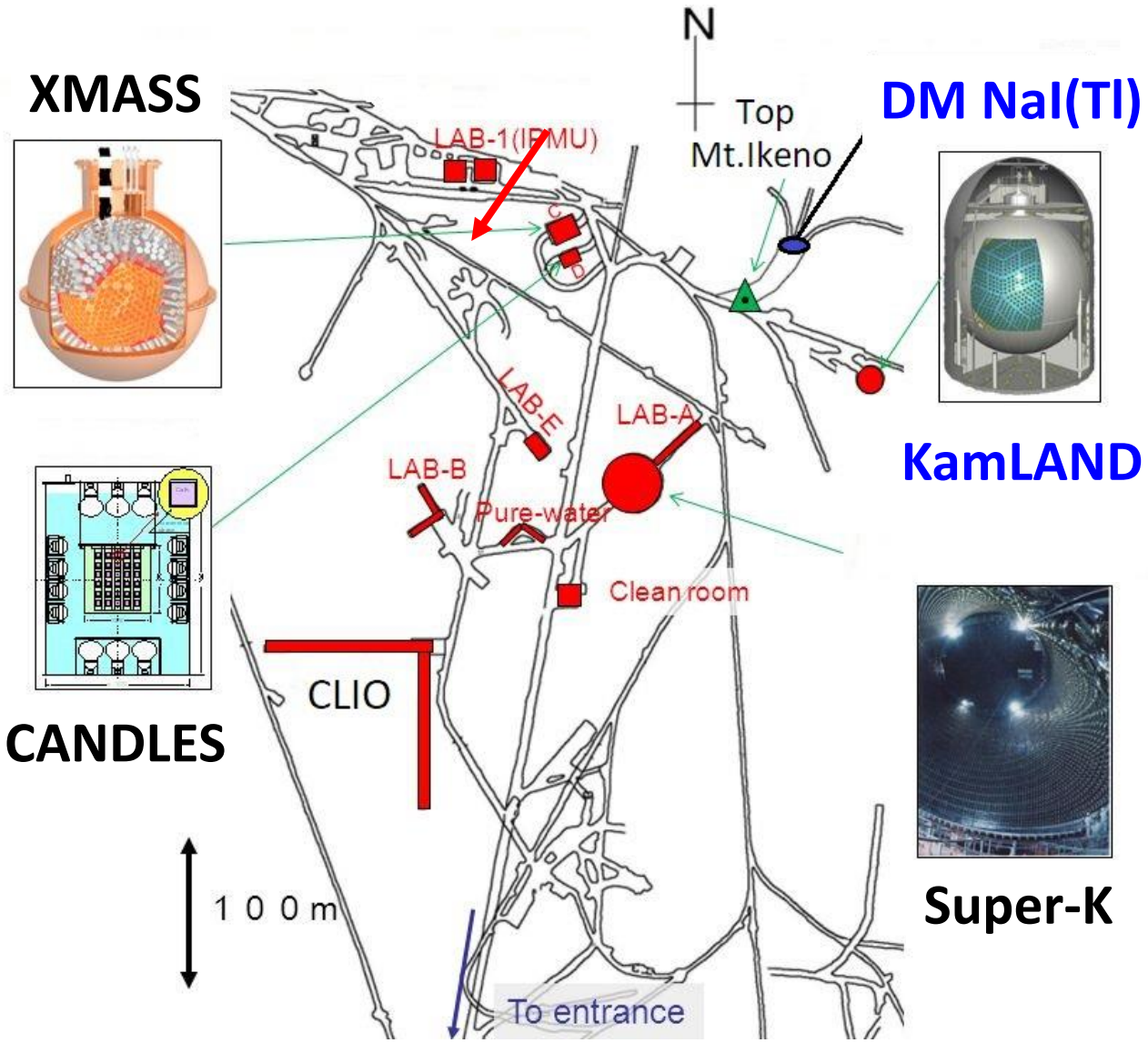
Status of direct Dark Matter search experiment at KamLAND

The University of Tokyo
Alexandre Kozlov

21 May, 2019, LRT 2019

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(Tl) Dark Matter detectors:** I.S.C. Laboratory, Tokushima U., Osaka U., Osaka Sangyo U., Tohoku U.

Two clean rooms (A, B) for the DM research.

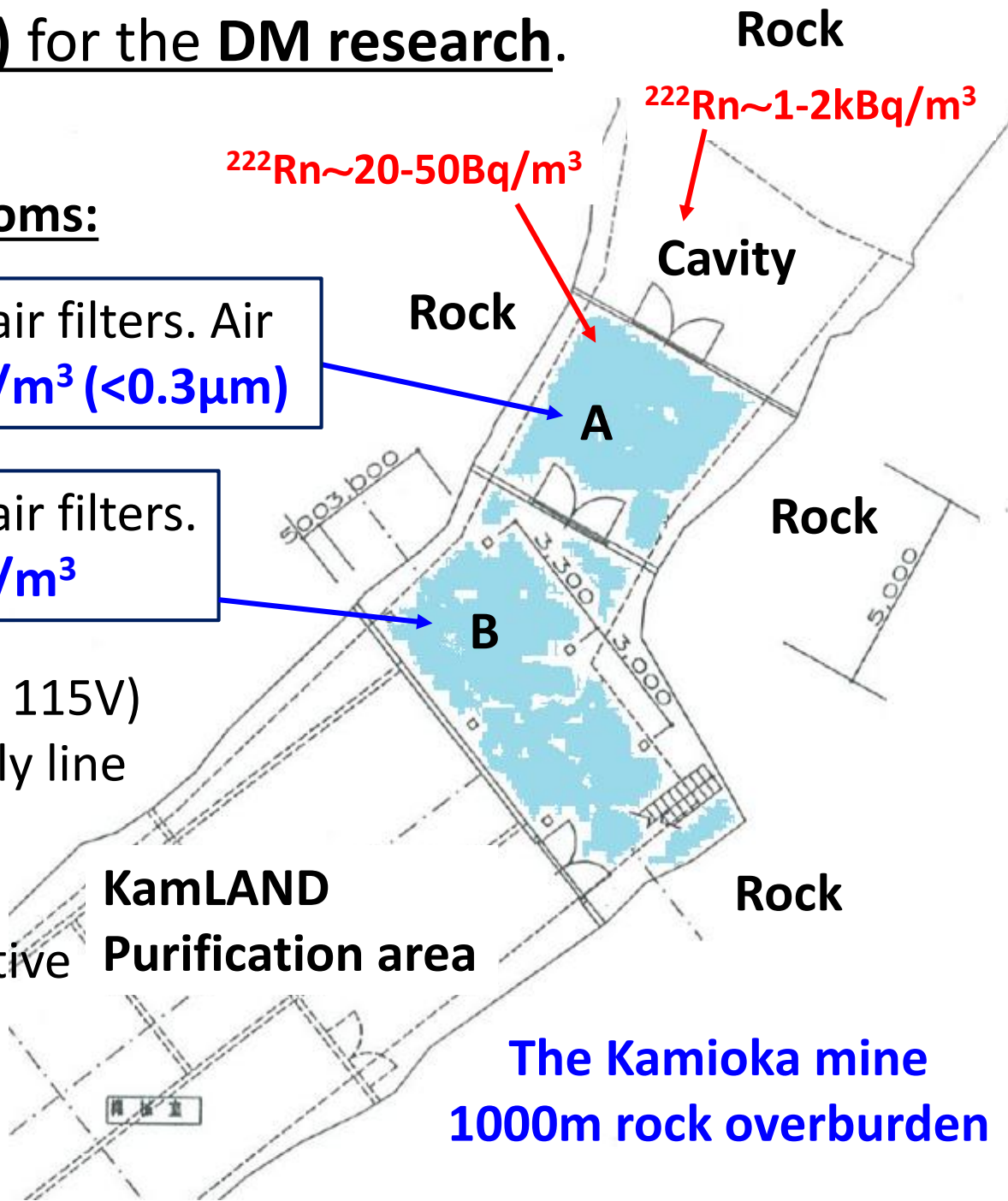
Conditions at the clean rooms:

Room A: 70m^3/min ULPA air filters. Air quality: **100-300 particles/m^3 (<0.3μm)**

Room B: 70m^3/min HEPA air filters. Air quality: **2000 particles/m^3**

- 17kWatt AVR unit (100V, 115V)
- Boiled off Nitrogen supply line
- Radon-less air supply:

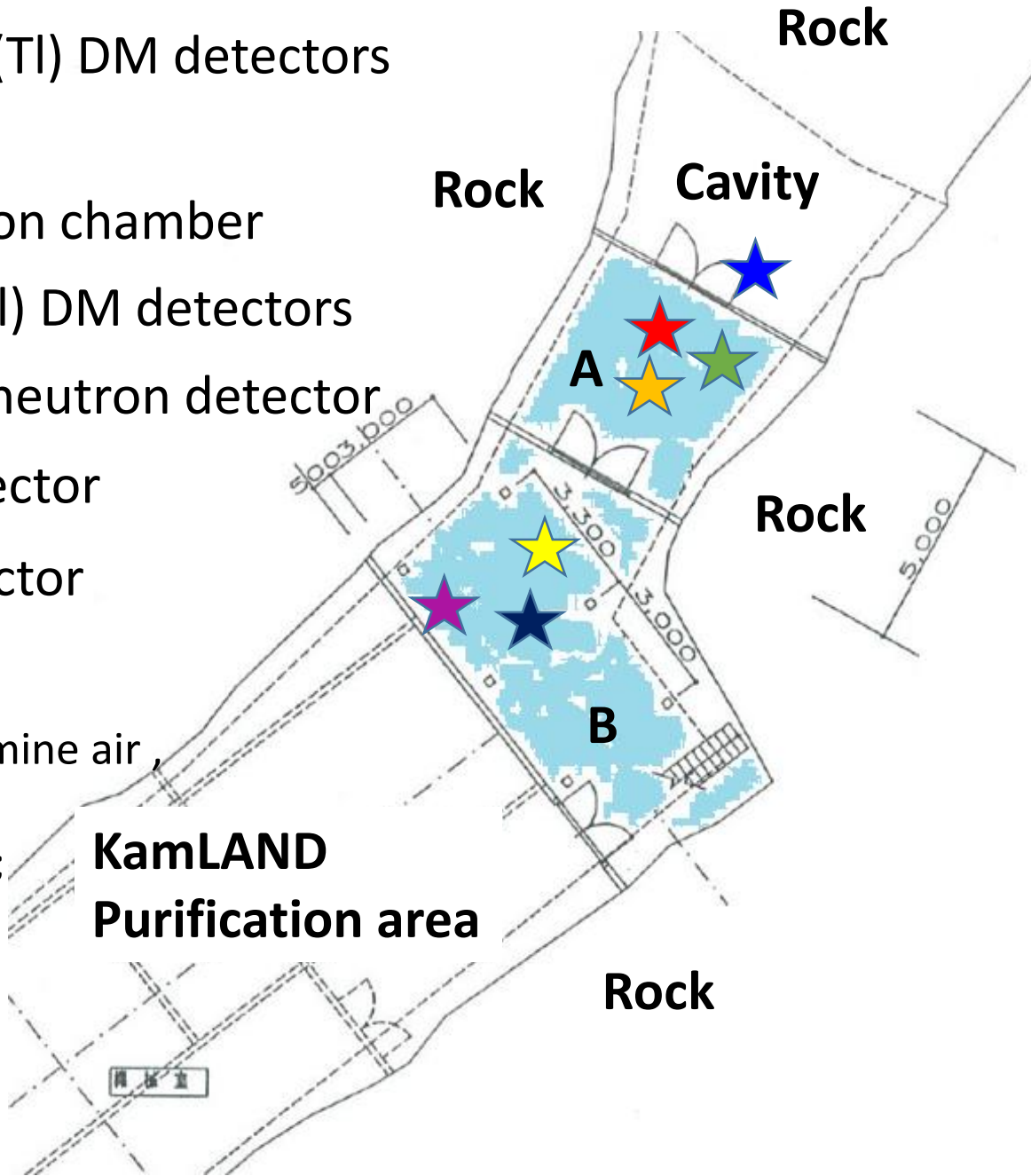
(5-10m^3 per hour) creates **a positive air pressure** relative to neighbour rooms.



The Kamioka mine
1000m rock overburden

Research infrastructure at the Kamioka mine

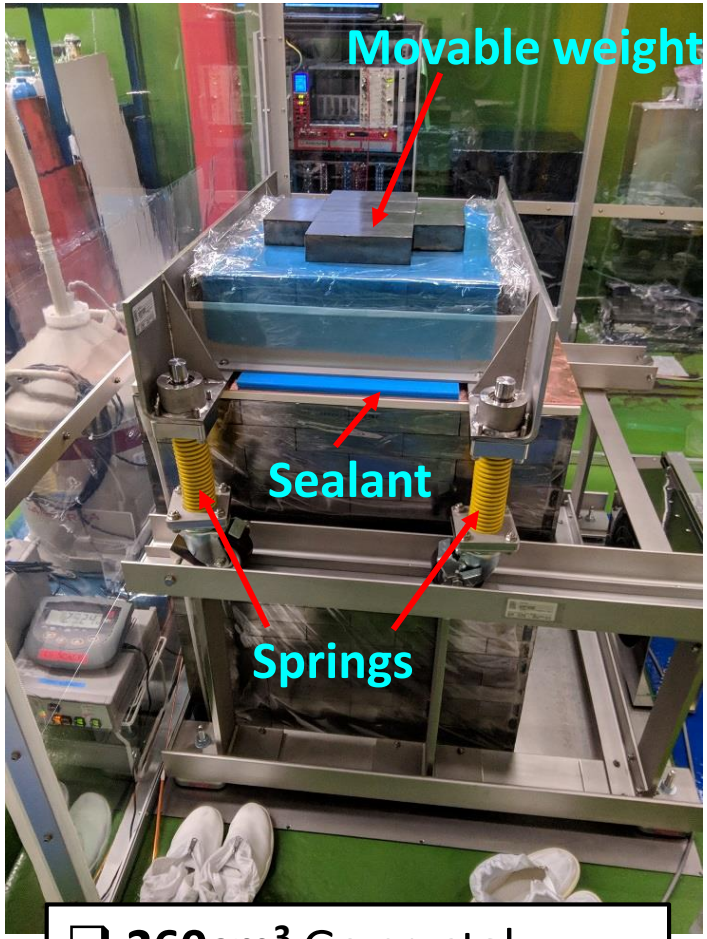
- Test setup for the NaI(Tl) DM detectors
- The HPGe detector
- The ion-pulse ionization chamber
- A new setup for NaI(Tl) DM detectors
- The ^{6}LiF/ZnS thermal neutron detector
- The NaI(Tl) radon detector
- The fast neutron detector



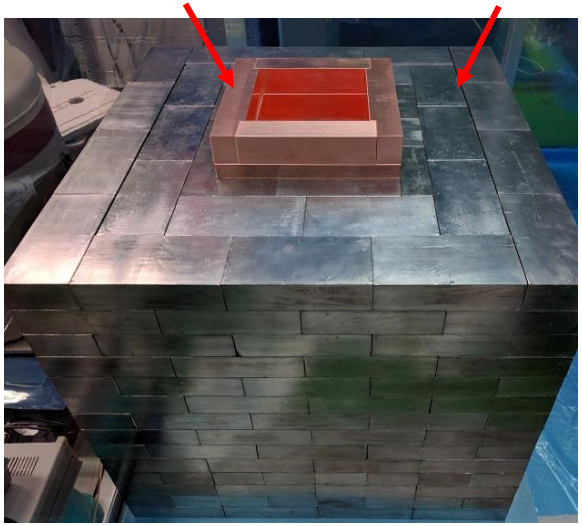
<u>All important parameters</u>:

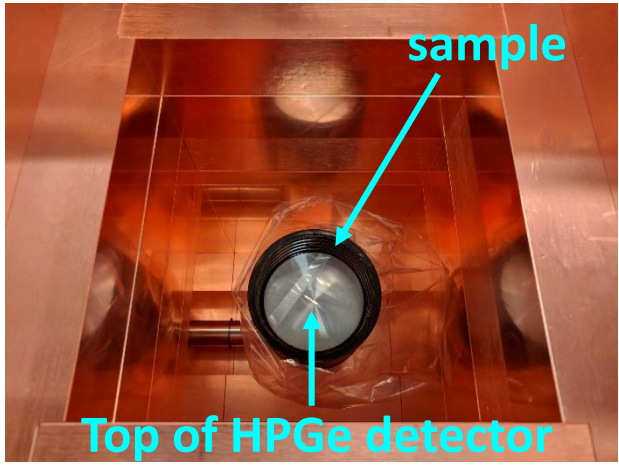
- ❑ (**T, P, humidity**) of inner and mine air , flow of a fresh air;
- ❑ flow of **nitrogen** to detectors;
- ❑ the **Radon activity** in the inner and mine air of the Cavity;
- ❑ the **neutron flux is** being monitored and recorded.

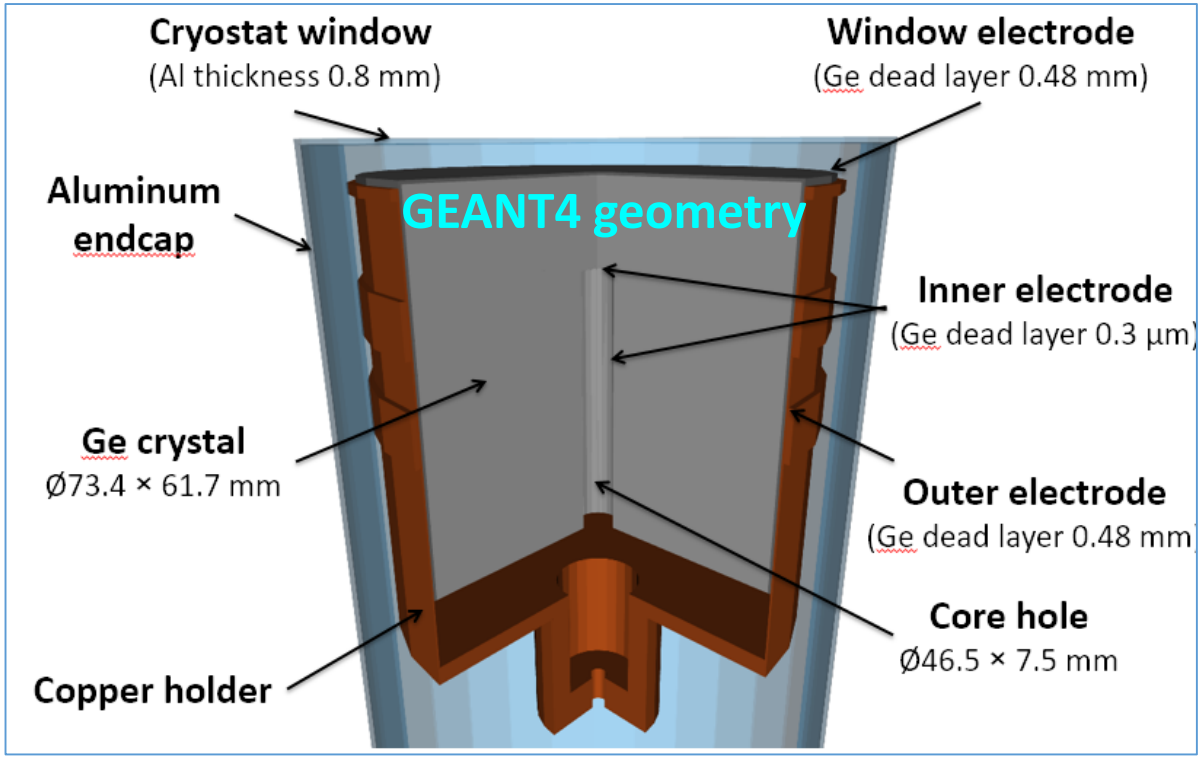
The HPGe detector



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

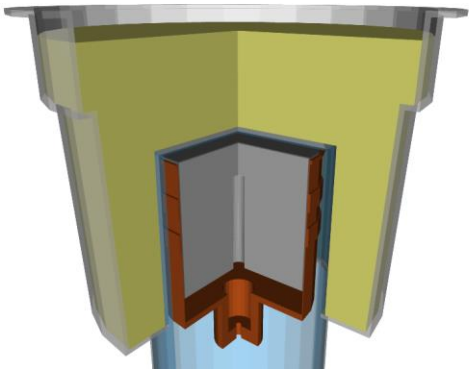


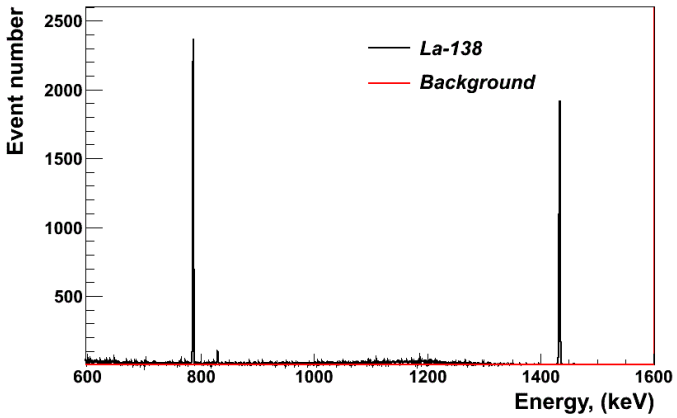


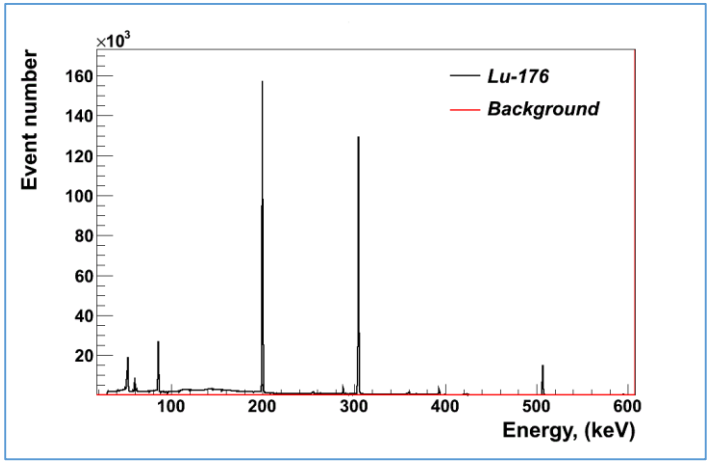


- ❑ **260cm³** Ge crystal
- ❑ All home-made design
- ❑ Inside of the clean tent
- ❑ Air flow via ULPA filters
- ❑ **5.5L/min of N_2** via MFC
- ❑ **Cu/Pb** 15y underground

The HPGe detector calibration



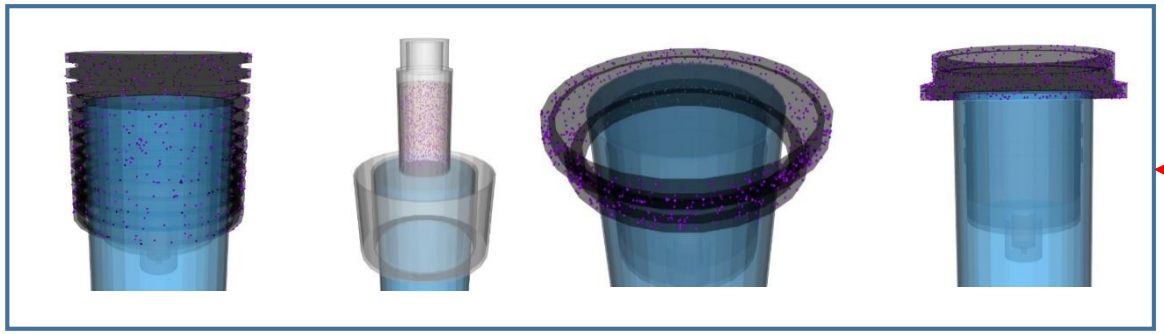




Marinelli beakers (0.7, 1.2L) are used for loose and liquid samples

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 Lu_2O_3**



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.

Online database for measured samples

Sample's Summary

Photo of the sample

RI Summary

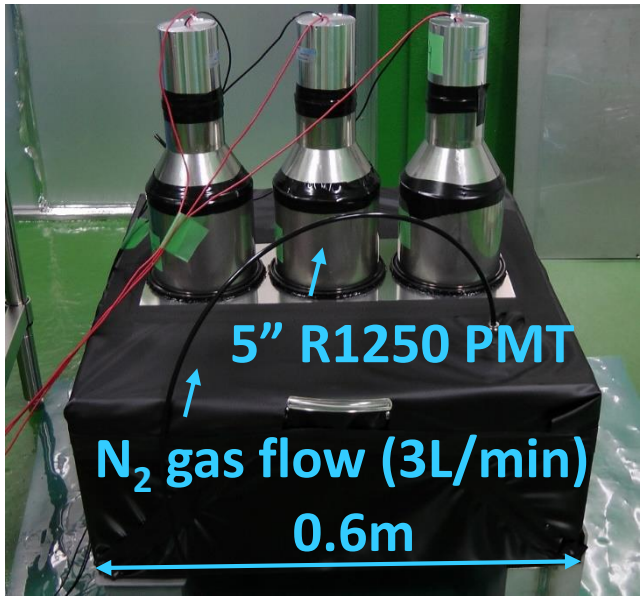
69	**Provider:** A.Kozlov **Experiment:** KamLAND2 **Material:** Activated carbon (powder) Kanto Chemical Co. Catalog 08304-08 for liquid scintillator purification **Chemical formula:** C **Dimensions:** Fully-filled L-size container **Mass:** 491 g **Density:** 0.4 g/cm^3 **Date of assembling:** 26/07/2017 **Data live time:** 72349.90 s	  G4_ID_069		ID_069

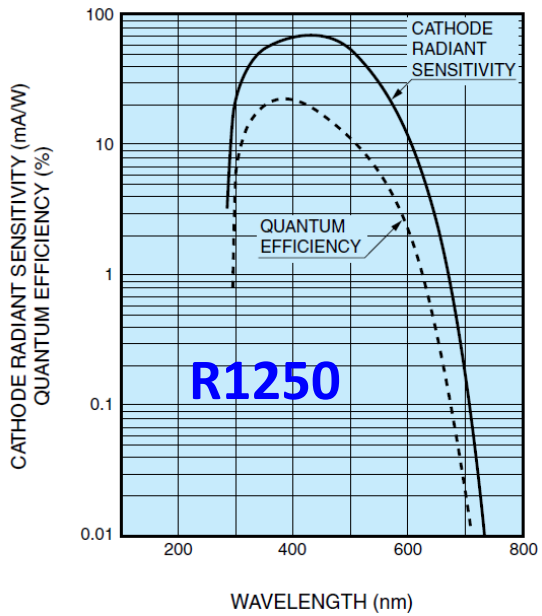
GEANT4 model's geometry

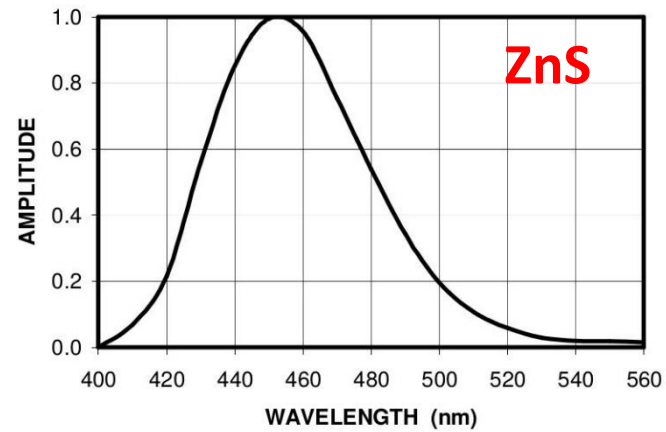
Table with GEANT4 γ-ray det. efficiency

Measured spectra (Click to magnify)

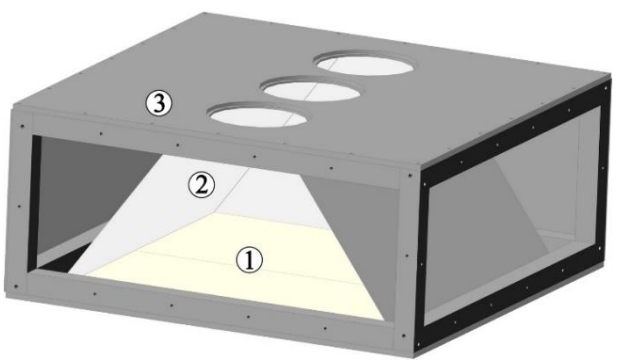
The ^{6}LiF/ZnS thermal neutron detector







A very bright scintillator:
95000 photons/MeV

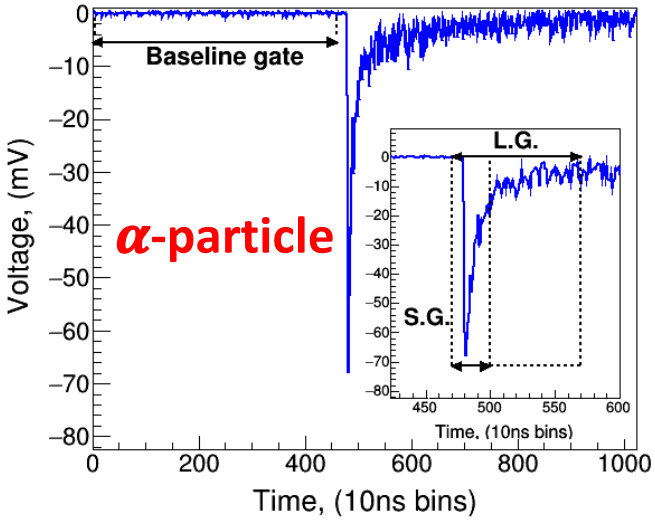


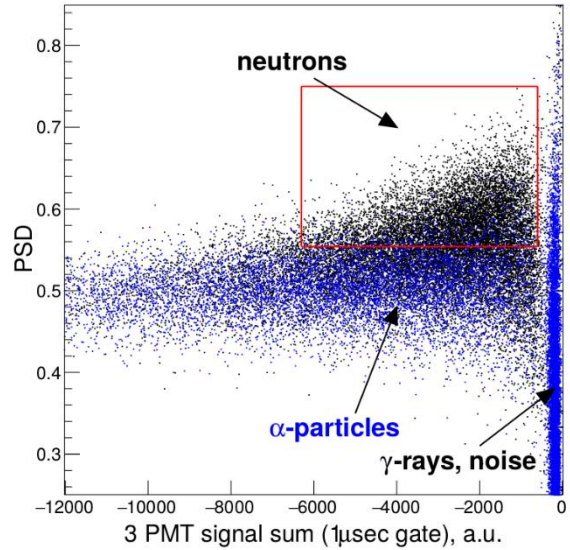
^{6}Li + n ⟶ α + t + 4.78MeV (941b at 0.025eV)

① **The ^{6}LiF/ZnS scintillator**
② **A light reflector**
③ **An aluminium box**

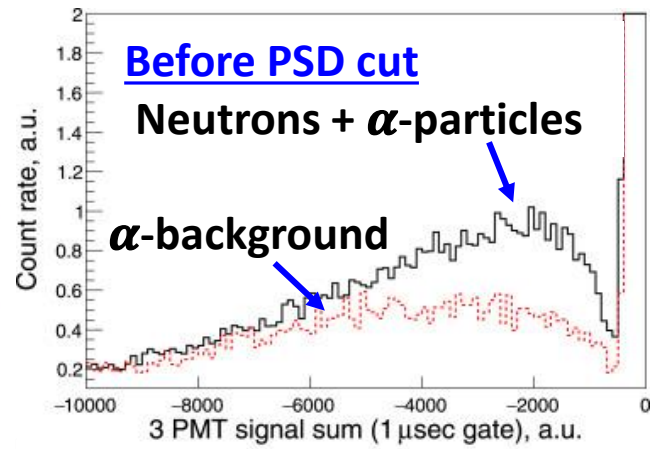
The detector is a thin sheet consisting of fine particles (~μm) of **^{6}LiF** and **ZnS:Ag** dispersed in a colourless binder (95% of **^{6}Li**). Features: insensitive to γ–rays, **12.2±0.1 mBq** of **natural α-emitters** (before PSD cut)

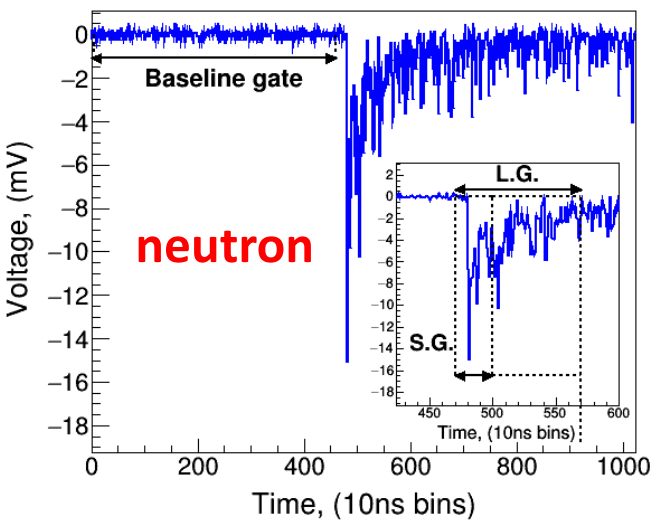
The ^{6}LiF/ZnS thermal neutron detector

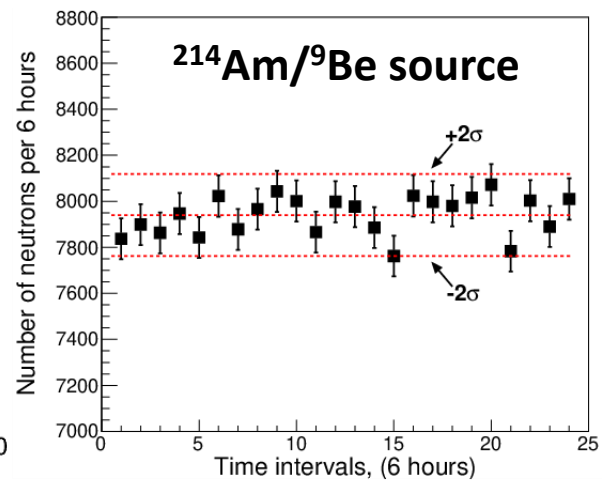


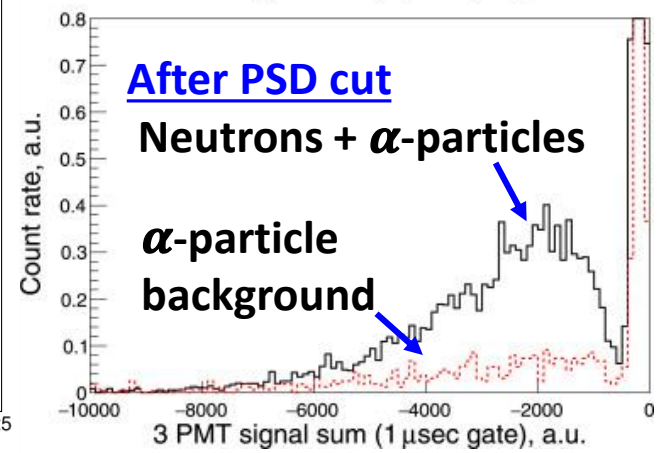


$$\mathbf{PSD} = \sum \frac{L.G. - S.G.}{L.G.}$$





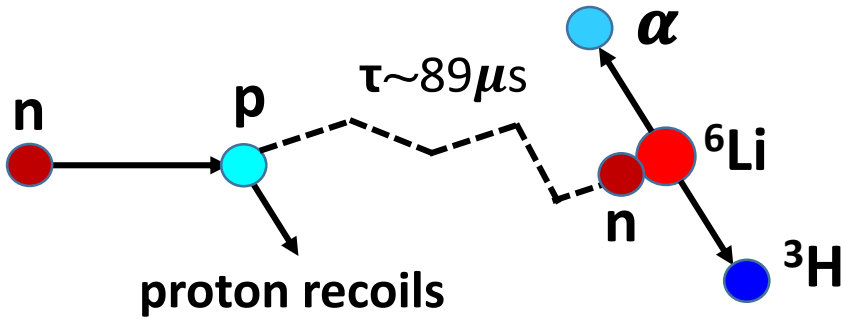




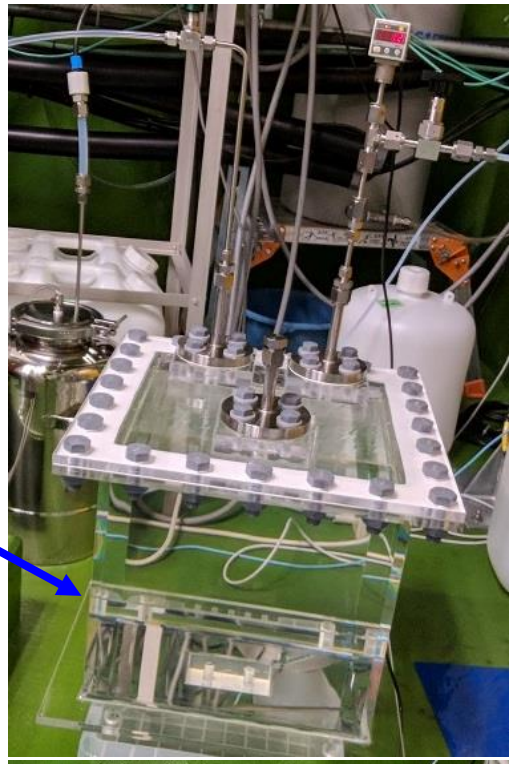
The thermal neutron flux at KamLAND: $(6.43 \pm 0.50)\times10^{-6}$ n cm^{-2} s^{-1}

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.)



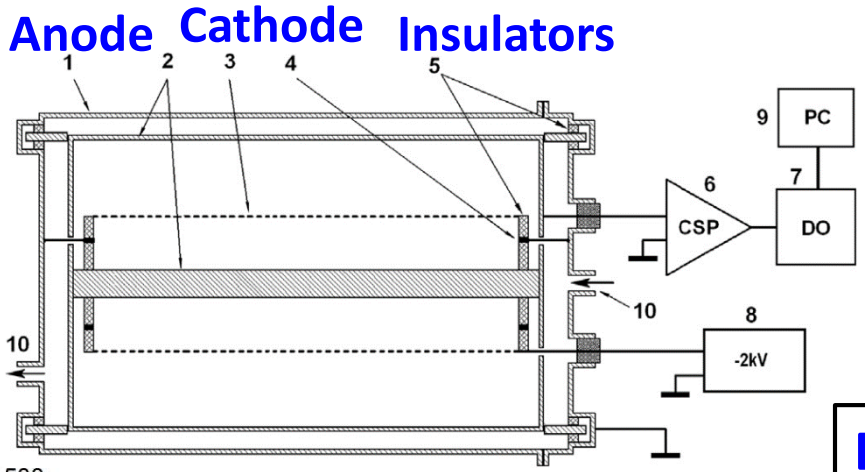
Detector tank filled with a 25 L of Li-LS sealed by N_2

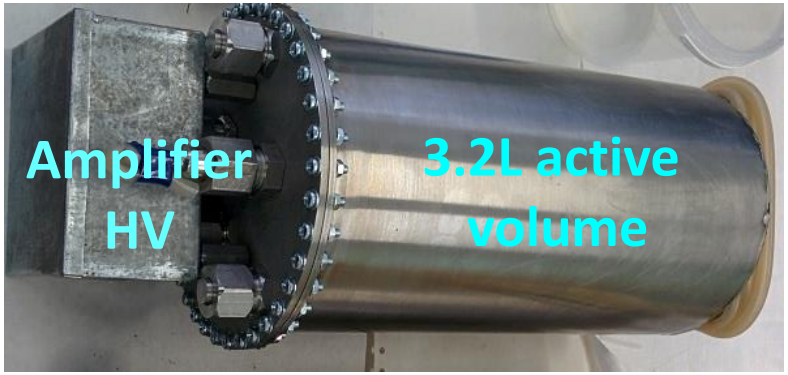


Liquid scintillator (LS) loaded with nat. Lithium (**7.6% of ^{6}Li**)
LS composition: 820cc of **pseudocumene** + **PPO**(5.4g/L)
Surfactant (TritonX-100) 180cc, **LiBr・H_2O + H_2O** 37g/L (the 140/50 mass ratio).

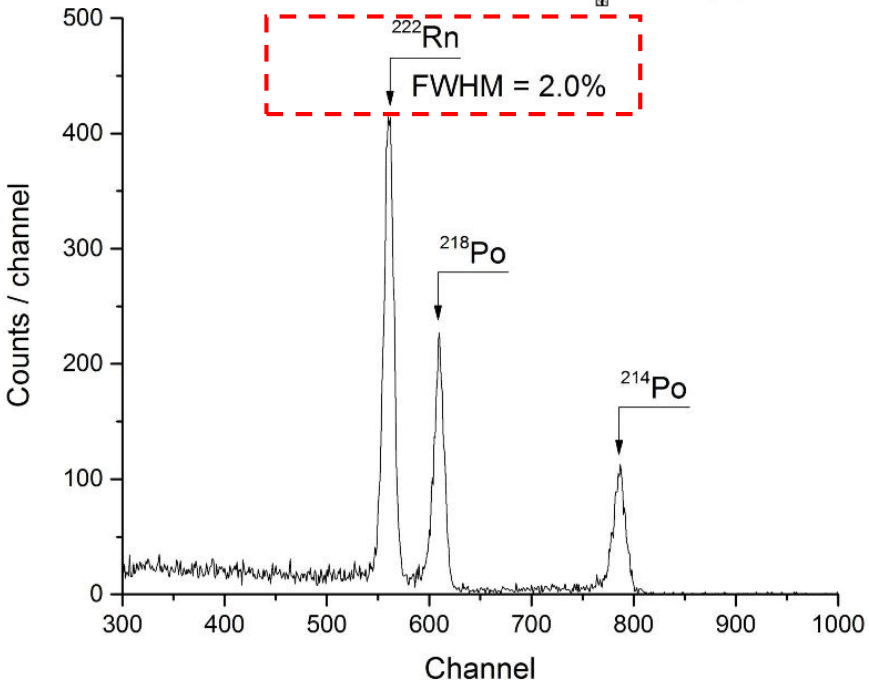
Photo-sensors: **4 Hamamatsu 5" R1250 PMTs** (low K-40)
DAQ: **CAEN DT5720** (4ch, 12bit, 250MS/s)
Shielding: **10cm of lead** to reduce the **γ-ray background**
Pulse-shape discrimination works for both prompt and delayed signals. A **94% γ-ray rejection** for a 90% eff. cut on the delayed signal was achieved.

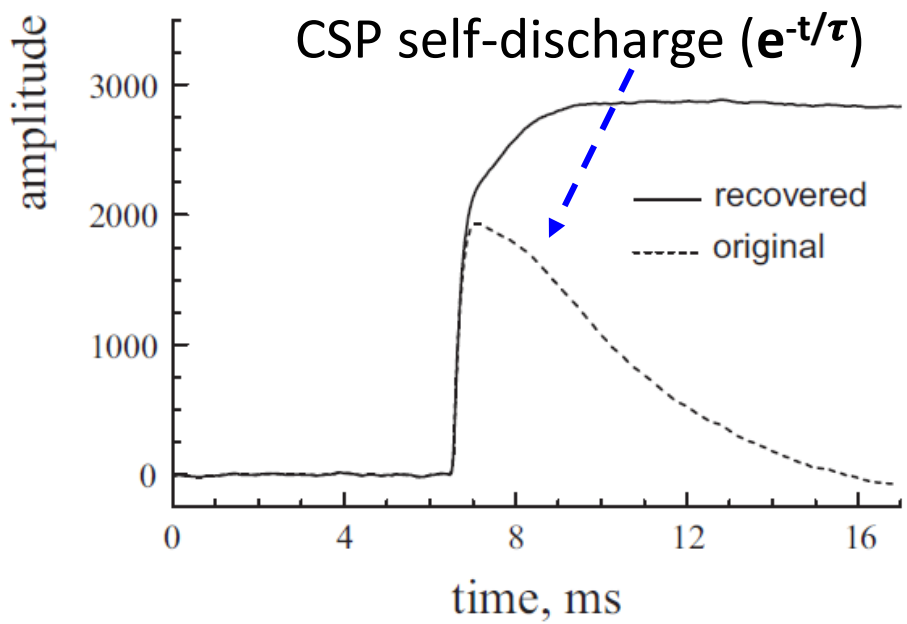
The ion-pulse ionization chamber





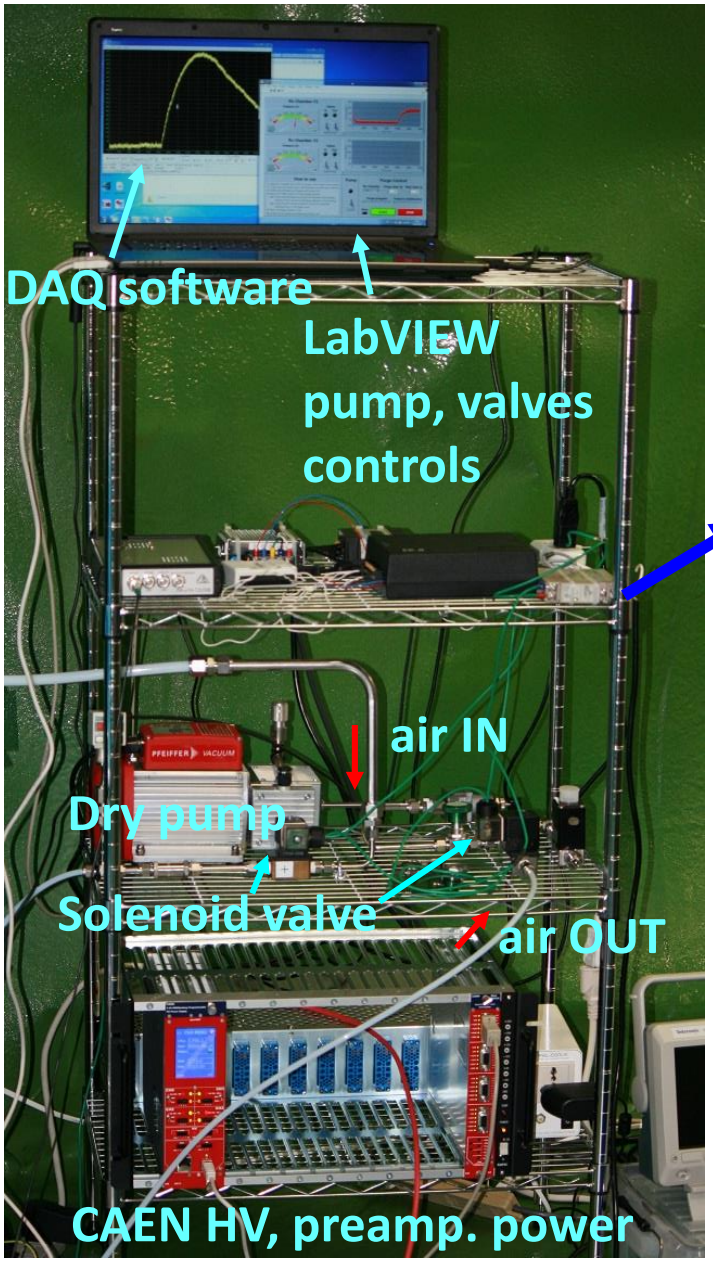
Energy resolution: 1.6-2.0% (FWHM)

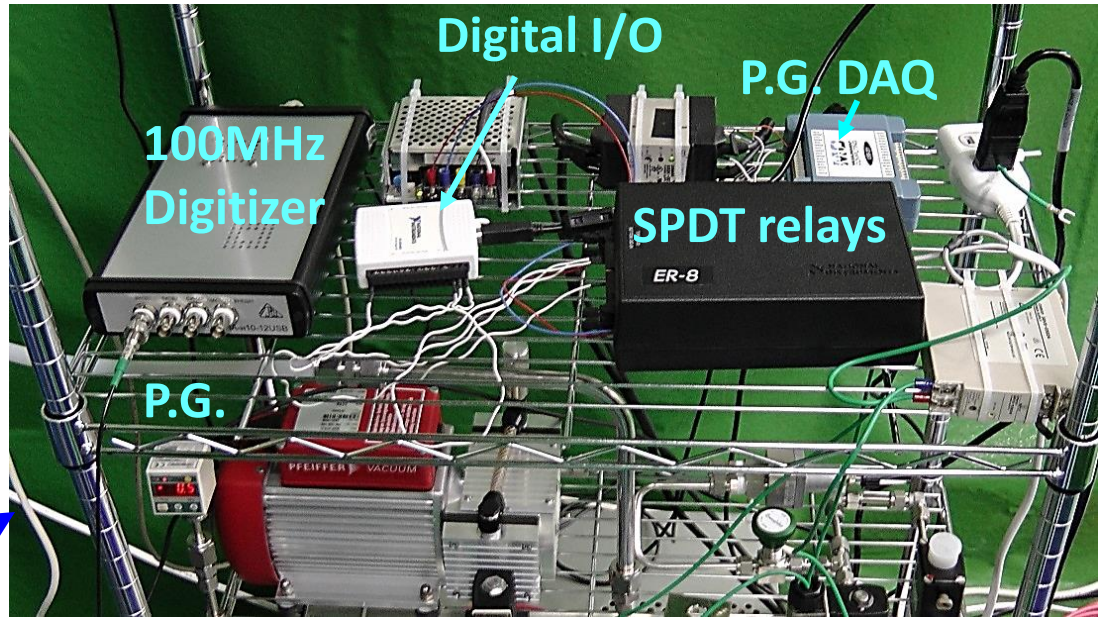


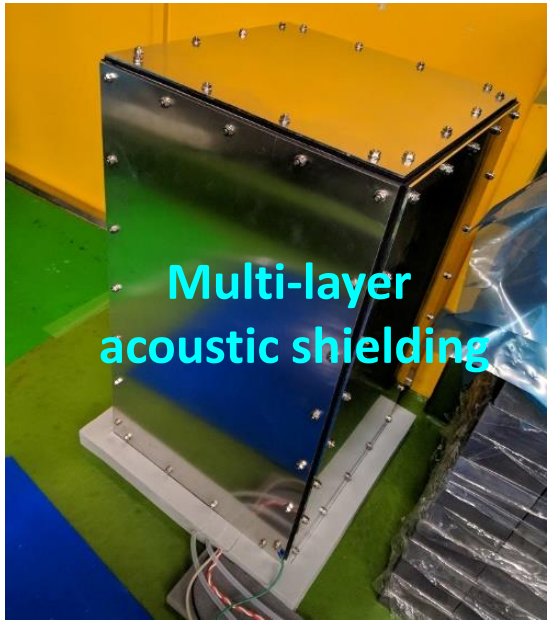


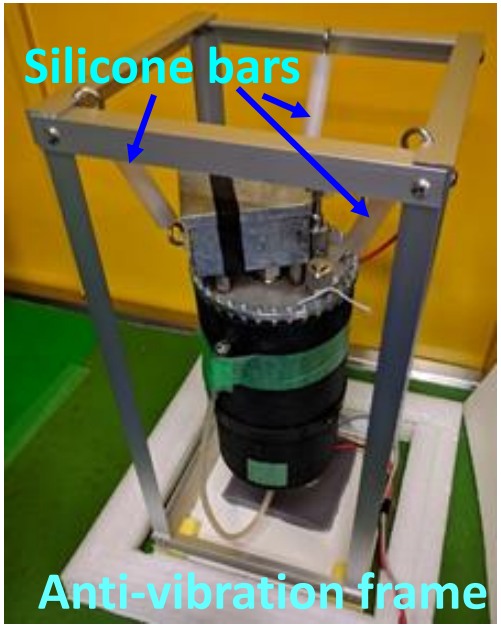
Allows direct detection of α–particles from the **^{222}Rn decay in the air**.

The ion-pulse ionization chamber

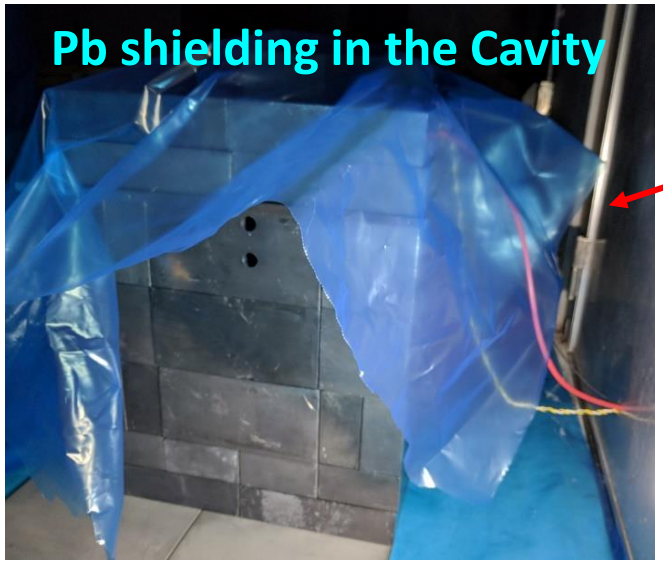




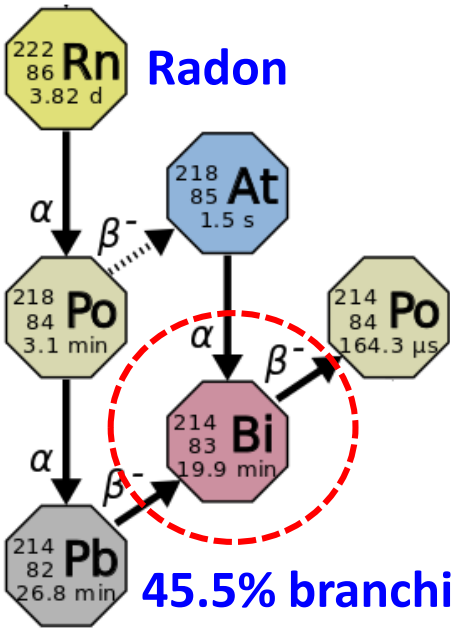


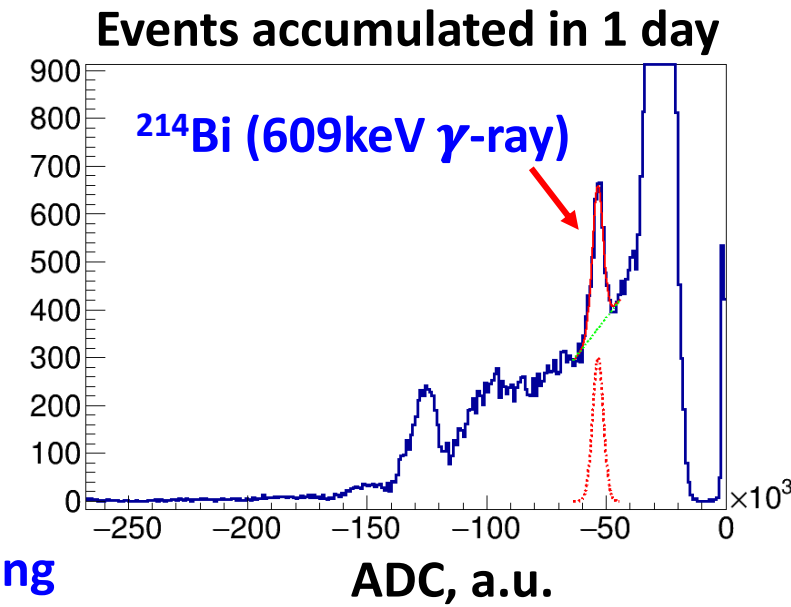


The NaI(Tl) radon detector



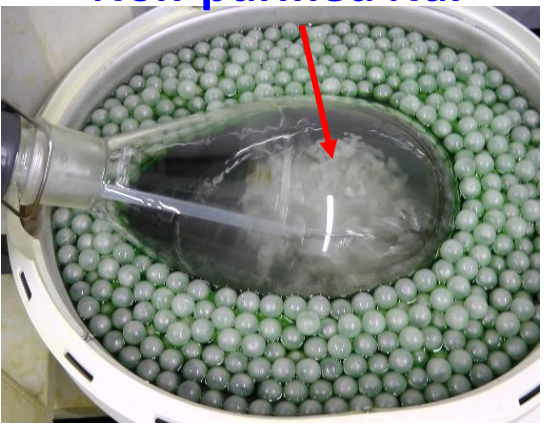
Bottom layer: **15cm-thick lead**
Walls: **10cm-thick double layer lead**
Inner layer: a high purity Pb (**^{210}Pb ~20Bq/kg**)
Volume of the air inside shielding: **9.7L**
The **609keV γ–ray** detection efficiency: **0.196%**
(calculated using the GEANT4 model)

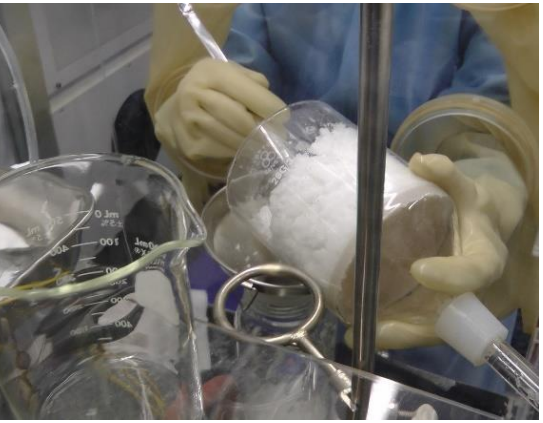


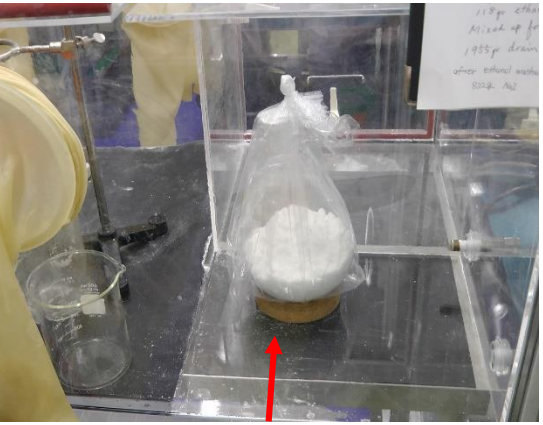


NaI(Tl) crystal + H3178 PMT directly connected to the **DT5730 CAEN w-f digitizer** (14-bit, 500 MS/s) is used to measure radon activity in the Cavity outside of the clean rooms. The ion-pulsed ionization chamber is difficult to use at that location due to a high radon activity (>1Bq/L) and relative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

Non-purified NaI







Purified NaI·2$H_2$0

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 NaI:

- ❑ Use of **specially produced NaI powder** in accordance with procedures developed by Horiba Corporation;
- ❑ NaI 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

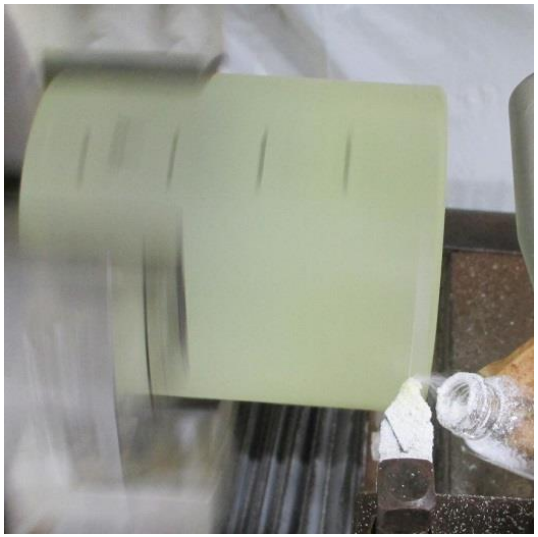
The NaI(Tl) ingot production (Step 1)

Crucible:

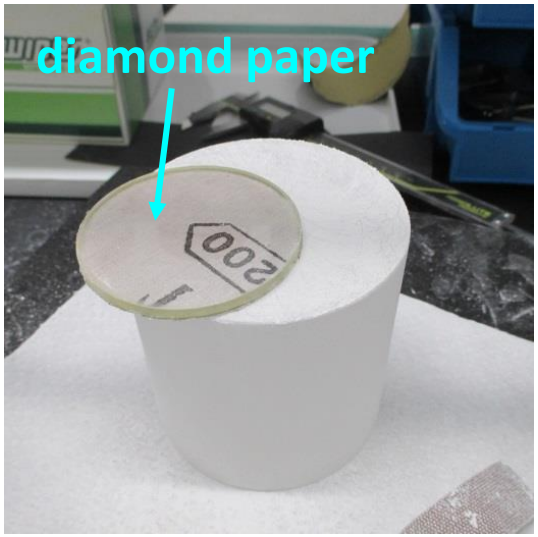
- Material – a coated, polished, **purified at a high temperature vacuum oven graphite**
- A new feature: a specially shaped bottom part – **no need to use a seed** to start crystal growth
- After cooling down NaI(Tl) crystals are **detached from the graphite crucible easily** due to a factor 10 **difference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

The NaI(Tl) ingot production (Step 2)

Machine cutting

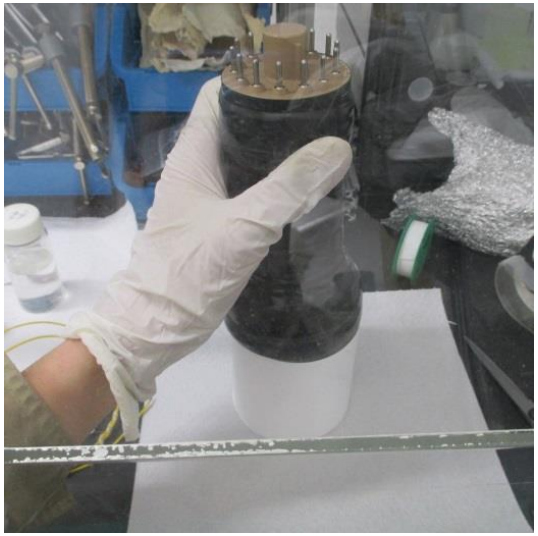


Samples for Tl test



Abrasion

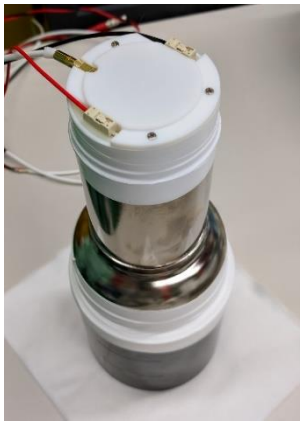
Humidity control



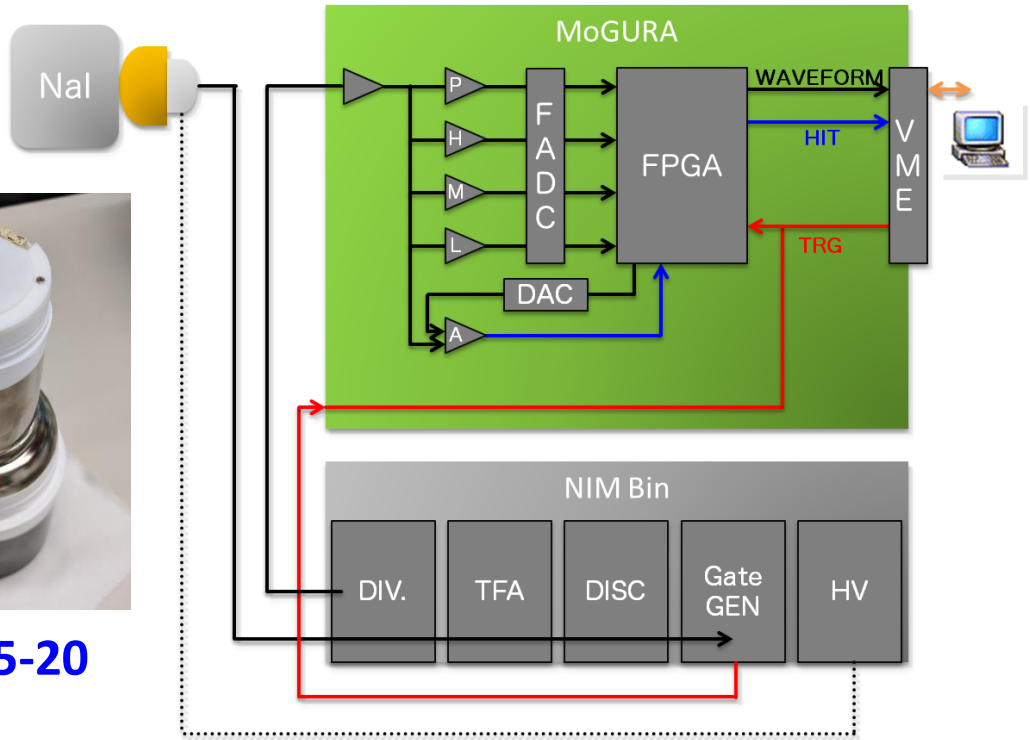
E. resolution test

Final encapsulation

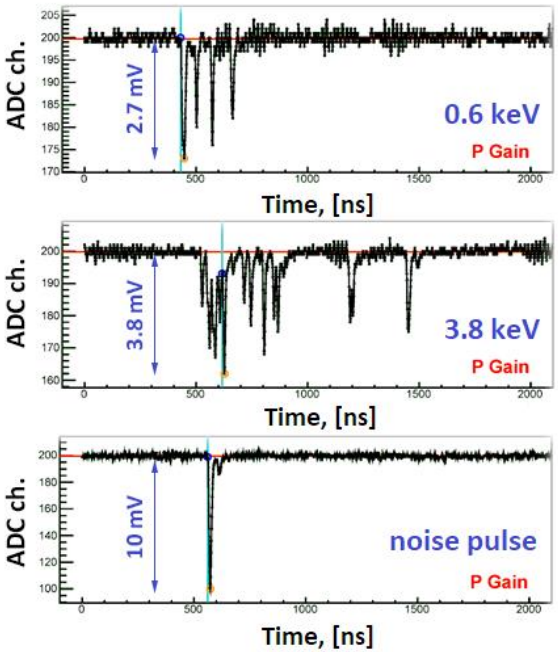
Test setup for the NaI(Tl) DM detectors



R11065-20

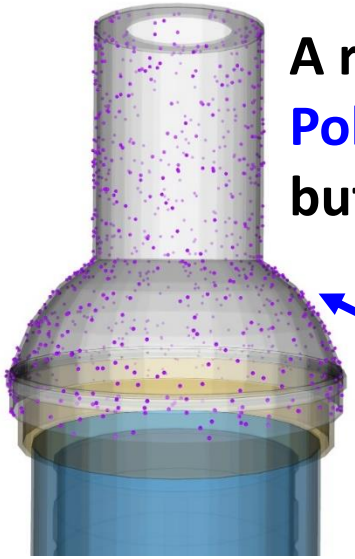


MoGURA + TFA filter



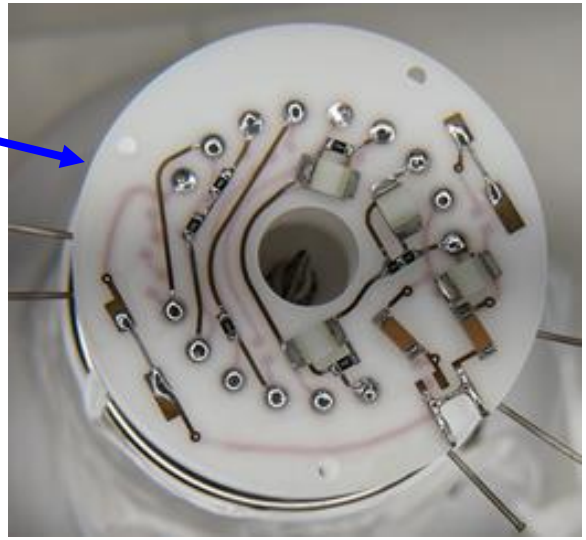
- **12ch** boards ⇒ scalable system
- **0.1mV-10V** (PHML gain channels) covers range from **1keV DM pulses** to **several MeV α-particles**
- **1ns, 5ns** sampling **FADC**
- Up to **10μs** waveform
- Analog/Digital discrimination

The R13444X 4-inch Hamamatsu PMT



A radio-pure Polyimide PCB but very fragile

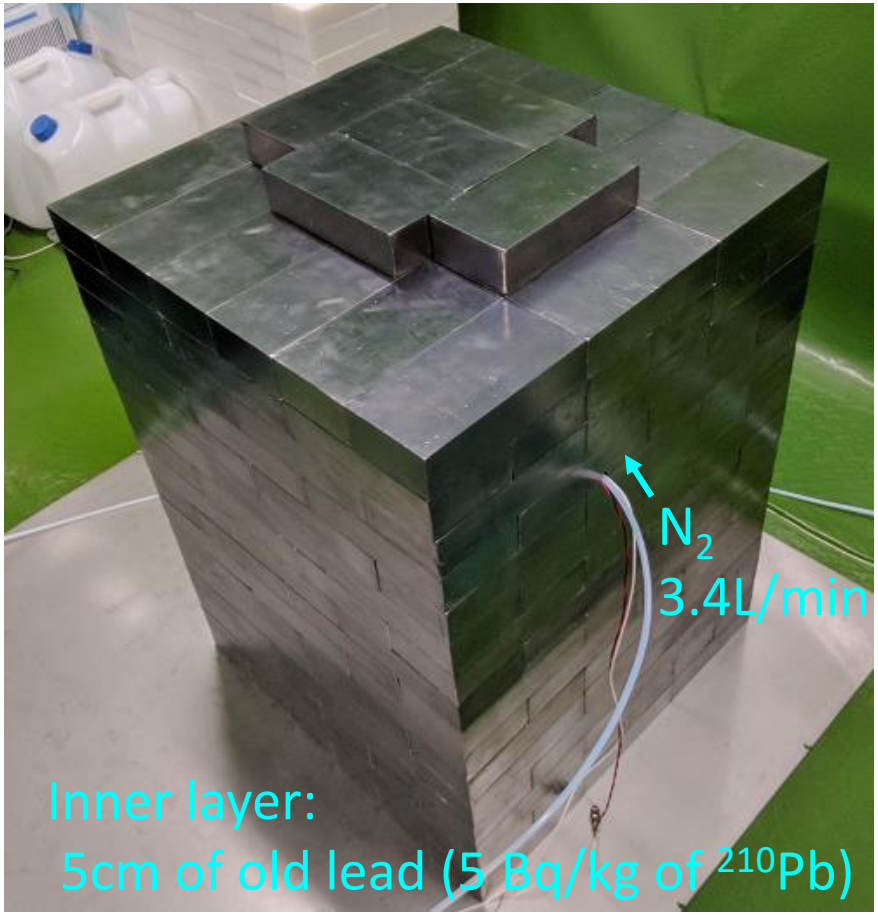
Simplified GEANT4 model

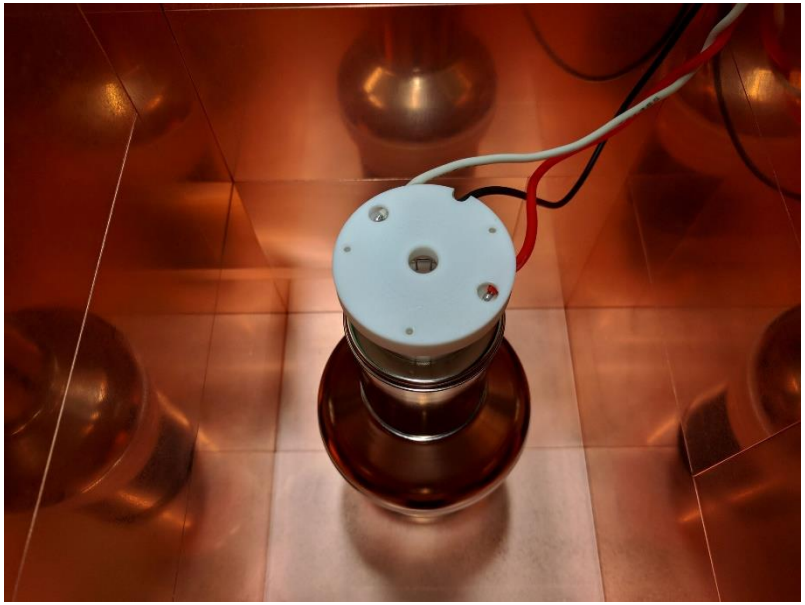


Voltage-divider components were selected at the HPGe detector. **Solder** is an alloy of **99.9999% pure tin** (Wako) and **old lead (~5Bq/kg** of ^{210}**Pb).**

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).
^{40}**K (assuming it is in the 5N Al sealant)**: 55-14mBq, 24-7mBq at 90%CL
^{60}**Co (assuming it is in the metal body)**: 7-1mBq, 7-4mBq at 90% CL

The new ultra-low background shielding

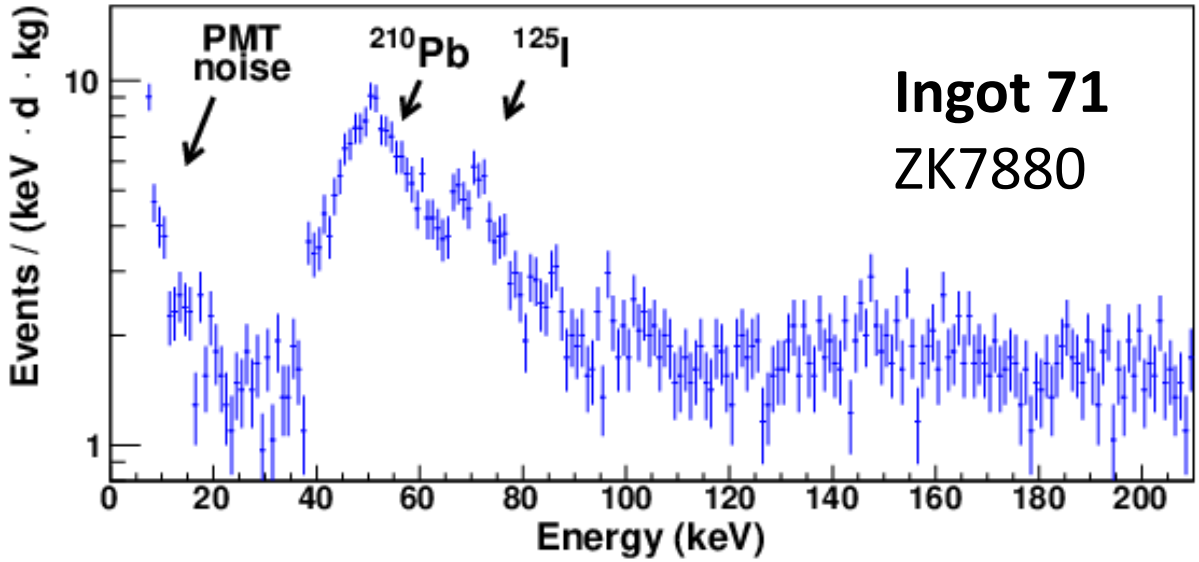


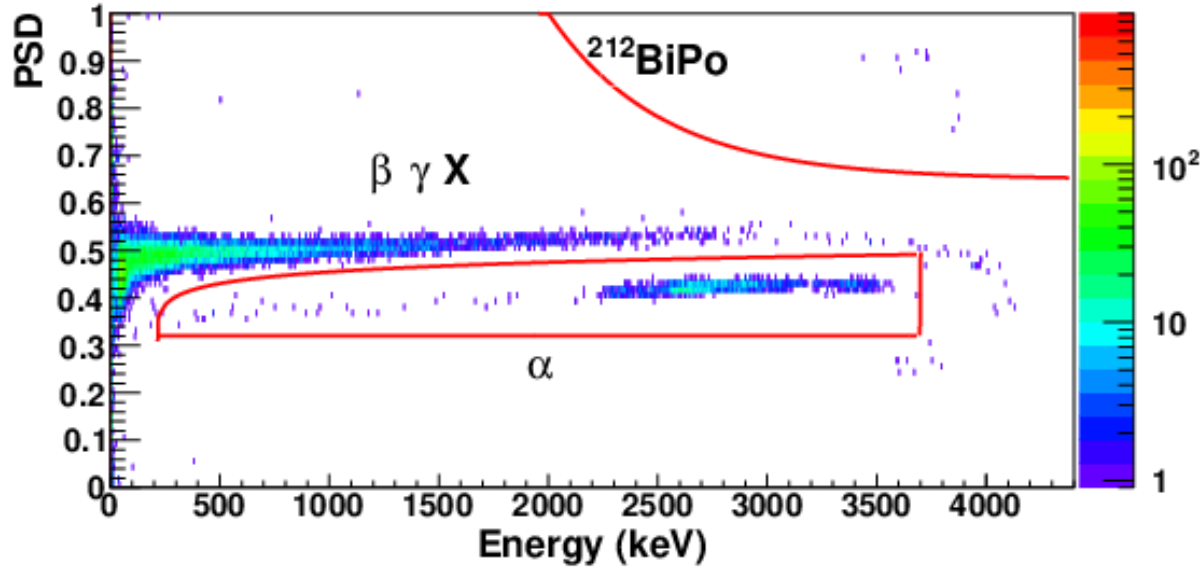


Cu bricks were cleaned in 4-steps: (**H_2SO_4+H_2O_2; $C_6H_8O_7$; H_2O; H_2O**) to remove **^{210}Pb** and other impurities; **18.2MΩ** ultra-pure water was used

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 ^{60}Co. After melting copper was cut into shielding bricks: (**50mm × 100mm × 200mm**).

Background for latest NaI(Tl) detectors





Radio-purity of the NaI(Tl) crystals

NaI(Tl)/ Isotope	^{238}U, ppt	^{232}Th, ppt	^{40}K, ppb	^{210}Pb, mBq
Ingot 71†	**9.7 ± 0.8**	**1.7 ± 0.2**	**<20**	**1.5**
Ingot 73‡	**3.6 ± 0.6**	**1.8 ± 0.7**	**<30**	**1.3**
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

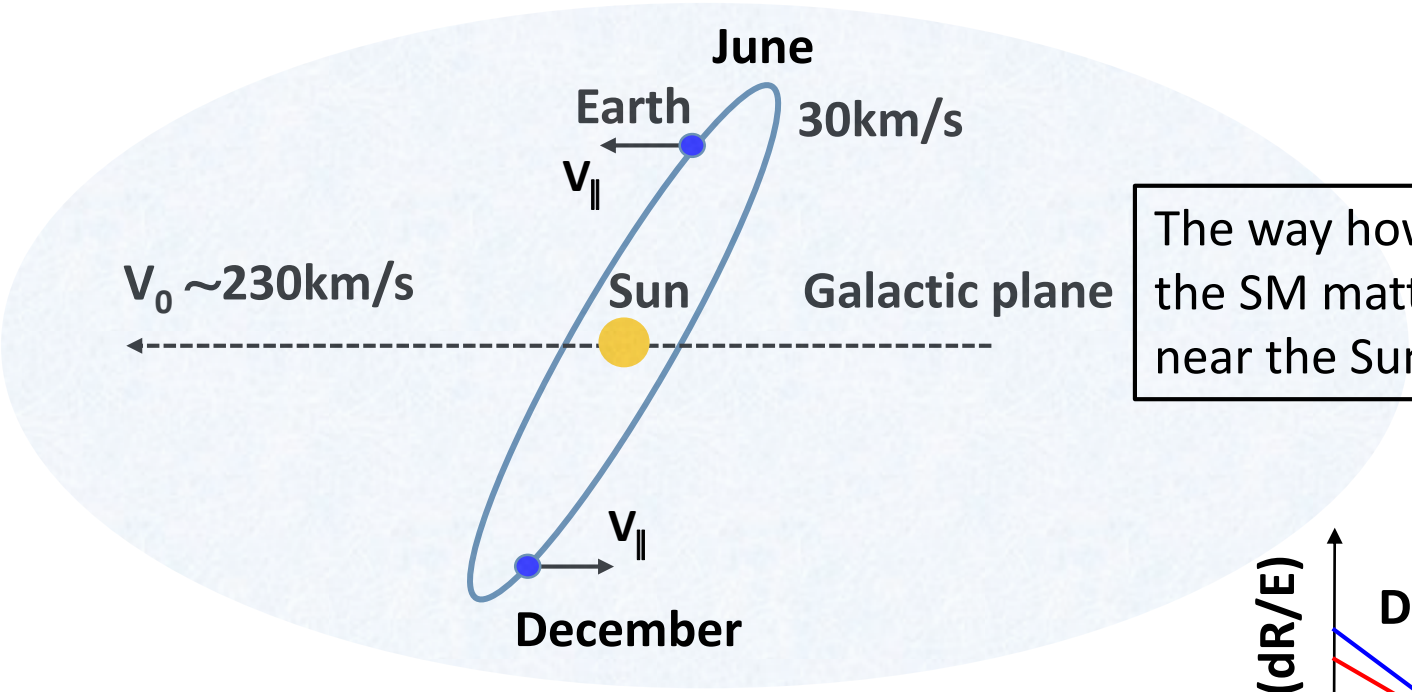
Still need: to find a stage where **^{222}Rn** contaminates the NaI material. Probably, need to make a closed system for NaI powder handling.

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(Tl) crystals** in Japan.
- We managed to produce NaI(Tl) crystals with the radio-purity 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.
- In April 2019, we received **JSPS funding** for construction of a large NaI(Tl) DM detector.

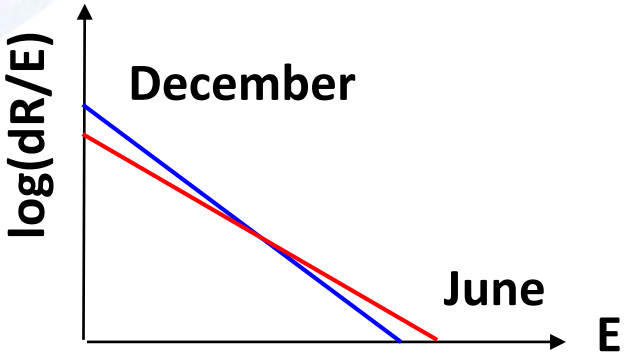
Backup slides

A hypothetical Dark Matter (DM) signal



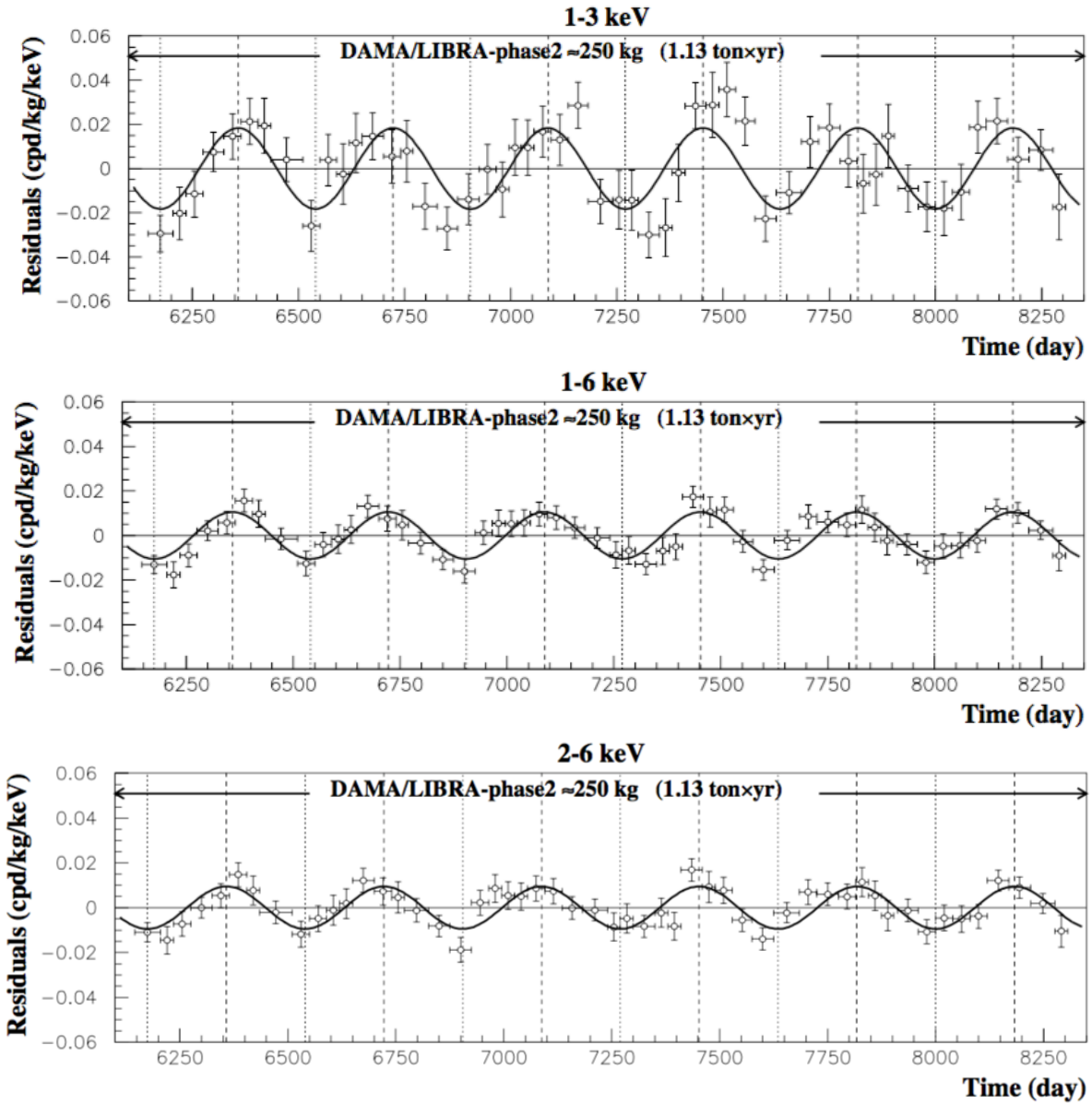
The way how DM interacts with the SM matter, its mass & density near the Sun are unknown.

$$R = S_0 + S_m \cos(2\pi(t-t_0)/1yr)$$



- Signal is caused by **Dark Matter particles scattering off detector nuclei**.
- 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 **9.5σ C.L**.

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