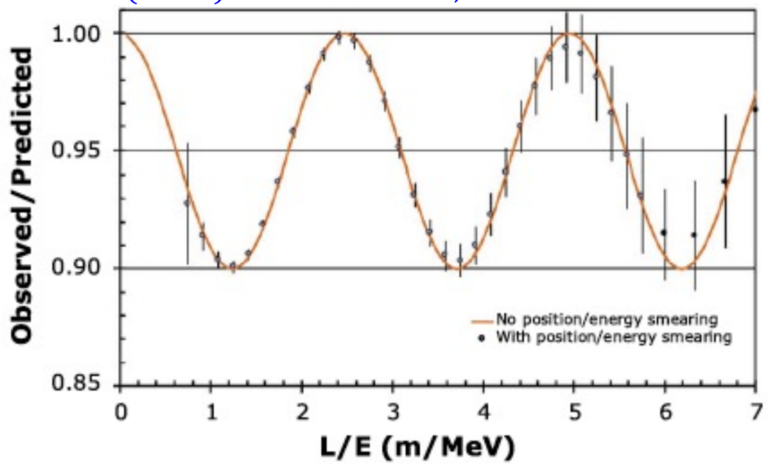


Runtime	5 calendar years
IsoDAR duty factor	80%
Livetime	4 years
Protons on target/year	$1.97 \cdot 10^{24}$
^{8}Li/proton ($\bar{\nu}_e$/proton)	0.0146
$\bar{\nu}_e$ in 4 years livetime	$1.15 \cdot 10^{23}$
IsoDAR@Yemilab mid-baseline	17 m
IsoDAR@Yemilab depth	985 m (2700 m.w.e.)

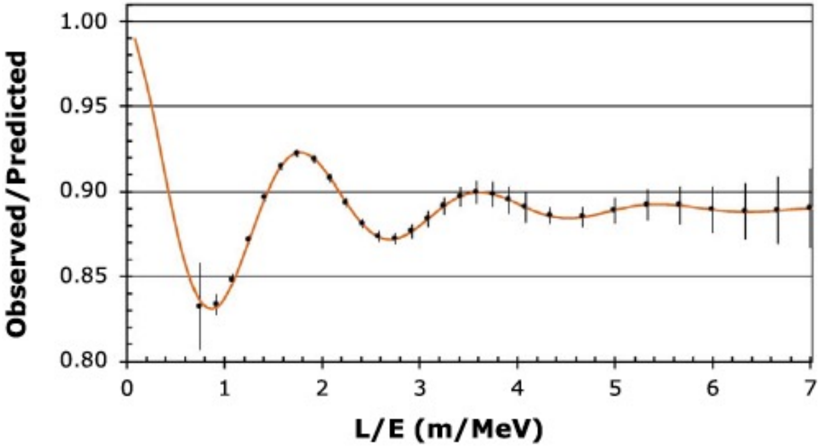
For each event, we measure the energy (E) and vertex(L) of neutrinos. → L/E

Sterile neutrino searches.

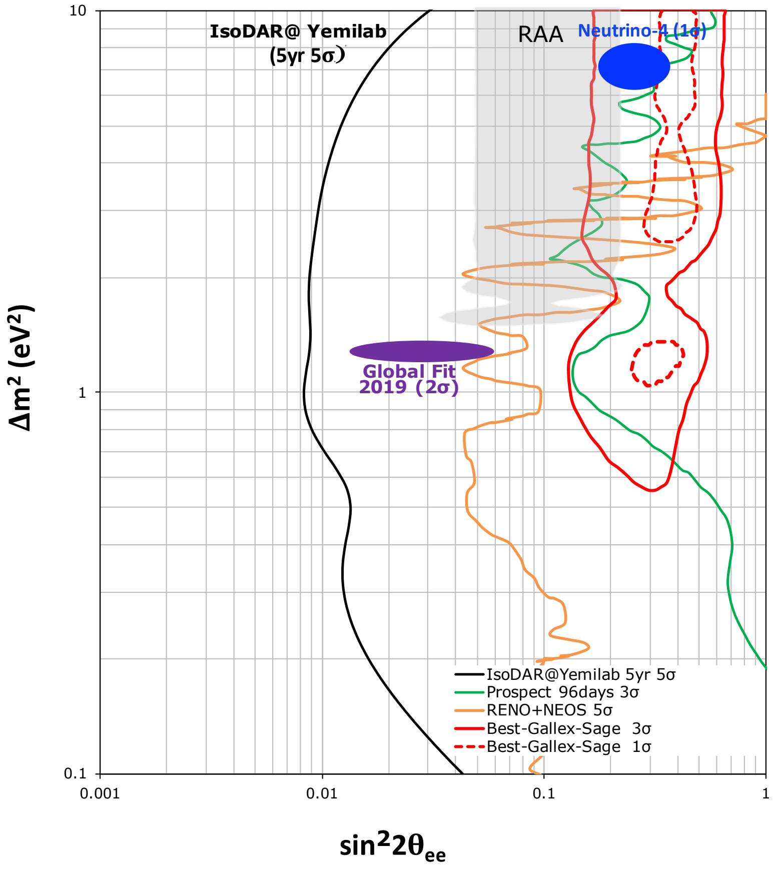
$(3+1):\ \Delta m^2 = 1\ eV^2, \quad \sin^2 2\theta = 0.1$



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

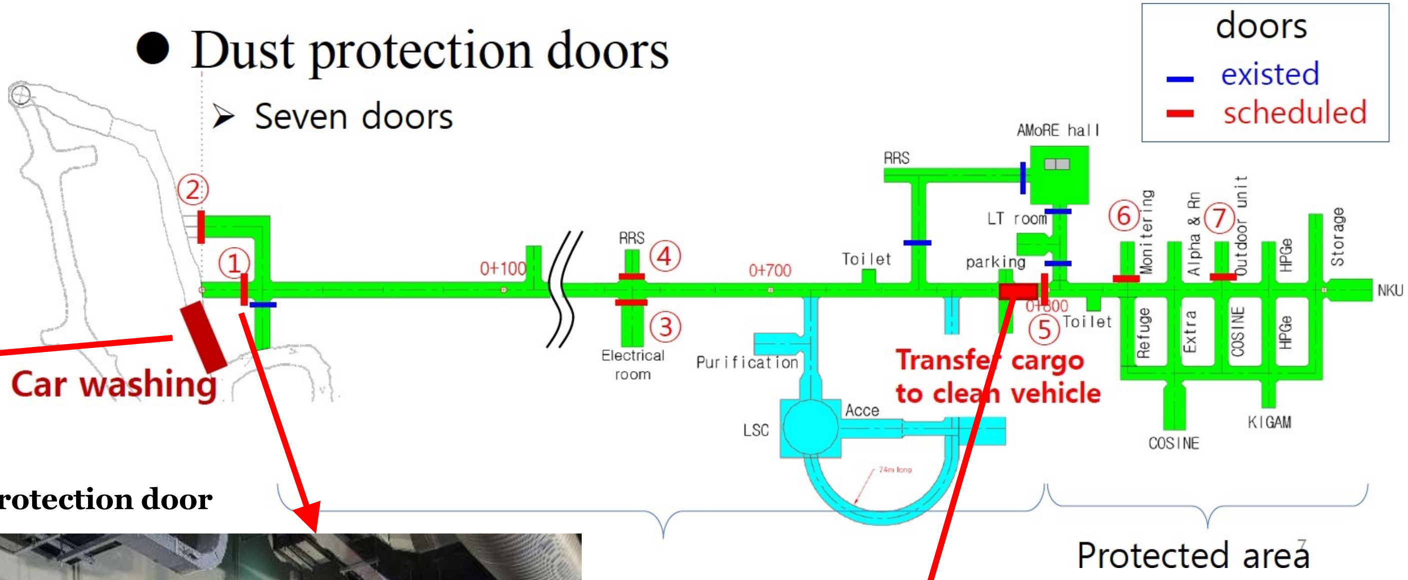


5σ sensitivity with 5 year run
Cover most of the confusing parameter spaces.

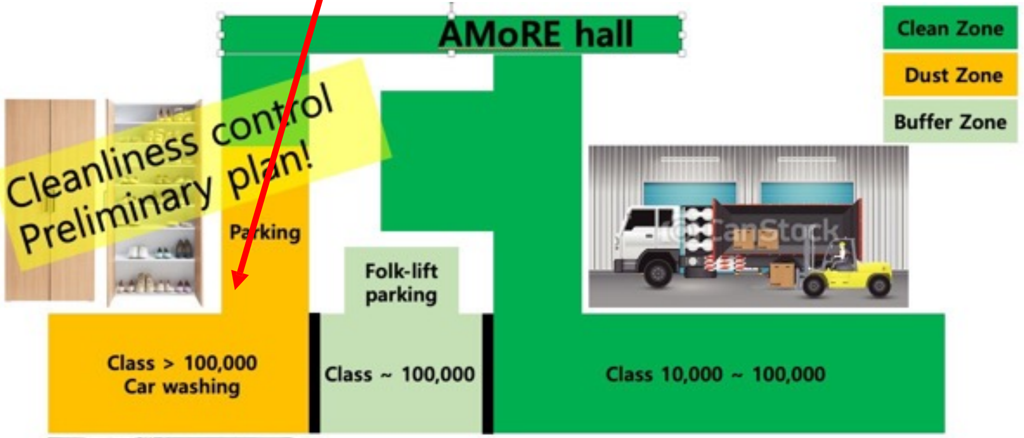


Clean environment concept at Yemilab

- Dust protection doors
  - Seven doors



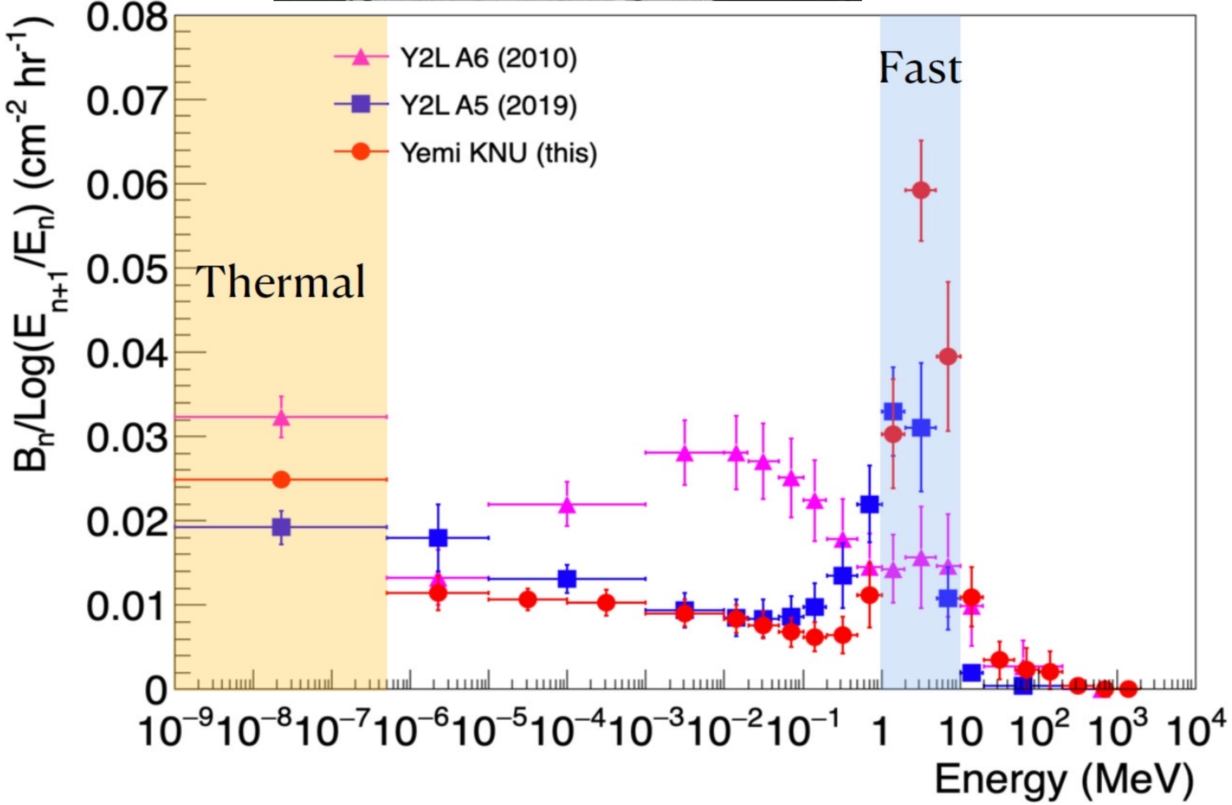
Dust protection door



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.



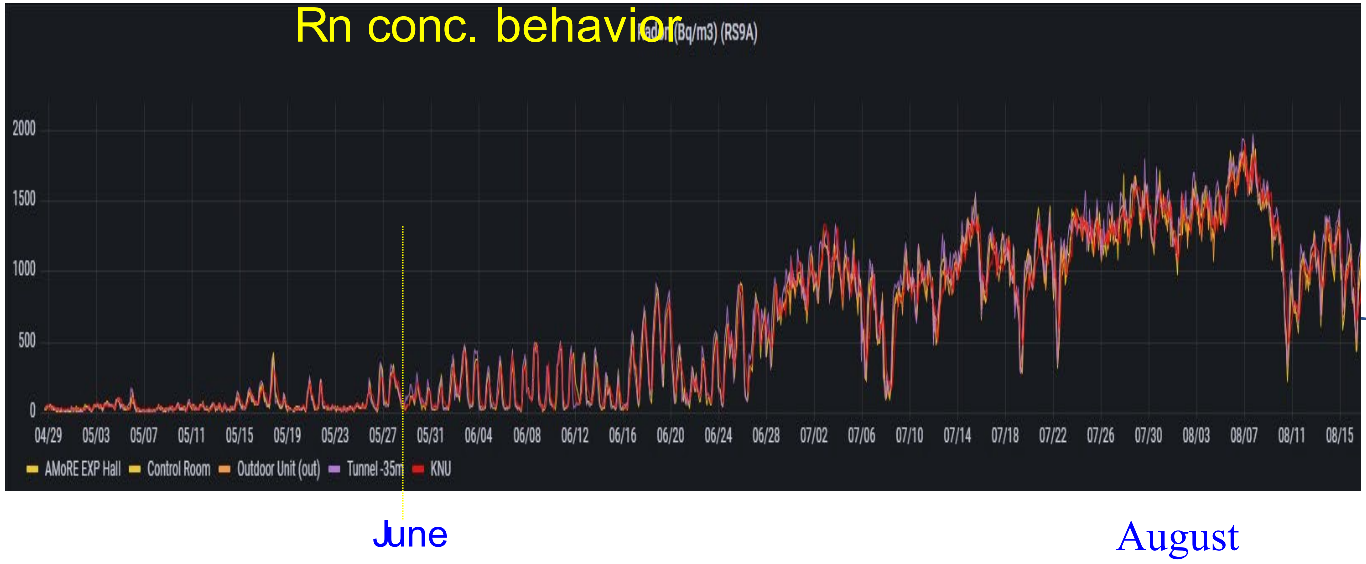
× 10^{-6}/cm_2 sec	Y2LA6	Y2LA5	Yemilab
Thermal	24.2 ± 1.8	14.4 ± 1.5	**18.6 ± 0.8**
Fast (1~10 MeV)	4.2 ± 0.9	7.1 ± 1.0	**12.4 ± 1.1**
Total	67.2 ± 2.2	44.6 ± 6.6	**49.5 ± 1.8**

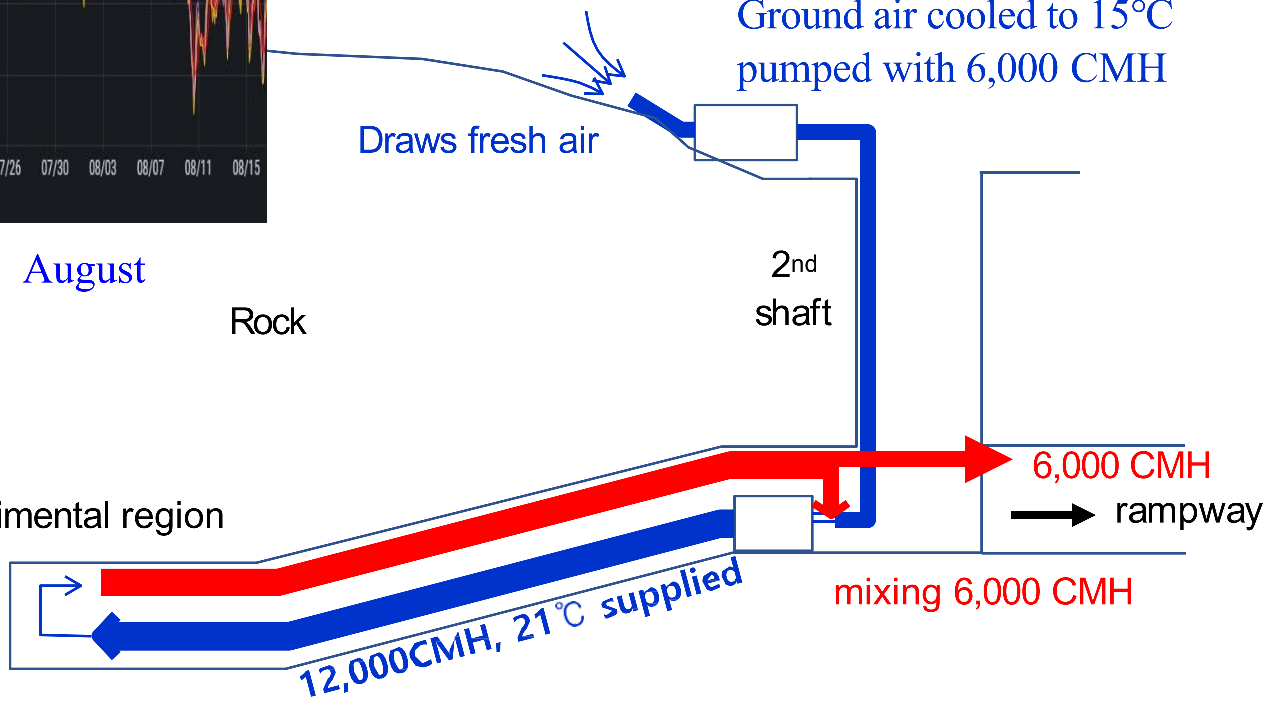
- **Y2L : More moderation by equipment**
- **Yemilab : A few hundreds of tons Shotcrete**
  - ~ 180 tons on AMoRE cavern

- **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**

Matter creation with NDBD

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

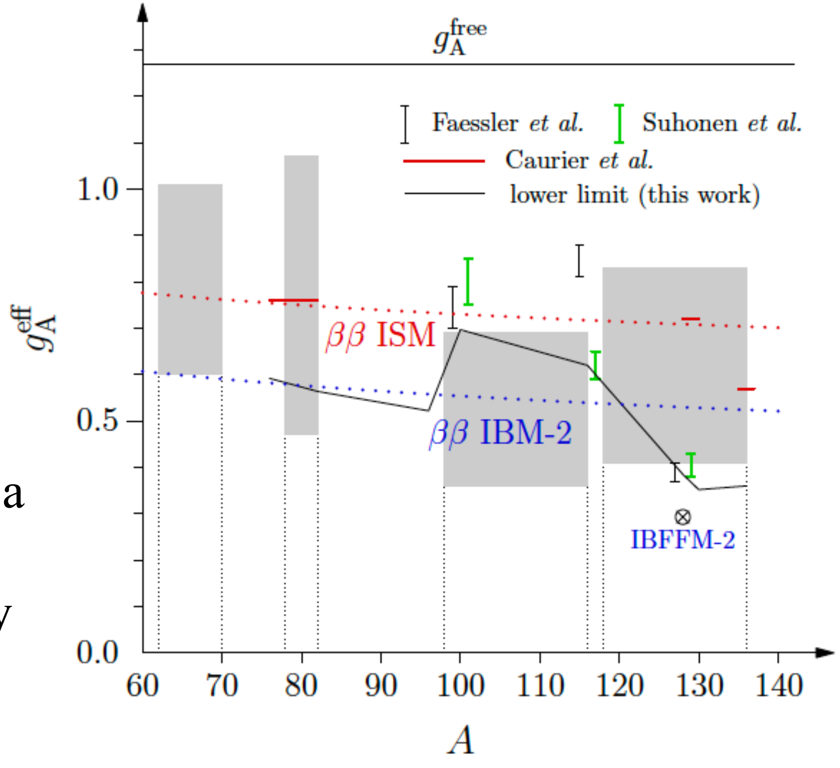
(1) Phase space

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

(2) Nuclear Matrix Element

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

g_A **:axial vector coupling constant**



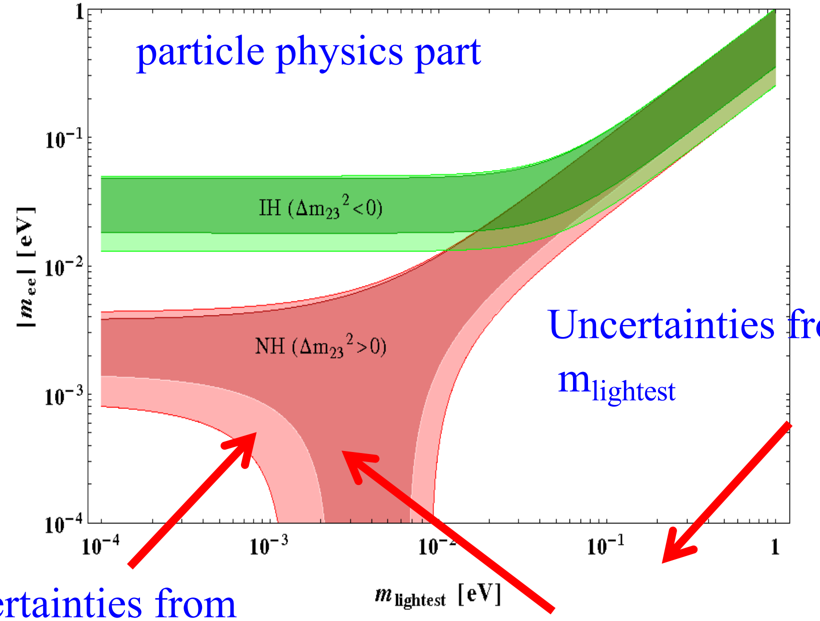
Suhonen, PRC96, 055501 (2017)

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 ;

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

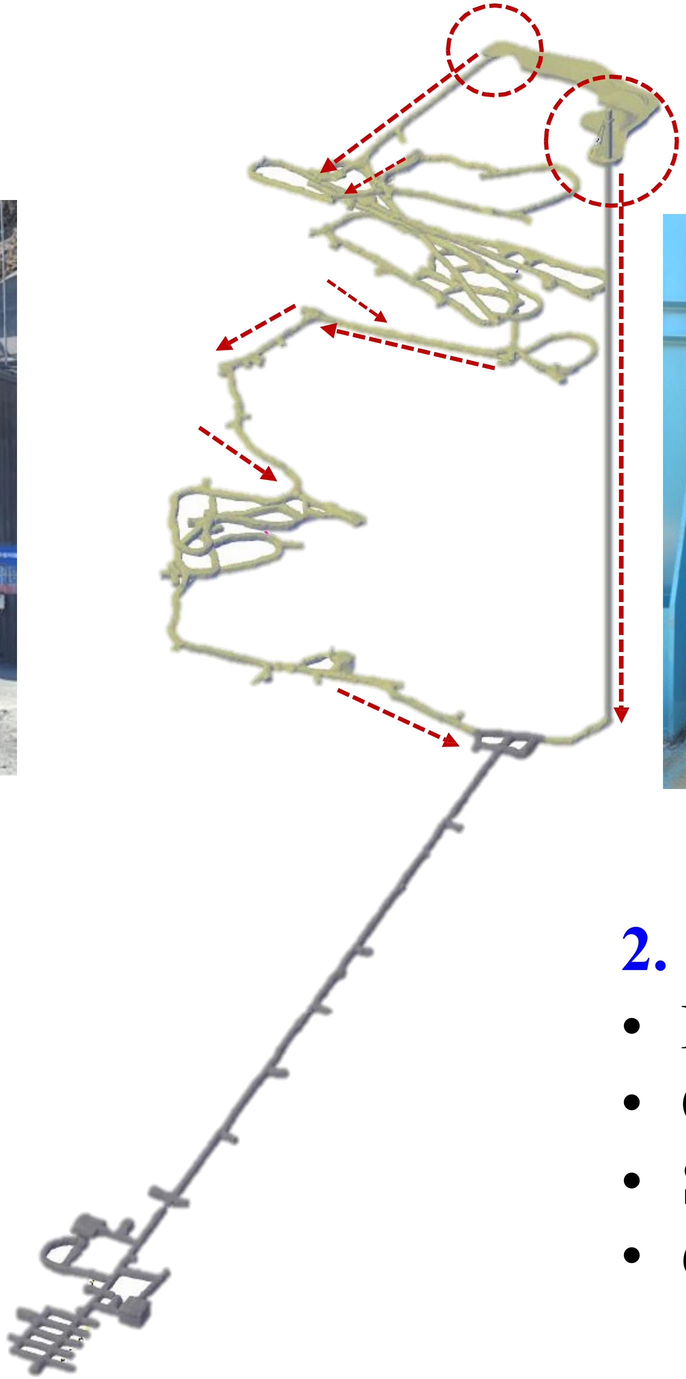
$m_{\beta\beta}$



Uncertainties from mixing angles

Uncertainties from phases

Access to Yemilab



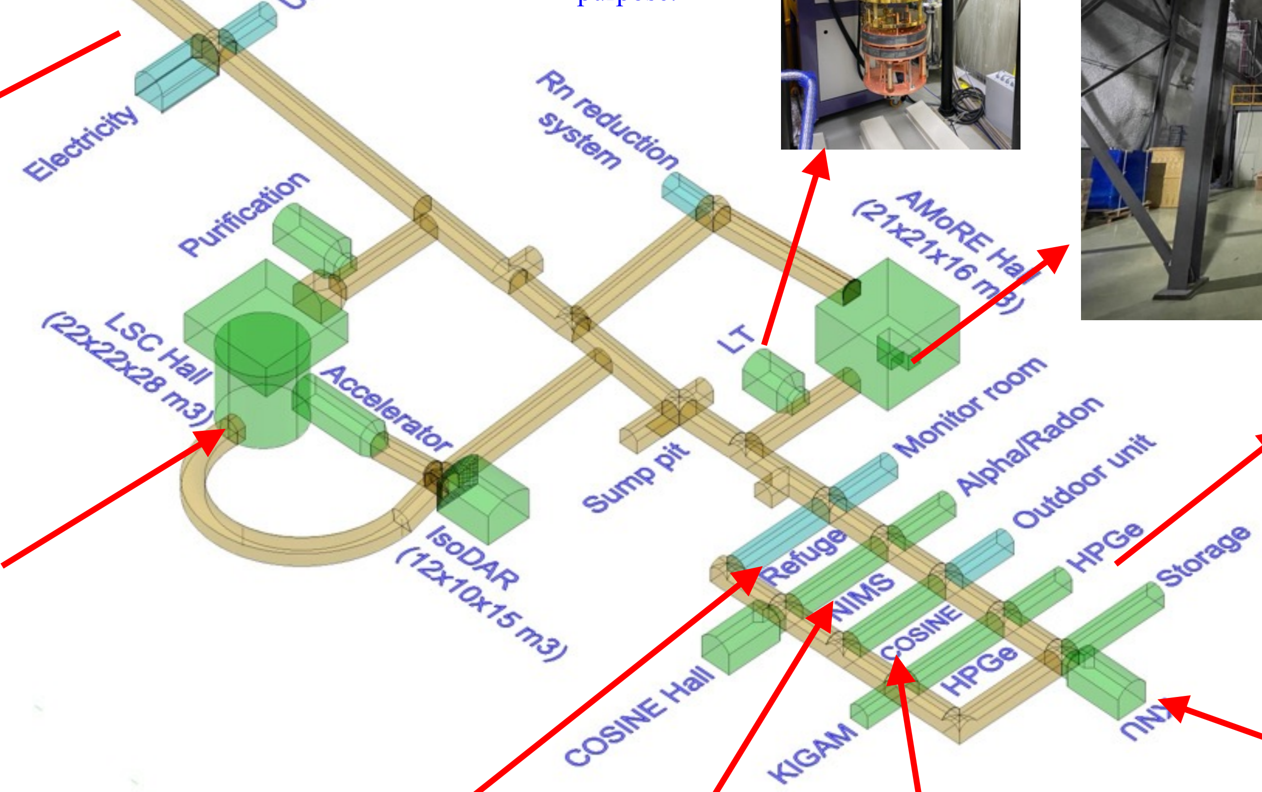
1. Rampway for cargo

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

2. Cage for people

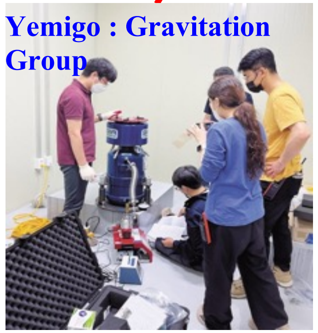
- Manufactured by SIEMAG
- Capacity : ~ 8 people, 1.5 tons
- Speed : 4 m/sec, 2.5 min
- 600m length of shaft

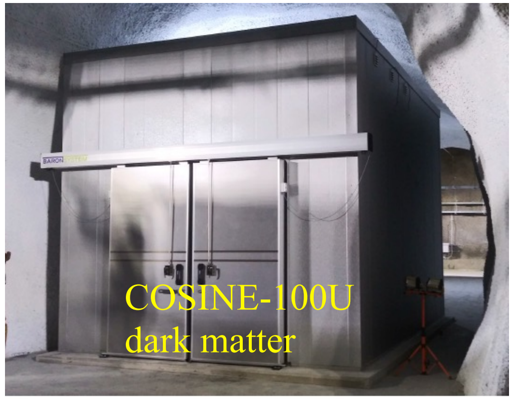
Experimental area of Yemilab



DR for R&D
Open to general
purpose.

KAERI radiation measurement

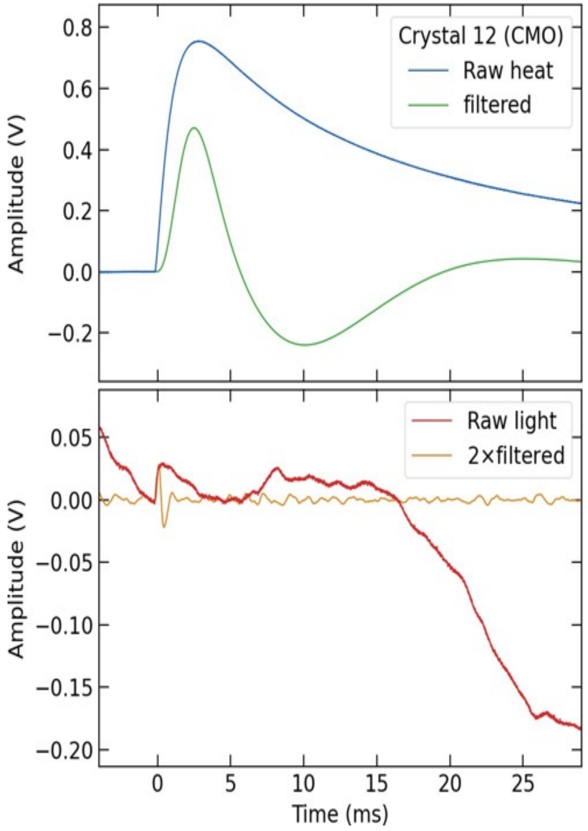


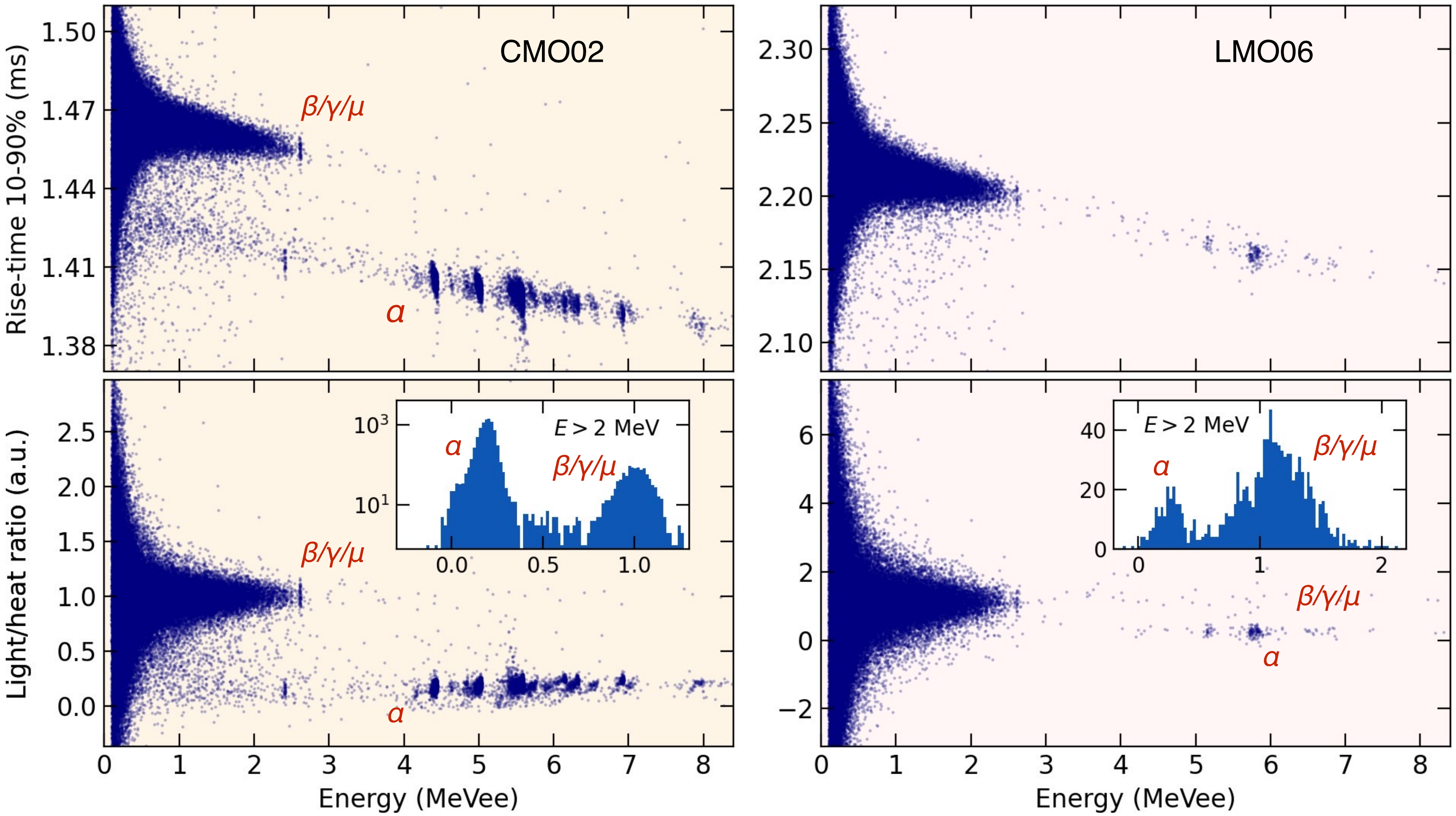


Kyungpook National
University : CPT conservation

Particle Identifications, CMO and LMO

Signal Shapes



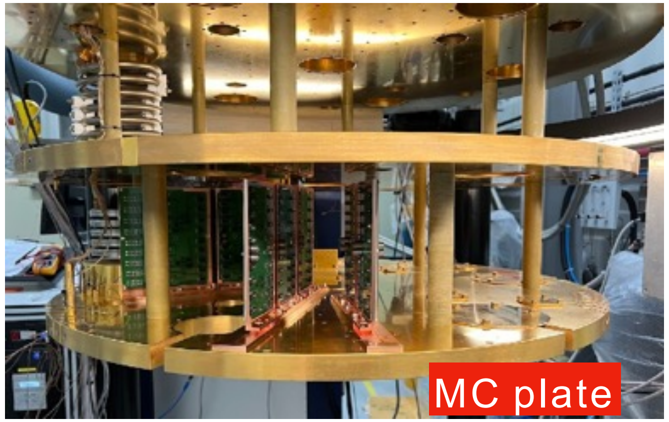


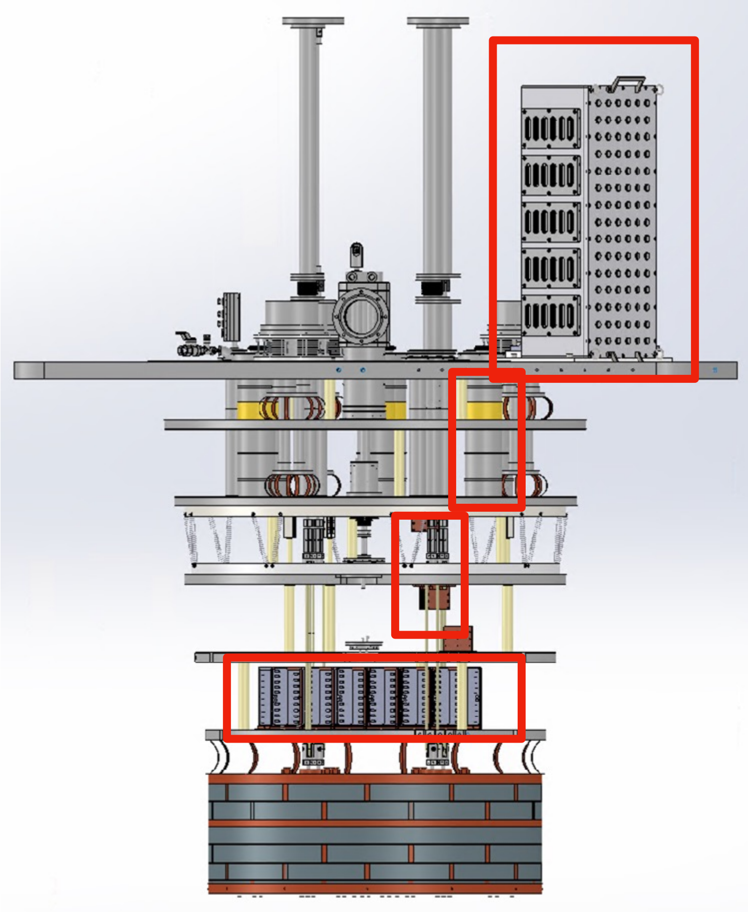
- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less contamination.

Vacuum Feedthrough & Wiring

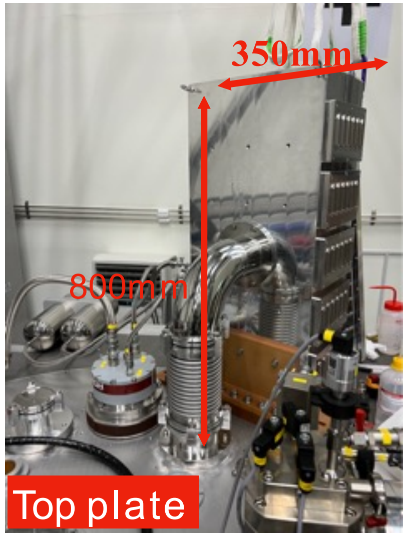
- Installed 270 SQUID & MMC channels for stage-1.

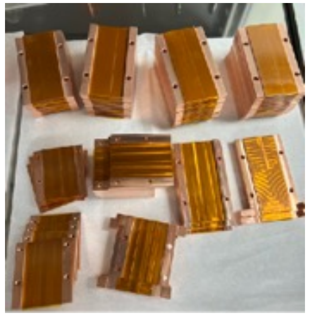
- **PCBs for MMC & Stabilization's filter circuits.**
- **ribbon wires ←→ detector wires.**

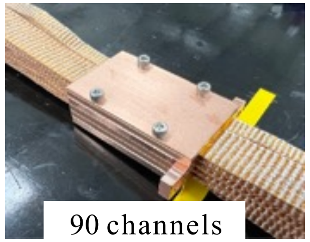




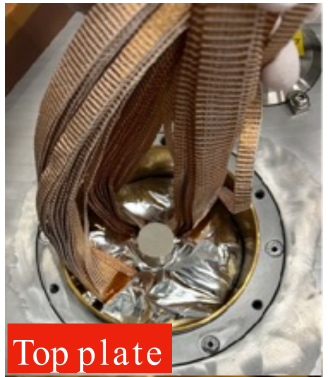
D-sub for MMCs

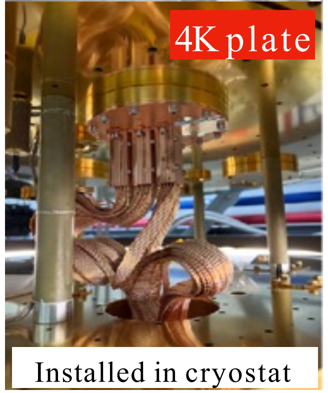






50K anchoring part with ribbon cable

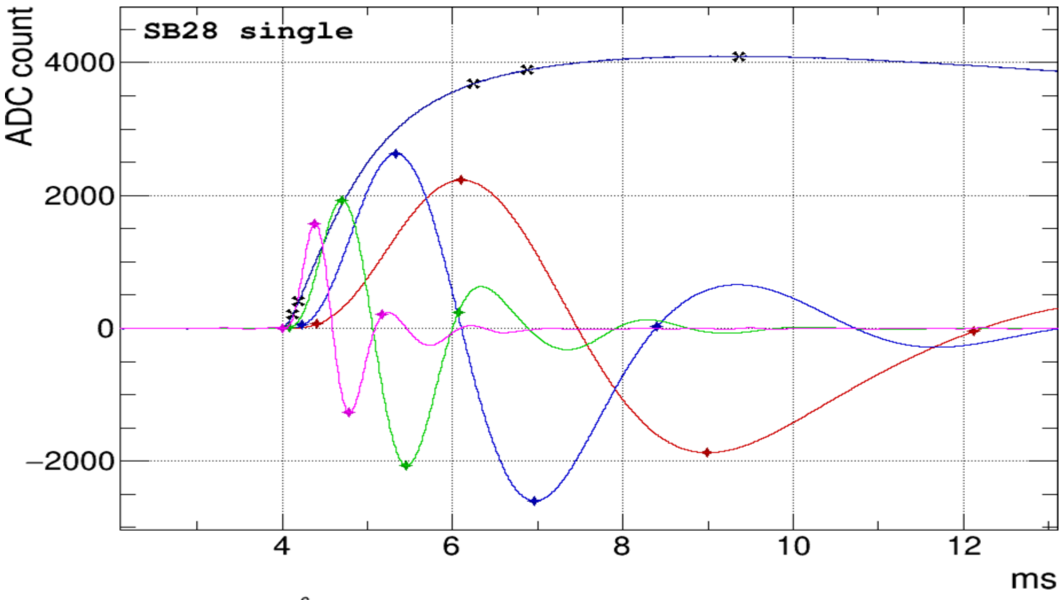




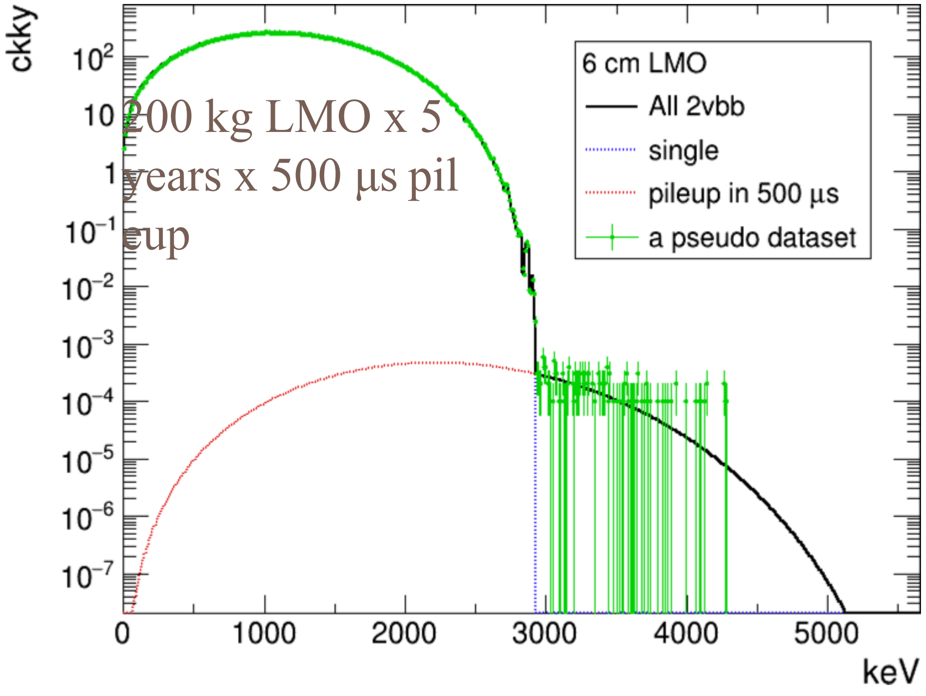
- Each bundle consists 90 channels of MMCs and SQUIDs

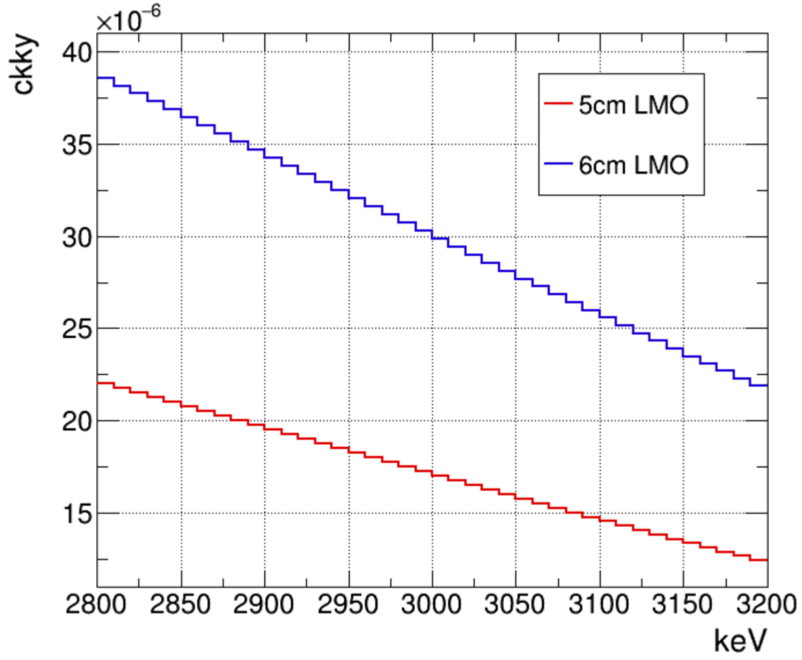
Pileup contribution of AMoRE-II

- Thanks to fast timing response of MMC, the pileup background of AMoRE-II is within the experimental requirement even with ~ 500g detector.
- Need multi-variable analysis to obtain the rejection efficiency high.



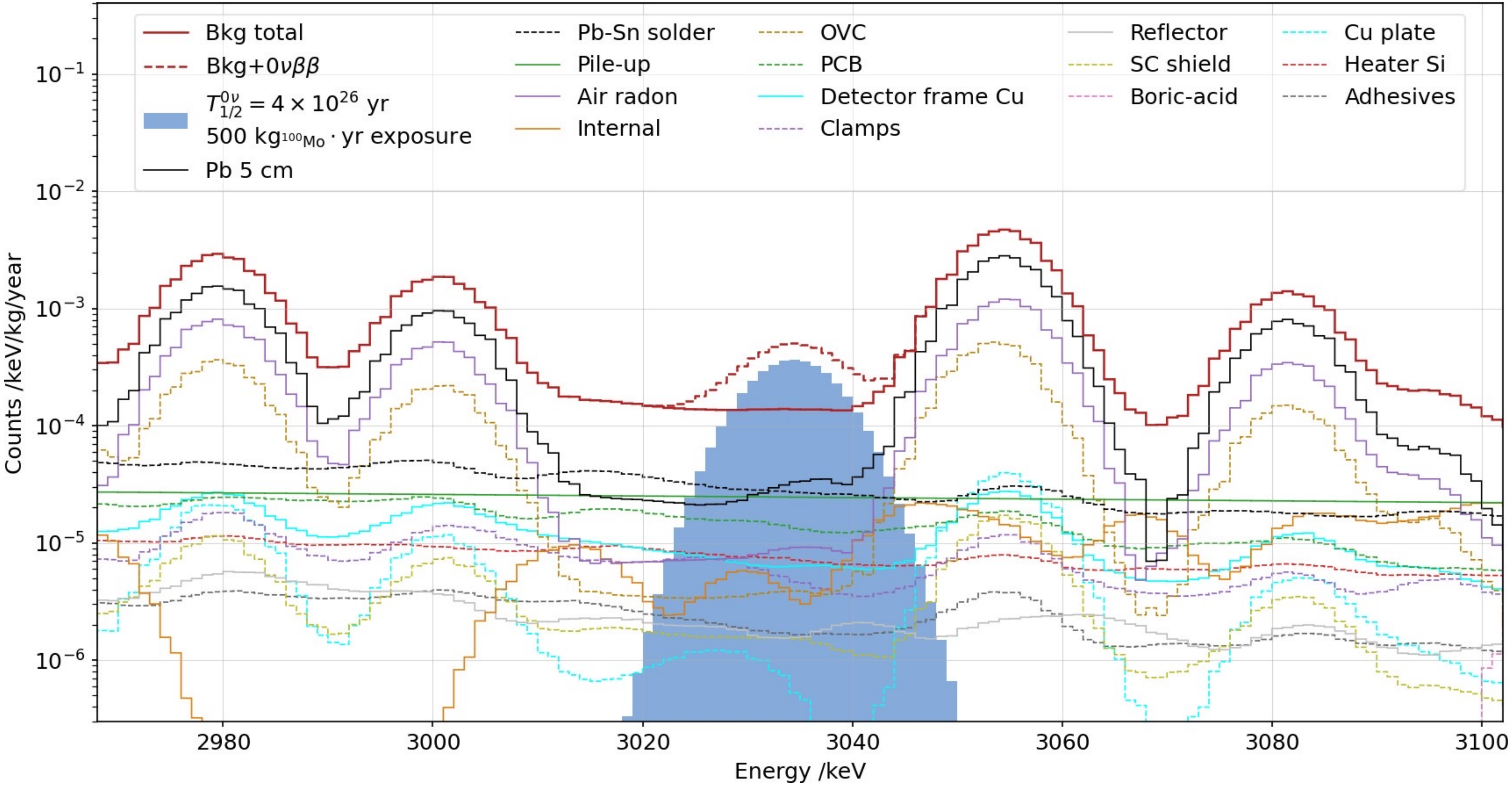
Pile-up backgrounds





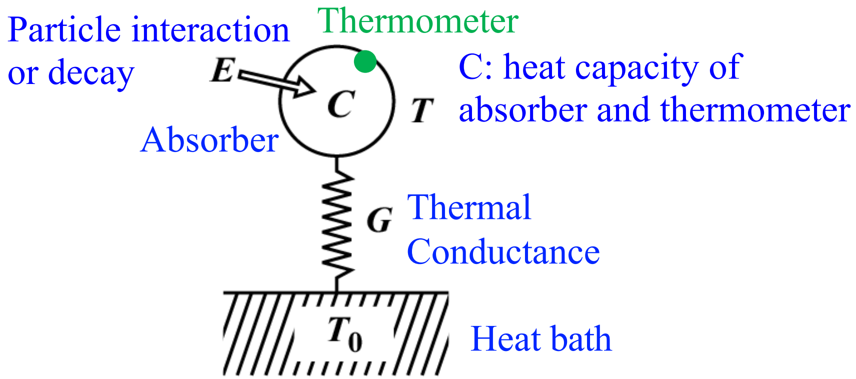
Background estimation

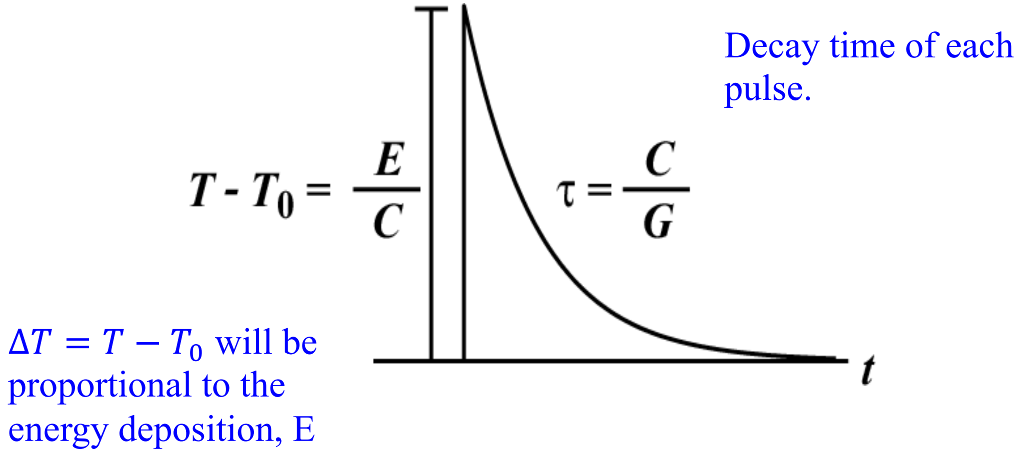
b~10^{-4} ckky, ***ΔE***=10 keV FWHM



Overview of AMoRE experiment

- AMoRE experiment aim to search $0\nu\beta\beta$ of ^{100}Mo ($Q_{\beta\beta}$=3.034 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.

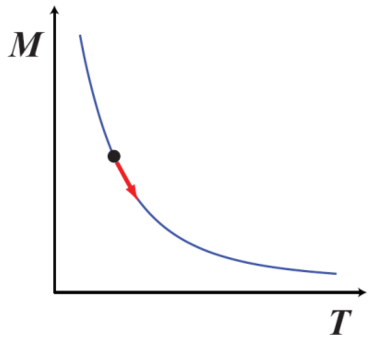




- A few inorganic crystals have Debye temperature(T_D), ~ 300 K. The heat capacity ($C \propto (\frac{T}{T_D})^3$) of such crystals of a few hundred grams are order of 10^{-10}-10^{-9} J/K at 10 mK temperature.
- ~3 MeV signal of neutrinoless double beta decay will increase the temperature of the crystal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

Thermometer - Metallic Magnetic Calorimeter (MMC)

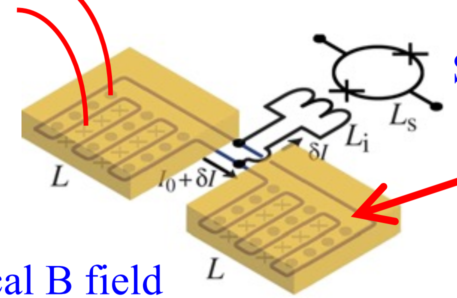
- Paramagnetic alloy, Au(Ag):Er (300-1000 ppm), in a magnetic field by persistent current in superconductive (Nb) wire.
- Magnetization (M) variation with temperature read by a SQUID



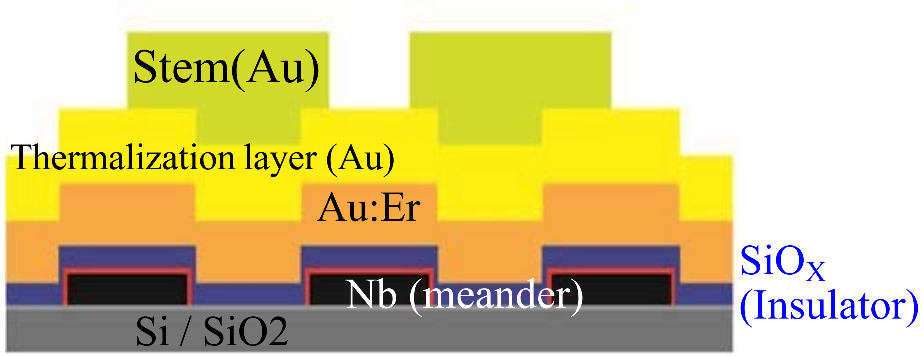
$$\delta E \rightarrow \delta M \rightarrow \delta L \rightarrow \delta \Phi_S \rightarrow \delta V$$

MMC SQUID

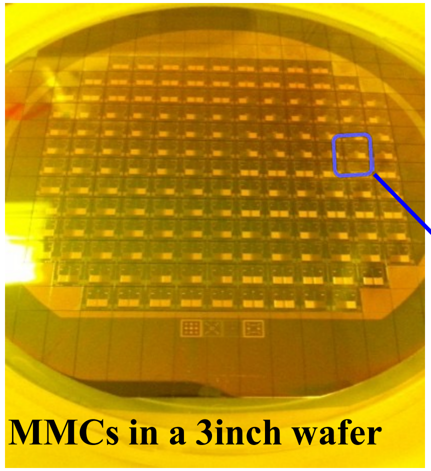
To Au foil on the crystal or light absorber

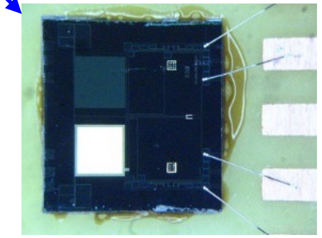


- Pro : High energy resolution, Fast, Large dynamic range, No bias heating
- Con : Complex, More wires & materials needed for SQUIDs and MMCs



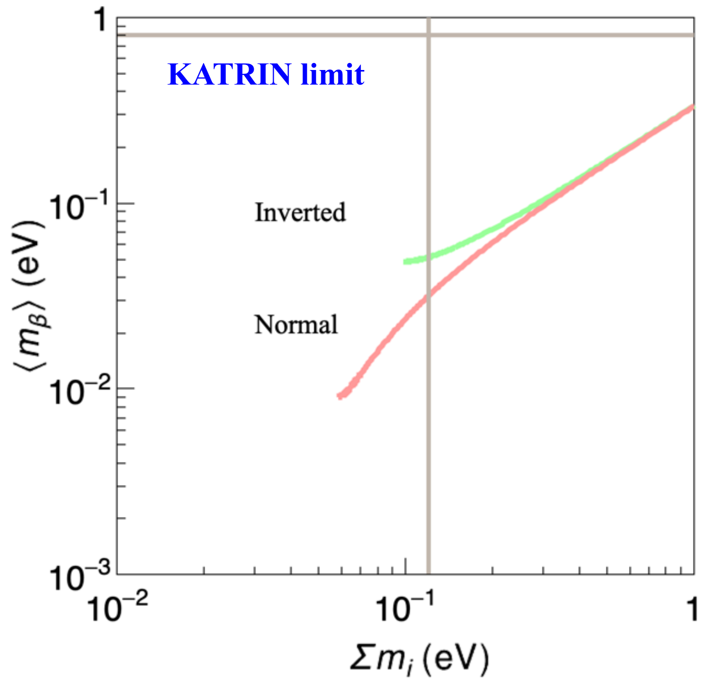
Cross section of MMC

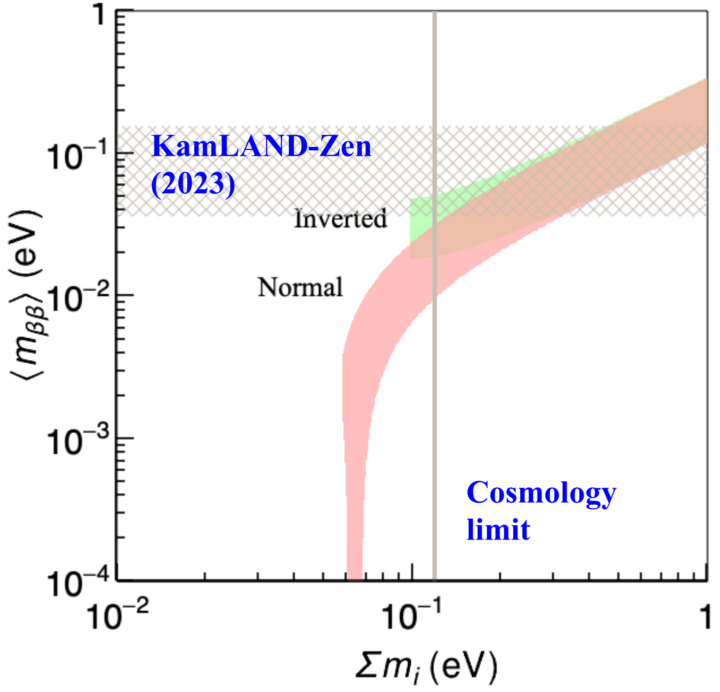


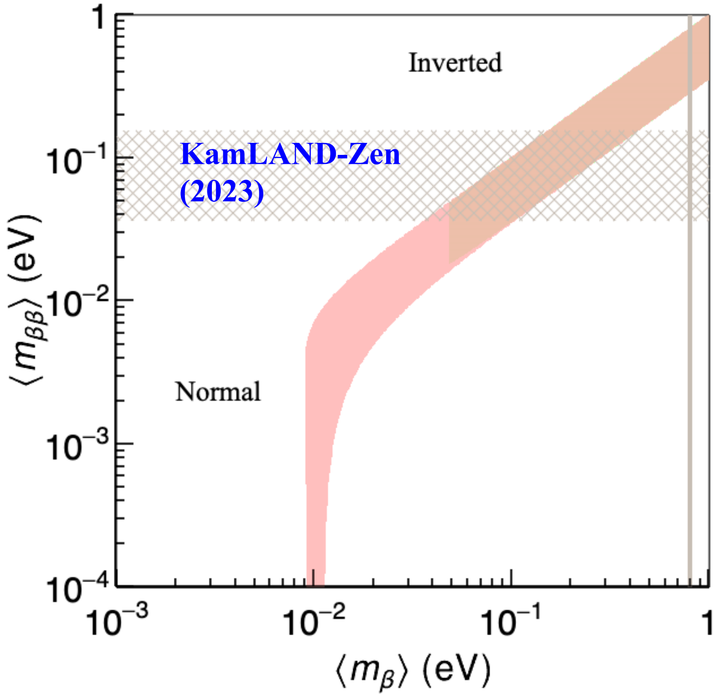


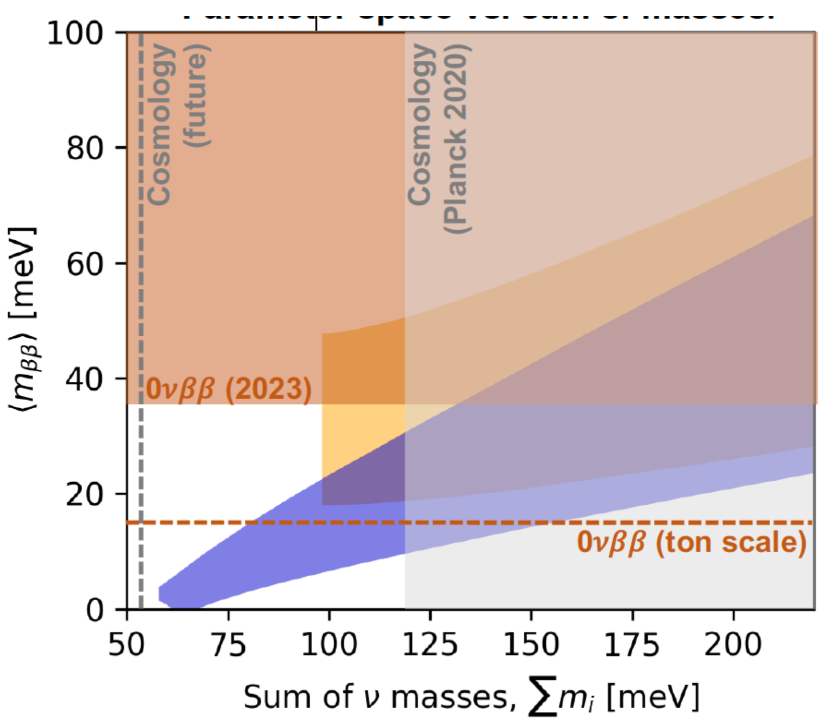
Current Mass Limits

- Neutrino mass is constrained by beta decays and cosmology.



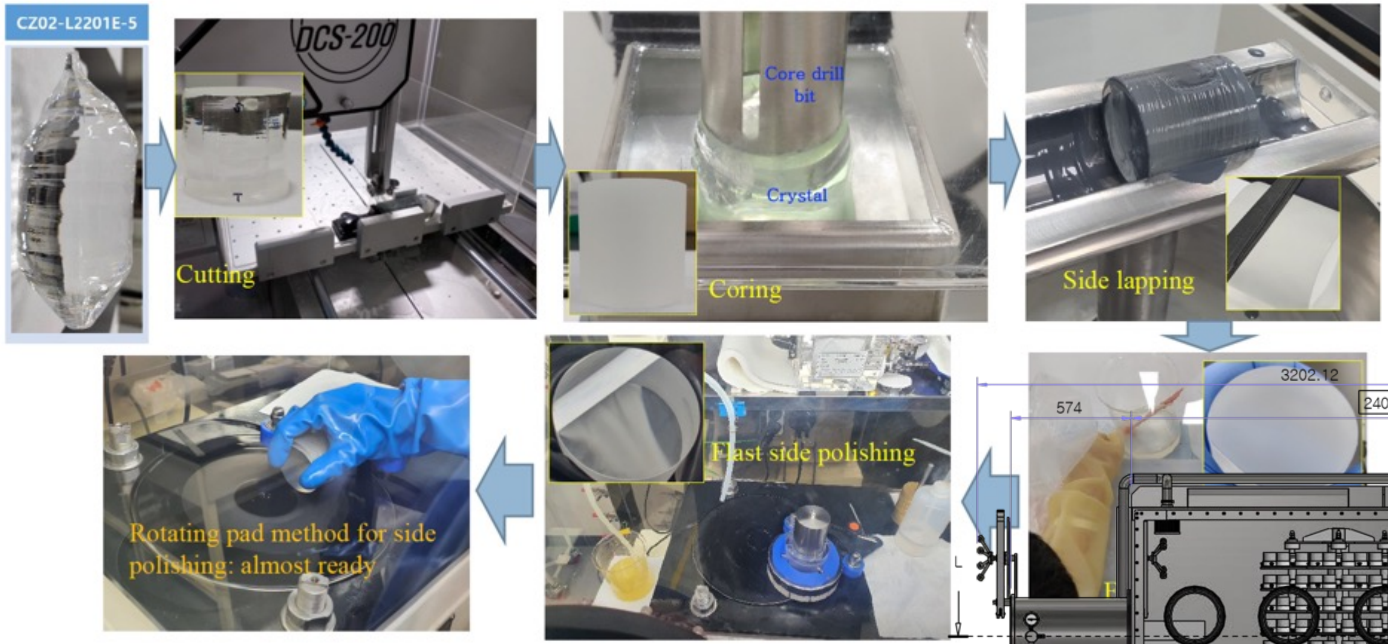


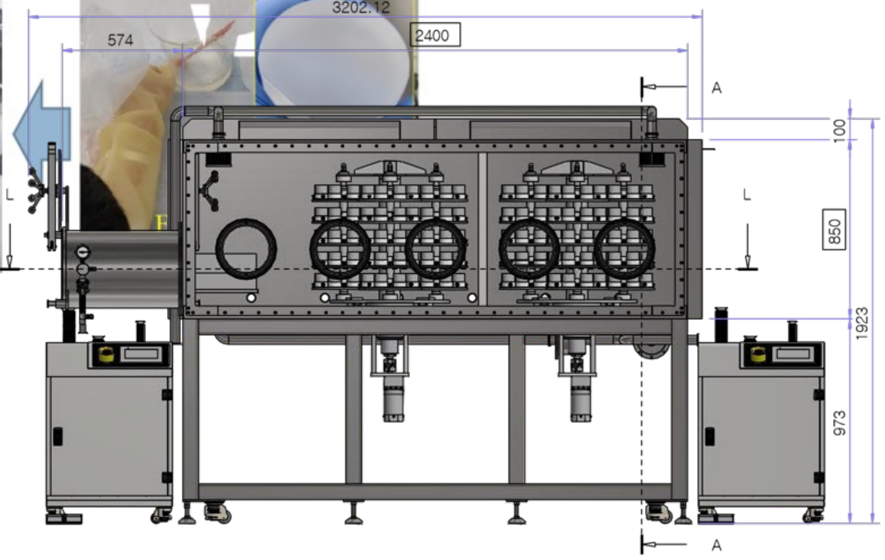




Crystal growing

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





- Dry box for crystal storage

Goal of CUP

AMORE
COSINE
NEOS
NEON
LZ
GBAR
SK

2000 -
KIMS, RENO, XMASS

- Discovery of Dark Matter and Neutrino Physics
- Construct world class underground laboratory
- Nurturing next generation astroparticle physicists
- World class research facility for ultra-rare events