Current status of dark matter and neutrino experiments
- focused on CUP projects -

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2023. 2. 20.

2023 Chung-Ang University BSM workshop

Outline

- Dark Matter
  - Status of low mass DM, Migdal effect
  - COSINE experiments
  - Low mass DM @ CUP
- DBD
  - Current and future DBD experiments
  - Matrix elements update
  - AMoRE-I & AMoRE-II
- LSC
  - IsoDAR Dark boson search

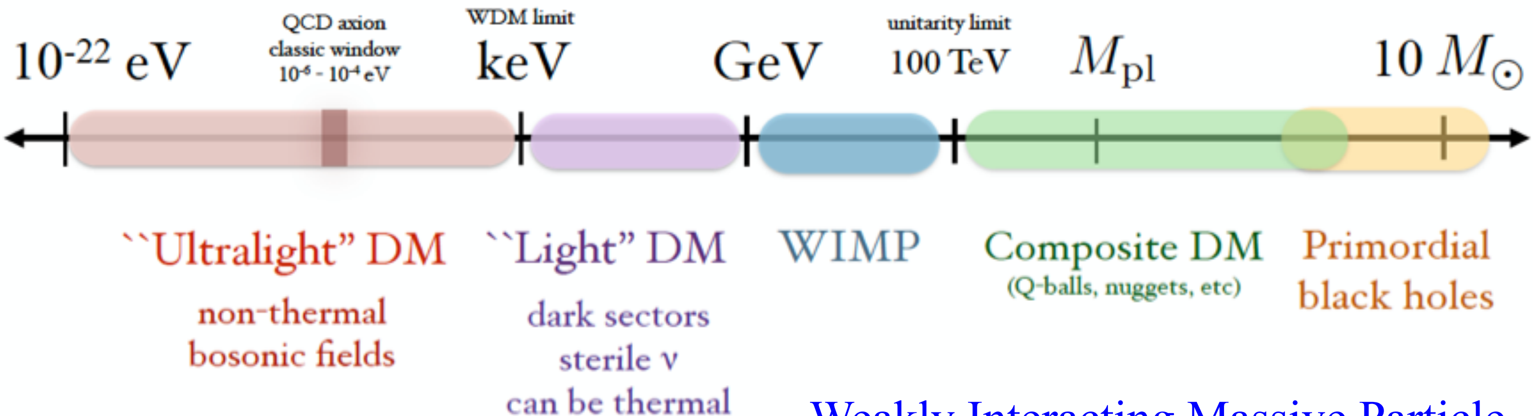
There are abundant candidates for DM

DM should be ;

1. Neutral
2. Stable or lifetime much longer than the Universe.
3. Massive enough for structure formation

DM ~ 5 X visible matter,

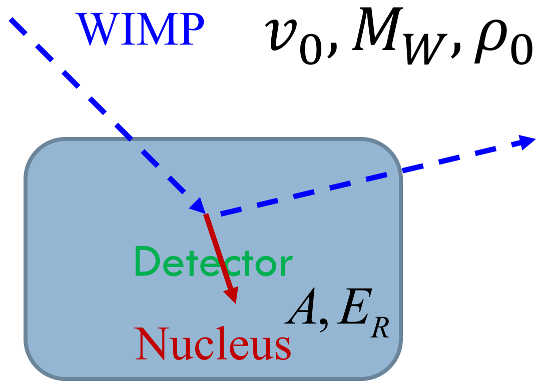
Many candidates in many orders of magnitude of mass.



Weakly Interacting Massive Particle

Tongyan Lin, 1904.07915

WIMP-nucleus interaction of Direct Search



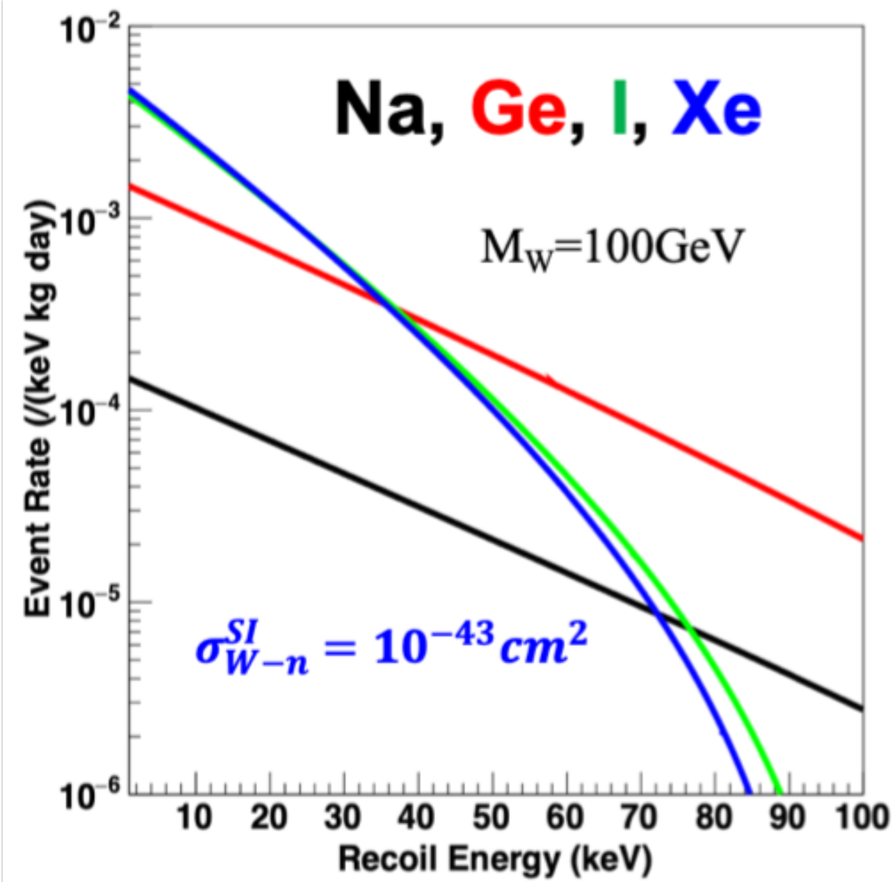
WIMP-Nucleus elastic scattering

The nuclear recoil spectra from the elastic scattering is smooth shape <~ 100 keV

WIMP-Nucleus interaction can be spin-independent (SI) or spin-dependent (SD).

$$\sigma_0^{SI} \propto \sigma_{W-n}^{SI} A^2$$

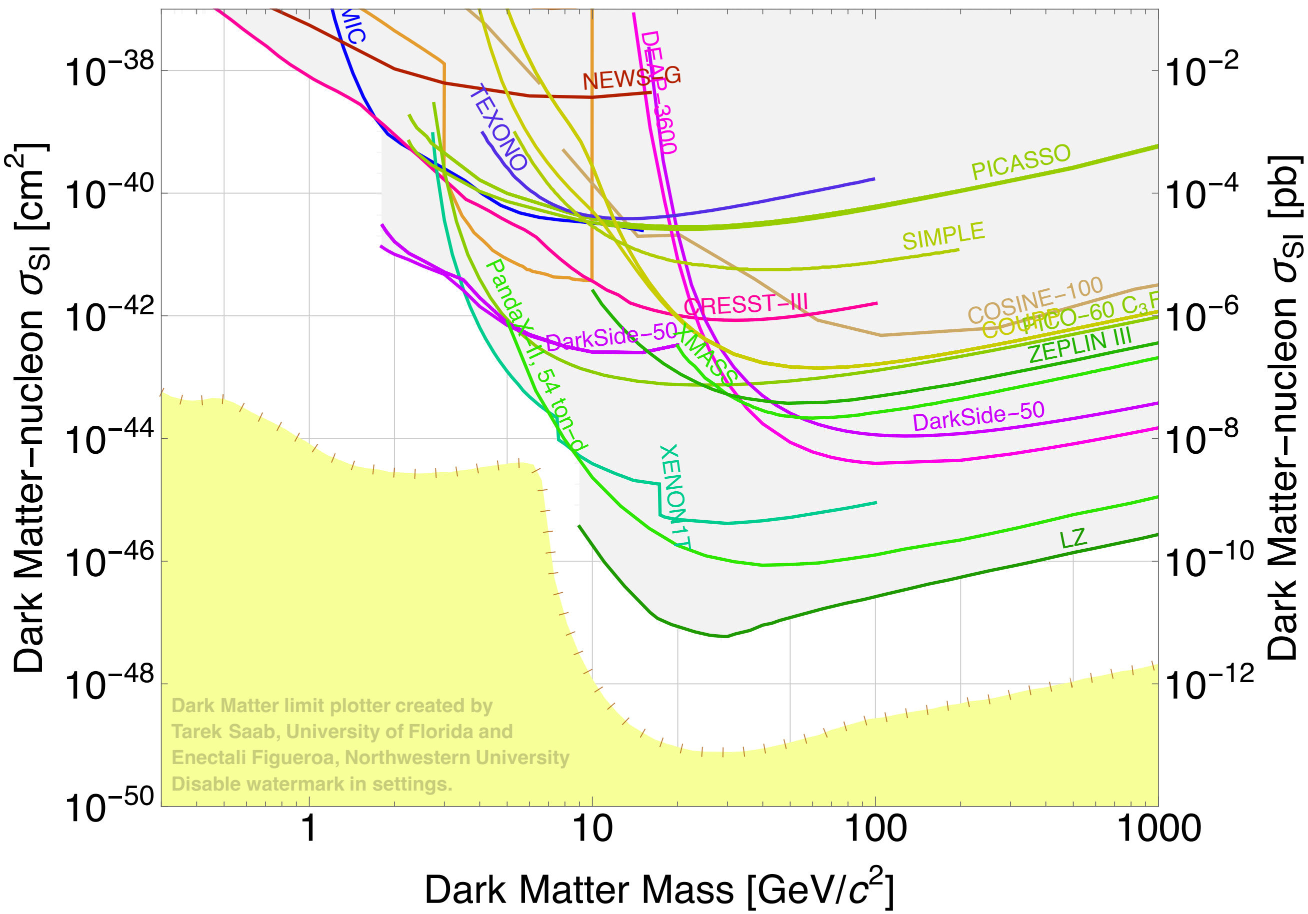
$$\sigma_0^{SD} \propto \frac{J+1}{J} \sigma_{W-p,n}^{SD} \langle S^{p,n} \rangle^2$$



Event rate unit,
dru : counts/keV/kg/day

Dark Matter Direct Search - status

- **Experiments gave upper limits on the cross section as a function of mass with SHM.**
- **DAMA island is many orders off the limits set by other experiments under the SHM. → DAMA anomaly**



DM-electron scattering

From Essig et al., JHEP05 (2016), 046

- Consider a LDM model based on vector portal, dark matter interacts with SM through dark photon, A' as an example.

$$\mathcal{L} \sim \frac{\epsilon}{2cos\theta_W} F_Y^{\mu\nu} F'_{\mu\nu}$$

ϵ: *kinetic mixing parameter*

θ_W: *Weinberg angle*

$$\overline{\sigma_e} = \frac{16\pi\mu_{\chi e}^2 \alpha \epsilon^2 \alpha_D}{(m_{A'}^2 + \alpha^2 m_e^2)^2} \approx \begin{cases} \frac{16\pi\mu_{\chi e}^2 \alpha \epsilon^2 \alpha_D}{m_{A'}^2}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2 \alpha \epsilon^2 \alpha_D}{(\alpha^2 m_e^2)^2}, & m_{A'} \ll \alpha m_e \end{cases} \qquad \alpha_D = g_D^2/4\pi$$

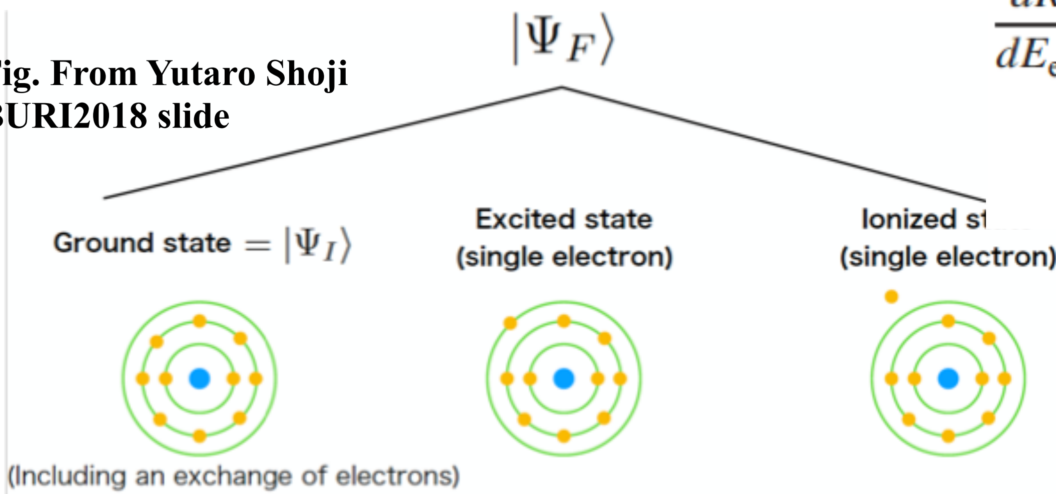
- The DM form factor is ;

$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \approx \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}, & m_{A'} \ll \alpha m_e \end{cases}$$

Migdal effect vs electron scattering

- Migdal effect : DM-nucleus interaction can transform a bound electron to be in excited state or ionized state.

Fig. From Yutaro Shoji BURI2018 slide



$$\frac{dR}{dE_{\rm ee}} = \int dE_{\rm nr} dv \frac{d^2R}{dE_{\rm nr}dv} \times \frac{1}{2\pi} \sum_{n,l} \frac{d}{dE_{\rm nr}} p^c_{q_e}(n, l \to E_{\rm ee} - E_{n,l}).$$

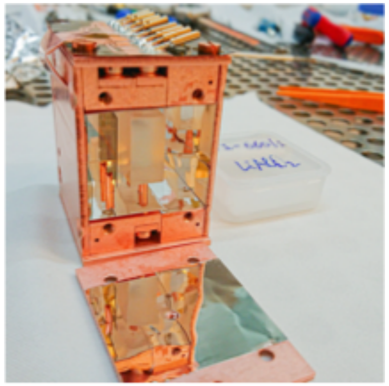
- Then, the transition probability is related to a dimensionless form factor of DM-electron scattering. → DM-nucleus scattering is related to DM-electron scattering.

$$\frac{dp_{nl\to E_e}}{d\ln E_e} = \frac{\pi}{2} |f^{\rm ion}_{nl}(p_e, q_e)|^2$$

$p^c_{q_e}$ is the probability for an atomic electron with quantum number (n, l) and binding energy $E_{n,l}$ to be ejected with a kinetic energy $E_{ee} - E_{n,l}$, and q_e is the electron momentum in the nucleus rest frame.

Low mass DM searches – spin dependent

- CRESST-III detectors consist of $CaWO_4$, Al_2O_3, Si or $LiAlO_2$ single crystals operated at temperatures around 15mK.
- A leading experiment for DM-nucleus interaction.



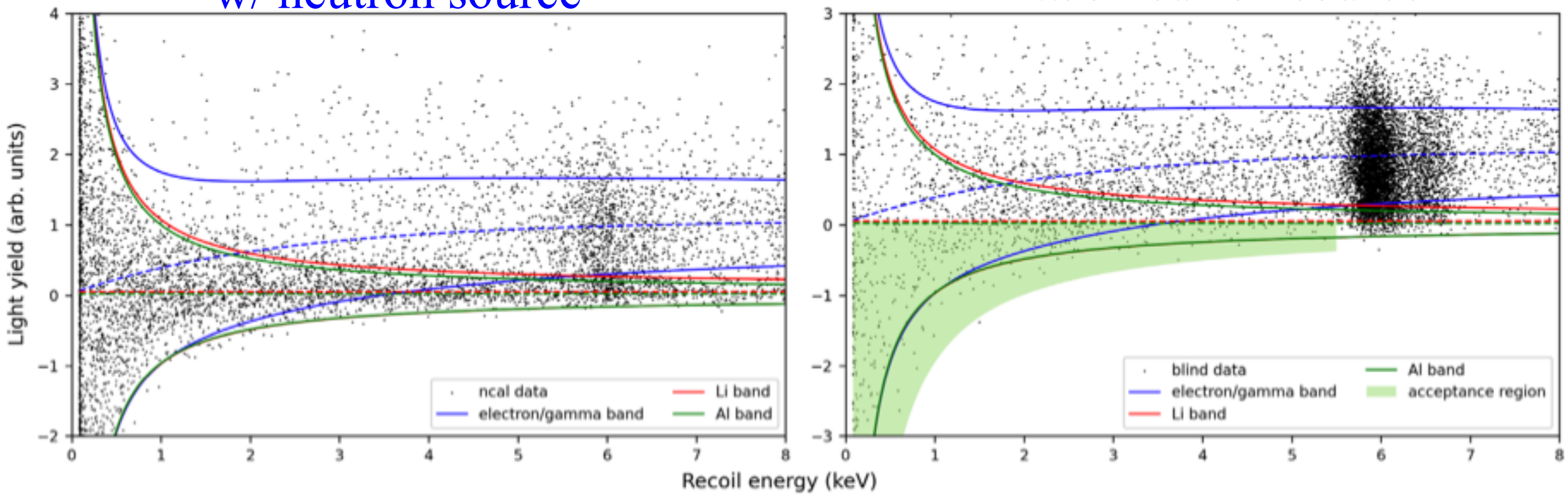
10.46 g $LiAlO_2$ crystal @ Gran Sasso lab.

Isotopes w/ proton spin : ${}^{6,7}_{3}Li, {}^{19}_{9}F, {}^{27}_{13}Al, {}^{19}_{9}F, {}^{23}_{11}Na, {}^{133}_{55}Cs, etc.$

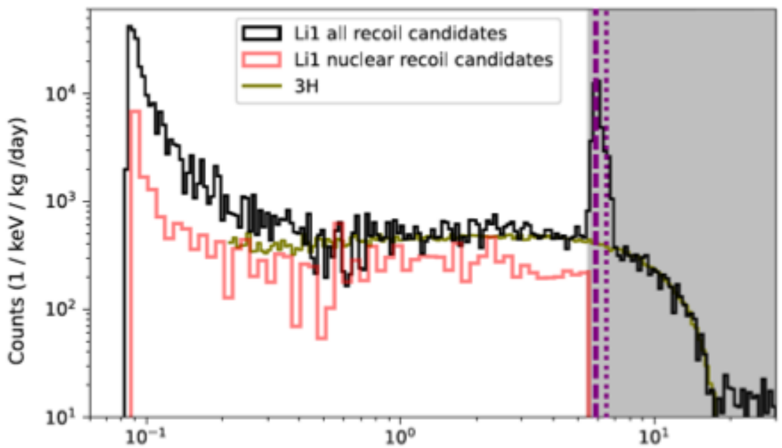
"Testing spin-dependent dark matter interactions with lithium aluminate targets in CRESST-III", PRD 106, 092008 (2022)

w/ neutron source

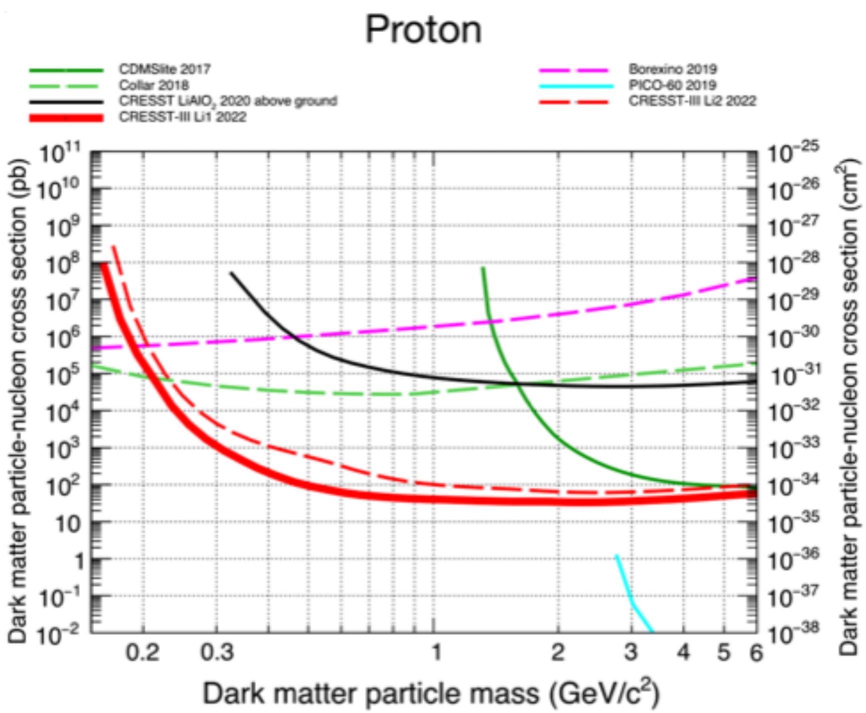
w/o neutron source

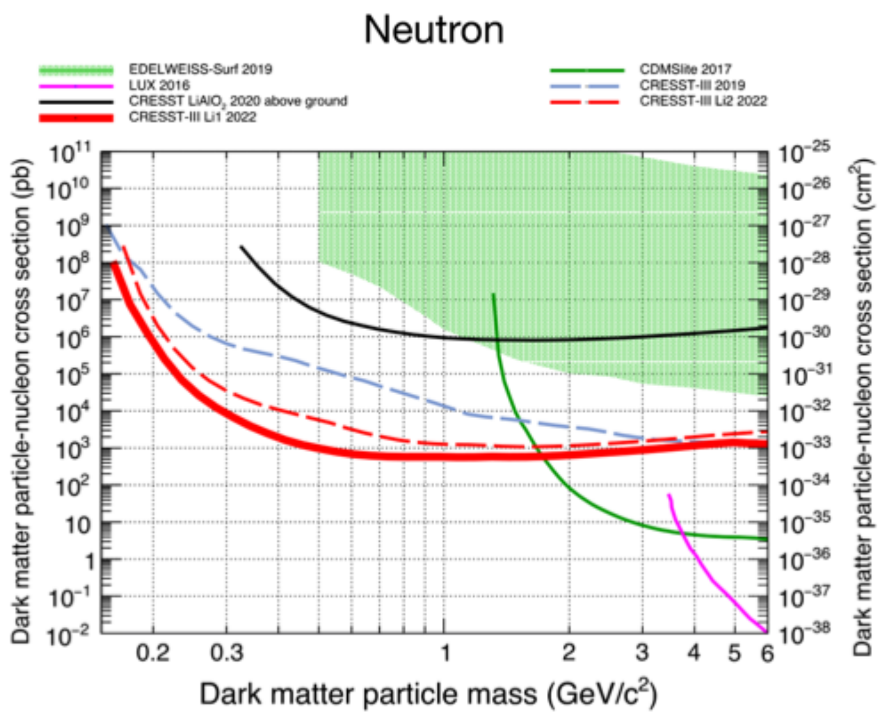


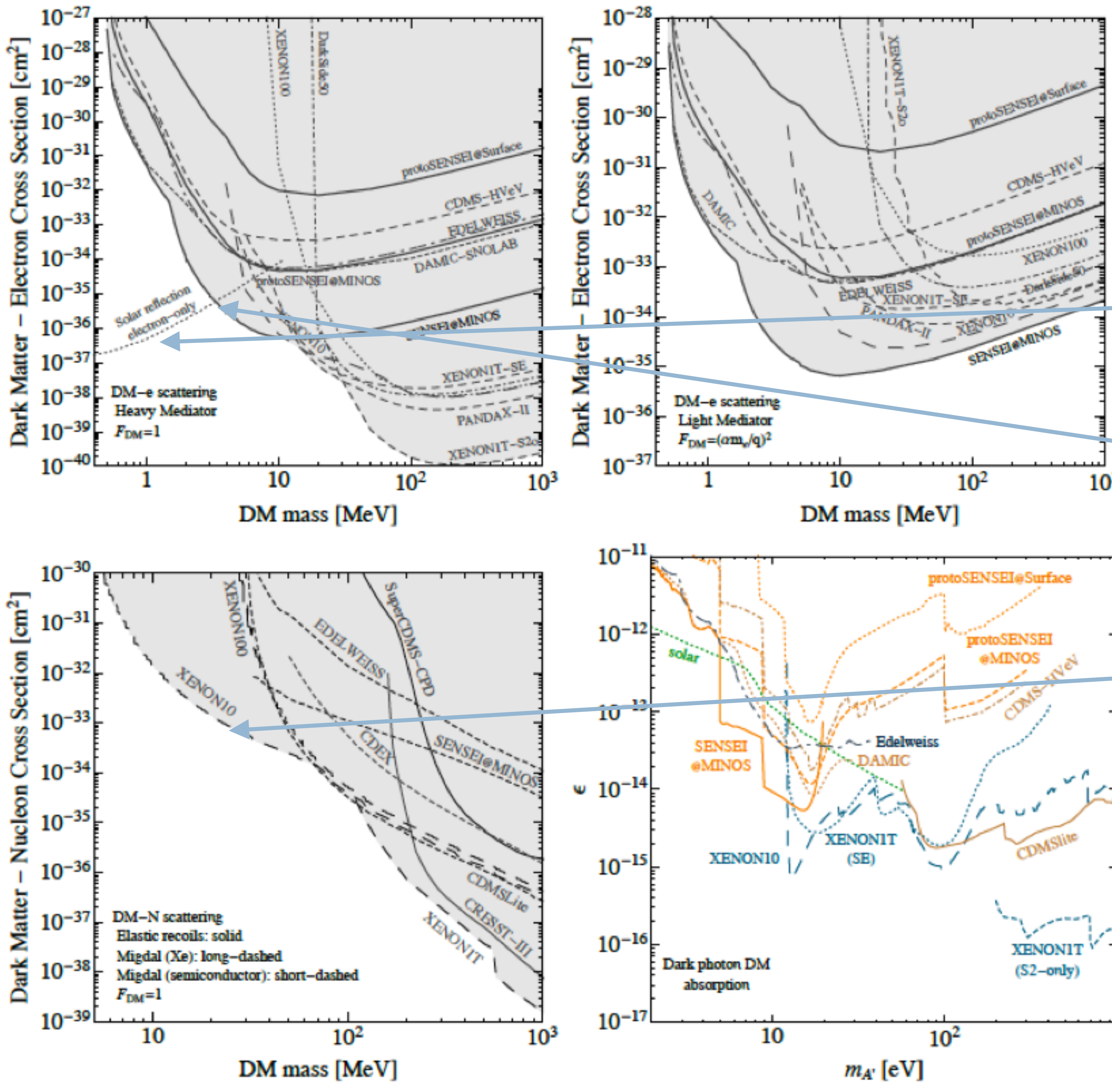
Results on spin-dependent DM searches



- Spin-dependent limits are less stringent than Spin-independent limits.







Essig, arXiv:2203.08297 (2022), SNOWMASS

Solar reflected DM bounds is interesting.

DM-electron limits improved by single electron measurements of SENSEI & DAMIC Will further improve with larger mass and lower backgrounds.

DM-Nucleon limits are improved to lower mass with Migdal effect of XENON data. Will be improved with XENONnT & LZ.

Cooley, arXiv:2209.07426 (2022), SNOWMASS

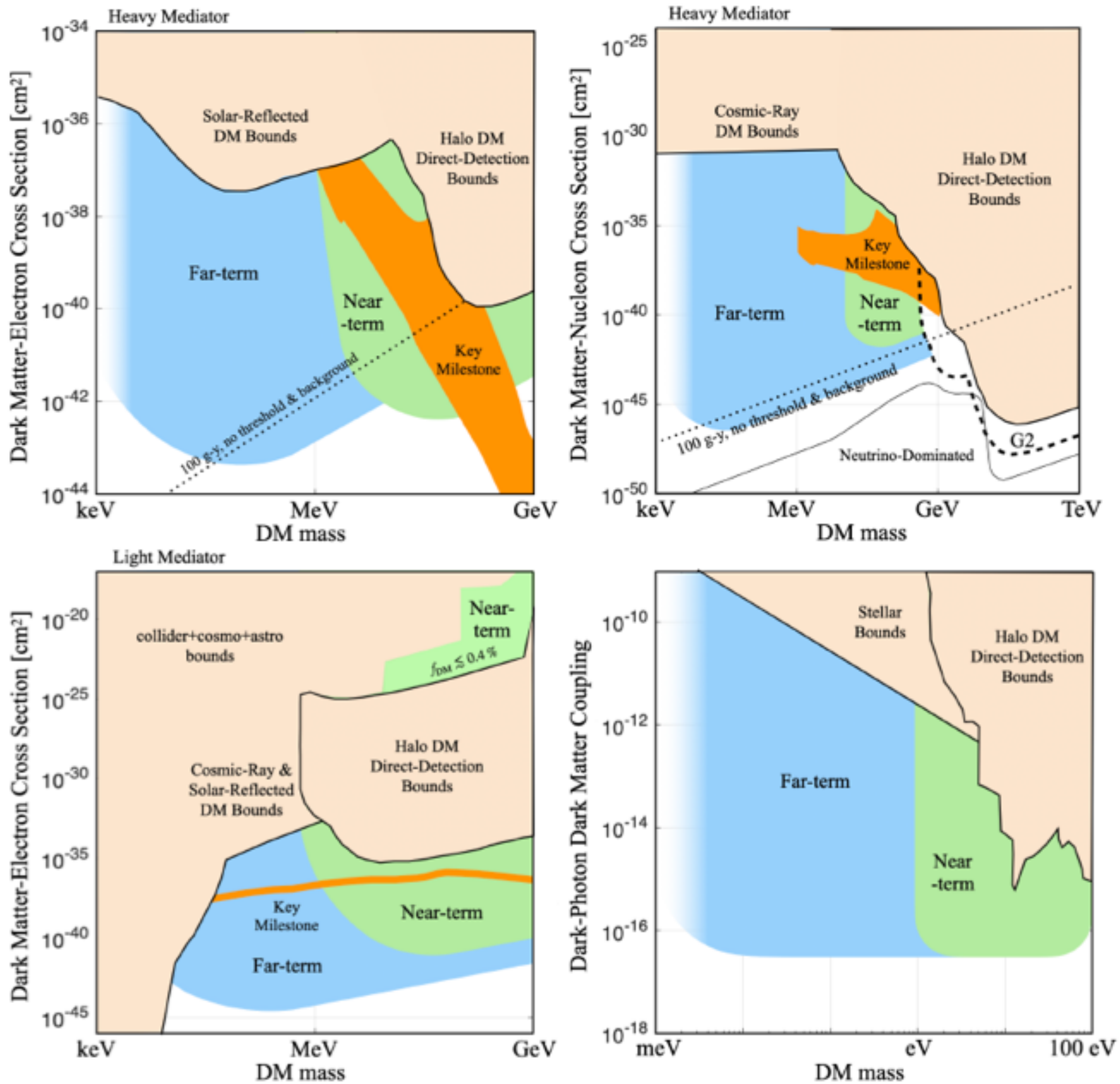
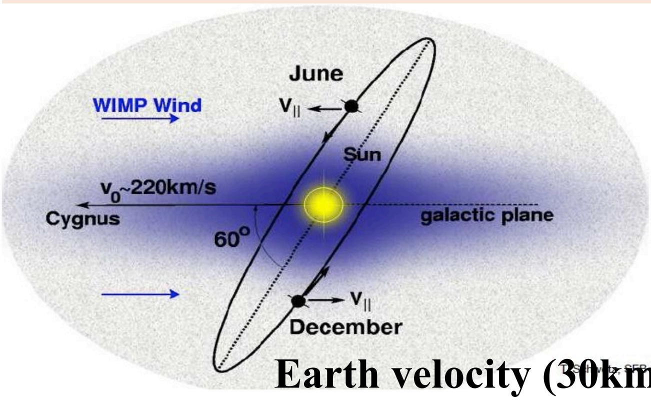
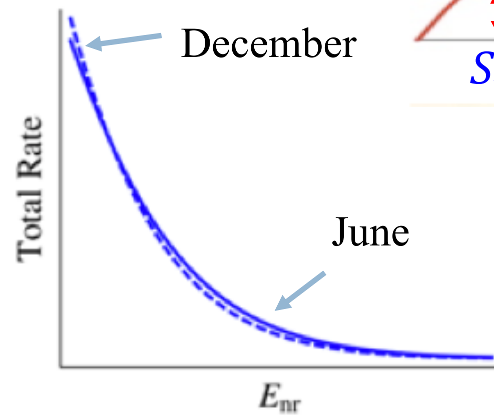


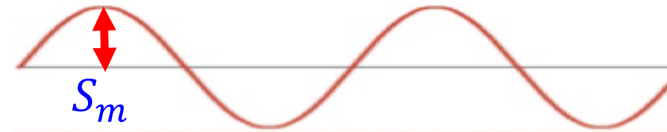
Figure 9: Figures are from Ref. [3] and updated from BRN report [33]. Current 90% c.l. constraints are shown in beige. Approximate regions in parameter space that can be explored in the next ∼5 years ("near-term", green) and on longer timescales ("far-term", blue). Orange regions labelled "Key Milestone" represent concrete dark-matter benchmark models and are the same as in the BRN report [33]. Along the dotted line DM would produce about three events in an exposure of 100 gram-year, assuming scattering off electrons in a hypothetical target material with zero threshold.

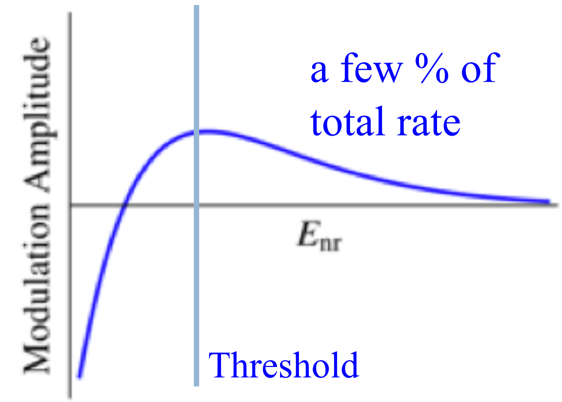
Potential Annual Modulation Signals

Yearly revolution → annual modulation







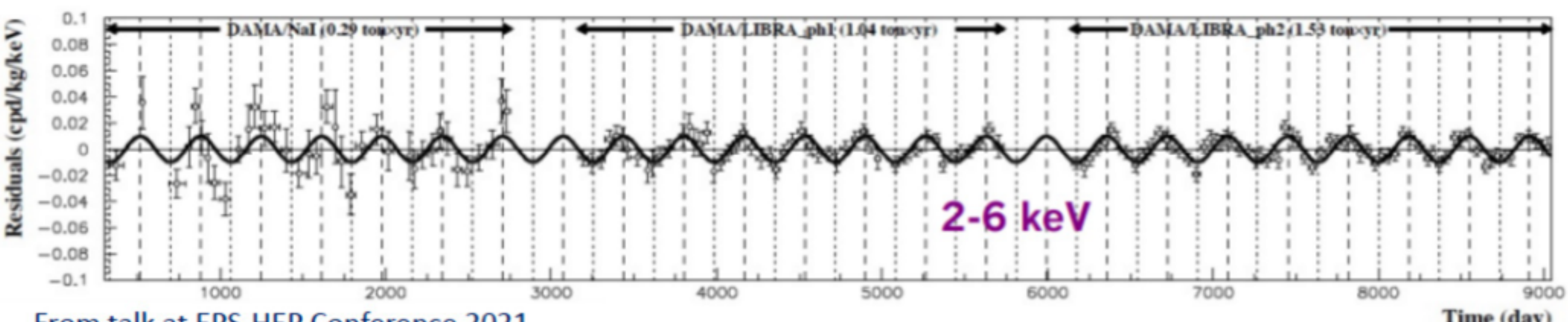


$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

S_0 : average event rate, S_m : modulation amplitude.

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

- DAMA/LIBRA annual modulation data



From talk at EPS-HEP Conference 2021

COSINE-100 detector

Hyunsu Lee

JINST 13 T02007 (2018)

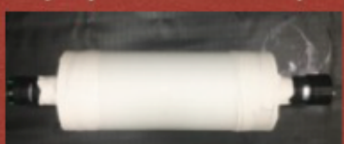
4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

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

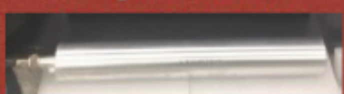
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector

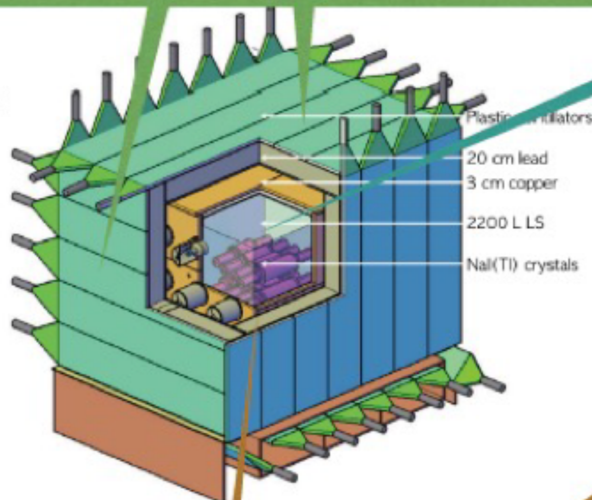
JINST 13 T06005 (2018)

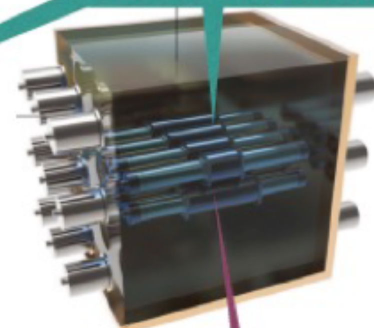
Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

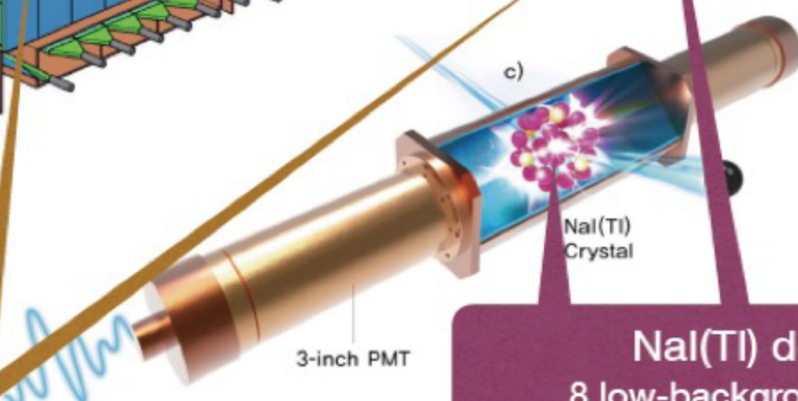


Thermal neutron detector
(^{3}He gas detector)









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

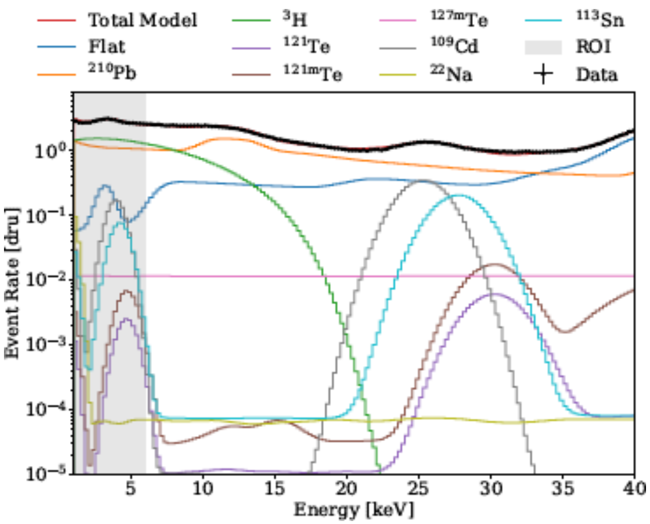
NaI(Tl) detector
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

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

Annual modulation (3 years data)

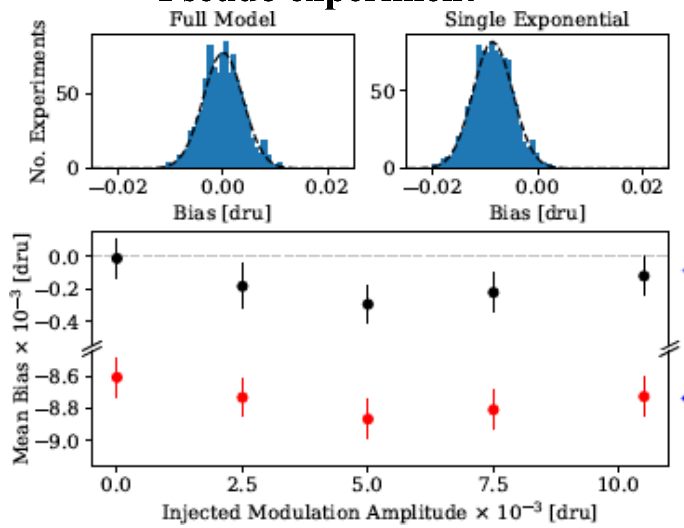
PRD 106, 052005 (2022)

Time dependent background modeling



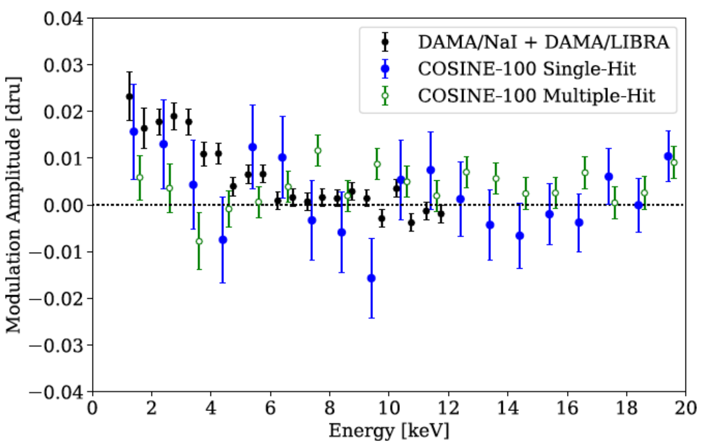
$$R(t) = \sum_i \left[C^i + \sum_j^8 A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t - t_0)}{T} \right)$$

Pseudo experiment



Full model

Single exponential



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

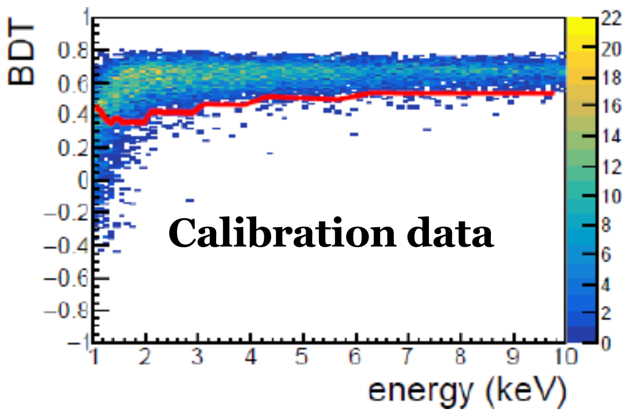
1-6 keV modulation amplitude

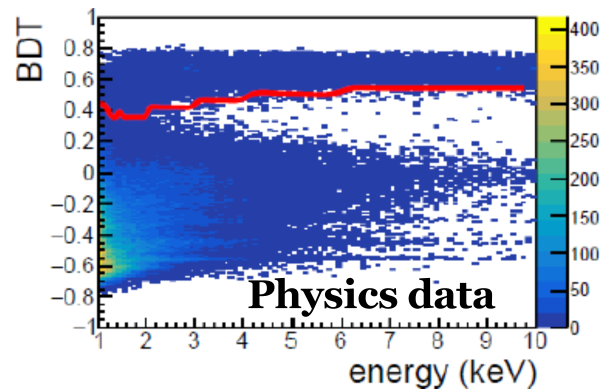
COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

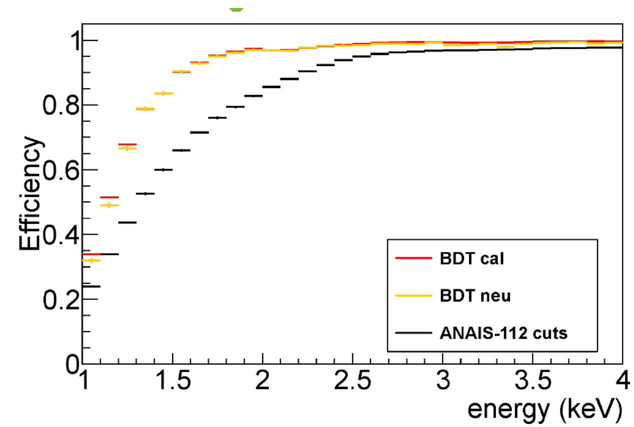
ANAIS-112 (3 years data revisiting)

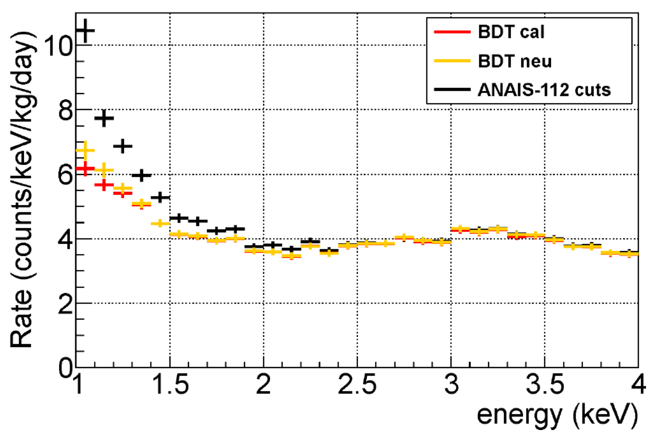
Amare et al., PRD103,102005 (2021)

Boosted Decision Tree (BDT)-based machine learning

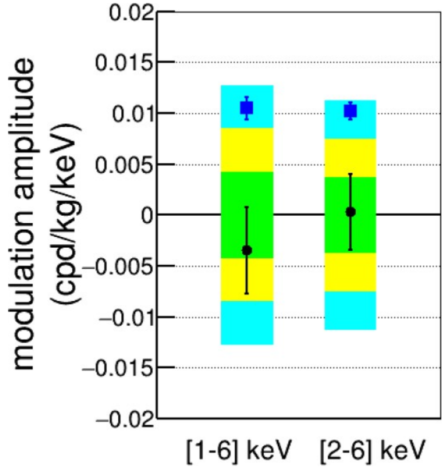




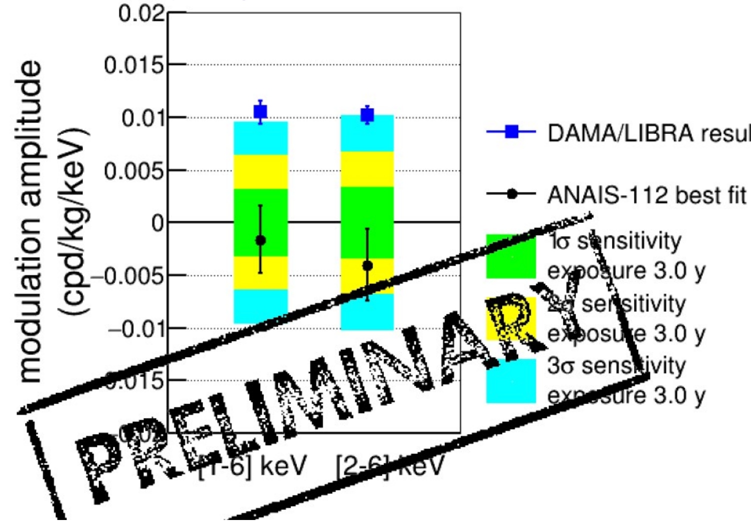




PRD result



Revisit with BDT



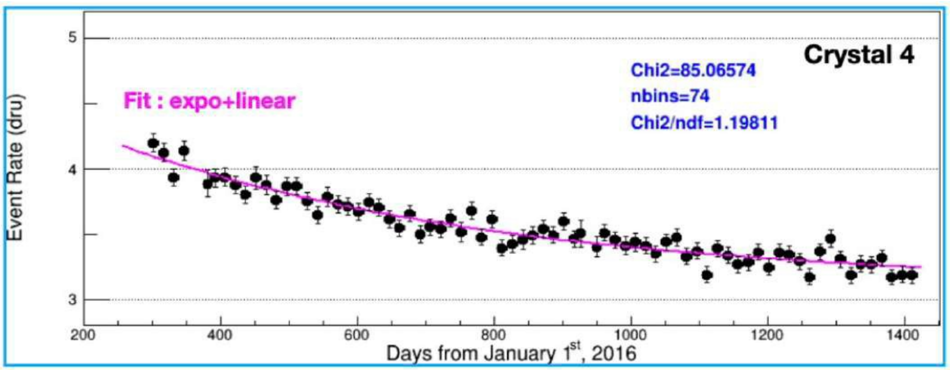
Incompatible with DAMA at 3.8σ(4.2σ) in 1-6 (2-6) keV region

COSINE data w/ DAMA/LIBRA's method

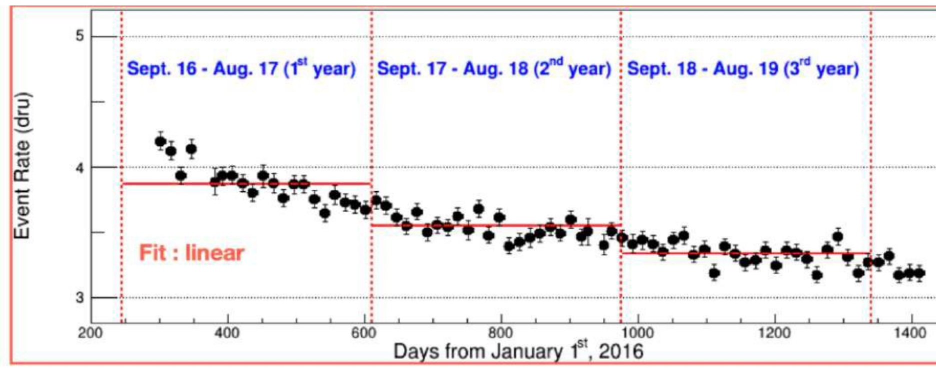
- DAMA/LIBRA group analyzed the modulation yearly, but never reported the yearly b ackground level. We applied DAMA/LIBRA's method to COSINE data.

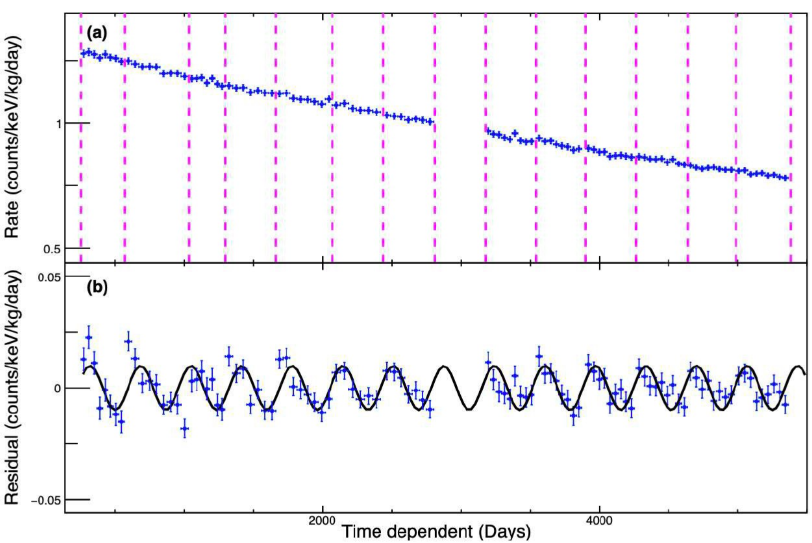
Buttazzo et al., JHEP 20, 137 (2020) "Annual modulations from secular variations: relaxing DAMA?"
Messina et al., JCAP 04, 037(2020) "Annual modulations from secular variations: not relaxing DAMA?"

COSINE/ANAIS method

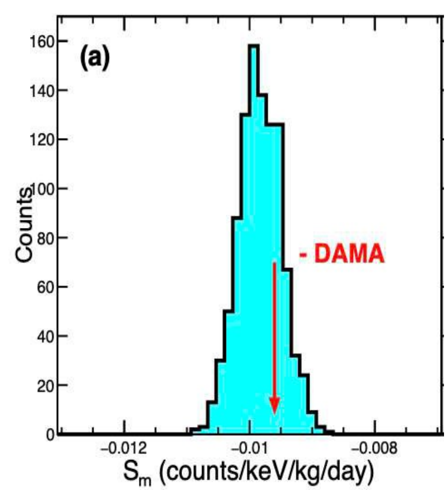


DAMA/LIBRA's method



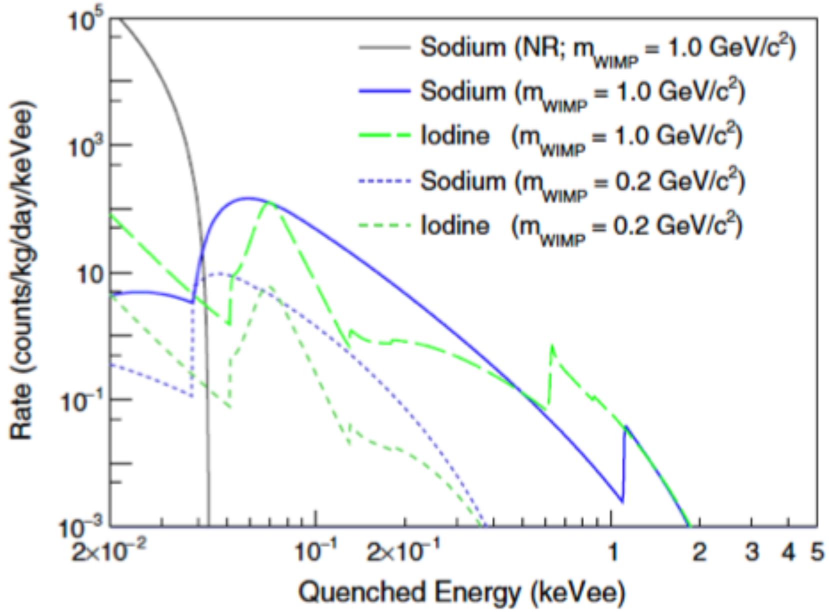


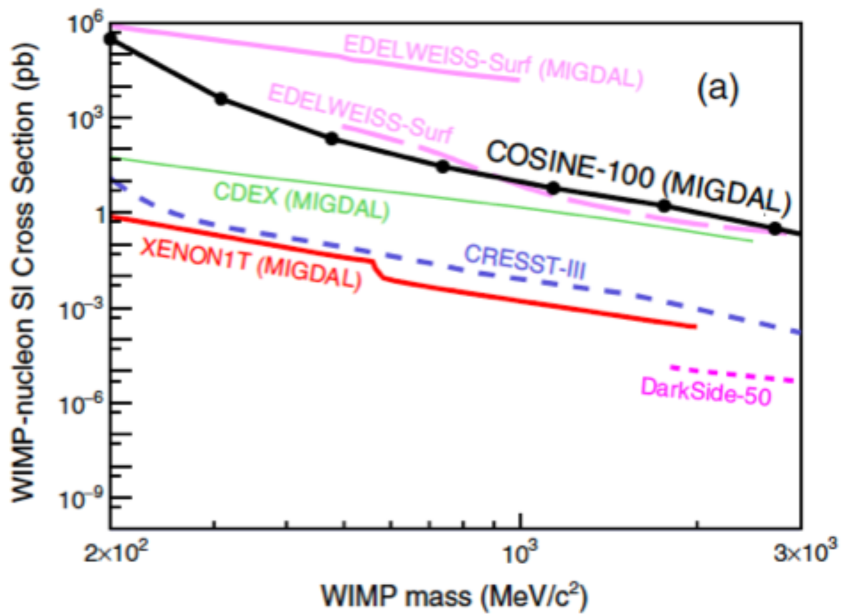
arXiv:2202.09672

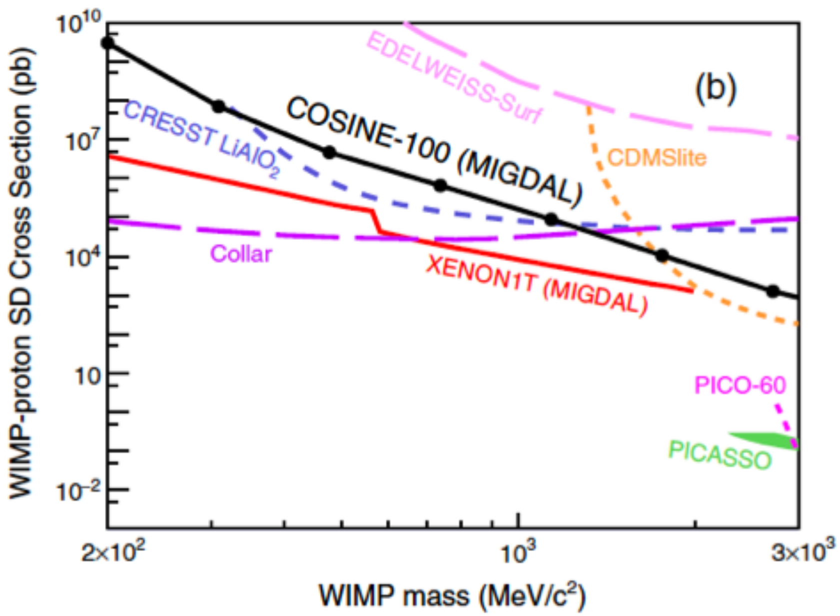


- Modulation amplitude but opposite phase is observed.
- DAMA group replied in a paper that repeating fit with linear varying term doesn't change their previous analysis.

Migdal effect with COSINE-100

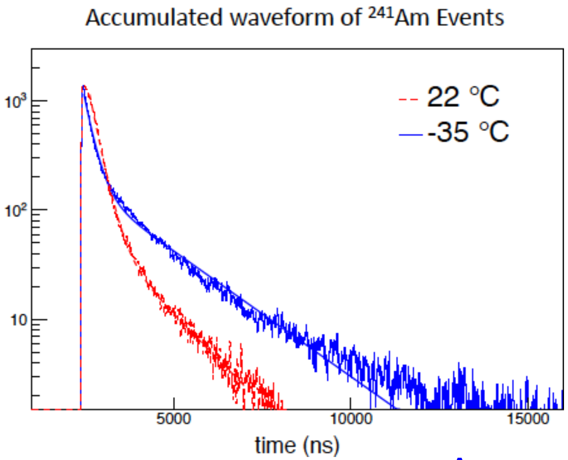




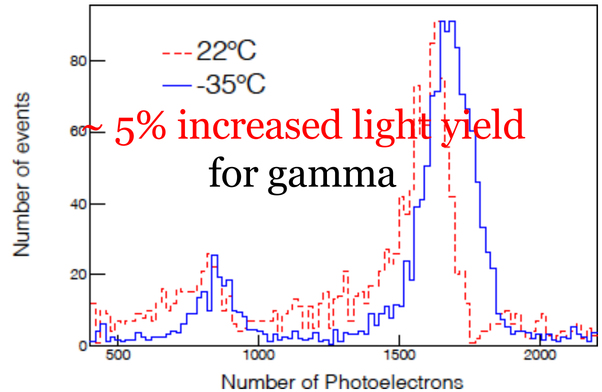


Low temperature (-30°C) response

PMT measurement

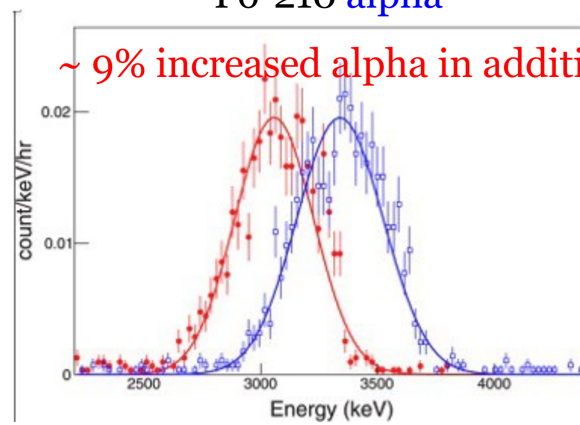


Am-241 measurement



~ 5% increased light yield for gamma

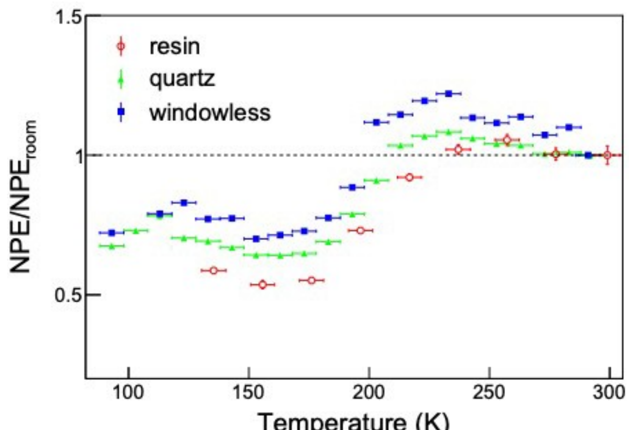
Po-210 alpha



~ 9% increased alpha in addition

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

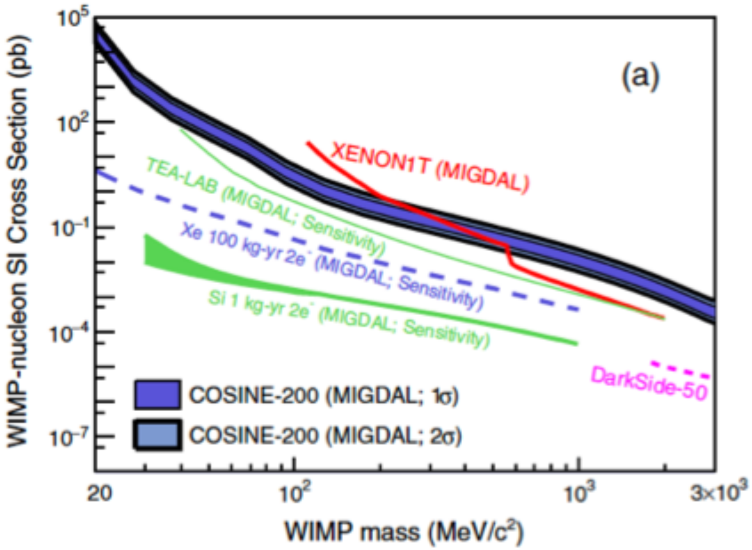
Yemilab facility is under construction

Hyunsu Lee

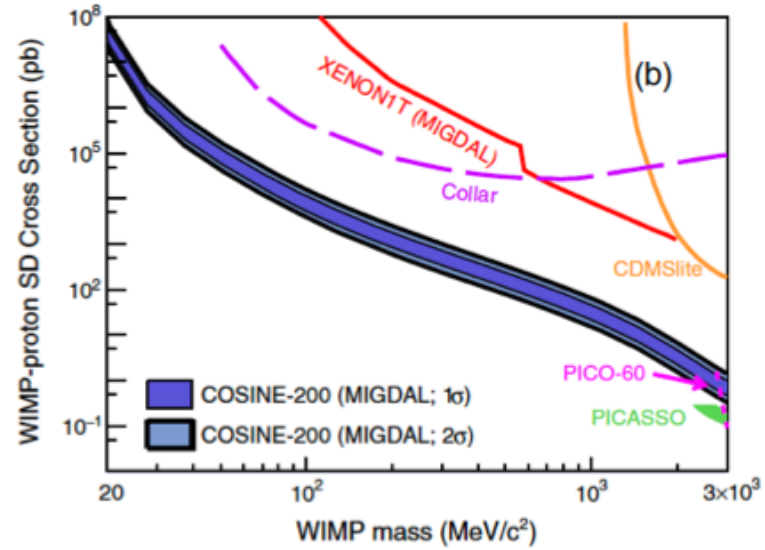
Sensitivites of COSINE-200

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

WIMP-proton spin-dependent

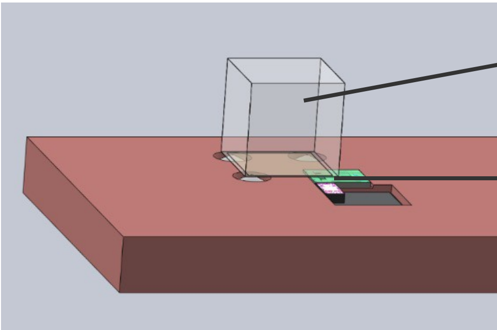


Low mass search with Migdal



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

Low Mass DM search @ CUP



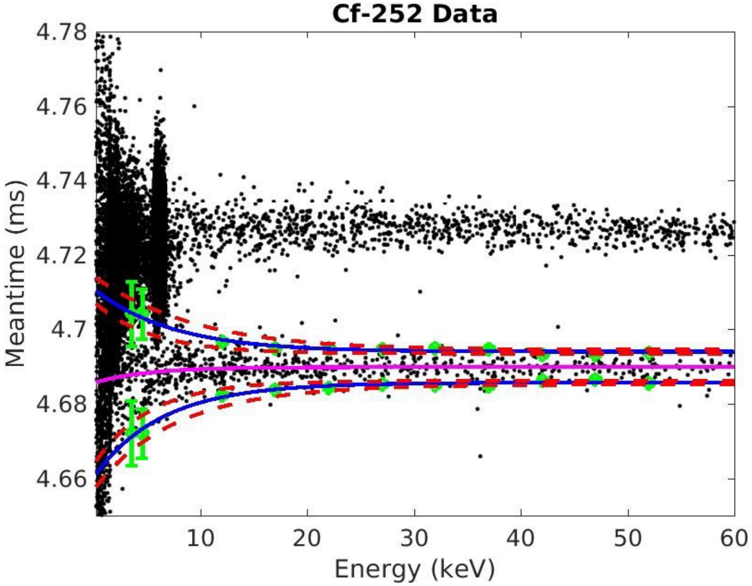
Many choices: **LiF, CaF$_2$, Sapphire(Al$_2$O$_3$)**(SD)
CaMoO4, Diamond (SI)

MMC

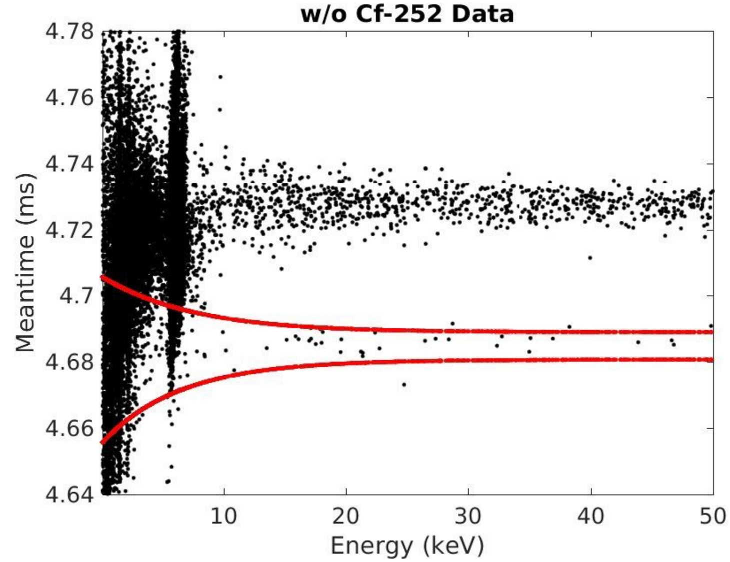
Yong-Hamb Kim

First trial with CaF$_2$ (5×5×5 mm^3, 0.4g) 30 mK at ground laboratory. $^{19}_{9}F$ is proton spin isotope.

w/ neutron source



w/o neutron source



- It is promising to see good PSD even w/o light detector.
- Preliminary energy threshold ~ 50 eV.
- Will test various crystals for optimization, and further @ underground

Are neutrinos Majorana particles ?

- In standard model (SM), the charged fermions (electrons) are Dirac particles, with 4 states, 2 spinors for electron and 2 spinors for positrons.
- SM has only left(right)-handed (anti)neutrinos.
- Since neutrinos are neutral, neutrinos and anti-neutrinos can be the same particle with different spin reducing to 2 states.

Dirac Neutrino Masses

$$L_D = -m_D(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R)$$

- Lepton # $is\ conserved$.
- Higgs mechanism needs right-handed neutrinos, ν_R.

$y^\nu: Yukawa\ Coupling \sim 10^{-12}$

Majorana Masses

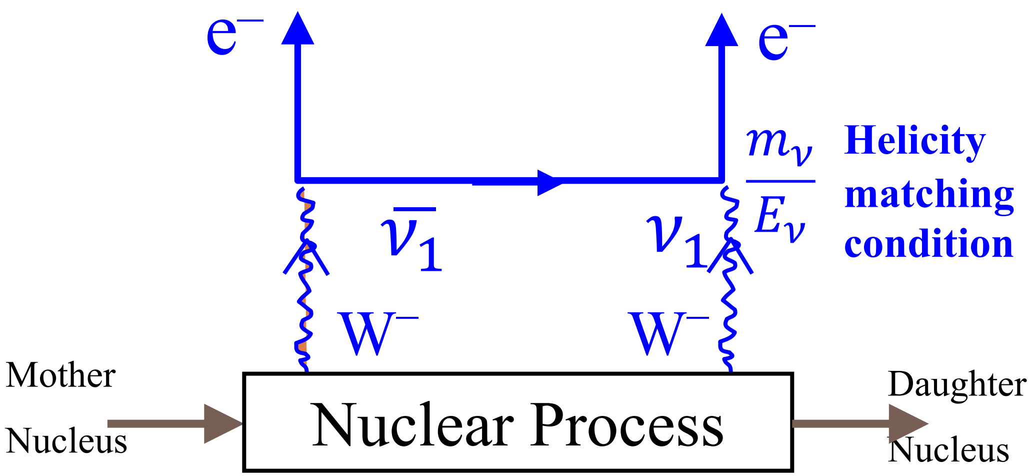
- "Majorana mass term" can be ; $L_R = -m_R/2\left[\overline{(\nu_R)^c}\nu_R + \overline{\nu_R}(\nu_R)^c\right]$
- $(\nu)^c = \nu \ \rightarrow$ Majorana particle (No L# is needed)
- See-Saw Mechanism gives two Majorana mass eigenstates,

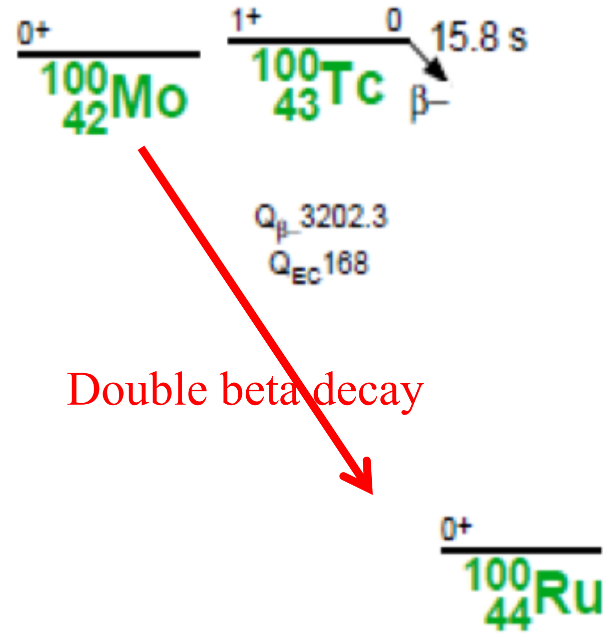
$$m_1 \simeq \frac{m_D^2}{m_R}$$
$$m_2 \simeq m_R$$

most promising BSM physics !

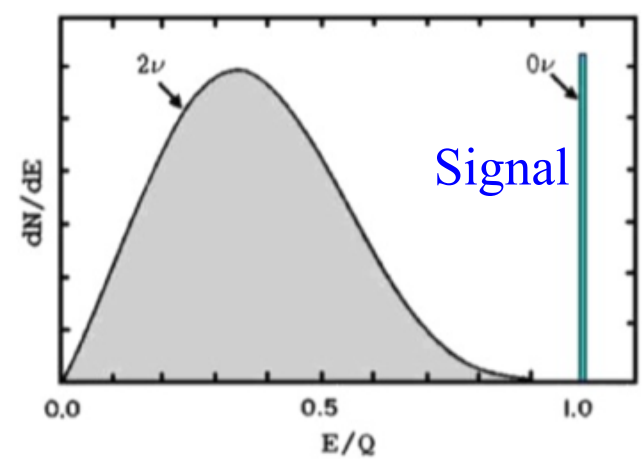
How to test if neutrinos are Majorana particles ?

- Seek neutrinoless double beta decay (0νββ)





- 1939, Furry already suggested to search 0νββ to check Majorana's theory. Furry PR56, 1184(1939)
- In the limit of m→0, it is not possible to distinguish between Dirac and Majorana neutrinos. (Dirac-Majorana confusion theorem)
- Lower energy is better to confirm Majorana nature.



More quantitatively…

for light neutrino exchange model.

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

Half-life Measured — **Phase factor** — **Nuclear Matrix Element** — **Effective 0νββ Neutrino Mass**

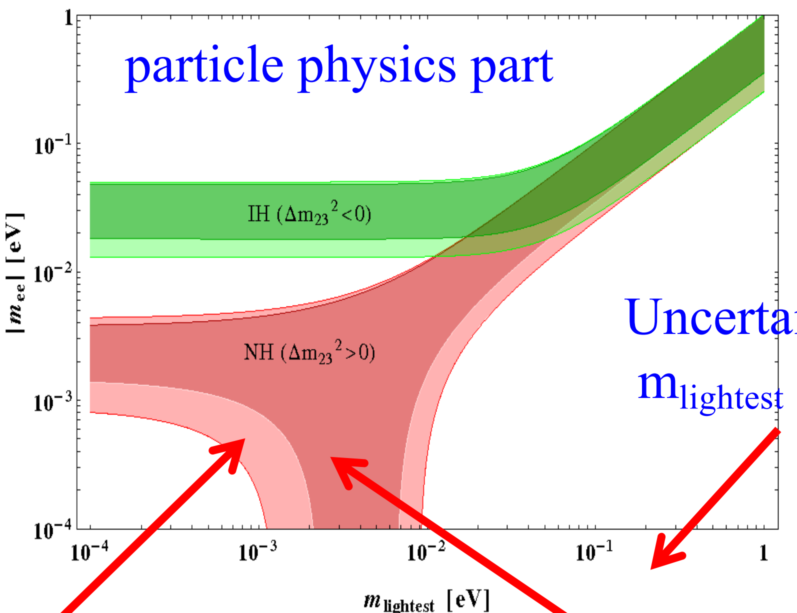
Effective 0νββ neutrino mass is ;

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| =$$

$$\left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$

particle physics part

$m_{\beta\beta}$

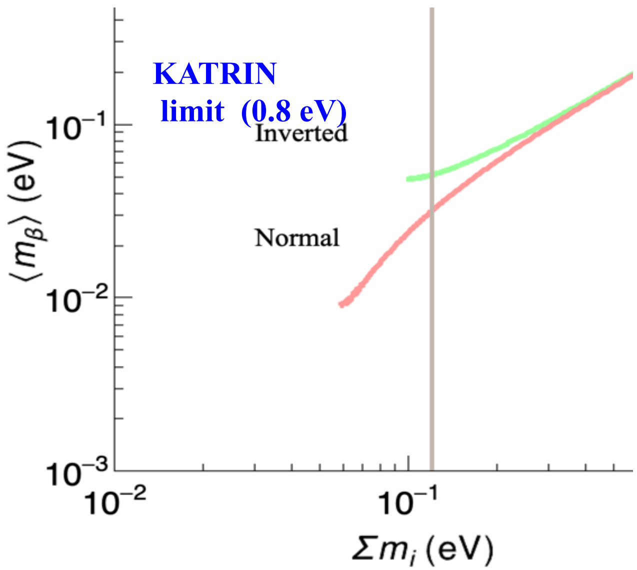


Uncertainties from m_{lightest}

Uncertainties from mixing angles

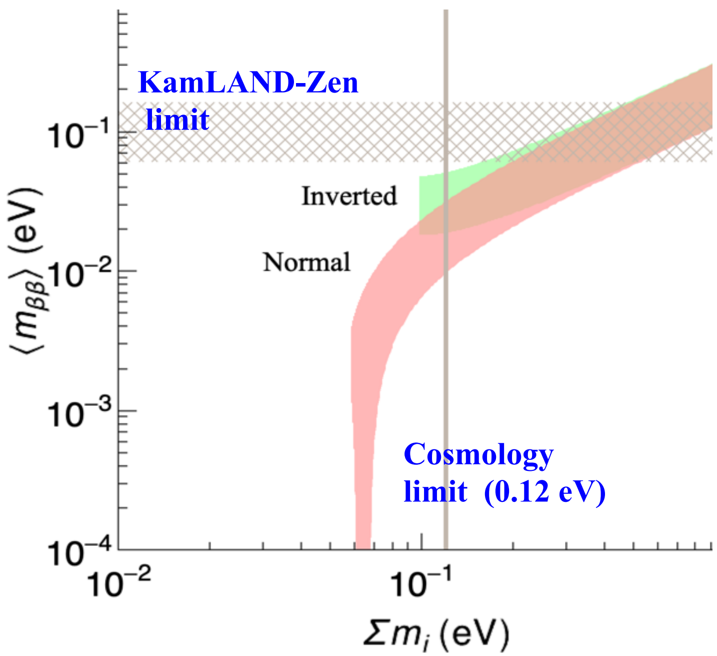
Uncertainties from phases

Neutrino mass limits

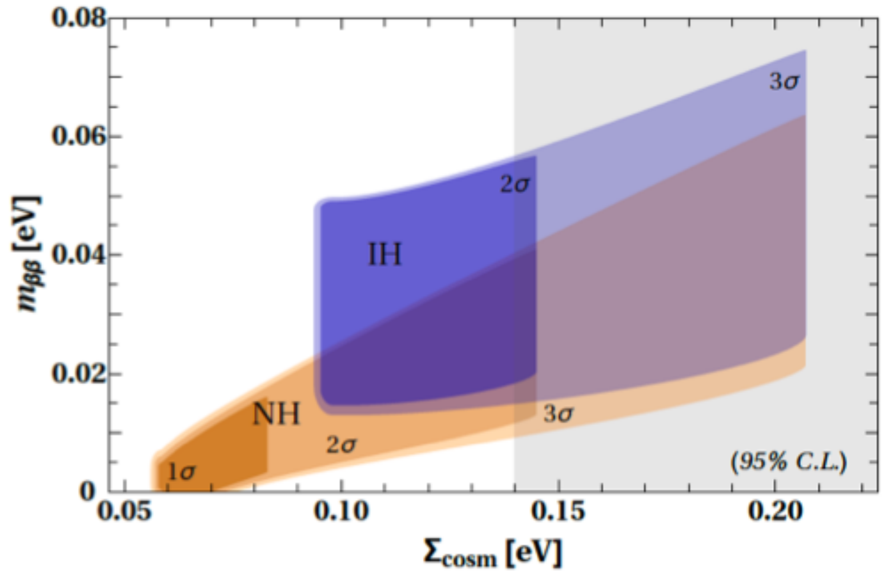


Current Neutrino Mass Limits

- Majorana nature of neutrinos is 80 year old question.
- Neutrino mass is ultra small, and we don't understand its origin.
- KATRIN's limit is more direct. No uncertainties.
- Neutrino mass is constrained by double beta decays and cosmology with model dependences.



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



Current best results for 0νββ

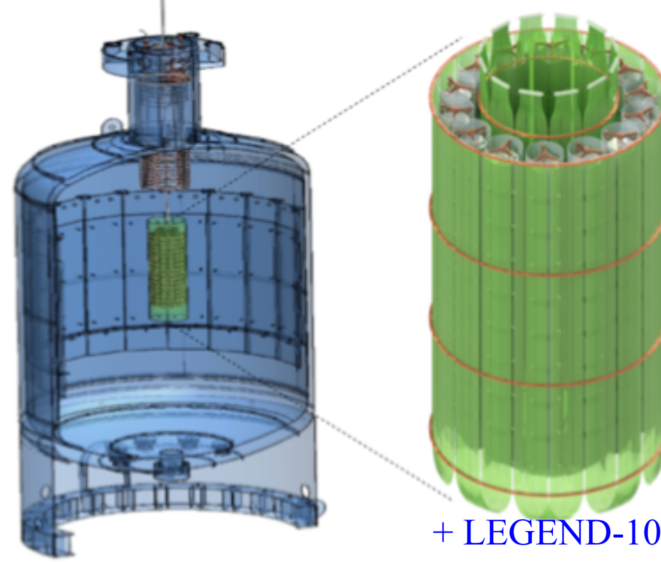
2023. 2. 12

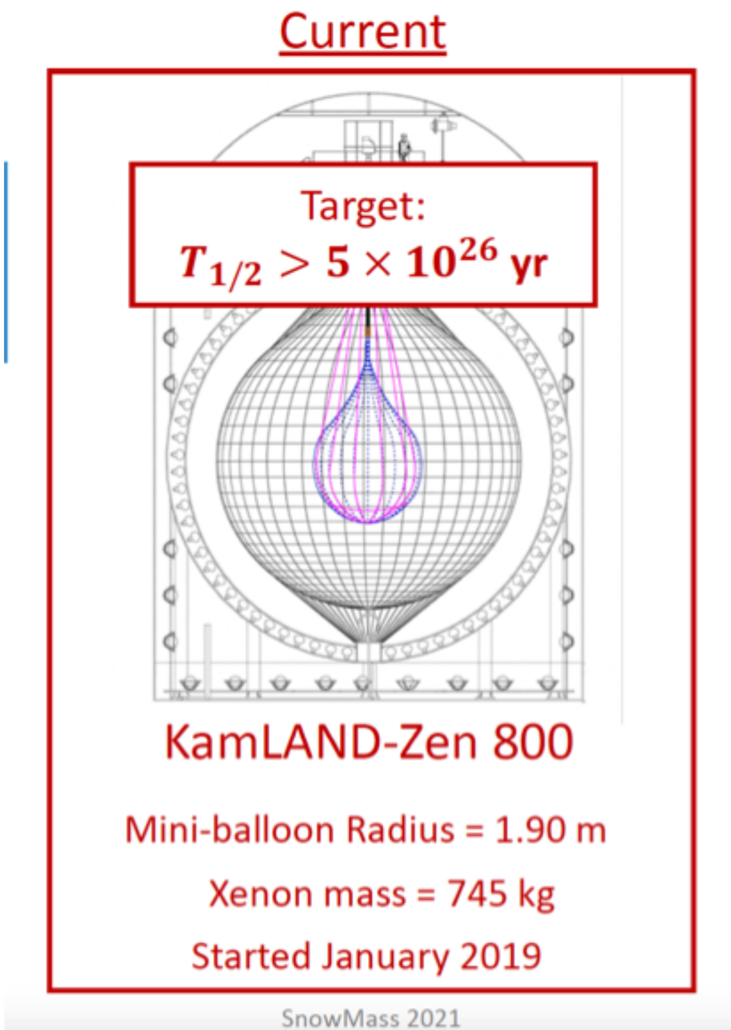
Nucl.	Q (keV)	Abun. (%)	$T^{2\nu}_{1/2}$ (10^{20} Y)	Exp	$T^{0\nu}_{1/2}$ (10^{24} Y)	M (meV)	Ref.
^{48}Ca	4270.0	0.187	0.53(0.1)	CANDLES	> 0.058	<3100-15400	PRC 78 058501 (2008)
^{76}Ge	2039.1	7.8	18.8(0.8)	GERDA-II	>180	<79-180	PRL125, 252502 (2020)
^{82}Se	2997.9	9.2	0.93(0.05)	CUPID-0	> 4.6	<263-545	PRL129, 111801 (2022)
^{100}Mo	3034.4	9.6	0.0688(0.0025)	CUPID-Mo	>1.8	<280-490	EPJC82, 1033 (2022)
^{116}Cd	2813.4	7.6	0.269(0.009)	AURORA	> 0.22	<1000-1700	PRD 98 092007 (2018)
^{130}Te	2527.5	34.5	7.91(0.21)	CUORE	> 22	<90-305	Nature 605, 53 (2020)
^{136}Xe	2458.0	8.9	21.8(0.5)	KamLAND-Zen	> 230	<36-156	PRL130, 051801 (2023)
^{150}Nd	3371.4	5.6	0.0934(0.0065)	NEMO-3	> 0.02	<1.6-5.3	PRD 94 072003 (2016)

Bolometer, Scintillation, Ionization

Near-future experiments

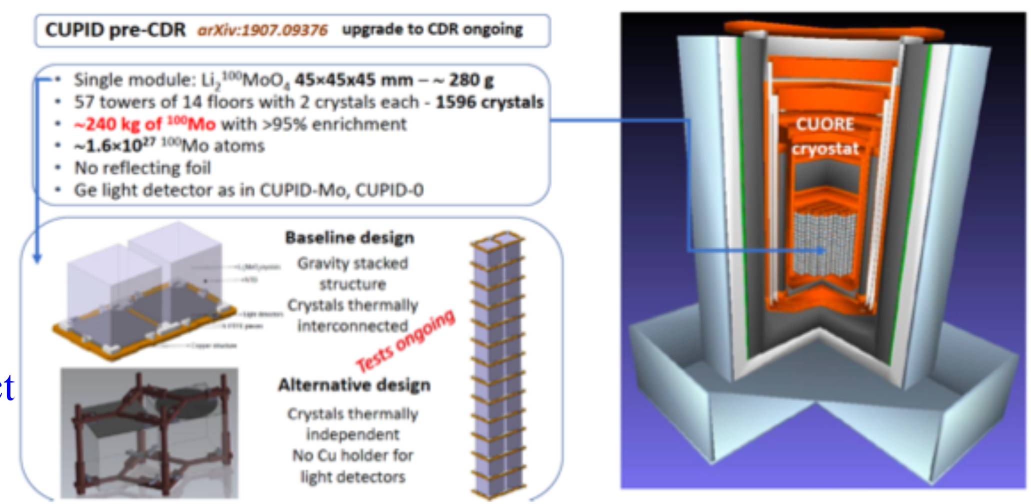
LEGEND-200 – ^{76}Ge Crystal detector





+ LEGEND-1000

CUPID – ^{100}Mo Cryogenic detector



KamLAND-Zen – ^{136}Xe Liquid Scintilltor detect

+ KamLAND2-Zen

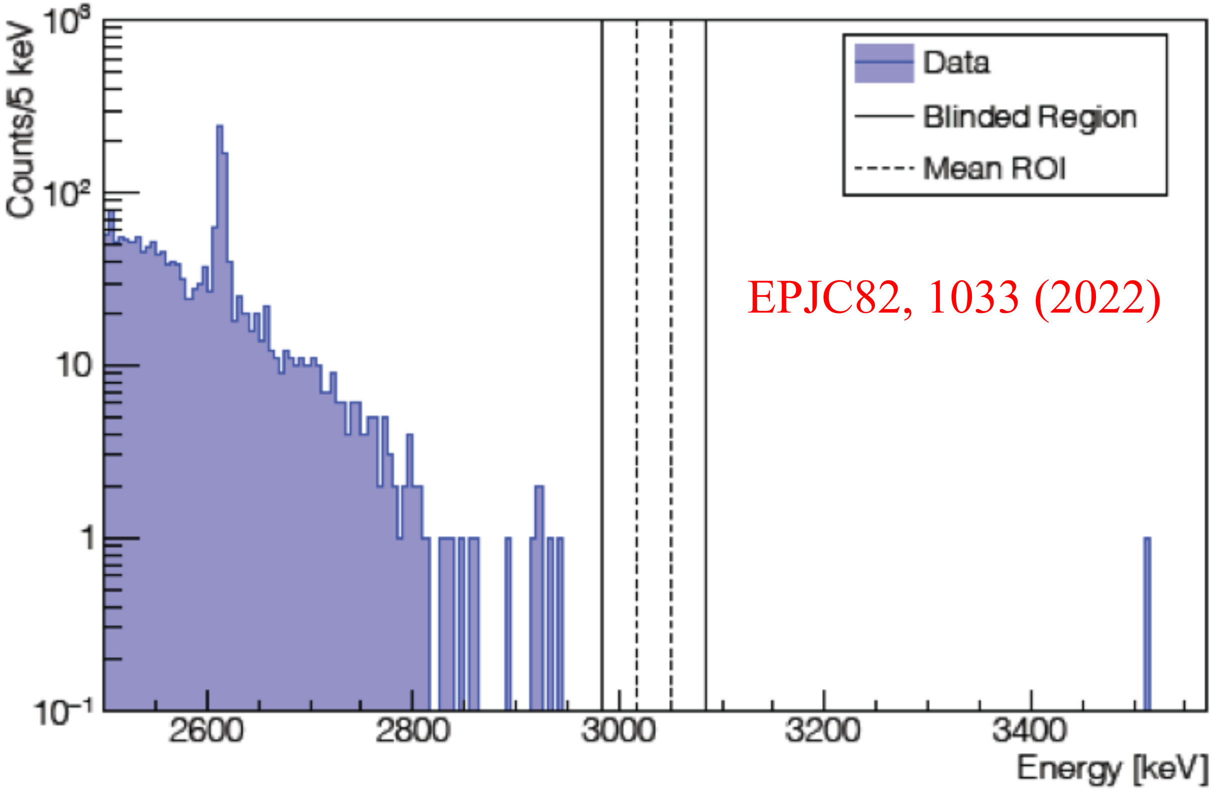
New Limits in 2022

CUPID-Mo

Exposure 1.47 kg year data(^{100}Mo),
Resolution 7.4(4) keV
Background ~5x10^{-3} ckky

$$T_{1/2}^{0\nu} > 1.8\times10^{24}\ year$$

~ 270 kg of Mo-100 scale experiment is proposed.

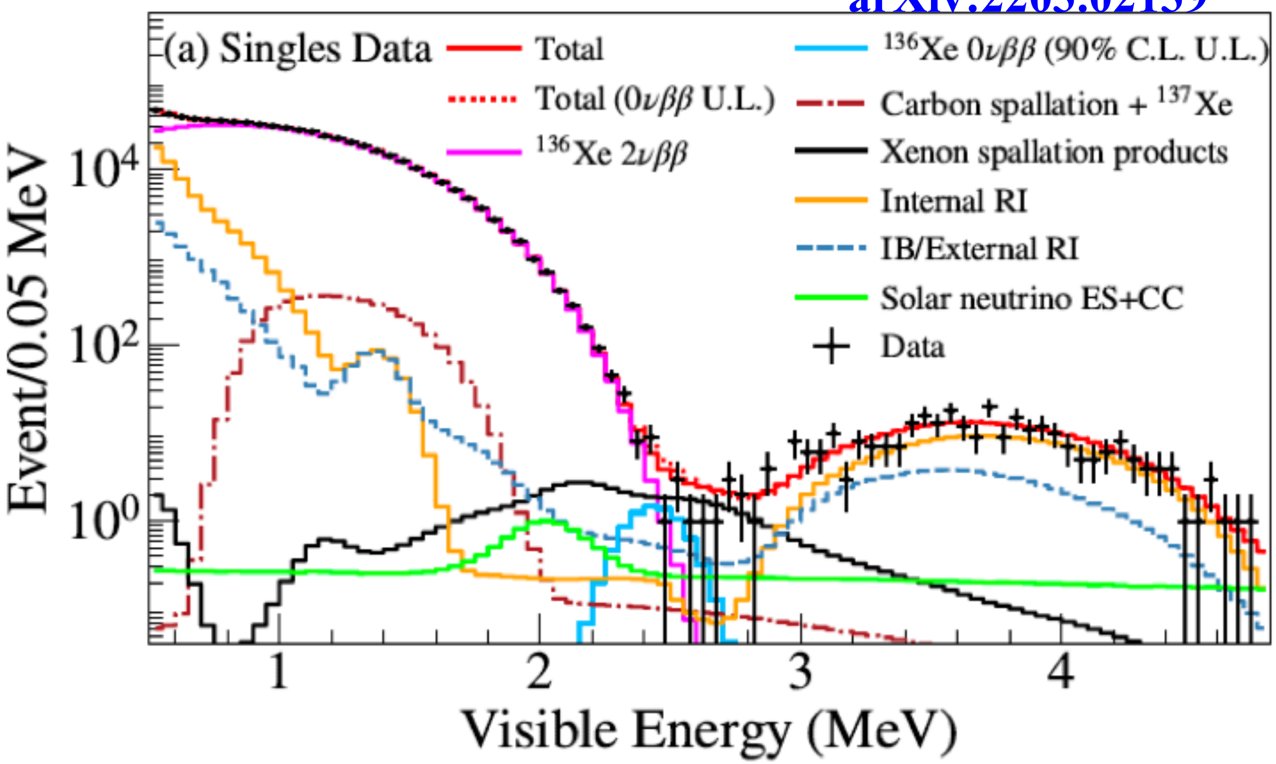


Kamland-Zen 800 kg

Exposure	510 kg year(^{136}Xe)
Resolution	247 keV
Background	2.35x10^{-3} ckky(isotope)

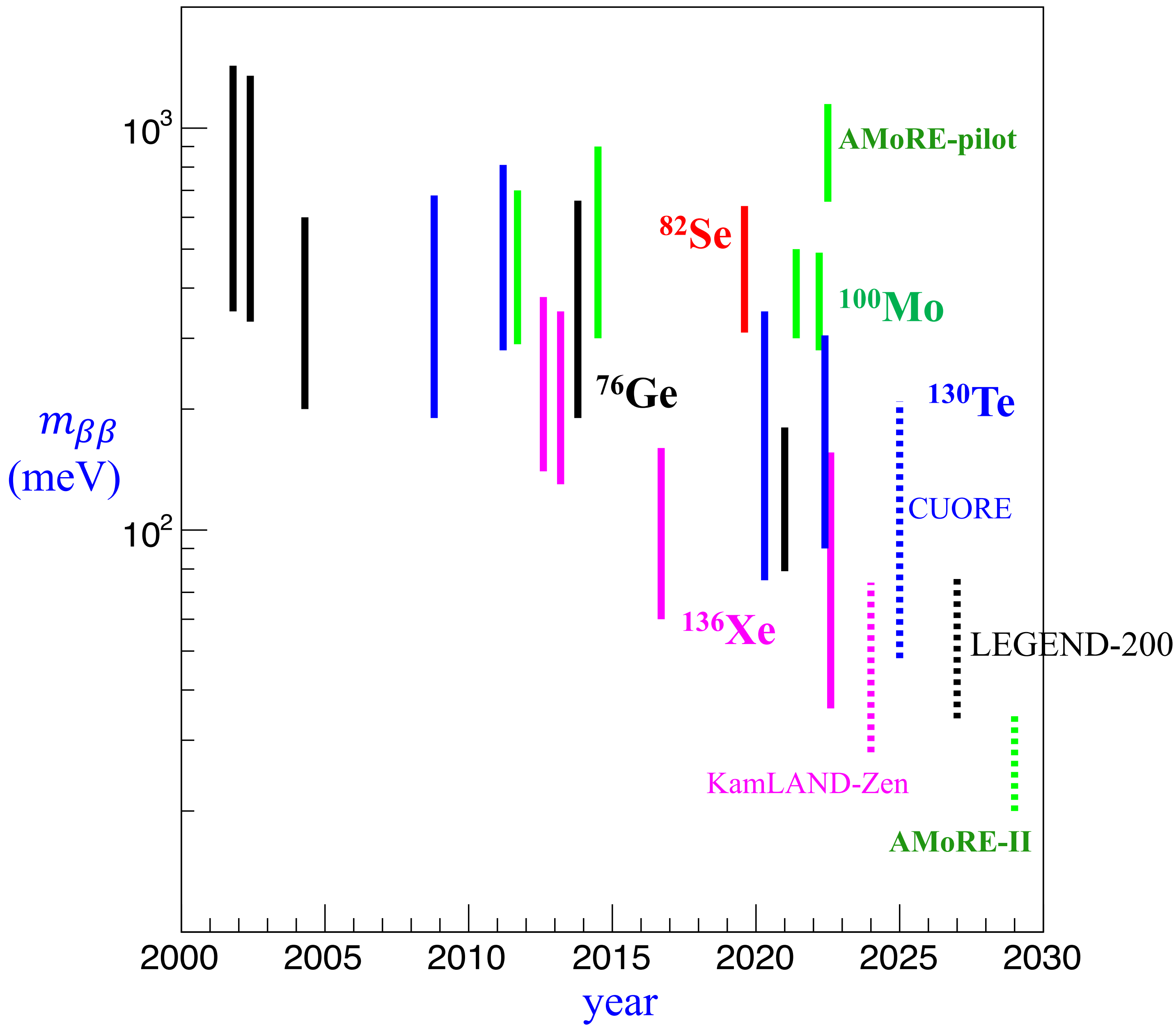
$T_{1/2}^{0\nu} > 2.3\times10^{26}\ year$

arXiv:2203.02139



- The Xenon spallation background is dominant. It may indicate Xe and Te experiments may be depth limited.

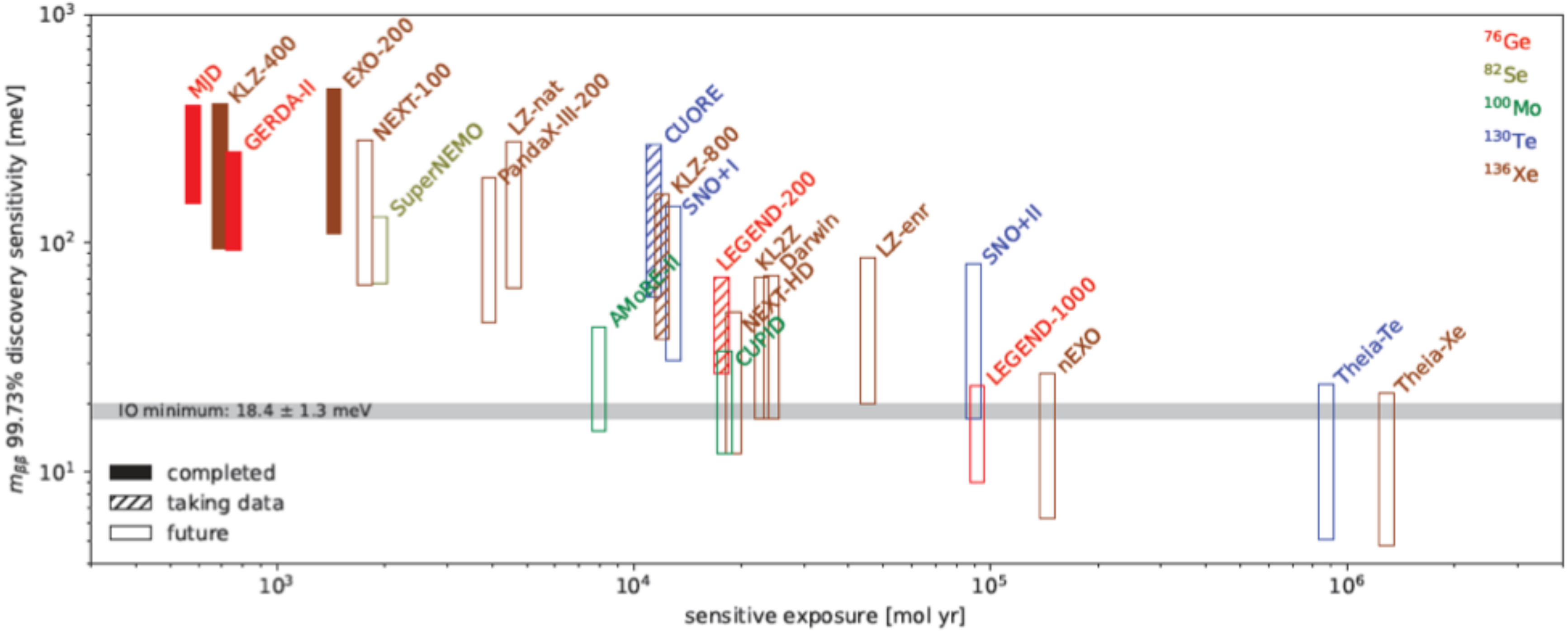
Recent Limits & Persepectives



Future

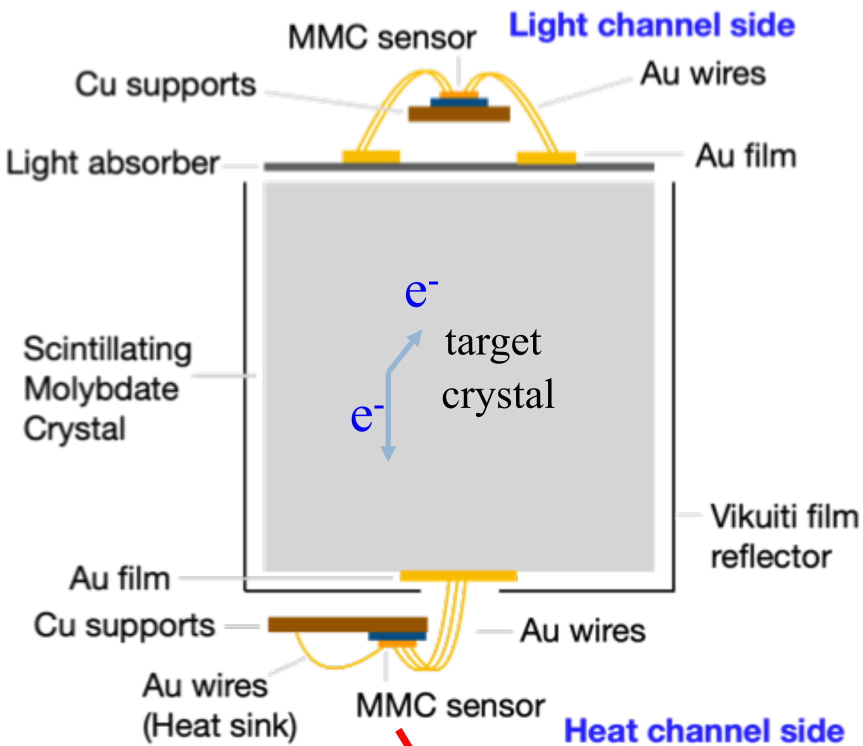
m_{bb} sensitivity vs exposure

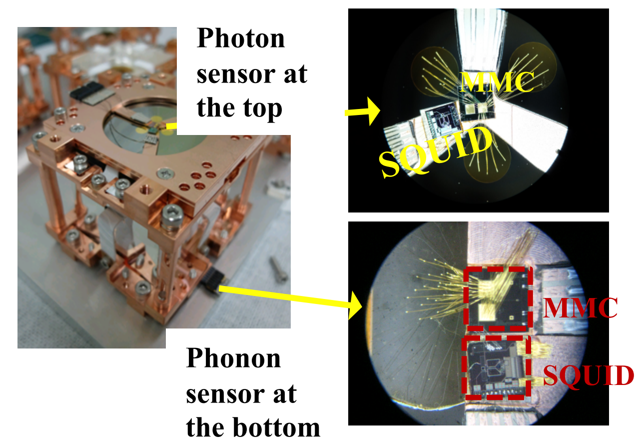
Adams et al., arXiv:2212.11099 (2022)

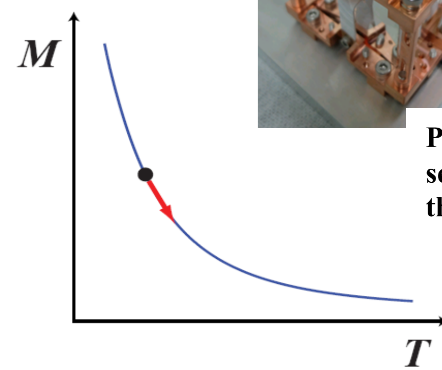


Principle of AMoRE detector

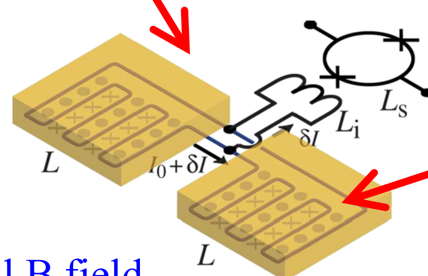
Decay→Phonons collected at Au foil → temperature of Au foil increase→magnetization of MMC decrese→ SQUID pick-up the change.







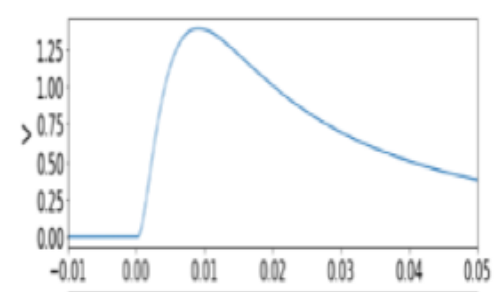
Au(Er) paramagnetic material



SQUIDS

Persistent current in superconductor

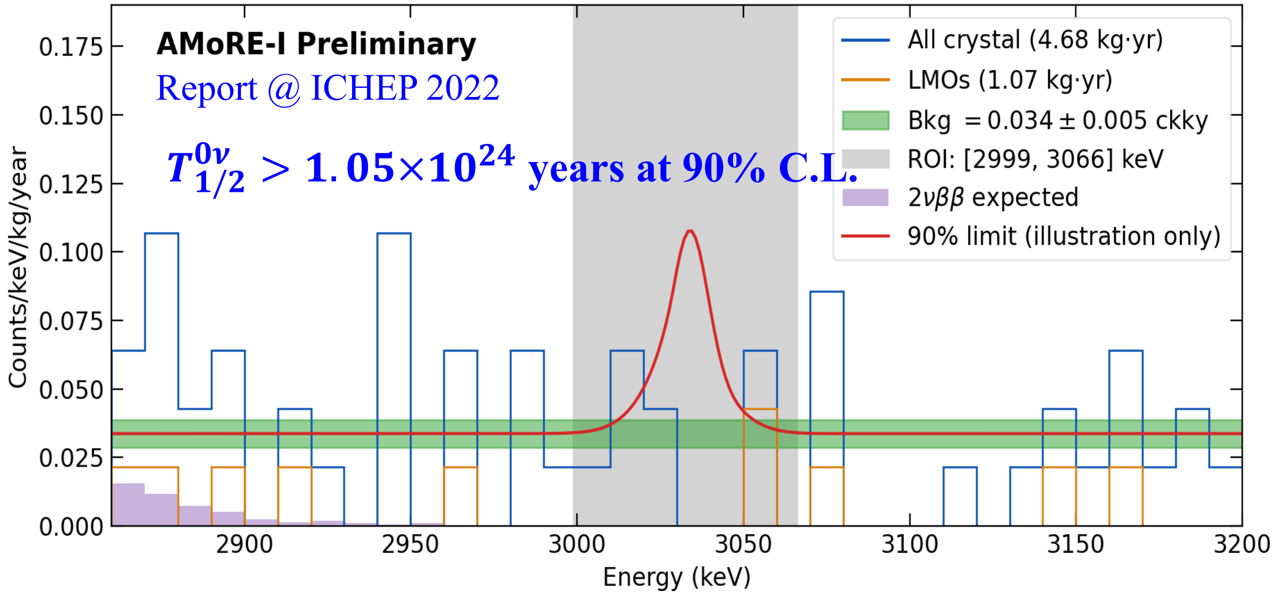
Local B field

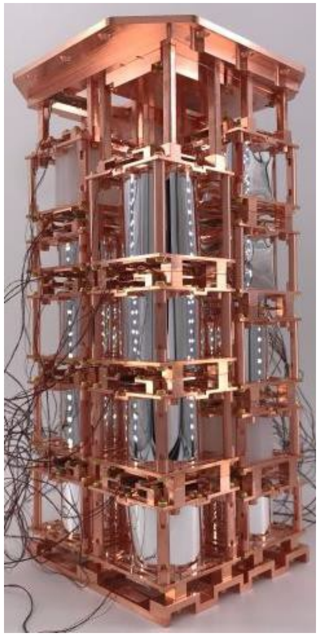


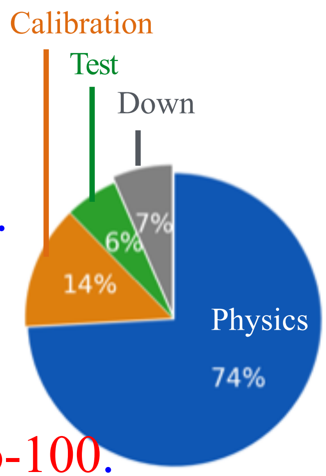
MMC: Metallic magnetic calorimeter

AMoRE-I : Running

- AMoRE-I began Aug. 2020 @ Y2L and runs stable.
- 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)







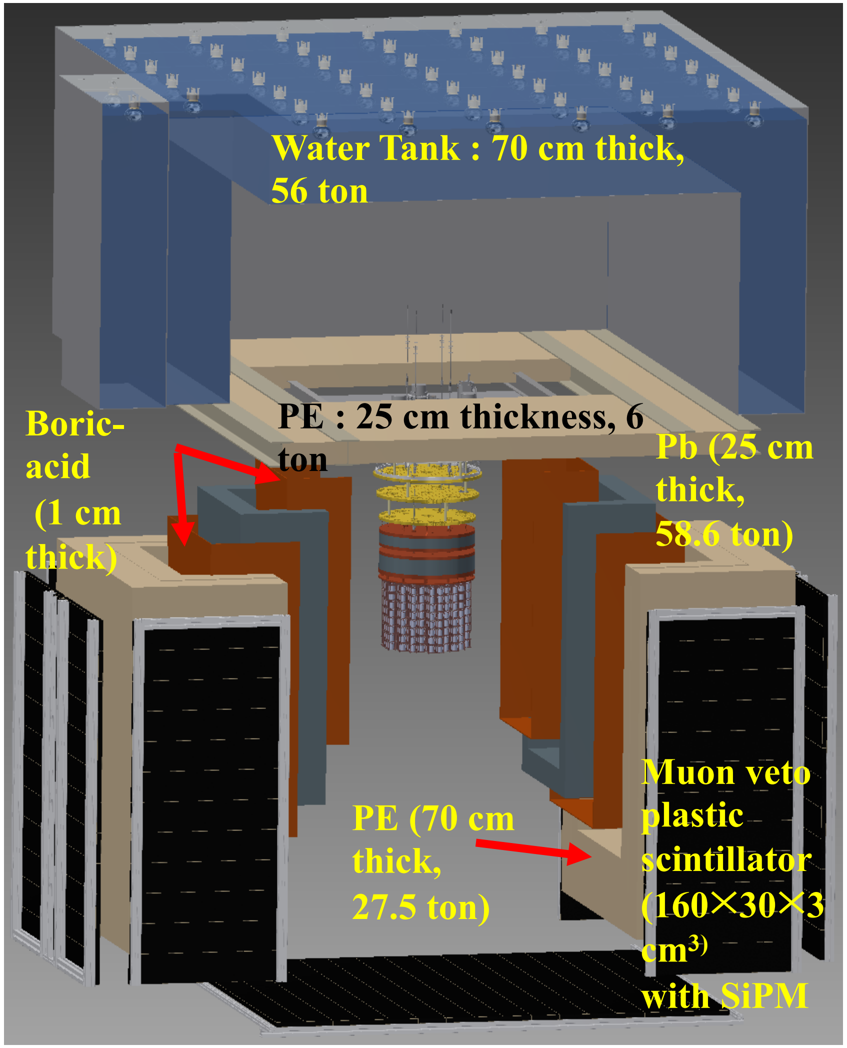
- Final data analysis is coming and will be reported in a few months.

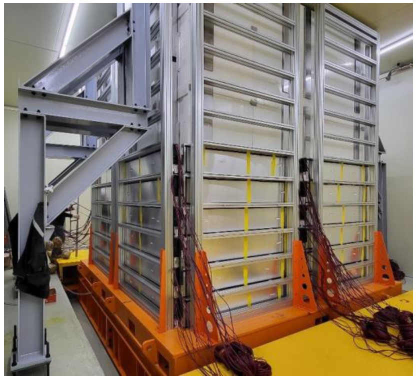
- Cf. $T^{0\nu}_{1/2} > 1.8\times10^{24}$ with 1.47 kg year of CUPID-Mo.
- We have > 4 kg year data and expect to be world best limit for Mo-100.

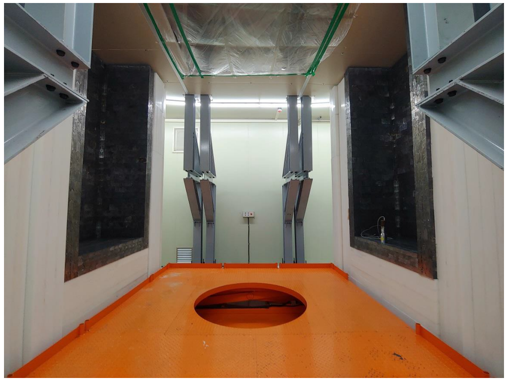
AMoRE-II : under preparation

- 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.

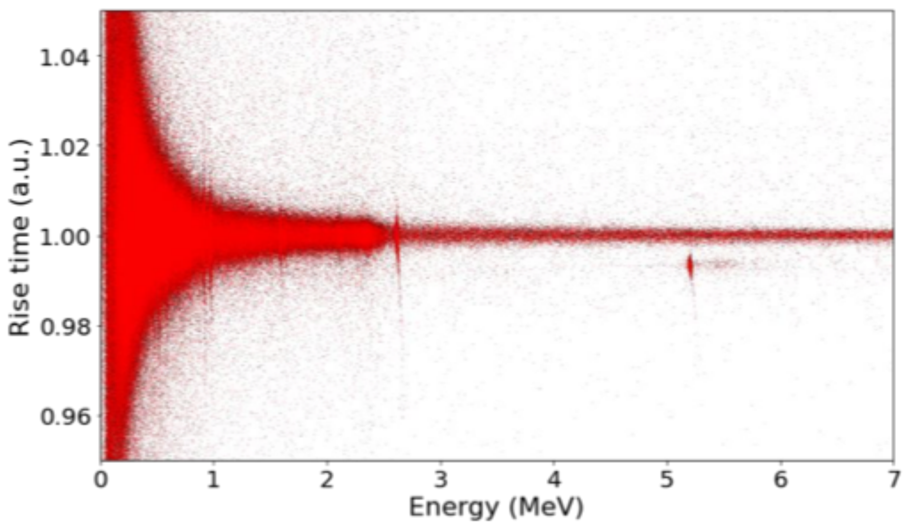


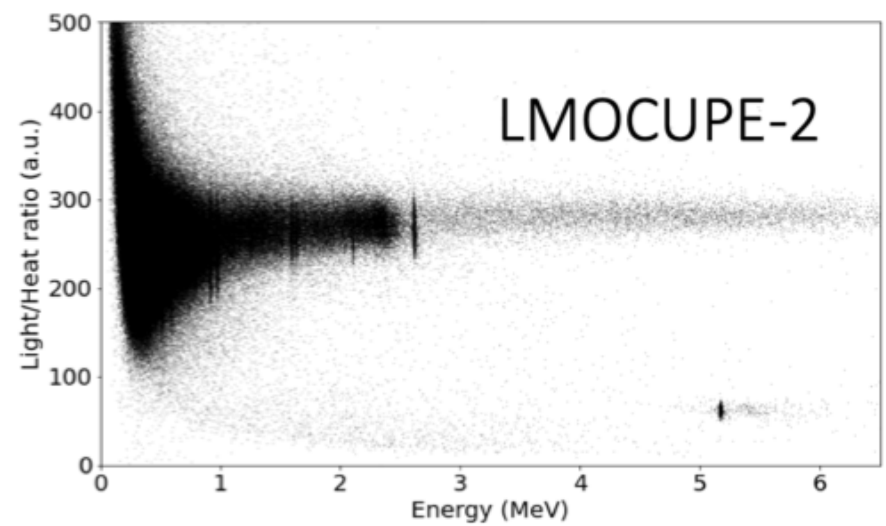




Recent developments

- Pulse shape discrimination w/o light detector data → Further background rejection is possible.
- For the first time, $Li_2{}^{100}MoO_4$ enriched crystal grown at IBS(Daejeon) shows satisfactory performance. Alpha rejection power is over 10.





- We have settled on the protocol for surface treatment of $Li_2{}^{100}MoO_4$ crystals. The performance is satisfactory Energy resolution (FWHM) < 10 keV.
- Cryostat is stable, and MMC-SQUID sensors are stable over years.

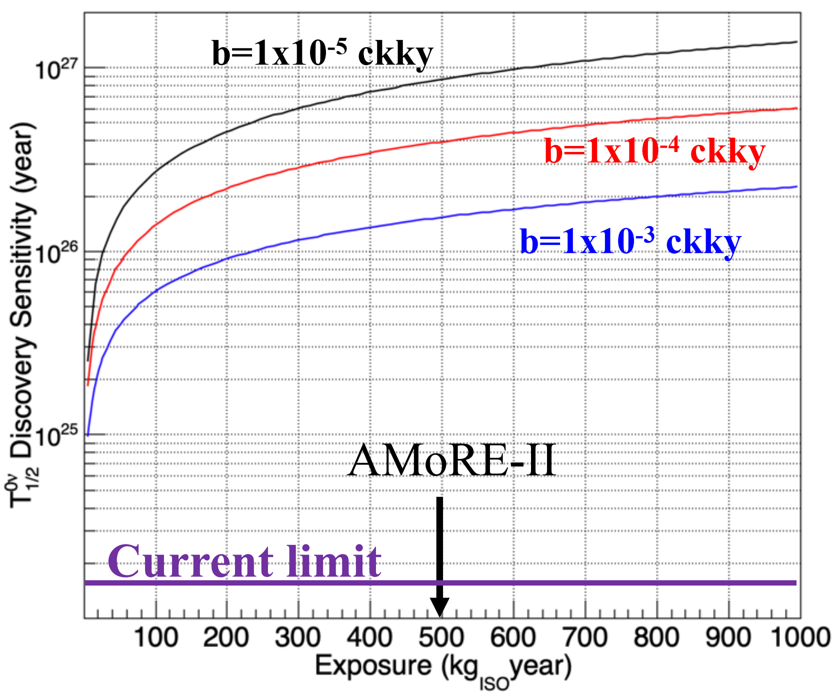
Sensitivity of AMoRE-II

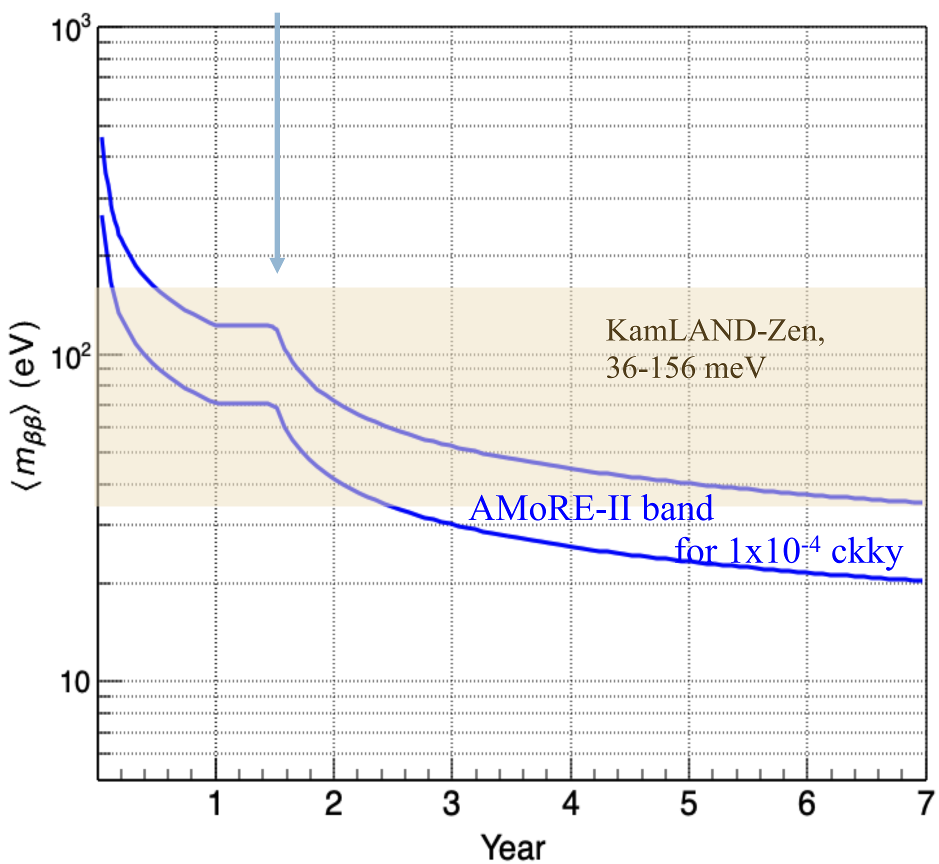
Discovery sensitivity :

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 :

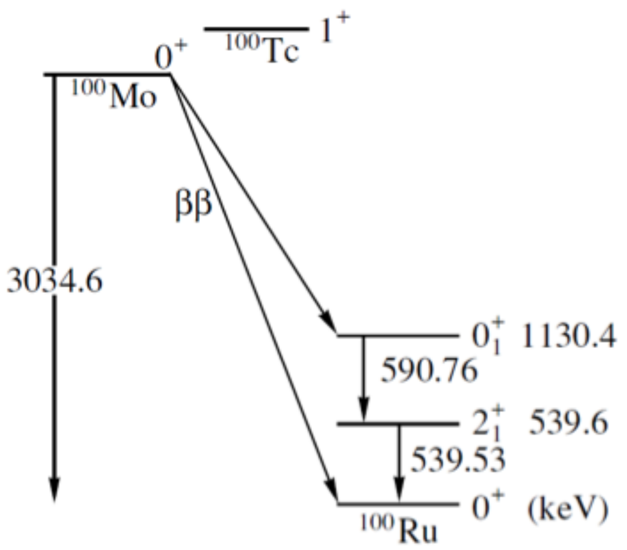
ckky=counts/(keV kg year)





Physics interests in Mo-100 data

- Bosonic neutrinos : Barabash and Smirnov et al., "Statistics of neutrinos and the double beta decay" PLB 783 (2012) 90
- Double beta decays to excited states can be sensitive to a Bosonic contribution to the neutrino wave function. The predictions are ;
  - T1/2 ~ 2.4×10^{22} yr, for Bosonic neutrinos
  - T1/2 ~ 1.7×10^{23} yr for Fermionic neutrinos .
  - The current limit T1/2 > 4.4×10^{21} yr
- At Y2L, $^{100}MoO_3$ powder measurements gave limits comparable. AMoRE-II will be much sensitive.

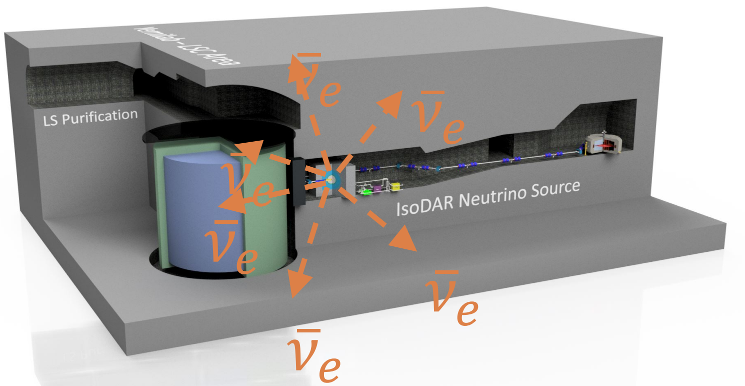


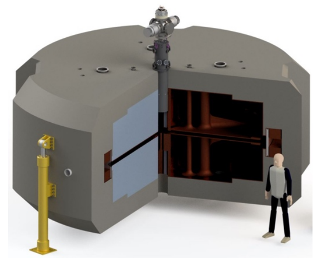
IsoDAR @ Yemilab

Janet Conrad

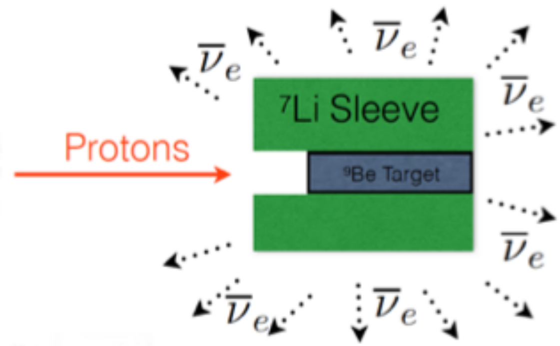
"IsoDAR@Yemilab: A report on the technology, capabilities, and deployment ", JINST 17, P090429 (2022)

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

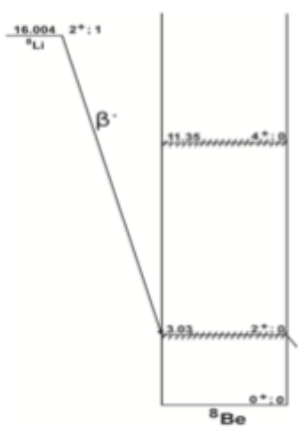


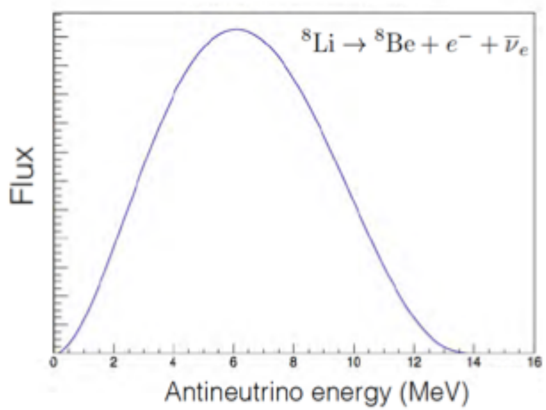
$p + {}^9\mathrm{Be} \to {}^8\mathrm{Li} + 2p$

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

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

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





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

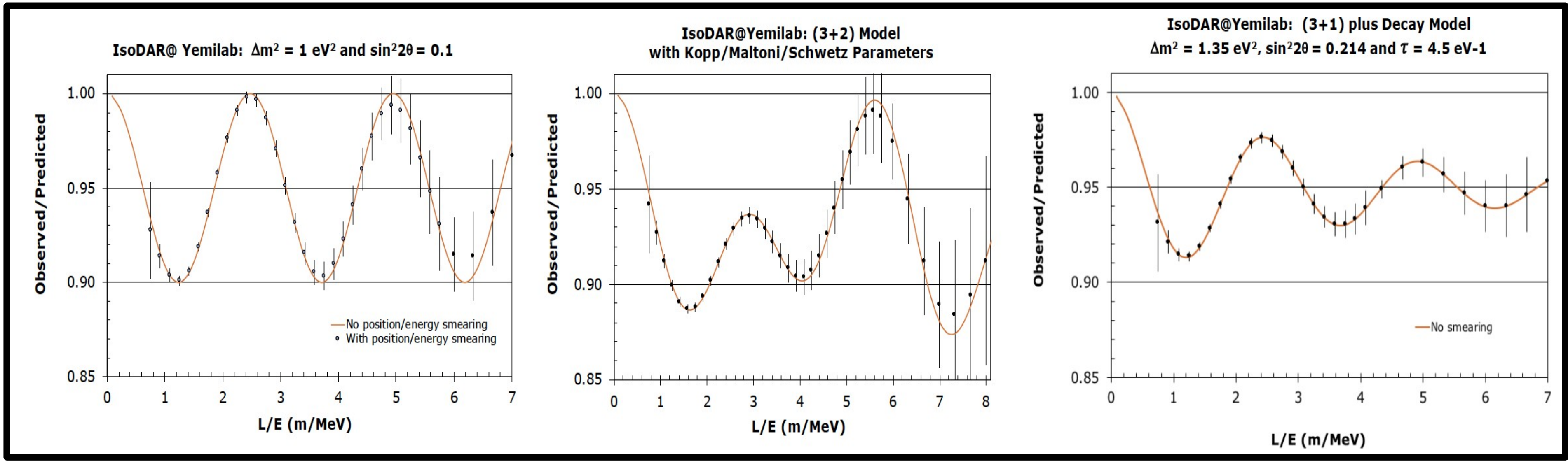
Runtime	5 calendar years
IsoDAR duty factor	80%
Livetime	4 years
Protons on target/year	$1.97 \cdot 10^{24}$
^{8}Li/proton ($\bar{\nu}_e$/proton)	0.0146
$\bar{\nu}_e$ in 4 years livetime	$1.15 \cdot 10^{23}$
IsoDAR@Yemilab mid-baseline	17 m
IsoDAR@Yemilab depth	985 m (2700 m.w.e.)

Sterile neutrino searches.

Janet Conrad

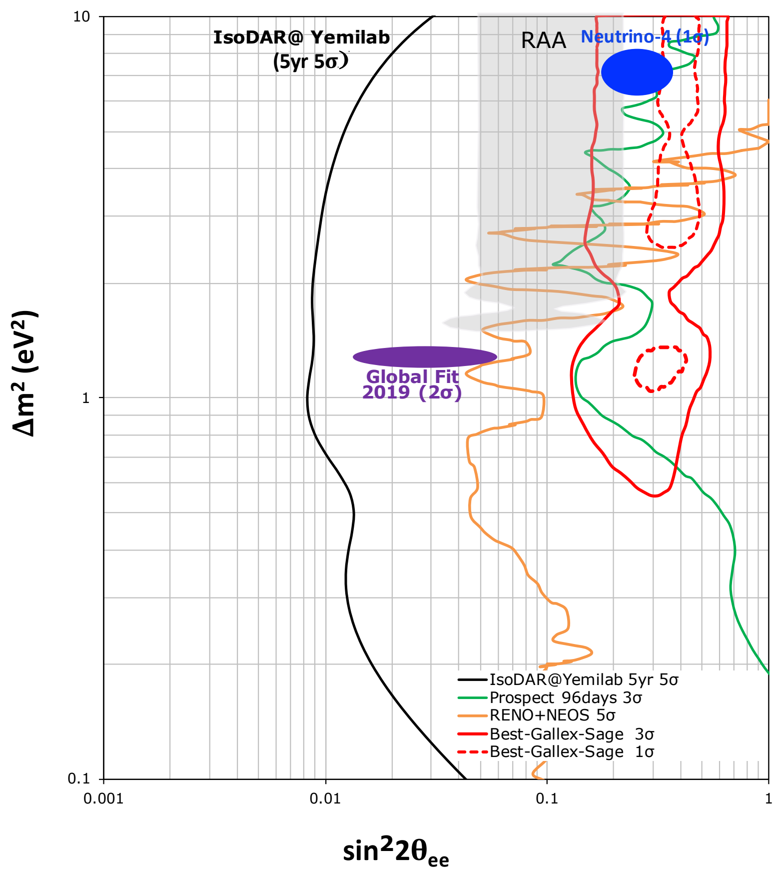
"Neutrino Physics Opportunities with the IsoDAR Source at Yemilab", PRD 105, 052009 (2022)

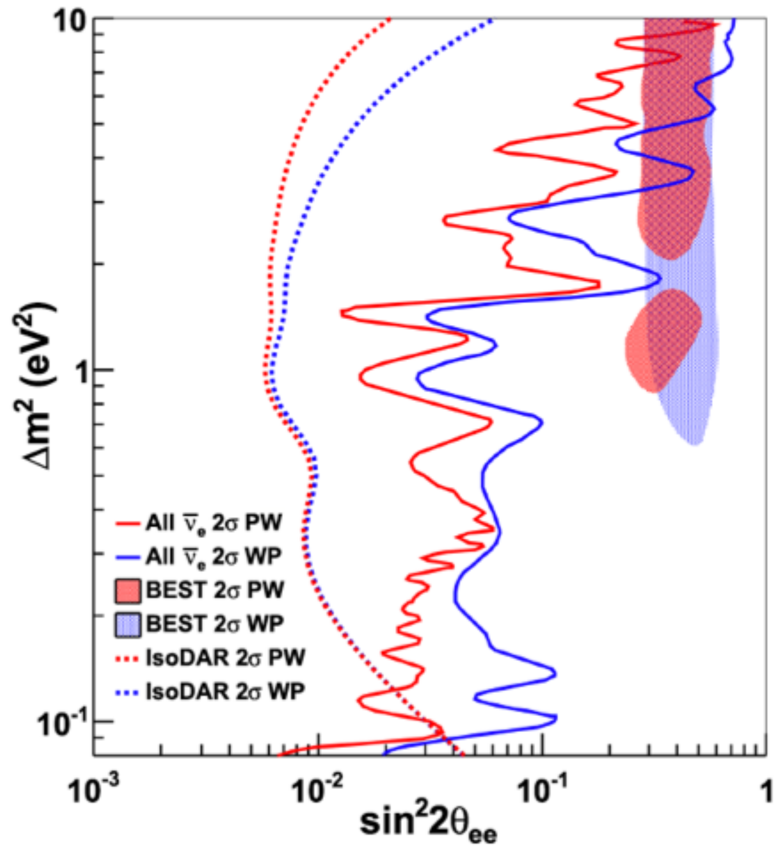
- With inverse beta decay, $\overline{\nu_e} p \rightarrow e^+ n$, short baseline oscillation is searched.
- Well known energy spectra and cross section unlikely with other experiments; reactor neutrinos, ~GeV neutrino-nuclear cross section, neutrino-nucleus CC interaction etc.
- With energy resolution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





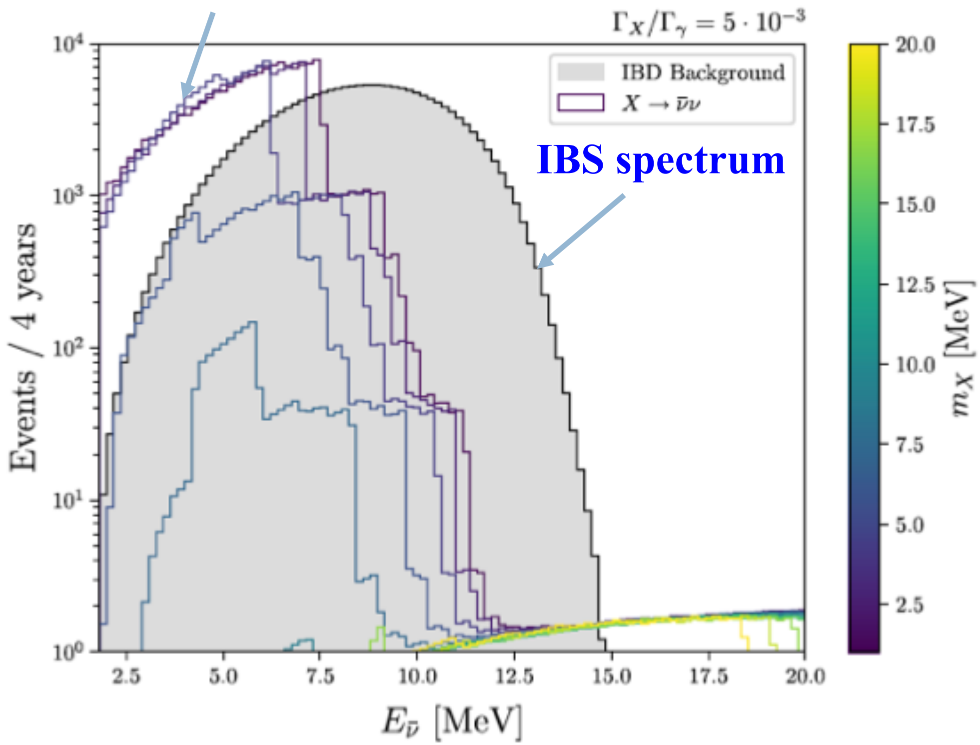
- Wave packet effect will show damping of the oscillation with a wave packet width $\sigma_x = 2.1\times10^{-4} nm$, which is lowest limit.
- Comment from Akhmedov and Smirnov : packet width should be much larger → No effect expected.

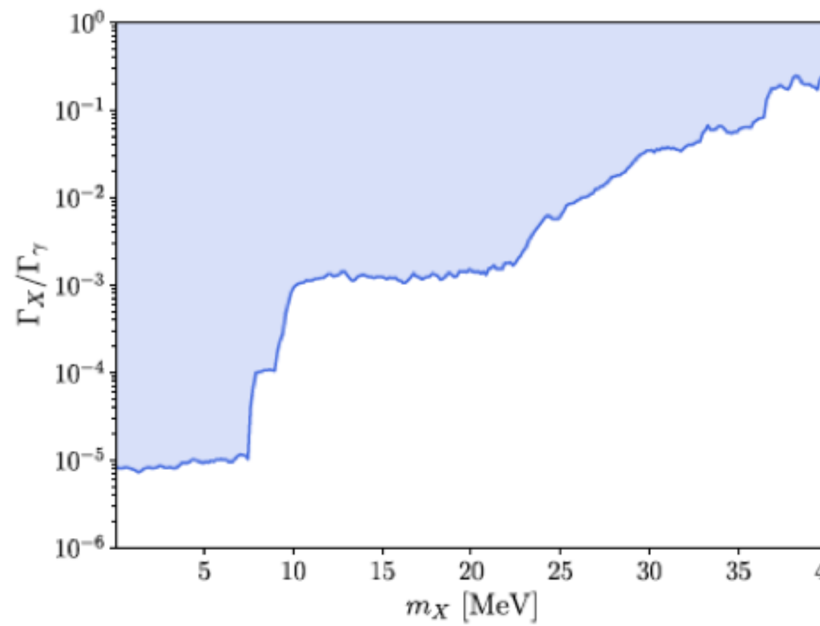
Akhmedov and Sminov, arXiv:2208.03736

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 $X \rightarrow \nu\bar{\nu}$





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.

Summary

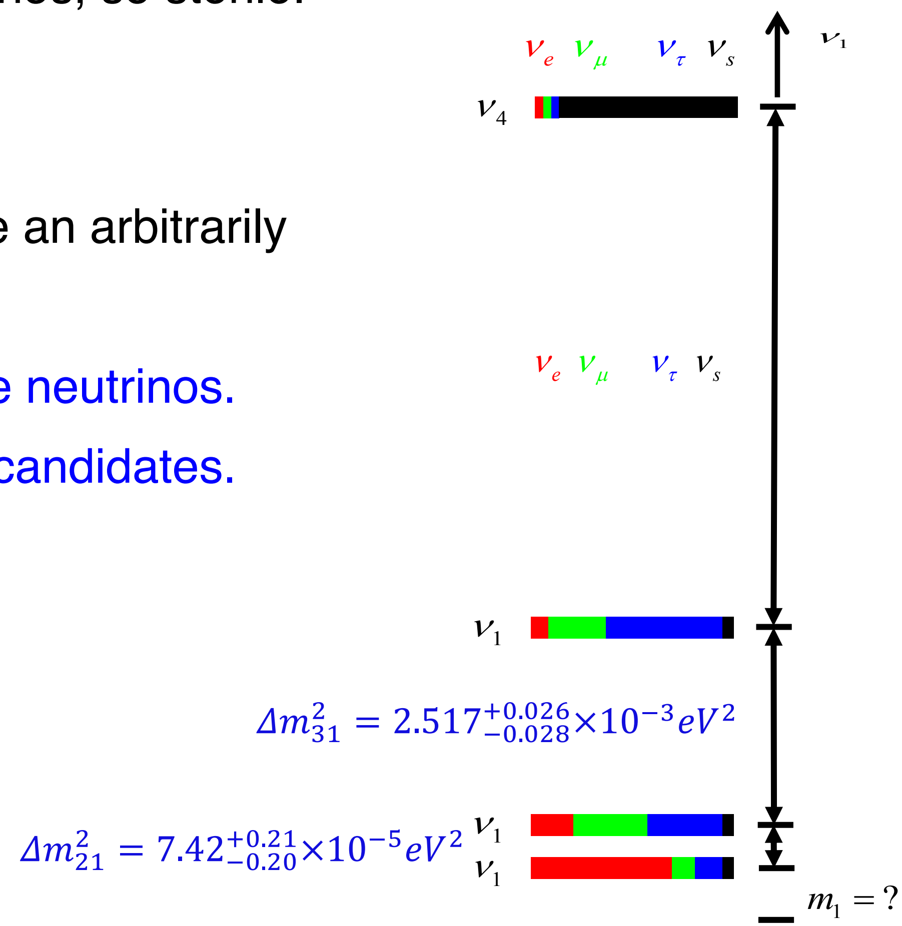
- A great efforts are made towards low mass DM in direct dark matter search experiments . New techniques are suggested and under developments.
- COSINE-100 & ANAIS experiments are contradictory to the DAMA conundrum. COSINE-200 and low mass DM search R&D show promising capabilities.
- Neutrinoless DBD experiments are progressing towards > Ton scale experiment. Multiple Isotopes should be pursued. Meanwhile, AMoRE-II experiment aims to be sensitive ~ $5x10^{26}$ years range for ^{100}Mo isotope and will produce new data for Mo-100.
- Large liquid scintillator detector coupled with a powerful accelerator have a large potential for dark sector physics and sterile neutrinos.

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

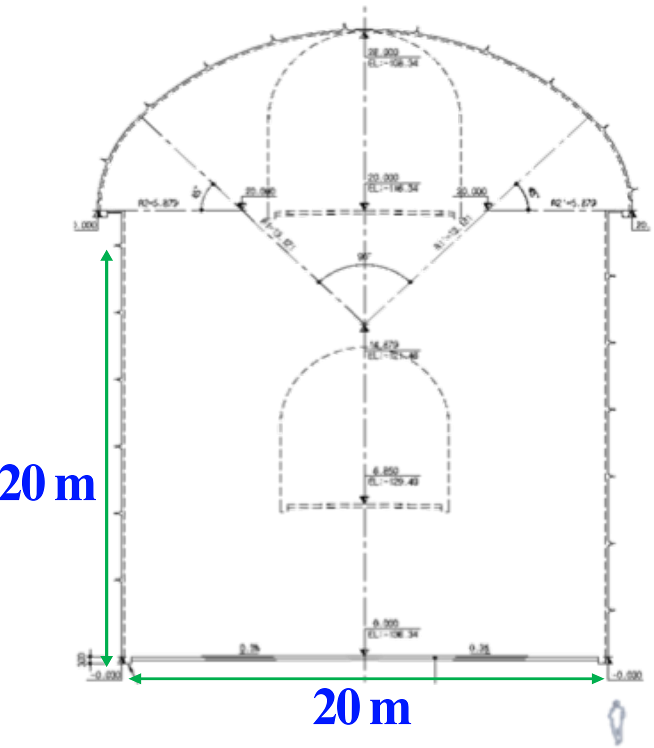
Disapperance Apperance

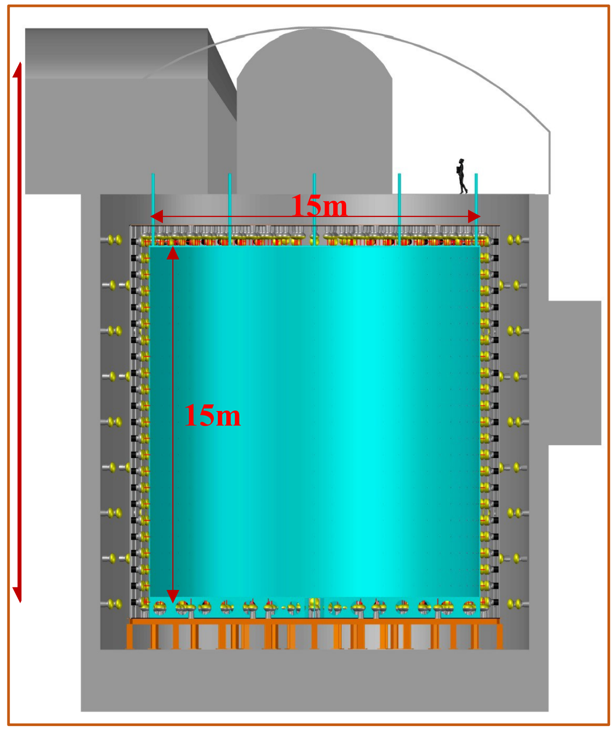


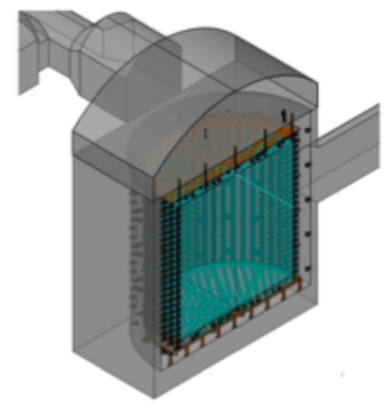
Liquid Scintillator Counter (LSC) @ Yemilab

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

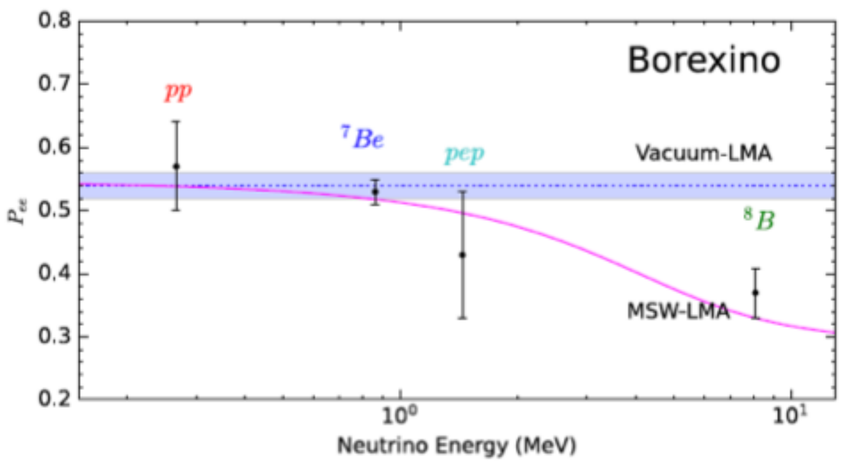
- Photocathode coverage with 3000 20" PMTs : 49% → $E_{resol} \sim 5.5\%/\sqrt{E(MeV)}$ expected.

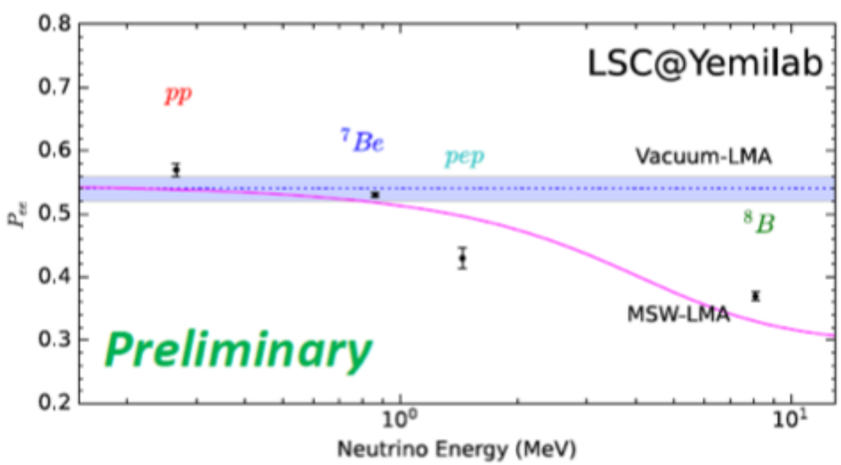
Cf. KamLAND : 34%, $E_{resol} \sim 6.5\%/\sqrt{E(MeV)}$

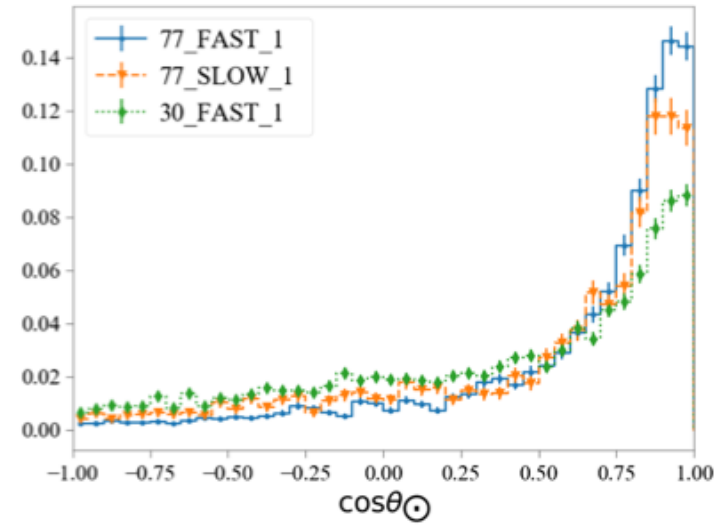
Solar Neutrinos

- 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)





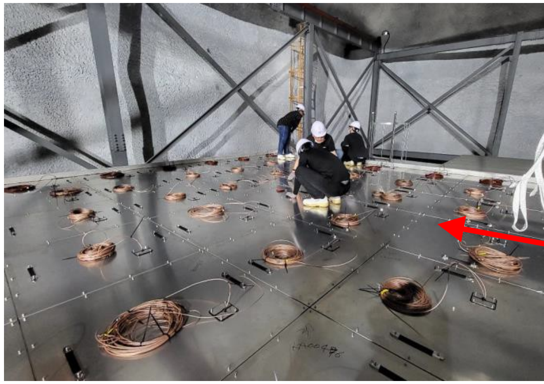


(a)

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

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

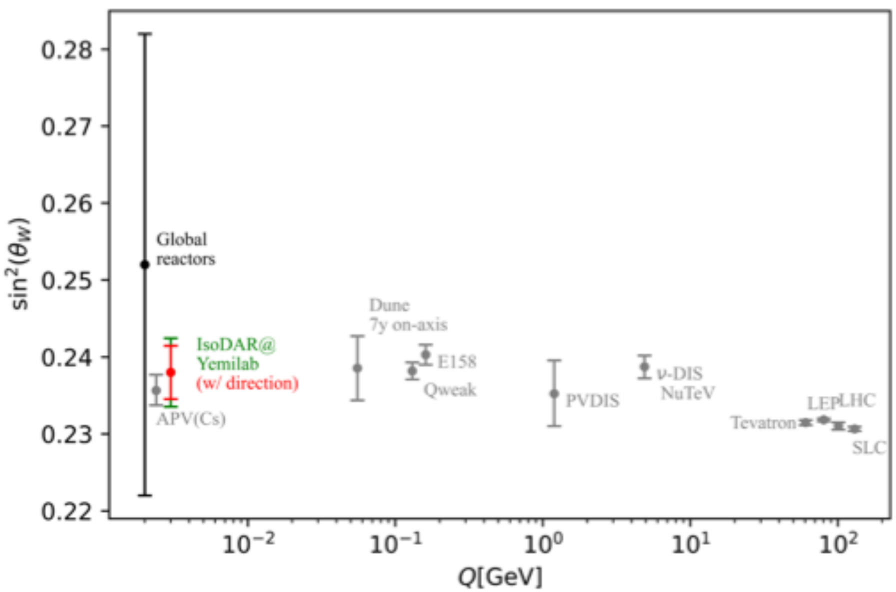
Overview of AMoRE-II setup



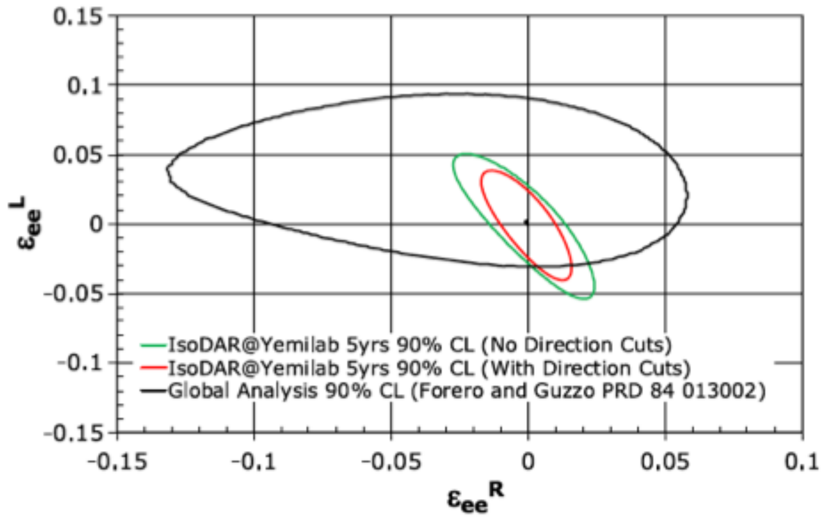
Other physics

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:

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

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

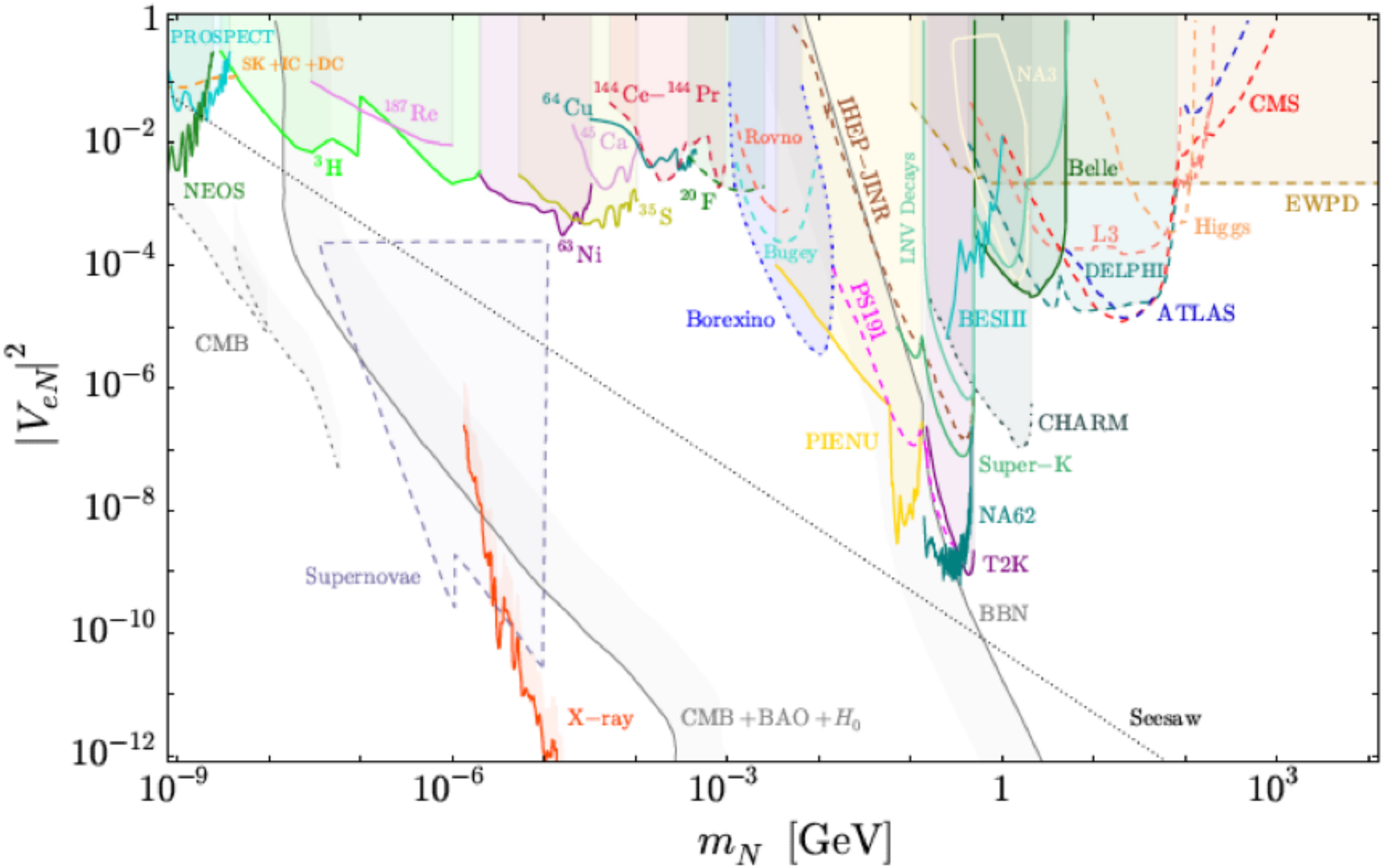
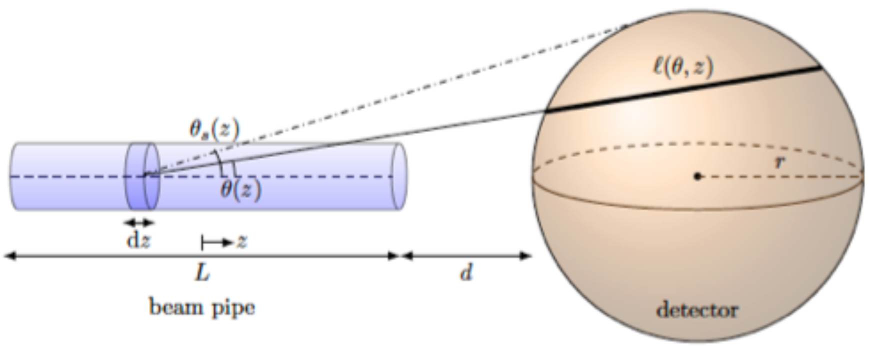


Figure 6. Constraints on the mass m_N of the sterile neutrino and its squared mixing $|V_{eN}|^2$ with the electron neutrino. The shaded regions are excluded by the searches and observations indicated and discussed in section 4. The diagonal line labelled 'Seesaw' indicates the canonical seesaw relation $|V_{eN}|^2 = m_\nu/m_N$ with $m_\nu = 0.05\,\text{eV}$.

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.

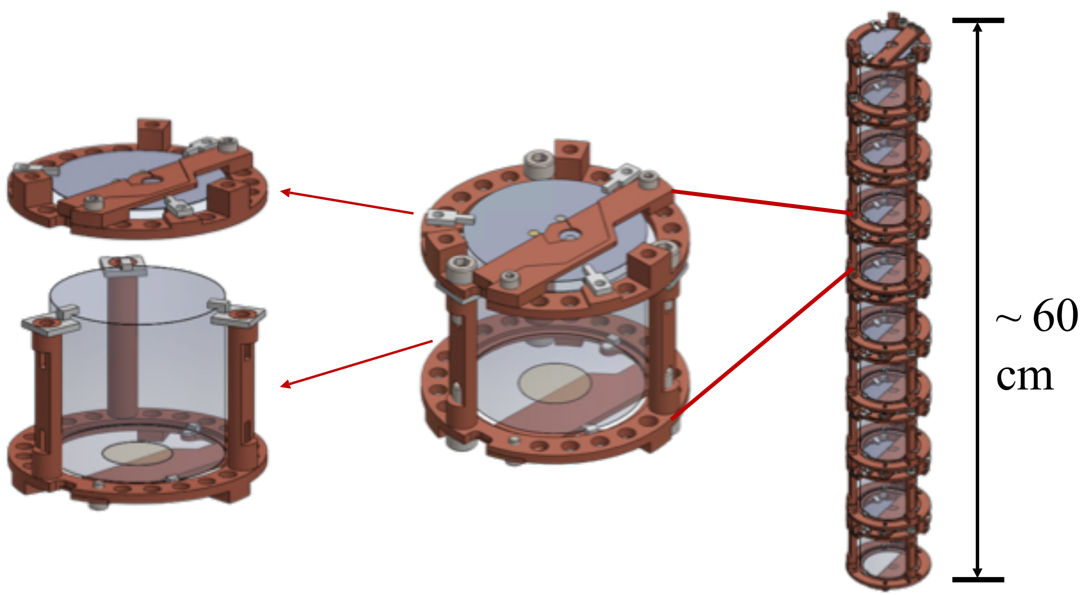


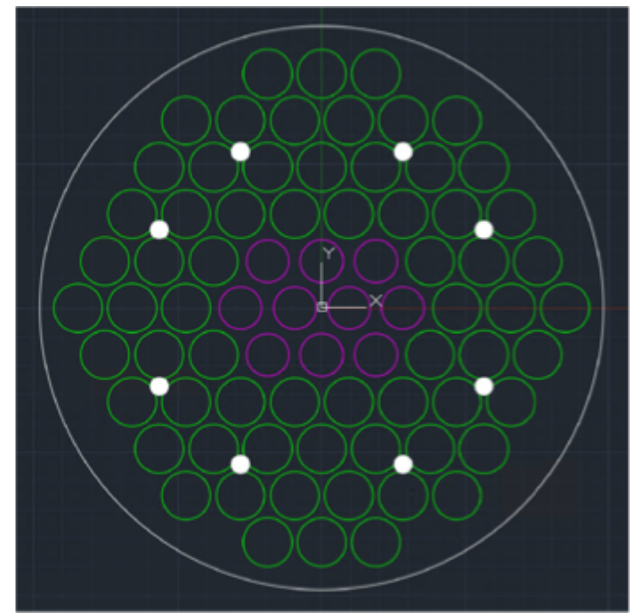
- This is going to be relevant for models with large DM-nuclear cross section (blind spot #2), where A. interaction is enhanced, B. density is enhanced.

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

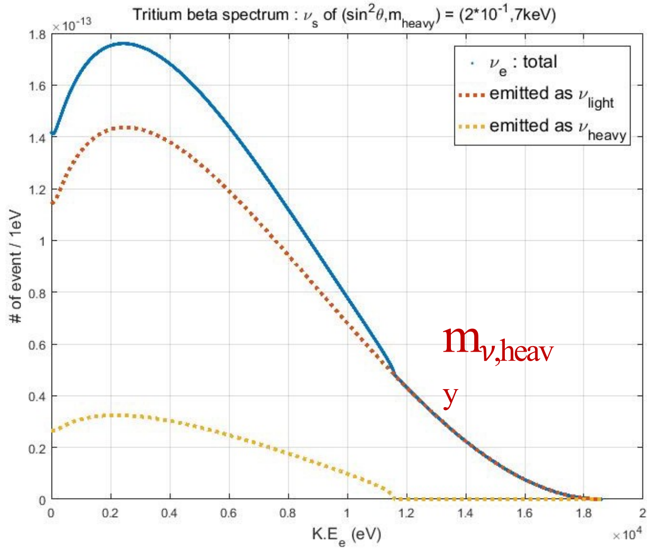
The heat detector is assembled with the light module.

Reduced the number of detector parts.

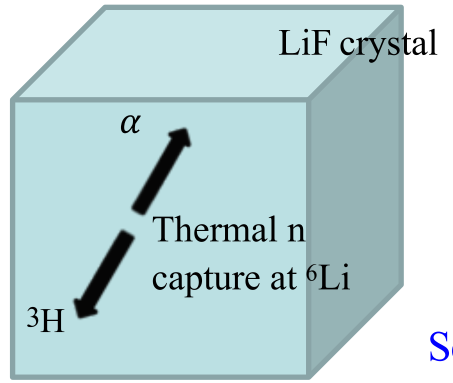
Reduce total copper mass (copper structure w/o screws: 297 → **182 g**)

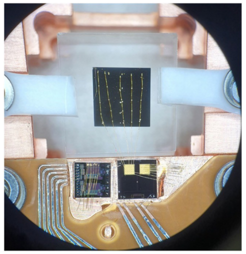
~keV mass sterile neutrino search

Yong-Hamb Kim



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

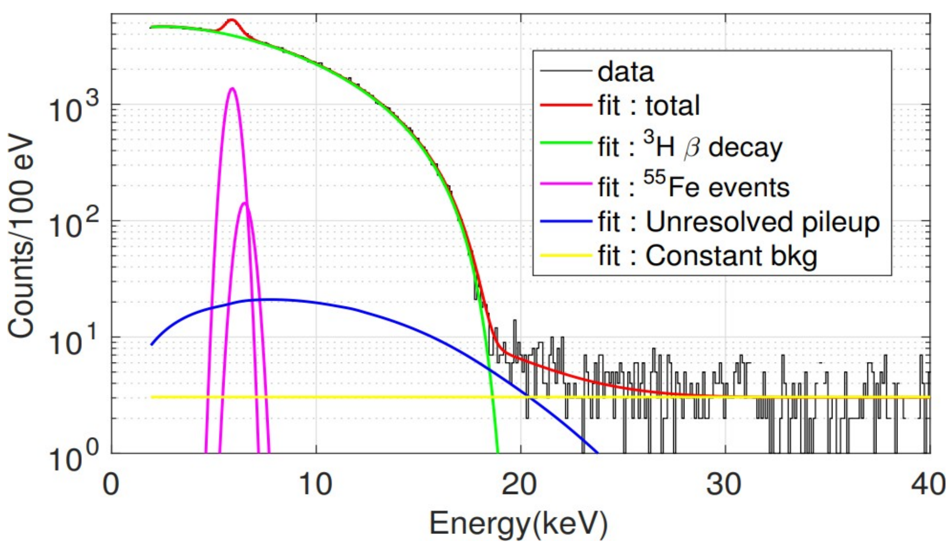


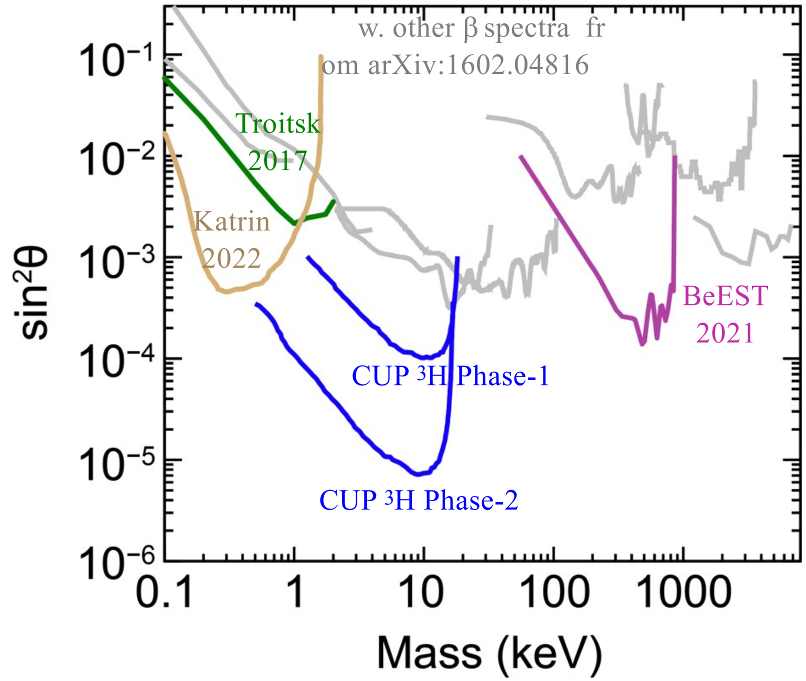


Sensitivities:

Phase 1 : 3 detectors × 40 Bq × 10 month

Phase 2 : 100 detectors × 100 Bq × 3 years

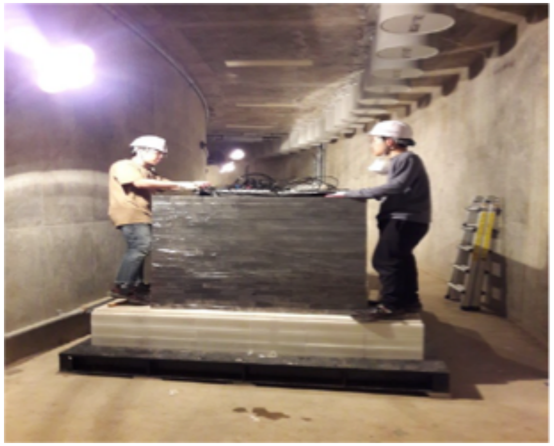




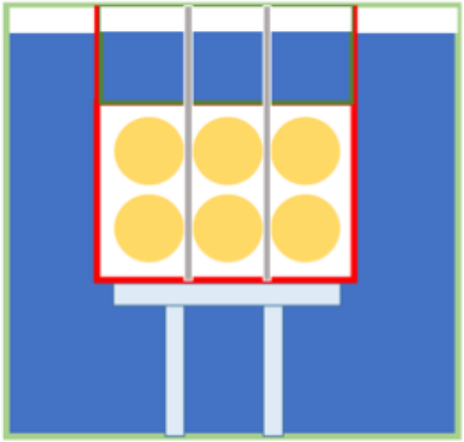
NEON neutrino coherent scattering experiment

Hyunsu Lee

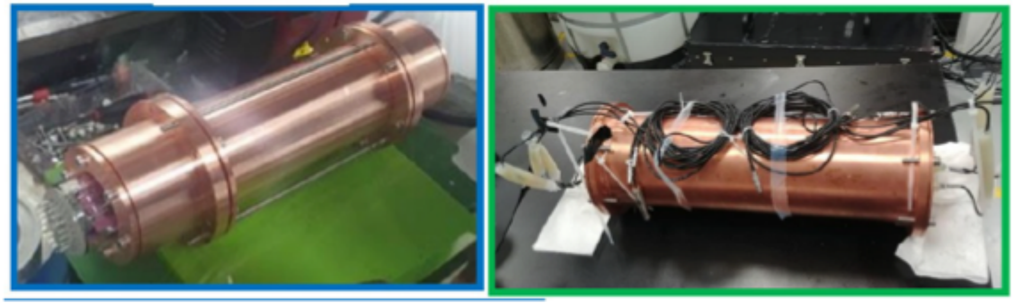
- Purpose
  - Observation of coherent neutrino nucleus scattering from reactor neutrino
  - Detector performance (long-term) of NaI(Tl) for COSINE-200

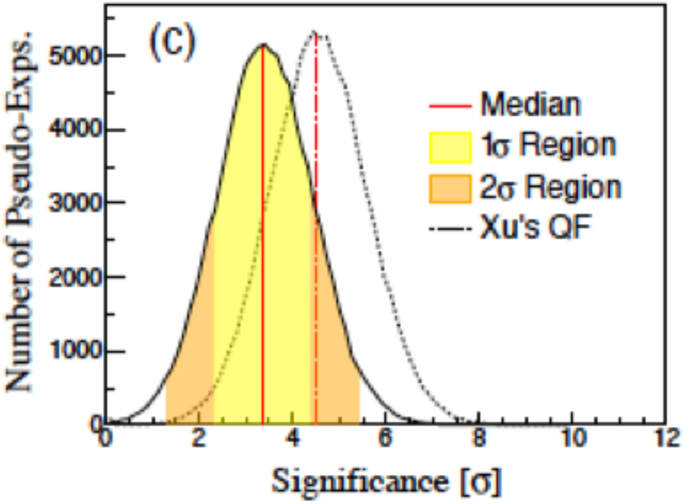


Tendon Gallery



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

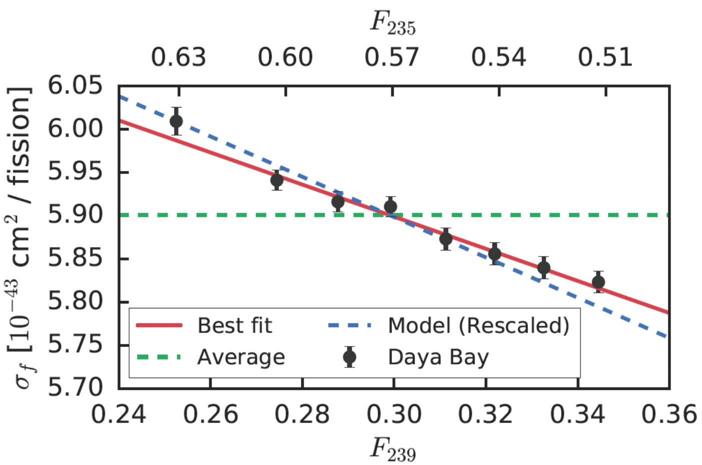




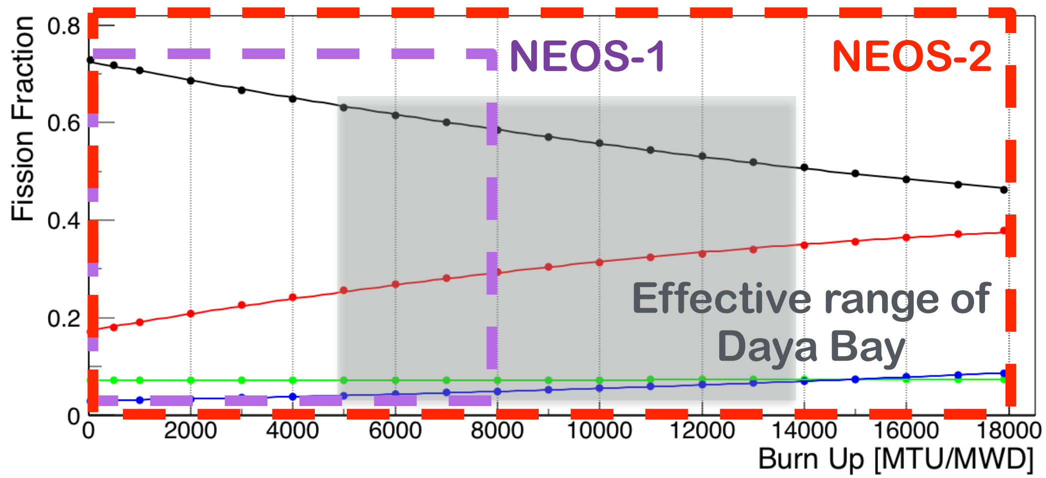
NEOS projects

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)

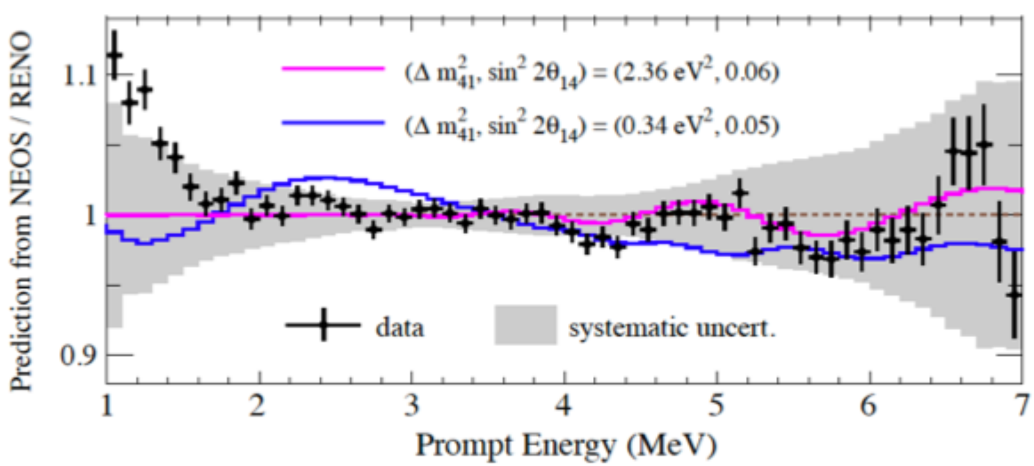


An et al., PRL 118, 251801 (2017)



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

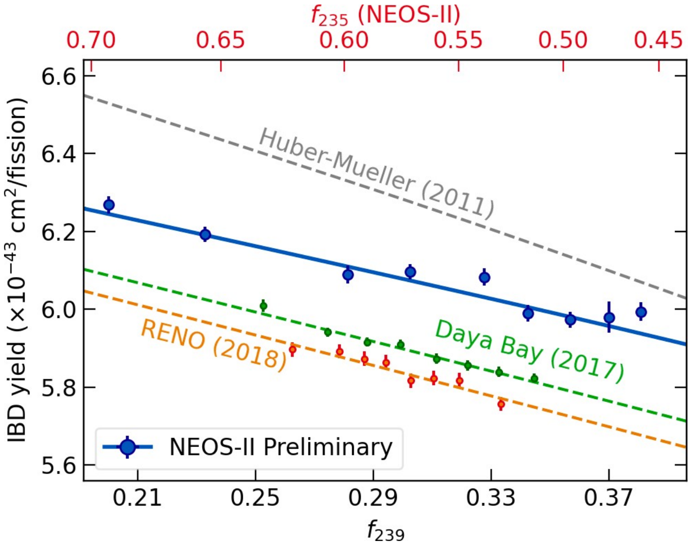
NEOS compared with RENO.

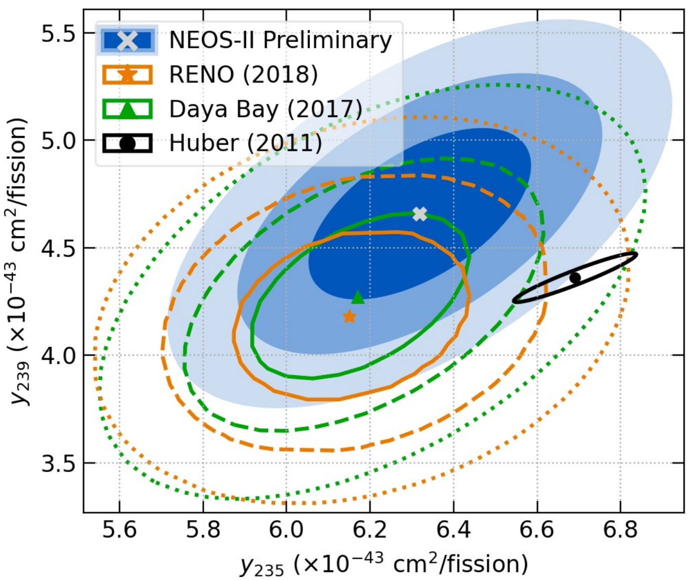


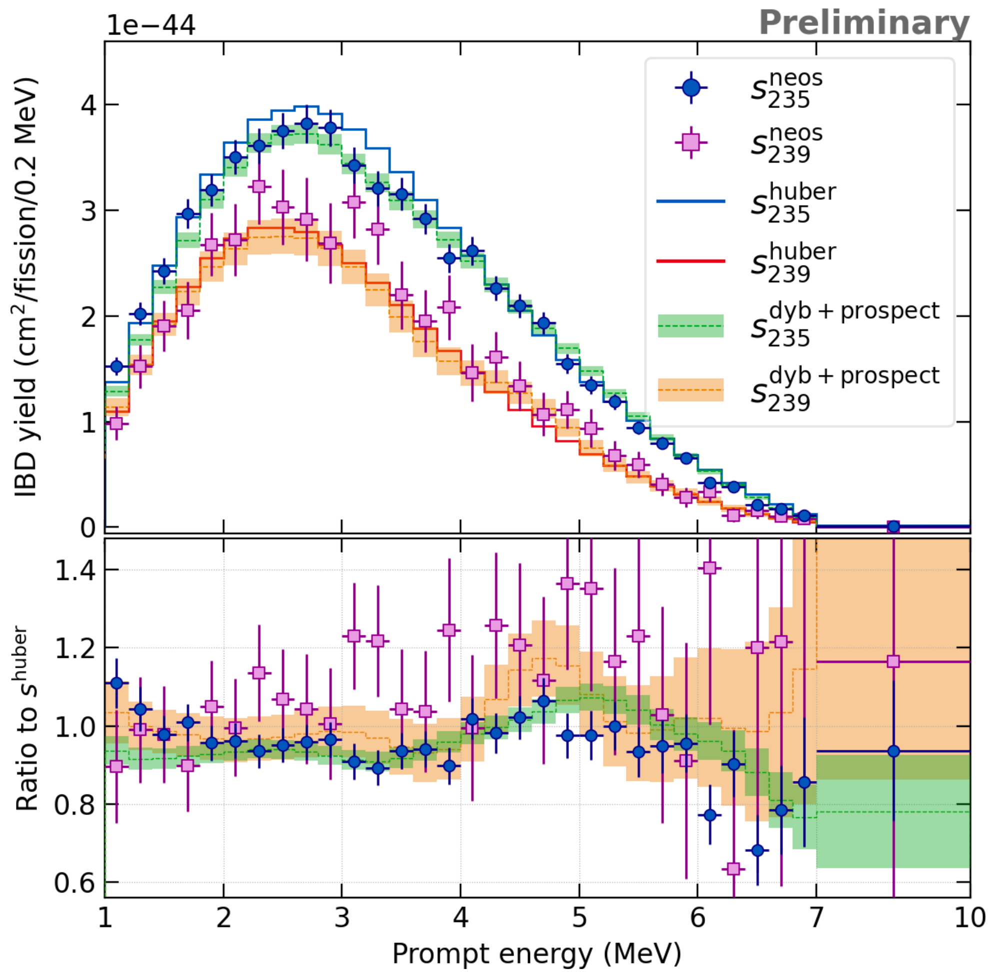
NEOS-II preliminary result

Yoomin Oh

Jinyu Kim @ ν-2022

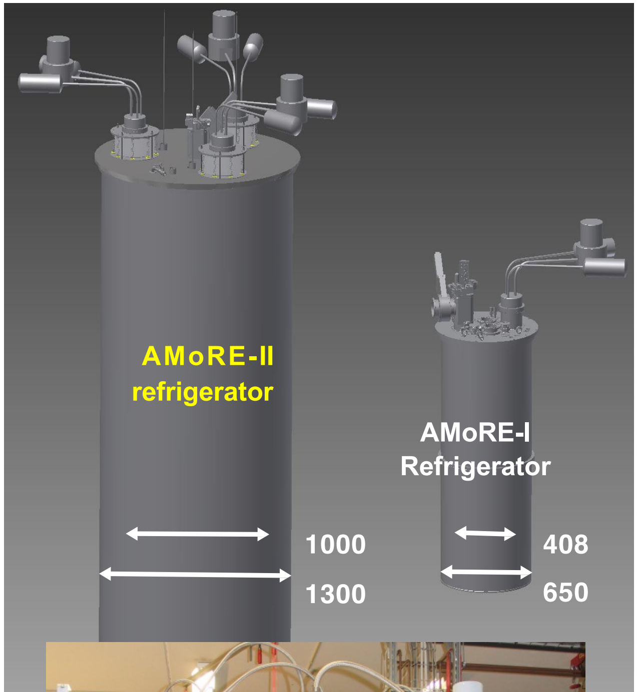


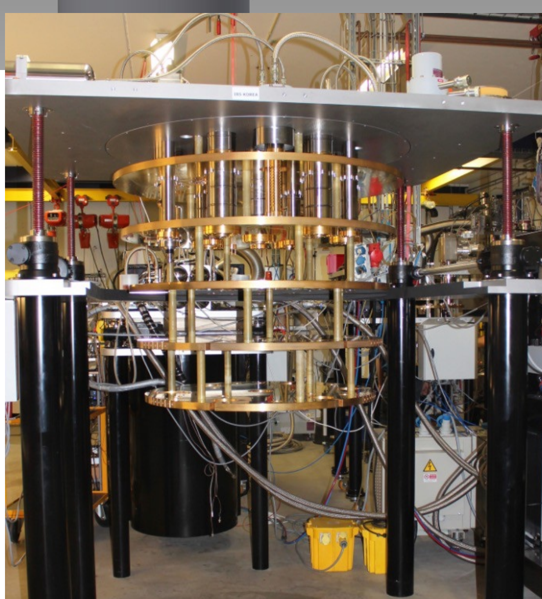




Dilution refrigerator & Cryostat

Yong-Hamb Kim

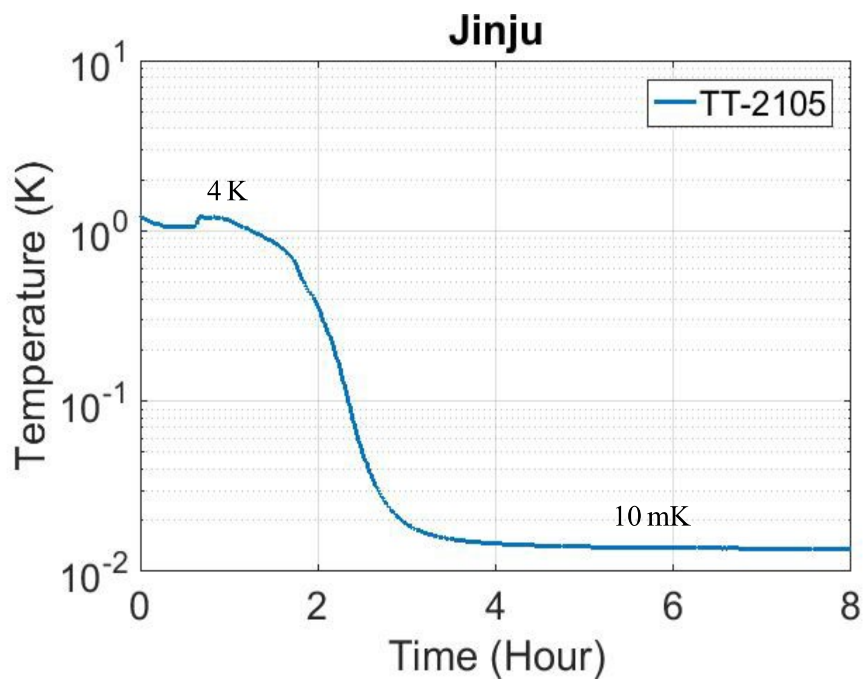




Large dilution Refrigerator from Leiden.

- **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



Yemilab

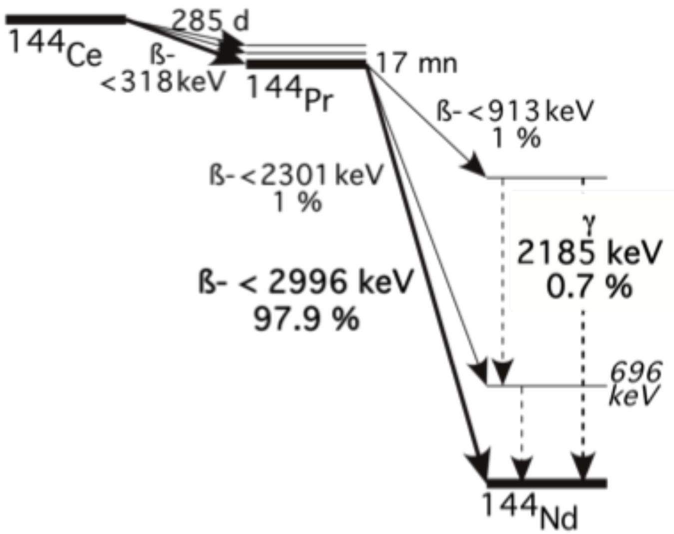
- Area
  - 4000m^2 for tunnel,
  - 1000 m^2 for maintenance,
  - 3000m^2 for experiments
- Mechanical
  - 39000m^3/hour ventilation
  - 200kW cooling power
  - Radonless air supply (~10000 m^3/hour from ground)
- Electrical
  - 2MW for electric power supply
  - 180kW UPS for 40 minutes for AMoRE-II
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

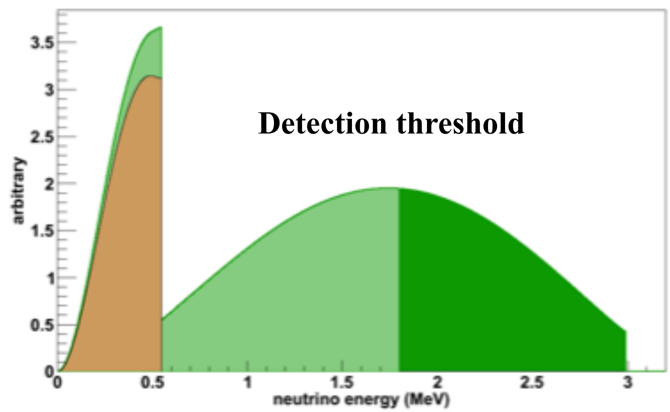
	Y2L	Yemilab
Depth (m)	700	1000
Area (m^2)	350	3000
Rock Radioactivity (ppm)	U : 3.9(1.4) Th : 10.5(6.5) K : 40000	U : 0.8(0.3) Th : 3.3(0.4) K : 11,800

Source @ Yemilab

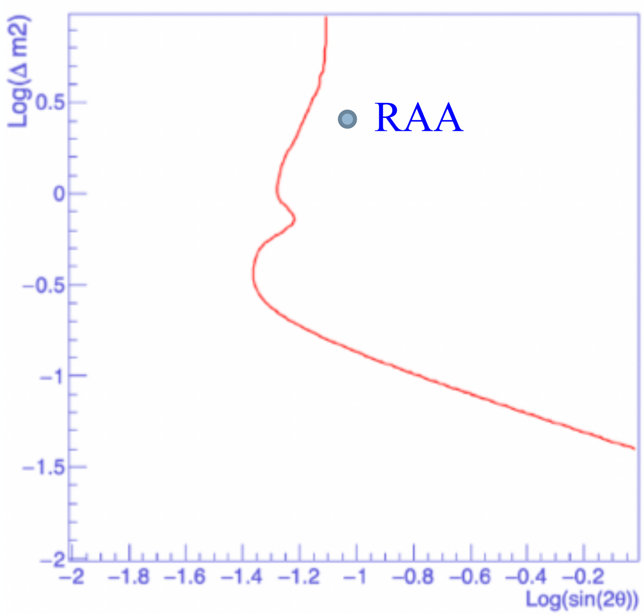
Marco Oallavicini

- Min. 4m distance



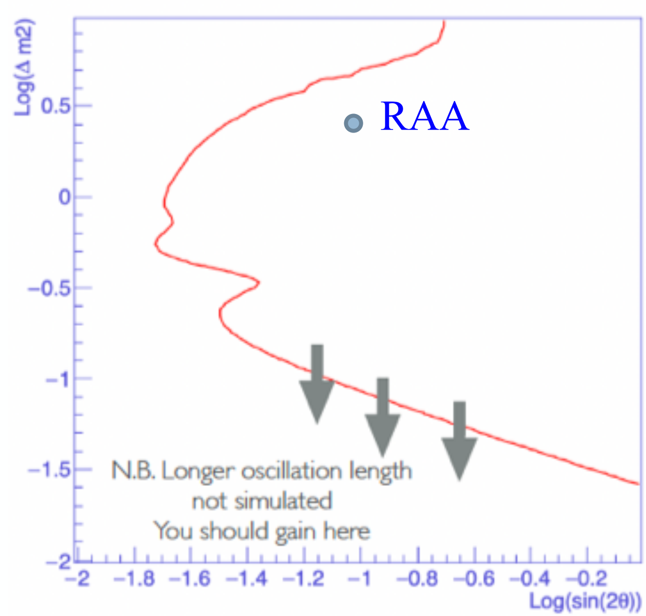


SOX original



Ce-144 100 kCi

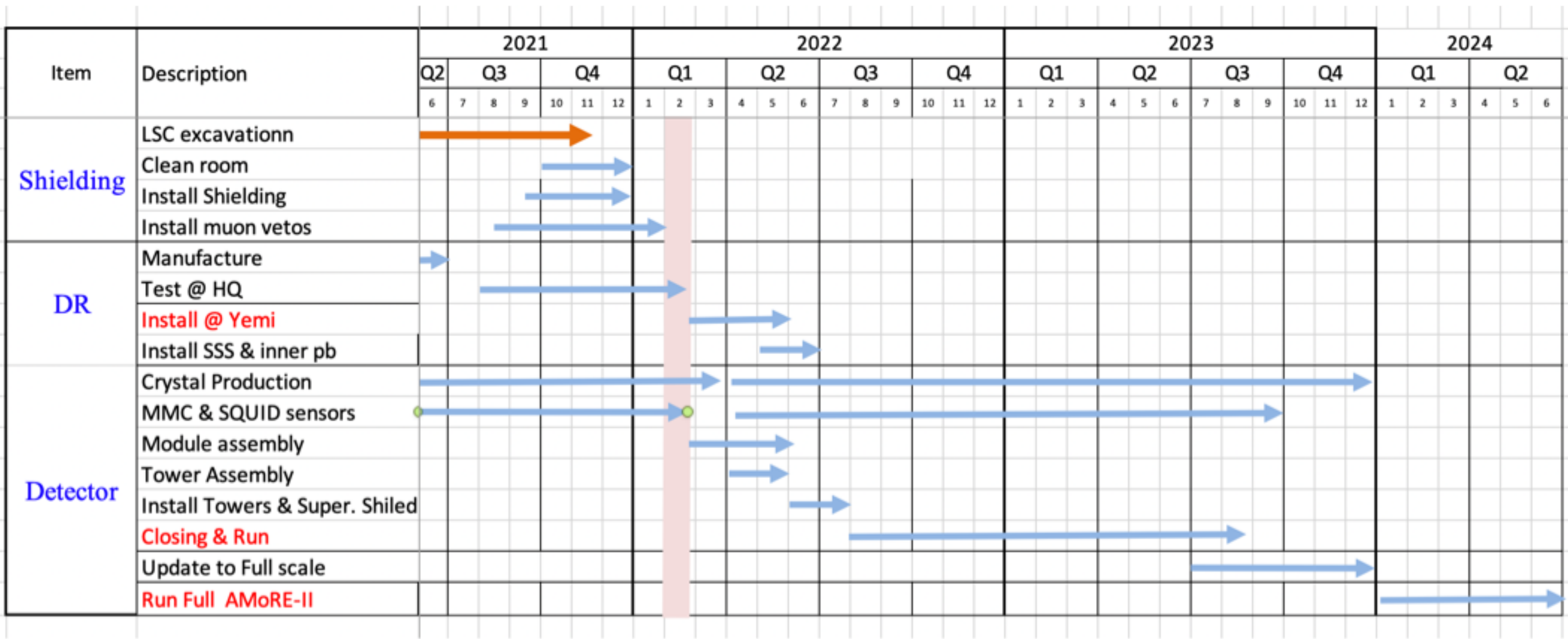
Yemilab



Ce-144 100 kCi

Schedule for AMoRE-II

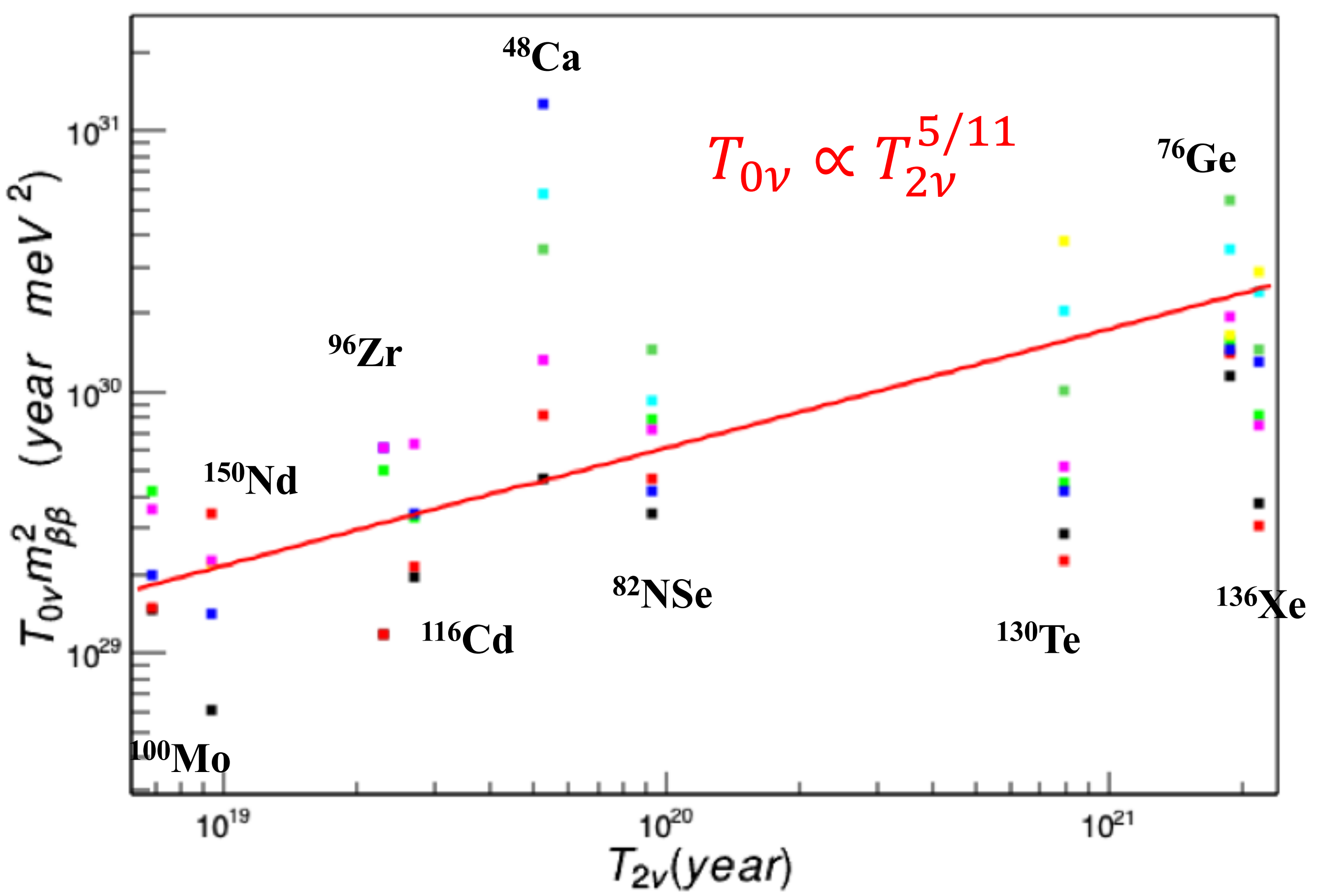
- The backgrounds will be estimated more clearly when we have first data of AMoRE-II with 90 crystals in 2022.
- Modular expansion is possible, increasing # of detectors.
- After AMoRE-II, ton scale experiment can be considered. ~ CUPID 1ton.
- CUPID & AMoRE discuss to collaborate for future combination.



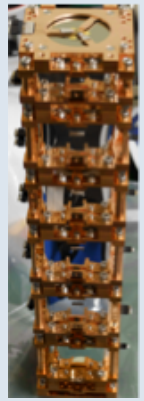
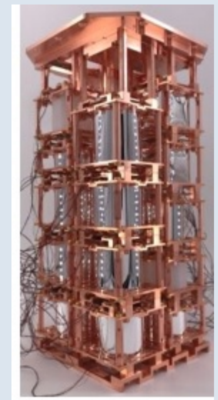
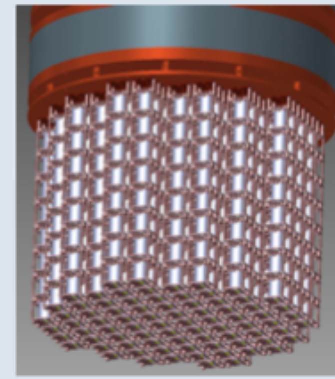
0νββ vs 2νββ T(1/2) - updated

- **A correlation between** 2νββ **half-life(measured) vs** 0νββ half-life (calculated)

$G_{0\nu} \propto Q^5, \; G_{2\nu} \propto Q^{11}.$ H. Ejiri's comment

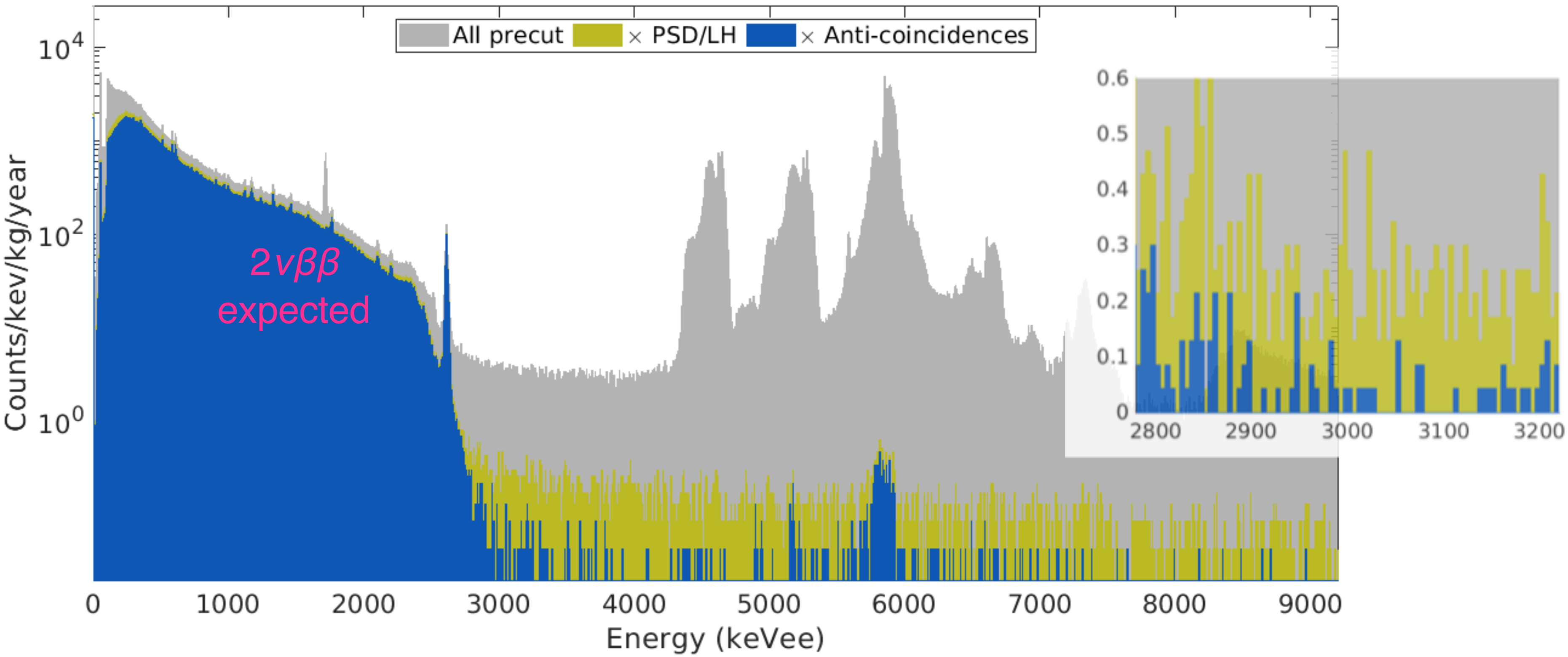


Plan of AMoRE Project

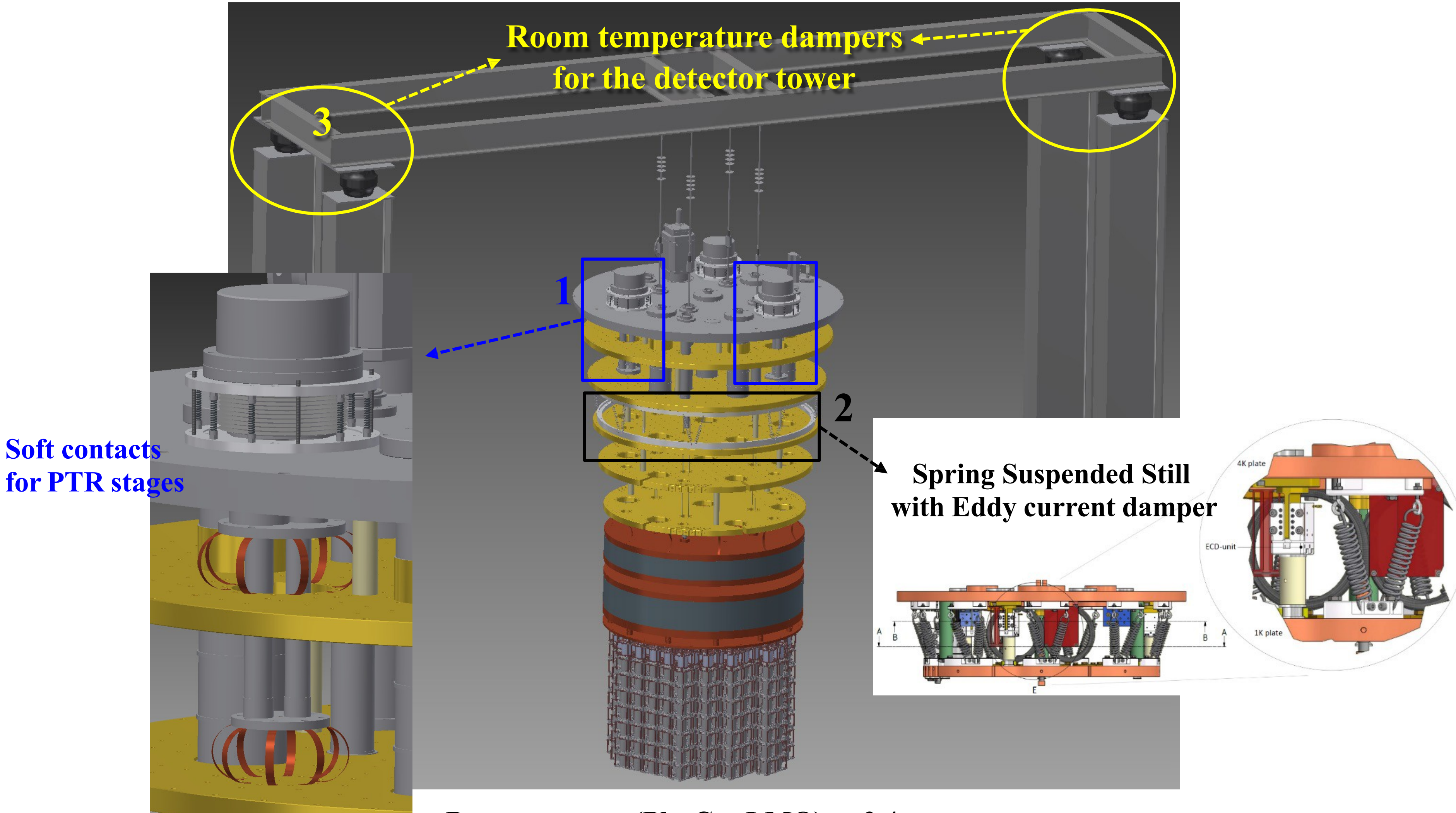
Phases	AMoRE-Pilot	AMoRE-I	AMoRE-II
Detector Setup (Not in scale)			
Crystals	$^{40}Ca^{100}MoO_4$ (CMO)	$(^{40}Ca,Li_2)^{100}MoO_4$	$Li_2{}^{100}MoO_4$ (LMO)
Crystal # & Mass	6, 1.9kg	18, 6.2kg	596, 178kg
Backgrounds (**ckky**)	$\sim 10^{-1}$	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$\sim 3.0\times10^{23}$	$\sim 7.0\times10^{24}$	$\sim 8.0\times10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	13-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2022	Yemilab / 2022-2027

Background spectrum - total

- All crystal excluding 1 LMO for very poor β/α discrimination power:
  - 13 CMO + 4 LMO: exposure = 4.68 kg_{XMO}·yr = 2.24 kg_{ISO}·yr.
- Anti-coincidence cuts reject events:
  - multiple hits : ΔT >2 ms ($\varepsilon \sim 99\%$),
  - Muon veto : ΔT > 10 ms ($\varepsilon \sim 99.7\%$),
  - ^{212}Bi α-decay event rejection : ΔT > 20 ms ($\varepsilon \sim 98\%$).



Vibration damping systems

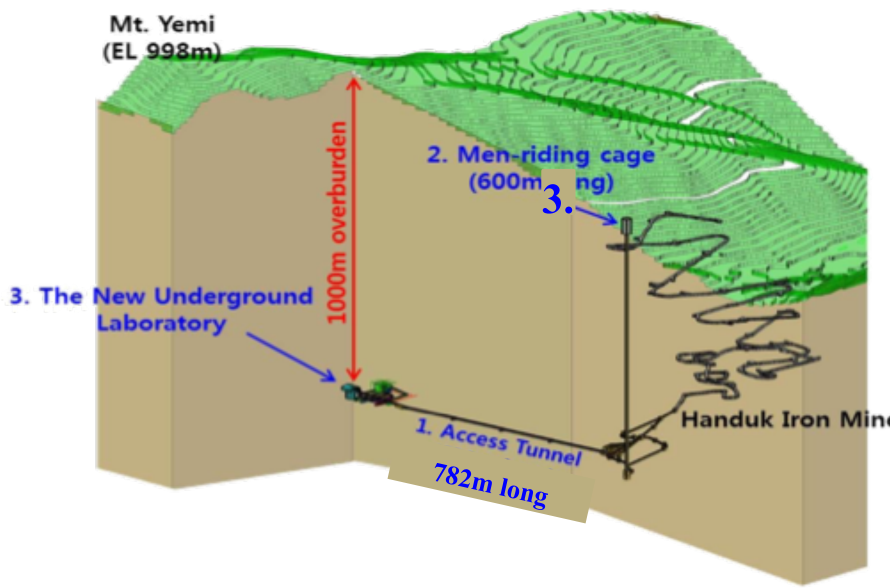


Detector tower (Pb+Cu+LMO): ~ 3.4 ton
Independent support of Kevlar strings + STS rods from room temp.
Cooling method: IVC exchange gas + soft copper foils

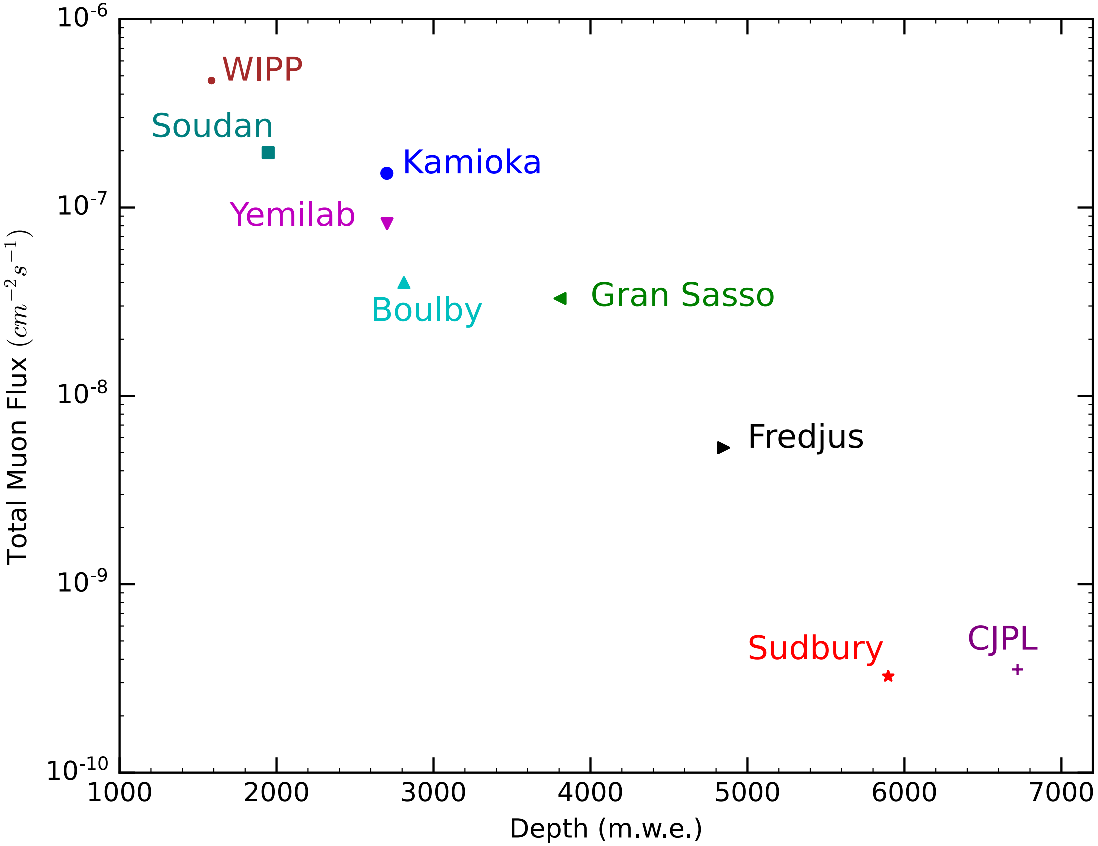
Yemilab for new discoveries.

- 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**

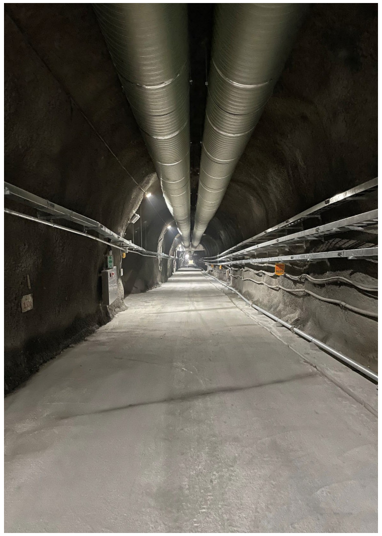


Muon rates



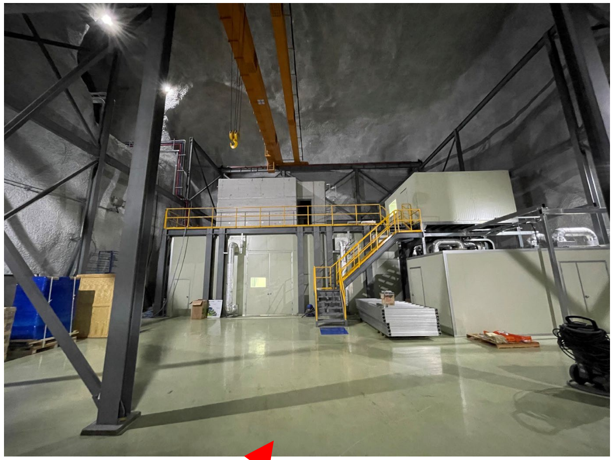
Total Muon Flux $(cm^{-2}s^{-1})$
Depth (m.w.e.)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1000
2000
3000
4000
5000
6000
7000
WIPP
Soudan
Kamioka
Yemilab
Boulby
Gran Sasso
Fredjus
Sudbury
CJPL

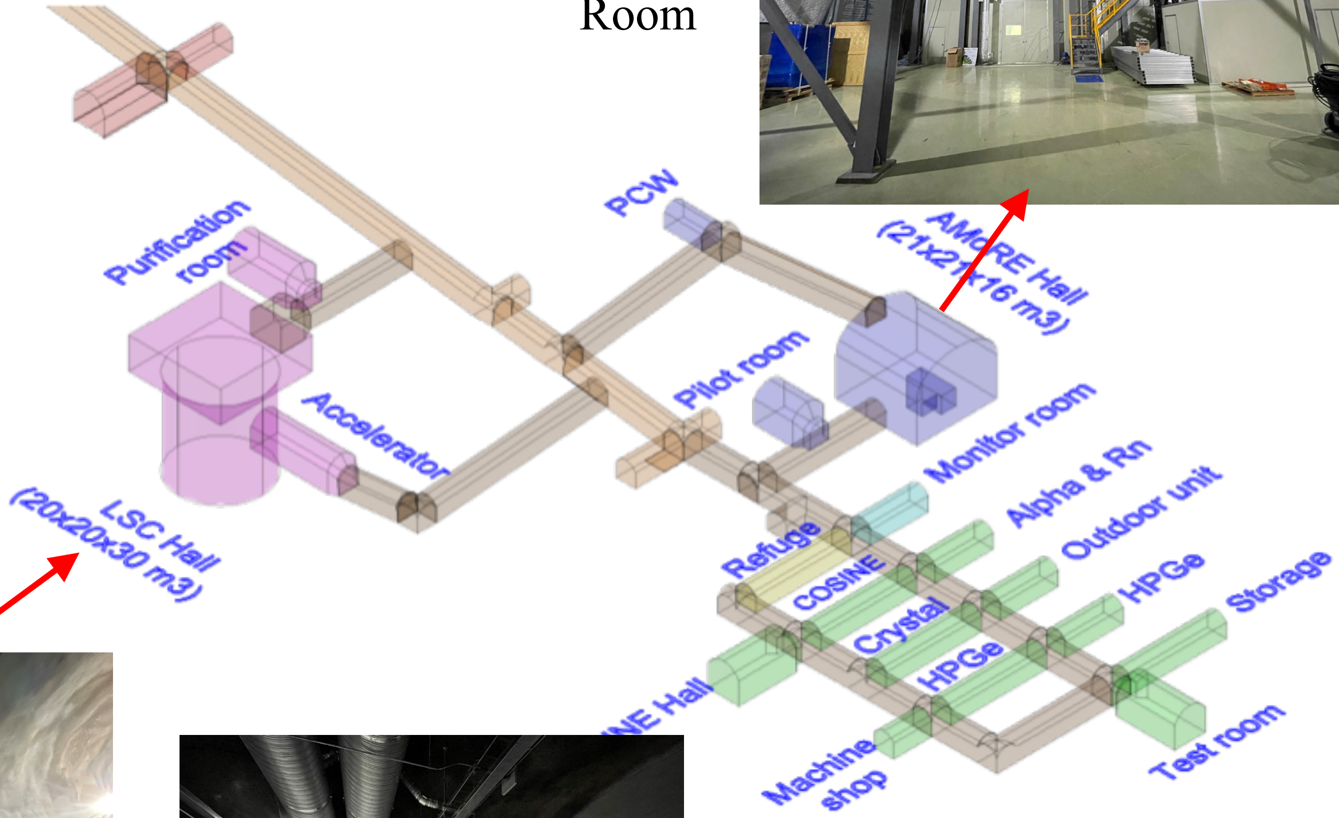
Yemilab halls



Access Tunnel

AMoRE Room



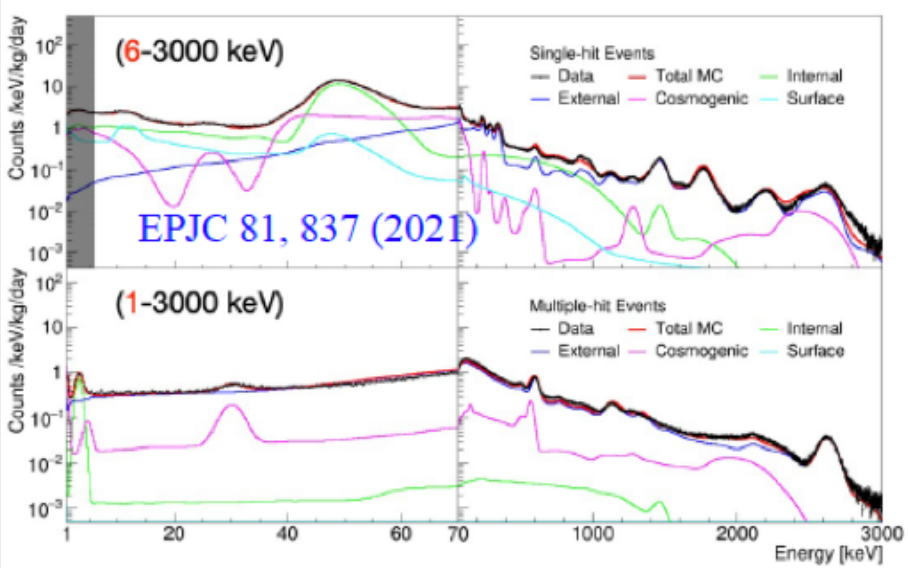


Large Scintillation Counter (LSC)

View at the Refuge

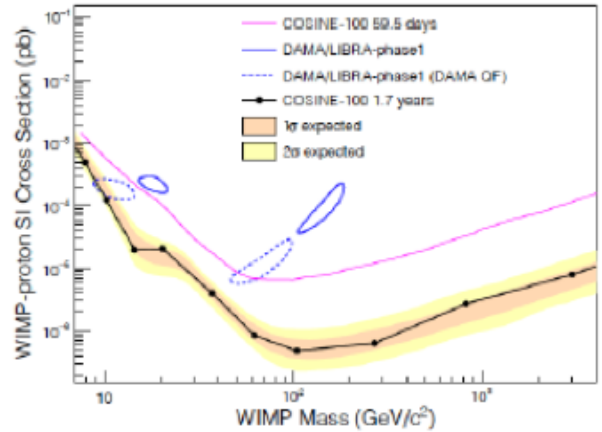
Recent achievements

Background modeling (1keV threshold)



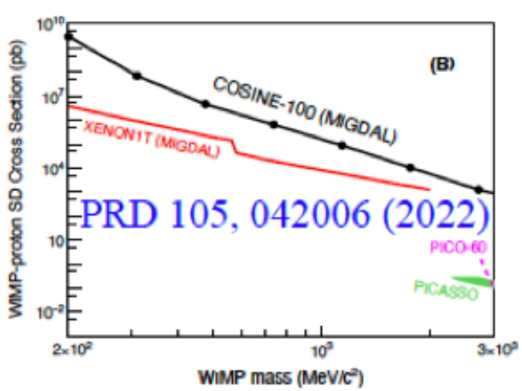
EPJC 81, 837 (2021)

WIMP Search (1.7 years)



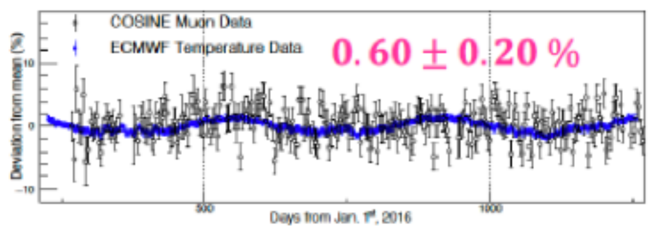
Sci. Adv. 7, eabk2699, (2021)

Low-mass DM with Migdal

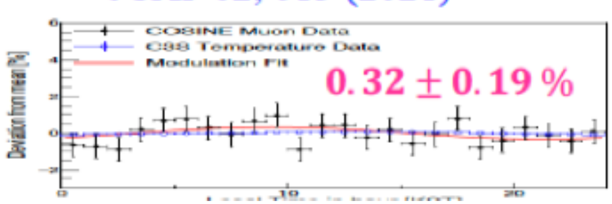


PRD 105, 042006 (2022)

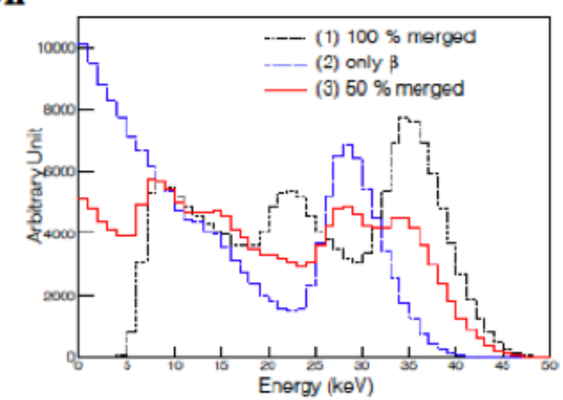
Annual & diurnal modulation of muon



JCAP 02, 013 (2021)



New isomers in ^{228}Ac



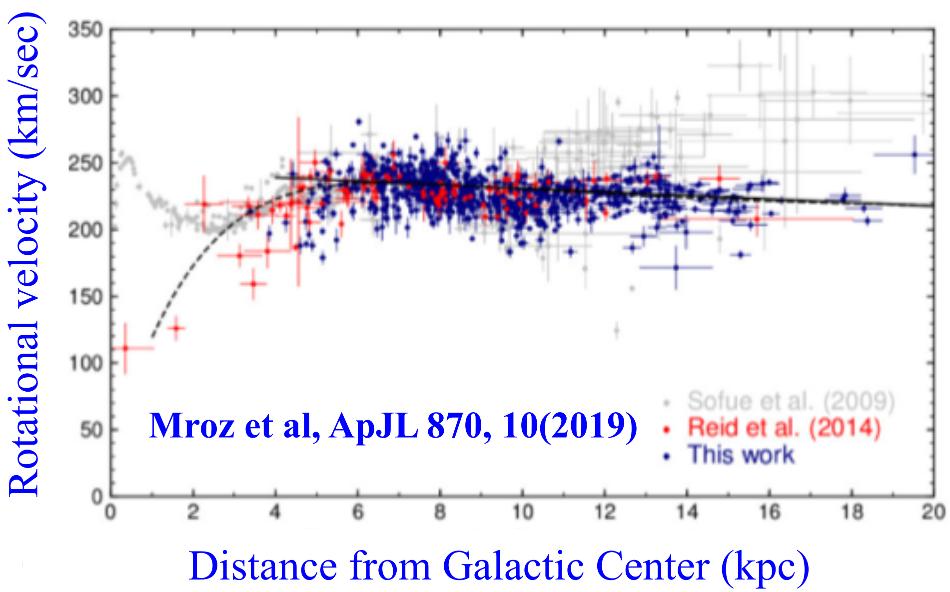
EPJC 81, 746 (2021)

Standard Halo Model (SHM) of Dark Matter

- An isothermal sphere having a smooth Maxwellian velocity distribution of dark matter particles.
- In our galaxy, SHM assumes ;
  - DM density @ Earth, ρ_0 = 0.3GeV/cc
  - Rotation Speed, v_0 ~ 220 km/sec
  - Escaping velocity, v_{esc} ~ 554 km/sec

$$f(\vec{v}) \propto e^{-\frac{3\vec{v}^2}{2\sigma_v^2}}, \; for\ |\vec{v}| < v_{esc},$$

$$v_0 = \sqrt{2/3}\sigma_v$$



NaI crystal development for COSINE-200

Hyunsu Lee

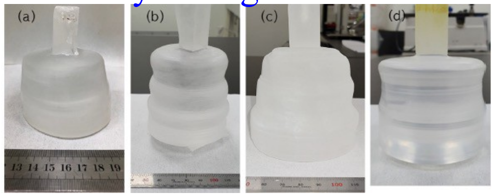
Powder purification performance

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

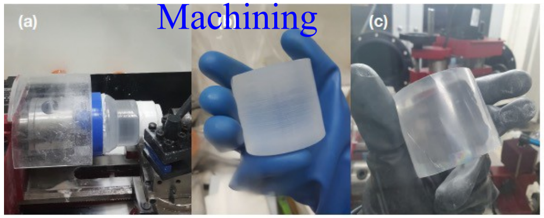
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

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

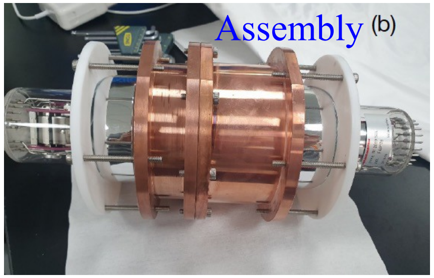
Crystal ingots

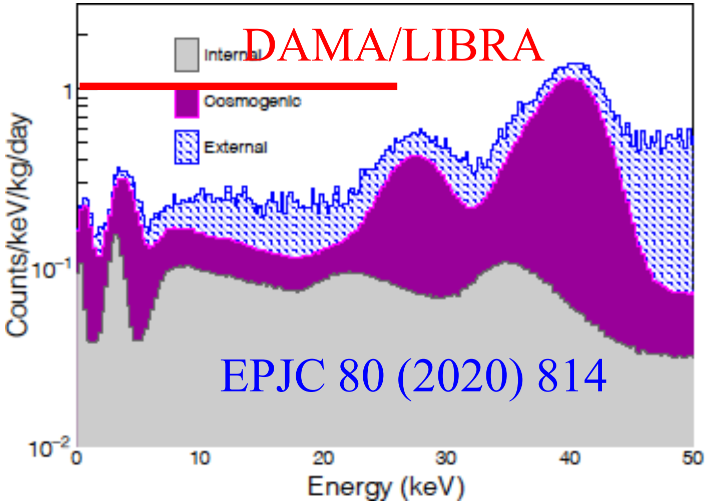


Machining



Assembly





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