Dark matter and neutrino experiments at Yemilab

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2022. 12. 12.

Light Dark World International Forum 2022

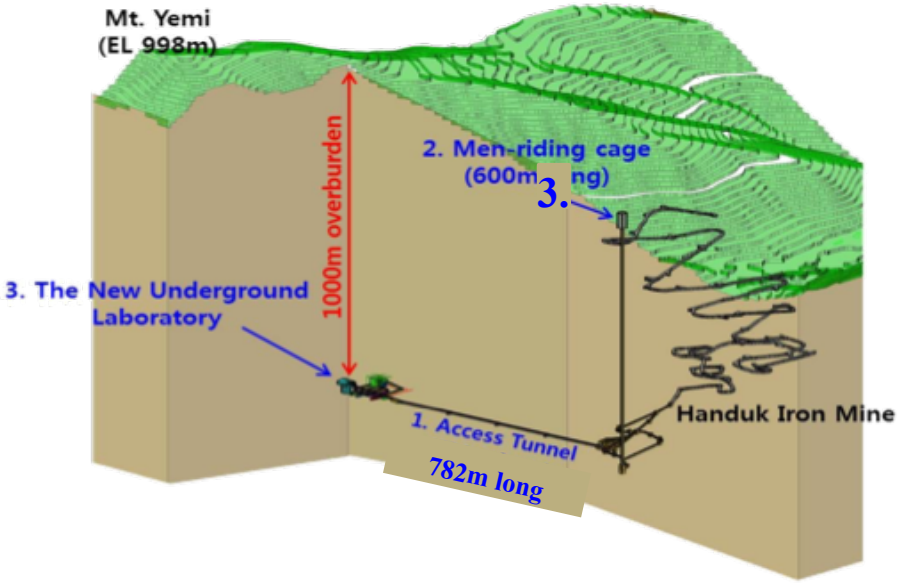
Introduction

- Yemilab - new underground laboratory in Korea.
- Dark Matter
  - COSINE-100
  - COSINE-200
  - Low mass DM
- DBD
  - AMoRE-I
  - AMoRE-II
- LSC
  - IsoDAR
  - Dark boson search
  - Solar Nu

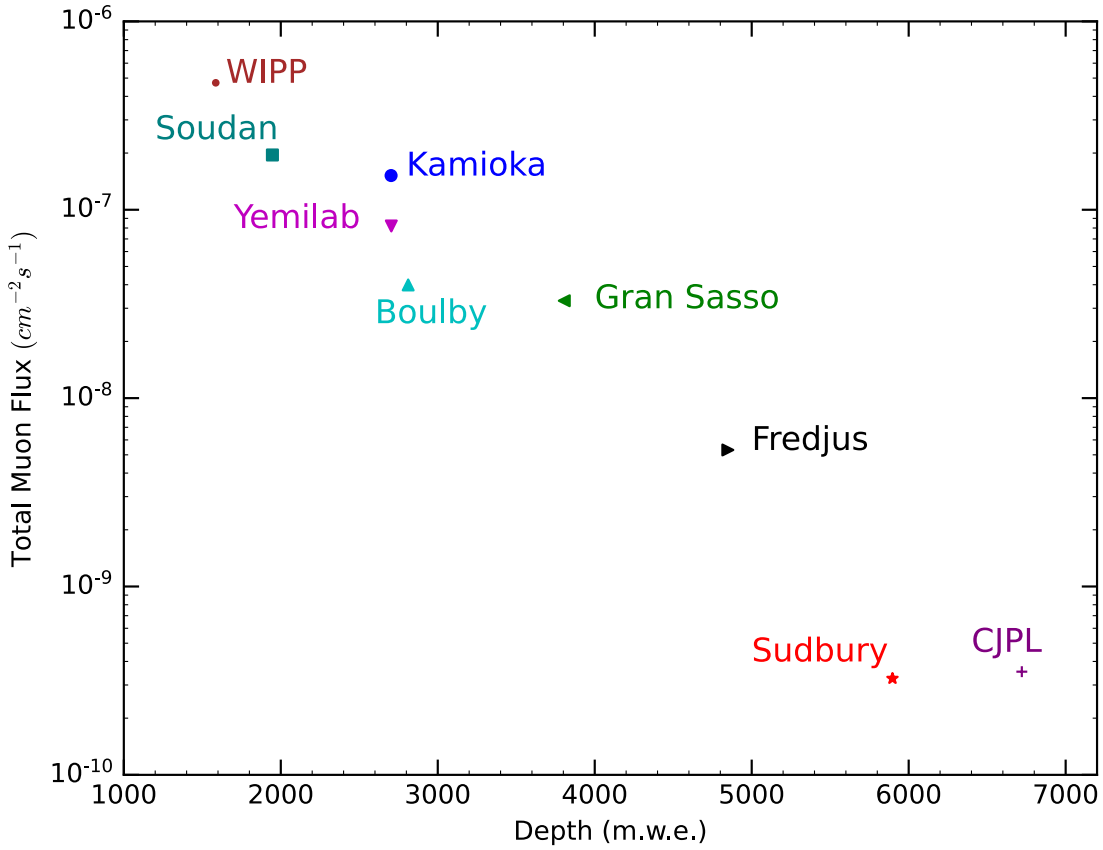
Yemilab for new discoveries.

- Yangyang underground lab (Y2L) is too small to perform larger experiments.
- IBS decided to build a new underground laboratory at Jeonseon area in South Korea.
- Tried to separate the lab from the mine operation as much as possible.
- Two access ways, ramp-way and man-riding elevator are utilized.
- Open to other researchers than IBS.

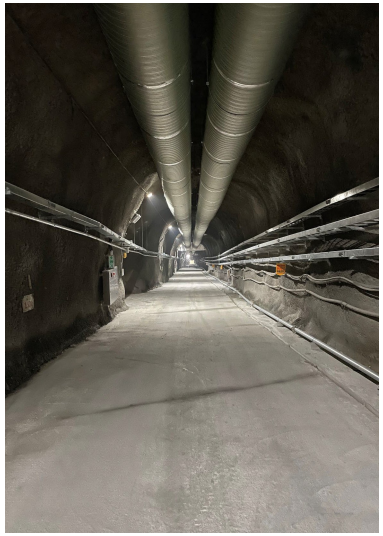
- **1000 meter underground.**
- **Construction cost ~30 M$**
- **2018-2022**



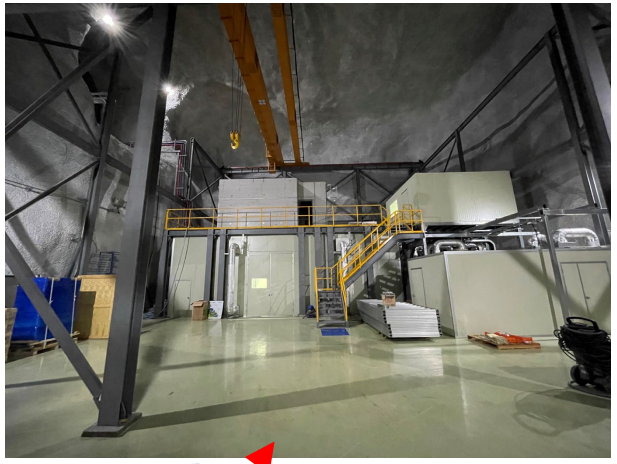
Muon rates


WIPP
Soudan
Kamioka
Yemilab
Boulby
Gran Sasso
Fredjus
Sudbury
CJPL
Total Muon Flux ($cm^{-2}s^{-1}$)
Depth (m.w.e.)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
7000

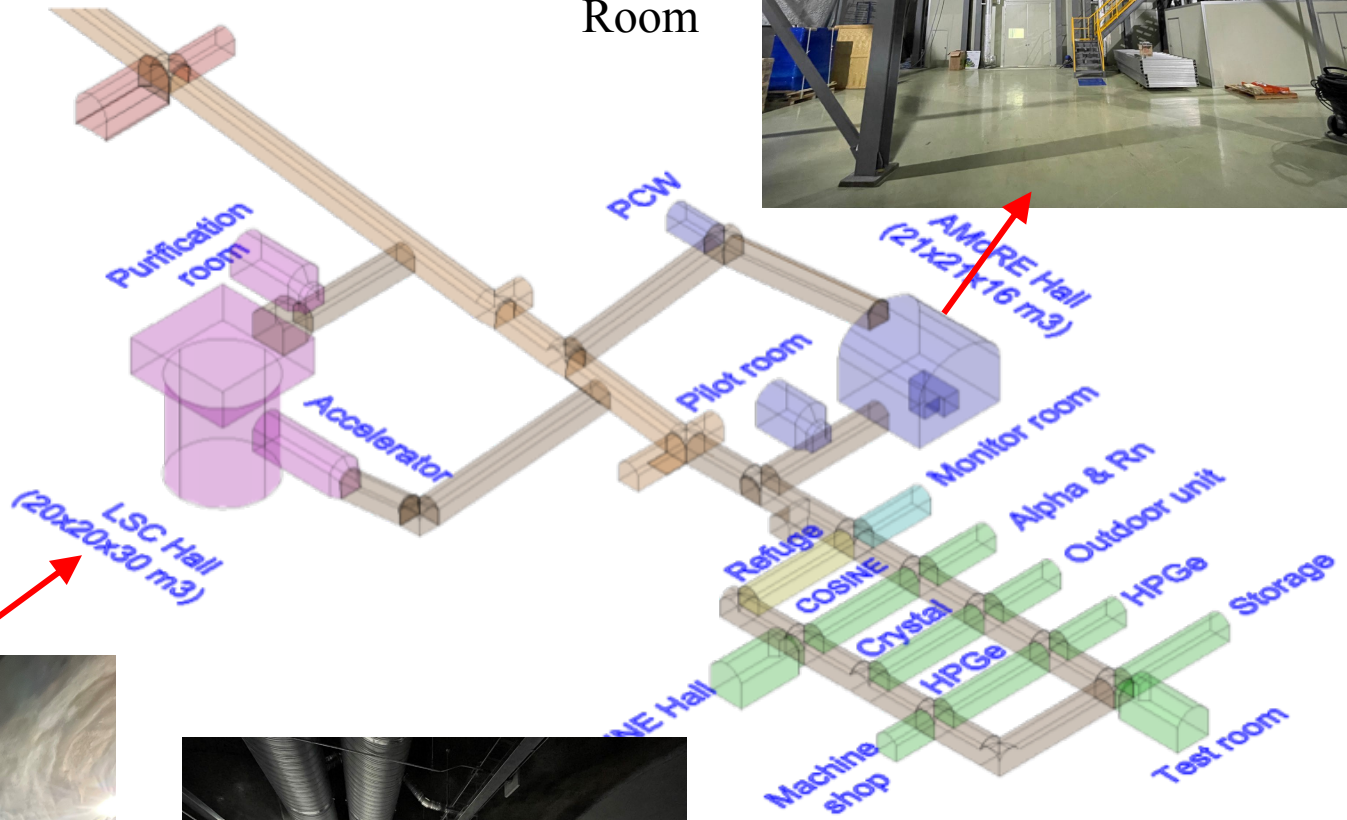
Yemilab halls



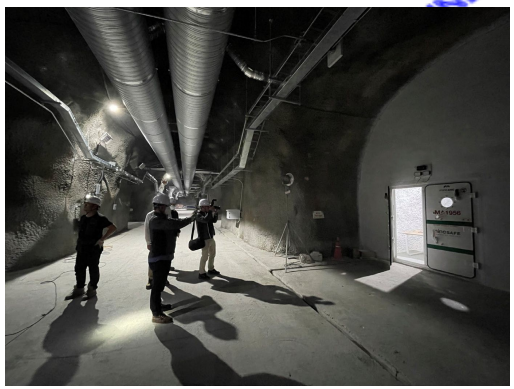
Access Tunnel



AMoRE Room



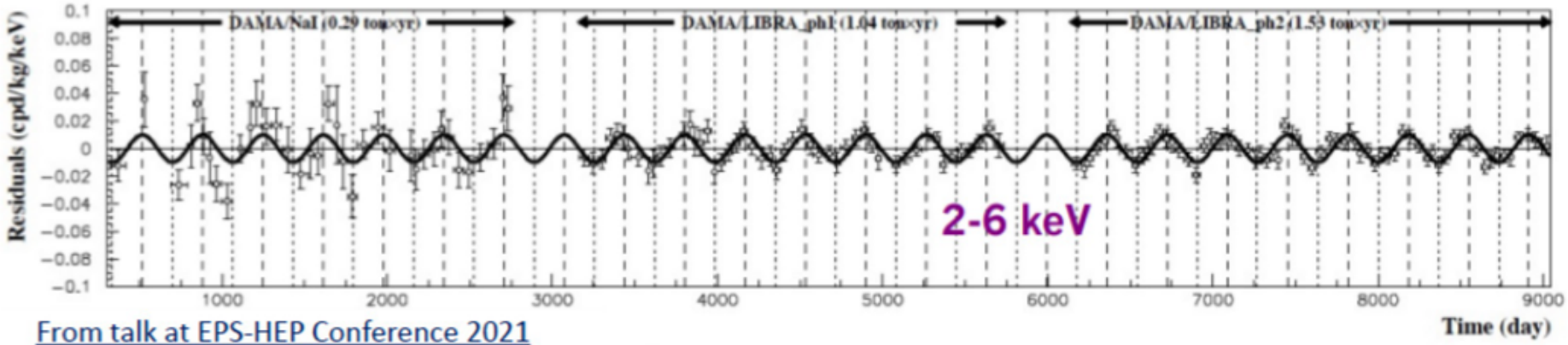
Large Scintillation Counter (LSC)



View at the Refuge

Dark Matter Searches

- DAMA/LIBRA confirmation



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

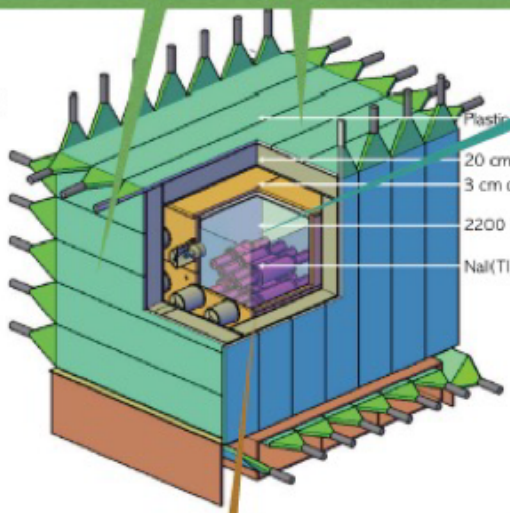
Nucl. Instrum. Meth. A 851 103 (2017)

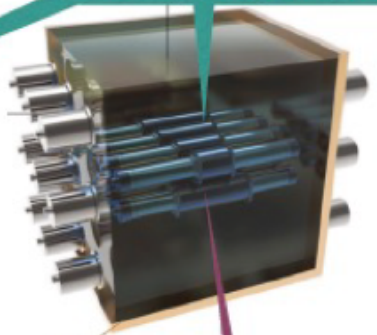
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

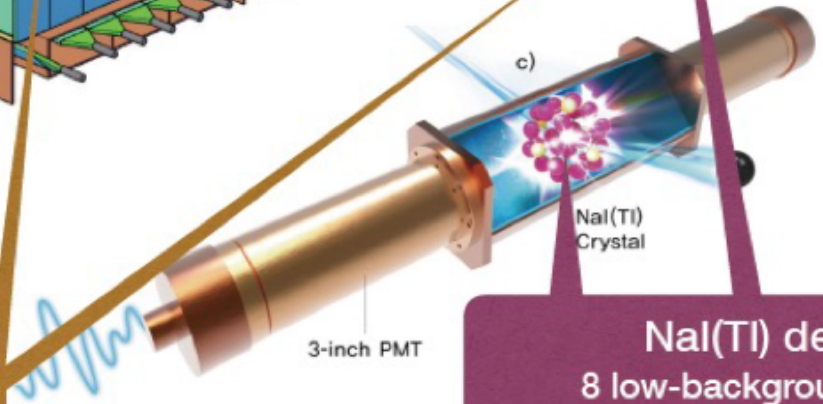
JINST 13 T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

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







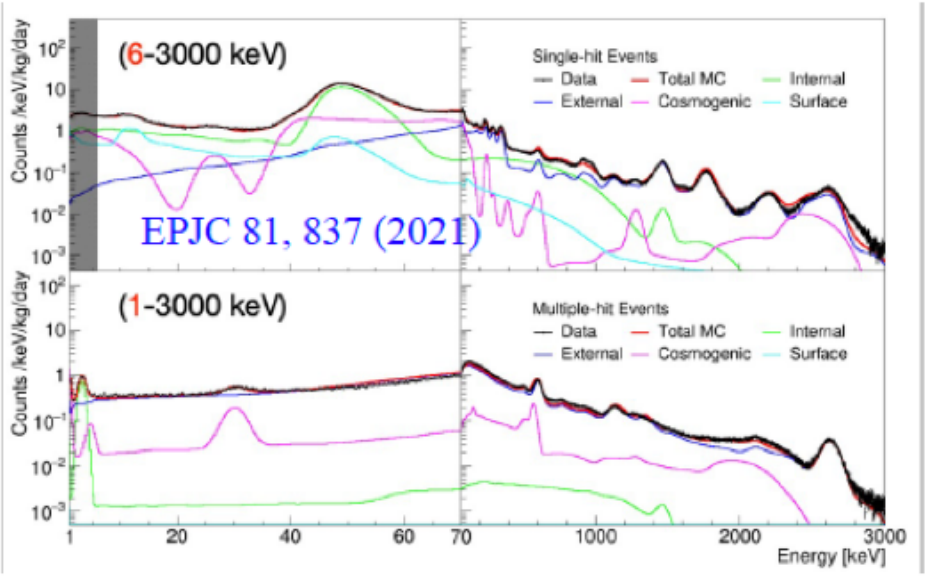
Shields
3-cm thick copper box
20-cm thick lead shielding

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)

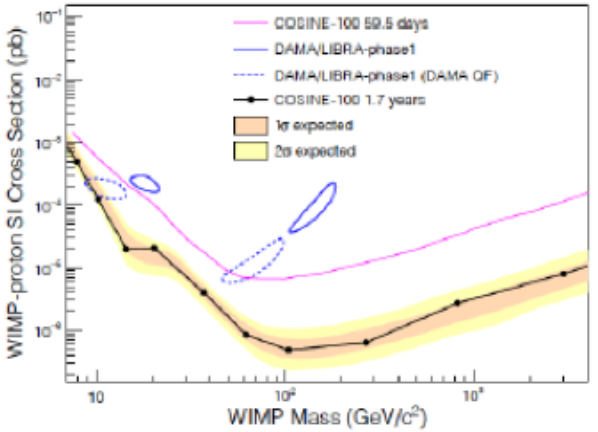
Recent achievements

Background modeling (1keV threshold)



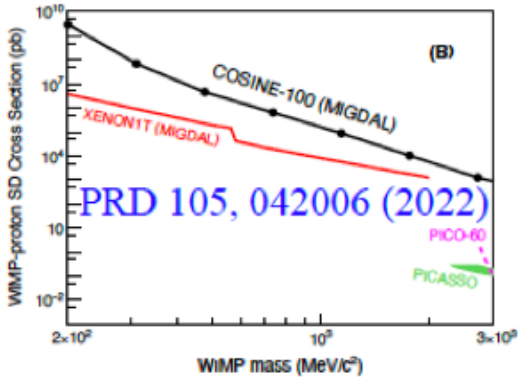
EPJC 81, 837 (2021)

WIMP Search (1.7 years)



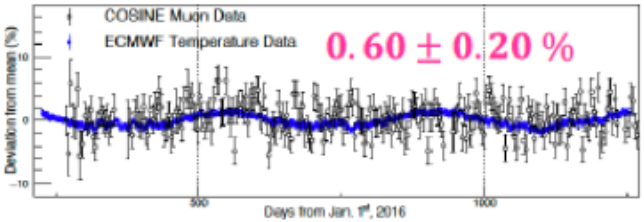
Sci. Adv. 7, eabk2699, (2021)

Low-mass DM with Migdal

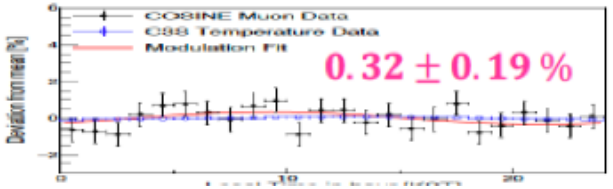


PRD 105, 042006 (2022)

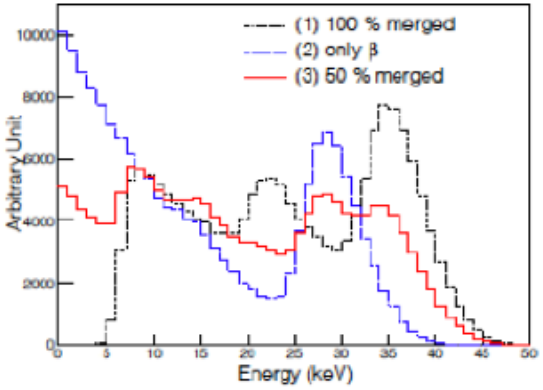
Annual & diurnal modulation of muon



JCAP 02, 013 (2021)



New isomers in ^{228}Ac

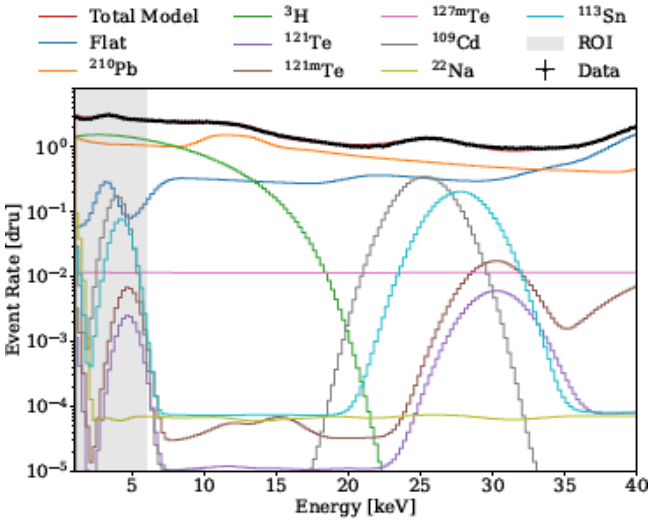


EPJC 81, 746 (2021)

Annual modulation (3 years data)

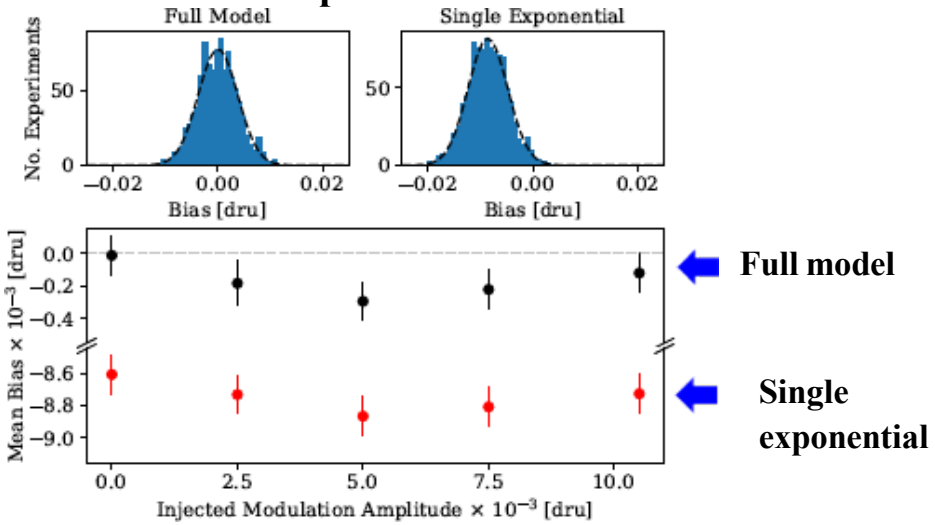
PRD 106, 052005 (2022)

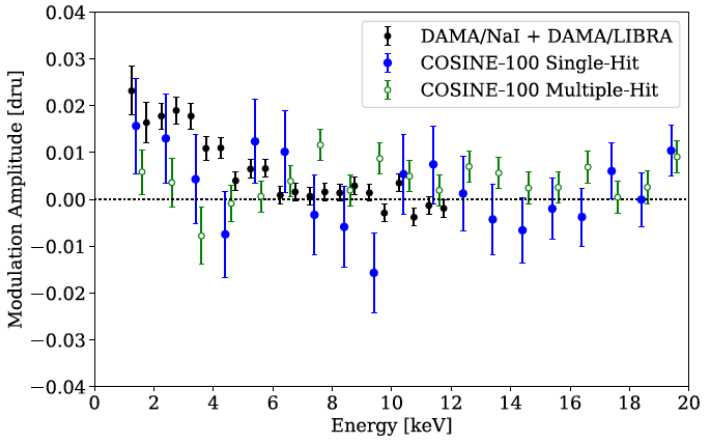
Time dependent background modeling



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

Pseudo experiment





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

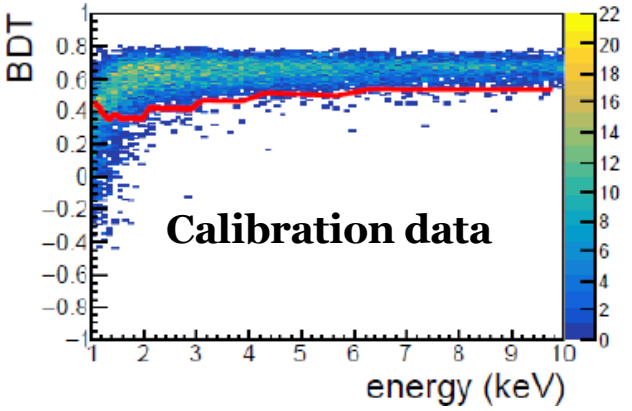
1-6 keV modulation amplitude

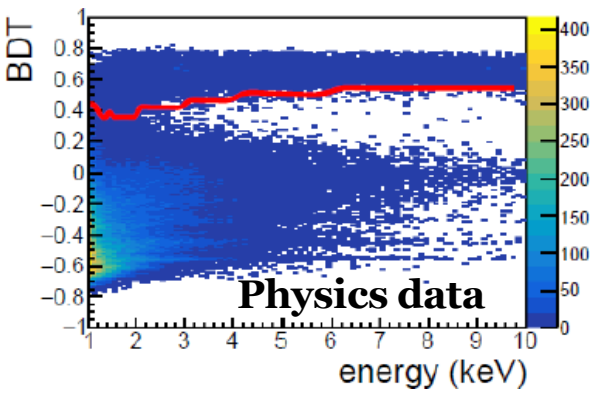
COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

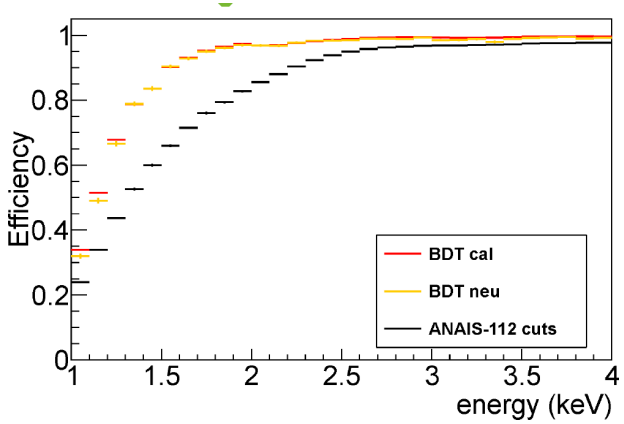
ANAIS-112 (3 years data revisiting)

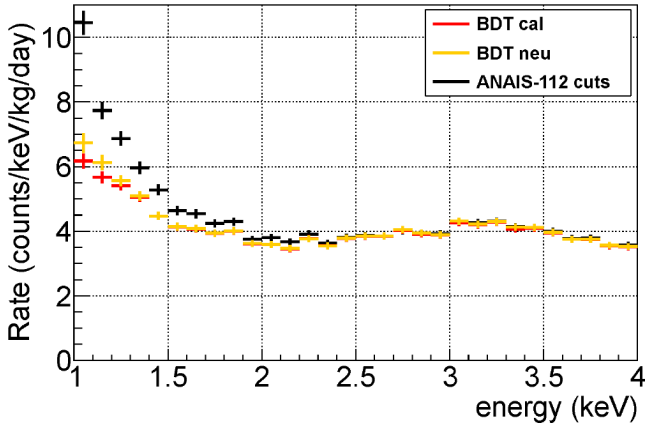
Boosted Decision Tree (BDT)-based machine learning

M.L. Sarsa @ IDM2022

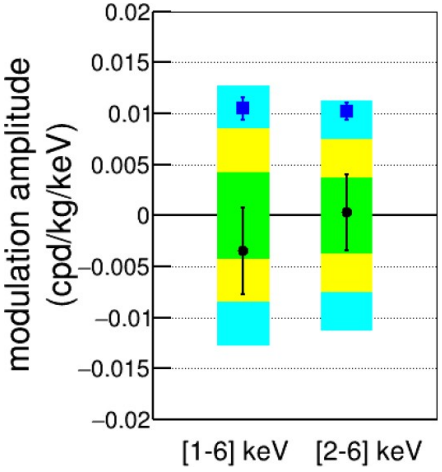




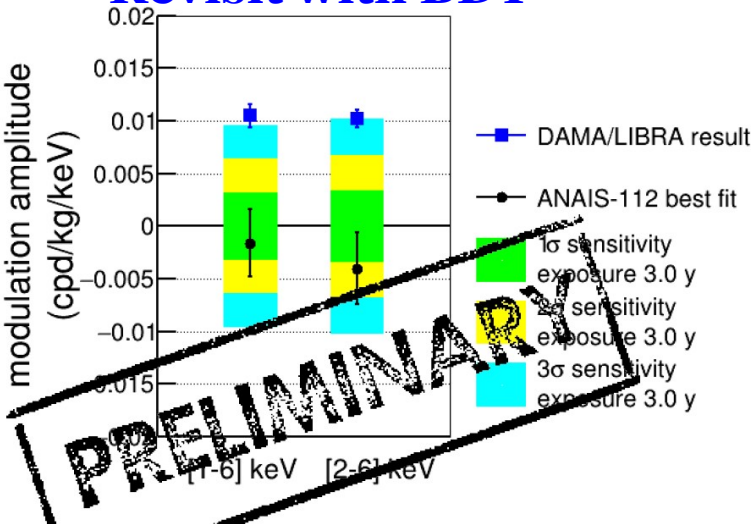




PRD result



Revisit with BDT



Incompatible with DAMA at $3.8\sigma(4.2\sigma)$ in 1-6 (2-6) keV region

NaI crystal development for COSINE-200

Hyunsu Lee

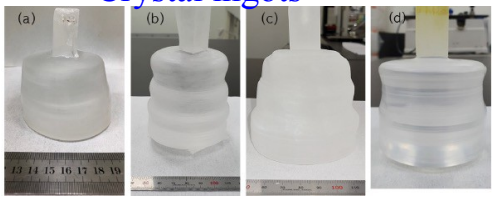
Powder purification performance

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

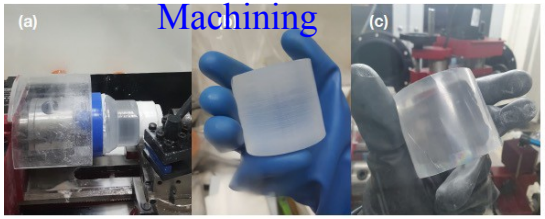
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

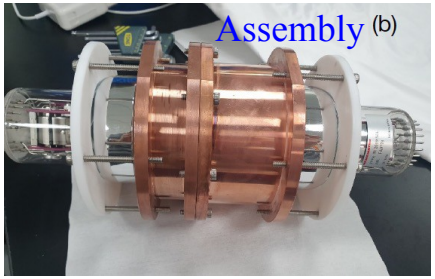
We produced ~ 400 kg low-background NaI powder
(Maximum production rate ~ 100 kg/month)

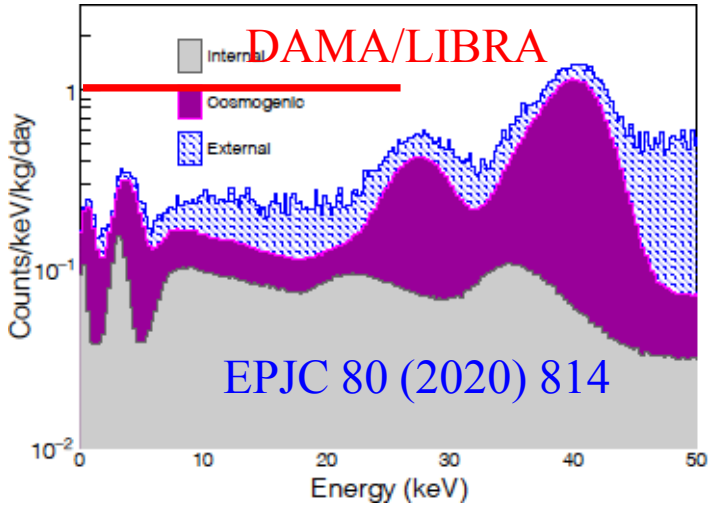
Crystal ingots



Machining



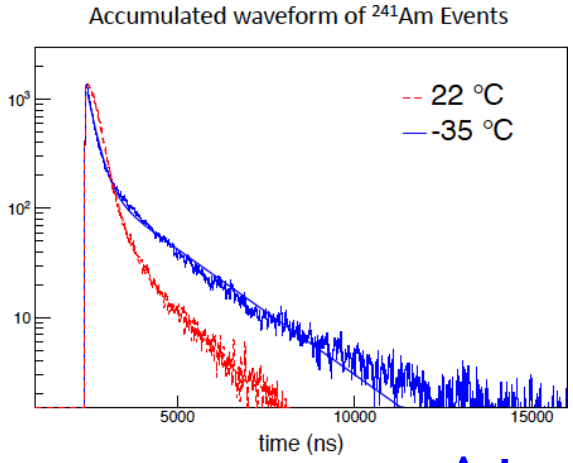




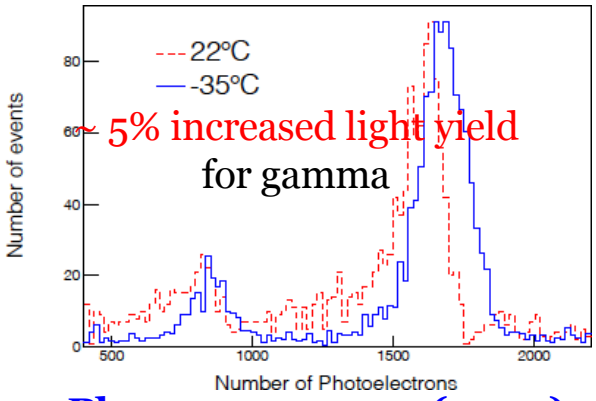
A proof of principle for low background NaI
Large crystal growing is going on

Low temperature (-30°C) response

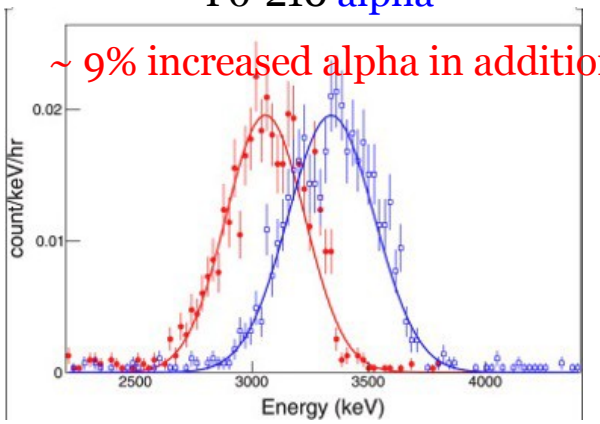
PMT measurement



Am-241 measurement

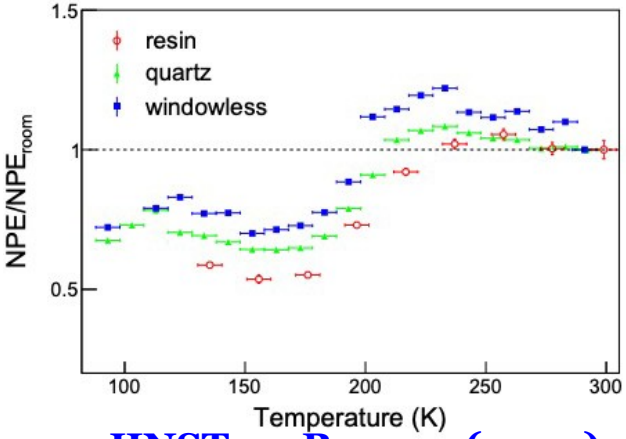


Po-210 alpha



Astropart. Phys. 141, 102709 (2022)

SiPM measurement



JINST 17, P02027 (2022)

~ 5-15% increased light yield at -30°C

COSINE-200 can be operated at -30°C

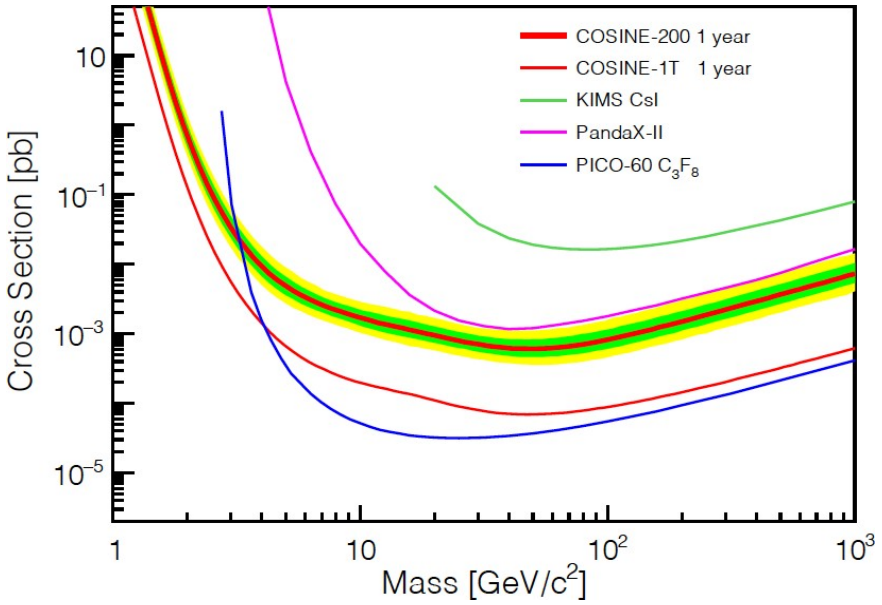
Yemilab facility is under construction

Hyunsu Lee

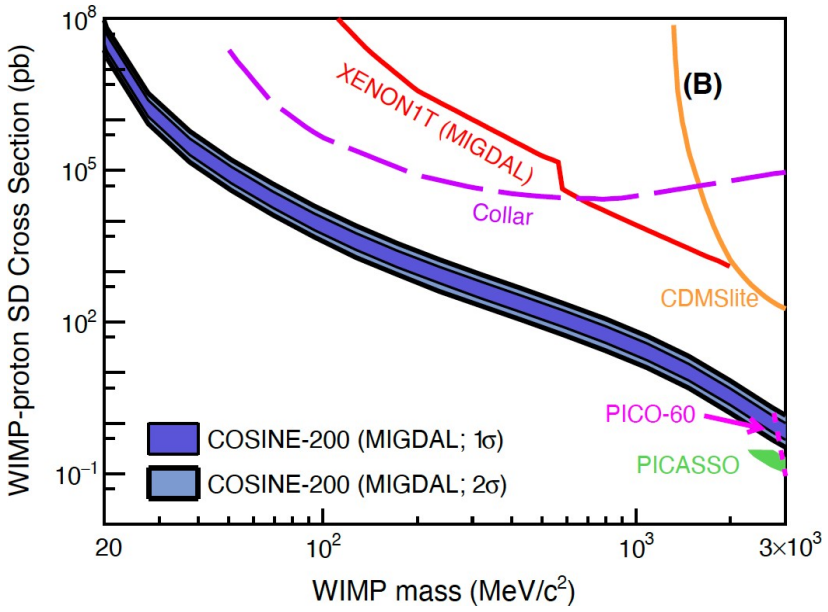
Sensitivites of COSINE-200

- Unambiguous conclusion on the DAMA/LIBRA with modulation data.
- Low mass spin dependent searches with new parameter space exploration.

WIMP-proton spin-dependent



Low mass search with Migdal



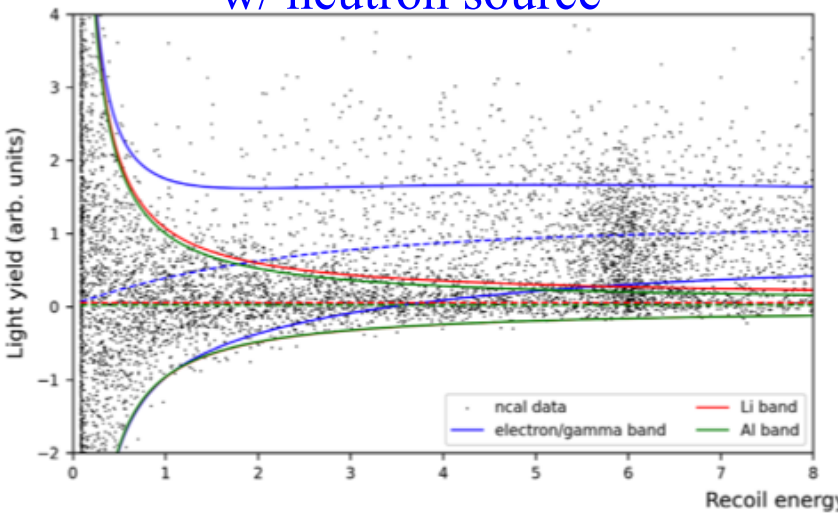
- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test of the COSINE-1T experiment

Low mass DM searches

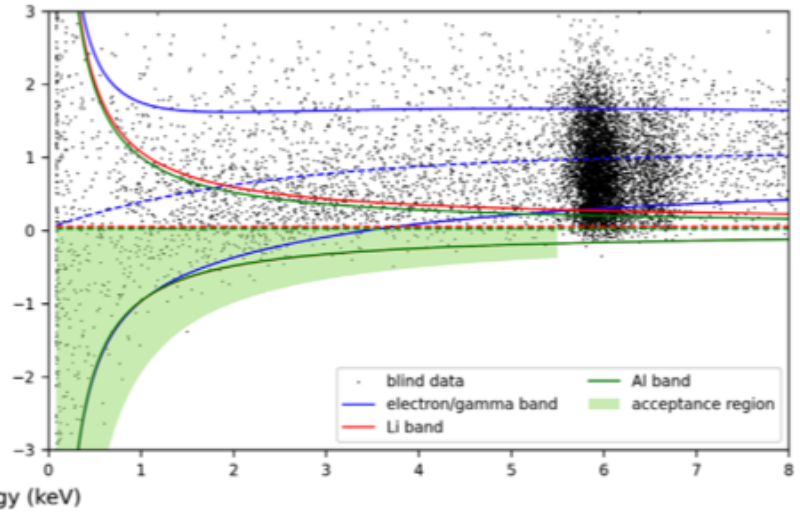
"Testing spin-dependent dark matter interactions with lithium aluminate targets in CRESST-III", PRD 106, 092008 (2022)

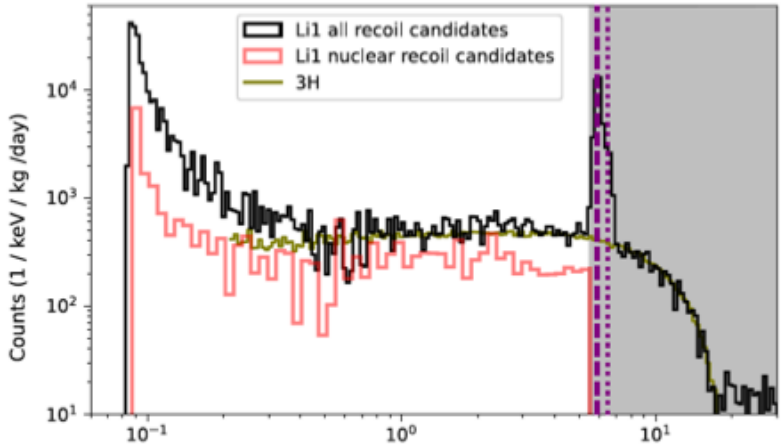
Spin dependent interacting isotopes : ${}^{6,7}_{3}Li$, ${}^{19}_{9}F$, ${}^{27}_{13}Al$ $etc.$

w/ neutron source

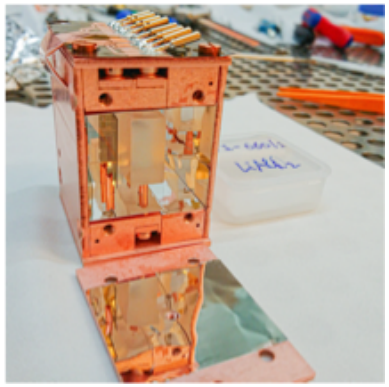


w/o neutron source

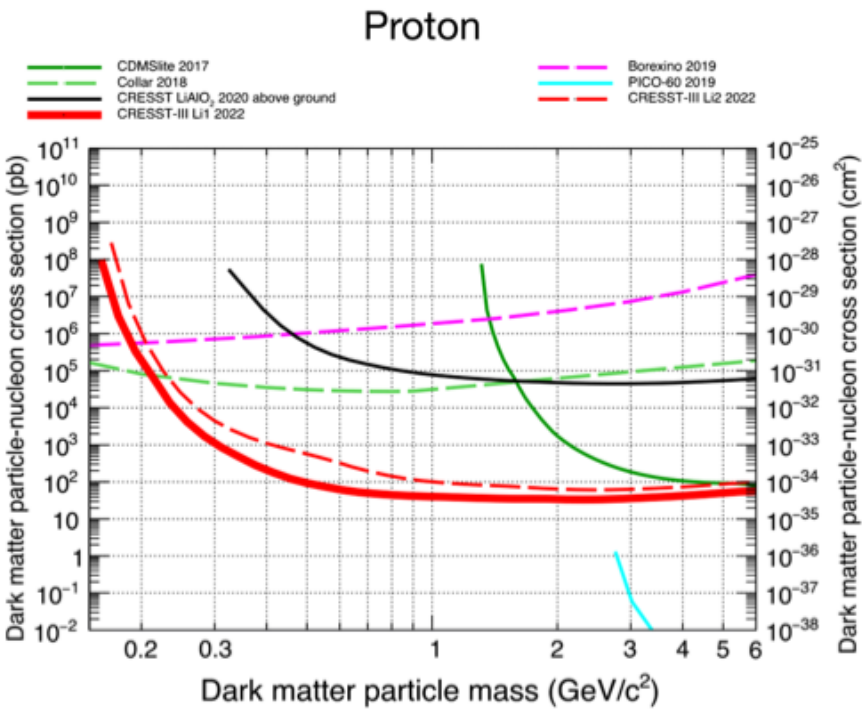


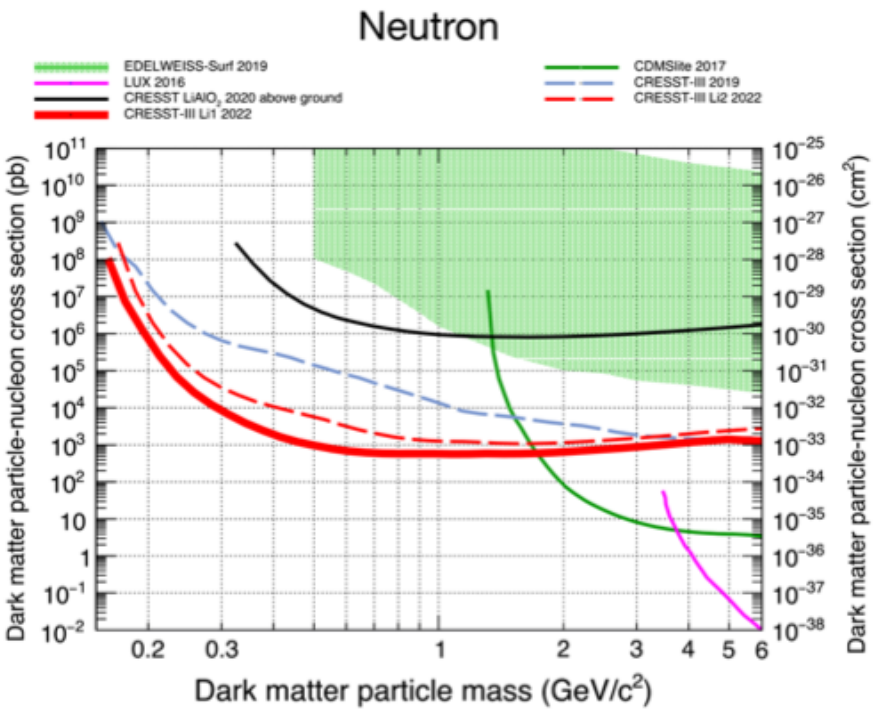


10.46 g $LiAlO_2$ crystal
@ Gran Sasso lab.

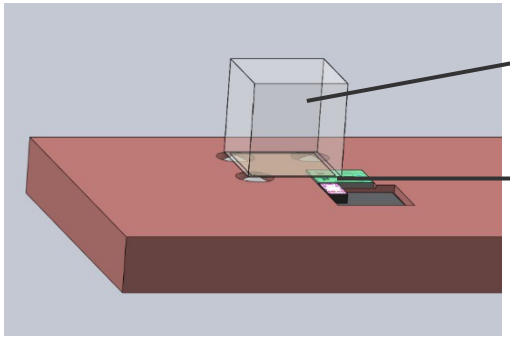


Results on spin-dependent DM searches





Low Mass DM search @ Yemilab



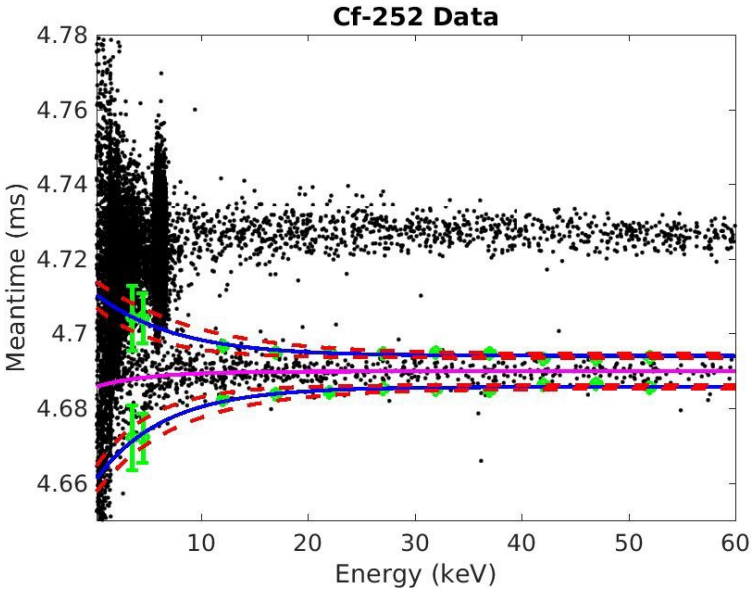
Many choices: **LiF, CaF_2, Sapphire(Al_2O_3)**(SD)
$CaMoO_4$, Diamond (SI)

MMC

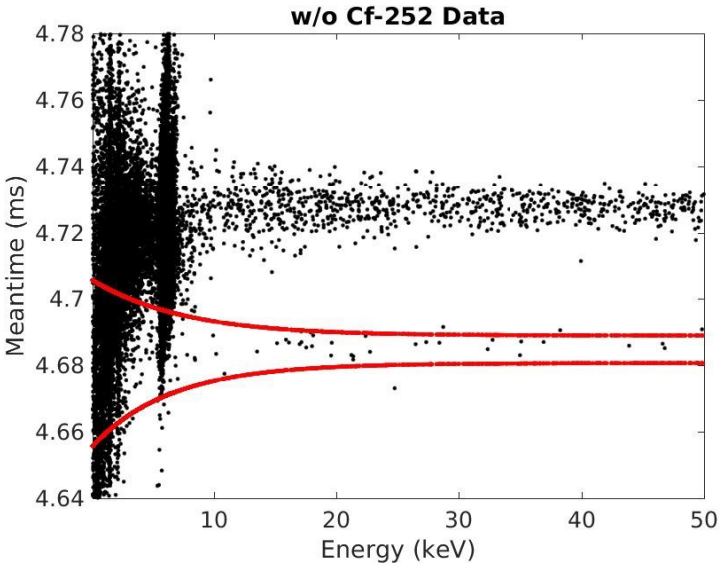
Yong-Hamb Kim

First trial with CaF_2 (5×5×5 mm^3, 0.4g) 30 mK in an ADR at ground laboratory.

w/ neutron source

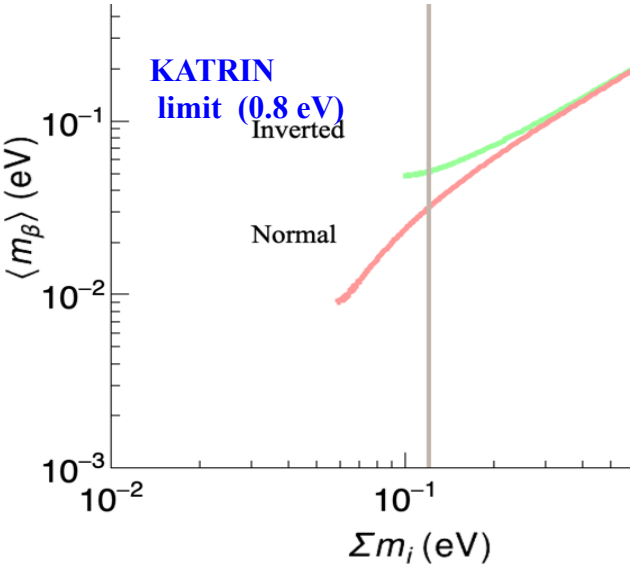


w/o neutron source



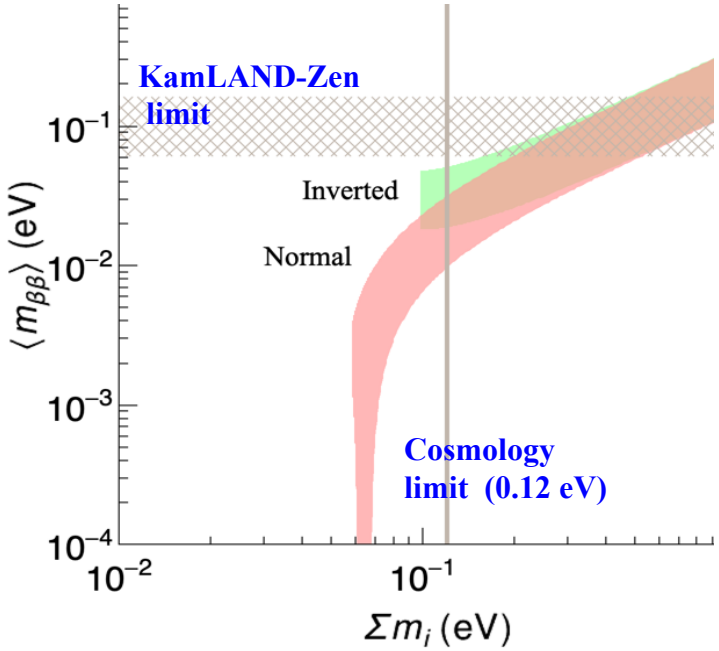
- It is promising to see good PSD even w/o light detector.
- Energy threshold ~ 50 eV.
- Will test various crystals for optimization.

Neutrinoless Double Beta Decay

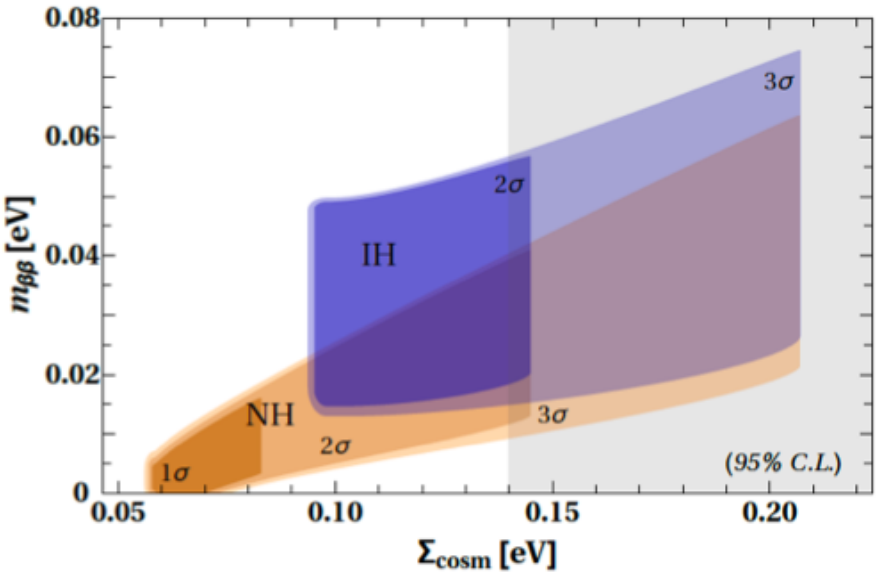


Current Neutrino Mass Limits

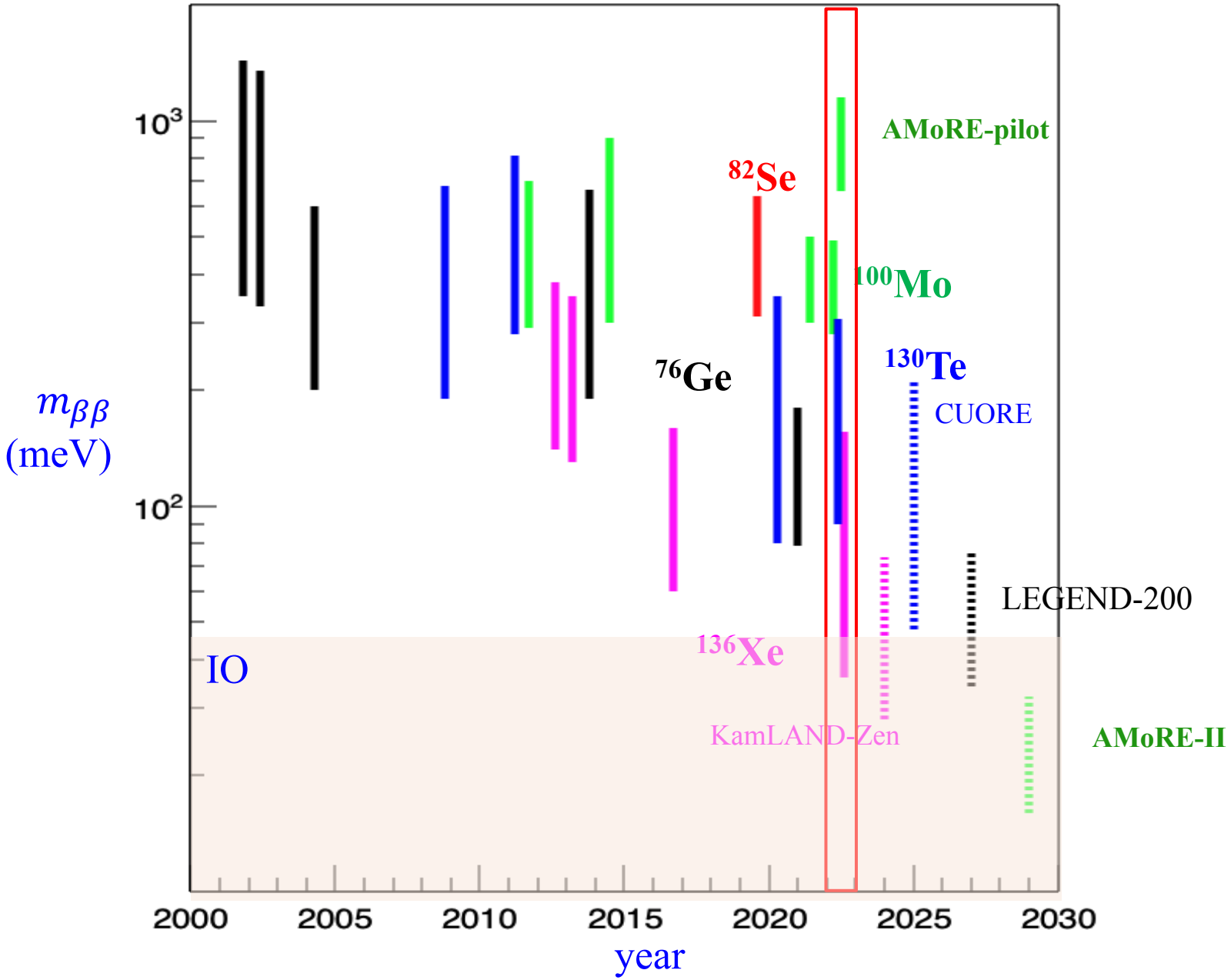
- Majorana nature of neutrinos is 80 year old question.
- Neutrino mass is ultra small, and we don't understand its origin. It is related to if neutrinos are Majorana particles.
- Neutrino mass is constrained by beta decays and cosmology.



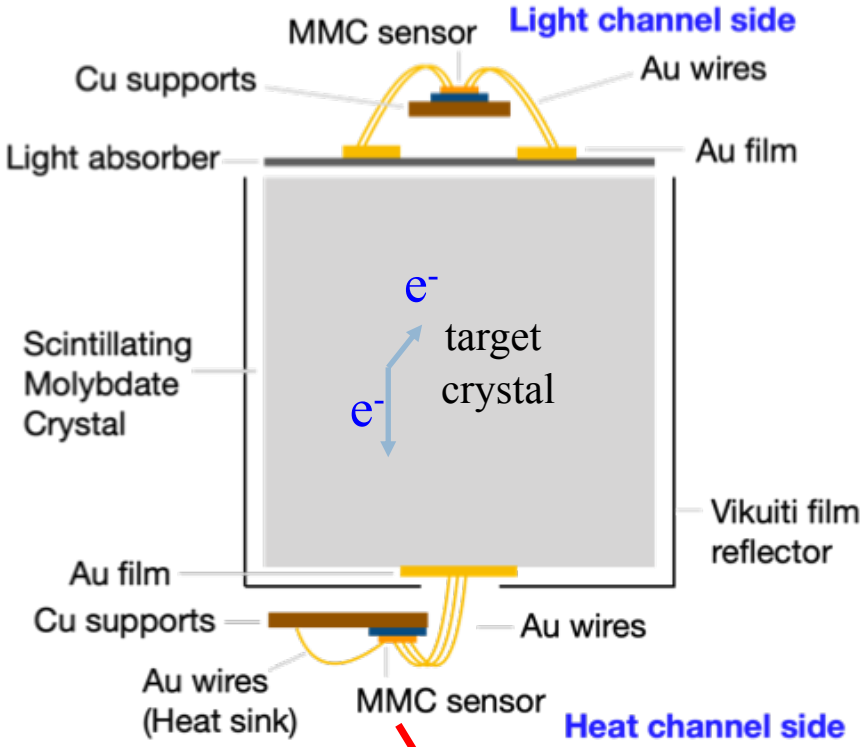
Dell'Oro et al., *JCAP* 12 (2015) 023



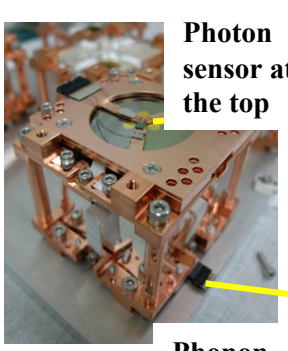
Recent Limits & Persepectives

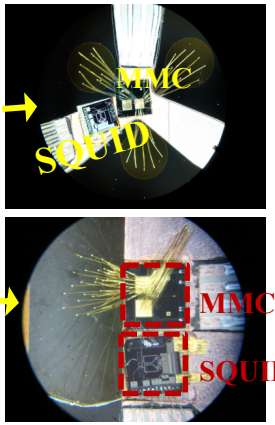


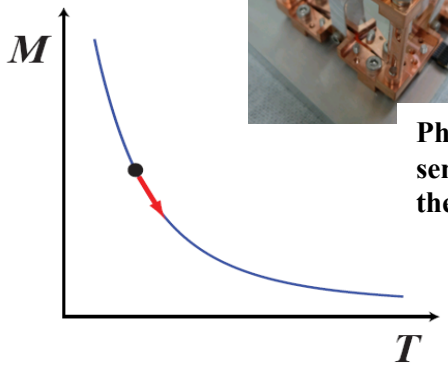
Principle of AMoRE detector



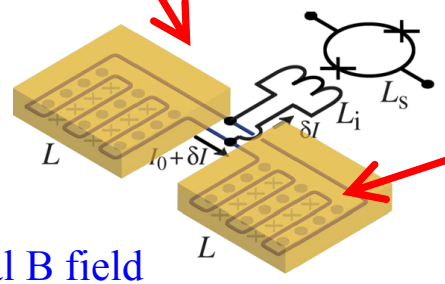
Decay→Phonons collected at Au foil → temperature of Au foil increase→magnetization of MMC decrese→ SQUID pick-up the change.







Au(Er) paramagnetic material

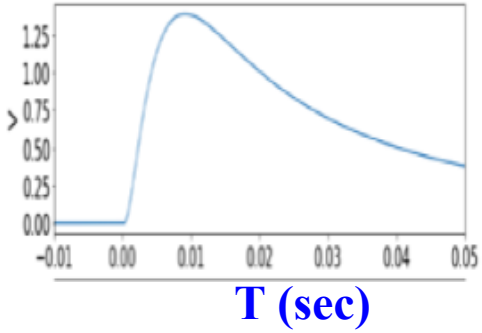


SQUIDS

Persistent current in superconductor

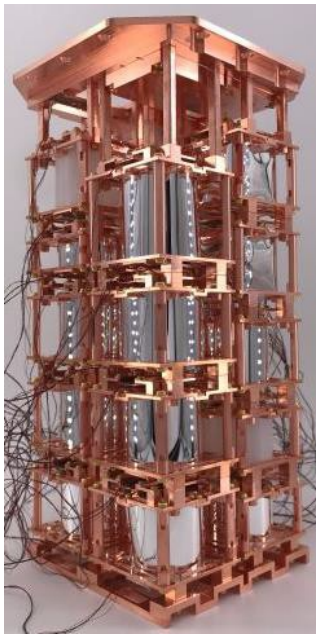
Local B field

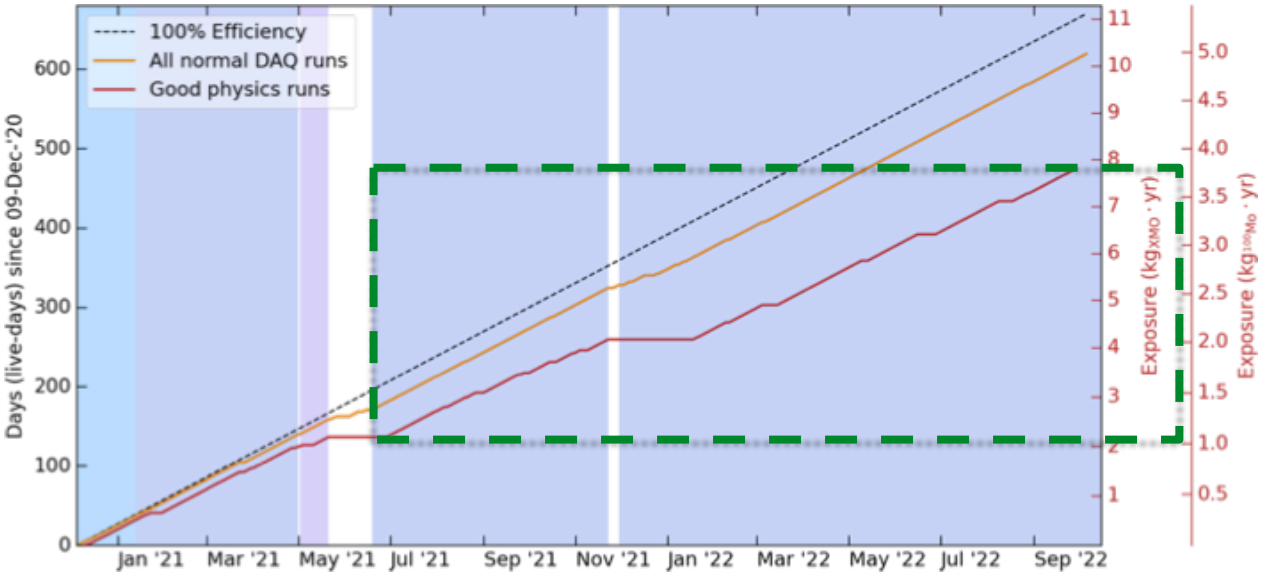
MMC: Metallic magnetic calorimeter

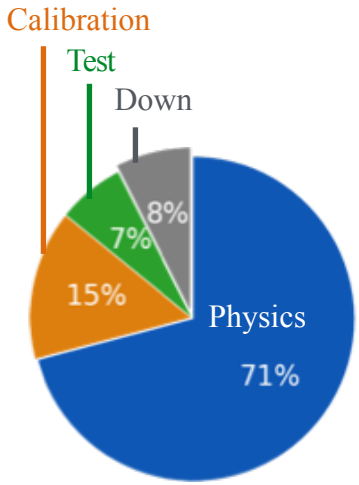


AMoRE-I : Running

- AMoRE-I began Aug. 2020 @ Y2L and runs stable.
- Purpose – Check further on detector performance & backgrounds.
- 13 $Ca^{100}MoO_4$ crystals (4.6 kg) and 5 $Li_2{}^{100}MoO_4$ (1.6 kg) crystals, ~3 kg of ^{100}Mo
- 20 cm Pb shields + neutron shields (boric acid+PE+b.PE)
- MMC sensor upgrade (AuEr→AgEr)

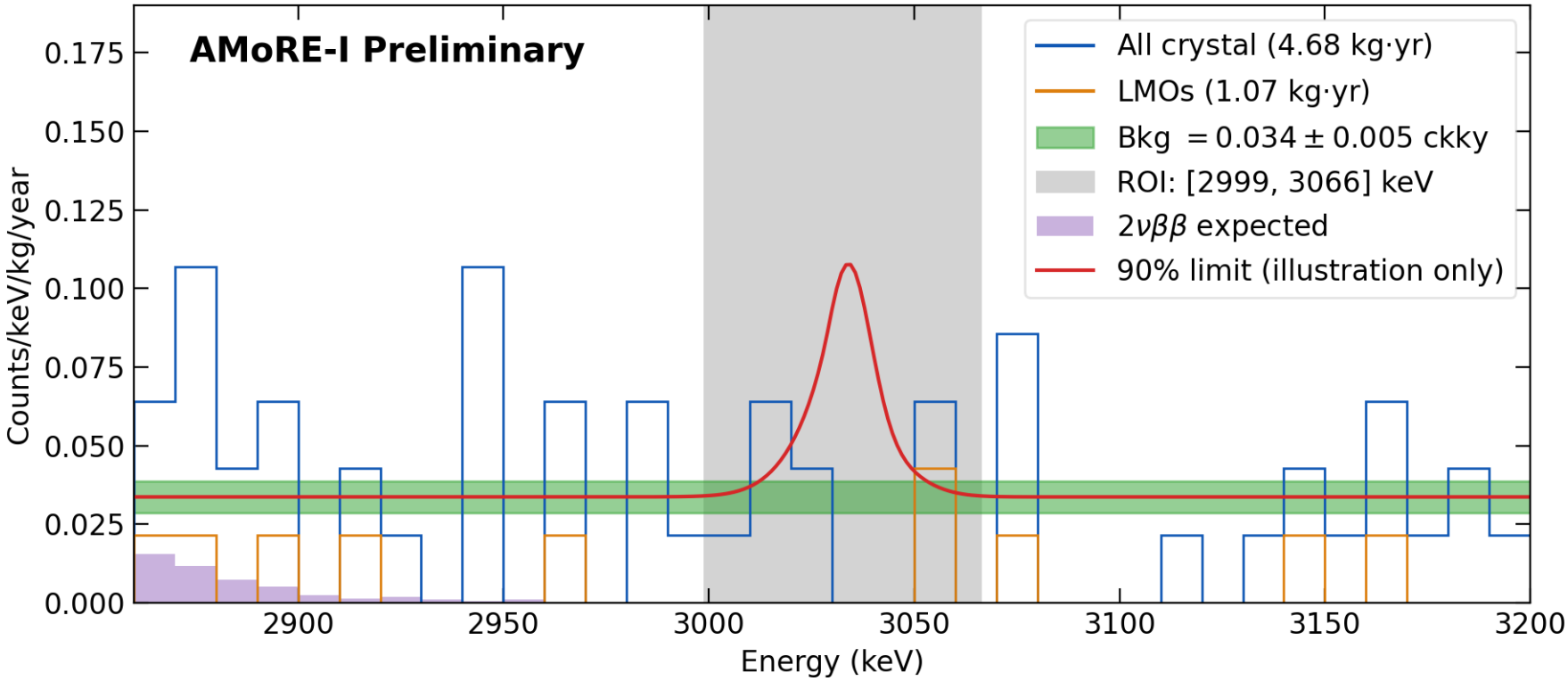






Preliminary data

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



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

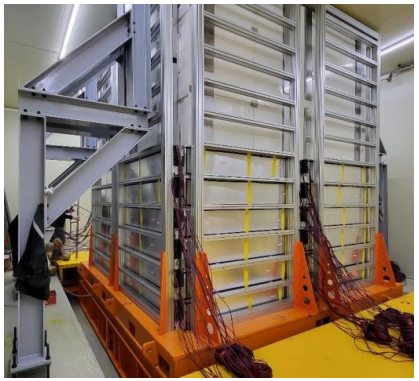
  Cf : $T^{0\nu}_{1/2} > 1.8\times10^{24}$. By Cupid-Mo group

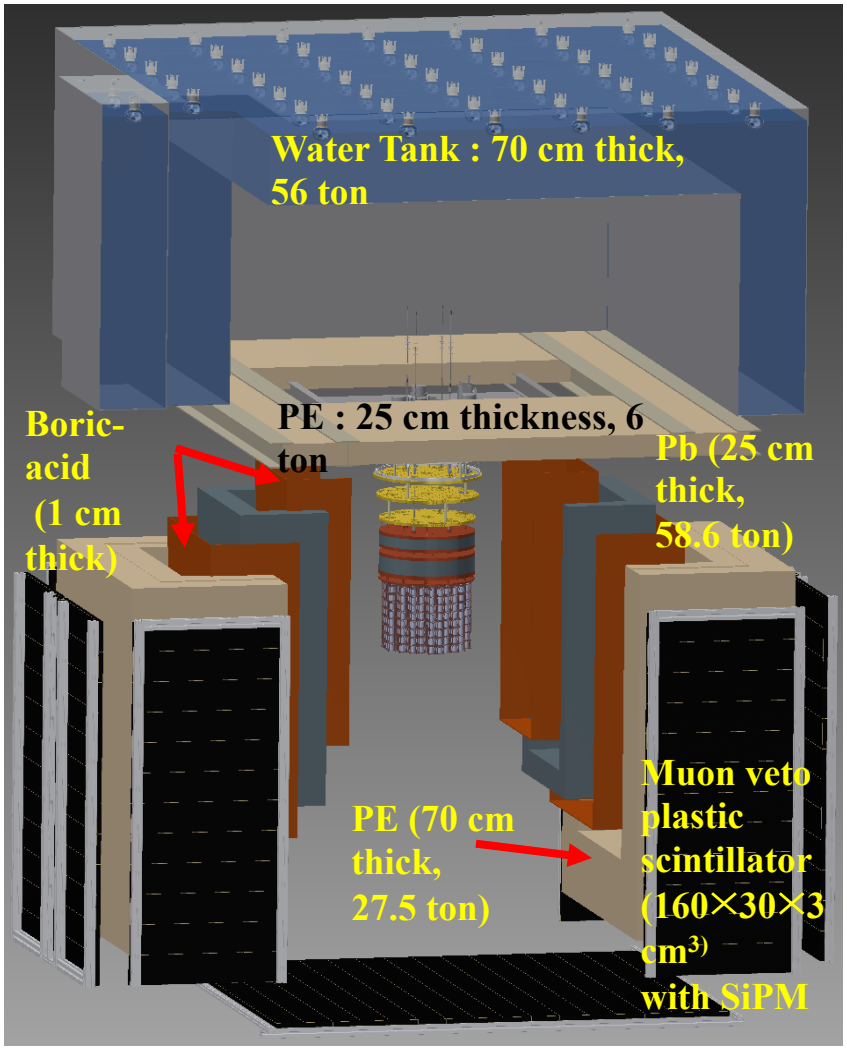
MeV	Total (5.28 kg y)	CMO (4.06)	LMO (1.22)
2.9-3.1	33 (evt.)	27	6
	0.031 (ckky)	0.033	0.025
2.86-3.2	61 (evt.)	48	13
	0.034 (ckky)	0.035	0.031

AMoRE-II : under preparation

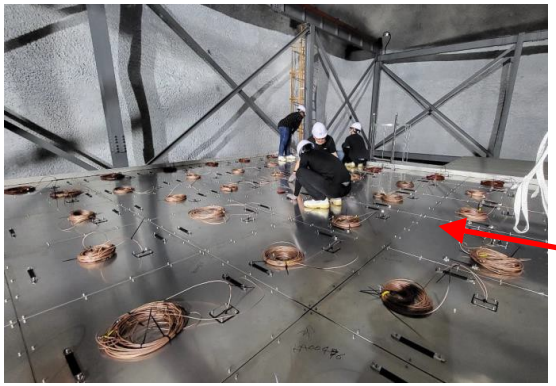
- 100 kg of ^{100}Mo @ Yemilab for 5 years
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 410 crystals) + 13 $^{40}Ca^{100}MoO_4$
- DR inside heavy shielding with Pb, PE, and water. s

- 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



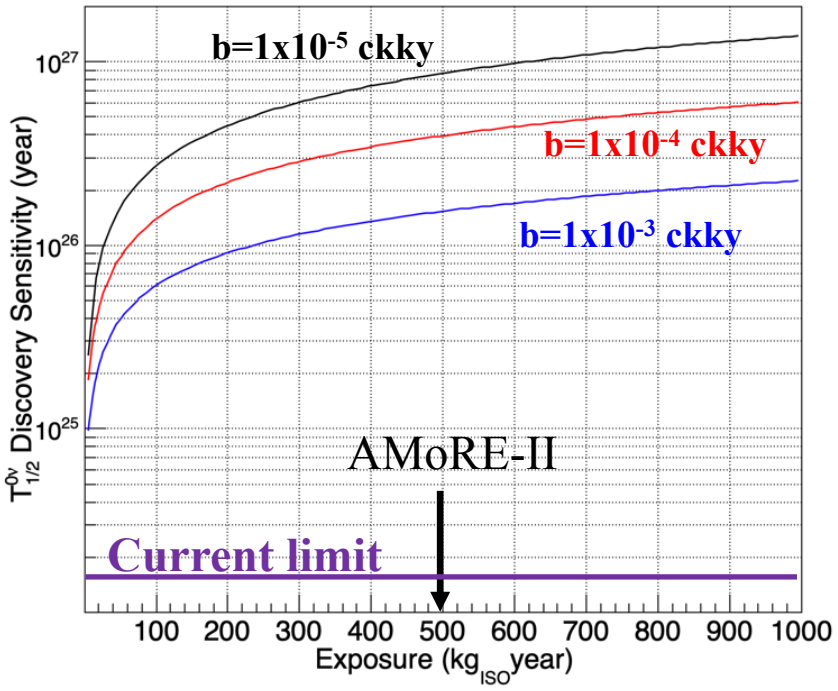
Sensitive of AMoRE-II

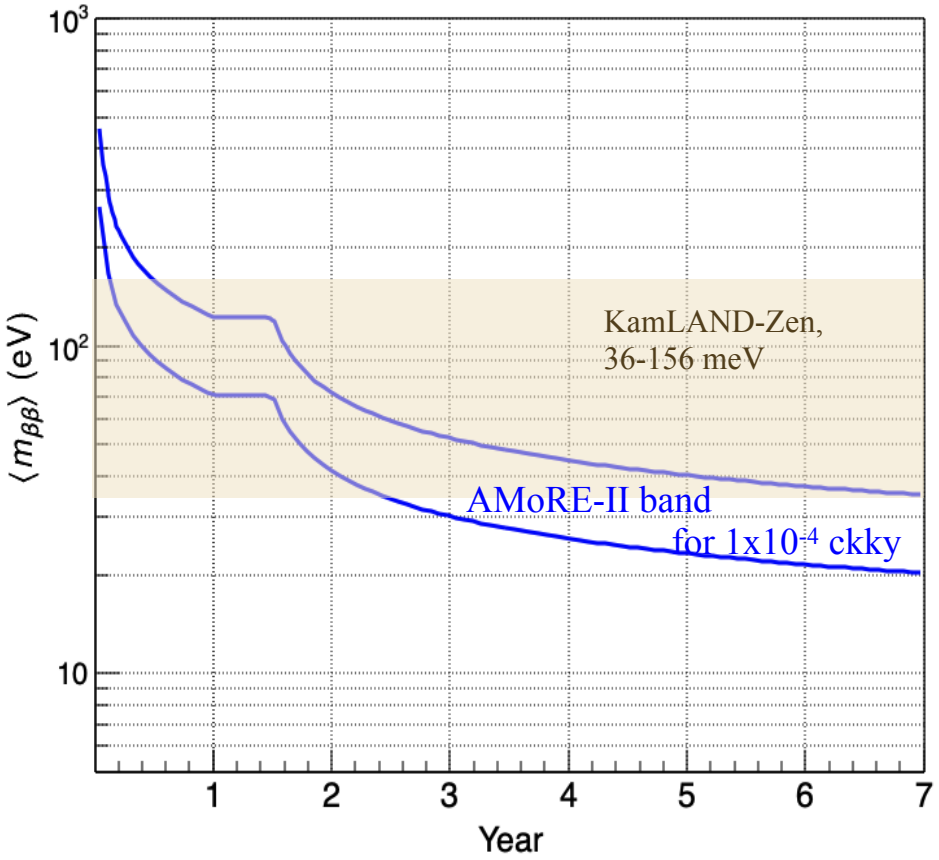
Discovery sensitivity :

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)



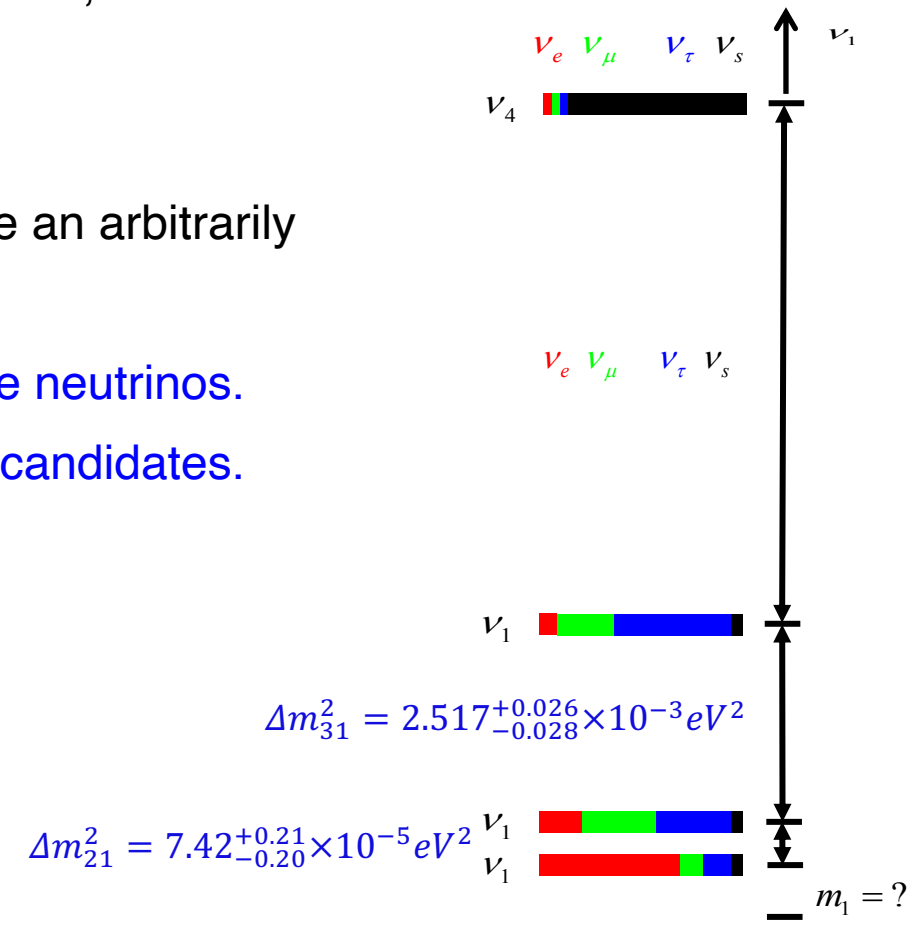


Sterile Neutrinos ?

- 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

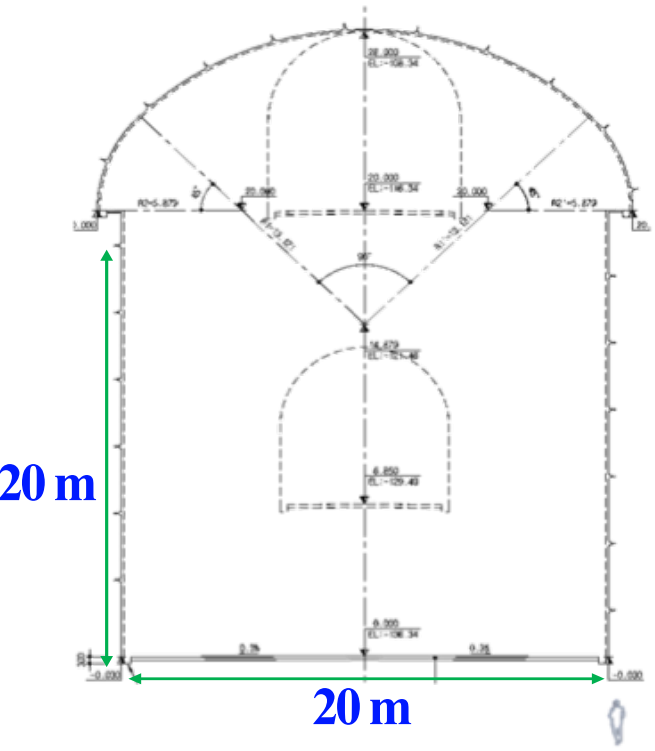
Disapperance Apperance

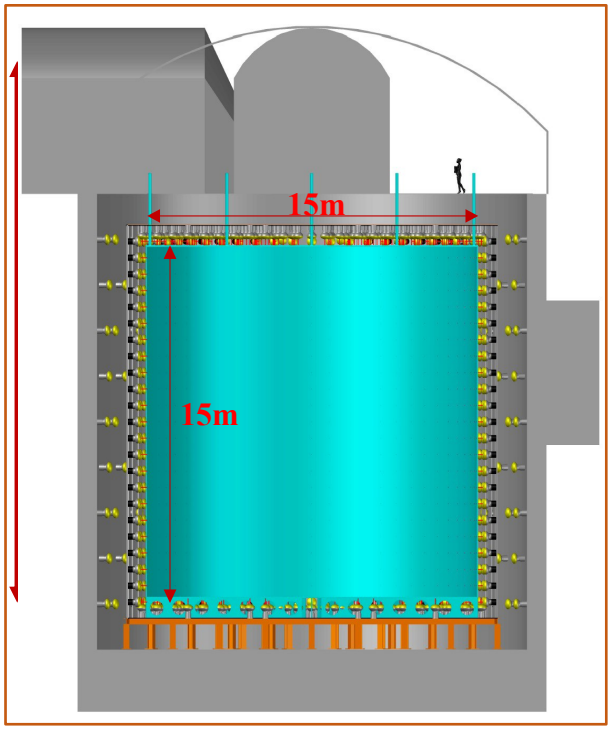


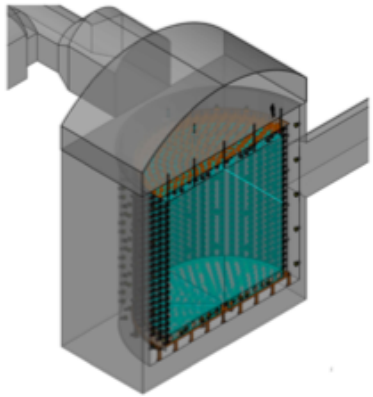
Liquid Scintillator Counter (LSC) @ Yemilab

Sunny Seo

LSC is multi-purpose large liquid scintillator detector.







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

- Photocathode coverage with 3000 20” PMTs : 49% → $E_{resol} \sim 5.5\%/\sqrt{E(MeV)}$ expected.

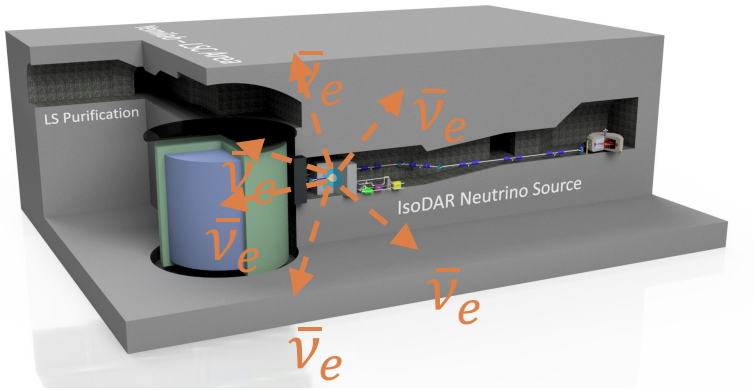
  Cf. KamLAND : 34%, $E_{resol} \sim 6.5\%/\sqrt{E(MeV)}$

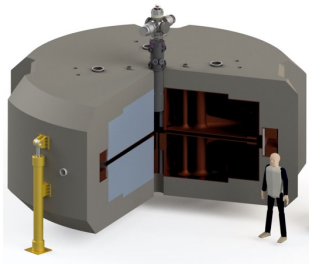
IsoDAR @ Yemilab

Janet Conrad

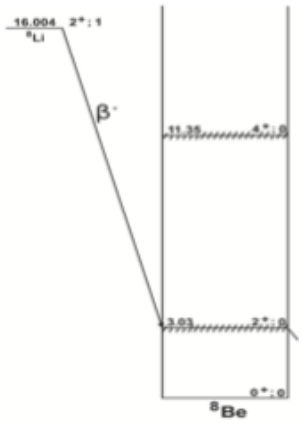
"IsoDAR@Yemilab: A report on the technology, capabilities, and deployment ", JINST 17, P090429 (2022)

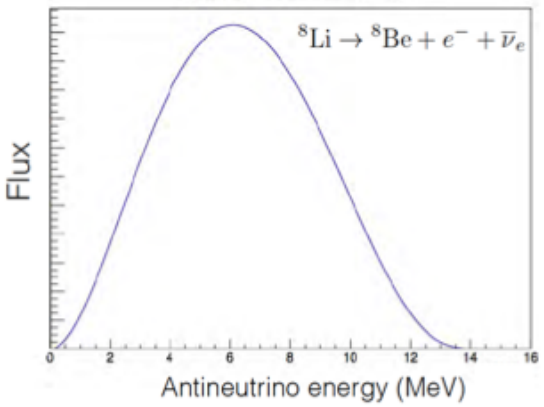
IsoDAR(isotope decay at rest) uses ^{8}Li Isotope Decay-at-rest

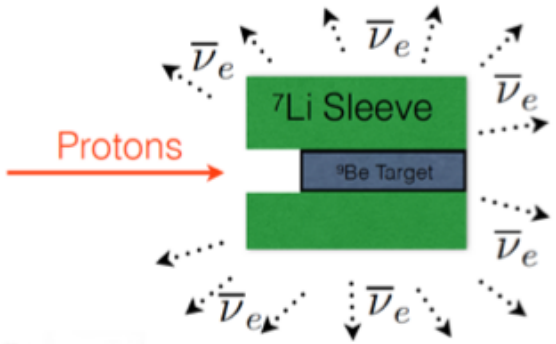




New J.Phys. 24 (2022) 2, 023038, https://arxiv.org/abs/2103.09352







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

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

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

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

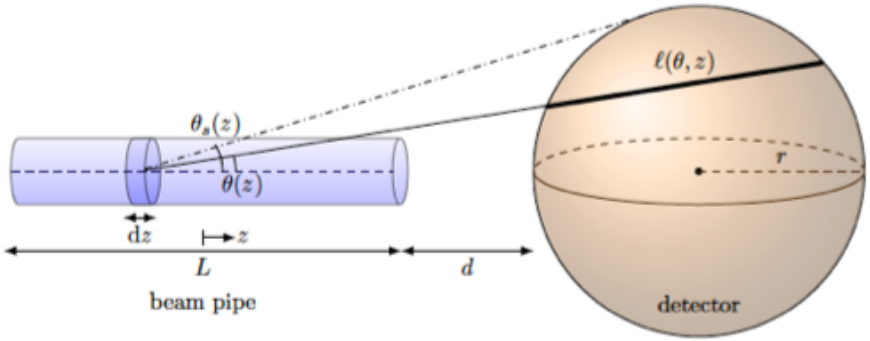
2M IBD events in 5 years.
~ 1000 events/day

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.)

Using underground accelerators to "accelerate" dark matter

Slide from Maxim Pospelov @ IDM2022

- Some of the underground Labs that host Dark Matter detectors, also have nuclear accelerators (e.g. LUNA, JUNA etc) in a completely different setting: studies of nuclear reactions.
- We propose to couple nuclear accelerators and dark matter detectors: accelerated protons (or other nuclei) can strike DM particles that can subsequently be detected with a nearby detector.



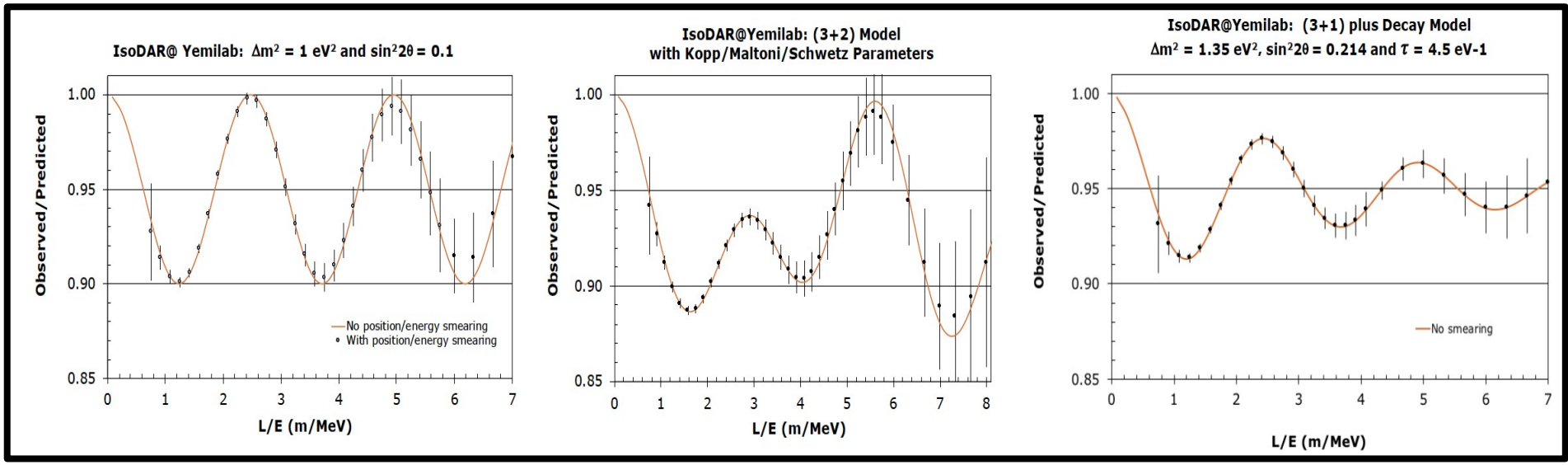
- This is going to be relevant for models with large DM-nuclear cross section (blind spot #2), where A. interaction is enhanced, B. density is enhanced.

Sterile neutrino searches.

Janet Conrad

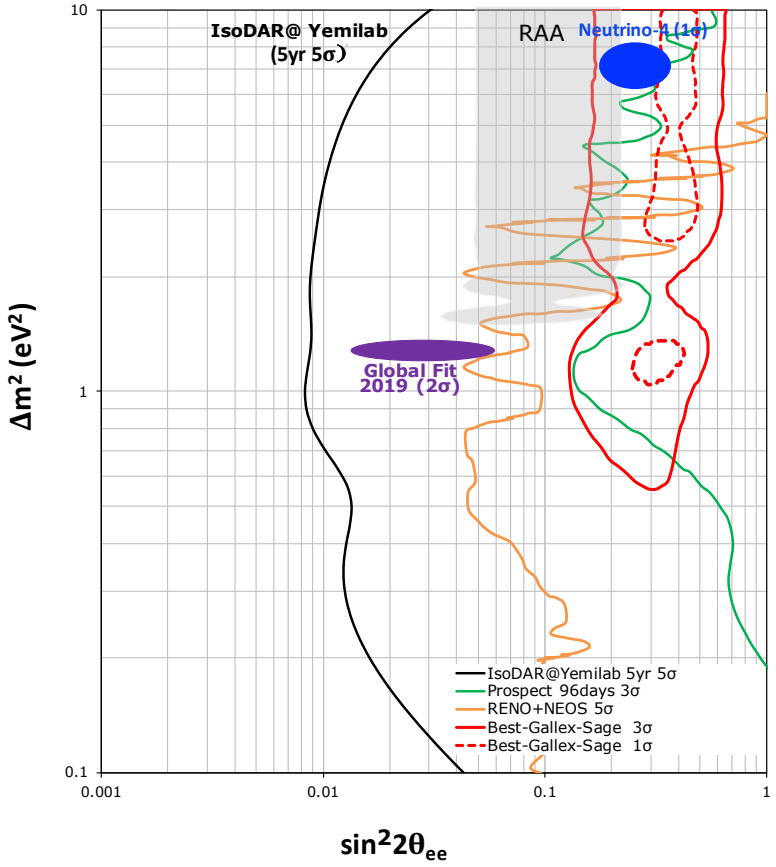
"Neutrino Physics Opportunities with the IsoDAR Source at Yemilab", PRD 105, 052009 (2022)

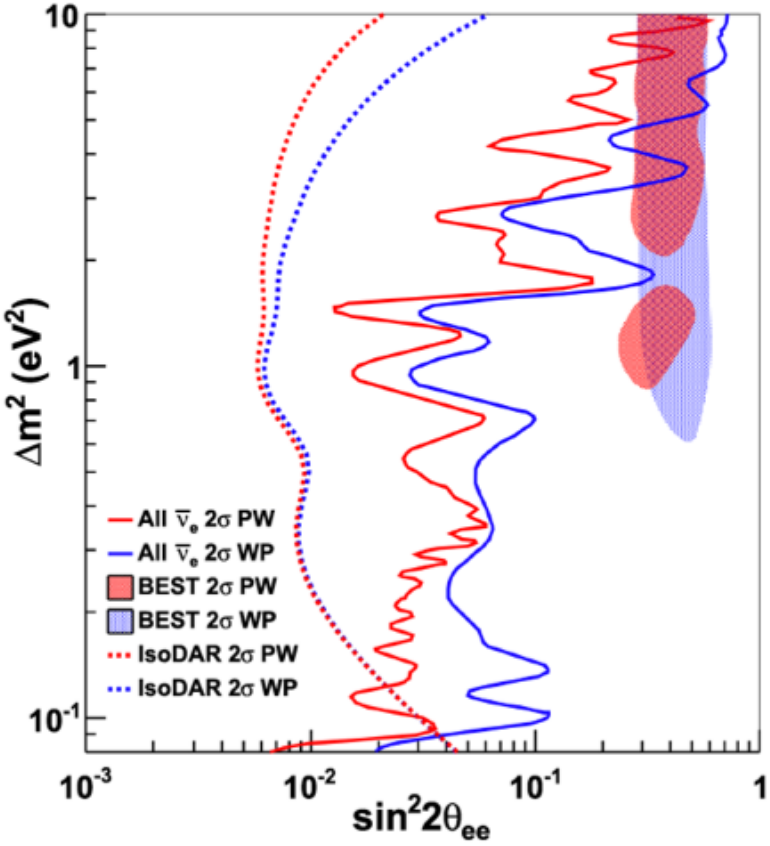
- With inverse beta decay, $\bar{\nu}_e p \rightarrow e^+ n$, short baseline oscillation is searched.
- Well known energy spectra and cross section unlikely with other experiments; reactor neutrinos, ~GeV neutrino-nuclear cross section, neutrino-nucleus CC interaction etc.
- With energy resolution $E_{resol} \sim 6.5\%/\sqrt{E(MeV)}$ and vertex resolution, $\sigma(vertex) = 12cm/\sqrt{E(MeV)}$



Sterile neutrino searches.

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



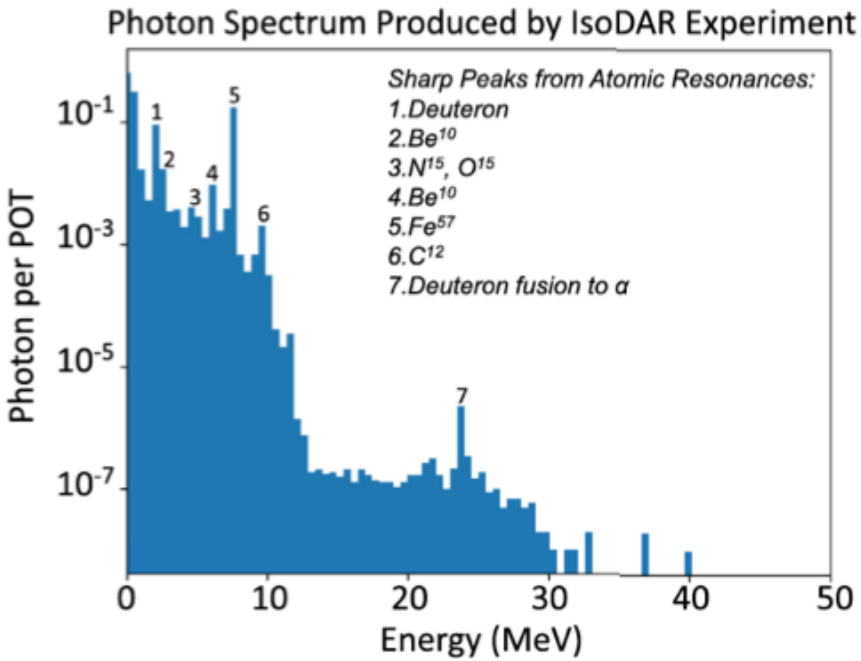


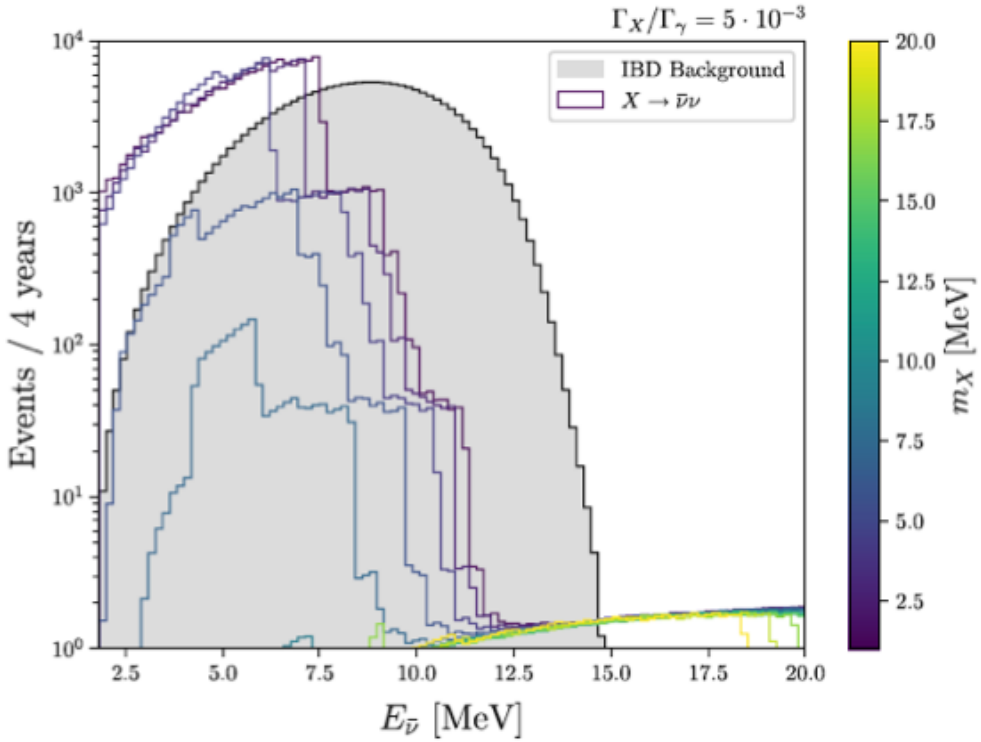
- Wave packet effect will show damping of the oscillation with a wave packet width $\sigma_x = 2.1 \times 10^{-4} nm$, which is lowest limit.
- Comment from Akhmedov and Smirnov : packet width should be much larger → No effect expected.

Akhmedov and Sminov, arXiv:2208.03736

Dark boson searches with IsoDAR

- Low mass mediators, light boson(X) particles, can be searched with the nuclear decays at the IsoDAR target and $X \rightarrow \nu\bar{\nu}$ decay and $\bar{\nu}$ detection in the LSC.

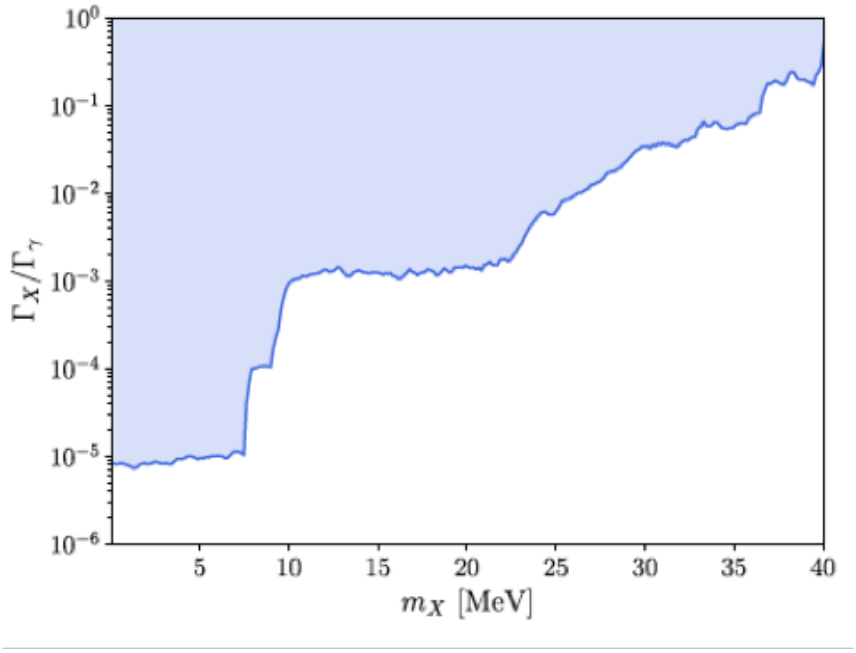




Expected $\bar{\nu}$ energy spectra for $X \rightarrow \nu\bar{\nu}$

Dark boson searches with IsoDAR

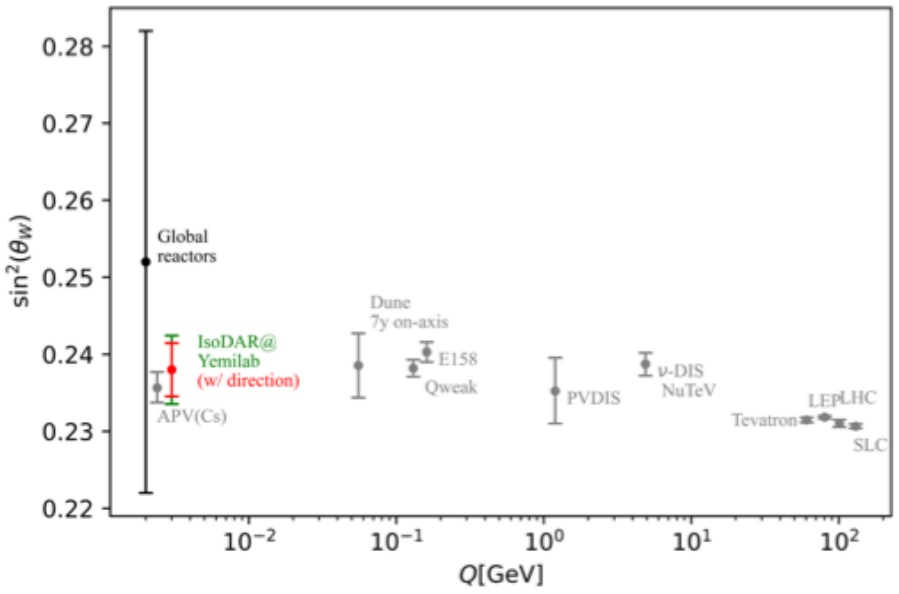
- Assume that the generic mediator X is coupled to both quarks and neutrinos.
- The production rate of this new mediator depends on its coupling with quarks and the mass, which can be expressed as a branching ratio for a given transition.



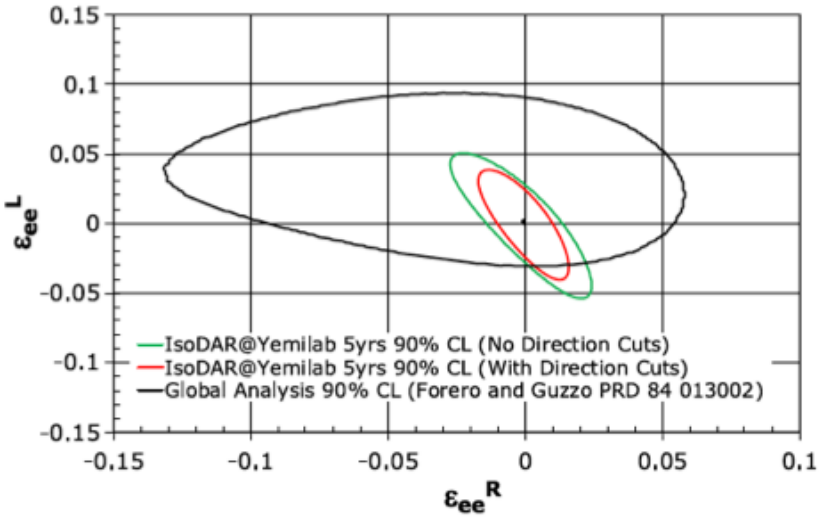
Other physics

Janet Conrad

- $\bar{\nu}e \rightarrow \bar{\nu}e, 7000\ detected\ events$



Non-standard interaction



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:

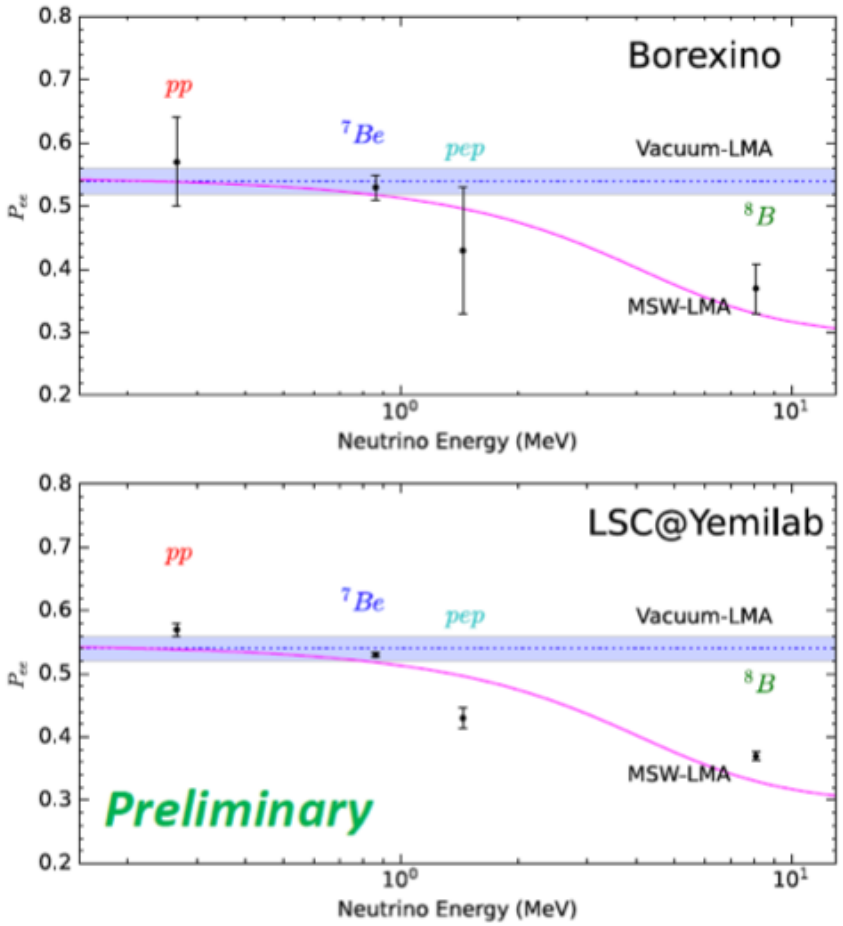
$$\bar{g}_R \equiv g_R^e + \varepsilon_{ee}^{eR}, \qquad \bar{g}_L \equiv 1 + g_L^e + \varepsilon_{ee}^{eL}.$$

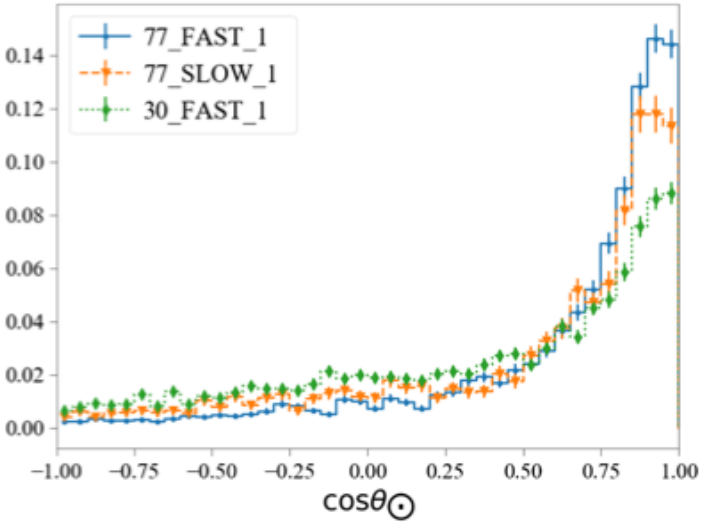
$$\sigma(\varepsilon_{ee}^{eR}, \varepsilon_{ee}^{eL}) = \frac{2m_e G_F^2 E_\nu}{\pi}\left(\bar{g}_L^2 + \frac{1}{3}\bar{g}_R^2\right).$$

Solar Neutrinos

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

Slow scintillator can reduce backgrounds.
“Slow-fluor scintillator for low energy solar neutrinos and neutrinoless double beta decay”, Dunger et al., PRD 105, 092006 (2022)





(a)

Reconstructed solar direction for ^{8}B neutrino events.

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

Summary

- We constructed Yemilab to house new experiments for dark matter and neutrinos.
- 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.
- LSC coupled with a powerful accelerator have a large potential for dark sector physics and sterile neutrinos.
- We welcome researchers who utilize Yemilab for basic and applied sciences.