INSTRUMENTATION FOR UNDERGROUND PHYSICS IN KOREA

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DIRECTOR OF CUP

2019. 7. 11.

KAIST-KAIX workshop for future Particle Accelerators

Ground & Underground Labs of CUP

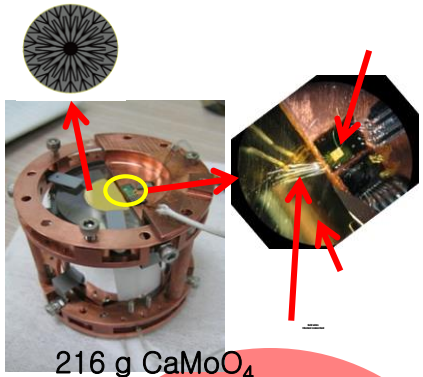
- **IBS-HQ is a ground laboratory in Daejeon city.**
- **Y2L was constructed in 2003 to house KIMS dark matter search experiment. (700m)**
- **NEOS site (10m depth) is made in Tendon Gallery of nuclear reactor near RENO experiment.**
- **Yemilab is under construction to be completed in 2020. (1100m depth)**

CUP Technology

For rare event search,

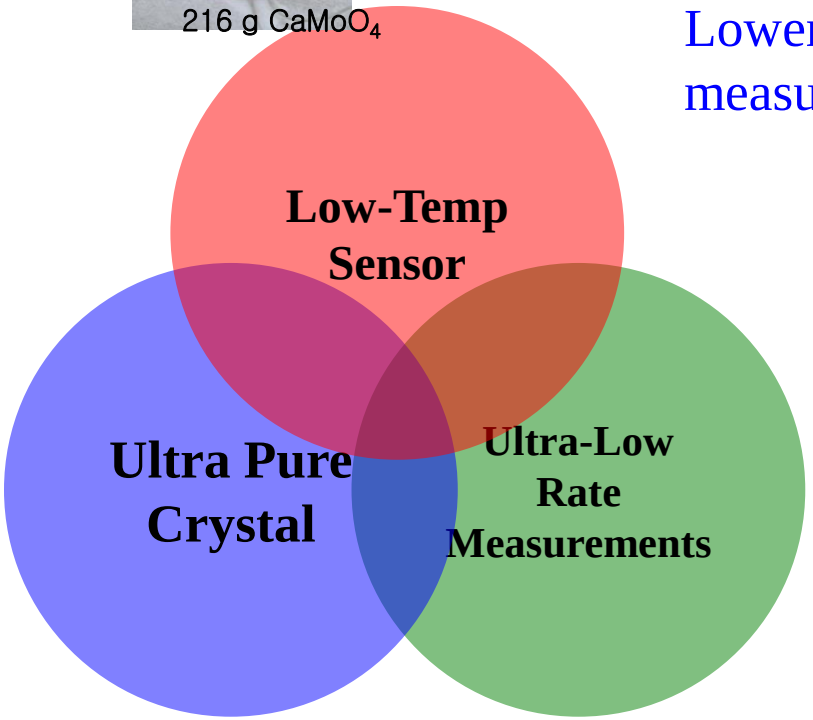
we need;

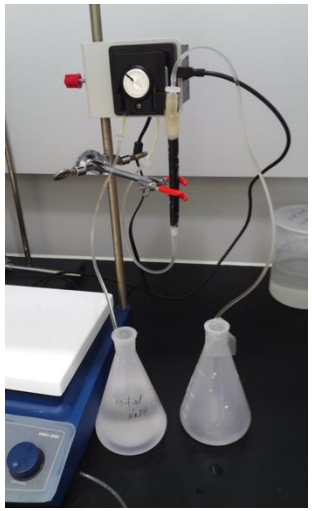
Larger signal,
Lower threshold,
Lower background.



We try to develop

Cleaner environment,
Purer material,
Lower-level of radioactivity measurements.

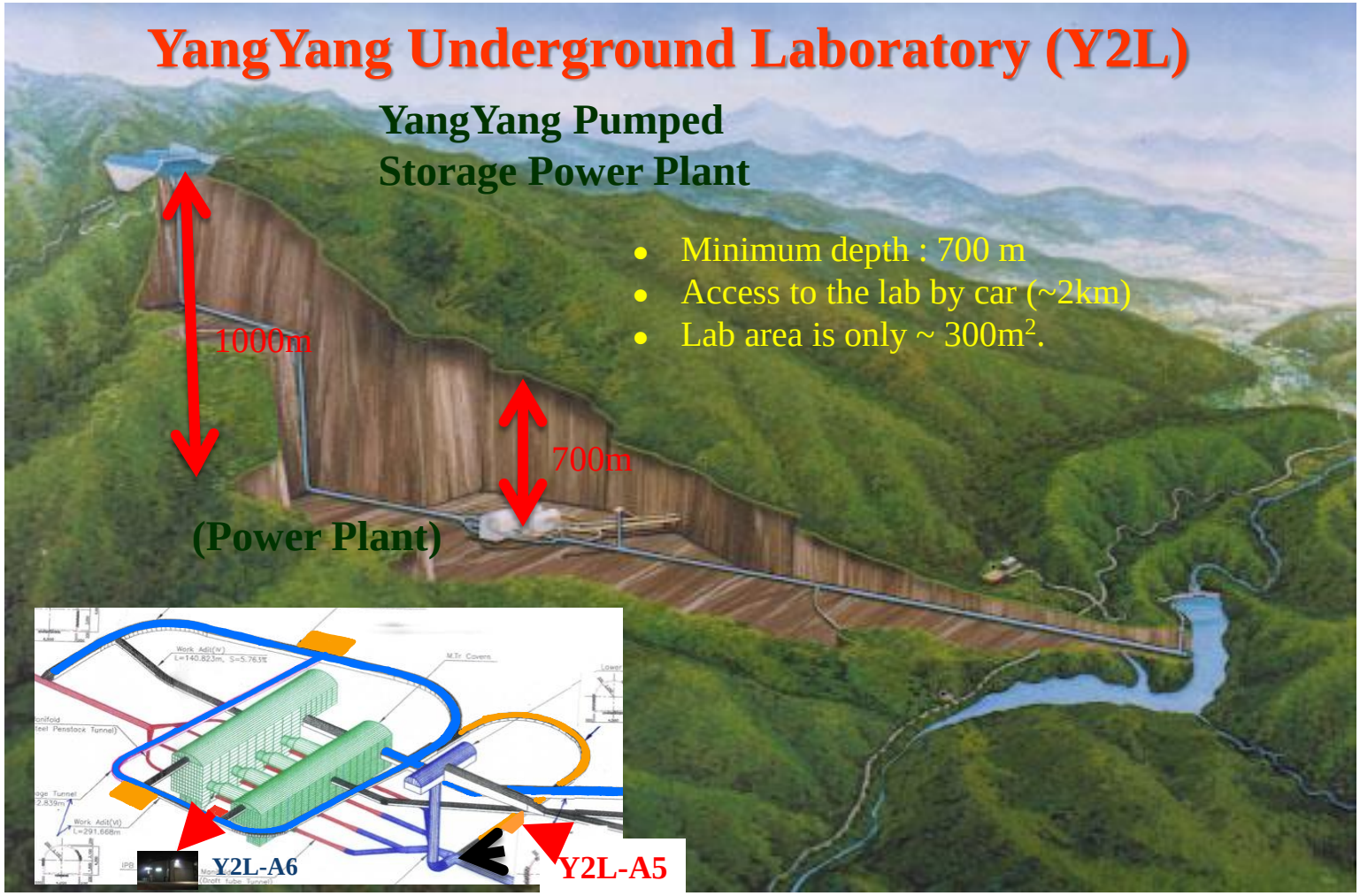




https://www.ibs.re.kr/cup/

Yangyang Laboratory (Y2L)

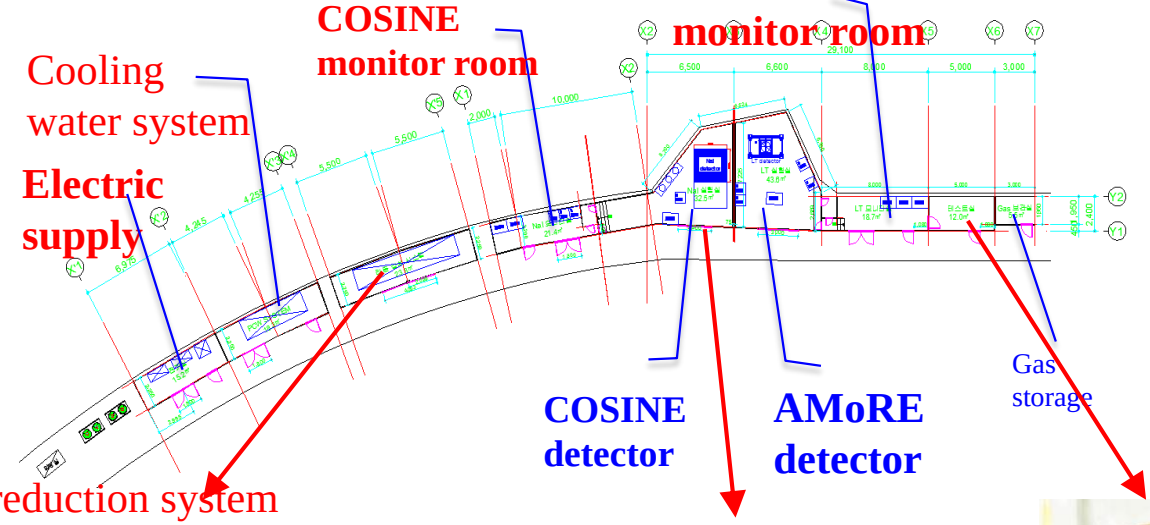
+ We need deeper and larger underground space.

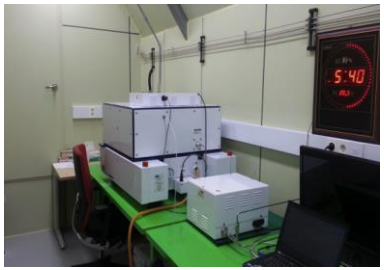


Y2L-A5

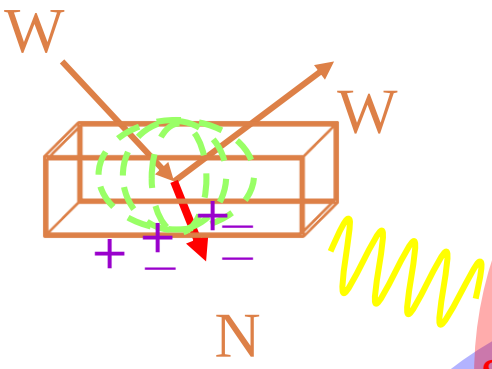
Y2L-A5 is built in slanting tunnel to use until we have new underground laboratory. COSINE & AMoRE experiment are running.

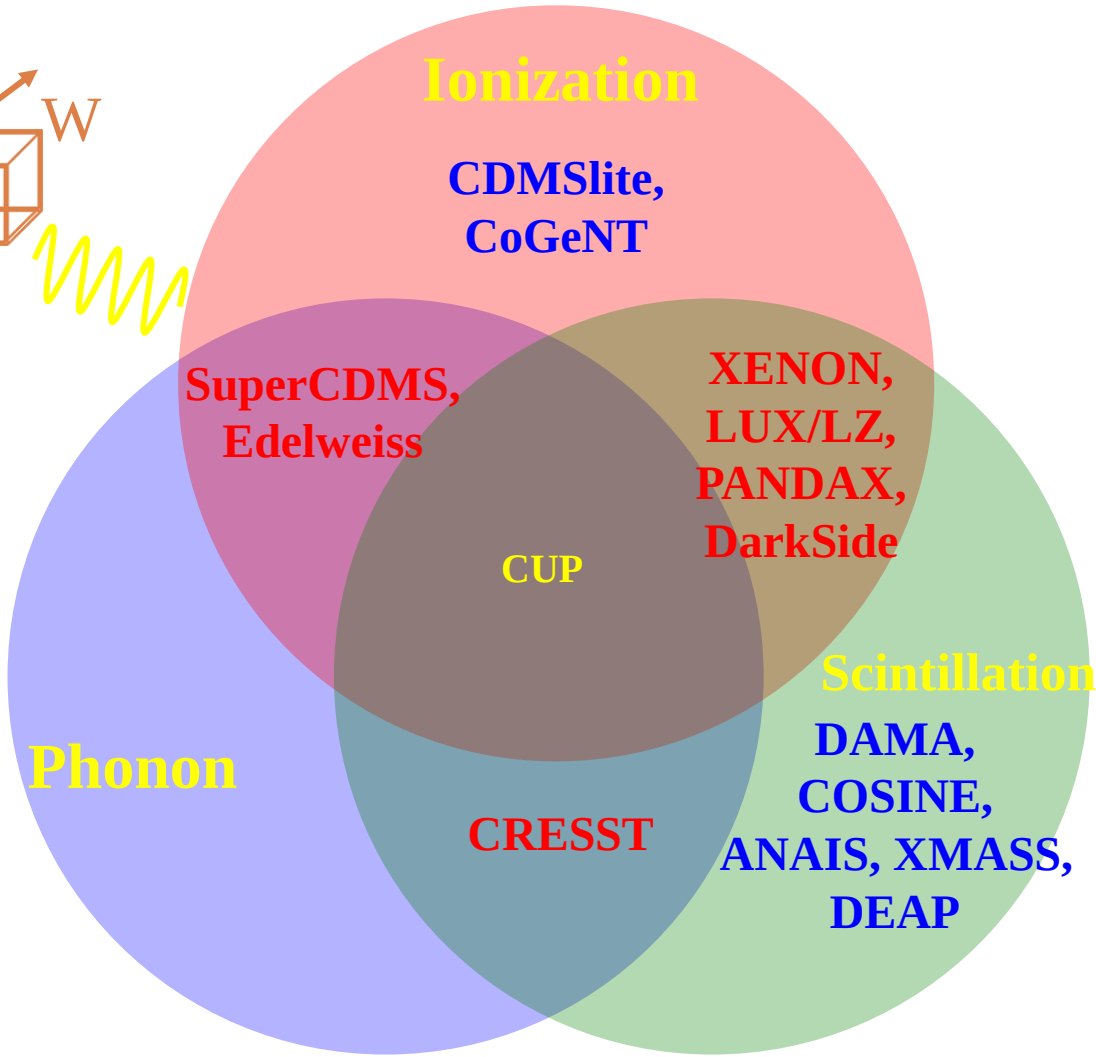
Y2L-A5 (200m^2)





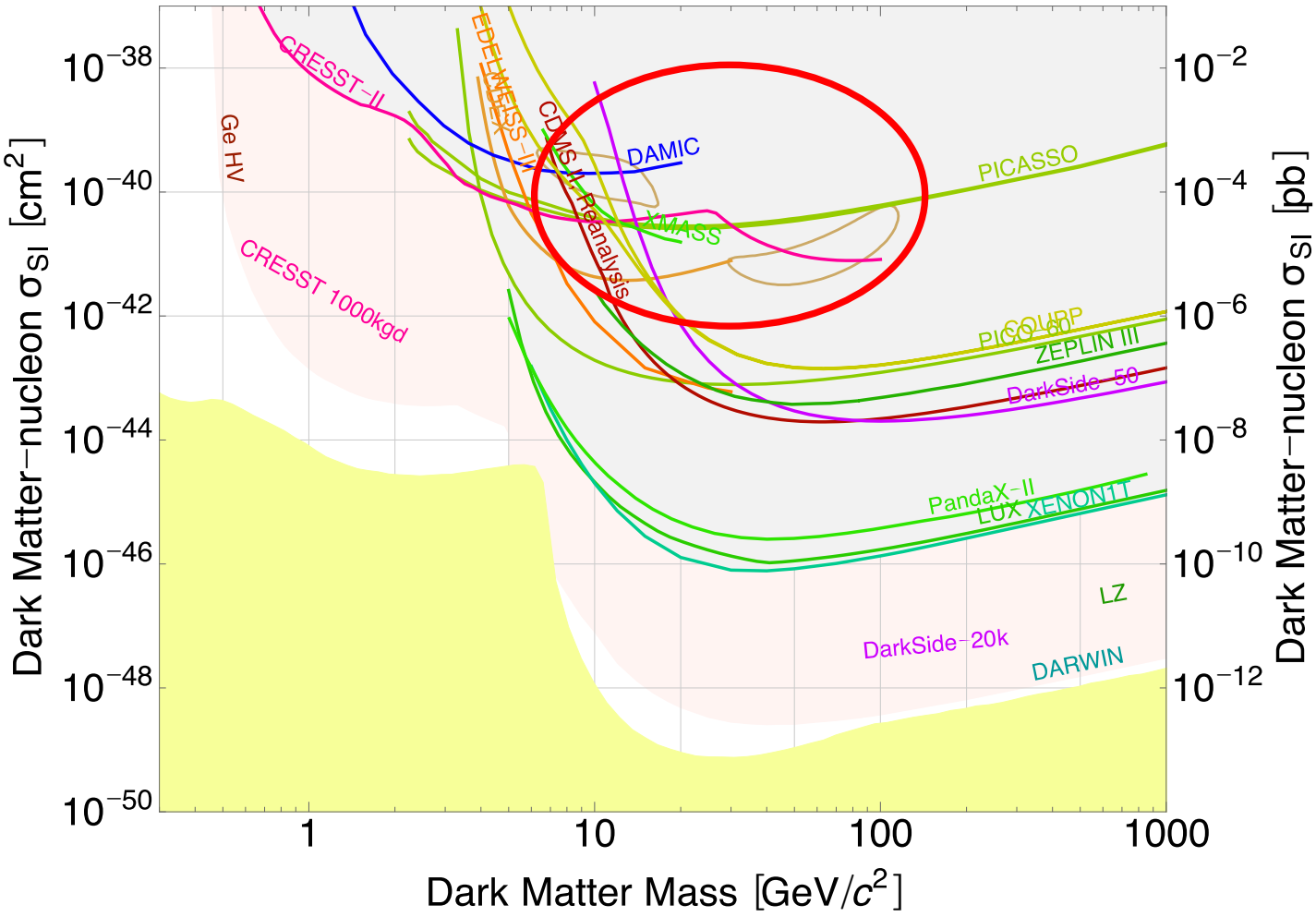
Detector Techniques for direct detection of WIMP





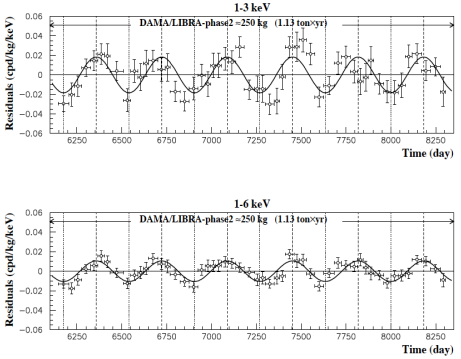
Direct Dark Matter Search

- Current limits of Spin-independent c.x.
- Close to reach neutrino floor, expect to see the neutrino coherent scattering.
- DAMA island is still there.



COSINE

- Purpose – Simple, Check DAMA signal.
- Collaboration : Yale, CUP, Sheffield, Sao Paulo U.
- Status : COSINE-100 is running at Y2L for 2.5 years.
- Results :
  1. Contradictory to DAMA interpretation as WIMPs with standard halo
  2. Showed ~1.5 sigma sensitivity for DAMA modulation signal with 1.5 years data.



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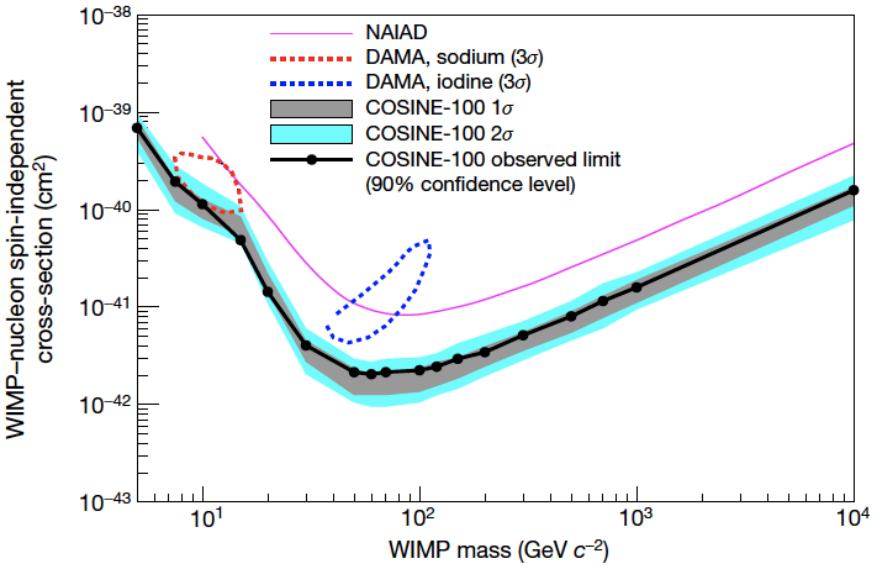
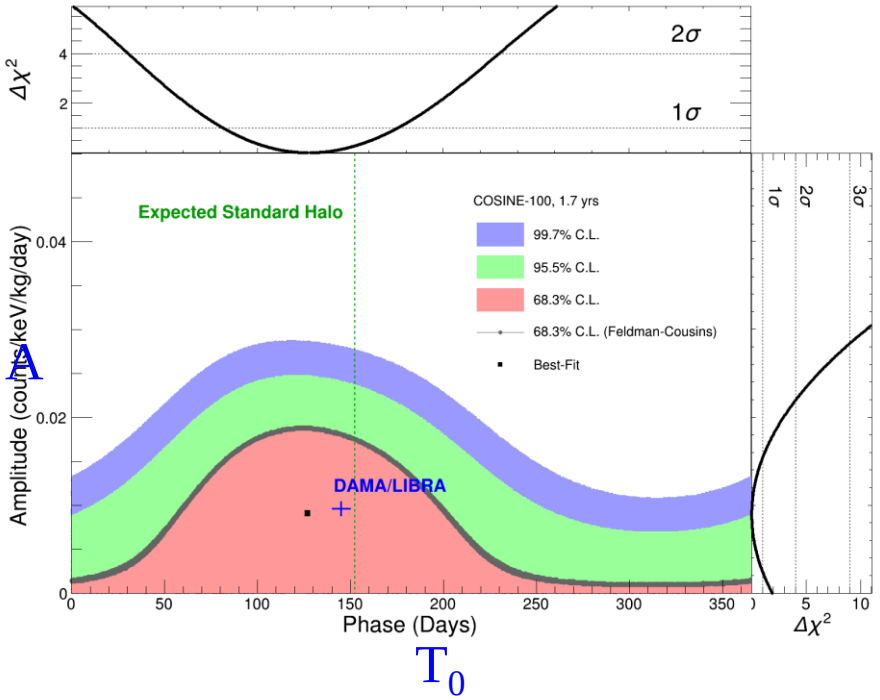
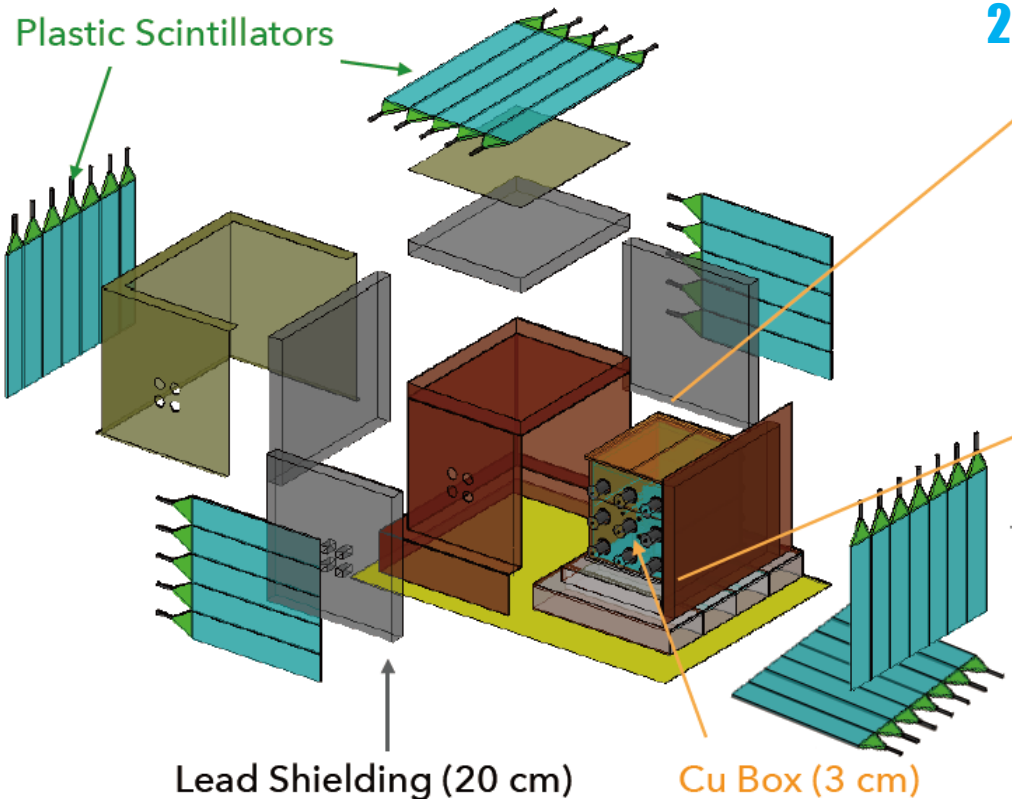


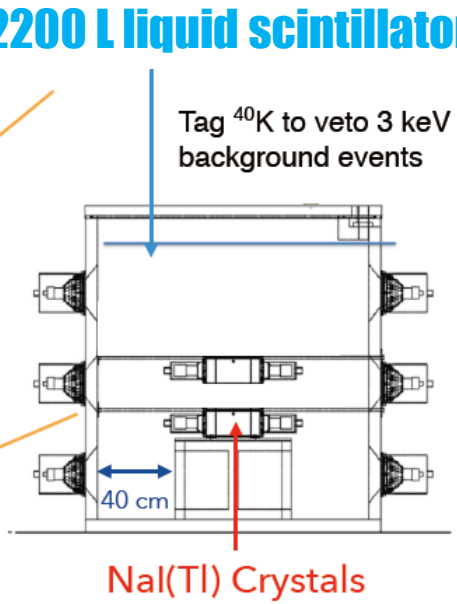
Accepted to PRL



COSINE-100 detector

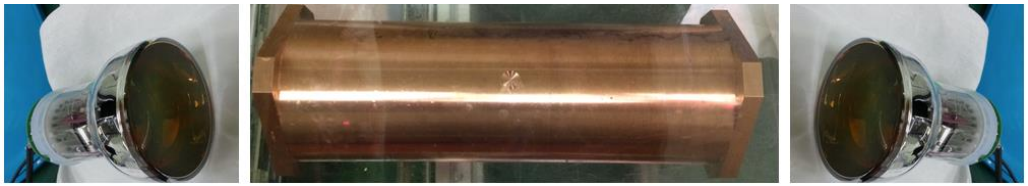
Due to relatively shallow depth, muon veto counters are installed.

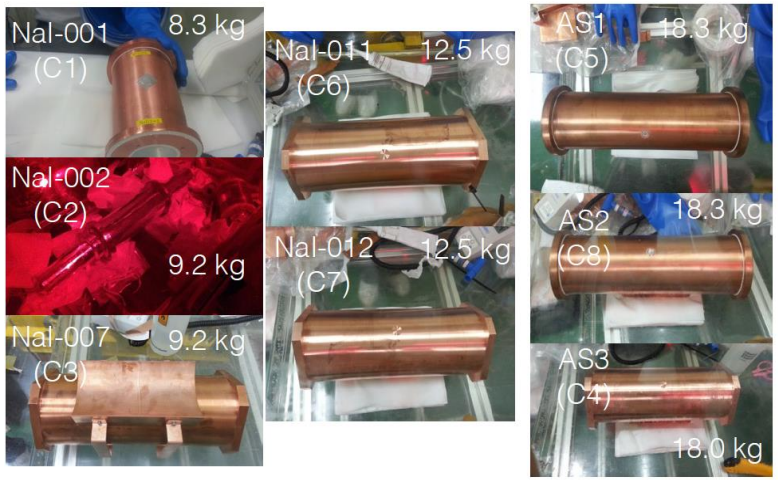




Crystal + PMTs

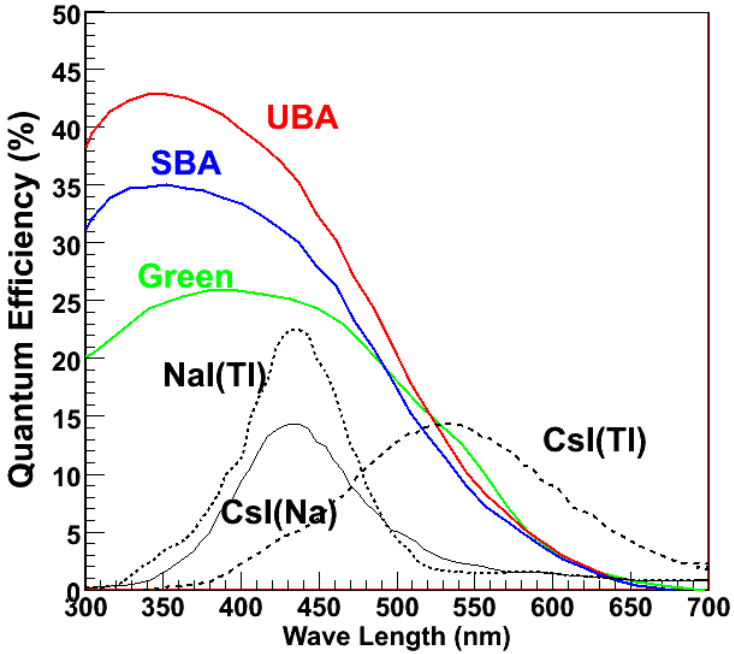
- Hamamatsu R12669SEL PMTs (SBA)
  Quantum Efficiency : 35% @ 420 nm





From KIMS

From DM-ICE



Both Anode & Dynode readout to increase dynamic range.

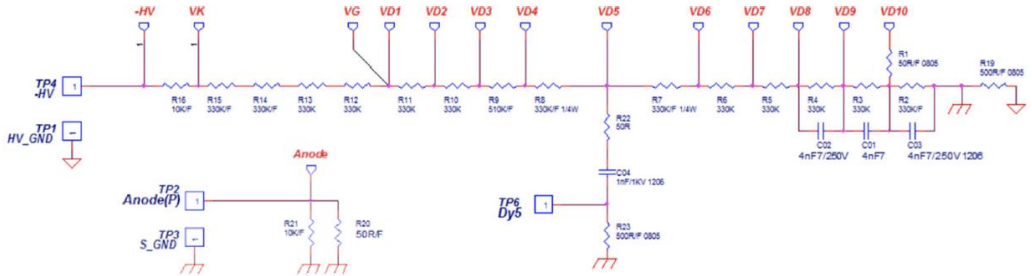


Fig. 11 Schematic of crystal PMT voltage divider

Light Yields in Scintillators

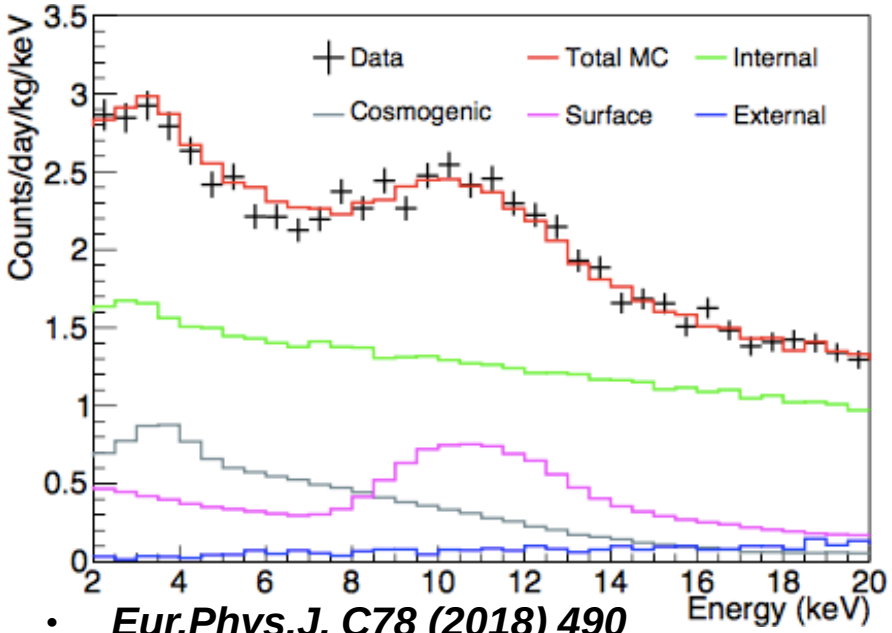
	Experiment	Photoelectrons/keV
Inorganic Scintillator	DAMA/NaI	~ 5.5
	DAMA/LIBRA	5.5-7.5
	KIMS-CsI	~5
	COSINE	14-15.5
	ANAIS	15
	CUP-NaI	~10
Liquid Argon	DarkSide(zerofield)	8.1(0.2)
	DEAP-3600	7.8(0.3)
Liquid Xenon	XMASS	13.9(1.2)
	XENON1t (zerofield)	8.9
Liquid Scintillator	Borexino	0.51
	KAMLAND	0.26

COSINE NaI detector has the highest No. of photoelectrons/keV among scintillators at underground.

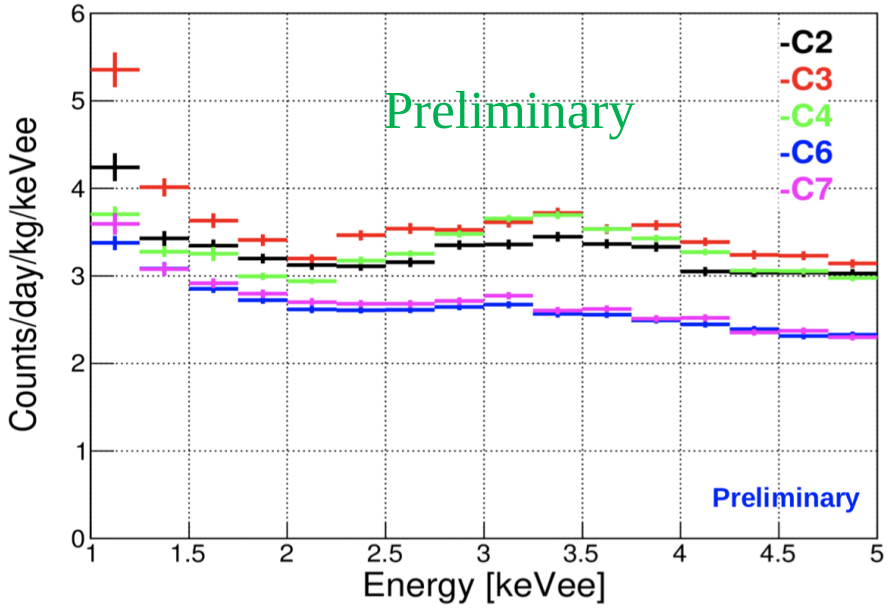
→ Both ANAIS and COSINE exp reached 1 keV threshold.

- Dual phase liquid XENON detectors will be higher in #pe+# of electrons.

Background spectra



- ***Eur.Phys.J. C78 (2018) 490***



- With bkg. understanding, 8 single-hit spectra are fit simultaneously with an assumed WIMP signal (Standard Halo Model as described in Savage et al.).
- Basically there is no room for WIMPs signal if they are from standard halo model.

Crystal growing

- Location of Alpha Spectra company is in high altitude (~1400m) → cosmogenic background high.
- Decided to develop lower background crystal at CUP.
- Powder purification (We have 1ton of Merck NaI powder)
  - Succeeded purification
  - A problem of drying. → Fixing with Enamel coating.

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

- This conical dryer was coated inside with PFA, which made PFA dusts included in final NaI powder.
- PFA coating → Enamel coating.
- Will be tested in this summer.

Crystal growing

- Crystal growing
  - Succeeded growing NaI crystal at CUP. Tens of test crystals are grown.
  - **Light Yield ~ 10.4 pe/keV**
  - **^{210}Pb is still high (~ mBq/kg). Almost identified the source.**

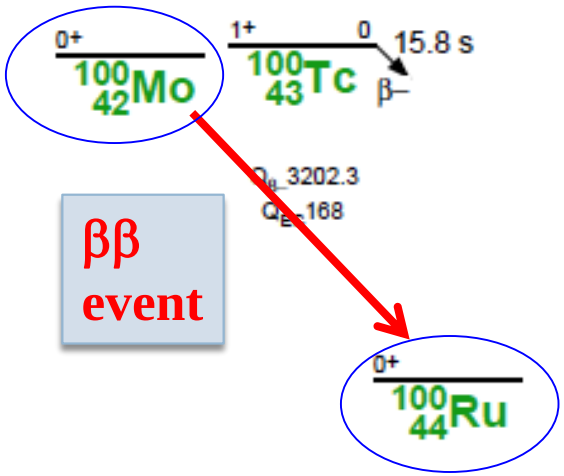
Search for Neutrinoless double beta decay - AMoRE

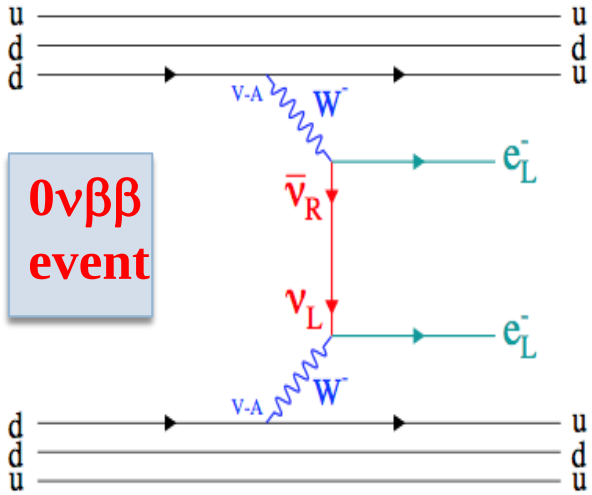
Observation of 0νββ

- **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.**

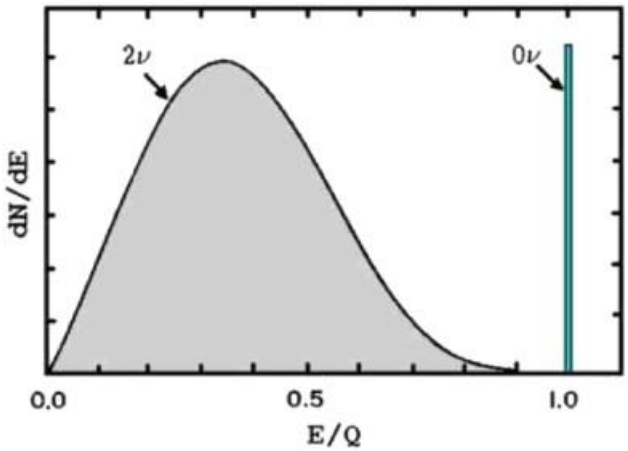
$$m_n \approx \frac{m_D^2}{m_N}$$

For light neutrino exchange model;





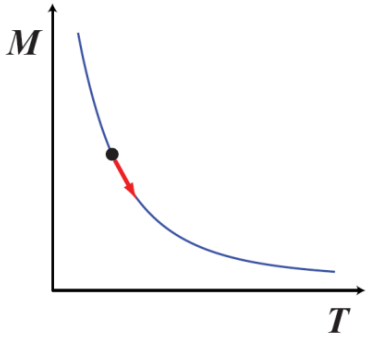
Signal :
sharp peak @ Q-value

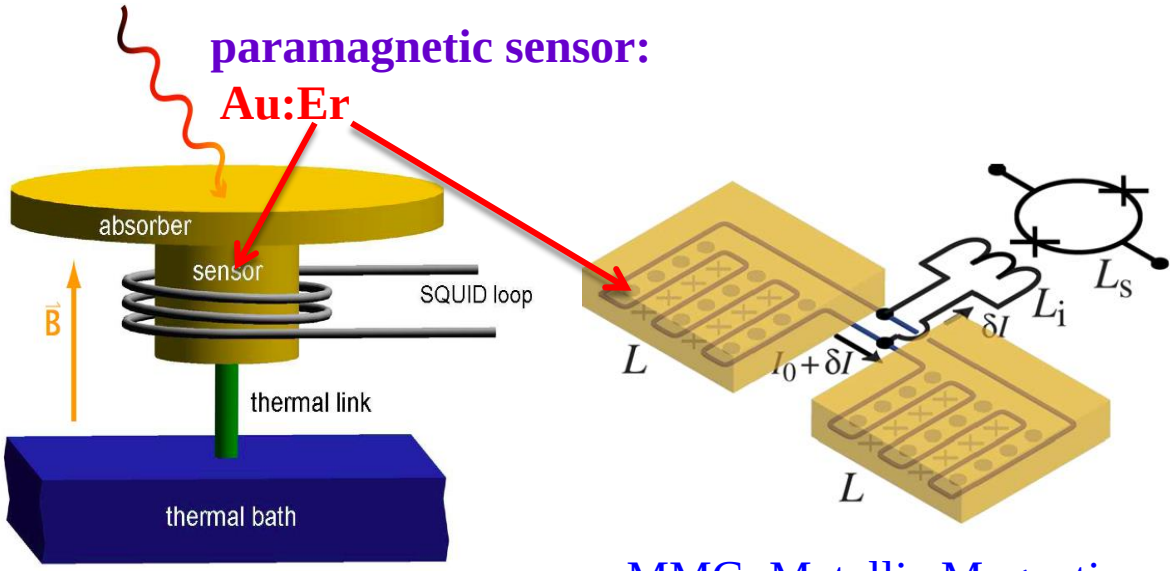


Thermal detectors at low Temp. for AMoRE

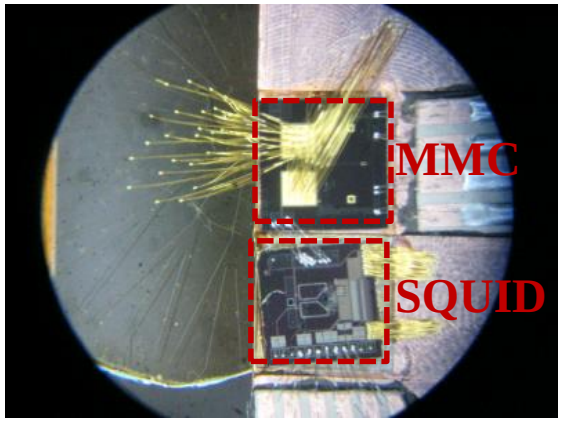
- Particle interaction is detected through a temperature change at mK temperature.

Energy (Heat) absorption
→ Change in Temperature in an absorber
→ Change in Magnetization in a paramagnetic alloy(Au,Ag:Er) in a constant magnetic field
→ Induced current measured with a SQUID.



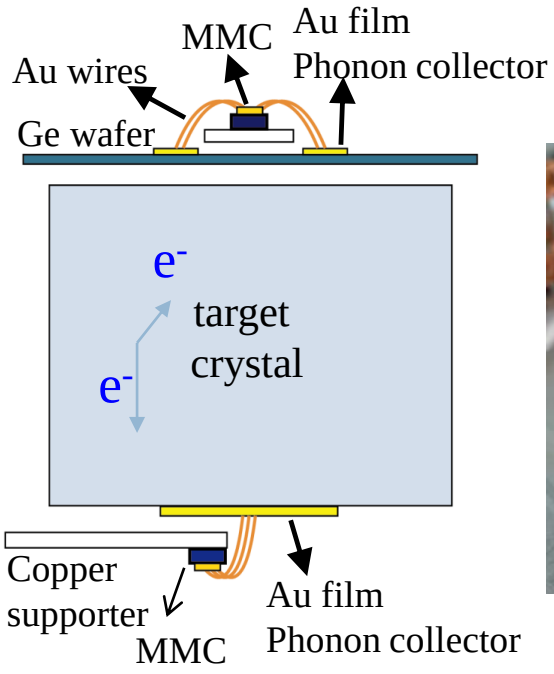


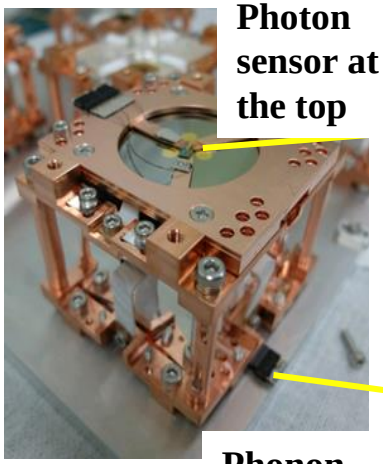
MMC: Metallic Magnetic Calorimeter



Principle of AMoRE Detector

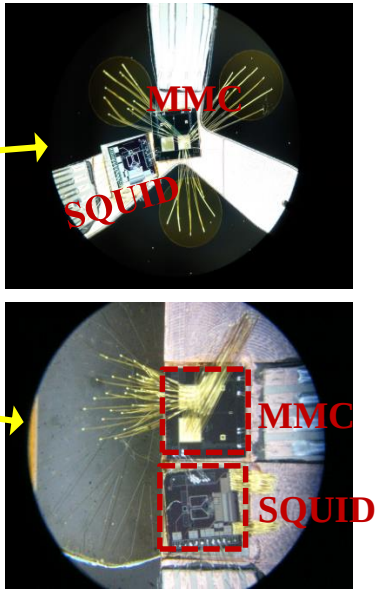
- **Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC**
- **For Each crystal, phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal).**

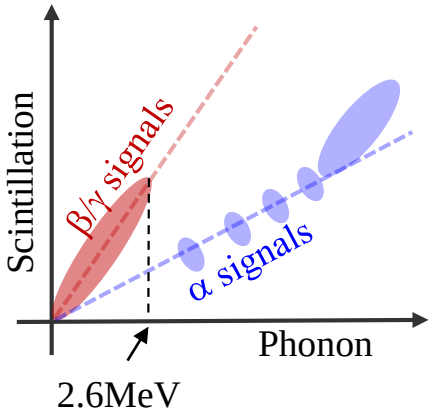




Photon sensor at the top

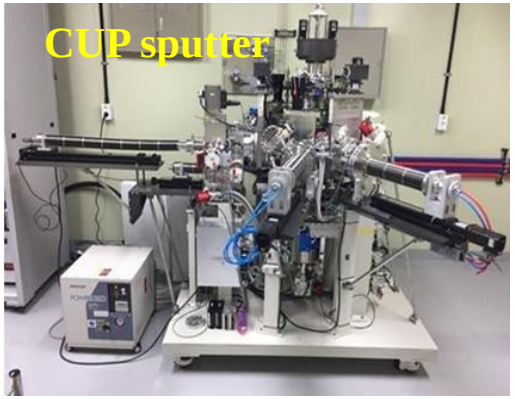
Phonon sensor at the bottom





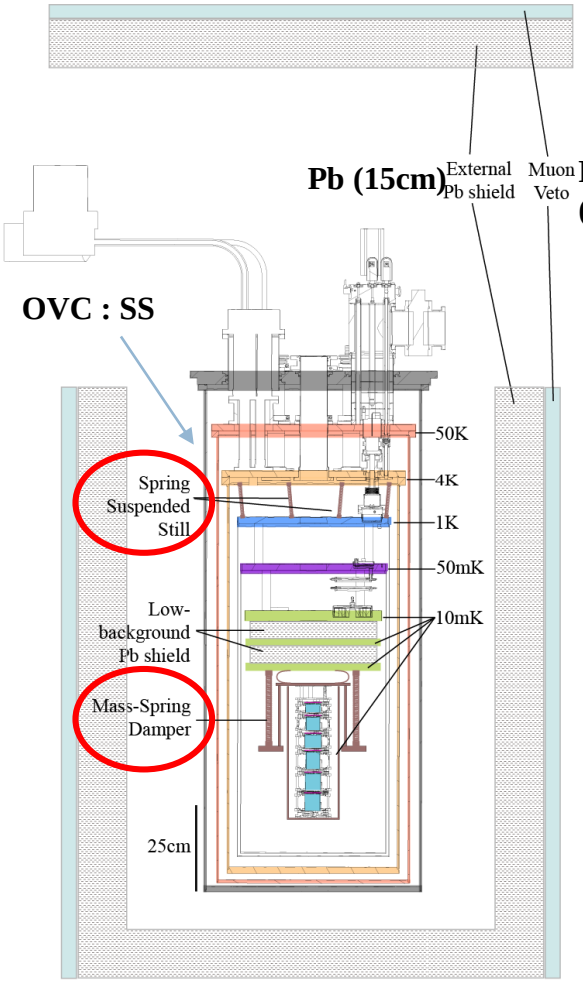
Fab facility for MMC

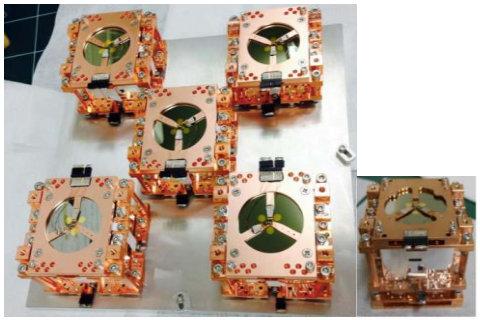
Fabrication facility	
Metal thin film system	Metallic magnetic calorimeter sputtering system
	Radon free environment e-beam evaporator system
Pattern lithography equipment	Maskless Micro Pattern Generator
	Dual Focus Micro-Pattern Mask Aligner
Metal film etching equipment	ICP-RIE (Inductively Coupled Plasma- Reactive Ion Etching) system
Insulation film growth equipment	LT-PECVD (Low-Temperature Plasma-enhanced chemical vapor deposition)
	Anodizing unit
Thick Au layer fabrication	Simple electroplating unit
Chip dicing	Dicing saw
Resist coating unit	Spin coating system Hot plate
Fabrication step verification	3D Measuring Laser Microscope
	Optic Microscope
Collector annealing system	Rapid thermal process system



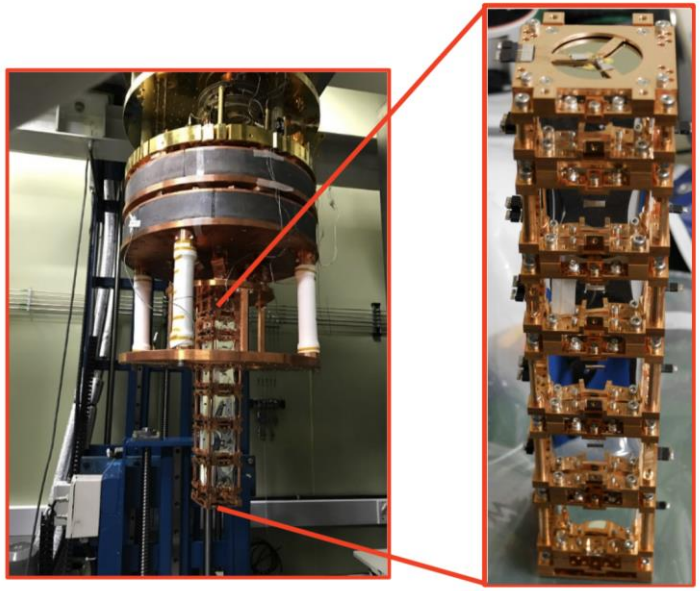
AMoRE-Pilot Setup

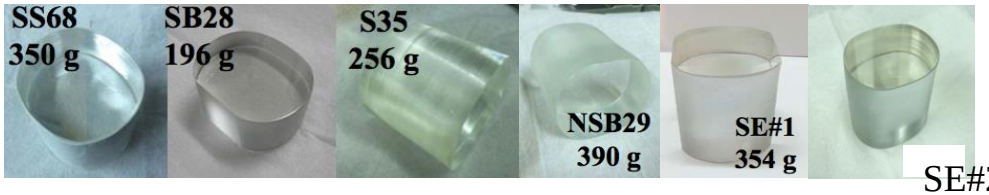
- **To demonstrate the detection principle and low backgrounds.**
- **6 crystals making total mass 1.89 kg.**
- **Two vibration reduction systems are installed.**





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

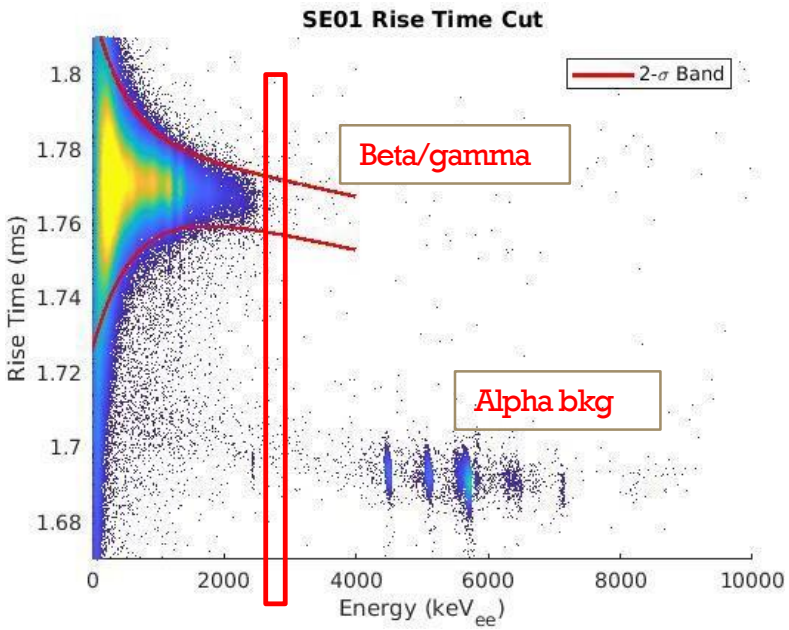


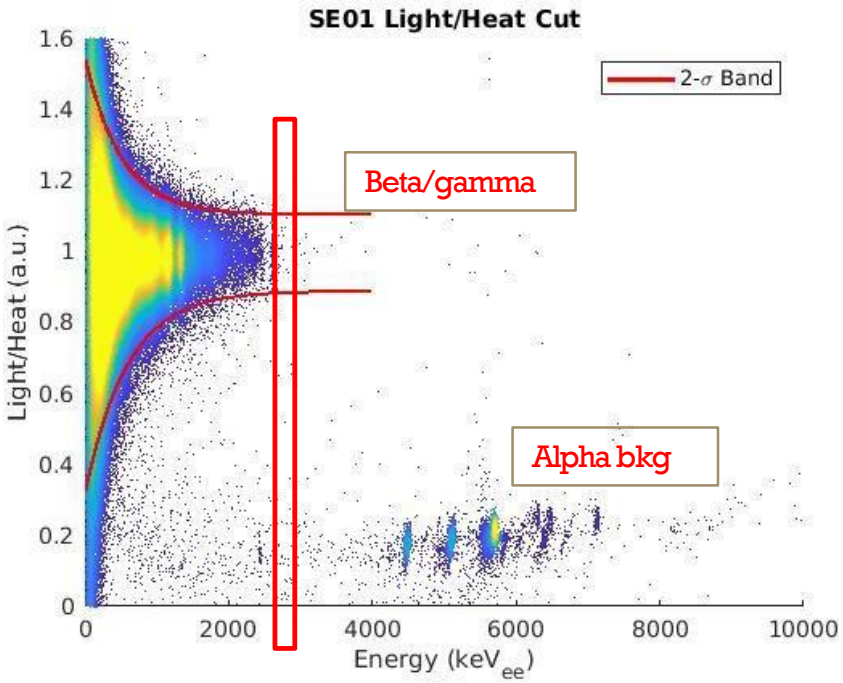


$^{40}Ca^{100}MoO_4$ crystals from Russian company, FOMOS.

PSD

arXiv:1903.09483

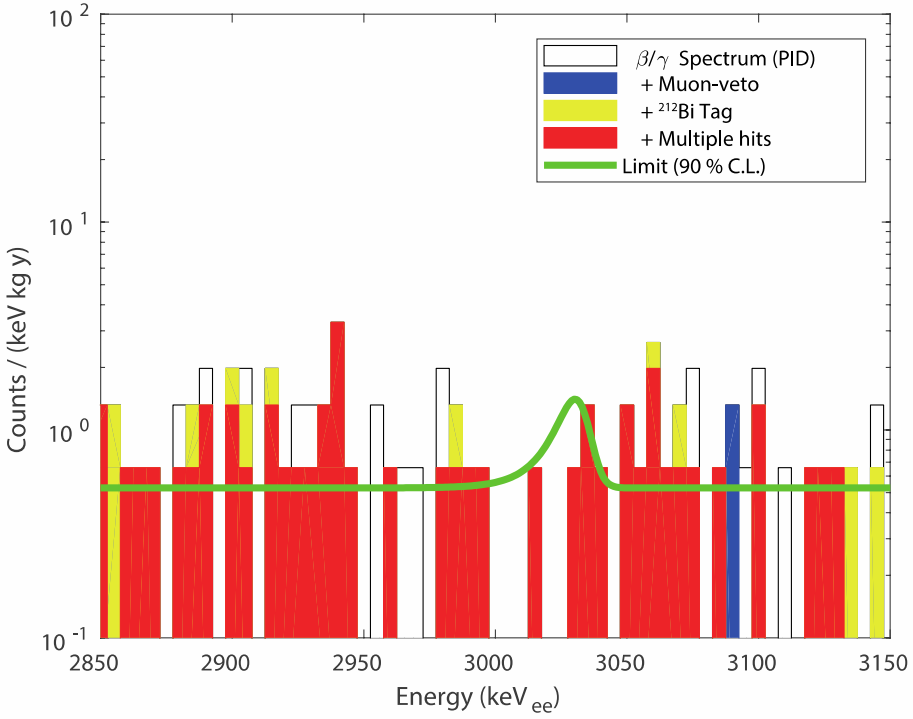




Unlike CUORE, scintillating bolometer can remove alpha backgrounds in ROI.

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

Background spectrum at ROI



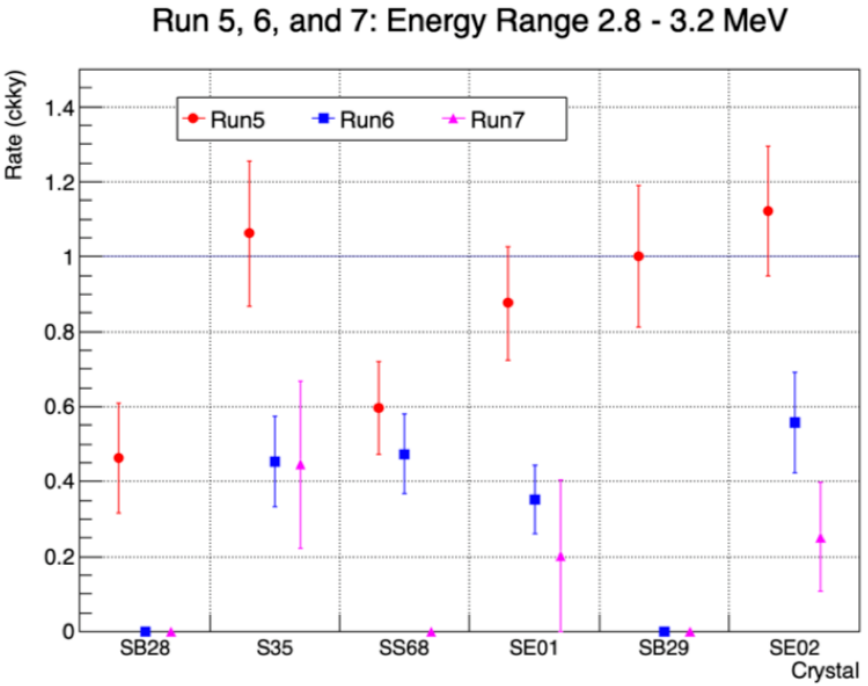
- 111 (kg day) exposure.

→ Final background level : 0.55 counts/k eV/kg/year.

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

NEMO best limit $1.1 \times 10^{24} years$

- Background levels are reduced by 70 % after removing active components a nd additional neutron shielding.



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

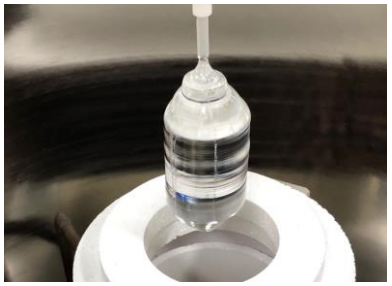
We have grown an enriched LMO crystal without any purification to check what level of contamination would be reached by only from crystal growing process.

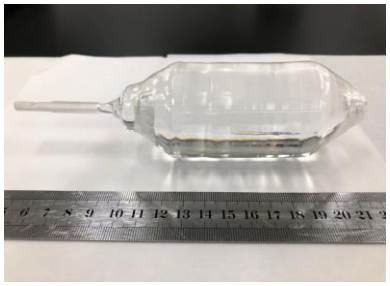
$Li_2CO_3+MoO_3 \rightarrow Li_2MoO_4+CO_2$

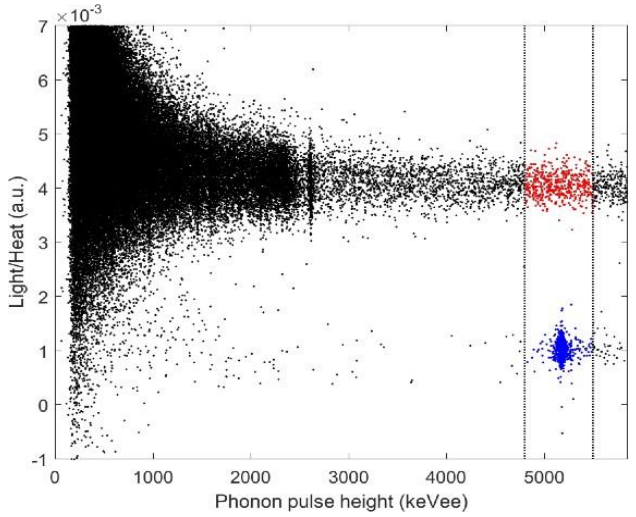
- Natural LMO tested at wet dilution refrigerator.
- 300 g crystal + MMC
- Light/Heat ratio gave DP~12.
- A problem of Au foil attachment. After a few months, the Au phonon collector seems unstable.

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

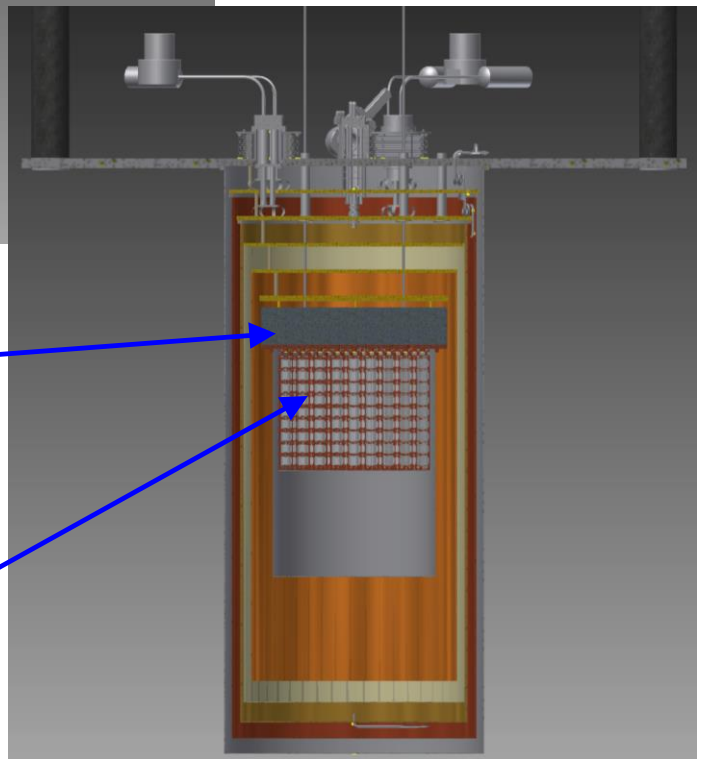






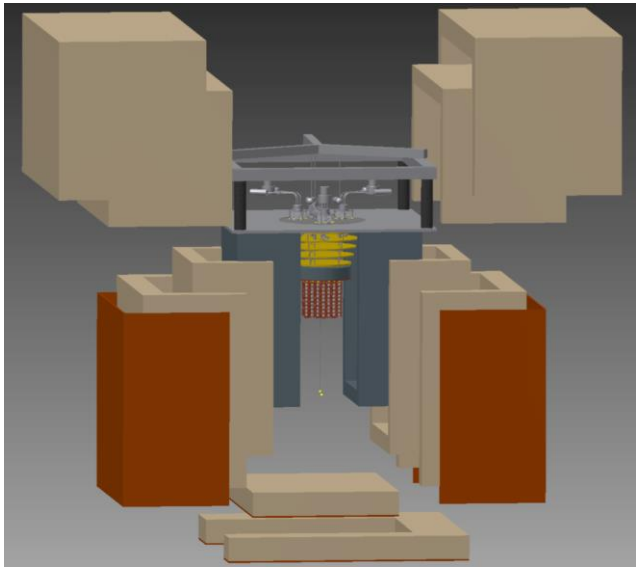
Design for AMoRE-II experiment

Tunnel
(20mx20mx16m(h))



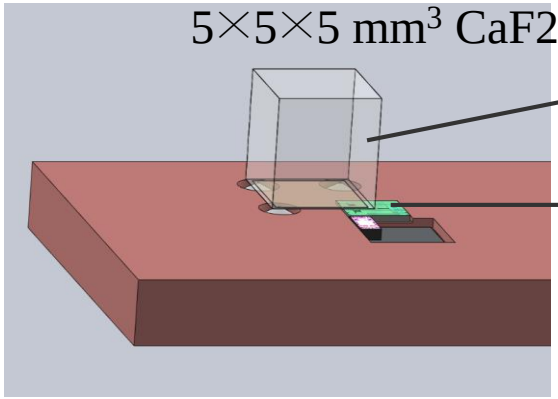
25 cm
Lead

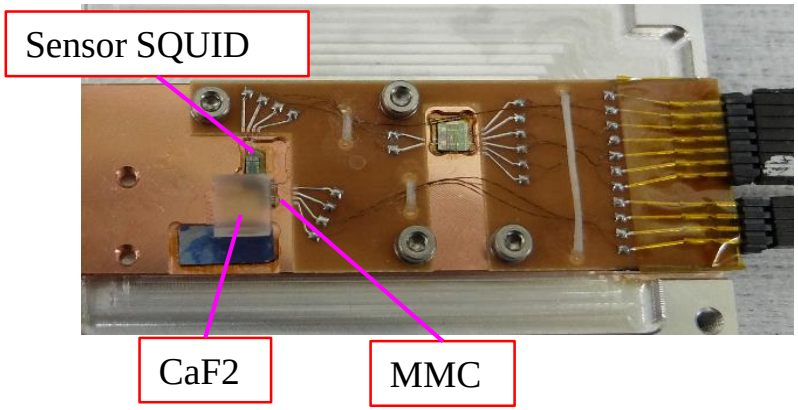
200 kg
crystals

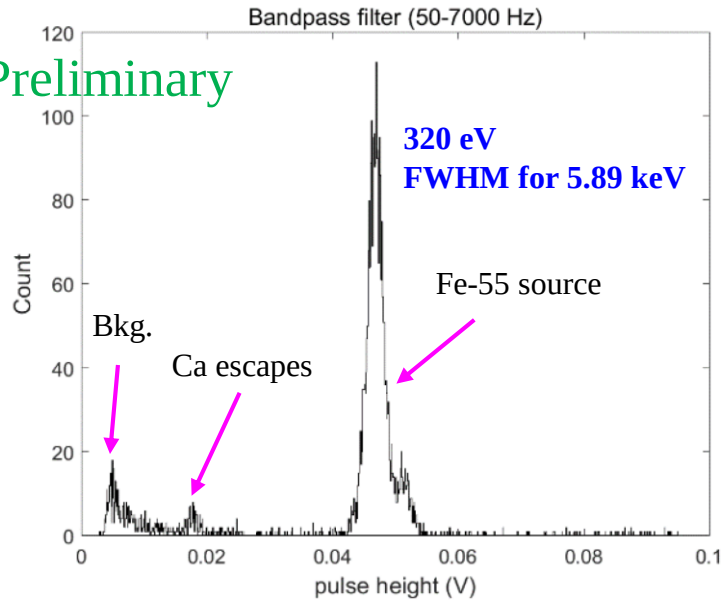


Low threshold detectors for DM exp

To use low temperature sensor for dark matter detector, we need to reduce the threshold energy.



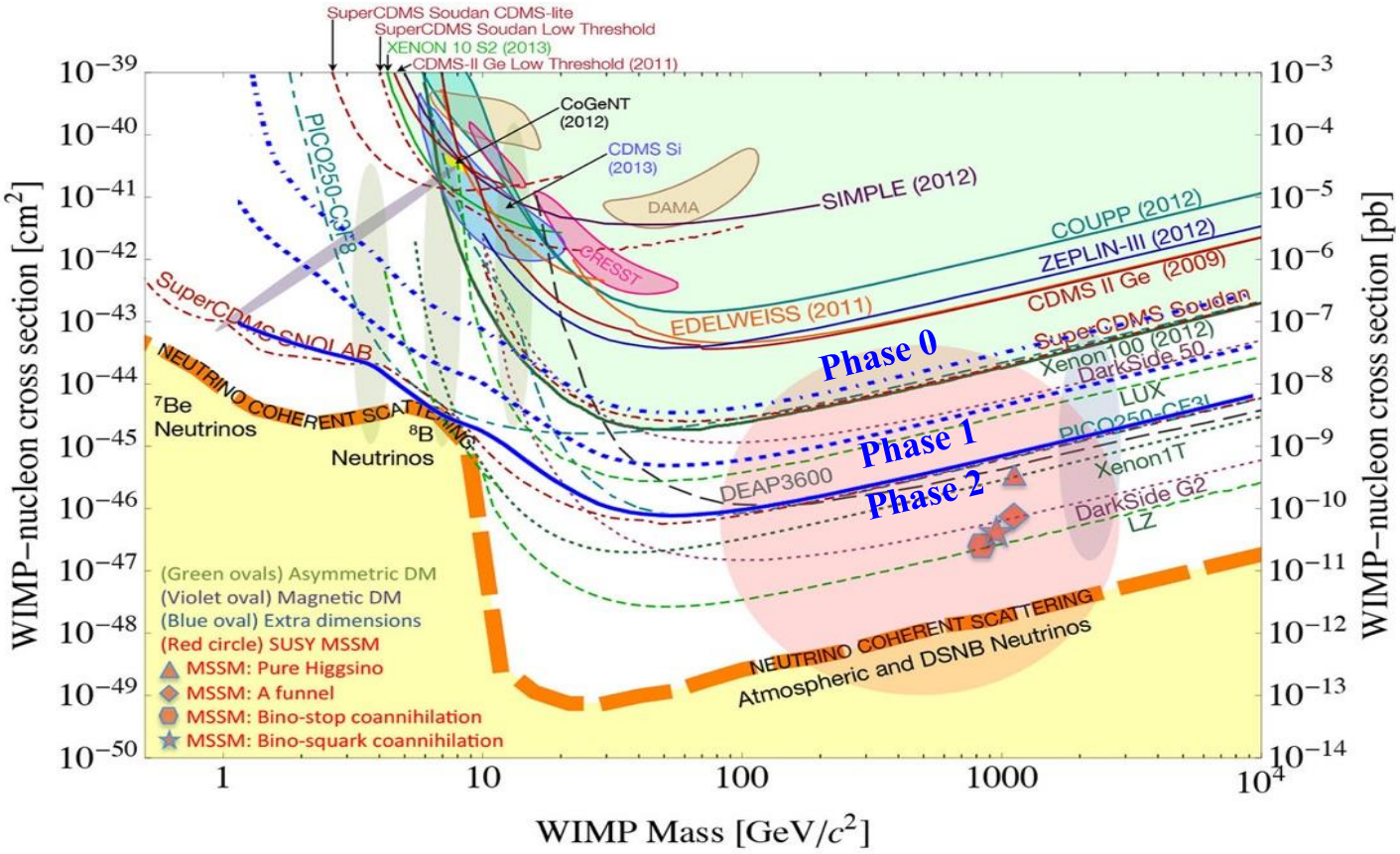




Baseline resolution indicates ~ 140 eV threshold @ 30 mK.
It is just beginning, and need to optimize the crystal size etc.

Low mass WIMP search

	Threshold	Background	Mass	Time line
Phase0	1 keV	1.0 dru	10 kg	2~3 years
Phase1	0.5 keV	0.1 dru	50 kg	3~6 years
Phase2	0.1 keV	0.01 dru	200 kg	6~10 years

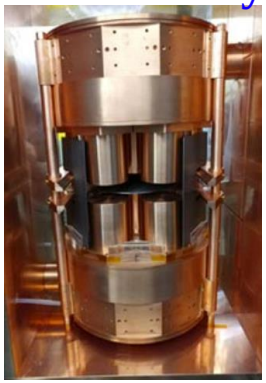


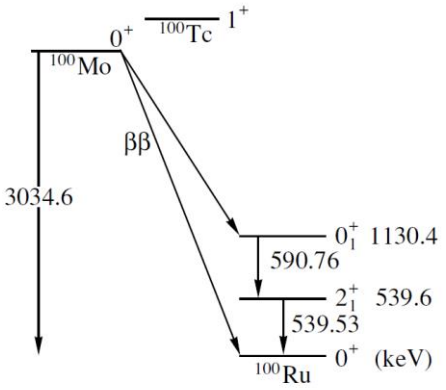
Purification & Measurements

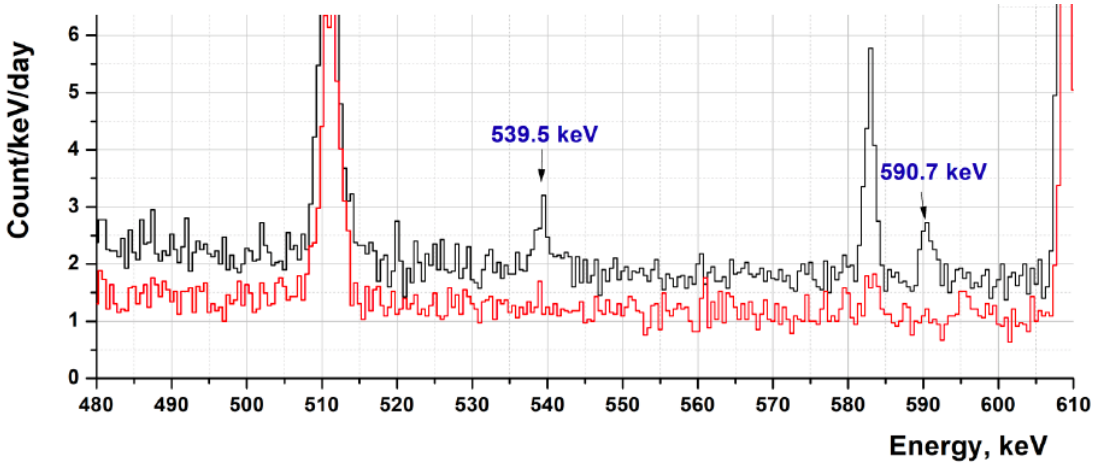
- Purification by recrystallization, sublimation, etc..

- Measurements by ICP-MS, HPGe-Array, Alpha counters….All techniques are developed well.
  - ICP-MS : sub-ppt(10^{-9}) level for U, Th with solid extraction method.
  - HPGe-Array : 14 HPGe crystals, two neutrino double beta decay to an excited state is observed.
  - Alpha counter : Surface contamination …

HPGe-Array

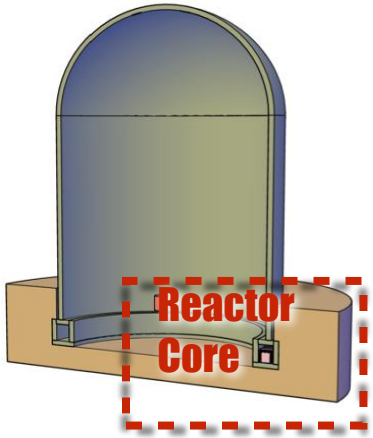






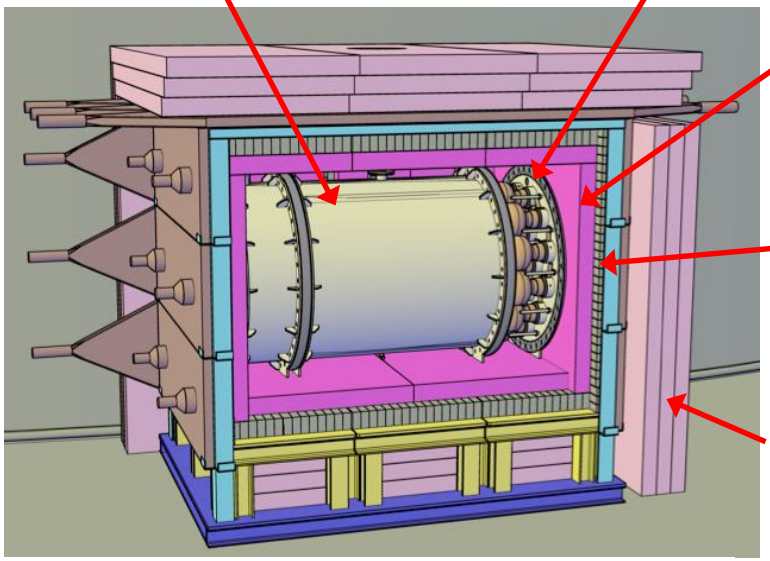
Search for sterile neutrinos with reactors - NEOS

- Tendon Gallery : ~25 m from 2.8 GW_{th} reactor
- Shallow (~10 m) concrete overburden



~ 1ton : LAB (90%) + UG-F (10%)
0.5 % gadolinium is loaded.

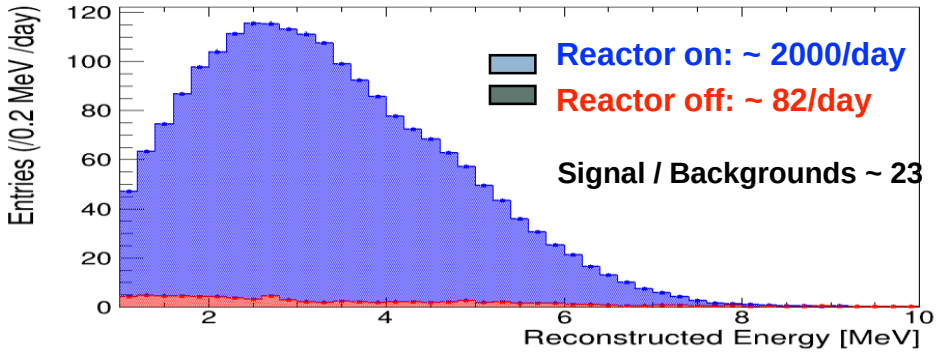
38 8” PMTs in mineral oil.

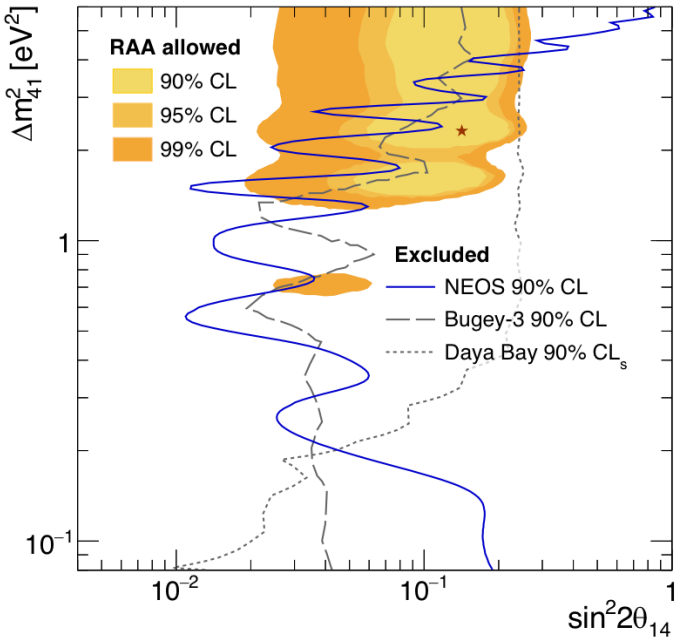


Borated PE (10 cm)

10 cm lead

4π muon veto detector

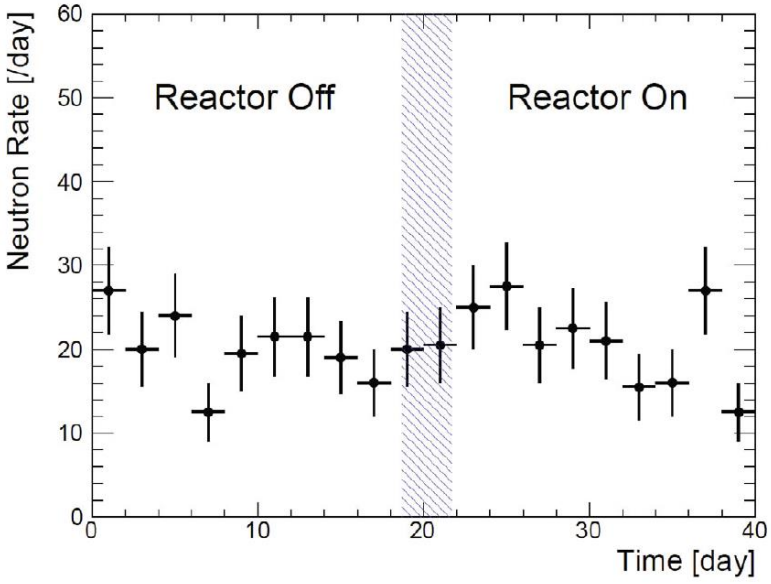




Best reactor neutrino anomaly parameter is excluded by NEOS.

- Neutron backgrounds :

Fast Neutron rates at Tendon Gallery are reduced by 100 times and no difference between reactor on/off .



- Very low threshold NaI(Tl) crystals can be used to detect reactor neutrino coherent scattering or neutrino-electron scattering.

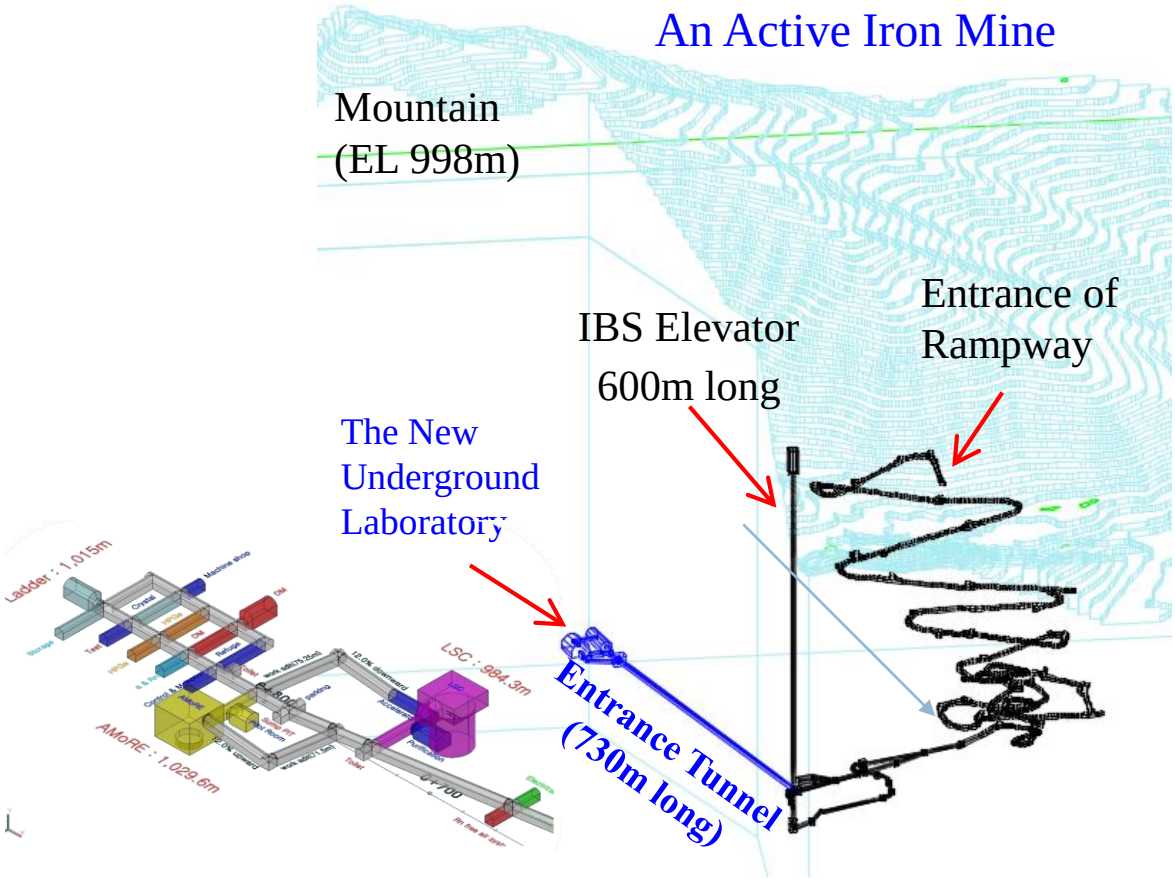
- Preliminary test with smaller size NaI(Tl) crystal directly coupled with PMTs show ~ 20 photoelectrons/keV ! – Promising.

Yemilab

Center for Underground Physics

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

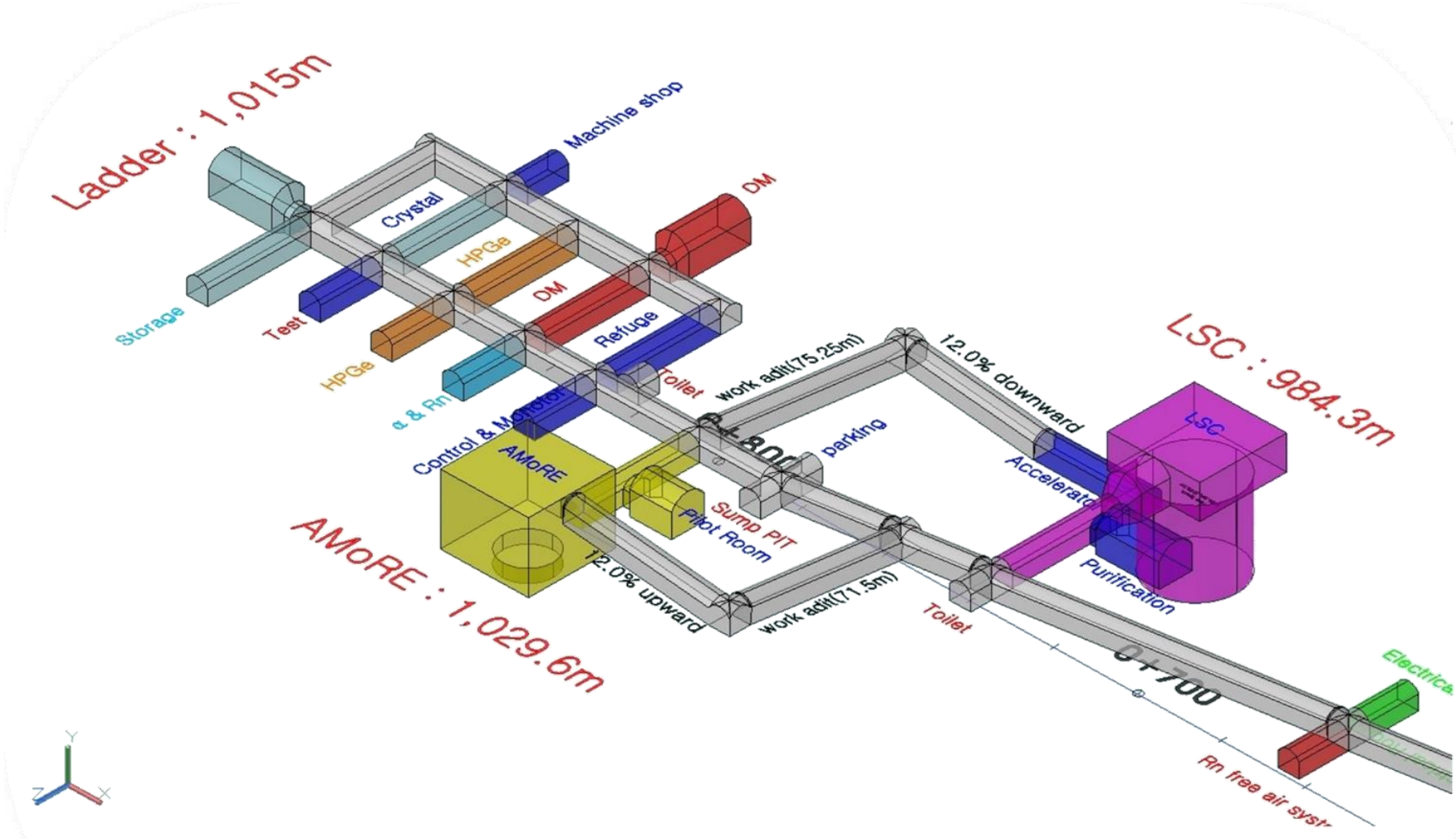
Bird's eye view of Handuk Iron Mine



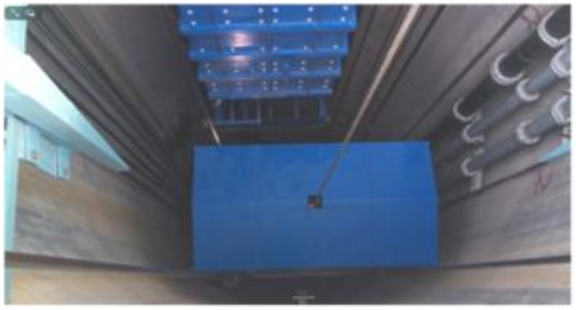
Large (>2000m^2), deeper (1100m depth)

The floor plan

- ~ 300m tunnel is excavated at present.
- 8 experiments with 12 space, 10 utility rooms



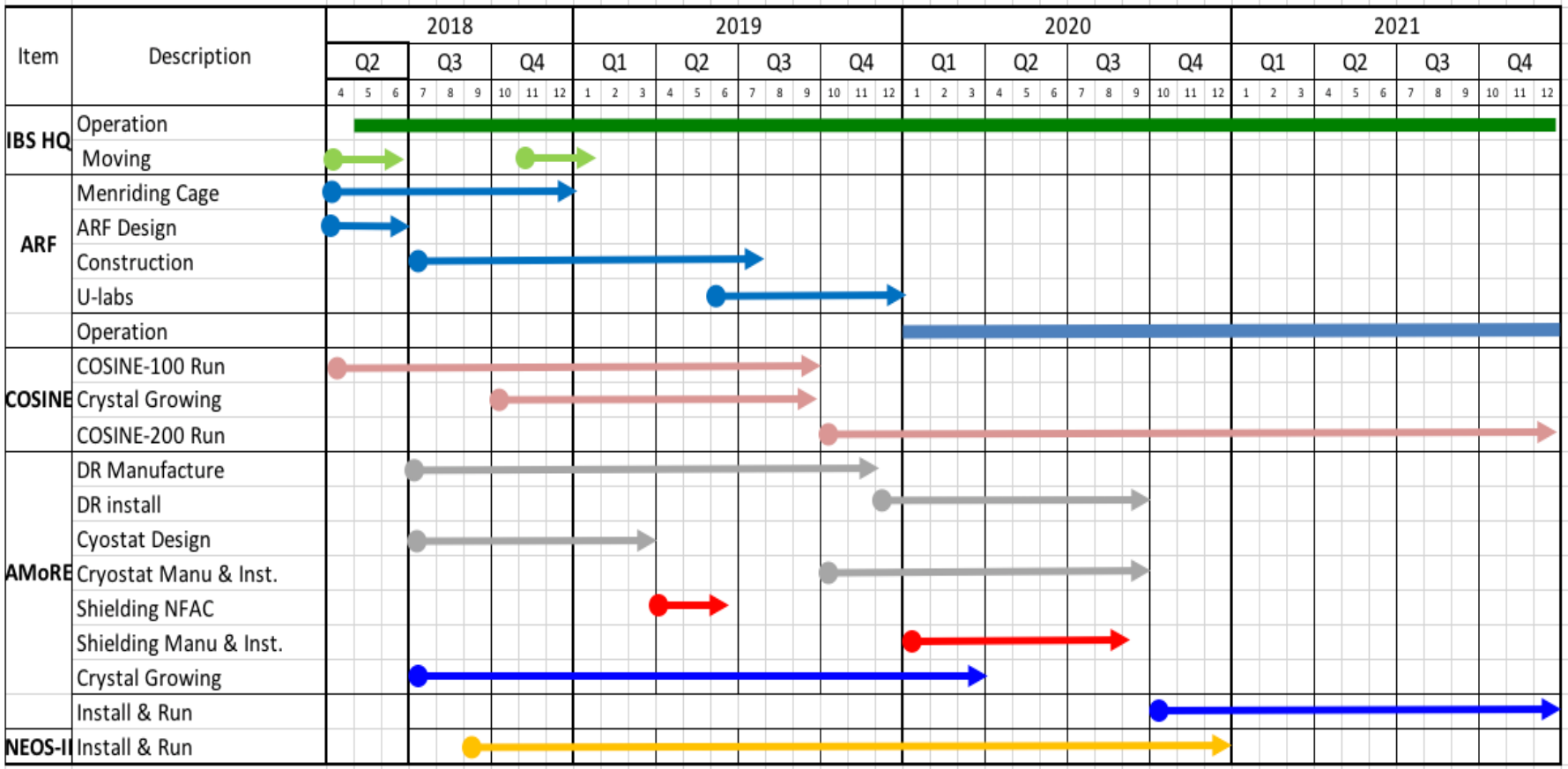
Construction



Summary

- CUP has strong and challenging astroparticle experimental programs.
- COSINE experiment is constraining DAMA signal and can close in the conundrum together with ANAIS.
- AMoRE project aim to be sensitive to 10^{27} year range for ^{100}Mo isotope. AMoRE-Pilot demonstrated detector performance and identified the background sources. Collaborative work with CUPID-Mo group is anticipated.
- Searching short baseline neutrino oscillation will continue at reactor site to sense the unexplored parameter space by collaborating HEP community.
- CUP is making future plan with a new Yemilab.

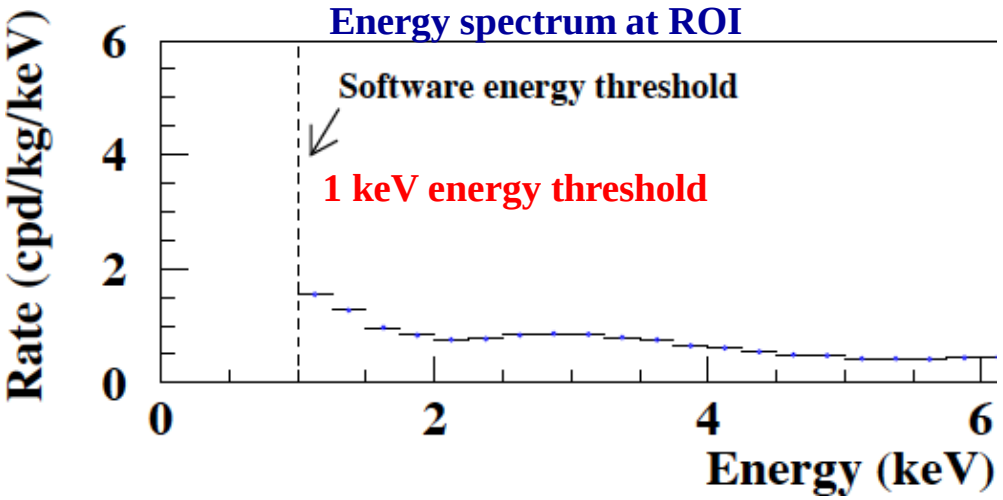
Schedule

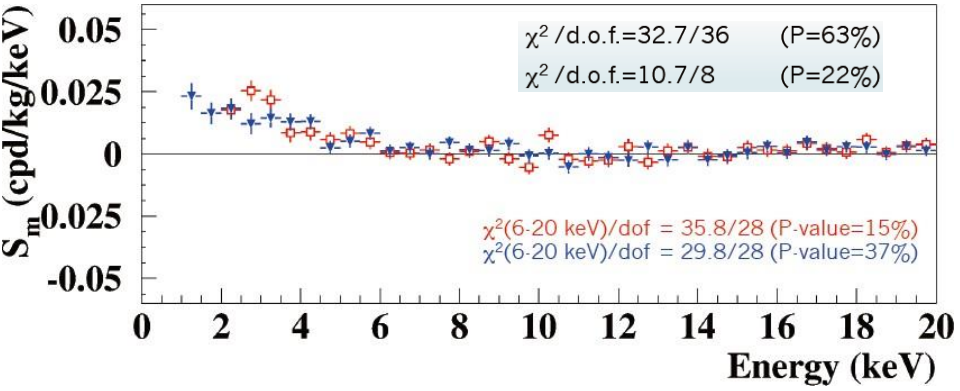

Item
Description
2018
2019
2020
2021
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
IBS HQ
Operation
Moving
ARF
Menriding Cage
ARF Design
Construction
U-labs
Operation
COSINE
COSINE-100 Run
Crystal Growing
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

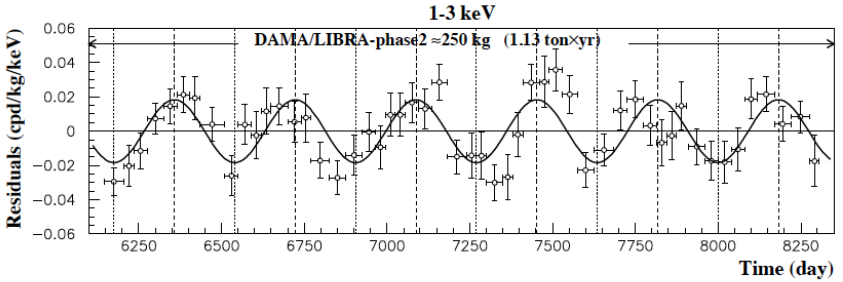
DAMA/LIBRA phase 2

Nucl. Phys. At. Energy
19 (2018) 307-325

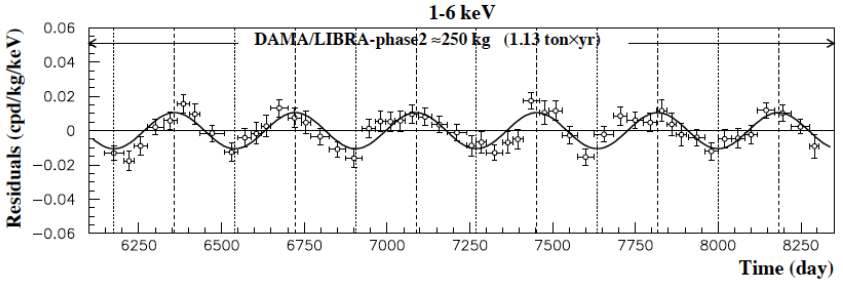
- Energy threshold reached 1keV with better PMTs
- Still there is modulation.
- Significance
  - ❖ 1-6 keV : **9.5σ** (phase 2)
  - ❖ 2-6 keV : **12.9 σ**(phase 1+2)
- Increased modulation amplitude below 2keV





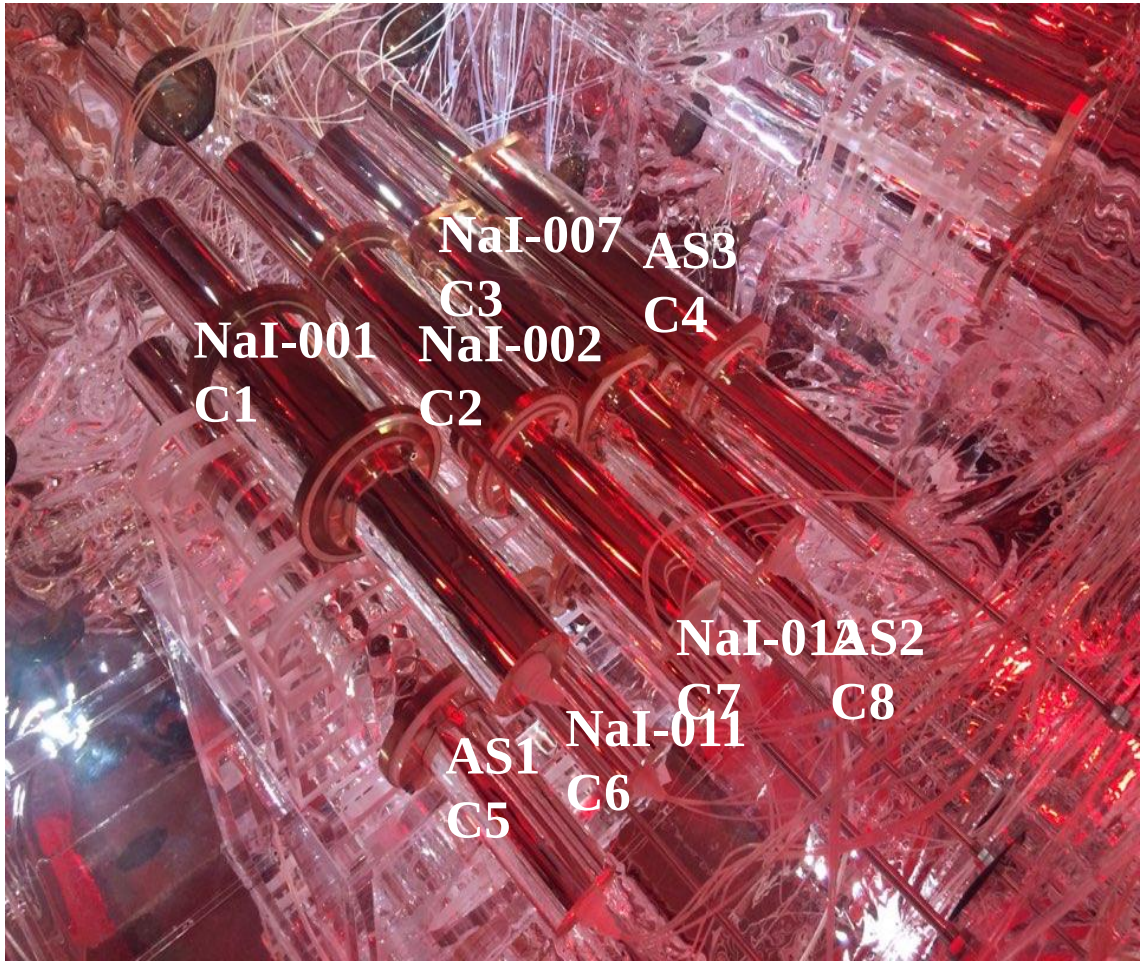


Modulation amplitude

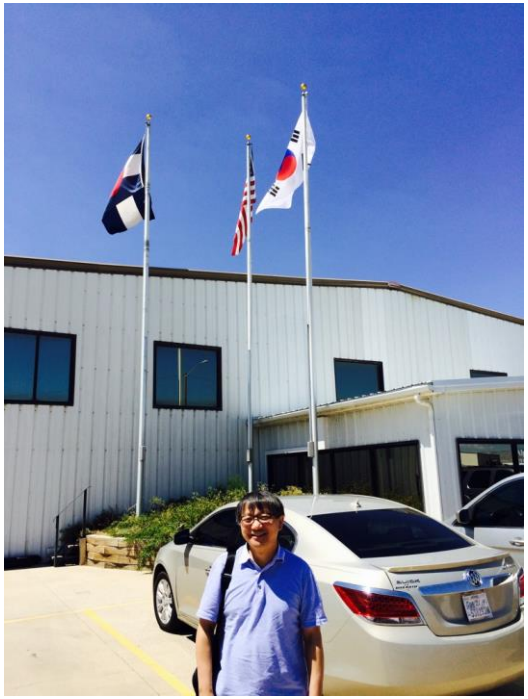


Crystal Installation for COSINE-100

- 8 crystals, total 106 kg
- Different quality crystals from crystal R&D with Alpha Spectra (US).



Alpha Spectra in Colorado. (2014. 8)



Result 2 : Modulation analysis

arXiv:1903.10098

$$R = C + P_0 e^{\left(-\frac{log2 \cdot t}{P_1}\right)} + A cos \frac{2\pi(t - t_0)}{T}$$

- Simultaneous fitting of 5 crystals.
- 1.7 years of data → 97.7 kg·yrs
- 15-day interval for binning
- 2.7 cpd/keV/kg on average in 2-6 keV