Yemilab의 현황과 미래

Yeongduk Kim
Institute for Basic Science

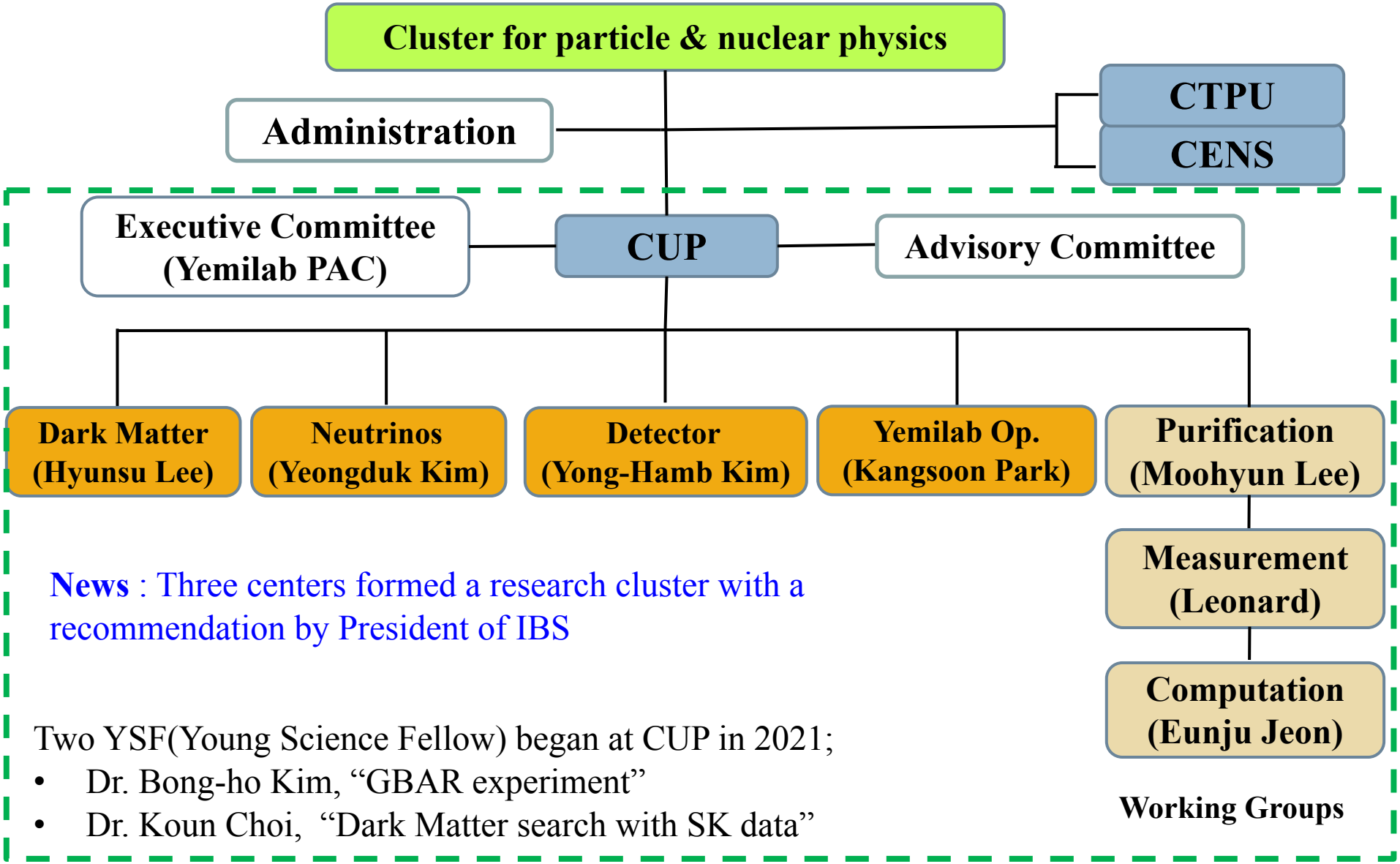
2022. 11. 18.

1st KSHEP Meeting at Pusan National University

Introduction

- CUP has operated Y2L from 2013 and constructed Yemilab in 2022.
- Yemilab is a world-class underground laboratory not only for CUP's projects but also for other projects.
  - CUP : COSINE-200, AMoRE-II, LMDM, LSC, +
  - Others : Microgravity, KAERI, KNU, KIGAM, KRISS, +
- CUP has a broader program over Yemilab.
  - NEOS
  - NEON
  - keV mass sterile neutrino search
- 1st Yemilab workshop on Oct. 16-18 this year, and I will summarize the presentations at this workshop.

Organization of CUP



News : Three centers formed a research cluster with a recommendation by President of IBS

Two YSF(Young Science Fellow) began at CUP in 2021;

- Dr. Bong-ho Kim, "GBAR experiment"
- Dr. Koun Choi, "Dark Matter search with SK data"

External proposals

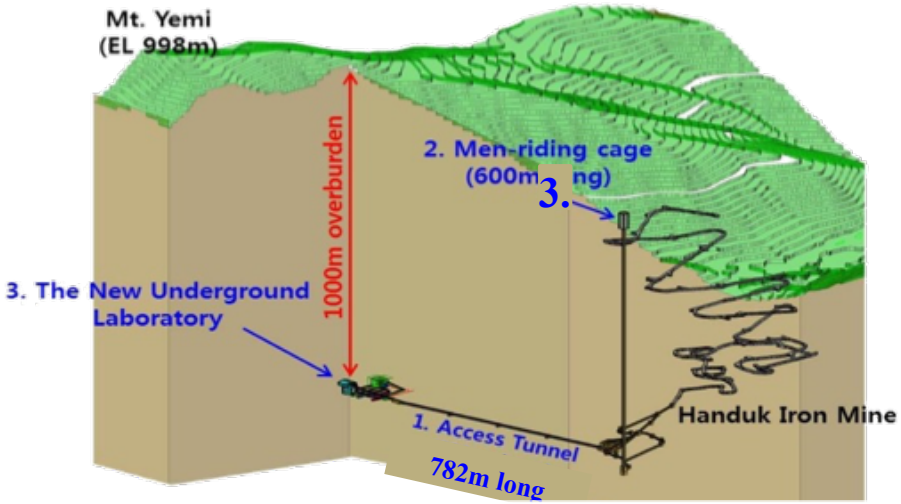
- 외부 기관 활용 Process
  - LOI 수령 (wiki 업로드)
  - 내부심사 (통과 후)
  - 활용 신청서 수령
  - 활용 확인서 작성 (예미렙 작성)
  - 사업계획서 (비용산정, 예미렙 작성)

########## 2022 ##########

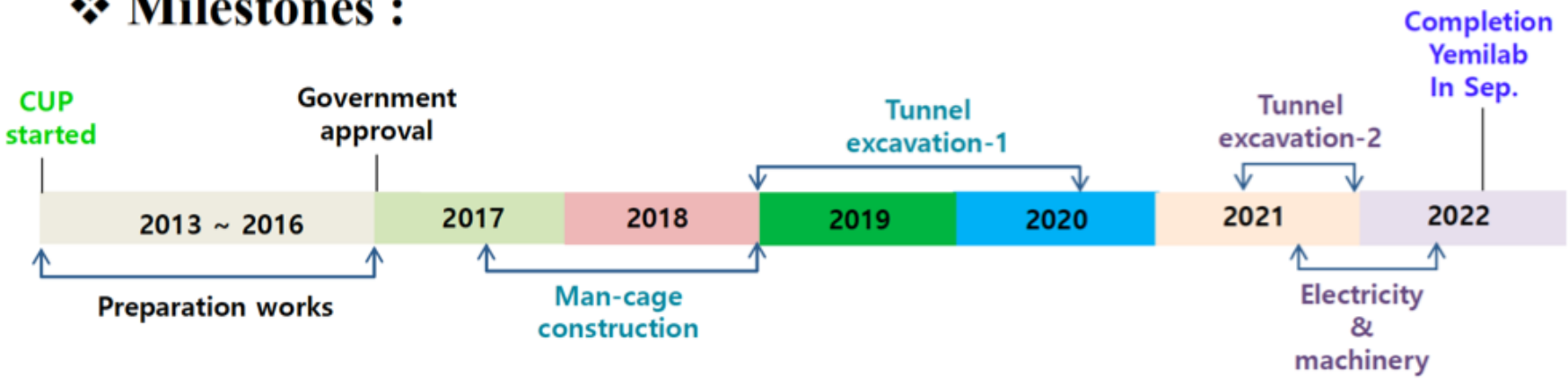
- 한국지질자원연구원 : 예미랩 지하실험실의 MS(microseismic) 모니터링 및 장기 안정성 평가
- 기상청 지진화산국 지진정보기술팀 : 지하 지진계 검증시설
- 스페이스린텍 : “Study of impacts and the mechanism of brain function detriments by gravity alteration”
- 국가수리과학연구소 : “Study of Micro-Gravity Signals using Superconducting Gravimeter (iGRAV)”
- 원자력연구원 : “Study of low-level gamma ray spectrometry using HPGe system in underground”
- 경북대학교 김홍주 교수 : “KNU’s underground lab for fundamental physics”

Yemilab for new discoveries.

- 1000 meter underground.
- Construction cost ~30 M$
- 2018-2022

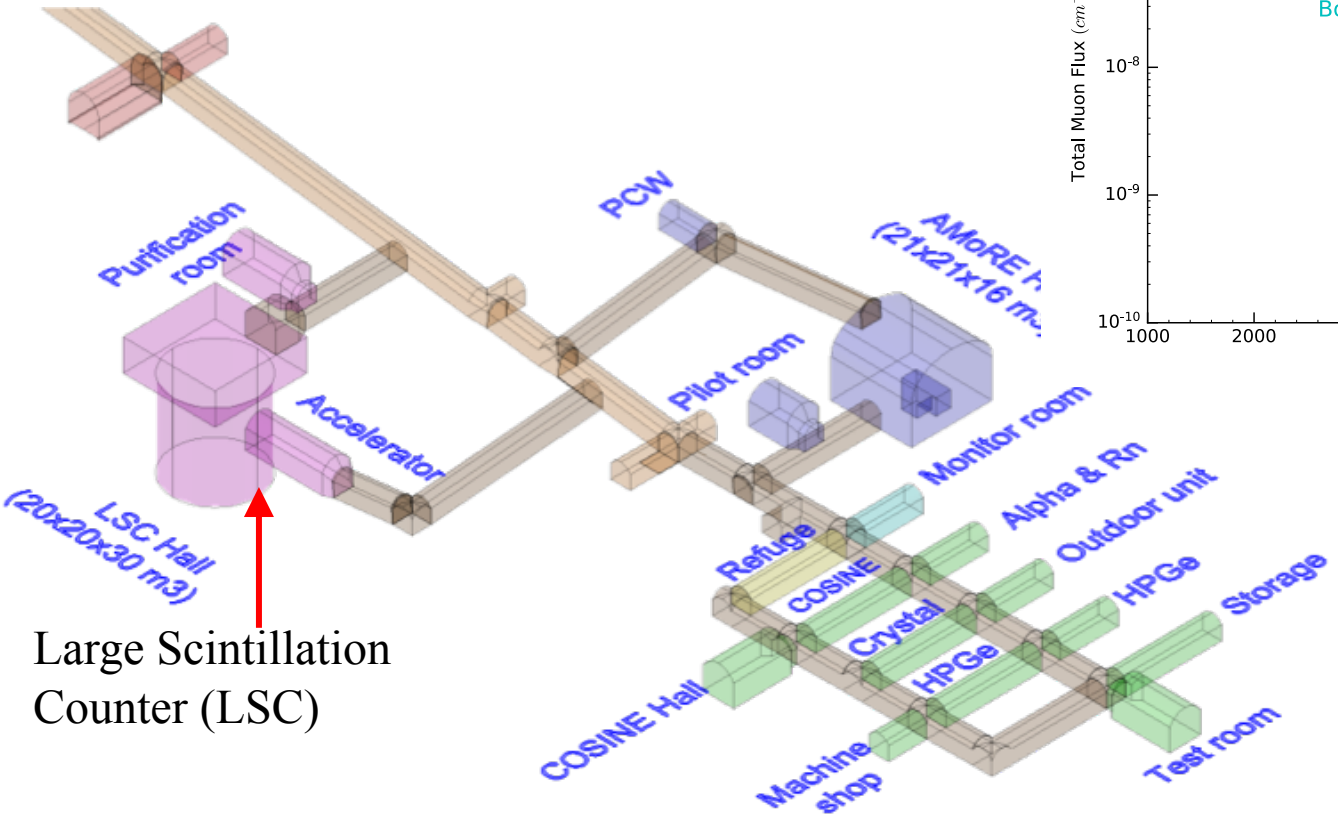


❖ Milestones :

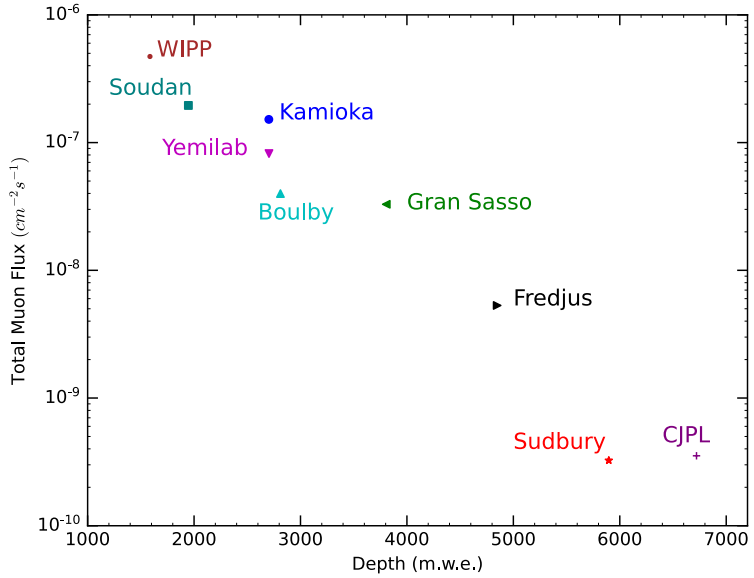


Yemilab

- Tried to separate the lab from mine operation as much as possible.
- Utilize two accessways, a ramp-way and a man-riding elevator.
- Open to researchers other than IBS.



Large Scintillation Counter (LSC)



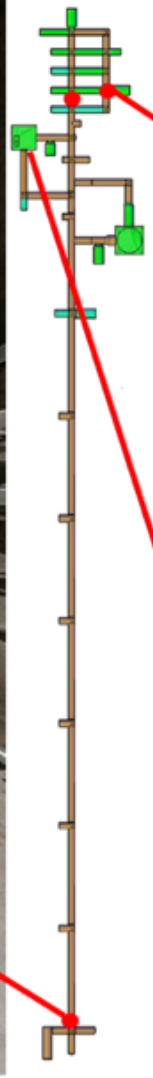
Yemilab

- Area
  - 4000m^2 for tunnel,
  - 1000 m^2 for maintenance,
  - 3000m^2 for experiments
- Mechanical
  - 39000m^3/hour ventilation
  - 200kW cooling power
  - Radonless air supply (~10000 m^3/hour from ground)
- Electrical
  - 2MW for electric power supply
  - 180kW UPS for 40 minutes for AMoRE-II
  - 360kW emergency generator

	Y2L	Yemilab
Depth (m)	700	1000
Area (m^2)	350	3000
Rock Radioactivity (ppm)	U : 3.9(1.4) Th : 10.5(6.5) K : 40000	U : 0.8(0.3) Th : 3.3(0.4) K : 11,800

Photos


Access tunnel (2022.08)



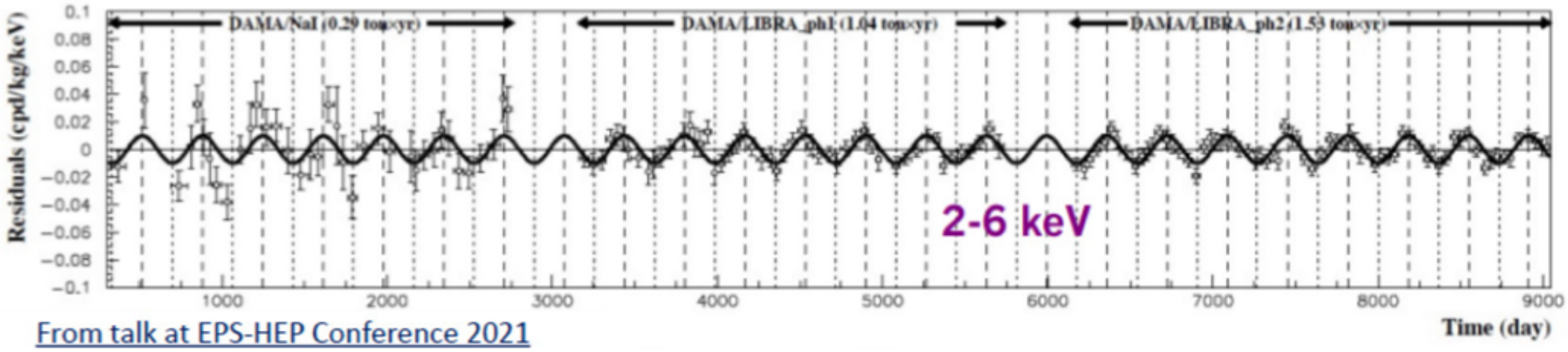

Ladder type tunnels (2022.08)


AMoRE Hall (2022.08)


LSC Hall (2021.08)
LSC
hall
Pit volume 6,280m3

Dark Matter Searches

- To check DAMA/LIBRA conundrum



From talk at EPS-HEP Conference 2021

- Low mass DM

- Dark Sector searches

COSINE-100 detector

Hyunsu Lee

JINST 13 T02007 (2018)

4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

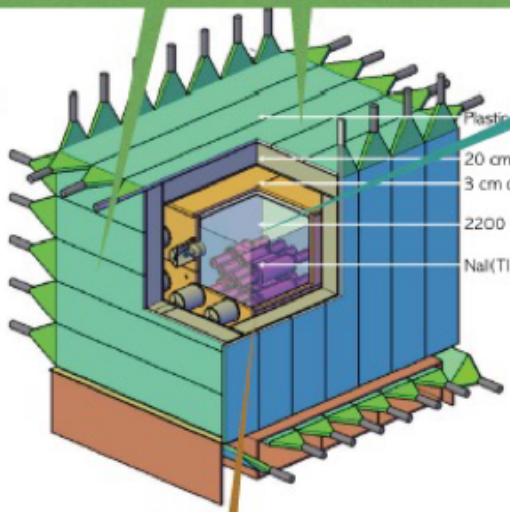
Nucl. Instrum. Meth. A 851 103 (2017)

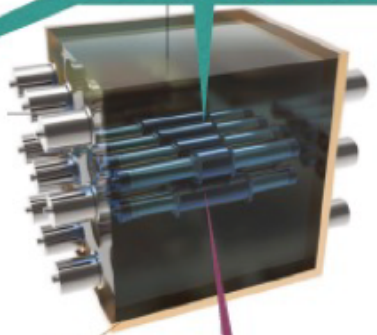
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

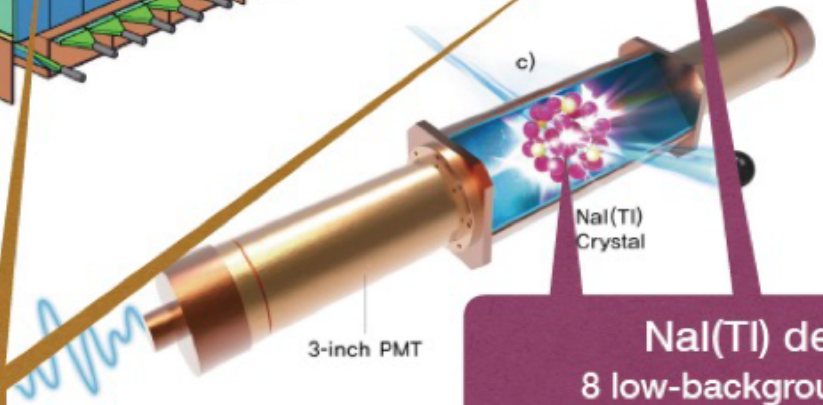
JINST 13 T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
(^{3}He gas detector)







Shields
3-cm thick copper box
20-cm thick lead shielding

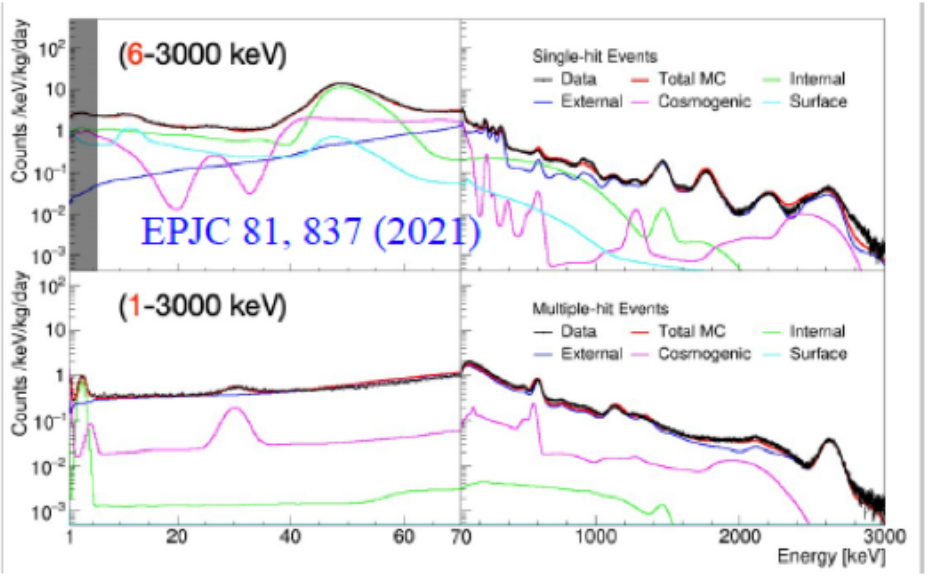
NaI(TI) detector
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

Eur. Phys. J. C. 78 107 (2018)

Recent achievements

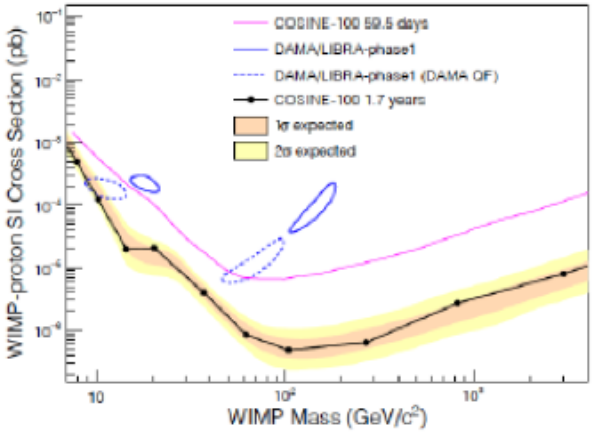
Hyunsu Lee

Background modeling (1keV threshold)



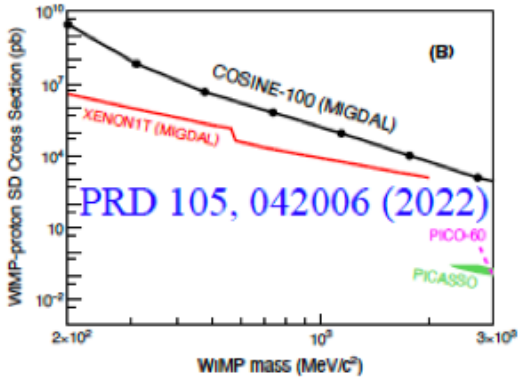
EPJC 81, 837 (2021)

WIMP Search (1.7 years)



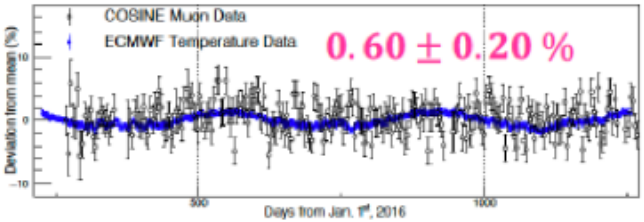
Sci. Adv. 7, eabk2699, (2021)

Low-mass DM with Migdal

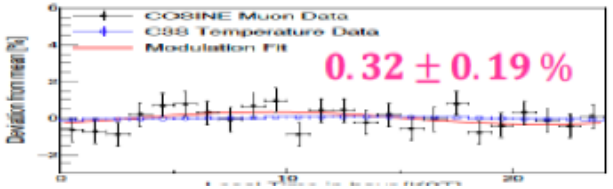


PRD 105, 042006 (2022)

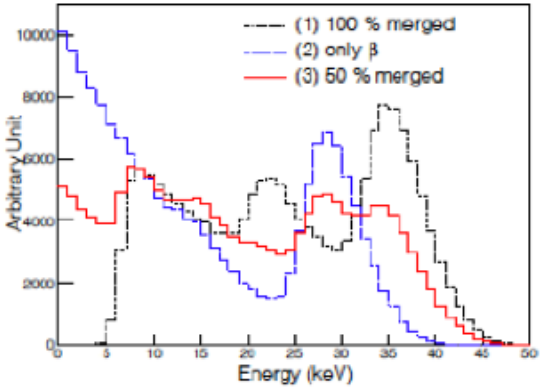
Annual & diurnal modulation of muon



JCAP 02, 013 (2021)



New isomers in ^{228}Ac

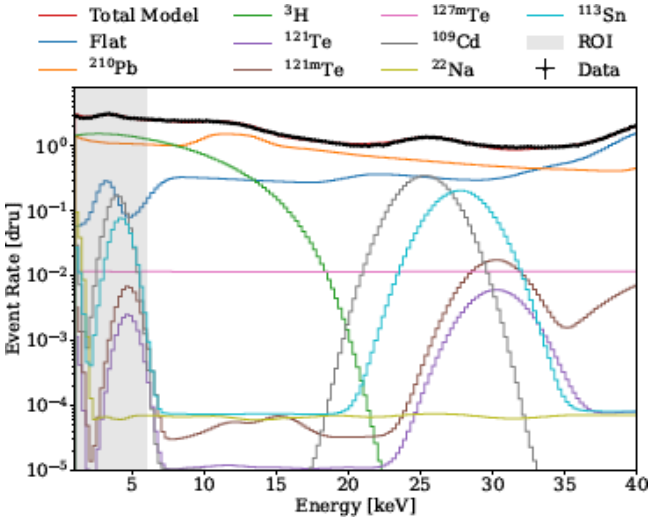


EPJC 81, 746 (2021)

Annual modulation (3 years data)

Hyunsu Lee

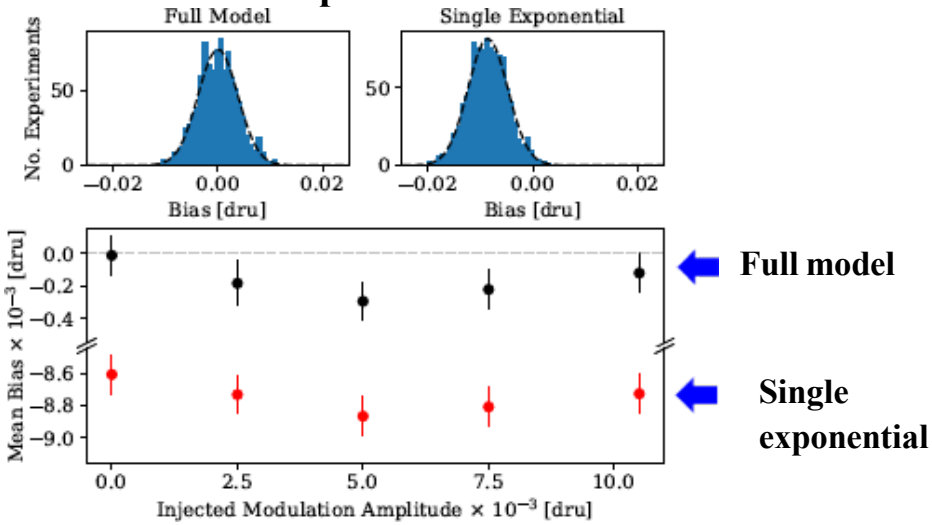
Time dependent background modeling

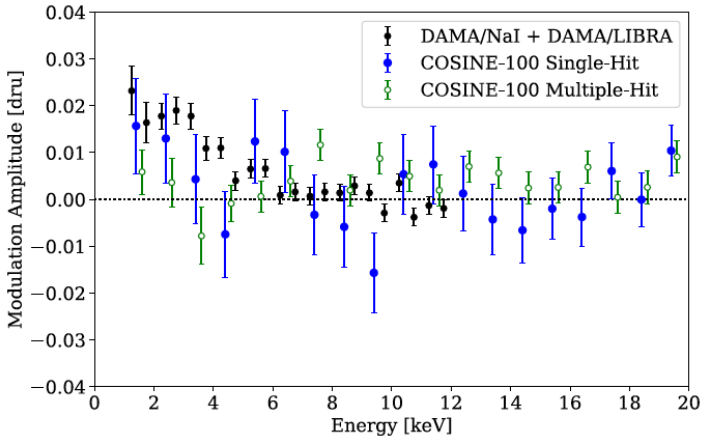


PRD 106, 052005 (2022)

$$R(t) = \sum_i \left[C^i + \sum_j^8 A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t - t_0)}{T} \right)$$

Pseudo experiment





Precise understanding of the time-dependent backgrounds is crucial for the annual modulation searches

1-6 keV modulation amplitude

COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

NaI crystal development for COSINE-200

Hyunsu Lee

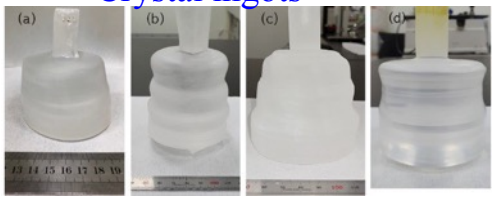
Powder purification performance

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)
K.A. Shin et al., JINST 15, C07031 (2020)

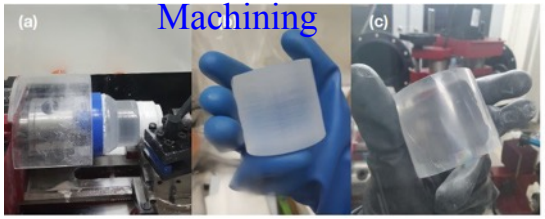
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

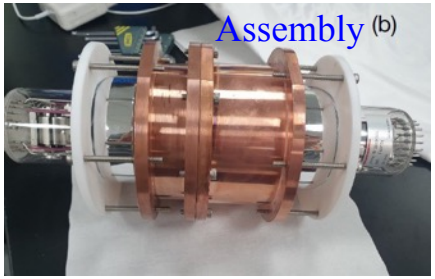
We produced ~ 400 kg low-background NaI powder
(Maximum production rate ~ 100 kg/month)

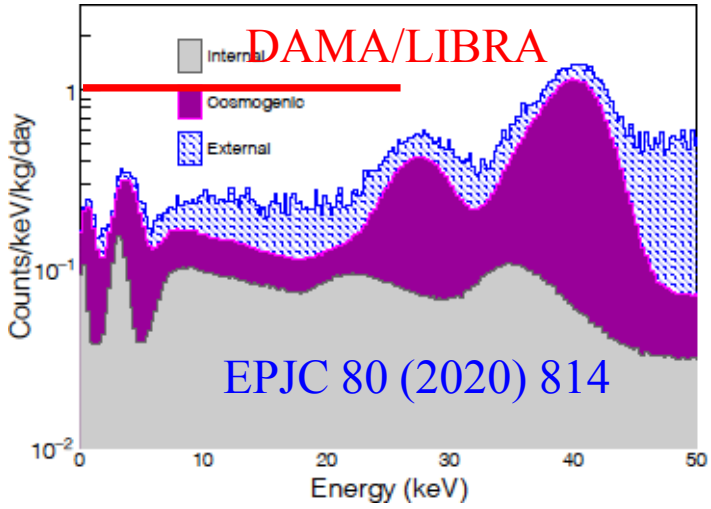
Crystal ingots



Machining







A proof of principle for low background NaI
Large crystal growing is going on

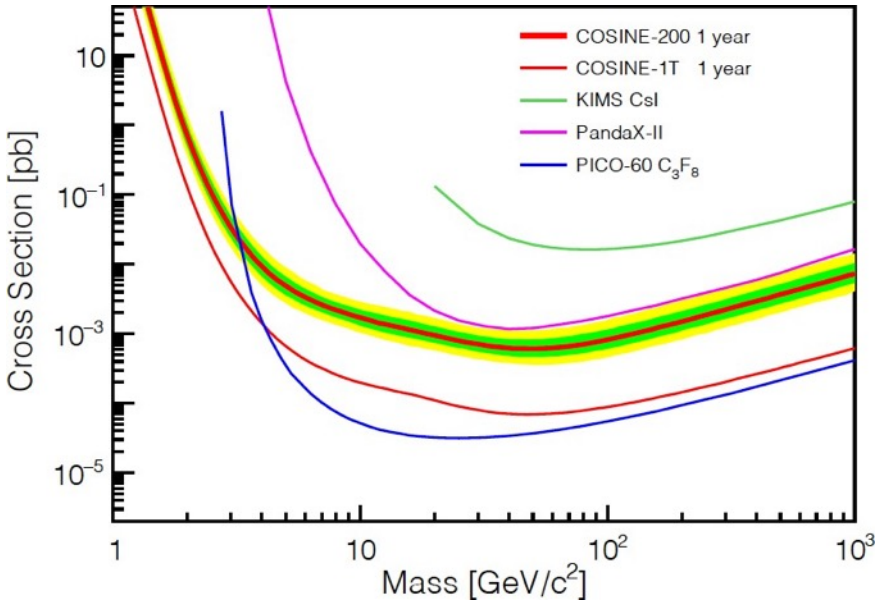
Sensitivites of COSINE-200

Hyunsu Lee

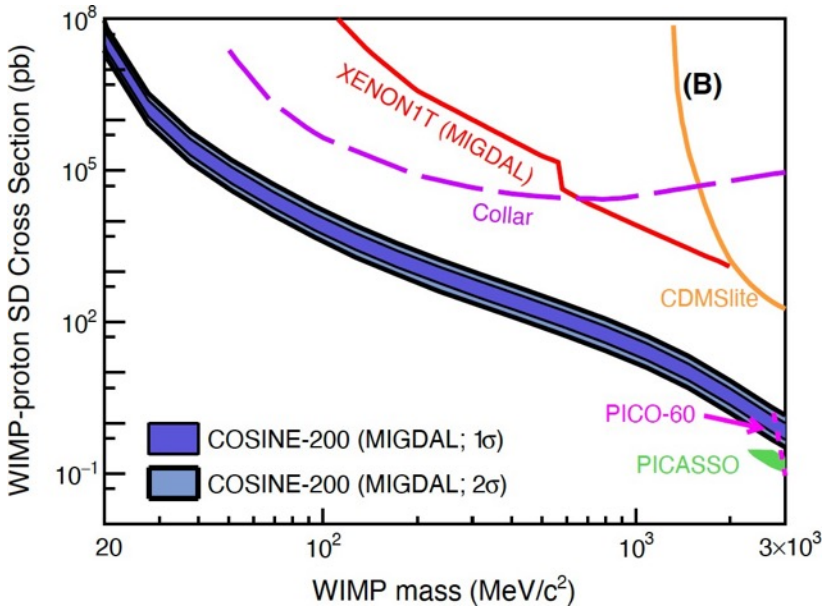
- Unambiguous conclusion on the DAMA/LIBRA

COSINE-200 sensitivities

WIMP-proton spin-dependent



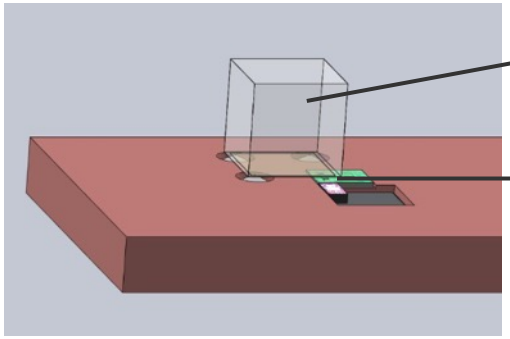
Low mass search with Migdal



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

Low Mass DM search

Yong-Hamb Kim

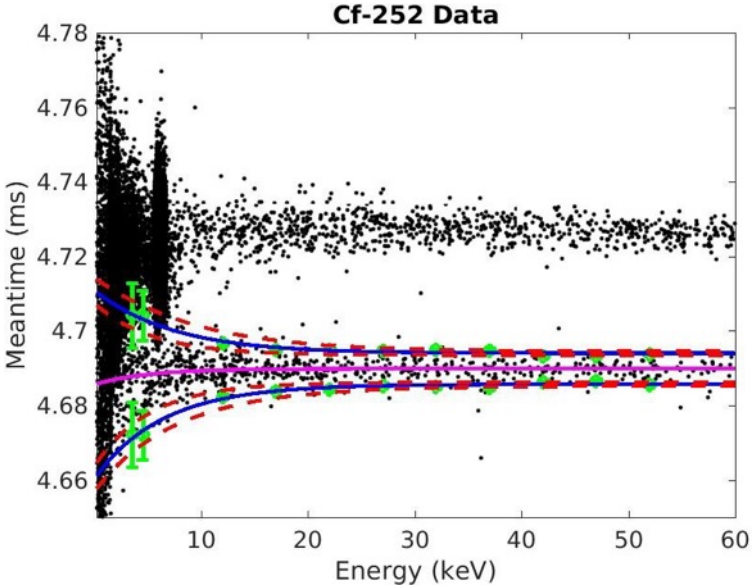


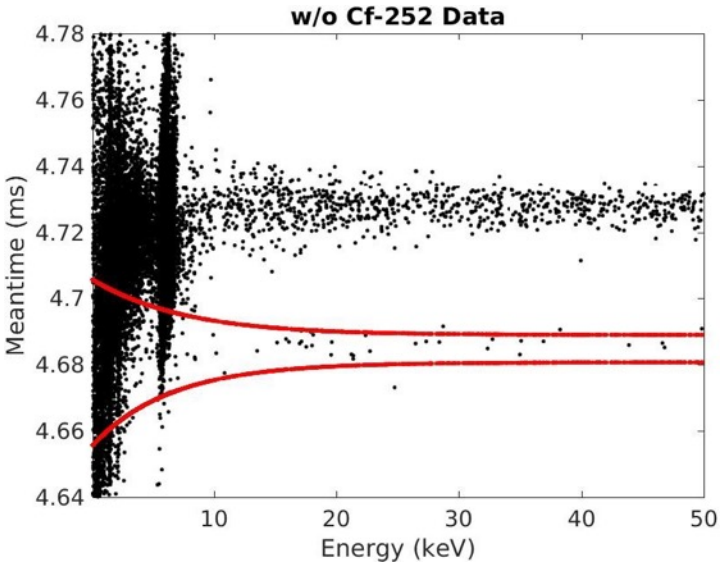
Many choices: **LiF, CaF_2, Al_2O_3, $LiAlO_2$**(SD)
$CaMoO_4$, Diamond (SI)

MMC

First trial with CaF_2 ($5\times5\times5$ mm^3) 30 mK in an ADR

Spin dependent interacting isotopes : ${}^{6,7}_{3}Li$, ${}^{19}_{9}F$, ${}^{27}_{13}Al$ etc.

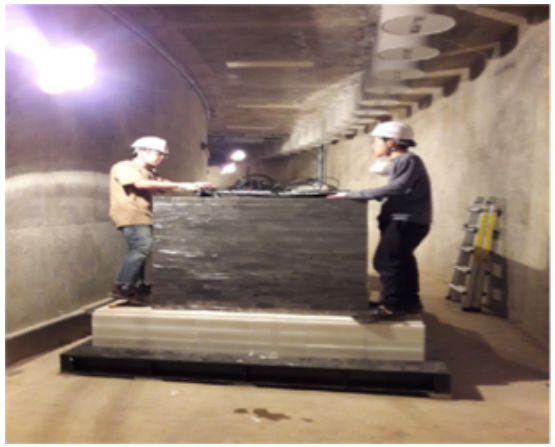




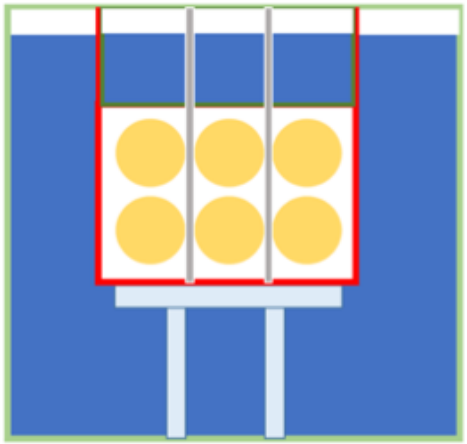
NEON neutrino coherent scattering experiment

Hyunsu Lee

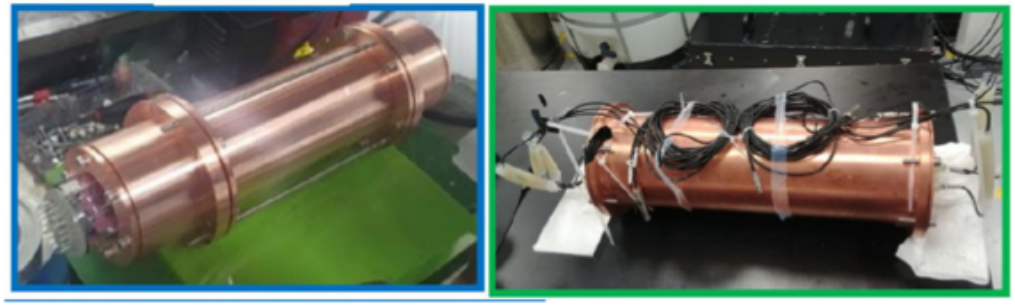
- Purpose
  - Observation of coherent neutrino nucleus scattering from reactor neutrino
  - Detector performance (long-term) of NaI(Tl) for COSINE-200

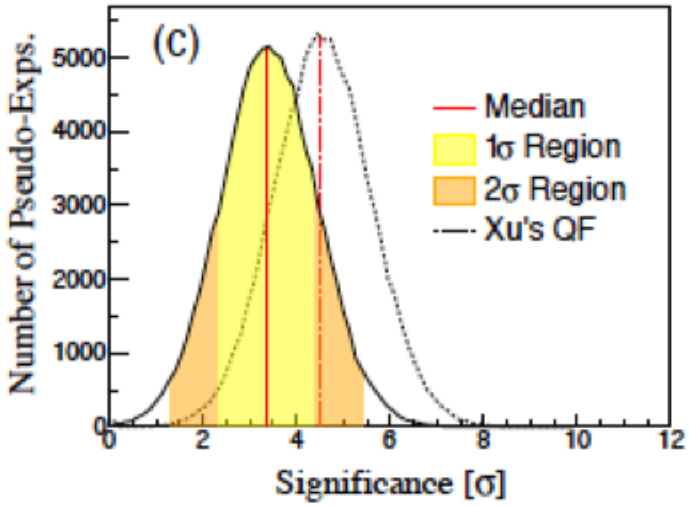


Tendon Gallery

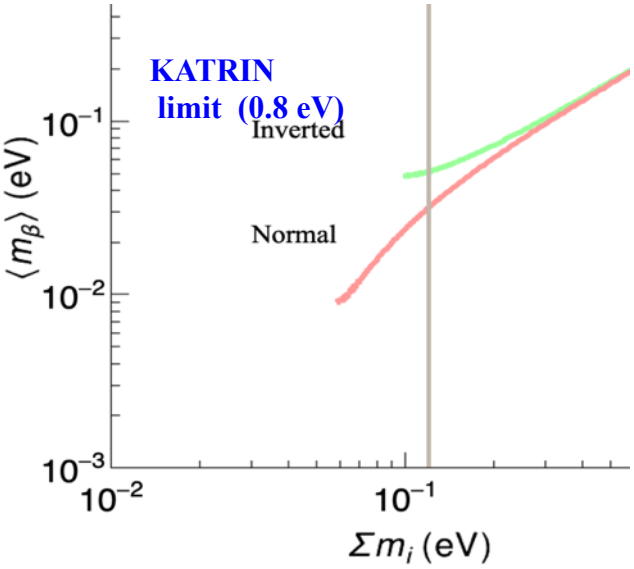


Improved encapsulation →
improved light output 20-26 PE/keV



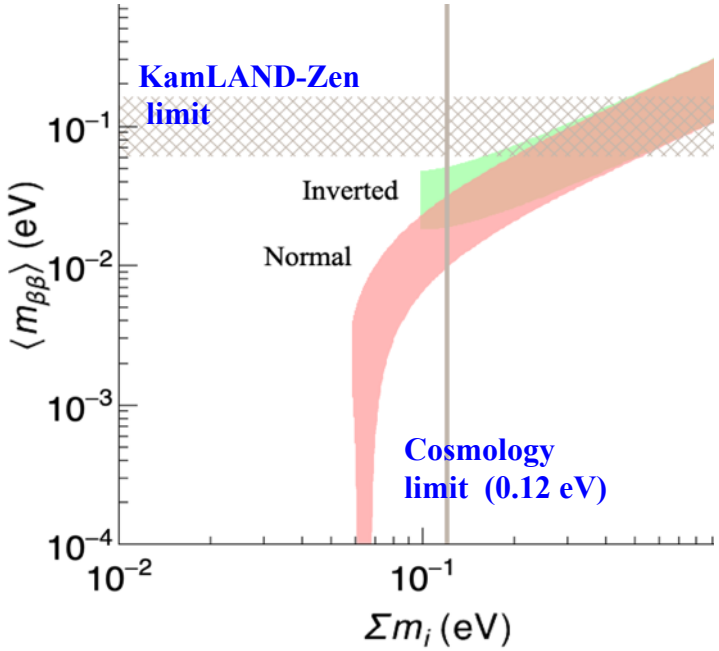


Neutrinoless Double Beta Decay

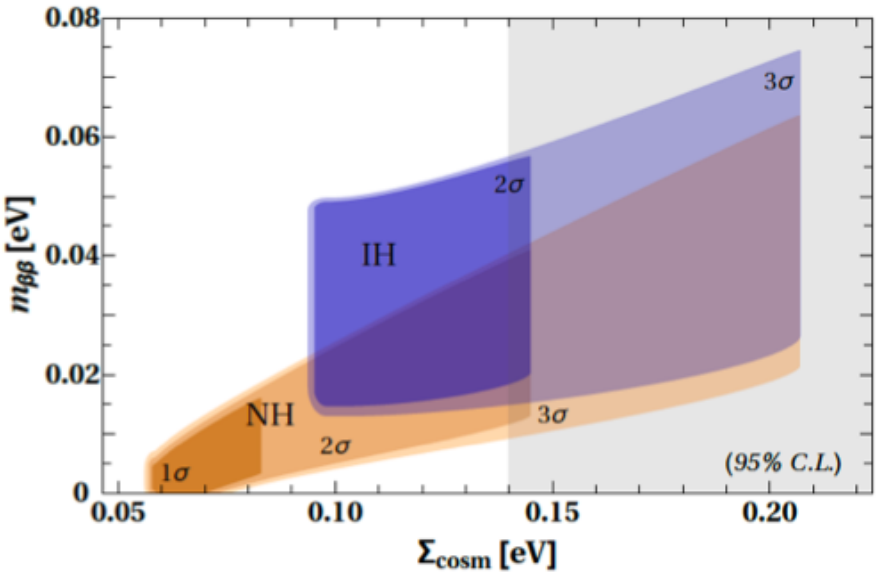


Current Neutrino Mass Limits

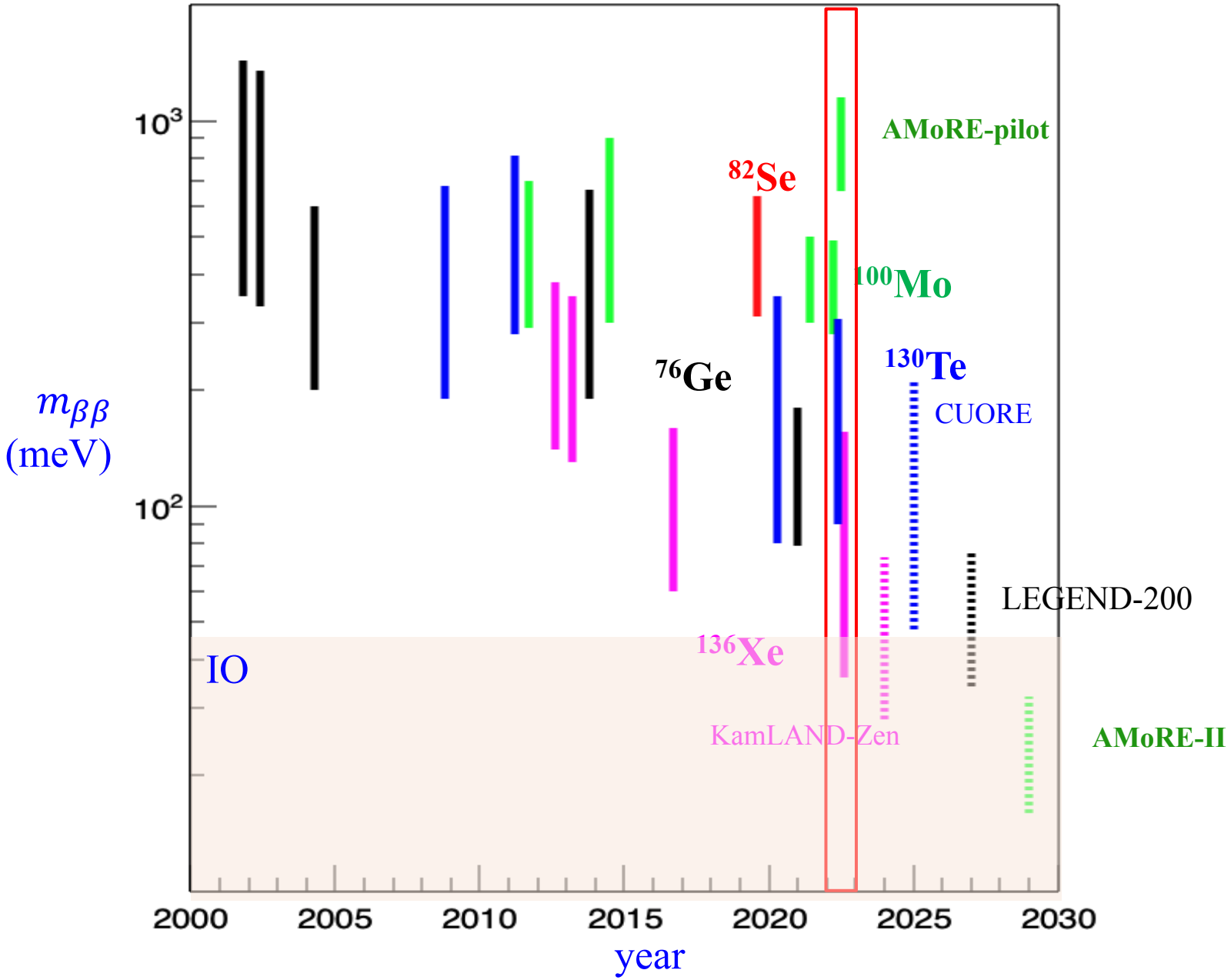
- Majorana nature of neutrinos is 80 year old question.
- Neutrino mass is ultra small, and we don't understand its origin. It is related to if neutrinos are Majorana particles.
- Neutrino mass is constrained by beta decays and cosmology.



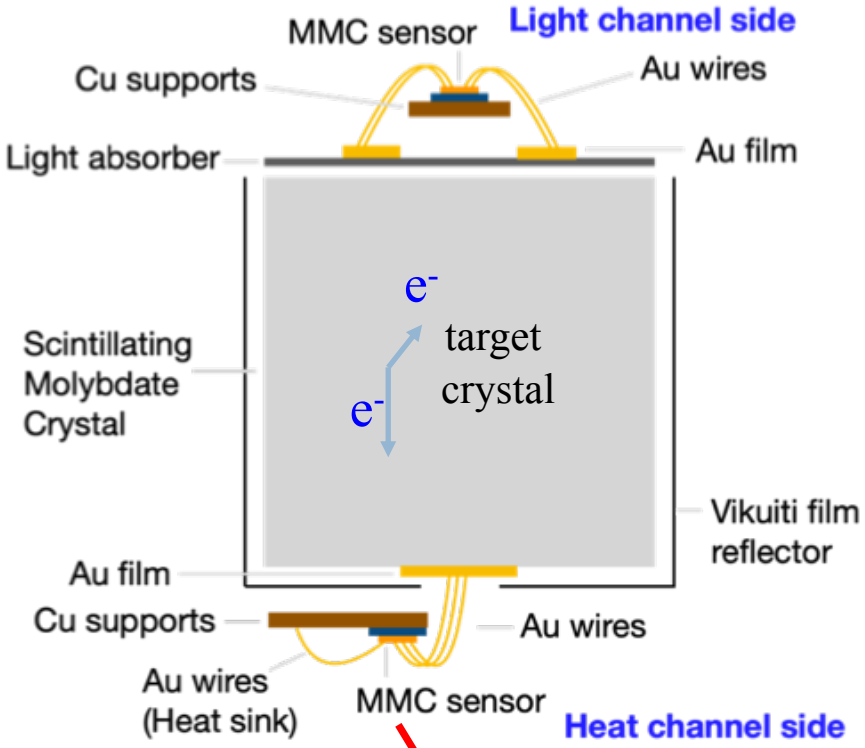
Dell'Oro et al., *JCAP* 12 (2015) 023



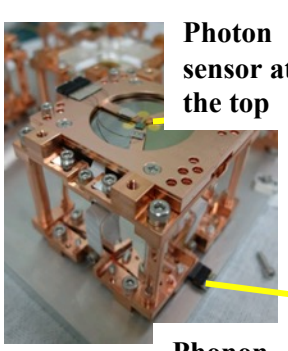
Recent Limits & Persepectives

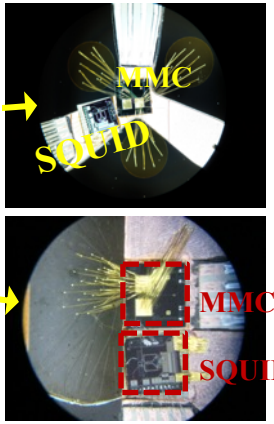


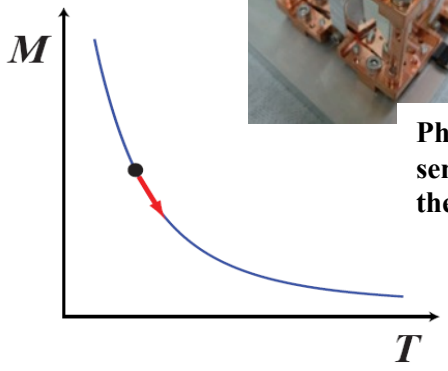
Principle of AMoRE detector



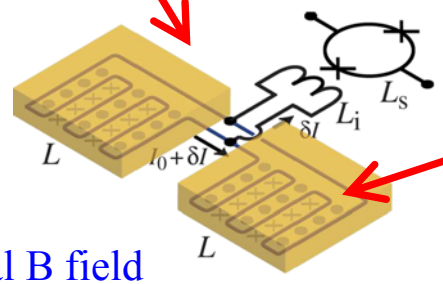
Decay→Phonons collected at Au foil → temperature of Au foil increase→magnetization of MMC decrese→ SQUID pick-up the change.







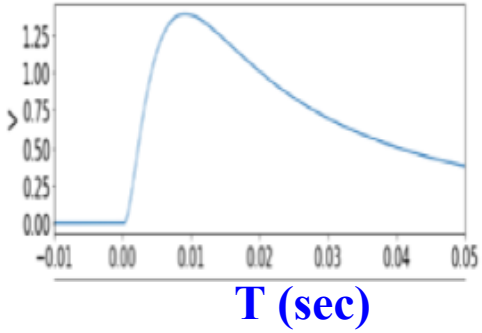
Au(Er) paramagnetic material



SQUIDS

Persistent current in superconductor

Local B field

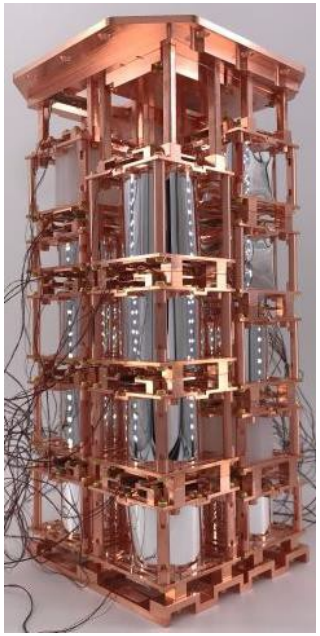


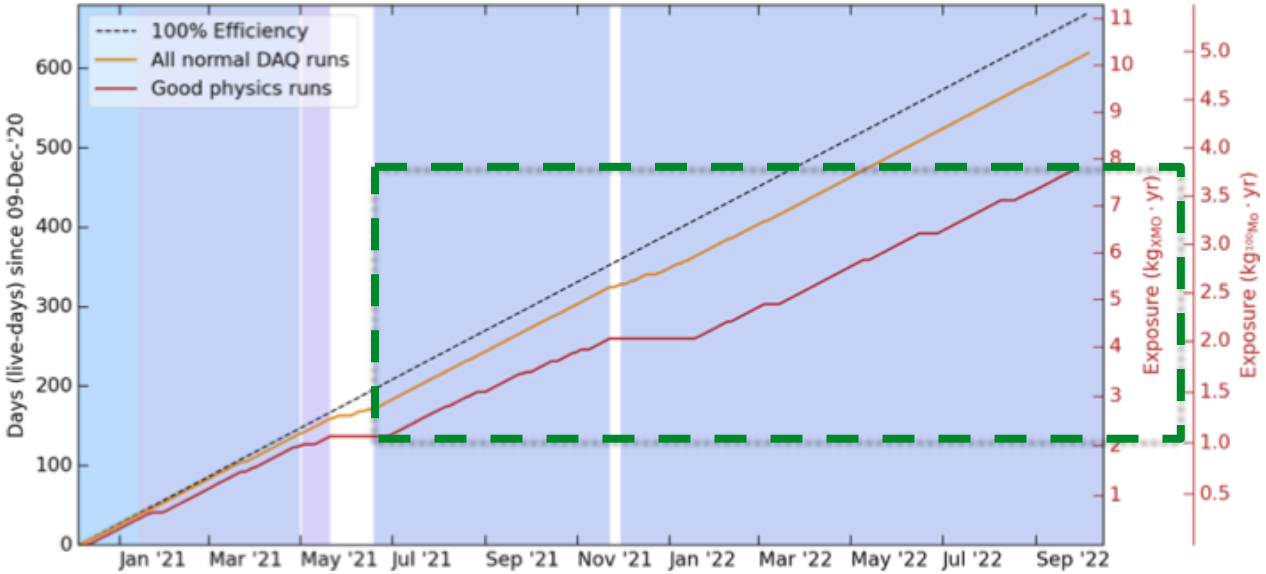
MMC: Metallic magnetic calorimeter

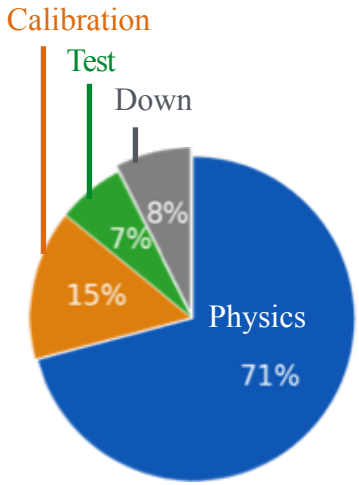
AMoRE-I : Running

Yoomin Oh

- AMoRE-I began Aug. 2020 @ Y2L and runs stable.
- Purpose – Check further on detector performance & backgrounds.
- Upgrades from Pilot
  - 13 CMO crystals (4.6 kg) and 5 LMO (1.6 kg) crystals, ~3 kg of ^{100}Mo
  - Outer Pb shields 15 cm → 20 cm to decrease rock gamma backgrounds.
  - Add more neutron shields (boric acid+PE+b.PE)
  - Stabilization heater for all crystals.
  - MMC sensor upgrade (AuEr→AgEr)
  - Capton PCB
  - SS screws → Copper or Brass screws.
  - Light Detector wafers are hard glued to holder.



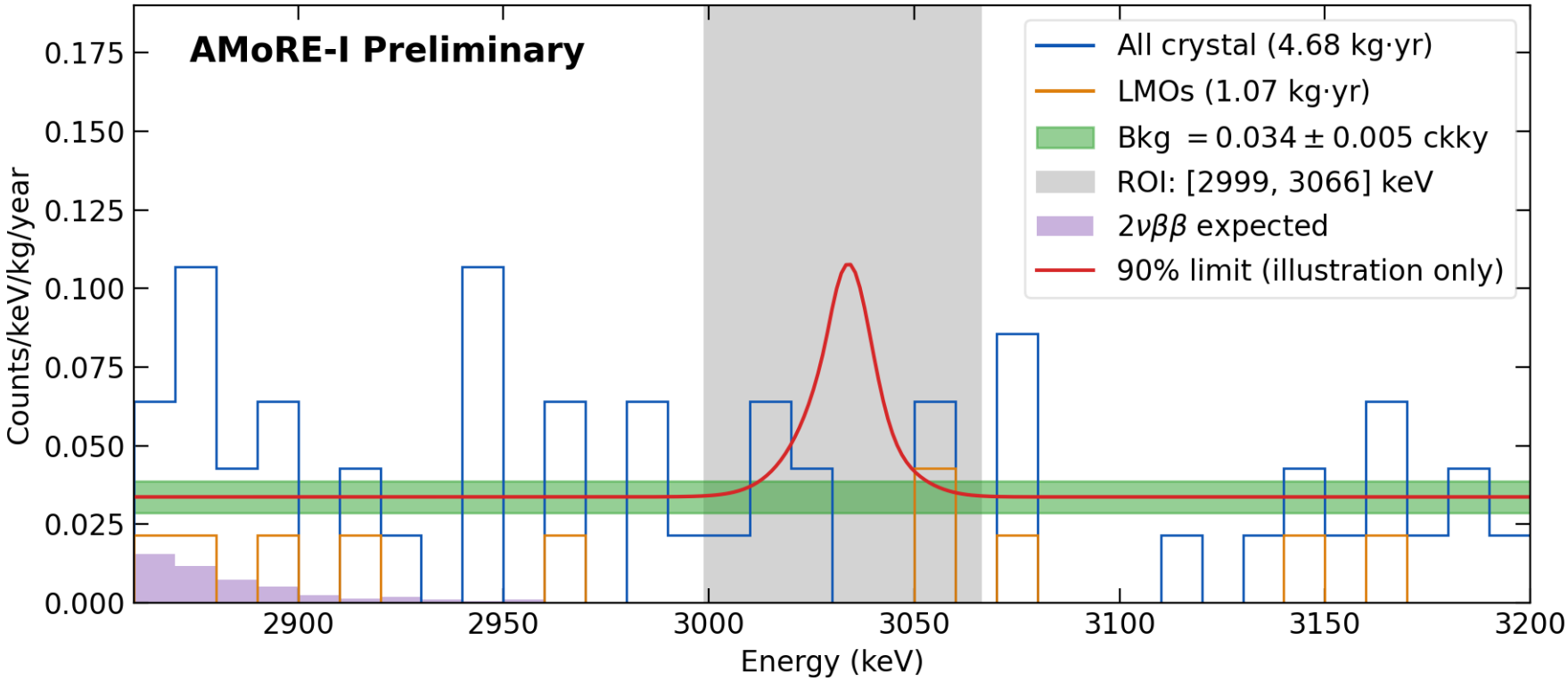




Preliminary data

Yoomin Oh

- Preliminary half-life limits are presented @ Neutrino 2022 and ICHEP 2022.
- Need the background analysis with alpha analysis.



- Background = 0.034 ± 0.005 ckky,
- $T_{1/2}^{0\nu} > 1.05\times10^{24}$ years at 90% C.L.,

  Cf : $T_{1/2}^{0\nu} > 1.8\times10^{24}$. By Cupid-Mo group

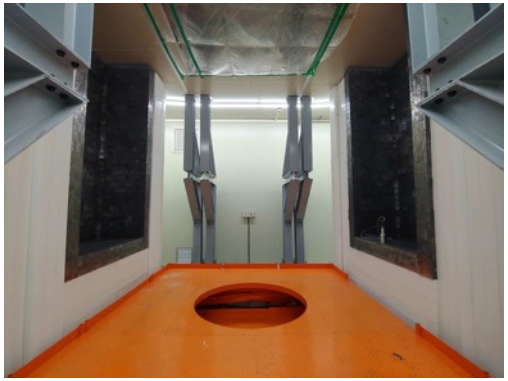
MeV	Total (5.28 kg y)	CMO (4.06)	LMO (1.22)
2.9-3.1	33 (evt.)	27	6
	0.031 (ckky)	0.033	0.025
2.86-3.2	61 (evt.)	48	13
	0.034 (ckky)	0.035	0.031

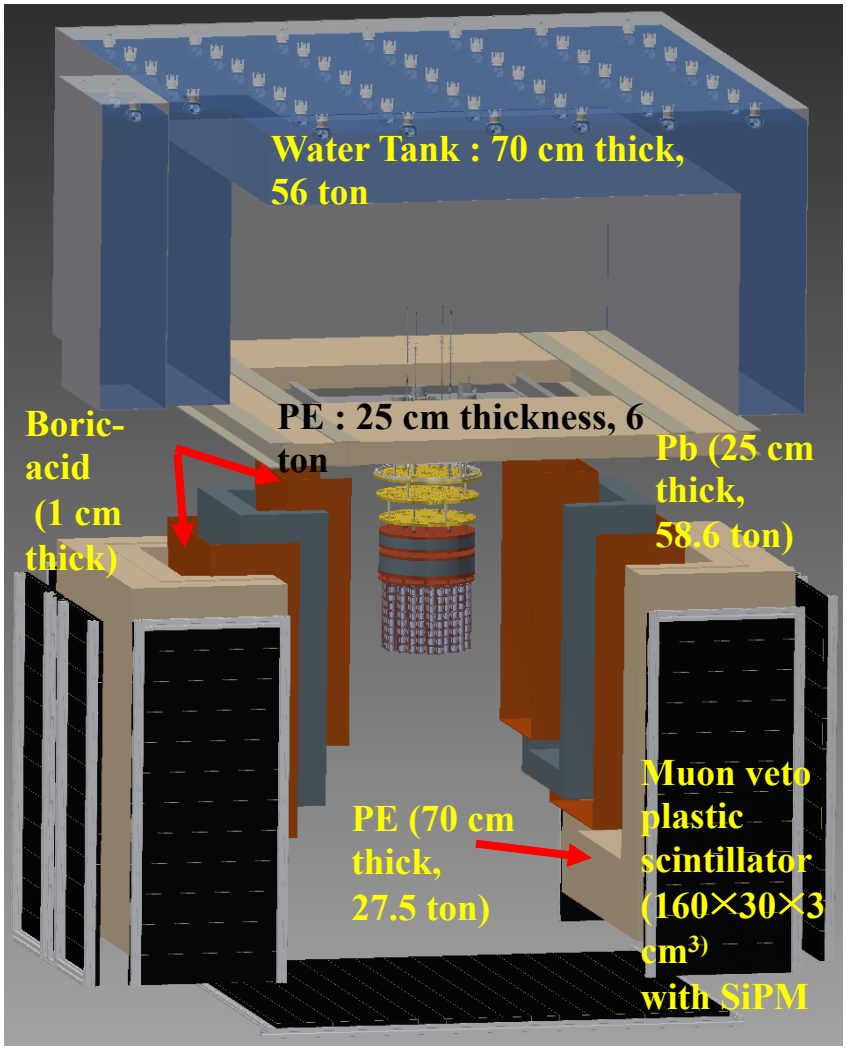
AMoRE-II : under preparation

Jaison Lee

- 100 kg of ^{100}Mo @ Yemilab for 5 years
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 410 crystals) + 13 $^{40}Ca^{100}MoO_4$
- DR inside heavy shielding with Pb, PE, and water. s

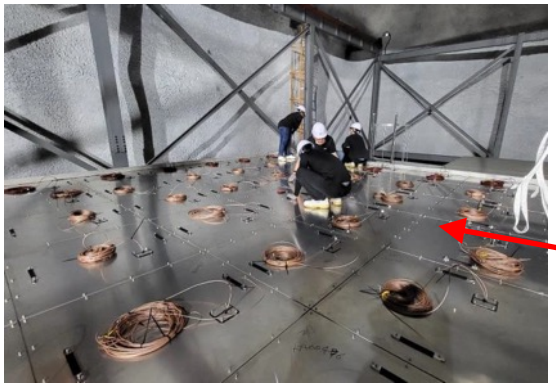
- 132 Plastic Scintillator muon detectors installed
- WC detector
  - Reflector (tyvek) was installed on the surf ace inside detector.
  - PMTs are installed and the door will be fin ished after installing DR.
  - Water purification system has been ready.





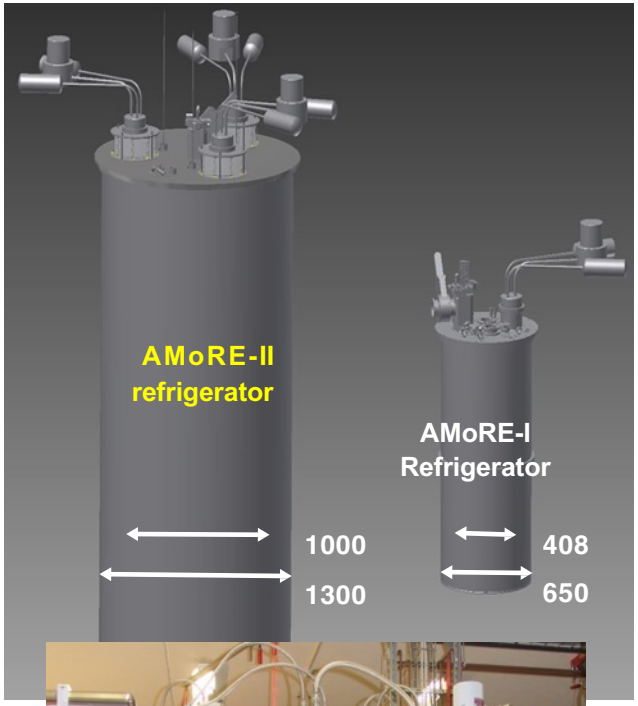
Overview of AMoRE-II setup

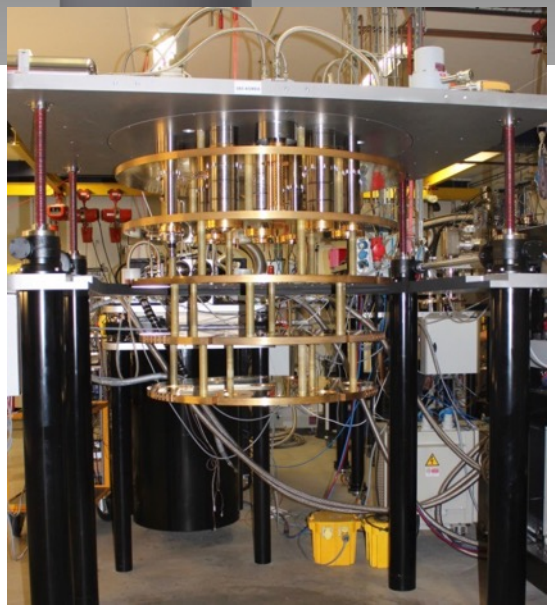
Jaison Lee



Dilution refrigerator & Cryostat

Yong-Hamb Kim

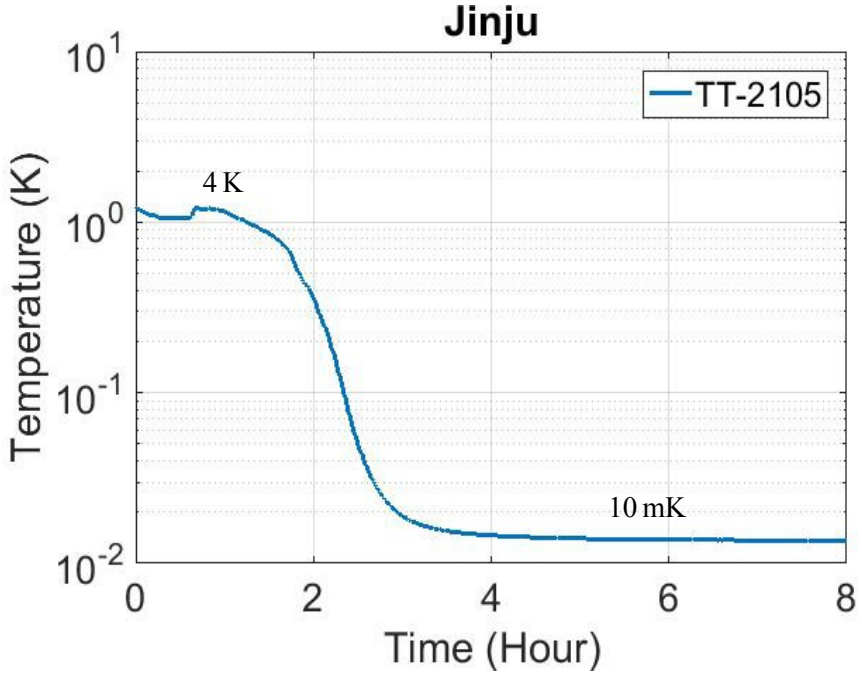




Large dilution Refrigerator from Leiden.

- **Three PTR (PT420 RM)**
- **2.4 mW @ 120 mK,**
- **> 5 μW @ 10 mK**
- **Delivered to IBS in Aug. 2021.**

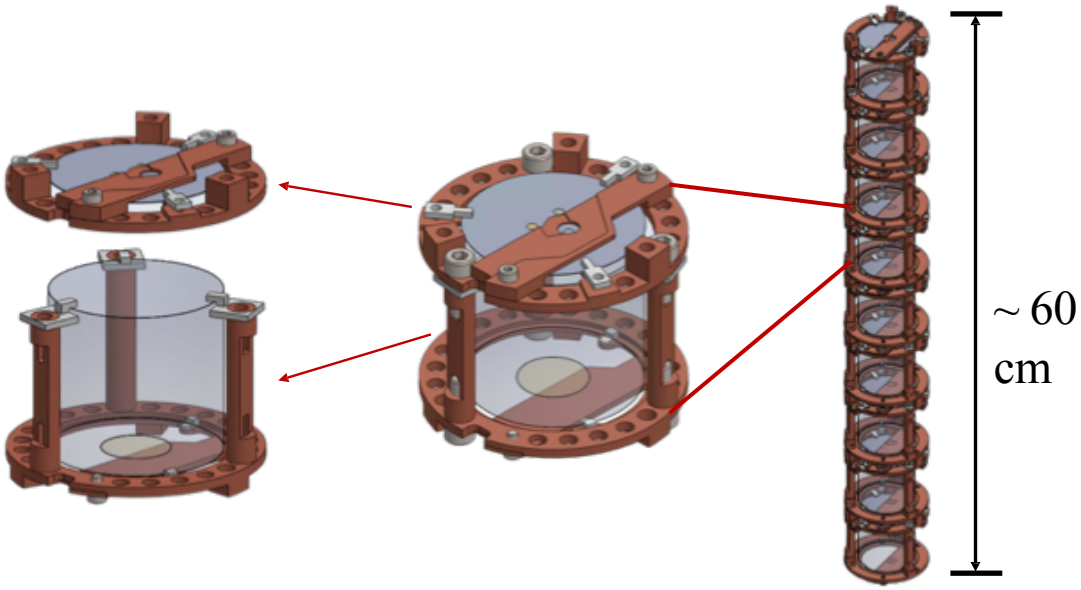
- With heavy LN2 supply, it takes 6 days to reach 4 K.
- Mass inside IVC: 0.9 t (Cu), ~ 4 t (Cu+Pb) to be added
- ~ 7 hours to reach 10 mK

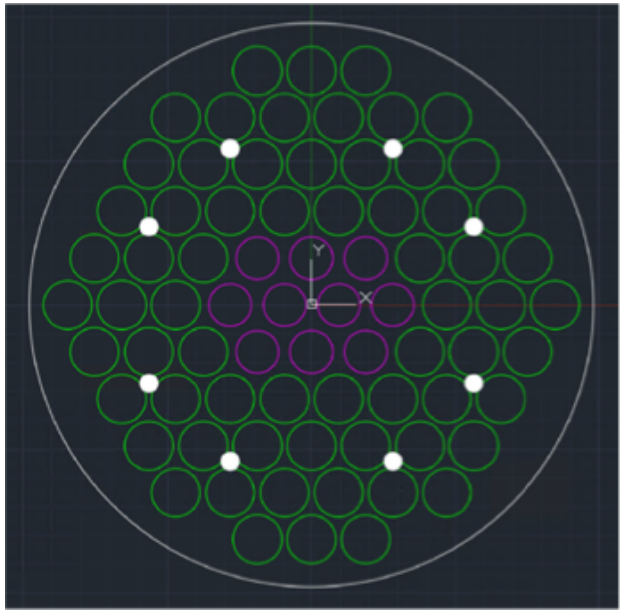


New module design for AMoRE-II

Yong-Hamb Kim

The AMoRE-II crystals are either 5cm or 6cm.





Total 76 towers ~ 200 kg of ^{100}Mo can be housed.
Cf. 100 kg of ^{100}Mo in AMoRE-II

The heat detector is assembled with the light module.
Reduced the number of detector parts.
Reduce total copper mass (copper structure w/o screws: 297 → **182 g**)

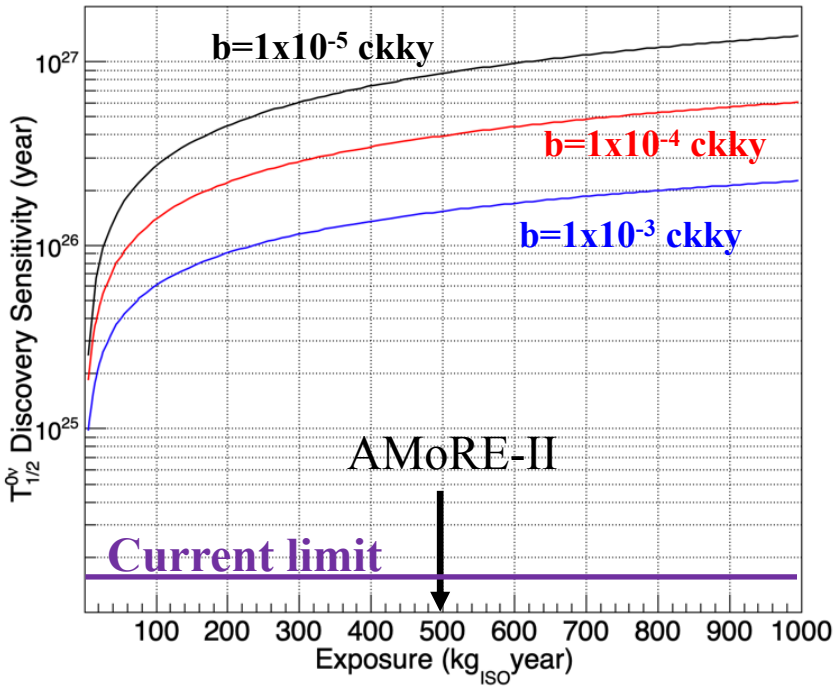
Sensitivity of AMoRE-II

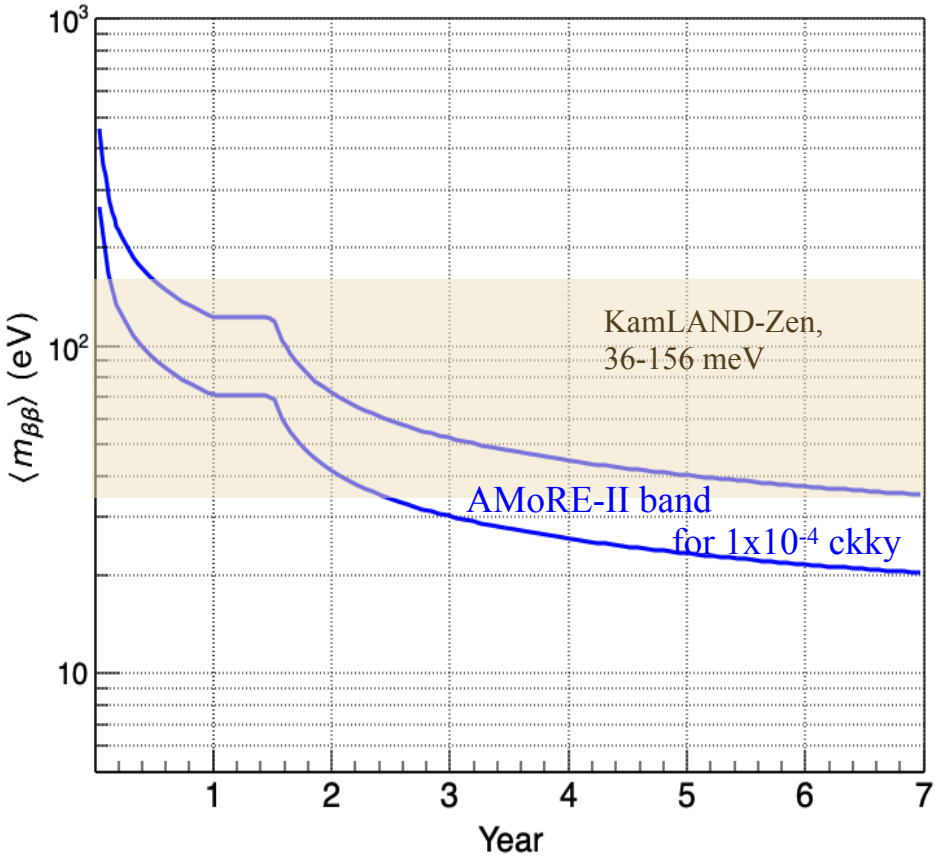
Discovery sensitivity :

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

Background Unit :

ckky=counts/(keV kg year)



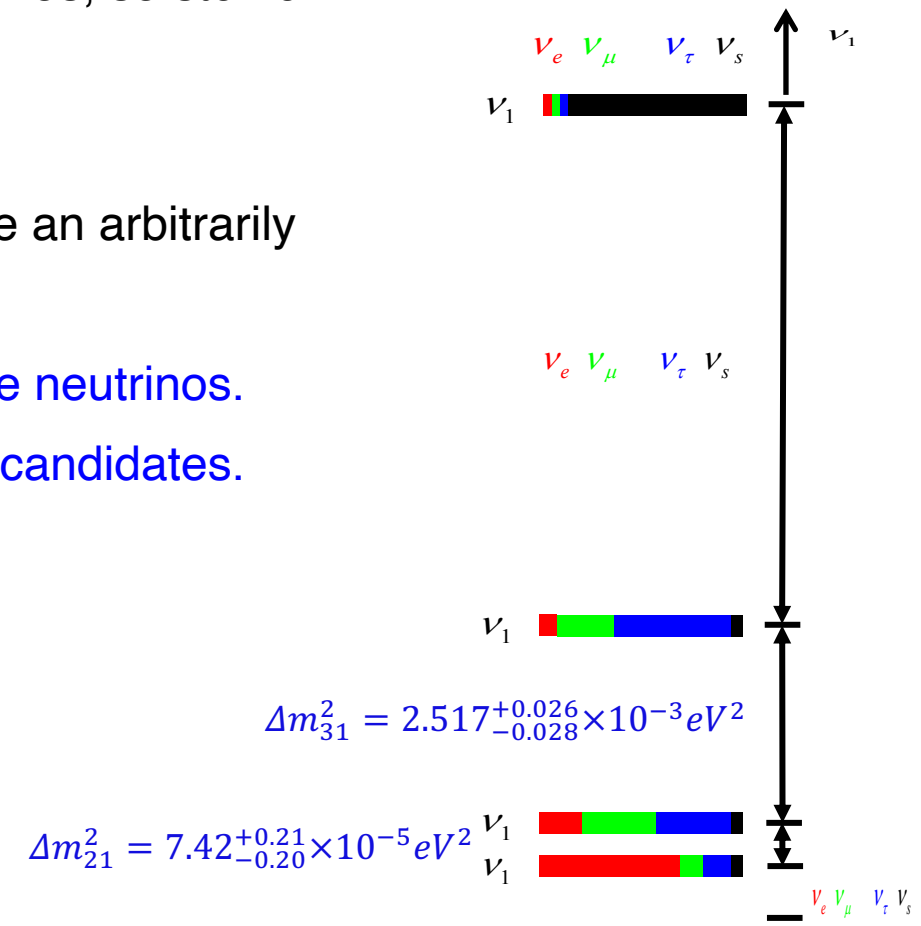


Sterile Neutrinos ?

- Three “Active” neutrinos are left-handed.
- Sterile neutrinos are right-handed neutrinos, so sterile.
  → 4th Flavor
- They can be Majorana particles.
- Being sterile, they can, in principle, have an arbitrarily mass.
- Sterile neutrinos can oscillate with active neutrinos.
- Heavy sterile neutrinos are dark matter candidates.

$\nu_e, \nu_\mu, \nu_\tau.$ → ν_s → ν_e, ν_μ, ν_τ

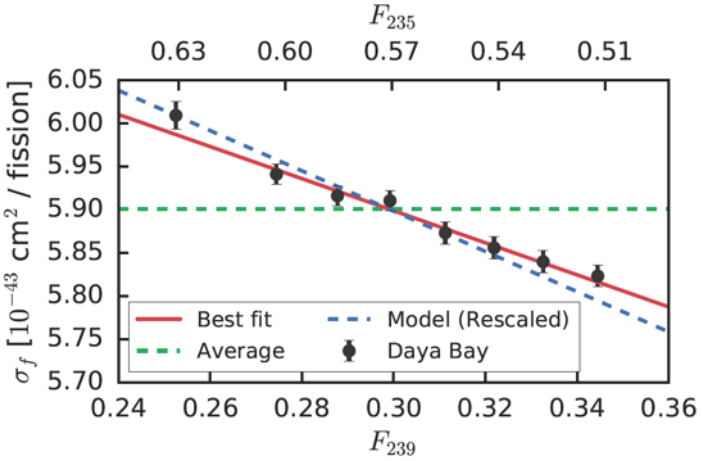
Disapperance Apperance



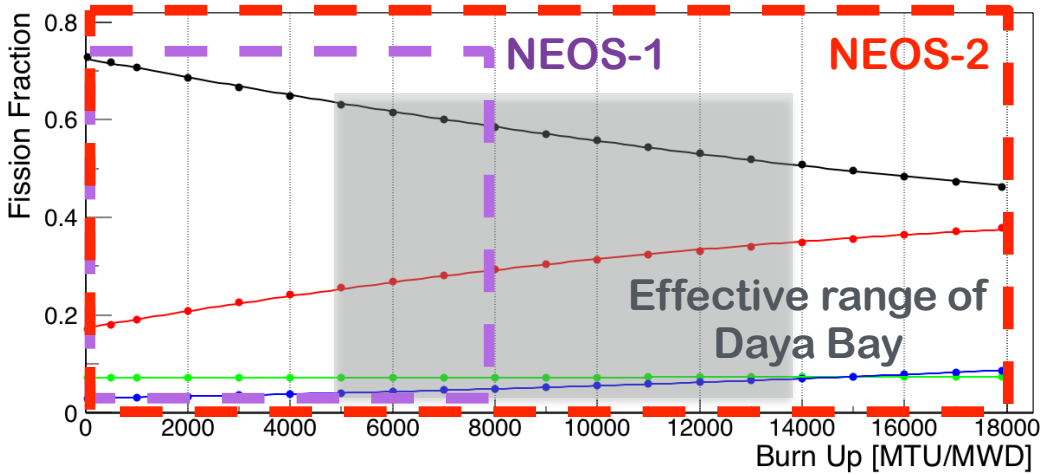
NEOS projects

Yoomin Oh

- NEOS-II covered whole burn-up cycle (1.5 years data) compared to NEOS (0.5 year data).
- PI : Yoomin Oh & Sunny Seo (CUP, IBS)

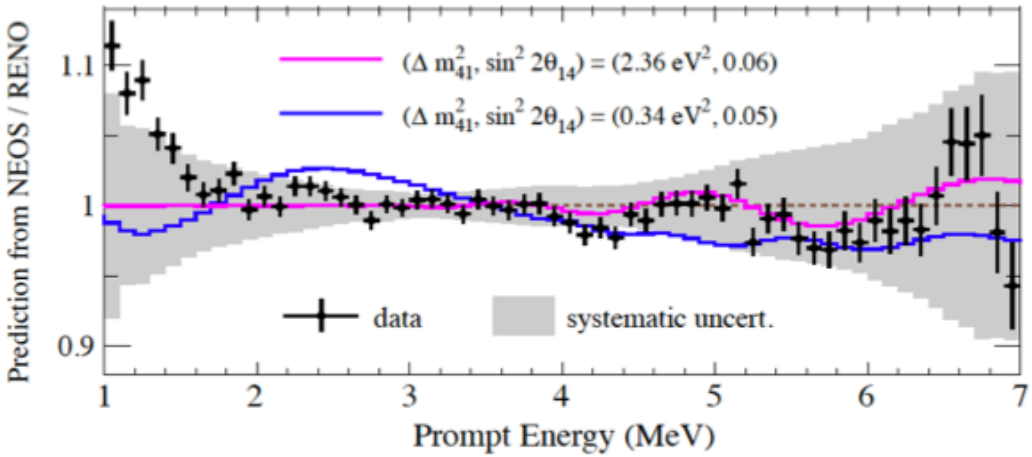


An et al., PRL 118, 251801 (2017)



RENO opened unfolded spectra.
Atif et al., arXiv:2011.00896

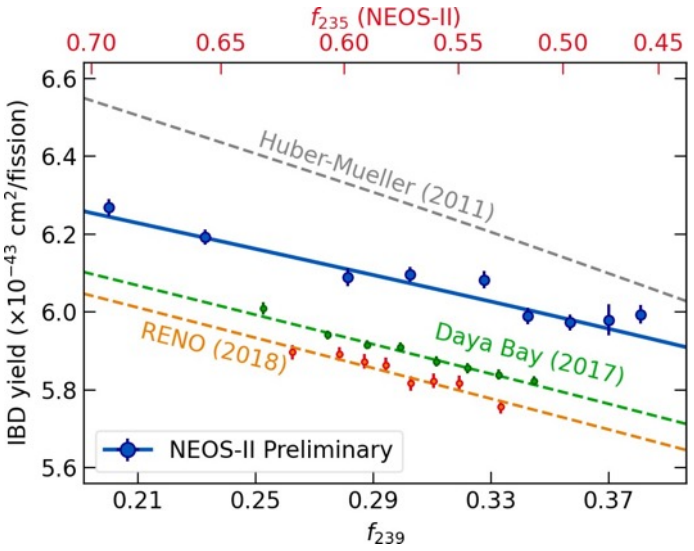
NEOS compared with RENO.

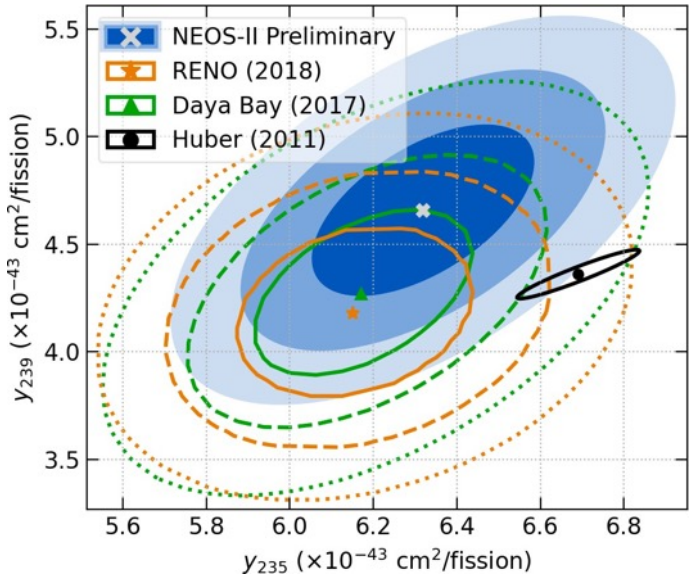


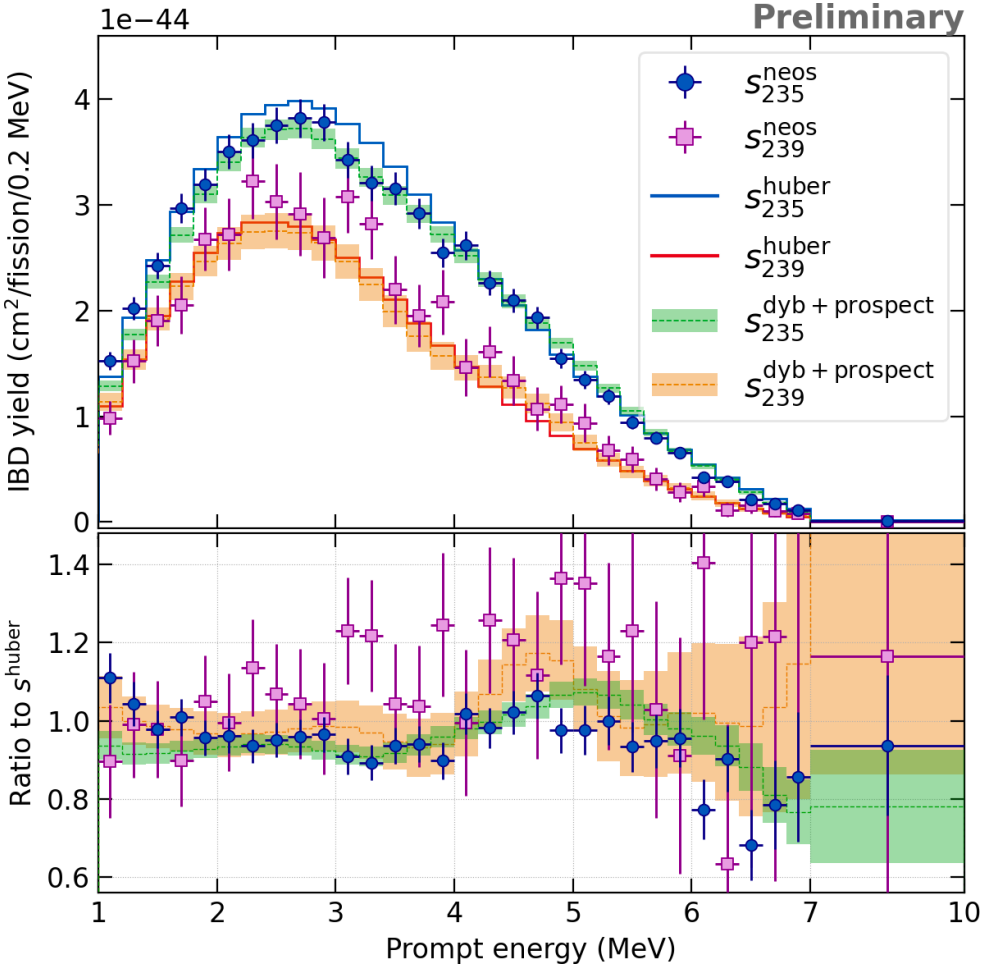
NEOS-II preliminary result

Yoomin Oh

Jinyu Kim @ v-2022

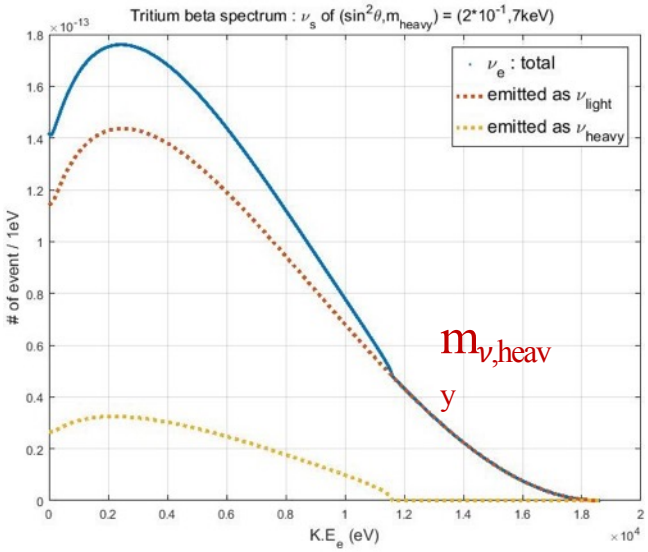




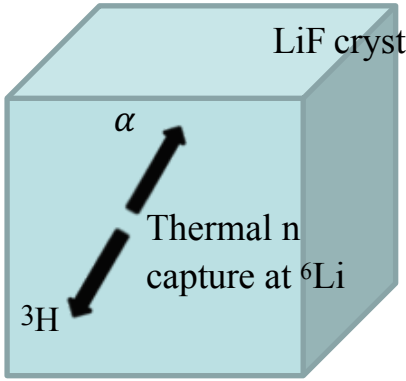


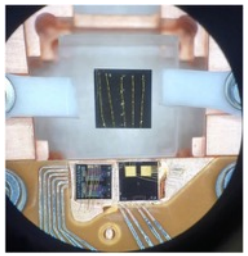
~keV mass sterile neutrino search

Yong-Hamb Kim



For $\sin^2\theta = 0.2$, $m_{\nu,heavy} = 7$ keV

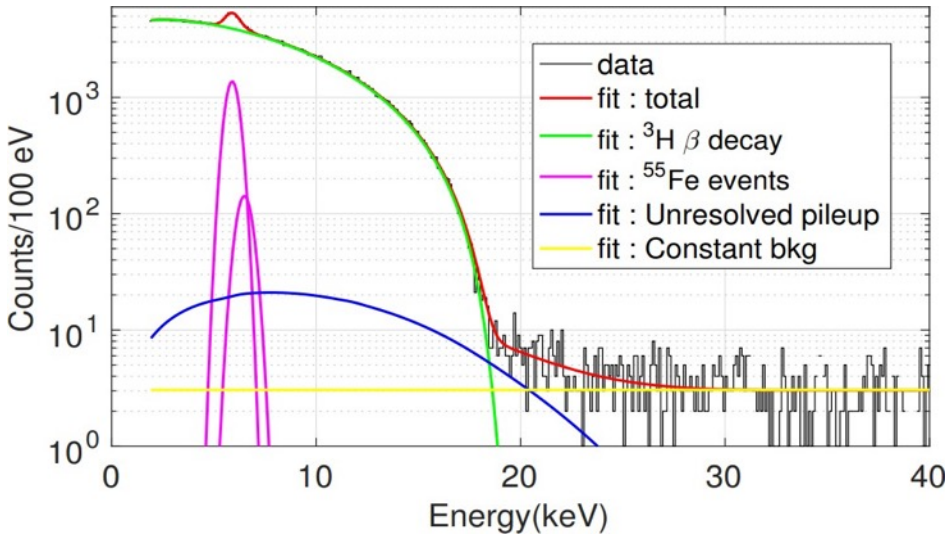


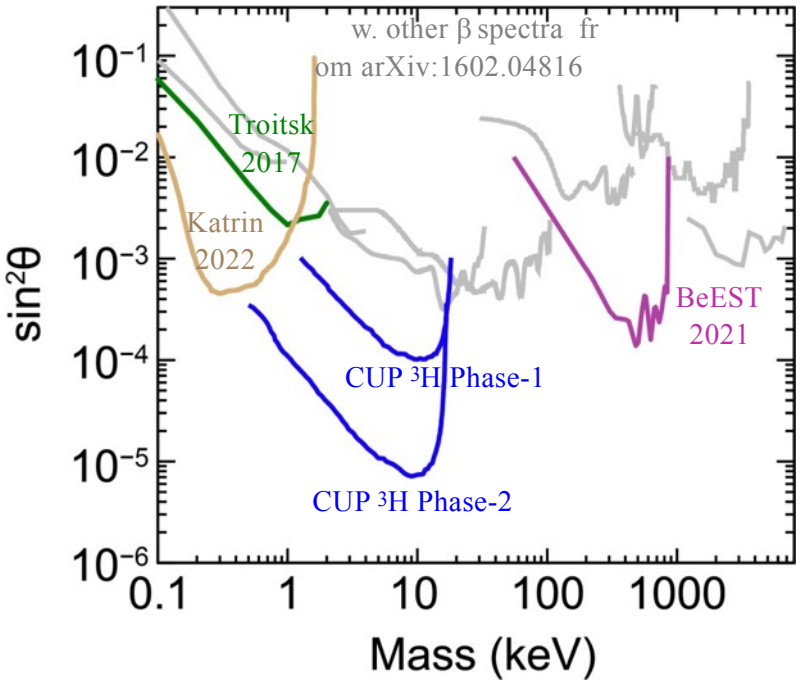


Sensitivities:

Phase 1 : 3 detectors × 40 Bq × 10 month

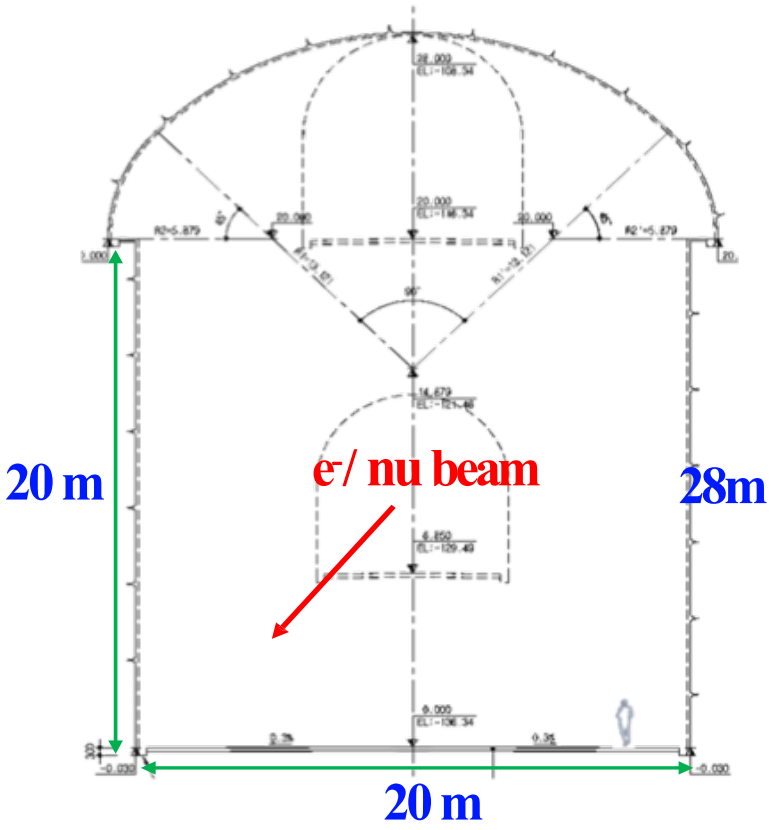
Phase 2 : 100 detectors × 100 Bq × 3 years

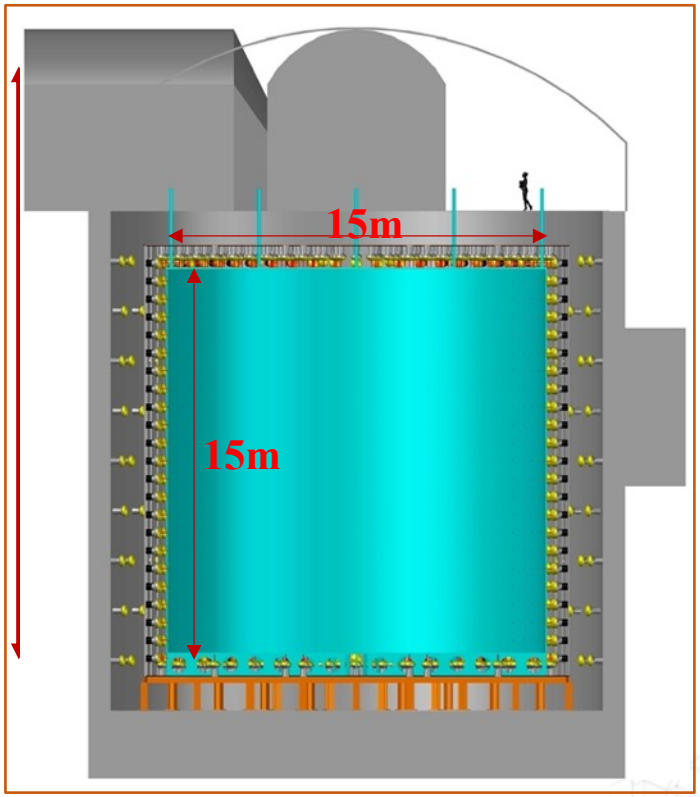


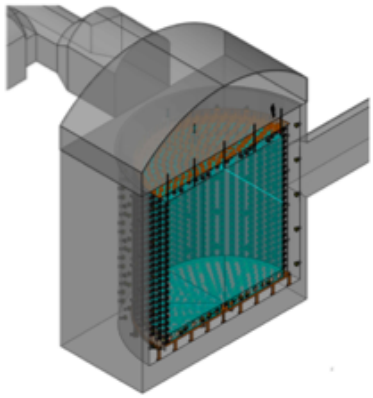


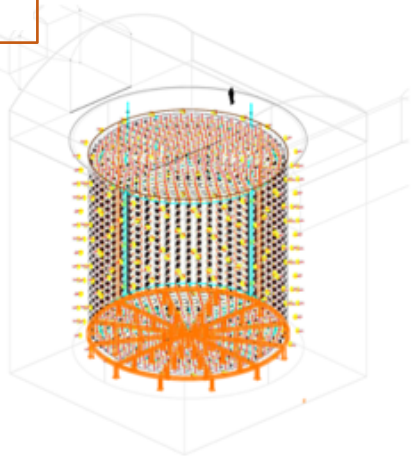
Liquid Scintillator Counter (LSC) @ Yemilab

Sunny Seo







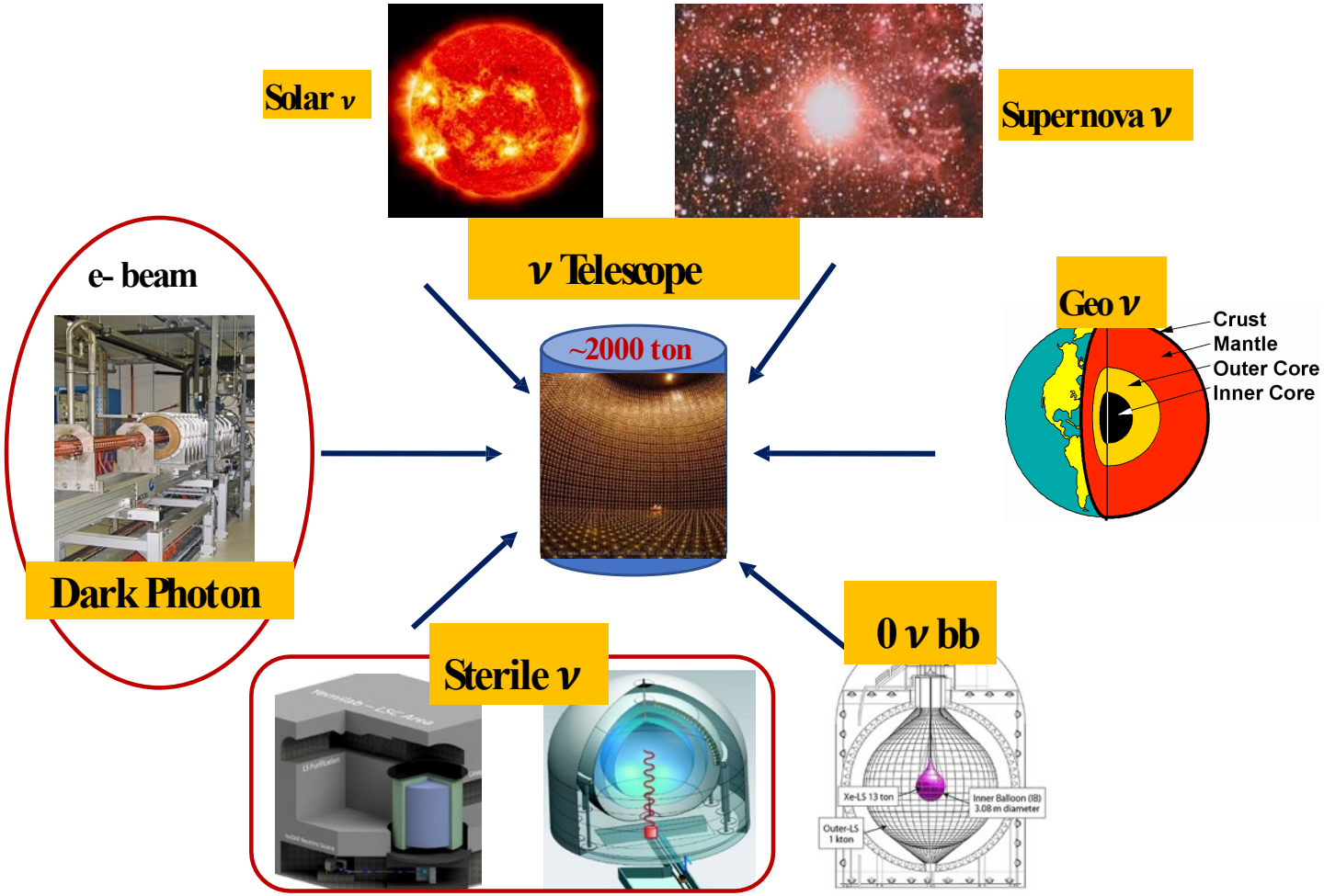


Target Acrylic tank : **2.26 kton**
Buffer SUS tank: 1.14 kton
Veto Concrete tank : 2.41 kton

- 20” PMTs coverage :
  - 3000 PMTs (49%), 4000 PMTs (65%)

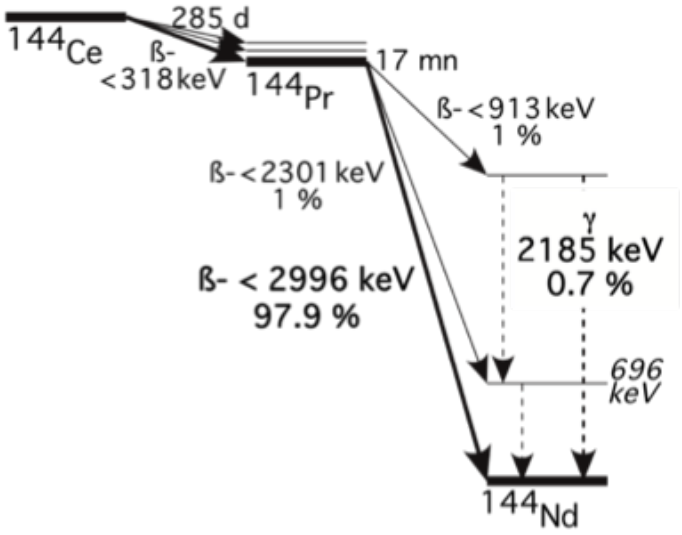
Broad Physics Program with LSC

Sunny Seo

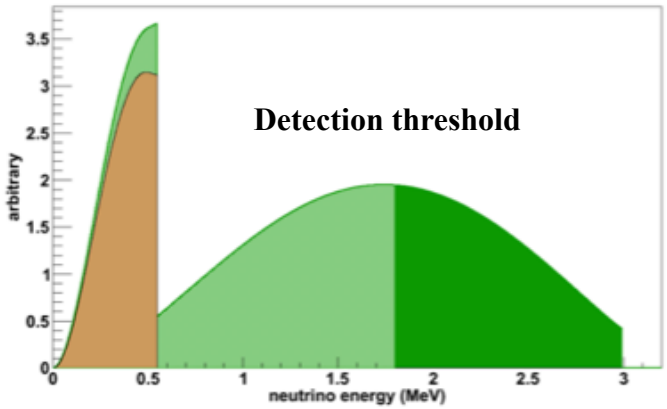


Source @ Yemilab

Marco Oallavicini

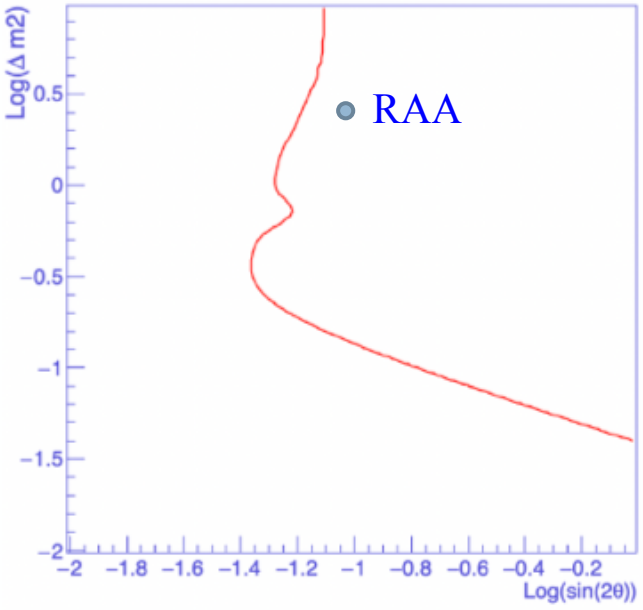


SOX original

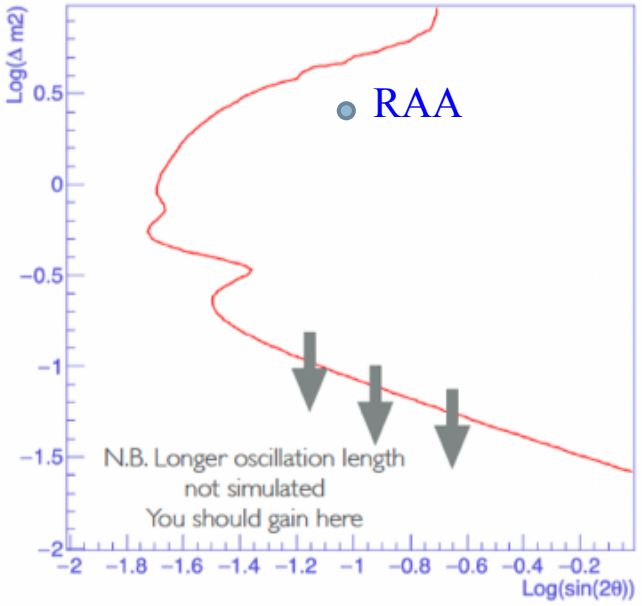


Yemilab

- Min. 4m distance



Ce-144 100 kCi



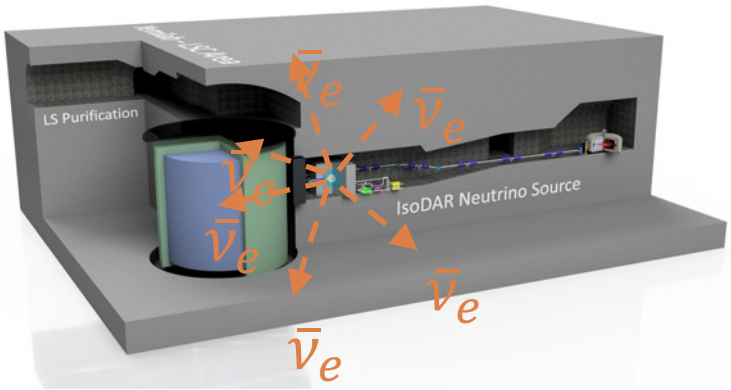
Ce-144 100 kCi

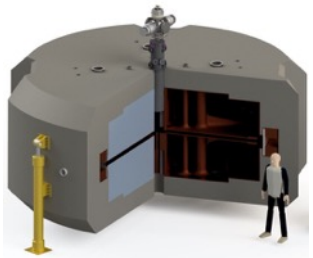
IsoDAR @ Yemilab

Janet Conrad

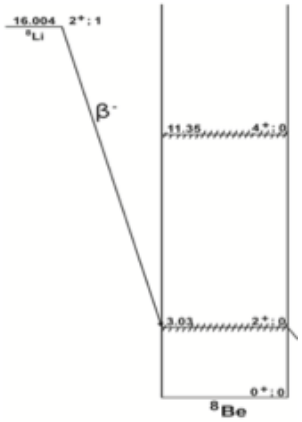
arXiv:2110.10635 : "IsoDAR@Yemilab"

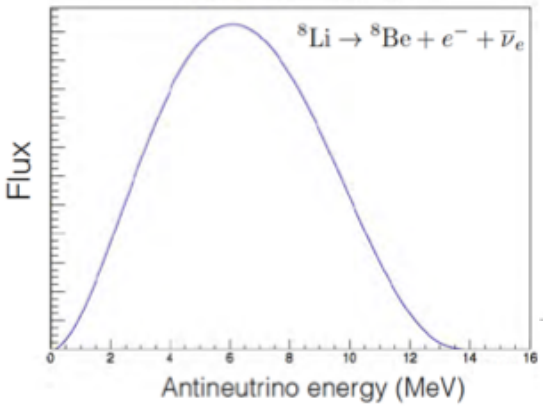
IsoDAR uses ^{8}Li Isotope Decay-at-rest

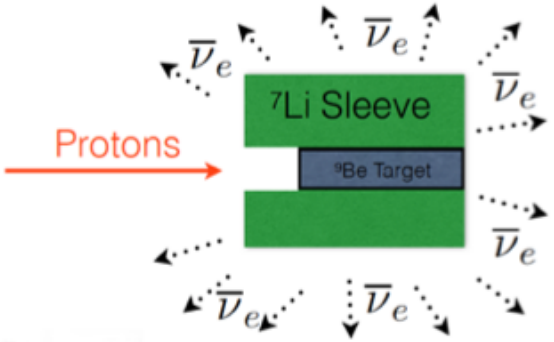




New J.Phys. 24 (2022) 2, 023038, htt ps://arxiv.org/abs/2103.09352







$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$

$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$

$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$

$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \bar{\nu}_e$

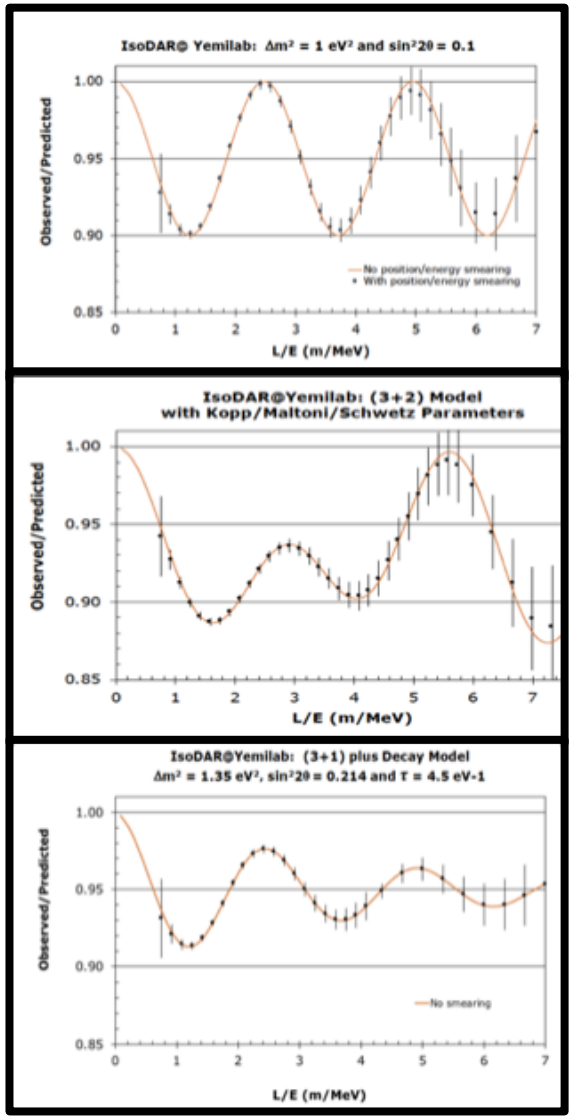
2M IBD events in 5 years.
~ 1000 events/day

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

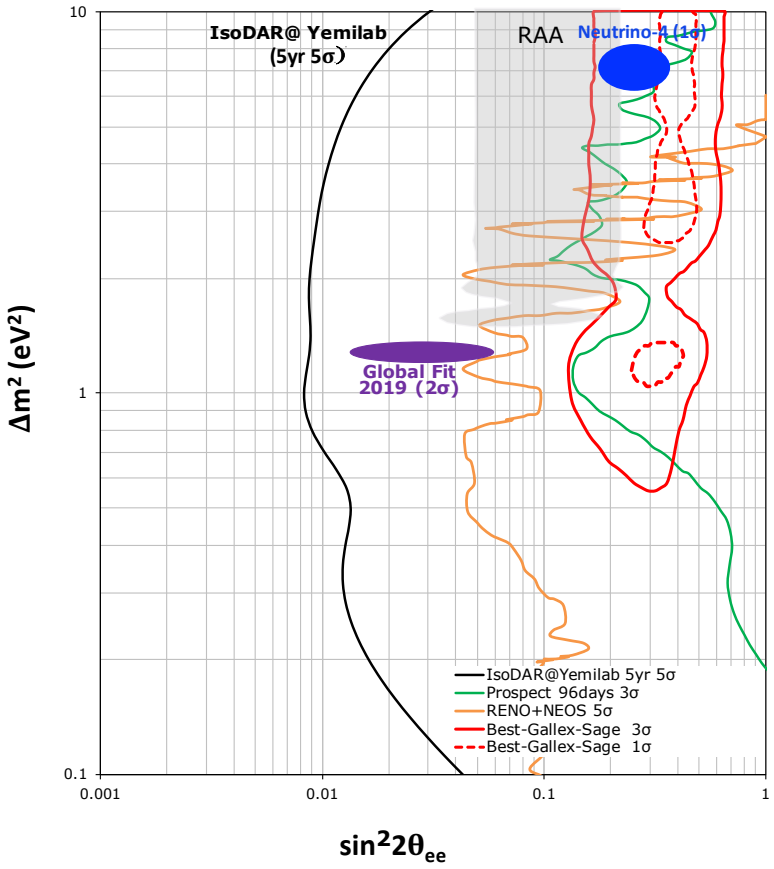
Expected results.

Janet Conrad

arXiv:2111.09480 : "Neutrino Physics Opportunities with the IsoDAR Source at Yemilab"



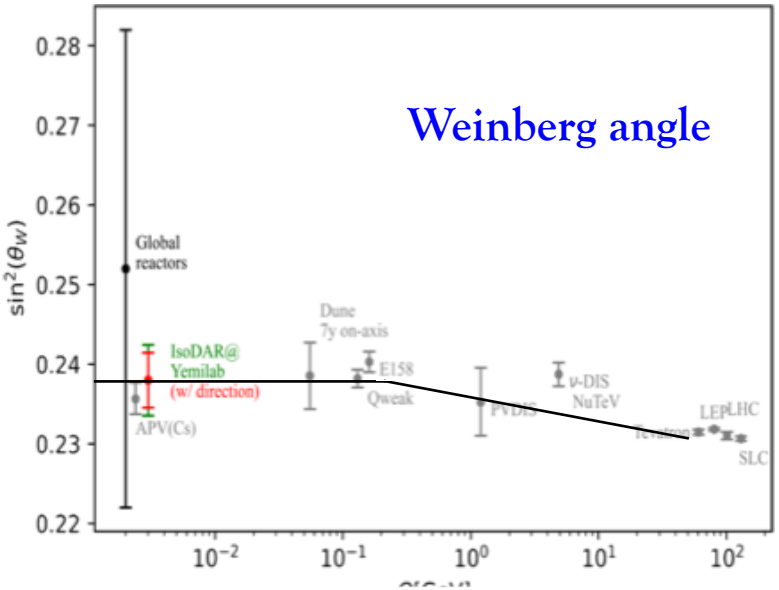
- $\bar{\nu}_e p \rightarrow e^+ n$
- Well known energy spectra and cross section unlikely with other experiments; reactor neutrinos, ~GeV neutrino-nuclear cross section, neutrino-nucleus CC interaction etc.

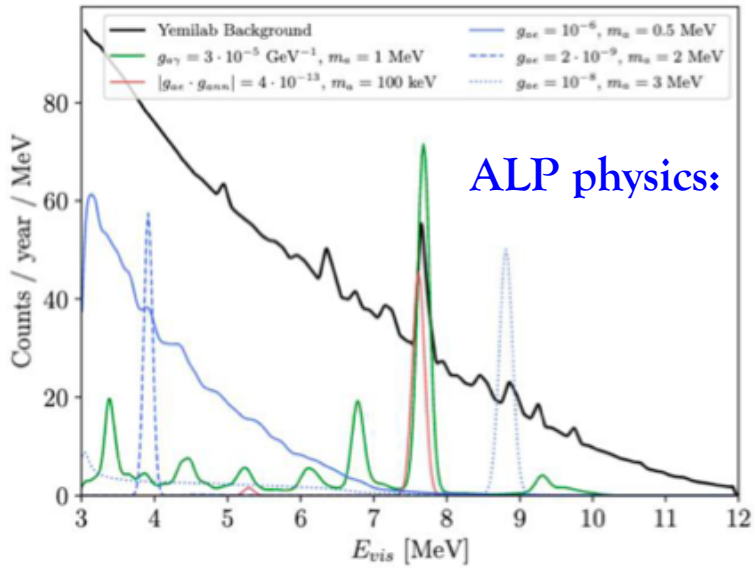


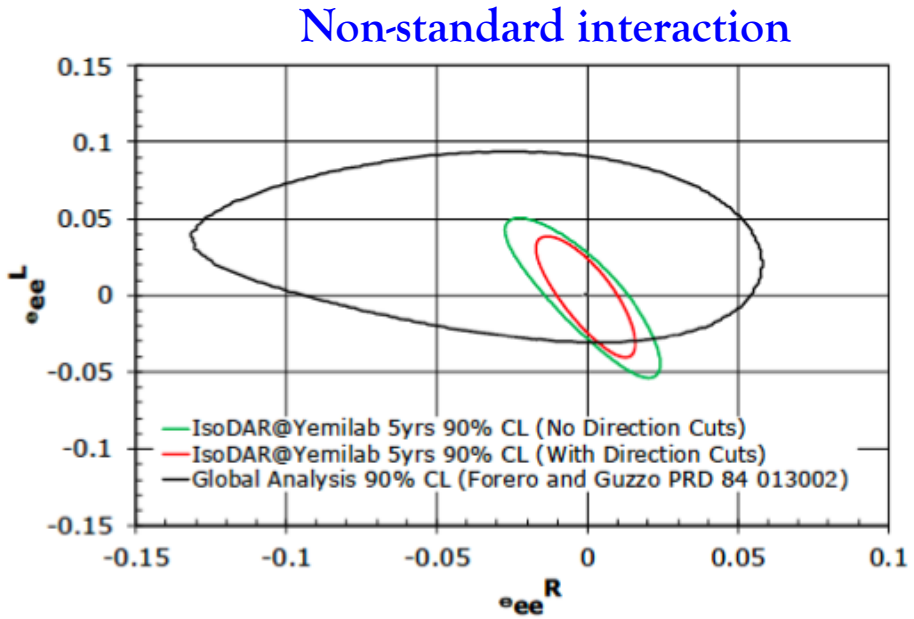
Other physics

Janet Conrad

arXiv:2111.09480 : "Neutrino Physics Opportunities with the IsoDAR Source at Yemilab"







Standard Model:

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{2G_F^2 m_e}{\pi}\left[\bar{g}_L^2 + \bar{g}_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - \bar{g}_L\bar{g}_R\frac{m_e T}{E_\nu^2}\right],$$

NSI's alter the Standard Model couplings:

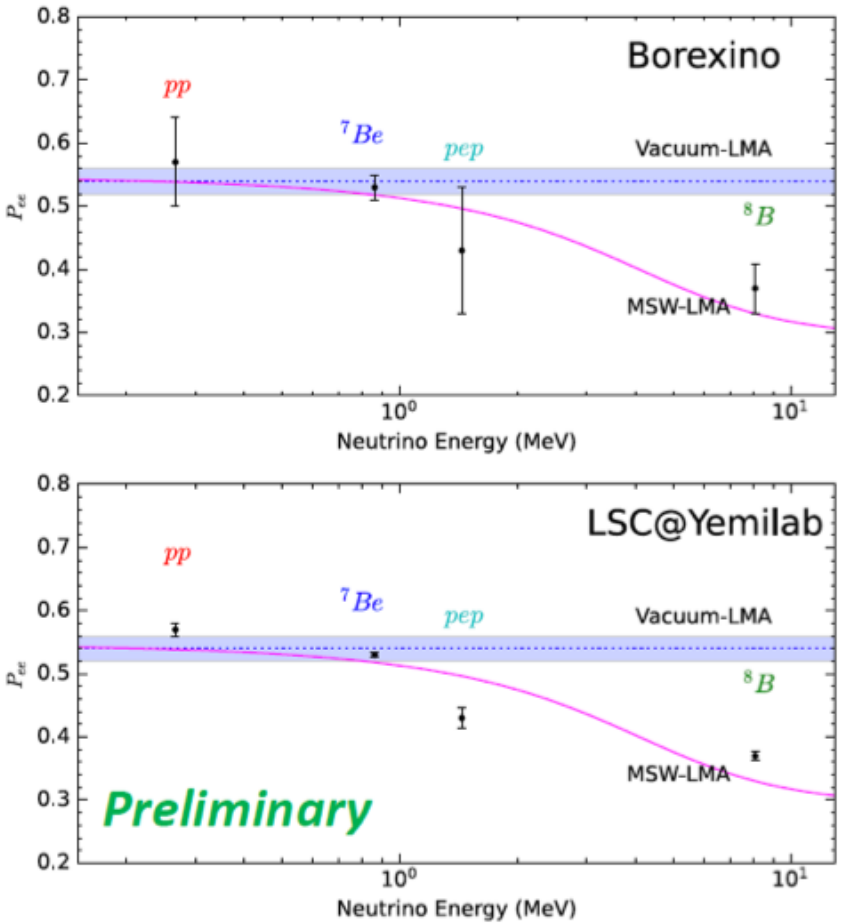
$$\bar{g}_R \equiv g_R^e + \varepsilon_{ee}^{eR}, \qquad \bar{g}_L \equiv 1 + g_L^e + \varepsilon_{ee}^{eL}.$$

$$\sigma(\varepsilon_{ee}^{eR}, \varepsilon_{ee}^{eL}) = \frac{2m_e G_F^2 E_\nu}{\pi}\left(\bar{g}_L^2 + \frac{1}{3}\bar{g}_R^2\right).$$

Solar Neutrinos

Sunny Seo

- Borexino data: **2007(2008) – 2016** @LNGS
- 300 ton LS (~2200 8” PMTs, ~6% @1MeV)
- Very low radioactive BKG



5 year operation @Yemilab
2.26 kton LS
Only satistical errors are counted.

arXiv:2203.01147 “Slow-Fluor Scintillator for Low Energy Solar Neutrinos and Neutrinoless Double Beta Decay”

Slow scintillator for background rejection.

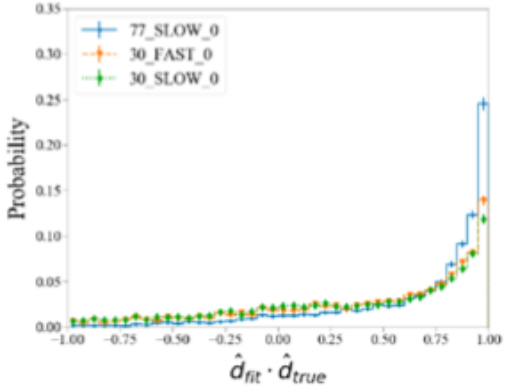


FIG. 6: Vertex (x-projection) and direction resolution of 1.25 MeV electrons for various configurations without bis-MSB.

Summary

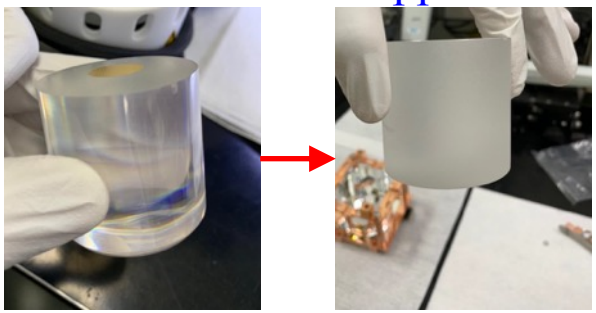
- COSINE-100, 200 experiments will close in the DAMA conundrum.
- COSINE-200 and low mass DM search R&D show promising capabilities.
- AMoRE experiment aims to be sensitive ~ 5×10^{26} years range for ^{100}Mo isotope and will be installed by end of 2024 in full scale.
- O(eV) Sterile neutrino searches are continuing with contradictory results. NEOS-II data for sterile neutrino and fuel decomposition is coming soon.
- LSC cavern will be ready soon and LSC physics including IsoDAR@Yemilab show interesting possibilities.
- We welcome researchers who utilize Yemilab for basic and applied sciences.

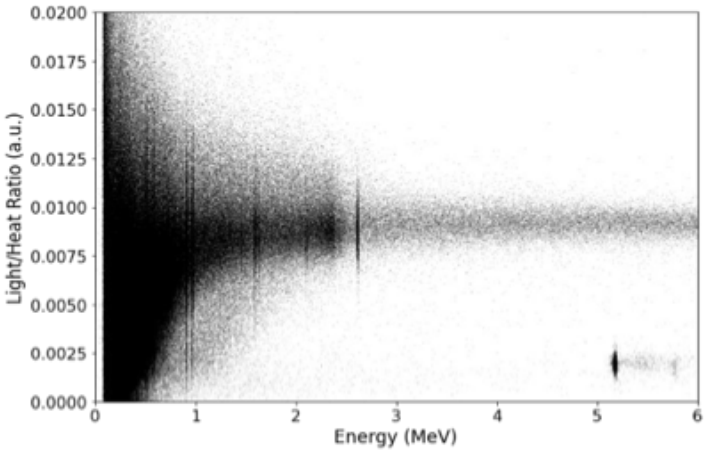
Recent progresses for LMO crystals

- Recently, we improved the detector performance.

(1) Polishing vs lapping(roughening)

Polished surface Lapped surface

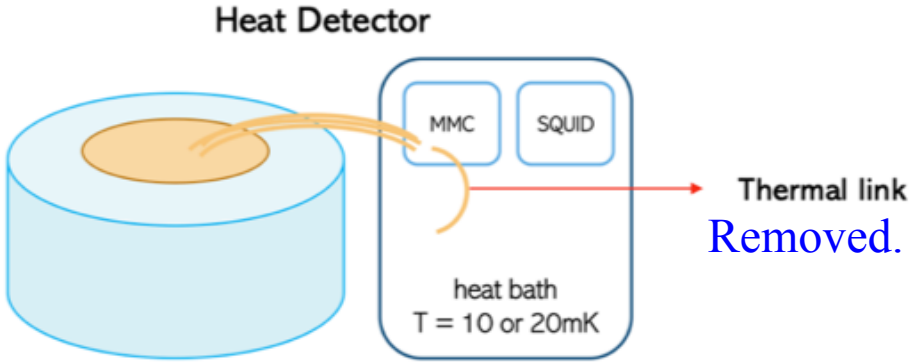


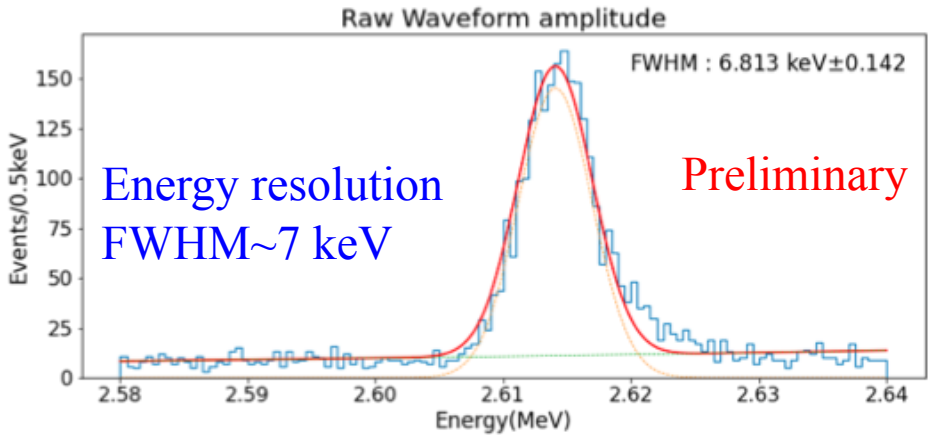


Lapping and thermal link removal :

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

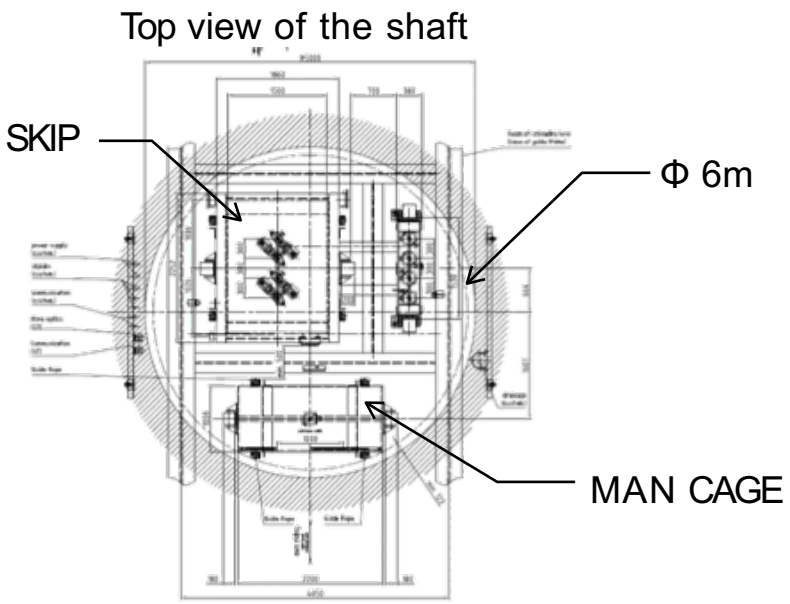
(2) Thermal link

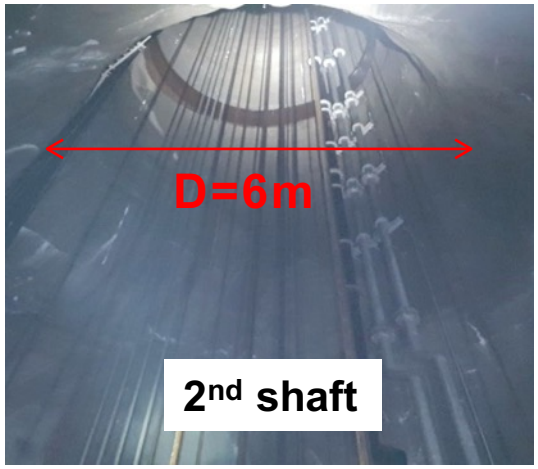




Now, AMoRE's energy resolution is close to CUPID-Mo in the test setup, still keeping the faster rise time.

Man-cage





- 2nd shaft will be main entrance to UL
  SIEMAG Tecberg(Germany) design
- 600 m moving distance
- 4 m/s cage speed → go down 600m in 2.5 minutes
- 1.5 ton payload
- Constructed by Handuk