The Mount Elbrus Conference, RUSSIA (September 13, 2017)

Search for new physics at KamLAND

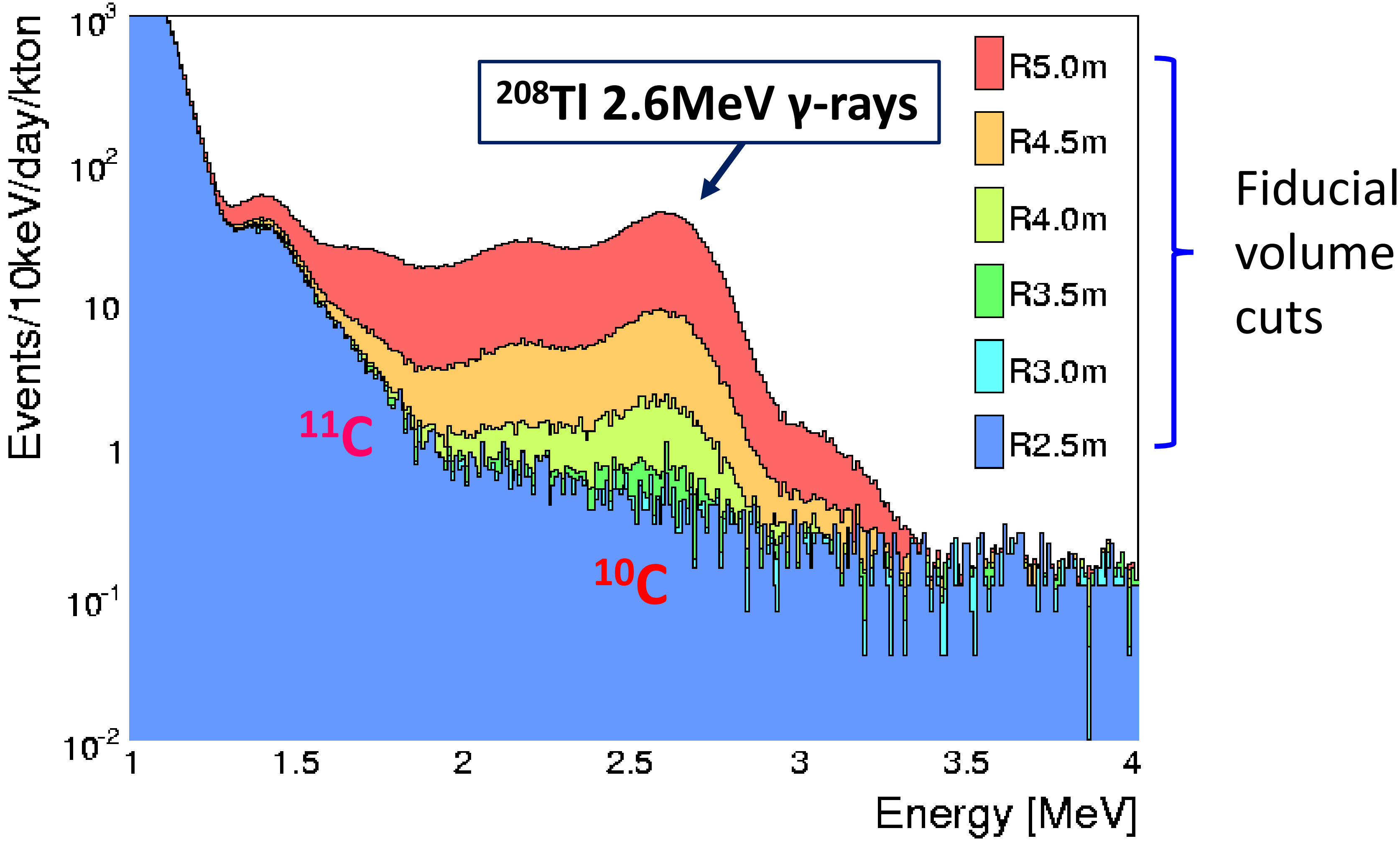
The University of Tokyo

Alexandre Kozlov

Talk's content

- **The KamLAND-Zen neutrinoless double-beta decay experiment using ^{136}Xe**.
  - Overview
  - Results
  - Future developments
- **Research infrastructure for rare event searches**.
  - Underground clean rooms
  - DAQ
  - Ultra-pure NaI(Tl) crystals
  - New ultra-low background 4-inch PMT
  - Supplementary detectors

Use of KamLAND for rare event searches



○ **Existence of ultra-low background region** at the center of KamLAND makes searches for Dark Matter, 0νββ signals possible.

In 2007 KamLAND's favorite isotope was ^{150}Nd

- However, by comparing sensitivity of experiments with all realistic 0ββν isotope candidates **^{136}Xe** was selected.
- Thanks to highly efficient Cold War's enrichment facilities it is the **cheapest** among enriched isotopes available in amounts needed for KamLAND (1-2tons).
- It has the **longest $T_{1/2}$ (2νββ),** and thus, the lowest non-removable **2νββ** background which is critical for KamLAND.
- It can be dissolved in large quantities in a liquid scintillator **without affecting transparency** and, thus, energy resolution.
- **^{136}Xe** has the **lowest level of U/Th** impurities compared with isotopes in a solid form. It can be **extracted from a scintillator by using nitrogen purge, and purified by distillation.**
- The **^{10}C** background we worried about for sometime can be effectively suppressed by **neutron tagging technique**.

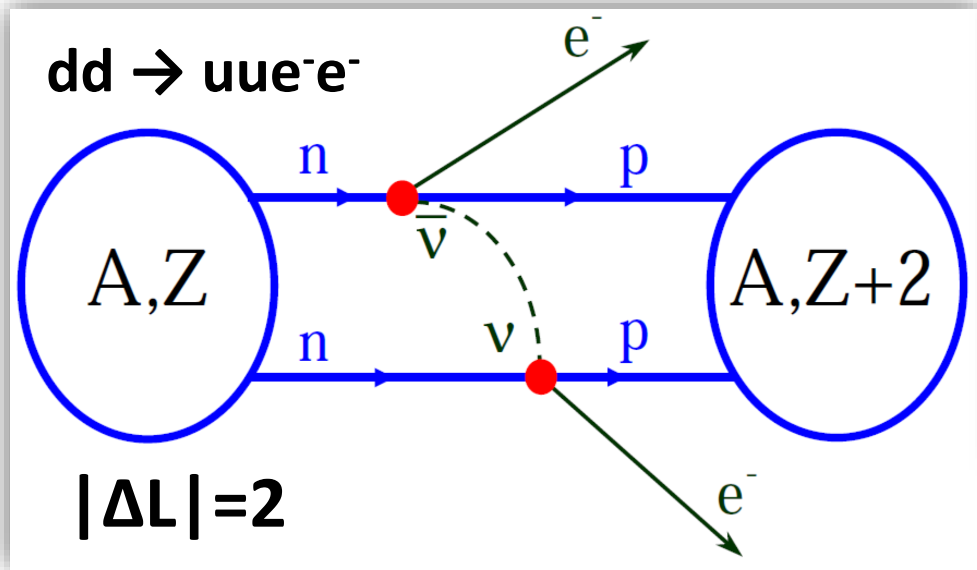
My talk at the KamLAND meeting at Caltech, March 2008

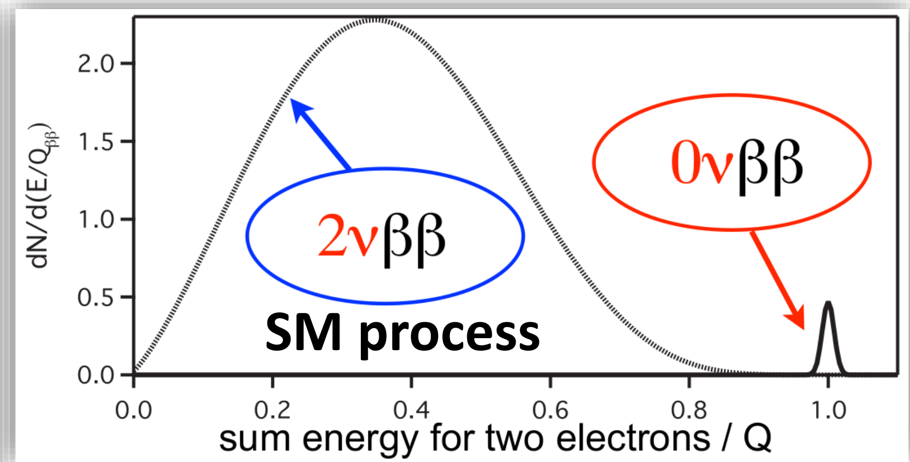
"Neutrinoless double beta decay experiment at KamLAND"

Summary

- During the solar neutrino phase the R&D for the medium size $0\nu\beta\beta$ experiment (200kg of enriched ^{136}Xe) needs to be completed. That includes a small balloon (1.5m radius) manufacturing, construction of the Xenon loading/extraction system etc
- Depending on results of the medium size experiment a larger Xenon experiment may start few years later. That should allow to start probing neutrino effective mass region corresponding to inverted hierarchy faster than CUORE, SuperNEMO or other $0\nu\beta\beta$ experiments.

The 0νββ test of seesaw mechanism





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

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

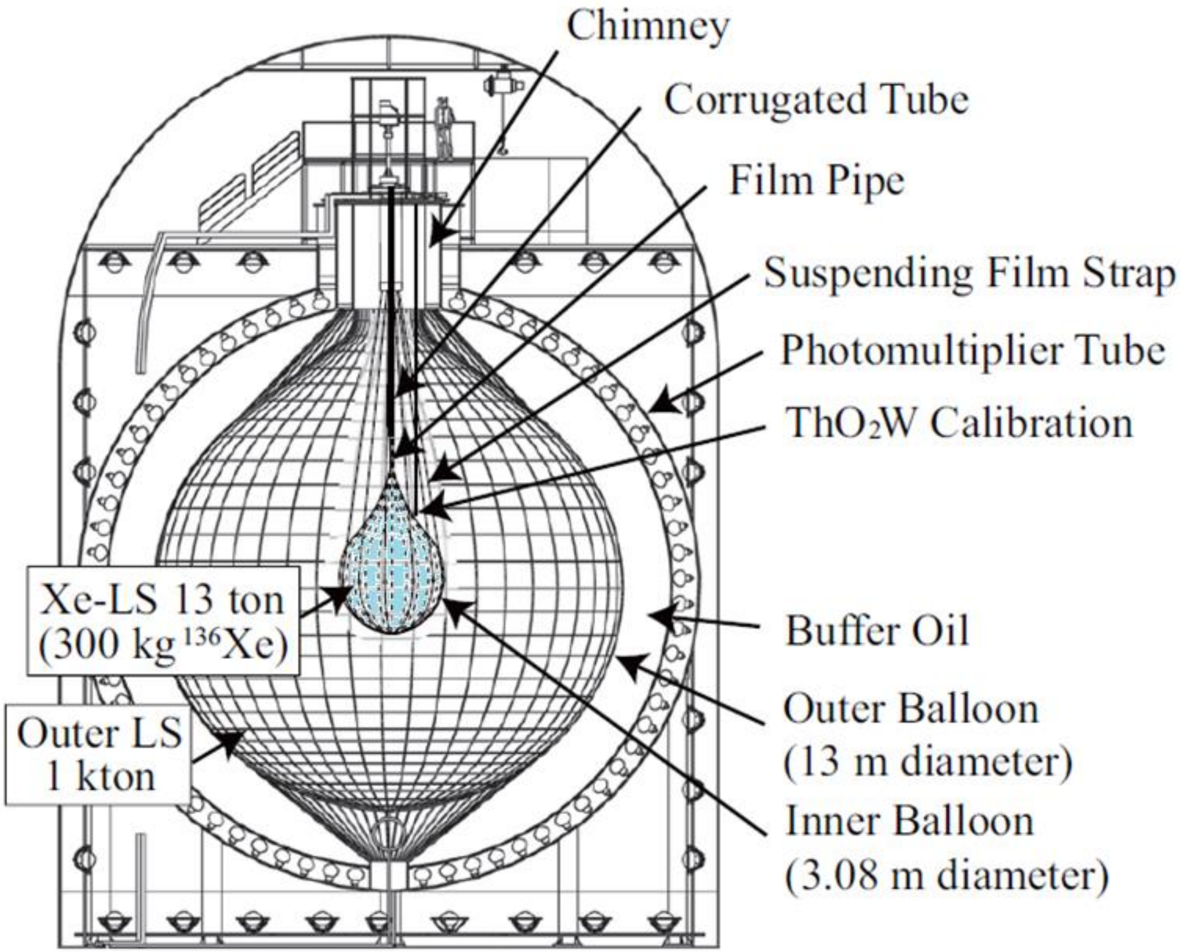
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\cdot|M^{0\nu}|^2\cdot m_{\beta\beta}^2$$

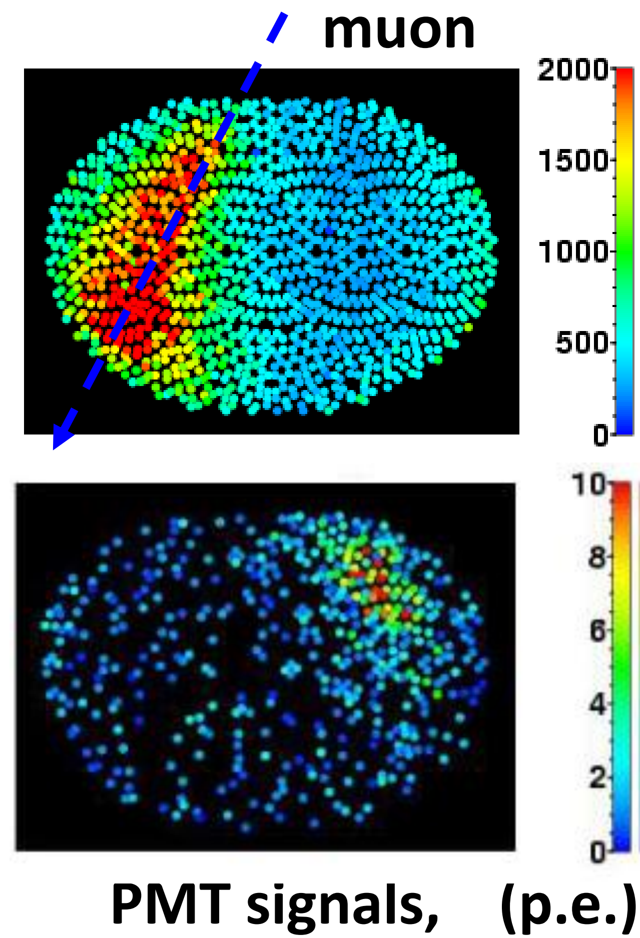
- $G^{0\nu}(Q_{\beta\beta},Z)$ – phase space factor
- $|M^{0\nu}|$ – nuclear matrix elements
- $m_{\beta\beta}$ – effective mass of neutrino

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

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

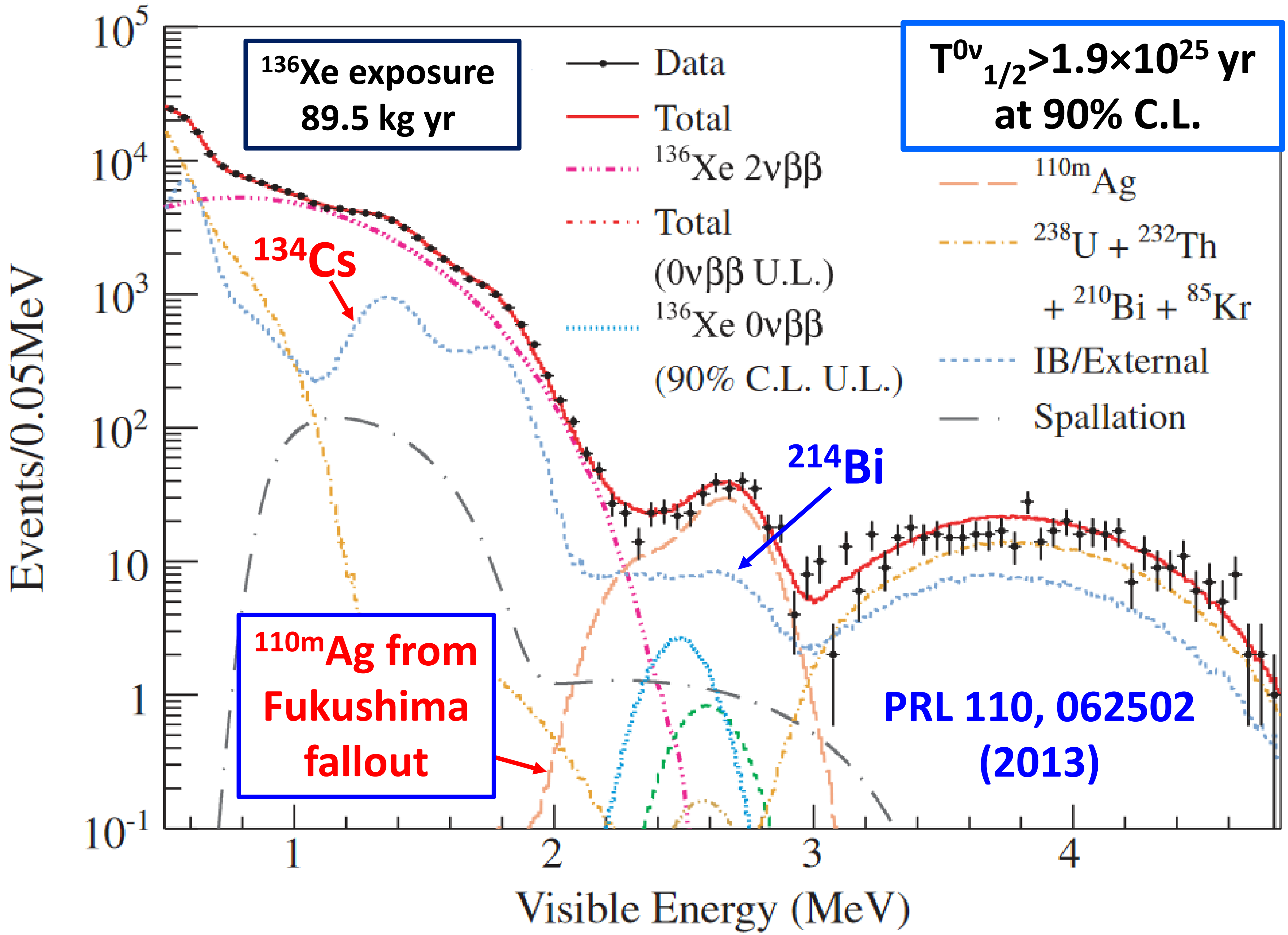
Structure of the KamLAND-Zen (year 2011)



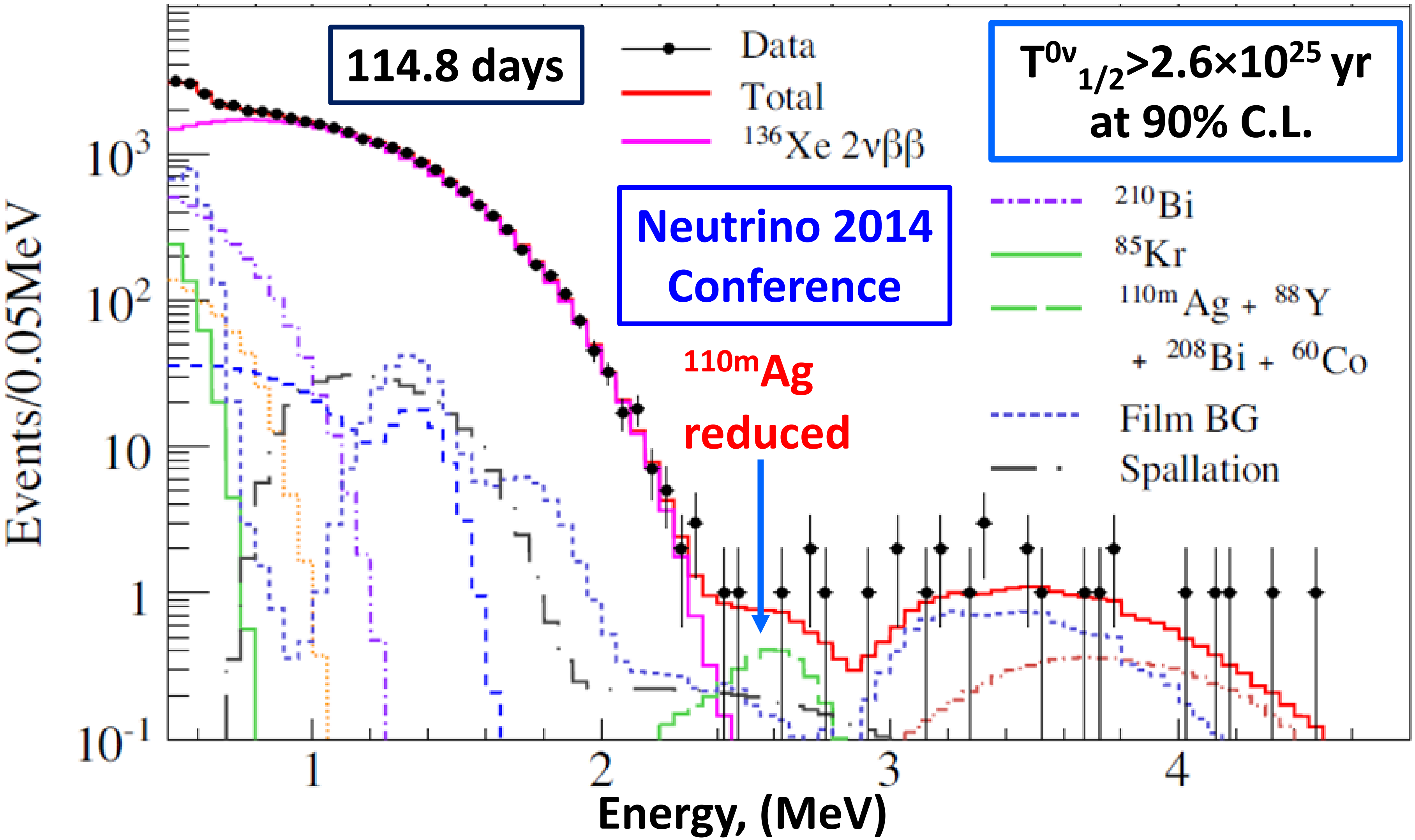


- **In 2011, enriched ^{136}Xe(2.5-3wt%) + Liquid Scintillator** in a **ø3.08m** mini-balloon made of a 25μm-thick Nylon film was deployed at KamLAND.
- It exploits the KamLAND detector **radio-purity, light sensors** (1879 PMTs 17&20-inch) and **data acquisition system**.

KamLAND-Zen 400: Phase I (year 2012)

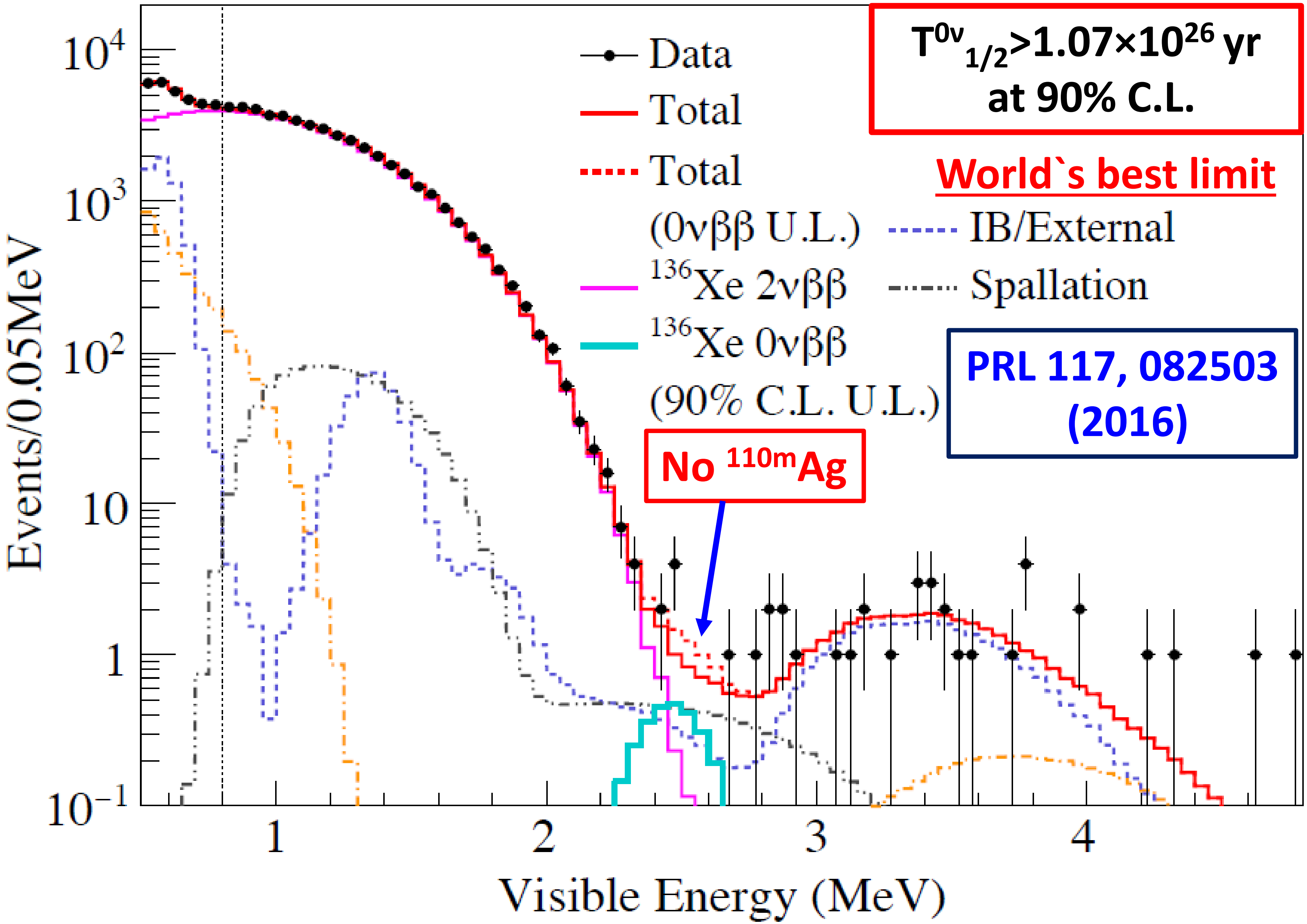


KamLAND-Zen 400: start of Phase II (year 2014)

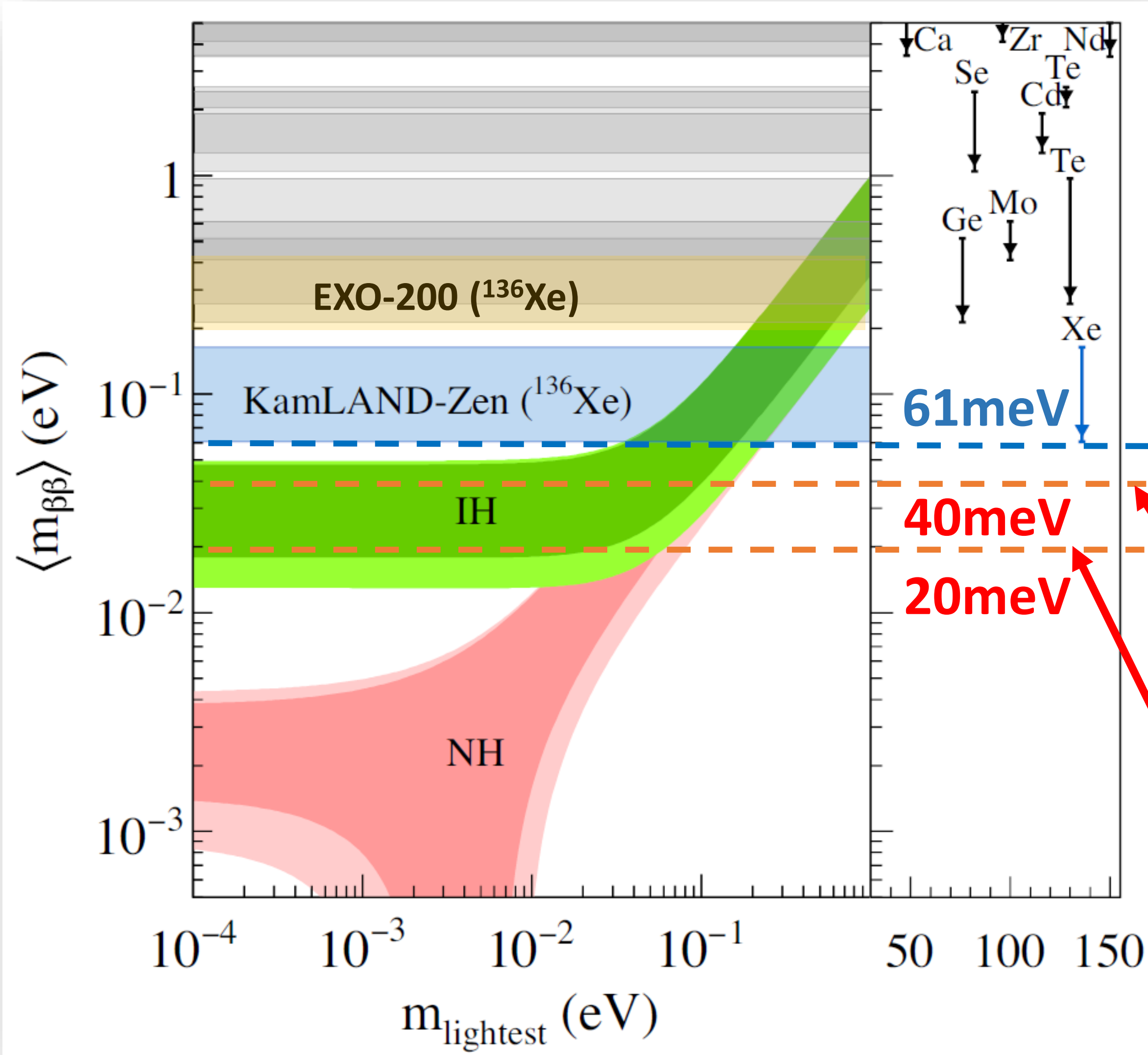


During **Phase II** the same mini-balloon was used but amount of enriched xenon was increased from **320kg** to **383kg**.

KamLAND-Zen 400: final result (year 2016)



First test of the IH mass region with KL-Zen 800



CP violation in the neutrino sector

⇕

baryon asymmetry of the Universe

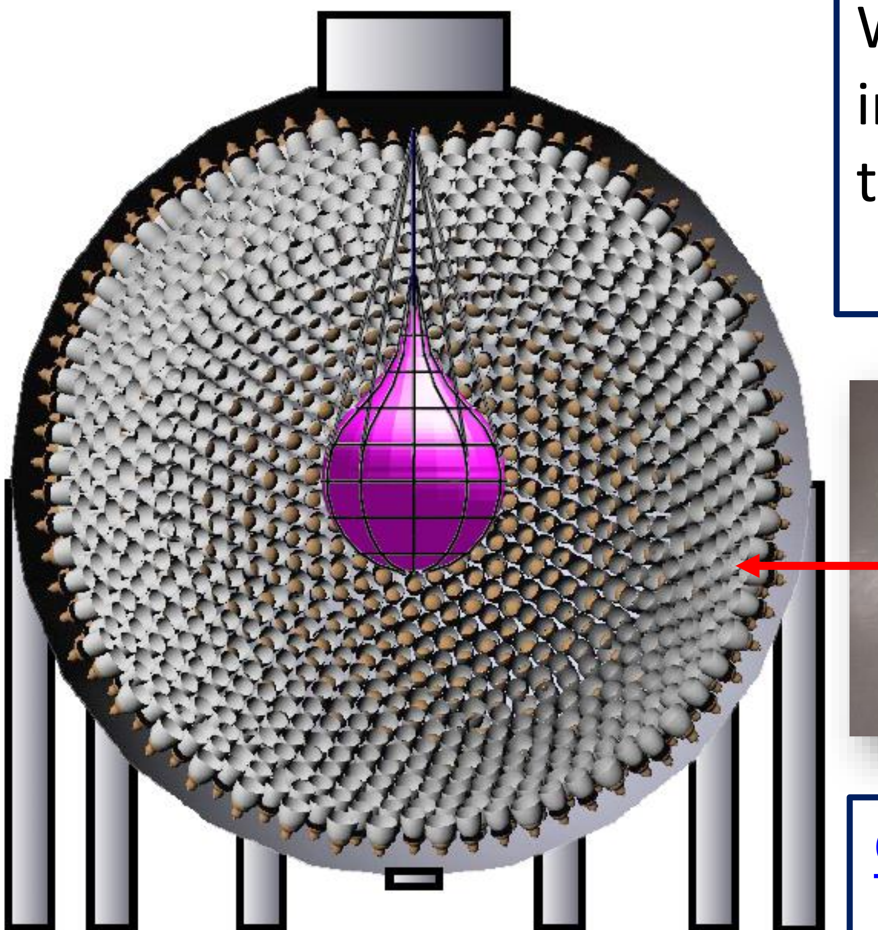
KL-Zen 400
(better than expected)

KL-Zen 800 (expected)
First result in 1.5-2 yrs

KL2-Zen (expected)
Upgrade & data taking start time depend on funding

Prediction for the $m_{\beta\beta}$ = 47±1 meV: **K. Harigaya, M. Ibe, and T. Yanagida** "Seesaw mechanism with Occam's razor" **PRD 86, 013002 (2012)**

KamLAND2-Zen to cover the IH mass region



We need to detect **more light** to improve energy resolution → reduce the **2νββ tail background.**

Sensitivity target: $m_{\beta\beta}$ ~ 20meV

Enriched xenon mass > 1000kg

Gain in number of detected photons

(after upgrade to KamLAND2)

New LAB scintillator: **1.4** times

High QE PMTs: **1.9** times

Light collecting cones: **1.8** times

The KamLAND-Zen summary

- **Accomplished:**
  - **The KamLAND-Zen 400** was completed in Oct 2015. Enriched xenon was extracted from liquid scintillator, purified by distillation, and returned back to a storage facility.
  - We published **world's best limit**: **$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr at 90% C.L.** (**$m_{\beta\beta}$ is 61-165meV** depending on choice of NME).
- **Ongoing**:
  - **A new mini-balloon** for 800kg of ^{136}Xe will be deployed into KamLAND this year.
  - During the **800kg** phase we may test **Yanagida's prediction** for **$m_{\beta\beta}$= 47±1meV**.
- **Future:**
  - We work on future **KamLAND2-Zen** project to cover most of the **IH mass region** down to **$m_{\beta\beta}$=20meV**.

DAMA/LIBRA DM claim test at KamLAND

- In **2011** I proposed to place an **"identical" NaI(Tl) detector** into the ultra-low background region **at the centre of KamLAND**. Purpose of the test is **to find out whether or not the modulated signal exists** **regardless of its possible interpretation**.
- However, development & construction of the Dark Matter detector required:
  - **high class underground clean rooms;**
  - **HPGe γ-ray, radon, neutron and other supplementary detectors but none of that was available at KamLAND.**
- Contrary to other neutrino or Dark Matter groups the KamLAND collaboration did not invest into research infrastructure for selection and handling of radio-pure materials. E.g. radio-impurities in detector components were measured by using commercial ICP-MS analysis.

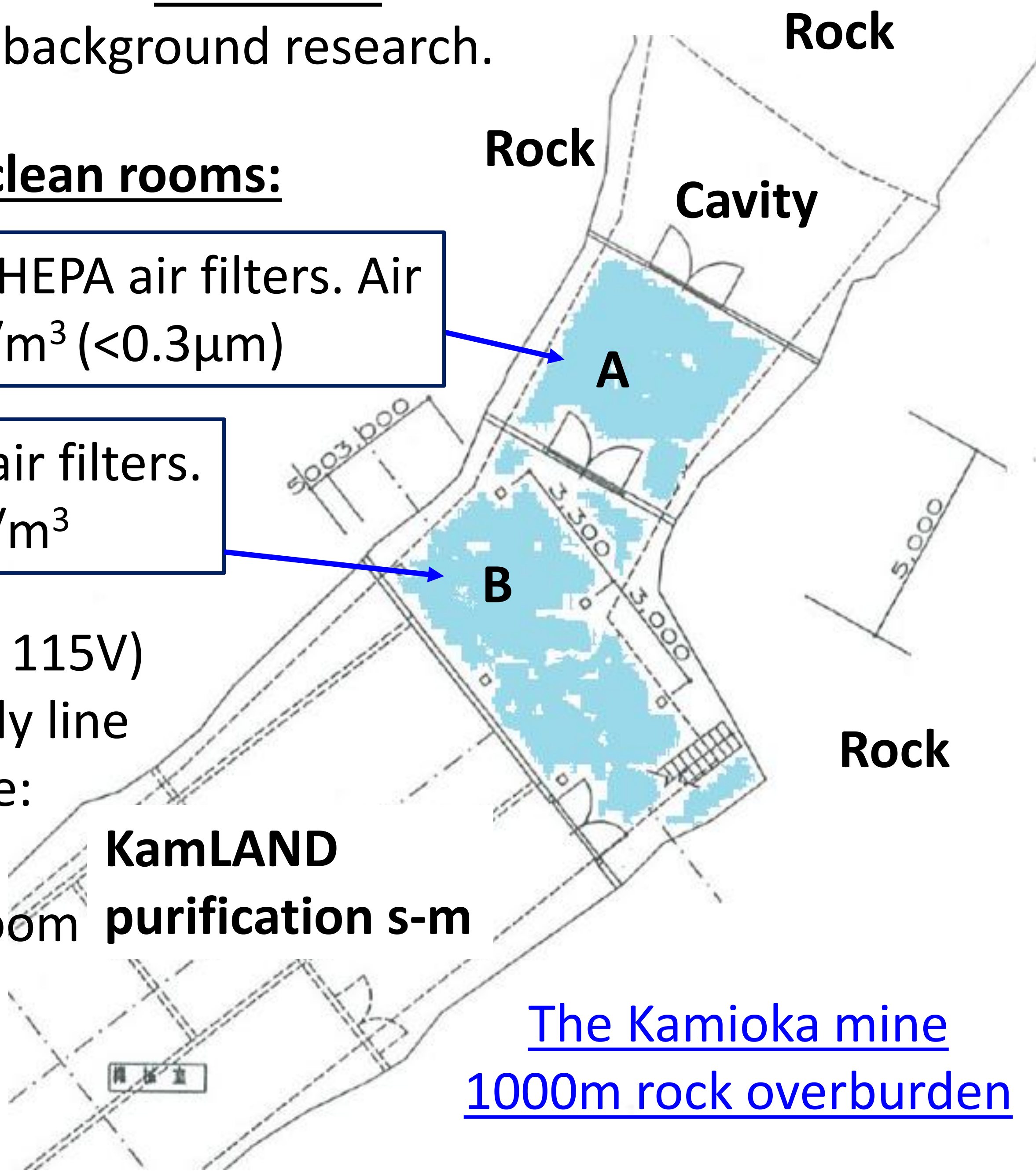
In 2012, I began development of **two clean rooms (A, B)** for ultra-low background research.

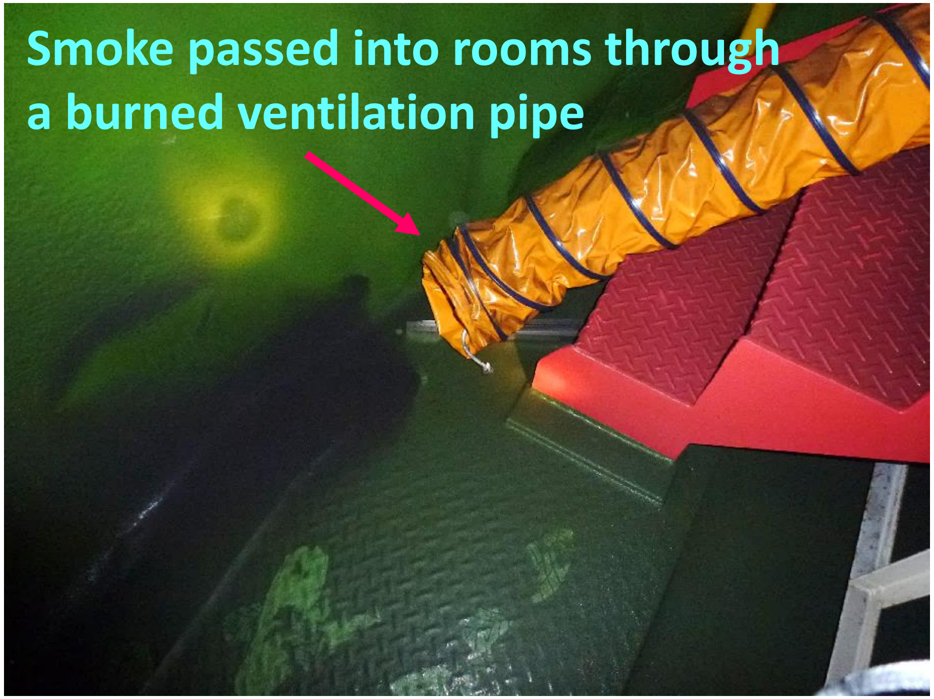
Current conditions at the clean rooms:

Room A: 60m^3/min ULPA/HEPA 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

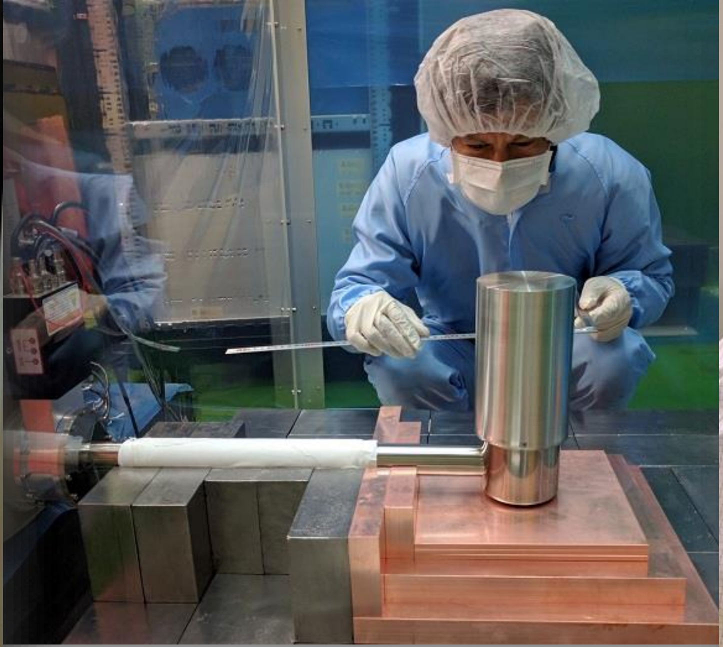
- 17kWatt AVR unit (100V, 115V)
- Boiled off Nitrogen supply line
- Radon-less air supply line: (5-10m^3 per hour)
- Air cond. units in each room





However, construction of clean rooms was cut-off by the **fire accident** at the KamLAND area **in November 2012**.
Full recovery required multiple repeating cleaning steps using:
A hot water, ethanol, ... done by myself alone causing > **1.5y delay**.

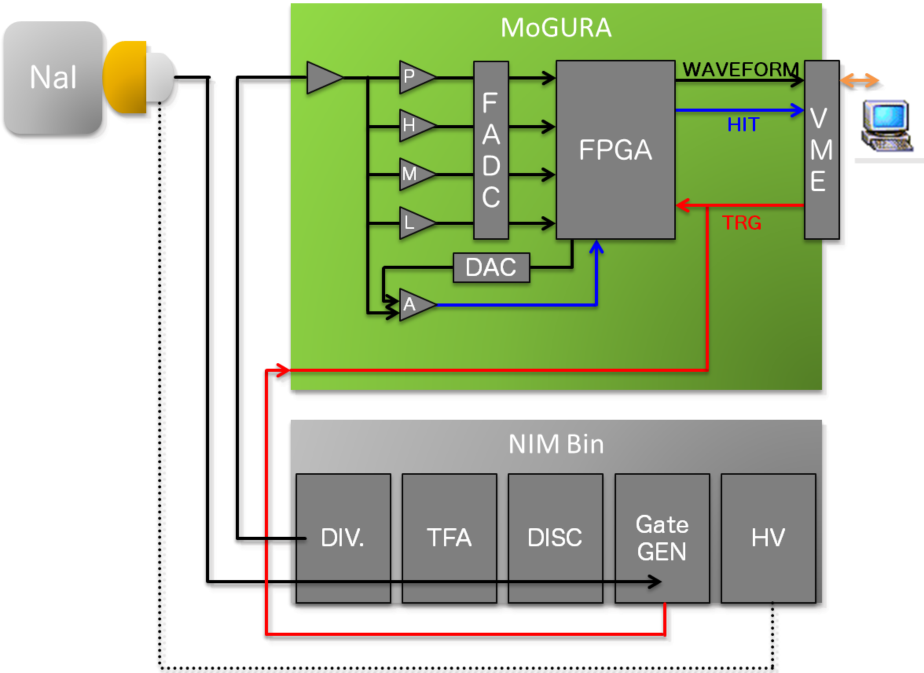
Tokyo U.
Dmitry Chernyak

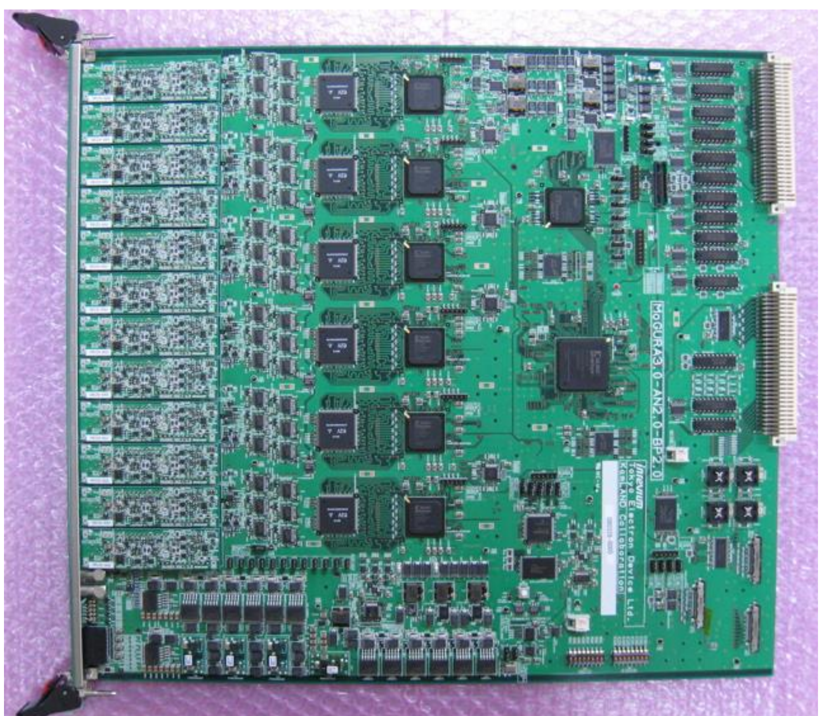


My collaborators

Tokyo U./Osaka U.
Yasuhiro Takemoto

- ❑ **Gas-type detectors (Radon, TPC): Baksan Neutrino Observatory** Institute for Nuclear Research Russian Academy of Science, Russia: Kuzminov Valery (Director), Gangapshev Albert, Kazalov Vladimir, Gavriljuk Yuri, Gezhaev Ali
- ❑ **NaI(Tl) ultra-pure crystals:** Tokushima U., Osaka U., Osaka Sangyo U., Tohoku U., I.S.C. Laboratory

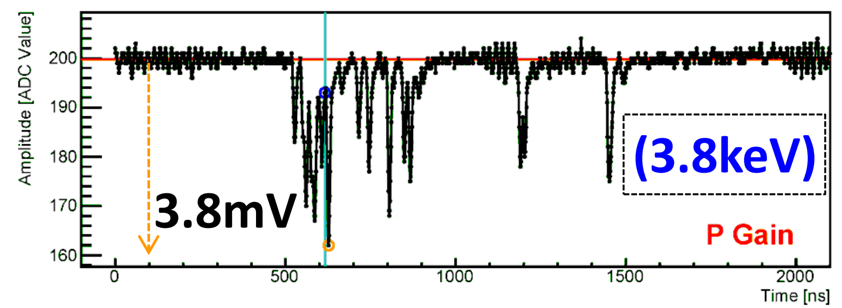


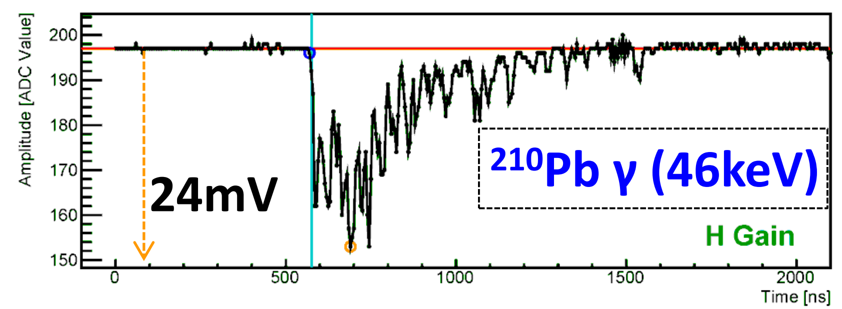


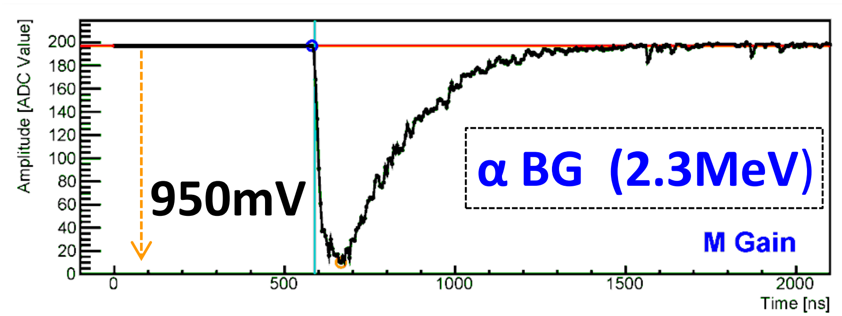
MoGURA based DAQ

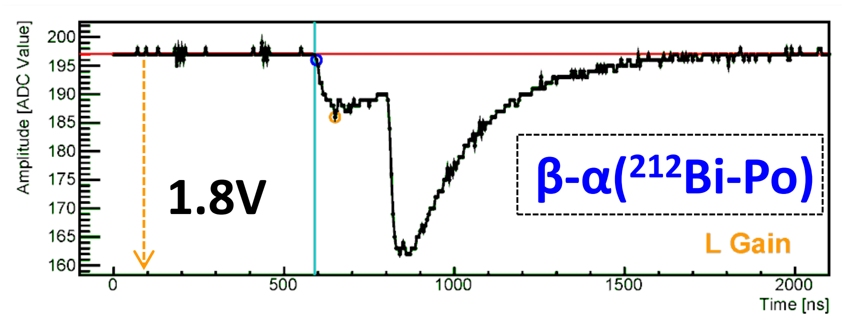
- **12ch** input VME 9U board
- **FADC**
  - **P** : 0.1mV/LSB, 8bit, 1GSPS
  - **H** : 0.5mV/LSB, 8bit, 200MSPS
  - **M** : 5 mV/LSB, 8bit, 200MSPS
  - **L** : 50 mV/LSB, 8bit, 200MSPS
  - 0.1mV ÷ 10V
- **FPGA**
  - Up to 10 μsec waveform buffer
- **HIT**
  - Analog discri.: >5mV
  - Digital discri.: >0.5mV
- **TFA** for PMT noise cut

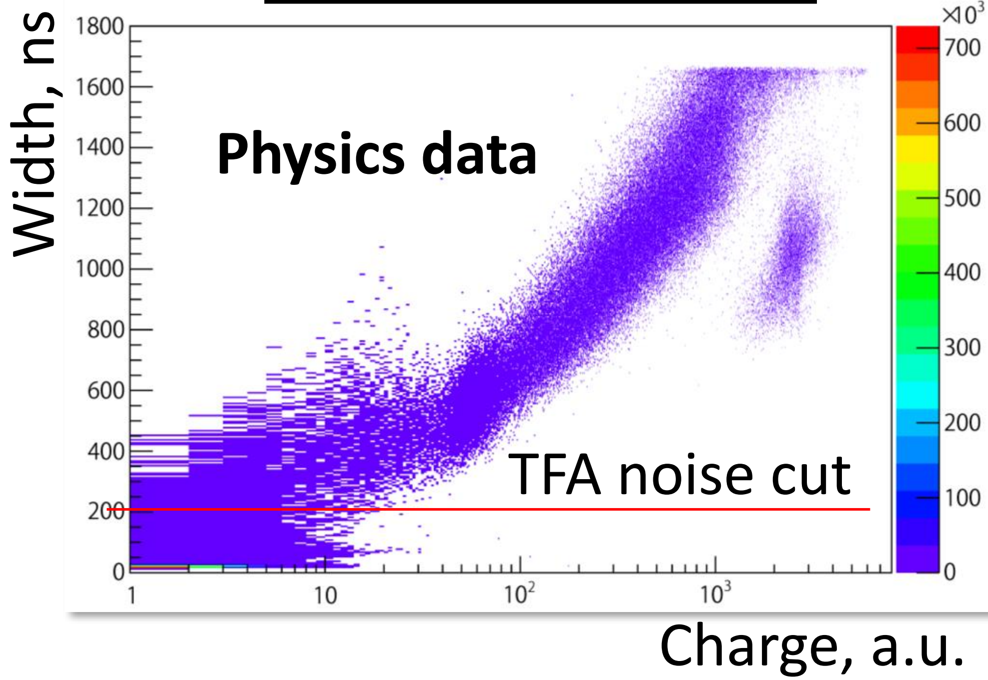
The NaI(Tl) data



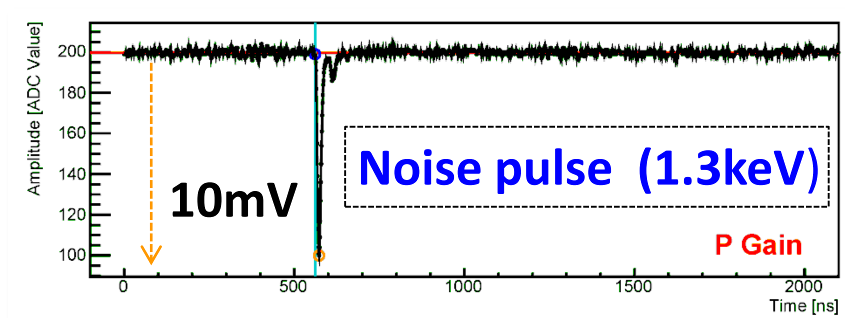




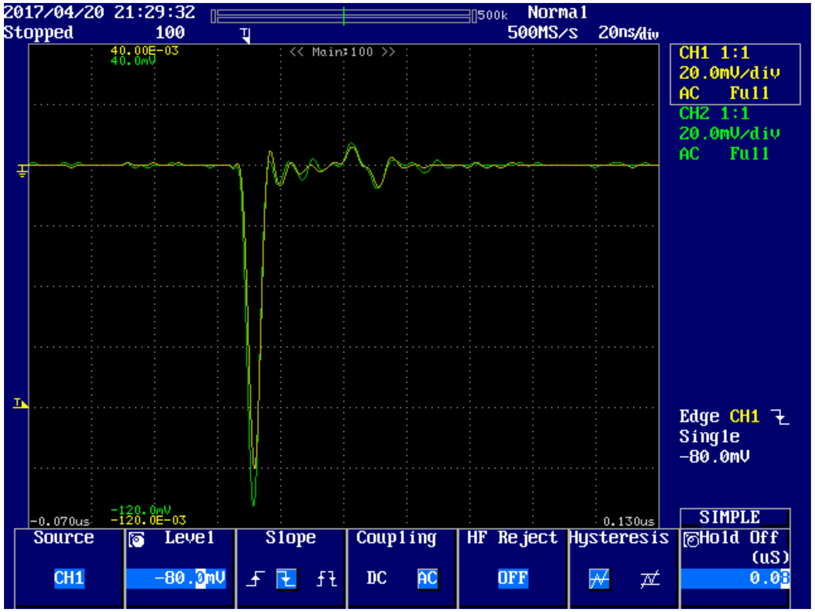


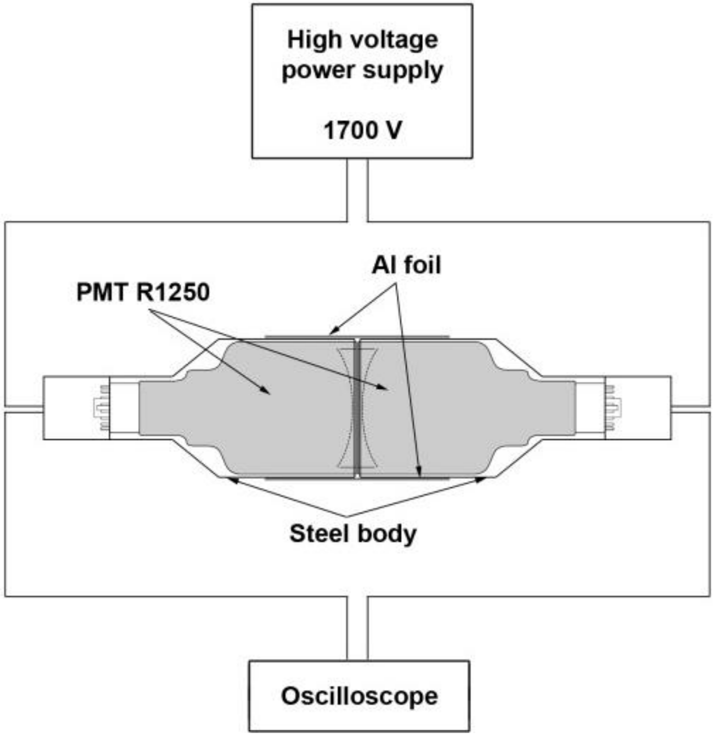


PMT noise >99.9% of data, from single to several narrow pulses (trains) was effectively cut by TFA .



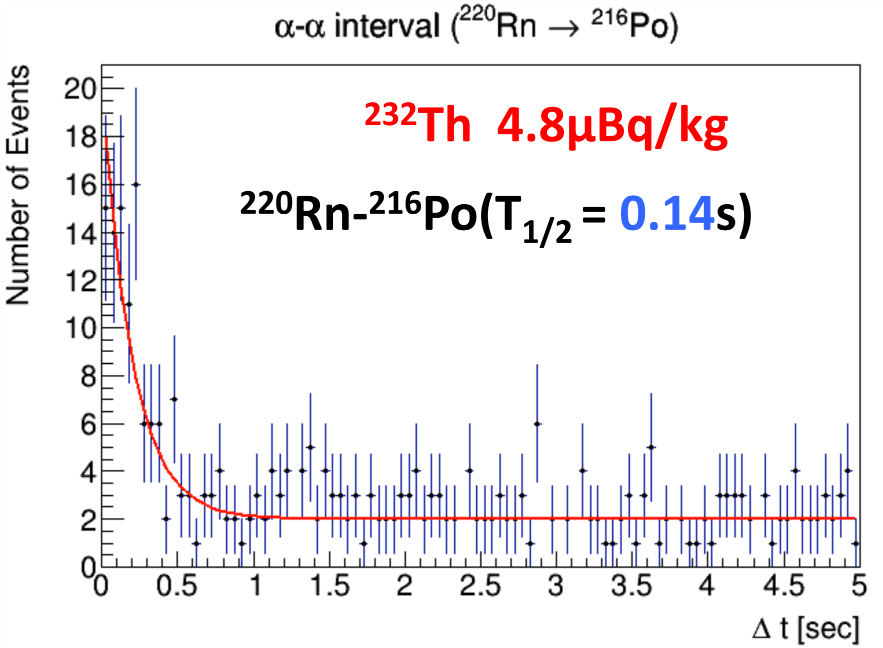
Problem of high intensity fast PMT noise

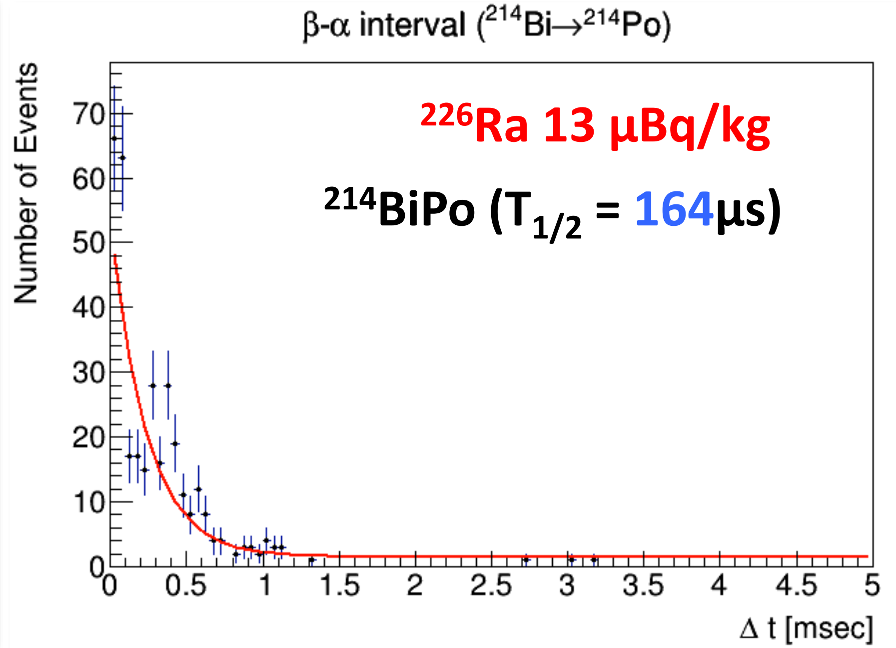


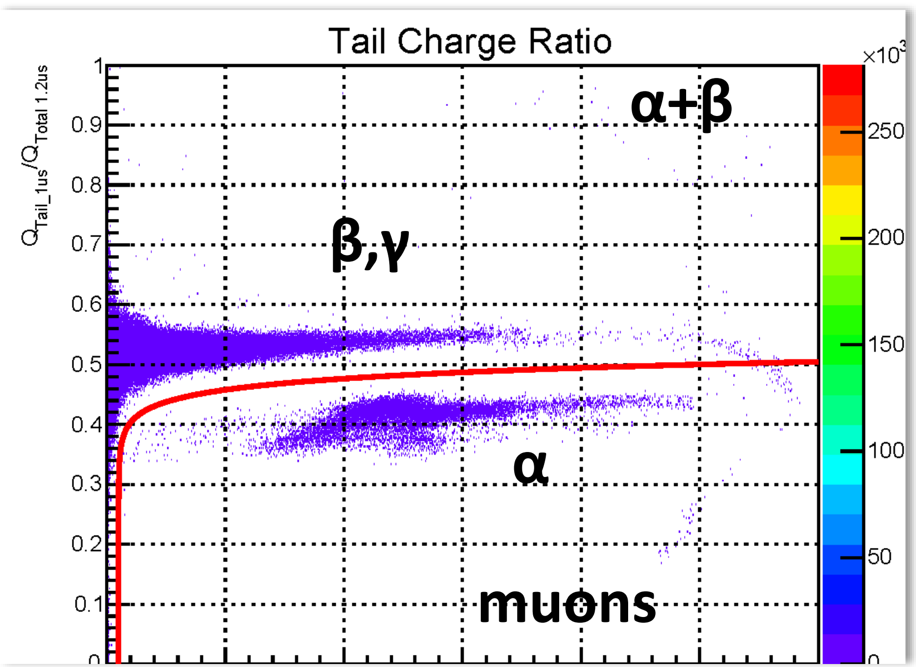


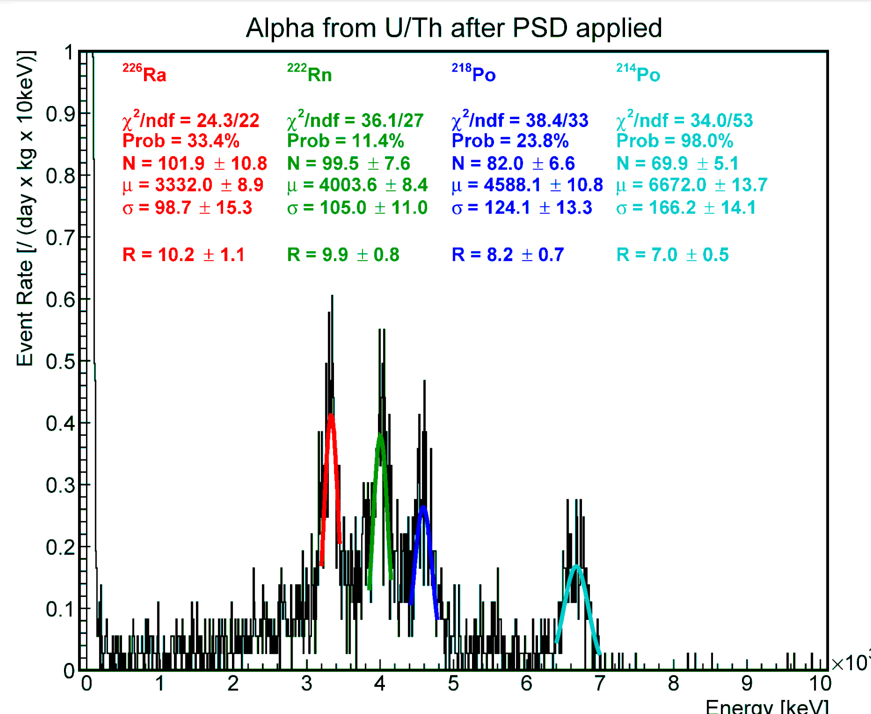
Coincident noise pulses in **face-to-face optically coupled PMTs**.

During development of the NaI(Tl) DM detectors we faced a problem of **intense high amplitude fast PMT noise** (~**10ns wide** pulses). The noise was observed for several **Hamamatsu PMT** types: **R6091**, **R11065-20** 3-inch PMTs, **R13444X** 4-inch PMT, **R1250** 5-inch PMT. Use of different DAQ hardware, opened or underground locations had no effect on this noise. **Existence of the noise was admitted by the Hamamatsu Photonics**. Most likely cause - **fast flashes of light in the PMTs.**


α-α interval (220Rn → 216Po)
232Th 4.8μBq/kg
220Rn-216Po(T1/2 = 0.14s)
Number of Events
Δ t [sec]


β-α interval (214Bi→214Po)
226Ra 13 μBq/kg
214BiPo (T1/2 = 164μs)
Number of Events
Δ t [msec]


Tail Charge Ratio
QTail_1us/QTotal 1.2us
α+β
β,γ
α
muons
×10³


Alpha from U/Th after PSD applied
226Ra
χ²/ndf = 24.3/22
Prob = 33.4%
N = 101.9 ± 10.8
μ = 3332.0 ± 8.9
σ = 98.7 ± 15.3
R = 10.2 ± 1.1
222Rn
χ²/ndf = 36.1/27
Prob = 11.4%
N = 99.5 ± 7.6
μ = 4003.6 ± 8.4
σ = 105.0 ± 11.0
R = 9.9 ± 0.8
218Po
χ²/ndf = 38.4/33
Prob = 23.8%
N = 82.0 ± 6.6
μ = 4588.1 ± 10.8
σ = 124.1 ± 13.3
R = 8.2 ± 0.7
214Po
χ²/ndf = 34.0/53
Prob = 98.0%
N = 69.9 ± 5.1
μ = 6672.0 ± 13.7
σ = 166.2 ± 14.1
R = 7.0 ± 0.5
Event Rate [/ (day x kg x 10keV)]
Energy [keV]
×10³

Impurity	DAMA/LIBRA	DM-ICE	ANAIS	KIMS	Our result
natK [ppb]	< 20	558	20 ~ 46	40 ~ 50	125
Th-chain [ppt]	0.5 ~ 7.5	13	0.8 ± 0.3	0.5 ± 0.3	0.3 ± 0.5
^{226}Ra [μBq/kg]	21.7 ± 1.1	900	10 ± 0.2	< 1	58 ± 4
^{210}Pb [μBq/kg]	24.2 ± 1.6	1500	600 ~ 800	470 ± 10	30 ± 7

We successfully develop highly radio-pure NaI(Tl) scintillators using the Bridgman method. For the latest **5×5inch crystal** we expect **radio-purity similar to that of the DAMA/LIBRA crystals.**

2013 3×3inch

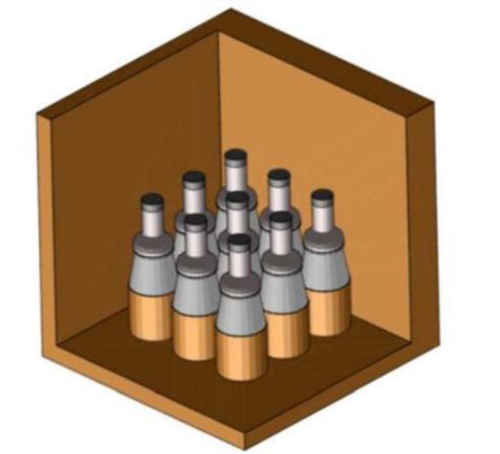
2014 3×3inch

2016 3×4inch

2017 5×5inch

The crystal is being encapsulated.

First phase of the NaI(Tl) experiment

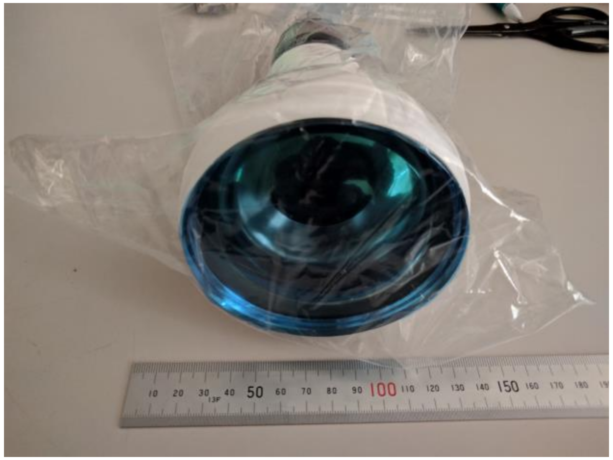


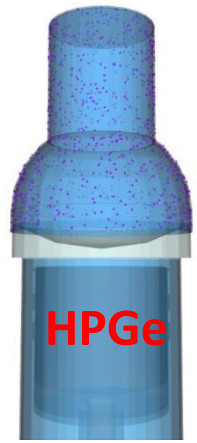
Four types of Pb bricks Including ultra-low background old lead were prepared and cleaned by a nitric acid.

Before preparing a detector for deployment at KamLAND we will build NaI(Tl) detector in a **standard Cu+Pb shielding at the underground clean room A**.

This year I purchased **600kg** of copper at **Mitsubishi Materials** specially melted for us only. Freshly manufactured (**1.5month or less old**) electroformed copper sheets were used to avoid ^{60}Co. Cu bars were cut into standard size bricks, surface milling, and cleaning according to the Majorana procedure was done. The HPGe measurements found **no ^{60}Co access** (UL 0.2mBq/kg at 90%CL).

Experimental ultra-low background PMT R13444X





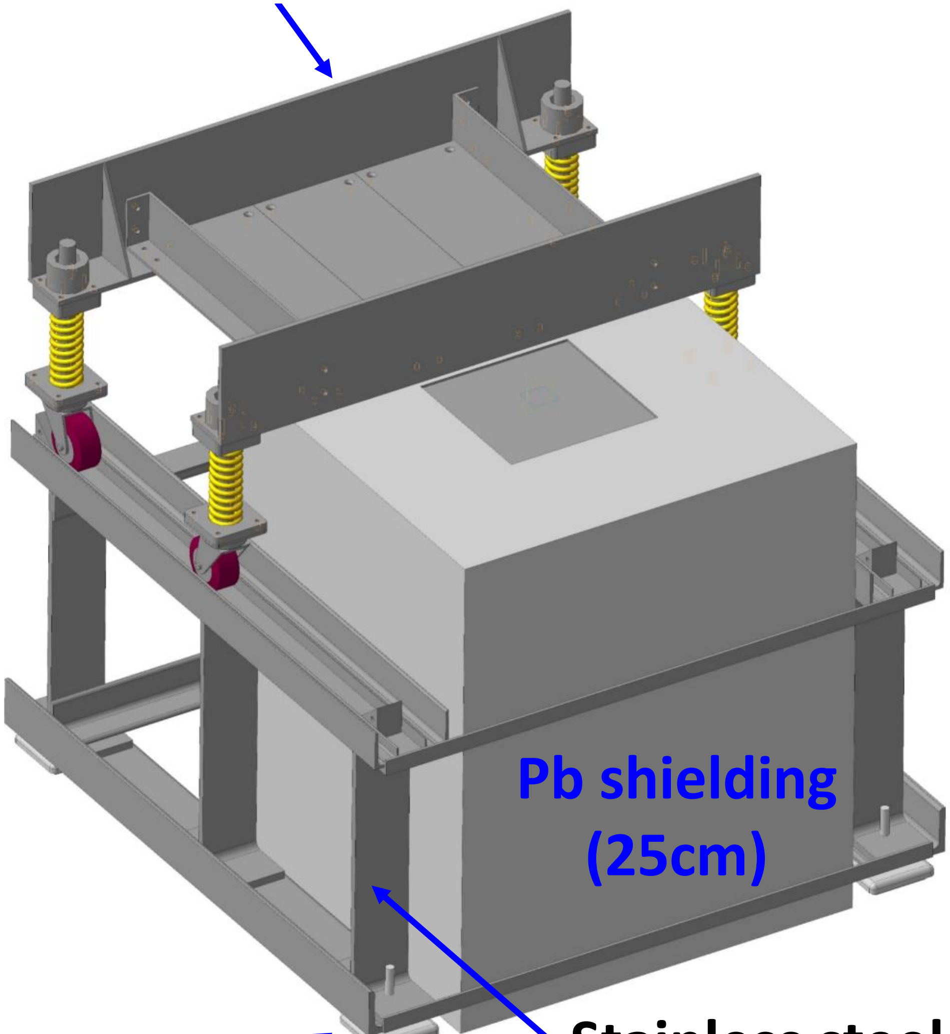
The **PMT is made** of about **37 components**. Materials: **Ni-Fe alloy, SUS304, ceramics, Al (5N), Ag, Ni, …** . Hard to make a realistic GEANT model based limited information available.

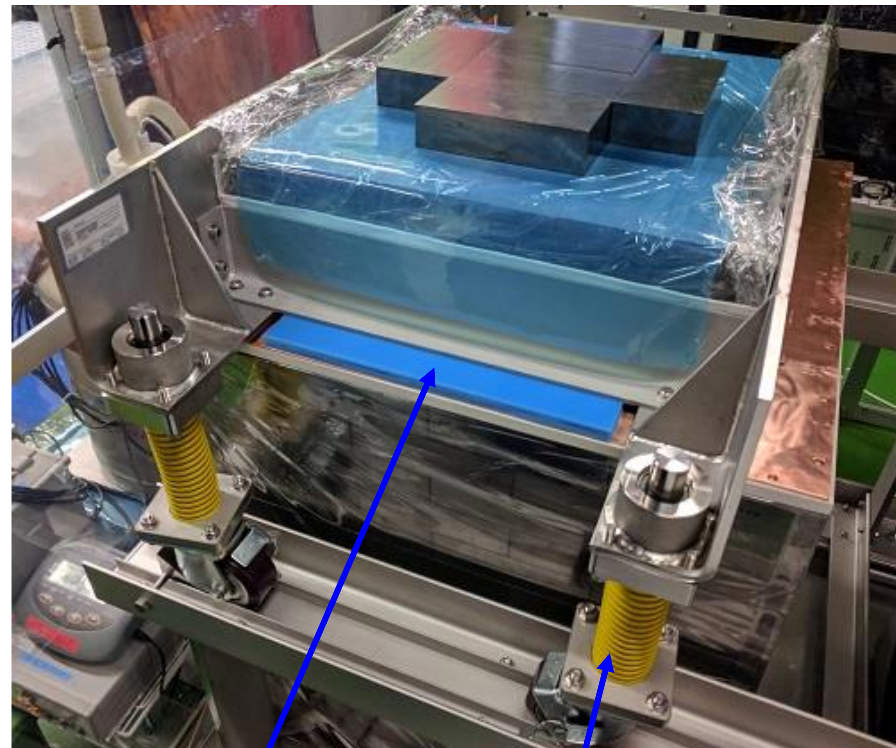
Need ~**1 month** long measurement at the HPGe detector **per PMT**, we are taking data now. Preliminary, confirmed presence of **^{40}K at few tens mBq/PMT, ^{60}Co at few mBq/PMT**. Search for radio-pure voltage divider parts with Hamamatsu.

- The **R13444X** is the largest (4-inch) ultra-low background Hamamatsu PMT with a metal body. Optical window is made of Synthetic Silica with the Bialkali photocathode. I purchased **two PMTs** this spring to check if it could be used as replacement for 3-inch Hamamatsu ultra-low background R11165-20 PMT.
- Spectral response maximum at 420nm (200-650nm range); **QE**@420nm : **34.9%** and **33.38%**. **Gain** at +1500V : 5×10^{6}**; TTS**: 13ns

Our HPGe detector shielding design

Cart for Pb bricks made of radio-pure stainless steel





plastic sealant

Springs used as a lifting mechanism

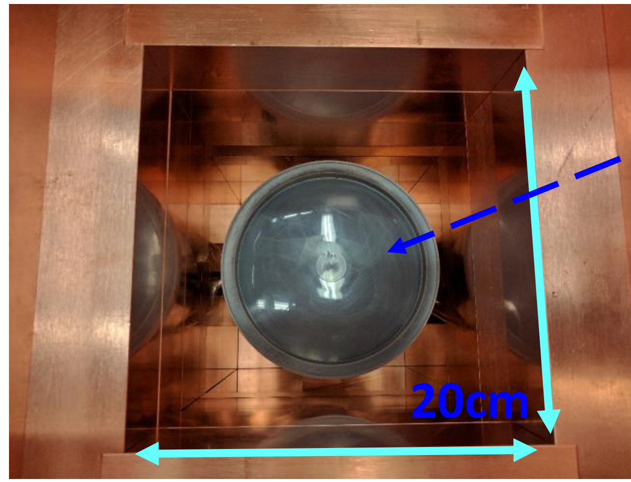
Stainless steel support frame

Level regulators

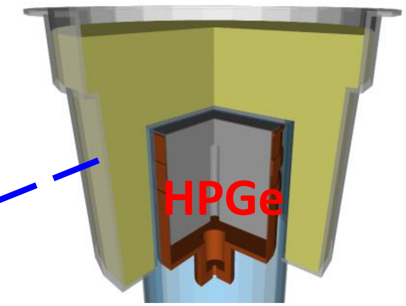
The HPGe detector located underground (2700m.w.e.)

Isotope	Energy, keV	Background, Events / day
^{40}K	1460.8	10.0
^{60}Co	1332.5	1.6
^{234m}Pa	1001	3.1
^{228}Ac	911.2	3.2
^{214}Bi	609.3	2.3
^{208}Tl	583.2	3.3
^{214}Pb	351.9	3.7
^{235}U	185.7	22.5
^{234}Th	92.6	25.0

25cmPb + 5cm Cu

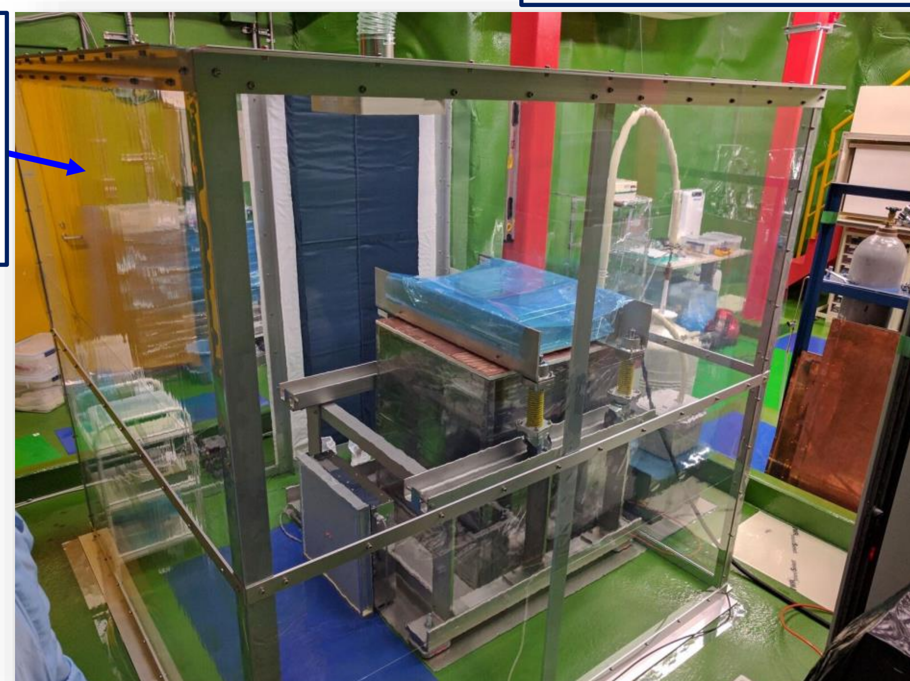


1.3L container



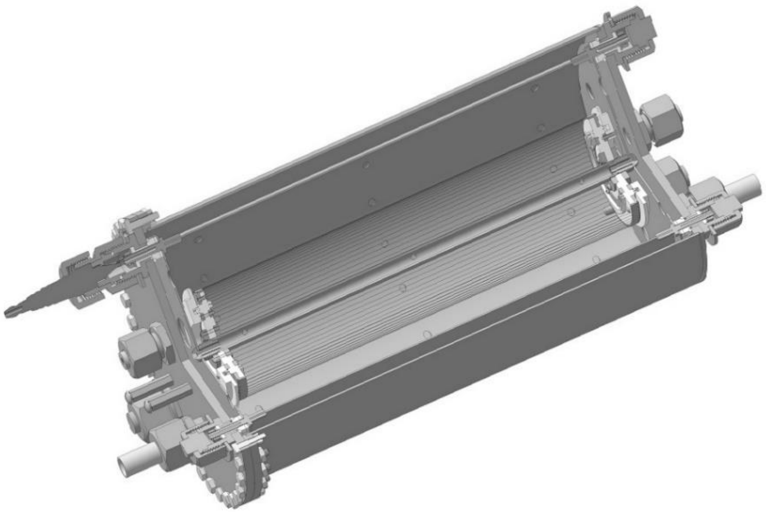
Enough space for e.g. 4-inch PMT

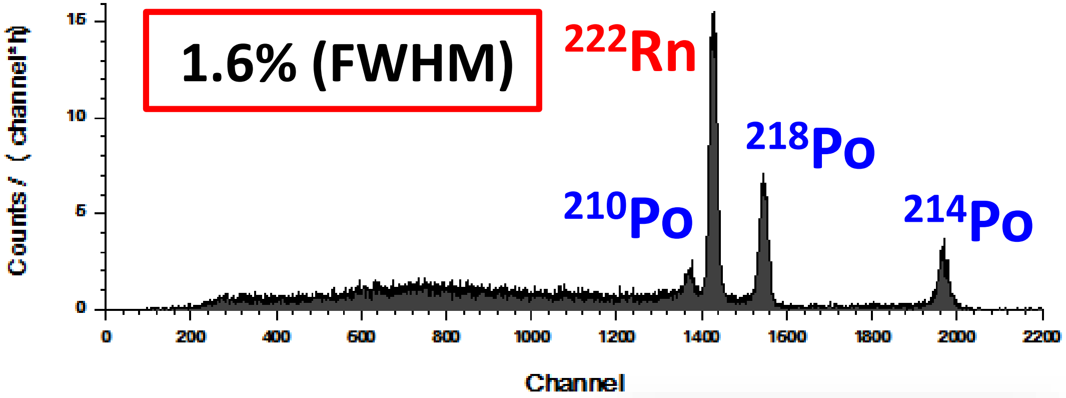
HPGe p-type 75% rel. eff. **Room B**



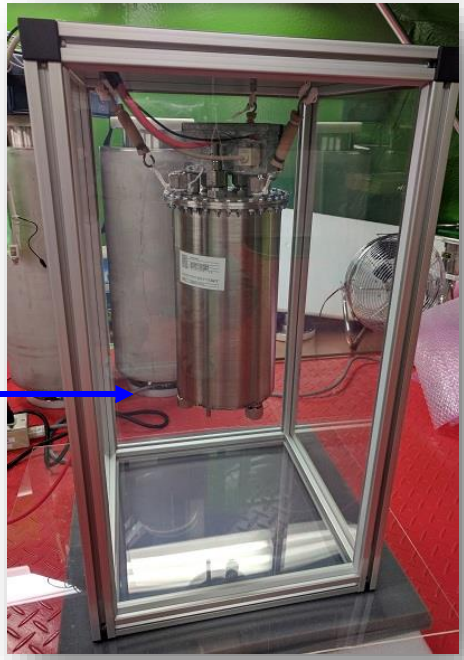
- Shielding materials were kept **10+ yrs underground**
- **Clean-room tent + radon-less air s-m**
- Detector's inner volume is purged with boiled off Nitrogen (**5.5L/min**)

BNO high resolution ion-pulse ionization chamber



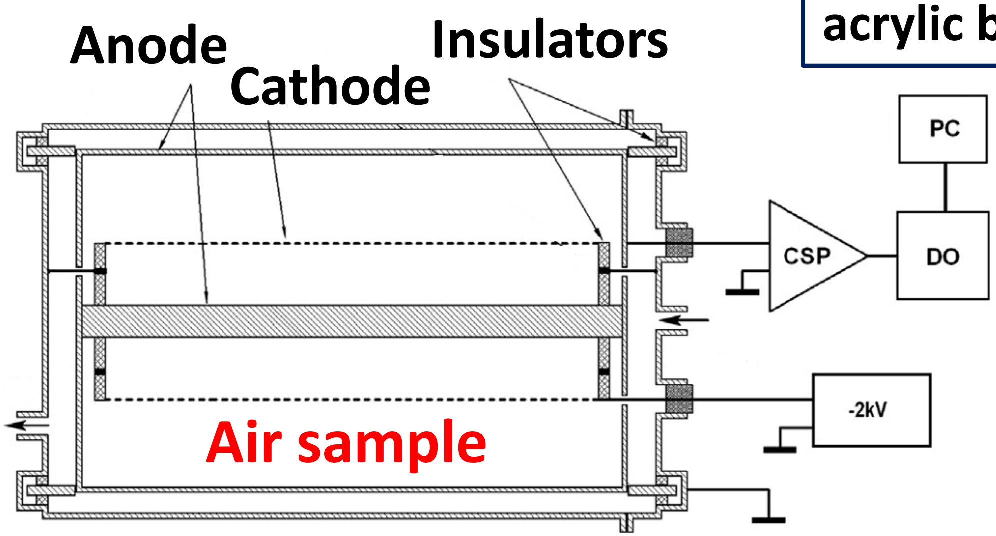


Direct detection of the Radon α-decay in the air.

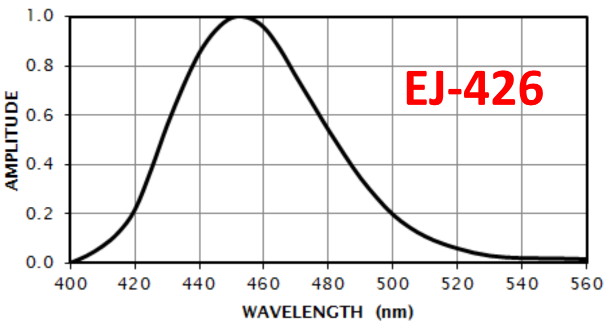


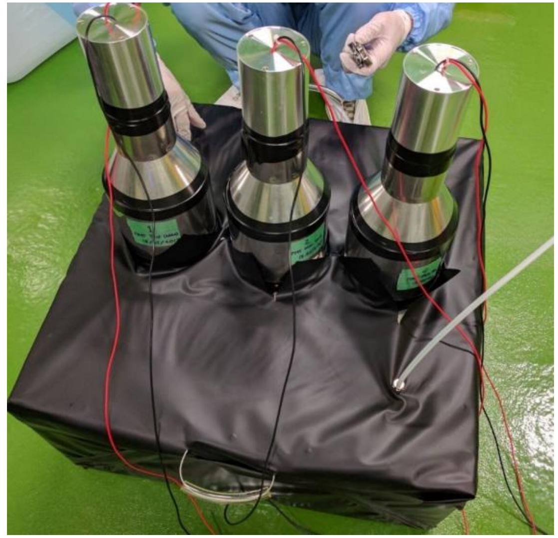
The 1st layer of acoustic shielding: a 5mm-thick acrylic box.

JSPS grant: 16K05371



Currently, we build a **second layer of acoustic shielding** to minimize interference between radon measurements and our every day activities at the mine.

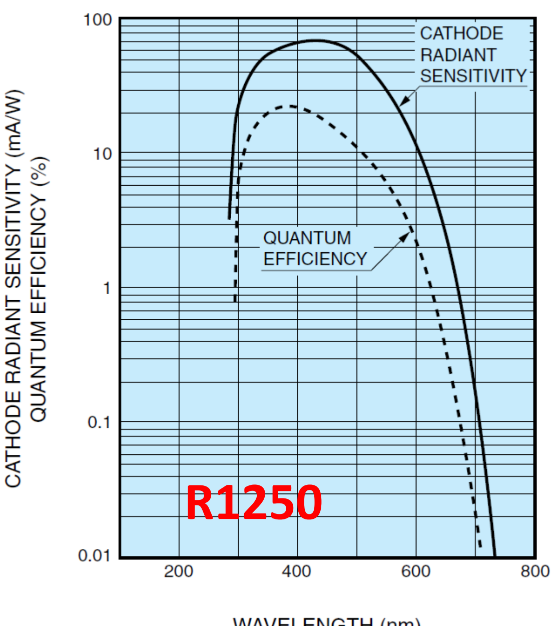




Hamamatsu **R1250 PMTs**
CAEN 4 channel waveform digitizer **N6724F** (100MHz)

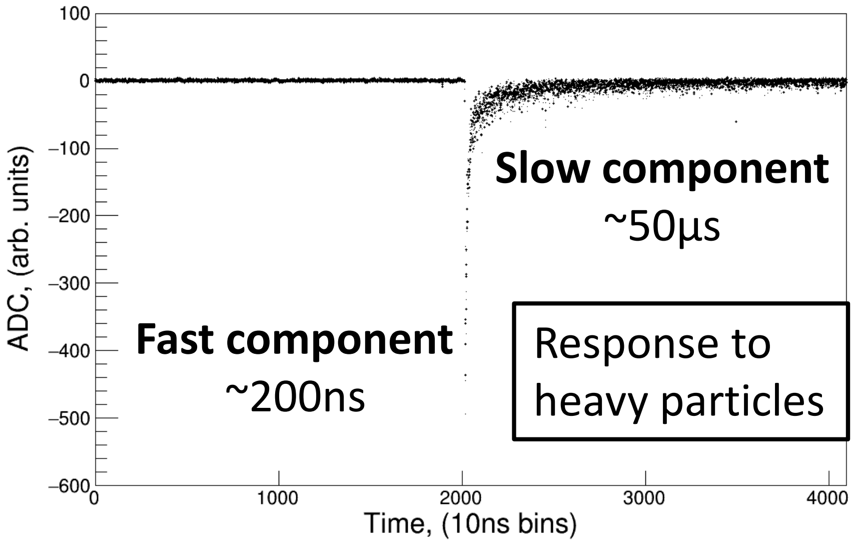
Conical light reflectors covered by **Tyvek** sheets. The Al box made air tight using the **Teflon sealant.**

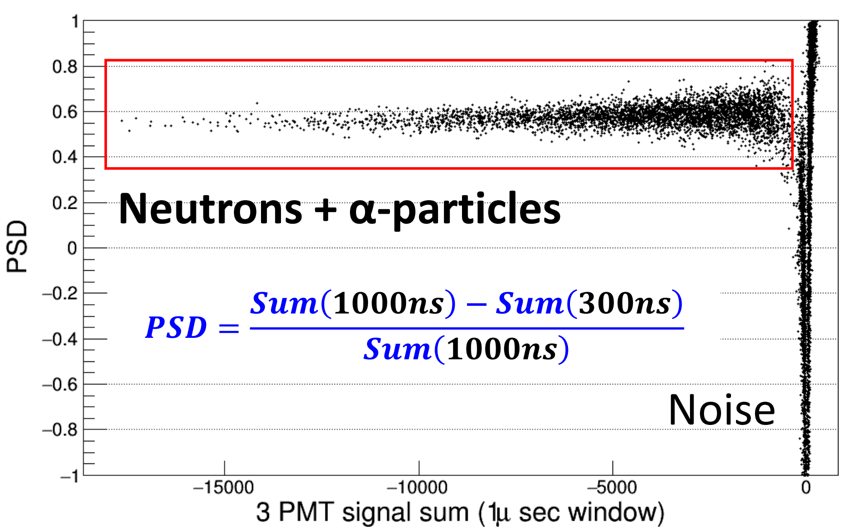
JSPS grant: 16K05371

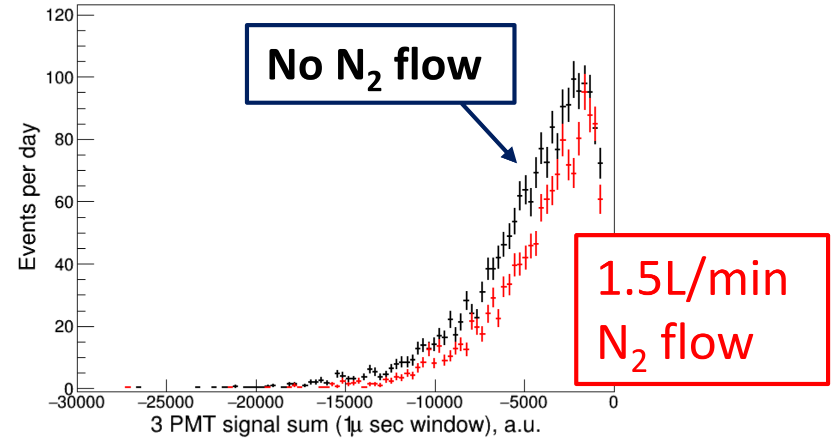


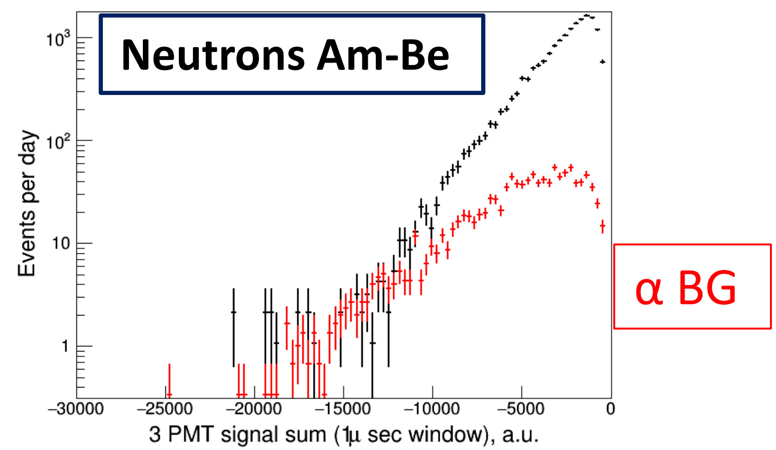
- Two 0.32mm-thick **EJ-426 scintillator** sheets (**0.25m × 0.5m each**) laminated by 0.25mm-thick clear polyester sheets from both sides were used.
- The EJ-226 is a homogeneous mixture of **LiF and ZnS:Ag** (mass ratio **1:2**), a **95% enriched ^{6}Li** was used. The ZnS:Ag light yield is **95000photons/MeV.**
- **$^{6}Li + n \rightarrow \alpha + {}^{3}H + 4.78MeV$ (σ = 941barn);**
- The thermal detection efficiency is **34%**;
- The detector is **non-sensitive to γ-rays**;

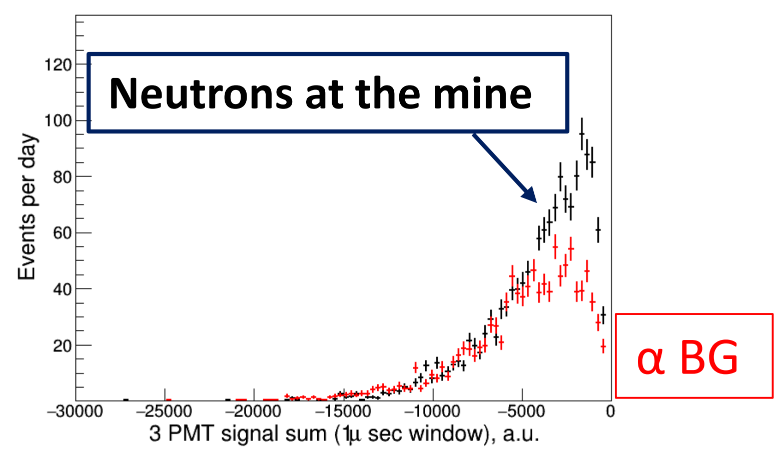
The thermal neutron detection at the Kamioka mine











Summary

- We successfully developed NaI(Tl) crystals with the level of RI that allows us to test DM claim made by DAMA/LIBRA collaborations.
- We plan to begin **construction of the NaI(Tl) detector in the Pb/Cu shielding at the clean room A during the year 2018**.
- The detector will consist of cylindrical **5 × 5-inch NaI(Tl) crystals attached to a single 4-inch R13444 PMT**.
- Currently, we select radio-pure components for the NaI(Tl) crystal cover, and the PMT's voltage-divider circuitry.
- We continue to build a **new research infrastructure**, including supplementary detectors (e.g. for thermal and fast neutrons) to be able to **keep various sources of background under control**.

Thank you!