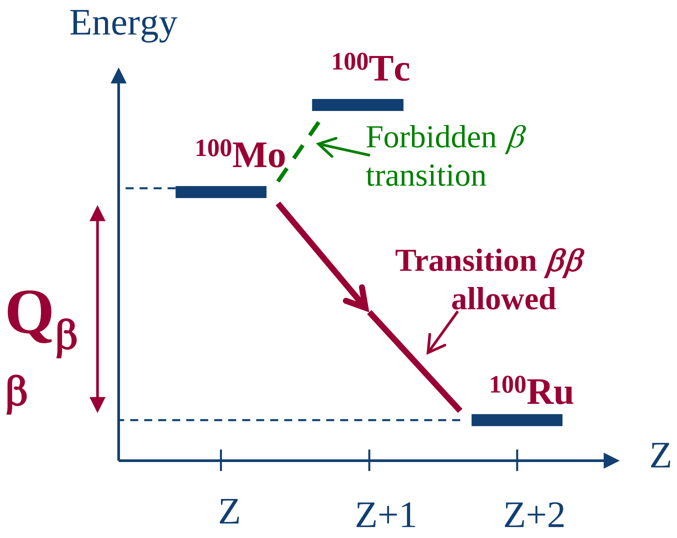
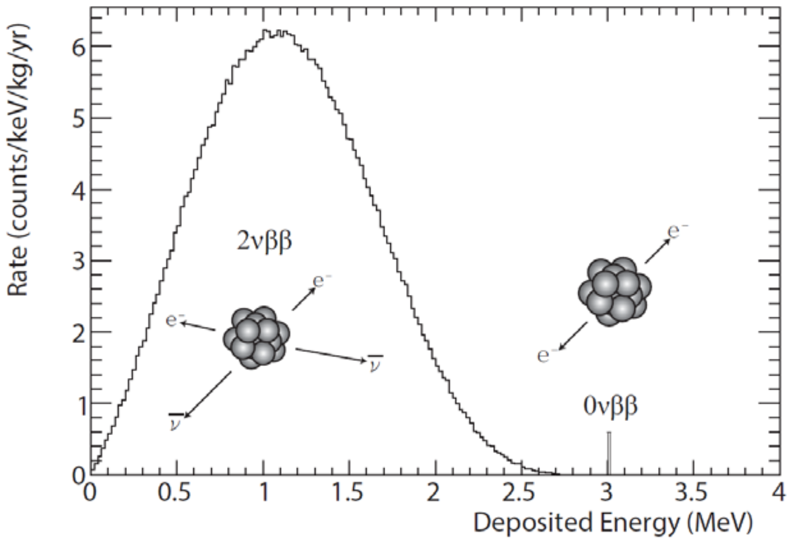
AMoRE:
Search for neutrinoless double beta decay of ^{100}Mo

Geon-Bo Kim
on behalf of the AMoRE collaboration
Center for Underground Physics
Institute for Basic Science

Neutrinoless Double Beta Decay (0νββ)





$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\,\nu_e$ (ΔL = 0, conserved)

$(Z, A) \rightarrow (Z+2, A) + 2e^-$ (ΔL = 2, violated)

- Majorana nature of neutrinos
- Absolute mass of Majorana neutrino

- Lapton number violation
- Extremely rare process

$T^{0\nu}_{1/2} > 1.1 \times 10^{24}$year (^{100}Mo, NEMO-3)

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

To be measured

Phase space factor

NME

Eff. ν mass

AMoRE

(Advanced Mo-based Rare Process Experiment)

Neutrinoless double beta decay

Metallic magnetic calorimeter

- International project search for **0νββ** of **^{100}Mo** using **CaMoO$_4$** scintillating crystals and **MMC**s.

8 countries, 18 institutions, ~90 collaborators

Why ^{100}Mo?

Candidates	$Q_{\beta\beta}$(MeV)	Natural Abundance(%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	**3.034**	**9.6**
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn →^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.479	8.9
^{150}Nd→^{150}Sm	3.367	5.6

Phys. Rev. C, 53, 695 (1996)
G. Pantis, F. Simkovic,
J. D. Vergados, and Amand Faessler

Advantages of ^{100}Mo

- Q-value (higher than natural γ-rays)
- High natural abundance
- High PSF&NME

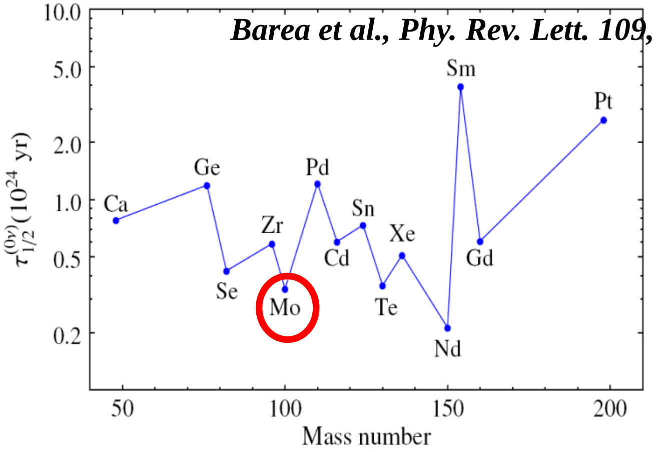
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

To be measured

Eff. ν mass

PSF
(Phase Space Factor)

NME
(Nuclear Matrix Element)



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

Expected half-lives for $<m_\nu> = 1$ eV

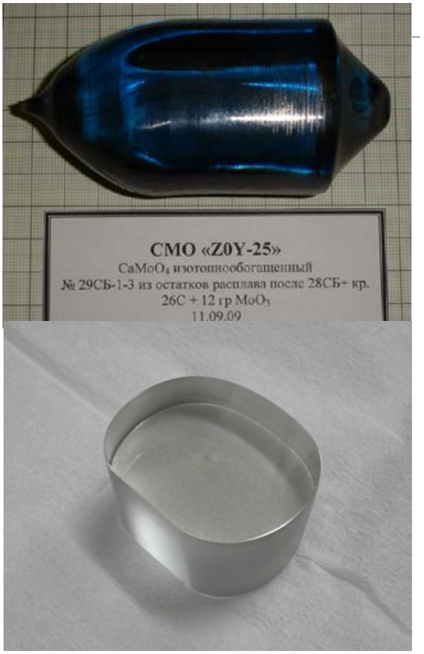
$^{40}Ca^{100}MoO_4$ crystals

- Enrichment of ^{100}Mo (natural abundance : 9.6%)
  - Gas-centrifuge method
  - Enrichment of ^{100}Mo is higher than 96%.

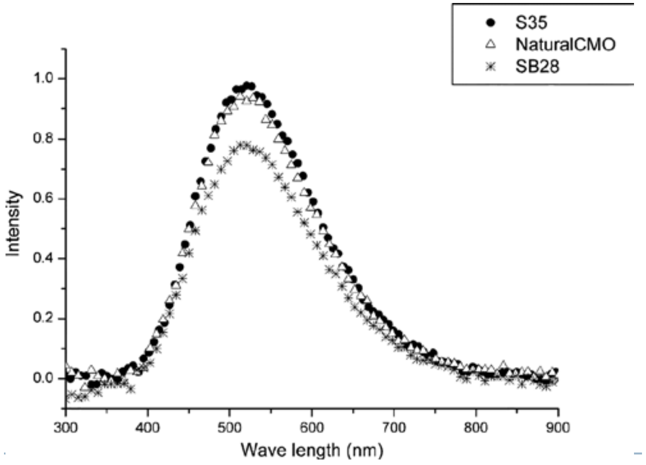
- Depletion of ^{48}Ca (natural abundance : 0.157%) in natural Ca
  - Electromagnetic separation
  - Composition of ^{48}Ca is less than 0.001 %.

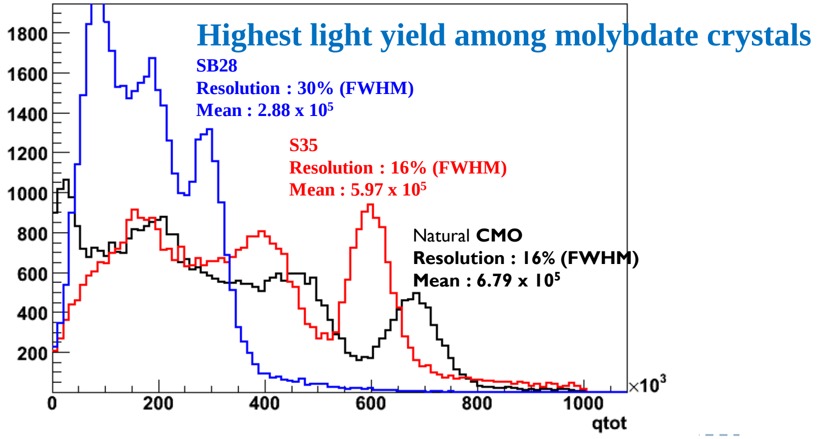
Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	**4.271**	0.187

^{48}Ca can makes background on the Q-value region of ^{100}Mo

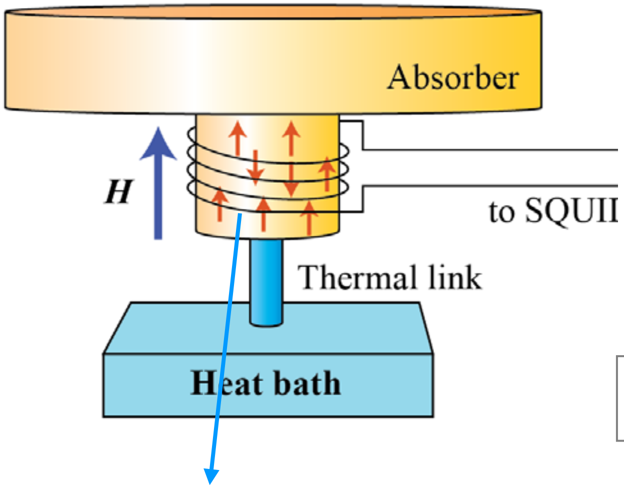


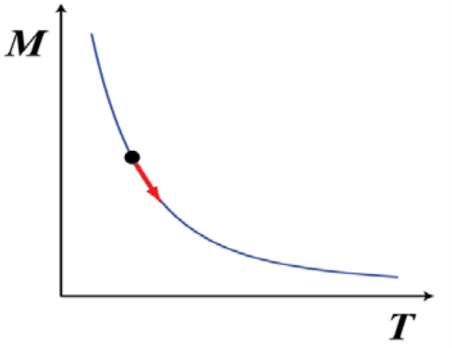
J. H. So, et al., IEEE trans. Nucl. Sci. 59 (5) (2012) 2214–2218.



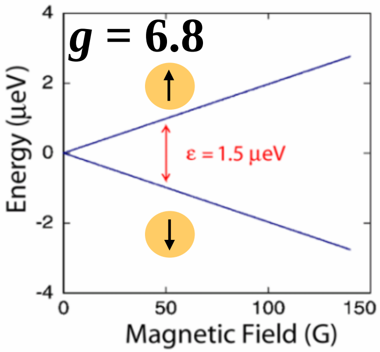


Metallic Magnetic Calorimeter





$$\delta E \rightarrow \delta T \rightarrow \delta M \rightarrow \delta \phi$$



5 mT → $\Delta\varepsilon$ = 1.5 μeV

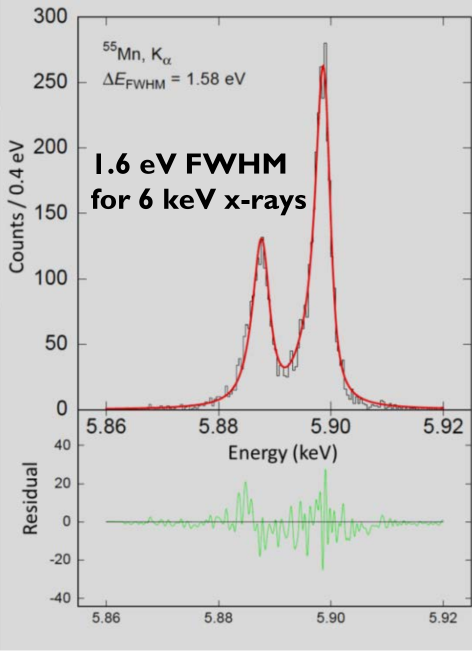
1 keV → 10^9 spin flips

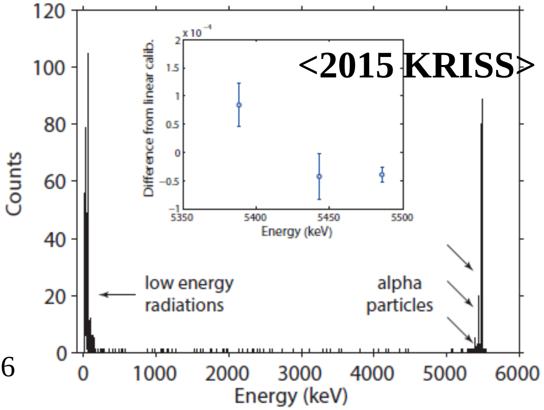
Statistical uncertainty is negligible

Measure temperature increases caused by particle interactions

- Magnetic material Au:Er (100~1000ppm, weakly-interacting paramagnetic system)
- Most of absorbed energy is converted to heat → High energy resolution
- Working at tens of mK

<2013 Heidelberg Univ.>





<2015 KRISS>

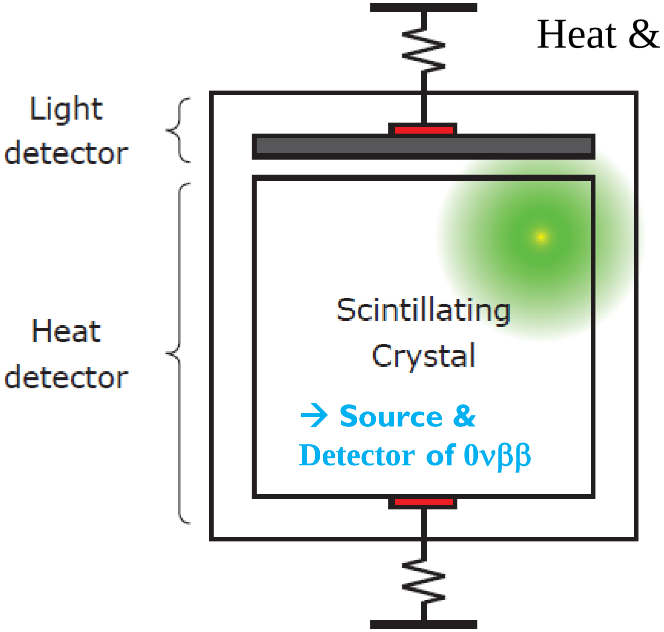
- **0.4keV FWHM for 60keV γ**
- **Good linearity from keV to MeV**
- **1.2keV FWHM Gaussian width for 5.5MeV α**

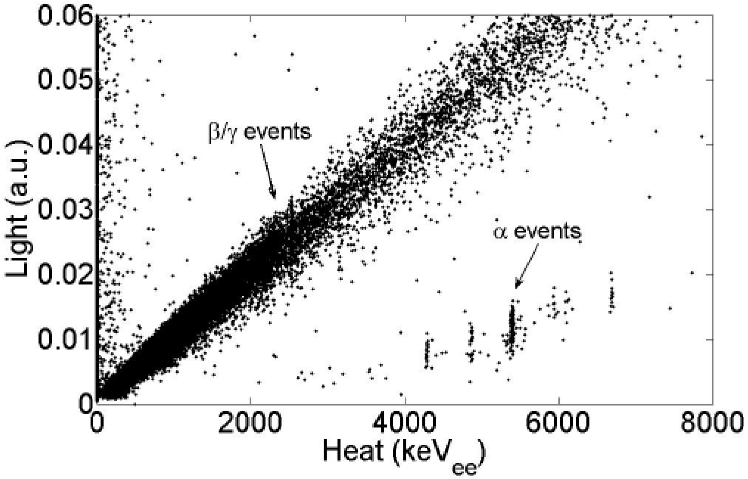
W. S. Yoon, et al., Nucl. Instr. and Meth. A 784 (2015) 143–146

AMoRE Detector Concept

G. B. Kim, et al., IEEE Trans. Nucl. Sci. 63 (2) (2016) 539–542

Simultaneous measurement of
Heat & Scintillation light using MMCs





Source = Detector

→ High detection efficiency

→ High energy resolution

Heat / Light simultaneous measurement

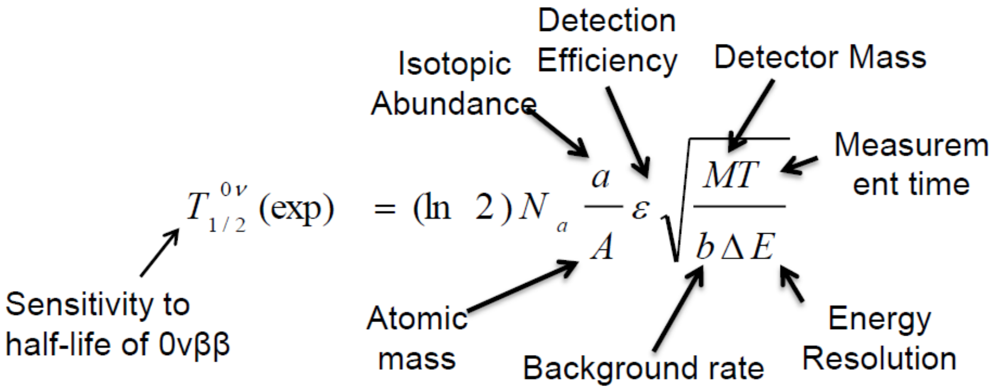
→ Particle discrimination

→ Rejection of α induced backgrounds

Attractive detection scheme!

Sensitivity on 0νββ and AMoRE

Sizeable background case



$$T^{0\nu}_{1/2}(\exp) = (\ln\ 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b \Delta E}}$$

"Zero" background case

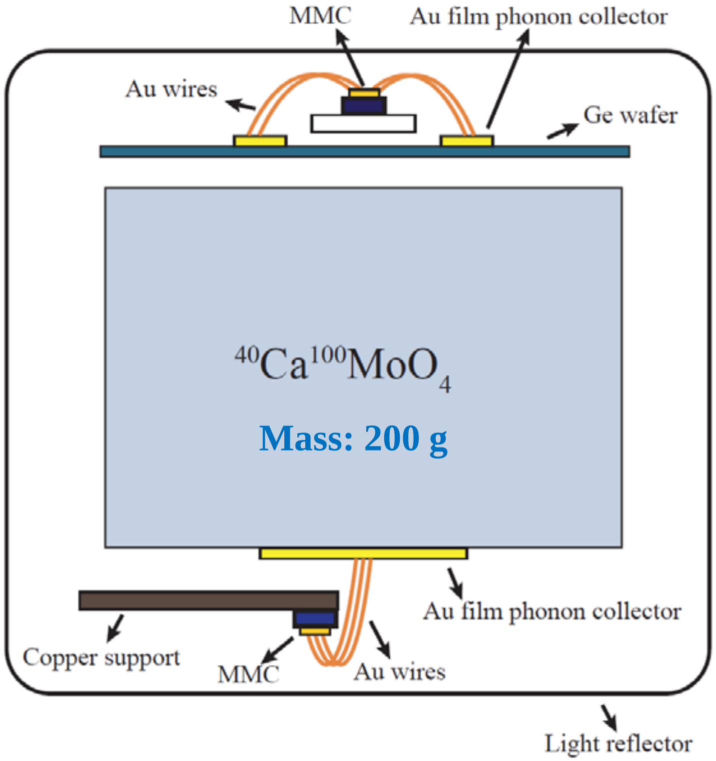
$$T^{0\nu}_{1/2}(\exp) = (\ln\ 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$

Toward zero background experiment!

- **Background reduction**
- High energy resolution with MMCs (~ 10 keV)
- α background rejection by Heat&Light simultaneous measurement
- Almost no γ background at ROI of ^{100}Mo (Q=3 MeV)
- **Detector mass**
- Enrichment of ^{100}Mo up to > 96 % with 200 g ~ 500 g crystals
- **Detection efficiency**
- "Source equals to detector" configuration

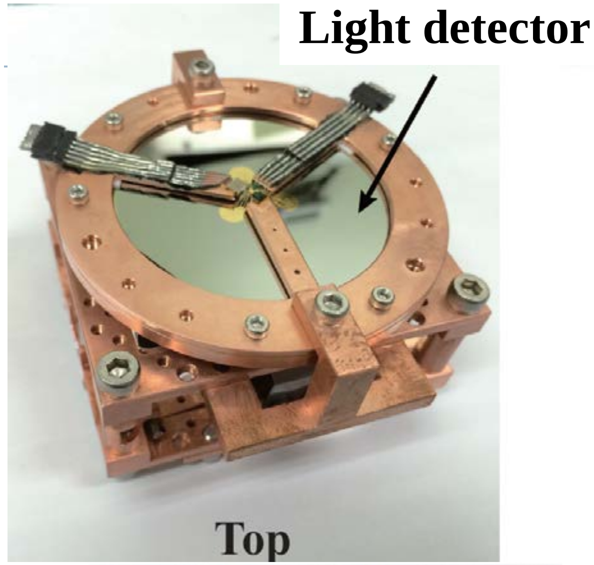
AMoRE prototype detector

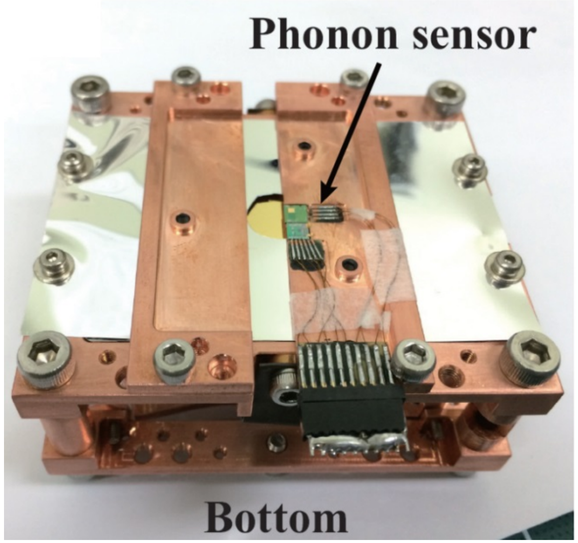
- Tested at an **above-ground lab**.
- With partial lead shield of 10 cm



Light (photon) detector

Heat (phonon) detector

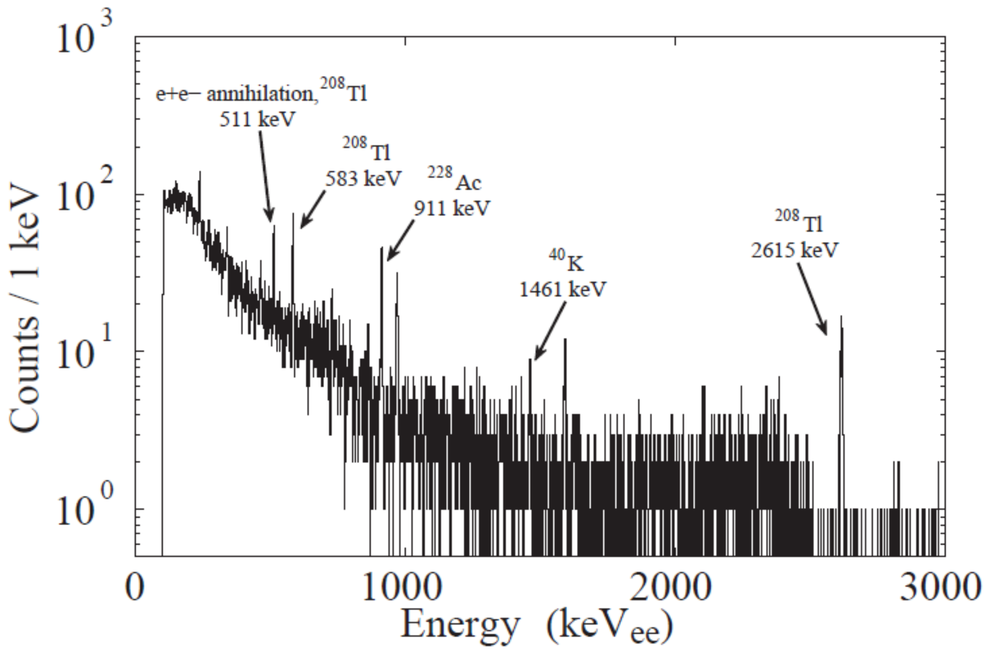


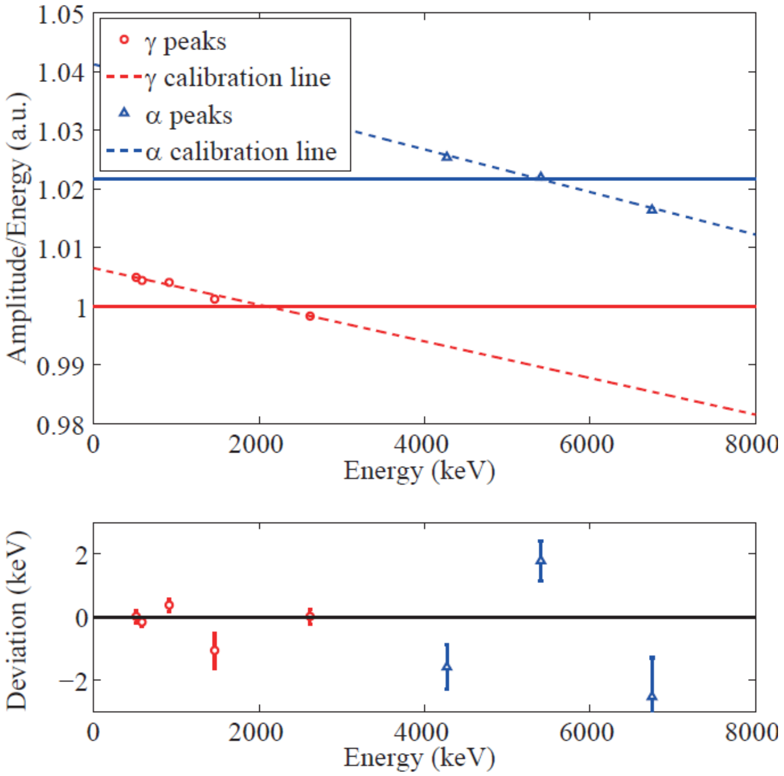


G. B. Kim, et al., IEEE Trans. Nucl. Sci. 63 (2) (2016) 539–542

Detector performances

above-ground measurement

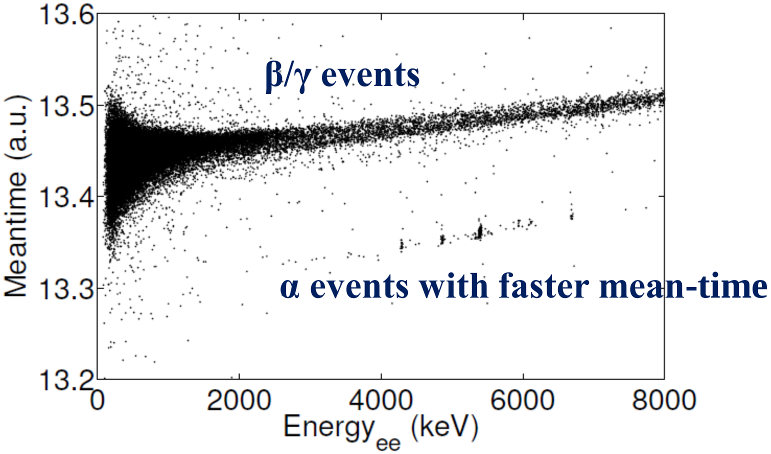




- FWHM Energy resolution: 8.7 keV @ 2.6 MeV (ROI: 3.0 MeV)
- Energy is well calibrated by quadratic polynomial function
- Deviation < 2 keV for γ-ray peaks

Detector performances

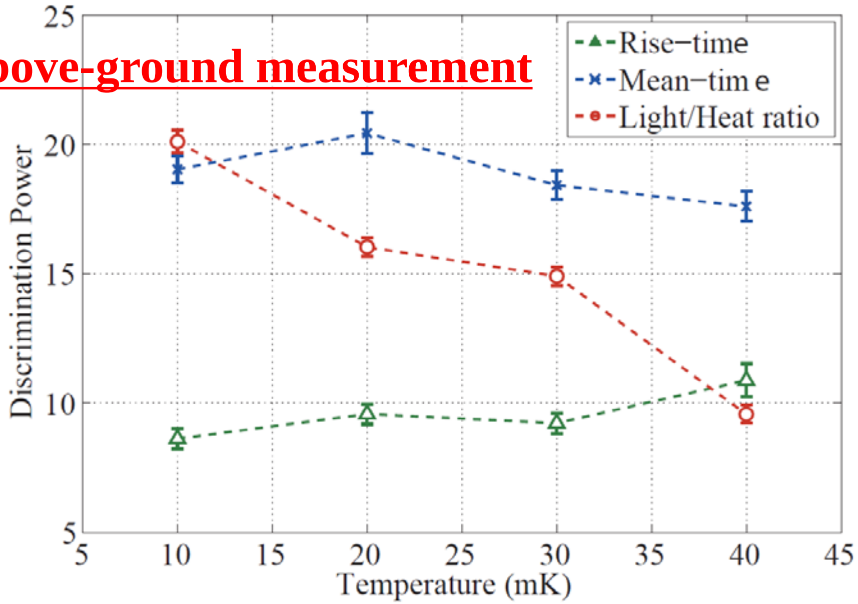
Pulse shape discrimination (PSD) in Heat signal



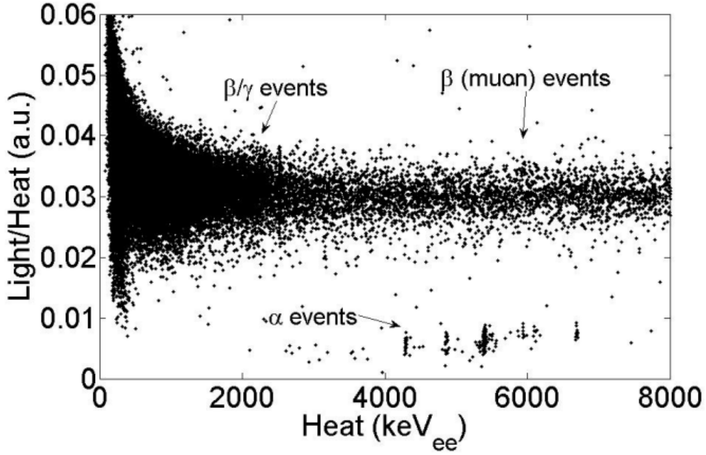
$$DP = (\mu_1 - \mu_2)/\sqrt{\sigma_1^2 + \sigma_2^2}$$

μ: mean values of distributions
σ: standard deviations of distributions

above-ground measurement



Particle discrimination by Heat/Light ratio



- Mean-time shows 18~20 σ separation power at 10 ~ 40 mK

AMoRE-Pilot Experiment

	Pilot	Phase I	Phase II
Total mass of crystal	1.5 kg	5 kg	200 kg

Five detector cells

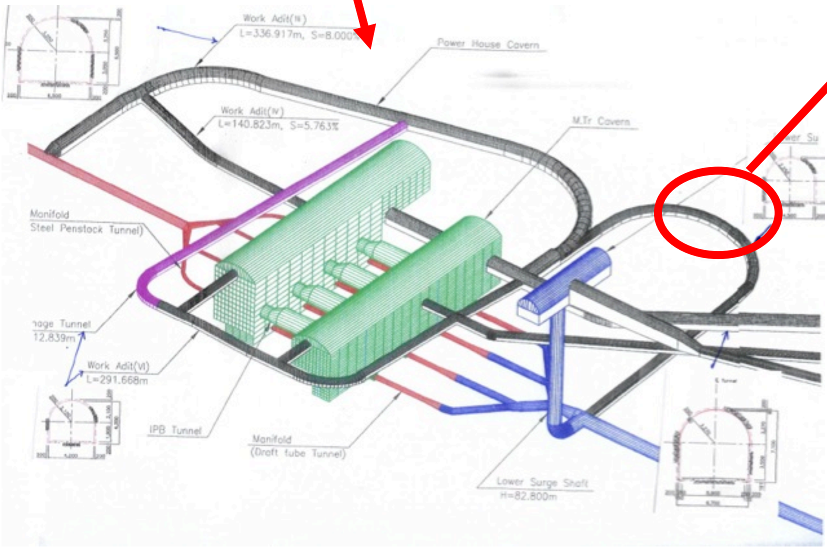
NOSV copper structure

PEEK crystal supports

PTFE&Cu crystal holders

- Five $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ crystals of total 1.5 kg
- 5 heat detectors + 6 light detectors
- Goal: 1 year measurement with zero background condition at **Y2L**
- **Now in a commissioning run**

YangYang underground Laboratory (Y2L)



In Yangyang pumped storage Power Plant

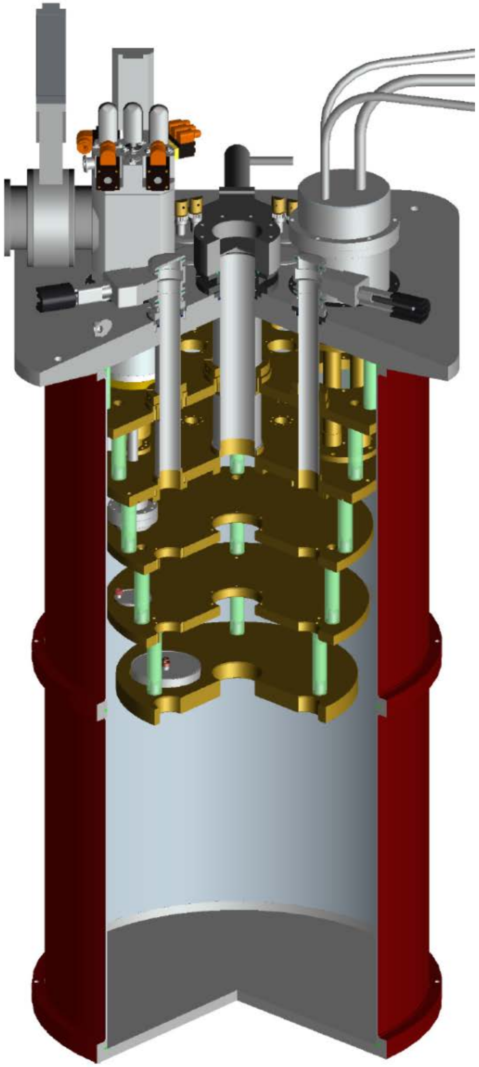
Minimum vertical depth : 700 m

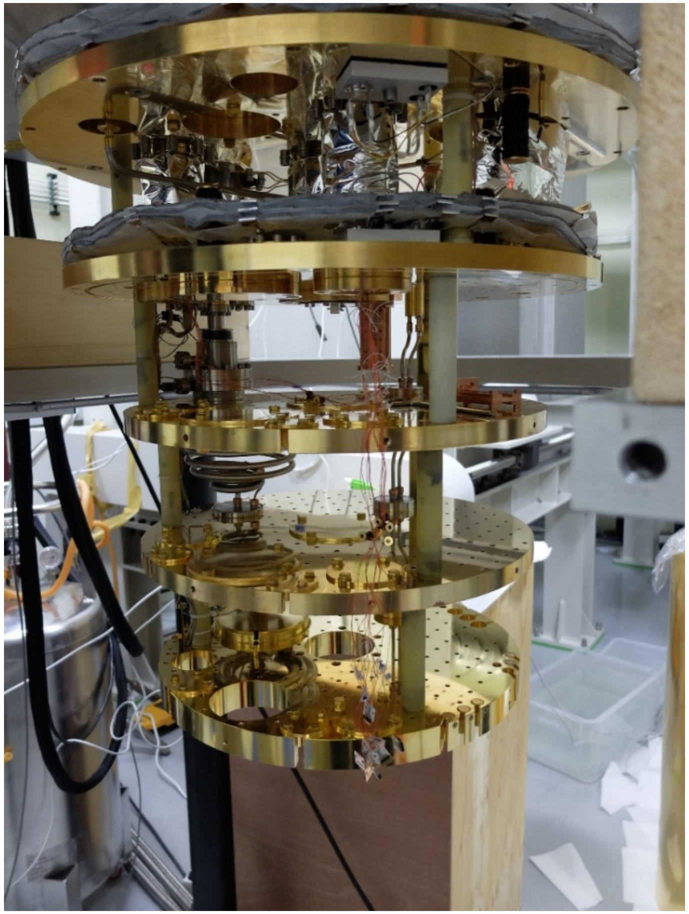
Access to the lab by car : around 2 km

Experiments

- KIMS : dark matter search experiment
- AMoRE : $0\nu\,\beta\beta$ decay search experiment

Refrigerator for AMoRE-Pilot

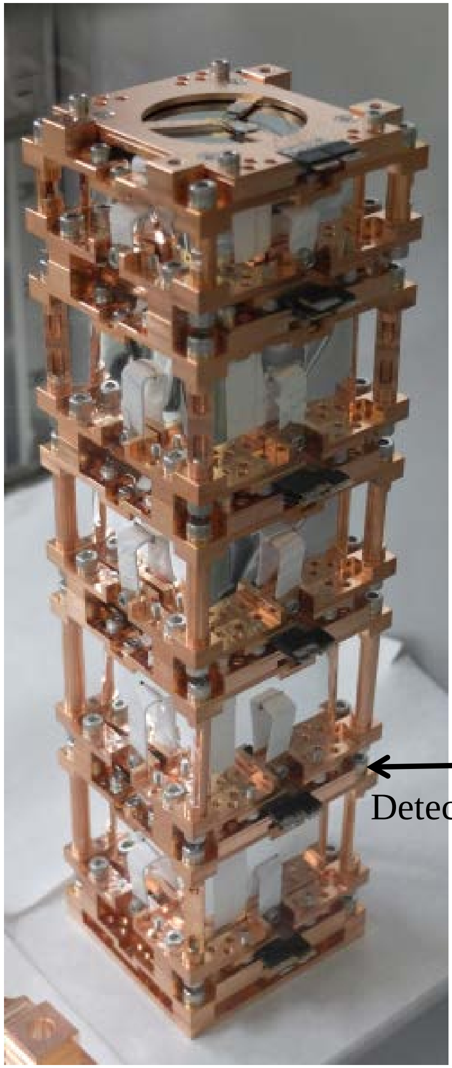


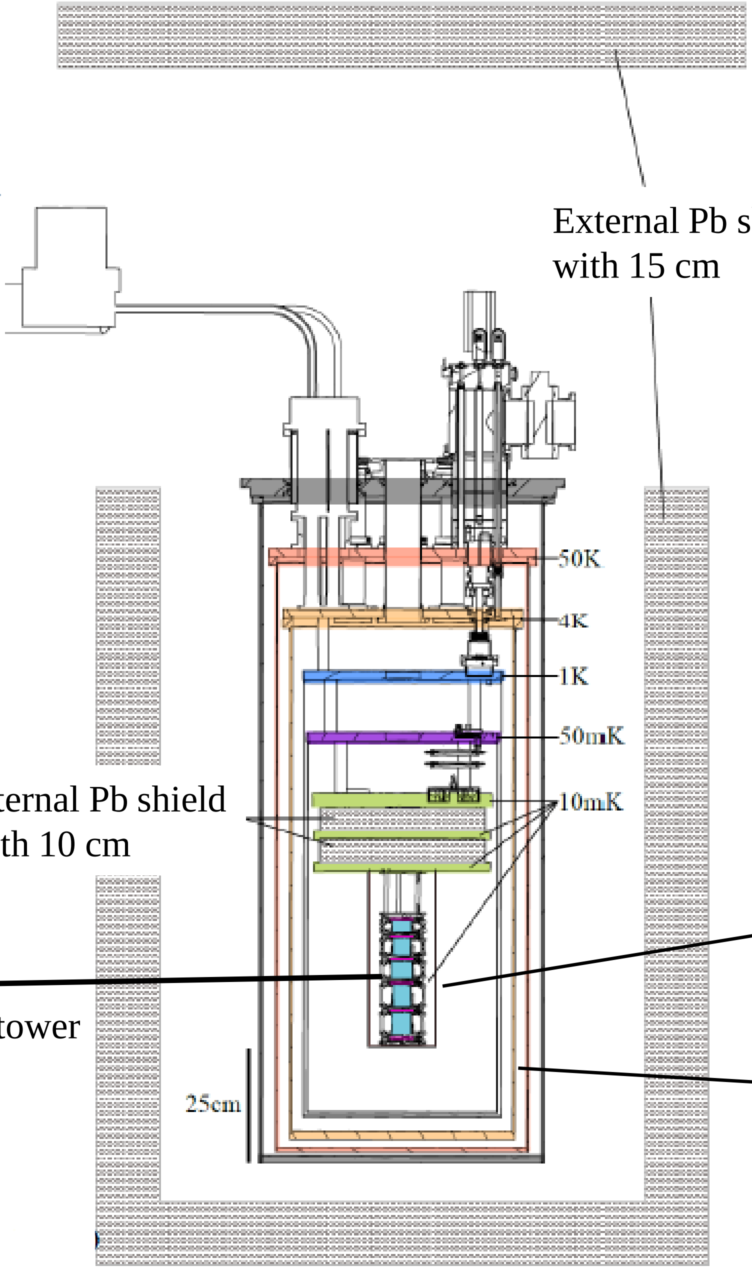


- CFDR for AMoRE-pilot and Phase-I
- Leiden : CF-1200-maglav
- 1.4 mW at 120 mK.
- Volume : (D) 408 mm x (H) 690 mm
- Copper cans on each temp. stages
- T_{min} : 8.7 mK as tested.
- $t_{cooling}$: ~one week with extra 180 kg

Pb and Cu and on the M.C.

Shieldings





External Pb shield with 15 cm

Internal Pb shield with 10 cm

Superconducting magnetic shield made by Pb

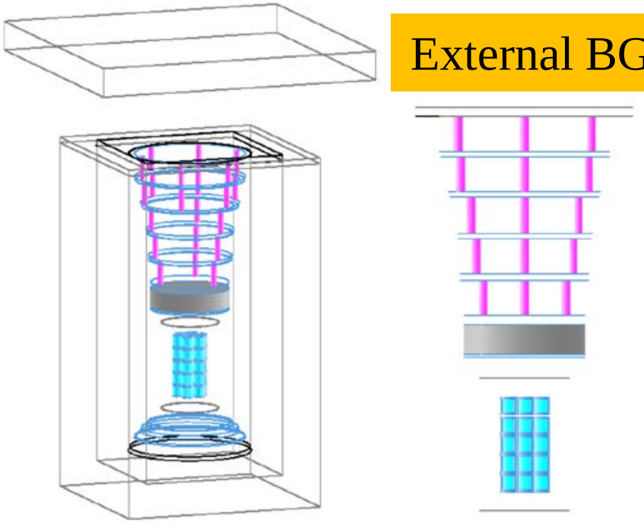
Detector tower

Thermal radiation shields made of Cu

Background Simulation

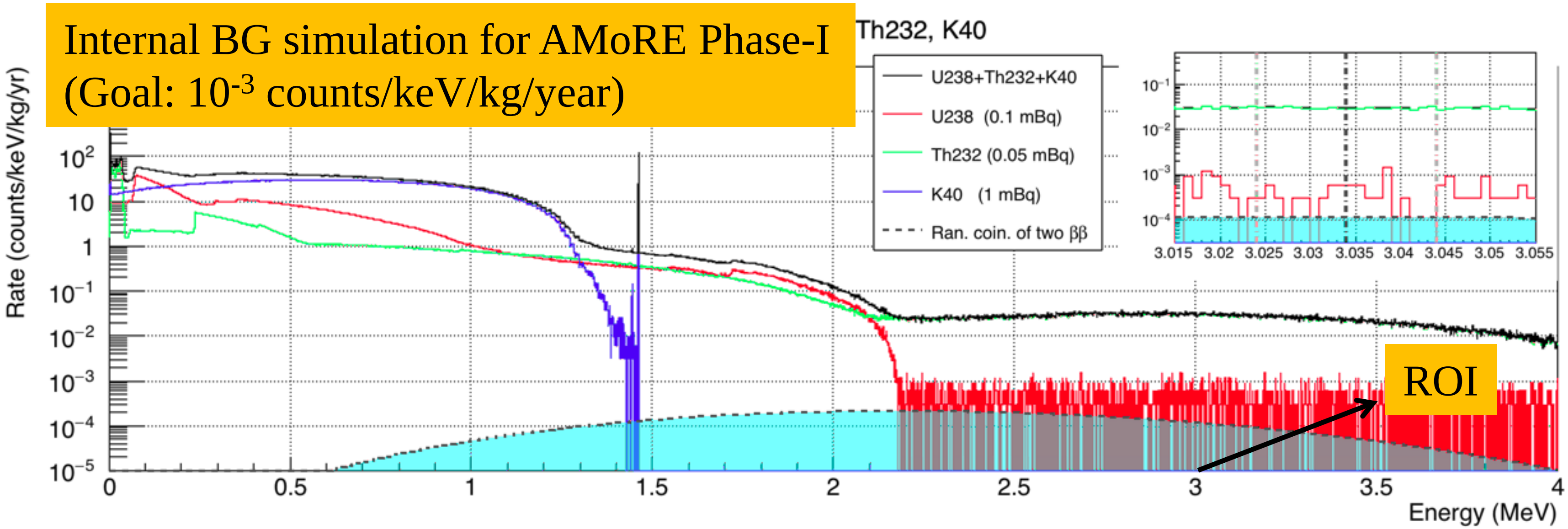
External BG simulation for AMoRE Phase-I

A. Luqman, et al., arXiv:1601.01249



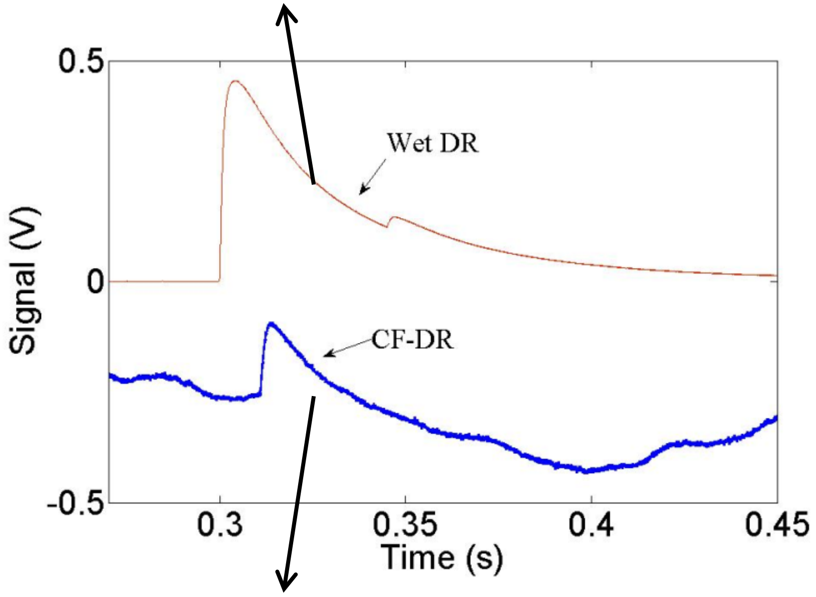
- The measured impurity level has been used for MC simulation.
- The external background can not give any events to Phase-I.
- We need more consideration about materials for Phase-II.
- The internal background of CMO crystals have been measure at Y2L.
- The most effective background is caused by ^{208}Tl in the crystals.

Internal BG simulation for AMoRE Phase-I
(Goal: 10^{-3} counts/keV/kg/year)



Current status of AMoRE-pilot

-Measured waveform from the **Prototype** detector
-Above-ground with Wet-DR
-Low vibration effect

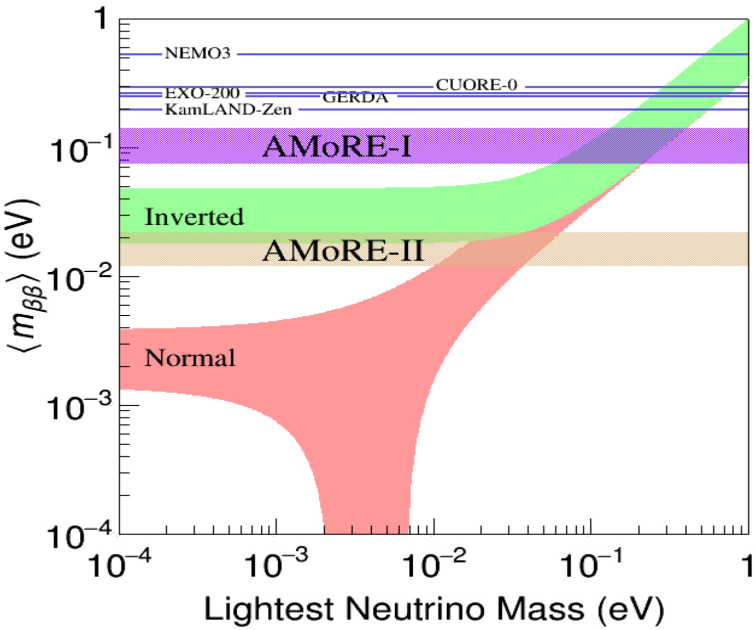


-Measured waveform from the **Pilot** detector
-Underground with CF-DR
-Huge vibration by pulse-tube

- There were two phases of commissioning run
- Collecting information on detector performances, background sources
- Currently we are focused on
  - Reduction of vibration induced noises
  - Get rid of radioactive background sources from detector, cryostat, shieldings

Summary of the AMoRE project

- Crystal: $^{40}Ca^{100}MoO_4$, doubly enriched scintillating crystals
- Detector: Cryogenic detector with MMC for heat and light measurement
- Temperature: ~20 mK
- Zero background measurement in ROI
- Location: Y2L (till Phase I) and a new lab (Phase II)
- Fully funded for Pilot, Phase I and II.



	Pilot	Phase I	Phase II
Total mass of crystal	1.5 kg	5 kg	200 kg
$T_{1/2}$ Sensitivity [years]	3.2×10^{24}	2.7×10^{25}	1.1×10^{27}
$<m_{\beta\beta}>$ Sensitivity [meV]	210-400	70-140	12-22
Location	Y2L	Y2L	New lab.
Schedule	2015-2017	2017-2019	2020-