Search for physics beyond the SM at KamLAND

The University of Tokyo

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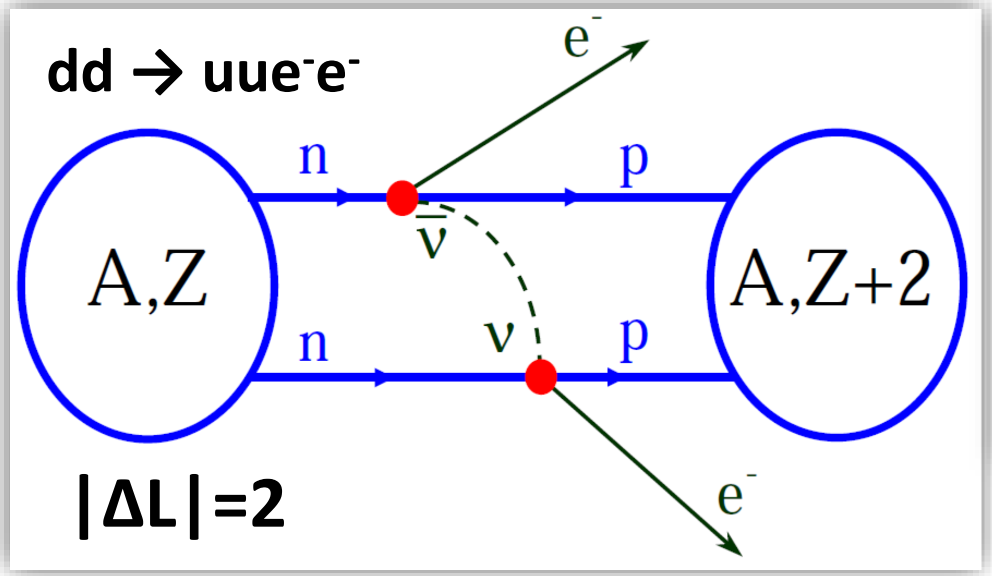
The 3rd international conference on particle physics and astrophysics
Moscow, October 2017

Outline

☐ Neutrinoless double beta decay search using **^{136}Xe-**loaded liquid scintillator located at the ultra-low background central region of the KamLAND.

☐ Development of ultra-low background **NaI(Tl)** detectors and related infrastructure for rare event searches.

The 0νββ test of seesaw mechanism



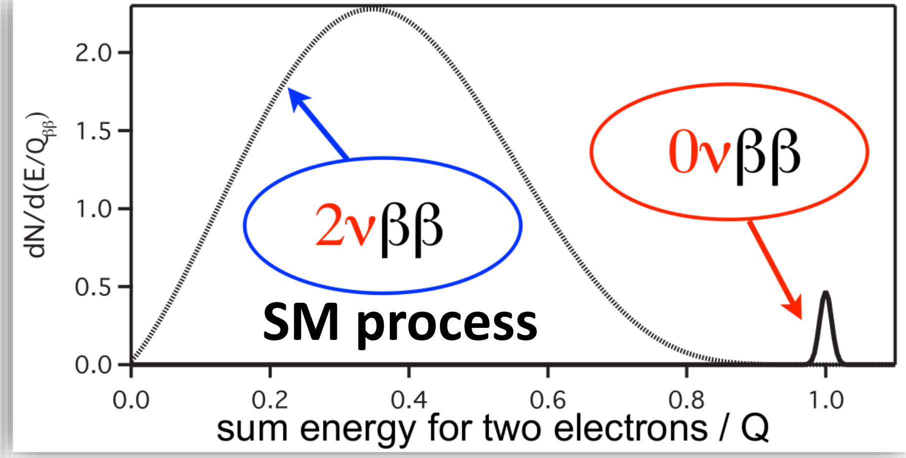
$dd \rightarrow uue^-e^-$

$|\Delta L|=2$

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

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot g^4_A \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2$$

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

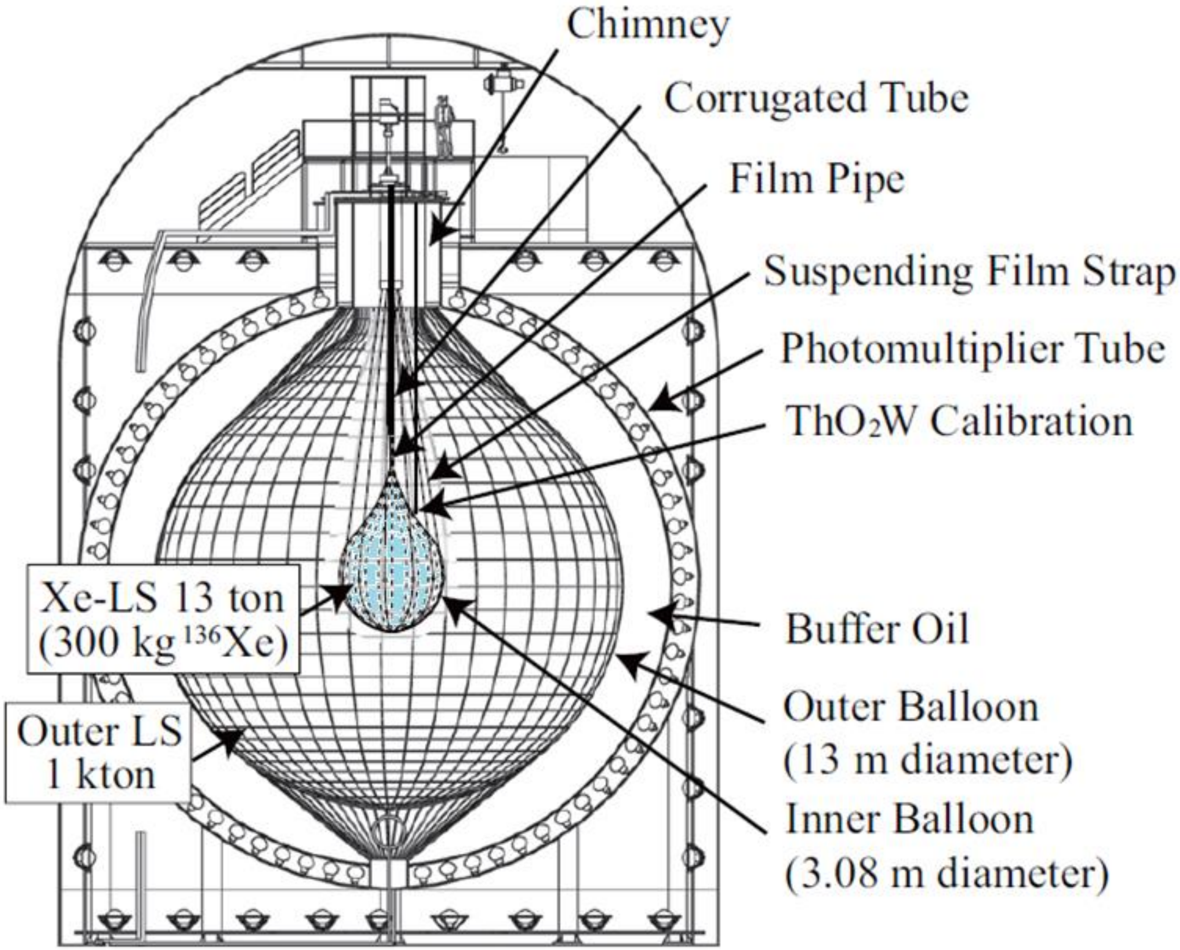


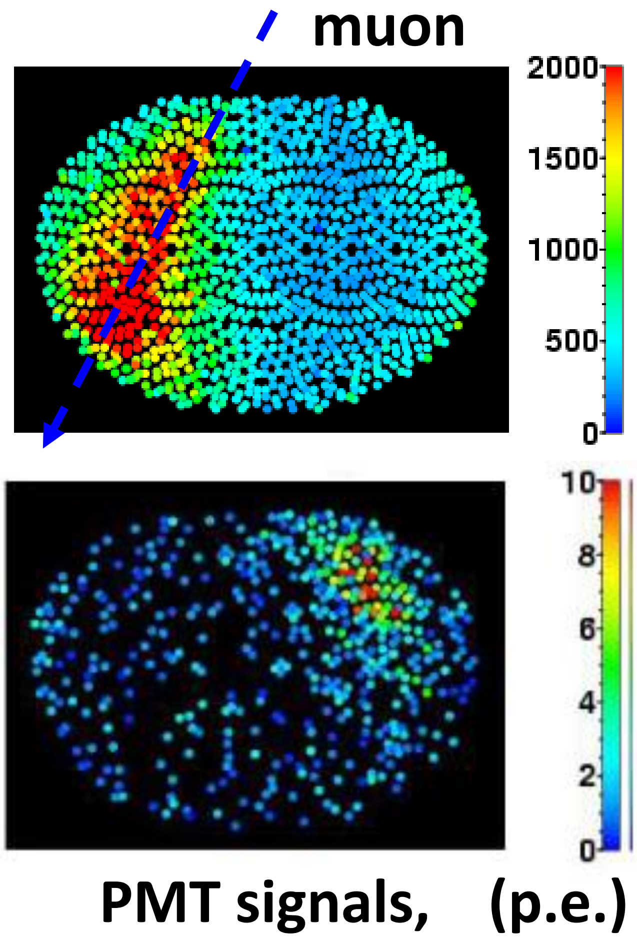
In calorimeters, as KamLAND, **sum of kinetic energies** of two electrons is measured

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

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

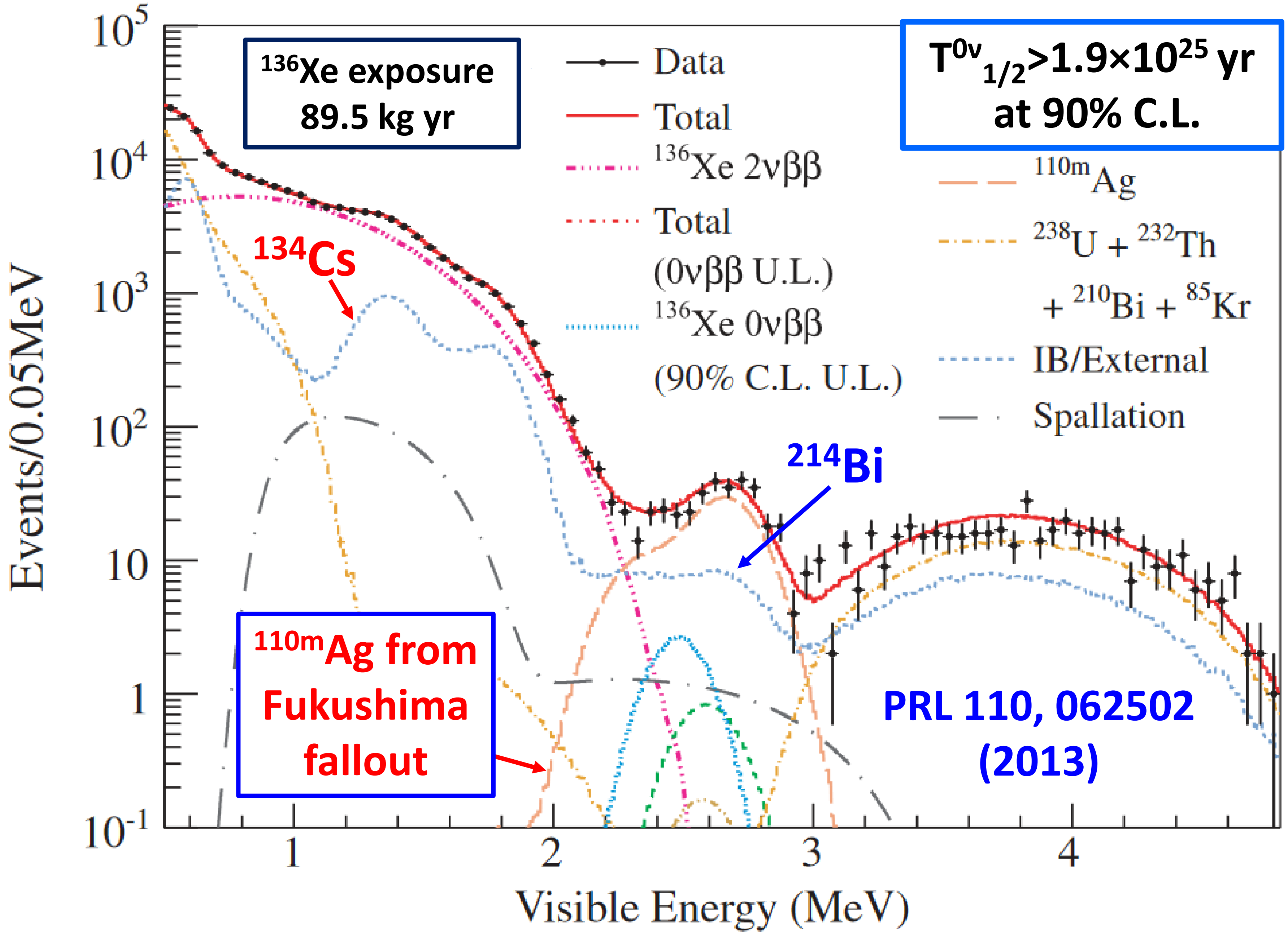
Structure of the KamLAND-Zen (year 2011)





- **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)



^{136}Xe exposure
89.5 kg yr

$T^{0\nu}_{1/2} > 1.9\times10^{25}$ yr
at 90% C.L.

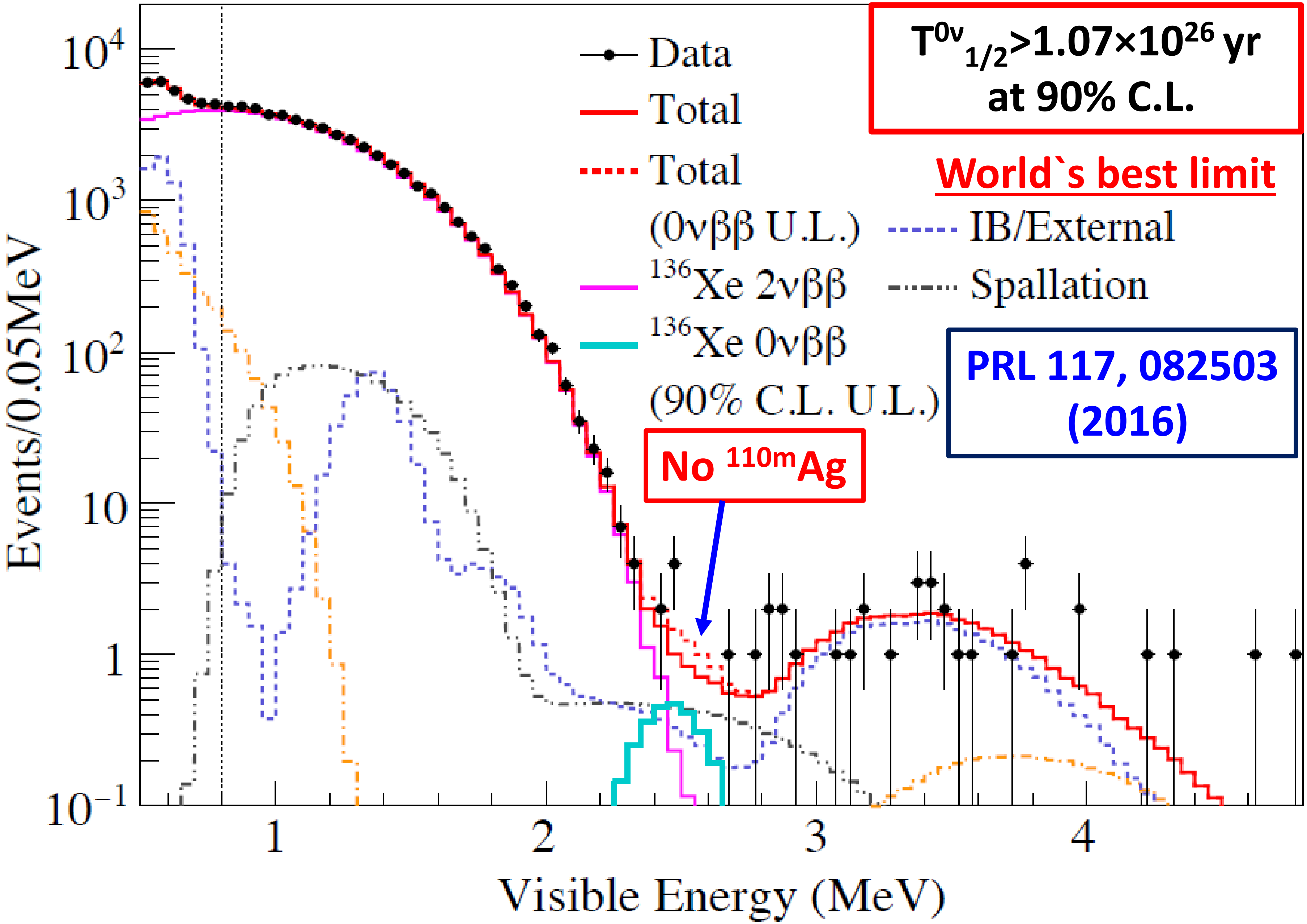
^{134}Cs

^{214}Bi

^{110m}Ag from
Fukushima
fallout

PRL 110, 062502
(2013)

KamLAND-Zen 400: final result (year 2016)



$T^{0\nu}_{1/2} > 1.07\times10^{26}$ yr at 90% C.L.

World`s best limit

No ^{110m}Ag

PRL 117, 082503 (2016)

Joint work with F. Simkovic to determine g_A using shape of the measured 2νββ spectrum

$$\left[T^{2\nu\beta\beta}_{1/2}\right]^{-1} \simeq \left(g_A^{\text{eff}}\right)^4 \left|M^{2\nu}_{GT-3}\right|^2 \frac{1}{\left|\xi^{2\nu}_{13}\right|^2} \left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)$$

$$\left(g_A^{\text{eff}}\right)^2 = \frac{1}{\left|M^{2\nu}_{GT-3}\right|} \frac{\left|\xi^{2\nu}_{13}\right|}{\sqrt{T^{2\nu-exp}_{1/2} \left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)}}$$

Can be calculated exactly

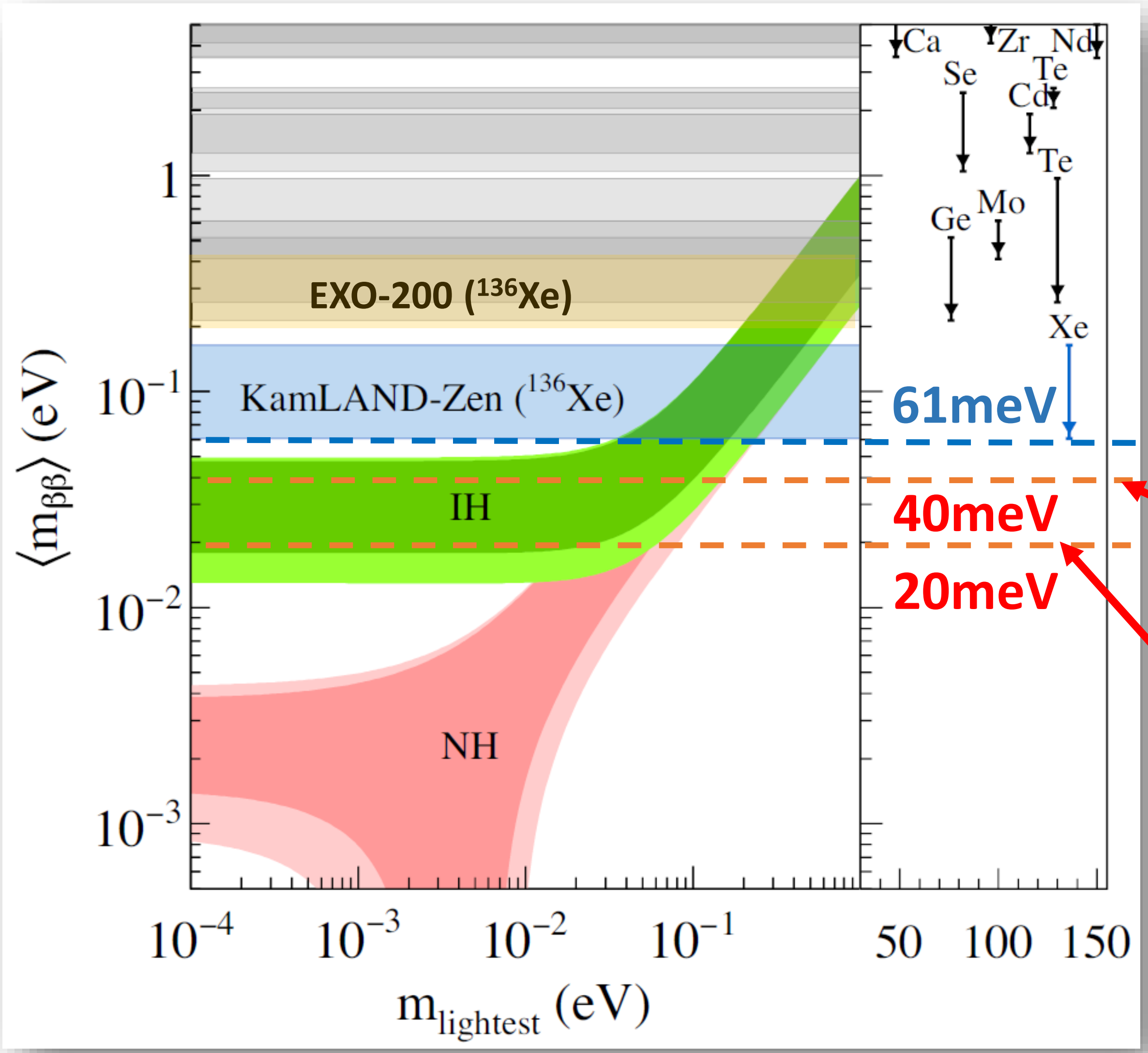
Extracted from the 2νββ spectrum shape

$$M^{2\nu}_{GT-1} \equiv M^{2\nu}_{GT}$$

$$M^{2\nu}_{GT-3} = \sum_n M_n \frac{4\, m_e^3}{\left(E_n - (E_i + E_f)/2\right)^3} \qquad \xi^{2\nu}_{13} = \frac{M^{2\nu}_{GT-3}}{M^{2\nu}_{GT-1}}$$

The g_A^{eff} can be deterimed with the **measured half-life, ratio of NMEs** and calculated **NME dominated by transitions through low lying states of the intermediate nucleus**.

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



KL-Zen 400 final

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

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**: **$T^{0\nu}_{1/2}>1.07\times10^{26}$ 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**.

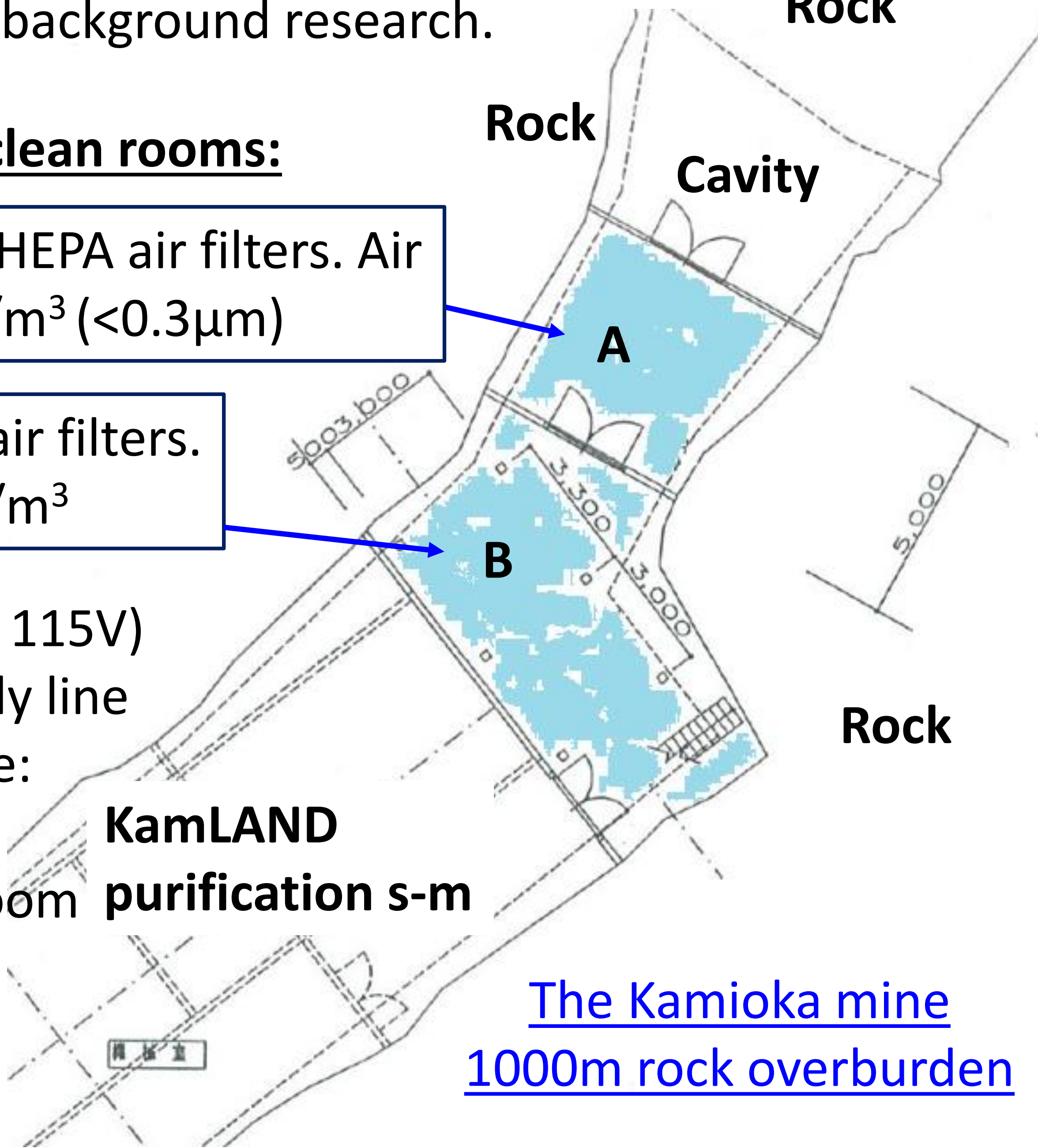
In 2012, I began development of **two clean rooms (A, B)** for ultra-low background research.

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

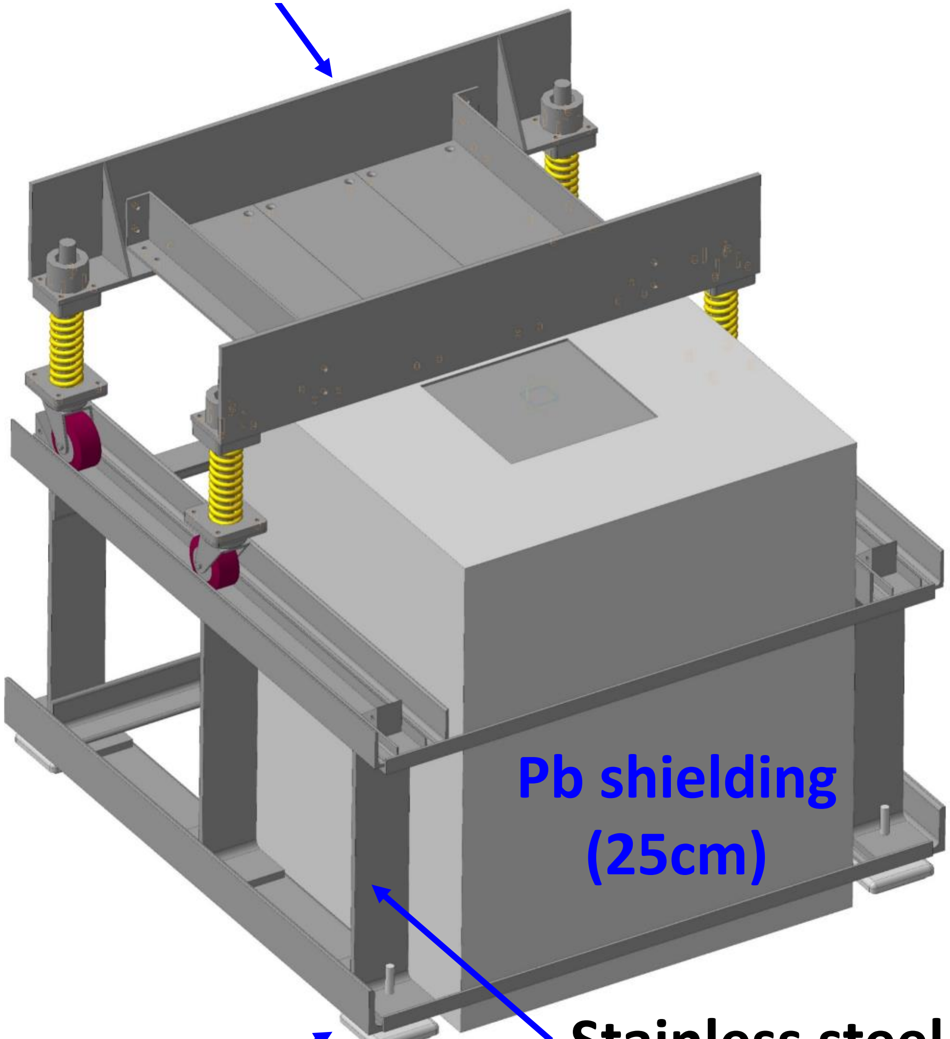
- ○ 17kWatt AVR unit (100V, 115V)
- ○ Boiled off Nitrogen supply line
- ○ Radon-less air supply line: (5-10m^3 per hour)
- ○ Air cond. units in each room

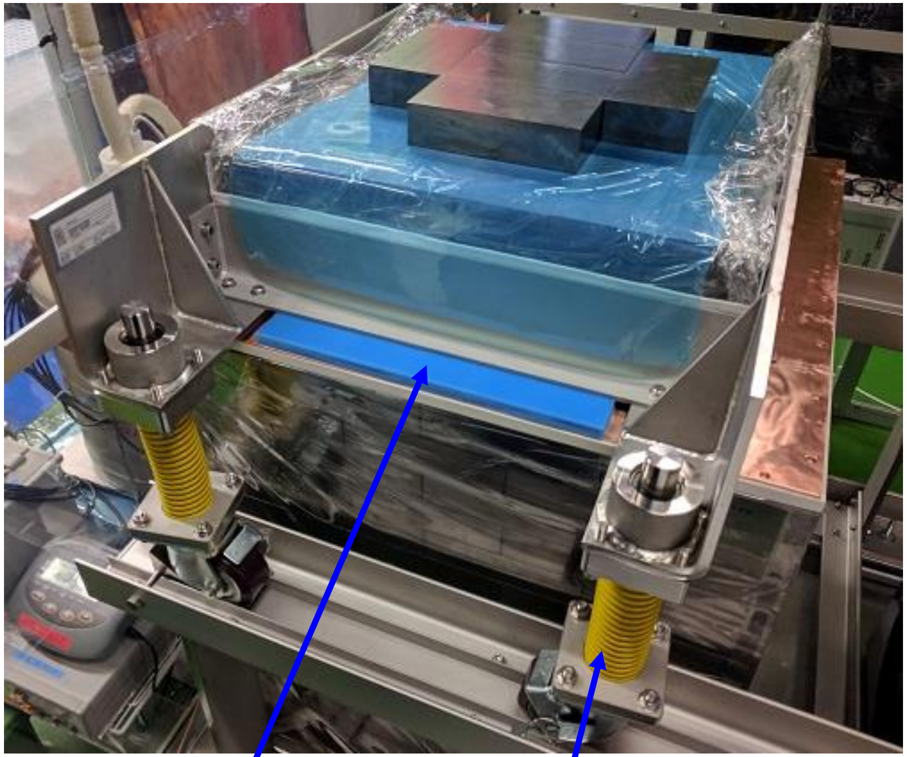


The Kamioka mine 1000m rock overburden

Our HPGe detector shielding design

Cart for Pb bricks made of radio-pure stainless steel





plastic sealant

Springs used as a lifting mechanism

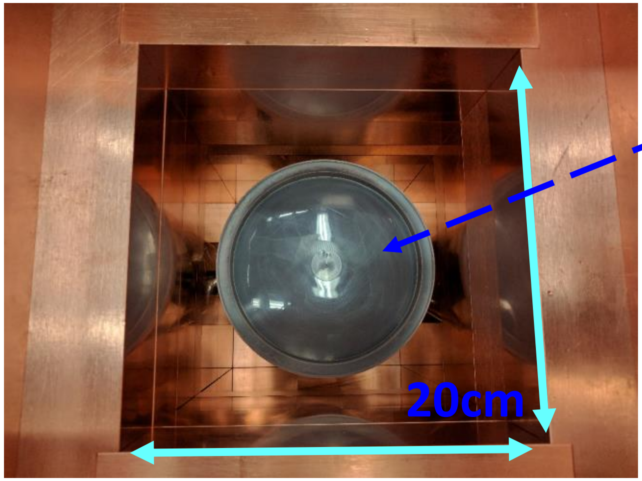
Stainless steel support frame

Level regulators

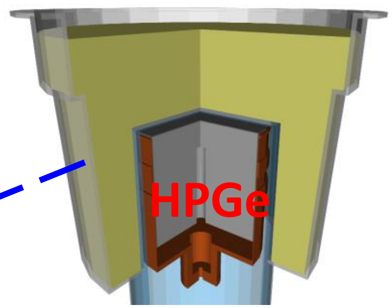
The HPGe detector located underground (2700m.w.e.)

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

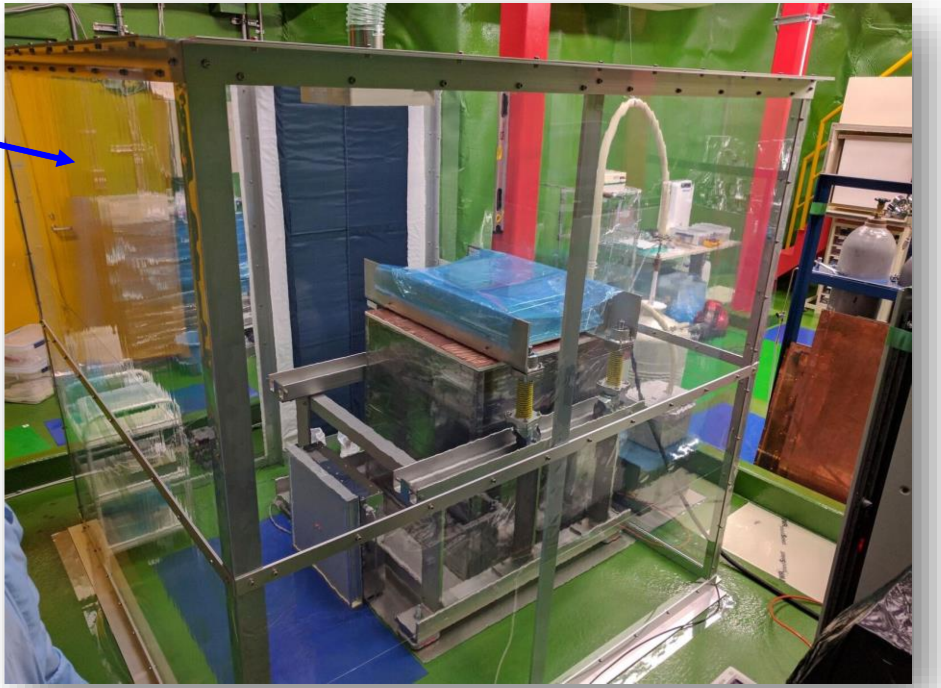


1.3L container



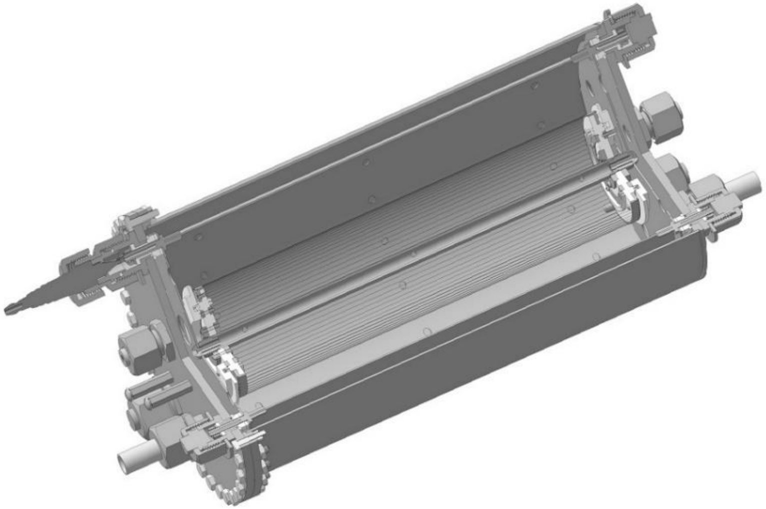
Enough space for e.g. 4-inch PMT

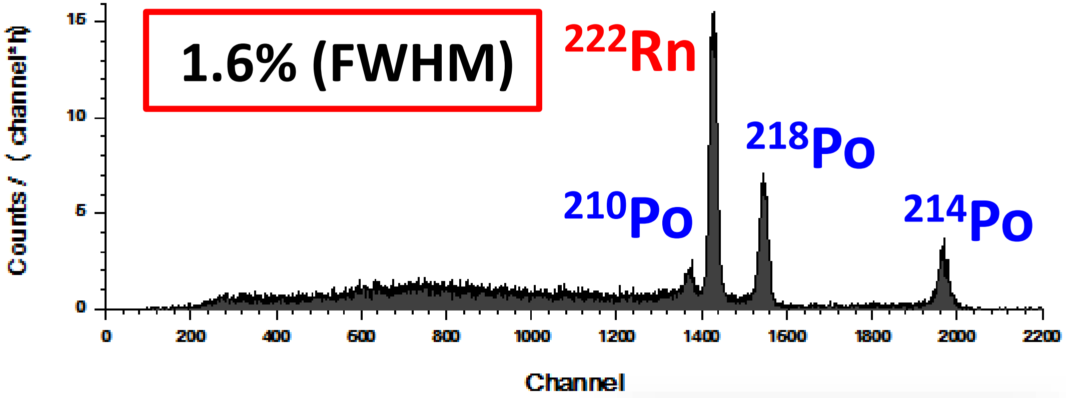
HPGe p-type
75% rel. eff.
Room B



- 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

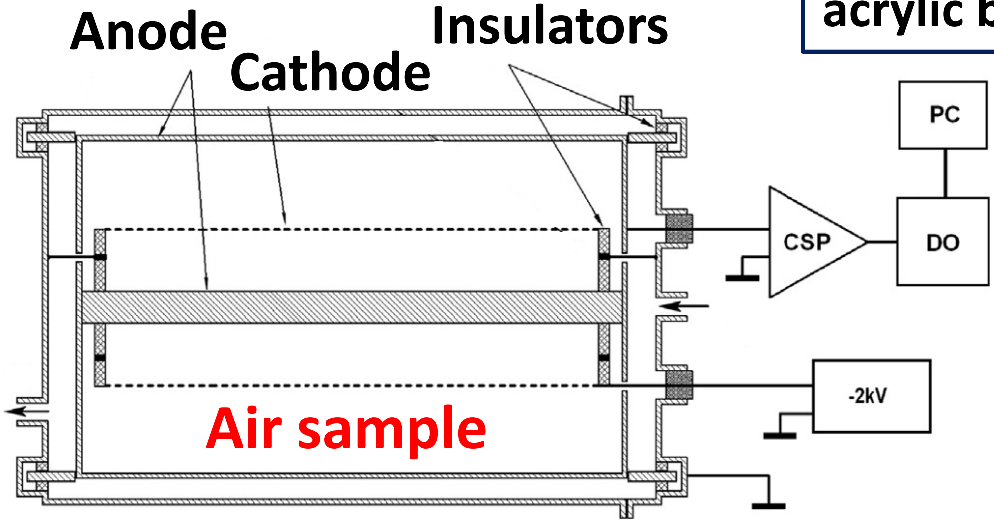




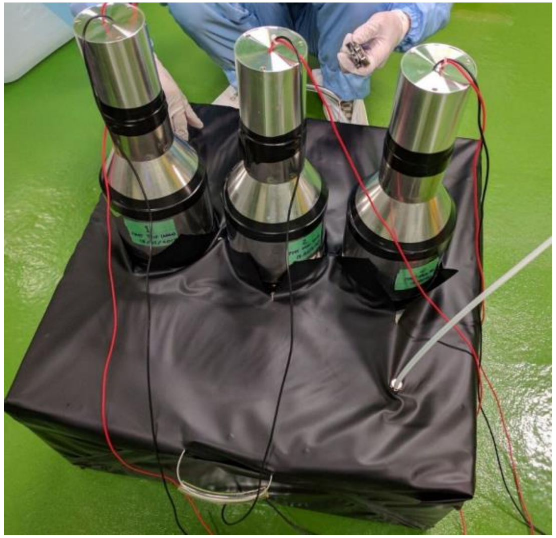
Direct detection of the Radon α-decay in the air.

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

JSPS grant: 16K05371



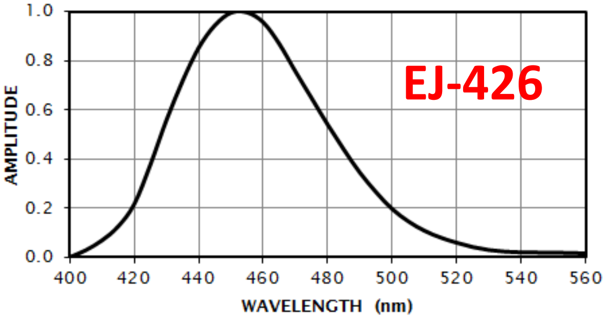
Currently, we build a **second layer of acoustic shielding** to minimize interference between radon measurements and our every day activities at the mine.

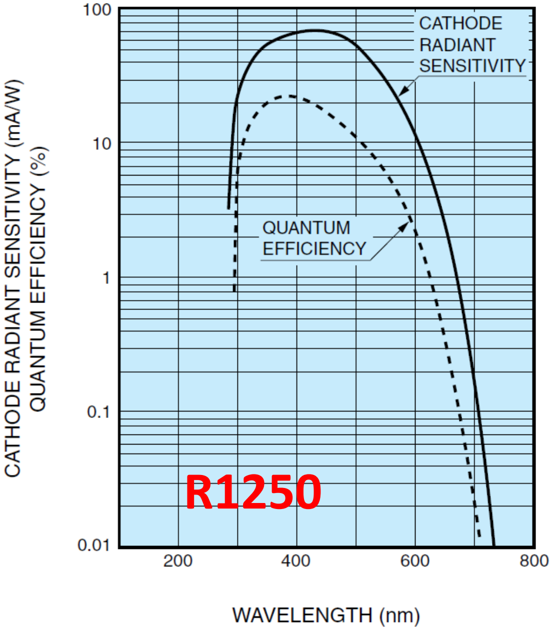


Hamamatsu **R1250 PMTs**
CAEN 4 channel waveform digitizer **N6724F** (100MHz)

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

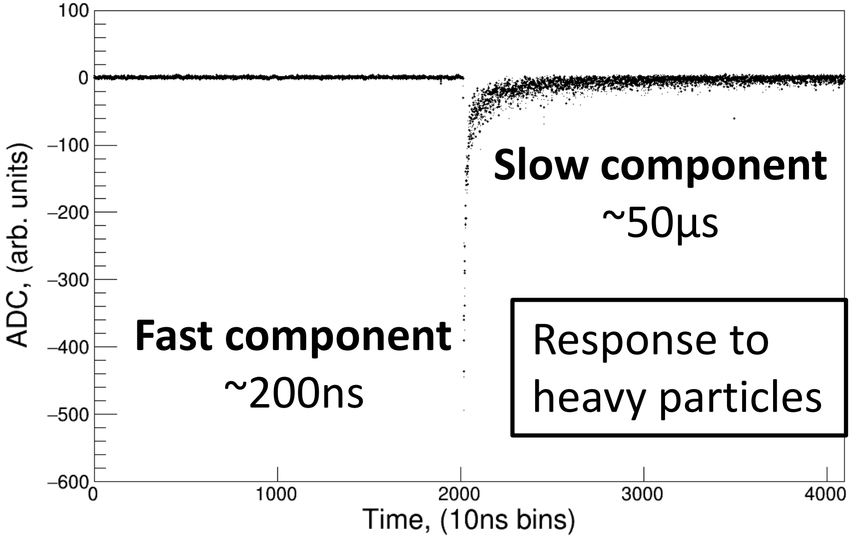
JSPS grant: 16K05371





- 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.**
- $^{6}\mathrm{Li} + n \rightarrow \alpha + {}^{3}\mathrm{H} + 4.78\,\mathrm{MeV}$ **(σ = 941barn);**
- The thermal detection efficiency is **34%**;
- The detector is **non-sensitive to γ-rays**;

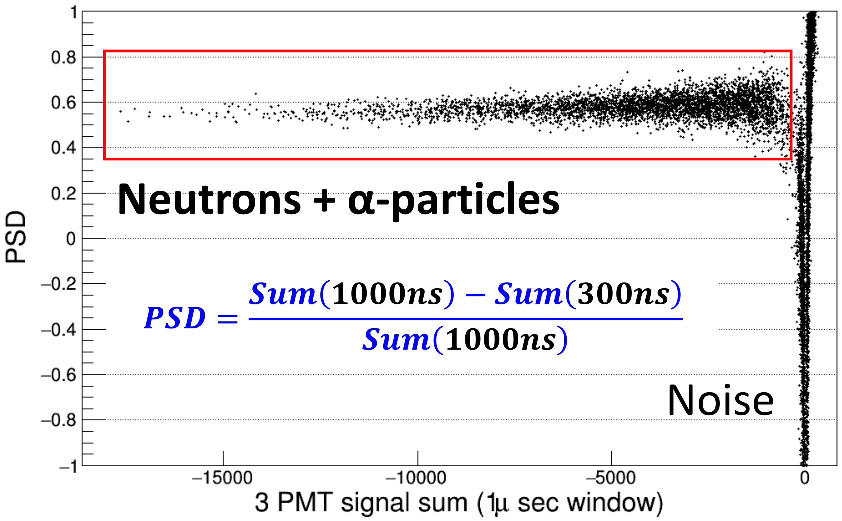
The thermal neutron flux variation monitoring at the Kamioka mine



Slow component
~50µs

Fast component
~200ns

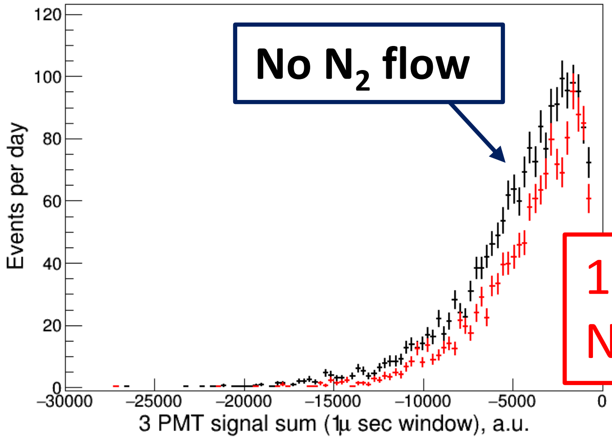
Response to heavy particles



Neutrons + α-particles

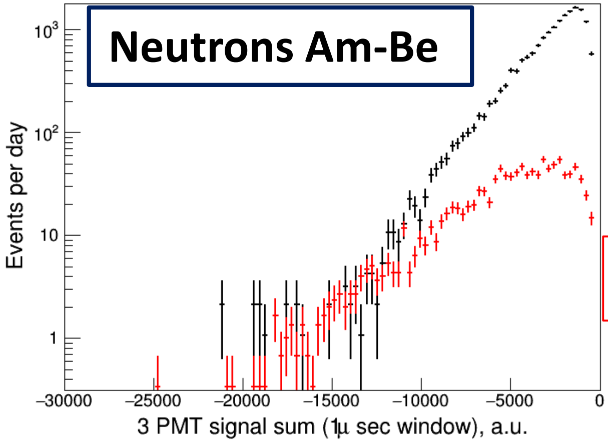
$$PSD = \frac{Sum(1000ns) - Sum(300ns)}{Sum(1000ns)}$$

Noise



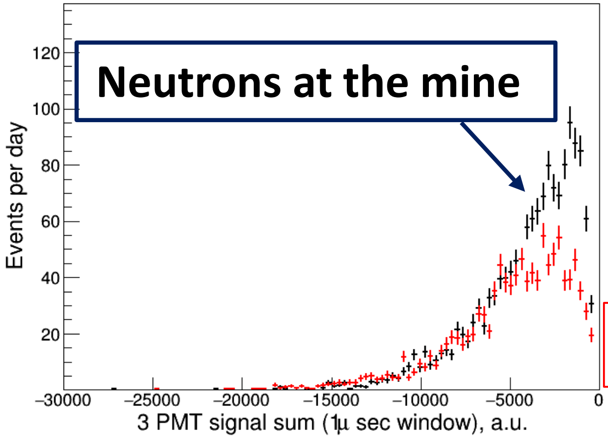
No N_2 flow

1.5L/min N_2 flow



Neutrons Am-Be

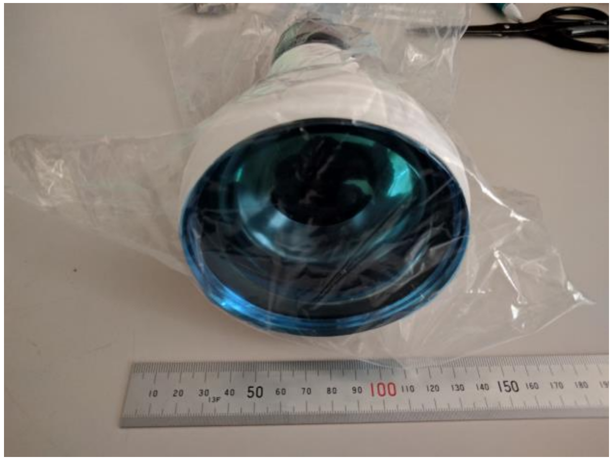
α BG

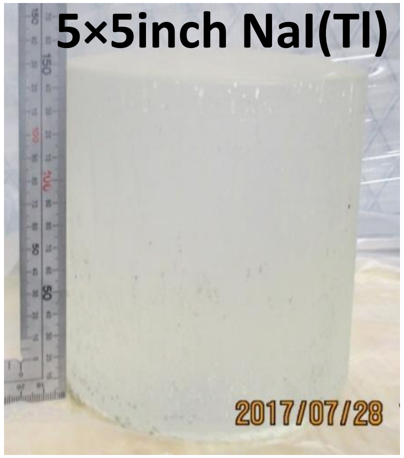


Neutrons at the mine

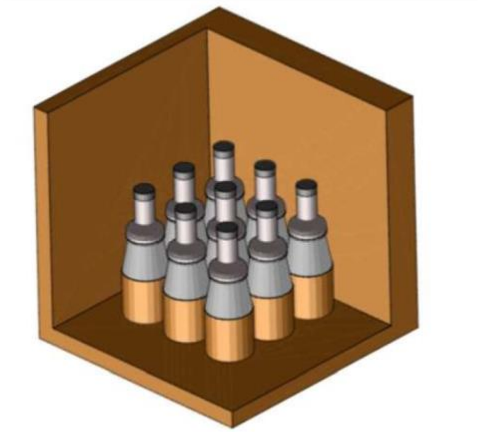
α BG

Impurity	DAMA/LIBRA	Our result
natK [ppb]	< 20	125
Th-chain [ppt]	0.5 ~ 7.5	0.3 ± 0.5
^{226}Ra [μBq/kg]	21.7 ± 1.1	58 ± 4
^{210}Pb [μBq/kg]	24.2 ± 1.6	30 ± 7





- The **R13444X** is **4-inch experimental ultra-low background Hamamatsu PMT** with a metal body. Optical window is made of Synthetic Silica with the Bialkali photocathode. Spectral response maximum at 420nm (200-650nm range); **QE**@420nm : **34.9%** and **33.38%**. **Gain** at +1500V : 5×10^6**; TTS**: 13ns

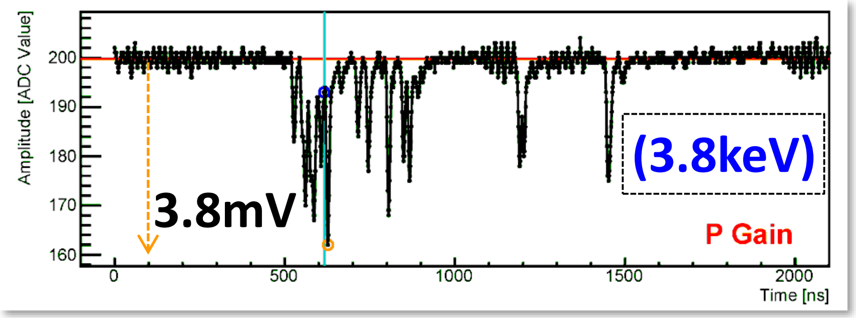


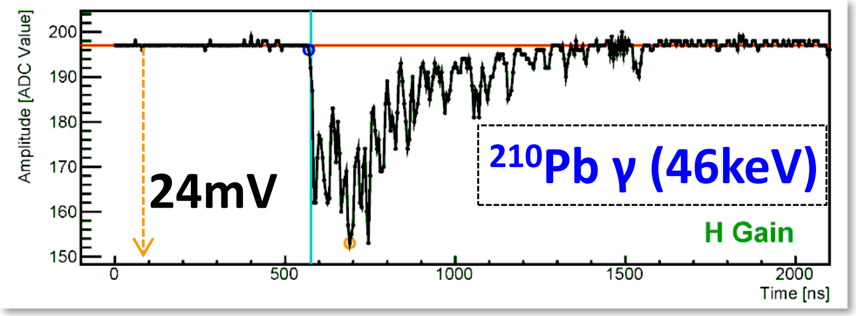
Shielding: Old lead + 600kg of copper melted at **Mitsubishi Materials** from freshly manufactured electroformed Cu sheets.

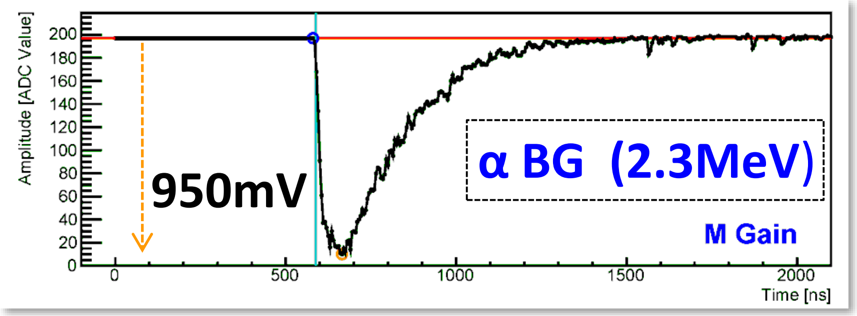
DM detector (Phase 1): 5-inch cylindrical NaI(Tl) crystals viewed by R13444 PMTs

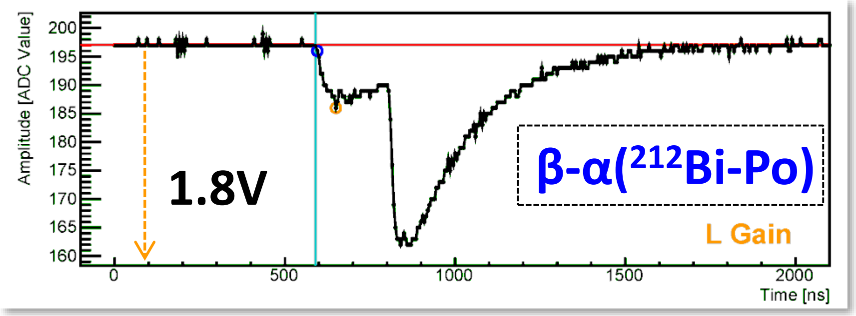
We developed radio-pure NaI(Tl) crystals using the Bridgman method. For the new **5×5inch crystal** we expect **radio-purity similar to that of the DAMA/LIBRA crystals.**

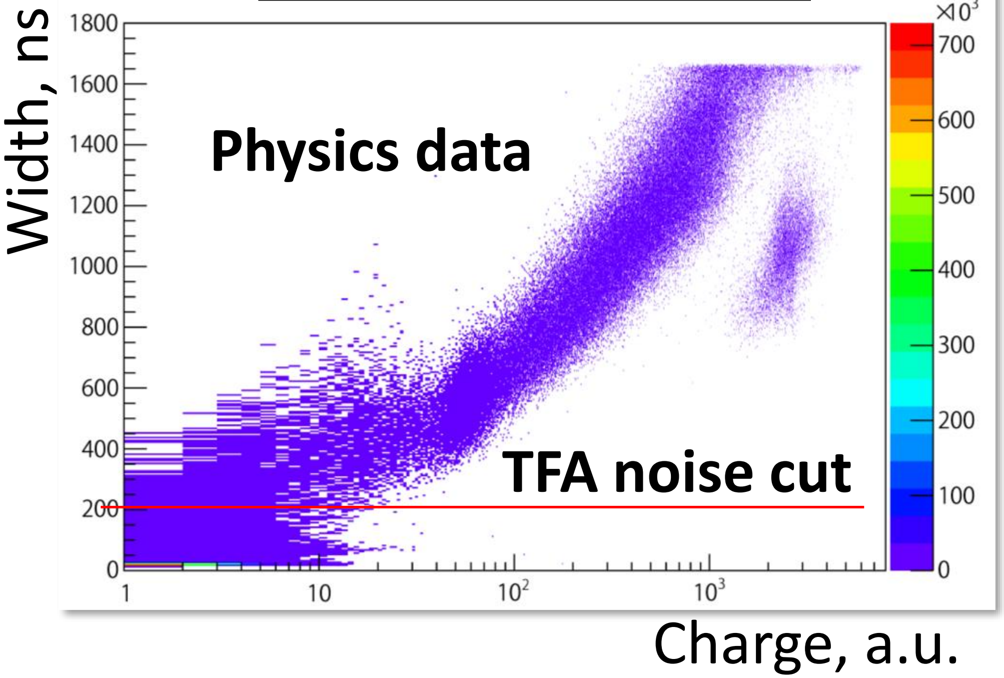
The NaI(Tl) data



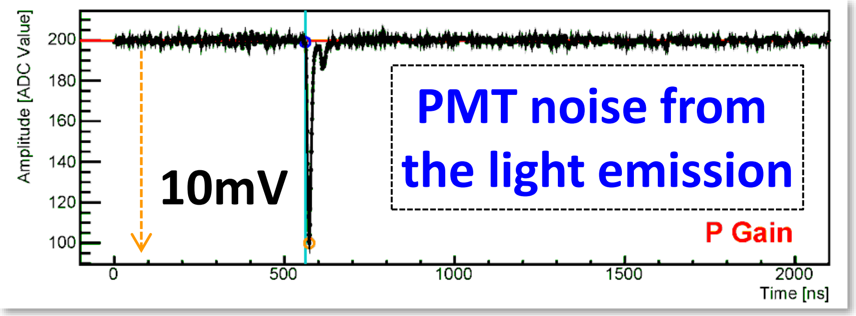








PMT noise >99.9% of data, from single to several narrow pulses (trains) was effectively cut by TFA .



Summary for the NaI(Tl) research

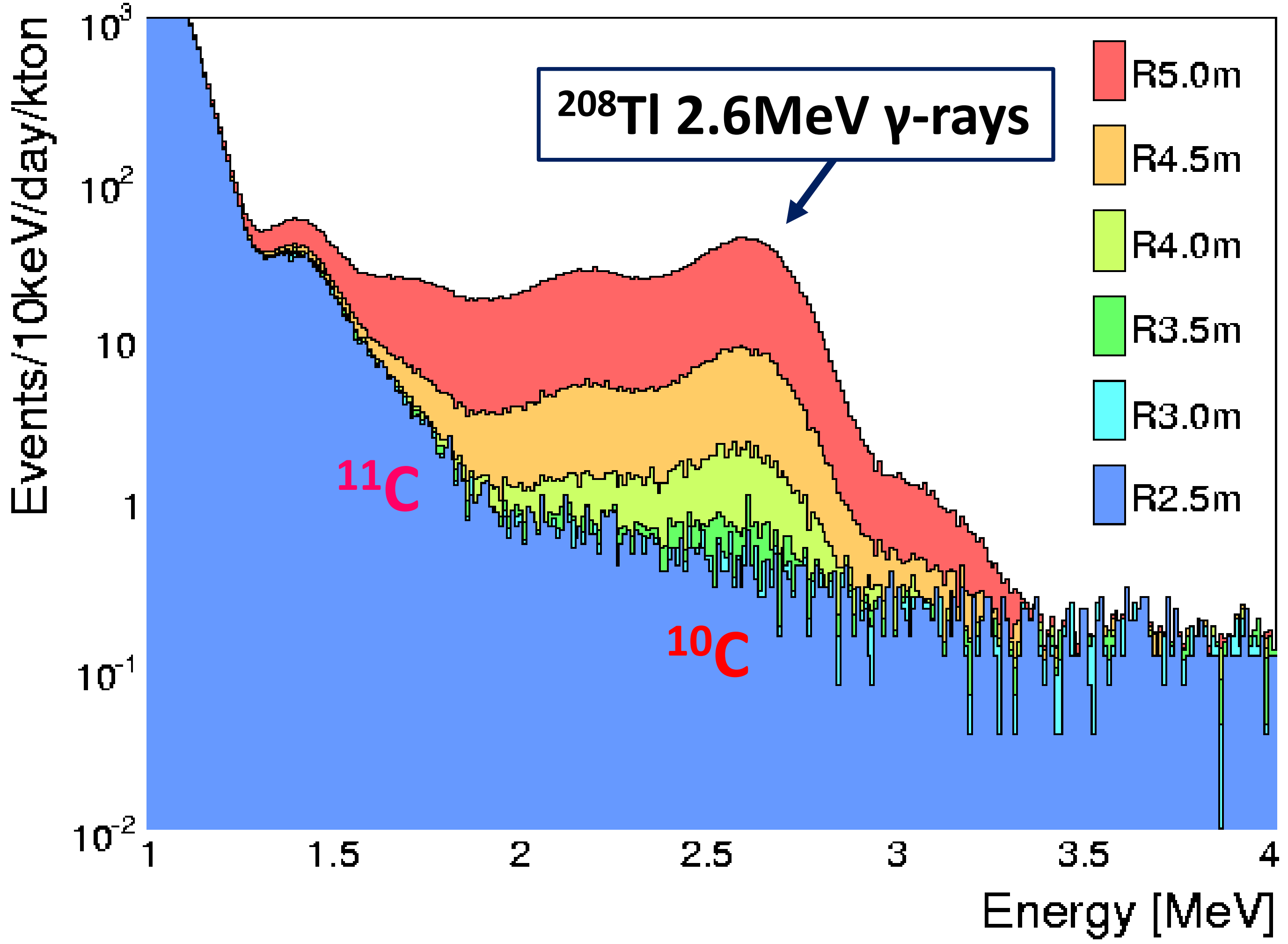
- We developed **5×5-inch highly radio-pure NaI(Tl) crystals** for rare event searches.

- In year 2018, we plan to start construction of the **NaI(Tl) DM detector** in a conventional Pb+Cu passive shielding that can be used for testing the **DM observation claim made by DAMA/LIBRA collaborations**. In more distant future, that detector could be deployed into the ultra-low background central region of KamLAND currently reserved for the KamLAND-Zen 0νββ experiment.

- We intend to use our crystals as a detector for **precision studies of the coherent neutrino scattering**. Possible neutrino sources are JPARC, and IsoDAR.

BACKUP SLIDES

Use of KamLAND for rare event searches


^{208}Tl 2.6MeV γ-rays

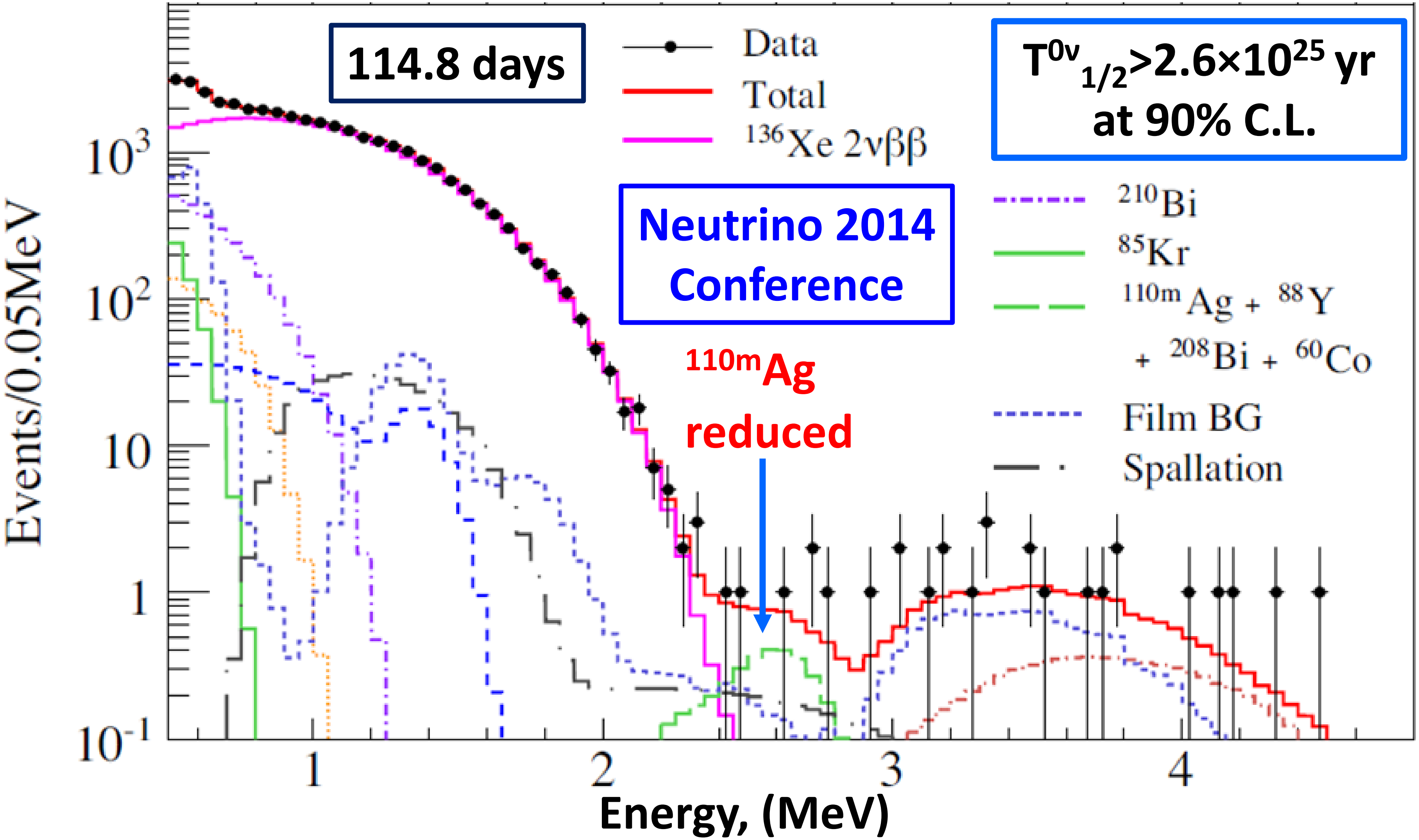
^{11}C

^{10}C

Fiducial volume cuts

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

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



114.8 days

$T^{0\nu}_{1/2} > 2.6\times10^{25}$ yr at 90% C.L.

Neutrino 2014 Conference

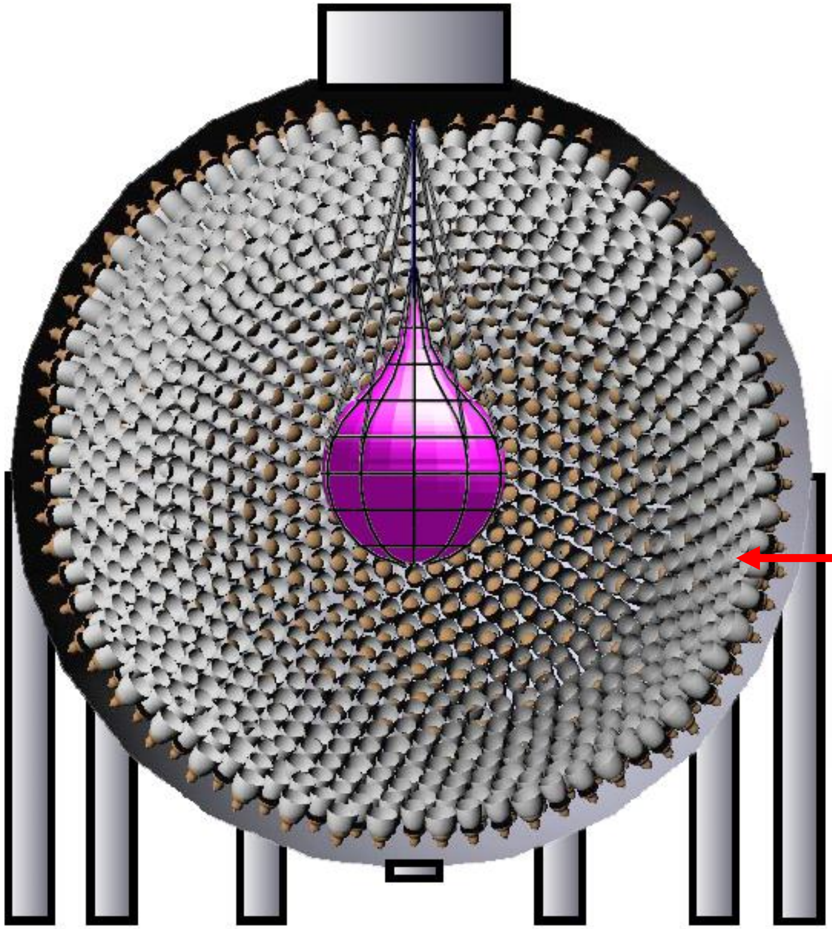
^{110m}Ag reduced

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

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



Gain in number of detected photons

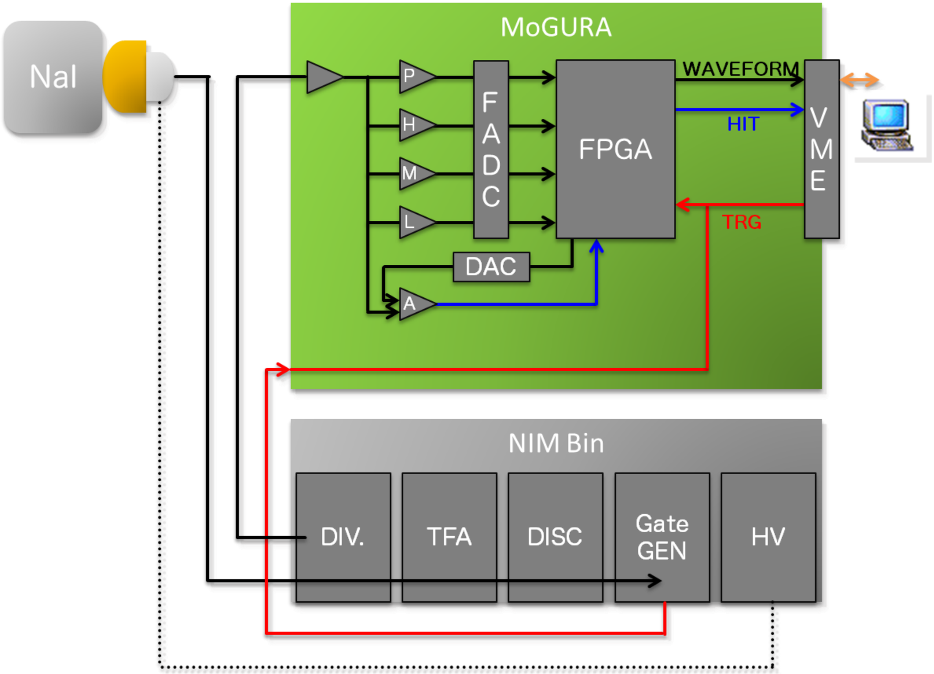
(after upgrade to KamLAND2)

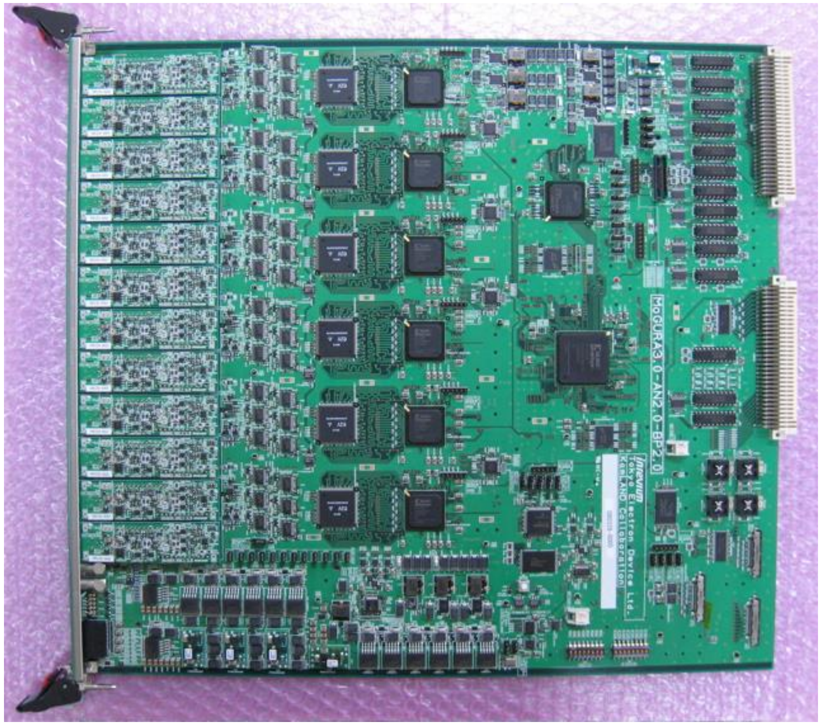
New LAB scintillator: **1.4** times

High QE PMTs: **1.9** times

Light collecting cones: **1.8** times

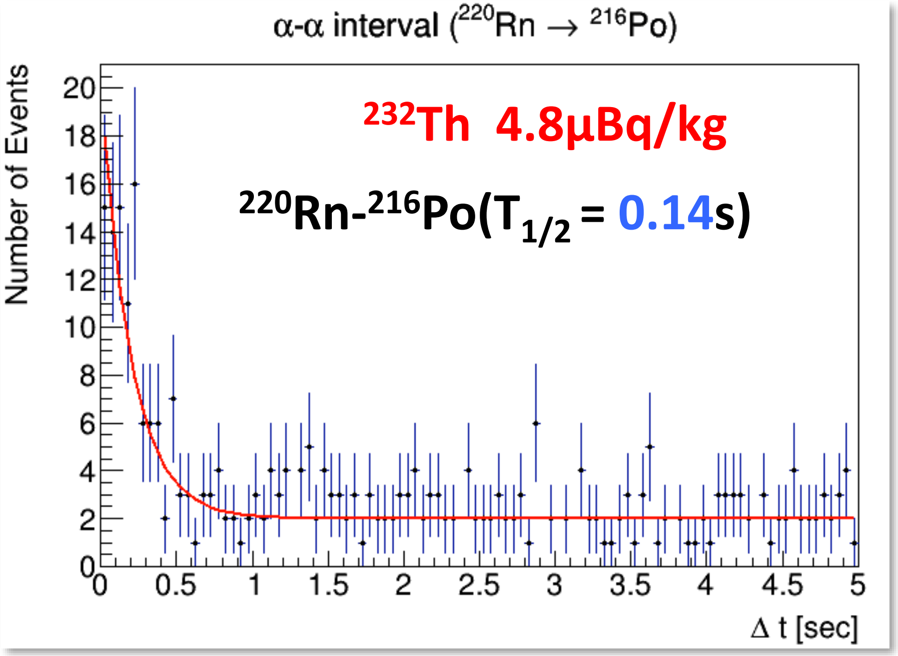
Enriched xenon mass > 1000kg

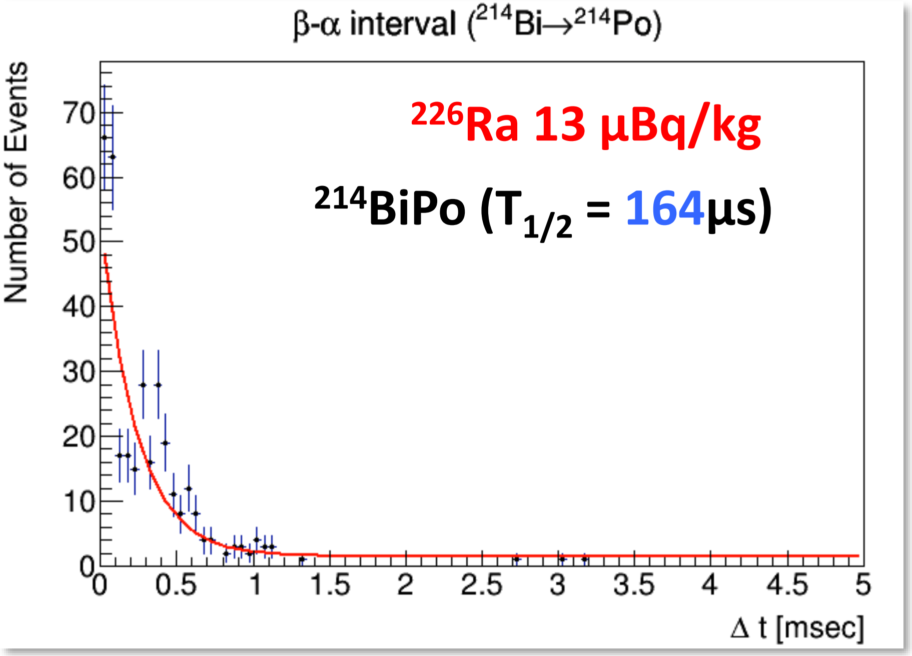


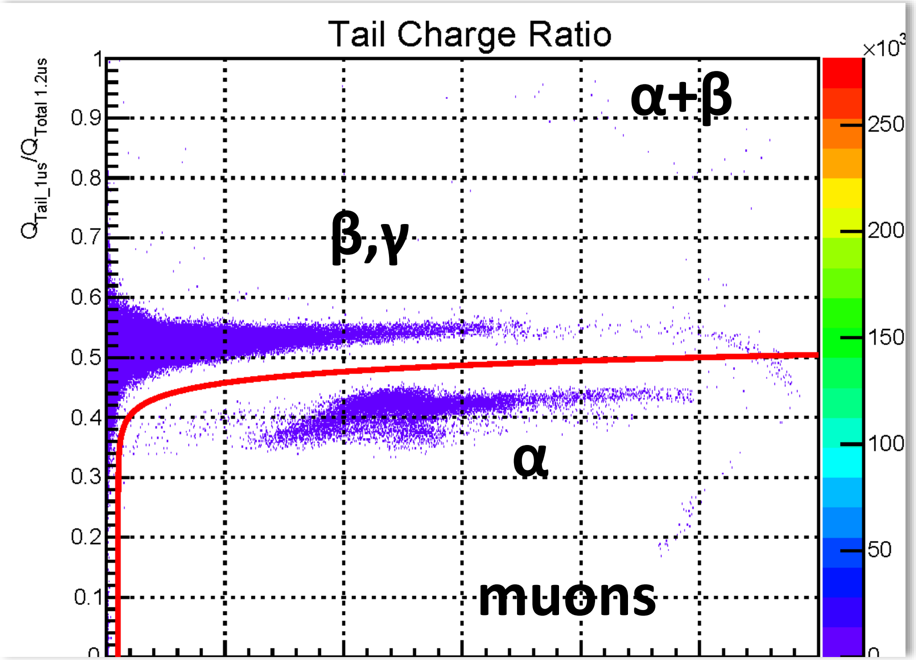


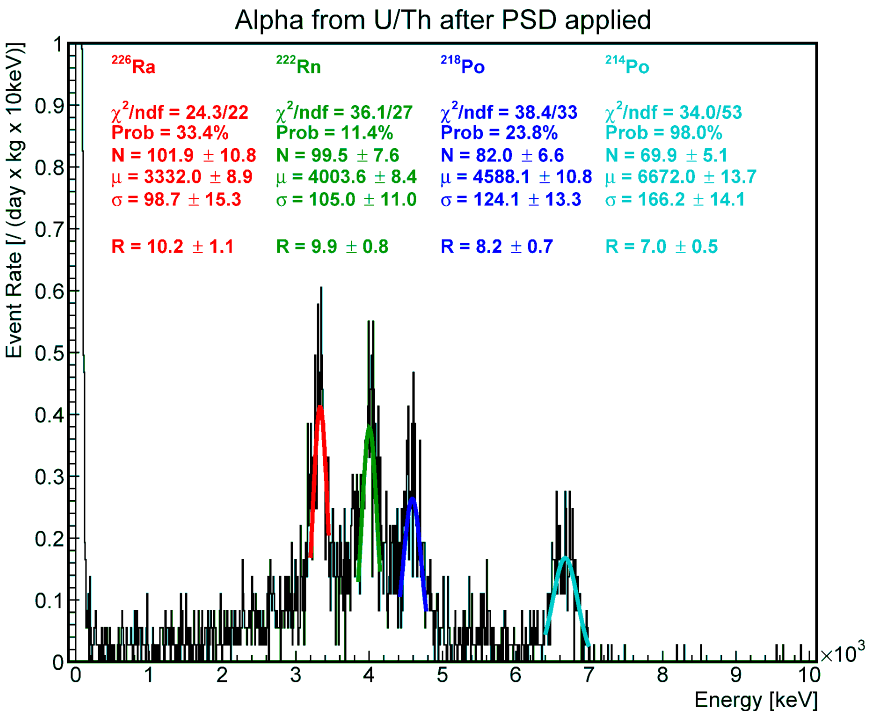
MoGURA based DAQ

- **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

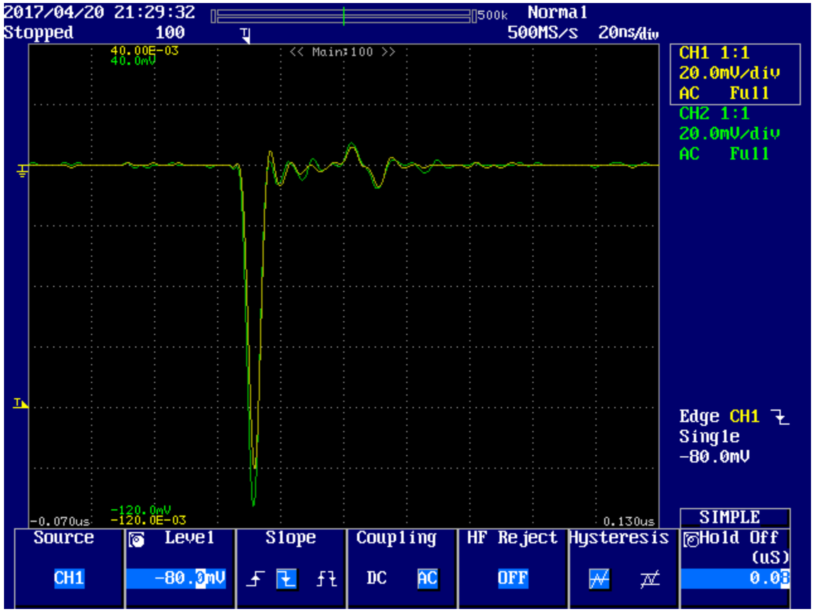

α-α interval (^{220}Rn → ^{216}Po)
^{232}Th 4.8μBq/kg
^{220}Rn-^{216}Po($T_{1/2}$ = 0.14s)
Number of Events
20
18
16
14
12
10
8
6
4
2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Δ t [sec]


β-α interval (^{214}Bi→^{214}Po)
^{226}Ra 13 μBq/kg
^{214}BiPo ($T_{1/2}$ = 164μs)
Number of Events
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Δ t [msec]


Tail Charge Ratio
$Q_{Tail\_1us}/Q_{Total\ 1.2us}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
α+β
β,γ
α
muons
×10³
250
200
150
100
50
0

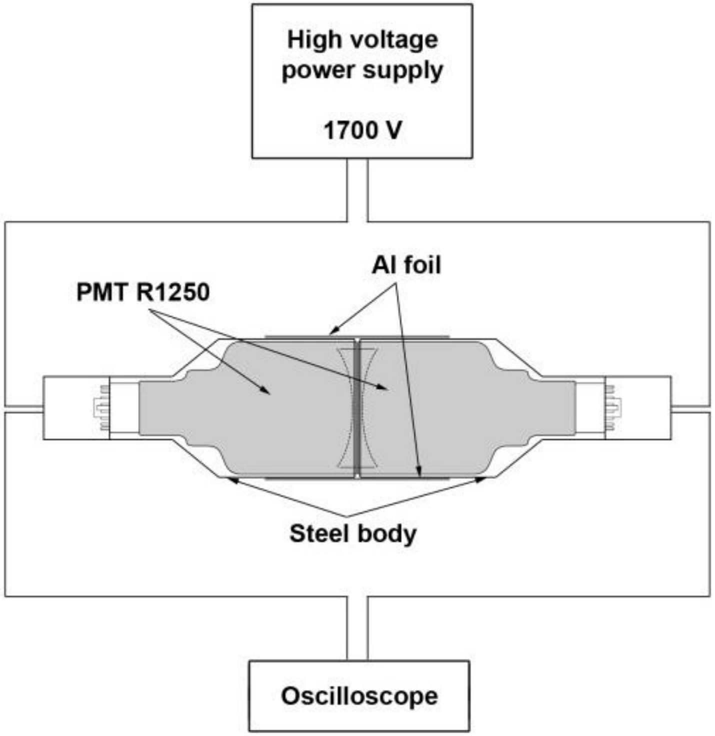

Alpha from U/Th after PSD applied
^{226}Ra
χ^2/ndf = 24.3/22
Prob = 33.4%
N = 101.9 ± 10.8
μ = 3332.0 ± 8.9
σ = 98.7 ± 15.3
R = 10.2 ± 1.1
^{222}Rn
χ^2/ndf = 36.1/27
Prob = 11.4%
N = 99.5 ± 7.6
μ = 4003.6 ± 8.4
σ = 105.0 ± 11.0
R = 9.9 ± 0.8
^{218}Po
χ^2/ndf = 38.4/33
Prob = 23.8%
N = 82.0 ± 6.6
μ = 4588.1 ± 10.8
σ = 124.1 ± 13.3
R = 8.2 ± 0.7
^{214}Po
χ^2/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)]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
10
×10³
Energy [keV]

Problem of high intensity fast PMT noise



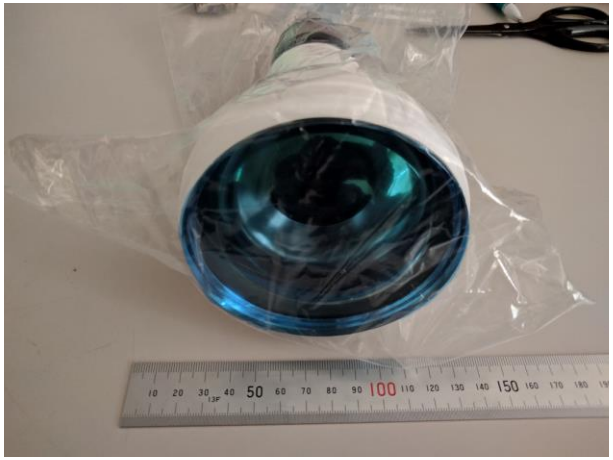
2017/04/20 21:29:32 500k Normal
Stopped 100 500MS/s 20ns/div
40.00E-03
40.0mV
<< Main:100 >>
CH1 1:1
20.0mV/div
AC Full
CH2 1:1
20.0mV/div
AC Full
Edge CH1
Single
-80.0mV
-0.070us
-120.0mV
-120.0E-03
0.130us
SIMPLE
Source: CH1
Level: -80.0mV
Slope
Coupling: DC AC
HF Reject: OFF
Hysteresis
Hold Off (uS): 0.03

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.**

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