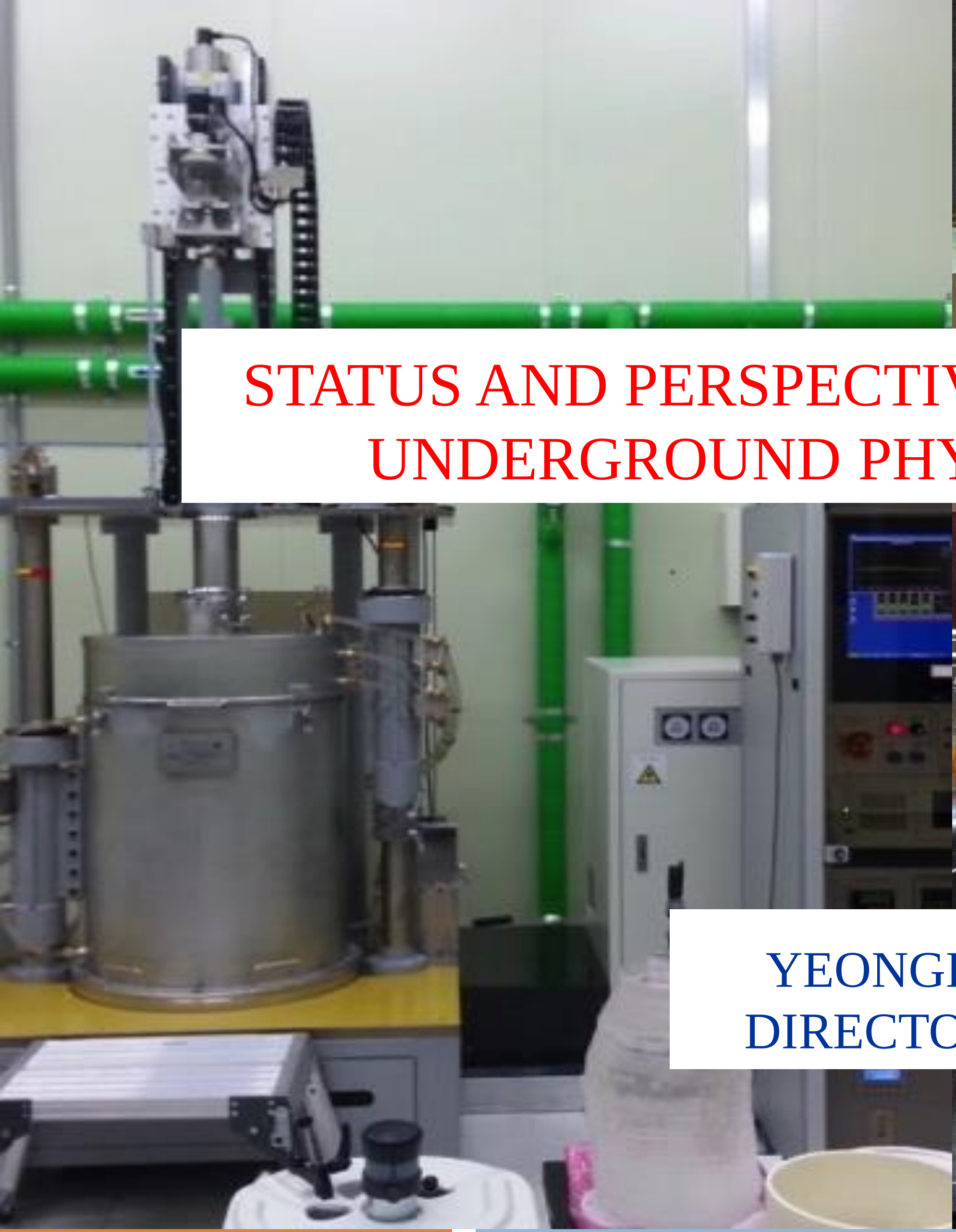
STATUS AND PERSPECTIVES OF THE CENTER FOR UNDERGROUND PHYSICS AT IBS, KOREA



YEONGDUK KIM
DIRECTOR OF CUP

2018. 11. 29.

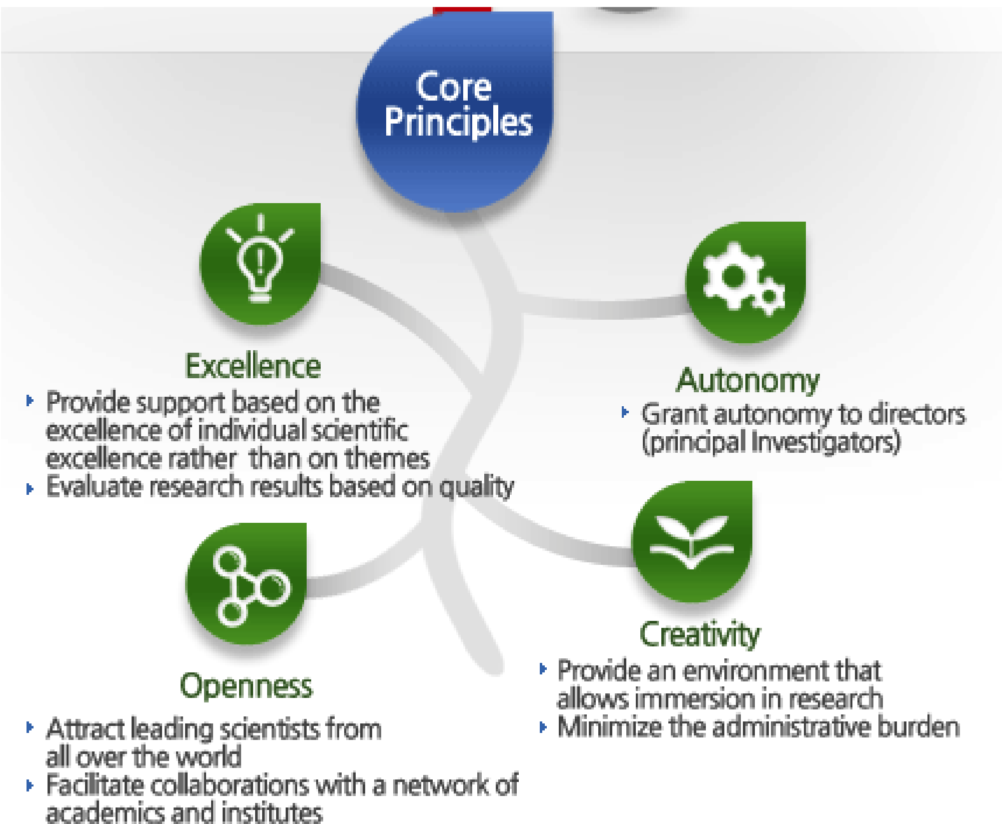
Gran Sasso, LNGS

Contents

- **Institute for Basic Science**
- **CUP**
- **Search for $0\nu\beta\beta$ – Status of AMoRE**
- **Search for sterile neutrinos – Status of NEOS**
- **Future plan**

Institute for Basic Science

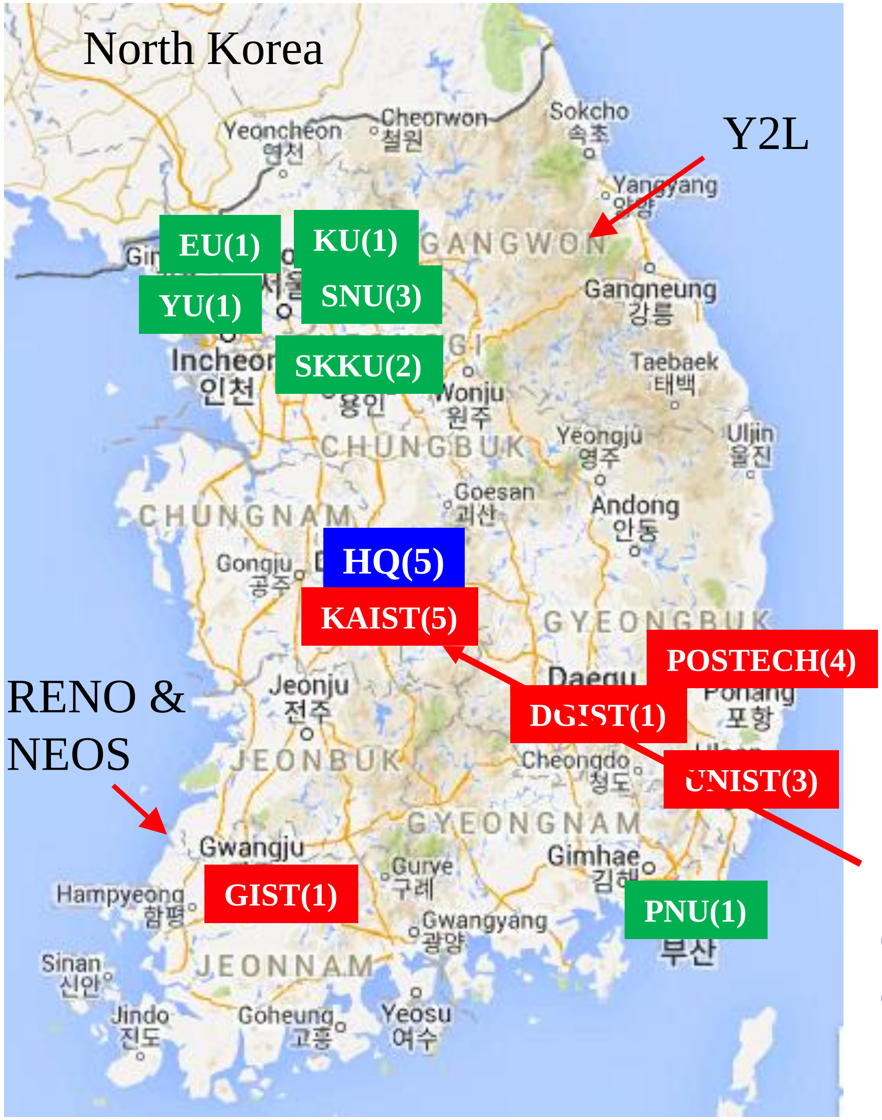
- Began to promote basic science of Korea in 2012.
- In 2017, 28 Research Centers are established.
- Radioactive Beam Accelerator Project is included.
- Benchmarking for Max Planck Institute and RIKEN.
- Each center budget : 3M – 10 M$ / year
- 5+3+3.. evaluation system.



1st, Se Jong Oh

Current, Doo chol Kim

Overview of IBS



- 28 Research Centers :
  1. Headquarter centers (5) :
  2. Campus centers (14) :
  3. Extramural centers (9)
- Radioactive Beam Accelerator Project is under construction.
- Each center budget : 3M – 10 M$ / year, Total 300 M$
- ~ 1000 employees.

CAPP (Center for Axion and Precision Physics)

CTPU (Center for Theoretical Physics of Universe)
CUP (Center for Underground Physics)

Rare Isotope Science Project (RISP) in Korea

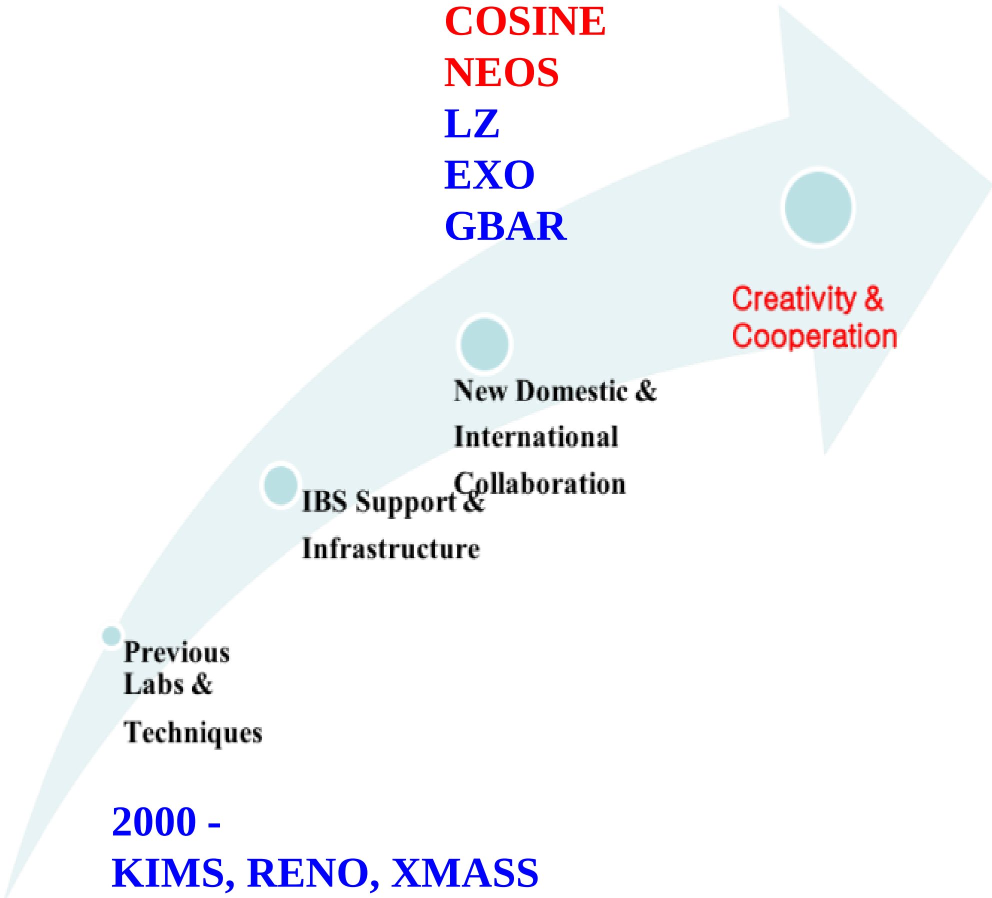
- **Project period: 2011 12. – 2021 12. (10.1 years)**
- **Project cost: ~$1.3 B**

-Accelerator and experimental systems: ~$ 420M
-Conventional facility: ~$560M
-Land: ~$ 320M

- **Nuclear Astrophysics**
- **Exotic nuclei**
- **Superheavy element search**

Goal of CUP

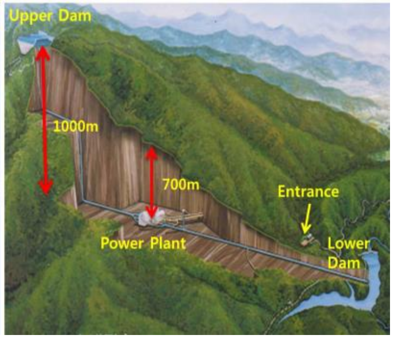
AMORE
COSINE
NEOS
LZ
EXO
GBAR



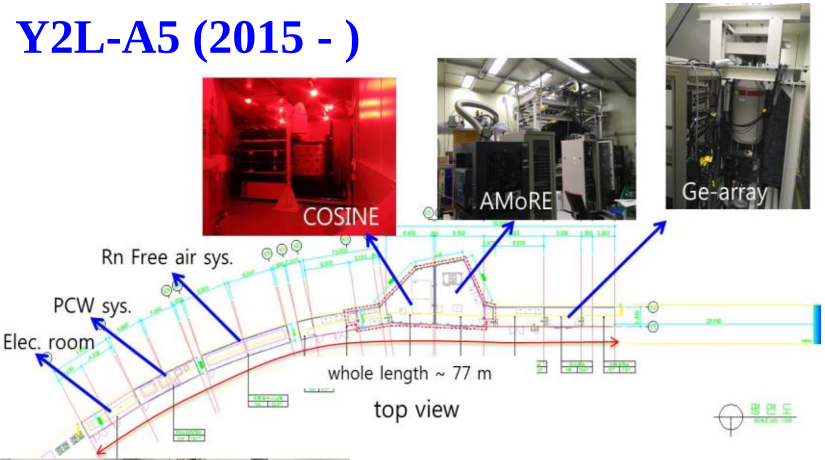
2000 -
KIMS, RENO, XMASS

- 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

CUP Facilities



Y2L-A5 (2015 -)



IBS-HQ (2018. 2 -)

ion refrigerator installed in t

+ Yemi Lab.

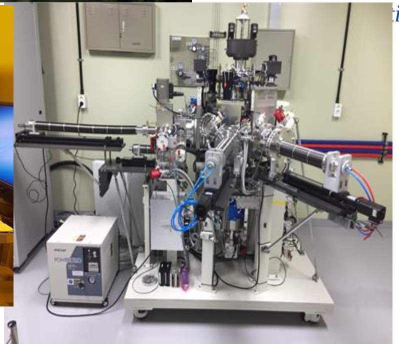
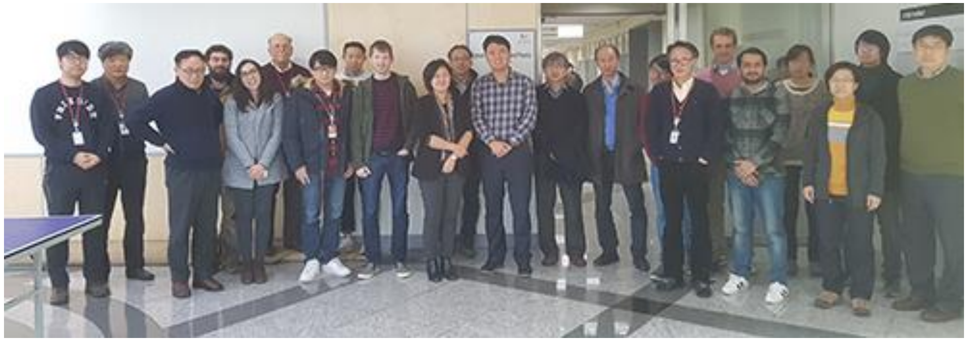
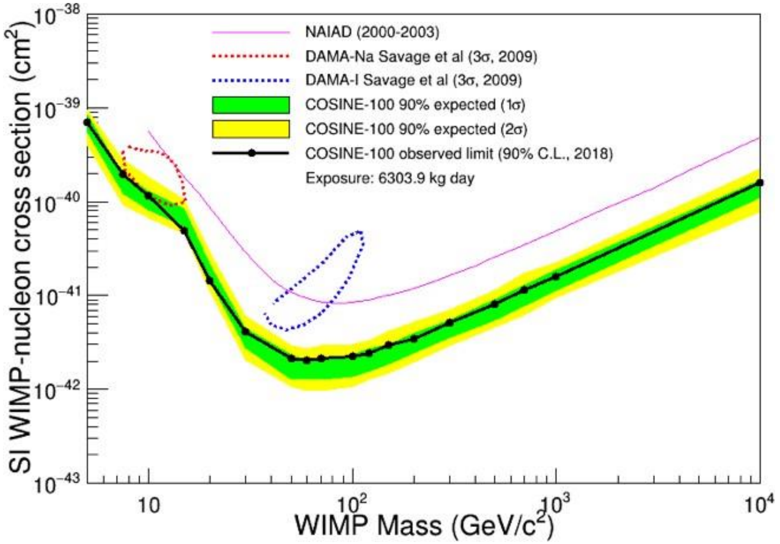


Figure I-14: CUP sputter installed in cl ass-1000 clean room

1. Dark Matter Search - COSINE

Joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals.
(Goal to **verify DAMA/LIBRA's observation**)



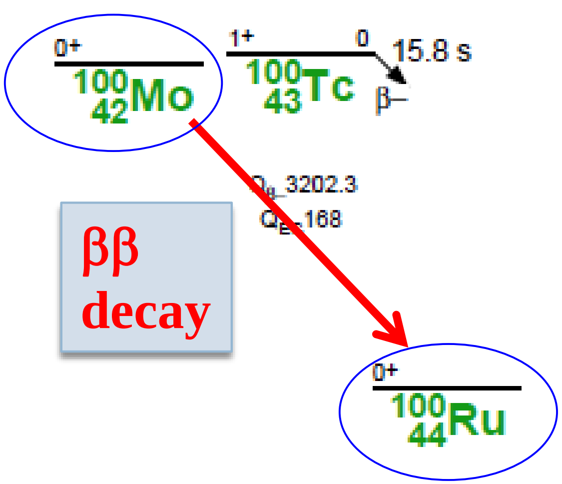


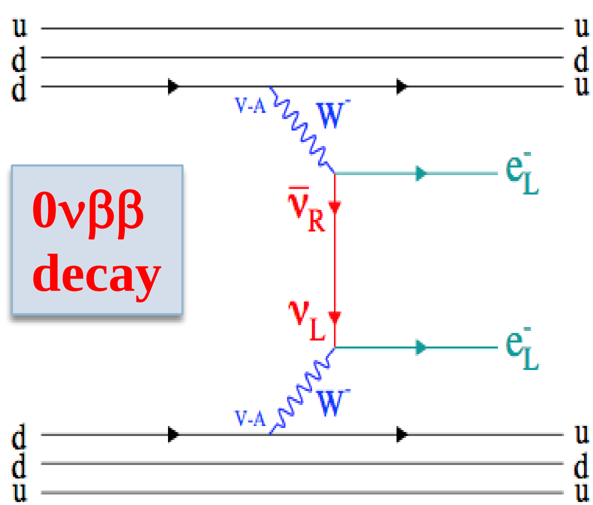
2. Search for Neutrinoless double beta decay - AMoRE

Observation of 0νββ

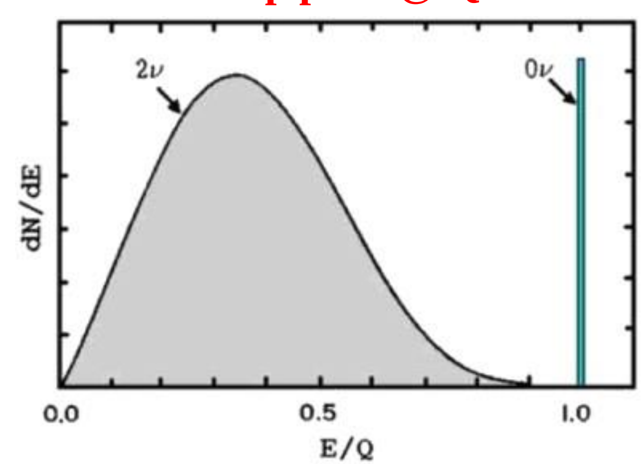
- **will confirm**
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.
- **will support on**
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

$$m_\nu \approx \frac{m_D^2}{m_N}$$





Signal :
sharp peak @ Q-value



Neutrino mass from 0νββ experiment

- **Half-lives of 0νββ inversely proportional to (effective neutrino mass)^2 by theory.**
- **To discover 0νββ, we need a good energy resolution and extremely low background at that energy.**

Phase factor

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

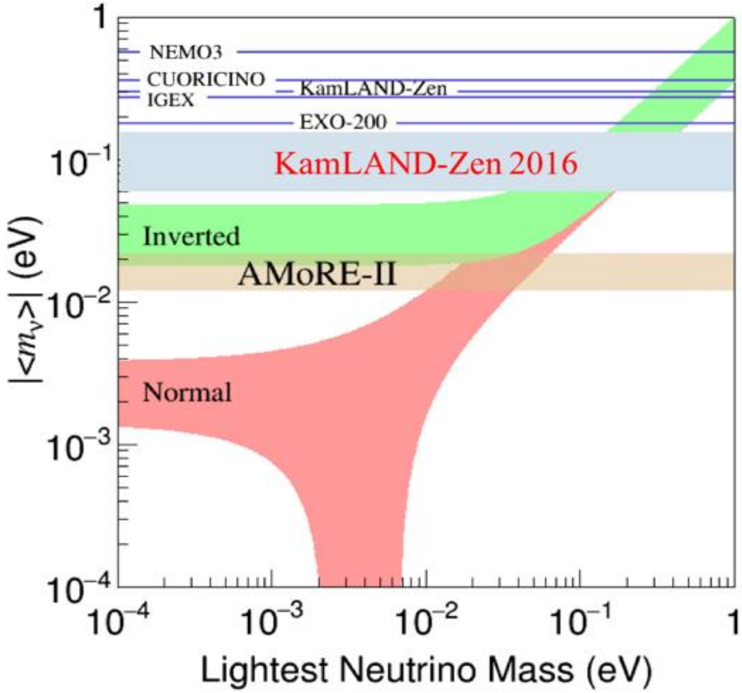
Half-life Measured

Nuclear Matrix Element

Neutrino Mass

$$T_{1/2}^{0n} \rightarrow m_{bb}$$

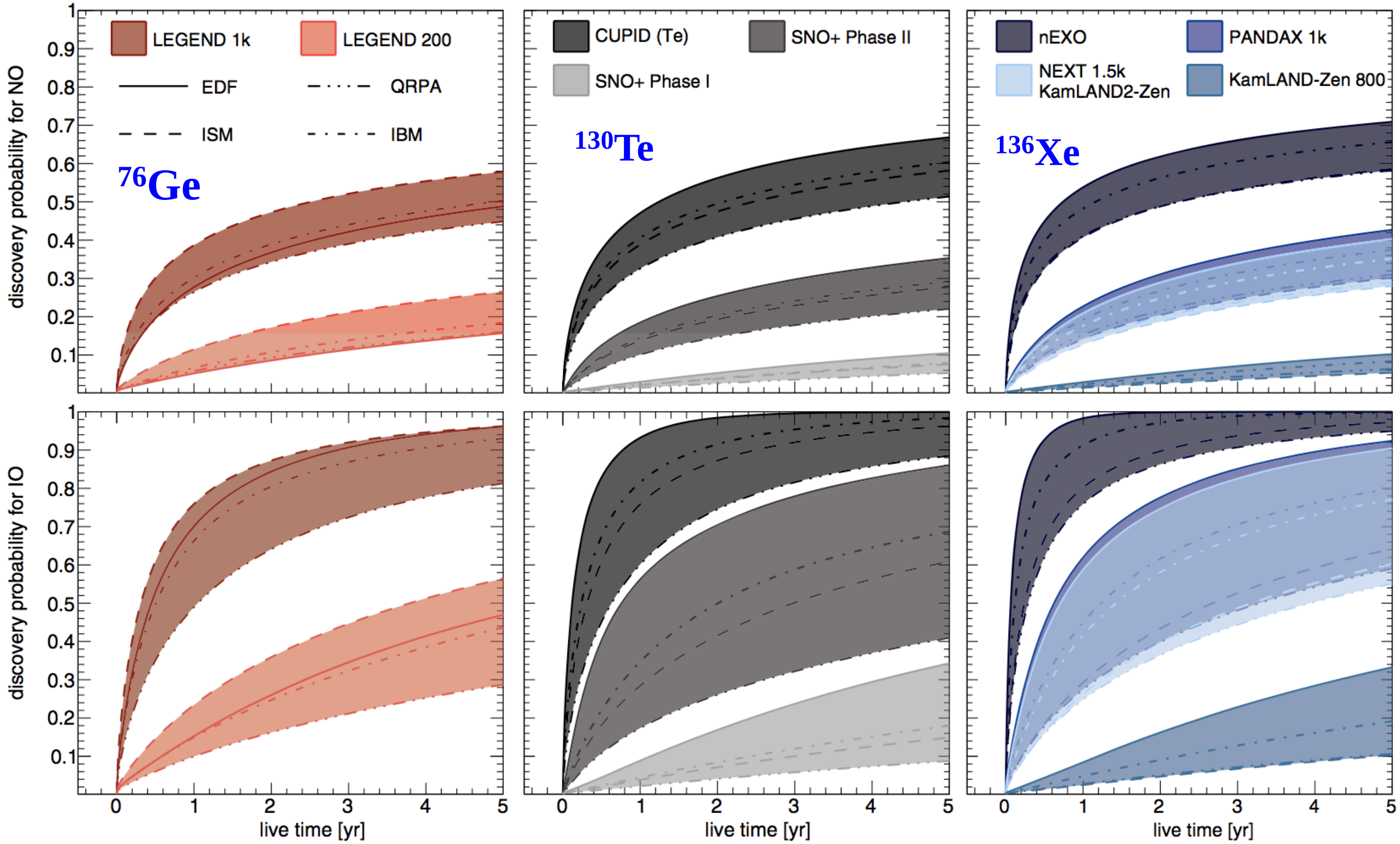
for light neutrino exchange model.



Discovery probability

- Discovery probability for NO and IO assuming logarithmic mass distribution and flat in the angles and phases.
- Even normal hierarchy, the probability is high ~ 50% in 5 years for next generation experiments.

Agostini, PRD 96, 053001 (2017)



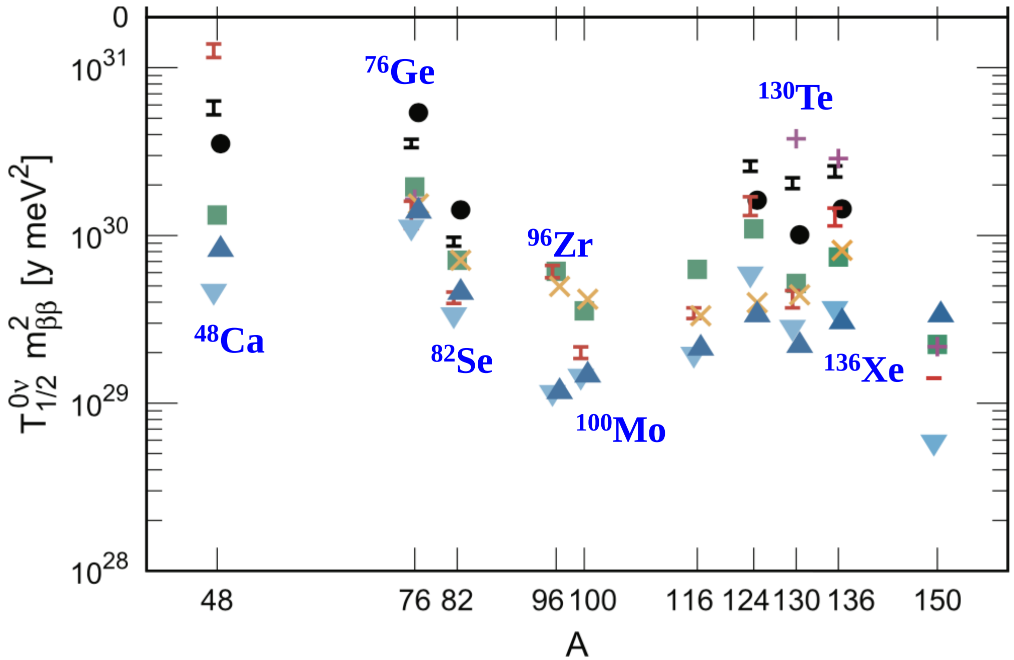
Current best results for 0νββ

Nucl.	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T_{1/2}$ (10^{24} Y)	M (eV)	Ref.
^{48}Ca	4270.0	0.187	0.44	CANDLES	> 0.058	<3.1-15.4	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	15	GERDA-II	>53	<0.15-0.33	Nature 544, 47 (2017)
^{82}Se	2997.9	9.2	0.92	CUPID-0	> 2.4	<0.38-0.77	PRL120, 232502 (2018)
^{100}Mo	3034.4	9.6	0.07	NEMO-3	>1.1	<0.33-0.62	PRD89, 111101 (2014)
^{116}Cd	2813.4	7.6	0.26	AURORA	> 0.22	<1.0-1.7	PRD98, 092007 (2018)
^{130}Te	2527.5	34.5	9.1	CUORE	> 15	<0.11-0.52	PRL120, 132501 (2018)
^{136}Xe	2458.0	8.9	21	KamLAND -Zen	> 107	<0.06-0.16	PRL117, 082503 (2016)
^{150}Nd	3371.4	5.6	0.08	NEMO-3	> 0.02	<1.6-5.3	PRD 94 072003 (2016)

Cryogenic experiments begin to produce the best limits in 2018.

Why ^{100}Mo ?

Expected Half-lives



- ^{100}Mo is expected to have a smallest half-life except ^{150}Nd.
- Natural abundance ~ 10 % → enrichment cost is moderate.
- Background will be low for Q>3MeV. (Q=3.034 MeV for ^{100}Mo)
- We need data for multiple isotopes to study the various models with data if discovery is done for any isotope.

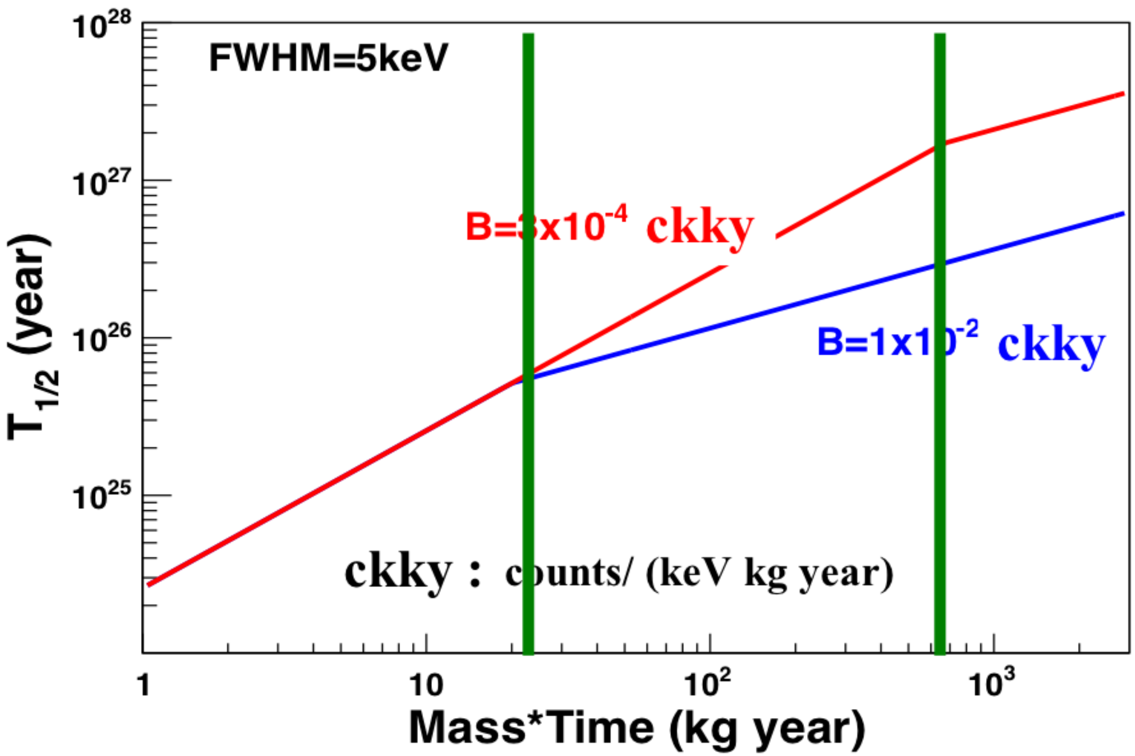
"zero" Backgrounds

- If "zero" backgrounds in ROI(Region of Interests), the half-life limits are proportional to the detector mass and DAQ time. If finite backgrounds, sqrt (MT).

$T_{1/2}^{0\nu} \propto MT \; (for\ zero\ backgronds)$

$T_{1/2}^{0\nu} \propto \sqrt{\frac{MT}{b\Delta E}}$(for finite backgrounds)

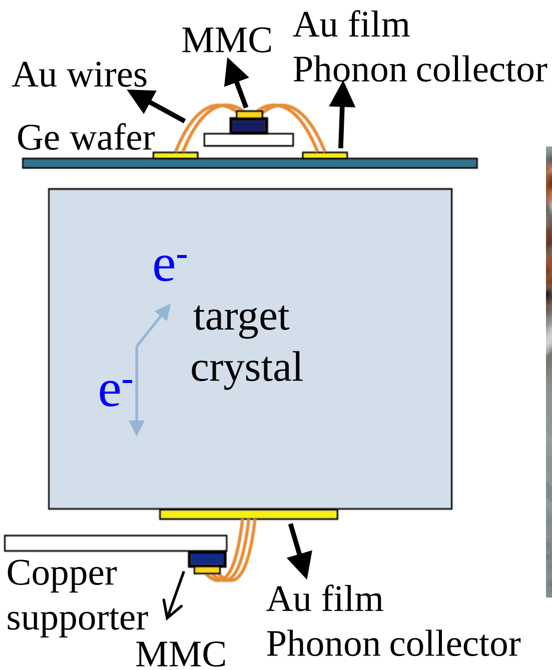
Background Unit : ckky : counts/ (keV kg year)

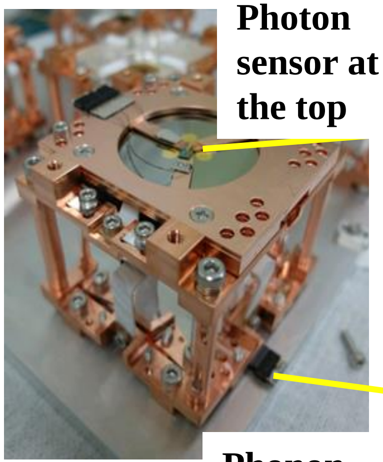


Overview of AMoRE Project

Principle of AMoRE detector

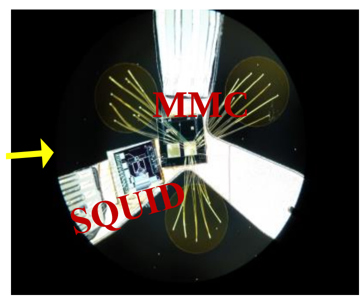
- **Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC**
- **For Each crystal, phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal).**

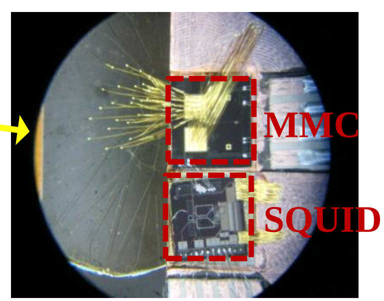


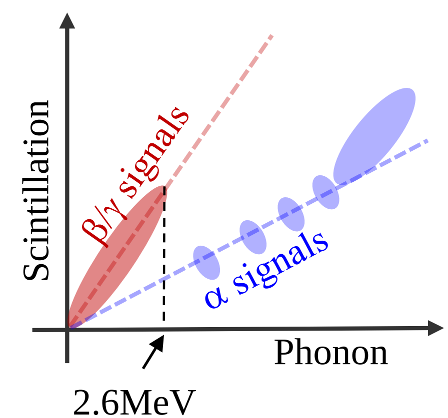


Photon sensor at the top

Phonon sensor at the bottom

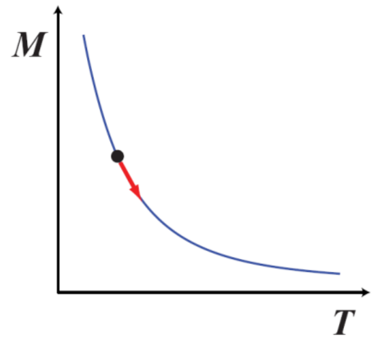


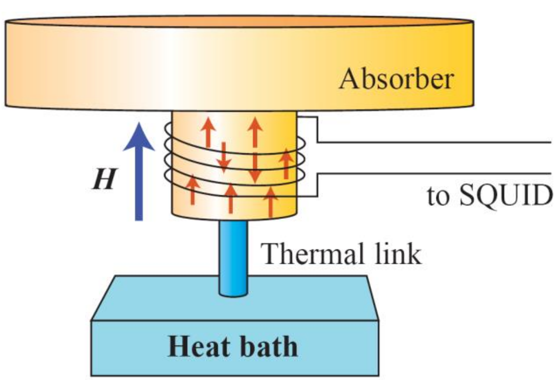


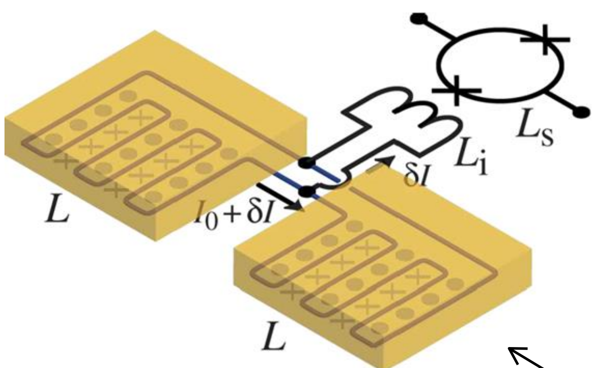


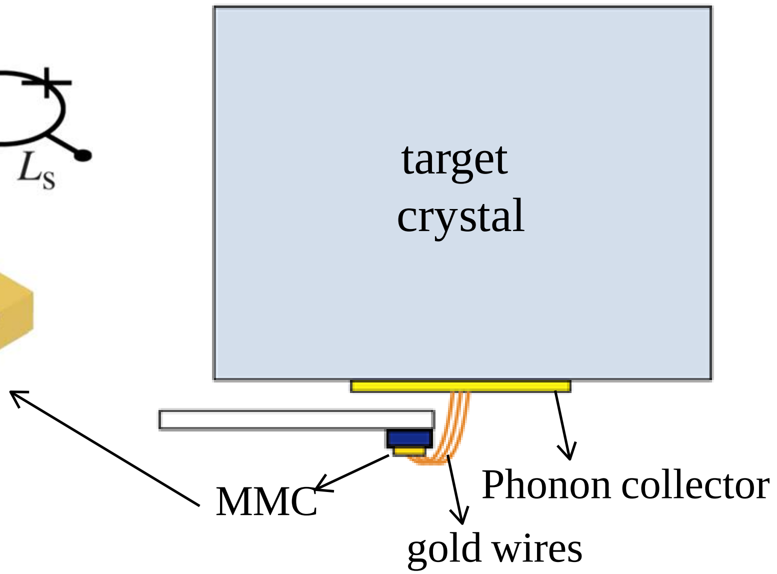
Metallic Magnetic Calorimeter (MMC)

- Paramagnetic alloy in a magnetic field
  Au:Er(300-1000 ppm), Ag:Er(300-1000 ppm)
  → Magnetization variation with temperature
- Readout: SQUID
- High energy & timing resolution, Good linearity, Large dynamic range, No bias heating, Absorber friendly
- More wires & materials needed for SQUIDs and MMCs









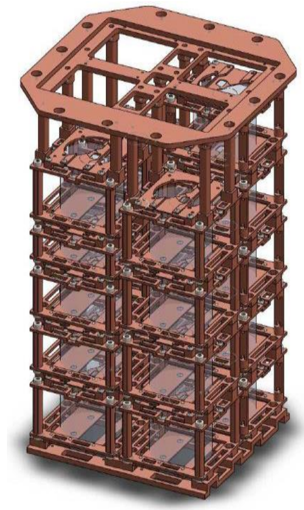
Plan of AMoRE Project

- 100 kg ^{100}Mo double beta decay experiment, largest experiment Q> 2614 keV
- One of two ^{100}Mo DBD projects.

$^{40}Ca^{100}MoO_4$

~ 1.9 kg

AMoRE Pilot



$(^{40}Ca,X)^{100}MoO_4$

~ 6 kg

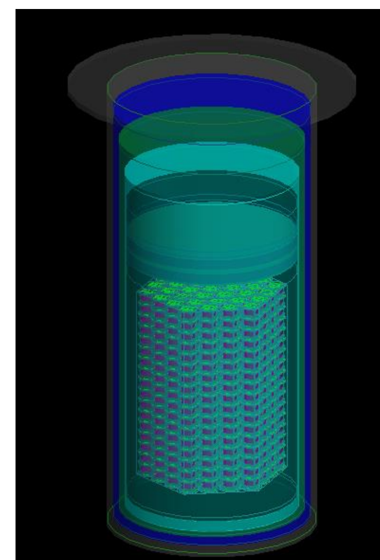
AMoRE-I

X = Li, Na, Pb…

$(^{40}Ca,X)^{100}MoO_4$

200 kg

AMoRE-II



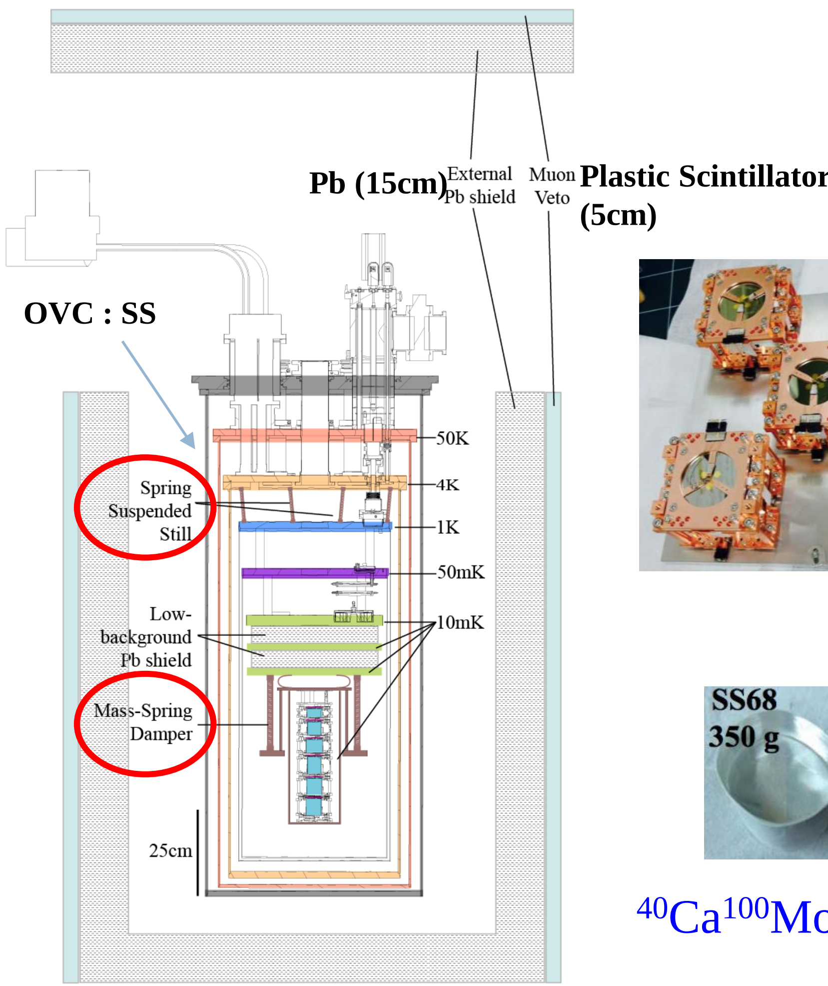
	Pilot	AMoRE-I	AMoRE-II
Crystal Mass (kg)	1.9	6	200
Background Goal(**ckky**)	$<10^{-1}$	$<10^{-3}$	$<10^{-4}$
Schedule	2015-2018	2019-2020	2021-2025

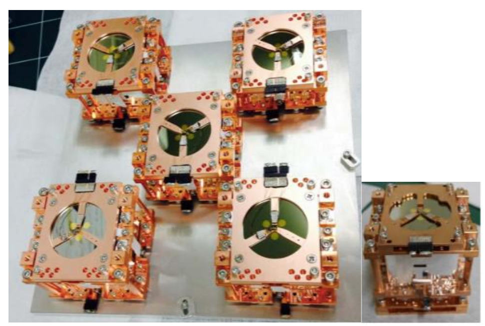
With AMoRE-II $T_{1/2}^{0\nu} > 8.2 \times 10^{26}$ years

13-25 meV

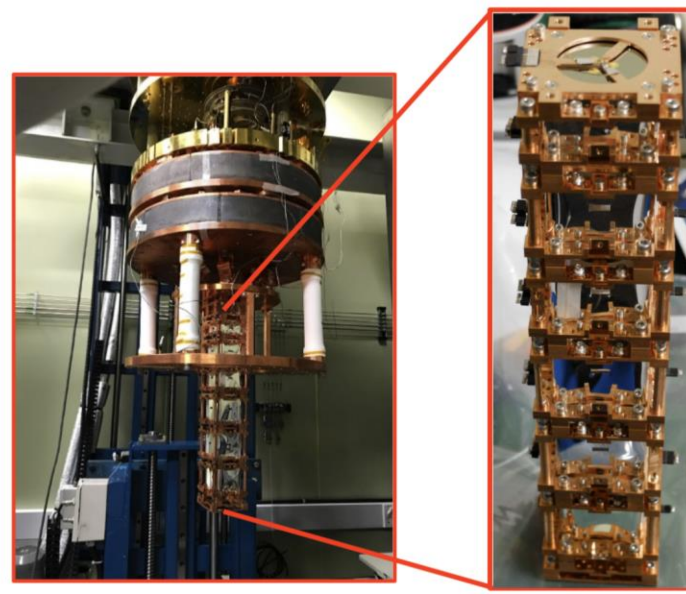
AMoRE-Pilot Setup

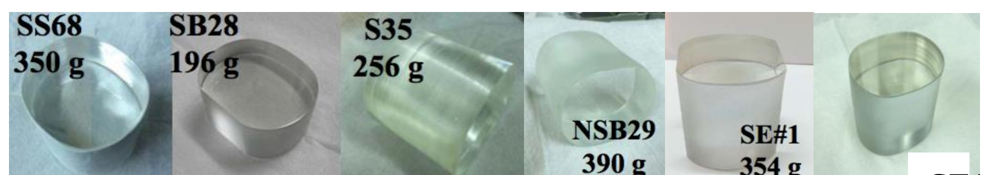
- To demonstrate the detection principle and low backgrounds.
- 6 crystals making total mass 1.89 kg.
- Two vibration reduction systems are installed.





12 detector channels
(6 heat detectors + 6 light detectors)

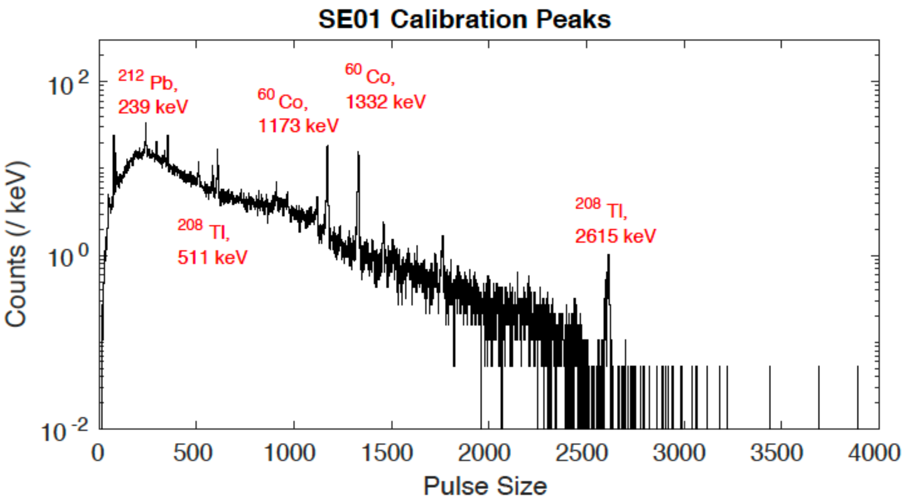


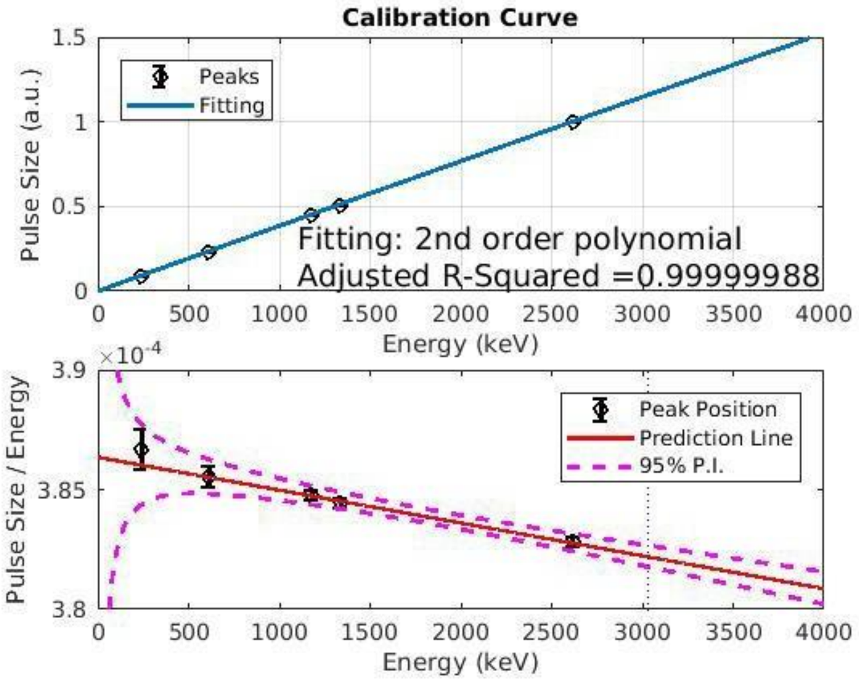


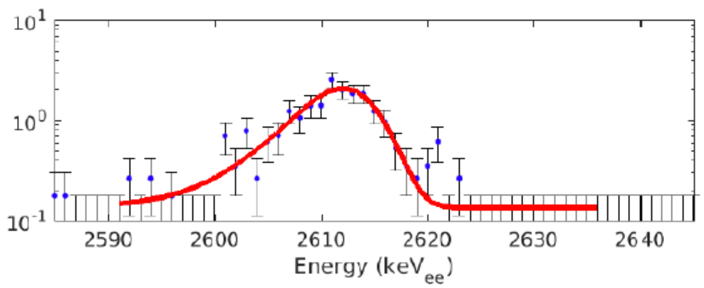
SE#2

$^{40}Ca^{100}MoO_4$ crystals from Russian company, FOMOS.

Energy Calibration



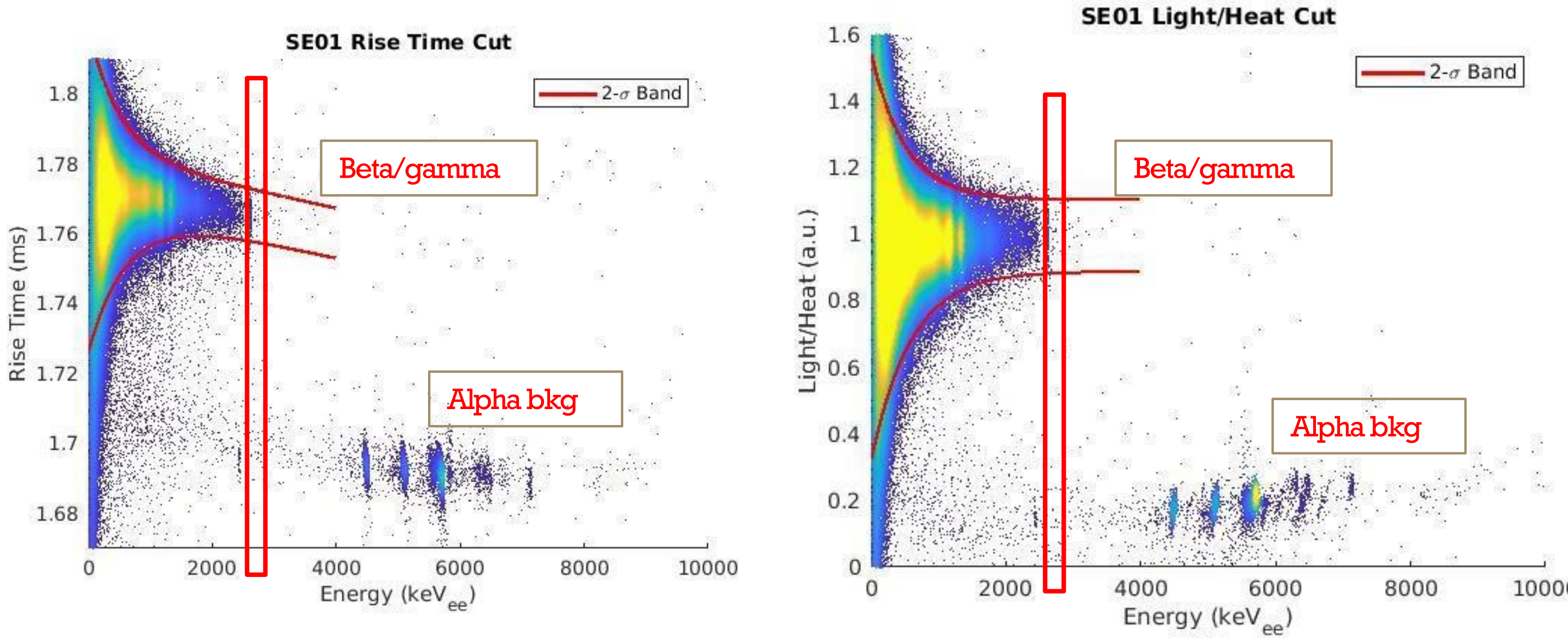




Energy Resolution at ROI (3034 keV)

10.6 – 17.3 keV (FWHM)

PSD



Discrimination Power (DP) in both Rise Time and Light/Heat ratio are used.

10 – 18 at least RT or L/H

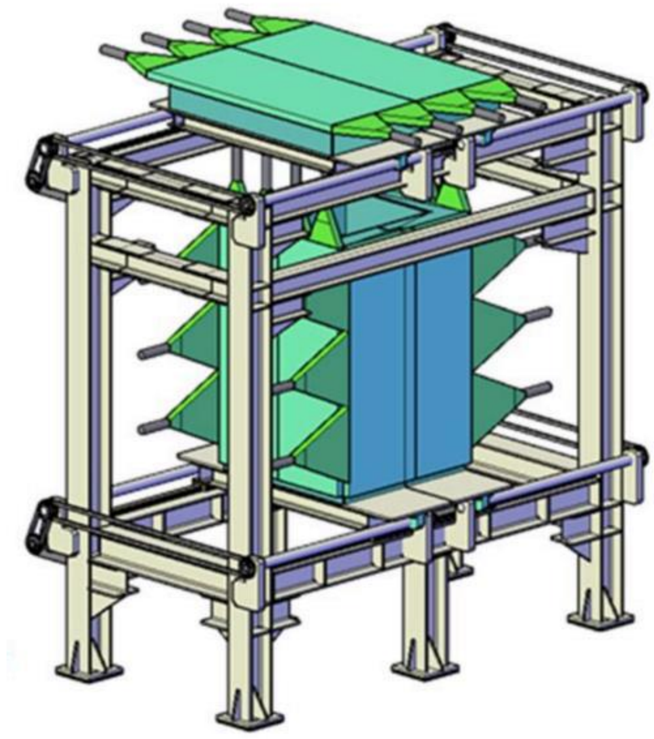
$$DP = \frac{|\mu_\beta - \mu_\alpha|}{\sqrt{\sigma_\beta^2 + \sigma_\alpha^2}}$$

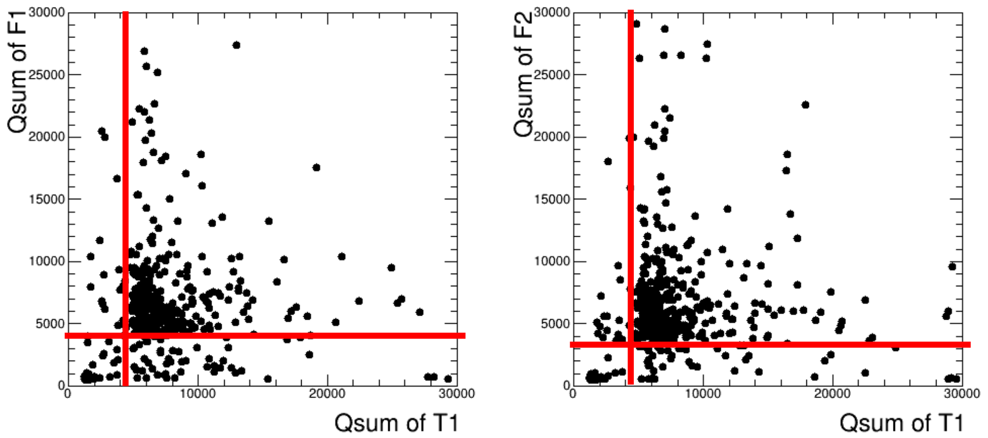
Crystal (mass)	$DP_{L/H}$	DP_{RT}
Crystal 1 (196 g)	7.07	18.0
Crystal 2 (256 g)	15.1	6.22
Crystal 3 (350 g)	14.1	4.12
Crystal 4 (354 g)	11.3	12.5
Crystal 5 (390 g)	10.2	9.64
Crystal 6 (340 g)	8.30	17.2

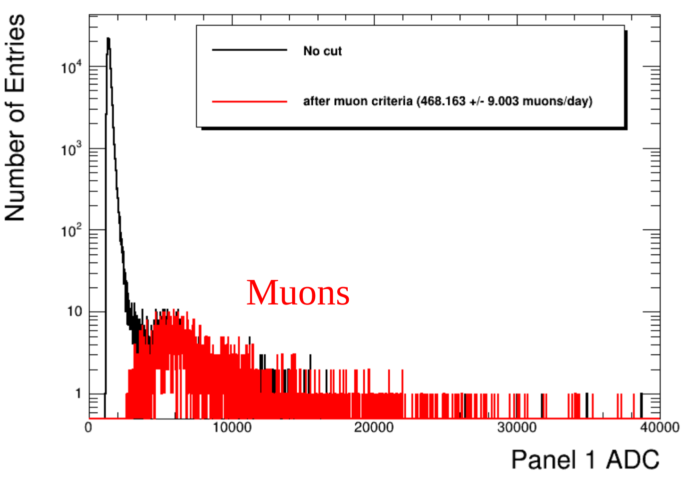
Muon veto counters

- 5cm plastic scintillator with multiple 2" PMTs.
- There is a gap between TOP and SIDES plates.
- About 2140 muons passing a day.

388 muons/day/m^2 on TOP plate.





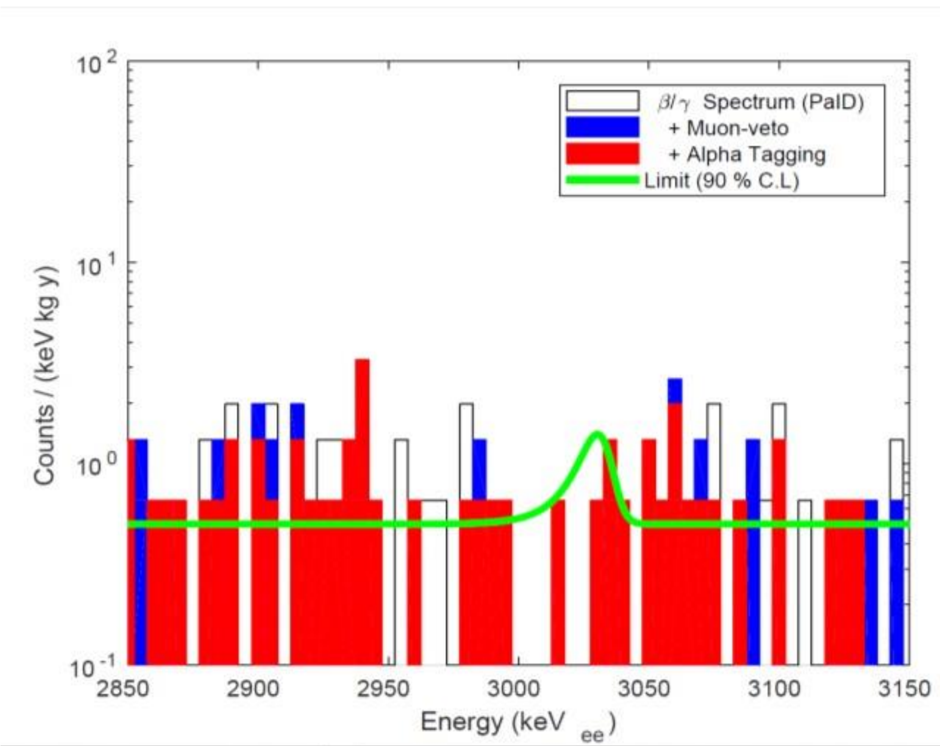


Background spectrum at ROI

- 111 (kg day) exposure.
- Total 80 events at ROI (2850-3150 keV)
- 17 events are vetoed by muon tagging (0.19 ckky) ($\Delta T < 100\mu$)
- 13 events are vetoed by Tl208 decay alphas. (0.14 ckky)

→ 50 events are left as backgrounds. → 0.55 ckky

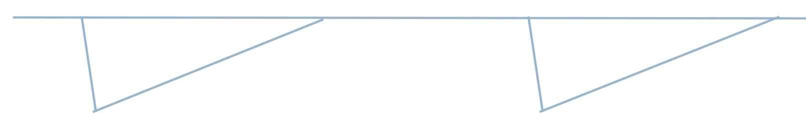
→ $T_{1/2}^{0\nu} > 9.5 \times 10^{22} years$ (90%)



(Q_α=6.207) (Q_β=5.001)

^{212}Bi. → ^{208}Tl → ^{208}Pb

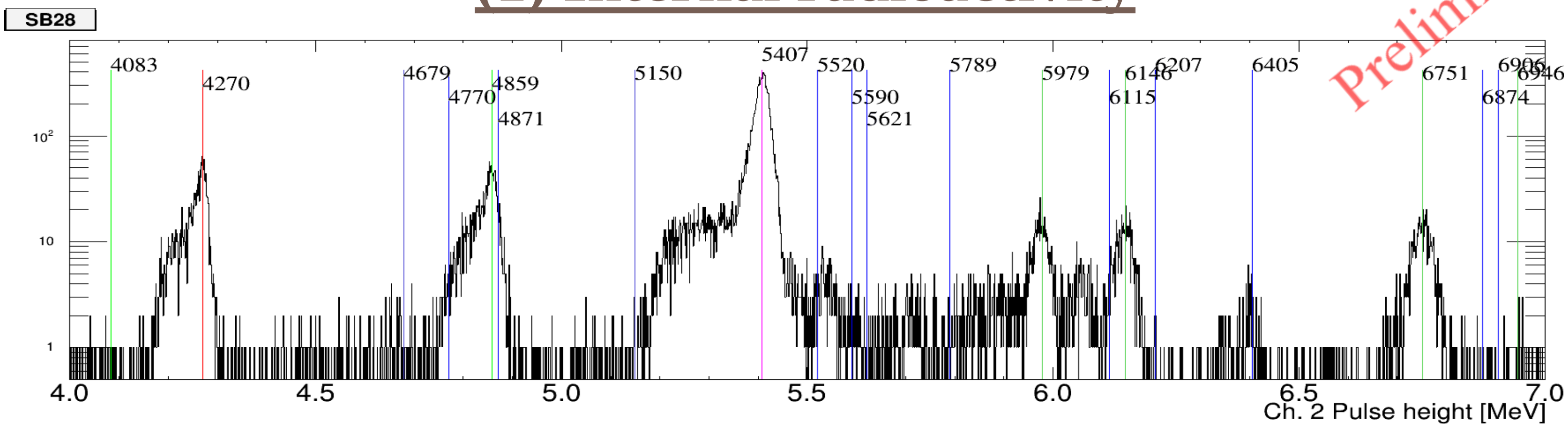
(T=3.1m)



30 min veto after each 6.2 MeV alpha

Now let's try to understand backgrounds

(1) Internal radioactivity



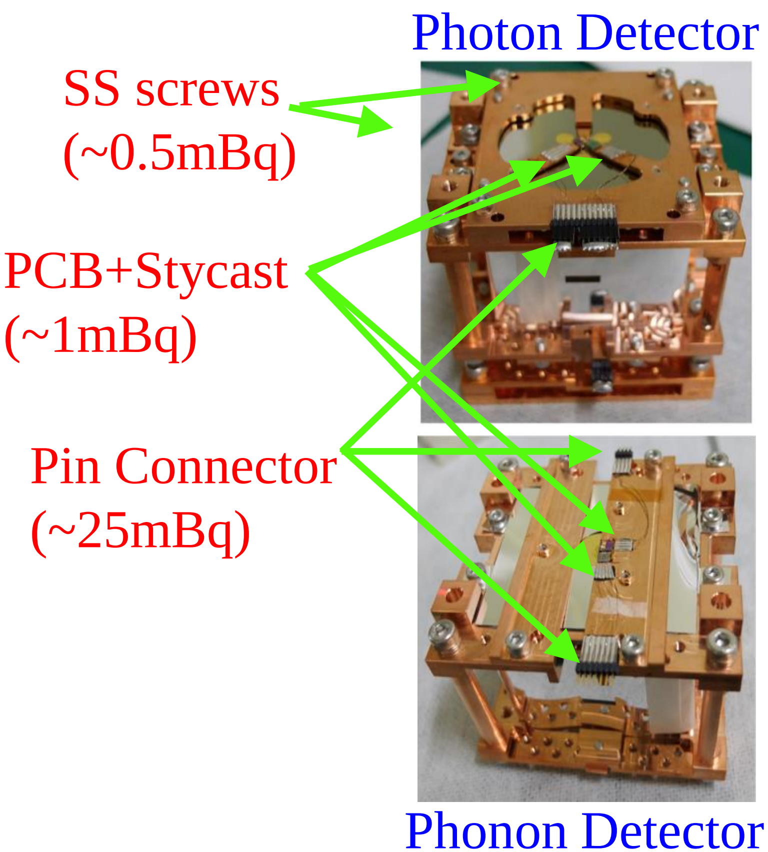
Activity (uB/kg)

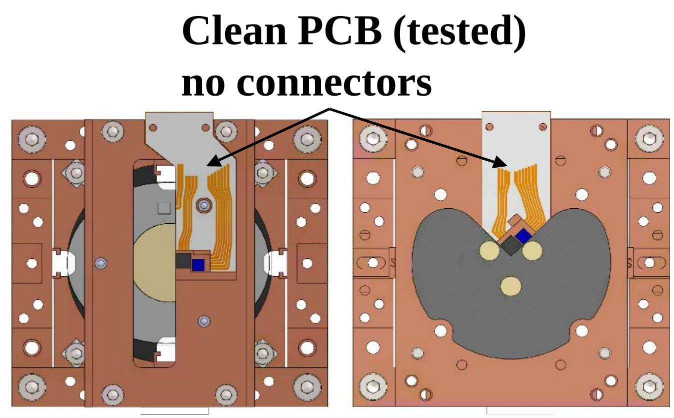
Crystal	Mass (g)	U-238 (^{214}Po)	U-235 (^{215}Po)	Th-232 (^{216}Po)
SB28	196	180(10)	310(10)	37(4)
S35	256	2490(30)	960(20)	870(20)
SS68	350	36(3)	79(5)	13(2)
SE01	354	136(5)	48(4)	12(2)
SB29	390	126(5)	315(9)	56(3)
SE02	340	31(3)	53(4)	11(2)

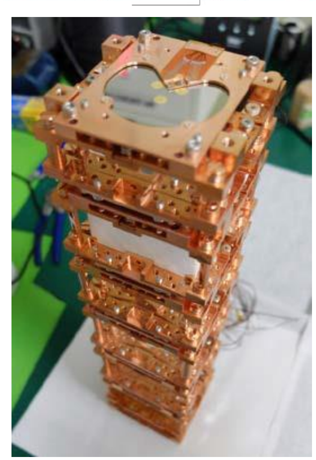
For AMoRE-I setup,
with 6.2 MeV alpha veto,
Th : 50 microBq/kg → ~10^{-3} ckky

(2) Radioactive components in detector unit

- Connectors, glue, and PCB boards were highly radioactive from HPGe measurements.
- Removed these parts for current run in Pilot setup.

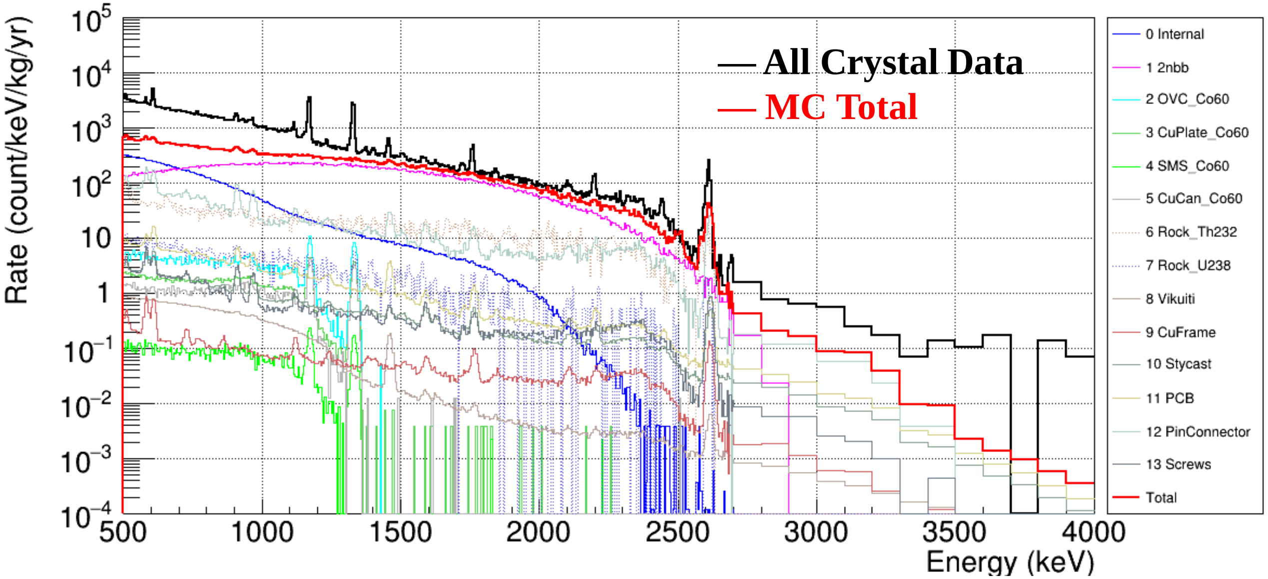


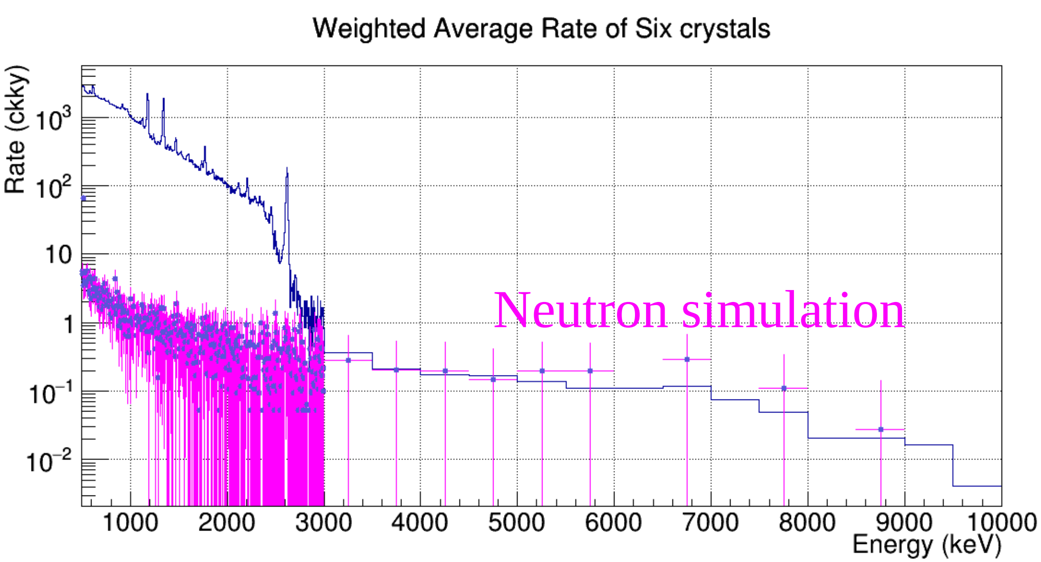




(3) Flat backgrounds up to 8MeV

Simulated spectra from the radioactivity measurements vs data.





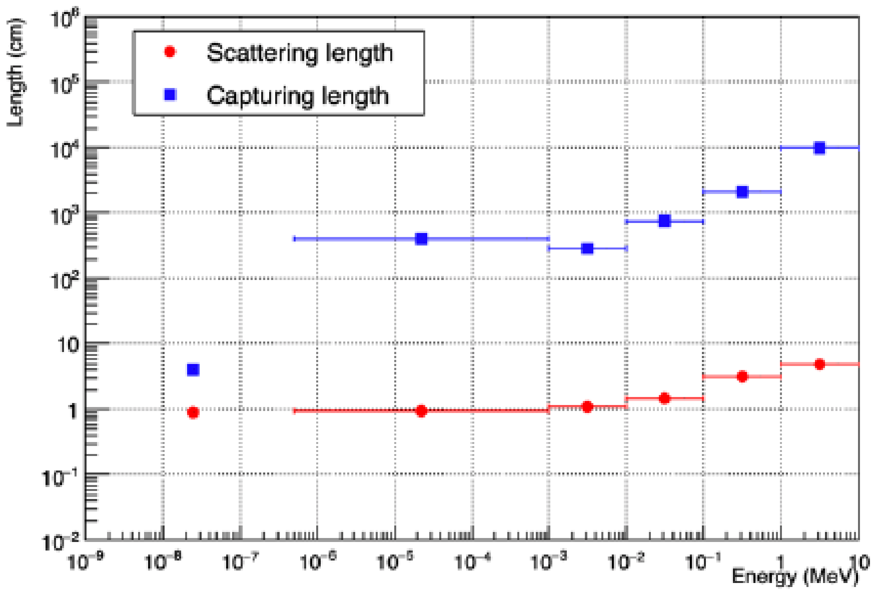
Comparison shows ;

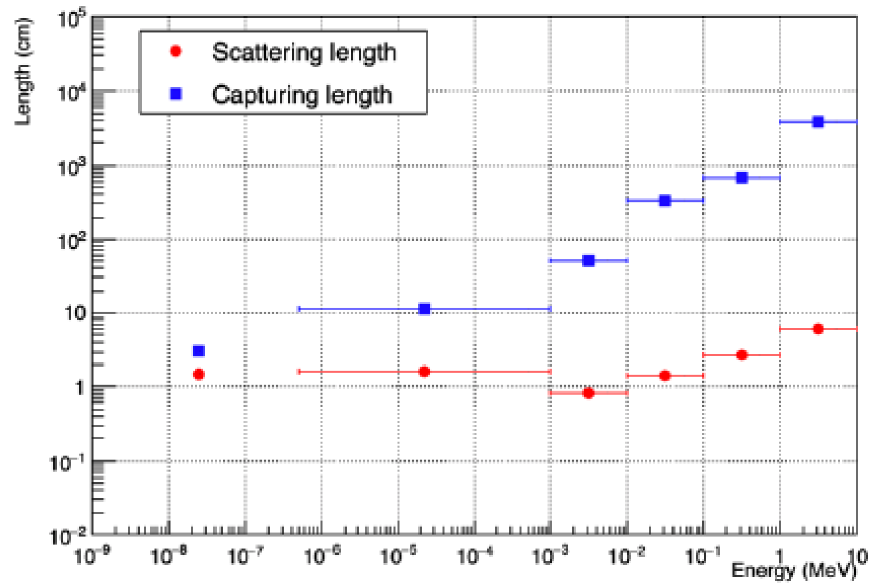
- Active components should be one of dominant backgrounds @ ROI.
- Data has more flat background at E>4MeV.

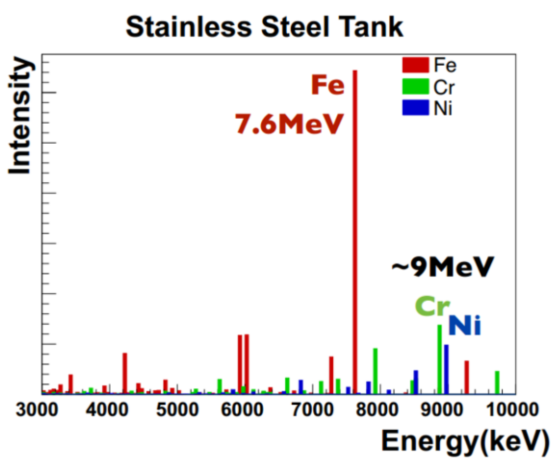
Flux(thermal neutron) measured ~ 2×10^{-5} /cm2/sec

Neutron capture

- Neutron capture and scattering length for materials are calculated from ENDF database
- Cu has larger capture probability than Fe, but Fe is abundant. Scattering lengths are similar.



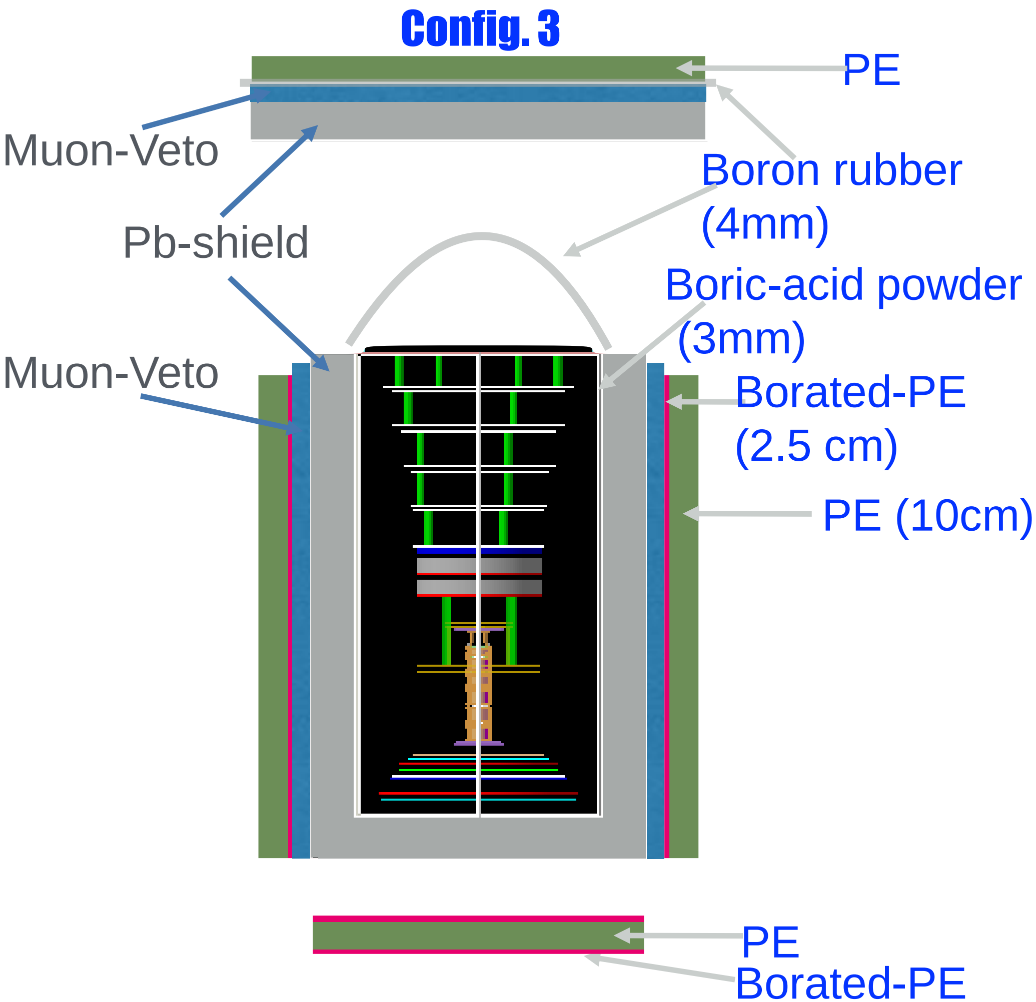


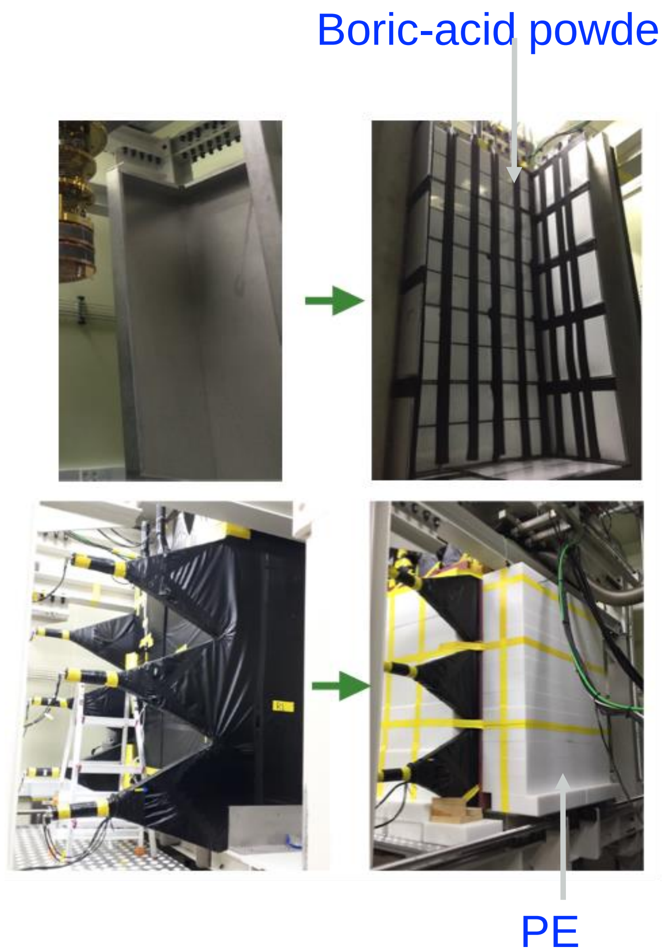


Fe at OVC, Pb container, etc. & Copper inside IVC may be the source.

Neutron Shielding for AMoRE-pilot

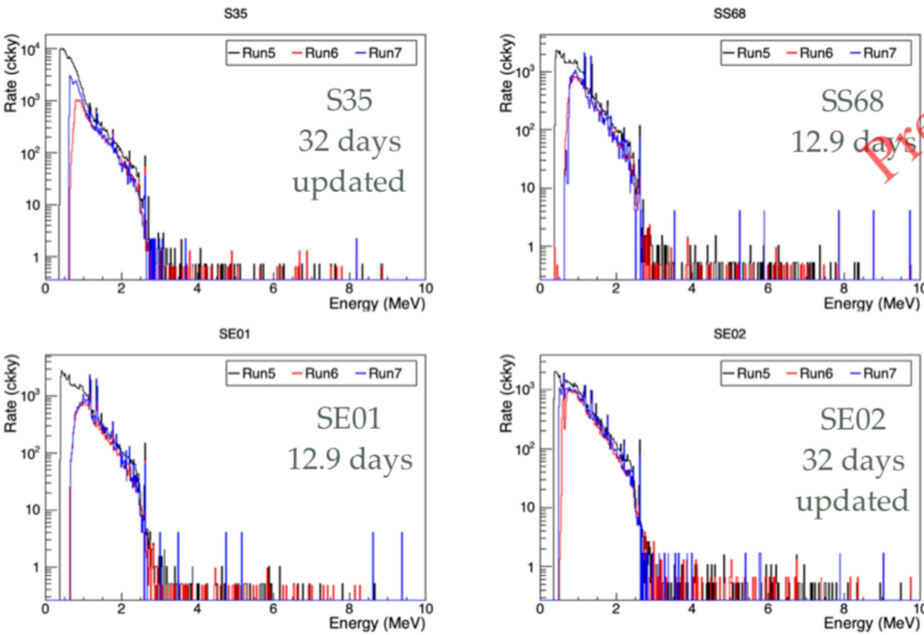
Additional neutron shielding are added inside and outside of Pb shielding to confirm the neutron capture backgrounds are removed.

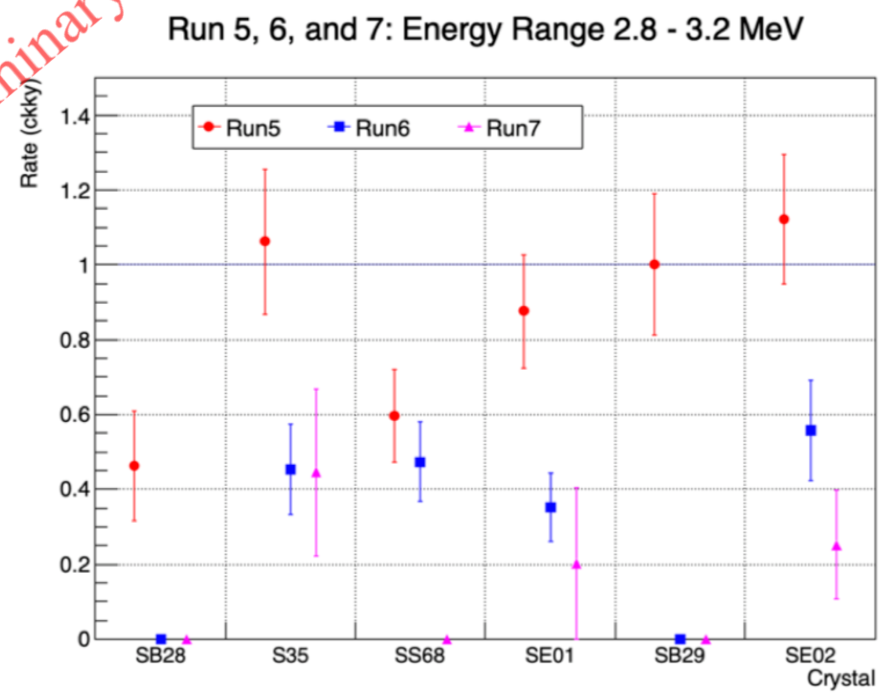


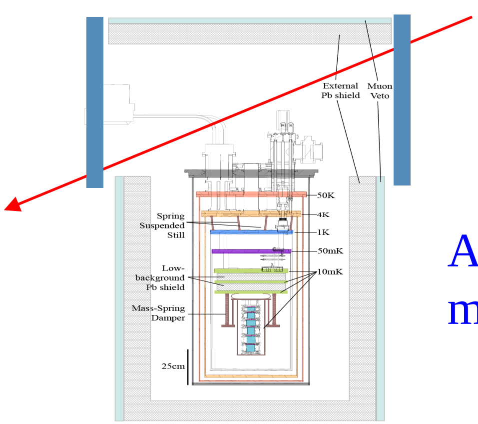


Background reduction in Pilot data

- **After removing active components and adding neutron shielding, we have reduction of backgrounds to ~ 50% and ~ 25% respectively.**

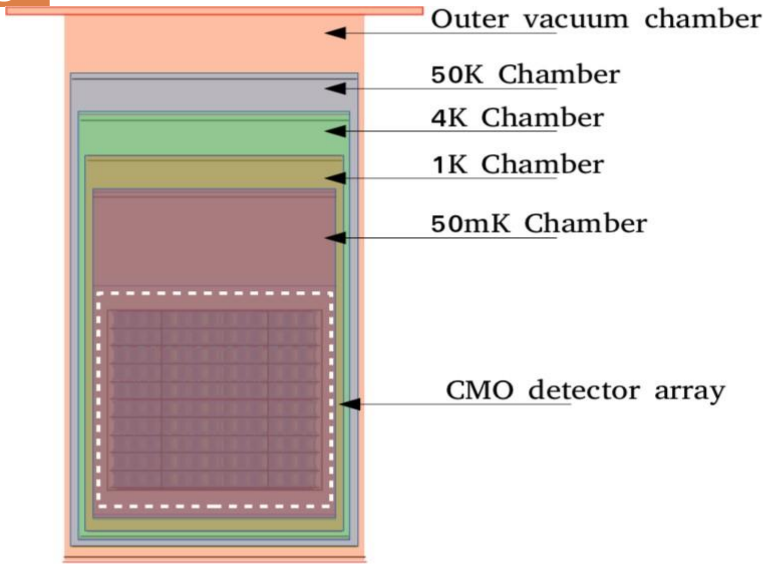




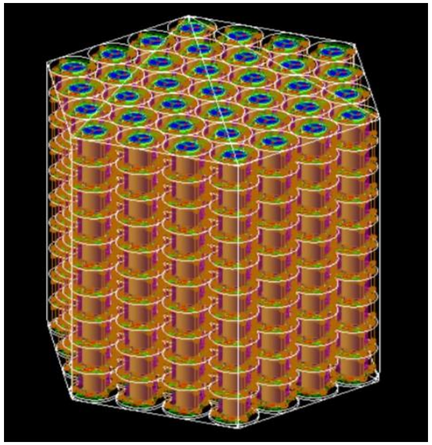


Additional muon veto and neutron shielding material will be installed for AMoRE-I run.

Muon & neutron simulation – AMoRE-II

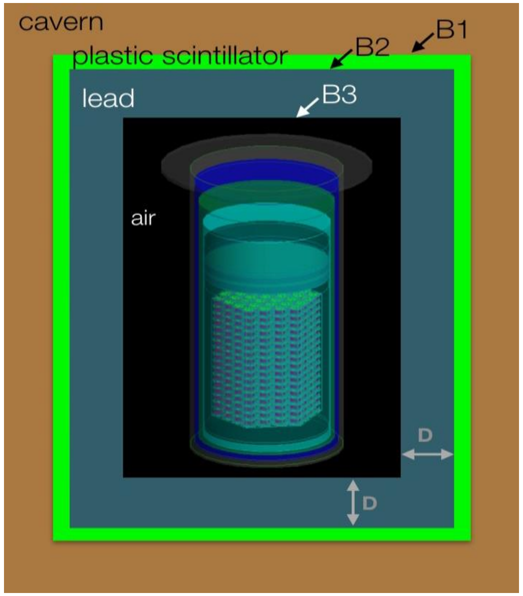


AMoRE-II setup

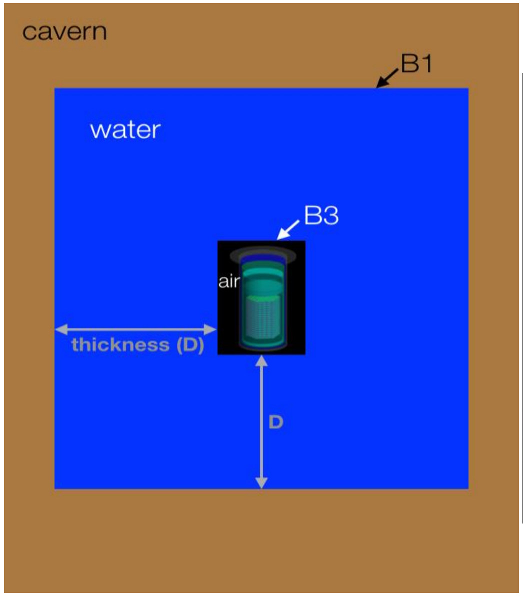


200 kg of CMO array are simulated to compare water and lead shieldings.

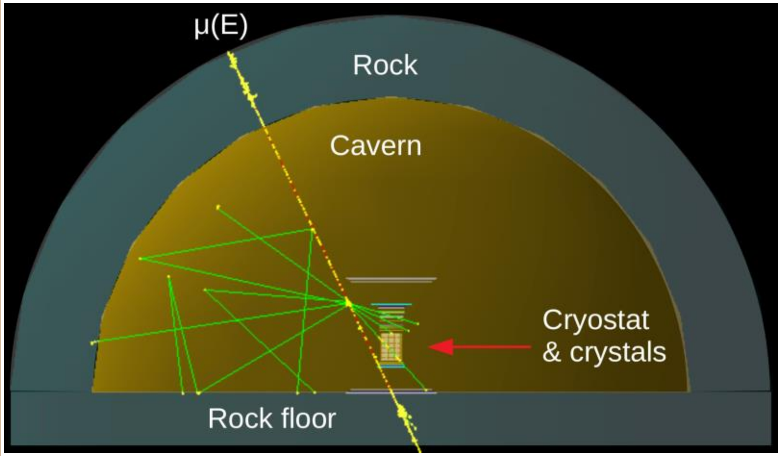
Pb shielding



Water shielding

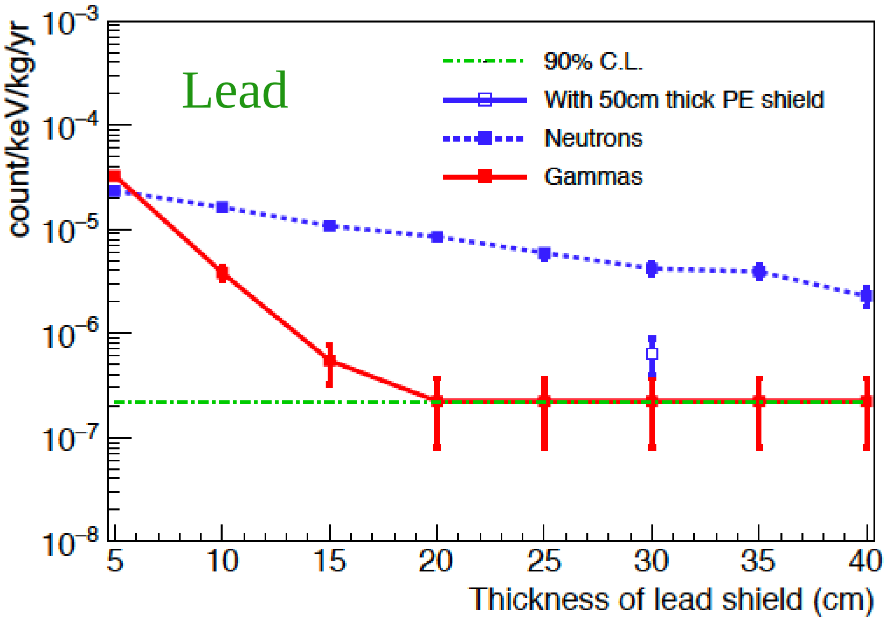


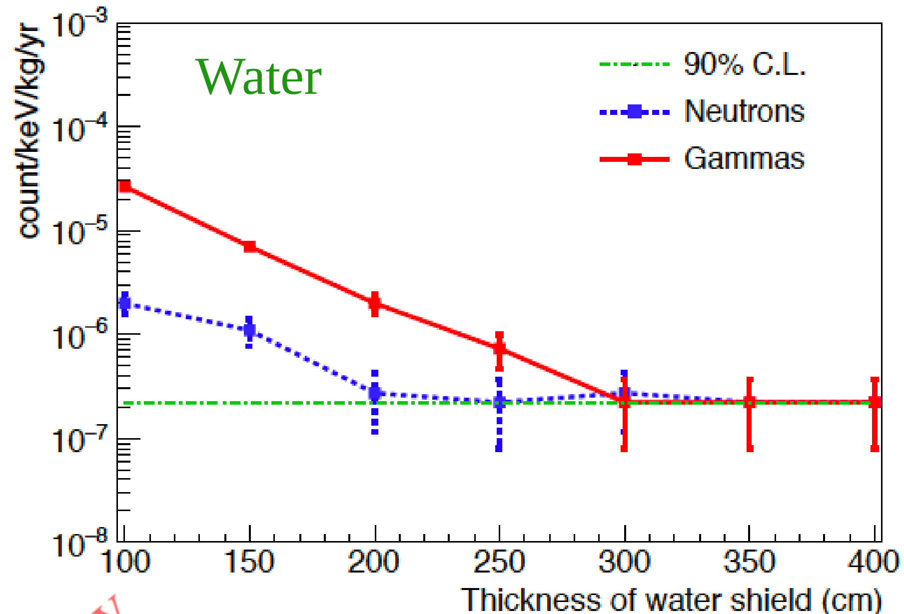
Geometry for muon simulation



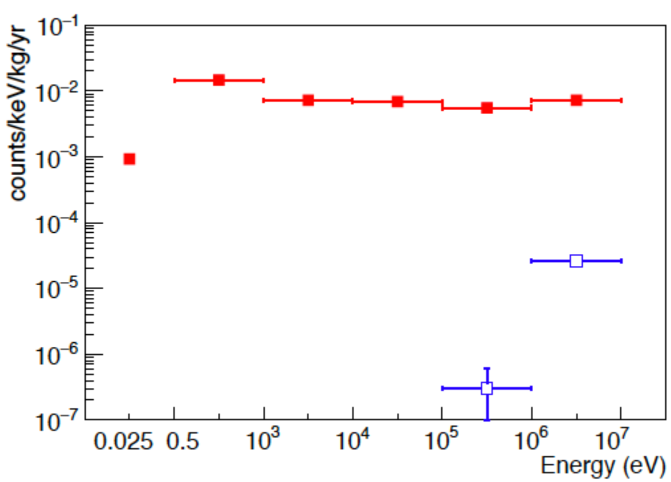
Results of AMoRE-II

- In both shielding, it is possible to have the backgrounds below 10^{-5} ckky.
- In case of lead shielding, need additional 50cm PE and BPE shielding.





Preliminary

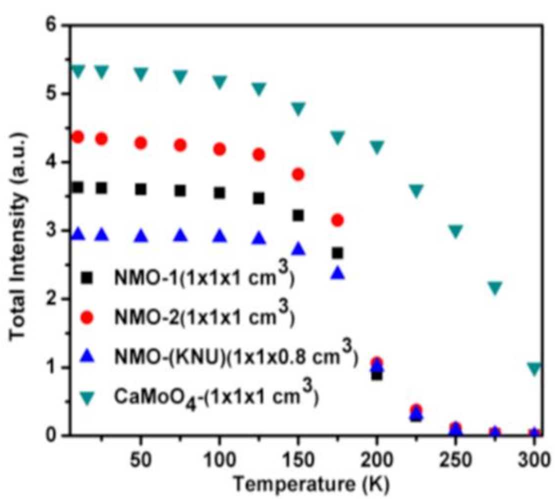


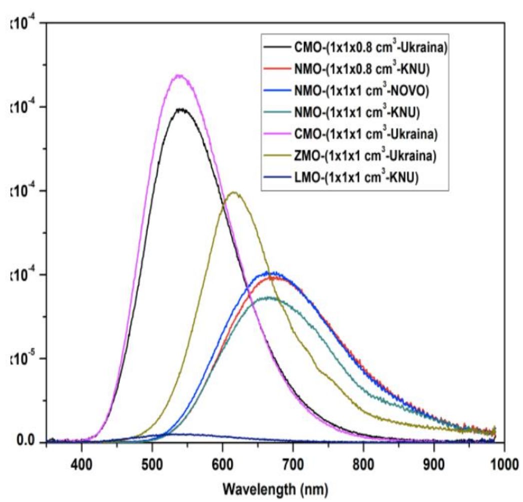
Rock neutrons, E<10 MeV
Simulation done with measured flux.

Decision on crystals for AMoRE-II

- CMO ($CaMoO_4$) is a very good crystal with the largest light output, but CMO has a disadvantage that we need ^{48}Ca depleted isotopes, expensive.
- LUMINEU group decided to use LMO (Li_2MoO_4), and we are working on LMO, PMO ($PbMoO_4$), & NMO ($Na_2Mo_2O_7$), crystals.

Crystal	Emission (nm)	LightYield(10K)		Decay time (μs)	density	Mo Fraction
		280nm	X-ray			
CMO(Ukra)	540	100	100	240	4.34	0.49
ZMO(NIIC)	614	63	35		4.37	0.436
LMO(KTI)	535	1	5	23	3.03	0.562
PMO(NIIC)	592	11	105	20	6.95	0.269
NMO(NIIC)	**663**	**75**	**9**	**750**	**3.62**	**0.558**



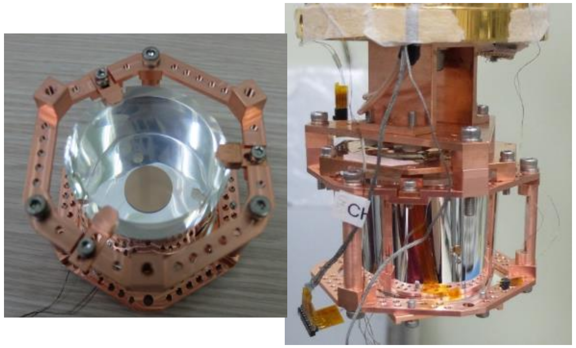


CMO ($CaMoO_4$)
LMO (Li_2MoO_4)
NMO ($Na_2Mo_2O_7$)
PMO ($PbMoO_4$)

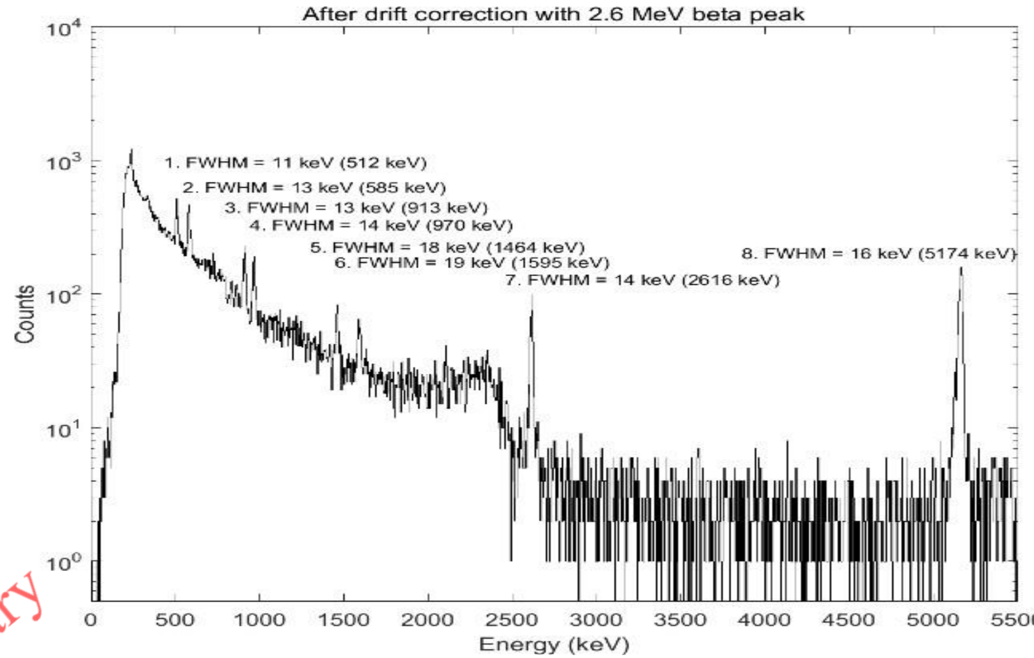
Test on Li_2MoO_4 crystals from NIIC

size : ϕ 5cm × h 4.7cm

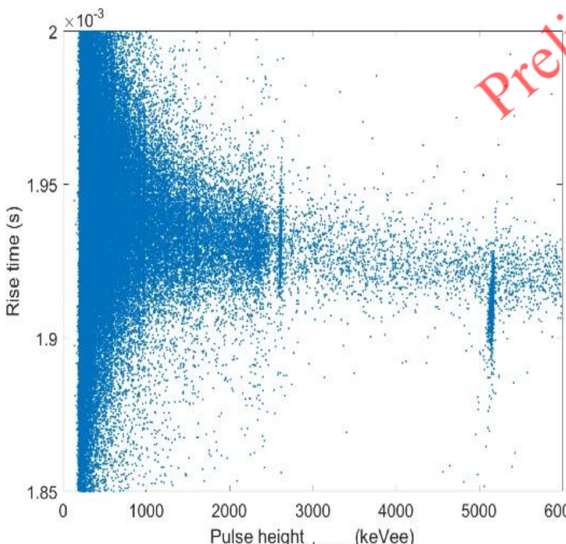
Polishing material - Diamond

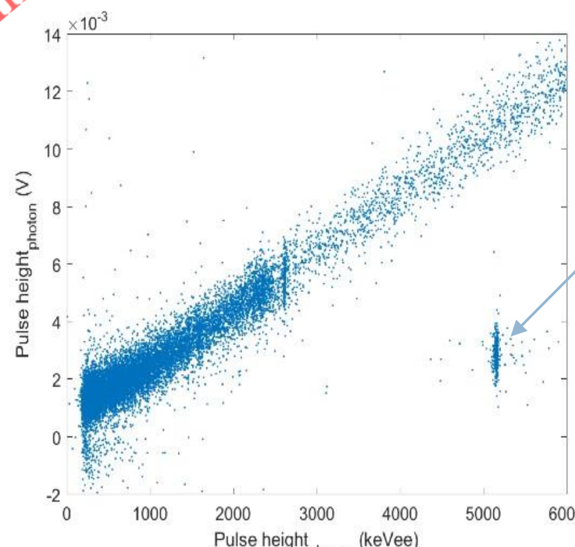


Crystal cleaning :
Methanol + O_2 plasma Asher



Preliminary





Muons at ground level

4.8 MeV alpha from ^{6}Li(n,t)alpha

DP ~ 9 from light/heat ratio

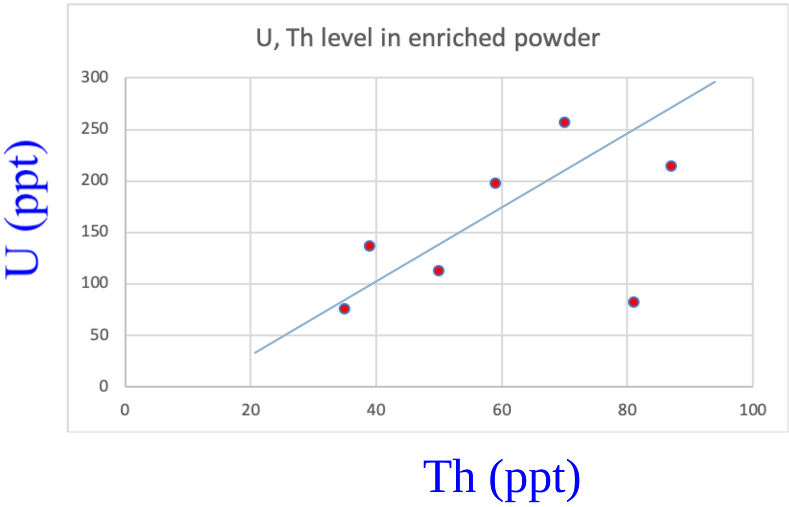
LMO+MMC is working !

Measurements for $^{100}MoO_3$ powder

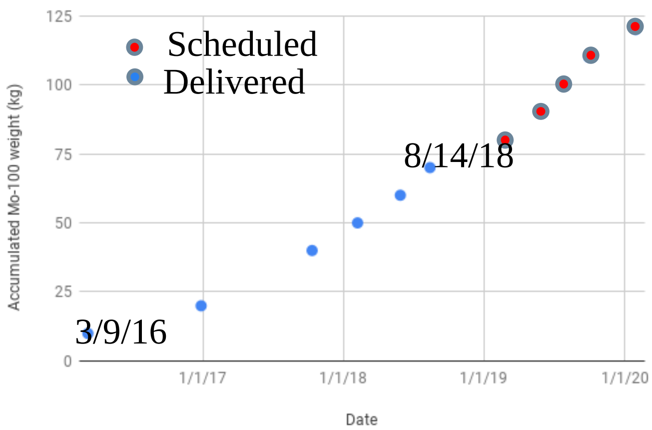
- 120 kg of $^{100}MoO_3$ powder (10 M$) from ECP, Russia.
- The finite background level is measured for the first time for ^{228}Th with HPGe Array detector (CAGe, 900 % relative efficiency).

Results :
- ^{226}Ra : 1.7±0.3mBq/kg, ^{228}Th : 0.26±0.06mBq/kg. (First measurement)
- Observed ^{88}Y produced by cosmic rays : 33±8 mBq/kg. → compared with the model.

ICP-MS measurements



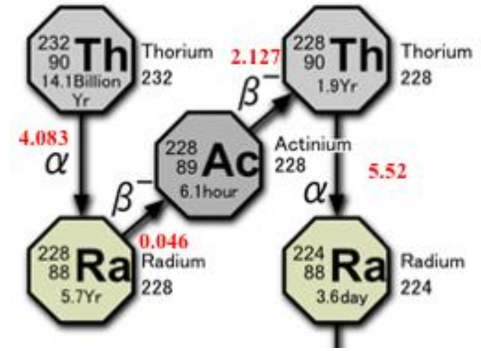
Schedule to deliver enriched powder



- **^{238}U : 76~257 ppt, ^{232}Th : 35~87 ppt**
- **U, Th chains are in equilibrium contrary to natural MoO3.**

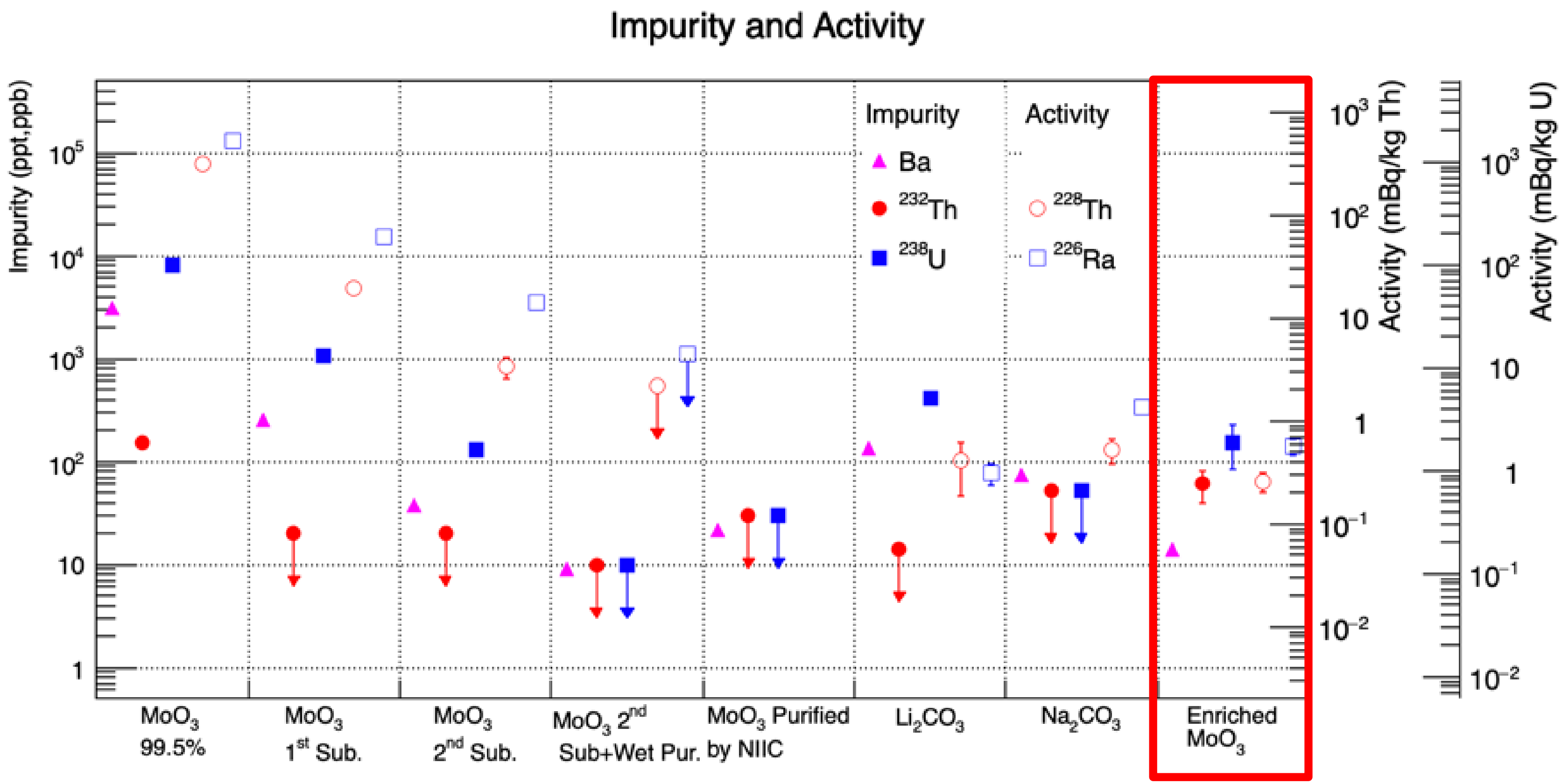
Summary of Chemical Purification Results

Ba is a good indicator for Ra since they are in the same family.
→ Both ^{226}Ra & ^{228}Ra (5.7 year) → ^{228}Th are related to Ba.



Impurities by ICP-MS (ppb for Ba, ppt for U,Th)

We have purified natural MoO_3 better than enriched powder.



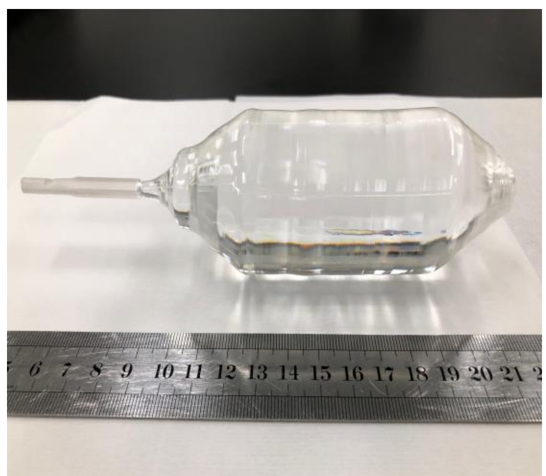
1st enriched $Li_2{}^{100}MoO_4$ crystal grown at CUP

We have grown an enriched LMO crystal without any purification to check what level of contamination would be reached by only from crystal growing process.

$Li_2CO_3 + MoO_3 \rightarrow Li_2MoO_4 + CO_2$

CZ02-L1803E

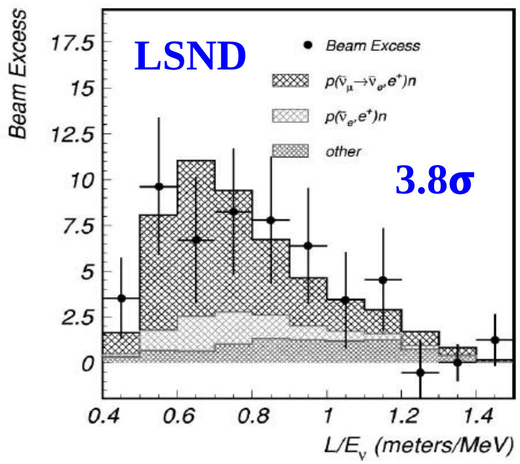
1. mass : 607.2 g (including seed)
2. diameter : 50.0 ~ 51.3 mm
3. Total length : 136.0 mm
4. Body length : 64.4 mm



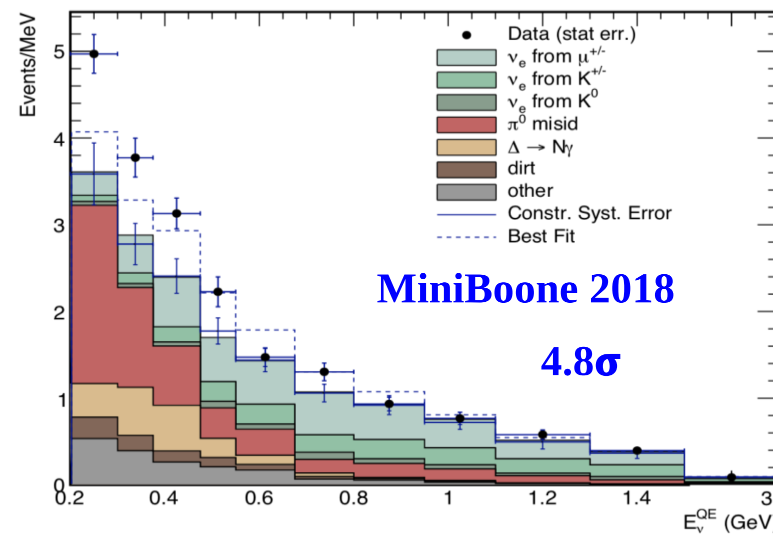
Crystals with Natural Mo

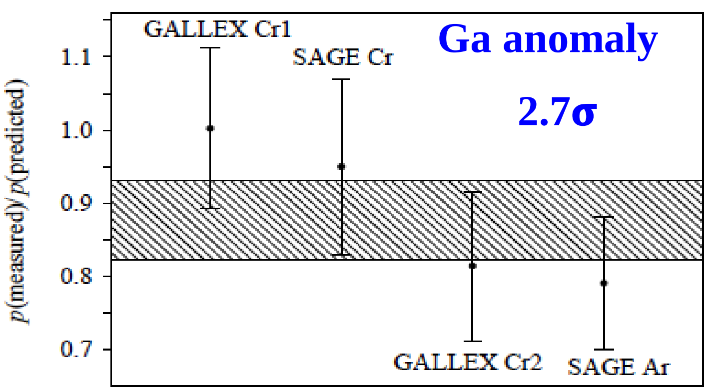
3. Search for sterile neutrinos - NEOS

- **All these anomalies indicate m_ν~ eV mass right-handed sterile neutrinos.**
- **Sterile neutrinos may show up in the oscillation at short baseline.**

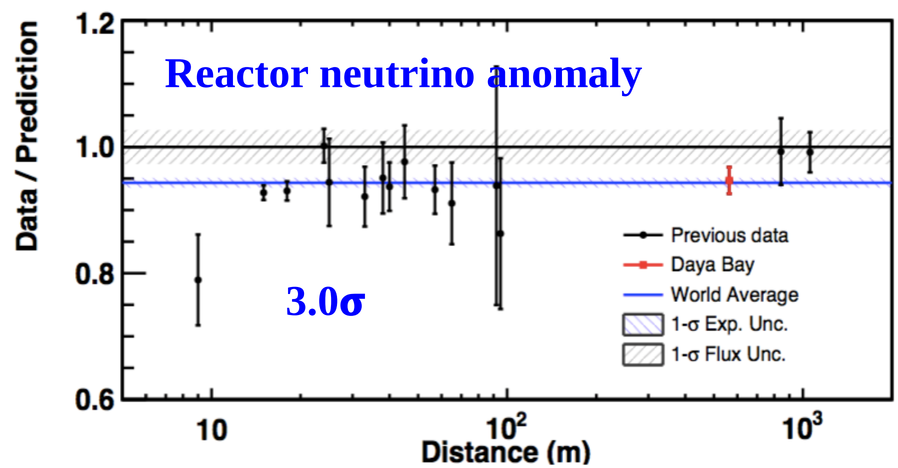


$\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations





[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



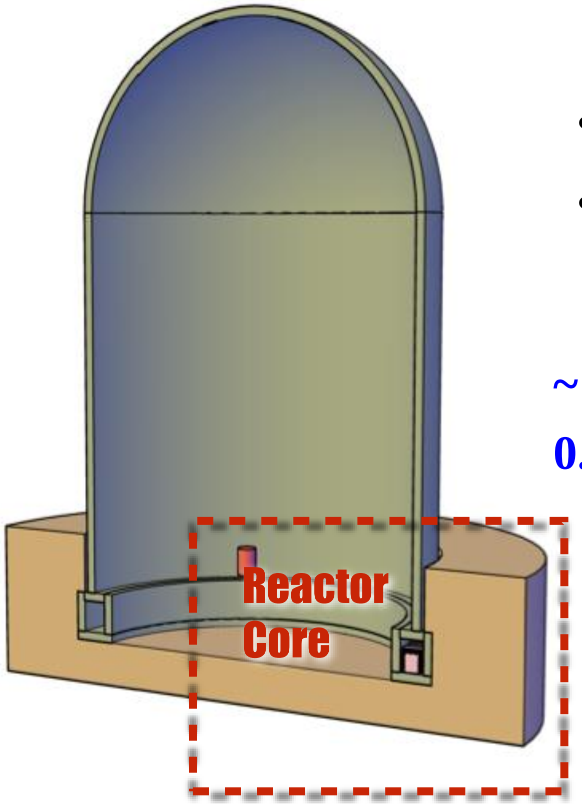
NEOS Experiment

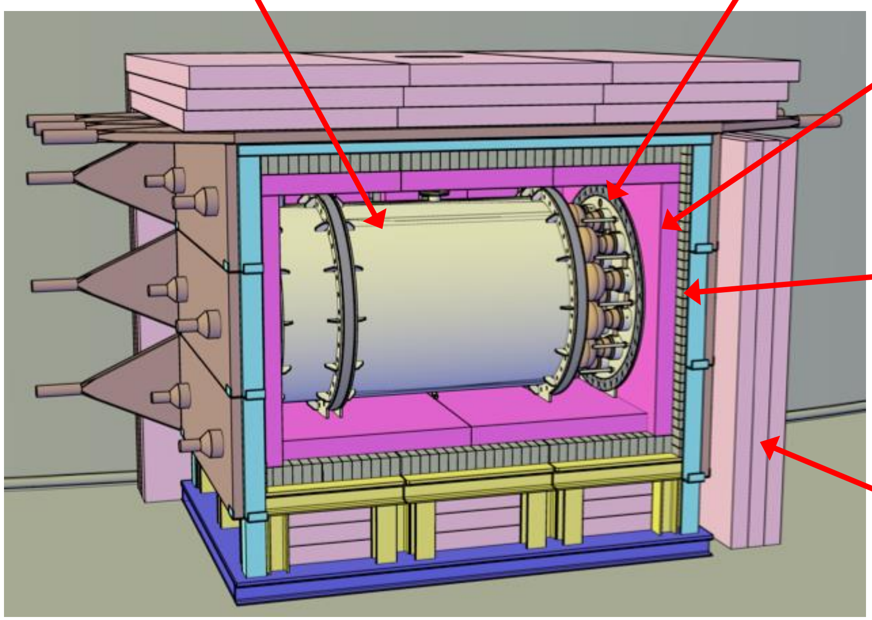
- Reactor Neutrino Oscillation already observed @ ~50 km and ~1 km.
- We have performed a quick experiment to check the reactor neutrino anomaly, NEOS, at a baseline of 24m from a nuclear reactor at RENO site.

KAERI KRISS 한국표준과학연구원 Korea Research Institute of Standards and Science
ibS 기초과학연구원 Institute for Basic Science

Tendon Gallery at Hanbit

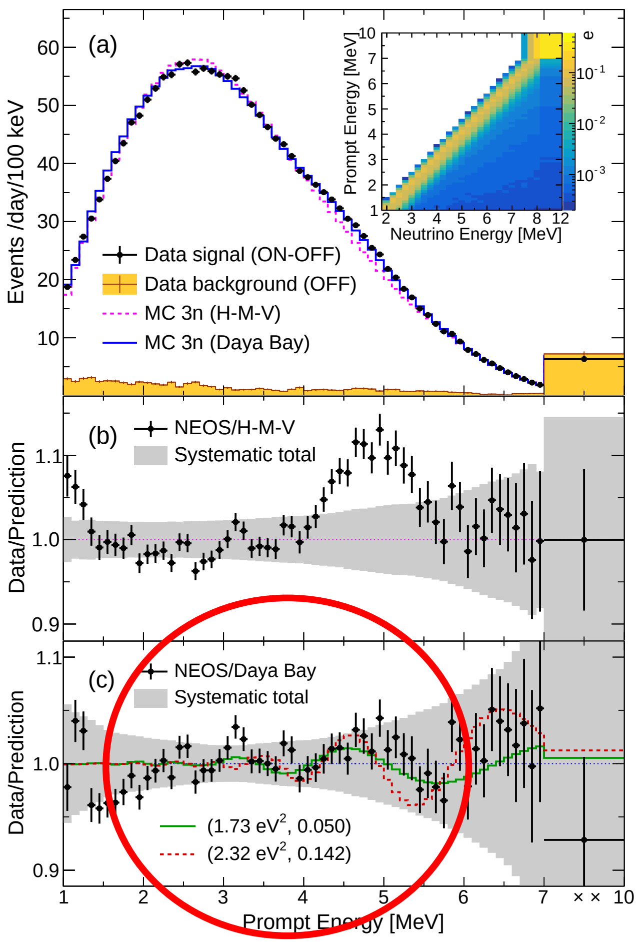
- ~25 m from 2.8 GW_{th} reactor
- ~10 m concrete overburden

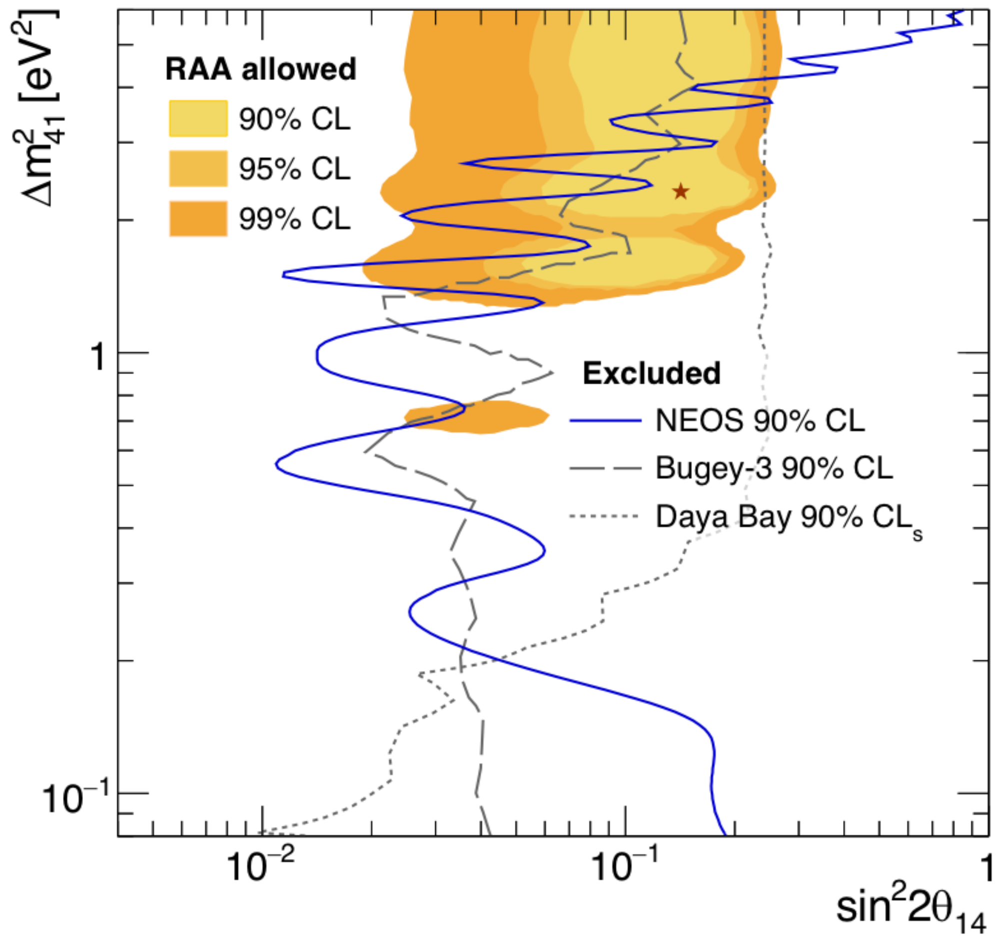




Final results from NEOS, PRL 118, 121802 (2017)

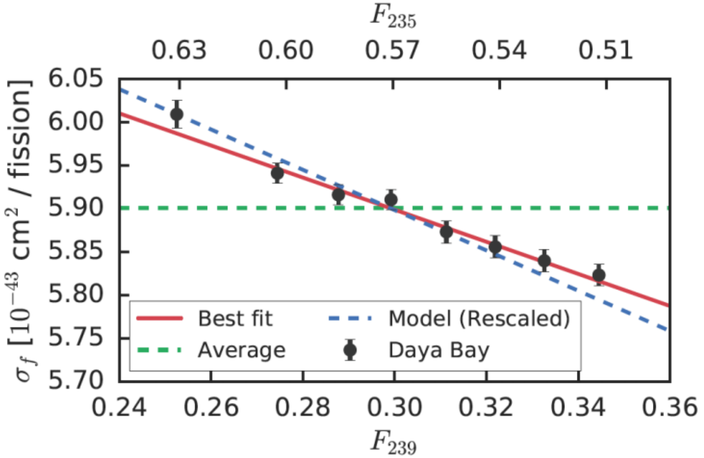
- NEOS data shows clean signal due to large overburden at Tendon gallery.
- We could give a most stringent limit at the reactor anomaly parameter region.



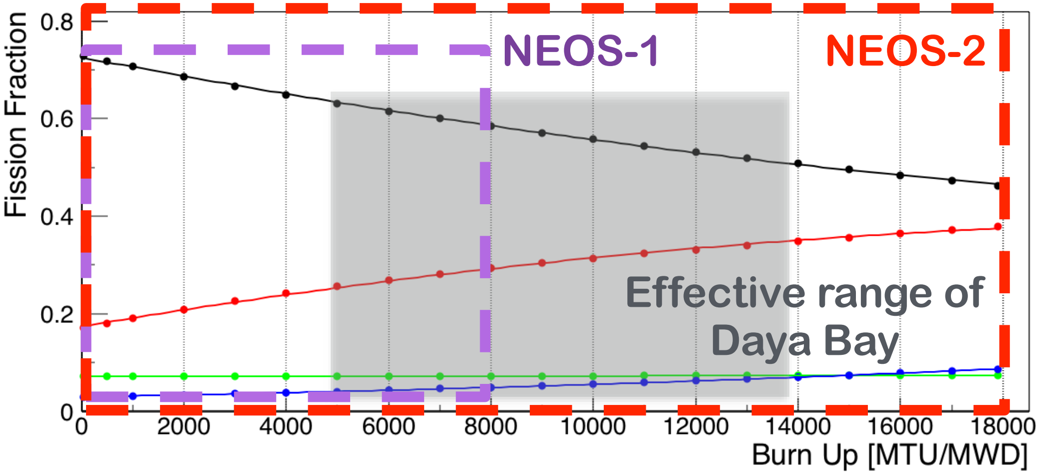


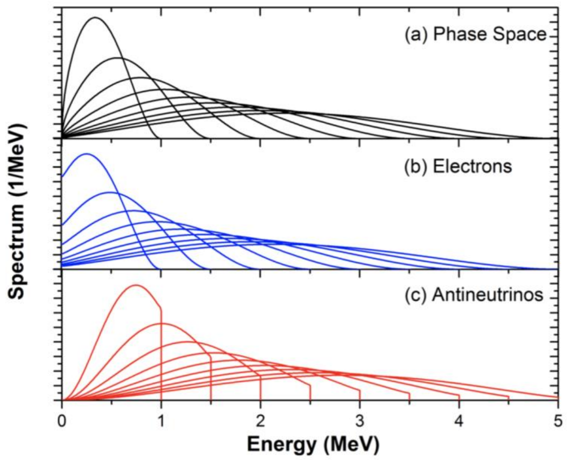
NEOS-II is running from Sep. 2018.

- To cover whole burn-up cycle (1.5 years data) to check Daya Bay claim.
- To measure antineutrino spectra more precisely.



F.P.An et al., PRL 118, 251801 (2017)

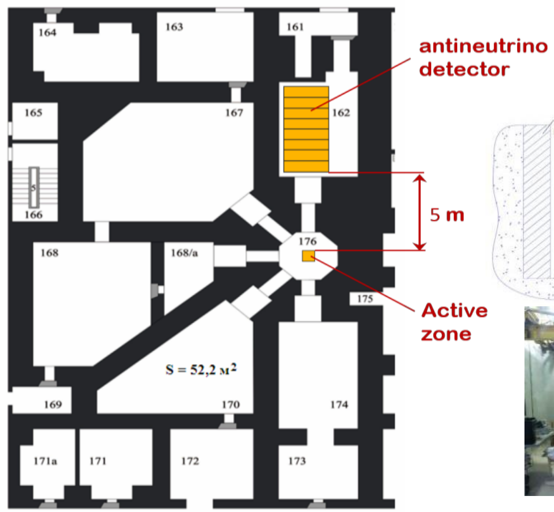




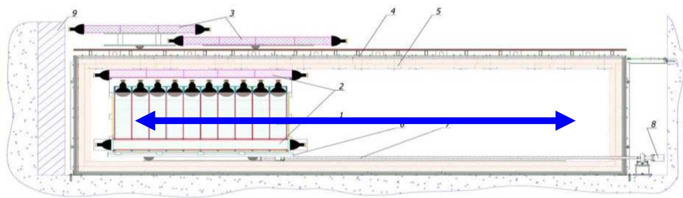
Discrete antineutrino spectra expected.

Sonzogni et al. PRC98, 014323 (2018)

Neutrino-4 experiment @ Reactor SM-3, RUSSIA



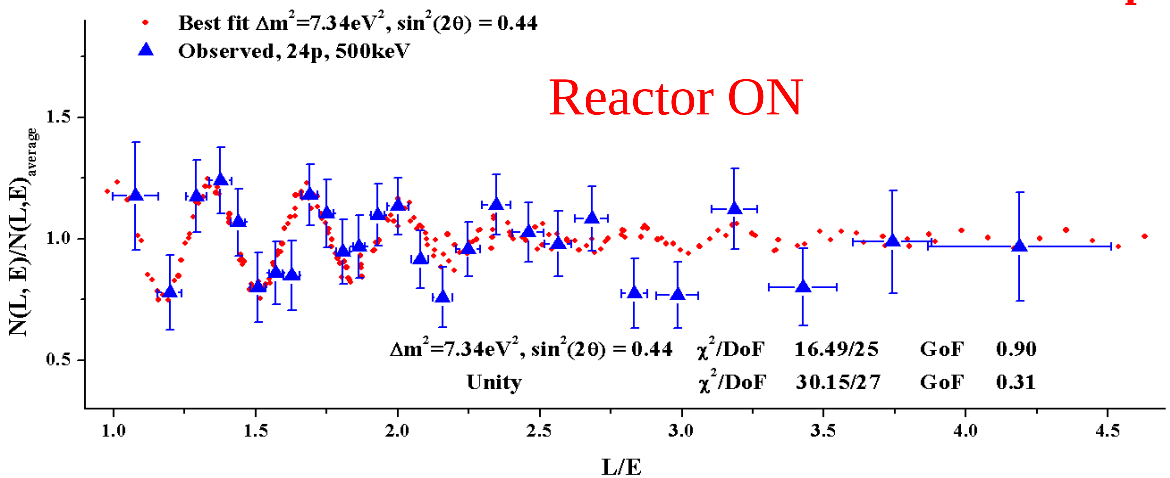
The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

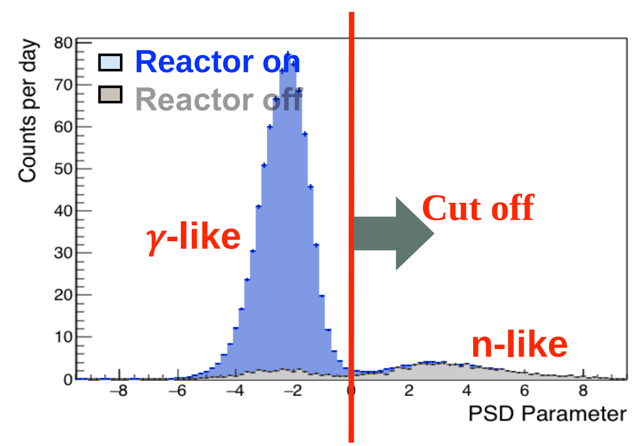


Detector segmented in 10 layers
Detector moved 7-11 meter
Total 24 positions for all layers.

It is under discussion to use NEOS scintillator for next phase of Neutrino-4 experiment to improve S/N ratio.

arXiv 1809.10561. Surprising figures !



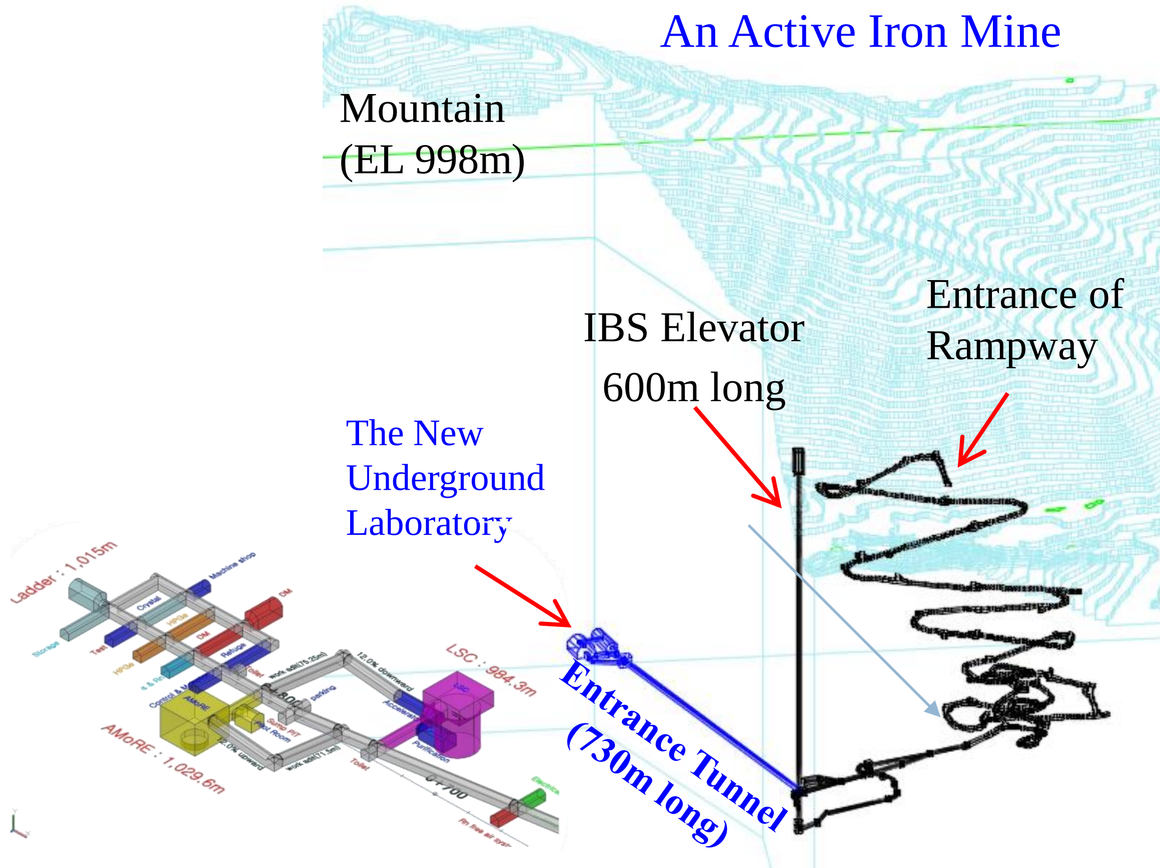


Future : a new underground lab.

Center for Underground Physics

- **Important Concepts**
- **An independent entrance (human vertical elevator) from mine activity.**
- **The construction starts early of 2019 and be completed by end of 2020.**

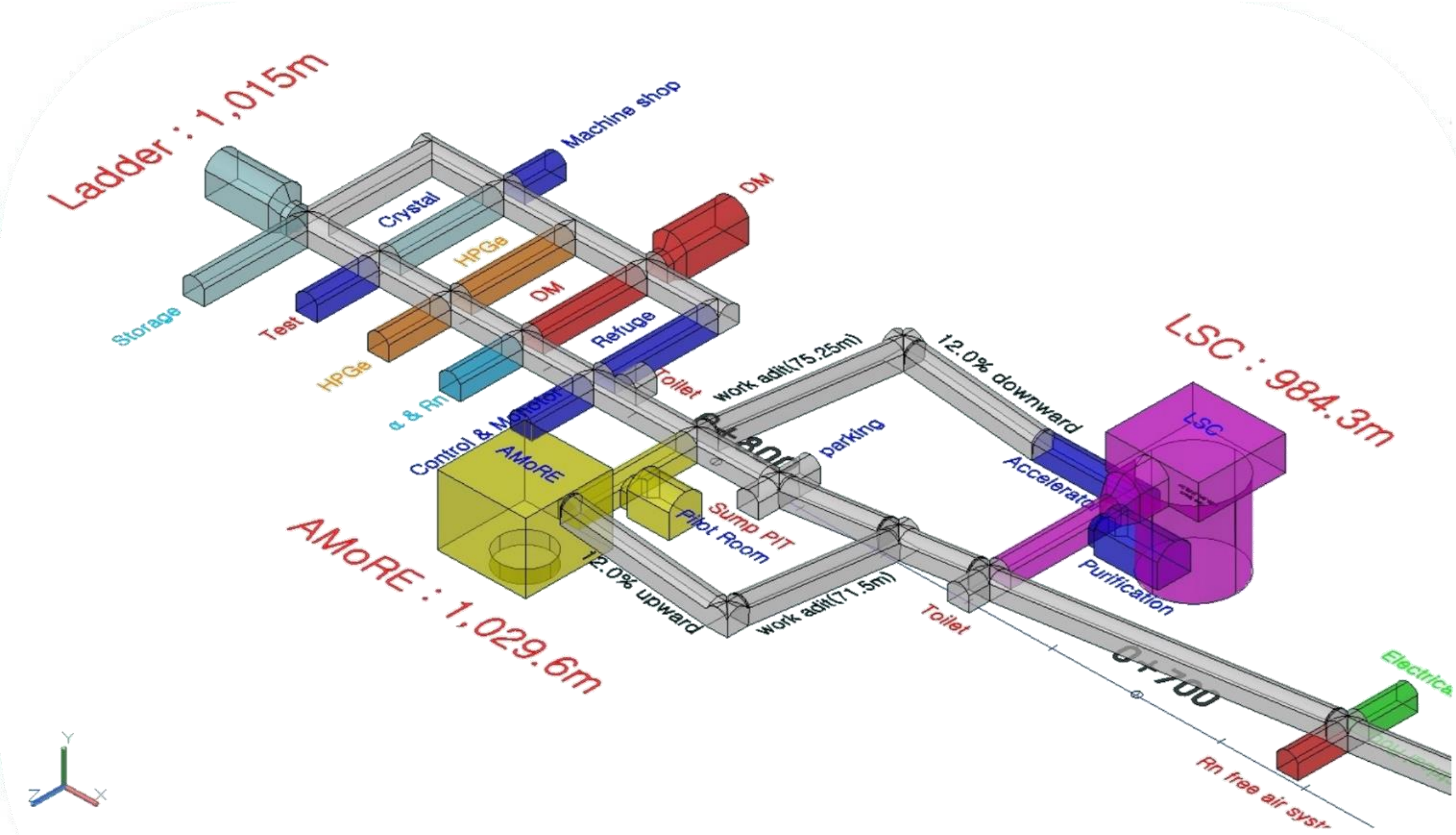
Bird view of Handuk Iron Mine



Large (>2000m^2), deeper (1100m depth)

The underground laboratories

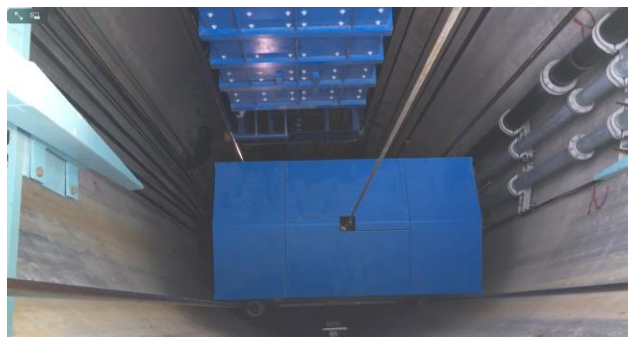
- 8 experiments with 12 spaces
- 10 utility rooms



Construction

Winder room

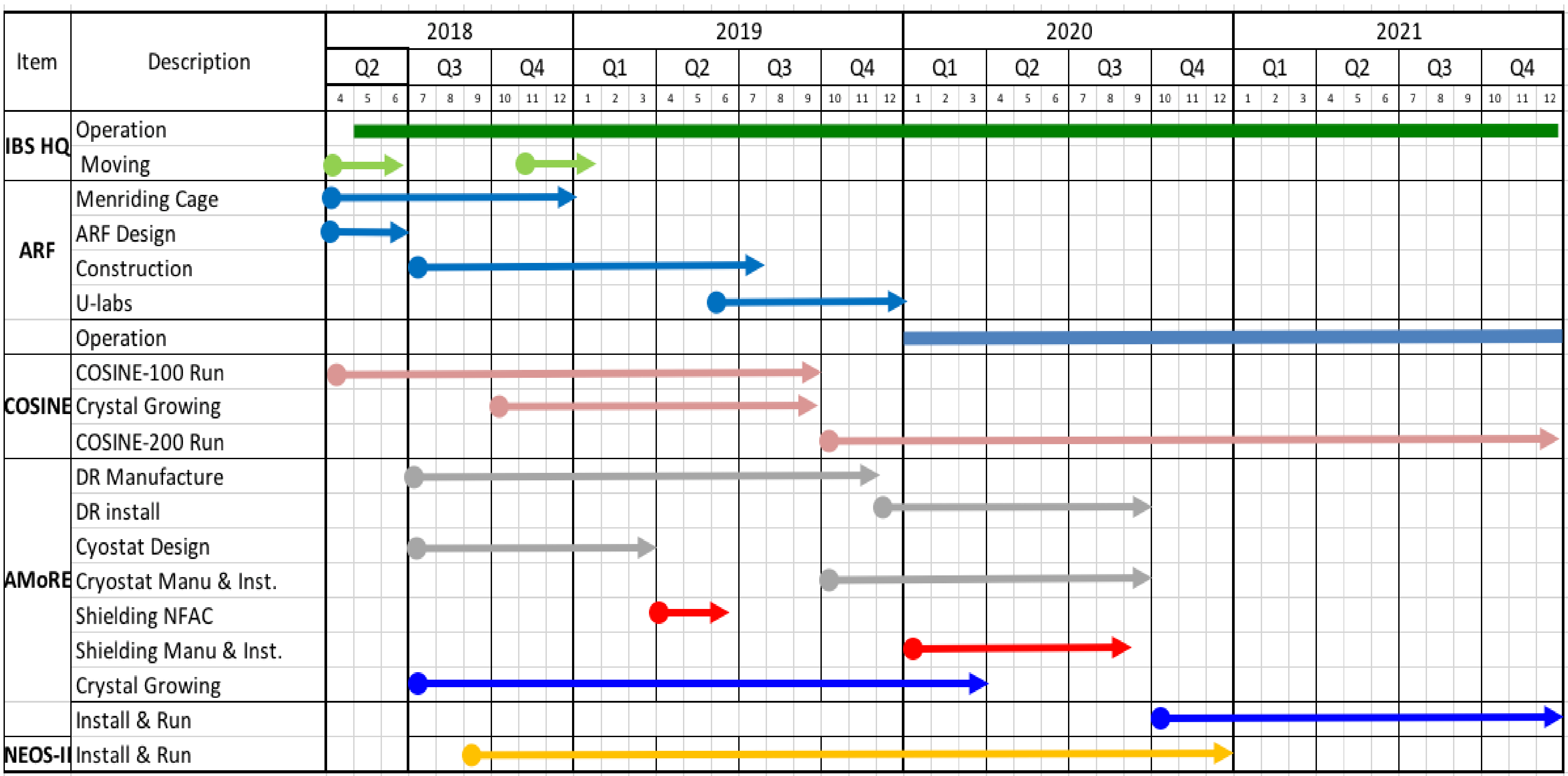
At bottom of shaft



Ground Lab.

IBS elevator

Schedule


Item
Description
2018
2019
2020
2021
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
IBS HQ
Operation
Moving
ARF
Menriding Cage
ARF Design
Construction
U-labs
Operation
COSINE
COSINE-100 Run
Crystal Growing
COSINE-200 Run
AMoRE
DR Manufacture
DR install
Cyostat Design
Cryostat Manu & Inst.
Shielding NFAC
Shielding Manu & Inst.
Crystal Growing
Install & Run
NEOS-II
Install & Run

Summary

- CUP has strong and challenging science programs including COSINE.
- AMoRE project aim to be sensitive to 10^{27} year range for ^{100}Mo isotope.
- Understood detector performance and identified background sources through AMoRE-Pilot. Will confirm low background further in AMoRE-I.
- AMoRE-II will begin end of 2020 at a new underground laboratory with a goal of "zero" background.
- Searching short baseline neutrino oscillation will continue at reactor sites to sense the unexplored parameter space by collaborating HEP community.
- CUP is making future plan for a new YEMI underground lab.

Grazie !

Comparison of cryogenic experiments

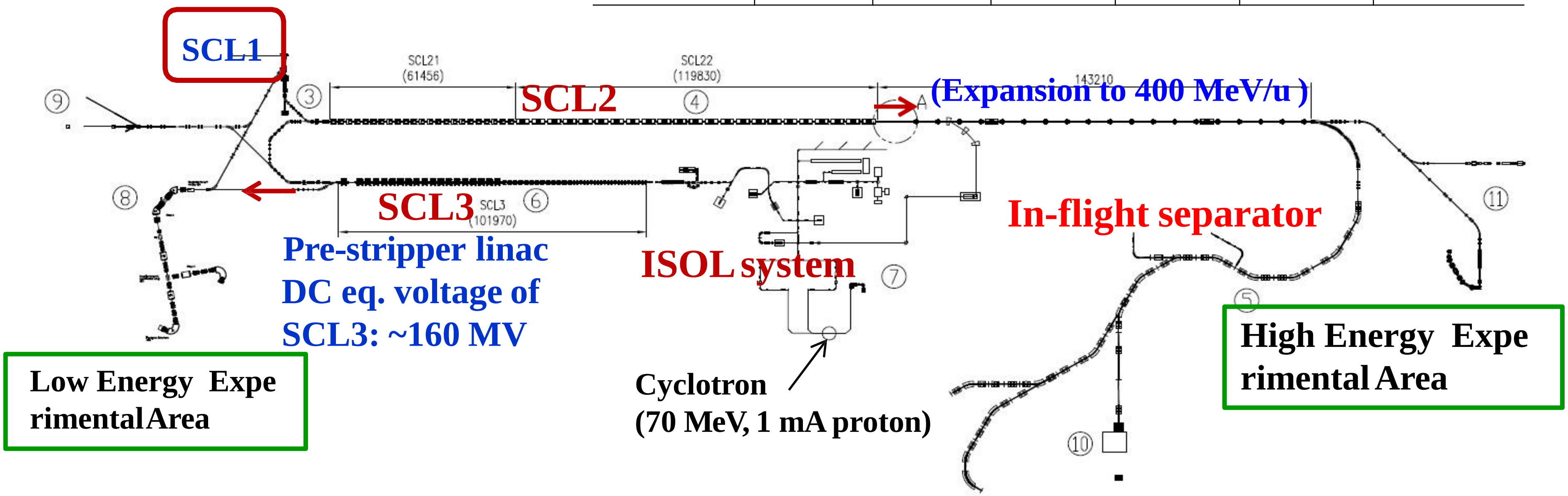
Exp	Q (keV)	Crystal	ΔE (keV)	T(rising) (ms)	Bkg@ROI (ckky)	Comment (Mass of isotope)
CUORE (^{130}Te)	2527.5	TeO2	7.7	~100	0.014	Copper holder surface
CUPID-0 (^{82}Se)	2997.9	ZnSe	23	~13.5	0.0032	muons, neutron capture(?)
CUPID-Mo (^{100}Mo)	3034.4	LiMoO4	~6	~16	0.06	Active components 5kg (2019)
AMoRE (^{100}Mo)	3034.4	CaMoO4 (X)MoO4	~15	~2	0.55 → ~0.1	Neutron capture 35 kg (2021) 100kg(2023)

Layout of accelerator and experimental systems

Total DC equivalent voltage: ~600 MV

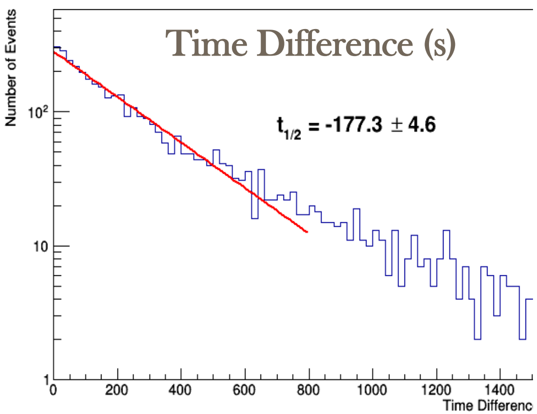
Decided not to be constructed

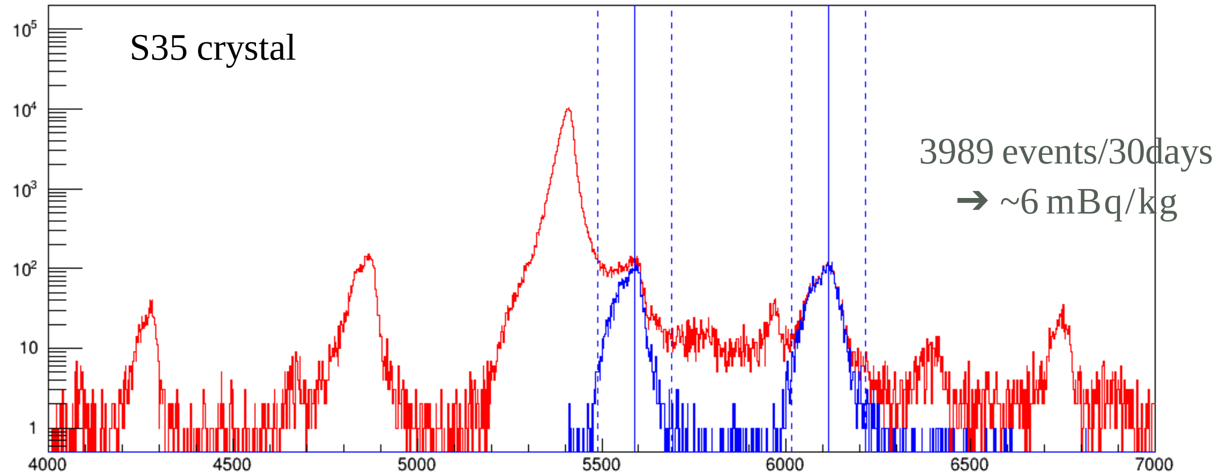
	Driver Sc-Linac (SCL1+SCL2)				Post (SCL3)	Cyclotron
Particle	**H**	**O**	**Xe**	**U**	RI beam	proton
E (MeV/u)	**600**	**320**	**251**	**200**	18.5	70
I (pμA)	660	78	11	8.3	-	1000
Power (kW)	**> 400**	**400**	**400**	**400**	-	70

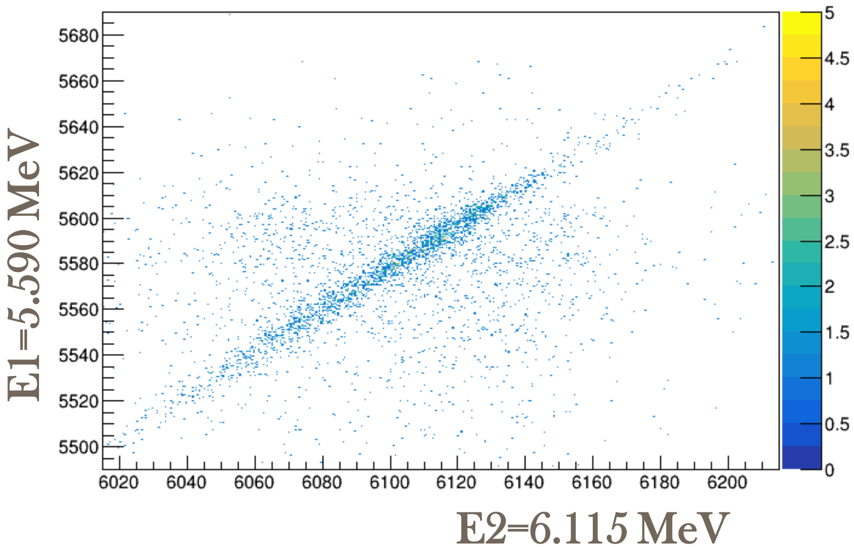


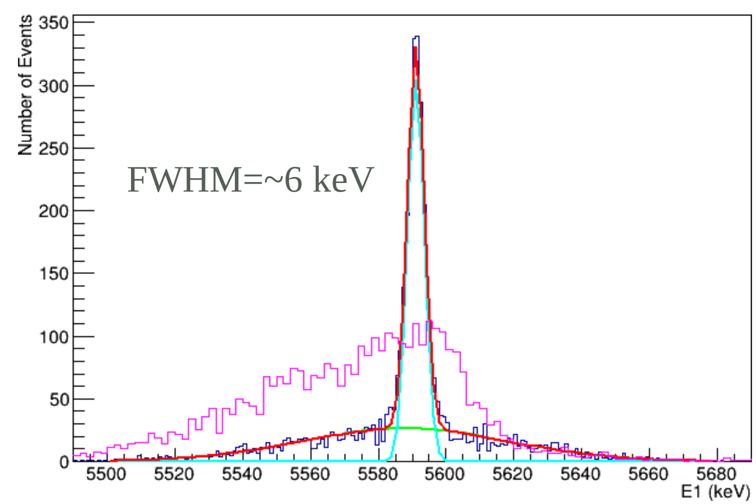
- **IF (In-flight) separation**
- **ISOL (ISotope On Line) separation**
- **ISOL+IF**

Analysis for alpha-alpha Events









→ Position dependence seems to be the dominant factor of the energy resolution.

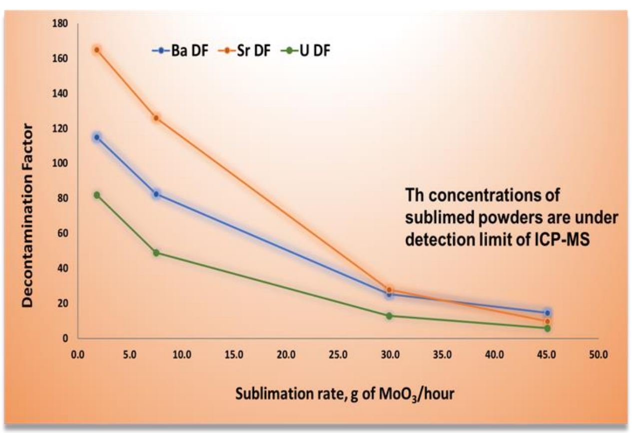
Identify critical radioactivity

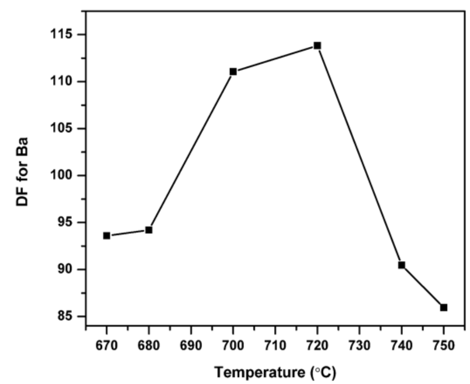
- Go through all known nuclei decaying β *with* Q > 3.02MeV in NNDC database.
- ^{110m}Ag(3010.5 keV) doesn't contribute for Mo experiment.
- Cosmogenic excitation is negligible after 1 year at underground.
- Only Thorium and Uranium natural radioactivity are critical for Q> 3.02MeV. → Great advantage to run high Q-value nuclei !

El	Decay	$T_{1/2}$	Q	Mother	Chain	Comment
			MeV	N/A		
^{26}Al	EC	7.4x10^{5}y	4.004	N/A		Long lifetime
^{56}Co	EC	0.21y	4.567	N/A		Short lifetime
^{88}Y	EC	0.29y	3.623	^{88}Zr (0.23 y)		Short lifetime
^{106}Rh	B-	30s	4.004	^{106}Ru(1.02y)		
^{126}Sb	B-	12.5d	3.670	^{126}Sn(2.3x10^{5}y)		Long lifetime
^{146}Eu	EC	4.61d	3.878	^{146}Gd (0.13 y)		Short lifetime
^{208}Tl	B-	3.05m	4.999	^{228}Th (1.91 y)	Th232	Main
^{209}Tl	B-	2.16m	3.970	^{233}U(159200y)	U233	2.1% branching
^{210}Tl	B-	1.3m	5.482	^{226}Ra(1600y)	U238	0.02% branching
^{214}Bi	B-	19.9m	3.269	^{226}Ra(1600y)	U238	Main

Purification, Ultra-clean crystals for AMoRE

- Chemistry group has been successful in powder purification for molybdate crystals.
- Sublimation, Co-precipitation are basic techniques.
- Recovery process from LMO are established for further purification.





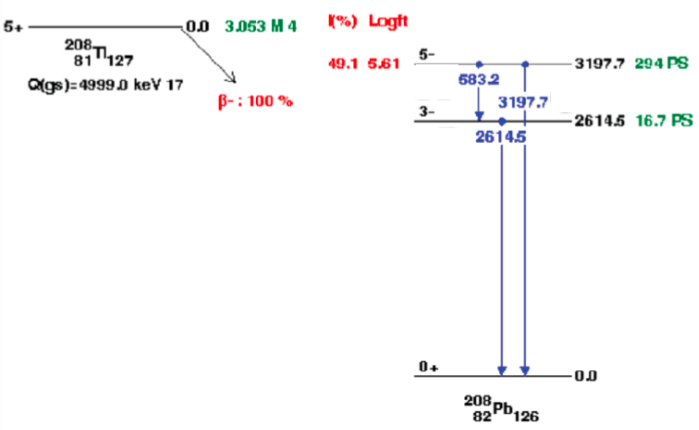
Measurements for Vikuiti Film

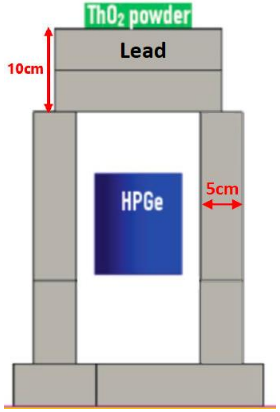
Results : 7.8m^2 film is measured !

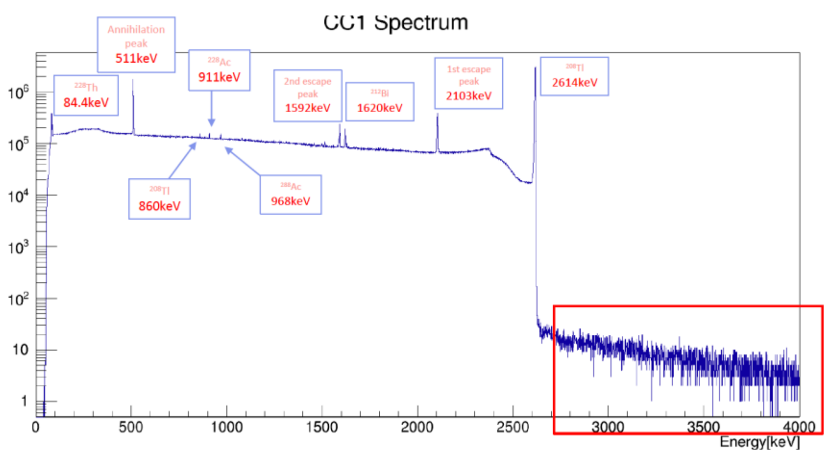
- ^{226}Ra : < 0.4 mBq/kg, ^{228}Th : < 0.6mBq/kg.
- Film roll is ordered specially for the measurement.

New limits for E>3MeV gammas from ^{208}Tl decay

- Do we have gammas E>3MeV from 208Tl decay ? Only upper limits.
- 2kg of ThO2 powder is measured. → The limits for 3198 and 3475 keV gammas are lowered by a factor of 10-20 ! These gammas will not contribute any background for double beta decay experiment.







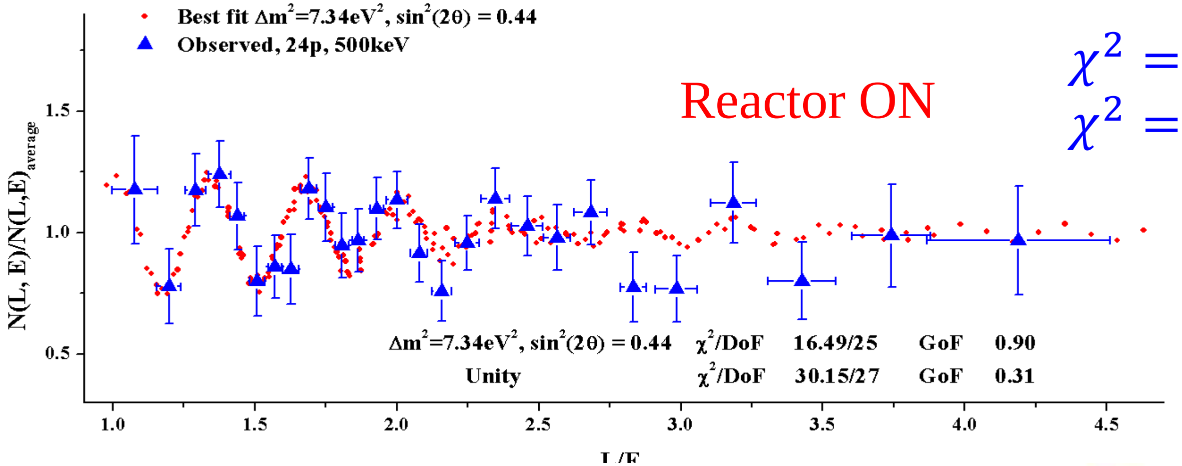
Indication of oscillation w/ ~ 3 sigma

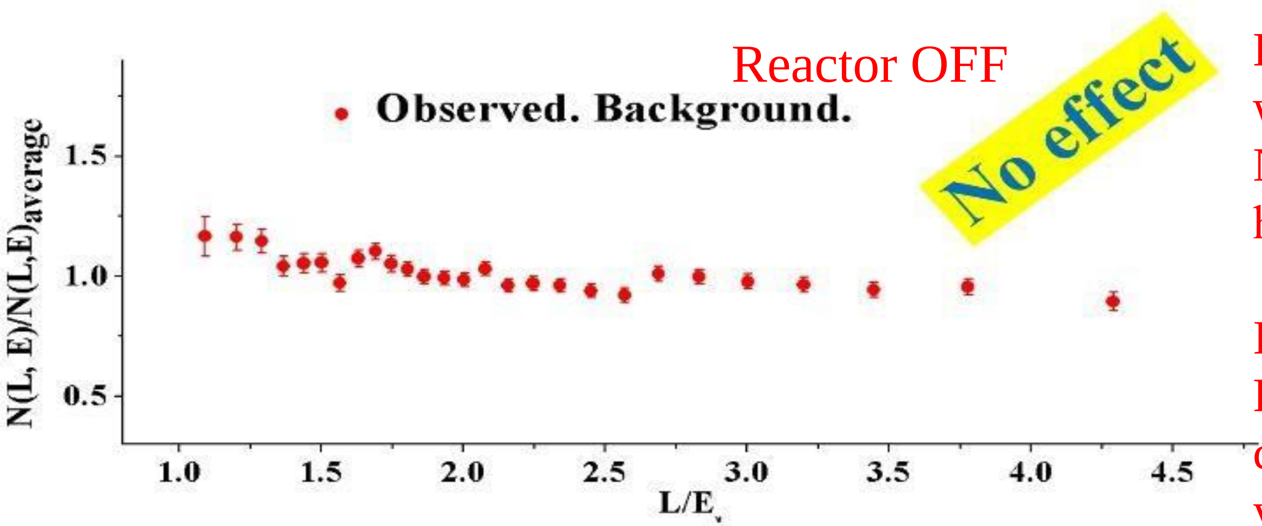
Oscillation pattern is shown in L/E

arXiv 1809.10561
Surprising figures !

$$\Delta m^2 = 7.34 eV^2, sin^2(2\theta) = 0.44$$

$$\chi^2 = 16.5/25, \textit{ for oscillation}$$
$$\chi^2 = 30.1/27, \textit{ for NULL}$$



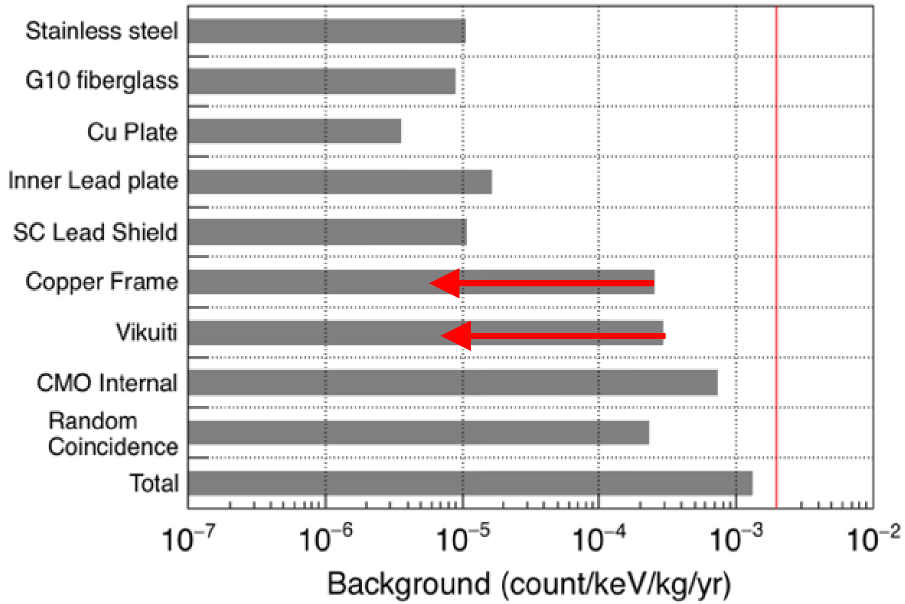


Before this result, CUP wanted to supply Gd-LS to Neutrino-4 exp to investigate high ΔM region.

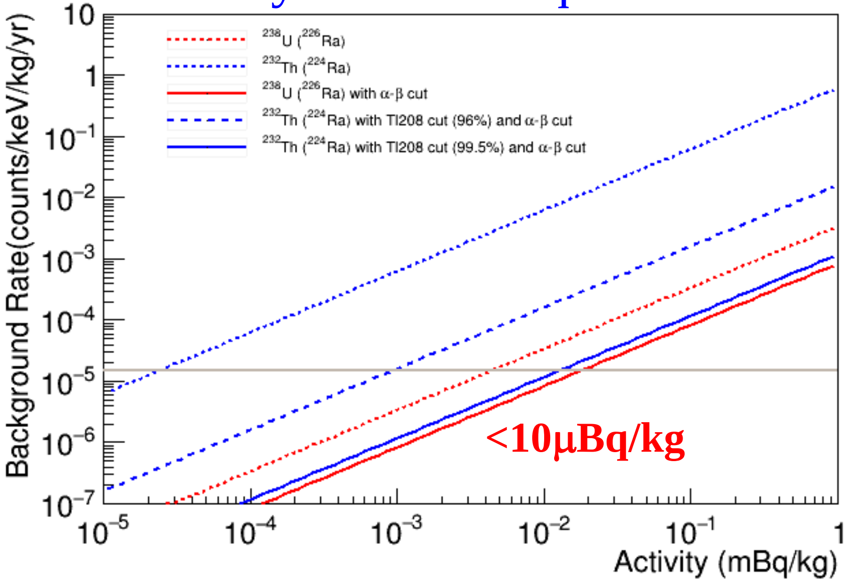
It is expected that PROSPECT (USA) will confirm this result within a year.

Estimation for AMoRE-I backgrounds

- Tried to identify critical components in the setup for AMoRE-II experiment.
- Currently, “Crystal Bulk” has largest contribution in $CaMoO_4$ crystal case.
- For AMoRE-II, the Crystal Bulk activity for zero background has been set.

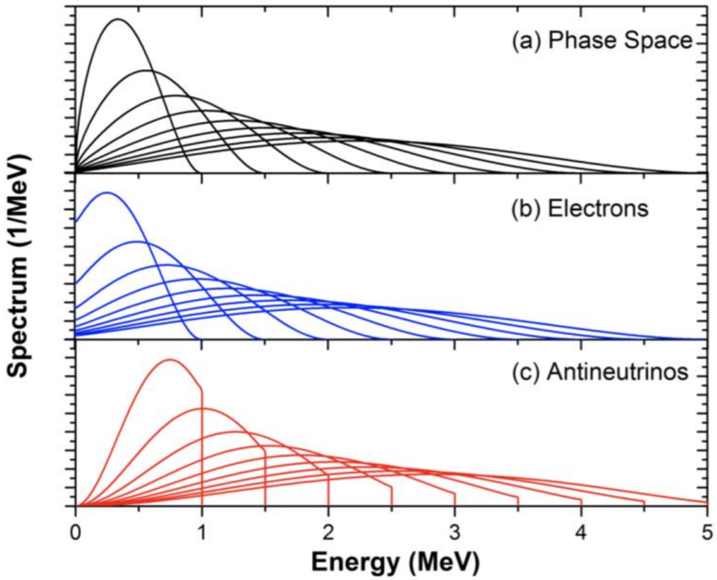


Crystal Bulk requirement

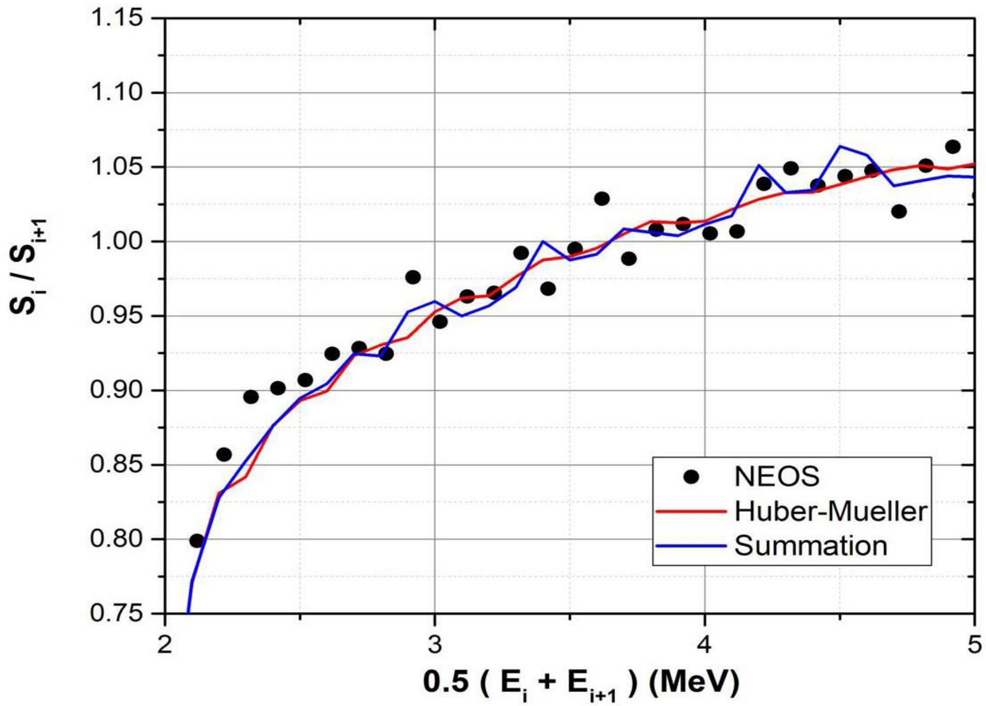


Fine structures in the spectra

Oscillation vs Fine structure in antineutrino spectra



Sonzogni et al. PRC98, 014323 (2018)

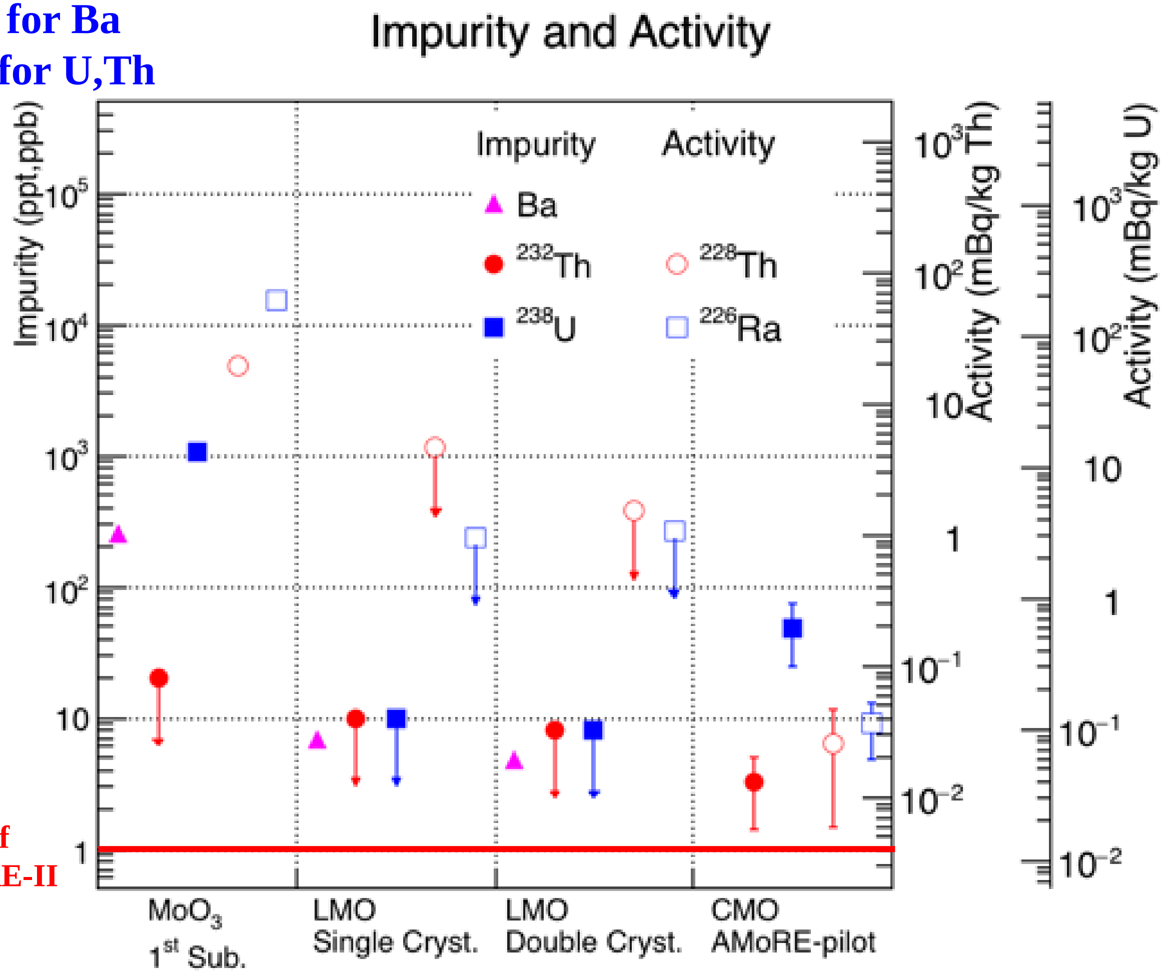


The agreement between NEOS and the summation calculation is good.

Summary of molybdate crystals

- Low temperature crystal tests are critical and under preparation.
- We have a good progress toward AMoRE-II crystals.
- Enriched LMO crystals will be grown at CUP and NIIC (Russia).

ppb for Ba
ppt for U,Th



Goal of AMoRE-II

Final decision of crystal will depend on background and particle identification power.