Advanced Mo-based Rare process Experiment

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on behalf of the AMoRE Collaboration

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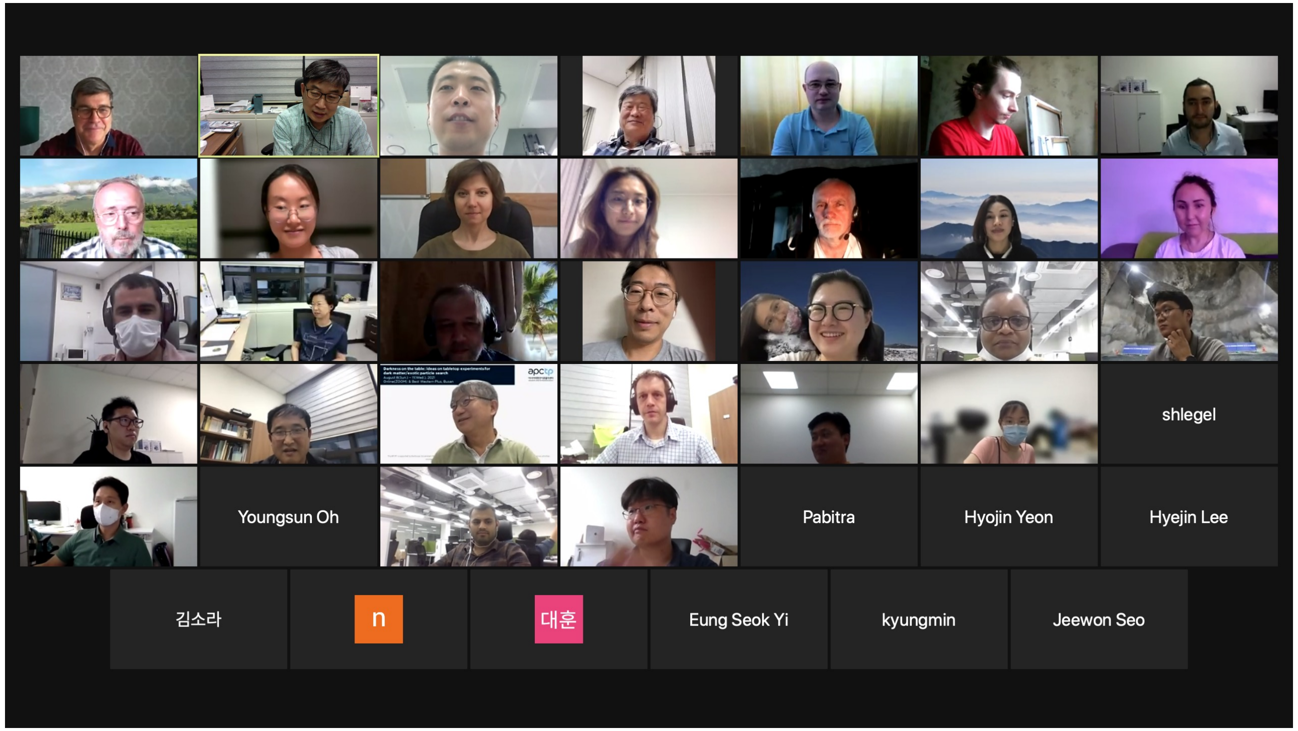
AMoRE collaboration



10 Countries, 26 Institutions - Korea, Germany, Ukraine, USA, Russia, China, Thailand, Indonesia, India, Pakistan

The AMORE-experiment's challenge

The goal of the **AMoRE** (**A**dvanced **Mo**-base **R**are process **E**xperiment) is to search for neutrinoless double beta decay (0υββ) of ^{100}Mo using Mo-based scintillating crystals and low-temperature sensors.

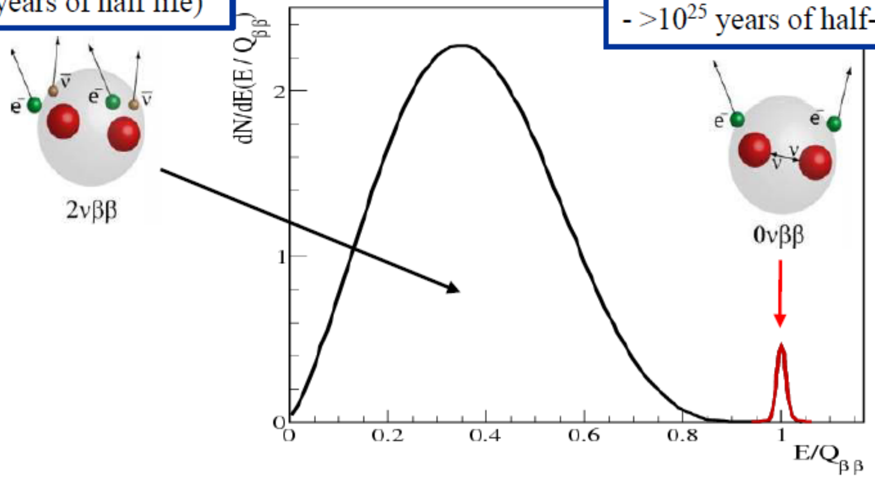
Experimental signature of 2νββ and 0νββ:

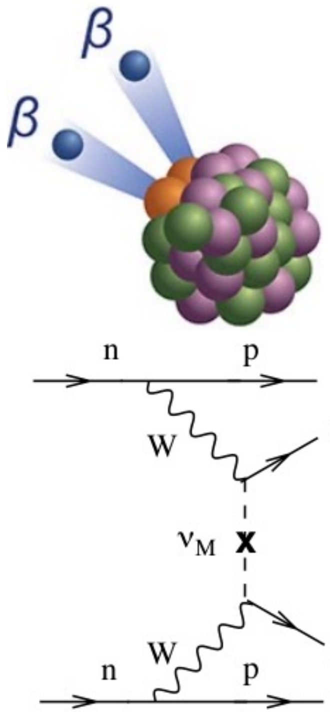
$$^{100}Mo \xrightarrow{2\nu\beta\beta} {}^{100}Ru + 2\beta^- + \bar{\nu}_e$$

$$^{100}Mo \xrightarrow{0\nu\beta\beta} {}^{100}Ru + 2\beta^-$$

$2\nu\beta\beta$ decay
- 2^{nd} order beta decay
- Rare nuclear decay
- ($>10^{18}$ years of half life)

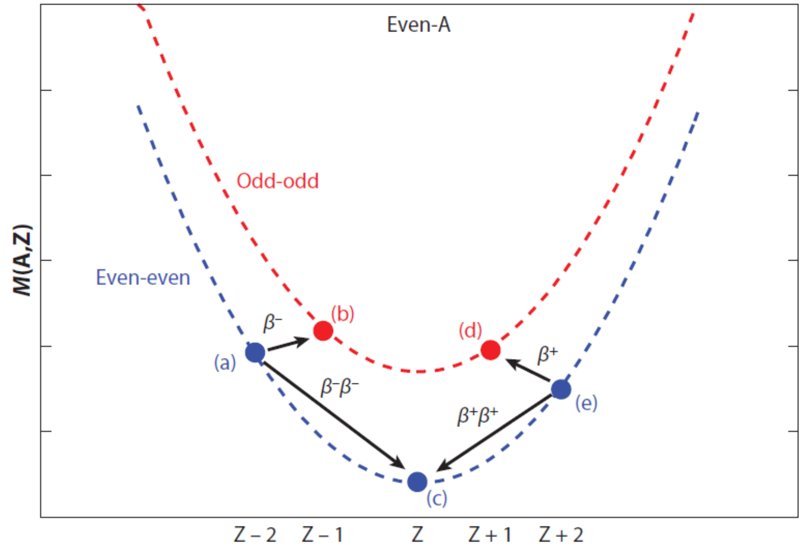
$0\nu\beta\beta$ decay
- Massive neutrino
- Majorana particle
- Beyond the SM model
- $>10^{25}$ years of half-life





To observe 2νββdecay, the single β-decay must be energetically forbidden due to energy conservation constraint.

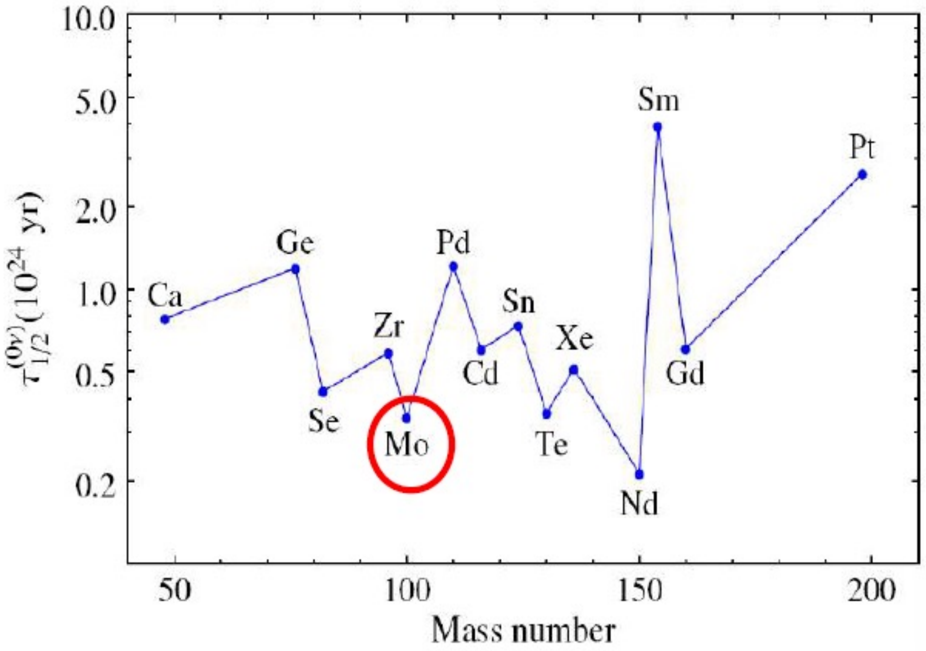
In total 35 isotopes available and > 9 of them can be used for 0νββ search.



- Lepton-number violation (**ΔL=2**)
- The nature of neutrino mass (**Dirac or Majorana?**)
- Type of neutrino mass hierarchy (normal, inverted)
- CP-violation in the lepton sector

Why ^{100}Mo is chosen for 0υββ experiment

- ✓ **High Q-value of 3034,34 keV**
- ✓ **High natural abundance of 9.7%**
- ✓ **Relatively short half-life (0υββ) expected from theoretical calculation**



Barea et al., Phy. Rev. Lett. 109, 042501 (2012)

Isotope	Q (MeV)	Abund. %
^{48}Ca	4,271	0,19
^{76}Ge	2,040	7,8
^{82}Se	2,995	8,7
^{100}Mo	3,034	9,7
^{116}Cd	2,802	7,5
^{124}Sn	2,228	5,8
^{130}Te	2,533	34,1
^{136}Xe	2,479	8,9
^{150}Nd	3,367	5,6

Production of ^{100}Mo and ^{48depl}Ca

- **Production of the ^{100}Mo isotope:**
  - JSC "PO Electrochemical Plant" (ECP), Krasnoyarsk, Russia
  - $^{100}MoO_3$ powder:
    - → ^{100}Mo enrichment: ~ 95%
    - → Radioactive purity:

ICP-MS at CUP	U: ~ 0.2 ppb	Th: ~ 0,05ppb
HPGe at BNO INR RAS	^{226}Ra: ≤ 8 mBq/kg	^{228}Ac: ≤ 3.5 mBq/kg

- **Calcium carbonate (calcium formate) enriched by ^{40}Ca and depleted by ^{48}Ca:**
  - Elektrokhimpribor (EKP), Lesnoy, Russia
  - $^{40}CaCO_3$ powder:
    - ^{48}Ca < 0,001%
    - Radioactive purity: U ≤ 0.1 ppb, Th ≤ 0,1 ppb, Sr= 1 ppm, Ba = 1 ppm, ^{226}Ra = 5 mBq/kg (late samples from NEOHIM 1.4 mBq/kg), ^{228}Ac (228Th) = 1 mBq/kg

- **Lithium carbonate (old USSR)**

$^{48depl}Ca^{100}MoO_4$ and $Li_2{}^{100}MoO_4$ crystals

- $^{48depl}Ca^{100}MoO_4$ – production of JSC "FOMOS-Materials“
  13 crystals, AMoRE-pilot, AMoRE-I

- $Li_2{}^{100}MoO_4$ – grow by Institute of Inorganic Chemistry SB RAS NIIC, (Low temp. gradient), AMoRE-I, AMoRE-II

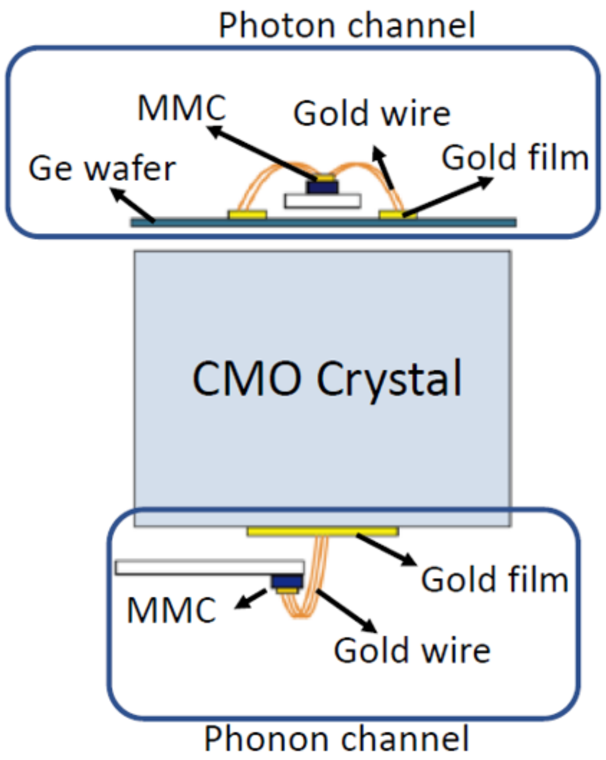
- $Li_2{}^{100}MoO_4$ – grow by Center for Underground Physics (CUP) (Czochralski method)

Absolute light yield of CMO crystals:

~ 4,900 ph/MeV, at room temperature, **(H.J. Kim et al., IEEE TNS 57 (2010) 1475)**
~ 30000 ph/MeV at a temperature of 10 mK

CMO crystals have the highest light yield among Mo-containing crystals.

Principle of AMoRE detector

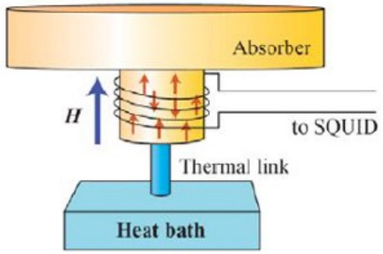


Scintillating crystal

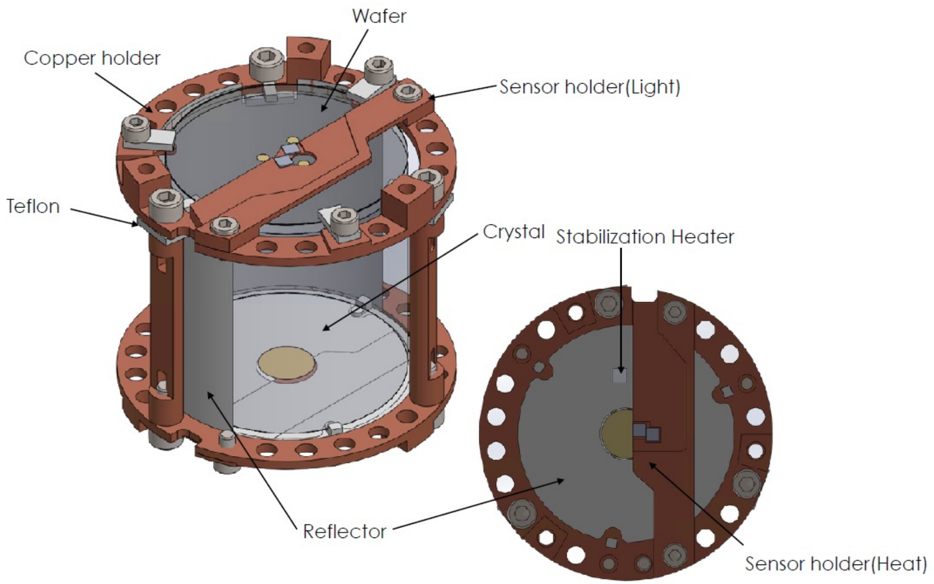
- $^{48depl}Ca^{100}MoO_4$
- ^{100}Mo enriched: > 95 %
- ^{48}Ca depleted: < 0.001 %

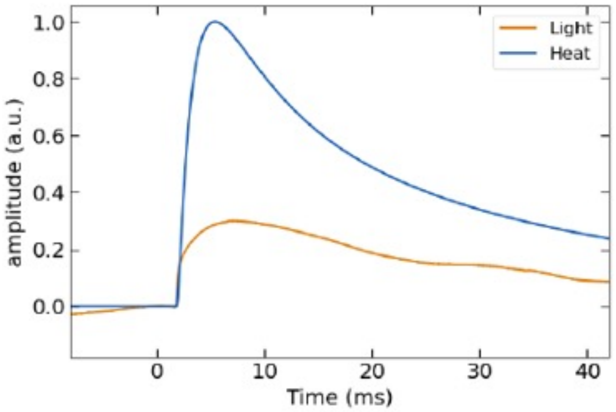
MMC & SQUID

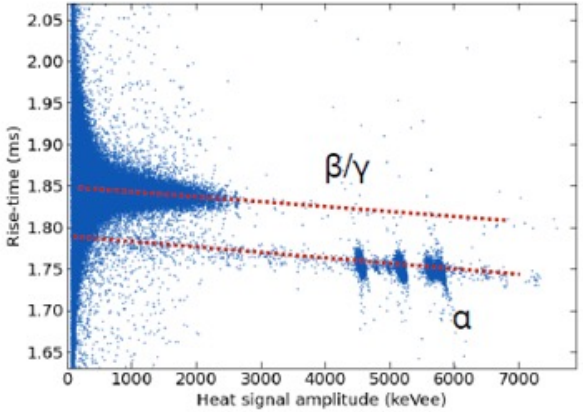
- MMC: Metallic Magnetic Calorimeter
- Magnetization changes with temperature.
- Magnetization change (flux) can be measured as a voltage by SQUID

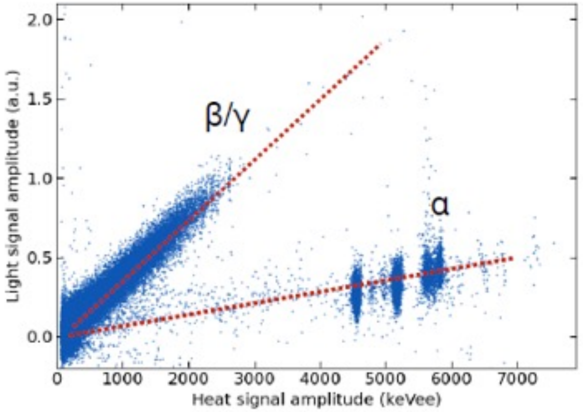


Detection process:
Energy → Temperature → Magnetization → Magnetic flux → **Voltage**

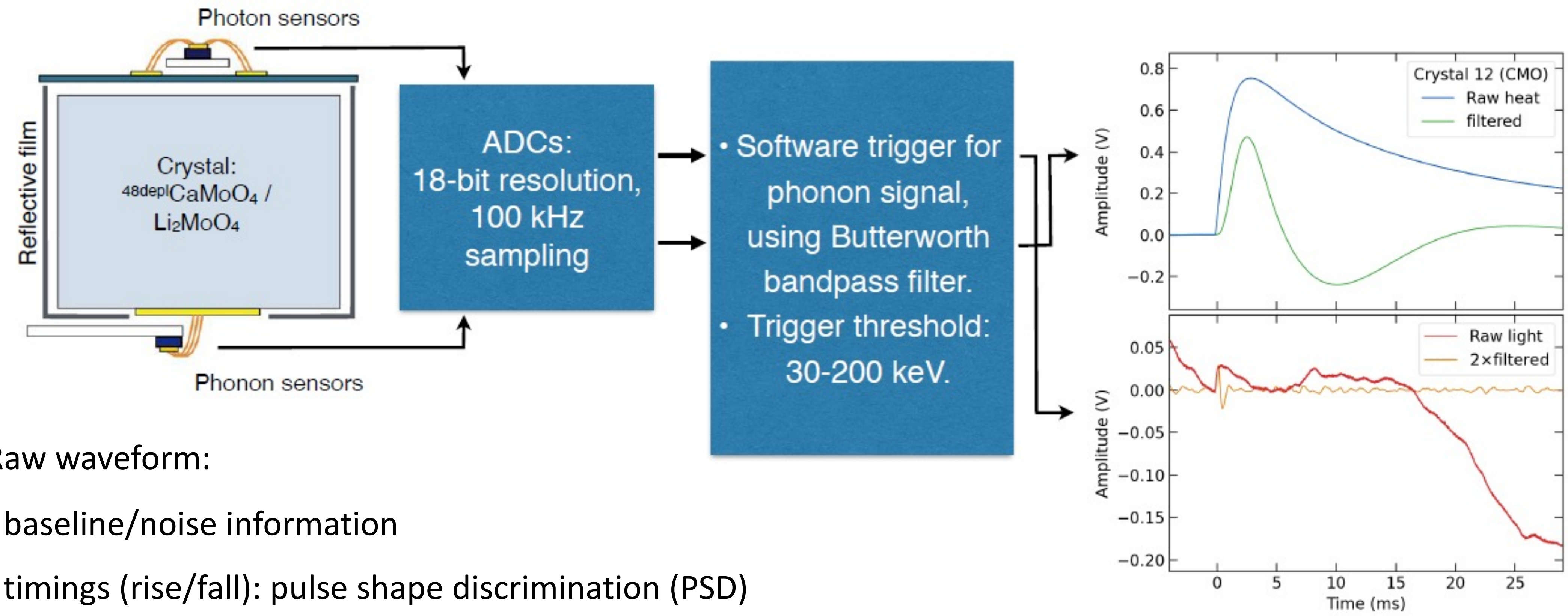








Signal processing and analysis



- Raw waveform:

- baseline/noise information
- timings (rise/fall): pulse shape discrimination (PSD)

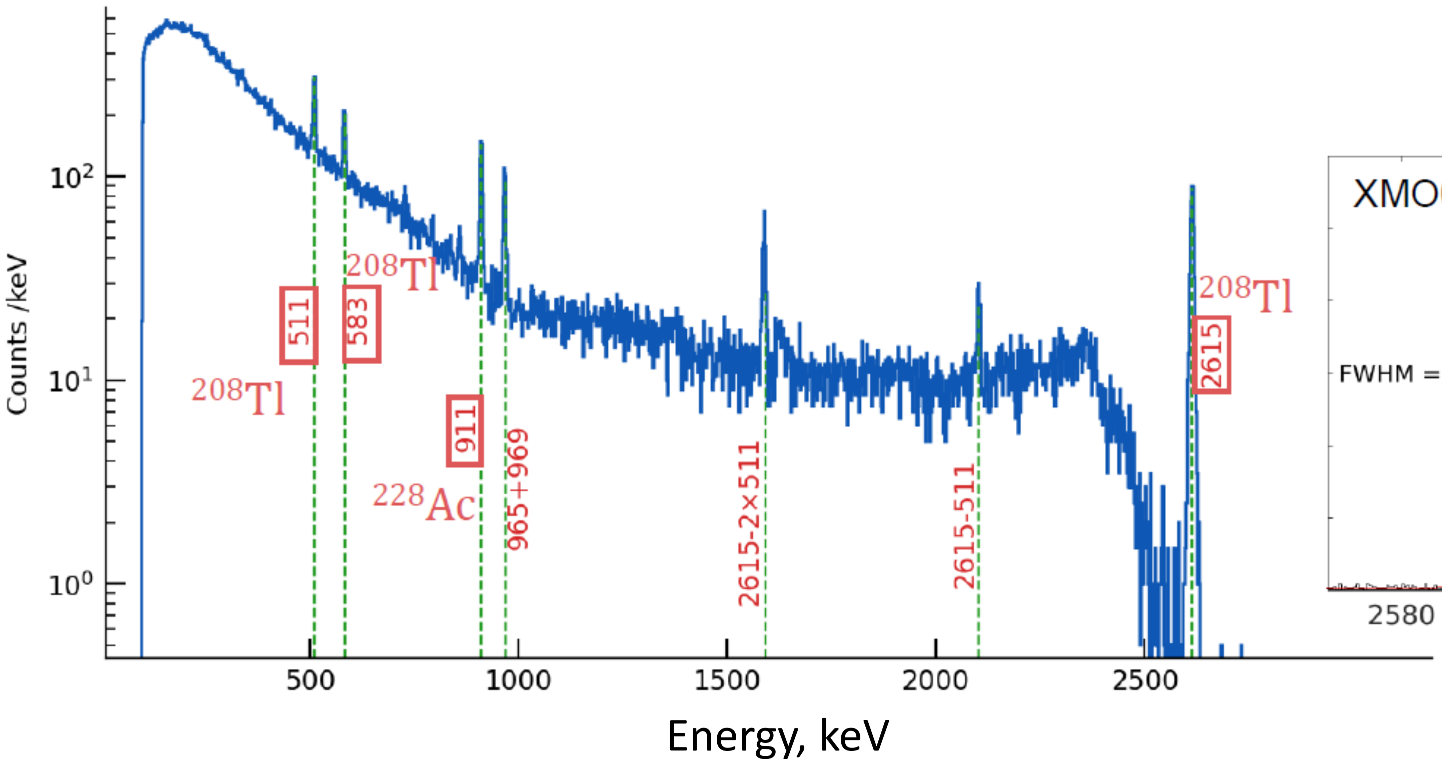
Reconstruction for improving energy resolution and β/α discrimination power (DP):

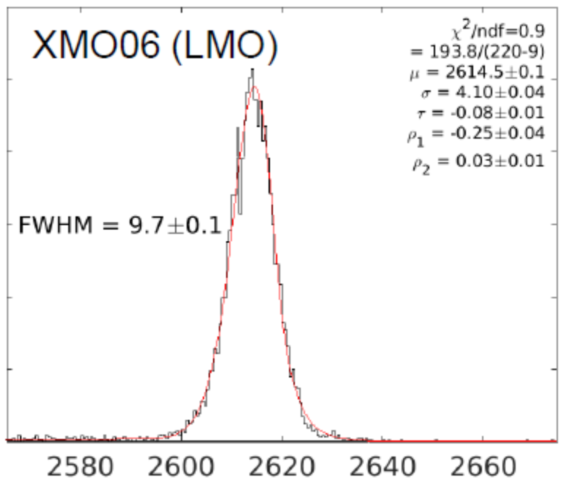
-Butterworth bandpass filter— mainly for noise suppression:

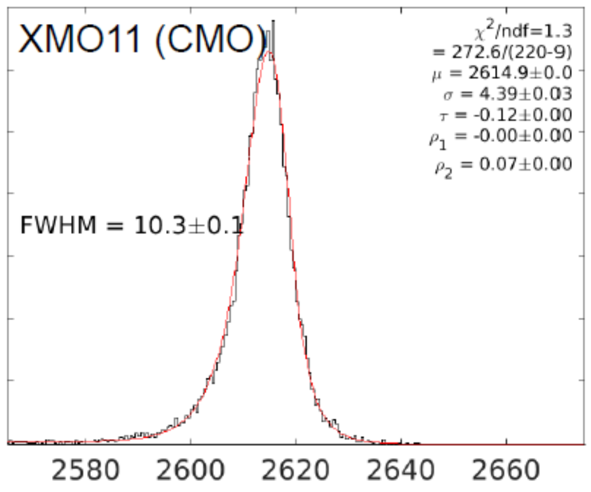
- pulse amplitude: pulse height or a least square fit to the template signal.

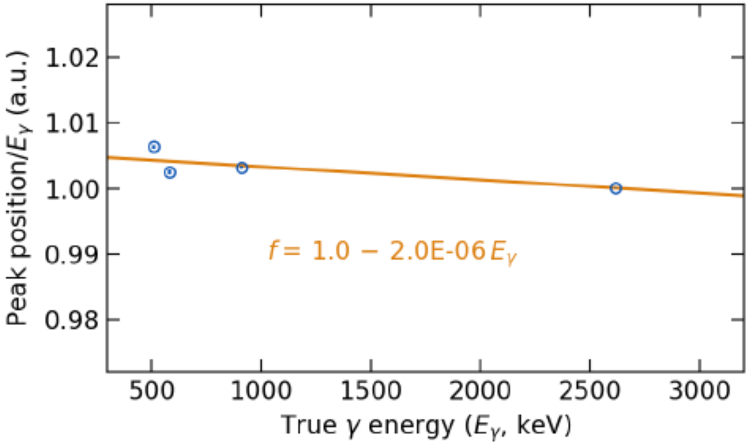
- Stabilization heater signal for gain drift corrections.

Energy calibration





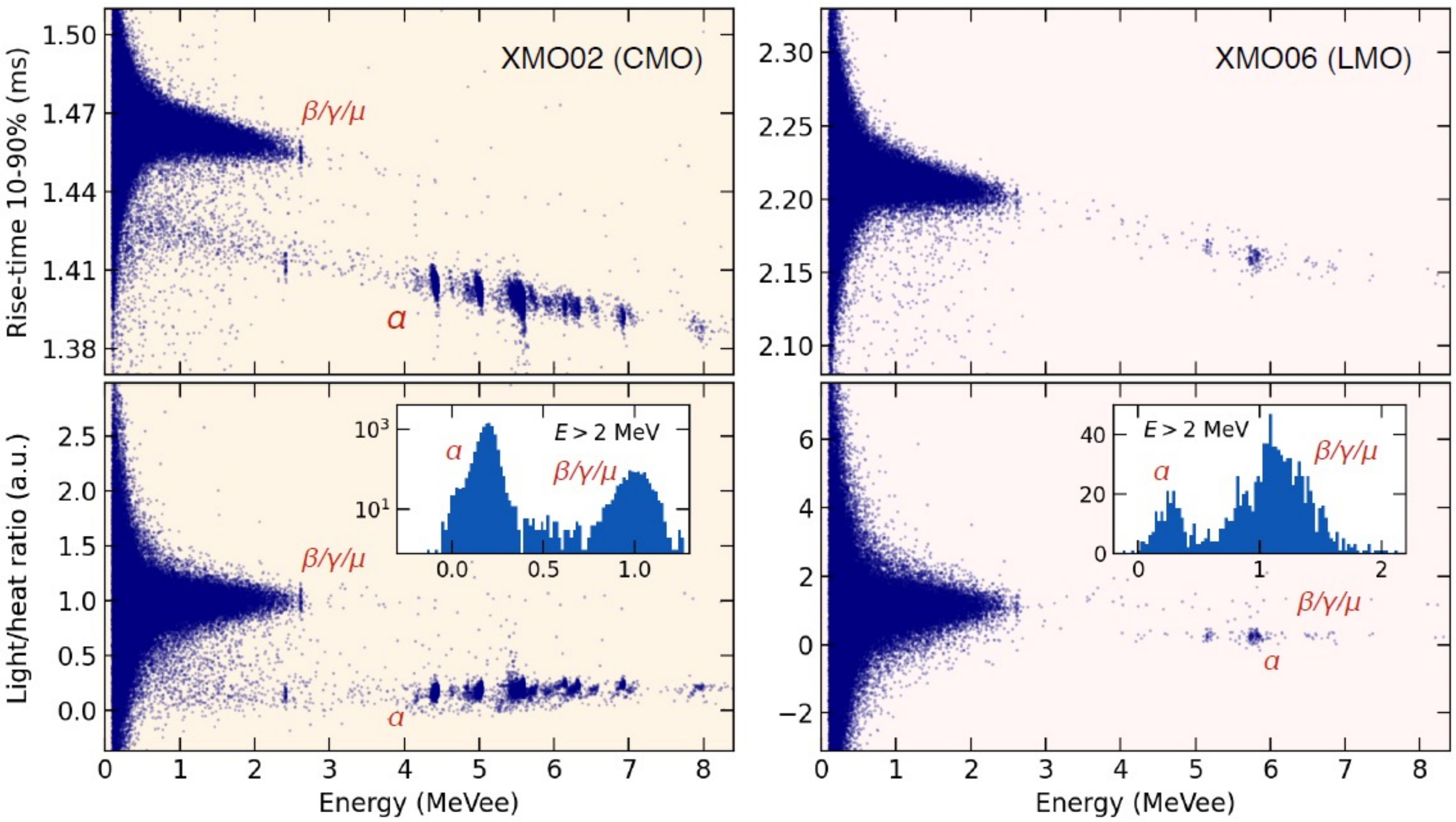


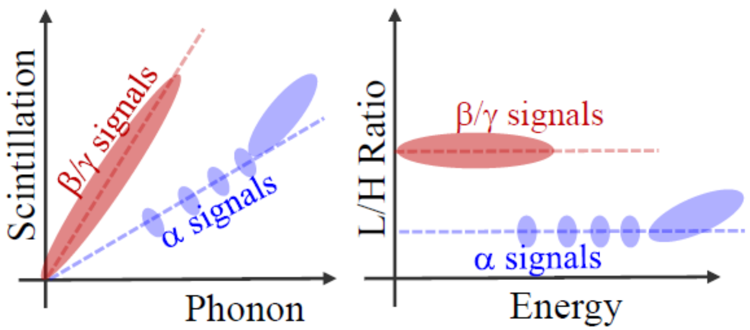


Calibration source: ^{232}Th-rich welding rods just outside of OVC.

- Slight non-linearity between signal amplitude and energy.

Particle IDentifications, CMO and LMO





Simultaneous heat & light measurements

- Particle discrimination for rejection of α-induced background

Discrimination Power (DP):

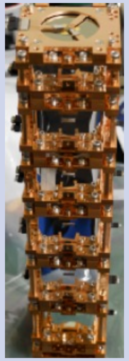
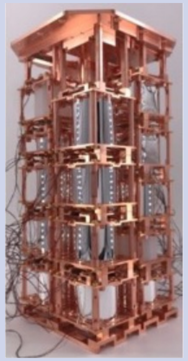
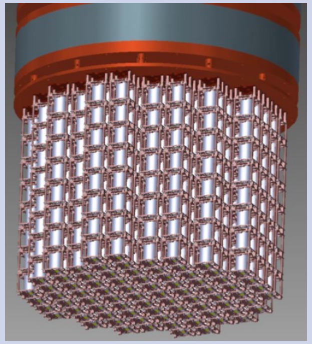
$$DP \equiv \frac{|\mu_{\beta/\gamma} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

μ - the mean value of the distribution

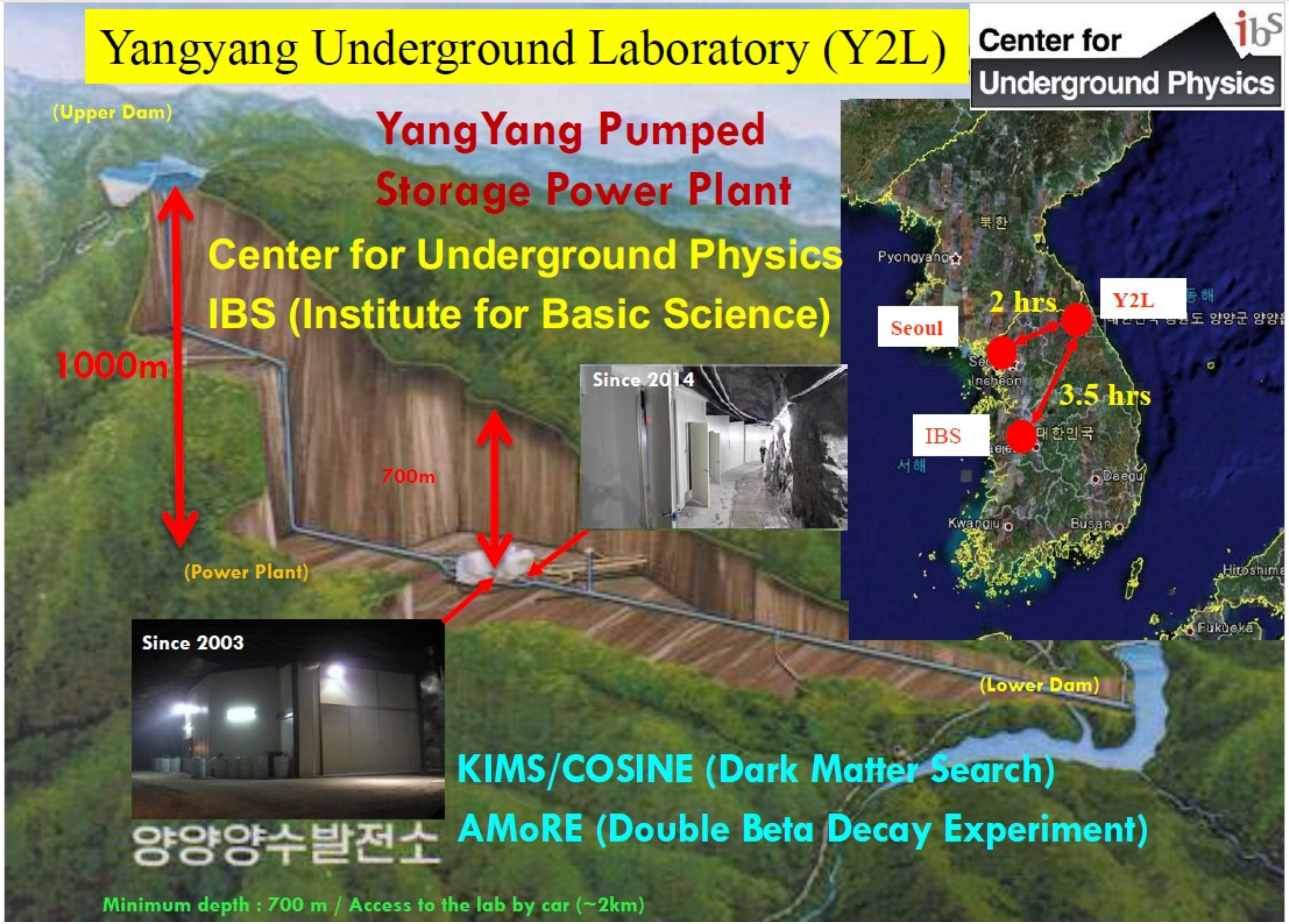
σ - standard deviation of this distribution

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

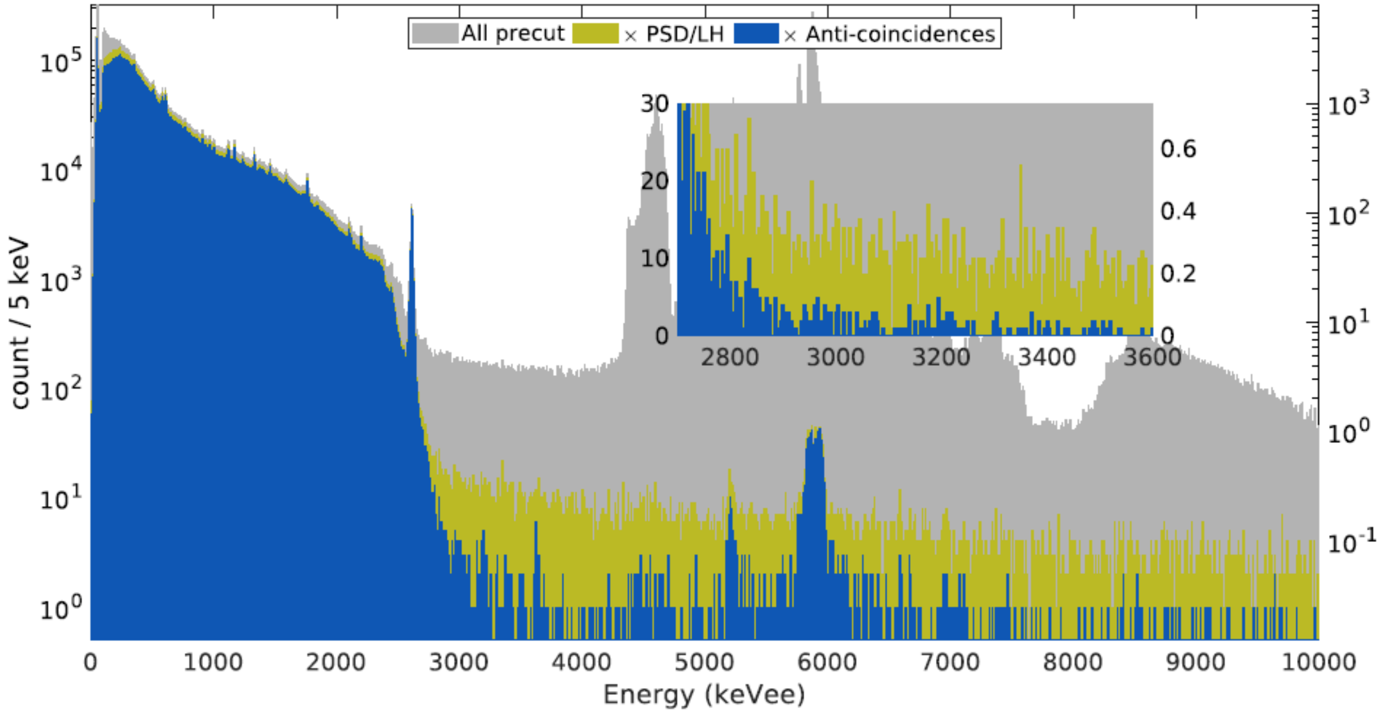
AMoRE project

Этапы эксперимента	Pilot	AMoRE-I	AMoRE-II
Crystal assembly			
Crystals	$^{48depl}Ca^{100}MoO_4$ (CMO)	$^{48depl}Ca^{100}MoO_4$, $^{nat}Li_2{}^{100}MoO_4$ (LMO)	$^{nat}Li_2{}^{100}MoO_4$
Crystal/Mass	6/1.9 kg	18/6.2 kg	~ 400/150 kg
Background Goal (counts/keV/kg/yr.)	10^{-1}	< 10^{-2}	< 10^{-4}
Sensitivity , $T_{1/2}(\text{yr.})$	~ $1.0\text{x}10^{23}$	~ $3.3\text{x}10^{24}$	~ $5.0\text{x}10^{26}$
Sensitivity, neutrino mass $m_{\beta\beta}$(мэВ)	1200-2100	140-270	13-25
Scheduled Dates	2015-2018	2020-2022	2024-2028
Location	Yangyang Underground Laboratory (Y2L), S. Korea	Y2L	Yemi Underground Laboratory (YemiLab), S. Korea

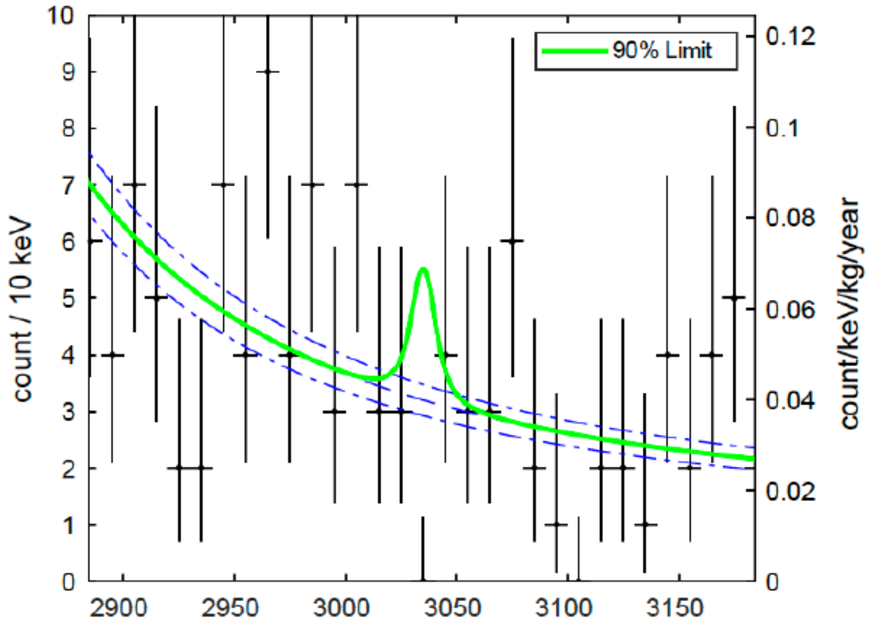
YangYang Underground Laboratory (Y2L)



Background spectra AMoRE-I after alpha background rejection



Live exposure	Bkg. @ $Q_{\beta\beta}$ / ckky
Total (8.02 kg_{XMoO_4} yr)	0.040±0.004
CMO (6.19 kg_{XMoO_4} yr)	0.039±0.004
LMO (1.83 kg_{XMoO_4} yr)	0.045±0.009



- 17 crystals excluding one LMO (for very poor β/α discrimination power)

  Exposure = 8.02 kgXMoO4 ・ yr = 3.88 kg100Mo ・ yr.

CMO has higher alpha backgrounds and rejection power is high

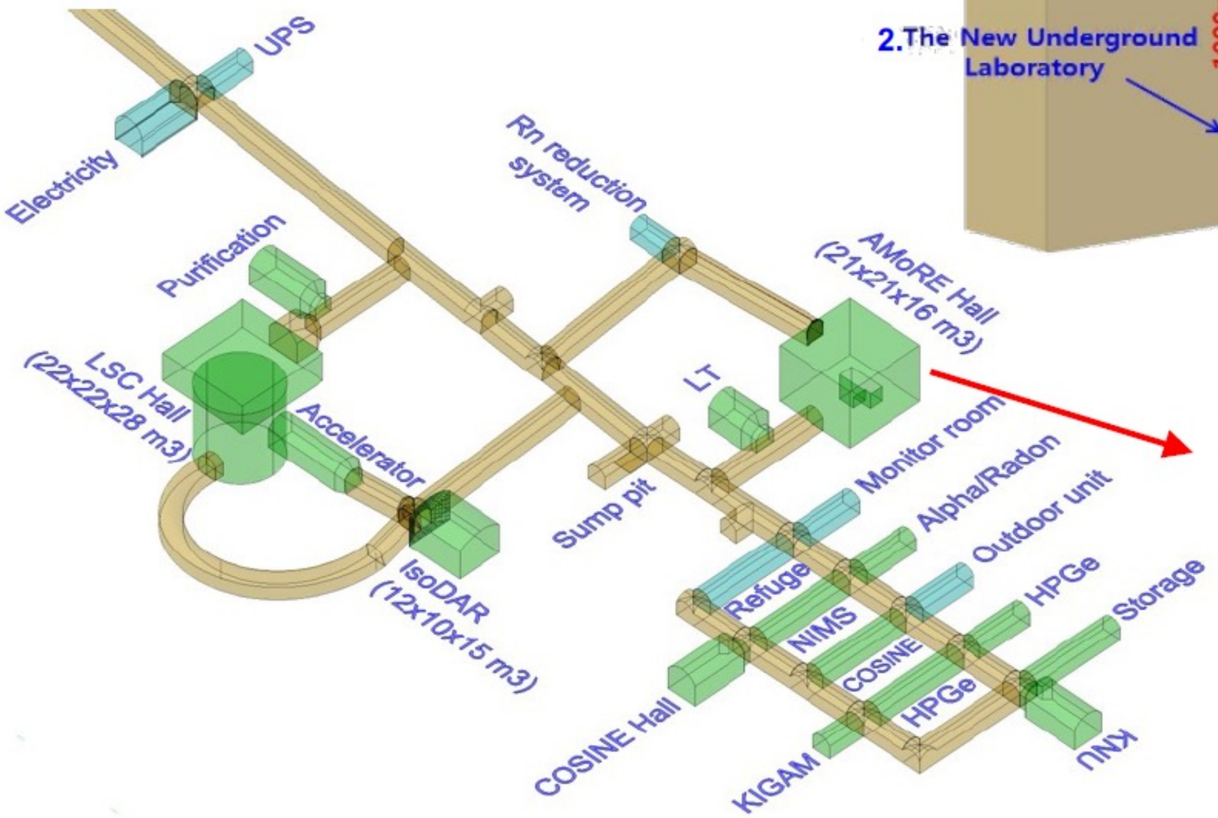
LMO has lower alpha backgrounds and rejection power is low

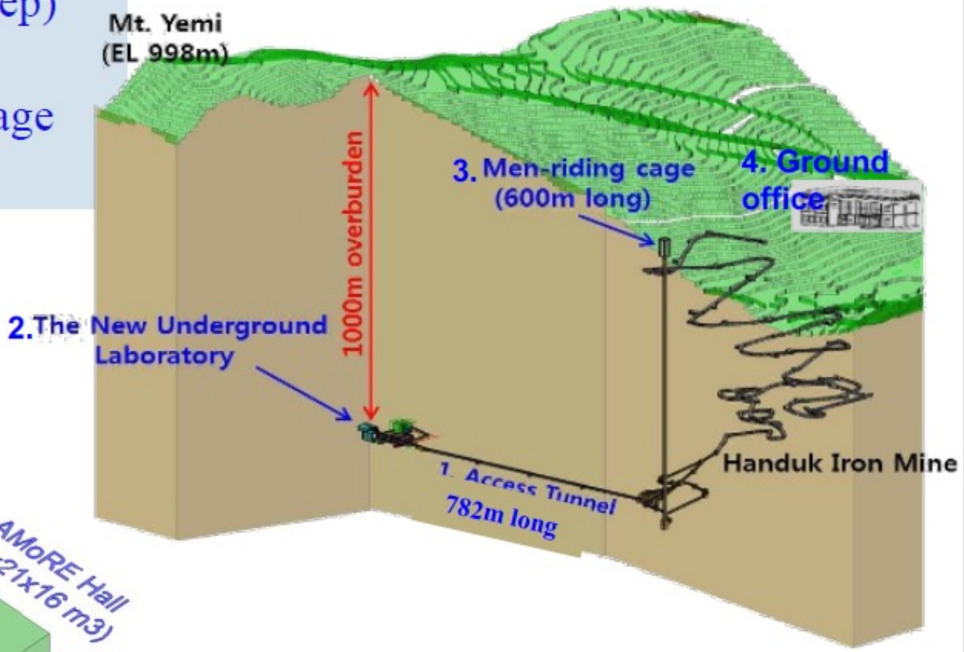
^{100}Mo 0νββ limit from AMoRE-I: $T_{1/2}^{0\nu\beta\beta} > 3{,}4\times10^{24}\ years$

Current best limit 1.8×10^{24} $years$ by CUPID-Mo

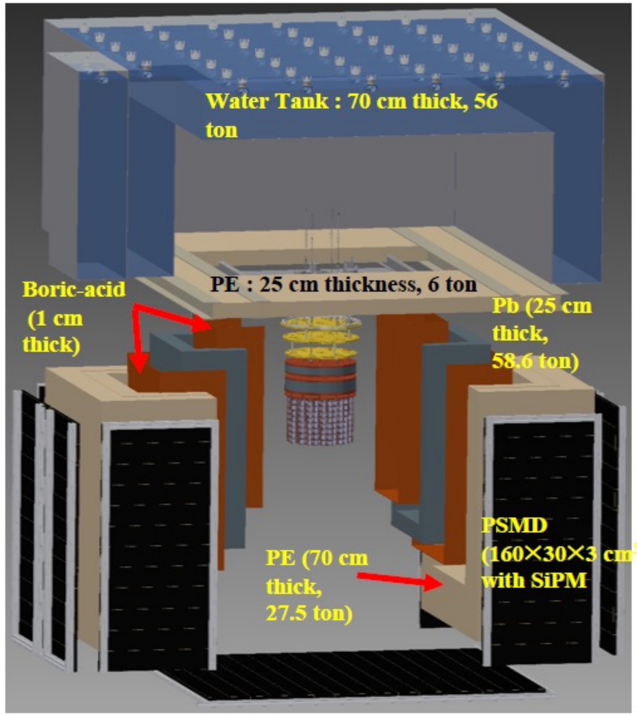
AMoRE-II @Yemilab

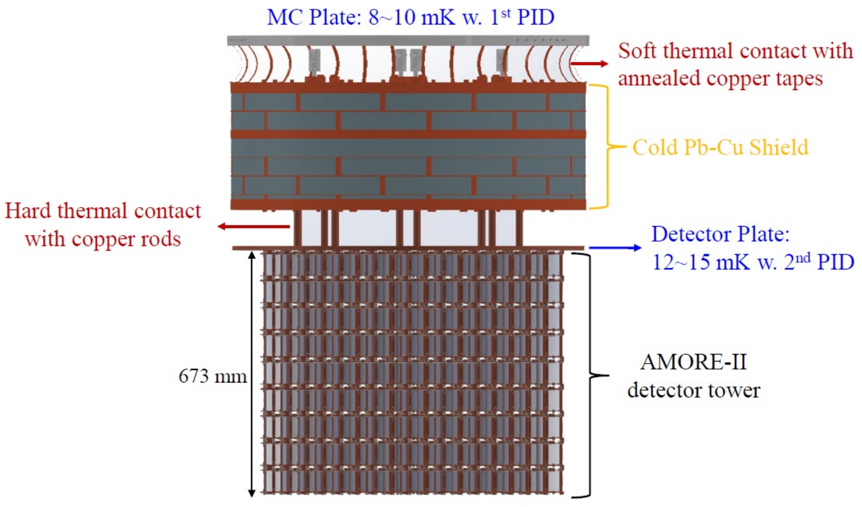
- Yemilab is constructed in 2022. (1000m deep)
- Lab space > 3000 m^2, 2.5 MW electricity.
- Two access ways: ramp-way, men-riding cage
- Open to other researchers IBS.



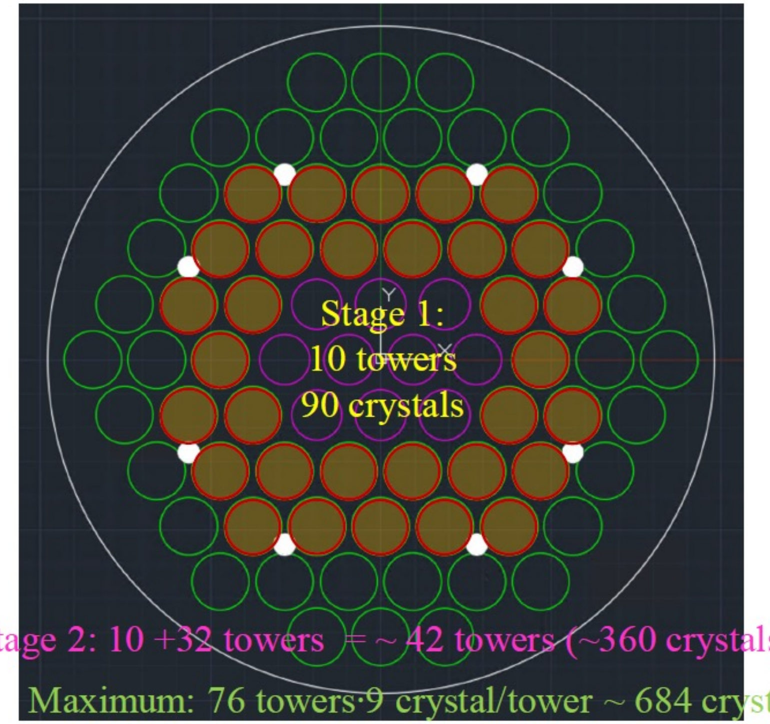


AMoRE-II detector





Preliminary

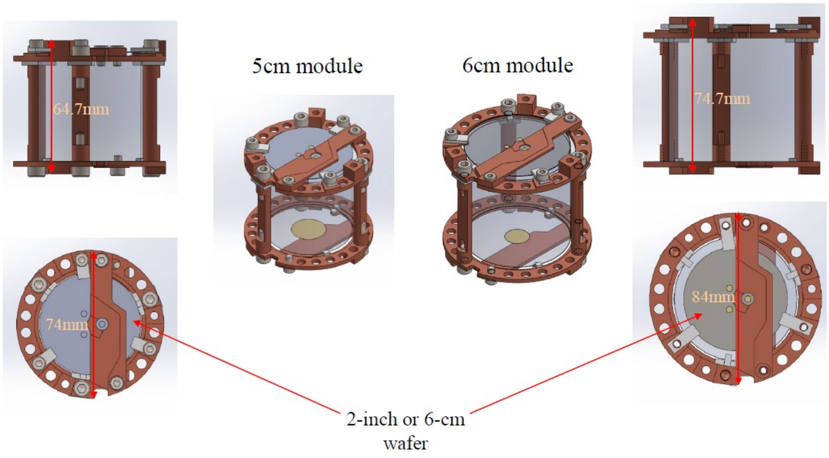


Stage 2: 10 +32 towers = ~ 42 towers (~360 crystals)

Maximum: 76 towers·9 crystal/tower ~ 684 crystals

Ultimate maximum: 50+26 towers·12 crystal/tower ~ 912 crystals

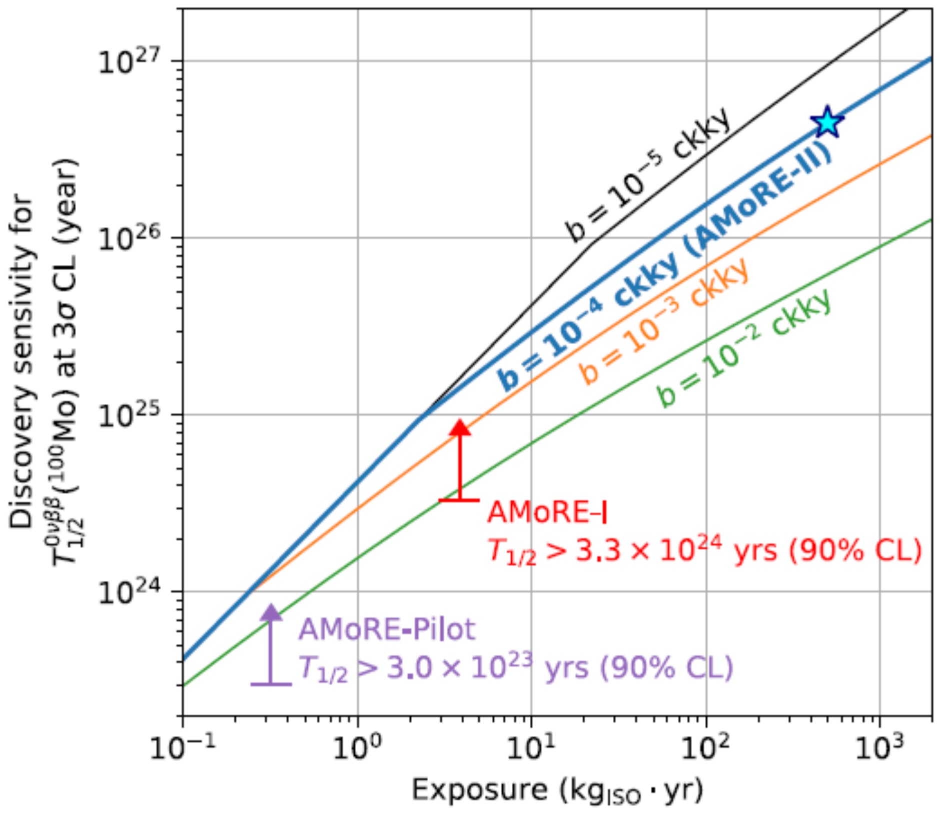
- The module designs are done for 5-cm and 6-cm LMOs.

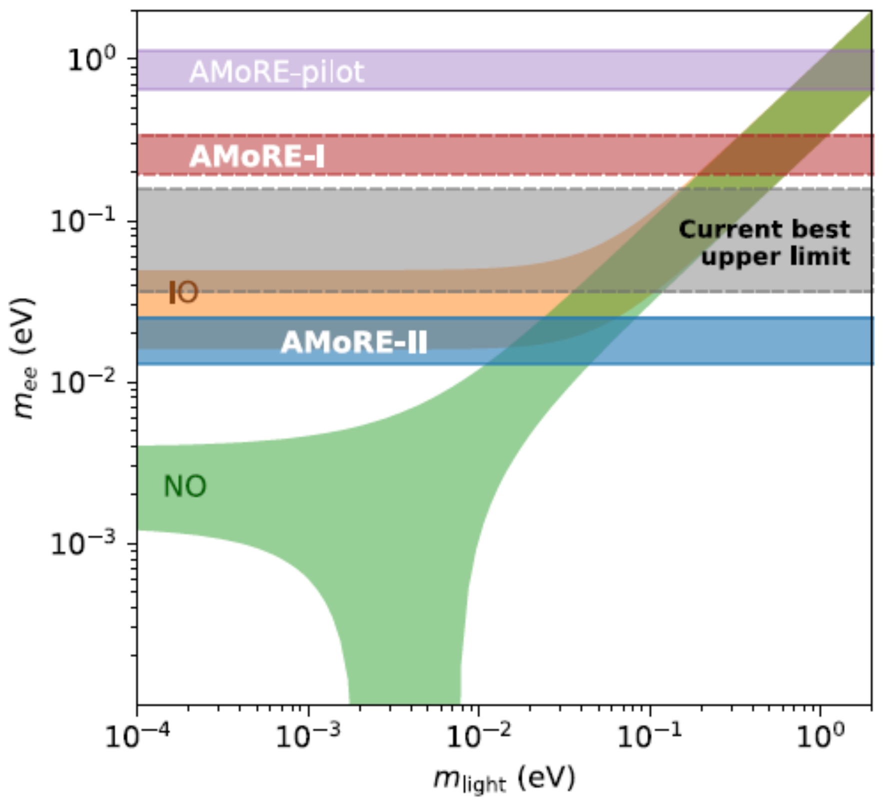


- LMO crystals: ∅5cm x H.5cm (310g) and ∅6cm x H.6cm (520g)
- Mass: ~80kg ^{100}Mo (~150kg crystal mass w. ~ 400 LMO crystals)

First Phase: 9 x10 ~ 24kg crystal mass

Limits & Sensitivities





(By KamLAND-Zen Phys. Rev. Lett. 130 (2023) 051801)

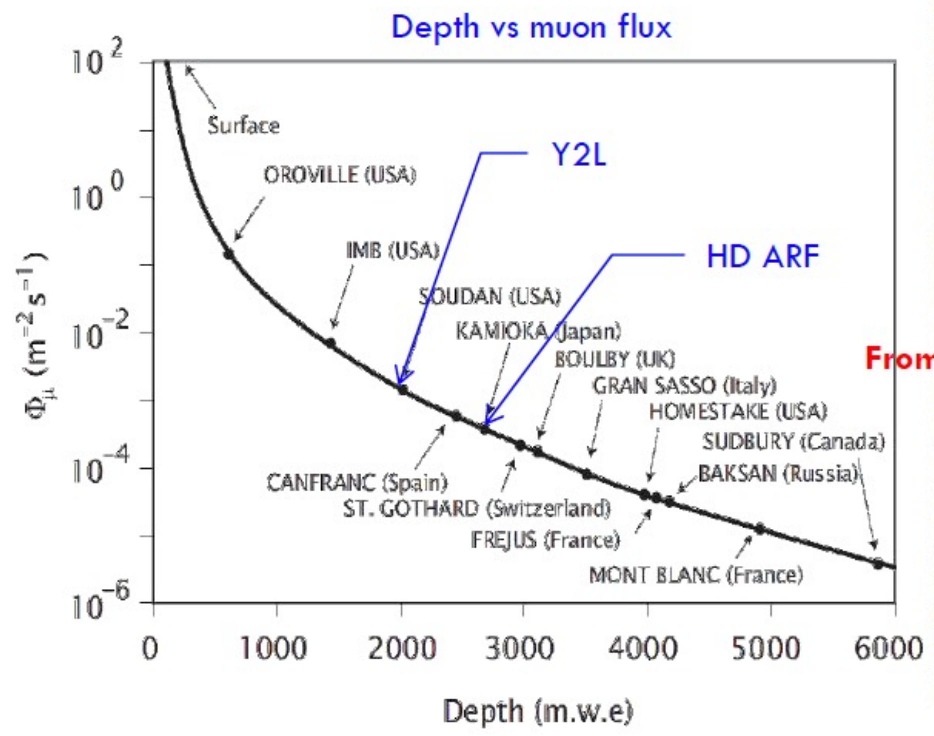
- AMoRE-I result corresponds to $m_{\beta\beta}$<200-340 meV
- AMoRE-II for $T_{1/2}^{0\nu\beta\beta} > 5 \times 10^{26}$ years by 100 kg of ^{100}Mo × 5 years running.

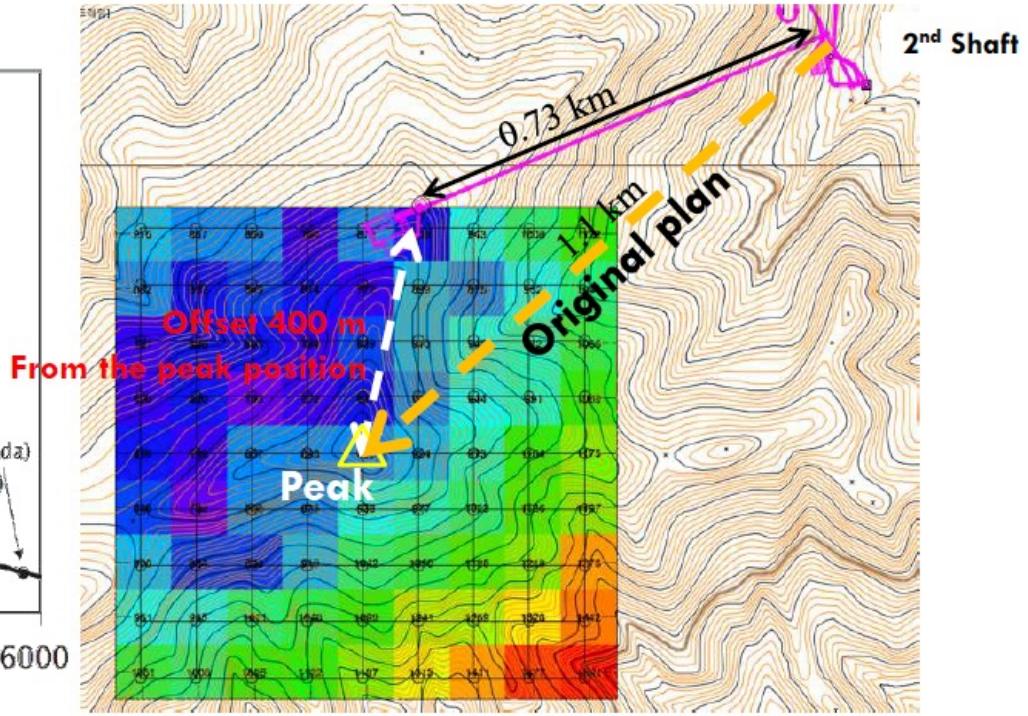
Thank you for your attention!

Back up slides

Cosmic ray muon background at YemiLab

- Access tunnel with more overburden shortened to ~730 m by a simulation study considering a detail profile of the landscape.

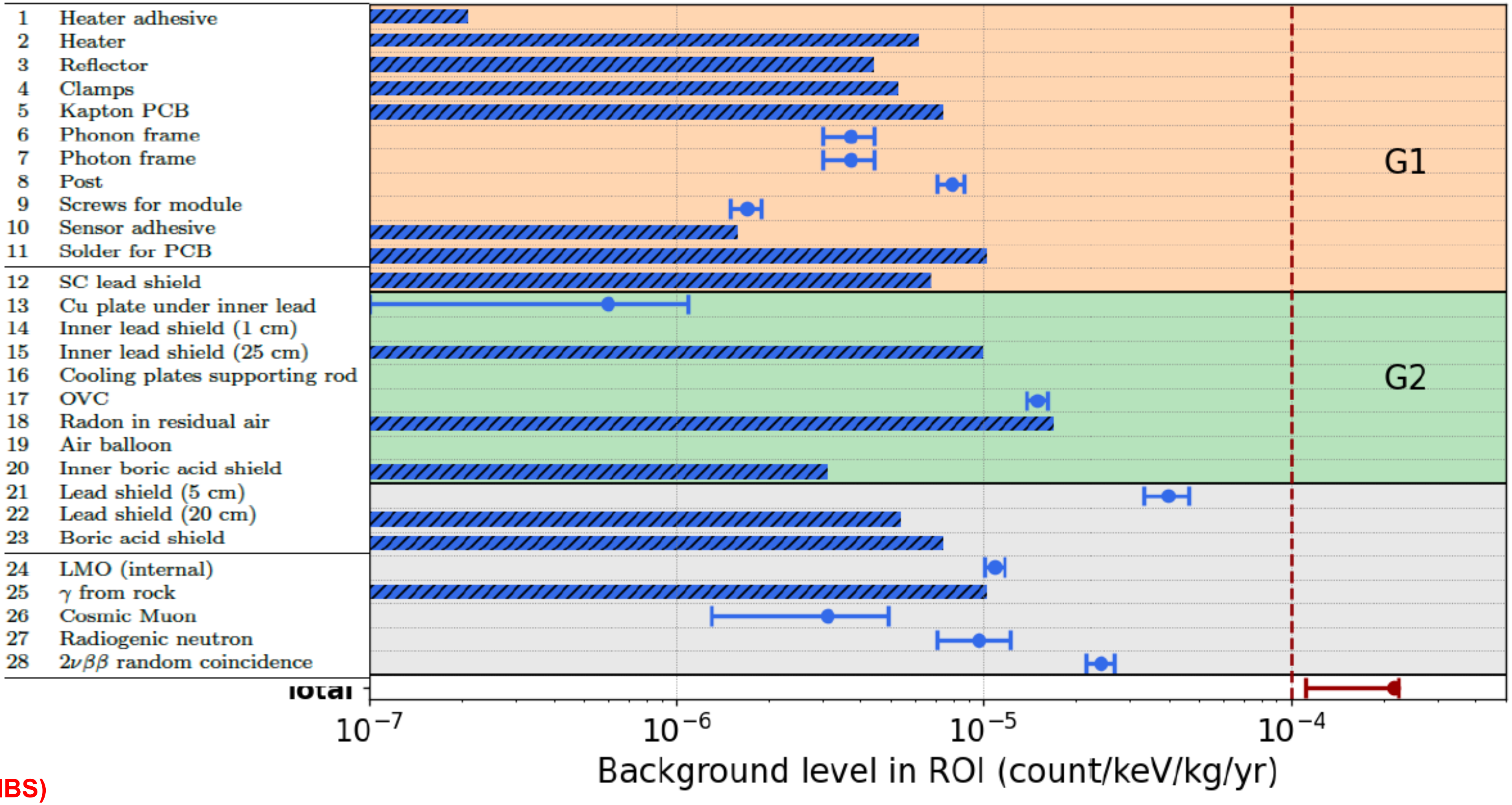




- Muon reduction rate @ HD with a simulation: ~ 8×10^{-6}

Background of AMoRE-II

- A few items will be improved by replacing the materials.
- Expect to reach 10^{-4} ckky level.



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NPB 2024, Hong Kong

Sensitivity of AMoRE-II