The Dark Matter Search at KamLAND

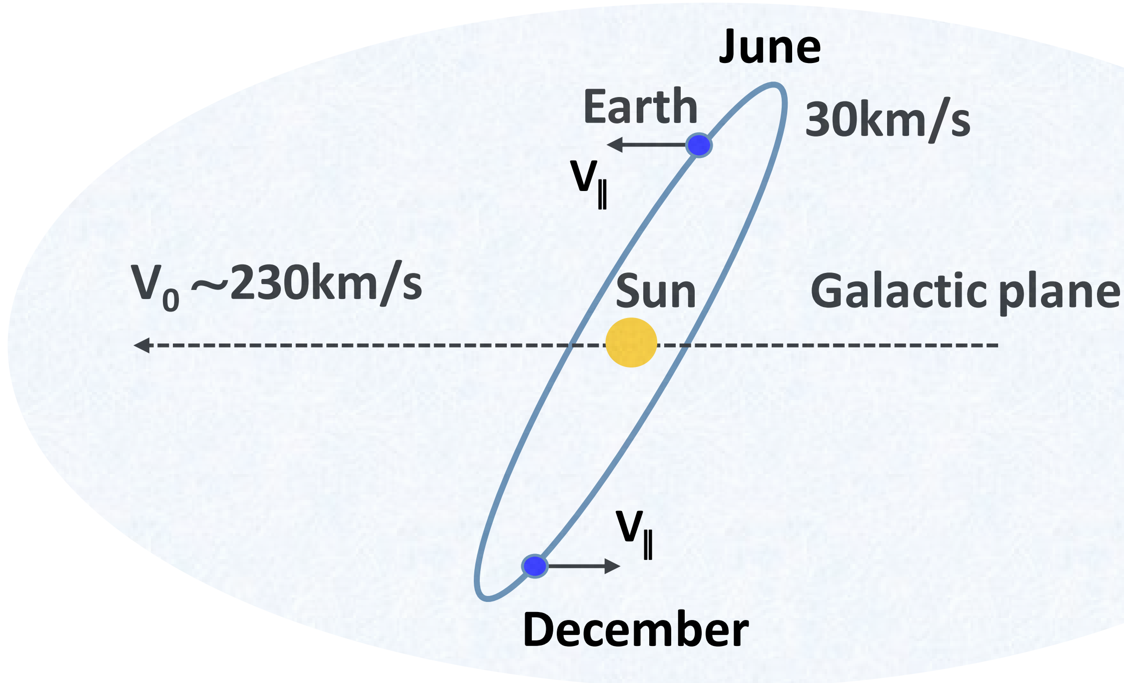
The University of Tokyo

Alexandre Kozlov

4th International conference on particle physics and astrophysics, Moscow

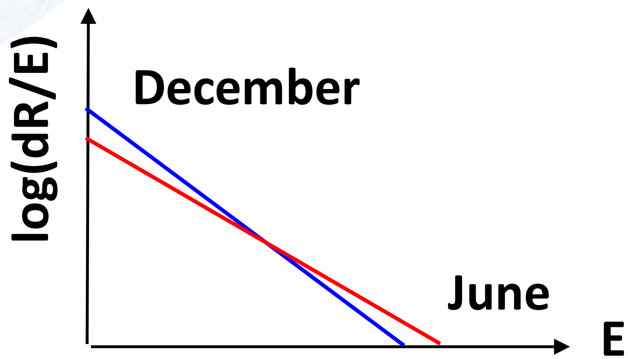
24 October 2018

A hypothetical Dark Matter (DM) signal



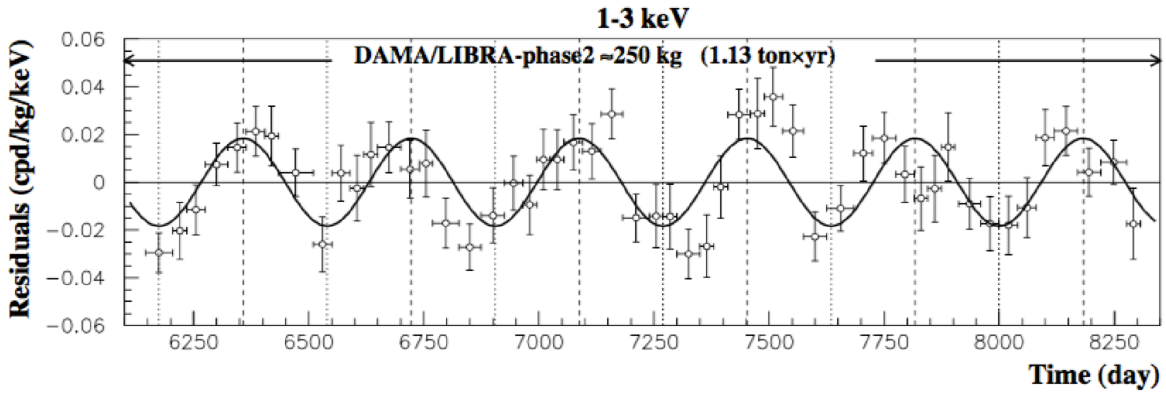
The way how DM interacts with the SM matter, its mass & density near the Sun are unknown.

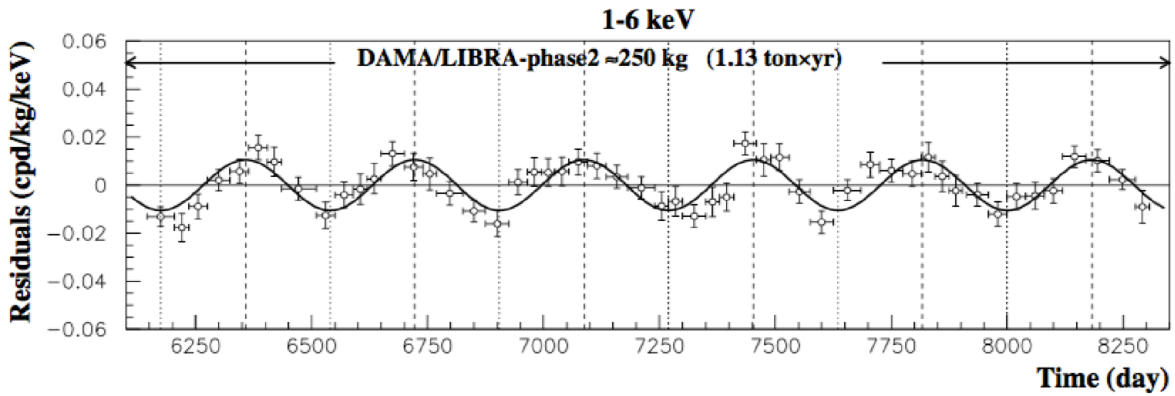
$$R = S_0 + S_m \cos(2\pi(t-t_0)/1yr)$$

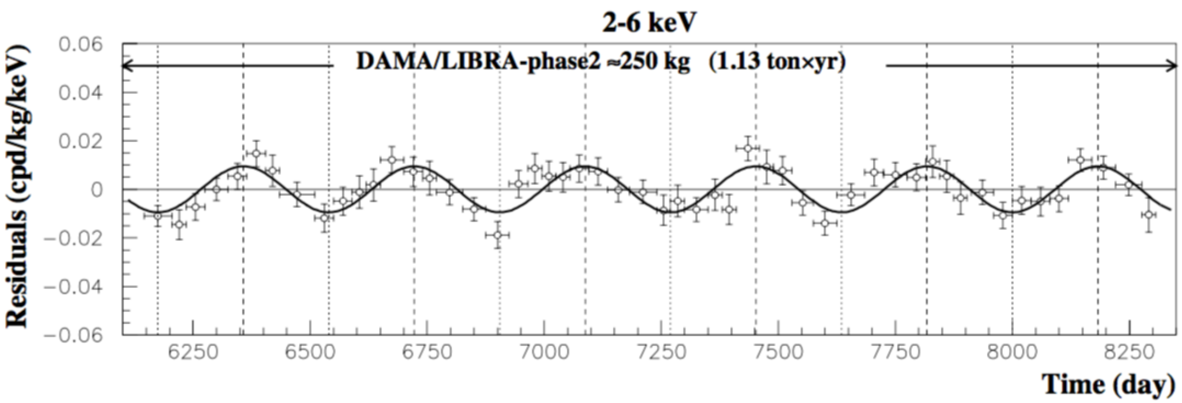


- Signal is caused by **Dark Matter particles scattering off detector nuclei**.
- Energy of the expected signal in the detector is in the range of **0-100keV**, which is **natural radioactivity dominant**.
- Fortunately, Earth motion around the Sun creates **annual modulation** of the measured energy spectrum (maximum is near June 2nd).

The DAMA/LIBRA-phase2 result







The **DAMA/LIBRA-phase2** favours the **presence of a 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.

Interpretation of the DAMA/LIBRA result

We consider two possible explanations:

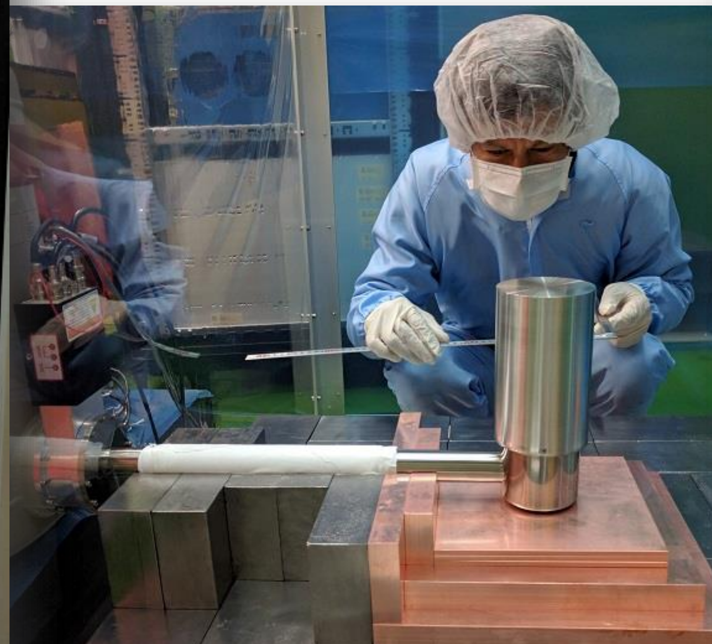
- ❑ The **Dark Matter signal**.
- ❑ **background variations** caused by seasonal effects (e.g. neutron flux intensity and energy spectrum dependence on the water content in rocks, etc).

What we can do:

1) Repeat an **“identical” experiment** at other locations.
2) **Reduce the background** below 1 ev/keV/kg/day.
3) Monitor possible **sources of background** (neutron, radon).

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.

From 2012, I develop **two clean rooms (A, B)** for an **ultra-low background research**.

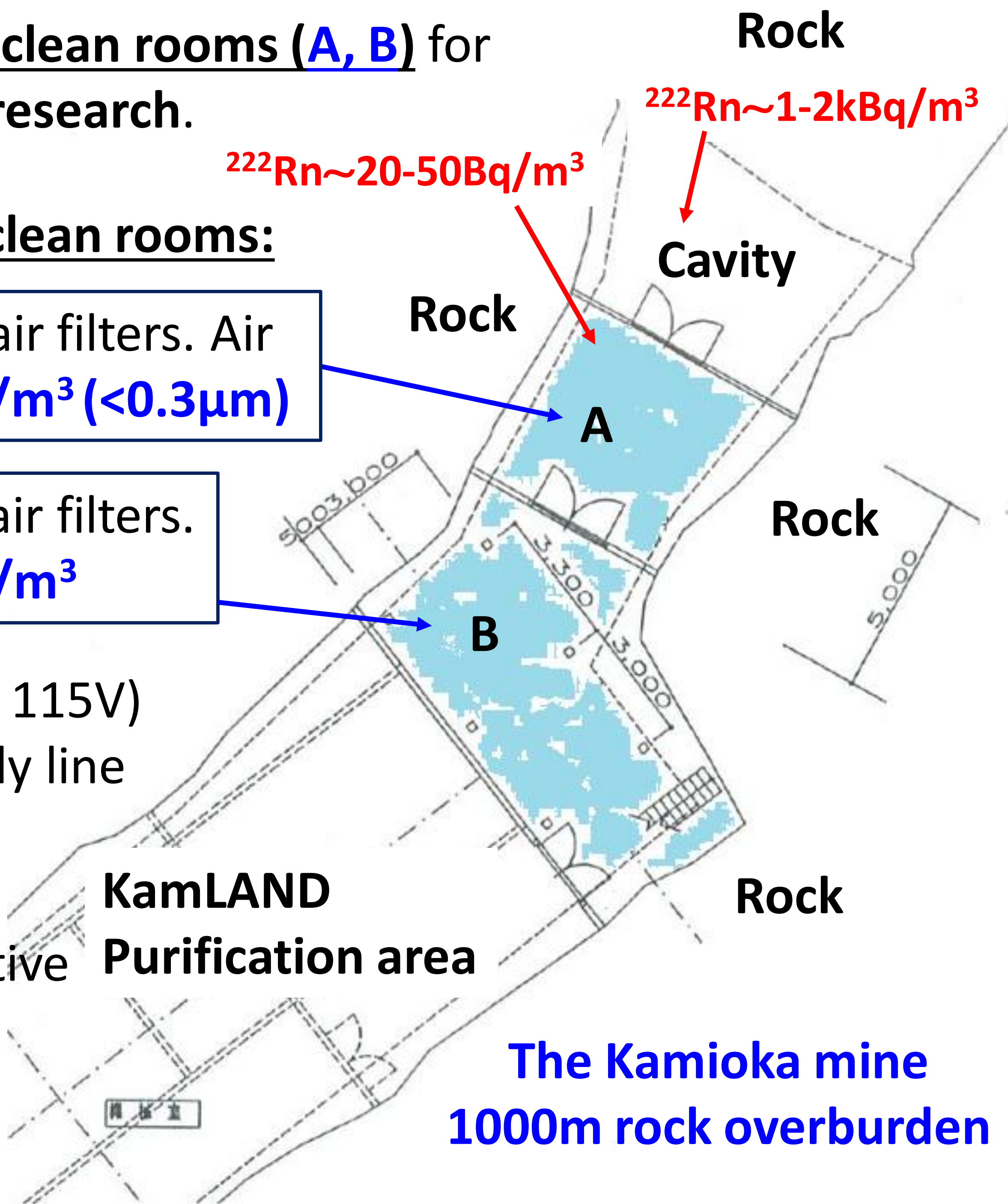
Current conditions at the clean rooms:

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**

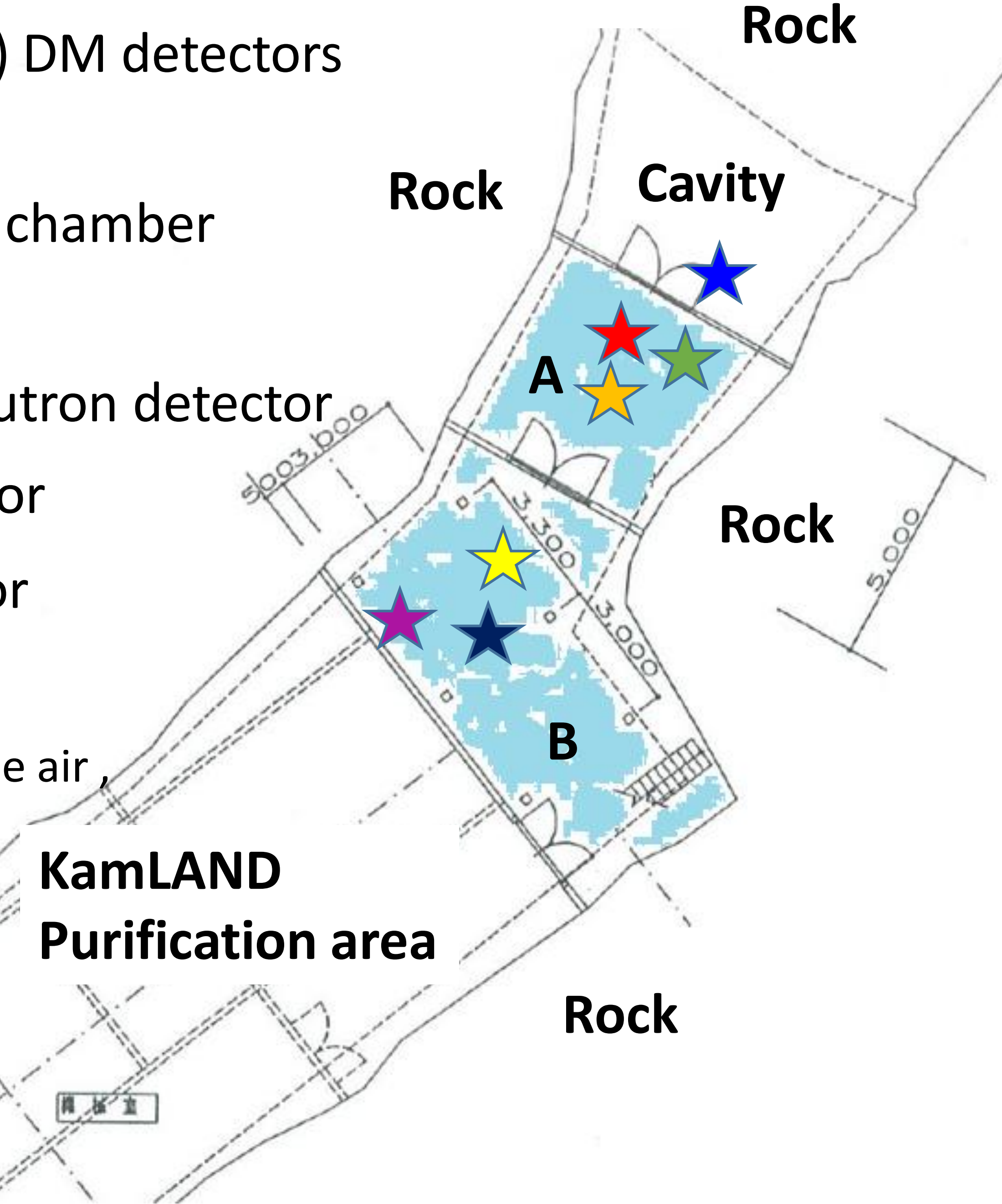
- 17kWatt AVR unit (100V, 115V)
- Boiled off Nitrogen supply line
- Radon-less air supply:

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



Research infrastructure at the Kamioka mine

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

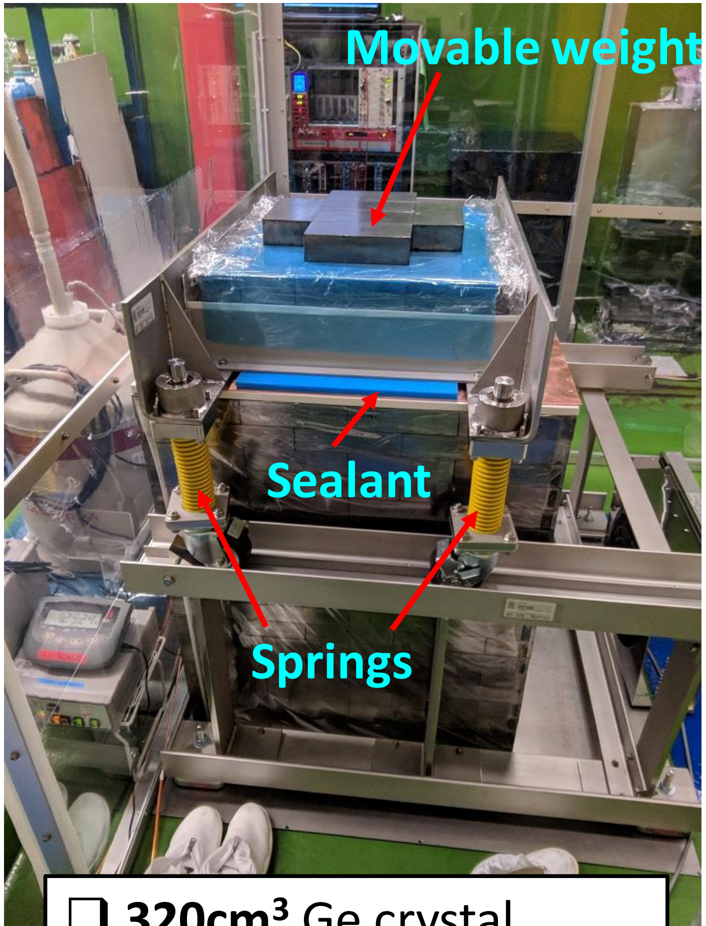


All important parameters:

- (**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**

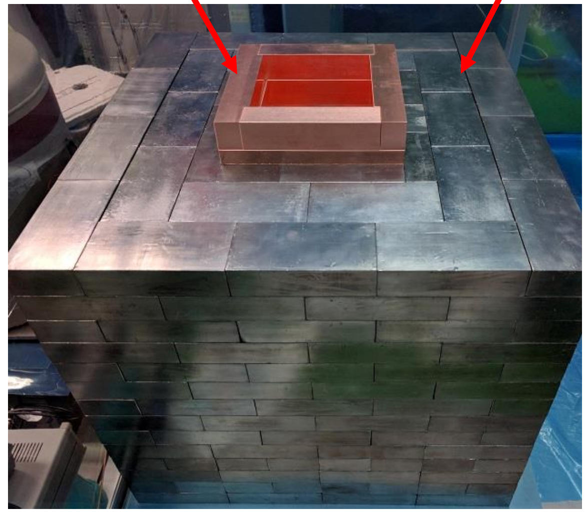
are being monitored and recorded.

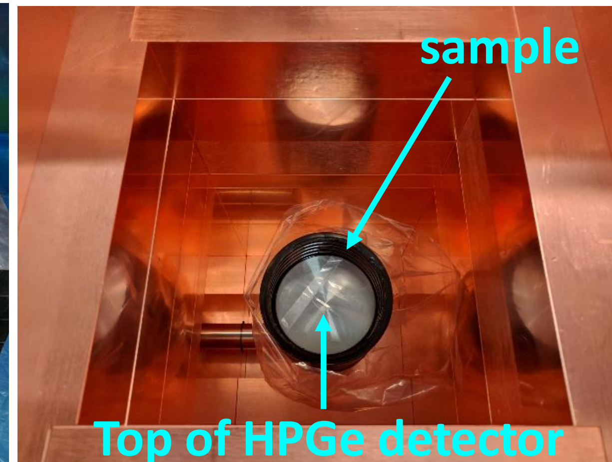
The HPGe detector

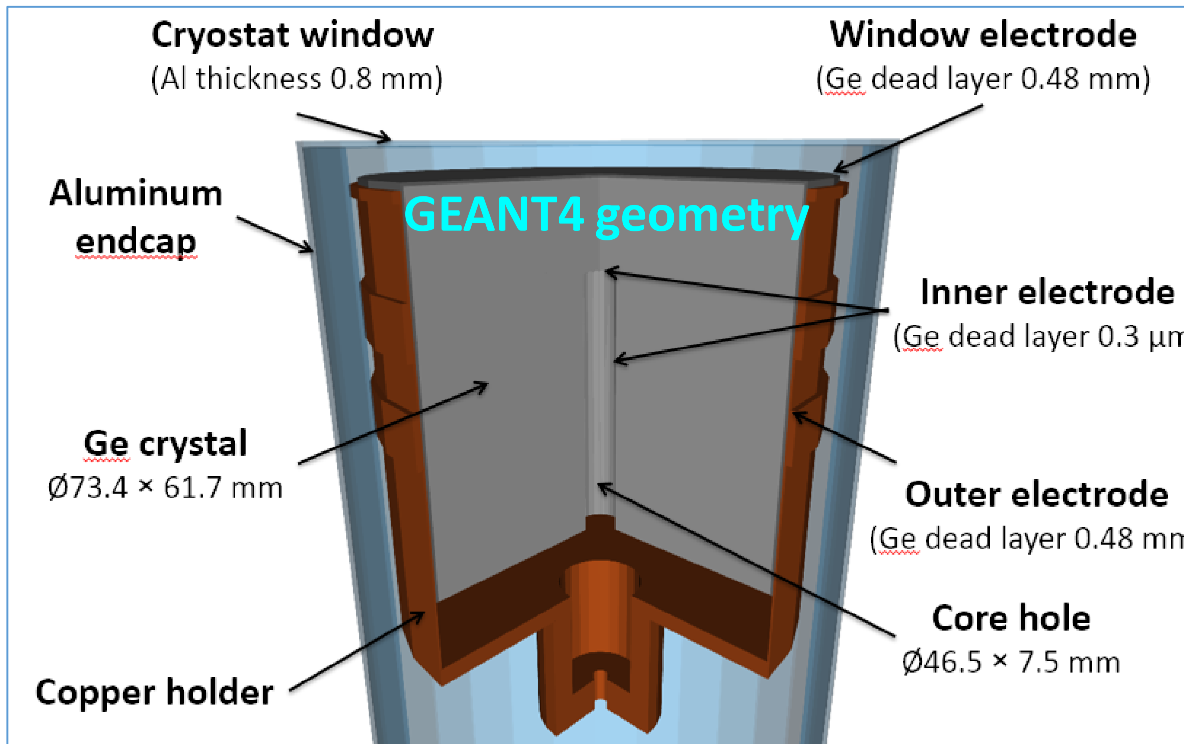


- **320cm³** Ge crystal
- All home-made design
- Inside of the clean tent
- Air flow via ULPA filters
- **5.5L/min of N_2** via MFC
- **Cu/Pb** 15y underground

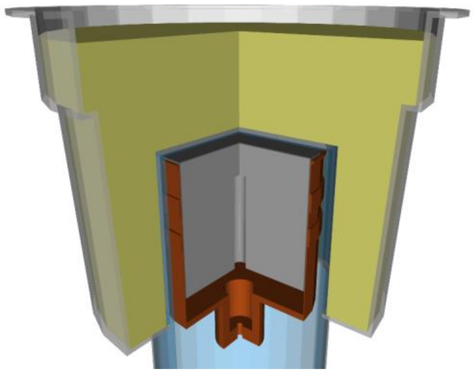
5cm-thick Cu 25cm-thick Pb (3 types of lead bricks)

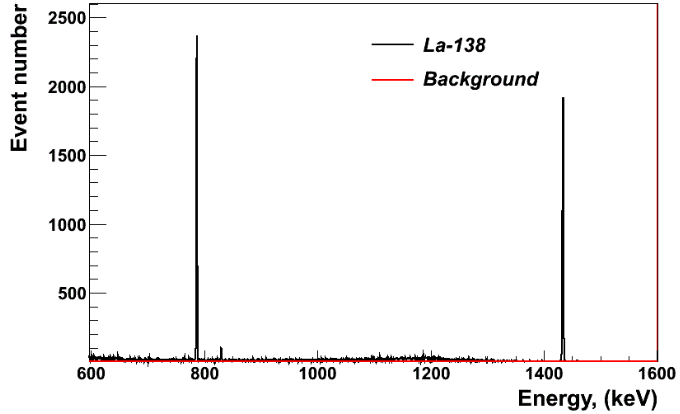


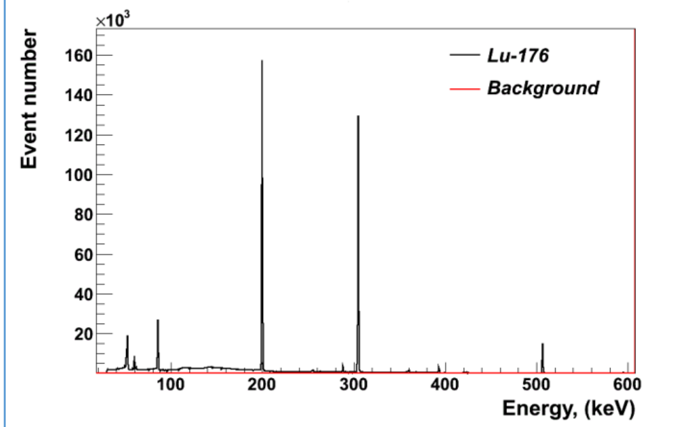




The HPGe detector calibration



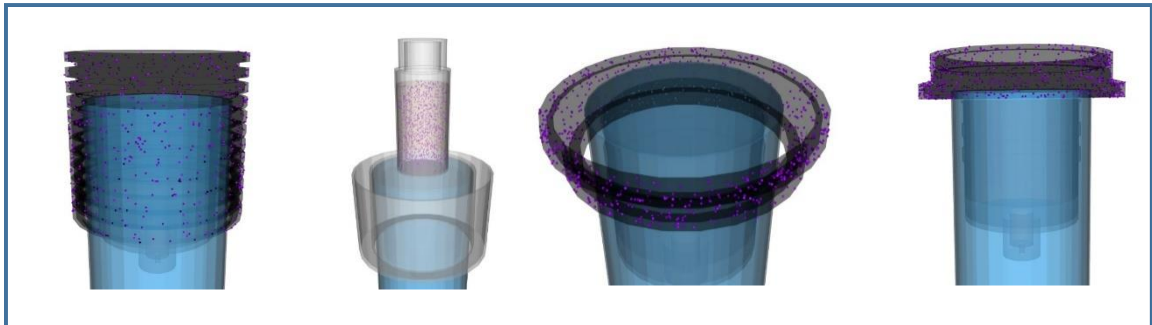




Marinelli beakers (0.7, 1.2L) are used for loose and liquid samples

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** Lu_2O_3



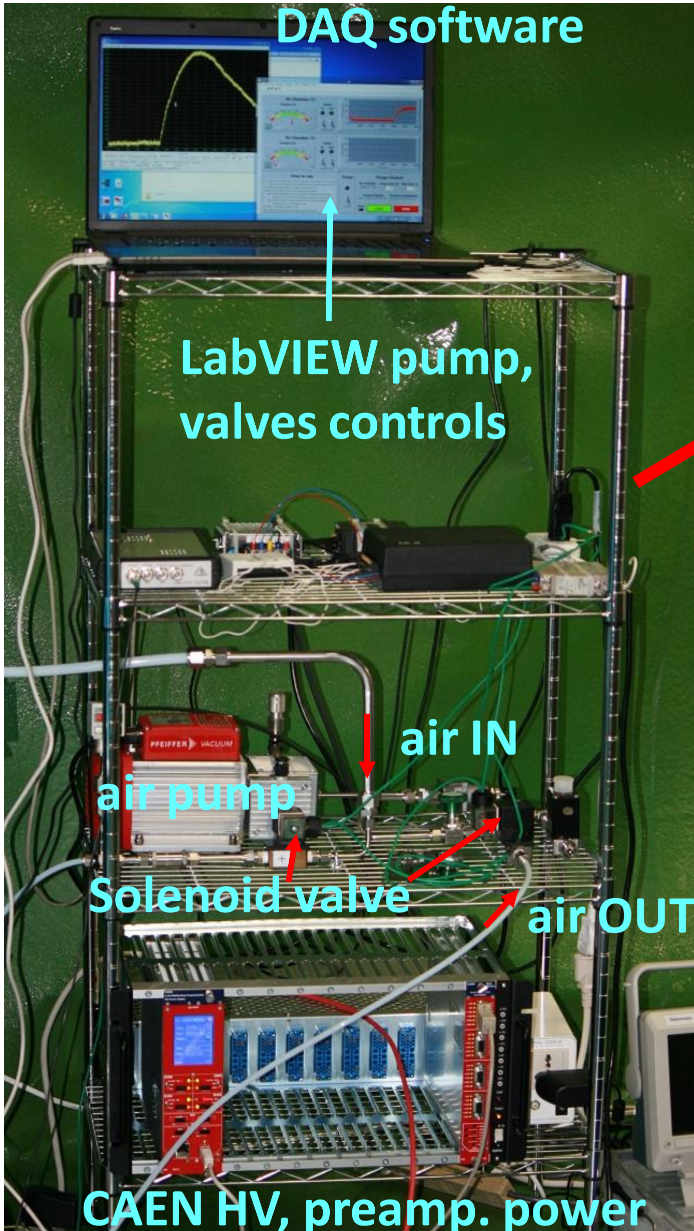
For every sample a realistic **GEANT4 model** is prepared to calculate the γ-ray detection efficiency

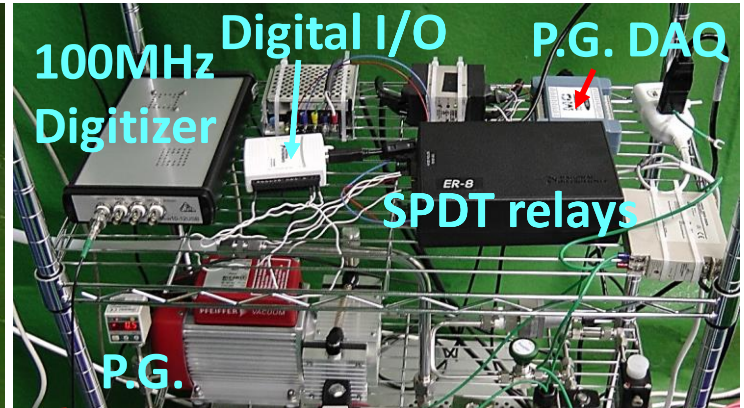
We made **extended sources with a small admixture of Lu and La** to verify correctness of the detector GEANT4 model based on the information provided by Canberra Corp.

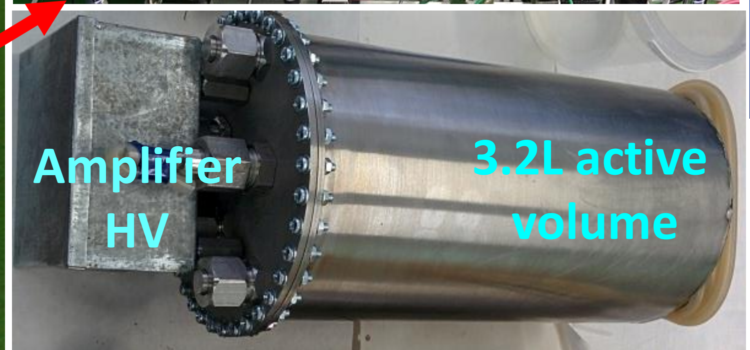
The ion-pulse ionization chamber

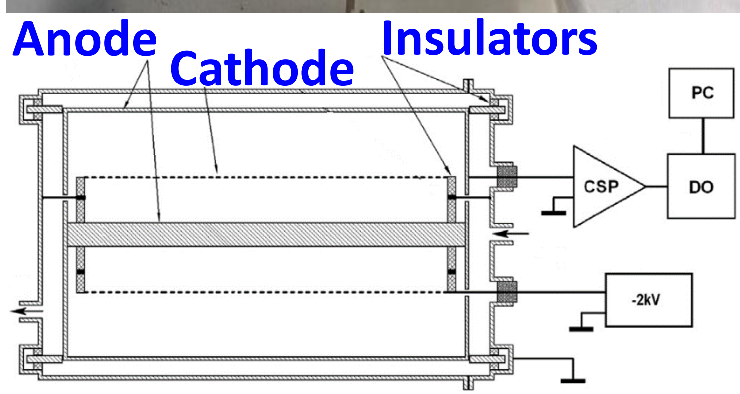
JSPS grant: 16K05371

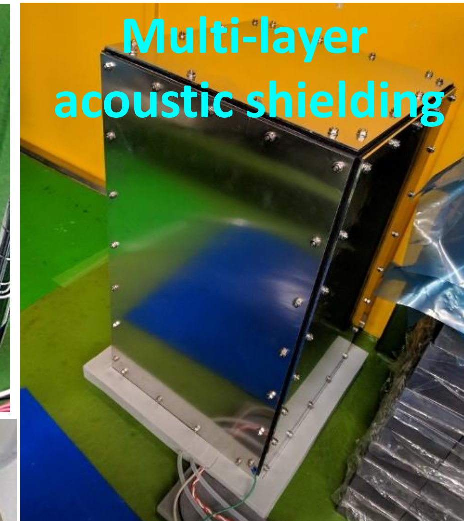
Used for a direct detection of α–particles from the ^{222}Rn decay in the Room A air.

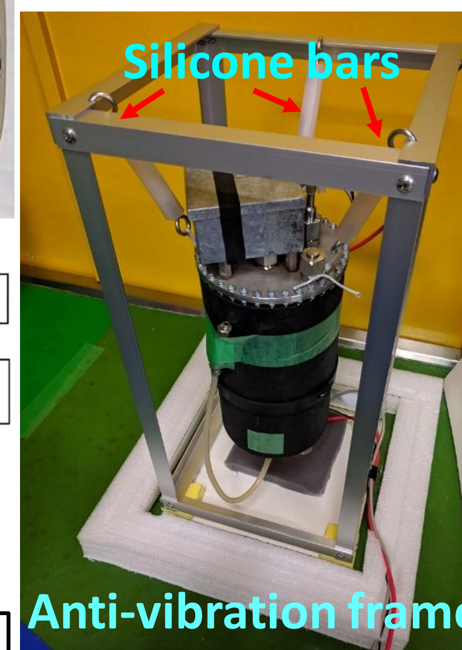








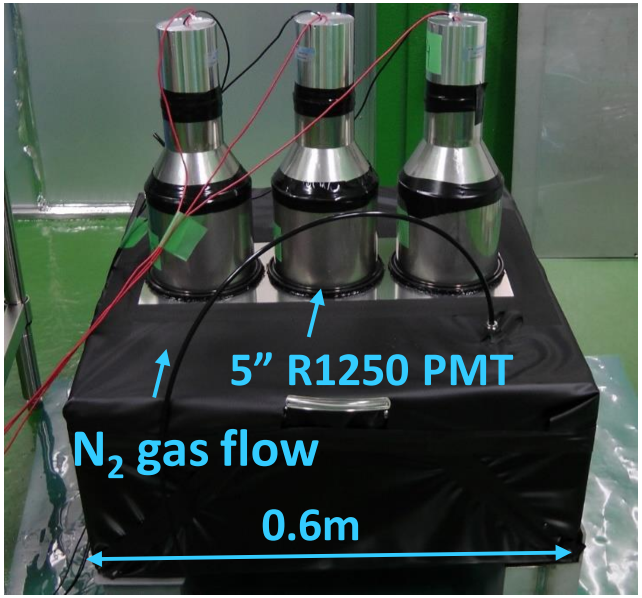




Energy resolution: 2% (FWHM)

The ^{6}LiF/ZnS thermal neutron detector

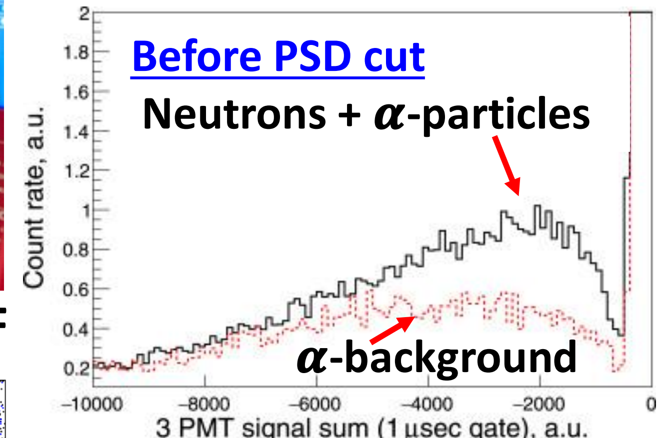
JSPS grant: 16K05371

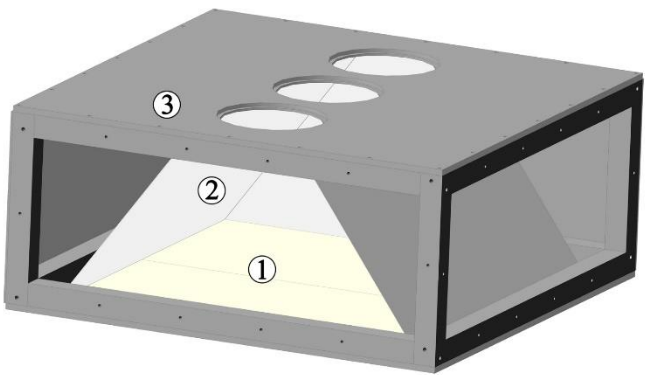


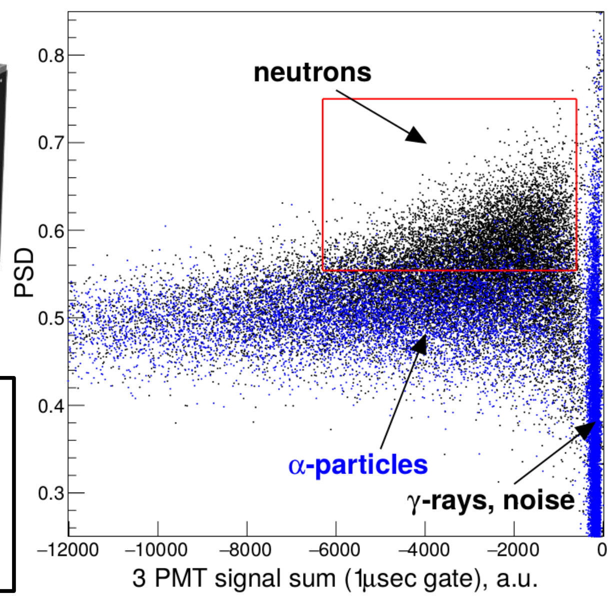
The thermal neutron flux: $(6.43 \pm 0.50)\times10^{-6}$ n cm^{-2} s^{-1}

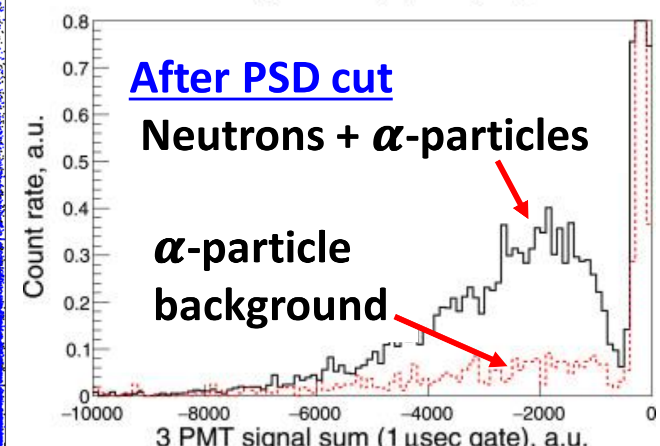
DAQ: w-f digitizer N6724F

$$^6\text{Li} + n \longrightarrow \alpha + t + 4.78\text{MeV}$$







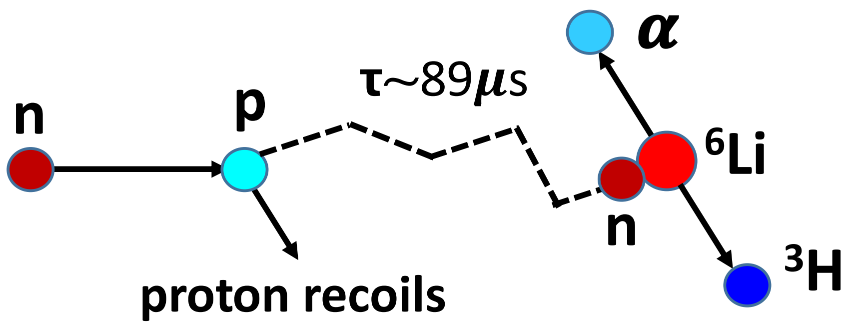


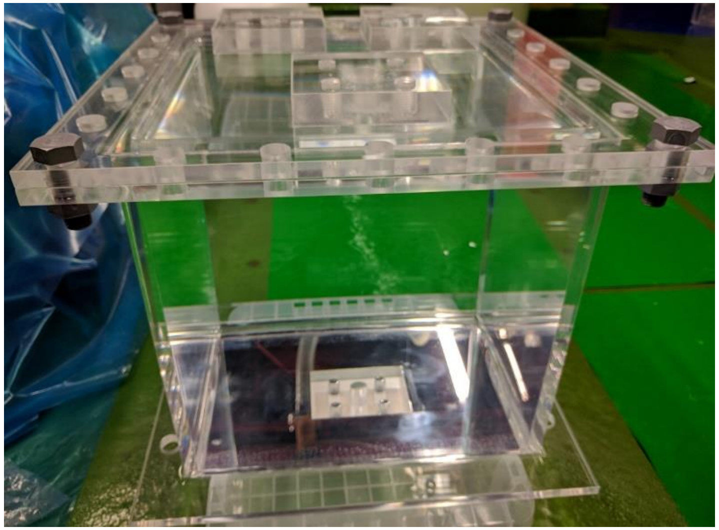
1. The ^{6}LiF/ZnS scintillator
2. A light reflector
3. An aluminium box

A.Kozlov, D. Chernyak, NIM A, vol 903, 21 September 2018, Pages 162-169

The fast neutron detector

Organic liquid scintillator loaded with Lithium was developed and tested by H. Watanabe and Y. Shirahata (Tohoku U.)





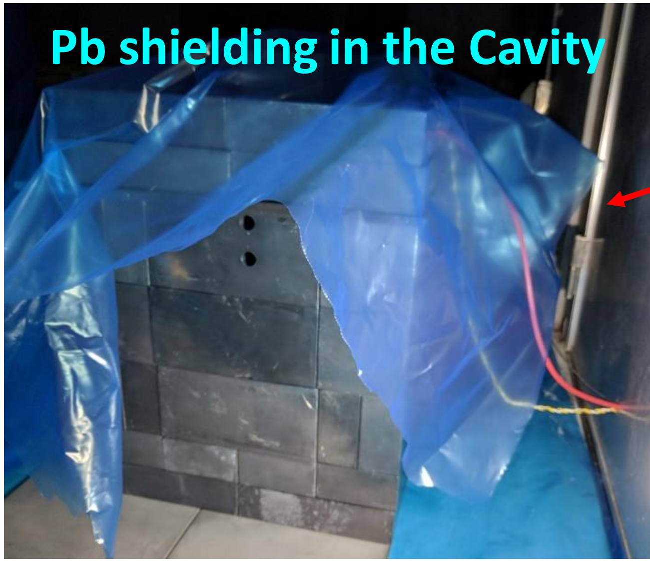
Acrylic tank (30×30×30cm)

Liquid scintillator (LS) loaded with nat. Lithium (**7.6% of ^{6}Li**)
Pure LS components: **pseudocumene** (PC) + **PPO**(5g/L)
PC : Surfactant (TritonX-100) mixing 82% : 18%
Nat. LiBr・H_2O 37g/L

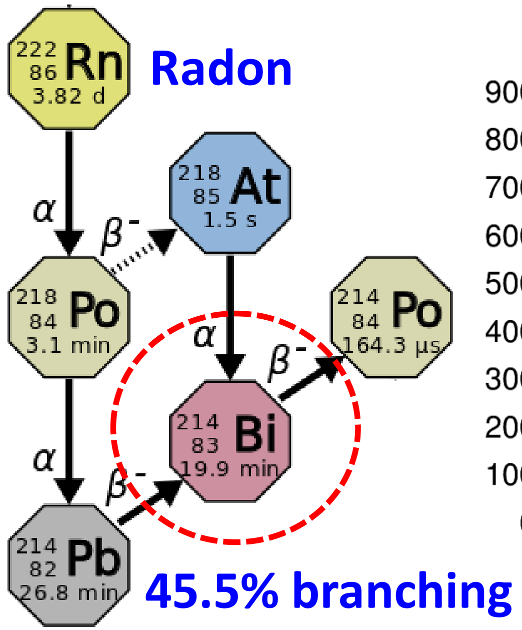
Photo-sensors: **4 Hamamatsu 5” R1250 PMTs** (low K.)
DAQ: **CAEN DT5720** (4ch, 12bit, 250MS/s)
Shielding: **10cm of lead** to reduce accidentals
Pulse-shape discrimination works for both prompt and delayed signals. A **94% γ-ray rejection** for a 90% eff. cut on the delayed signal was achieved.

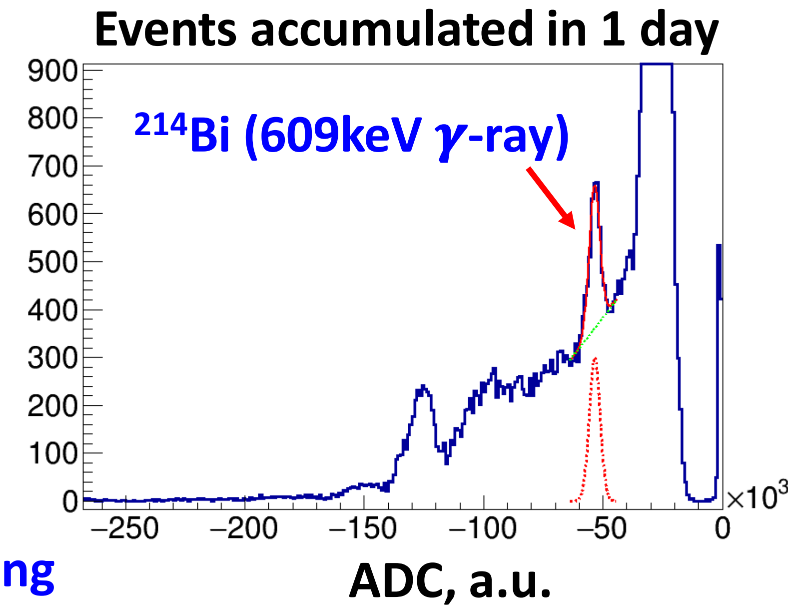
A magnetic stirrer used to mix scintillator with a water solution of LiBr

The NaI(Tl) radon detector



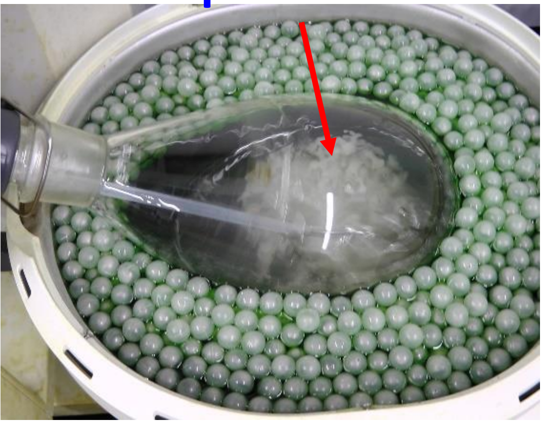
Bottom layer: **15cm-thick lead**
Walls: **10cm-thick double layer lead**
Inner layer: a high purity Pb (**^{210}Pb ~20Bq/kg**)
Volume of the air inside shielding: **9.7L**
The **609keV γ–ray** detection efficiency: **0.196%**
(calculated using the GEANT4 model)

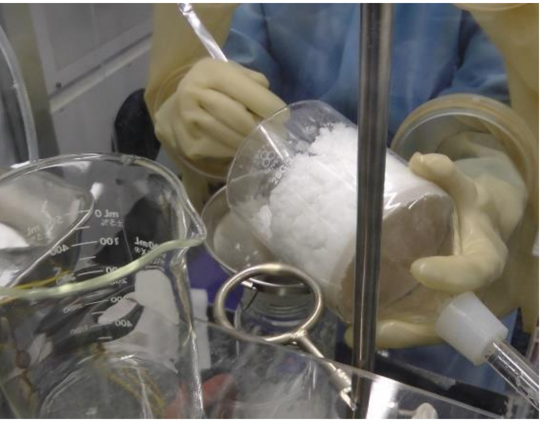


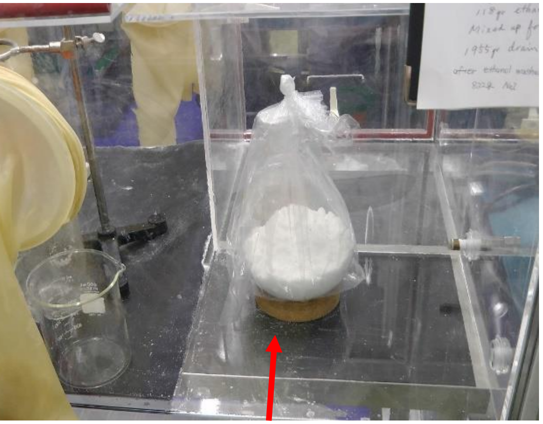


2×2cm NaI(Tl) crystal + H3178 PMT directly connected to the **DT5730 w-f digitizer** (14-bit, 500 MS/s) was used to measure radon activity in the Cavity outside of the clean rooms. The ion-pulsed ionization chamber is difficult to use at that location due to a high radon activity (>1Bq/L) and relative humidity >94%.

Non-purified NaI







Purified NaI·$2H_20$

Partner: I.S.C. laboratory

K. Imagawa, K. Yasuda

Purification techniques:

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

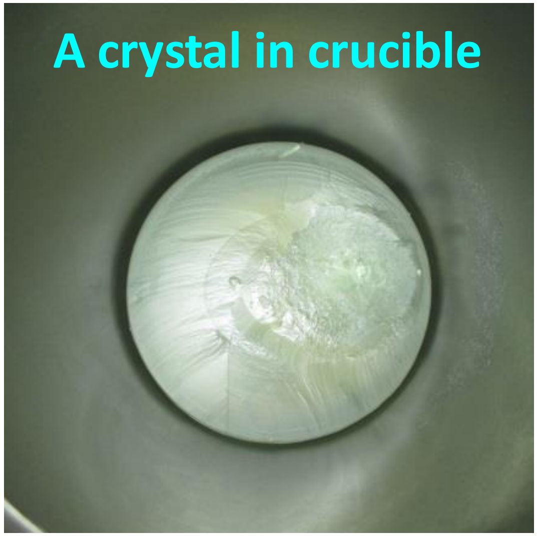
Steps used to minimize Radon daughters activity in NaI:

- ❑ Use of **specially produced NaI powder in accordance with** procedures developed by the 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)

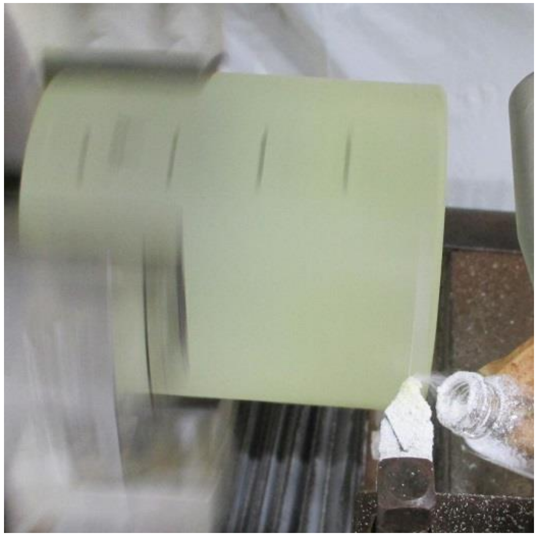


Crucible:

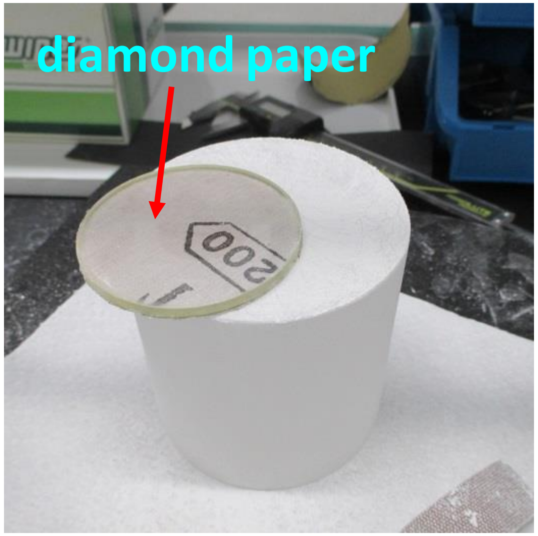
- Material – a coated, polished, **purified (in a vacuum oven) graphite**
- A new feature: a specially shaped bottom part – **no need to use a seed** to start crystal growth
- After cooling down NaI(Tl) crystals are **detached from the graphite crucible easily** due to a factor 10 **difference in the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

The NaI(Tl) ingot production (Step 2)

Machine cutting

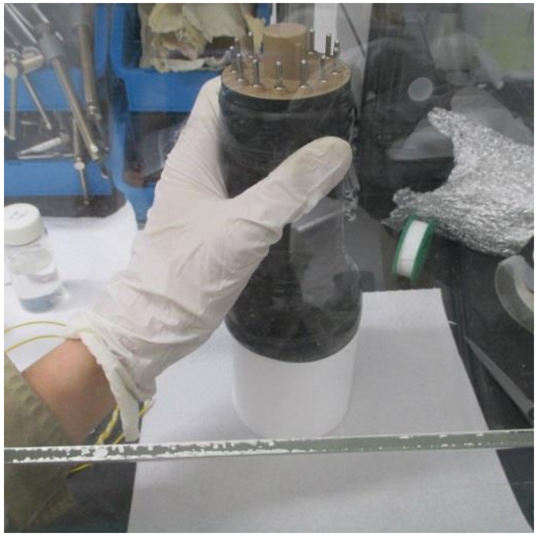


Samples for Tl test



Abrasion

Humidity control

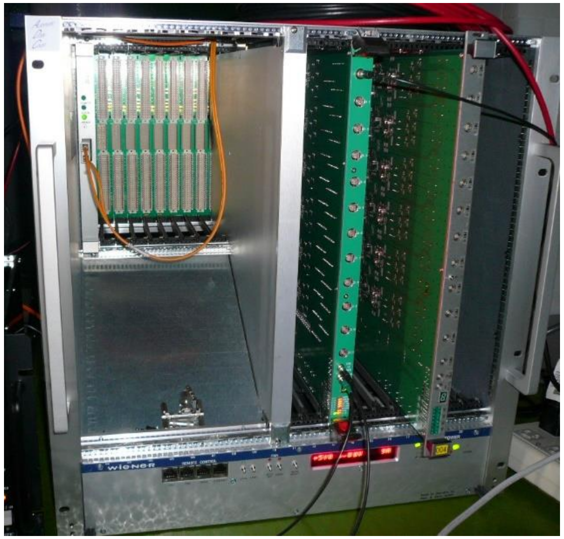


E. resolution test

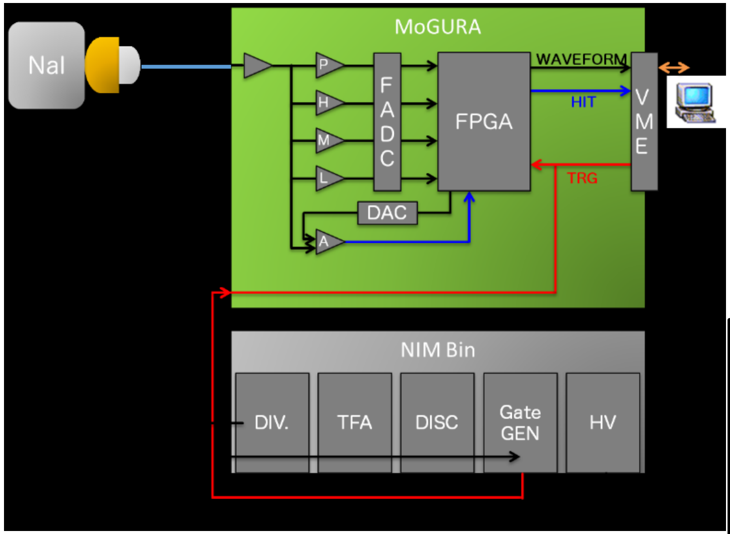
Encapsulation

Test setup for the NaI(Tl) DM detectors

Mogura DAQ developed with Tokyo Electron Device Ltd



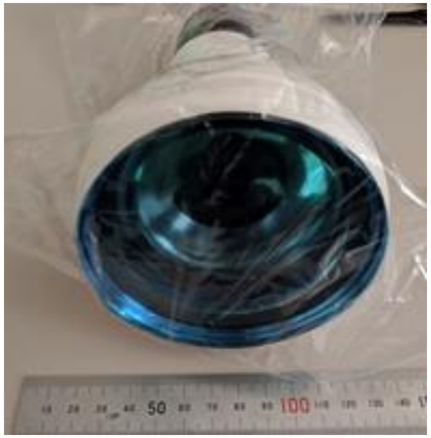
Mogura DAQ (9U VME)



Mogura + TFA filter

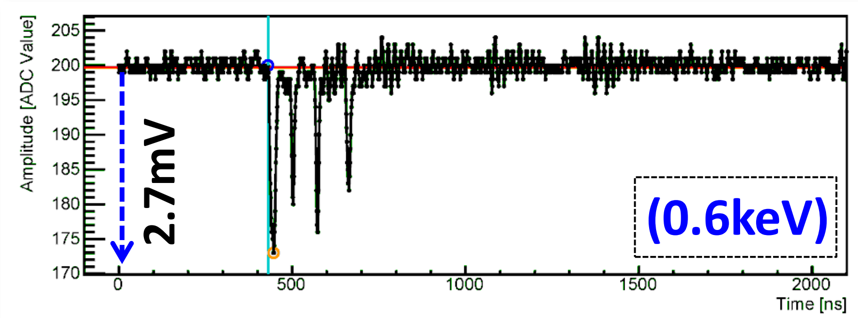
Bottom: >**30cm of lead**
Walls: **15cm of lead**
Inner: **5cm** of special **Cu**
Flushed with **3L/min of N_2**

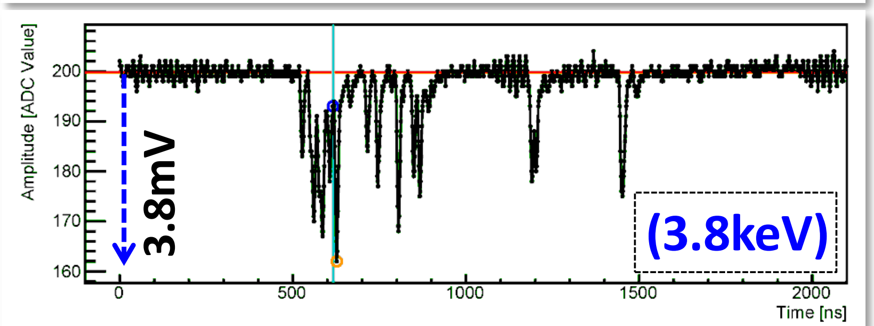
- **12ch** Input ⇒ scalable
- **0.1mV-10V** (PHML gain channels) covers energy range **from 1keV DM pulses to several MeV α-particles**
- **1ns, 5ns** sampling FADC
  ⇒ essential for rejection of
  low-E short pulses (PMT noise)
- **10μs** waveform
- Analog/Digital discrimination

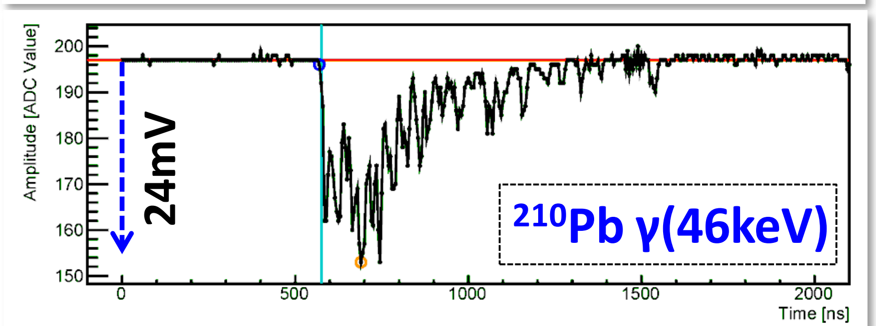


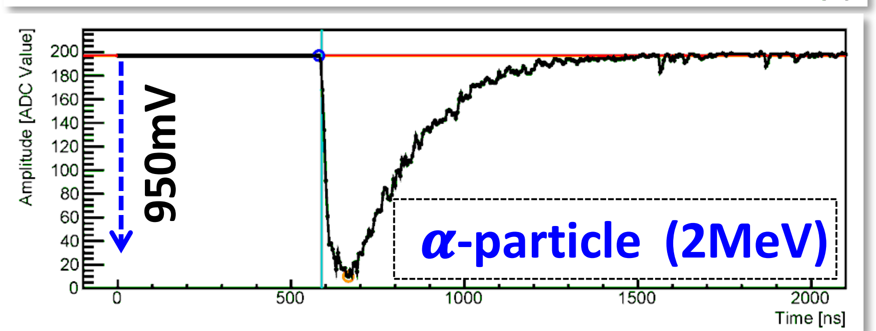
Hamamatsu metal body high QE ultra-low background PMTs: **R11065-20, R13444X**

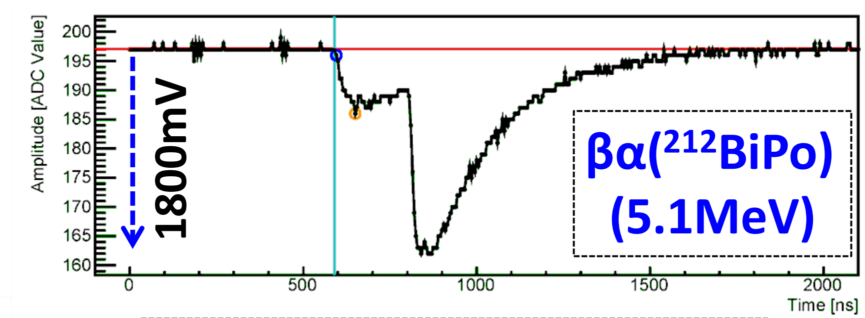
NaI(Tl) signal characteristics

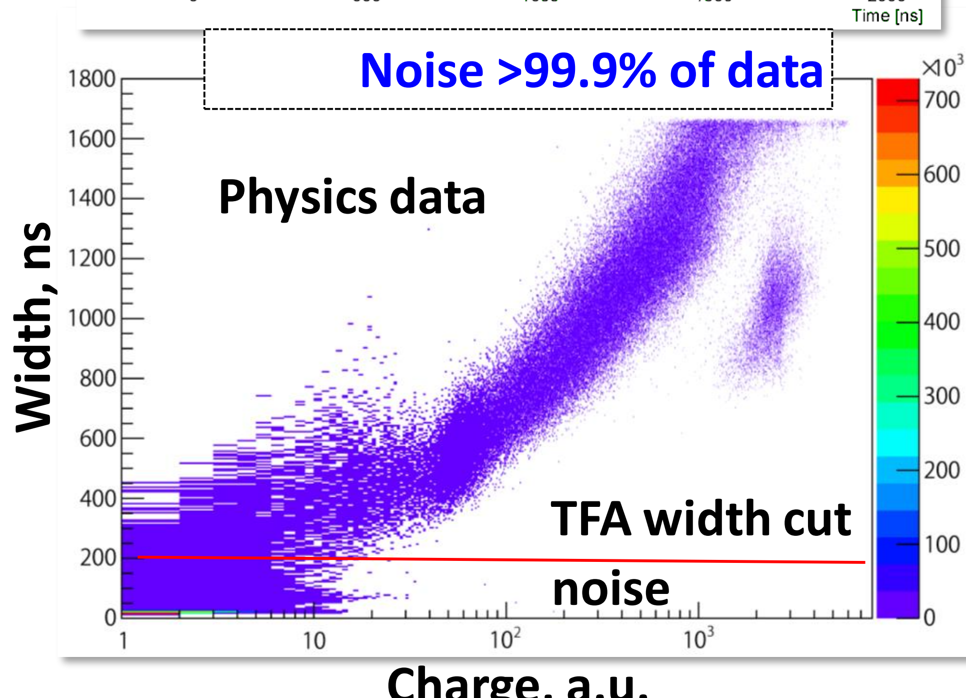


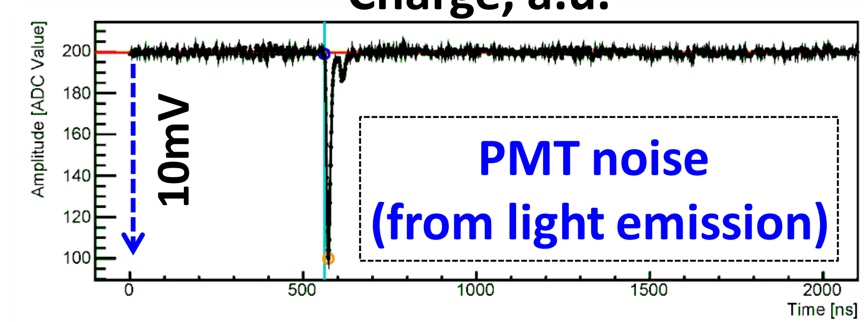




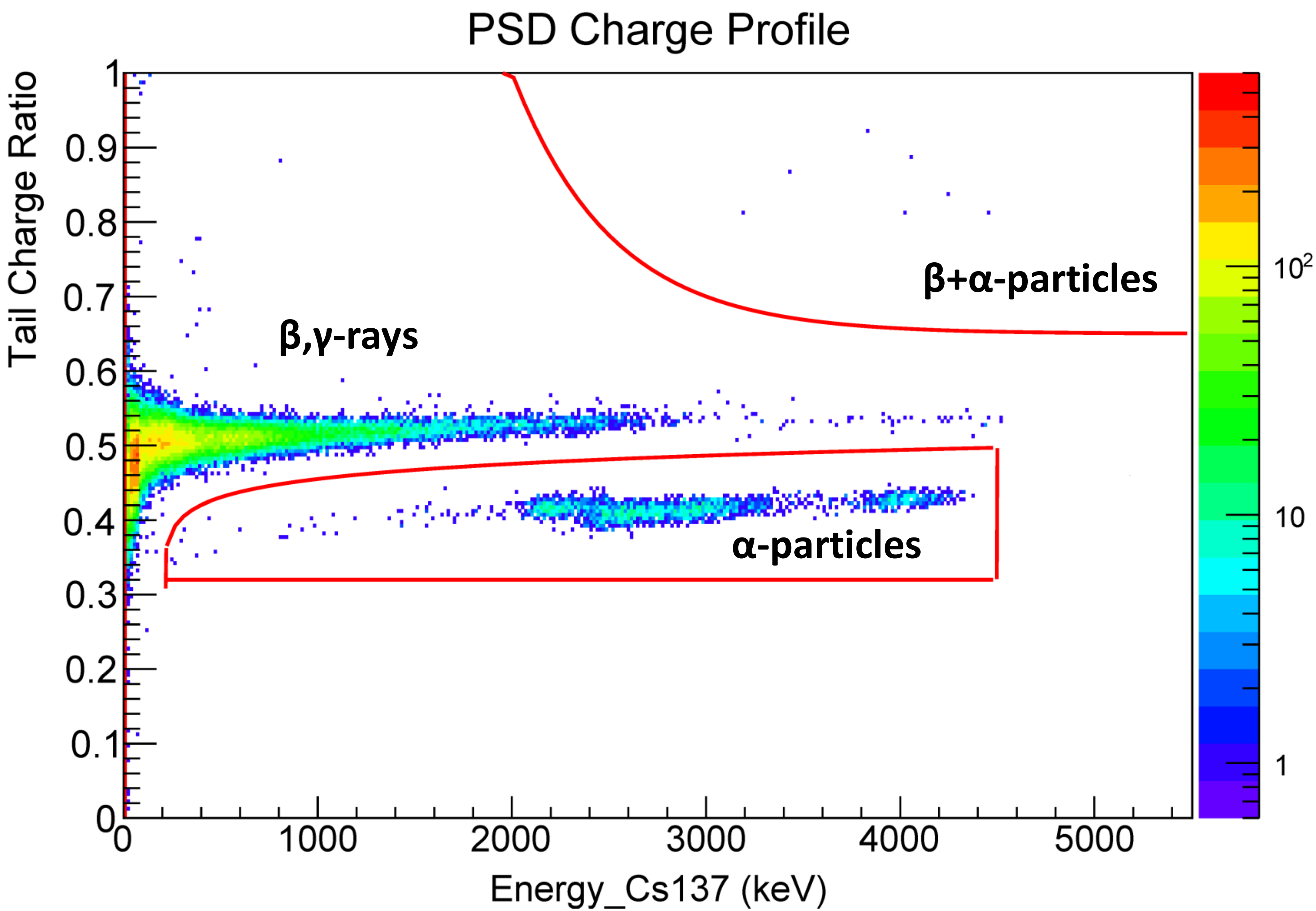




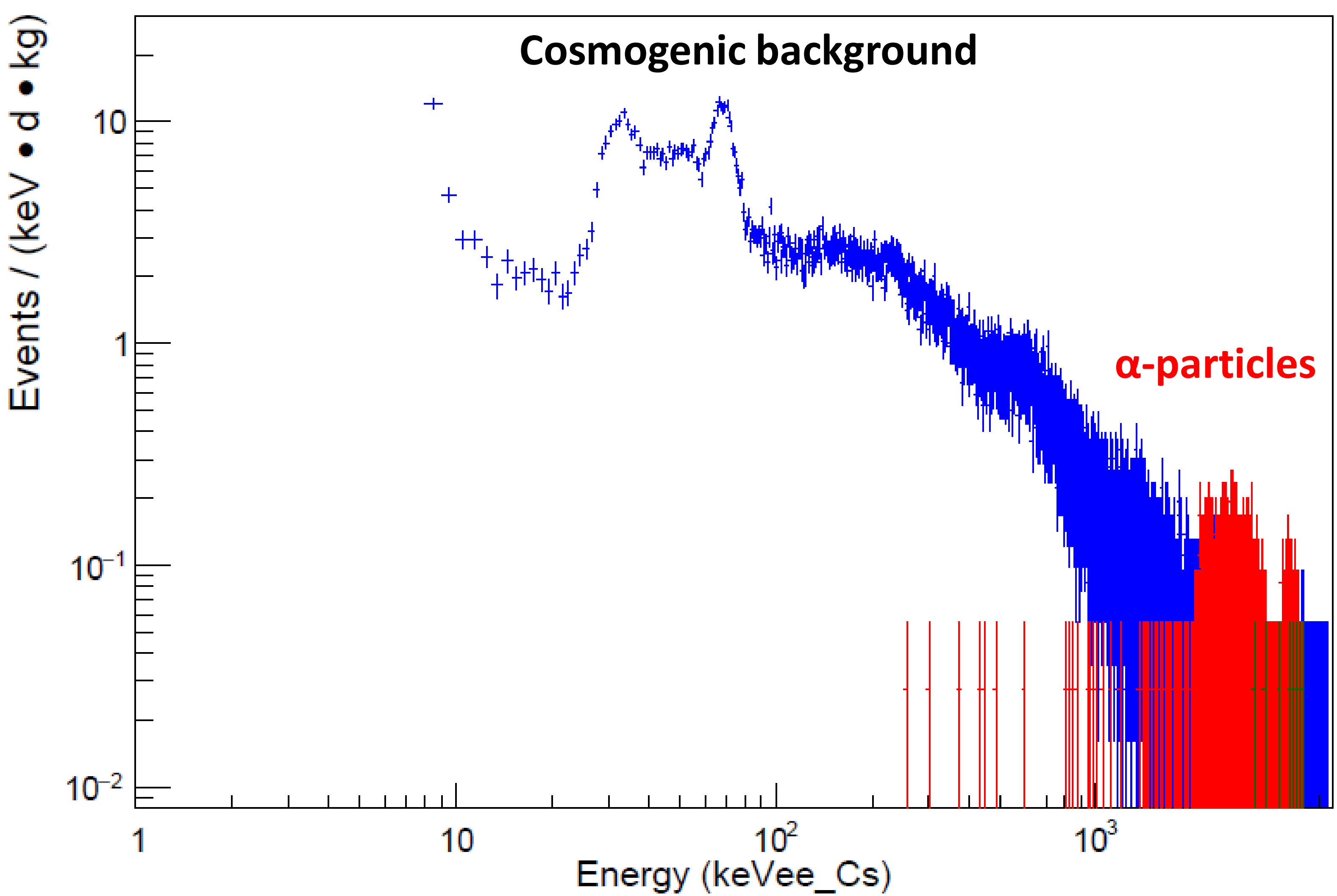




The PSD discrimination (ingot #71 , 28days)

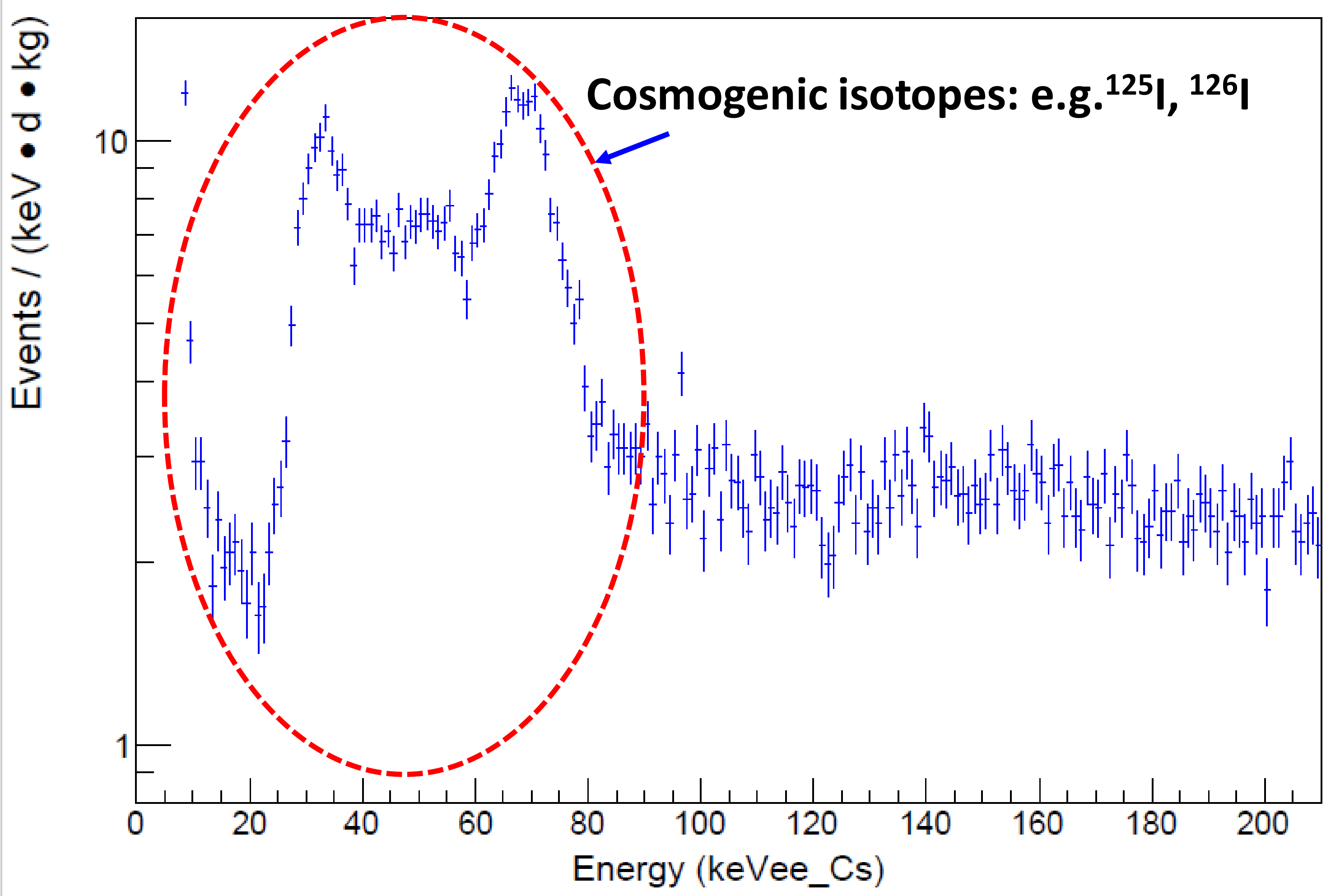


Background (Ingot #71, 28days)



Thorium: **1±0.3ppt**, Uranium: **11±0.5ppt** (DAMA/LIBRA **0.7-10ppt** for U/Th).
One more NaI(Tl) crystal of a higher purity level is being produced now.

Ingot #71 (manufactured on Sept 14, 28days)



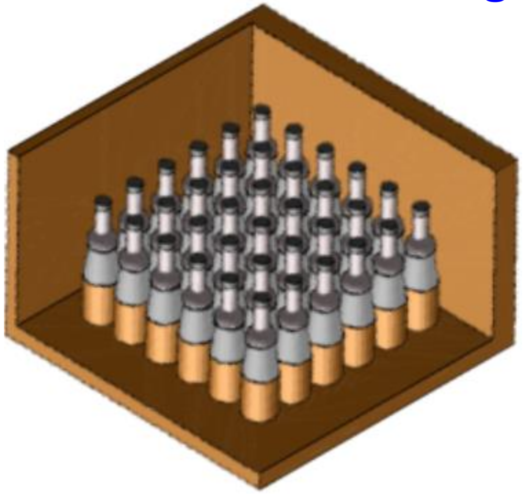
Background at low energies is dominated by **isotopes with a short half-life** created in NaI by **cosmic-ray muons** on the surface. A cooling down period required for decay of a major part of the cosmogenic background is **> 6 months**.

The NaI(Tl) Dark Matter detector

- Detector options : **120kg** and **250kg+ of NaI(Tl) in a solid shielding**. Each module will be composed of a **5×5-inch NaI(Tl) crystal** in an acrylic case connected to a **3" or 4" Hamamatsu PMT** with a metal body.
- Deployment to KamLAND will be possible after the end of the KamLAND-Zen 800 experiment (3-4years from now).
- Right now, we stock shielding materials, screen components for ultra-low background photomultipliers.
- **Copper** was specially melted using freshly manufactured (**less than 1.5 month**) electroformed copper to avoid **^{60}Co** (measured activity **0.3mBq/kg UL at 90% CL**).
- **Copper bricks** were cleaned in 4-steps: (**H_2SO_4+H_2O_2; $C_6H_8O_7$; 18.2MΩ H_2O; 18.2MΩ H_2O**) to remove **^{210}Pb and other impurities**
- **Lead blocks** were cleaned in a **triple HNO_3 baths** to remove surface contamination. For the most old lead machine cutting was done before acid cleaning.

Lead after acid cleaning

Cu bricks after cutting

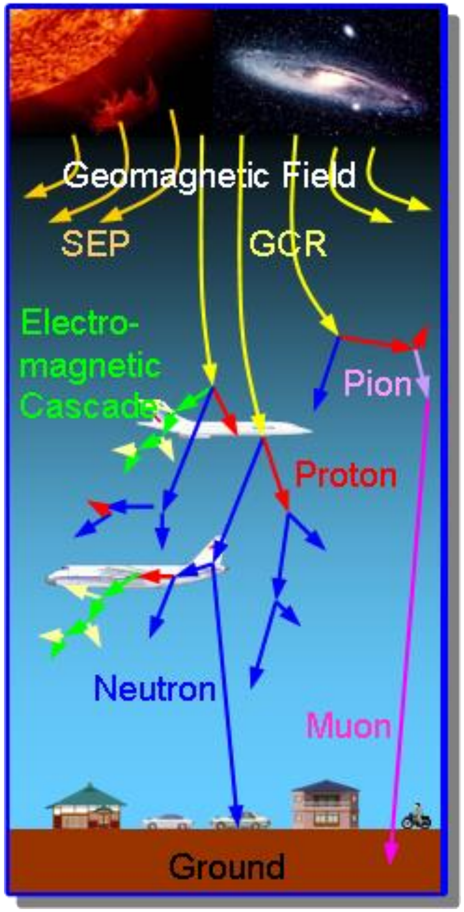


Summary

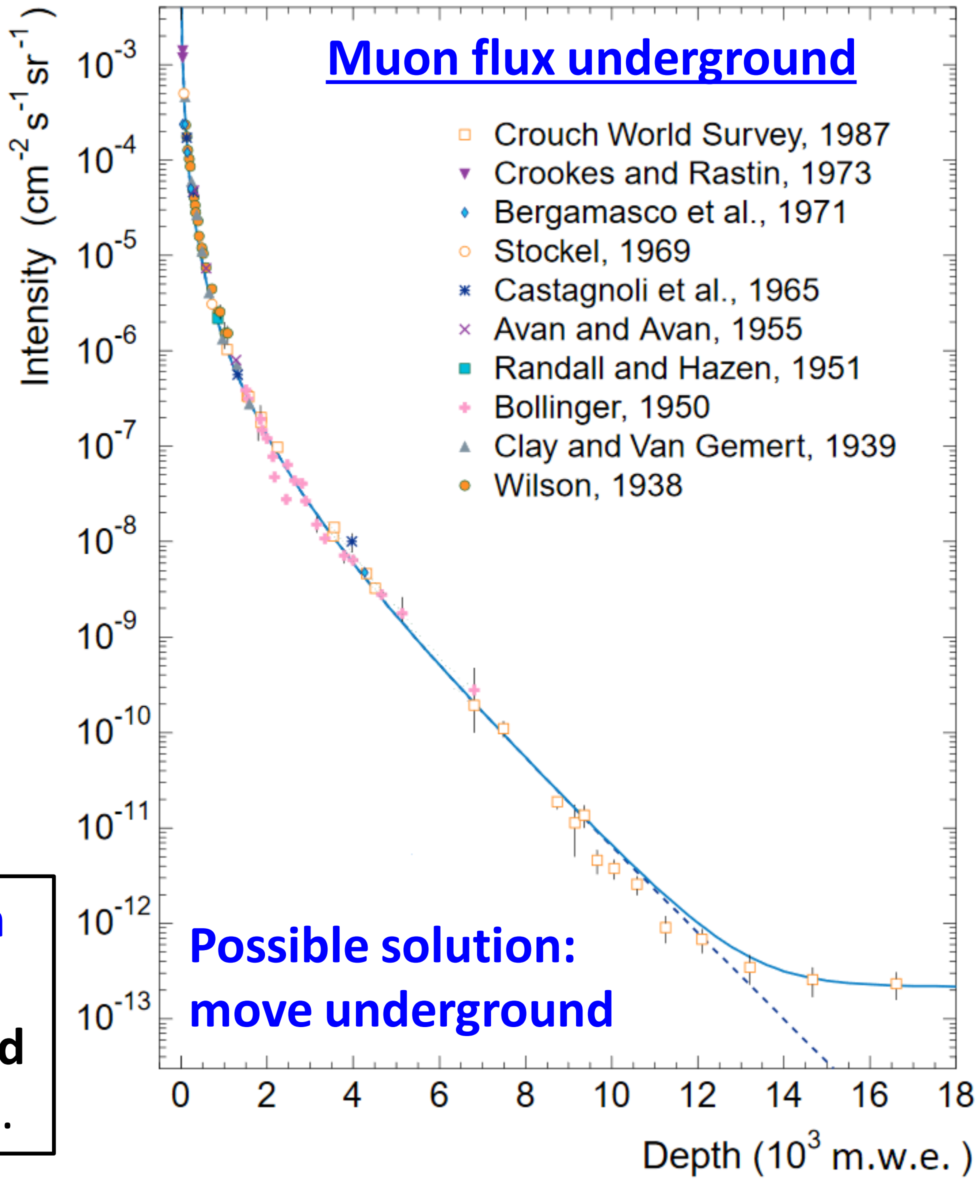
- We developed research infrastructure for the **Dark Matter search experiment** based on ultra-low background NaI(Tl) segmented detectors.
- Together with our partners we created a **laboratory for mass production of NaI(Tl) crystals** and achieved level of radio-purity of detectors used by the DAMA/LIBRA collaboration.
- Beginning of the full-scale detector construction depends on the Japanese government funding.

Thank you!

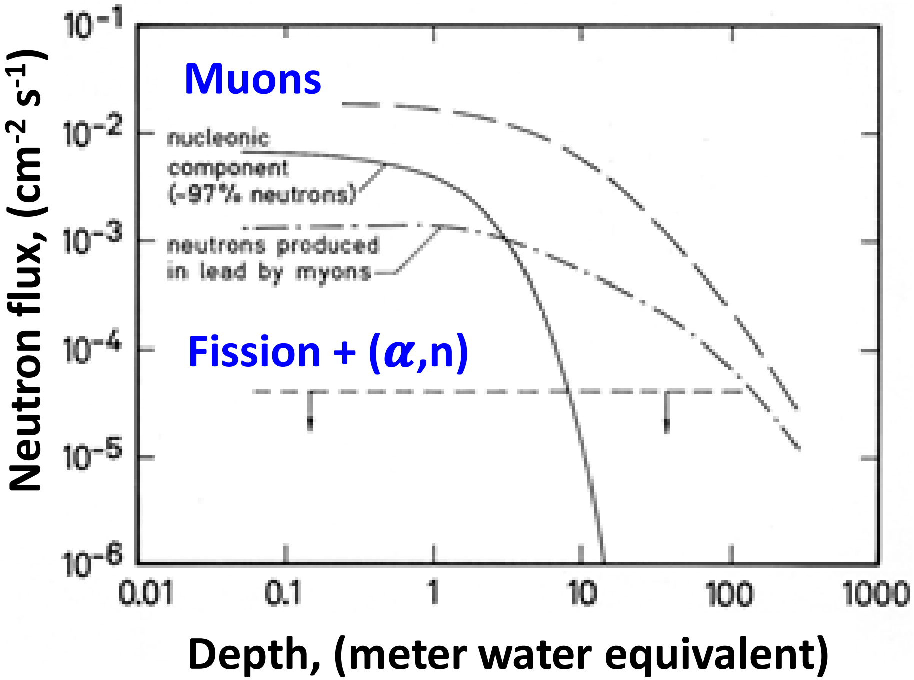
Other limits on search for a new physics

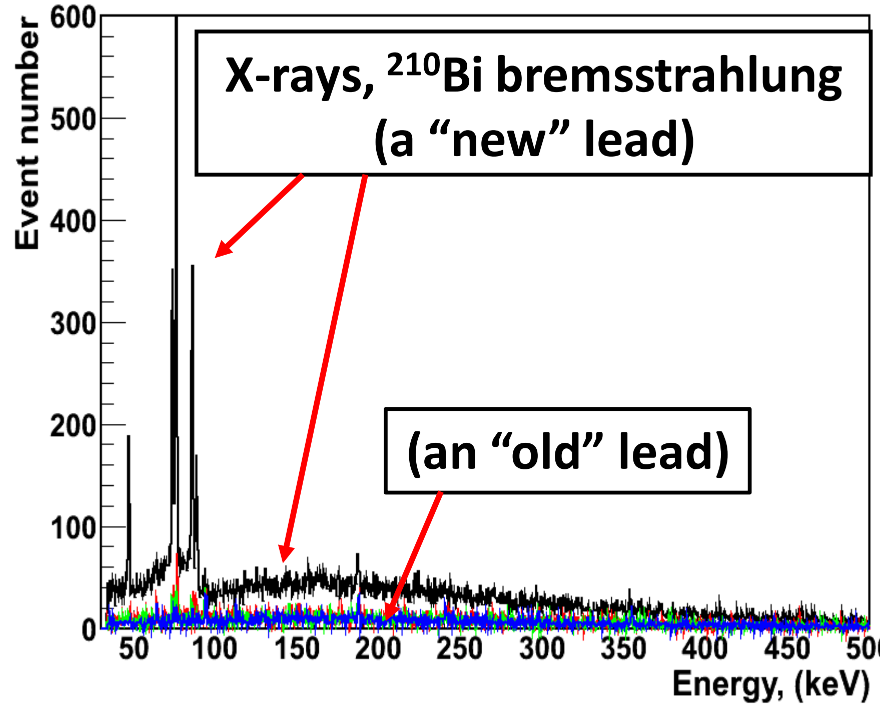


Muons, fast neutrons created by **high energy cosmic rays** in the Earth's atmosphere are source of **background in experiments at the Earth's surface**.



Sources of background other than muons





- ❑ The **Radon** that is present in the ground water and underground air (depends on the Uranium content in rocks);
- ❑ The **neutron background** produced by a spontaneous fission of heavy elements and in the (α,n) reactions at depth>100m;
- ❑ **Radioactive impurities** existing in detector components (a difference between our "new" and "old" lead is shown as an example).

Muons

Construction of an ultra-low background detector

- **High-class clean rooms** are needed for handing detector materials, detector construction & operation to avoid dust particles that contain **natural (e.g. U, Th, K) and artificial unstable nuclei (e.g. ^{137}Cs).** That includes clean rooms at commercial companies that produce materials and detector components, and which we often cannot control well.
- Production of pure materials often require construction of **purification systems on-site**, as well as **cleaning of the surfaces exposed to Radon** and, thus, contaminated by **^{210}Pb ($T_{½}$ = 22.2y)** and **^{210}Po ($T_{½}$ = 138d).**
- Some materials, as **Cu**, are easily **activated on the surface by fast neutrons,** e.g. via the **$^{63}Cu + n \longrightarrow {}^{60}Co + \alpha$** reaction **$86.4 \pm 7.8$ (kg · day)$^{-1}$** ^{60}Co (**$T_{½}$ = 5.3y**) nuclei are produced. This sets a stringent limit on the production time, storage and ways of transportation of cooper and other materials (e.g. Ge).
- All that work requires **sensitive and reliable research infrastructure** for control of materials radio-purity and background sources underground.