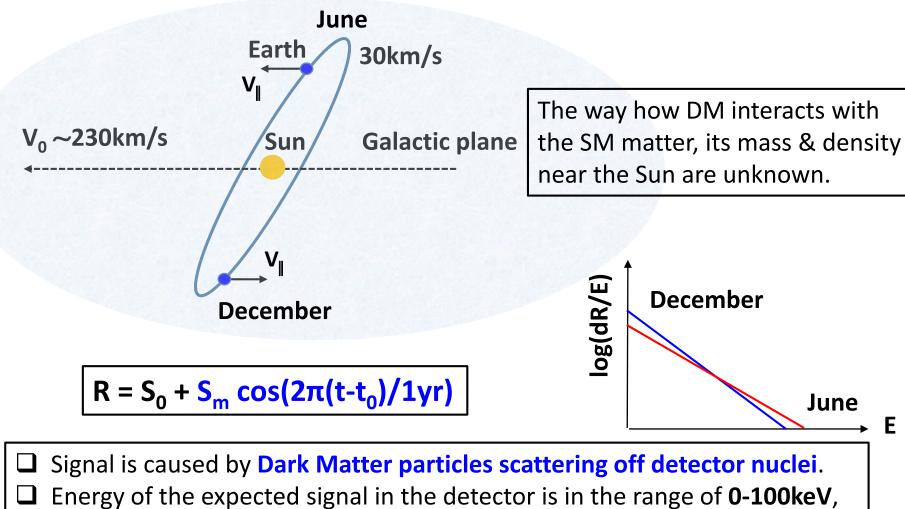
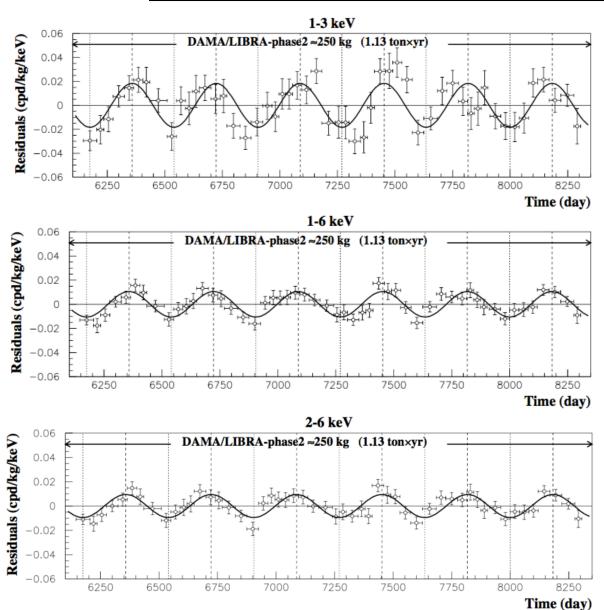


A hypothetical Dark Matter (DM) signal



- ☐ Energy of the expected signal in the detector is in the range of **0-100keV**, which is **natural radioactivity dominant**.
- ☐ Fortunately, the Earth motion around the Sun creates **annual modulation** of the measured energy spectrum (maximum is near June 2nd).

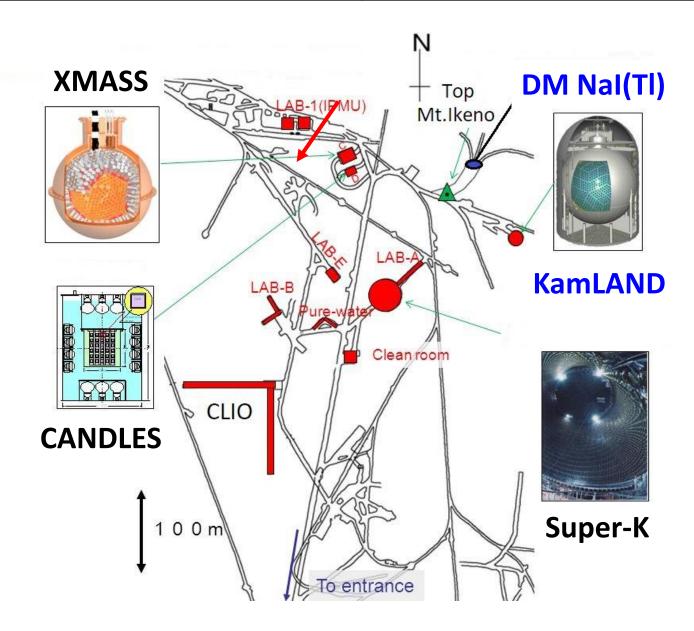
The DAMA/LIBRA-phase2 result



The DAMA/LIBRA-phase2 data favours presence of modulated DM signal with proper features at 9.5 c.L.

Averaged background rate is ~1 ev/keV/kg/day. The modulation effect is just few per cent.

The Kamioka underground laboratory



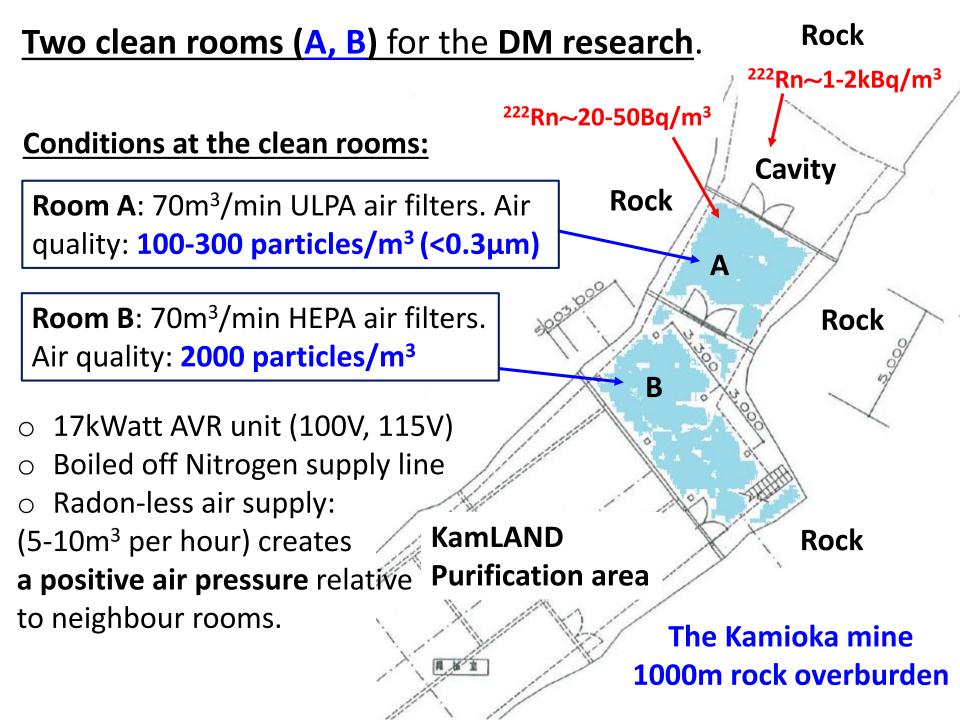
The Dark Matter project collaborators

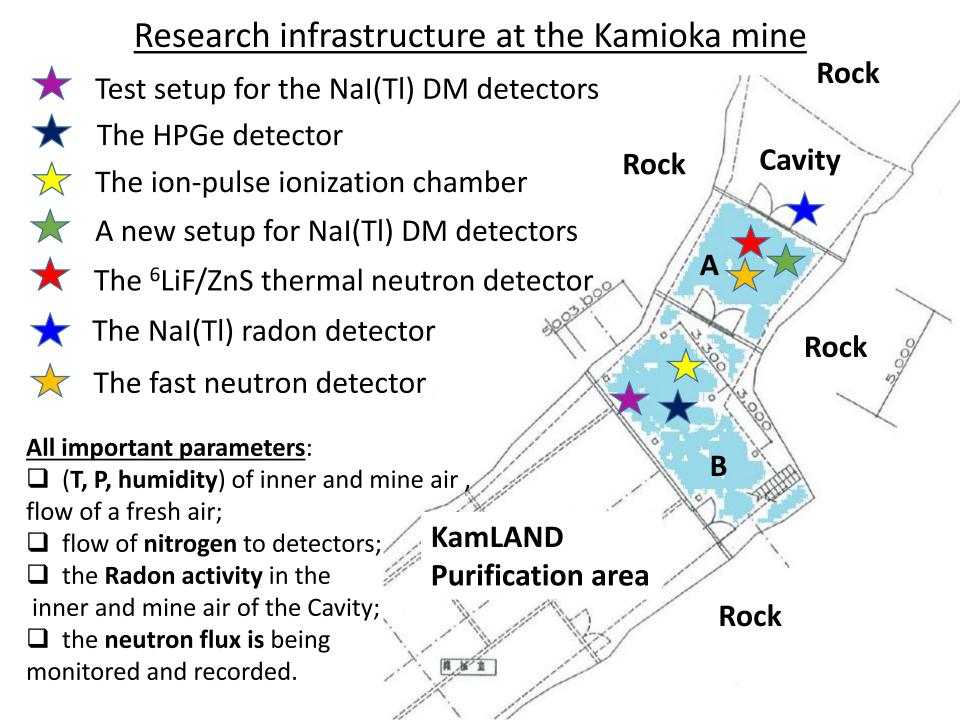


D. Chernyak (Tokyo U.)

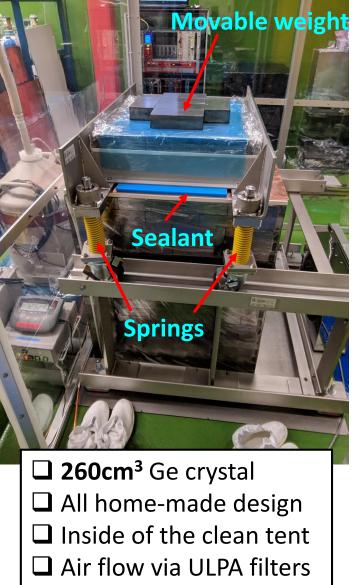
Y. Takemoto (Osaka U.)

- ☐ Gas-type detectors: Baksan Neutrino Observatory, Institute for Nuclear Research, Russian Academy of Science
- □ NaI(TI) Dark Matter detectors: I.S.C. Laboratory, Tokushima U., Osaka U., Osaka Sangyo U., Tohoku U.





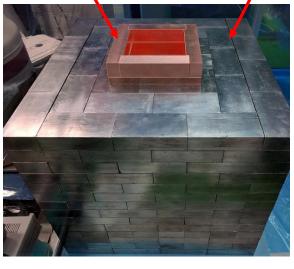
The HPGe detector

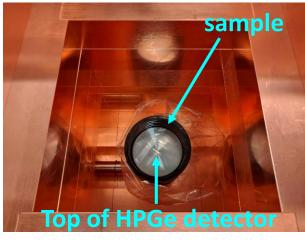


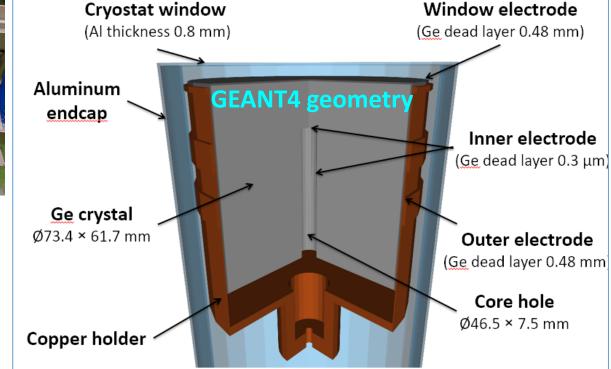
☐ 5.5L/min of N₂ via MFC

☐ Cu/Pb 15y underground

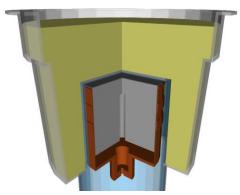
5cm-thick Cu 25cm-thick Pb (3 types of lead bricks)



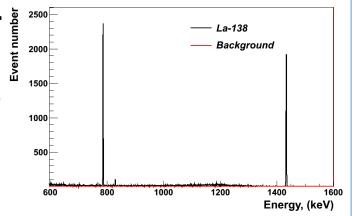




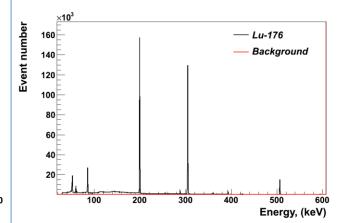
The HPGe detector calibration



Marinelli beakers (0.7, 1.2L) are used for loose and liquid samples



Natural Lanthanum contains 0.08881%71 of 138 La emitting γ -rays: 0.789MeV, 1.435 MeV and 36.4keV X-ray. We used 99.99% pure La_2O_3



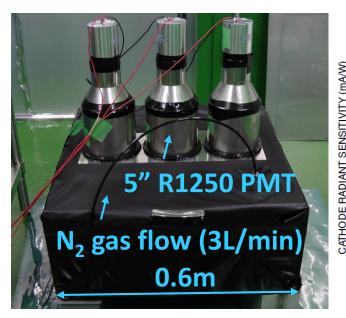
Natural Lutetium contains 2.599%13 of 176 Lu emitting γ -rays: 401keV, 306.8keV, 201.8keV, 88.3keV as well as 64.0keV and 55.1keV X-rays. We used 99.9% pure Lu₂O₃

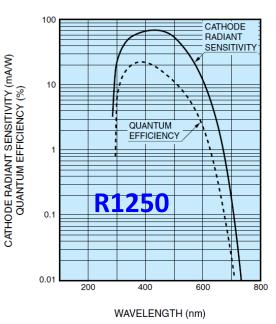


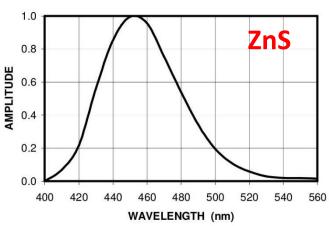
For every sample a realistic **GEANT4 model** is prepared to calculate the γ -ray detection efficiency

We made **extended sources with a small admixture of Lu and La** to verify correctness of the detector GEANT4 model based on the information provided by Canberra Corp.

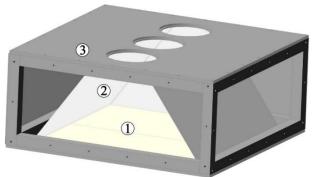
The ⁶LiF/ZnS thermal neutron detector







A very bright scintillator: 95000 photons/MeV

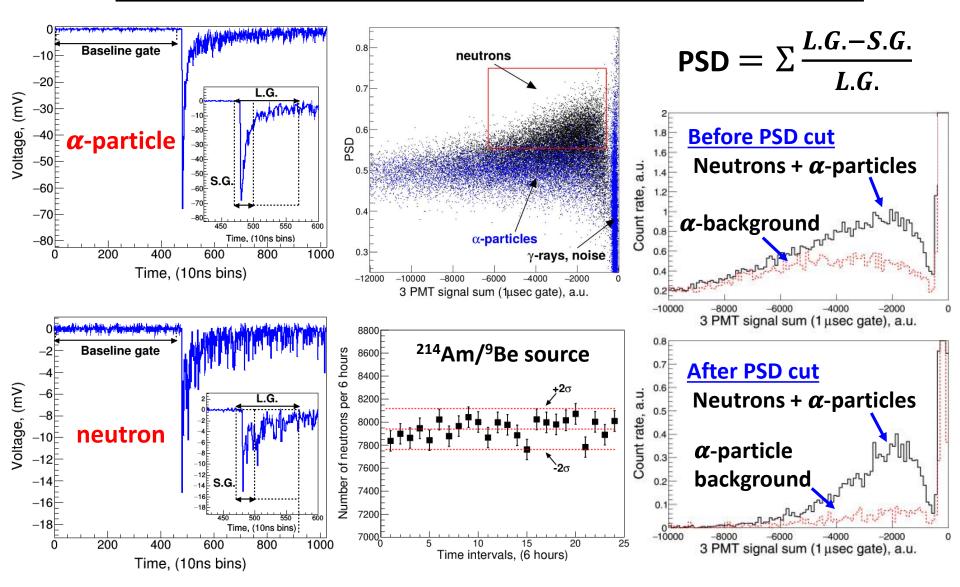


⁶Li + n → α + t + 4.78MeV (941b at 0.025eV)

- 1) The 6LiF/ZnS scintillator
- 2 A light reflector
- (3) An aluminium box

The detector is a thin sheet consisting of fine particles ($\sim \mu$ m) of ⁶LiF and ZnS:Ag dispersed in a colourless binder (95% of ⁶Li). Features: insensitive to γ -rays, 12.2 \pm 0.1 mBq of natural α -emitters (before PSD cut)

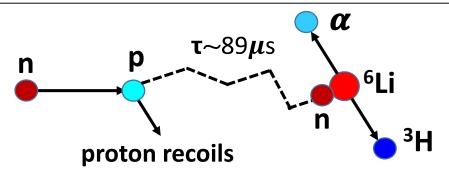
The ⁶LiF/ZnS thermal neutron detector



The thermal neutron flux at KamLAND: $(6.43 \pm 0.50) \times 10^{-6}$ n cm⁻² s⁻¹

The fast neutron detector

Recipe of the scintillator loaded with a water solution of LiBr was developed by H. Watanabe and Y. Shirahata (Tohoku U.)



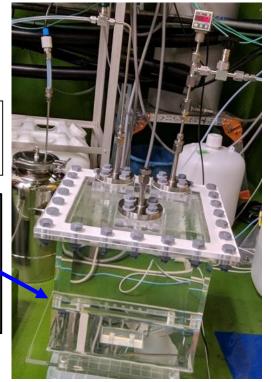
Detector tank filled with a 25 L of Li-LS sealed by N₂

Liquid scintillator (LS) loaded with nat. Lithium (**7.6% of** ⁶Li) LS composition: 820cc of **pseudocumene** + **PPO**(5.4g/L) **Surfactant** (TritonX-100) 180cc, **LiBr** • **H**₂**O** + **H**₂**O** 37g/L (the 140/50 mass ratio).

Photo-sensors: 4 Hamamatsu 5" R1250 PMTs (low K-40)

DAQ: CAEN DT5720 (4ch, 12bit, 250MS/s)

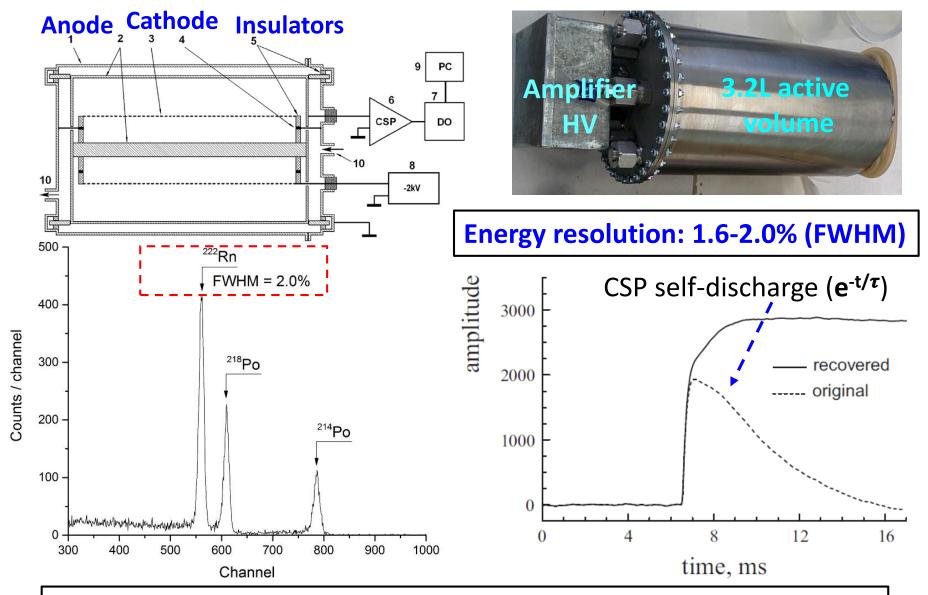
Shielding: 10cm of lead to reduce the γ -ray background Pulse-shape discrimination works for both prompt and delayed signals. A 94% γ -ray rejection for a 90% eff. cut on the delayed signal was achieved.





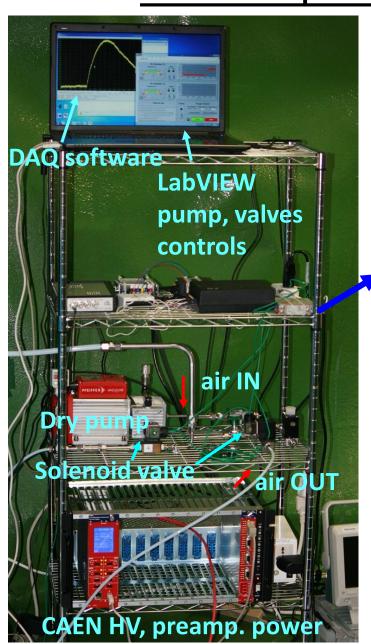
A magnetic stirrer was used to mix Li-loaded scintillator for 2-5 hours

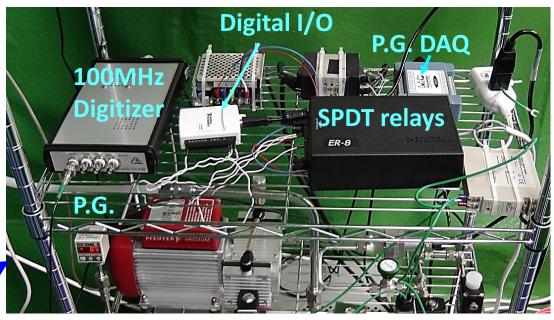
The ion-pulse ionization chamber

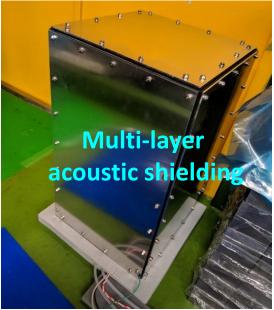


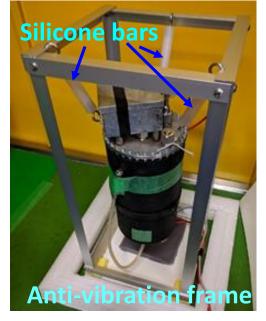
Allows direct detection of α -particles from the ²²²Rn decay in the air.

The ion-pulse ionization chamber









The NaI(TI) radon detector



Bottom layer: 15cm-thick lead

Walls: 10cm-thick double layer lead

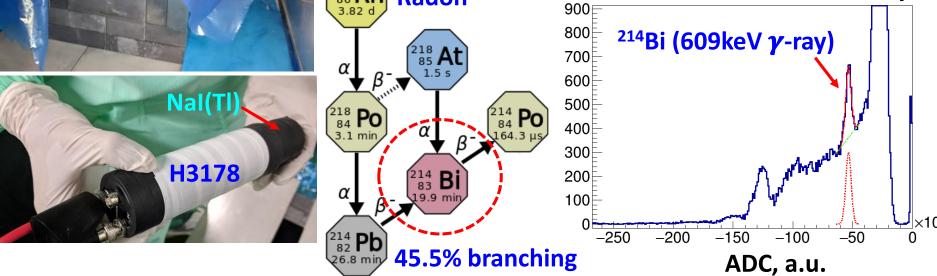
Inner layer: a high purity Pb (210Pb ~20Bq/kg)

Volume of the air inside shielding: 9.7L

The **609keV** γ -ray detection efficiency: **0.196%**

Events accumulated in 1 day

(calculated using the GEANT4 model)

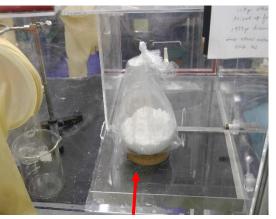


Radon

Nal(Tl) crystal + H3178 PMT directly connected to the DT5730 CAEN w-f digitizer (14-bit, 500 MS/s) is used to measure radon activity in the Cavity outside of the clean rooms. The ion-pulsed ionization chamber is difficult to use at that location due to a high radon activity (>1Bq/L) and relative humidity >94%.



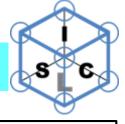




Purified Nal·2H₂0



I.S.C. laboratory



Purification techniques:

- ☐ re-crystallization from an ultrapure water solution
- ☐ Use of **sorbents** "tuned" to certain elements (e.g. Pb)

Steps used to minimize Radon daughters activity in Nal:

- ☐ Use of **specially produced NaI powder** in accordance with procedures developed by Horiba Corporation;
- Nal is handled in clean rooms and a glove box flushed with a pure nitrogen;
- ☐ Minimized exposure to air between purification steps;
- ☐ Use of **continuous nitrogen purge** during all stages of purification and drying process.

Radio-purity control techniques at Kamioka:

- ☐ HPGe measurements
- ☐ Direct measurements using the low background shielding

The NaI(TI) ingot production (Step 1)









Crucible:

- ☐ Material a coated, polished, **purified at a** high temperature vacuum oven graphite
- □ A new feature: a specially shaped bottom part
 − no need to use a seed to start crystal growth
- ☐ After cooling down NaI(TI) crystals are detached from the graphite crucible easily due to a factor 10 difference in the thermal expansion coefficients.

The NaI(TI) ingot production (Step 2)



Machine cutting



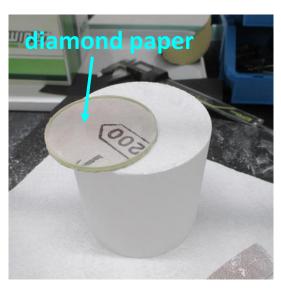
Humidity control



Samples for TI test



E. resolution test

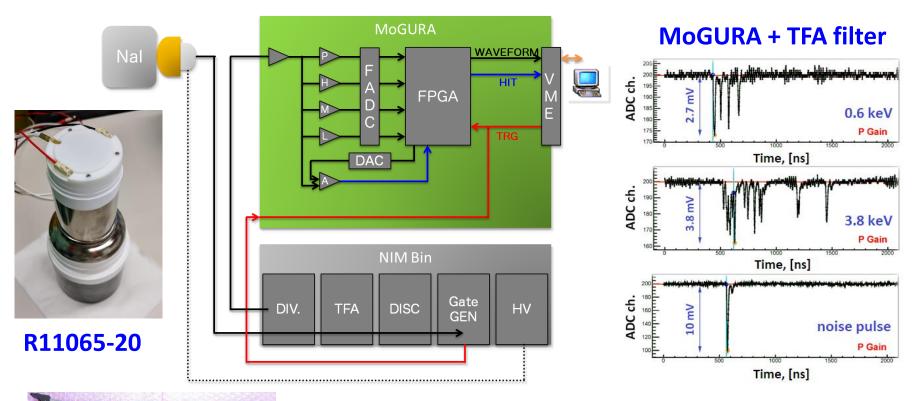


Abrasion



Final encapsulation

Test setup for the NaI(TI) DM detectors





- **12ch** boards ⇒ scalable system
- 0.1mV-10V (PHML gain channels) covers range from 1keV DM pulses to several MeV α -particles
- 1ns, 5ns sampling FADC
- Up to **10μs** waveform
- Analog/Digital discrimination

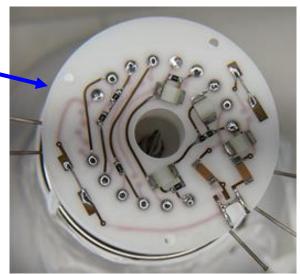
The R13444X 4-inch Hamamatsu PMT



A radio-pure

Polyimide PCB
but very fragile

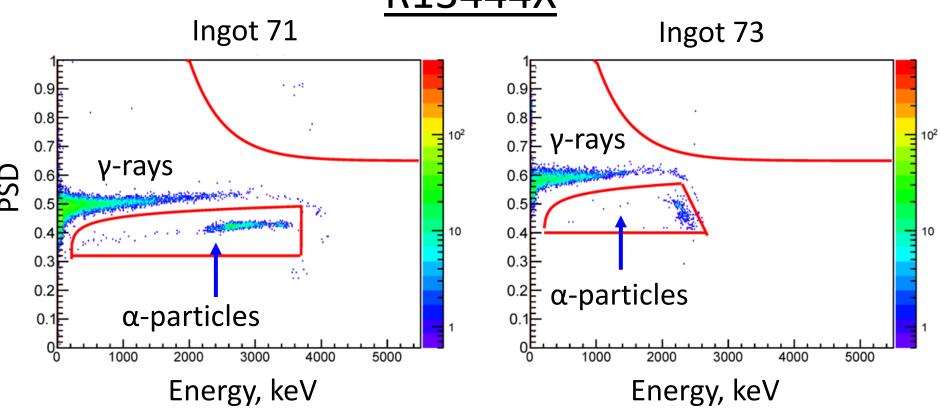




Voltage-divider components were selected at the HPGe detector. Solder is an alloy of a 99.9999% pure tin (Wako) and old lead (~5Bq/kg of ²¹⁰Pb).

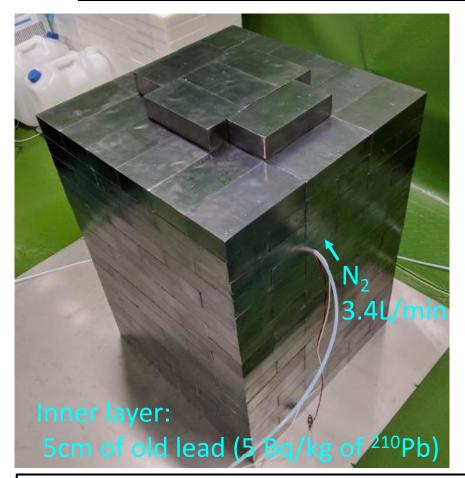
The **R13444X**: a metal (42% Ni, 57%Fe) body, a bialkali photocathode, optical window made of a synthetic silica. The spectral response we had chosen: 200-650nm. **QE@420nm** equal to **34.9%** and **33.38%** (ZK7879, ZK7880 units). ⁴⁰K (assuming it is in the 5N Al sealant): 55-14mBq, 24-7mBq at 90%CL ⁶⁰Co (assuming it is in the metal body): 7-1mBq, 7-4mBq at 90% CL

Background data for NaI(TI) crystals with R13444X



Two experimental R13444X PMTs to various degree demonstrate saturation effects even at a very low (1250V) voltage. The voltage dividers installed on these PMTs are identical and may need some tuning to improve linearity.

The new ultra-low background shielding

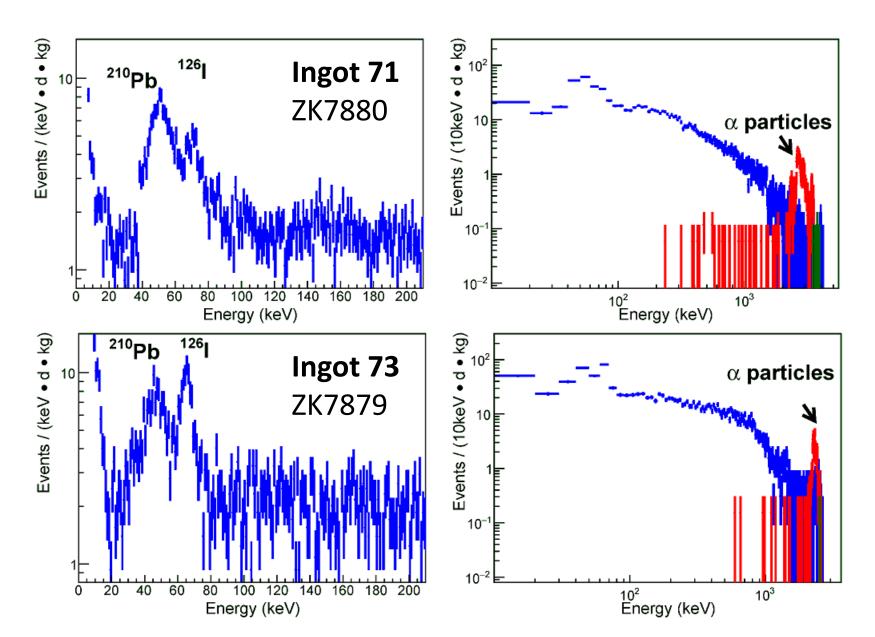




Cu bricks were cleaned in 4-steps: $(H_2SO_4+H_2O_2; C_6H_8O_7; H_2O; H_2O)$ to remove ²¹⁰Pb and other impurities; **18.2M** Ω ultra-pure water was used

We used a >99.99% pure copper from **Mitsubishi Materials** specially melted for us. 2 tons of freshly manufactured (**1.5 month or less old**) electroformed copper sheets were used to avoid ⁶⁰Co. After melting copper was cut into shielding bricks: (**50mm × 100mm × 200mm**).

Background for latest NaI(TI) detectors



Radio-purity of the NaI(TI) crystals

NaI(TI)/ Isotope	²³⁸ U, ppt	²³² Th, ppt	⁴⁰ K, ppb	²¹⁰ Pb, mBq
Ingot 71†	9.7 ± 0.8	0.96 ± 0.23	40*	1.29 ± 0.06
Ingot 73‡	2.2 ± 0.1	1.0 ± 0.6	12.5*	0.98 ± 0.05
DAMA det.	0.7 - 10	0.7 - 10	20	0.024

- † Purified by a 2-times re-crystallization from the water solution
- ‡ Purified by a 3-times re-crystallization from the water solution
- * Preliminary: contribution from the PMT needs verification

Still need: to find a stage where ²²²Rn contaminates the NaI material. Probably, need to make a closed system for NaI powder handling.

Summary

- We created underground clean-room laboratory for the DM research at the Kamioka mine.
- Our commercial partner constructed a new laboratory for production of the ultra-low background NaI(TI) crystals in Japan.
- We managed to produce NaI(TI) crystals with the radiopurity level similar to that achieved by the DAMA/LIBRA collaboration.
- We built several supplementary detectors to monitor most possible sources of the periodic background at the Kamioka mine.
- Currently, waiting for funding decision in April 2019.