AMoRE

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1st Yemilab Workshop @ High-1

Outline

- Overview of AMoRE project
- AMoRE-Pilot experiment
- AMoRE-I results
- AMoRE-II construction
- Summary

Rarity Frontier
- Searching for very rare events expected to occur from some new physics yet to be discovered -

Overview of AMoRE experiment

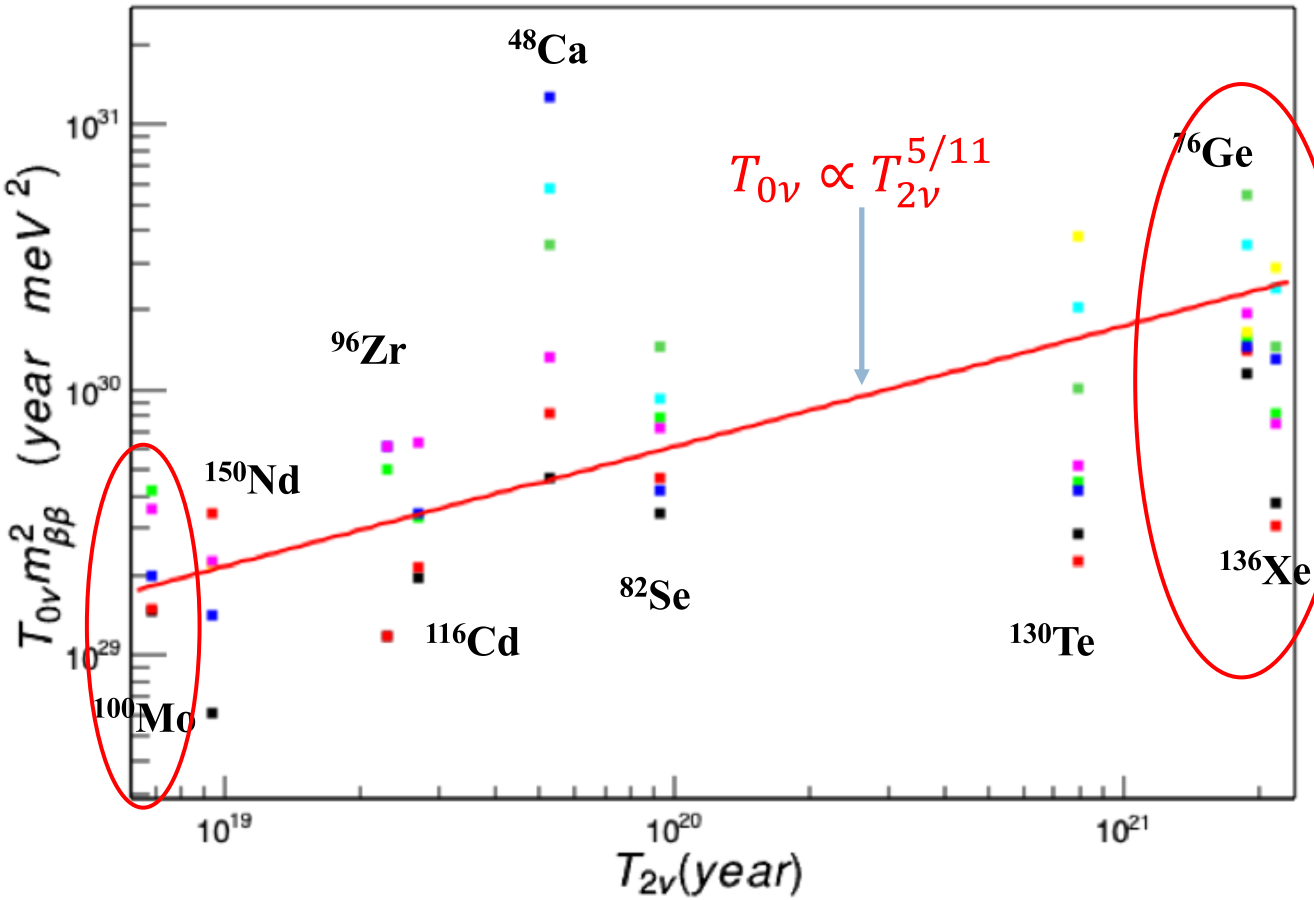
- ^{100}Mo
  - $Q_{\beta\beta}$=3034 keV
  - Natural abundance : 9.74%
- Detector
  - Use Mo-containing scintillating bolometer : $(^{40}Ca,X)^{100}MoO_4$
  - Phonon and photon sensors made of MMCs+SQUIDs to separate alphas (background) and betas (signal).

* Molybdate crystals : $CaMoO_4$ (CMO), $LiMoO_4$ (LMO), Na_2MoO_7 (NMO)

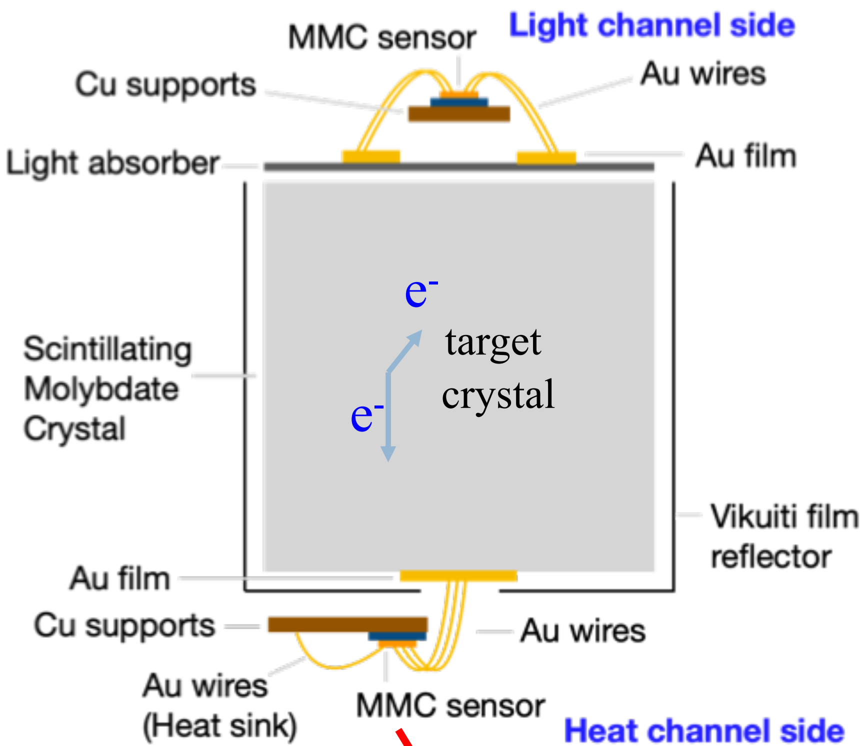
0νββ vs 2νββ T(1/2)

- **A correlation between** 2νββ **half-life(measured) vs 0νββ half-life (calculated)**
- It is important to run multiple isotopes since the real mechanism can be understood with a comparison between multiple isotope data.

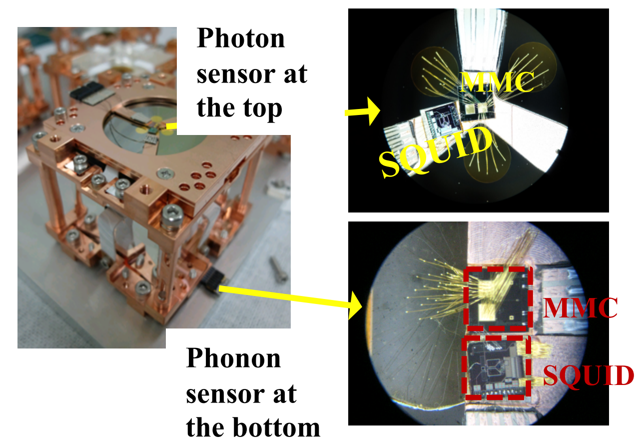
$G_{0\nu} \propto Q^5, \; G_{2\nu} \propto Q^{11}.$ H. Ejiri's comment

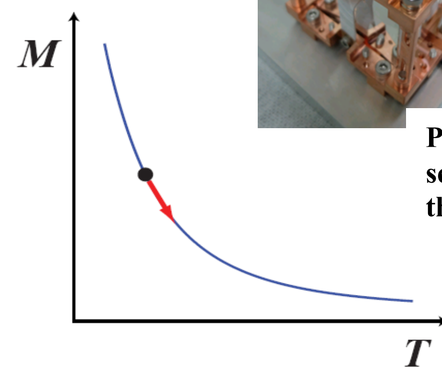


Principle of AMoRE detector

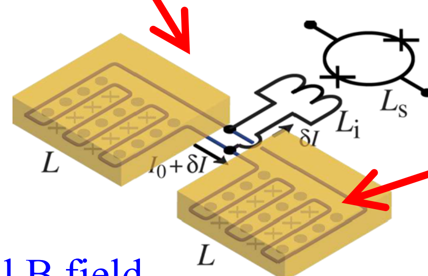


Decay→Phonons collected at Au foil → temperature of Au foil increase→magnetization of MMC decrese→ SQUID pick-up the change.



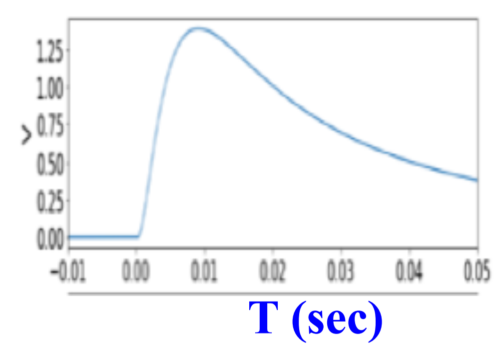


Au(Er) paramagnetic material



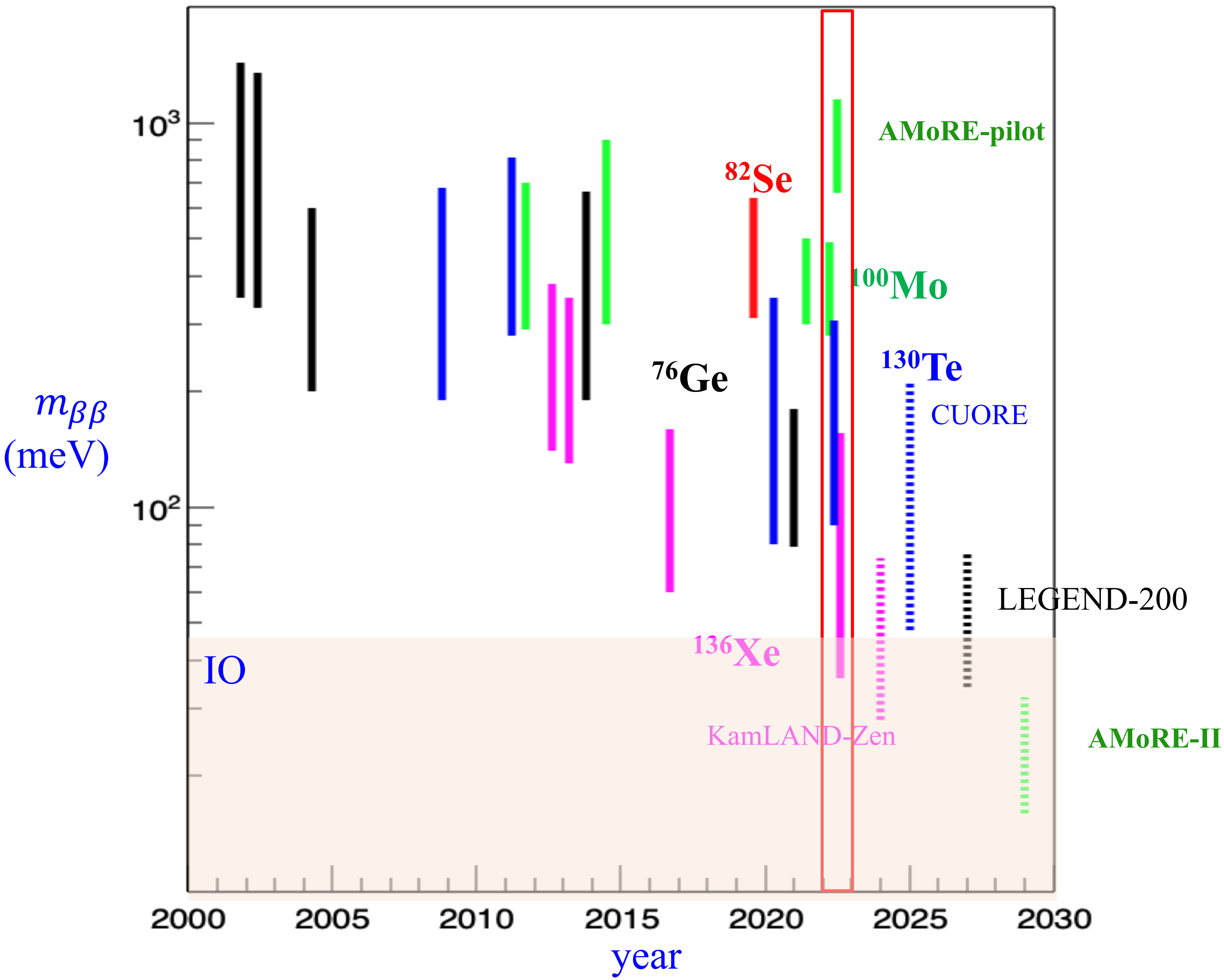
Persistent current in superconductor

Local B field

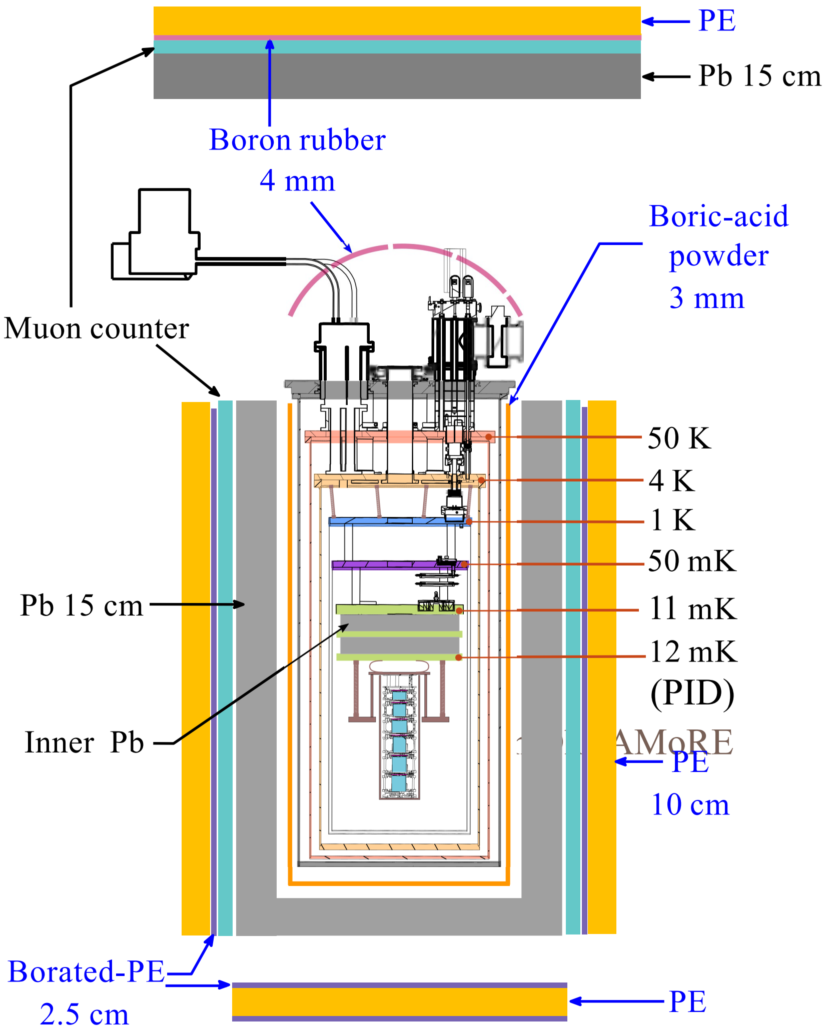


MMC: Metallic magnetic calorimeter

Recent Limits & Persepectives

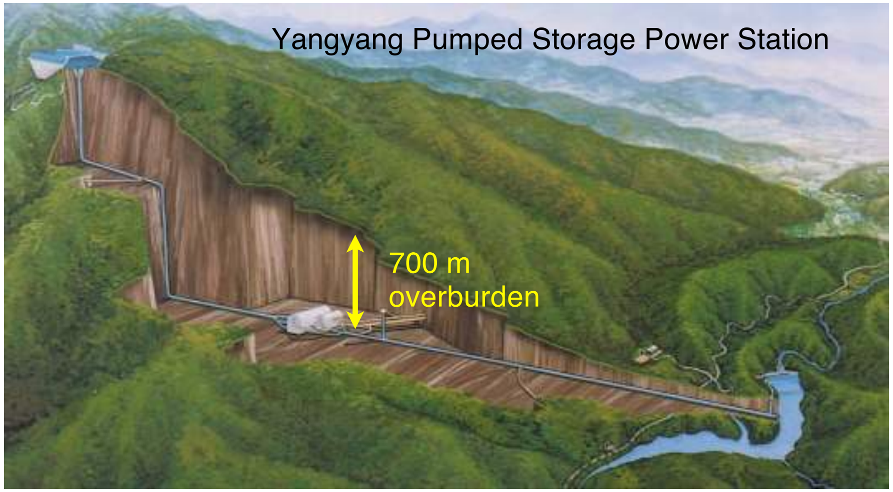


AMoRE-Pilot - Finished

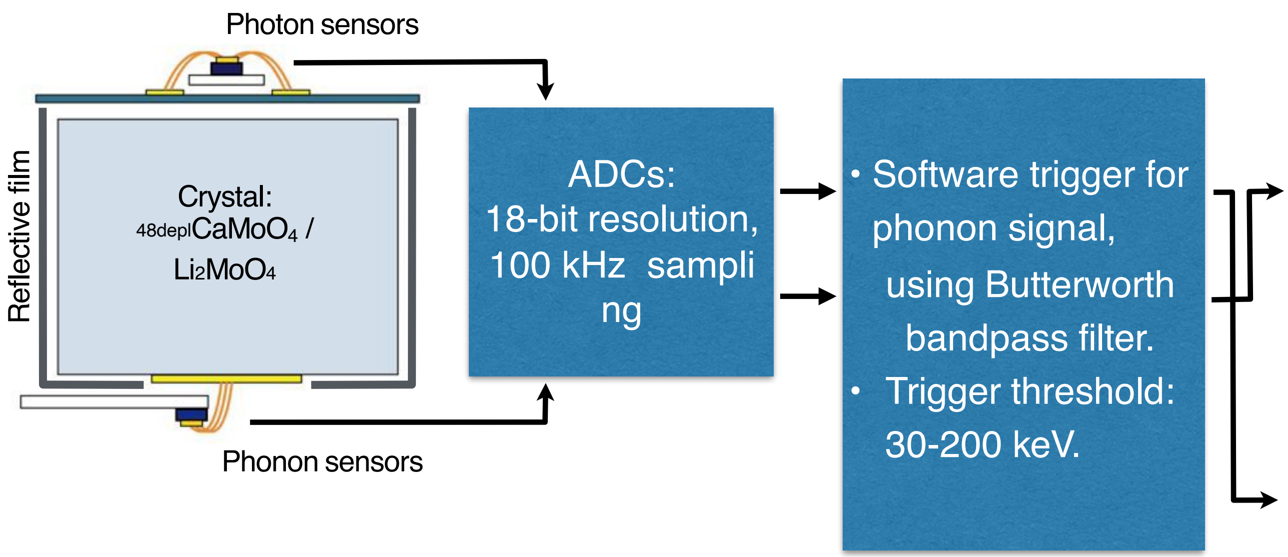


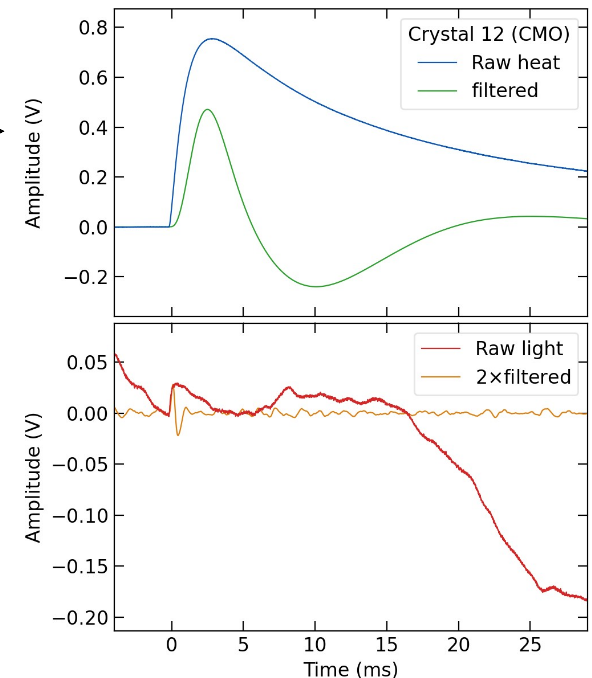
+ More enhanced shielding for AMoRE-I

- Cryogen-free dilution refrigerator.
- For AMoRE-pilot and AMoRE-I.
- Now operating at 10 mK with 1.2 μW cooling power.
- Pb (γ), boron, and polyethylene (n).
- Plastic scintillator muon counter.
- Yangyang Underground Laboratory (Y2L) at 700 m depth.



Signal processing and analysis



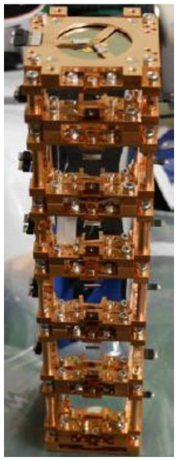


- Raw waveform:
  - baseline/noise informations.
  - timings (rise/fall): pulse shape discrimination (PSD).
- Reconstruction for improving energy resolution and β/α discrimination power (DP):
  - Butterworth bandpass filter— mainly for noise suppression:
    - pulse amplitude: pulse height or a least square fit to the template signal.
  - Stabilization heater signal every 10 seconds for gain drift corrections.

AMoRE-Pilot : Demonstration of detectors

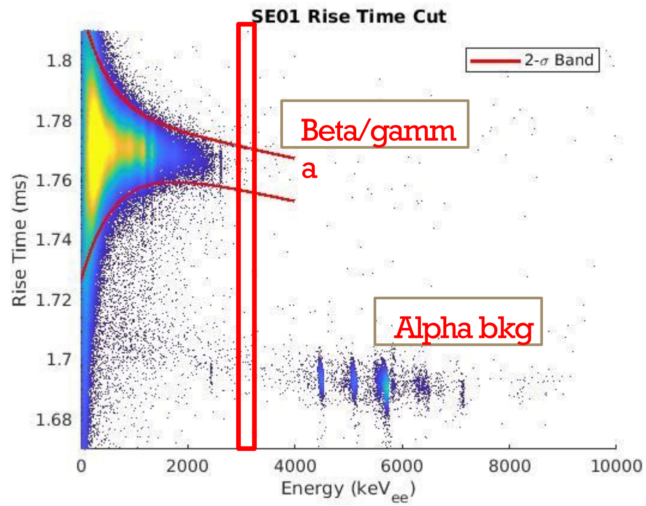
$^{40}Ca^{100}MoO_4$

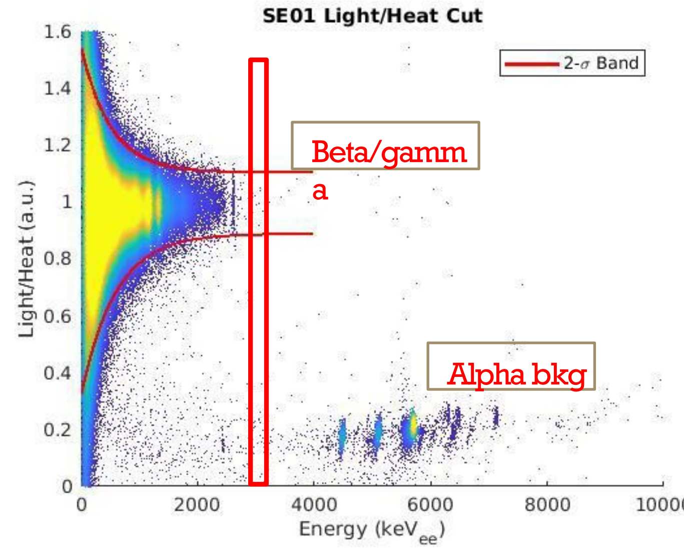
~ 1.9 kg

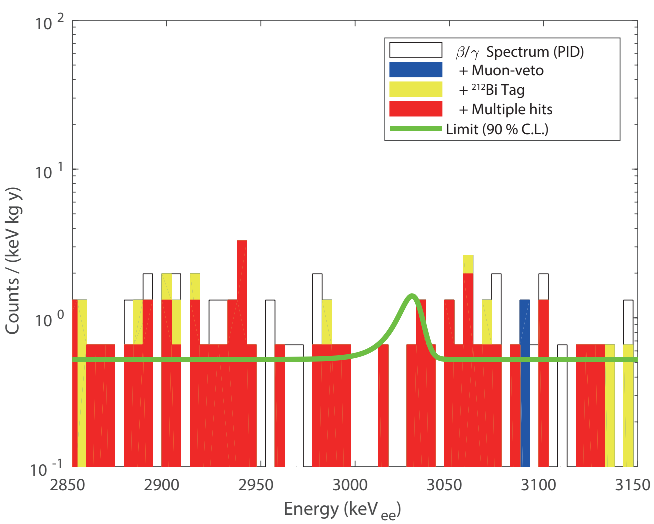


Alpha Backgrounds are effectively rejected with PSD & Light/Heat raio.

EPJC 79, 791 (2019)







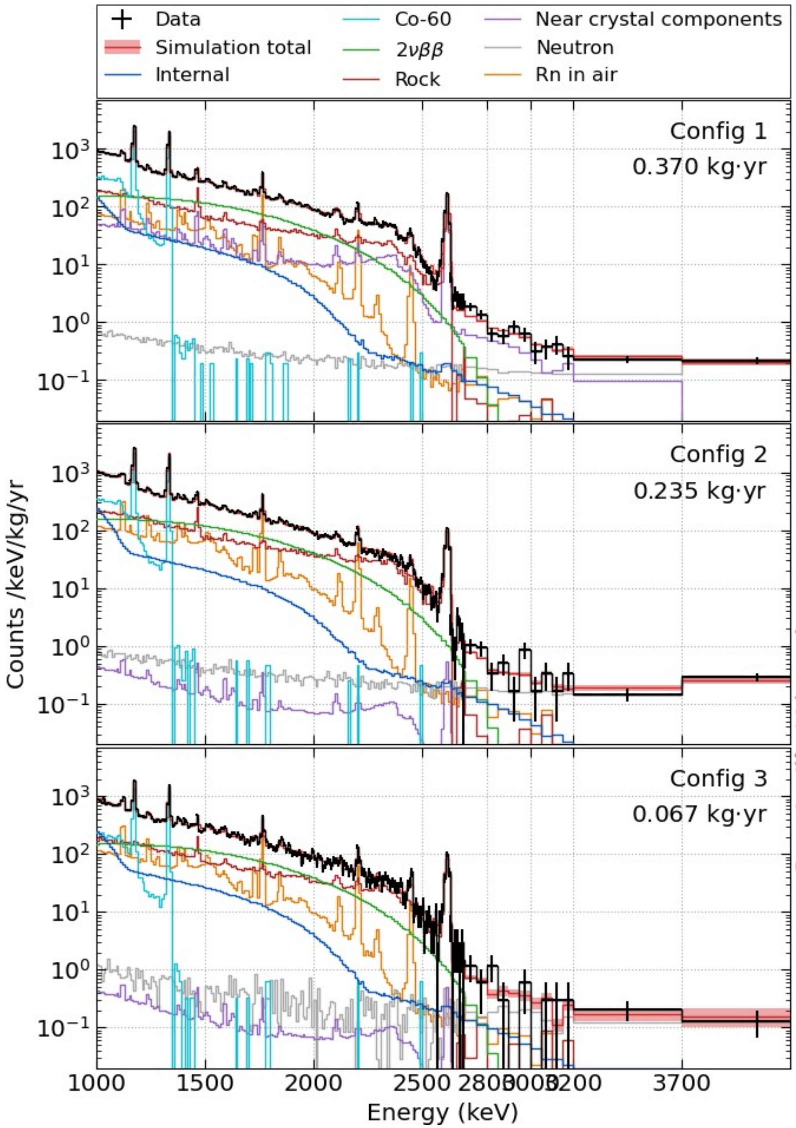
- 111 (kg day) exposure.

→ Final background level : 0.55 ckky

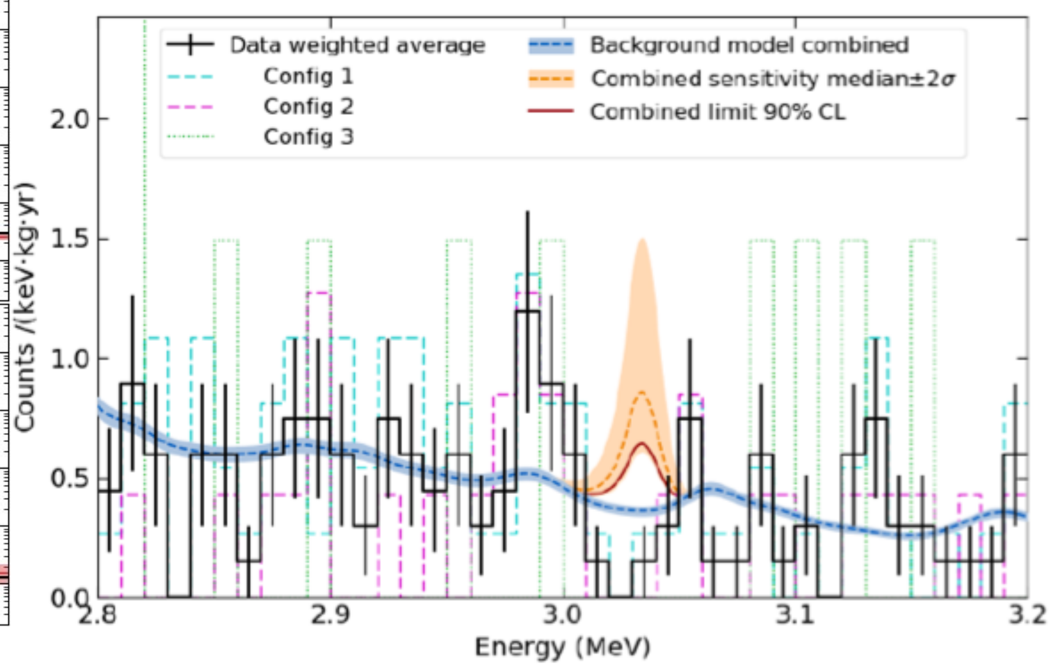
→ $T_{1/2}^{0\nu} > 9.5\times10^{22} years$

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

Final data of AMoRE-Pilot



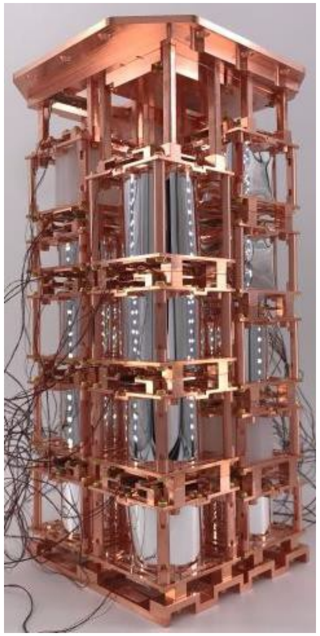
- AMoRE-Pilot experiment began in 2015 @ Y2L to demonstrate the concept.
- 6 CMO crystals are used.
- ~ 2 years of data with different configurations to reduce the backgrounds.
- Final 0νββ half-life limit is 3.43x10^{23} year.



AMoRE-I : Running

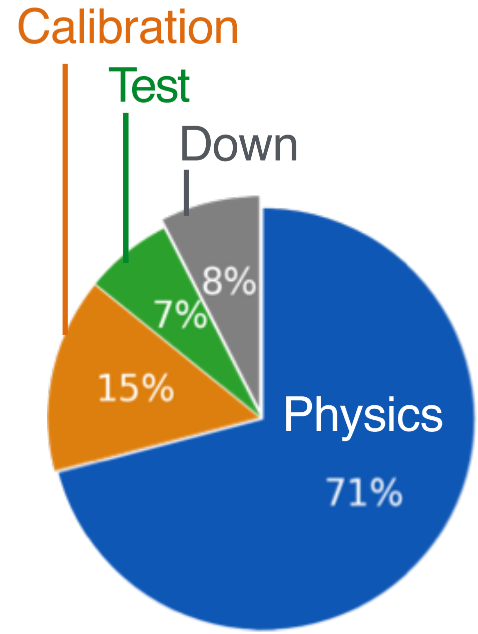
- AMoRE-I setup began in 2019, but it took time to operate the cryostat.
- AMoRE-I run began Aug. 2020 @ Y2L
- Purpose – Check further on detector performance & backgrounds.
- Upgrades from Pilot
  - 13 CMO crystals (4.6 kg) and 5 LMO (1.6 kg) crystals, ~3 kg of ^{100}Mo
  - Outer Pb shields 15 cm → 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.

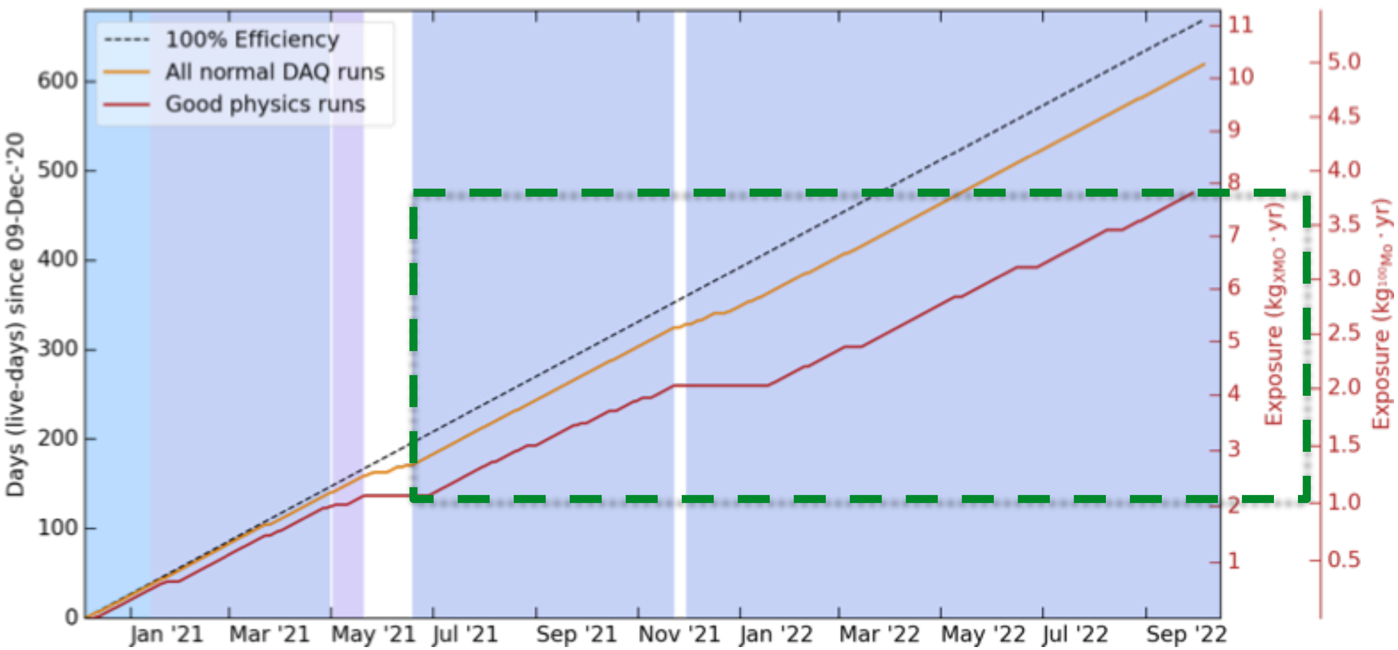
- Detectors are stable for years.



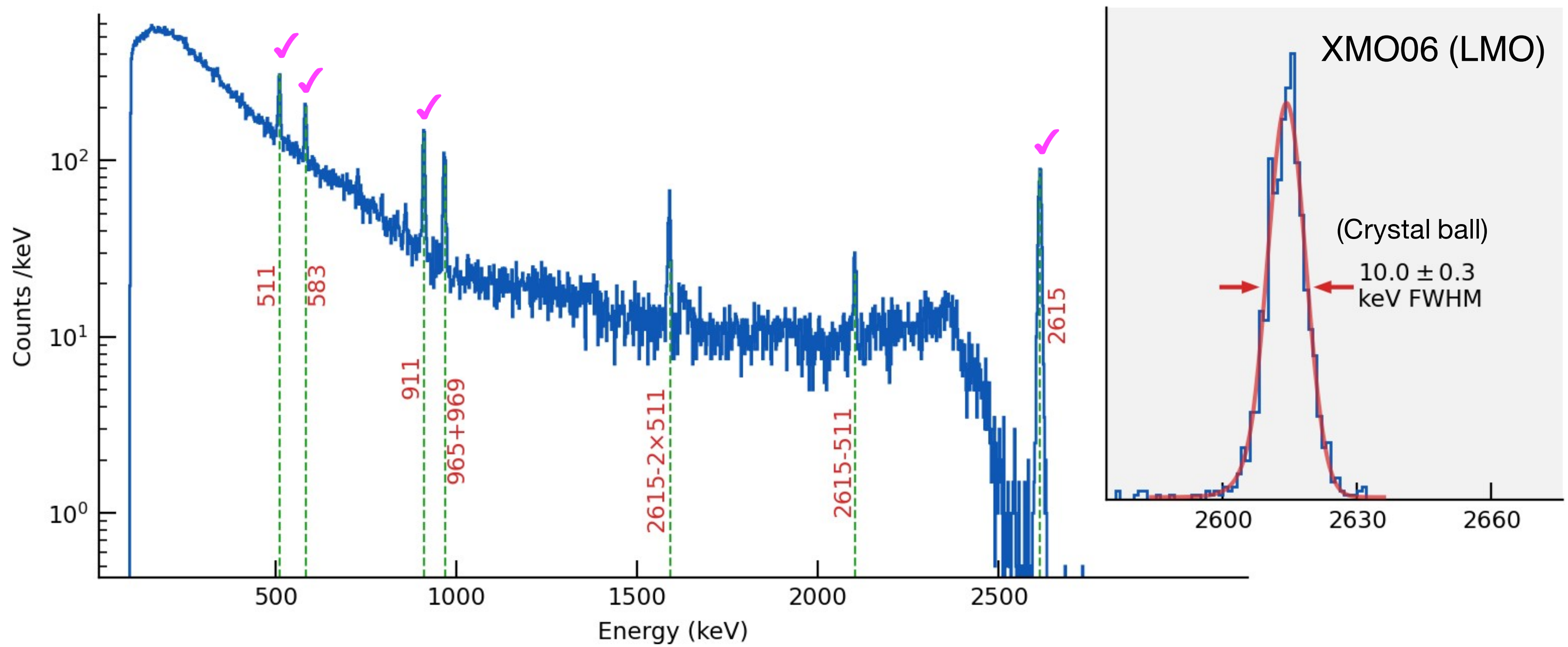
AMoRE-I exposure

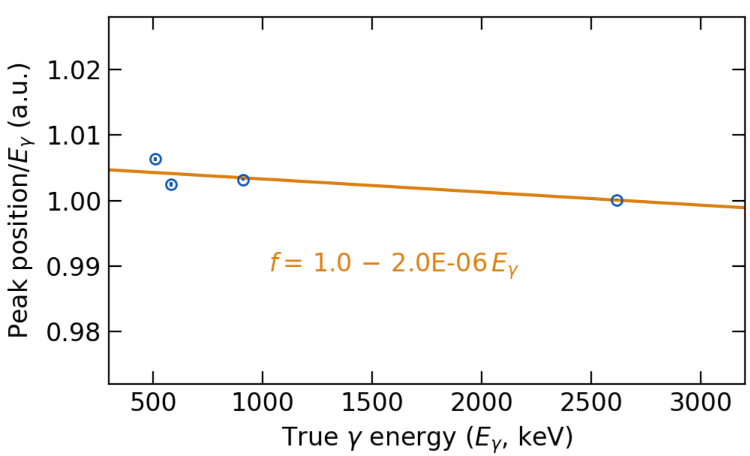
- 20 months' operation with the full detector configuration.
- Exposure at 12 mK after removal of the radioactive Al plates
- ~ 6 kg_{XMO}·yr ~ 3 $kg_{Mo\text{-}100}$·yr
- ~ 2 × CUPID-Mo exposure (1.48 $kg_{Mo\text{-}100}$·yr).





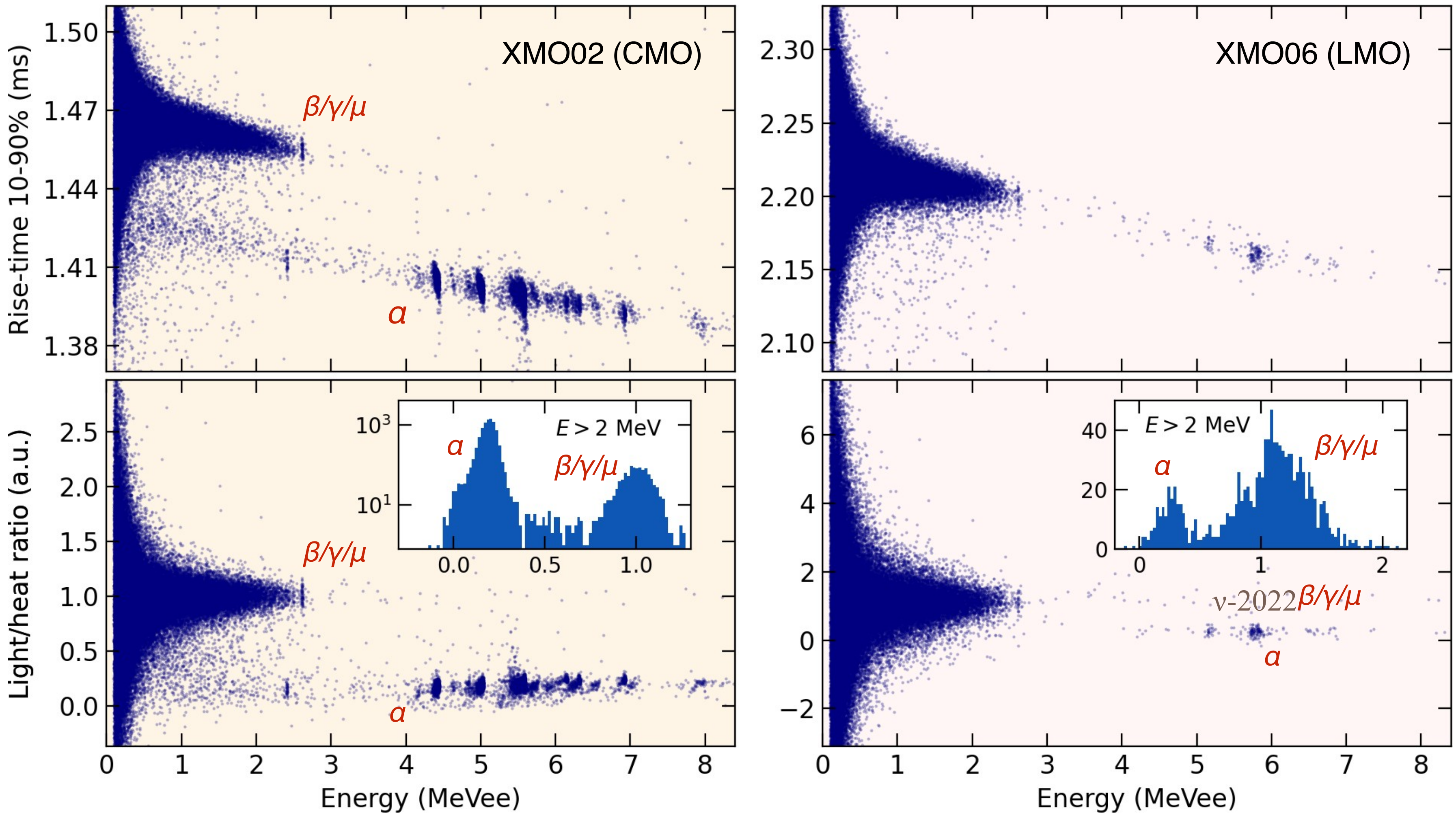
Energy calibration





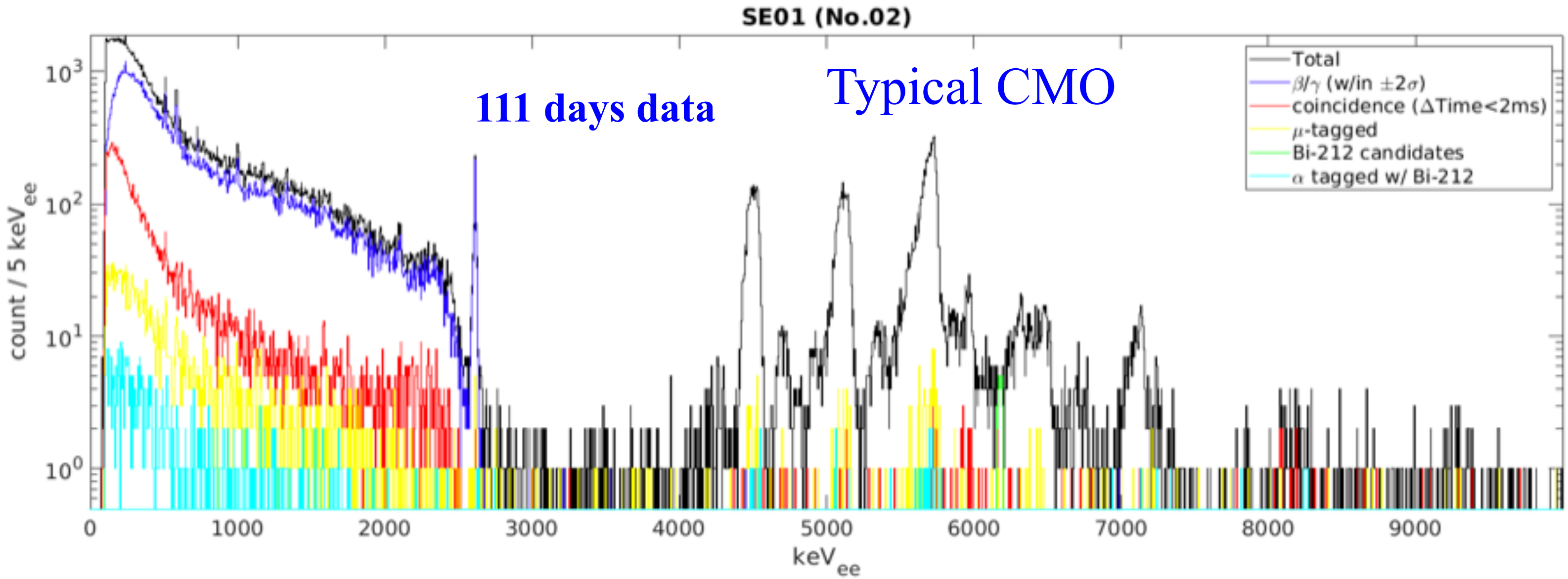
- Calibration source: ^{232}Th-rich welding rods just outside of OVC.
- Slight non-linearity between signal amplitude and energy.
- Energy resolution: [10-30] keV FWHM at 2615 keV, ~15 keV in average.

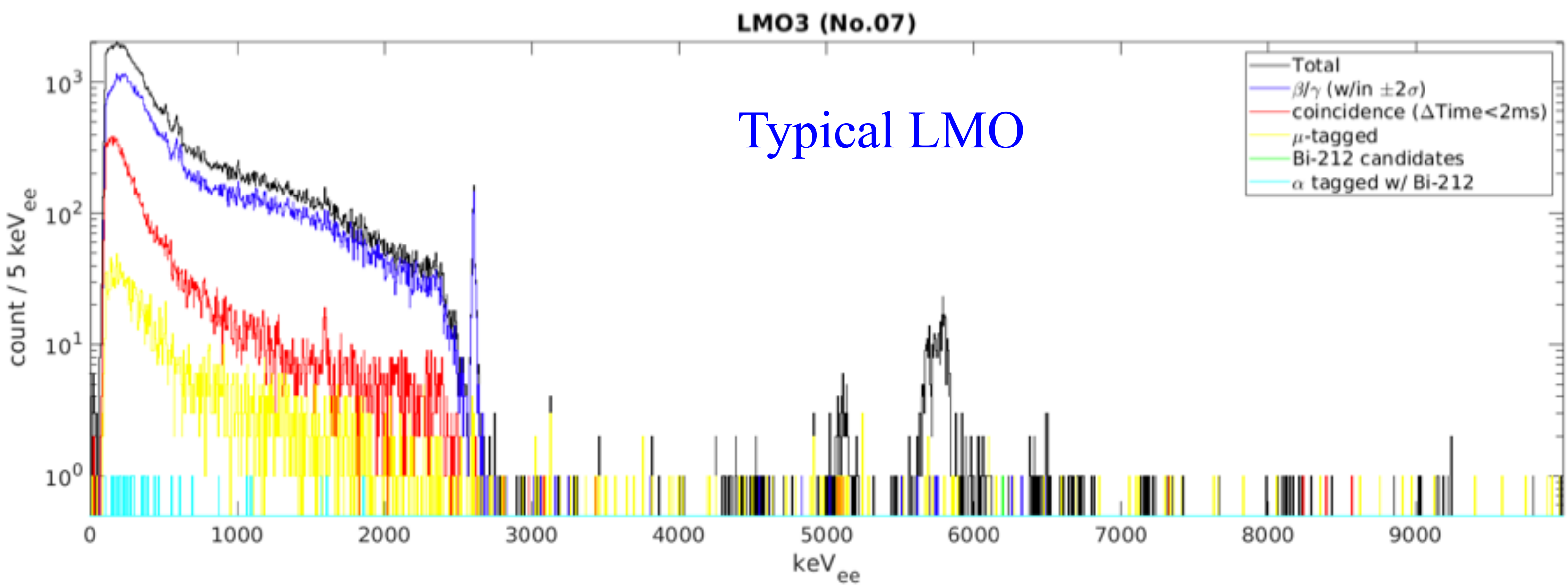
Particle IDentifications, CMO and LMO



- CMO shows better discrimination power — light yield: CMO > LMO.
- LMO has much less *α* contamination.

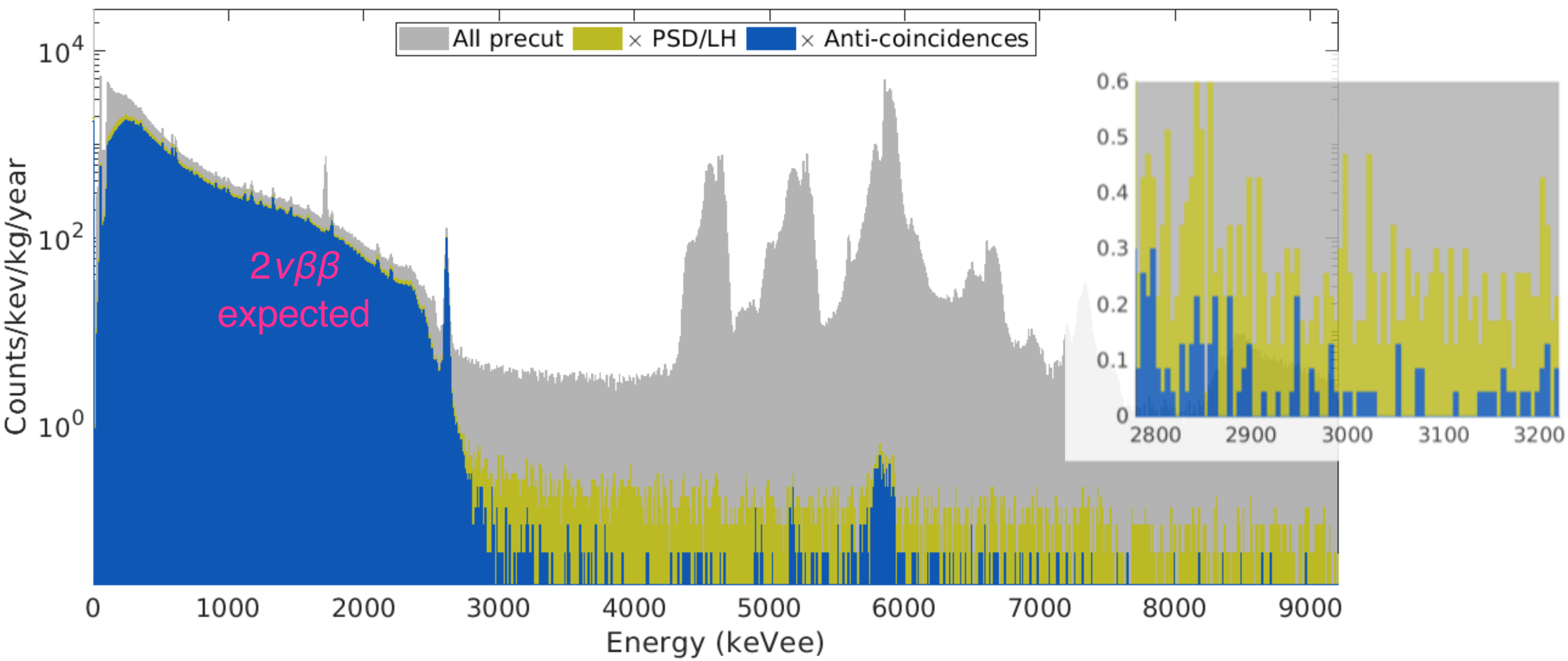
AMoRE-I


SE01 (No.02)
111 days data
Typical CMO
Total
β/γ (w/in ±2σ)
coincidence (ΔTime<2ms)
μ-tagged
Bi-212 candidates
α tagged w/ Bi-212
count / 5 keV$_{ee}$
keV$_{ee}$
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10^0
10^1
10^2
10^3


LMO3 (No.07)
Typical LMO
Total
β/γ (w/in ±2σ)
coincidence (ΔTime<2ms)
μ-tagged
Bi-212 candidates
α tagged w/ Bi-212
count / 5 keV$_{ee}$
keV$_{ee}$
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10^0
10^1
10^2
10^3

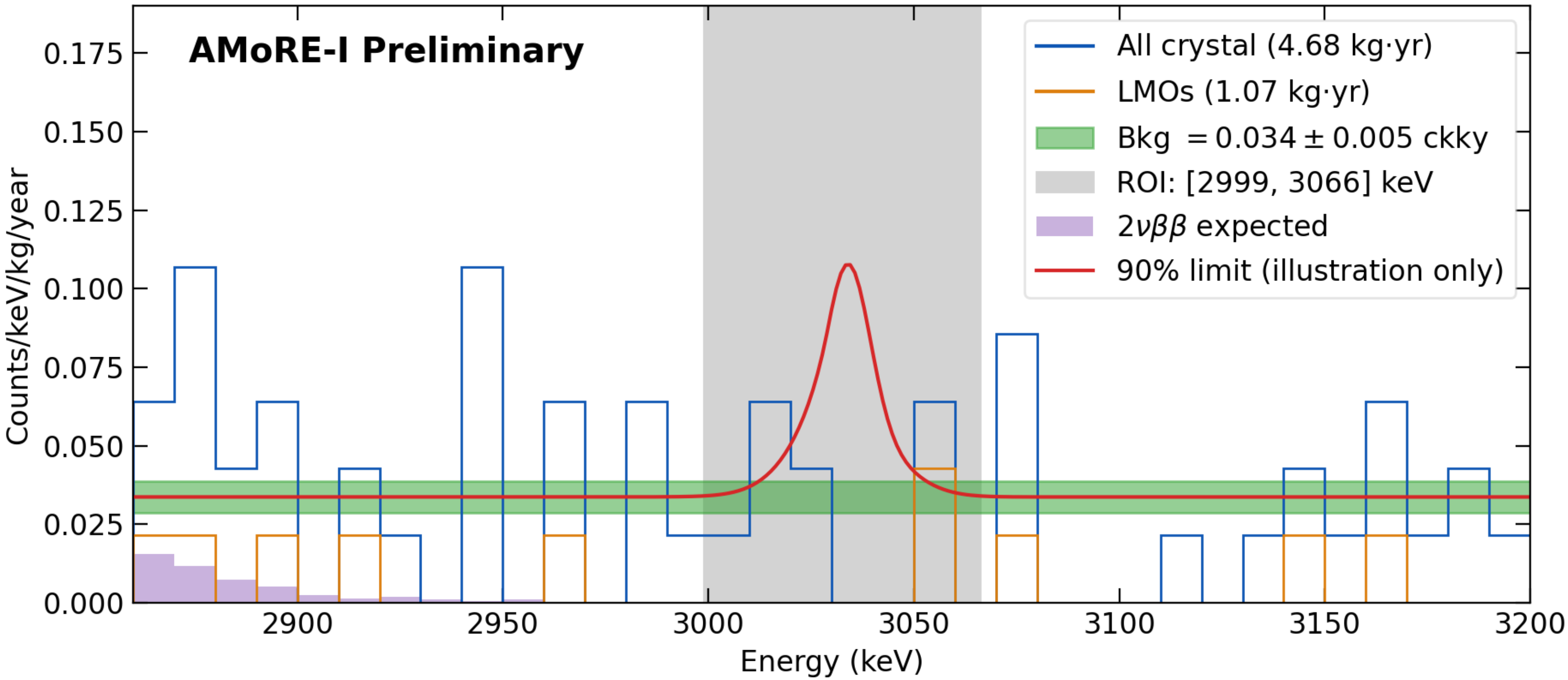
Background spectrum - total

- 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 ($\varepsilon \sim 98\%$).



Preliminary data

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

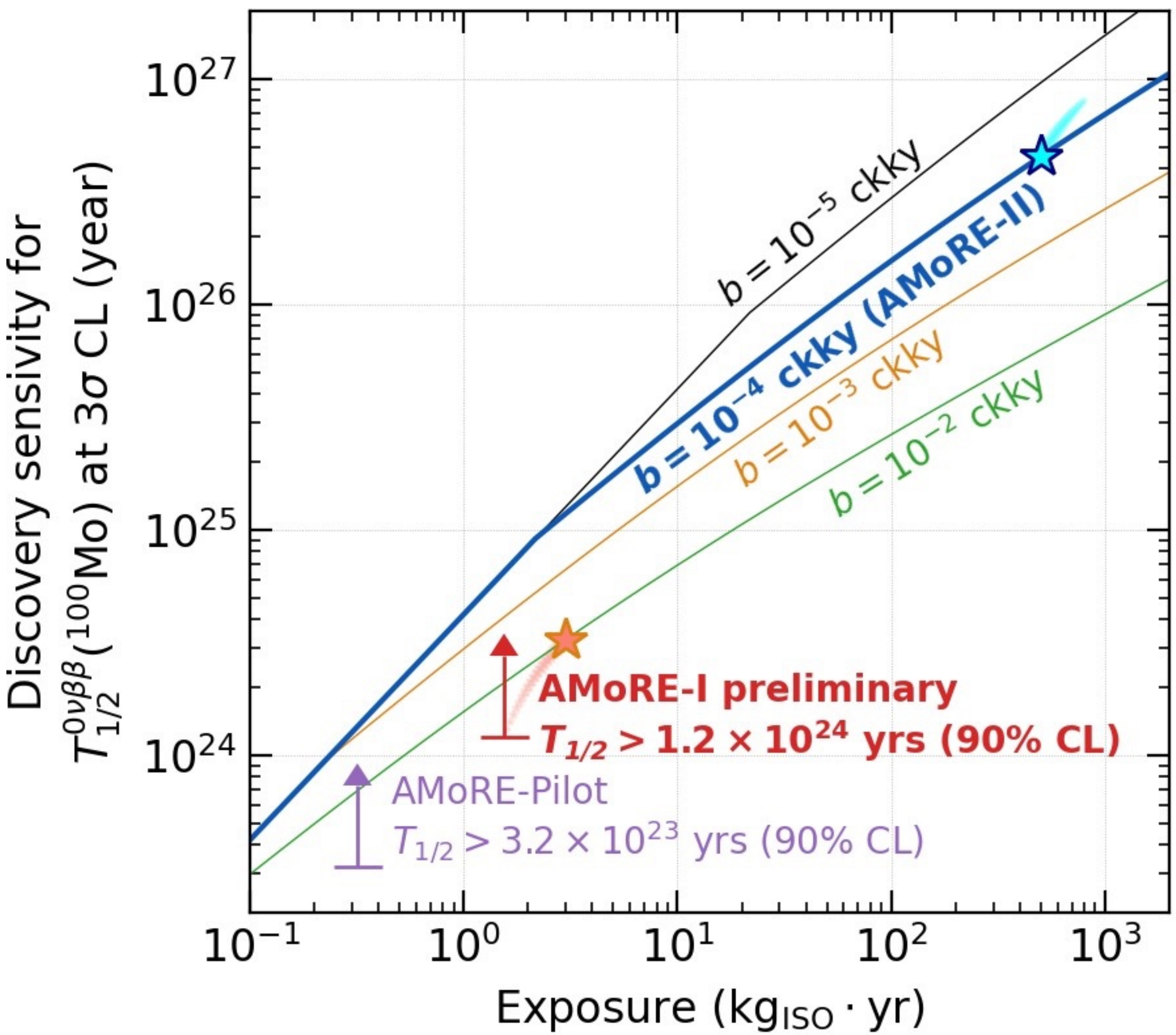


- Background = 0.034 ± 0.005 ckky,
- $T_{1/2}^{0\nu} > 1.05\times10^{24}$ years at 90% C.L.,

  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

Sensitivities of AMoRE-I



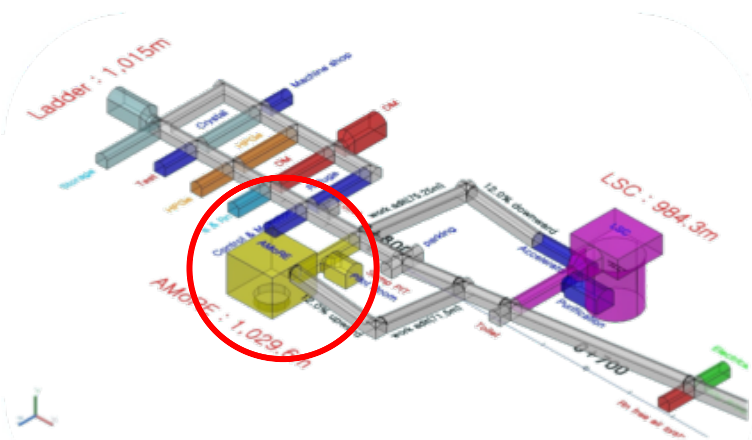
Crystal decision for AMoRE-II

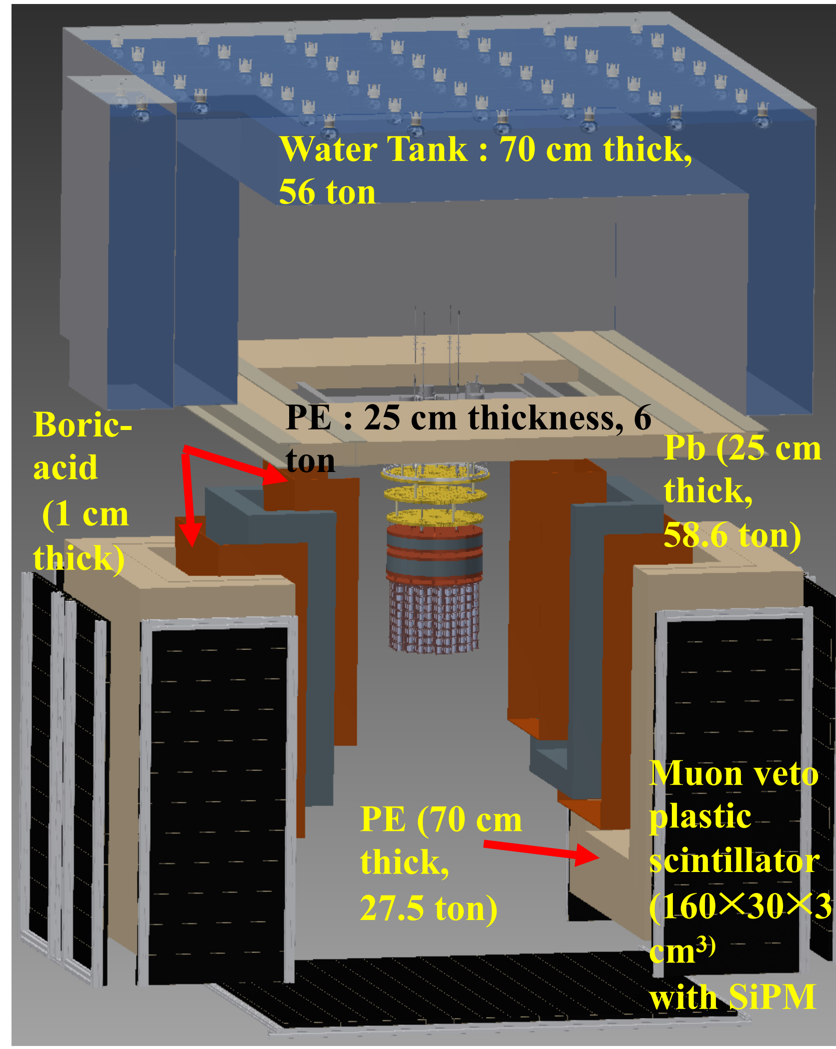
- LMO has light output smaller than CMO by a factor ~ 8. (Cf. ~ 20 @ 10 K)
- But, DP w/ light detector is similar between these two crystals.
- Crystal growing is easier for LMO, and ^{48}Ca depletion is necessary for CMO.
- CMO has PSD w/o light detector, ~ DP > 10.
- LMO crystal is chosen for AMoRE-II

Crystals	Scintillation				Mechanical		Thermal		Pro Con
	λ_{em} (nm)	Eg (eV)	τ (μs) @10K	E_{scin} (Rel.)	Dens. (g/cc)	Mo Fraction	T_D (K)	T_M (C)	
CMO (CARAT)	540	3.78[1]	240	100	4.32	0.49	446	1445	High light out High melt T, difficult growing, high bkg, 48Ca
NMO-I (NIIC)	663	3.50	750	9	3.62	0.558	332	687	 Cleavage plane
LMO (CUP)	535	4.26.[2]	23	5	3.03	0.562	~~765~~ 316	705	Low melt. T, easy growing, low bkg, high T_D Low light, hygroscopic,
$PbMoO_4$	592	3.20[4]	20	105	6.95	0.269		1065	High light out Low Mo fraction, higher bkg

AMoRE-II : under preparation

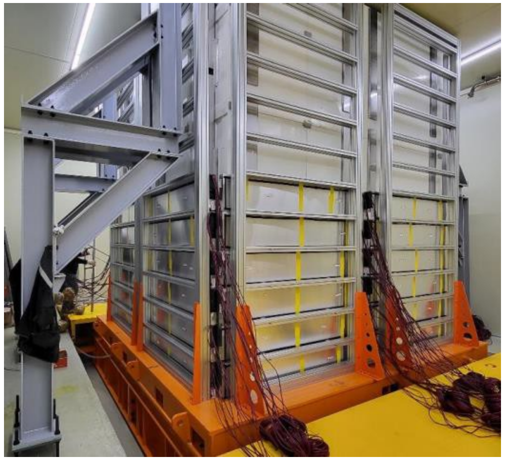
- 100 kg of ^{100}Mo running @ Yemilab for 5 years
- $Li_2{}^{100}MoO_4$ crystals in 5 and 6 cm cylinder. (~ 410 crystals) + 13 $^{40}Ca^{100}MoO_4$
- DR inside heavy shielding with Pb, PE, and water.



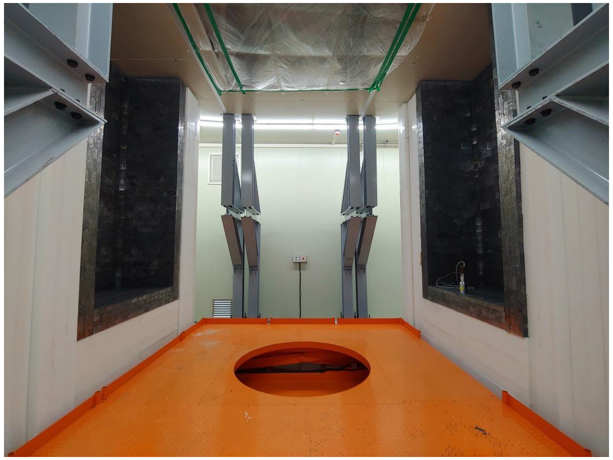


Overview of AMoRE-II setup

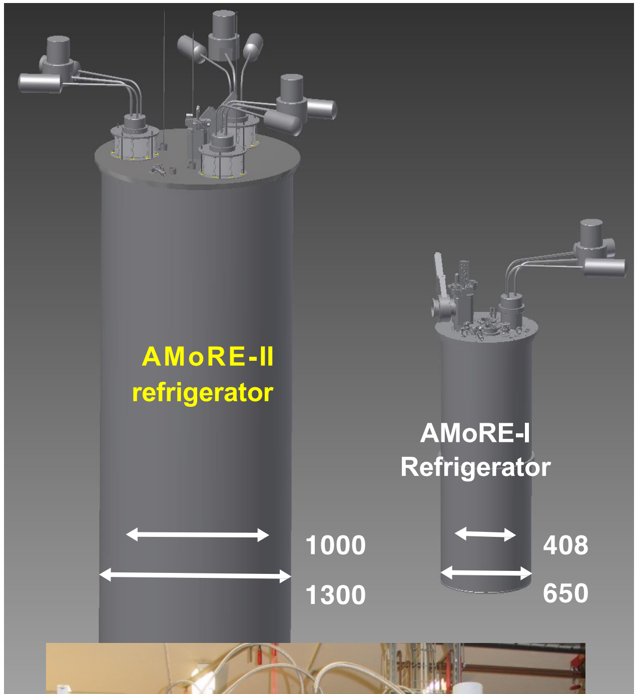
Detector room

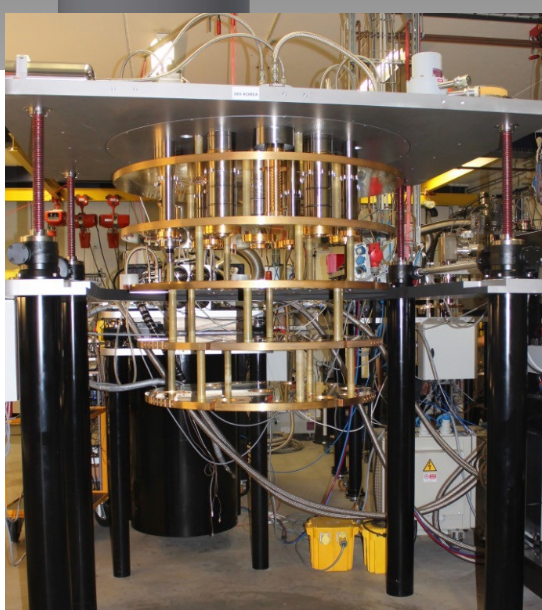


- PS detector
  - 102 detectors out of 132 were installed.
  - 30 detectors will be installed after closing detector.
- WC detector
  - Reflector (tyvek) was installed on the surface inside dete ctor.
  - PMTs are installed and the door will be finished after ins talling DR.
  - Water purification system has been ready.



Dilution refrigerator & Cryostat

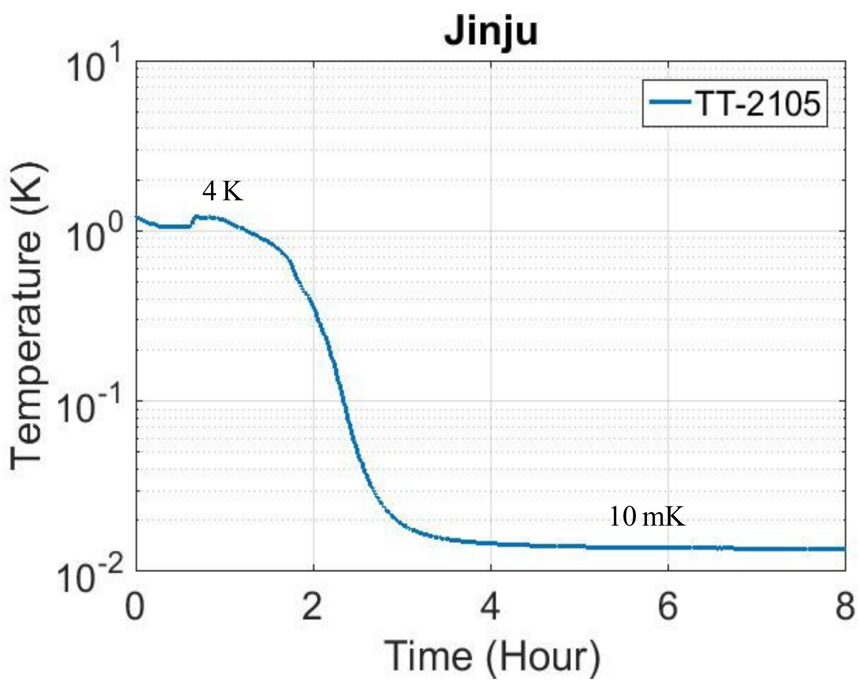




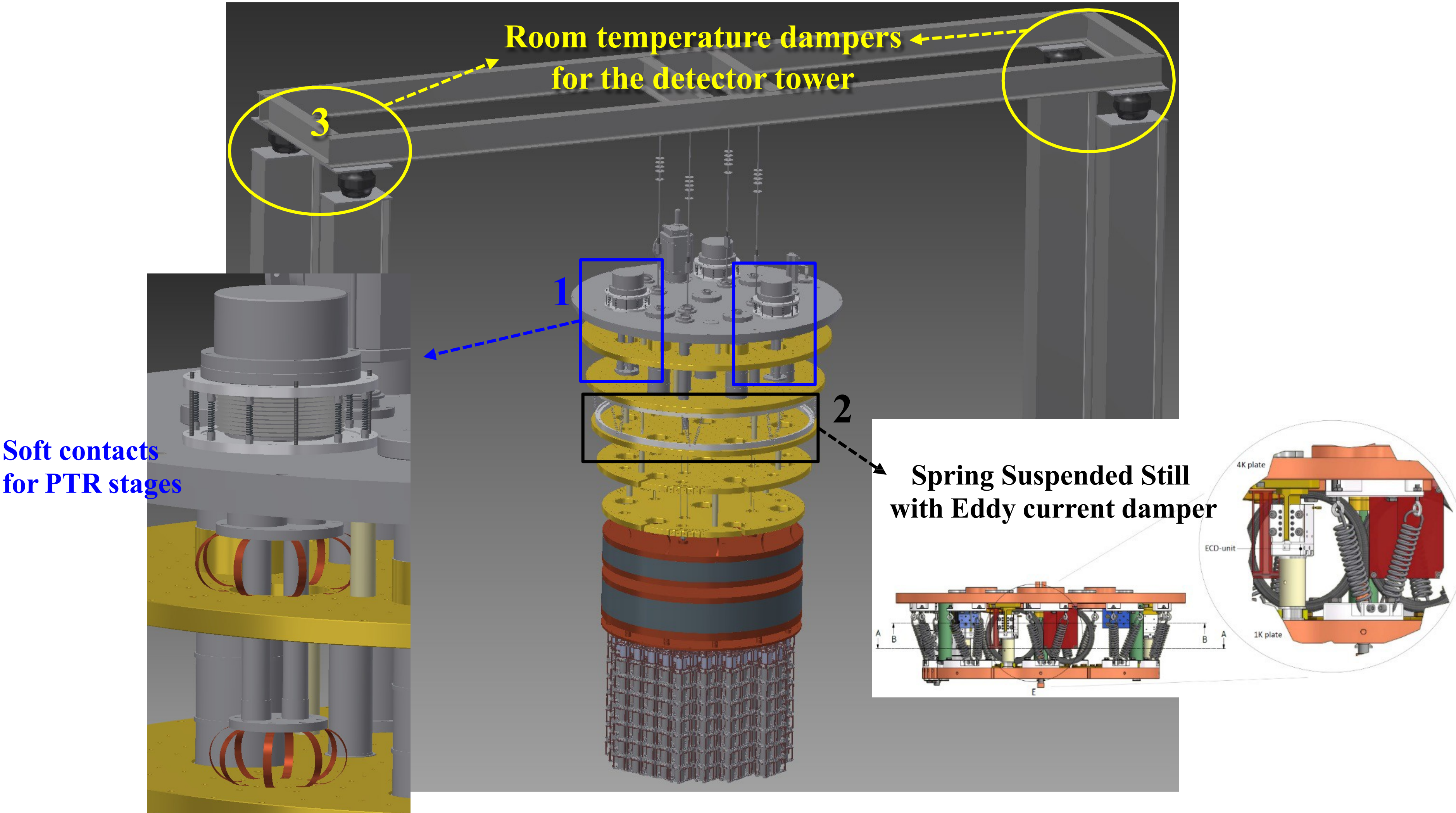
Large dilution Refrigerator from Leiden.

- **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



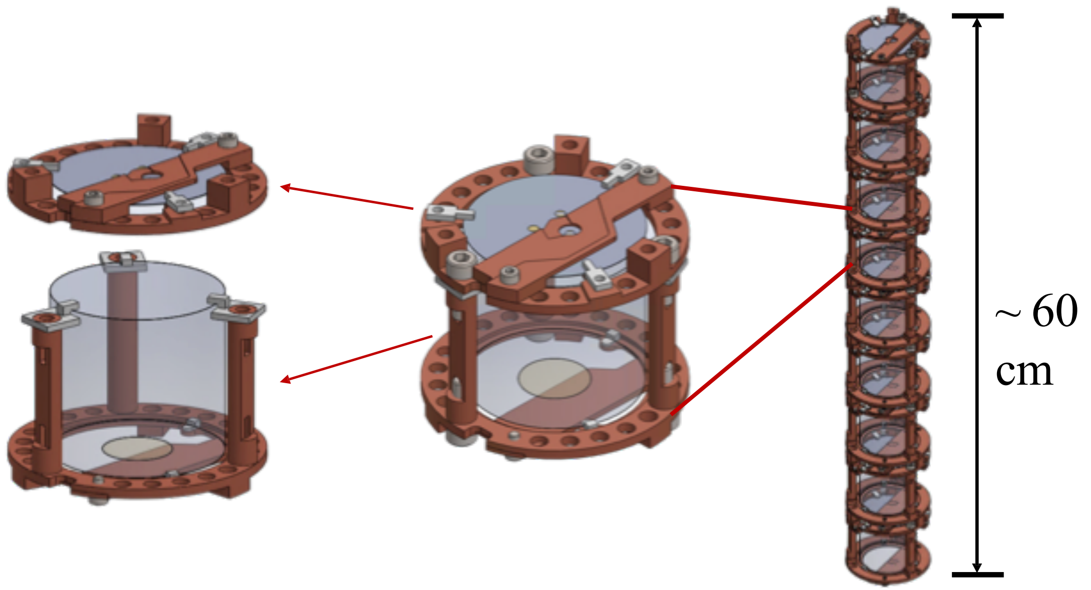
Vibration damping systems

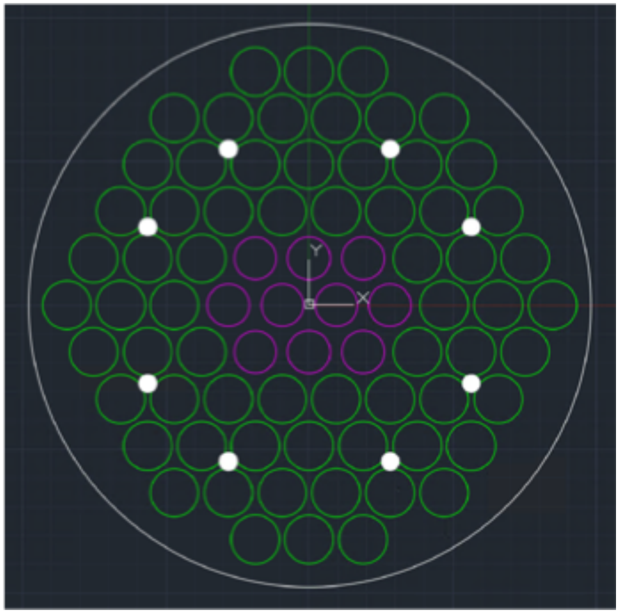


Detector tower (Pb+Cu+LMO): ~ 3.4 ton
Independent support of Kevlar strings + STS rods from room temp.
Cooling method: IVC exchange gas + soft copper foils

New module design for AMoRE-II

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.

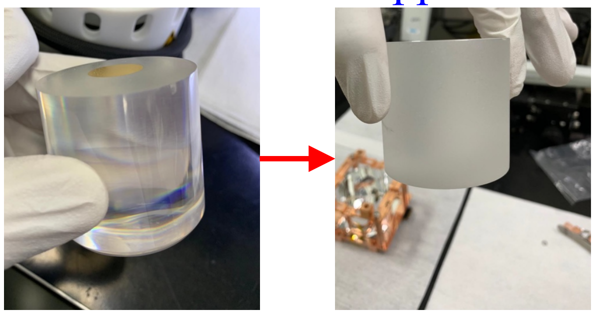
Reduce total copper mass (copper structure w/o screws: 297 → **182 g**)

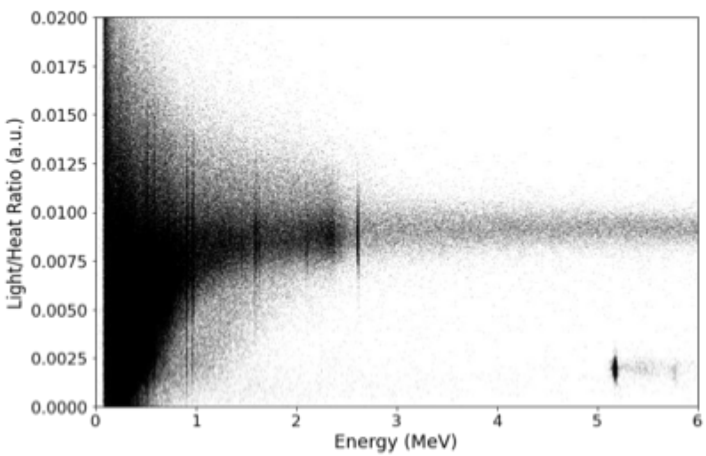
Recent progresses for LMO crystals

- Recently, we improved the detector performance.

(1) Polishing vs lapping(roughening)

Polished surface Lapped surface

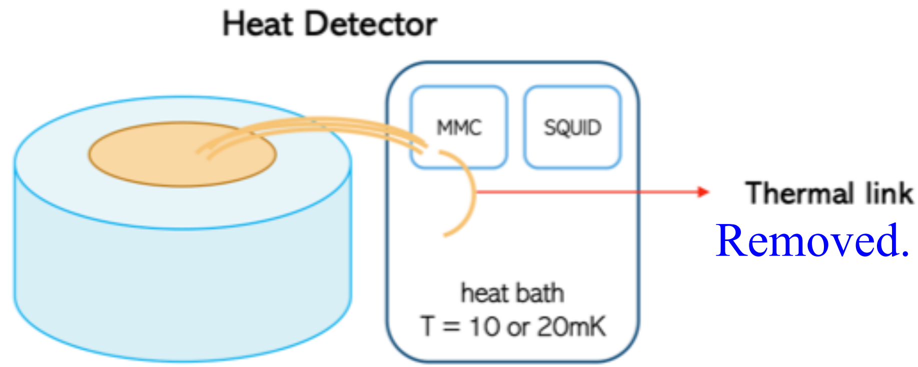


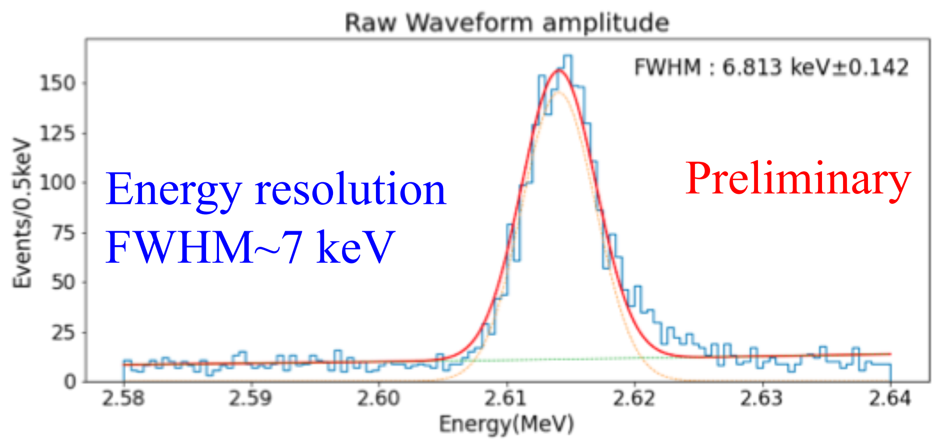


Lapping and thermal link removal :

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

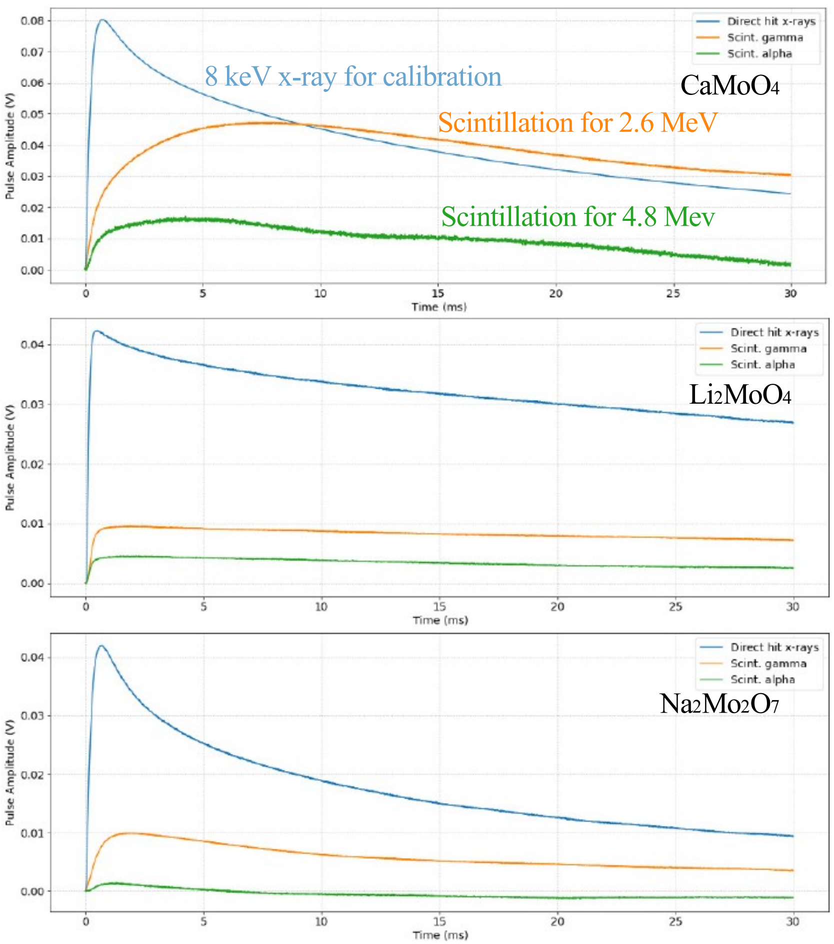
(2) Thermal link





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

Light yield comparisons



- $CaMoO_4$, Li_2MoO_4, $Na_2Mo_2O_7$ crystals are compared.
- Light collection, scintillation decay time, alpha particle quenching.

- LMO has fast scintillation → more sensitive signal though low light yield.
- CMO has slow scintillation → excellent PSD

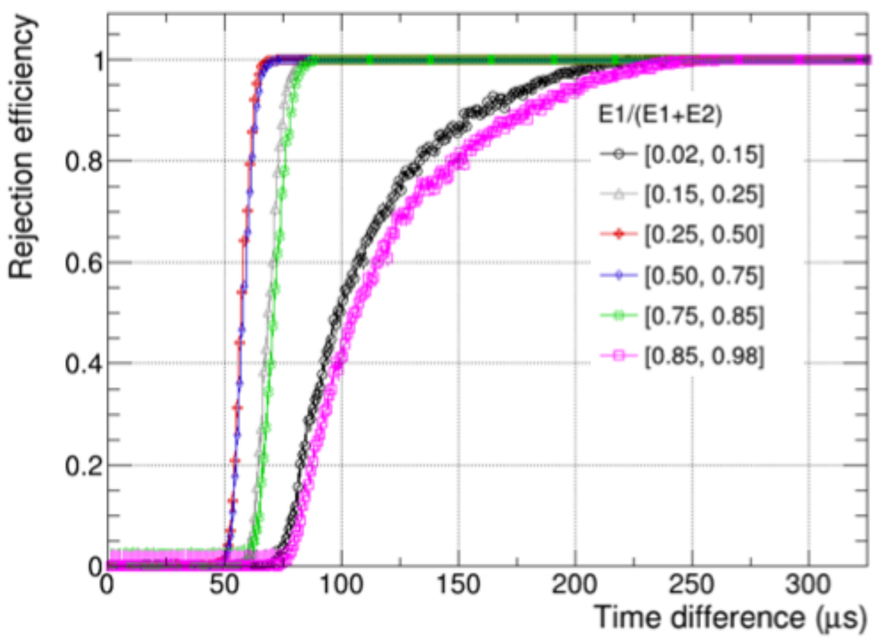
- Need to build a light collection simulation

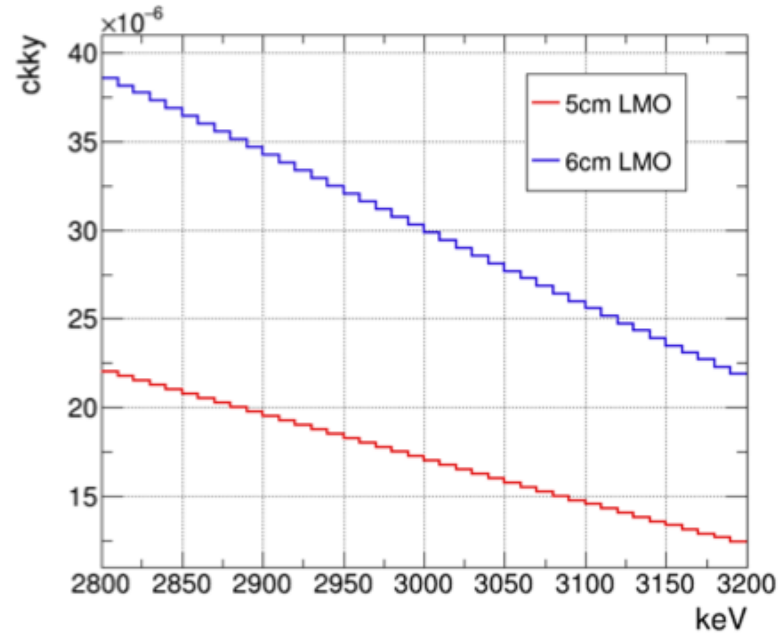
Preliminary

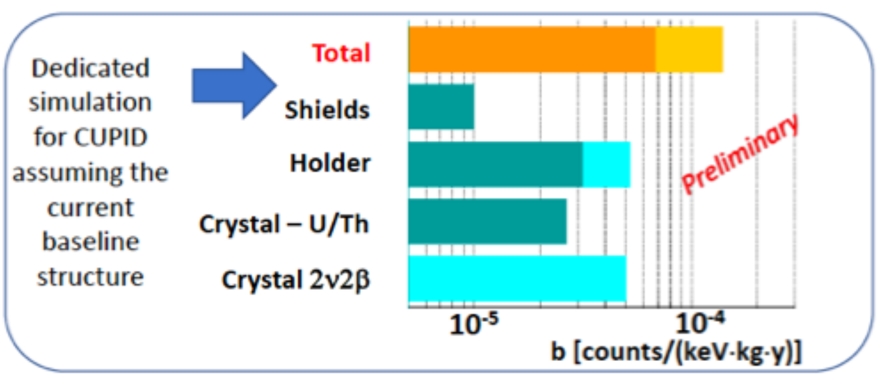
	A_1	$\tau_1[\mu s]$	A_2	$\tau_2[\mu s]$	$A_1\tau_1/A_2\tau_2$	Light yield [%]
LMO	0.0299 ± 0.0005	45.3 ± 1.2	0.0016 ± 0.0001	451.3 ± 12.8	1.8 ± 0.2	0.064 ± 0.003
NMO	0.0028 ± 0.0001	31.3 ± 1.9	$0.0004\pm5e-06$	661.2 ± 7.1	0.37 ± 0.05	0.093 ± 0.004
CMO	0.0668 ± 0.002	10.9 ± 0.4	$0.0011\pm5e-06$	2246.7 ± 24.377	0.3 ± 0.024	0.44 ± 0.012

Pileup background estimation

- A realistic estimation assuming real spectra and noise data from AMoRE-pilot
- Crystal size is important – pile up event rate is proportional to square of single rates.
- 6cm crystal is acceptable.



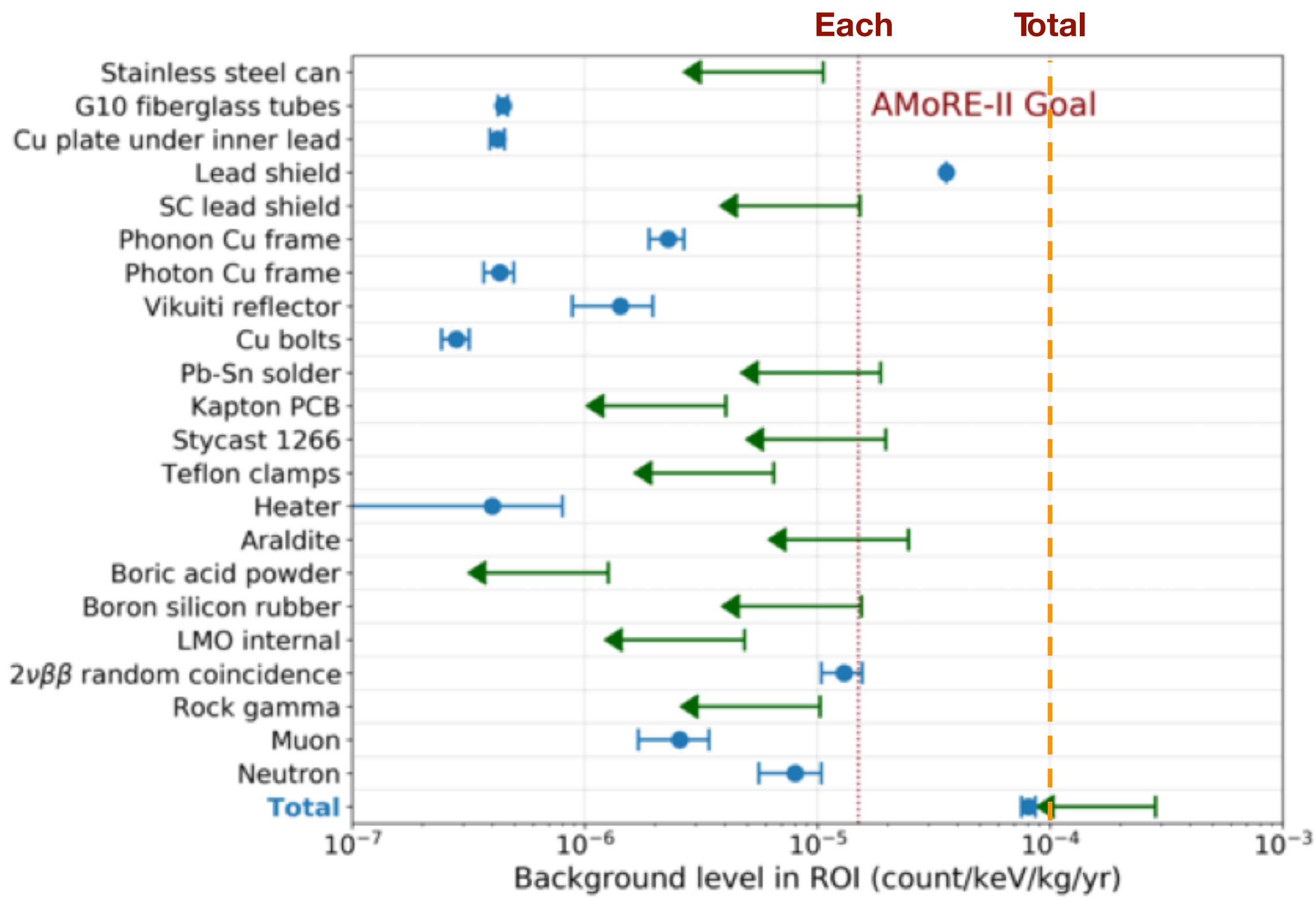




Compare with CUPID-Mo

Updated AMoRE-II backgrounds estimation

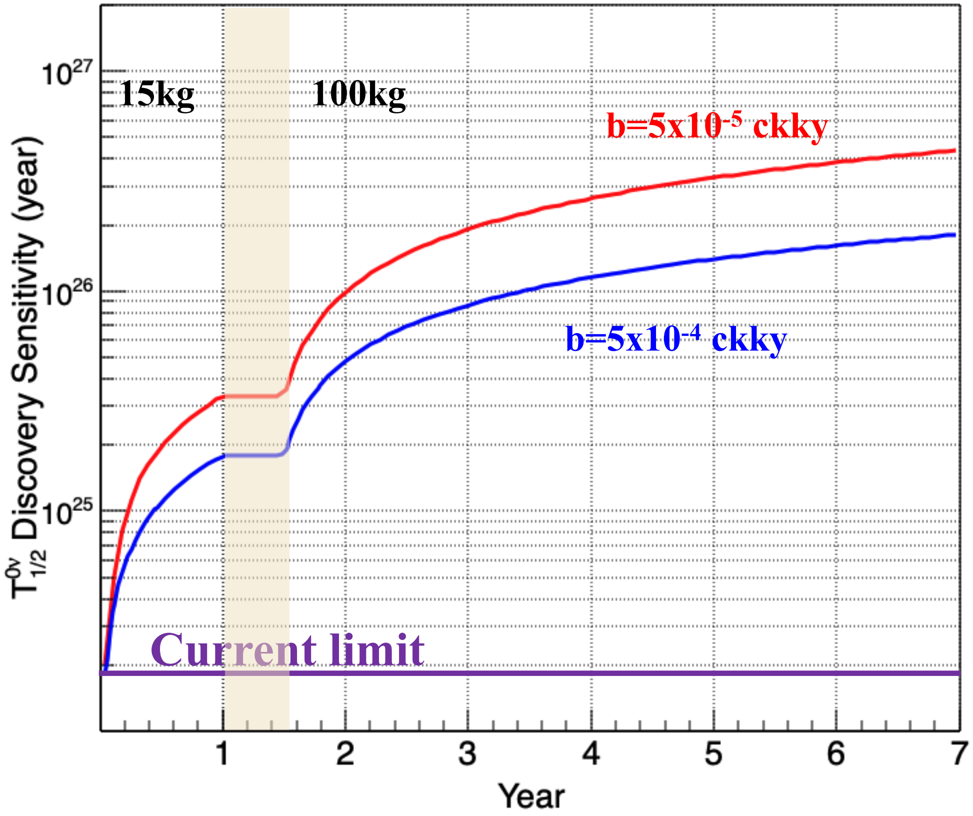
- Total backgrounds are satisfactory for AMoRE-II requirements.
- Possible to reduce by upgrading Pb shielding ~ 10 ton (inner 5cm out of 25cm)



AMoRE-II

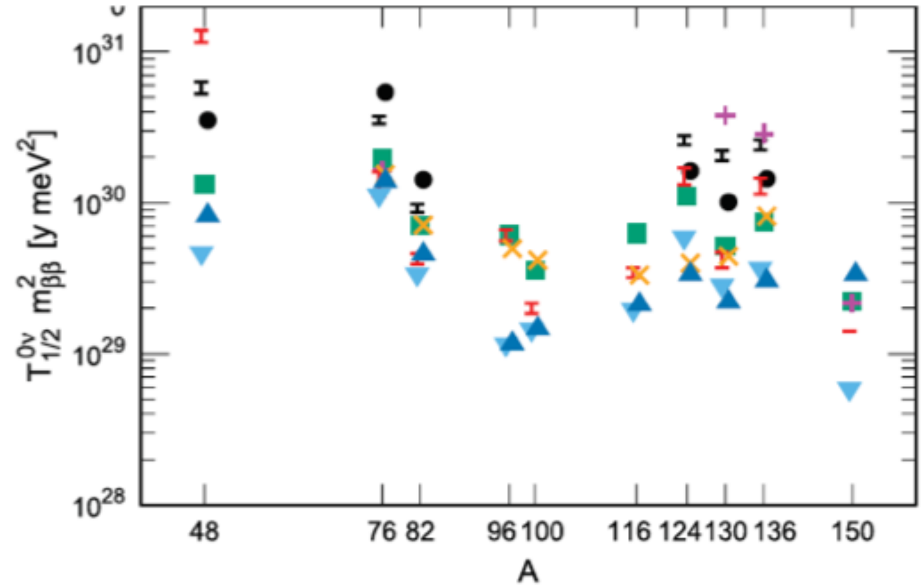
- Discovery sensitivity with a significance of at least 3 sigma (99.7%).
- With a realistic estimation ; 70% of detection efficiency and 70% of physics run

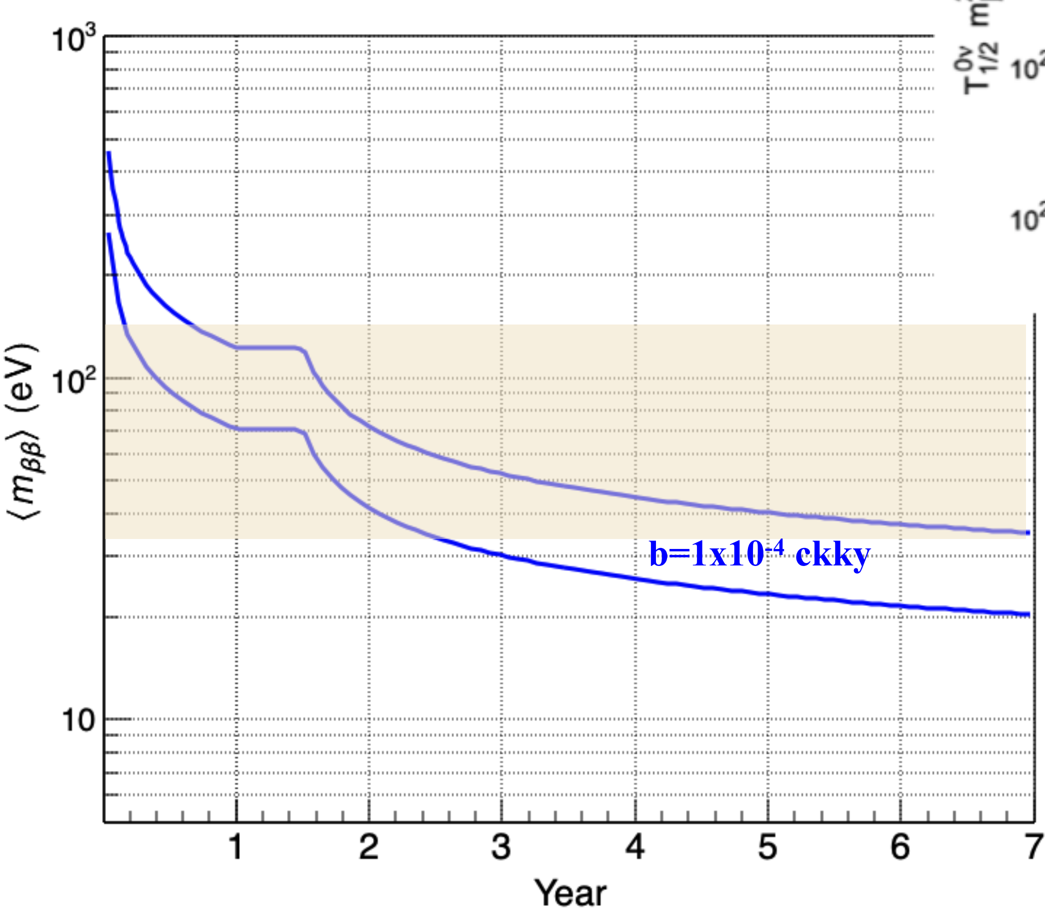
Upgrade to full scale



Neutrino mass limits

Current best limit by KamLAND-Zen is compared with AMoRE-II expectation





KamLAND-Zen, 36-156 meV

AMoRE-II band

Summary

- The AMoRE experiment aims to be sensitive to close to the ~$5x10^{26}$ year range for ^{100}Mo isotope in 5 years of running and will be installed by middle of 2024 in full scale.
- The AMoRE group established a unique detection system among competent leading double beta decay experiments.
- $0\nu\beta\beta$ can be discovered at anytime with new sensitivities.

Appendix

4. Crystals

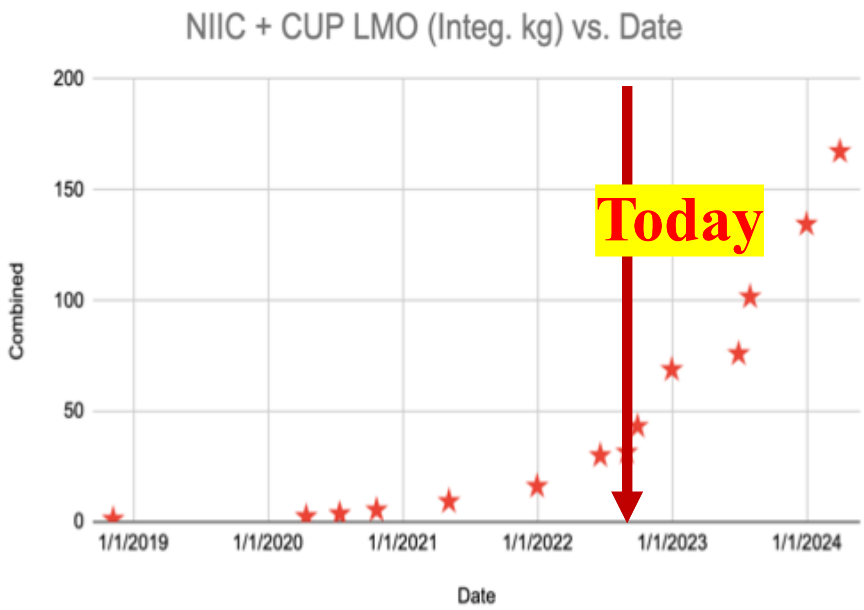
CUP

- All 23 crystals for phase-I are grown and the surfaces are treated.

NIIC

- 40 additional crystals are delivered.
- Previous 27 crystals will be treated on surfaces.

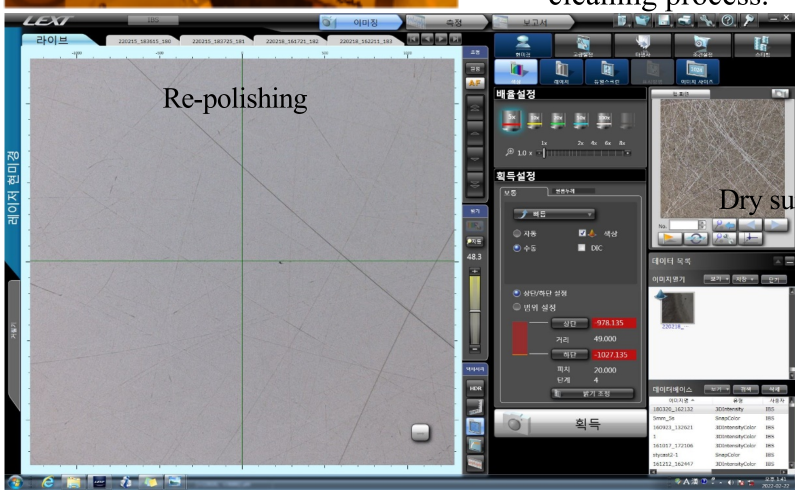
Basically, about 2/3 crystals are lapped and 1/3 crystals polished.



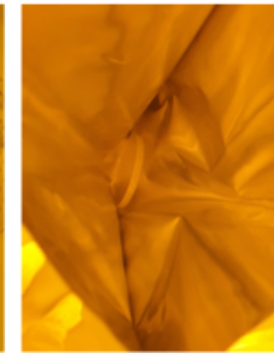
Crystal surface treatment R&D

Packing/ storage test : more [nicely simply easily] handling LMO crystal

- When the oil-packed LMO was opened after 3 months, only one of them did not dry out. Once dried, the crystal surface could not be cleaned with a our cleaning process.



1. Packing method test



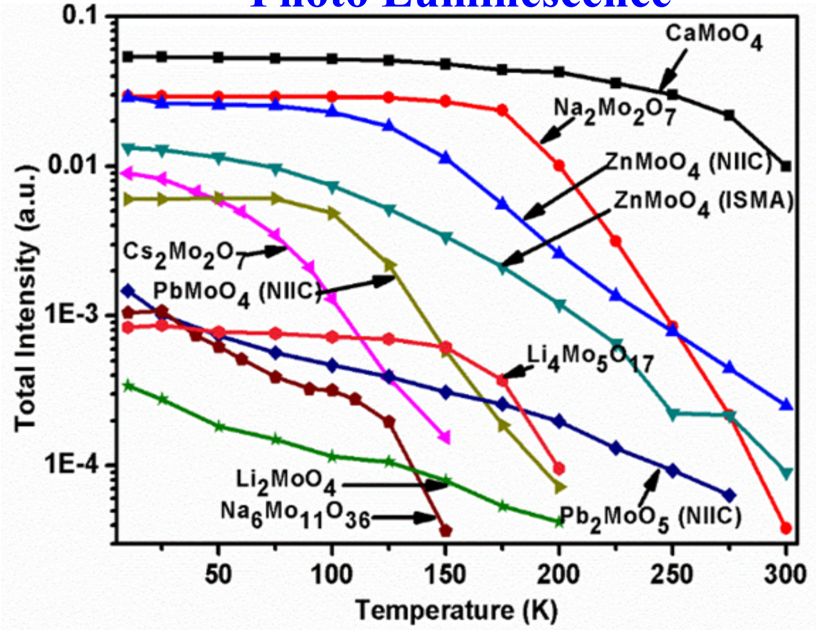
Plan: 4 weeks later open the vacuum packing
Steps: 1.Cleaning 2.check the surface 3.if ok 4.deposition 5.bonding

CUP

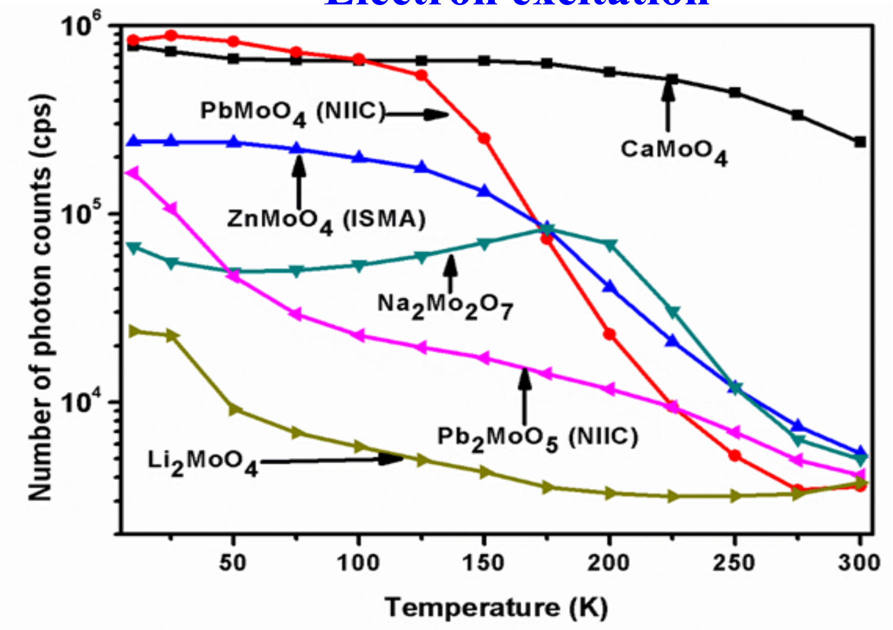
1. LMO inside vacuum oil . Few day or during the a week

AMoRE-II Crystal R&D:

Photo Luminescence



Electron excitation



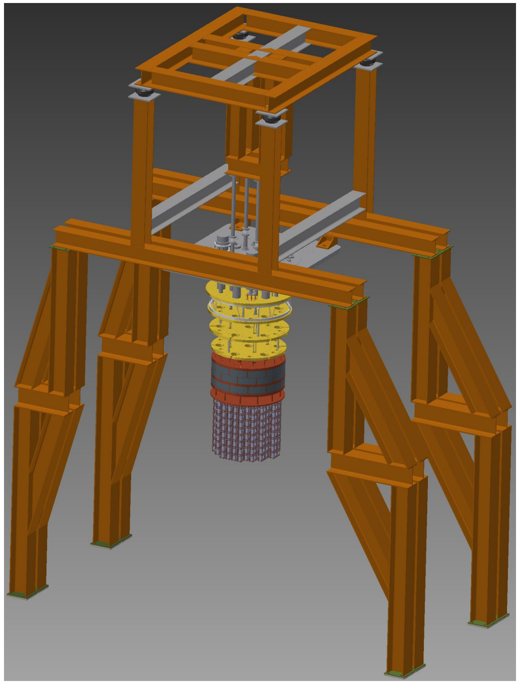
Crystals	λ_{em}	Decay time [μs]	E_(LED) [%]	E_(^{90}Sr) [%]
$CaMoO_4$	540	237	100	100
$ZnMoO_4$ (ISMA)	620	—	22	32
$PbMoO_4$ (NIIC)	545	20	13	105
Pb_2MoO_5 (NIIC)	600	5	3	22
Li_2MoO_4	540	23	1	5
$Cs_2Mo_2O_7$	701	363[31]	12	1
$Na_2Mo_2O_7$	663	756[36]	55	9

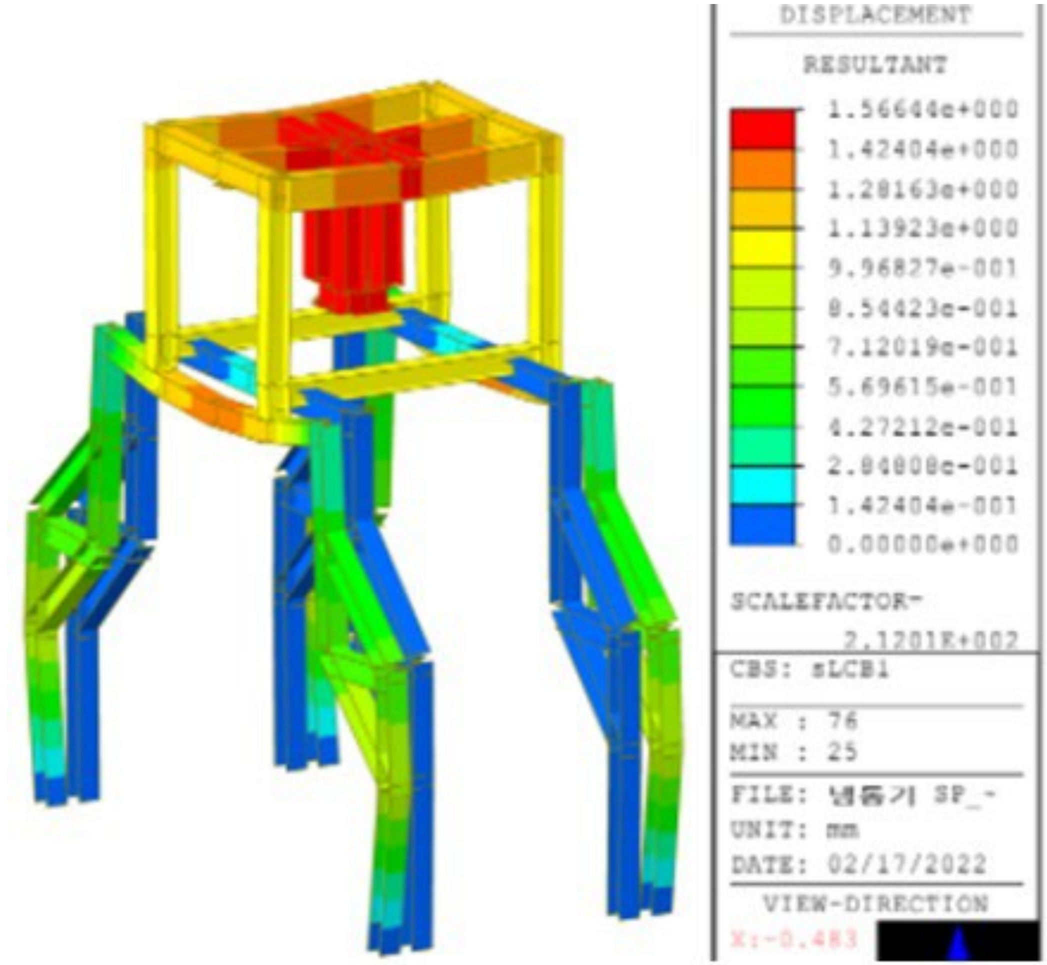
λ_{em}, peak emission wavelength; E_(LED), energy deposited by a 280 nm UV LED source; E_(^{90}Sr), energy deposited by a ^{90}Sr beta source.

LMO has a small light output, 5% of CMO down to 10K.

H.J. Kim et al., Crystal Research & T echnology, Nov. 2019

Yemilab installation



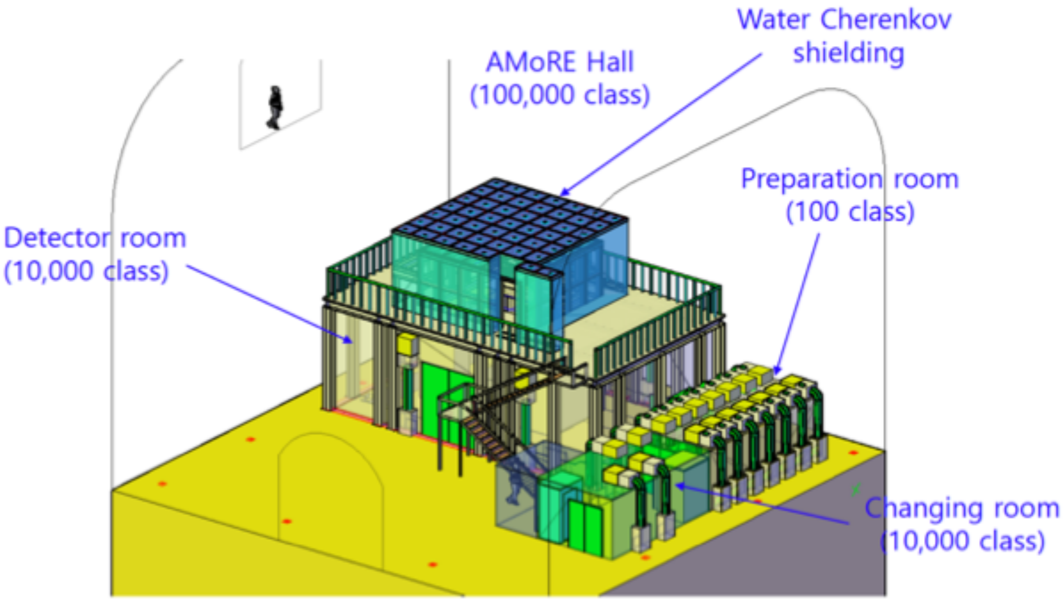


Reinforcement : 1.6 mm displacement

Add more beams to reduce the displacement less than 1 mm

construction will start at end of March (1 month)

Construction is ongoing..

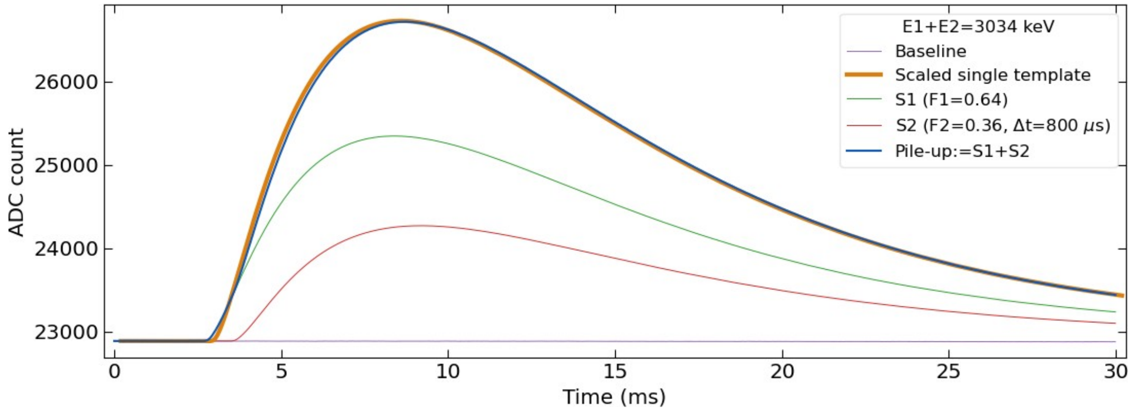


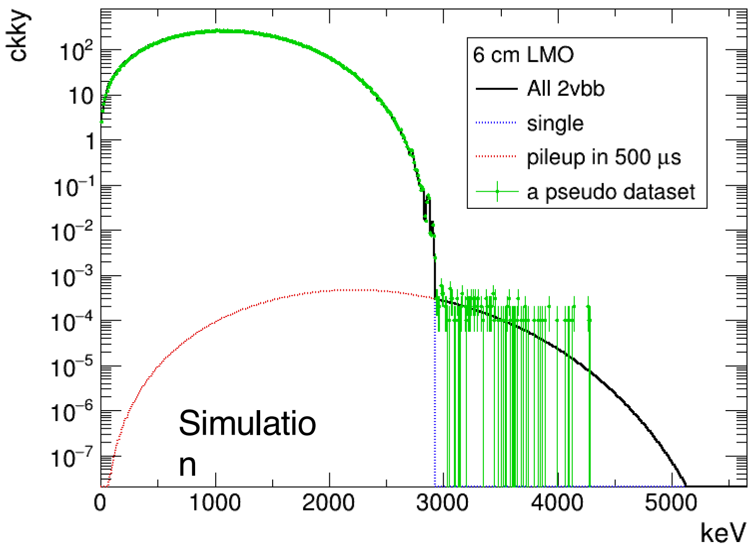
Preparation Room

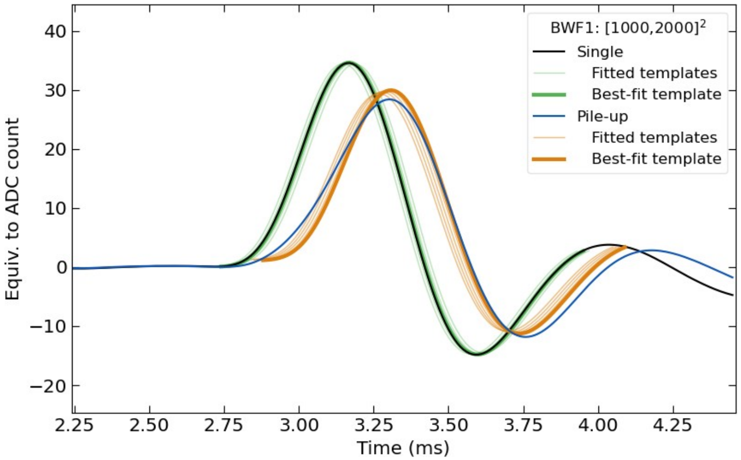
- 4x7x2.5 m
- 100 class (14 BFUs)

2νββ Pile-up event rate estimation

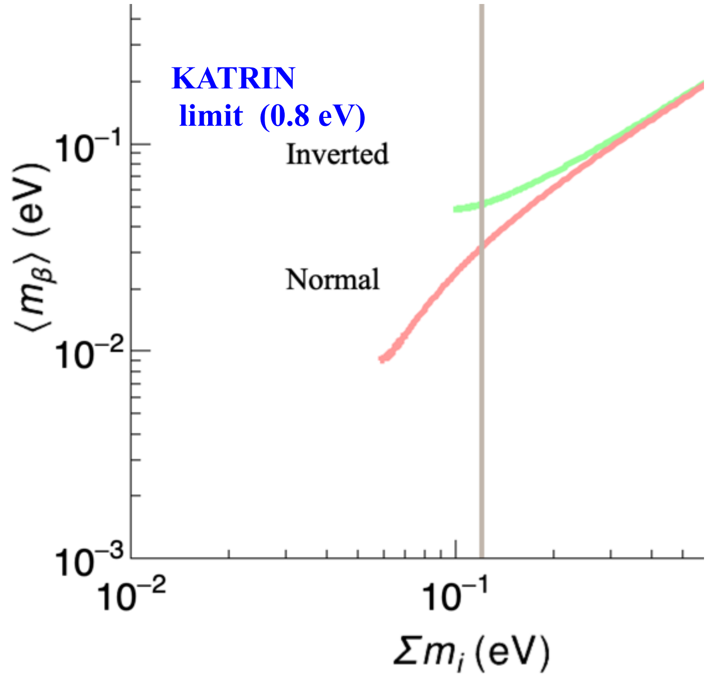
- Inevitable background after all others are removed since 2νββ lifetime of Mo-100 is short.
- Using template fitting and boosted decision tree method, the backgrounds can be rejected down to 2×10^{-5} ckky level for 6cm crystal thanks to the short rise time of MMC sensor. → Advantage of AMoRE to CUPID-Mo.



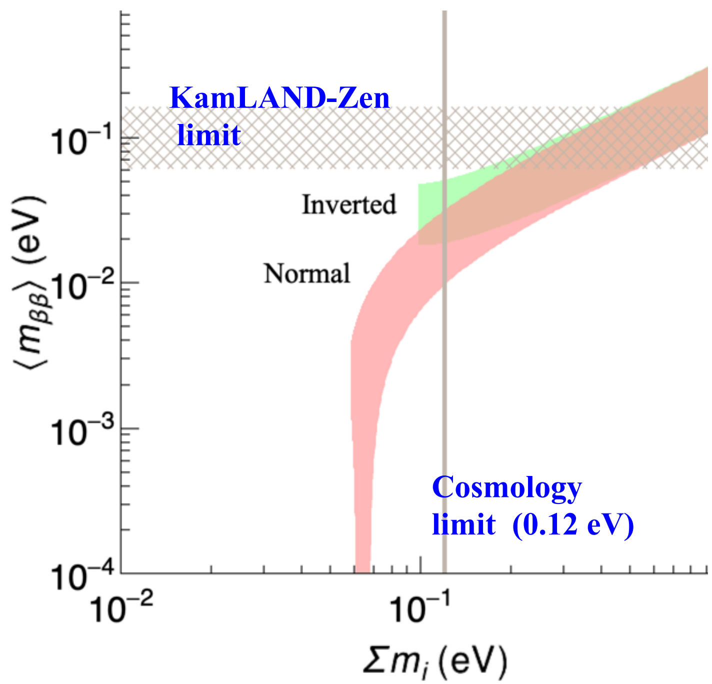




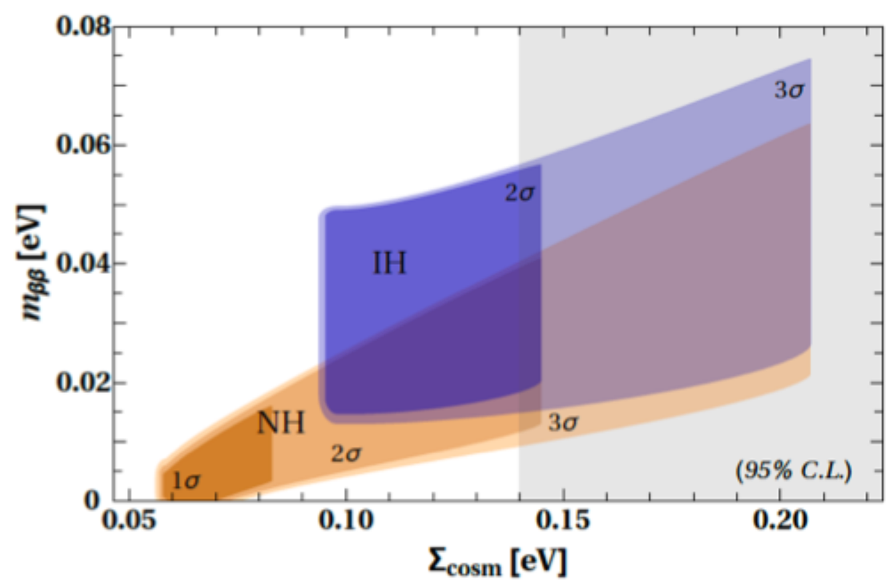
Current Mass Limits



- 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.



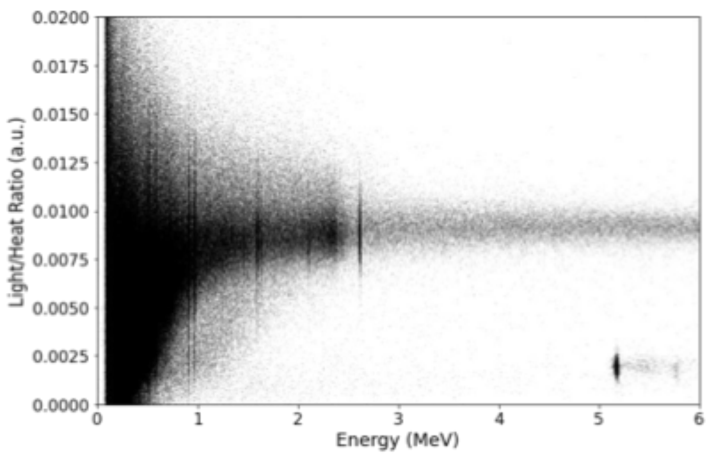
Dell'Oro et al., *JCAP* 12 (2015) 023



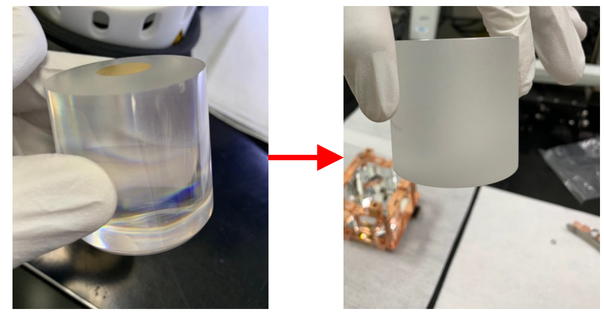
AMoRE-II – under construction

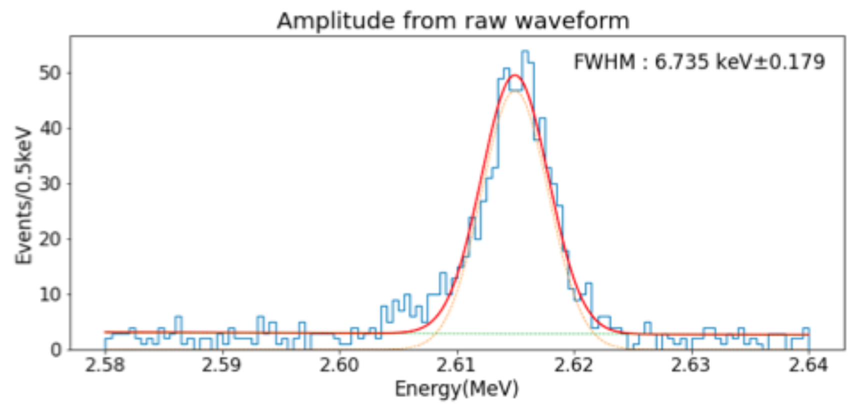
- Recently, we improved the detector performance.

(1) Polishing vs lapping(roughening)



Polished surface Lapped surface



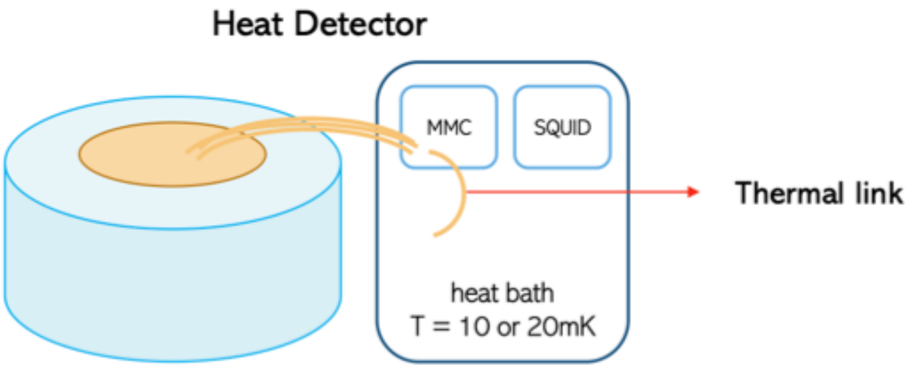


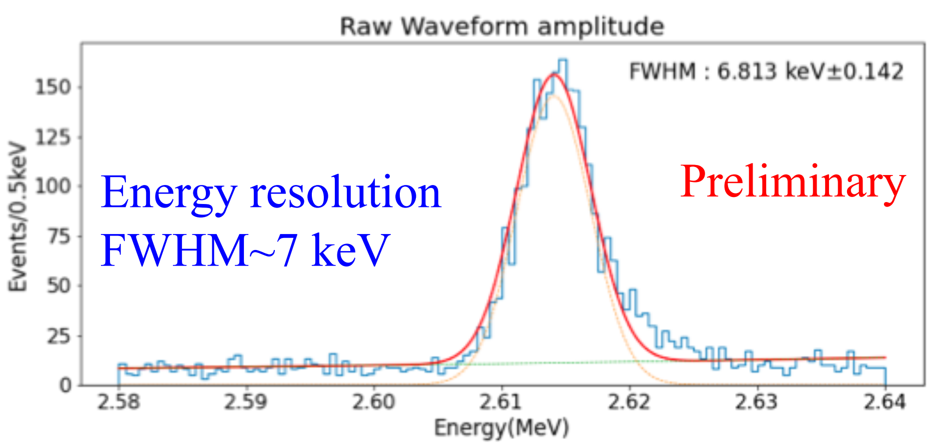
Lapping effects :

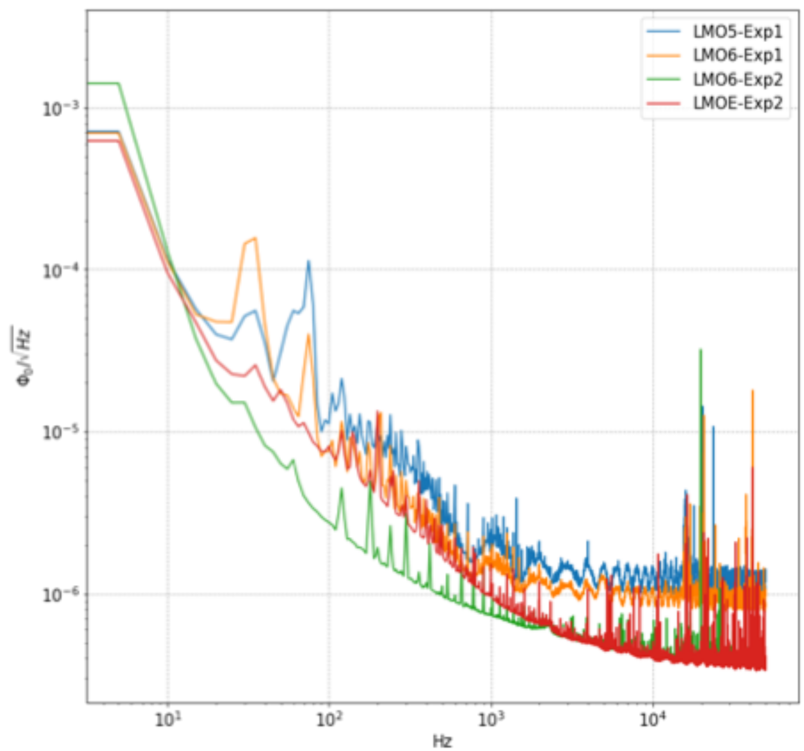
- Better energy resolution ~ 7 keV FWHM.
- Larger light output → DP factor > 10.
- Signal slower, rising time 3.2 ms → 4.8 ms. → Disadvantage of larger pileup effect, but still within AMoRE-II requirement.

(2) Thermal link to heat bath

- Tested if removing the thermal link of MMC sensor improves the performance.





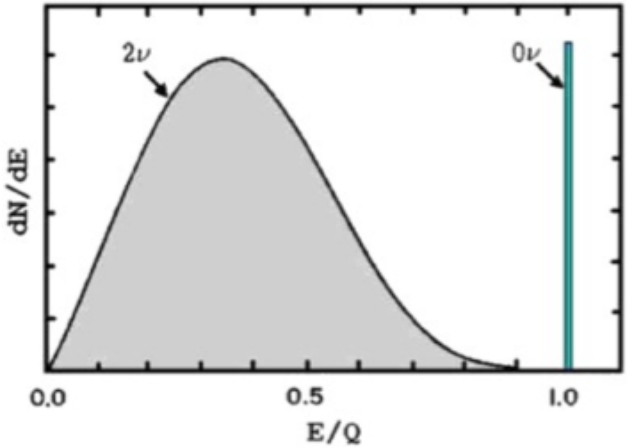


Now, AMoRE's energy resolution is close to CUPID-Mo in the test setup, still keeping the faster rise time.

Now, how sensitive are the 0νββ experiments ?

- **0νββ needs a good energy resolution and extremely low backgrounds.**
- **Discovery sensitivities depend on background and exposure**

Signal : sharp peak @ Q-value

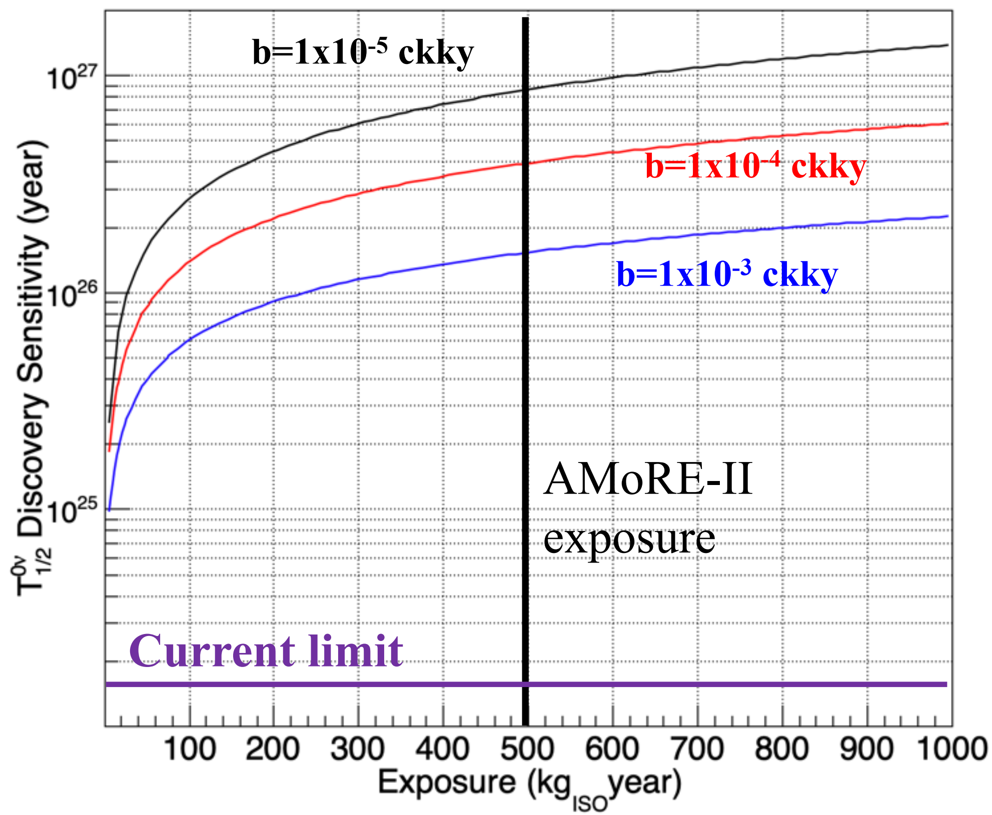


Background Unit :
ckky=counts/(keV kg year)

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{MT}{b\Delta E}} \text{(for finite backgrounds)}$$

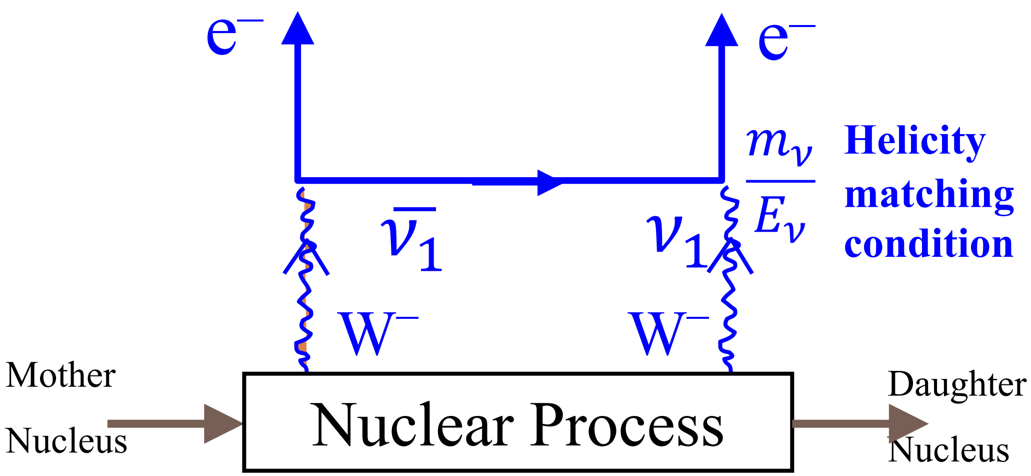
$$T_{1/2}^{0\nu} \propto MT\ (for\ \text{“0”}\ backgronds)$$

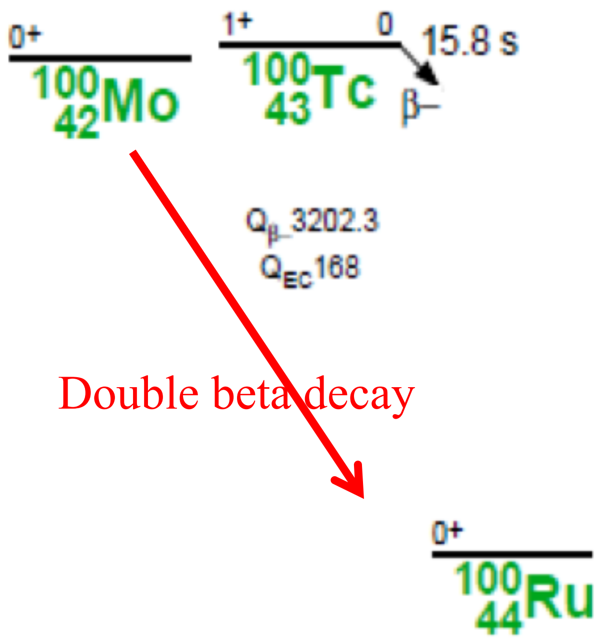
Discovery sensitivity :
The half-life for which an experiment has a 50% chance to measure a signal above background with a significance of at least 3 sigma (99.7%).



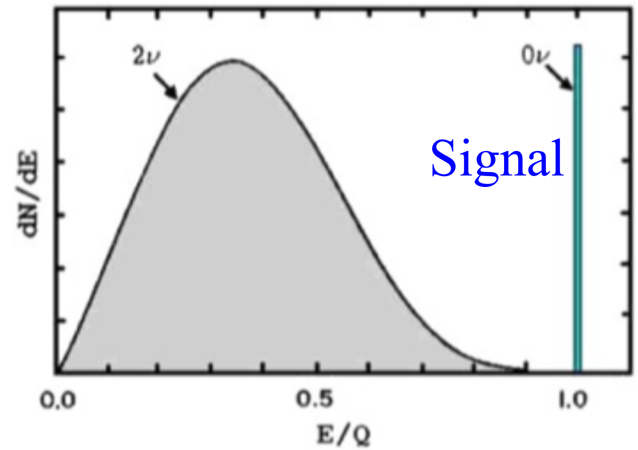
How to test if neutrinos are Majorana particles ?

- 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.

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

Phase factor

Half-life Measured

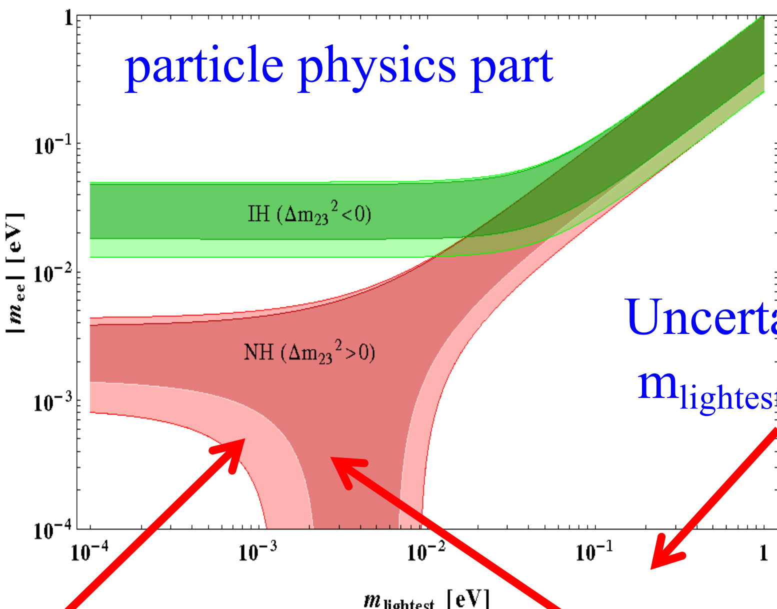
Nuclear Matrix Element

Effective 0νββ Neutrino Mass

Effective 0νββ neutrino mass is ;

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right| =$$
$$\left|c_{13}^2 c_{12}^2 e^{2i\eta_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\eta_2} m_2 + s_{13}^2 e^{-2i\delta} m_3\right|$$

$m_{\beta\beta}$



Uncertainties from $m_{lightest}$

Uncertainties from mixing angles

Uncertainties from phases

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 # $is\ conserved$.

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

- Higgs mechanism needs right-handed neutrinos, ν_R.

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,

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

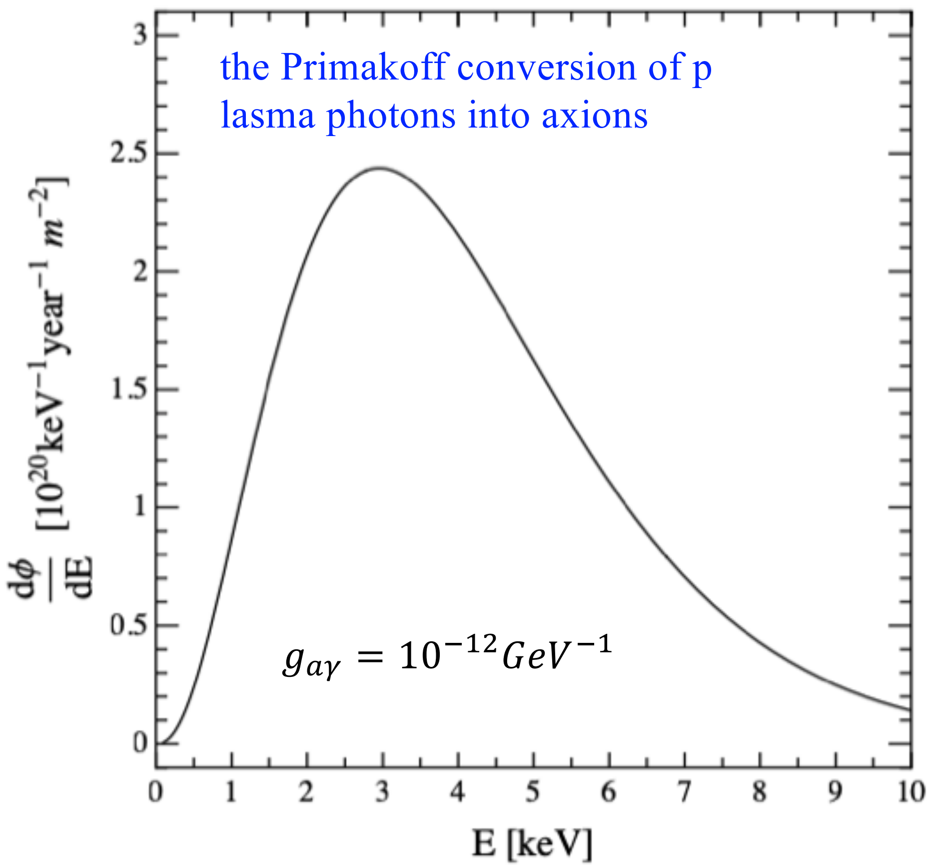
$$m_2 \simeq m_R$$

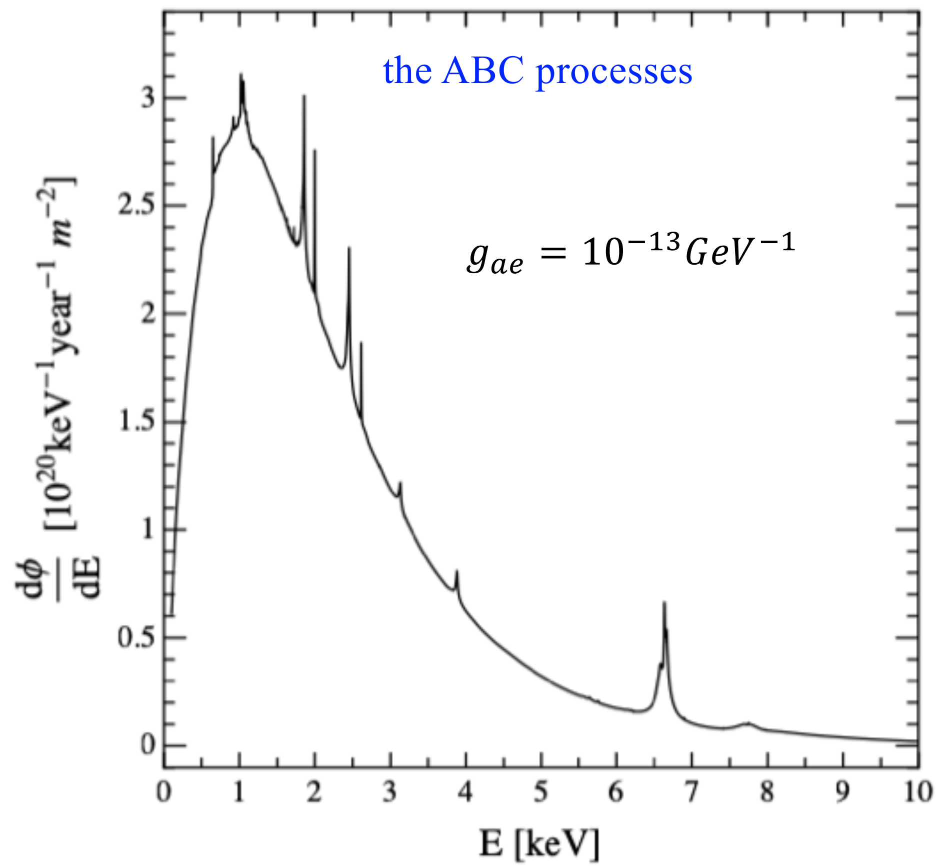
most promising BSM physics !

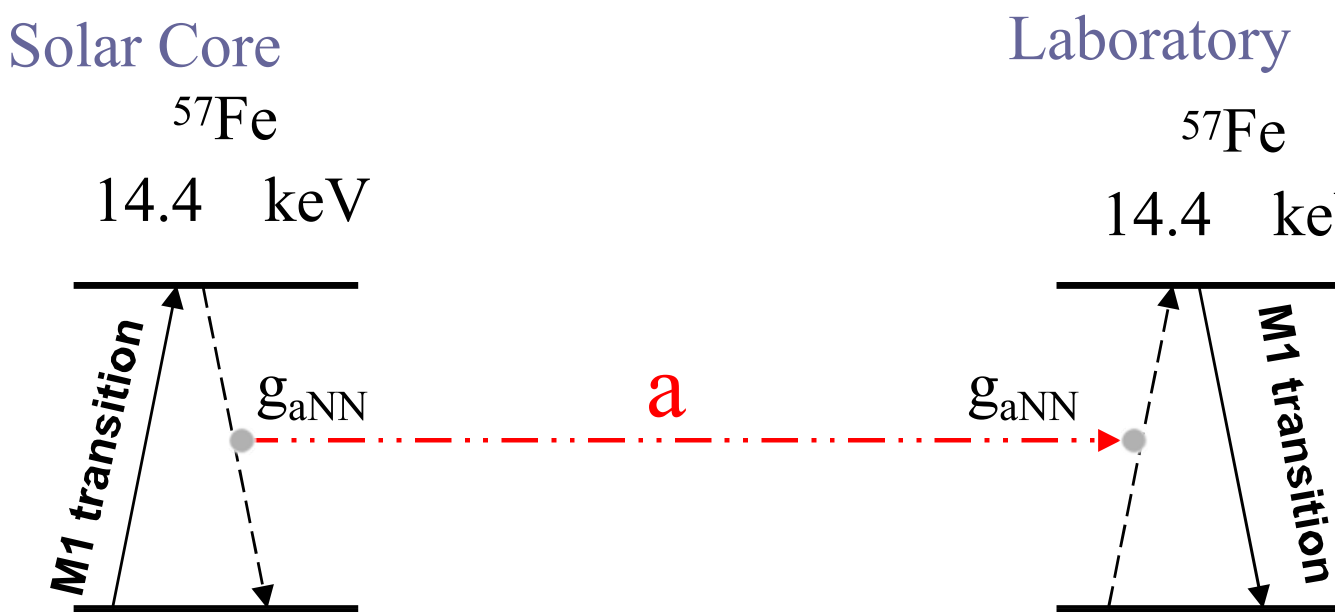
^{7}Li solar axions at underground

- AMoRE experiment use $Li_2{}^{100}MoO_4$ crystals.
- Inside the Sun, pp chain has ^{7}Be neutrinos.
- ^{7}Be decays to the excited state of ^{7}Li with 10 % branching.
- This could generate discrete energy axions.
- AMoRE's detector can be resonant with the 7Li solar axions wit h sufficient thermal broadening.

Detection of solar axions







1. Thermal excitation
2. Emission of a monoenergetic axio n.

Thermal width (1.3 keV): 2.2 eV
Recoil shift: 0.0018 eV
Natural width: 4.7×10^{-9} eV

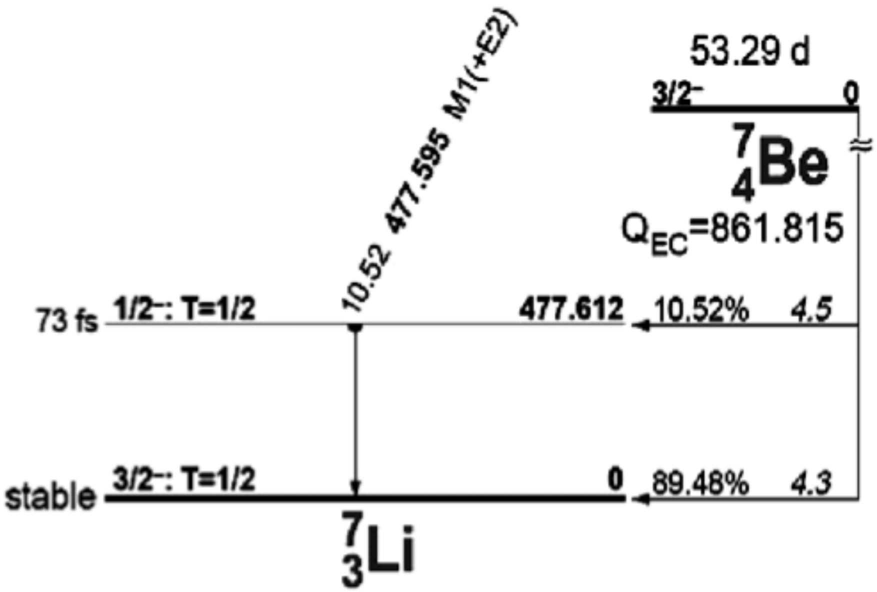
3. Resonant excitation of a target ^{57}Fe nucleus by the axion.
4. Emission of gamma/IC.
5. Detection.

Thermal width (300 K): 0.01 eV
Recoil shift: 0.0018 eV
Natural width: 4.7×10^{-9} eV

The method was proposed by S.Moriyama [PRL 75(1995)3222].
Other natural isotopes with low-lying levels, de-excitated via M1-transitions, can be (and are) also u sed; for example, ^{83}Kr (9.4 keV).

^{7}Li solar axion

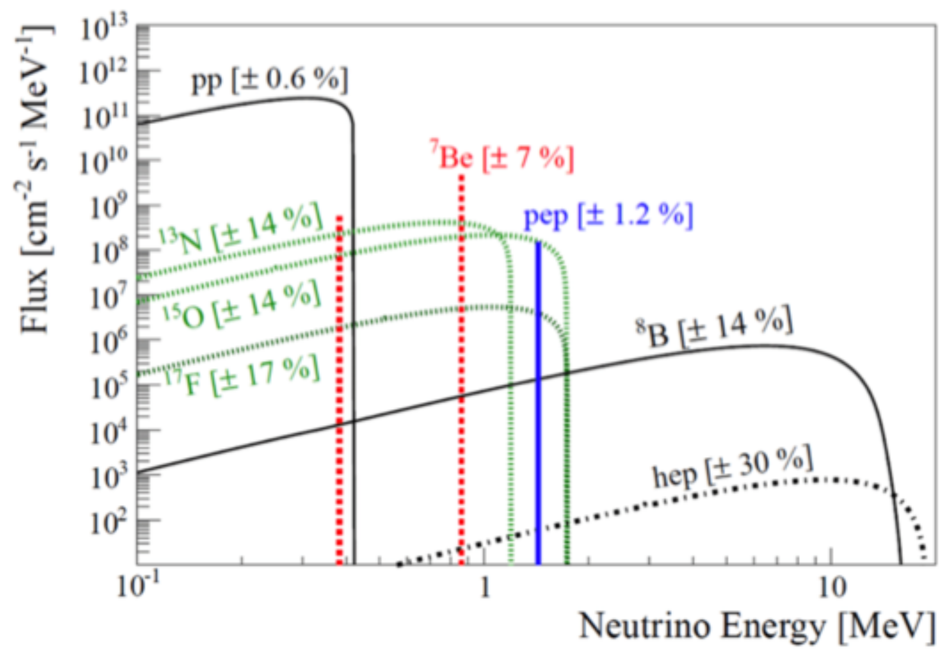
^{57}Fe solar axions allow to exclude axion mass values between ~2 keV (E<<14.4 keV) and (on today) 0.145 keV [A.V.Derbin et al., PAN 74 (2011) 596].



4.8×10^{9} $\nu/(cm^{2}\ s)$

^{7}Li is created in the pp chain (the main energy source of the Sun).

7Be neutrino flux @ Earth



Model

$$\frac{\Gamma_a}{\Gamma_b} = \left(\frac{k_a}{k_\gamma}\right)^3 \frac{1}{2\pi\alpha} \frac{1}{1+\delta^2} \left[\frac{g_0\beta + g_3}{\left(\mu_0 - \frac{1}{2}\right)\mu_3 + \mu_3 - \eta}\right]^2$$

k_a and k_γ are momenta.
μ_0~0.88 : isoscalar magnetic moment
μ_3 ~4.71 : *isovector magnetic moment*
β =1, η = 0.5 : nuclear structure dependent.

Isoscalar and isovector axion-nucleon coupling

$$g_0 = -\frac{m_N}{f_a}\frac{1}{6}\left[2S + (3F - D)\frac{1+z-2w}{1+z+w}\right]$$

Derbin, JETP Letters, 81, 365 (2005)

$$g_3 = -\frac{m_N}{f_a}\frac{1}{2}(D+F)\frac{1-z}{1+z+w}$$

m_N=939MeV, F=0.46, D=0.806
S : flavor singlet axial vector matrix element, ~0.5

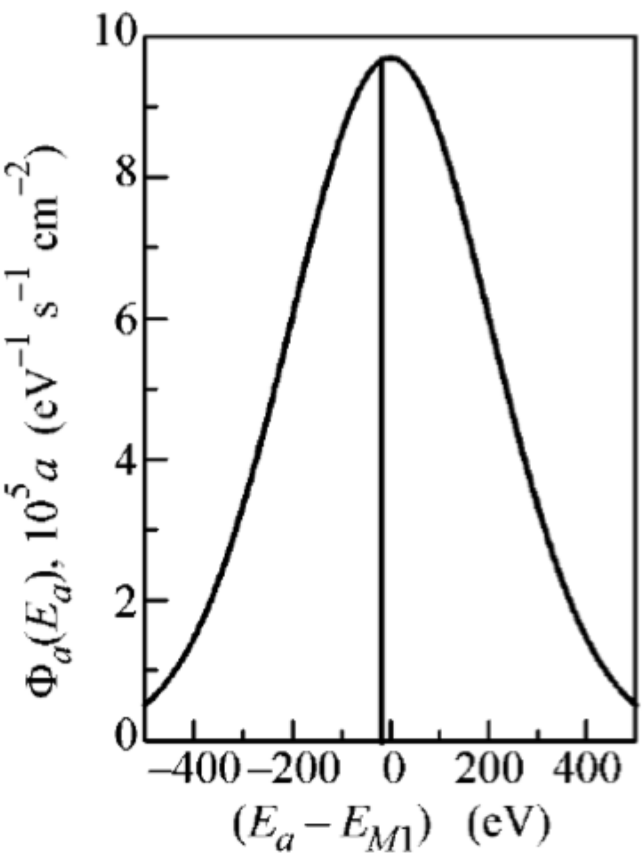
Now, the rate of excitation

$$R_N = \int_{-\infty}^{+\infty} dE_a \frac{d\Phi(E_a)}{dE_a}\sigma_D(E_a),$$

$$\sigma_D(E_a) = \sigma_0 \frac{\Gamma_a}{\Gamma_\gamma}\frac{\sqrt{\pi}\Gamma}{\sqrt{2}\sigma(T_E)}\exp\left[-\frac{(E_a - E_\gamma)^2}{2\sigma(T_E)^2}\right],$$

$$R = 1.3\times10^{-17}\left(\frac{m_a}{1 \ \text{eV}}\right)^4 \text{g}^{-1}\text{day}^{-1}.$$

Energy spectrum Doppler broadened.



If we would observe a gamma peak at 478 keV with area S, mass of axion would be :

$$m_a = 1.55\times10^{11}\times\left(\frac{S}{\epsilon t[s]N_7}\right)^{1/4} \text{ eV}$$

ϵ : *efficiency*
T[sec] : measurement time
N_7 : # of 7Li nuclei in the sample

Derbin, JETP Letters, 81, 365 (2005)

Sensitivities of by-product experiments

- AMoRE-I and AMoRE-II use Li_2MoO_4 crystals.
- Advantages :
  1. Large mass of Li-7 (x 100 times)
  2. Higher efficiency since 7Li is inside the detector. (x 10)
  3. Lower background (x 10) (for only AMoRE-II case)
  4. Longer measurement time (x 10)
- Disadvantage
  1. Worse energy resolution (x 1/5)

- FOM ~ 10^4

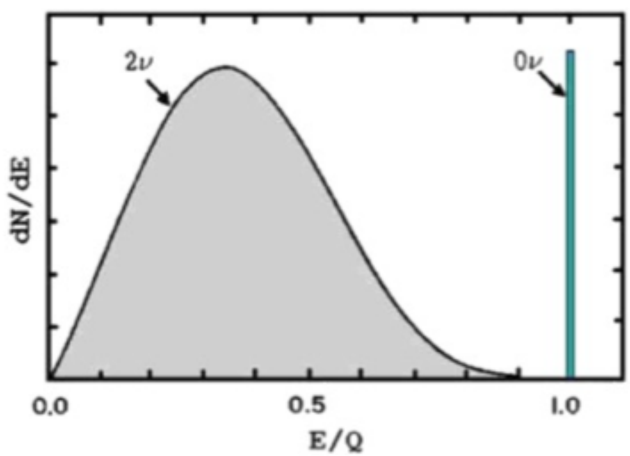
	LiF exp	AMoRE-I	AMoRE-II	HPGe
N_7	$1.4x10^{25}$	$1.03x10^{25}$	$1.3x10^{27}$	$1.2x10^{25}$
efficiency	2.27%	12.8%	20%	4.5%
resolution	1.6 keV	10keV	10 keV	3 keV
Measurement Time (days)	169	365	1825	300
Background (/keV/day)	1.30	3.5	0.1	0.3
S_90 (counts)	37	226	86	27
Ma (keV)	8.27	7.23	1.05	5.94

Now, how sensitive are the $0\nu\beta\beta$ experiments ?

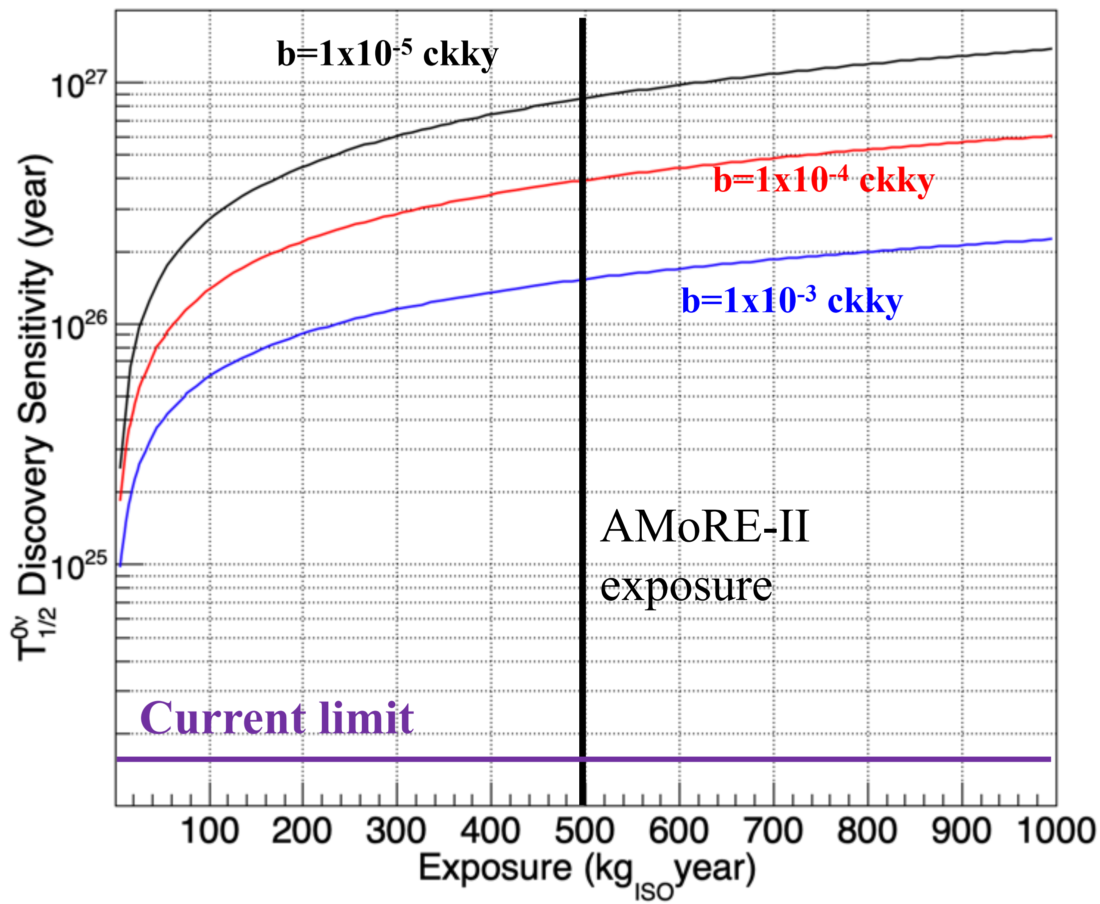
- $0\nu\beta\beta$ **needs a good energy resolution and extremely low backgrounds.**
- **Discovery sensitivities depend on background and exposure**

Discovery sensitivity with a significance of at least 3 sigma (99.7%).

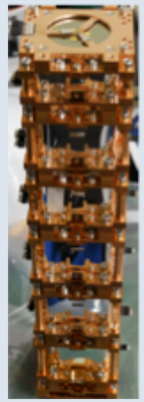
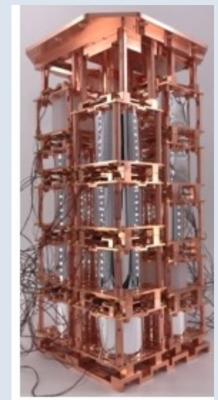
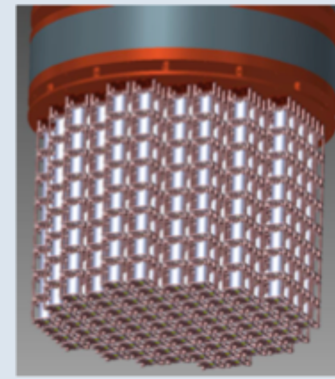
Signal : sharp peak @ Q-value



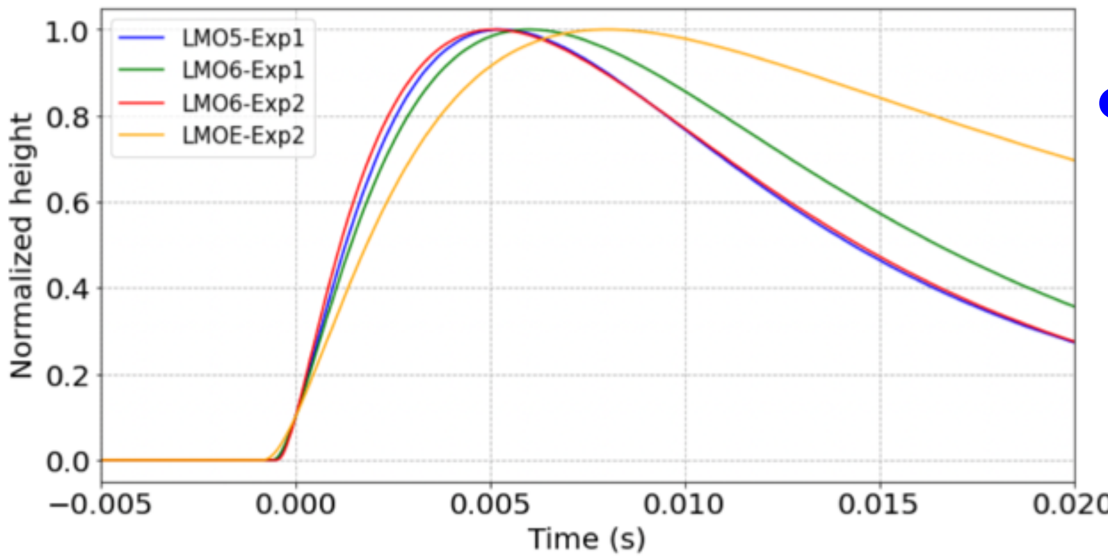
Background Unit :
ckky=counts/(keV kg year)



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**)	$\sim10^{-1}$	$<10^{-2}$	$<10^{-4}$
$T_{1/2}$(year)	$\sim3.0\text{x}10^{23}$	$\sim7.0\text{x}10^{24}$	$\sim8.0\text{x}10^{26}$
$m_{\beta\beta}$ (meV)	1200-2100	140-270	13-25
Location/Schedule	Y2L / 2015-2018	Y2L / 2020-2022	Yemilab / 2022-2027

Towards further improvements.



- Pulse shape dependence on the surface condition

- Noise dependence on the environments.