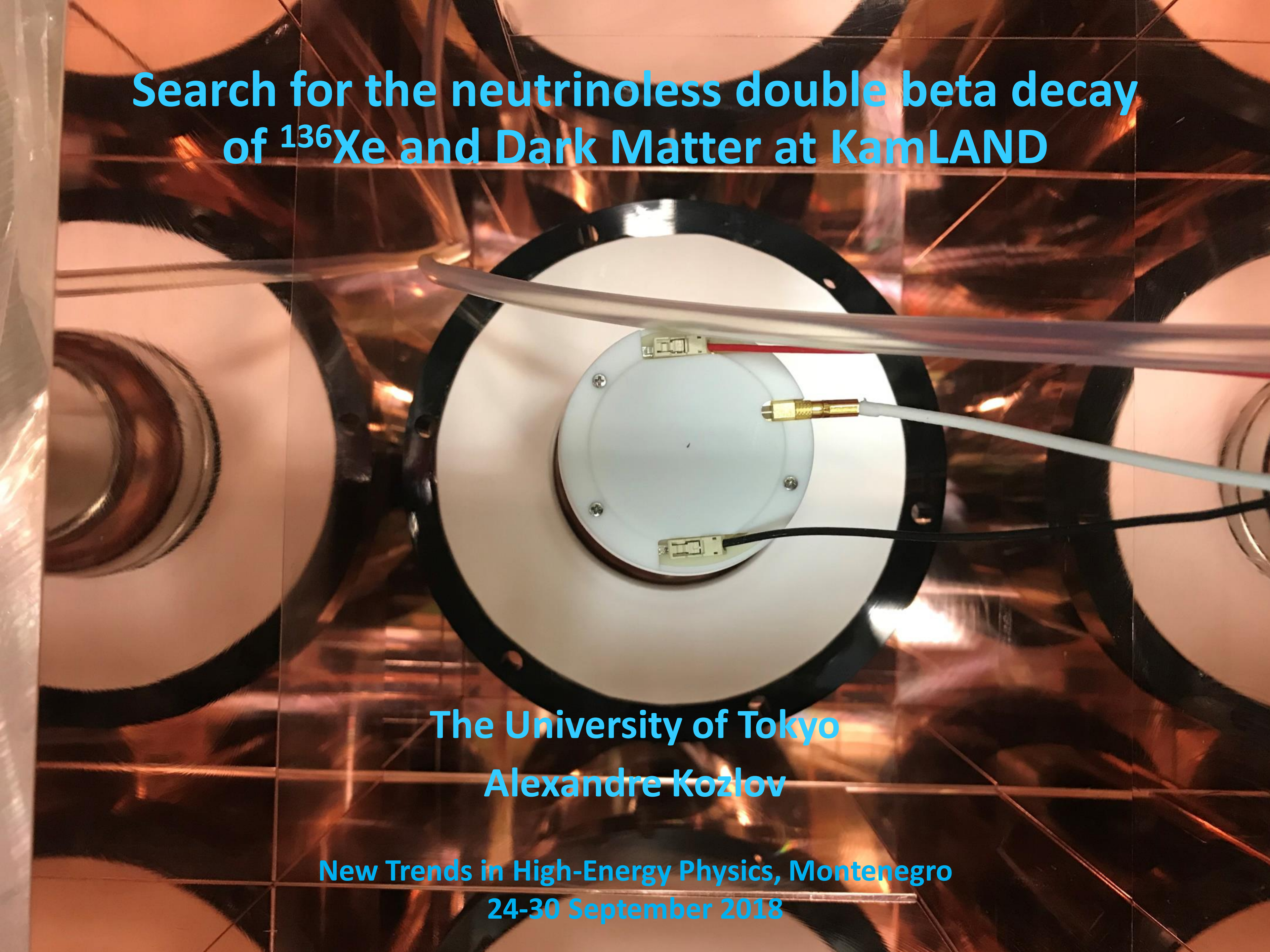
Search for the neutrinoless double beta decay of ^{136}Xe and Dark Matter at KamLAND

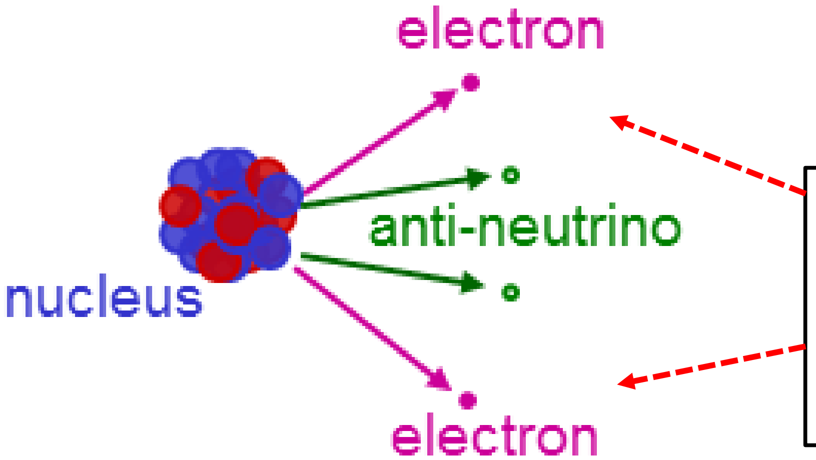


The University of Tokyo

Alexandre Kozlov

New Trends in High-Energy Physics, Montenegro
24-30 September 2018

Double beta decay (2vββ) allowed by SM

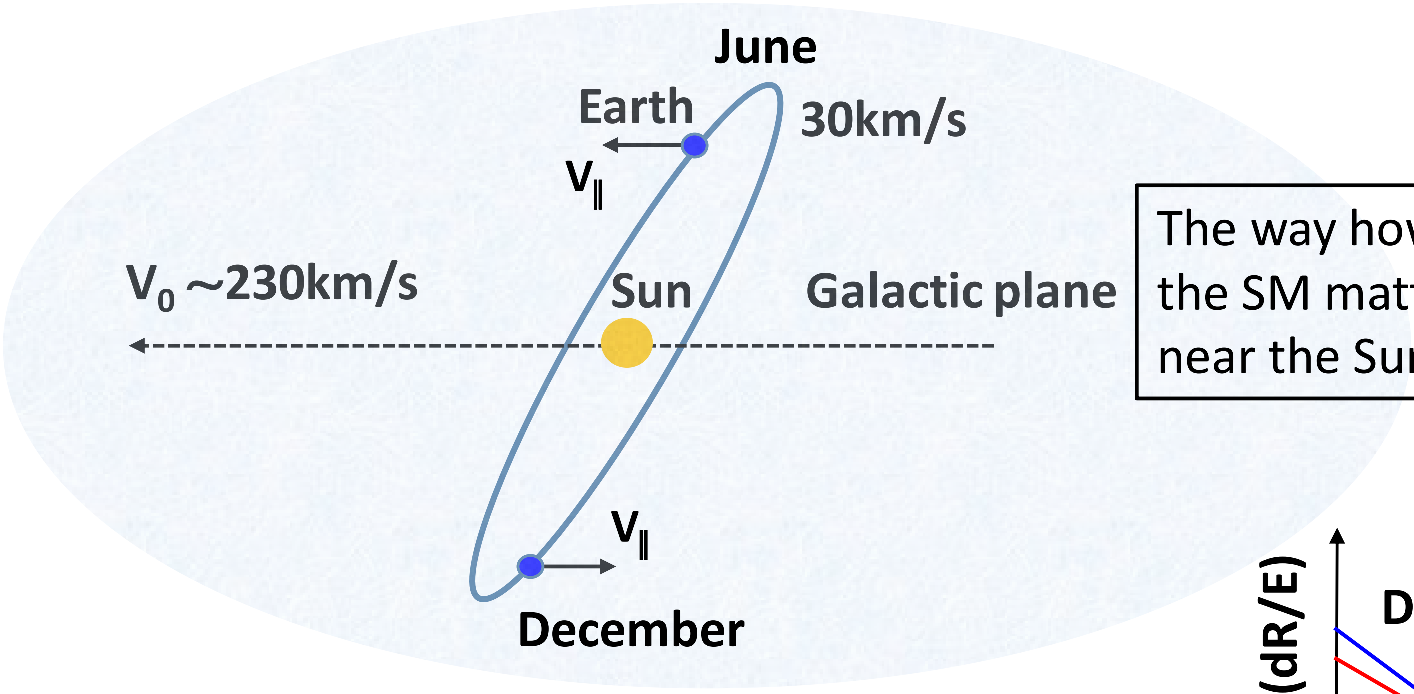


Two neutrino double beta decay

We need to detect **2 electrons** with a relatively low kinetic energy in presence of **intense γ/β background from a natural radioactivity**.

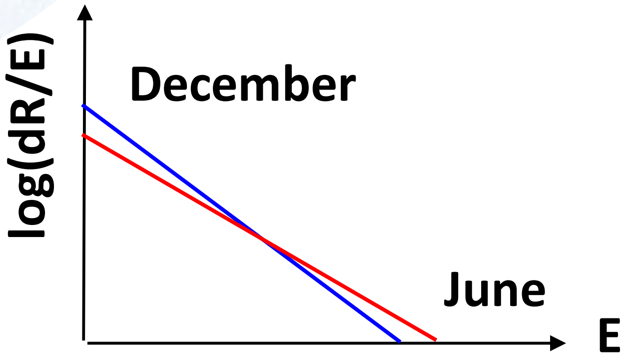
It is the slowest nuclear decay observed so far. The most attractive nuclei (**^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe**) have a half-life **$T_{½} \sim 10^{19}$-10^{21}y** , and **$Q_{\beta\beta} \sim$ 2-3MeV**. Energy of the 2vββ decay overlaps with that for decays of nuclei from the **Uranium/Thorium** chains (ordinary materials contain **10^{-6} - 10^{-9} g/g of U/Th**).

A hypothetical Dark Matter (DM) signal



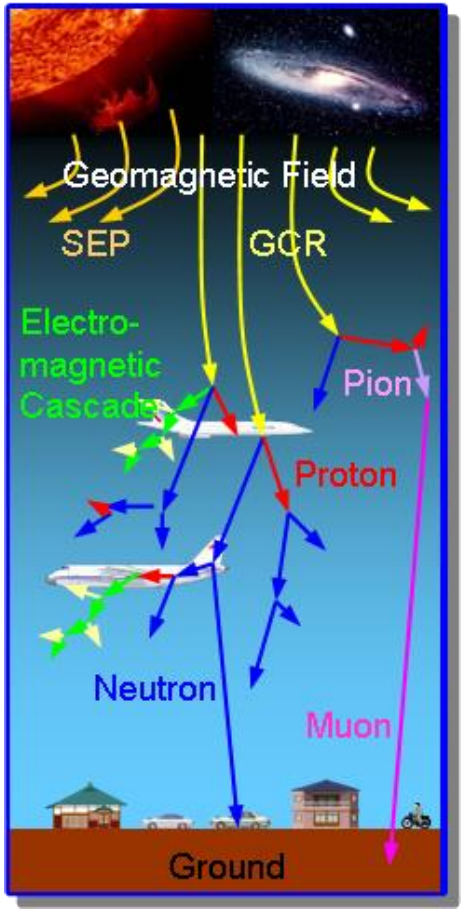
The way how DM interacts with the SM matter, its mass & density near the Sun are unknown.

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



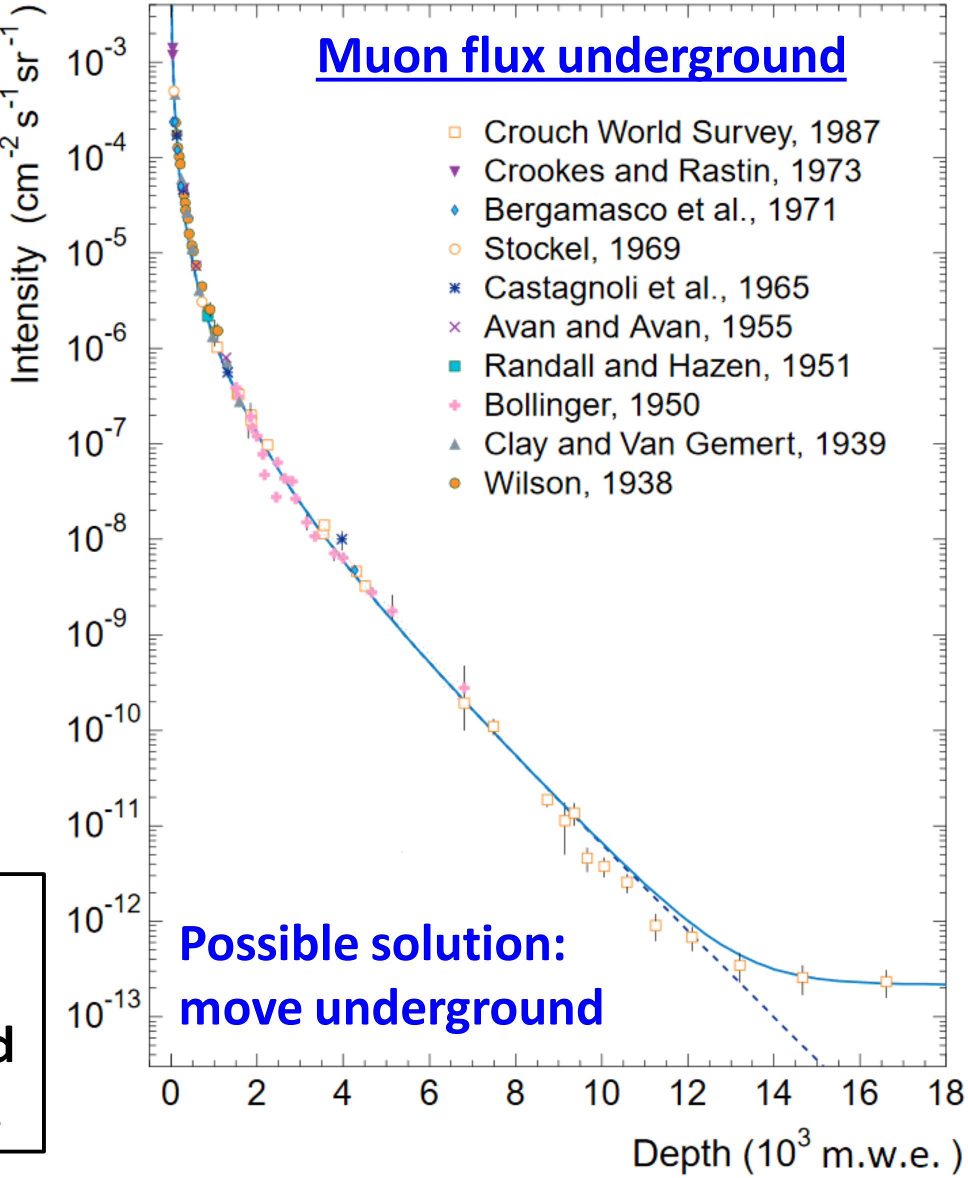
- ☐ Signal is caused by **Dark Matter particles scattering off detector nuclei**.
- ☐ Energy of the expected signal in the detector is in the range of **0-100keV**, which is **natural radioactivity dominant**.
- ☐ Fortunately, Earth motion around the Sun creates **annual modulation** of the measured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

Other limits on search for a new physics



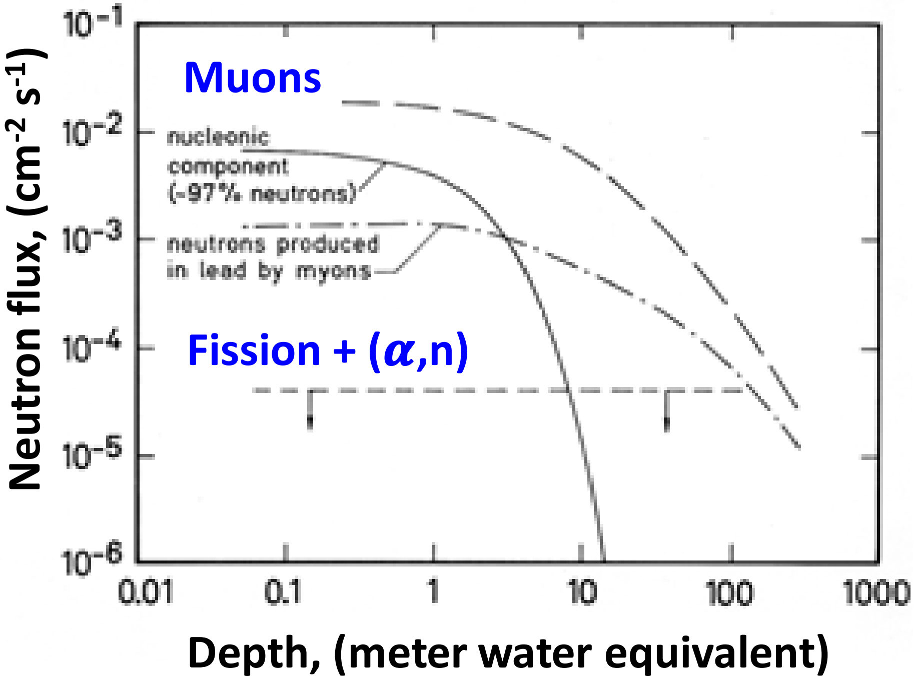
Muons, fast neutrons created by **high energy cosmic rays** in the Earth's atmosphere are source of **background in experiments at the Earth's surface**.

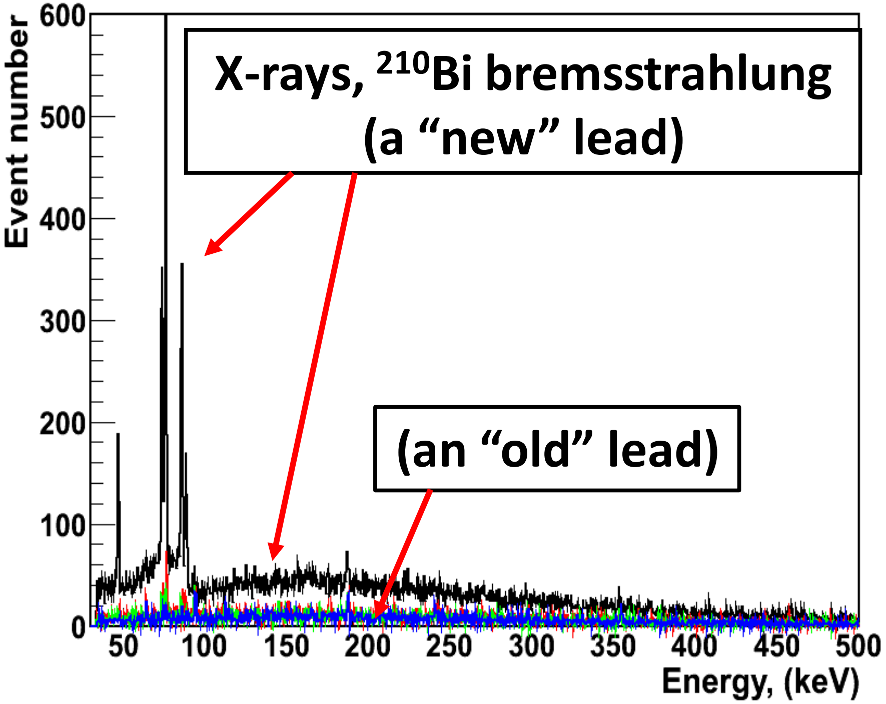
Muon flux underground



Possible solution: move underground

Sources of background other than muons



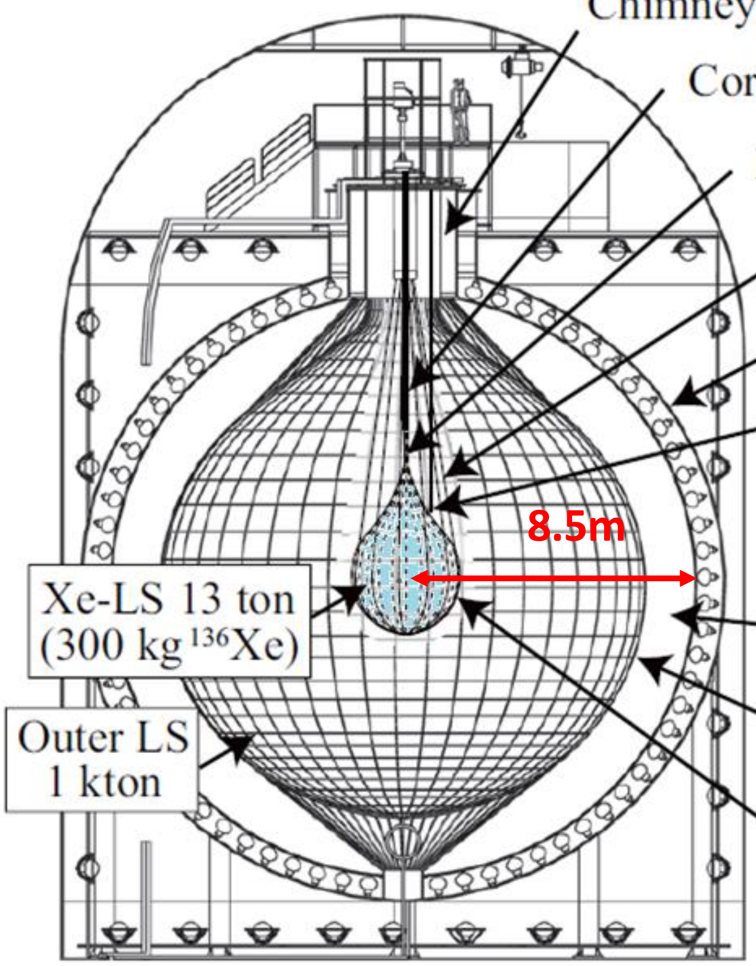


- ☐ The **Radon** that is present in the ground water and underground air (depends on the Uranium content in rocks);
- ☐ The **neutron background** produced by a spontaneous fission of heavy elements and in the (α,n) reactions at depth>100m;
- ☐ **Radioactive impurities** existing in detector components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

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 **$^{63}\mathrm{Cu} + n \longrightarrow {}^{60}\mathrm{Co} + \alpha$** 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.

The KamLAND-Zen overview



Chimney

Corrugated Tube

Film Pipe

Suspending Film Strap

Photomultiplier Tube

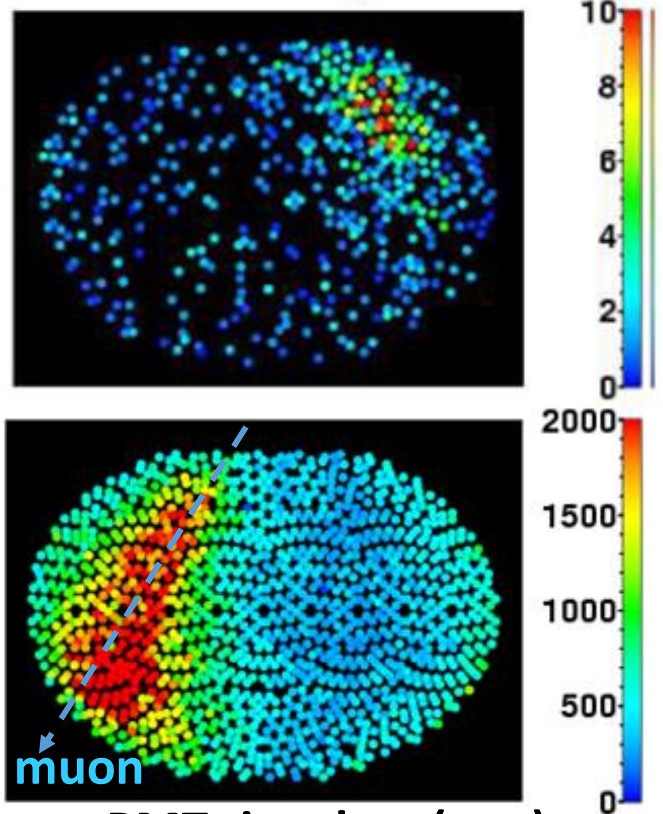
ThO_2W Calibration

Surrounded by rock (γ-ray source)

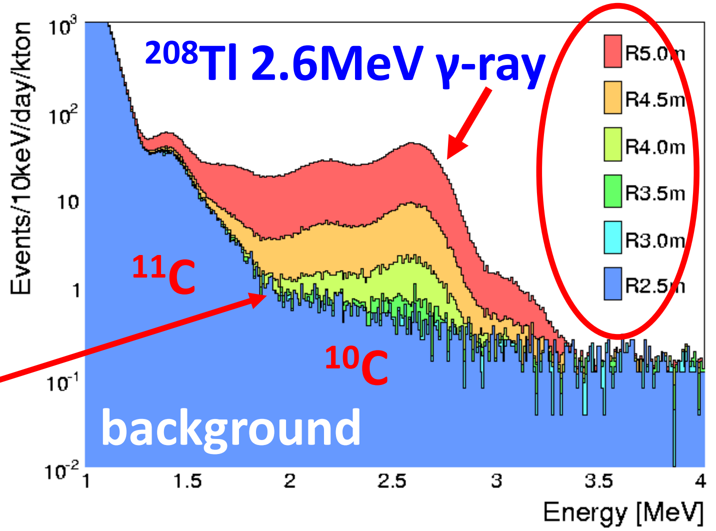
Buffer Oil

Outer Balloon
(13 m diameter)

Inner Balloon
(3.08 m diameter)

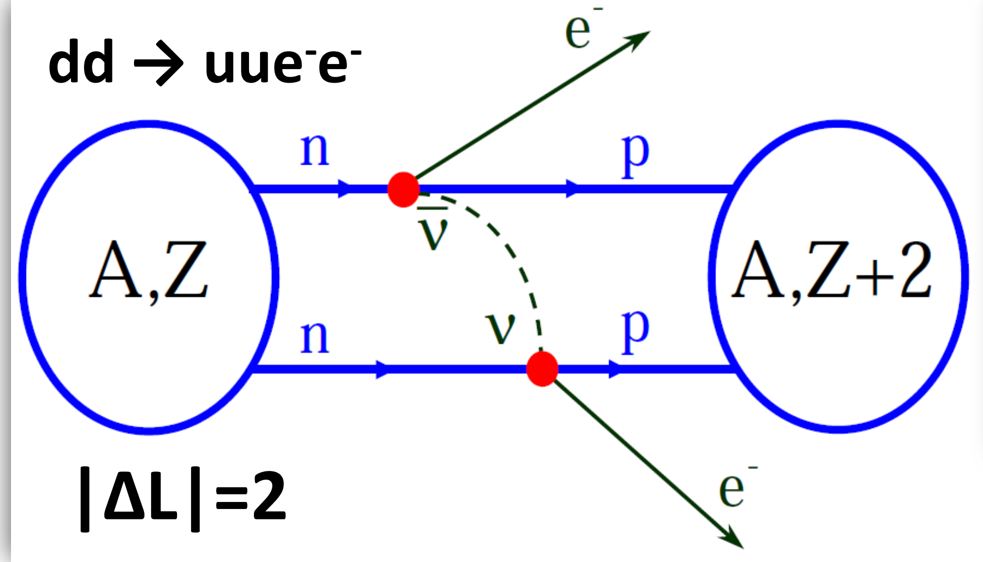


PMT signals, (p.e.)



Self-shielding effect: 6.5m of scintillator & 2m of oil (both liquids are highly radio-pure).

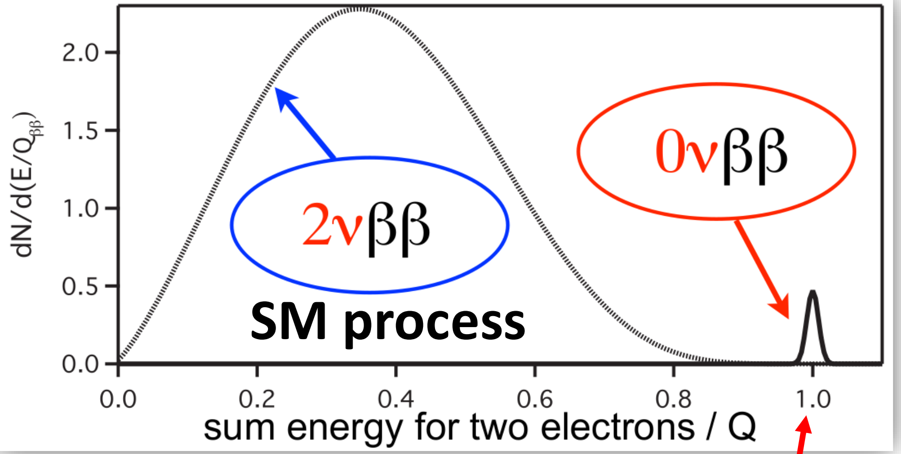
The 0νββ test of seesaw mechanism



Test of the **Leptogenesis** (Fukugita & Yanagida) as explanation for **baryon asymmetry of the Universe**

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\cdot|M^{0\nu}|^2\cdot \boxed{m_{\beta\beta}^2}$$

- $G^{0\nu}(Q_{\beta\beta},Z)$ – phase space factor
- $|M^{0\nu}|$ – nuclear matrix elements
- $m_{\beta\beta}$ – effective mass of neutrino

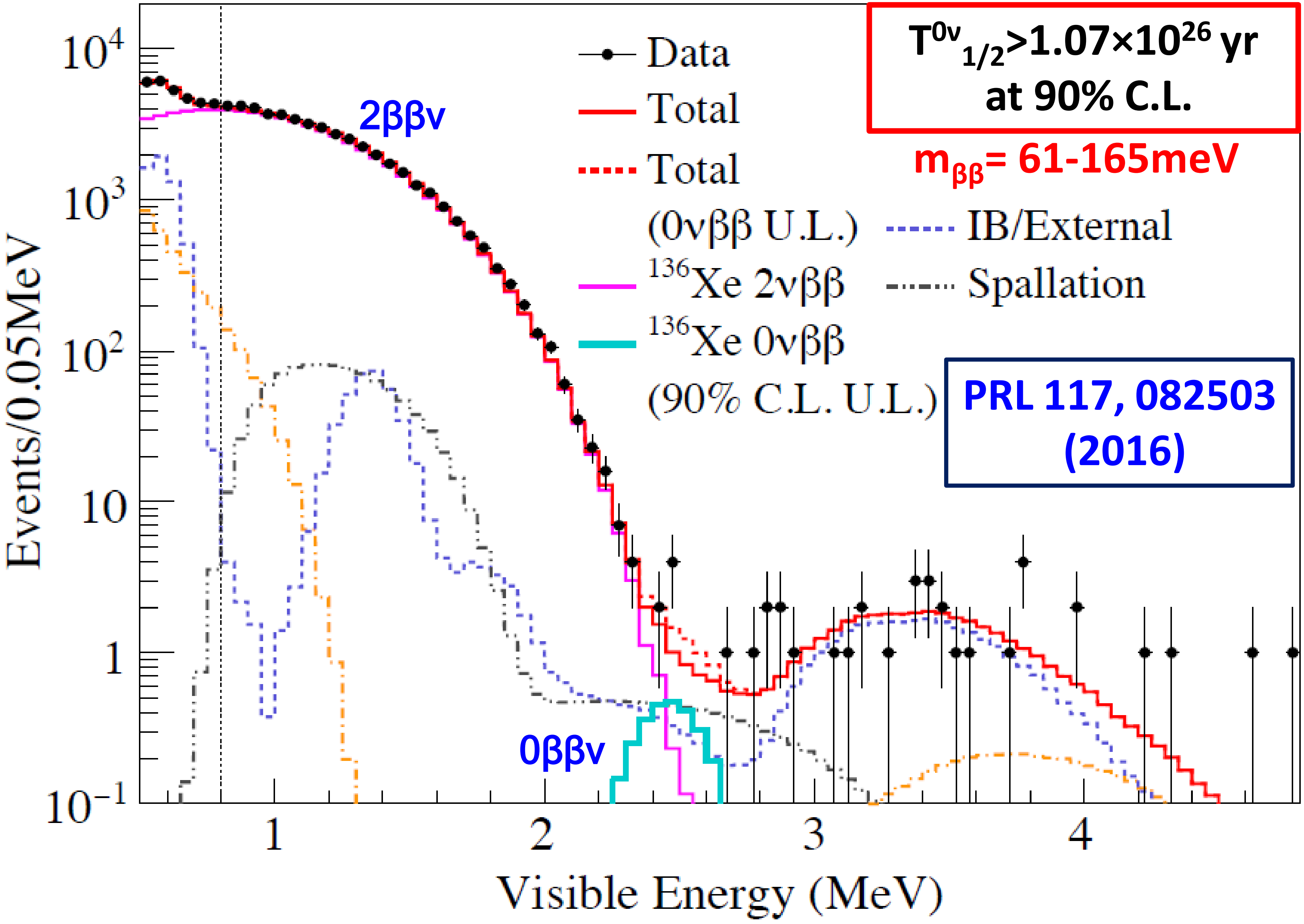


In calorimeters, as KamLAND, **sum of kinetic energies** of two electrons is measured

☐ The **only** method to measure **the absolute neutrino mass** below quasi-degenerate region.

☐ **Neutrino sector** is the **only place** where **physics beyond SM** was already observed.

KamLAND-Zen 400: final result (year 2016)

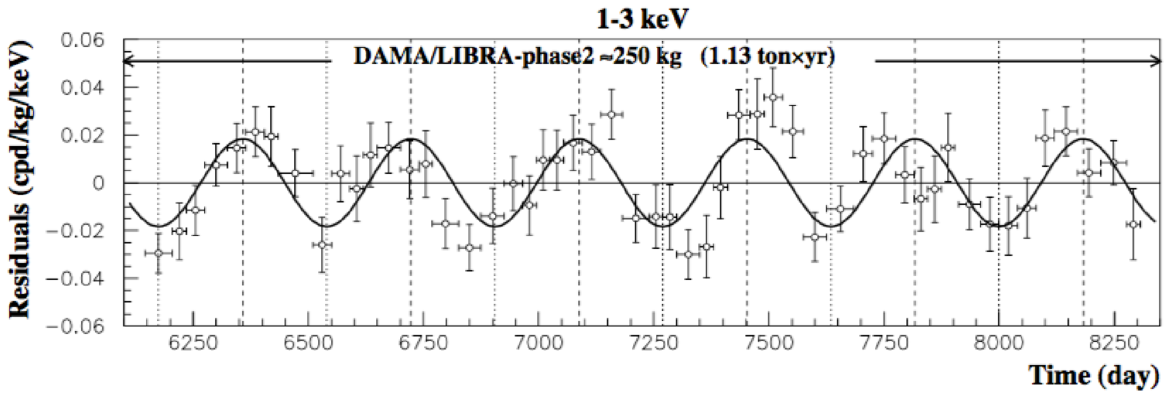


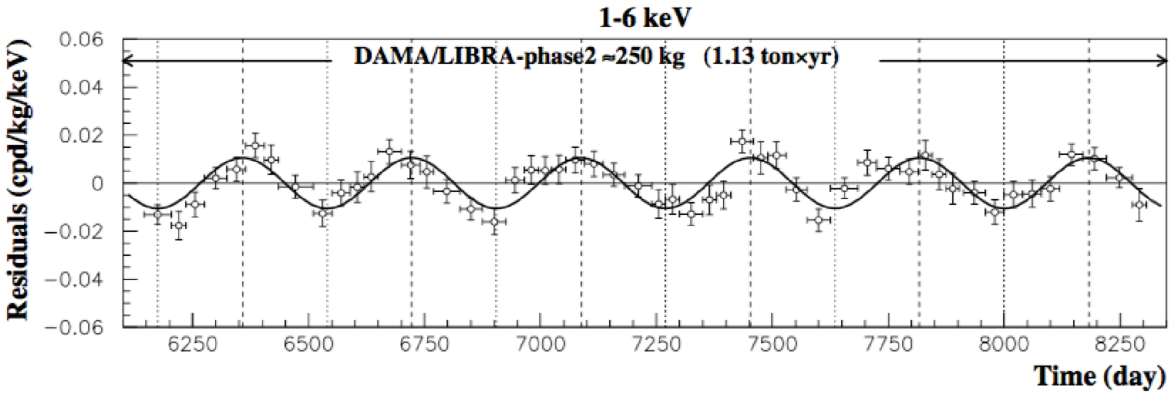
$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr at 90% C.L.

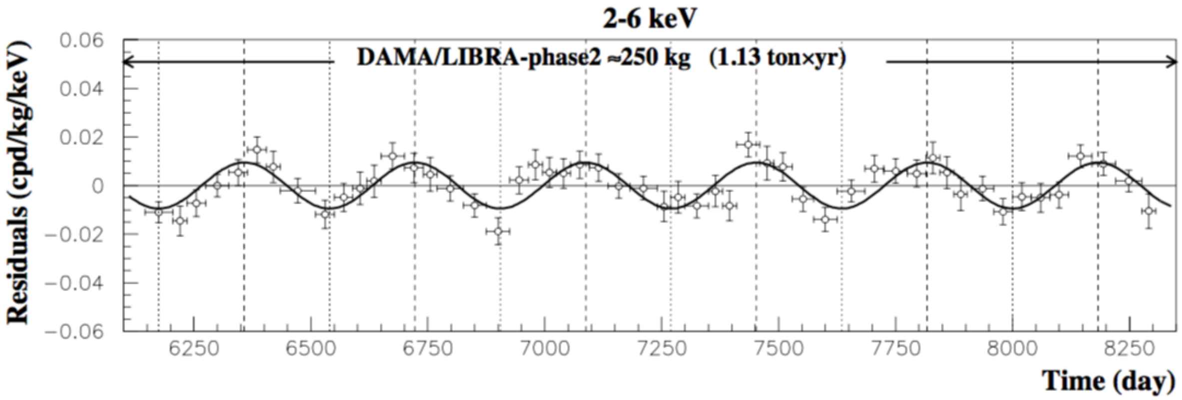
$m_{\beta\beta}$= 61-165meV

PRL 117, 082503 (2016)

The DAMA/LIBRA-phase2 result







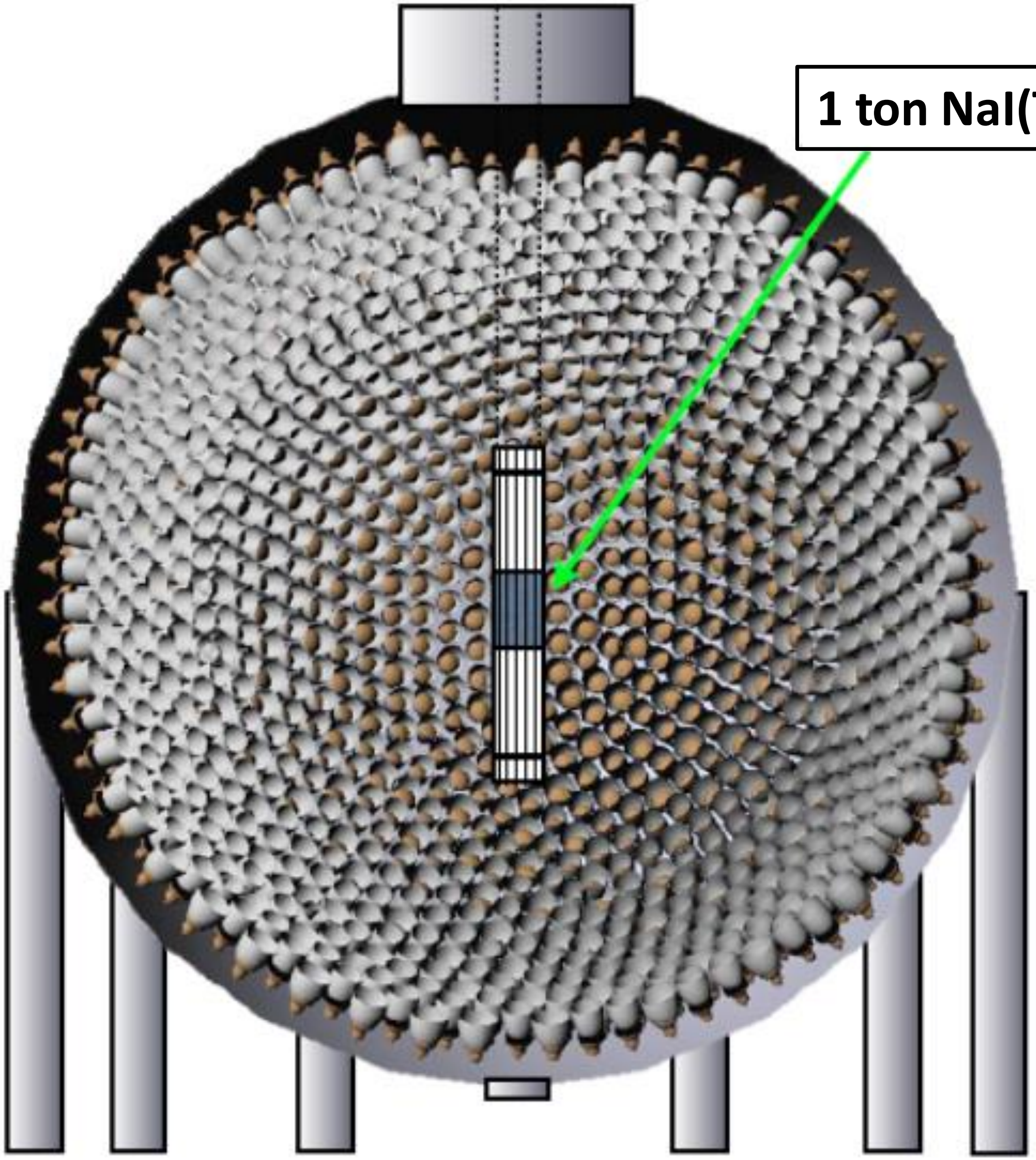
The **DAMA/LIBRA-phase2** favours the **presence of a modulated DM signal** with proper features at **9.5σ C.L.**

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

It is essential to:

1) Repeat an **"identical" experiment** at other locations
2) **Reduce the background** below 1 ev/keV/kg/day

The KamLAND2-PICO futuristic view



1 ton NaI(Tl) Dark Matter detector

The same idea: use the central, "background-free" part of **KamLAND** as an **active shielding for the Dark Matter detector**.

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**.

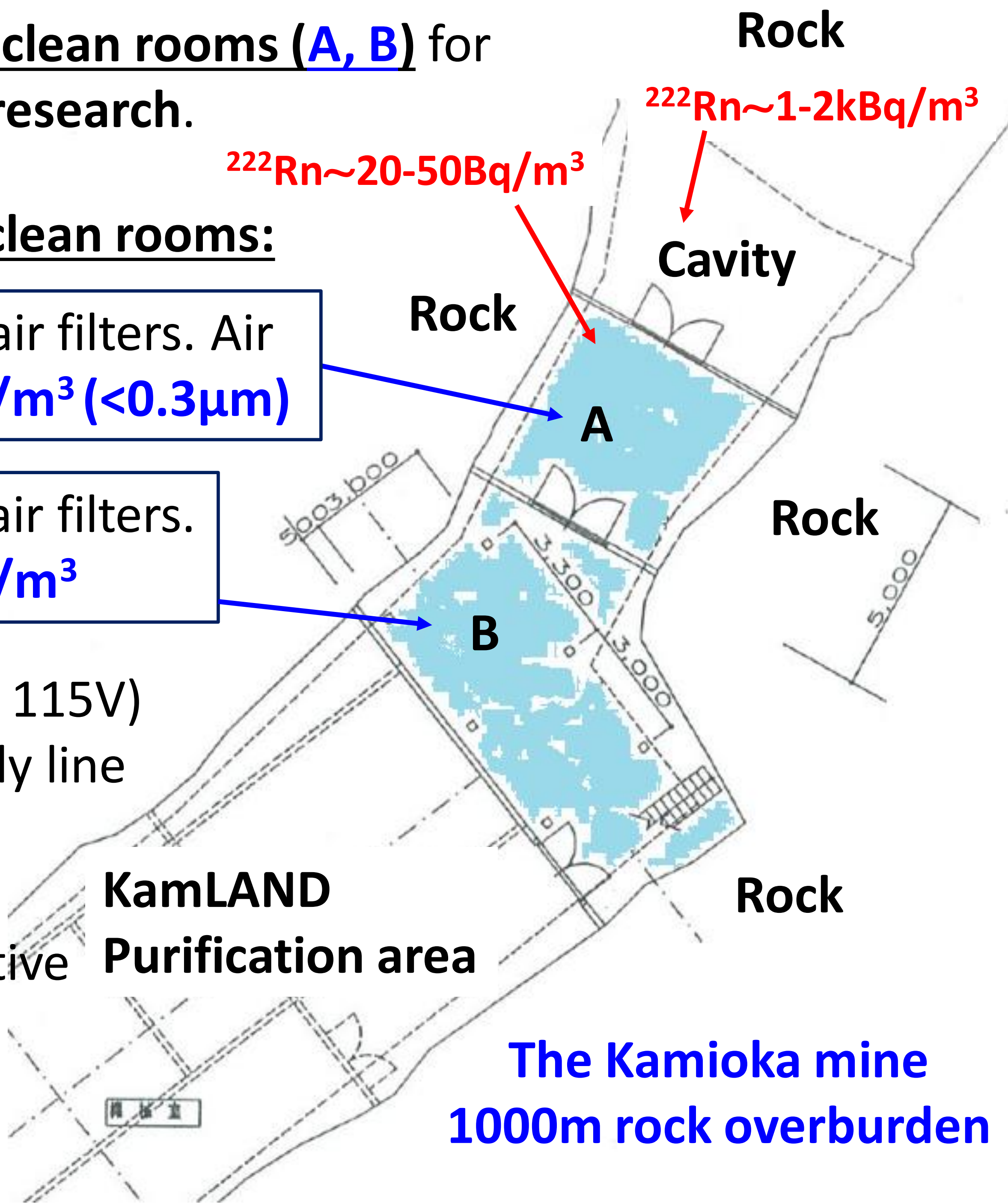
Current conditions at the clean rooms:

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:

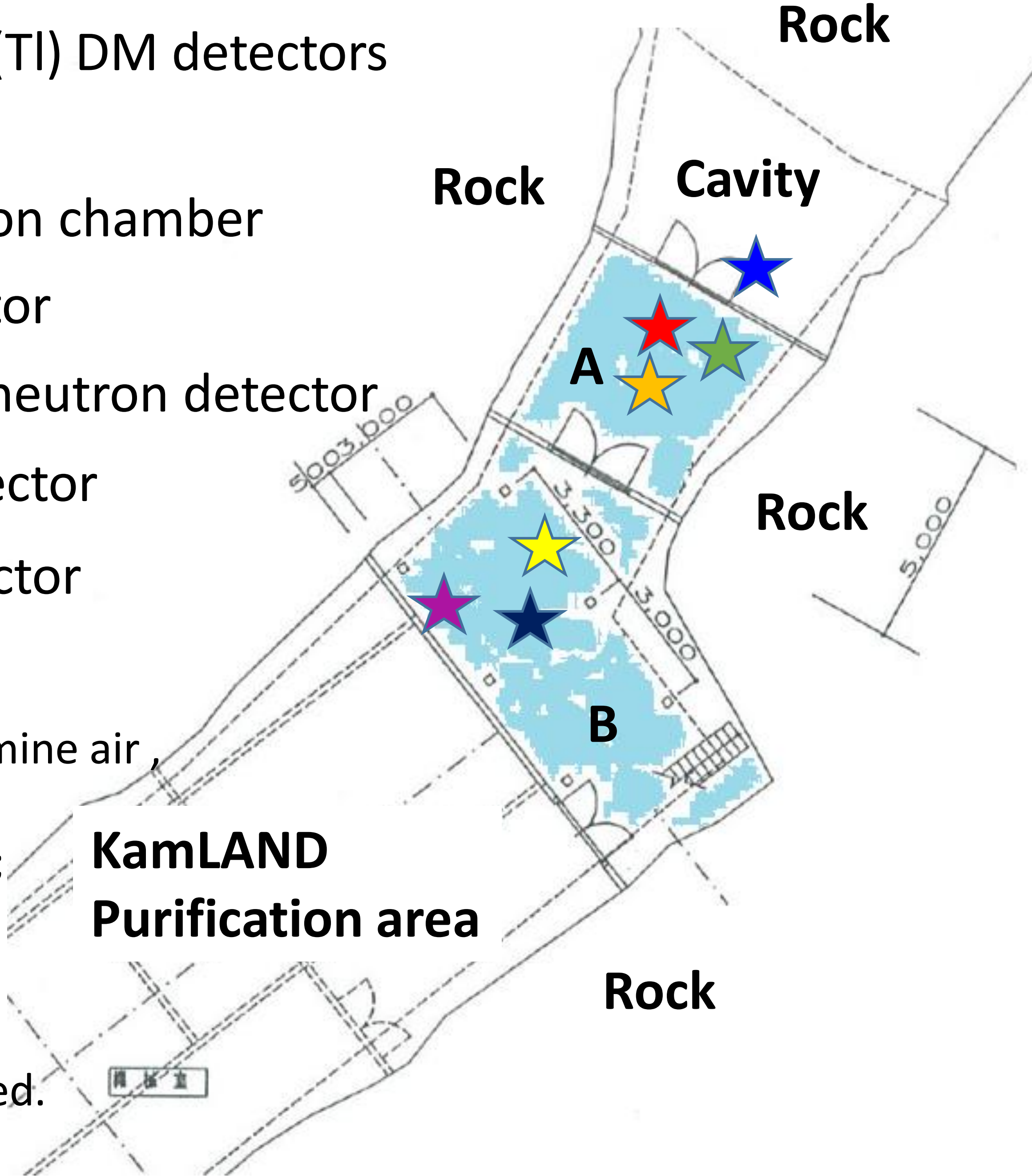
(5-10m^3 per hour) creates **a positive air pressure** relative to neighbour rooms.



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
- ★ 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;

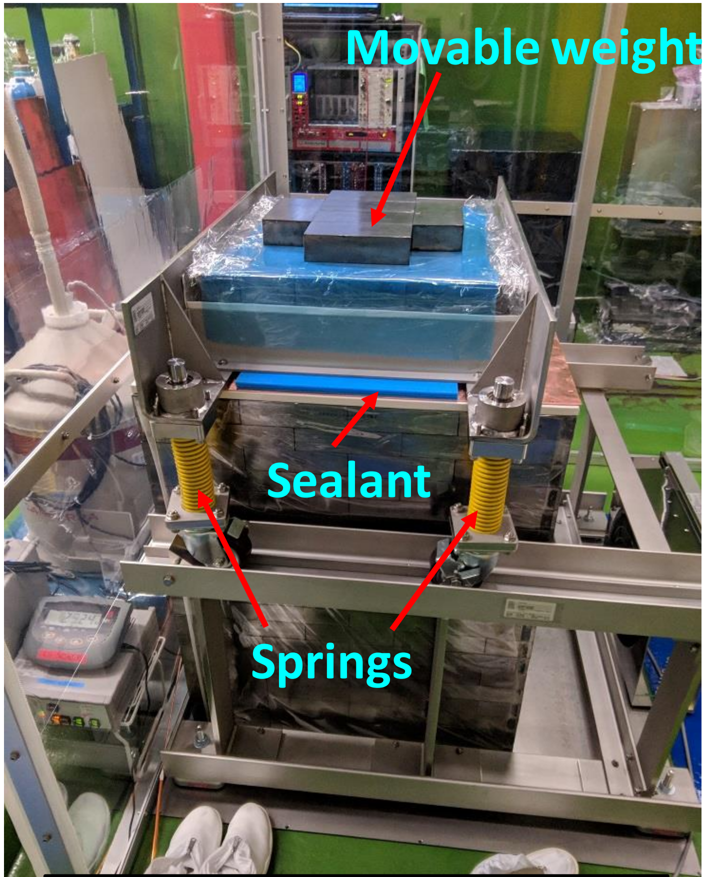
☐ flow of **nitrogen** to detectors;

☐ the **Radon activity** in the inner and mine air of the Cavity;

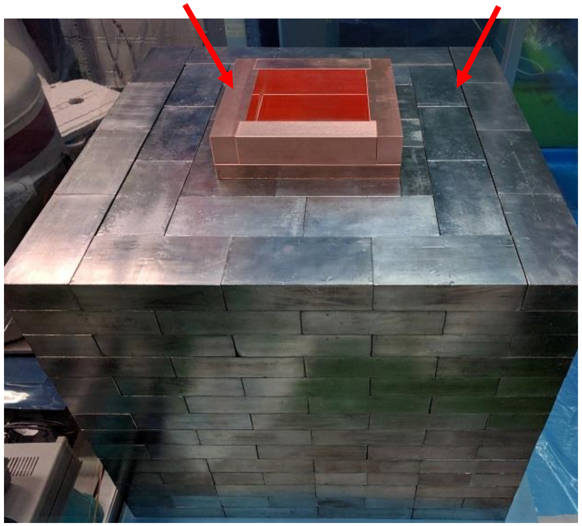
☐ the **neutron flux**

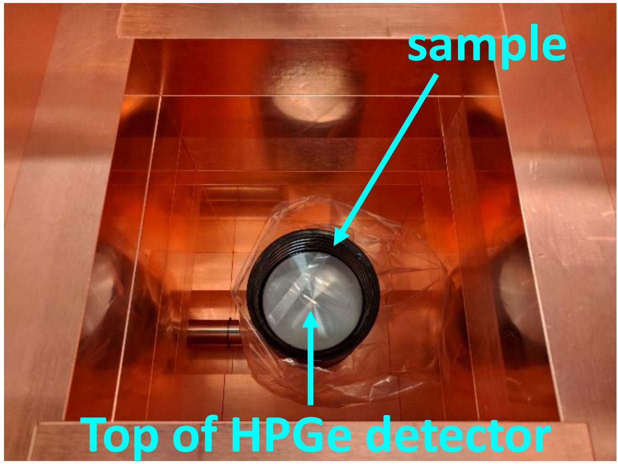
are being monitored and recorded.

The HPGe detector

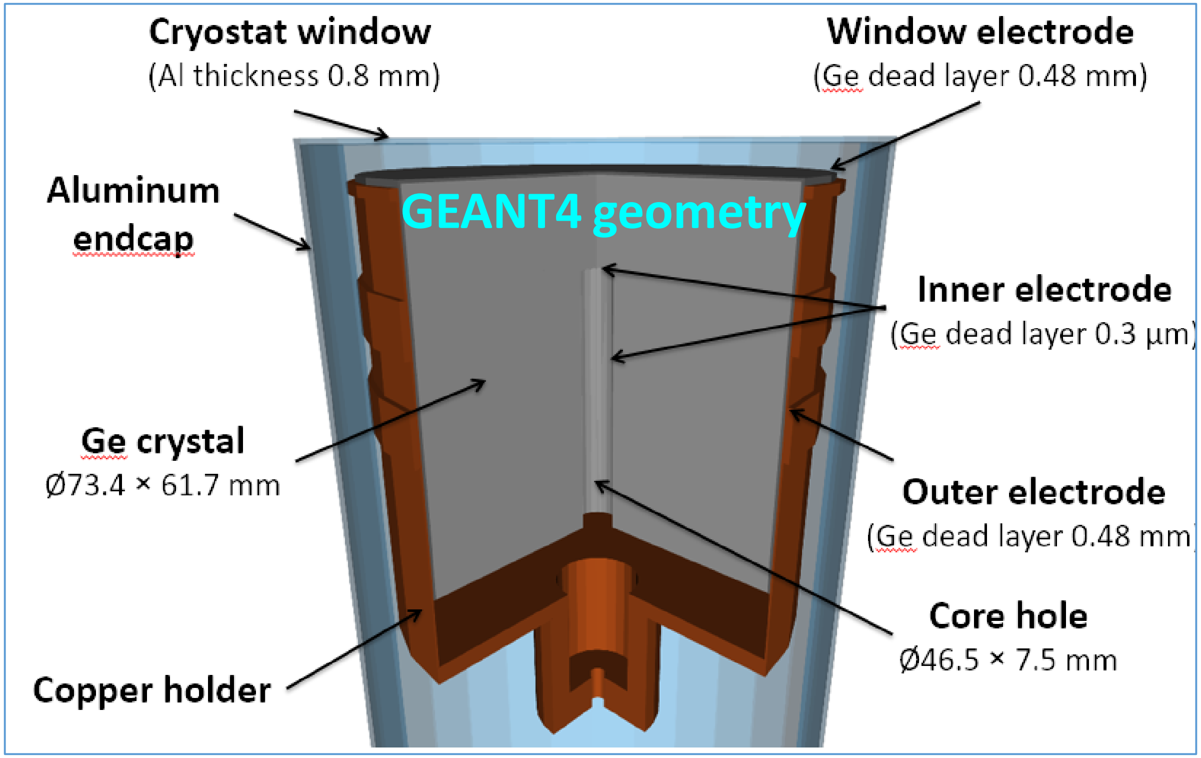


5cm-thick Cu 25cm-thick Pb (3 types of lead bricks)

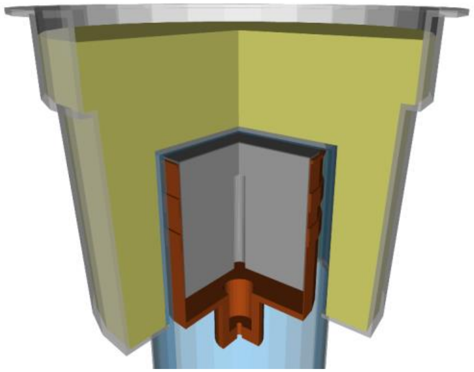




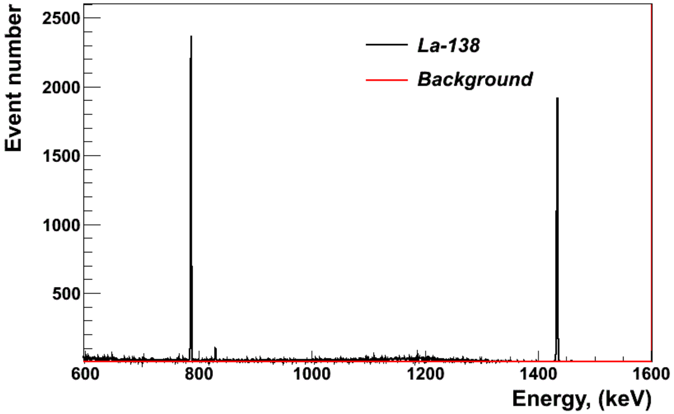
- ☐ **$320cm^3$** Ge crystal
- ☐ All home-made design
- ☐ Inside of the clean tent
- ☐ Air flow via ULPA filters
- ☐ **5.5L/min of N_2** via MFC
- ☐ **Cu/Pb** 15y underground



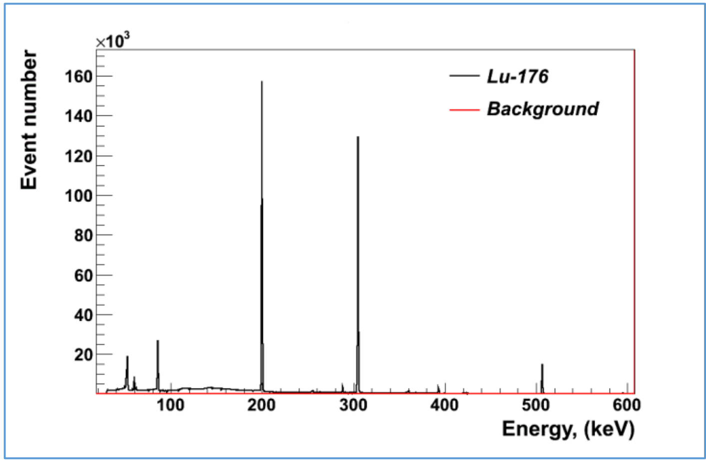
The HPGe detector calibration



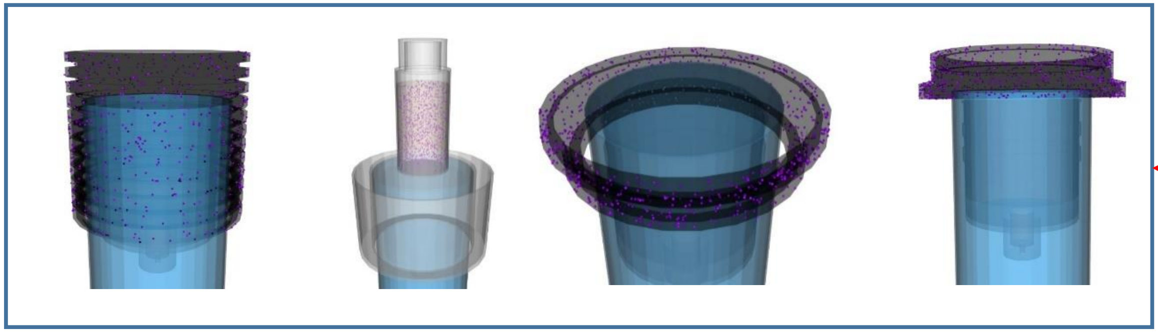
Marinelli beakers (0.7, 1.2L) are used for loose and liquid samples



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**



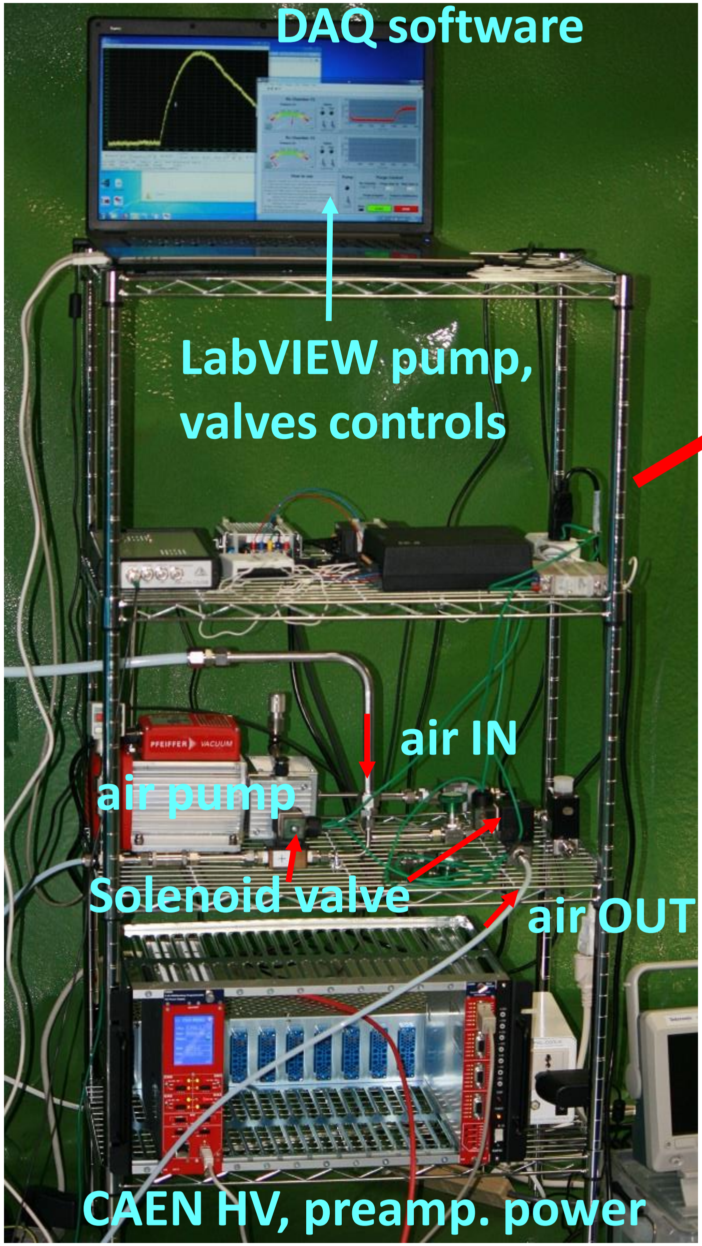
For every sample a realistic **GEANT4 model** is prepared to calculate the γ-ray detection efficiency

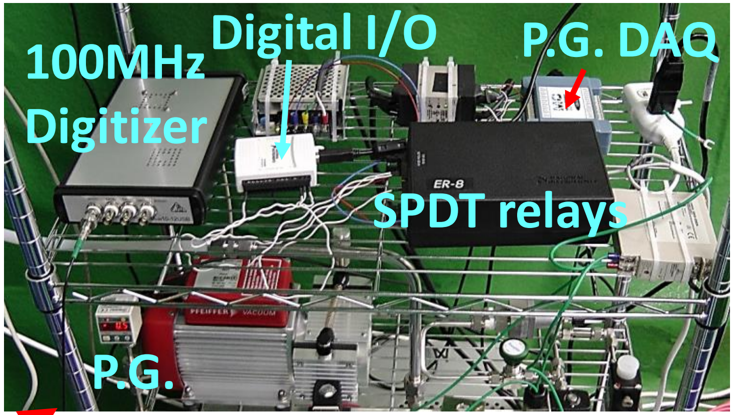
We made **extended sources with a small admixture of Lu and La** to verify correctness of the detector GEANT4 model based on the information provided by Canberra Corp.

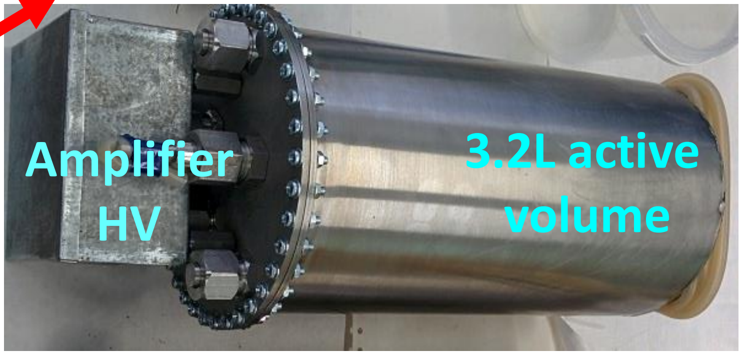
The ion-pulse ionization chamber

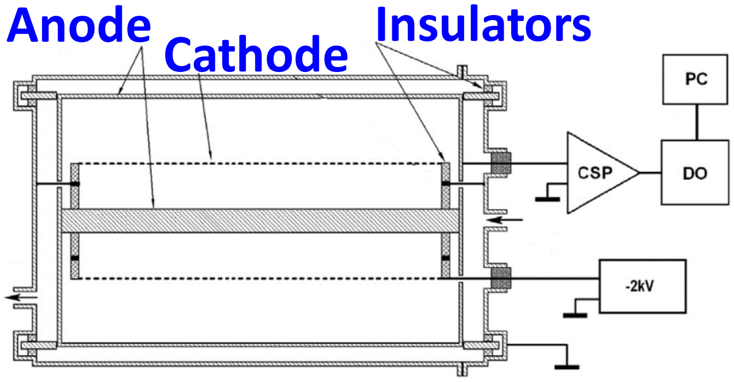
JSPS grant: 16K05371

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

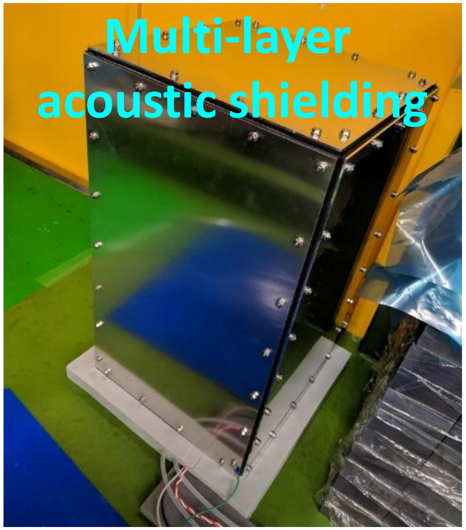


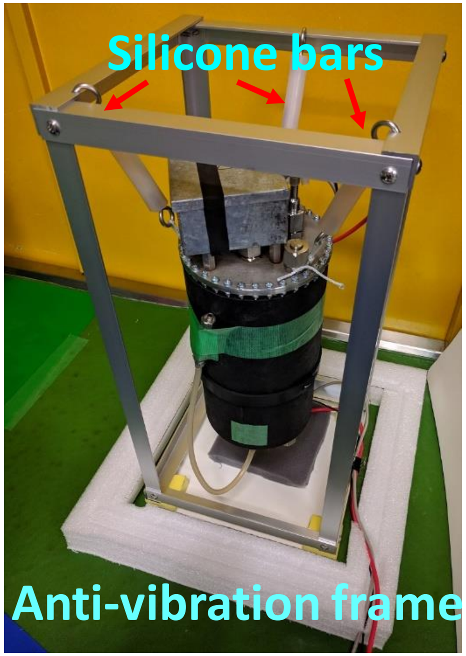






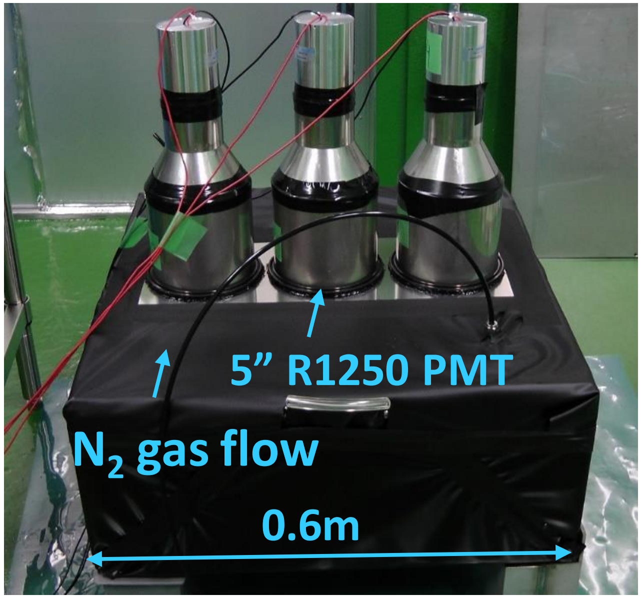
Energy resolution: 2% (FWHM)





The ^{6}LiF/ZnS thermal neutron detector

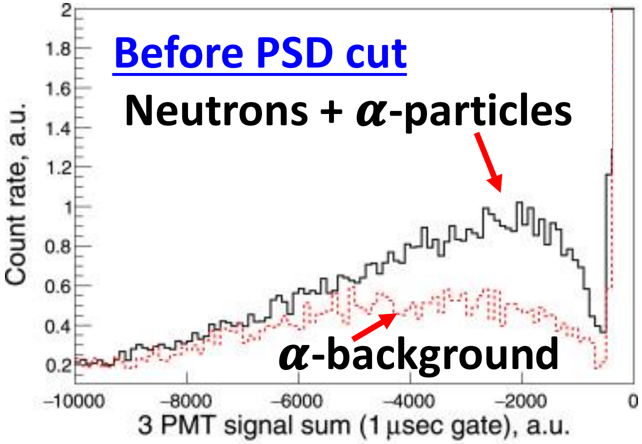
JSPS grant: 16K05371

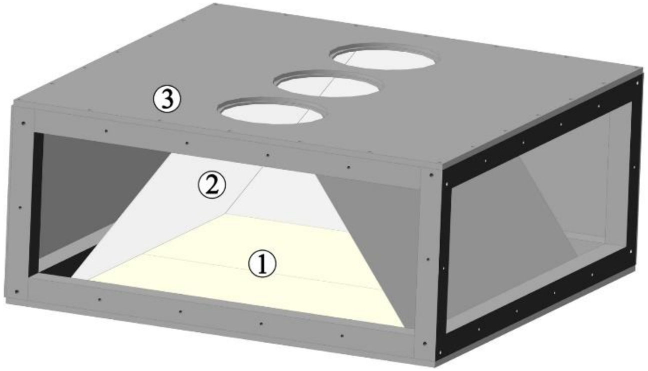


The thermal neutron flux: $(6.43 \pm 0.50)\times10^{-6}$ n cm^{-2} s^{-1}

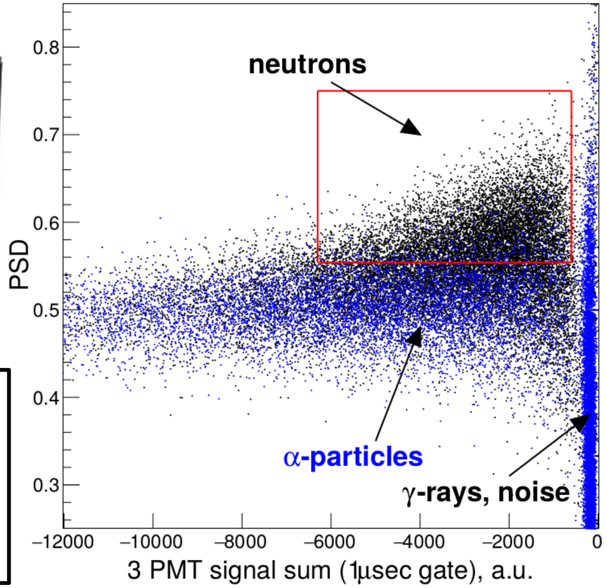
DAQ: w-f digitizer N6724F

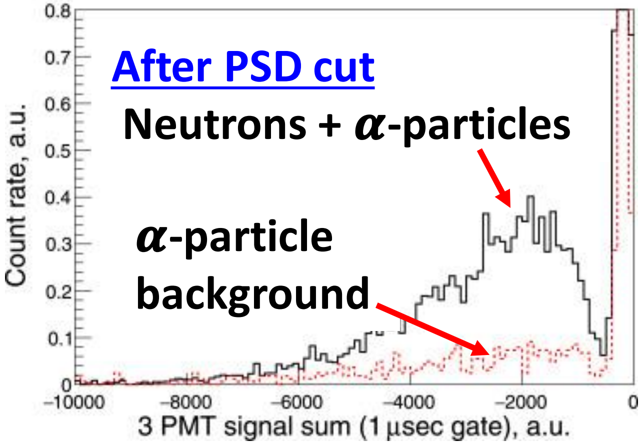
$$^6\mathrm{Li} + \mathrm{n} \longrightarrow \alpha + \mathrm{t} + 4.78\mathrm{MeV}$$





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

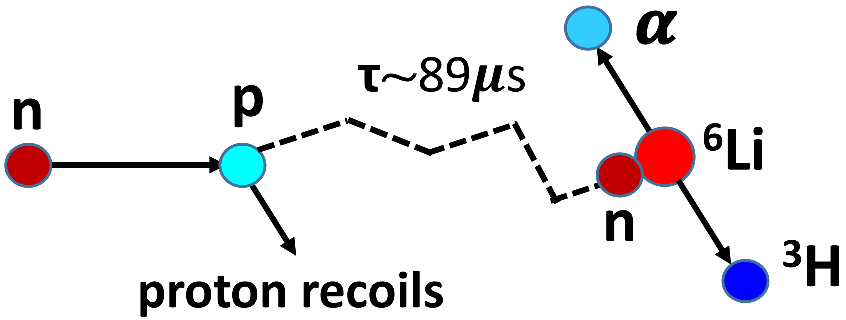


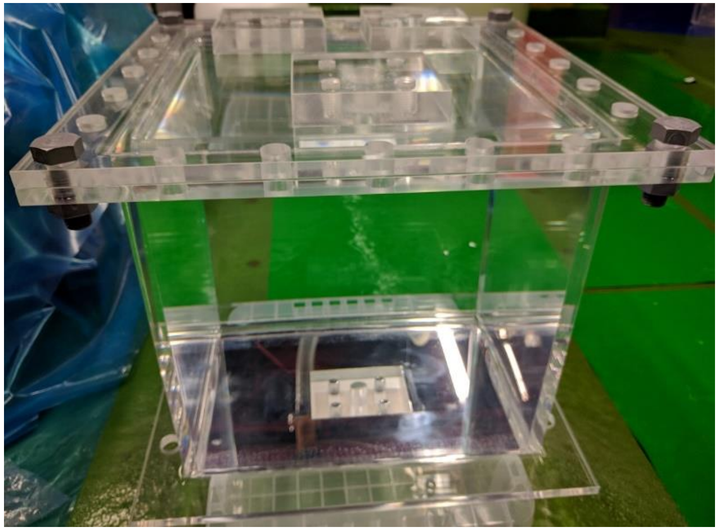


A.Kozlov, D. Chernyak, NIM A, vol 903, 21 September 2018, Pages 162-169

The fast neutron detector

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





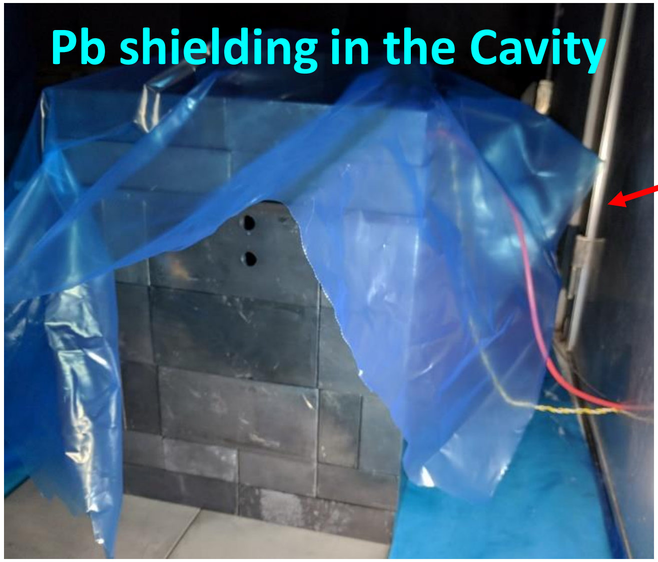
Acrylic tank (30×30×30cm)

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

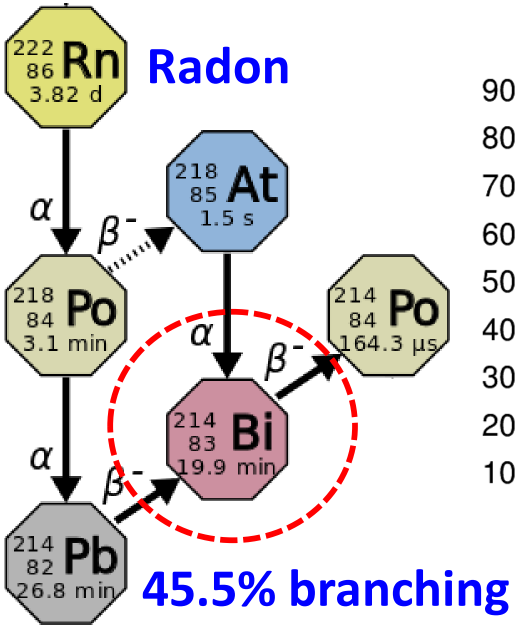
Photo-sensors: **4 Hamamatsu 5” R1250 PMTs** (low K.)
DAQ: **CAEN DT5720** (4ch, 12bit, 250MS/s)
Shielding: **10cm of lead** to reduce accidentals
Pulse-shape discrimination works for both prompt and delayed signals. A **94% γ-ray rejection** for a 90% eff. cut on the delayed signal was achieved.

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

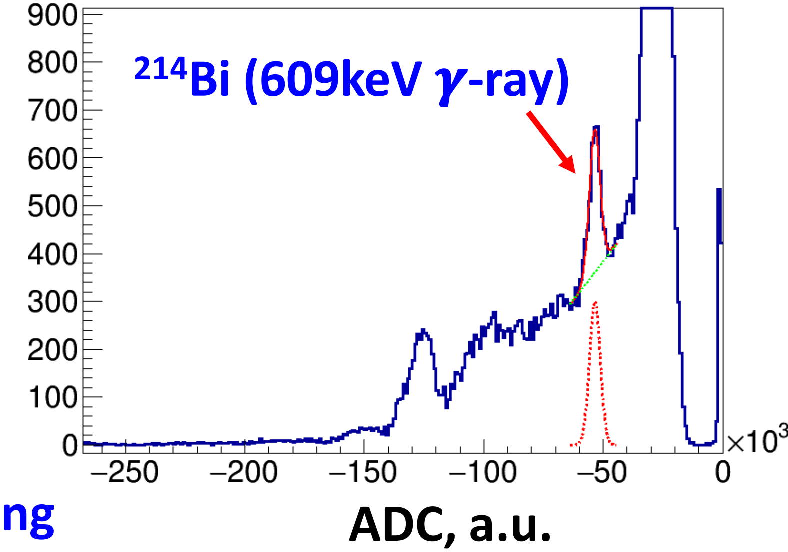
The NaI(Tl) radon detector



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)



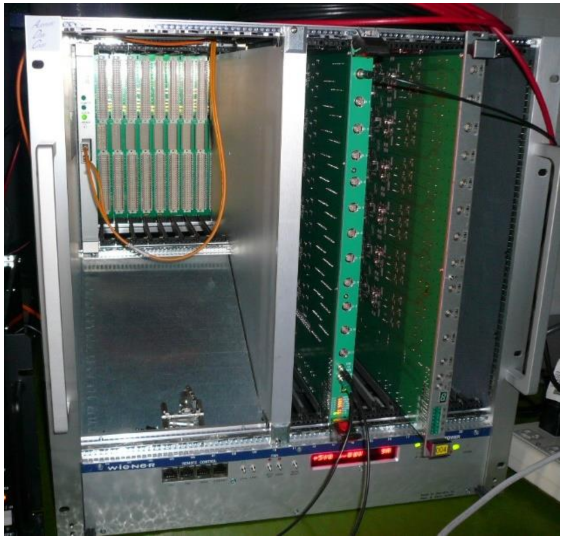
Events accumulated in 1 day



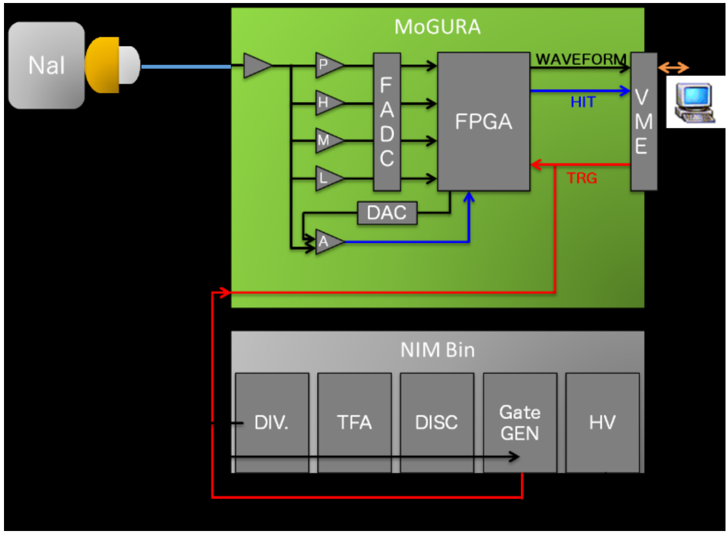
2×2cm NaI(Tl) crystal + H3178 PMT directly connected to the **DT5730 w-f digitizer** (14-bit, 500 MS/s) was used to measure radon activity in the Cavity outside of the clean rooms. The ion-pulsed ionization chamber is difficult to use at that location due to a high radon activity (>1Bq/L) and relative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

Test setup for the NaI(Tl) DM detectors

Mogura DAQ developed with Tokyo Electron Device Ltd



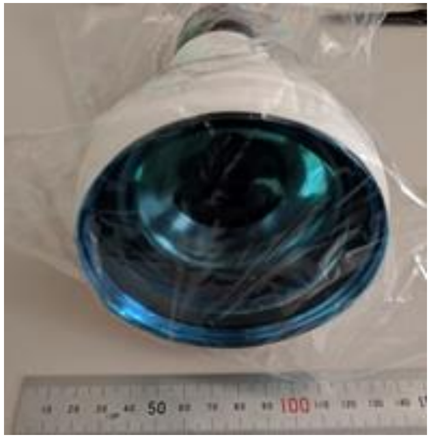
Mogura DAQ (9U VME)



Mogura + TFA filter

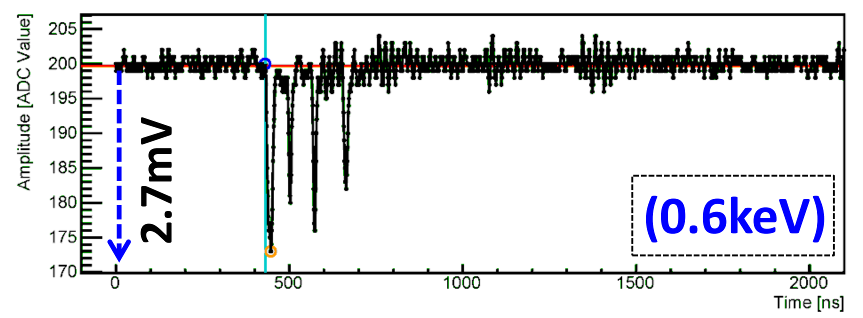
Bottom: >**30cm of lead**
Walls: **15cm of lead**
Inner: **5cm** of special **Cu**
Flushed with **3L/min of N_2**

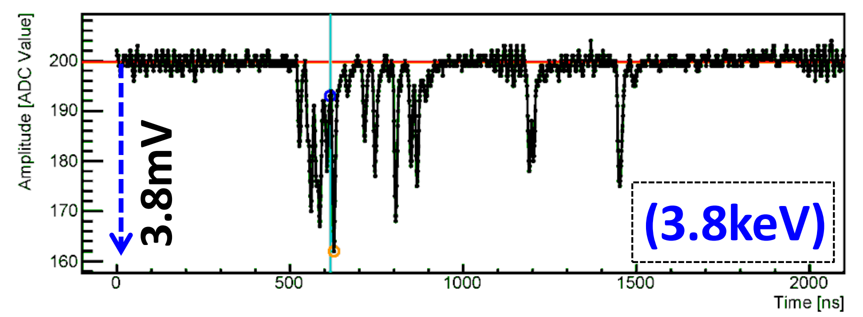
- **12ch** Input ⇒ scalable
- **0.1mV-10V** (PHML gain channels) covers energy range **from 1keV DM pulses to several MeV α-particles**
- **1ns, 5ns** sampling FADC
  ⇒ essential for rejection of
  low-E short pulses (PMT noise)
- **10μs** waveform
- Analog/Digital discrimination

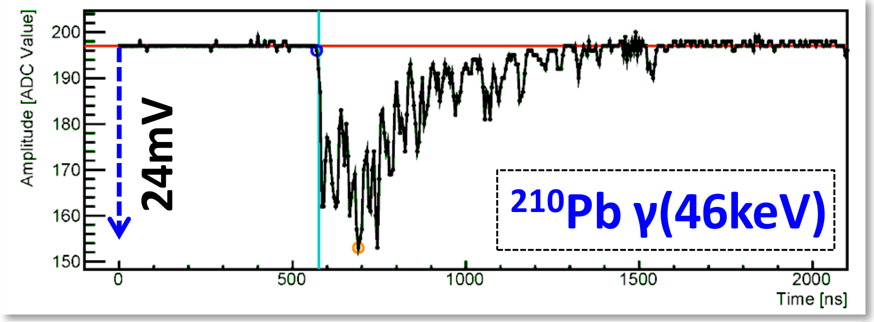


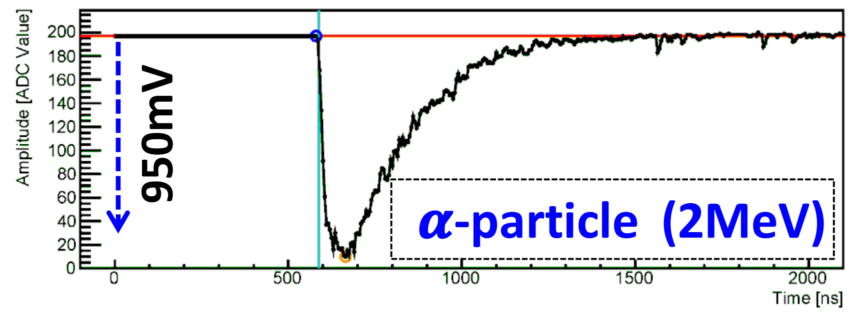
Hamamatsu metal body high QE ultra-low background PMTs: **R11065-20, R13444X**

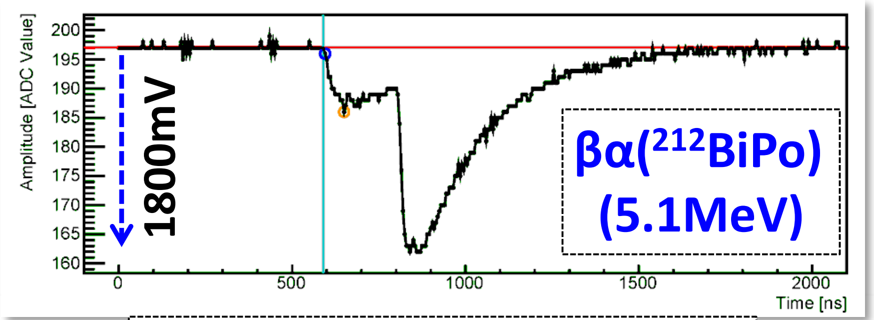
NaI(Tl) signal characteristics

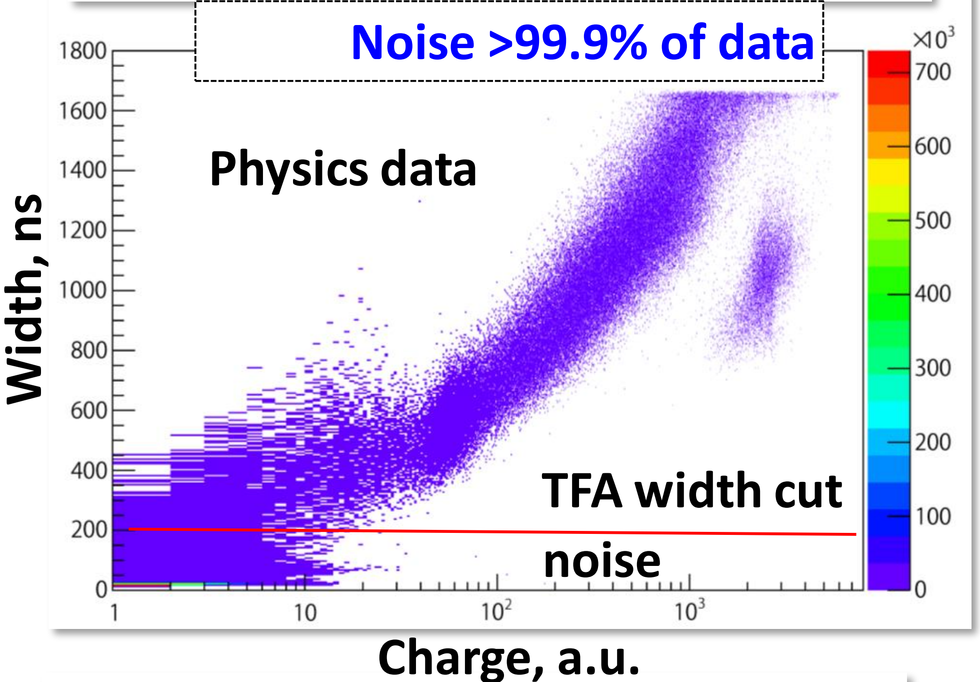


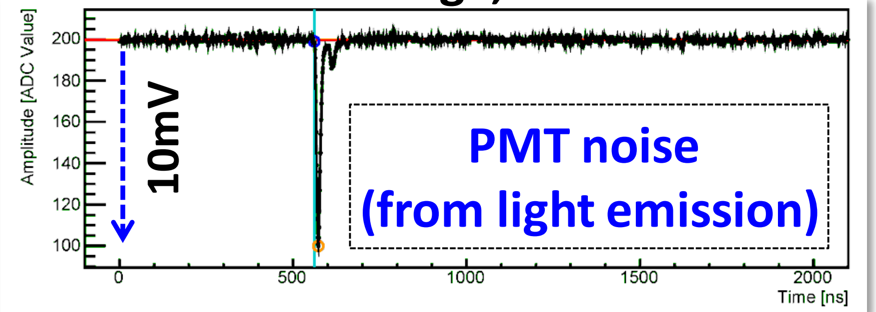




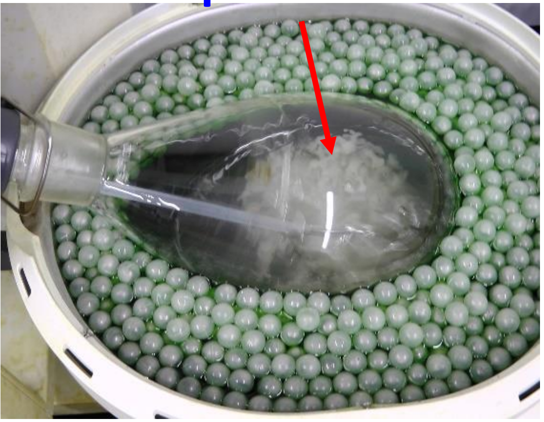


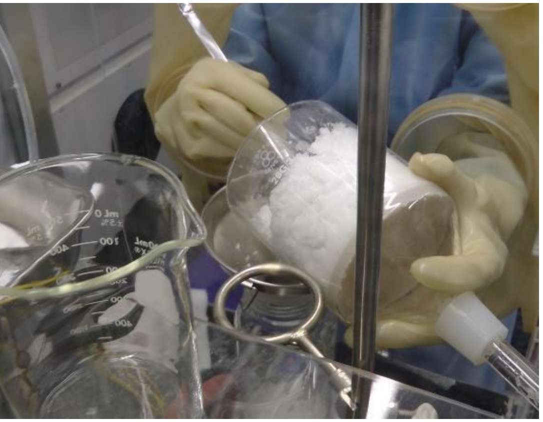


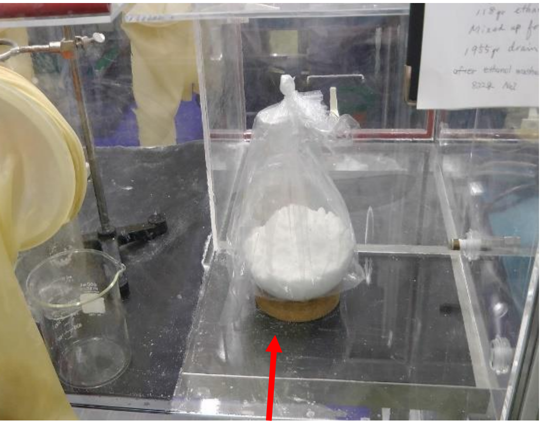




Non-purified NaI







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)

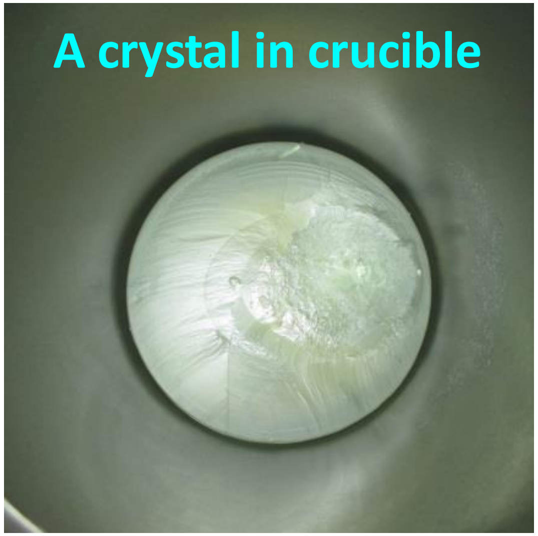
Steps used to minimize Radon daughters activity in NaI:

- ☐ 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)

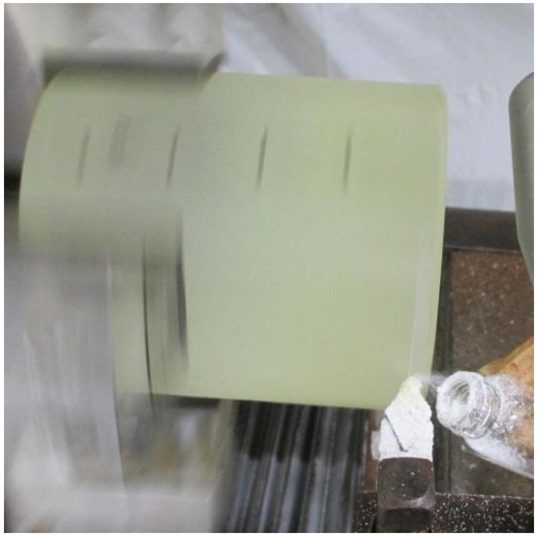


Crucible:

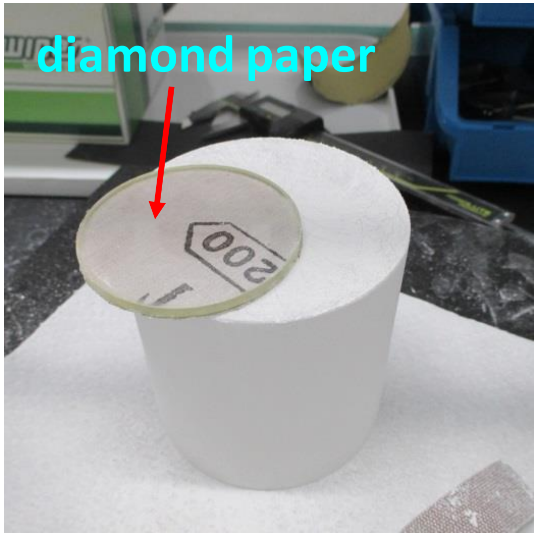
- ☐ Material – a coated, polished, **purified (in a vacuum oven) graphite**
- ☐ A new feature: a specially shaped bottom part – **no need to use a seed** to start crystal growth
- ☐ After cooling down NaI(Tl) crystals are **detached from the graphite crucible easily** due to a factor 10 **difference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

The NaI(Tl) ingot production (Step 2)

Machine cutting

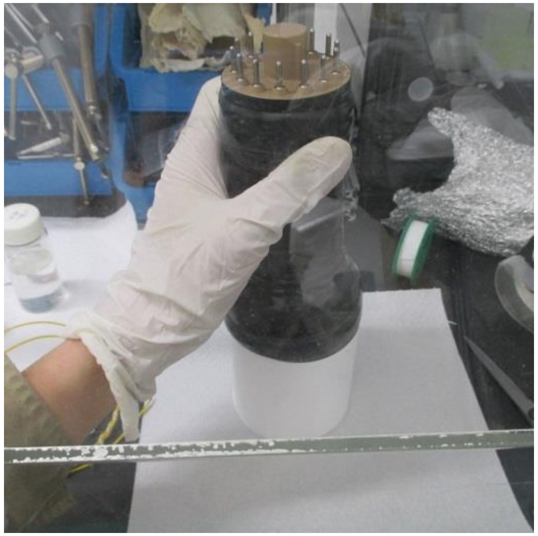


Samples for Tl test



Abrasion

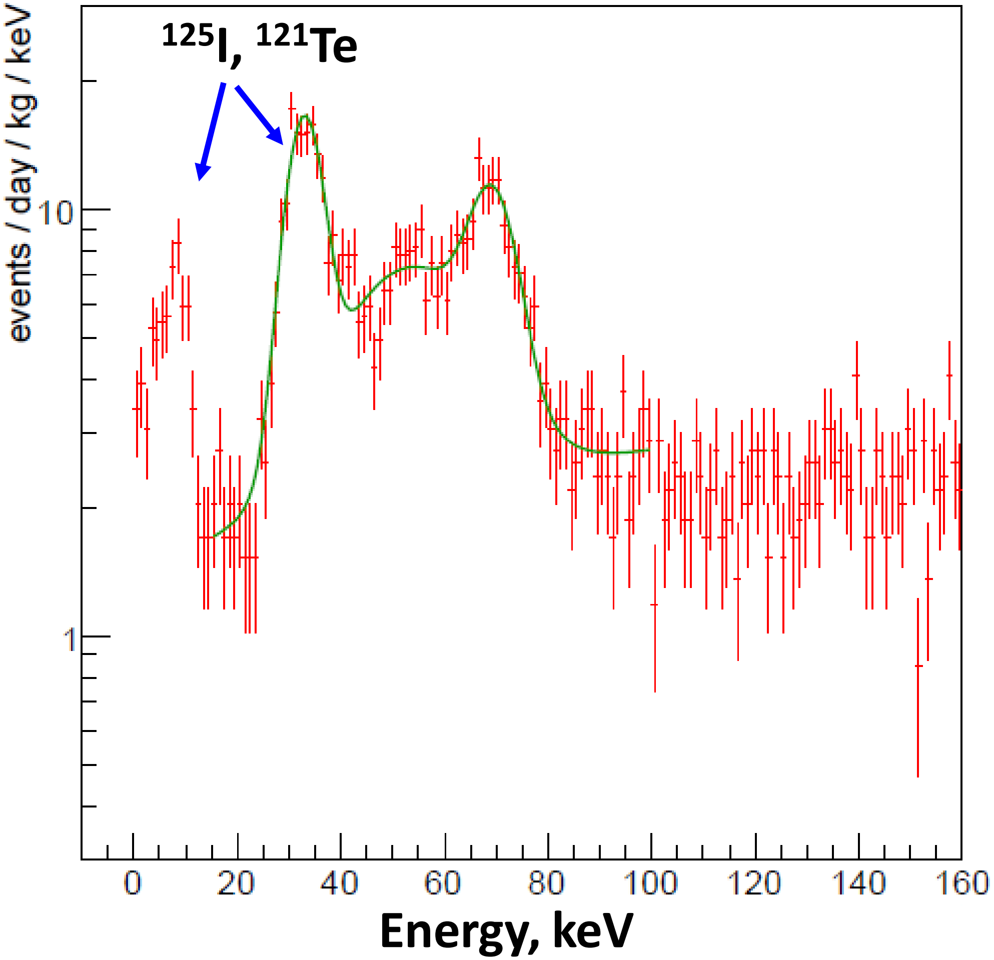
Humidity control



E. resolution test

Encapsulation

Ingot #71 (manufactured on Sept 14)



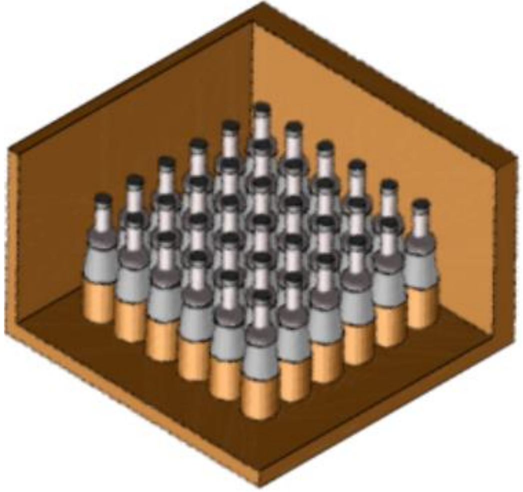
Background at low energies is dominated by cosmogenically produced isotopes with a short life time.

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

☐ Filling of the **KamLAND-Zen 800** mini-balloon with ^{136}Xe will start next month. During the next several years search for the neutrinoless double beta decay of ^{136}Xe will continue using a twice larger Isotope mass and more radio-pure mini-balloon.

☐ 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. Beginning of the detector construction depends on the Japanese government funding.

Thank you!