STATUS OF THE CENTER FOR UNDERGROUND PHYSICS

YEONGDUK KIM
DIRECTOR OF CUP

2019. 5. 9.

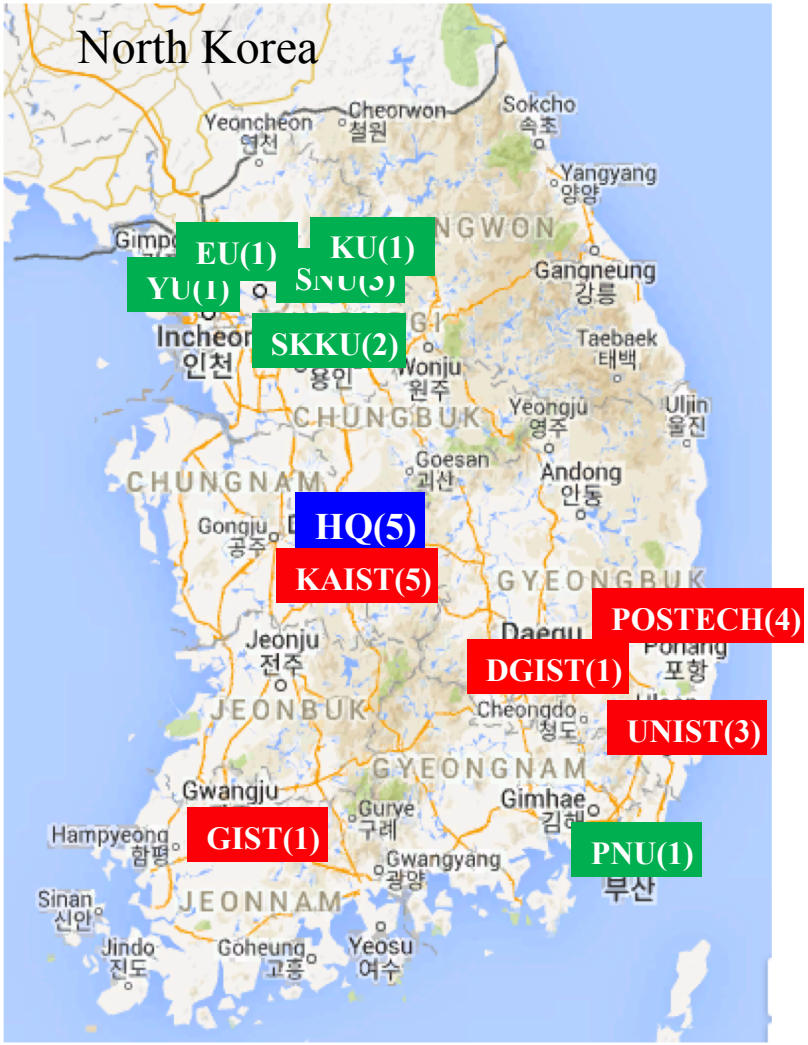
FKPPL meeting, Jeju Island

Contents

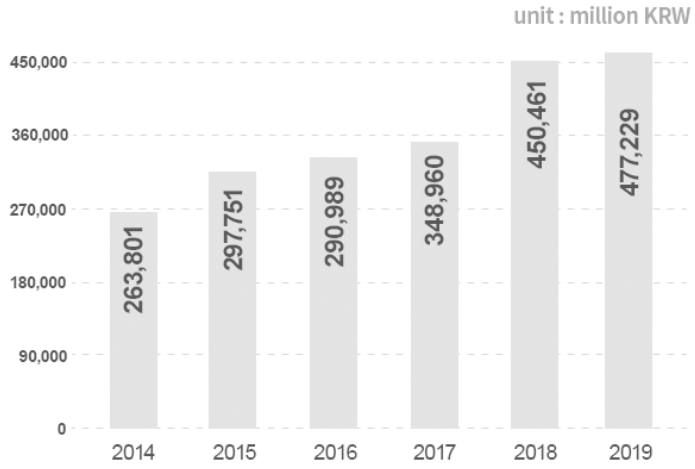
- **Center for Underground Physics**
- **Dark Matter : COSINE-100 experiment**
- **0νββ – Status of AMoRE**
- **Search for sterile neutrinos – Status of NEOS**
- **Future plan**

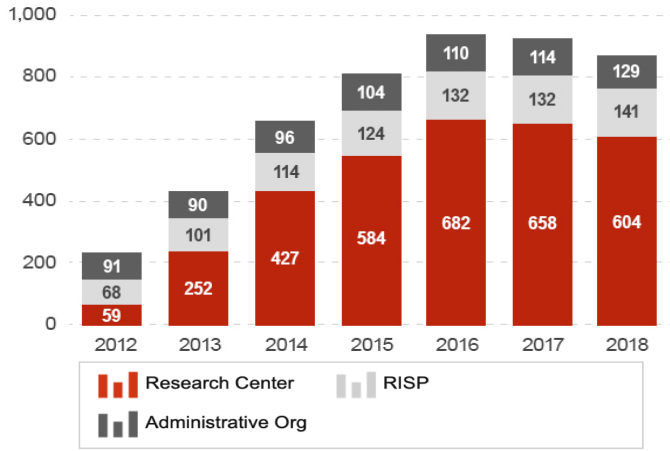
https://www.ibs.re.kr/cup/

Overview of IBS



- Established to promote basic science of Korea in 2012.
- Benchmarked MPI & RIKEN.
- 29 Research Centers :





IBS HQ in Daejeon

Plot size: 260,000㎡, **Total floor area:** 72,574㎡

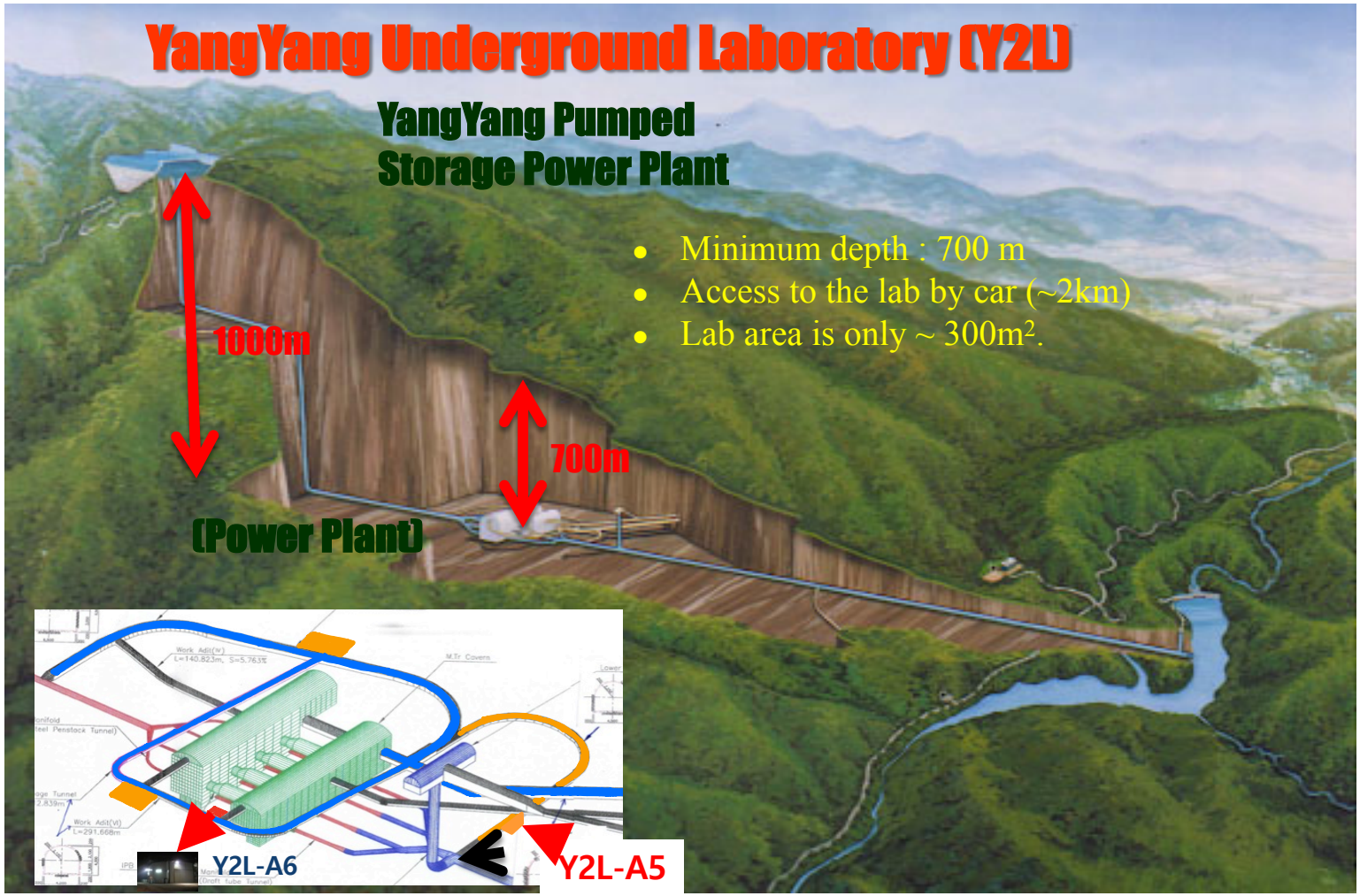
A: Administration Building, **B:** Theory Building, **C:** Experiment Building,

D: Laboratory Animal Resource Facility, **E:** Dormitory, **F:** Science Culture Center

Ground & Underground Labs of CUP

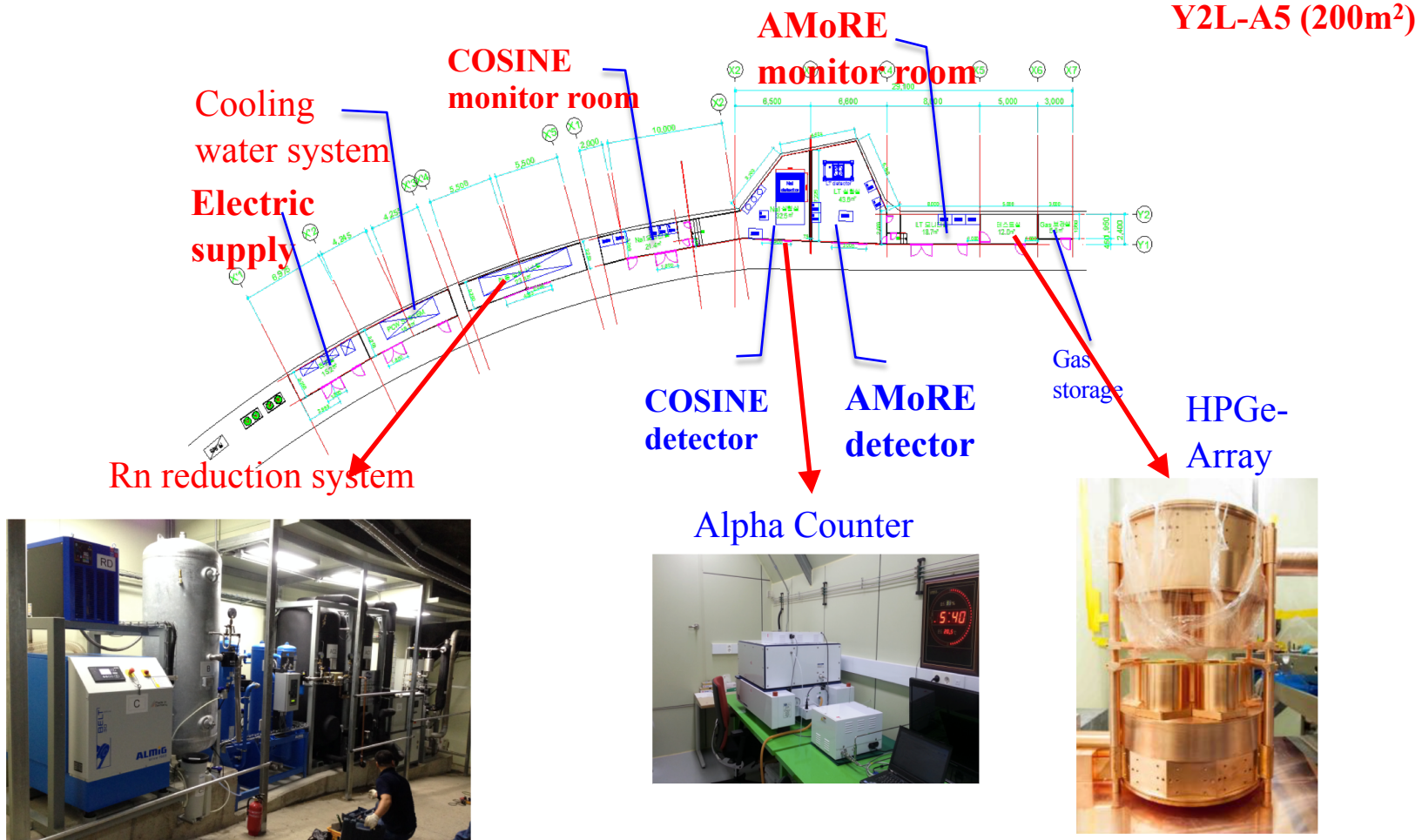
- **IBS-HQ is a ground laboratory in Daejeon city.**
- **Y2L was constructed in 2003 to house KIMS dark matter search experiment. (700m)**
- **NEOS site (10m depth) is made in tendon Gallery of nuclear reactor near RENO experiment.**
- **Yemilab is under construction to be completed in 2020. (1100m depth)**

Yangyang Laboratory (Y2L)



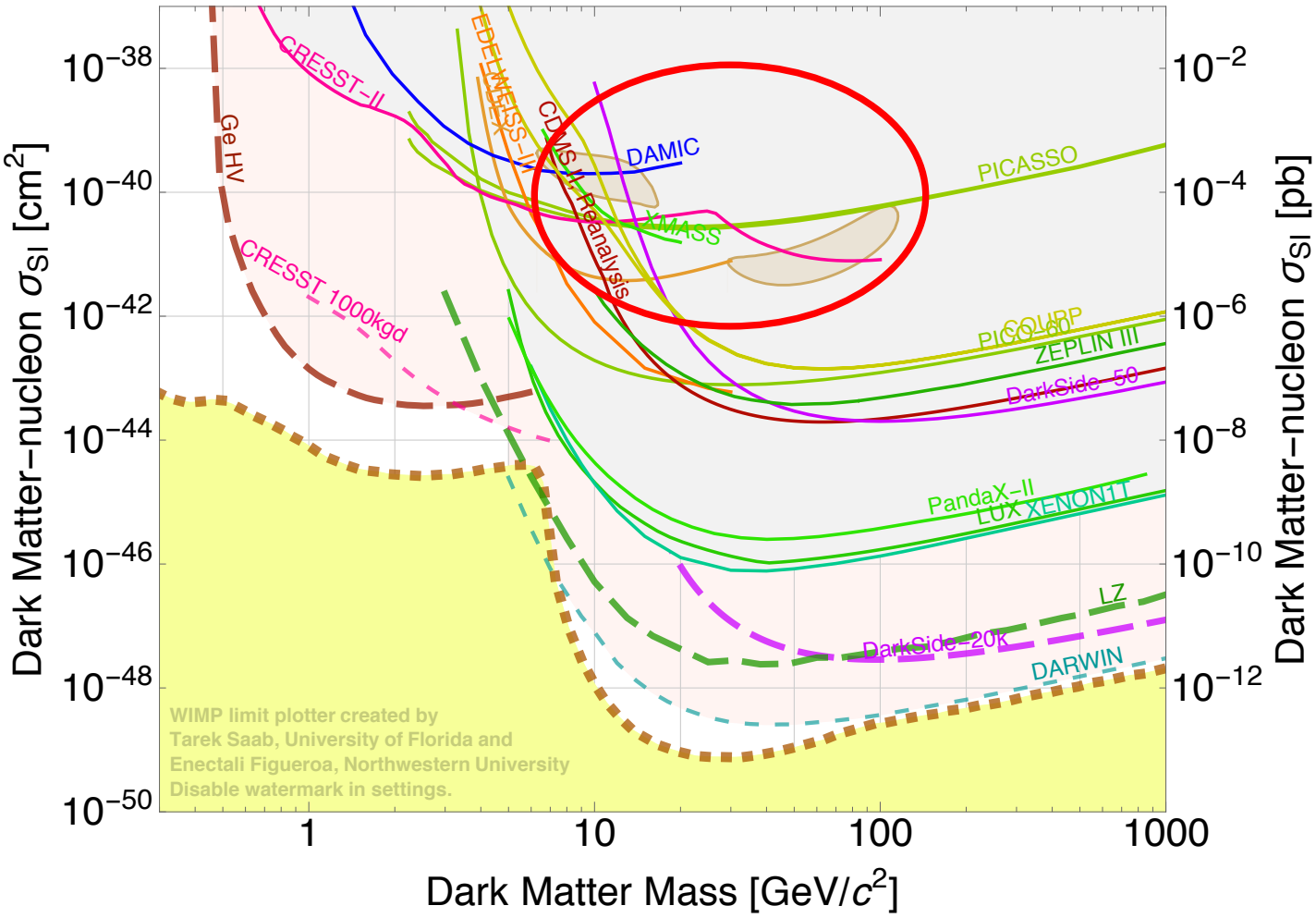
Y2L-A5

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



1. 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.



Modulation Signals – Freese, RMP

For Standard Halo Model (SHM), an isothermal sphere with an isotropic Maxwellian velocity distribution, annually modulating recoil rate can be approximated by ;

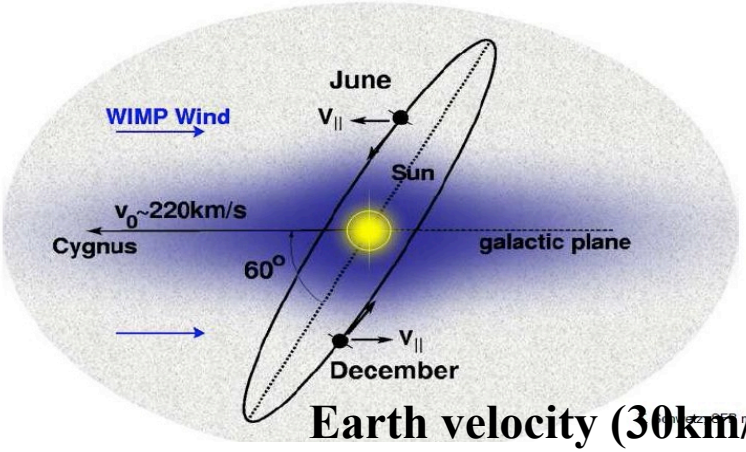
$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)cos\omega(t-t_0)$$

S_0 : time-averaged rate.

S_m : modulation amplitude.

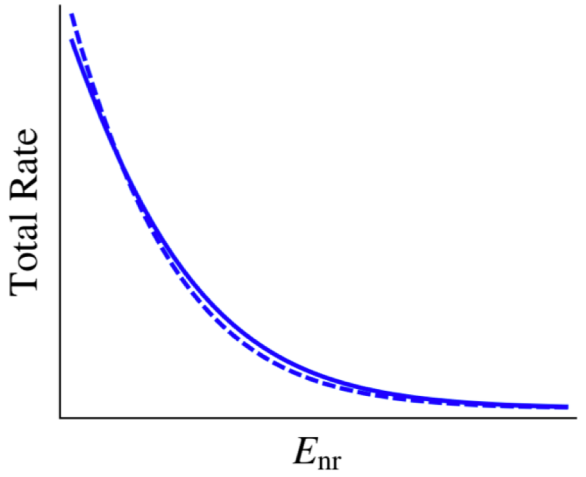
t_0 : phase (~June 1), $\omega = \frac{2\pi}{T}$

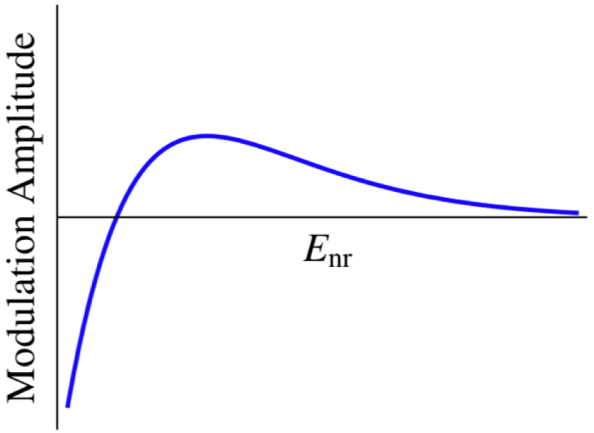
Yearly revolution → annual modulation



Earth velocity (30km/s)

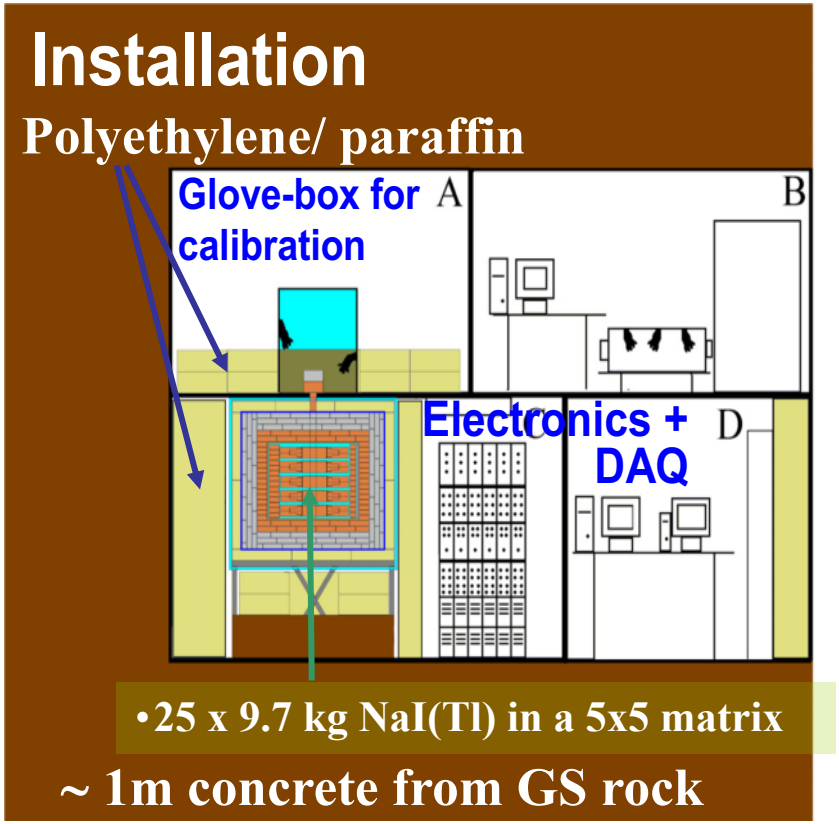
SHM



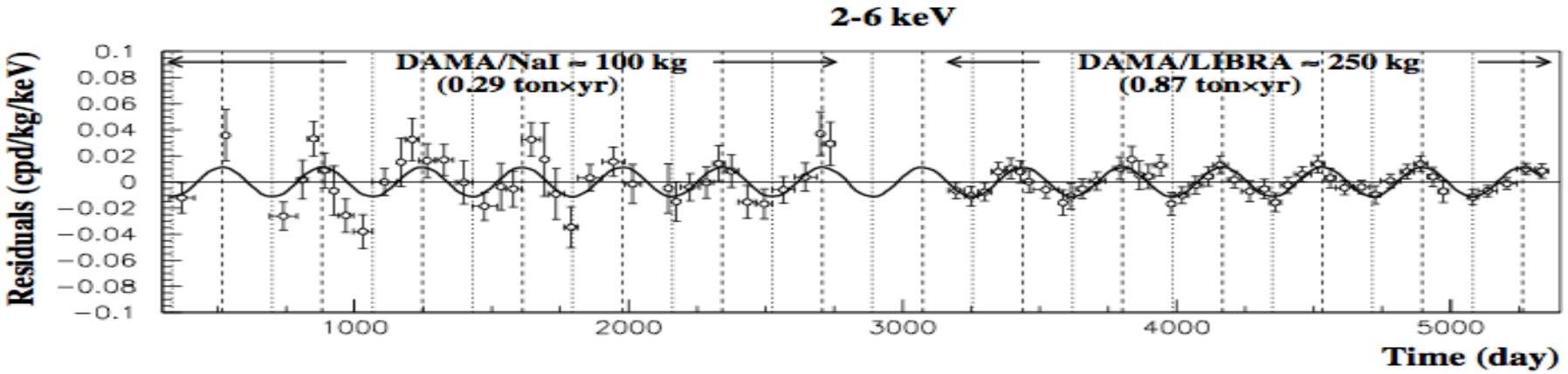


Bernabei, NOVE2008

The DAMA/LIBRA set-up



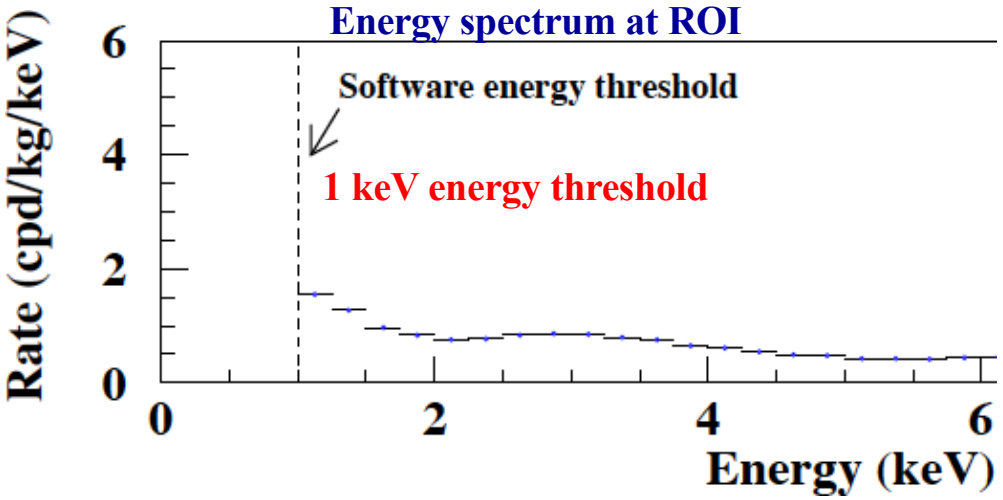
- DAMA group reported modulation for 14 years consistently. → "DAMA anomaly"
- Direct check for DAMA is necessary even though other experiments rejected DAMA modulation based on standard WIMP-nucleon interaction.

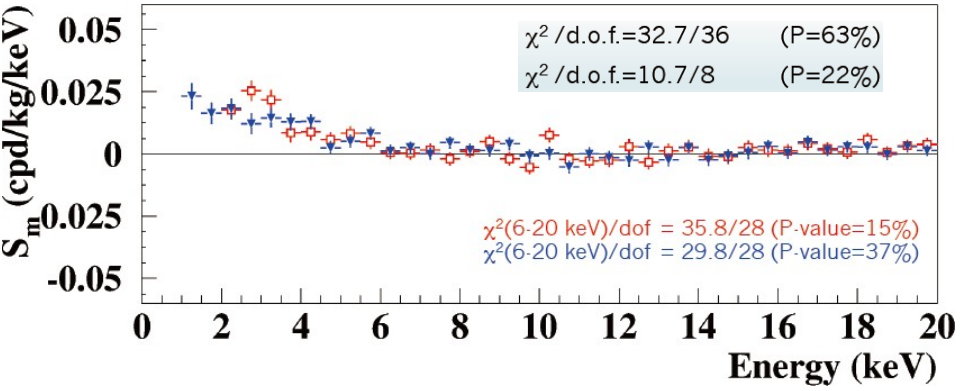


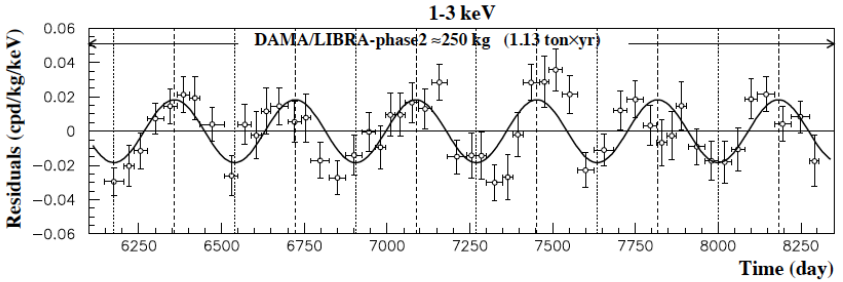
DAMA/LIBRA phase 2

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

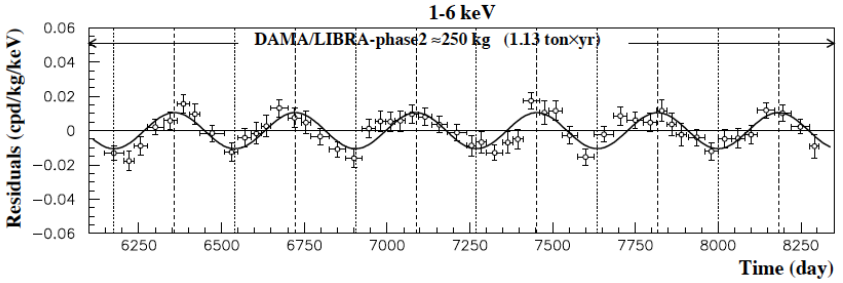
- Energy threshold reached 1keV with better PMTs
- Still there is modulation.
- Significance
  - ❖ 1-6 keV : **9.5σ** (phase 2)
  - ❖ 2-6 keV : **12.9 σ**(phase 1+2)
- Increased modulation amplitude below 2keV







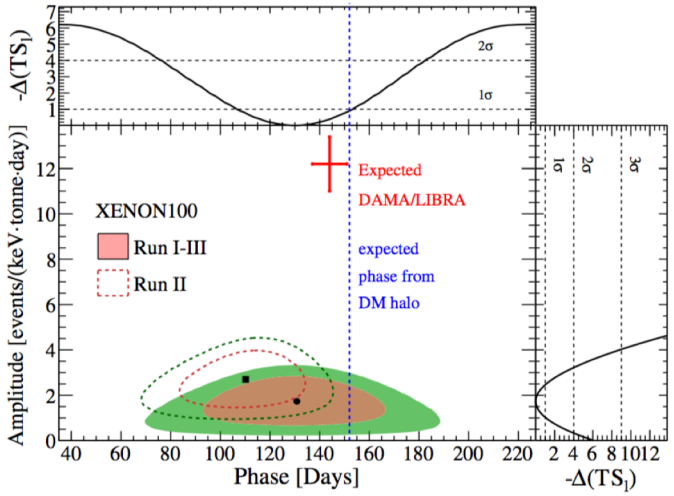
Modulation amplitude



Null modulation results from other experiments

XENON100 : PRL118, 101101 (2017)

4 years XENON100 data (2010 Jan – 2014 Jan.)



Fixing T=1 yr,

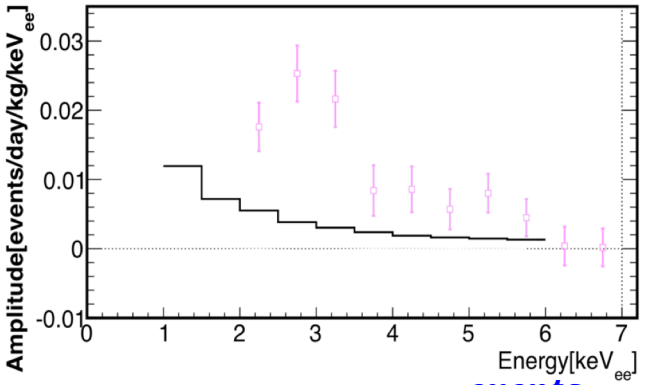
→ S_m = (1.67 ± 0.73) events/(keV · tonne · day)

→ t_0 = (136 ± 25) days.

Excluded by 5.7 σ.

XMASS : Phys. Rev. D 97, 102006 (2018)

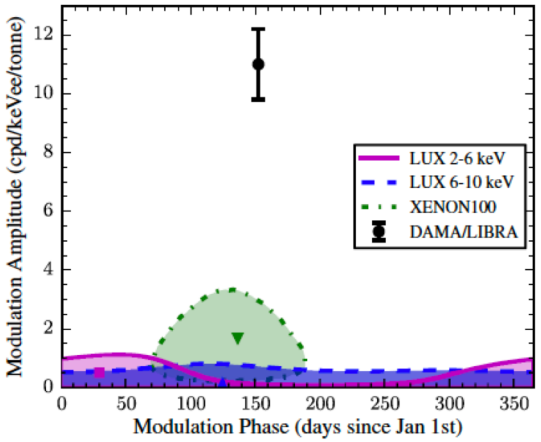
2.7 years (2013 Nov–2016 Jul)



$S_m < (1.3\text{-}3.2)\times 10^{-3} \frac{events}{keV\ kg\ day}$

0.0011 cpd/keV/kg @ 50 days
Factor 10 smaller than DAMA
Excluded by 9.2 σ

LUX : PRD98, 062005 (2018)



No modulation is observed, less than 1/10 of DAMA

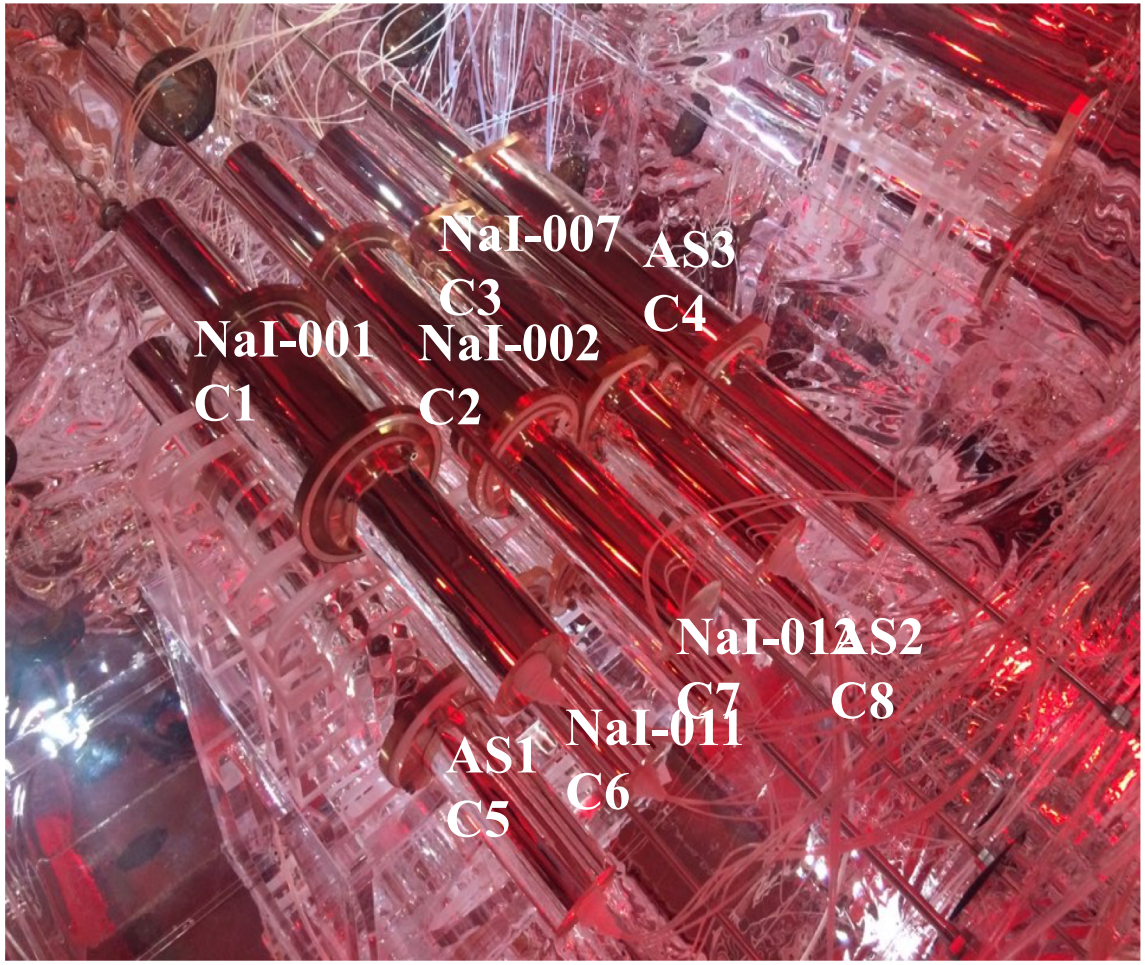
COSINE-100 : DM-ICE+KIMS

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

PI : Reina Maruyama Hyunsu Lee

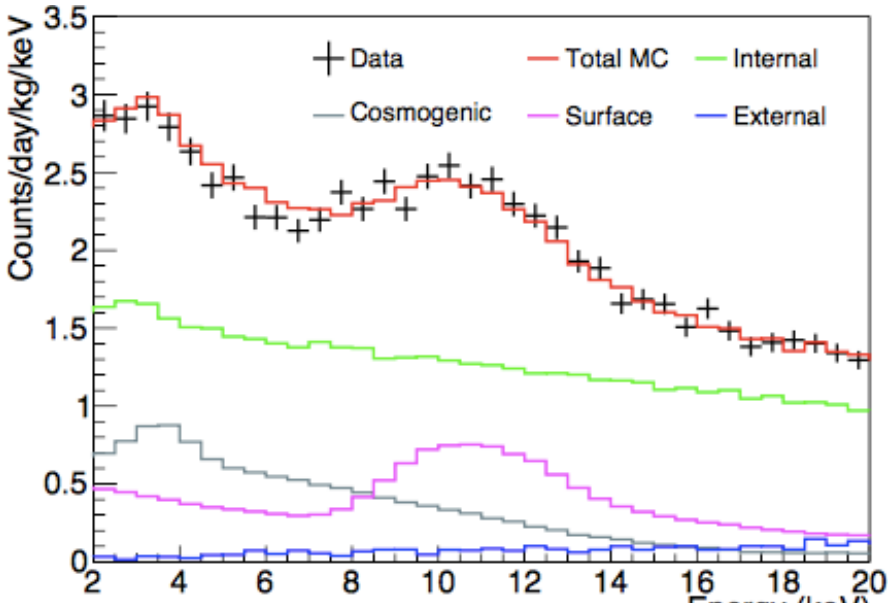
Crystal Installation for COSINE-100

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

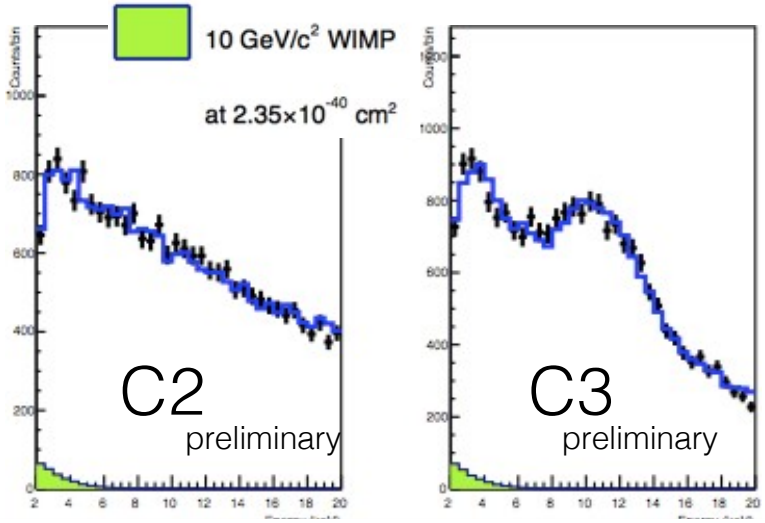


Alpha Spectra in Colorado. (2014. 8)

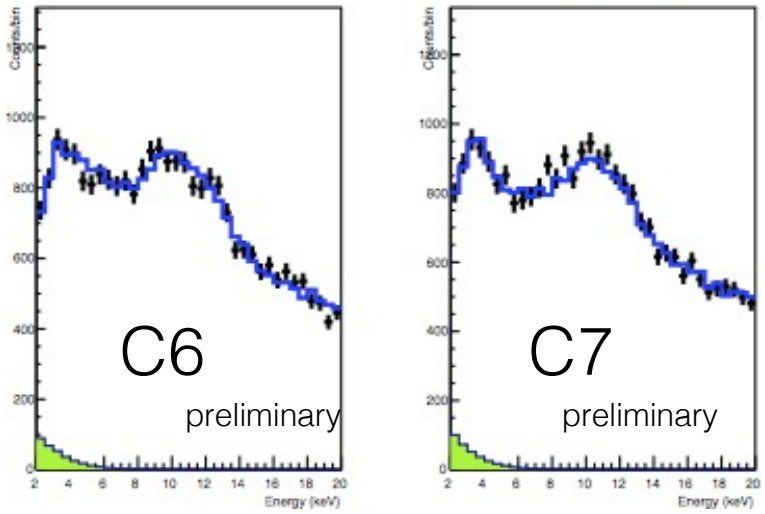
Result 1 : WIMP Search, 59.5 days of Data



· ***Eur.Phys.J. C78 (2018) 490***



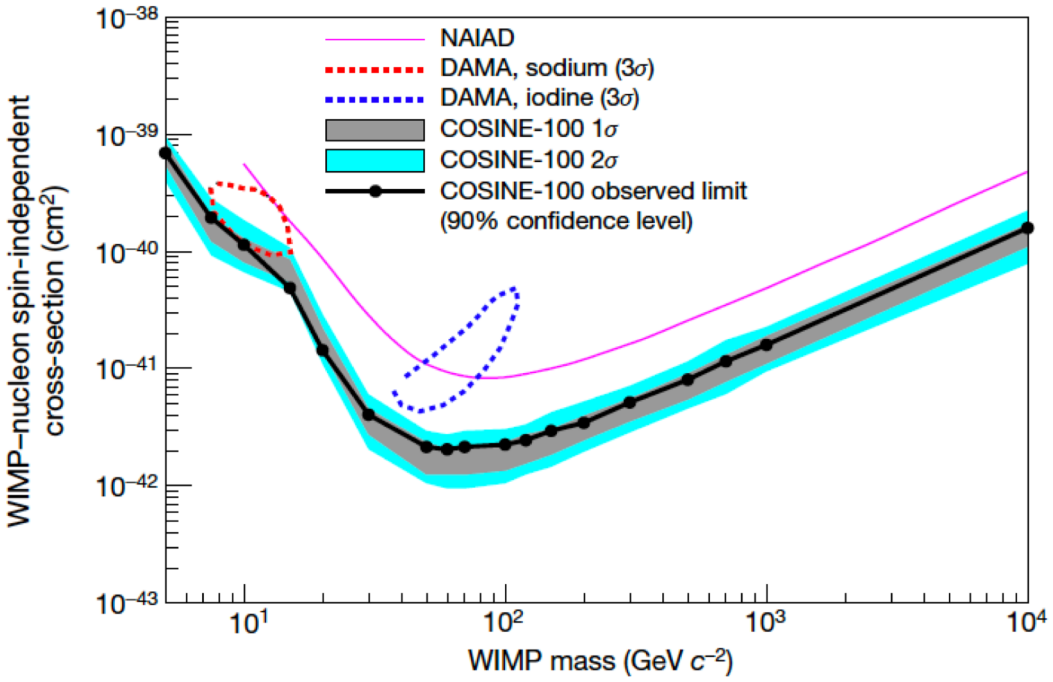
Overlay of DAMA-Na Signal at 10 GeV/c2



- 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.

Spin independent WIMP-nucleon cross section limit

Published in Nature Vol 564, 83, 2018
– First result constraining DAMA result with NaI crystals.



- COSINE-100 excludes DAMA/LIBRA-phase1's signal as spin-independent WIMP with Standard Halo Model in NaI(Tl)
- Consistent with null results from other direct detect experiments with different target medium

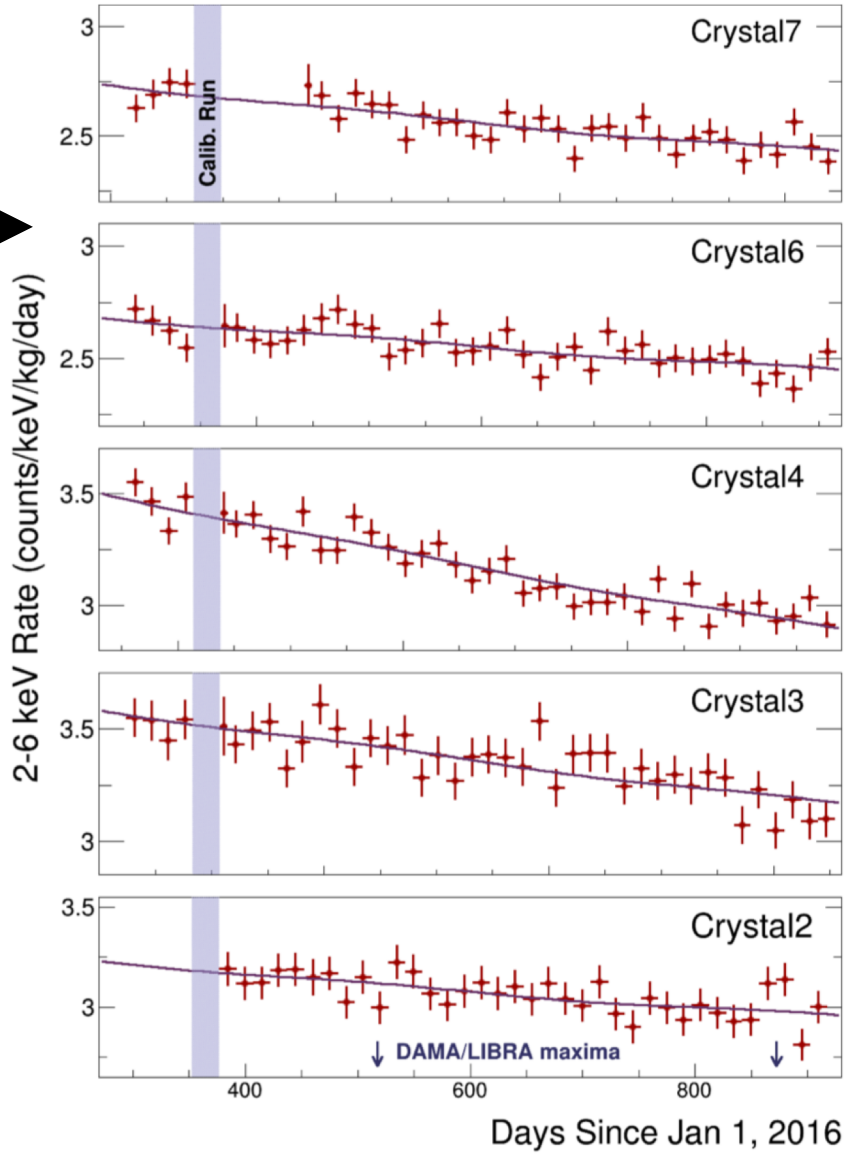
This results will give tension for isospin violating models explaining DAMA along with null results with other experiments.

Result 2 : Modulation analysis

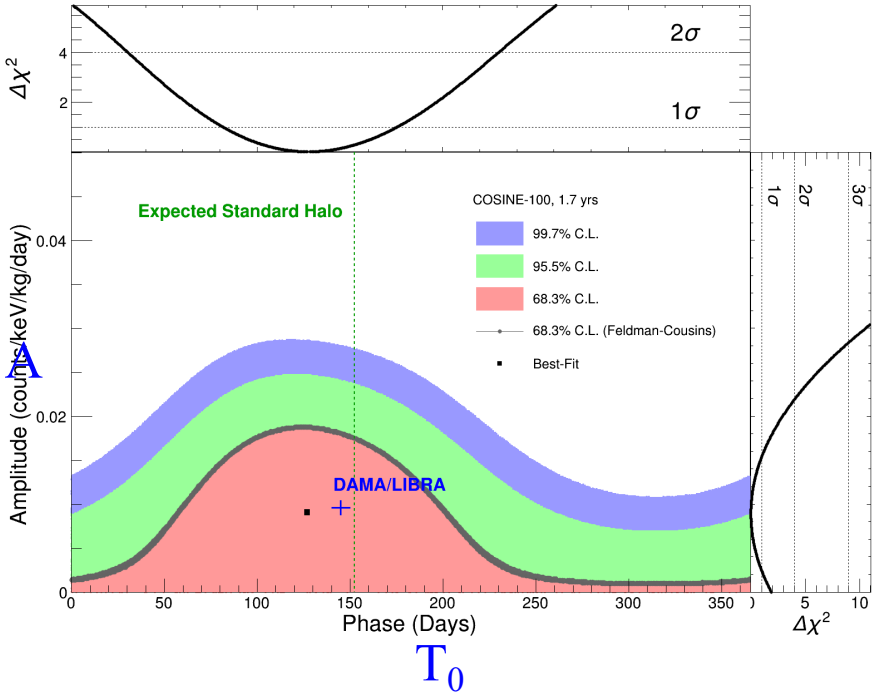
arXiv:1903.10098

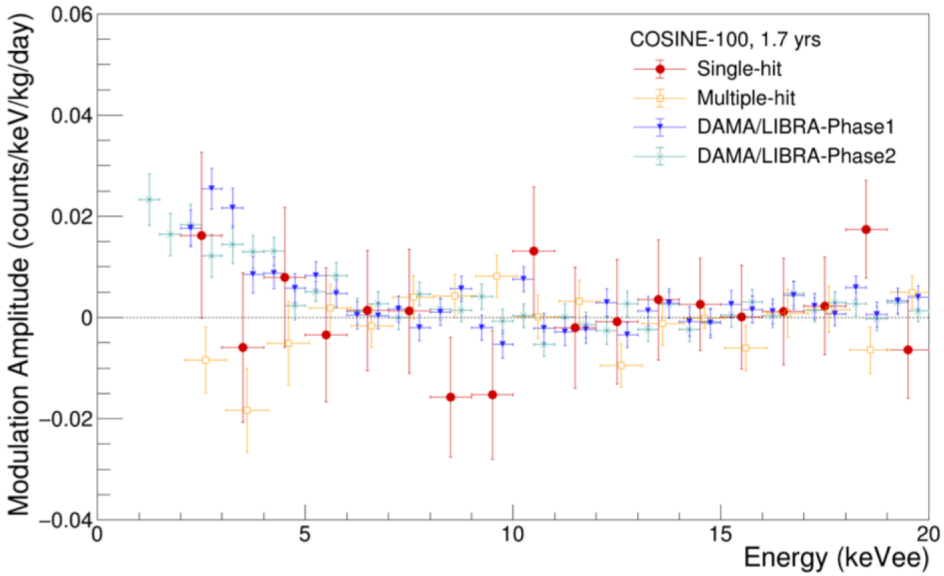
$$R = C + P_0 e^{\left(-\frac{log2 \cdot t}{P_1}\right)} + A cos \frac{2\pi(t - t_0)}{T}$$

- 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



arXiv:1903.10098



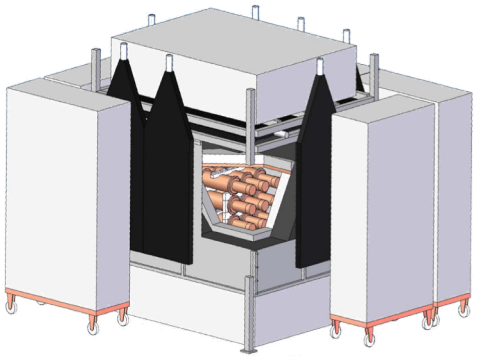


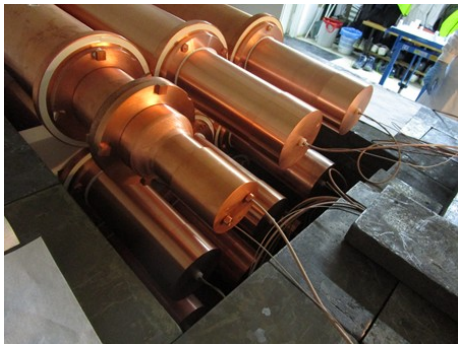
Configuration	χ^2	*d.o.f.*	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5
COSINE-100	175.6	175	0.473	0.0083±0.0068	152.5 (fixed)
COSINE-100 (Without LS)	194.7	175	0.143	0.0024±0.0071	152.5 (fixed)
ANAIS-112	48.0	53	0.67	-0.0044±0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1+Phase2)	71.8	101	0.988	0.0095±0.0008	152.5 (fixed)

COSINE-100 data is consistent with both Null/DAMA modulation w/ 68% CL.

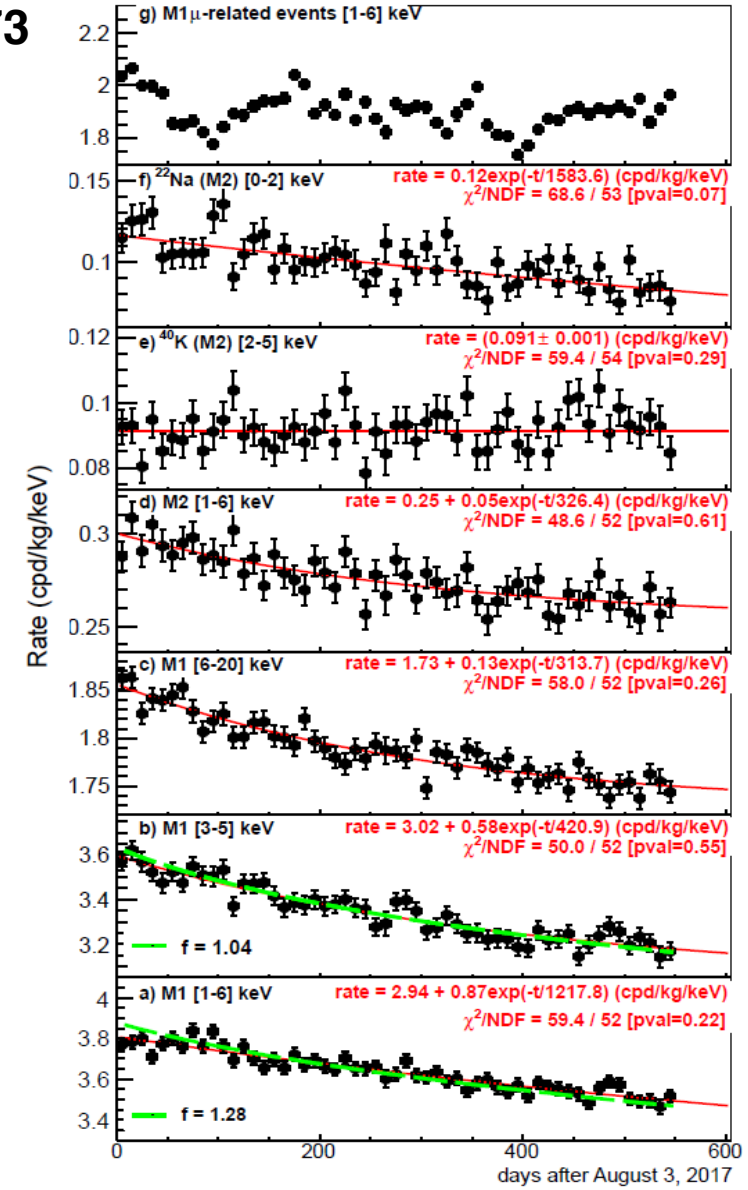
ANAIS

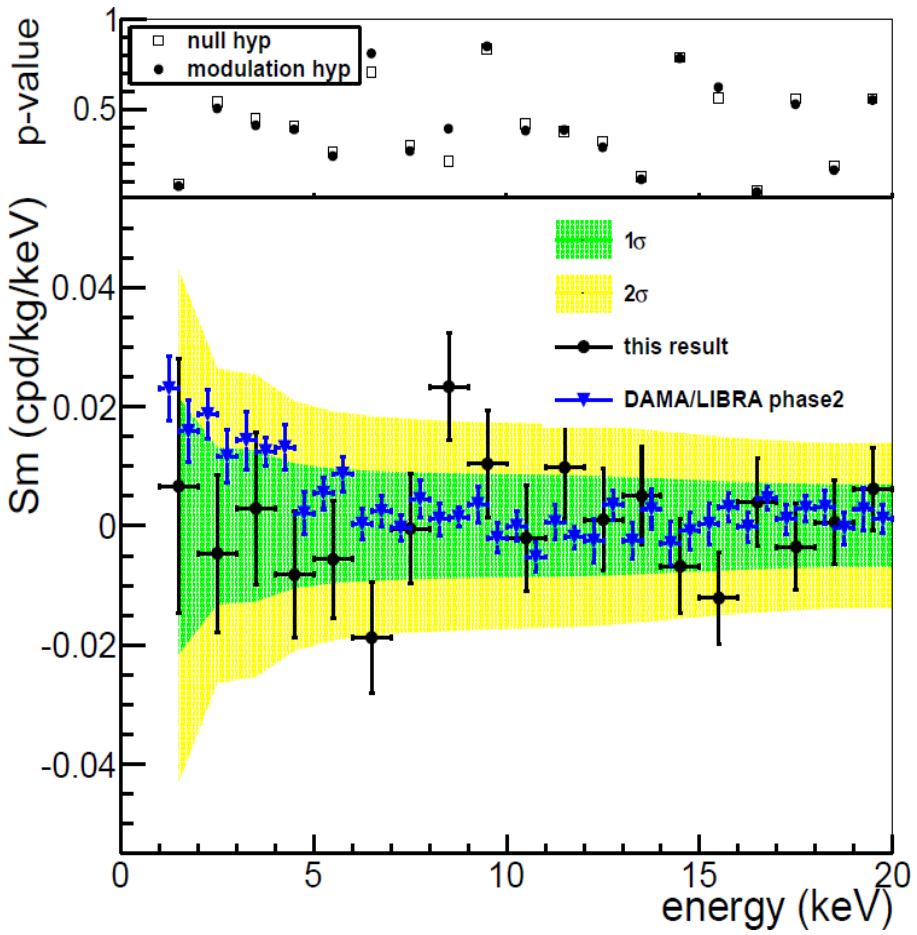
arXiv:1903.03973





- Runs at Canfranc, Spain
- 9X12.5kg → 112.5 kg, Alpha Spectra
- Data taken from Aug. 2017
- 157.55 kg·yrs data

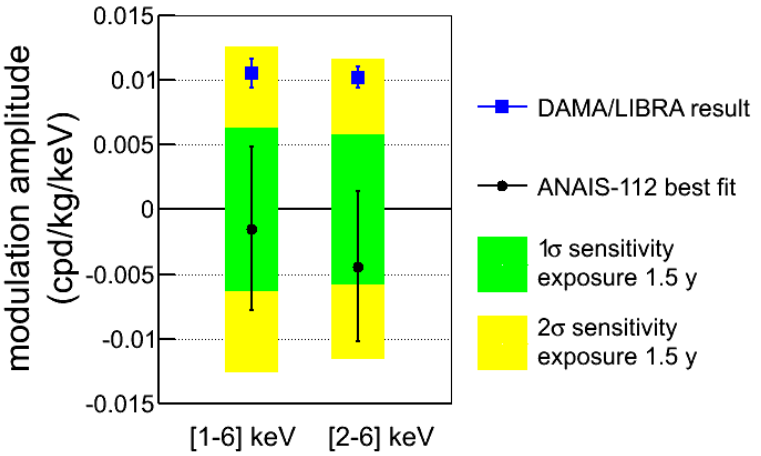




- Modulation amplitudes calculated from 1to 20 keV
- All the amplitudes in the RoI are compatible with 0.

S_1 = −0.0044 ± 0.0058 (2-6 keV)

S_1 = −0.0015 ± 0.0063 (1-6 keV)



M. Sarsa's talk

COSINE-100 & ANAIS will try to combine the data to reach 3 sigma level.

COSINE-200 (Phase-II)

- Goal : Background less than DAMA/LIBRA (1 dru)
  - Needs a factor two or more improvement
  - Powder purification/crystal growing/detector assembly will be done at IBS, Korea

Powder purification performance

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

	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

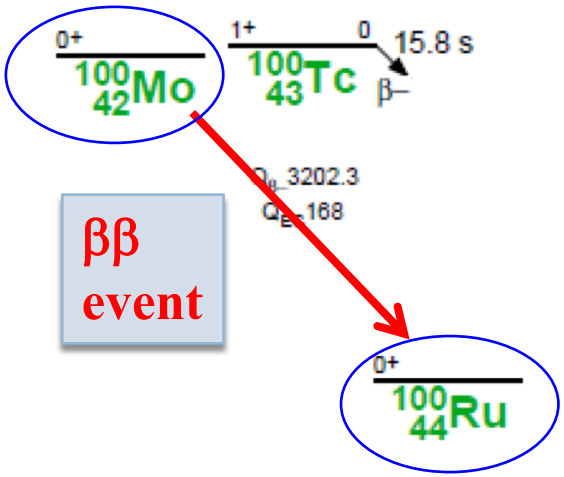
2. Search for Neutrinoless double beta decay - AMoRE

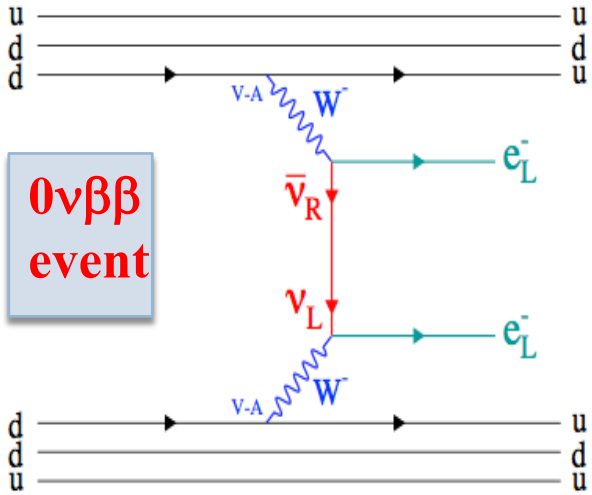
Observation of 0νββ

- **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.

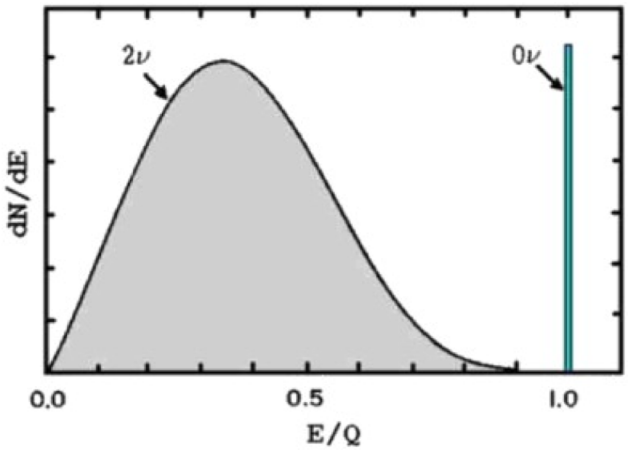
$$m_\nu \approx \frac{m_D^2}{m_N}$$

For light neutrino exchange model;





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 a sharp peak @ Q-value, we need a good energy resolution and extremely low background at that energy.**

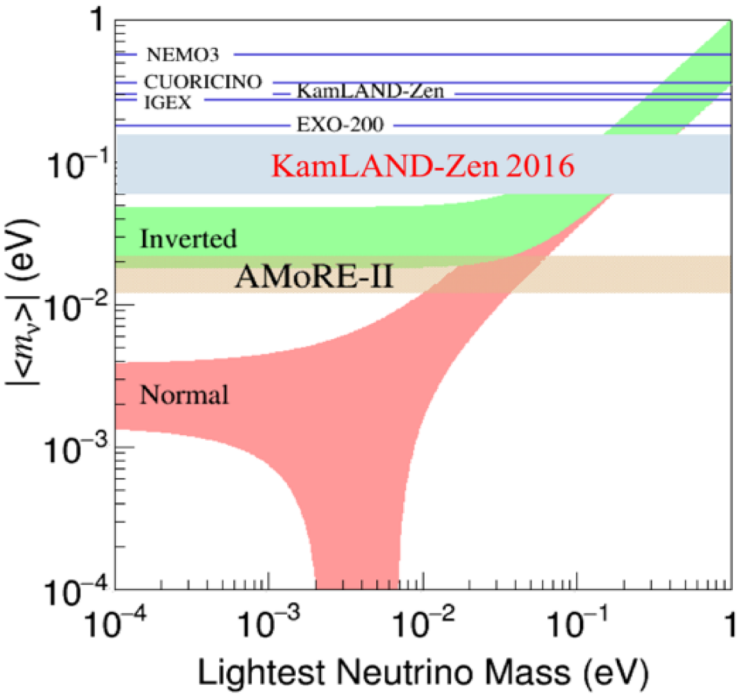
for light neutrino exchange model ;

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**

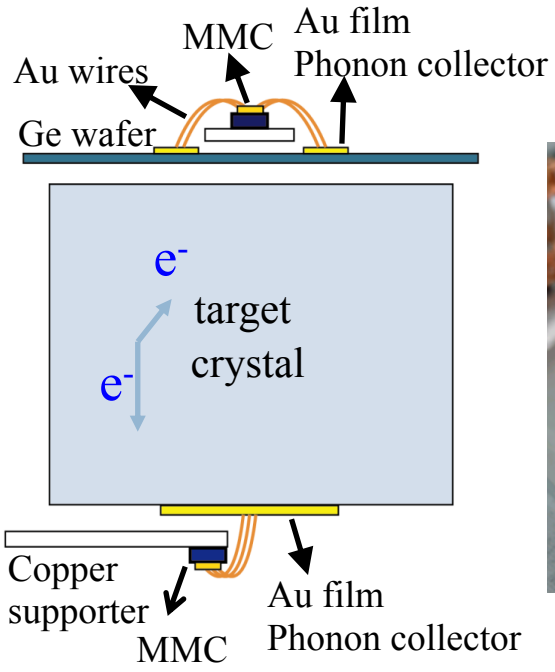
$$T_{1/2}^{0\nu} \rightarrow m_{\beta\beta}$$

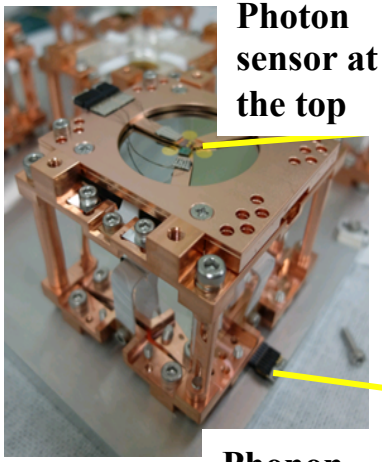


Overview of AMoRE Project

Principle of AMoRE detector

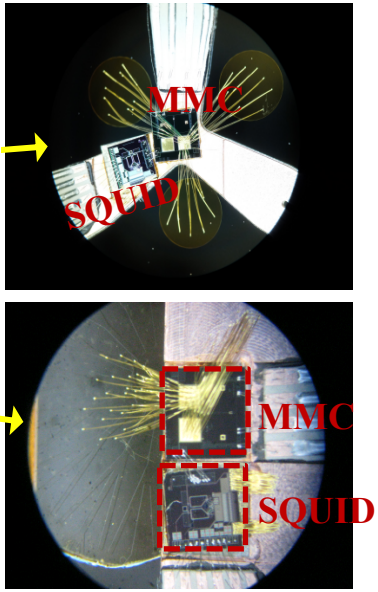
- **Use Mo containing Scintillating Bolometer : $(^{40}Ca,X)^{100}MoO_4$ + MMC**
- **For Each crystal, phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal).**

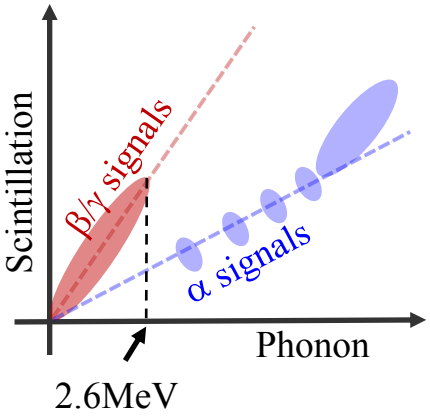




Photon sensor at the top

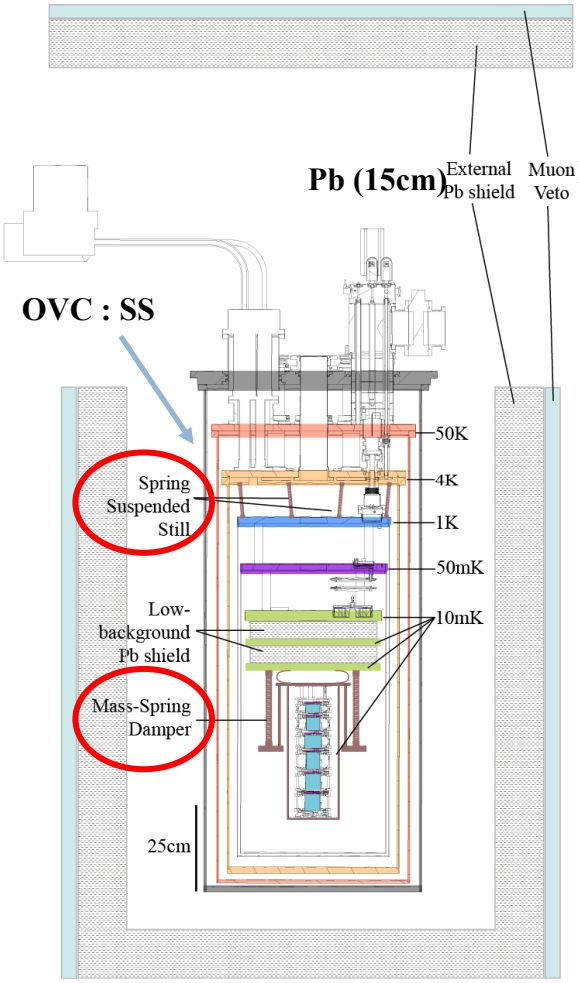
Phonon sensor at the bottom

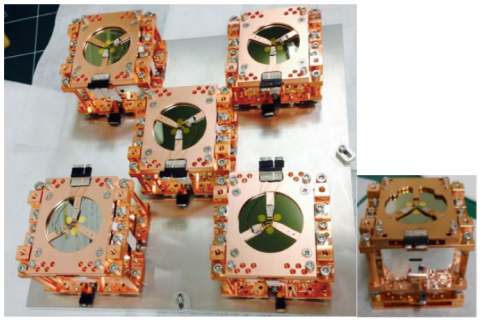




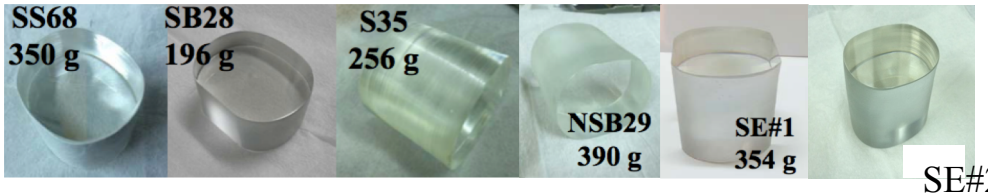
AMoRE-Pilot Setup

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



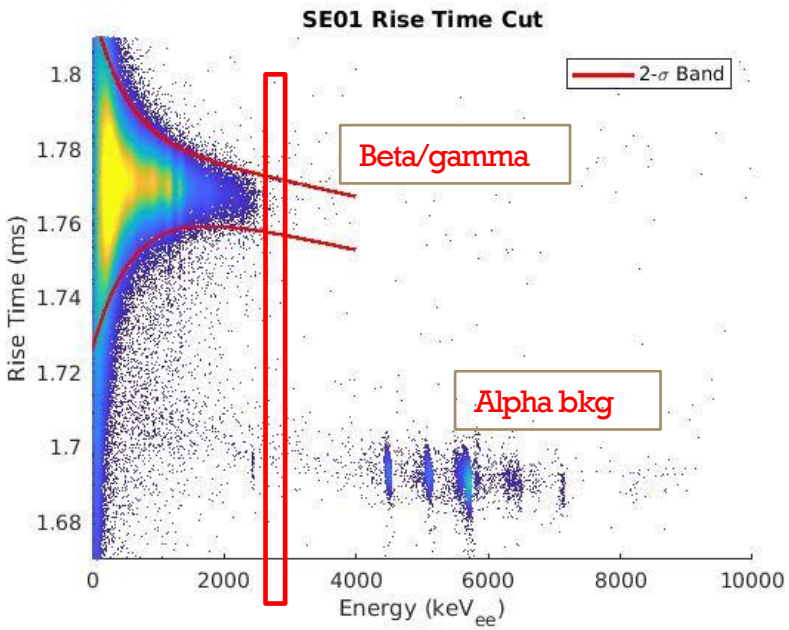


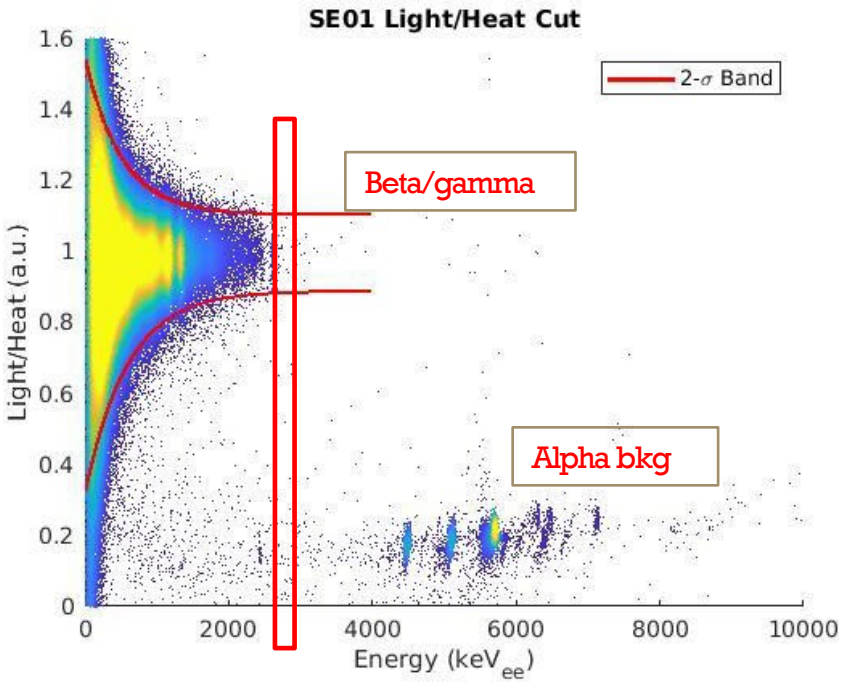
12 detector channels
(6 heat detectors + 6 light detectors)



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

PSD

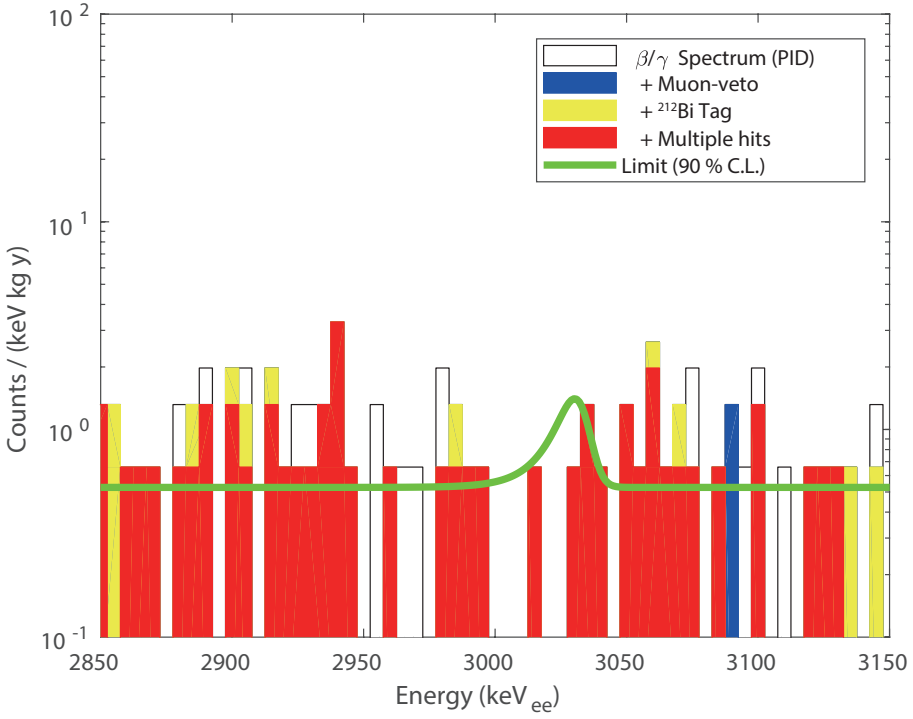




Unlike CUORE, scintillating bolometer can remove alpha backgrounds in ROI.

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



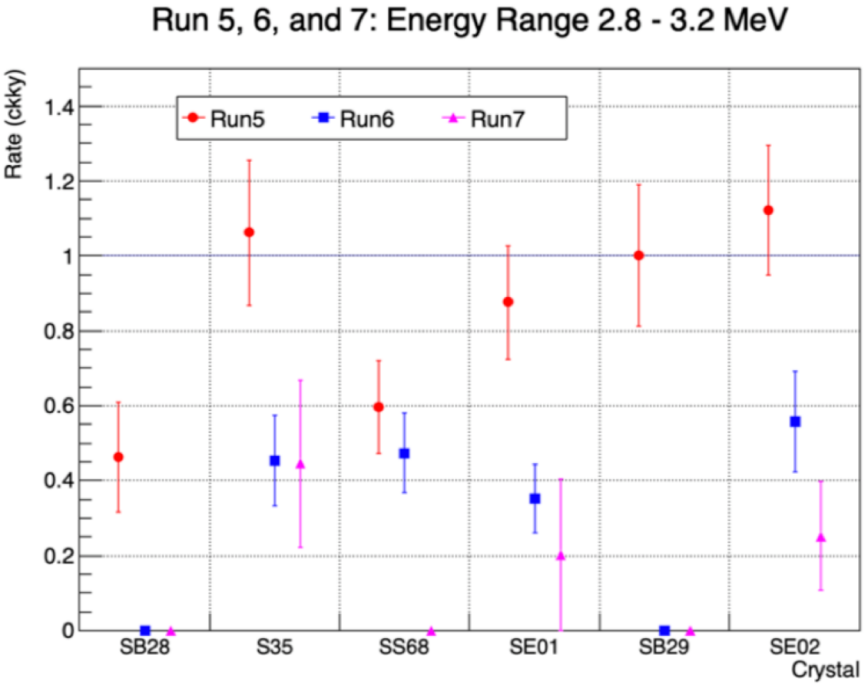
- 111 (kg day) exposure.

→ Final background level → 0.55 ckky

→ $T_{1/2}^{0\nu} > 9.5\times10^{22} years$

NEMO best limit $1.1\times10^{24} years$

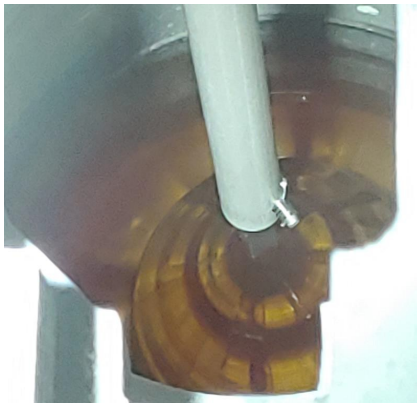
- Background levels are reduced by 70 % after removing active components a nd additional neutron shielding.



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

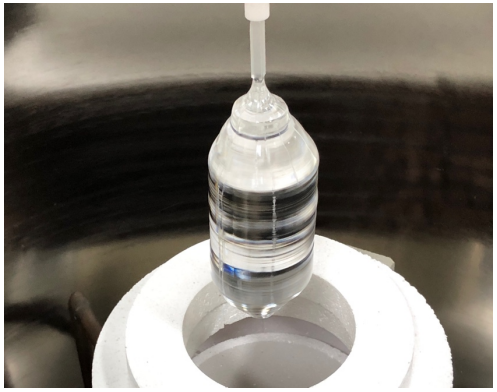
We have grown an enriched LMO crystal without any purification to check what level of contamination would be reached by only from crystal growing process.

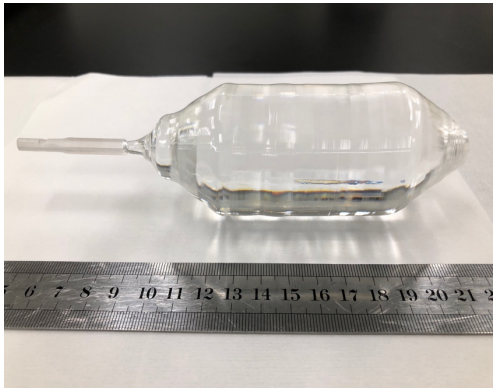
$Li_2CO_3+MoO_3 \rightarrow Li_2MoO_4+CO_2$



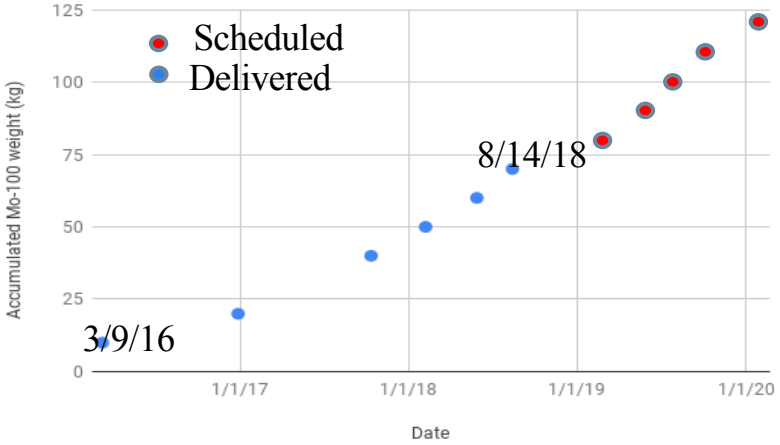
CZ02-L1803E

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





Schedule to deliver enriched powder



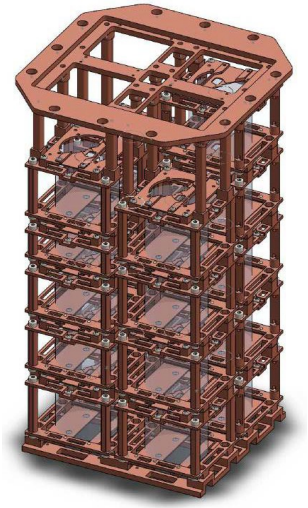
Plan of AMoRE Project

- **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

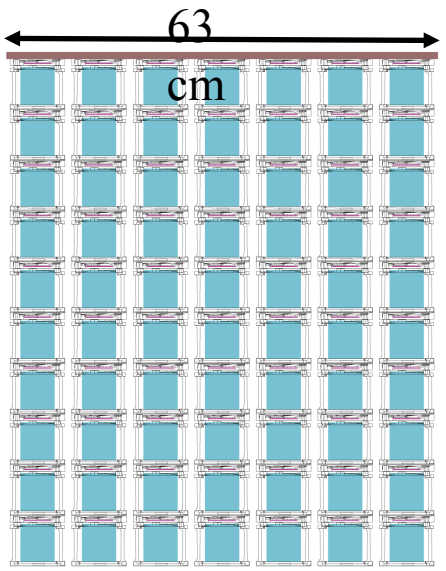
AMoRE-I

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

CUPID-Mo collaboration

Follow up of LUMINEU collaboration (ANR-French funding, 2012-2017)

http://cupid-mo.mit.edu

7 countries, 15 institutions, ~110 scientists

France – Italy collaboration

CUPID-Mo

Similar to AMoRE

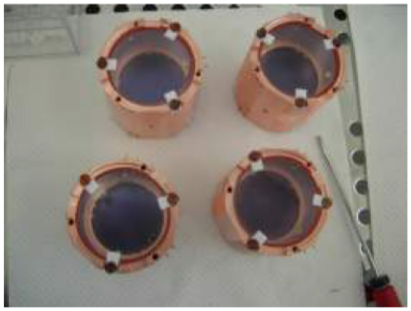
- CSNSM Orsay, CEA/DRF Gif-sur-Yvette, IPNL Lyon, LAL Orsay, FRANCE

CUPID-Mo

CUPID-Mo demonstrators

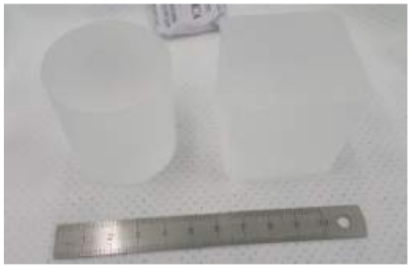
Phase I:

- 20 cylindrical $Li_2^{100}MoO_4$ crystals
  $\rightarrow$ $\sim$ **2.5 kg of ^{100}Mo**
- Edelweiss set up at LSM
- **Start physics data taking end July 2018**



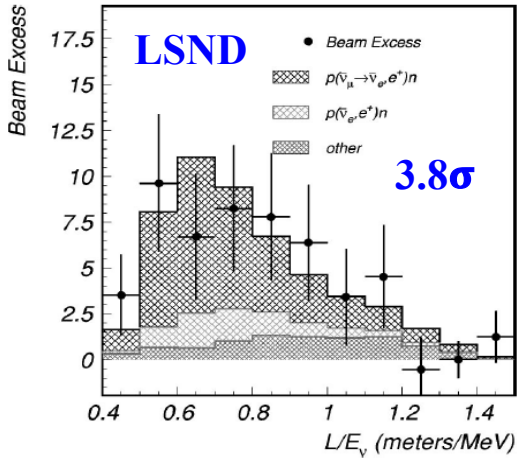
Phase II:

- Additional 26 cubic crystals (20 + 26 cryst.)$\rightarrow$ $\sim$ **5 kg of ^{100}Mo**
- CUPID-0 set up at LNGS
- **Planned start data taking mid-2019**

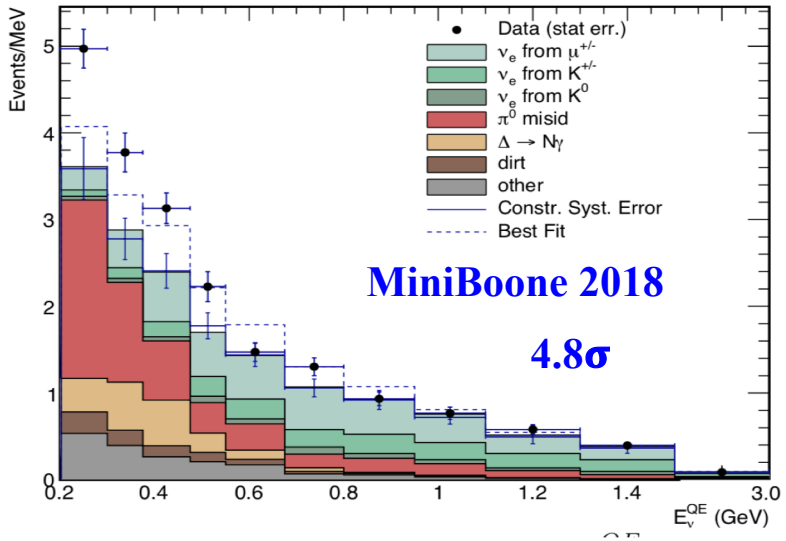


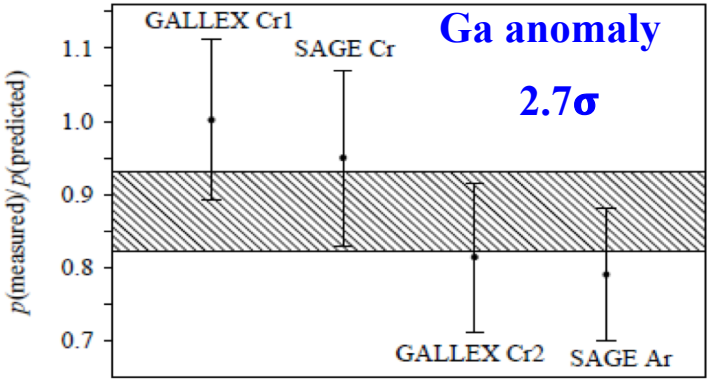
3. Search for sterile neutrinos - NEOS

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

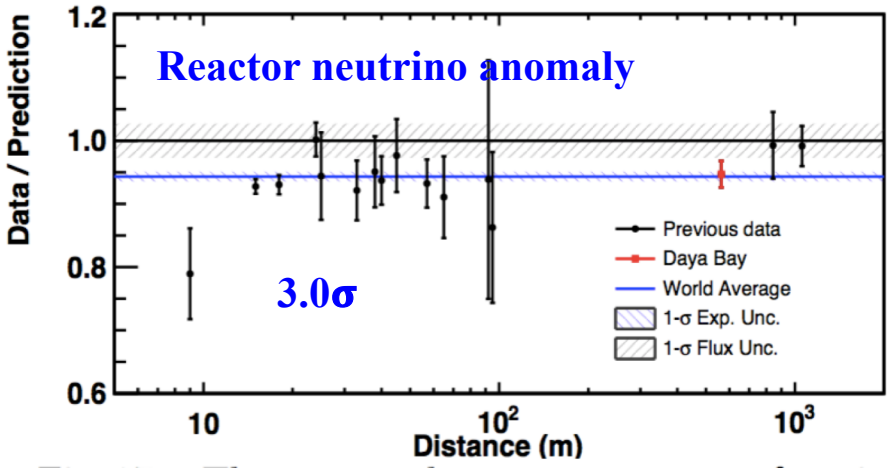


$\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations



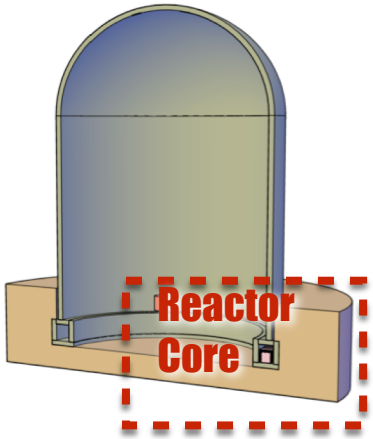


[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



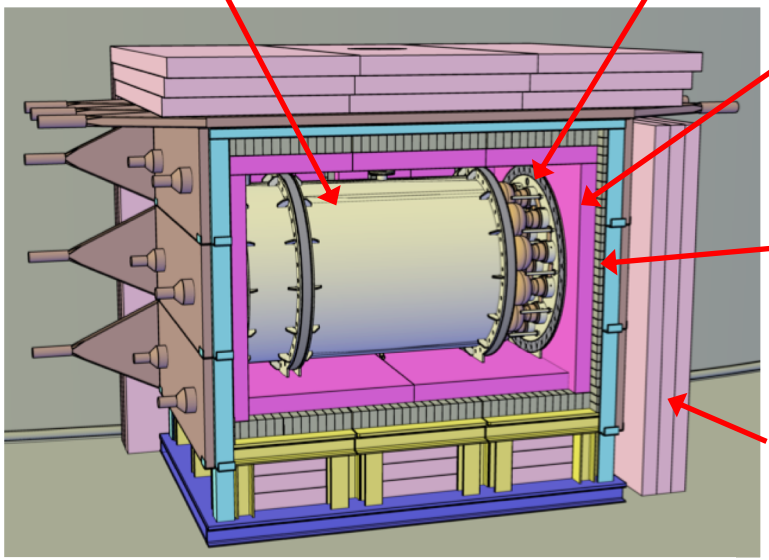
NEOS reactor neutrino experiment

- 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.

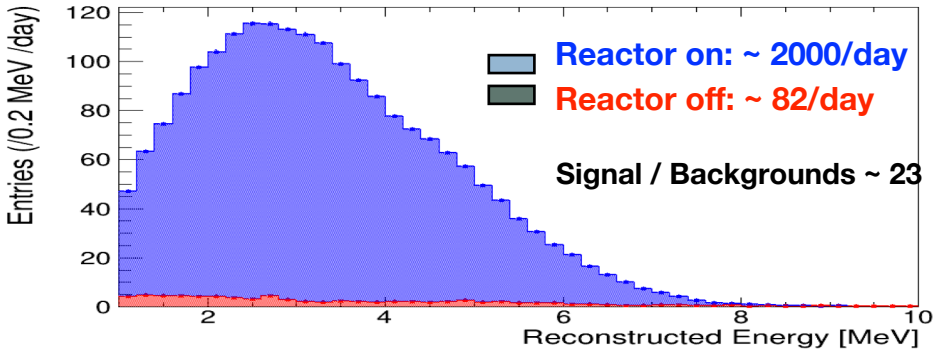
38 8" PMTs in mineral oil.

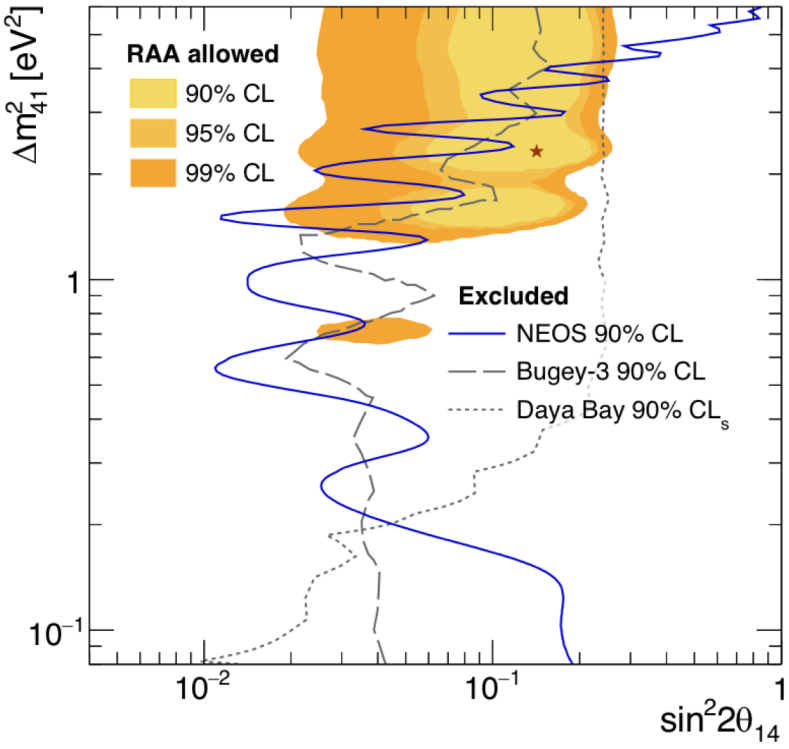


Borated PE (10 cm)

10 cm lead

4π muon veto detector





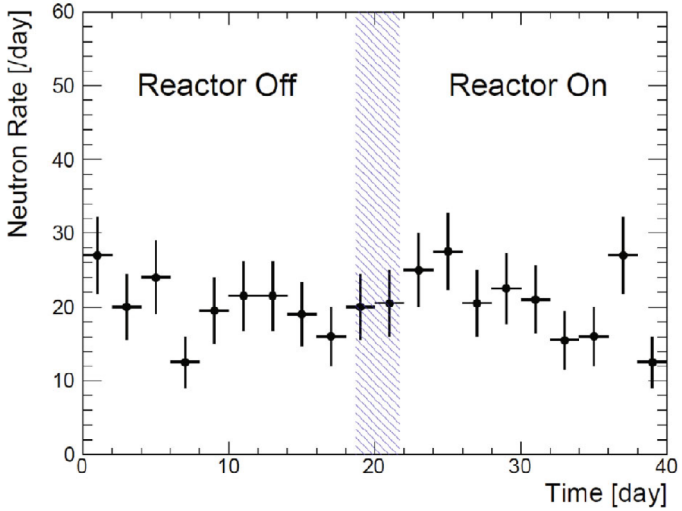
Best reactor neutrino anomaly parameter is excluded by NEOS.

Table 2. Results of neutron rate measurements at the KT1 laboratory and the tendon gallery with the reactor off and on.

	Live Time [days]	Neutron Event Rate [/day]
KT1 Laboratory	3.36	$2\,261 \pm 26(\text{stat.}) \pm 116(\text{syst.})$
Tendon Gallery (off)	18.7	$20.0 \pm 1.0(\text{stat.}) \pm 1.5(\text{syst.})$
Tendon Gallery (on)	17.5	$21.8 \pm 1.1(\text{stat.}) \pm 1.1(\text{syst.})$

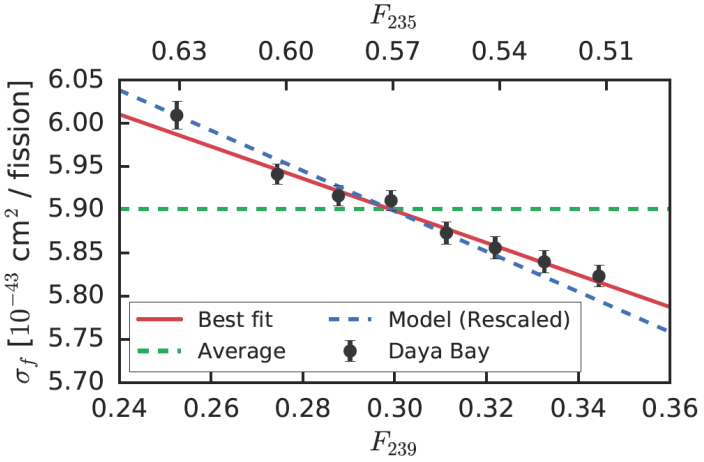
Neutron backgrounds :
Fast Neutron rates at Tendon Gallery are reduced by 100 times and no difference between reactor on/off .

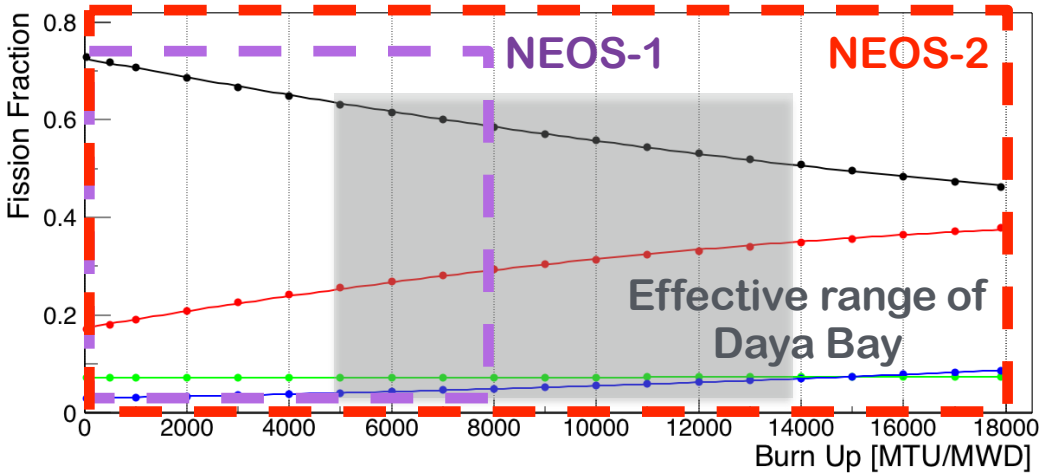
Reactor neutrino coherent scattering, neutrino-electron scattering can be studied further at Tendon Gallery.



NEOS-II is running now.

- NEOS-II plan to cover whole burn-up cycle (1.5 years data) compared to NEOS (0.5 year data) to check Daya Bay claim.
- PI : Yoomin Oh & Sunny Seo (CUP, IBS)
- Issues : PROSPECT experiment didn't see 5MeV bump…
- What are unknown factors in reactor neutrino deficit ? Is really due to theoretical problem in 235U neutrino estimation ?

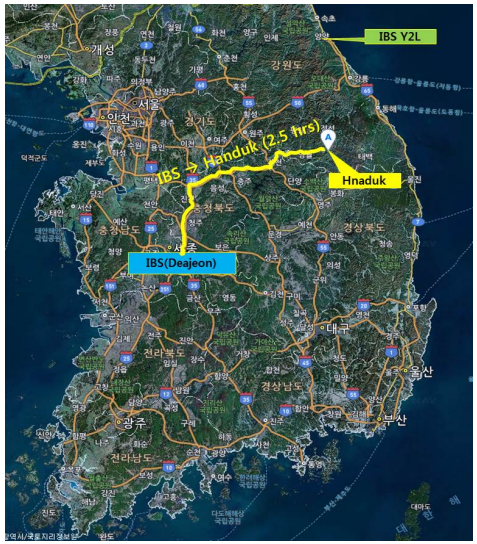




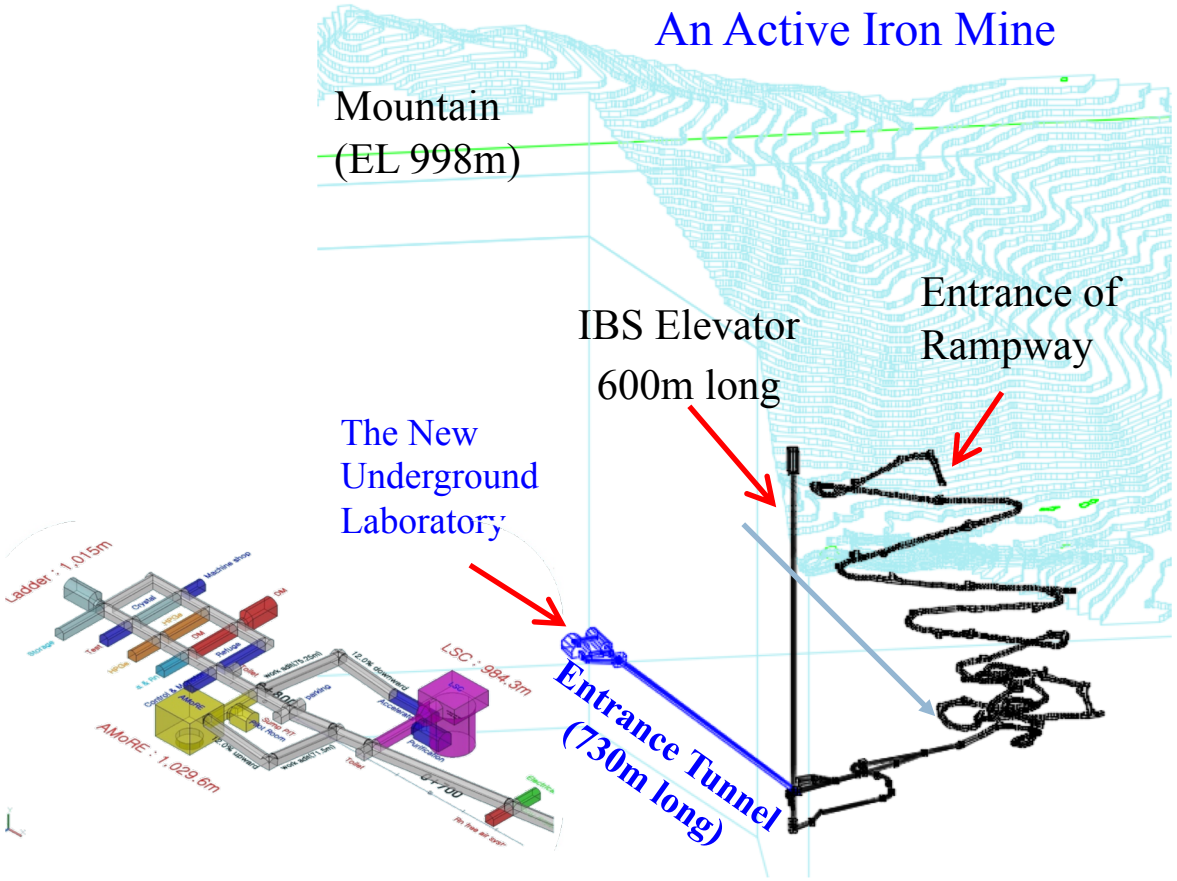
F.P.An et al., PRL 118, 251801 (2017)

Future : a new underground lab.

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



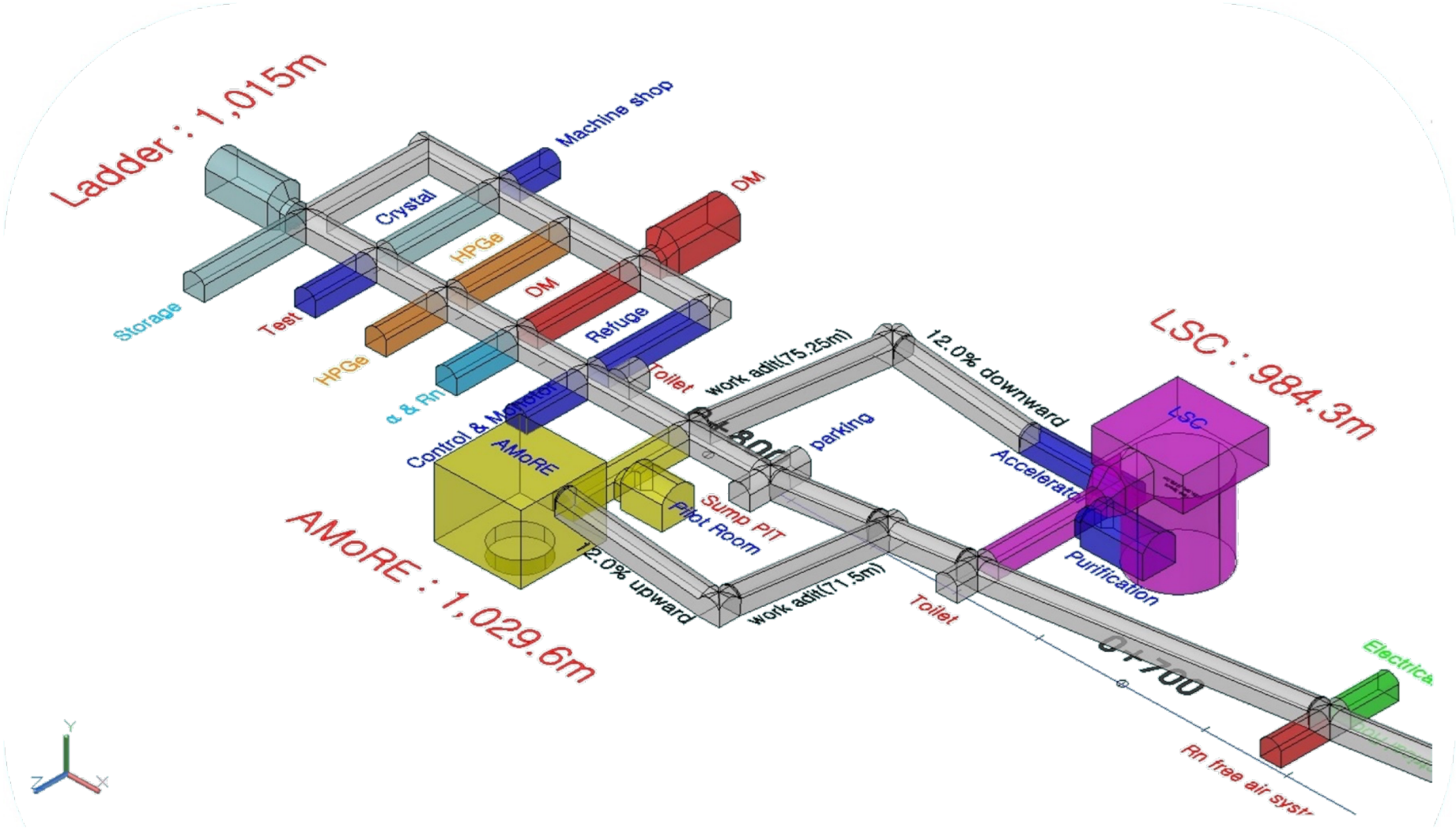
Bird view of Handuk Iron Mine



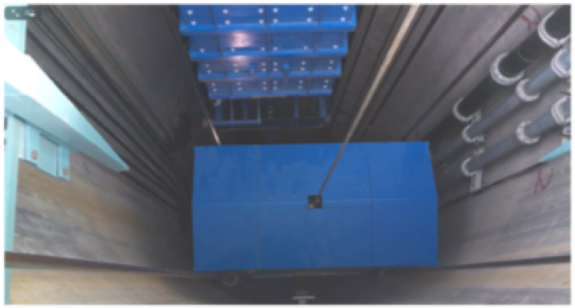
Large (>2000m²), deeper (1100m depth)

The underground laboratories

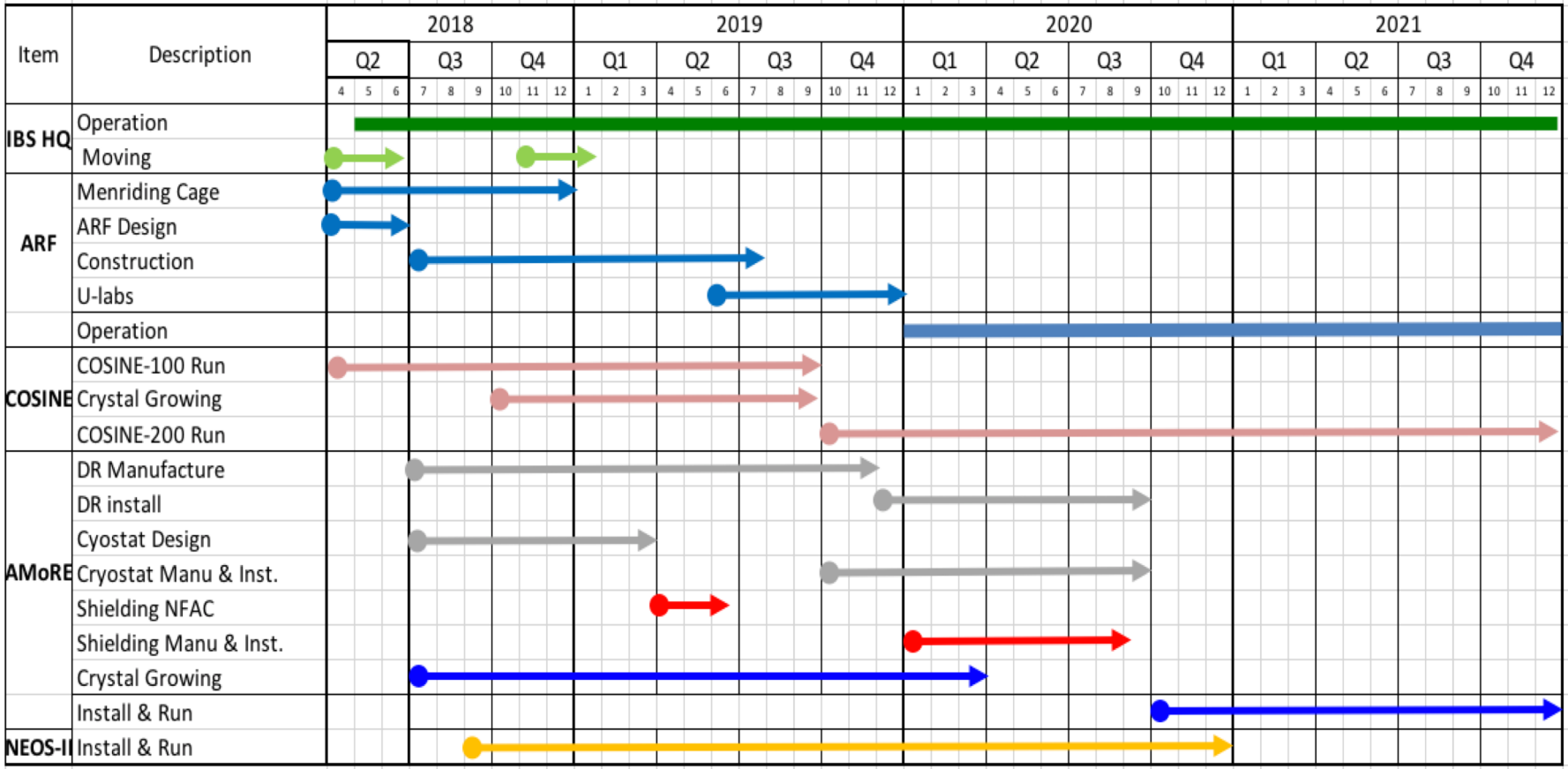
- 8 experiments with 12 spaces
- 10 utility rooms



Construction

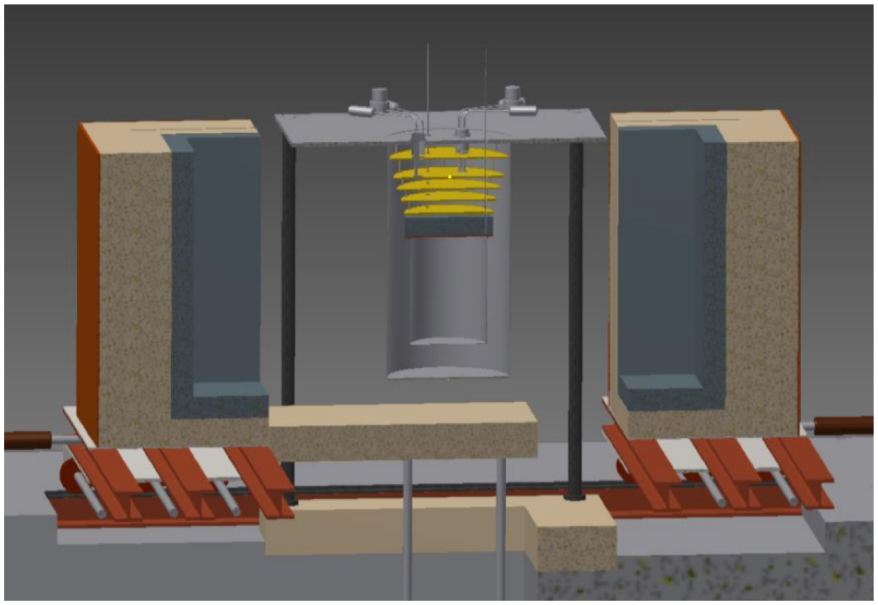


Schedule

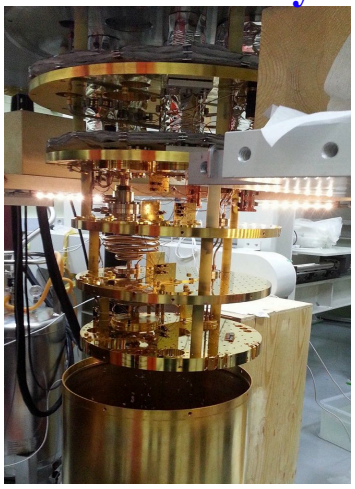

Item
Description
2018
2019
2020
2021
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
Q1
Q2
Q3
Q4
4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
IBS HQ
Operation
Moving
ARF
Menriding Cage
ARF Design
Construction
U-labs
Operation
COSINE
COSINE-100 Run
Crystal Growing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

Experiments to be installed

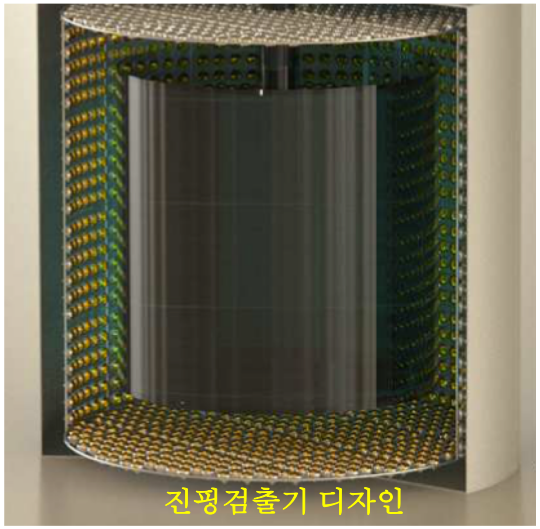
AMoRE-II



Low temp. Test facility



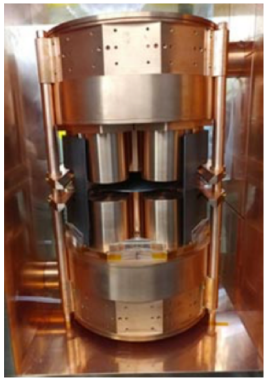
kT LS Chamber



Radon reduction system

Next generation dark matter exp.

HPGe-Array & Detectors



+ gravitational wave detector test.
Earthquake studies
Biological
Environmental
Measurements.

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. Collaborative work with French CUPID-Mo group is anticipated.
- AMoRE-Pilot is making good progress in detector performance and identifying the background sources.
- 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 for a new YEMI lab.