Low background technologies for astroparticle experiments

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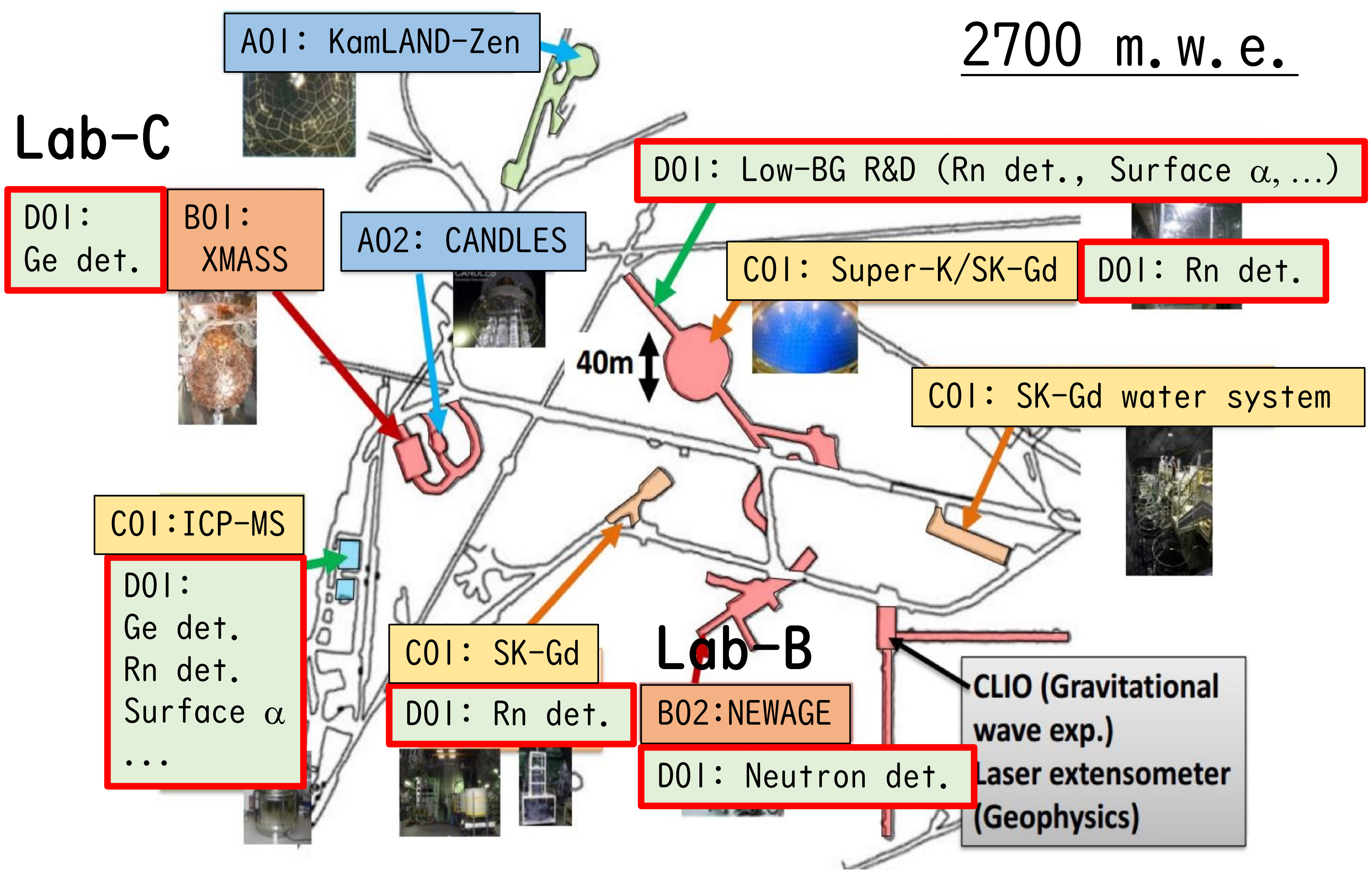
Contents

- Kamioka Underground Laboratory
- Cooperation overview
- Material screenings with HPGe detectors
- Rn assay in $Gd_2(SO_4)_3$ water
- Environmental neutron measurements in the underground
- Laser-induced emission spectroscopy for Gd^{3+}
- Summary

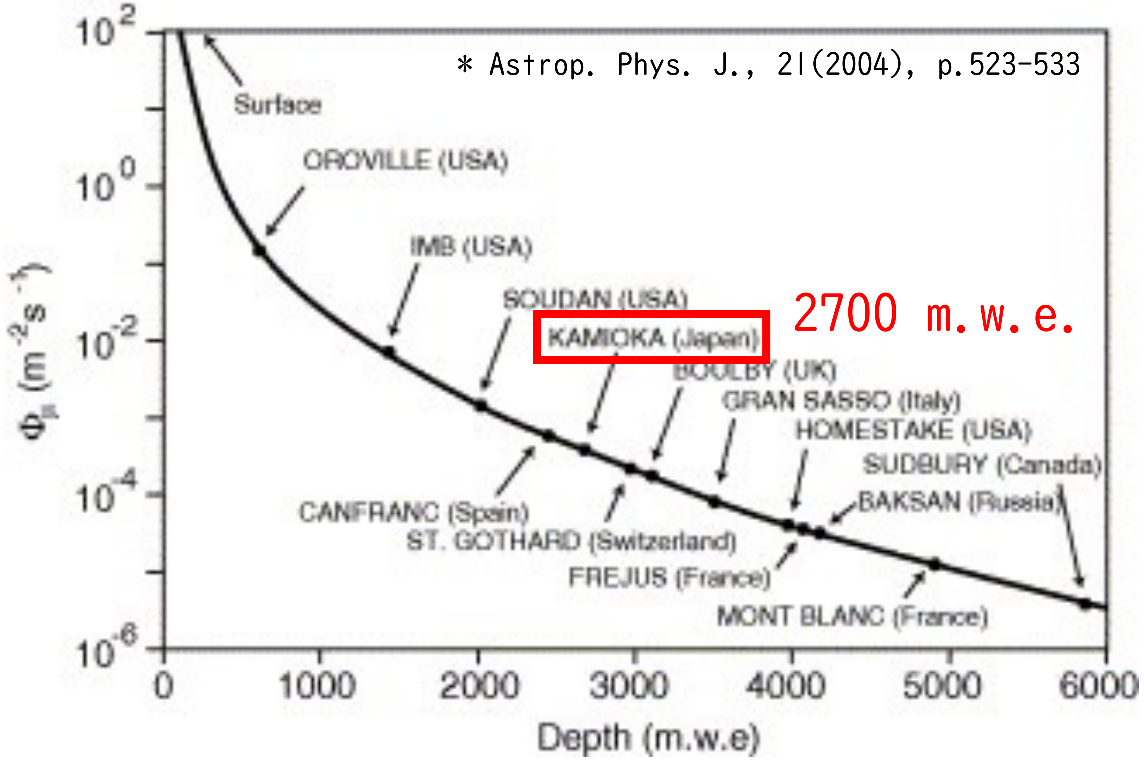
Kamioka underground laboratory

Kamioka Underground Laboratory

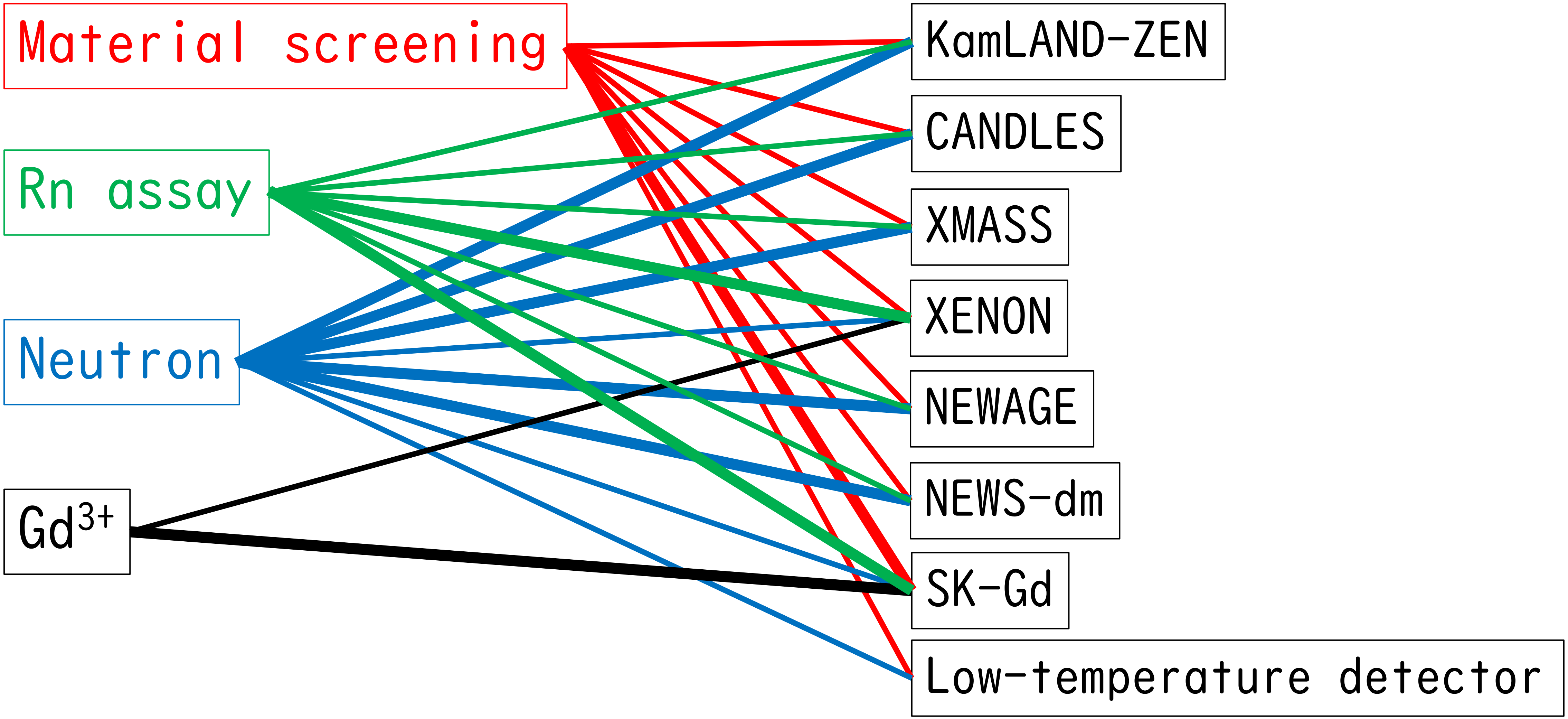


Kamioka Underground Laboratory

- Cosmic ray μ is 10^{-5} times less than on the ground.
  - Cosmogenic radioactive nuclei & Neutrons originating from nuclear spallation due to cosmic ray μ are suppressed.



Cooperation overview

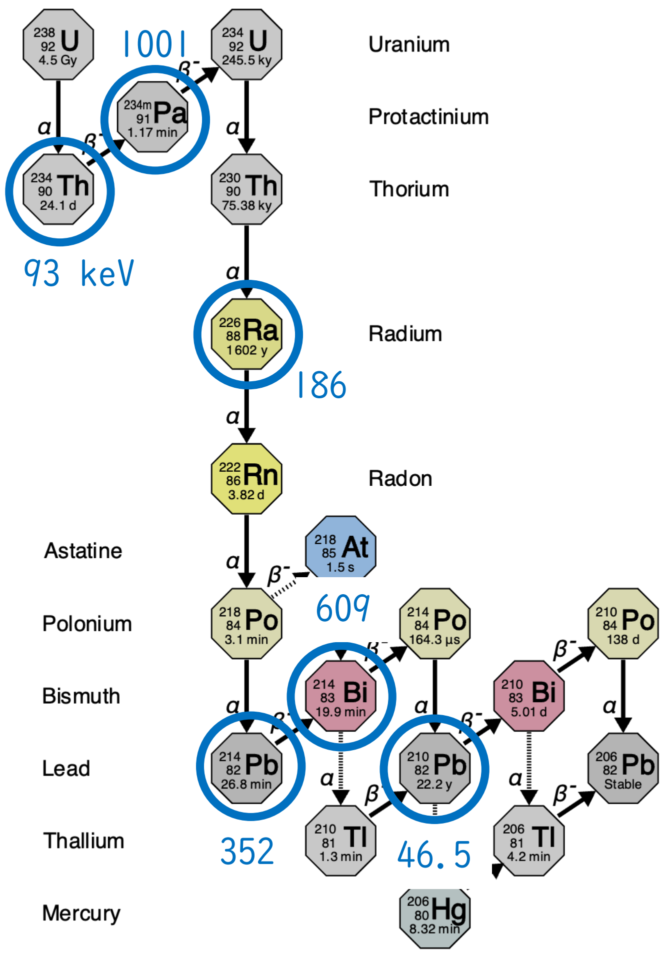


*HPGe: High-Purity Germanium

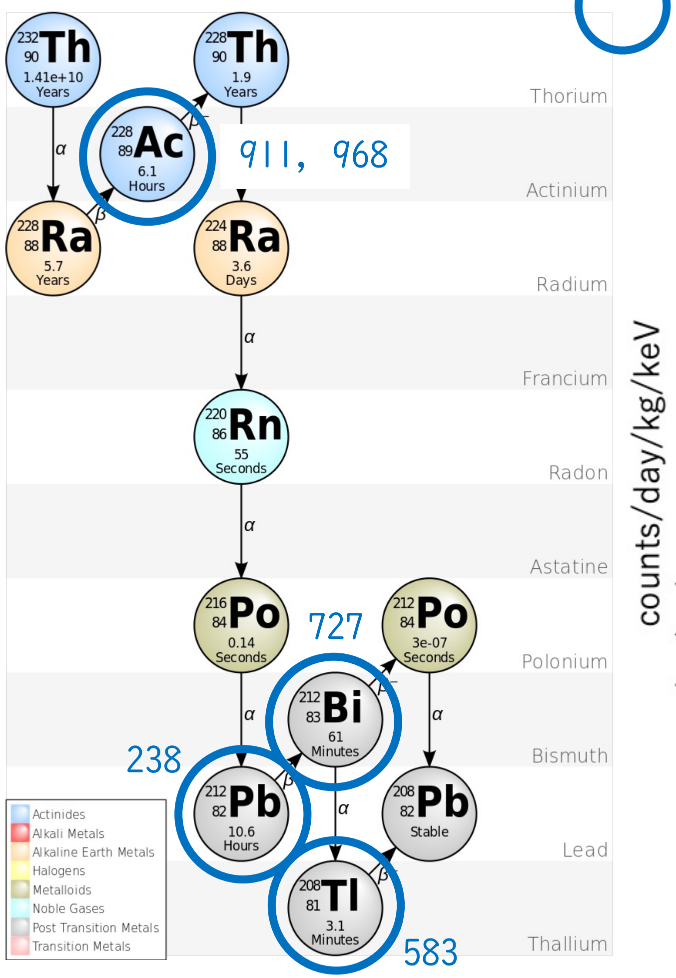
Material screening with HPGe* detectors

Measurement using HPGe detectors

Uranium series

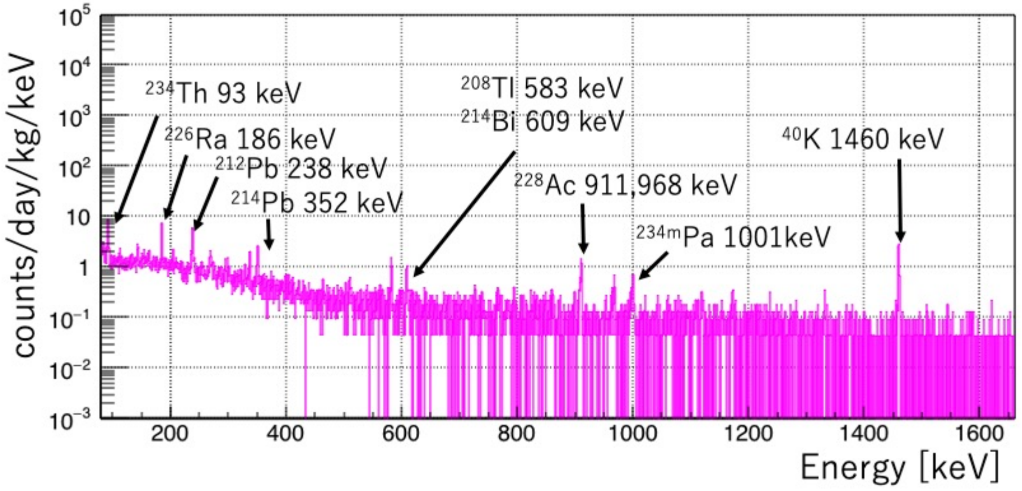


Thorium series



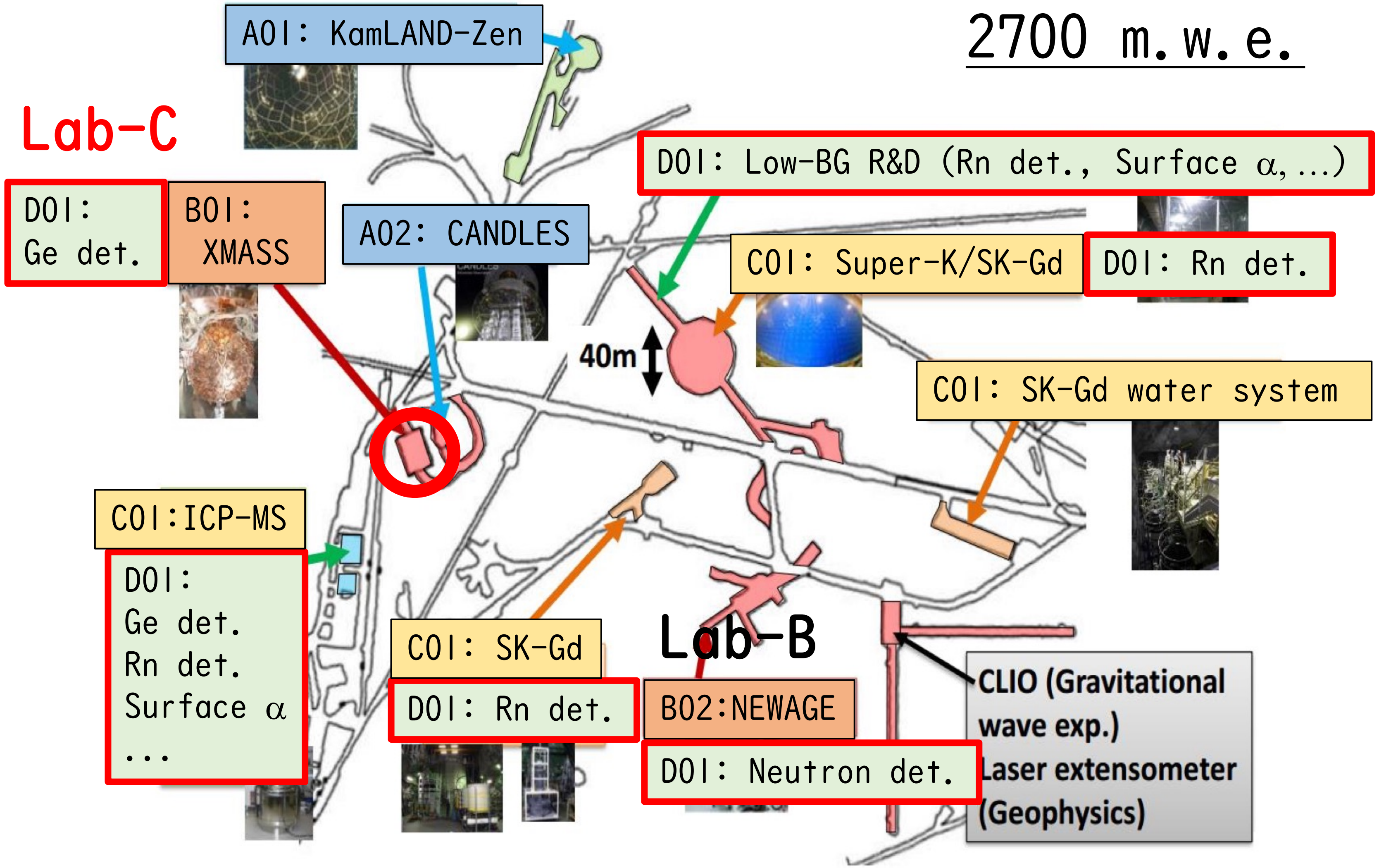
- Nuclei whose gamma rays are detected by HPGe detectors
- The numbers are the energies of gamma rays (keV)

Germanium detector background



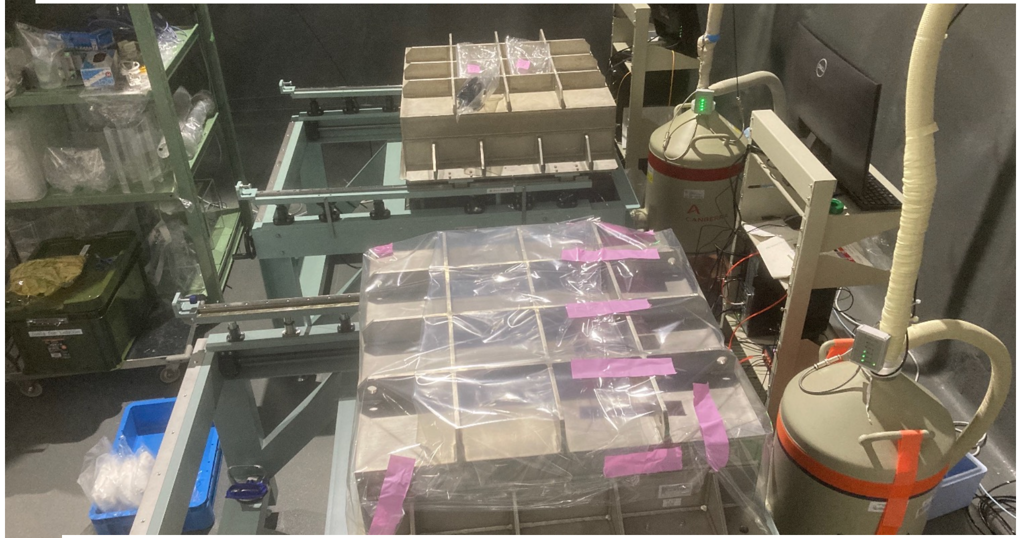
<u>Detector sensitivity depends on the background</u> (Only a slight improvement even if measured for more than one month)

Two HPGe detectors in Lab-C



Two HPGe detectors in Lab-C

Ge01: Developed in XMASS collaboration
Delivered in 2016



Ge02: Developed in this project (UGAP)
Delivered in 2021

- P-type Coaxial HPGe detectors
  - Relative efficiency*: >80%
  - Low background Aluminum endcap
  - Developed in collaboration with Mirion Technologies (T2FA series)
  - Transported from France to Japan by sea to prevent cosmogenic activation

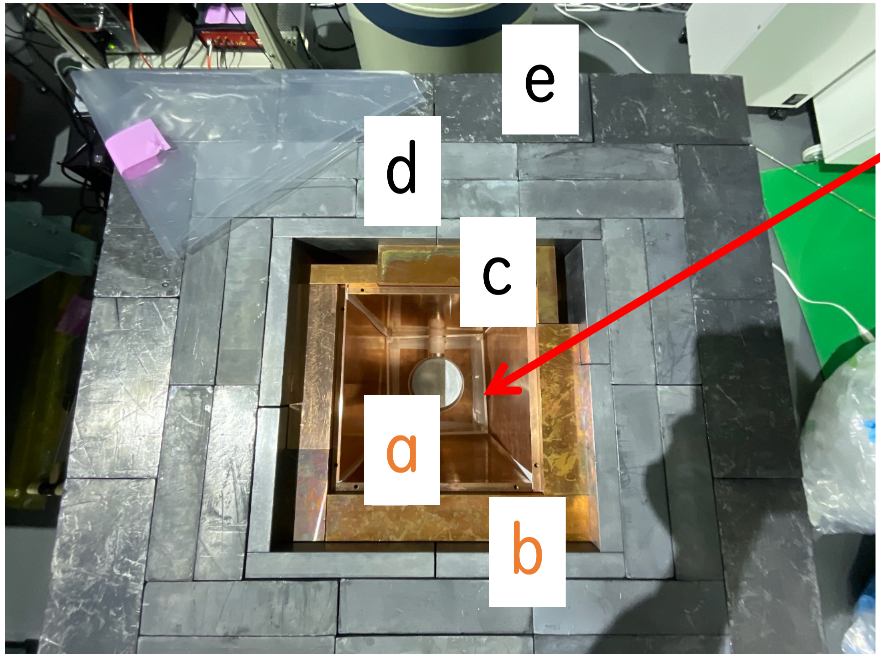
* Relative efficiency to a NaI(Tl) detector with a diameter & length of 3 inches for 1332.5 keV gamma total absorption peak from a ^{60}Co point source placed 25 cm on the detector.

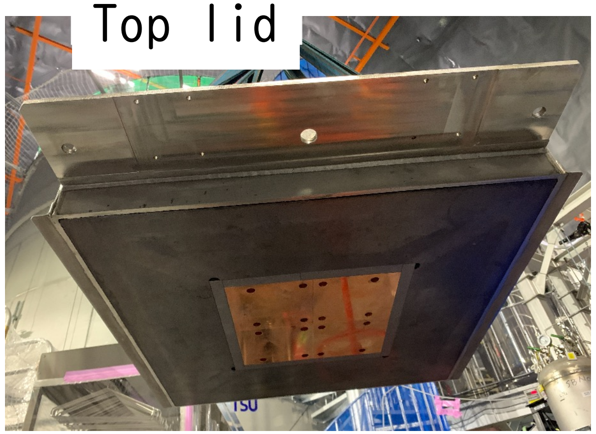
GeO2: Photos at the time of delivery

Performance

- Relative efficiency: 82.5%
- Energy resolution (FWHM)
  - 0.81 keV for 122 keV gammas (^{57}Co)
  - 1.74 keV for 1332 keV gammas (^{60}Co)

Ge02: Radiation shield



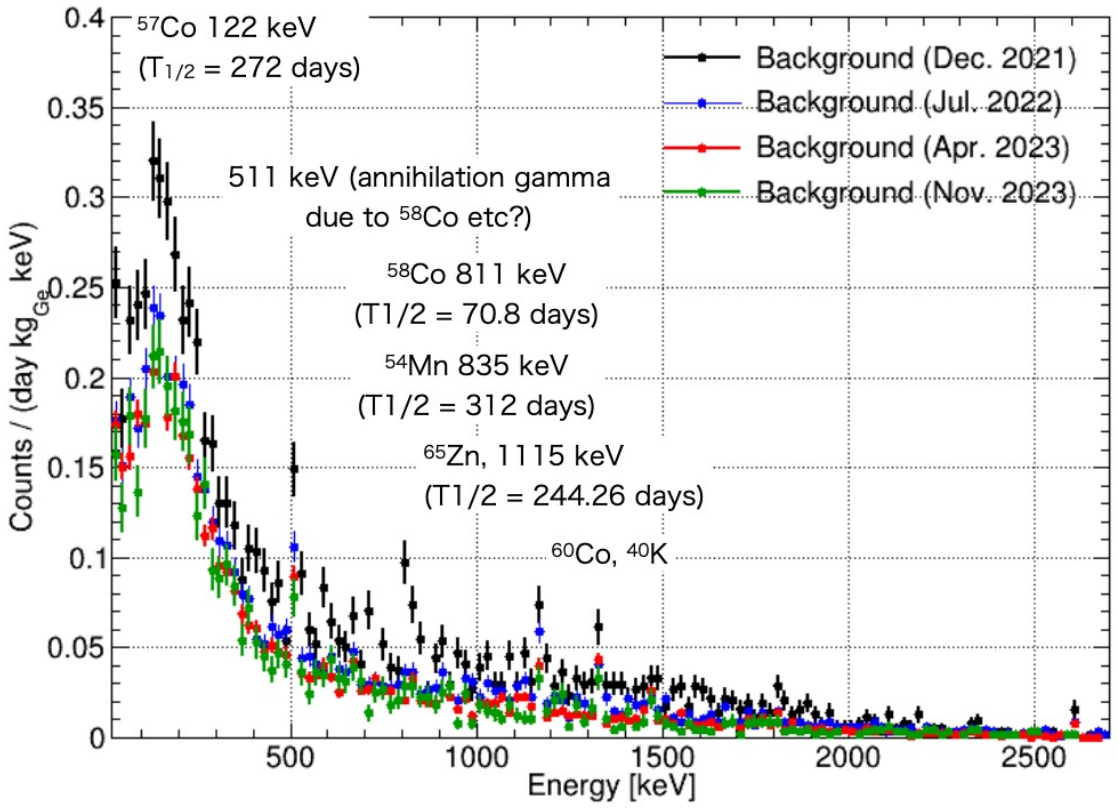


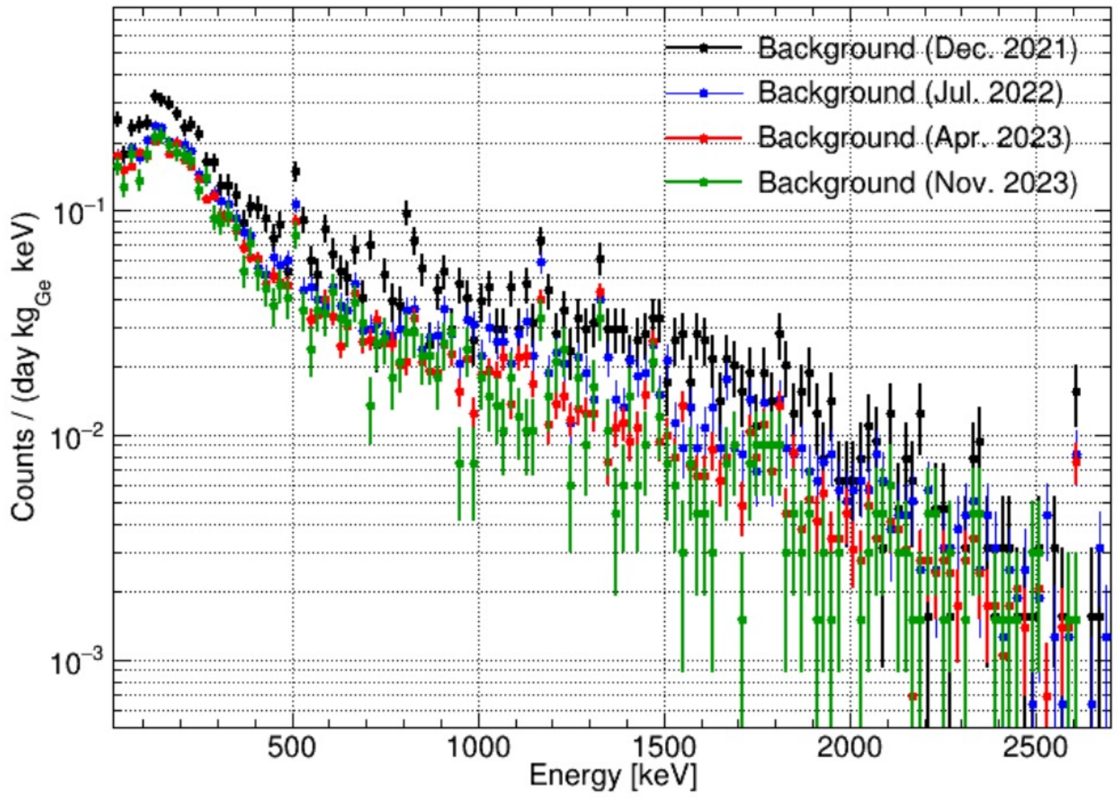
Sample space with Rn free air:
capable of measuring 0 (10 kg) of gadolinium sulfate

a: 1 cm 6N grade CU
(surface etching with HNO_3*)
b: 5 cm OFHC Cu
c: 2.5 cm Pb (^{210}Pb: 5 ± 3 Bq/kg)
(surface etching with HNO_3*)
d: 10 cm Pb (^{210}Pb: ~35 Bq/kg)
except for the top lid
e: 10 cm Pb (^{210}Pb: ~180 Bq/kg)

* Surface etching with HNO_3:
Soak in 4% HNO_3 solution for 20 min.

Ge02: Background spectrum

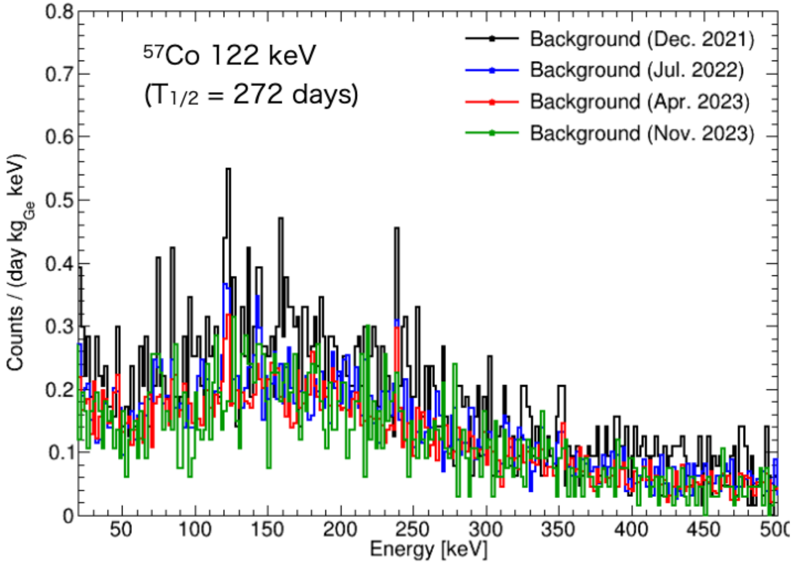


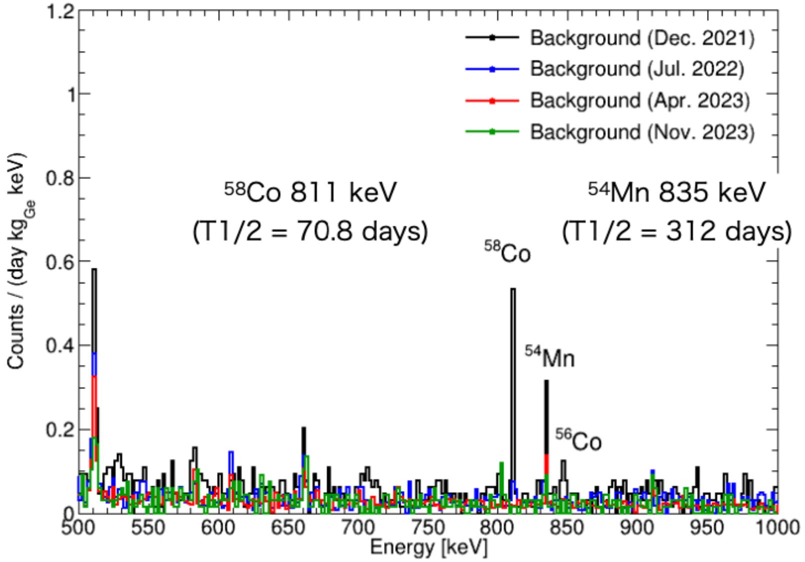


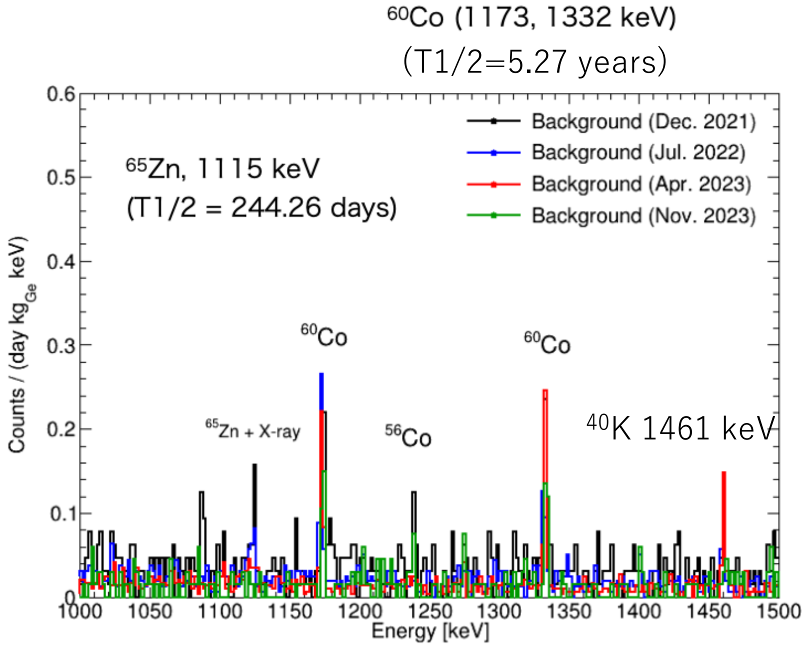
Count rate in 40-2700 keV:

140.3±2.1 cpd/kg_{Ge} (Dec. 2021) → 100.0±1.1 cpd/kg_{Ge} (Jul. 2022) → 84.3±0.8 cpd/kg_{Ge} (Apr. 2023) → 80.0±1.5 cpd/kg_{Ge} (Nov. 2023)

GeO2: Background spectrum



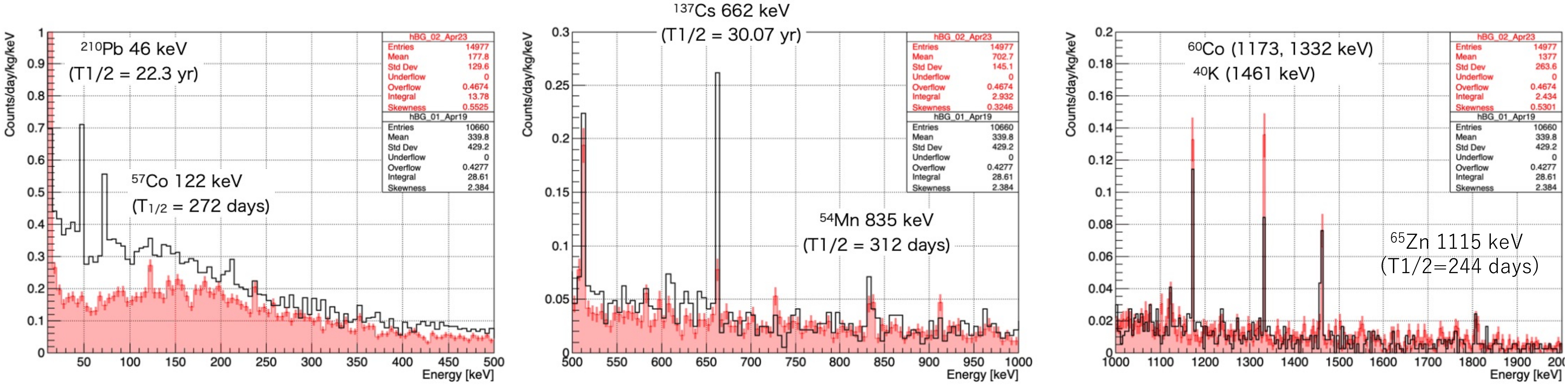




Nucleus with relatively short half-lives are steadily decreasing.

Background spectrum comparison between G01 and G02

Ge01: Oct. 2018 & Apr. 2019 (LT = 44 days), Ge02: Apr.-Jul. 2023 (LT = 86 days)



<u>Count rate in 40-2700 keV:</u>

Ge01: 140.3±2.1 cpd/kg_{Ge} → Ge02: 84.3±0.8 cpd/kg_{Ge} (30% improvement)

- ^{137}Cs and ^{210}Pb peaks have been dramatically improved.
- Continuous components below 600 keV have also been improved.

Ge01 & Ge02: Background spectrum

https://doi.org/10.1093/ptep/ptad136

Detector	Ge01	Ge02			
Date	Dec. 2019	Dec. 2021	Jul. 2022	Apr. 2023	Nov. 2023
Measurement time (d)	23.0	19.0	47.2	86.2	19.9
Count rate (kg_{Ge}^{-1} day^{-1})					
Integral 40 – 2700 keV	112.6	140.2	100.0	84.3	80.0
^{208}Tl, 2614 keV	0.08±0.04	0.25±0.09	0.16±0.05	0.13±0.03	0.03±0.03
^{214}Bi, 609 keV	0.39±0.10	0.25±0.09	0.38±0.07	0.23±0.04	0.24±0.08
^{60}Co, 1333 keV	0.41±0.10	0.66±0.14	0.48±0.08	0.68±0.07	0.48±0.12
^{40}K, 1461 keV	0.44±0.11	0.31±0.10	0.44±0.07	0.42±0.05	0.18±0.07
^{137}Cs, 662 keV	1.29±0.18	0.53±0.13	0.38±0.07	0.32±0.05	0.42±0.11
^{210}Pb, 46.5 keV	3.24±0.29	0.69±0.14	0.64±0.09	0.59±0.06	0.27±0.09

Nuclei have relatively short half-lives are steadily decreasing.

G02:Comparison with HPGe detectors around the world

https://doi.org/10.1093/ptep/ptad136

	Site	Detector	Crystal mass [kg]	Relative efficiency [%]	FWHM at 1333 keV [keV]	BG rate 60 – 2700 keV [kg_{Ge}^{-1} d^{-1}]
Japan	Kamioka	Ge02 (This work)	1.68	80	1.82	81.3±0.7
		Ge01 [2]	1.68	80	2.39	104.5
Italy	LNGS	Gator [16]	2.2	100.5	1.98	89.0±0.7
		GeMPI [16]	2.2	98.7	2.20	24±1
UK	BUGS	Belmont [2]	3.2	160	1.92	90.0
		Merrybent [2]	2.0	100	1.87	145.0
Spain	LSC	GeOroel [2]	2.31	109	2.22	128.7
		Asterix [2]	2.13	95.1	1.92	171.3
		GeAnayet [2]	2.26	109	1.99	461.2
US	BHUC	Maeve [17]	2.0	85	3.19	956.1
Swiss	LVdA	GeMSE [16,18]	2.0	107.7	1.96	88±1

We have developed an ultra-low BG HPGe detector with the world's highest level of sensitivity.

G02:Comparison with HPGe detectors around the world

*STELLA at LNGS, TAUP2023

detector	total and peak background count rate [d^{-1} kg^{-1}_{Ge}]			
	40-2700 keV	352 keV	583 keV	1461 keV
GeMi	555 ± 7	4.1 ± 1.0	1.4 ± 0.5	6.1 ± 0.8
GePV	498 ± 5	2.6 ± 0.7	1.8 ± 0.4	3.2 ± 0.4
GsOr	442 ± 5	2.0 ± 0.5	0.76 ± 0.35	4.2 ± 0.5
GePaolo	222 ± 2	1.1 ± 0.3	0.31 ± 0.16	1.8 ± 0.2
GeCris	115 ± 2	0.29 ± 0.22	< 0.13	0.88 ± 0.22
GeMPI	71 ± 2	< 0.07	< 0.06	0.24 ± 0.03
Ge02	84±1	0.44±0.05	0.25±0.04	0.42±0.05

We have developed an ultra-low BG HPGe detector with the world's highest level of sensitivity.

$Gd_2(SO_4)_3$ screening for SK-Gd

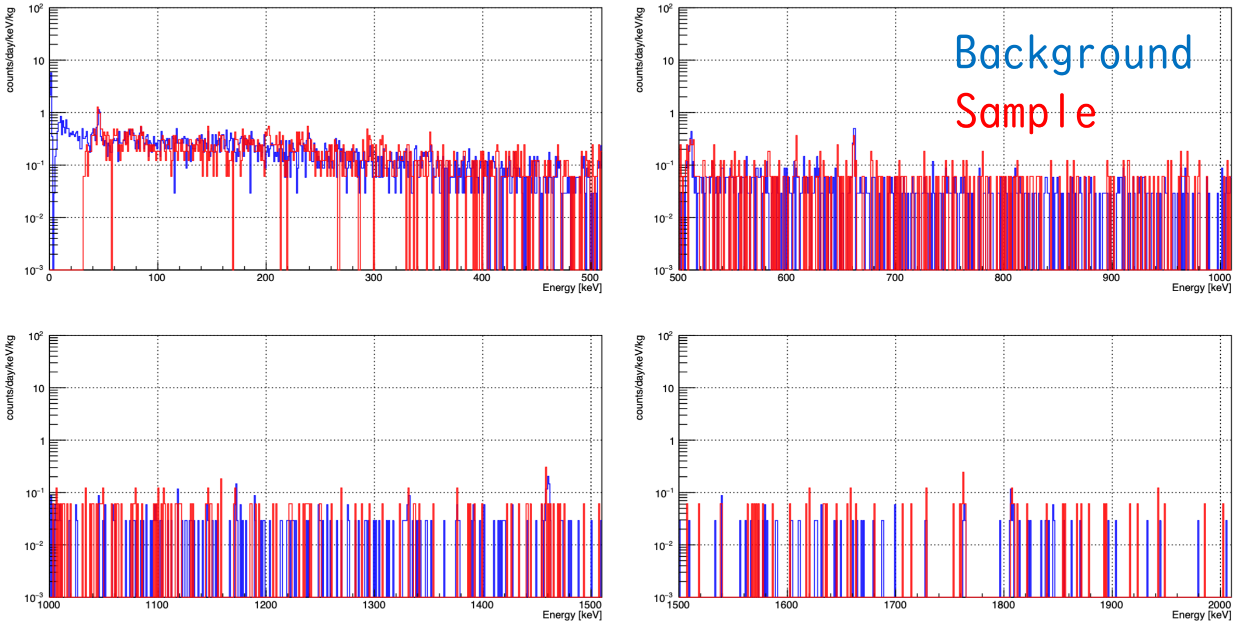
- $Gd_2(SO_4)_3$ dissolved in Super-Kamiokande
  - 13 tons in 2020
  - 26 tons in 2022
- Requirements for RI in $Gd_2(SO_4)_3$ for SK-Gd

Chain	Isotope	Criterion [mBq/kg]	Physics target
^{238}U	^{238}U	< 5	SRN
	^{226}Ra	< 0.5	Solar
^{232}Th	^{232}Th	< 0.05	Solar
	^{228}Ra	< 0.05	Solar

- Select an appropriate method for each nucleus
  - ^{238}U, ^{232}Th: ICP-MS
  - Other nuclei: HPGe detector

$Gd_2(SO_4)_3$ screening with HPGe

- In 2022, 26 tons of $Gd_2(SO_4)_3$ dissolved in SK-Gd was delivered in 37 lots.
  - HPGe detector measurements were performed on 34 lots using Ge01 & G02. The other lots were measured by European collaborators.



Typical spectrum of $Gd_2(SO_4)_3$ screening

20 days required to measure each lot

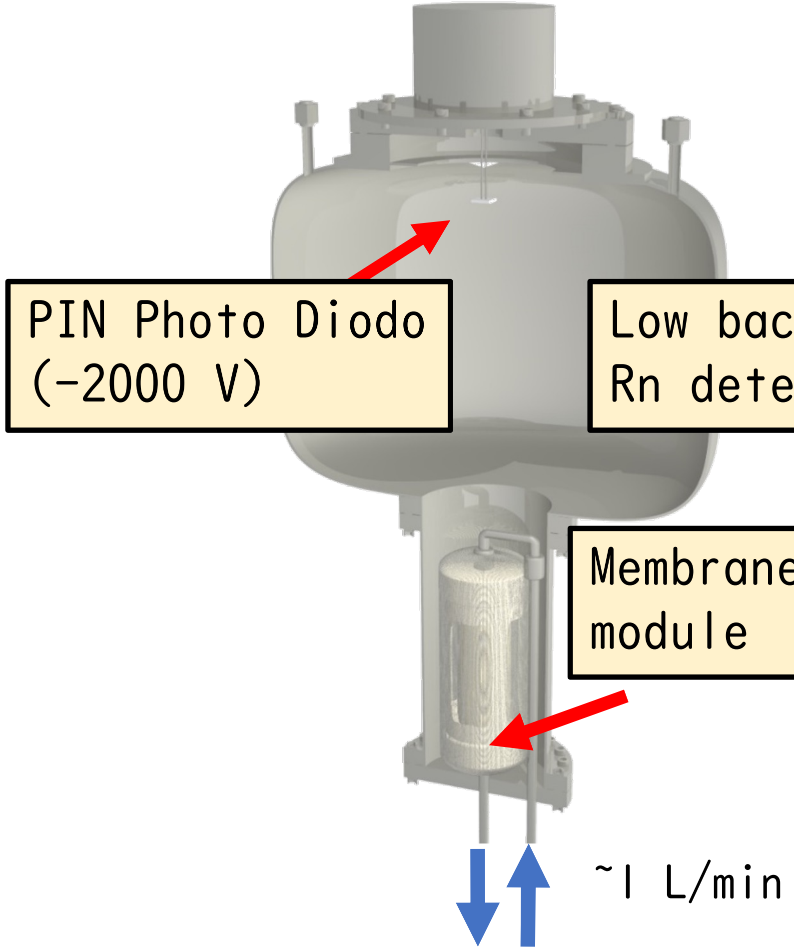
Rn assay in $Gd_2(SO_4)_3$ water

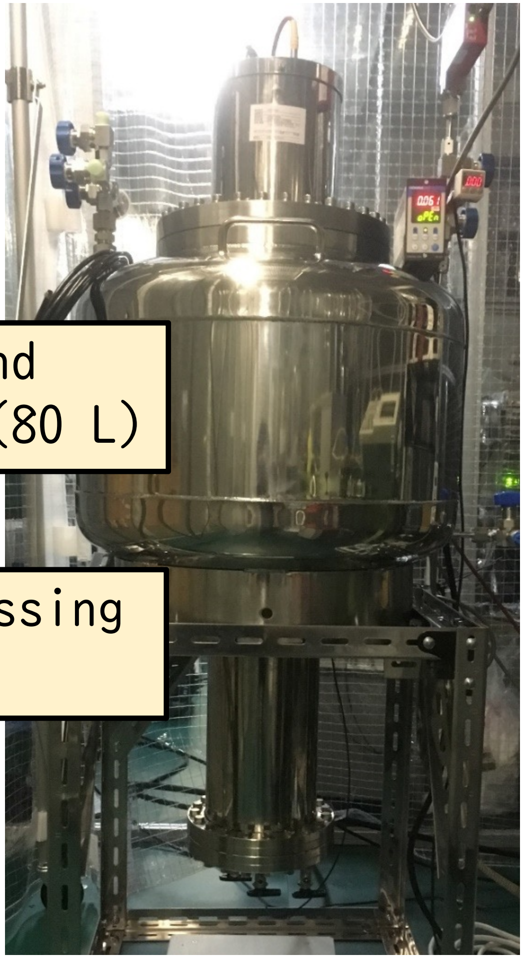
Continuous measurement of ^{222}Rn in $Gd_2(SO_4)_3$ water

- Motivation
  - **SK-Gd:** β-decay of ^{214}Bi in the ^{222}Rn daughter nucleus becomes a background in solar neutrino observation.
  - **XENONnt:** ^{222}Rn affects the dead time of neutron veto water Cerenkov detector.
- Required sensitivity
  - The background is <1 mBq/m^3.
- Development policy
  - Improve the existing water radon detector*.

* C. Mitsuda et al., NIMA 497 (2003) 414.

Continuous measurement of ^{222}Rn in $Gd_2(SO_4)_3$ water

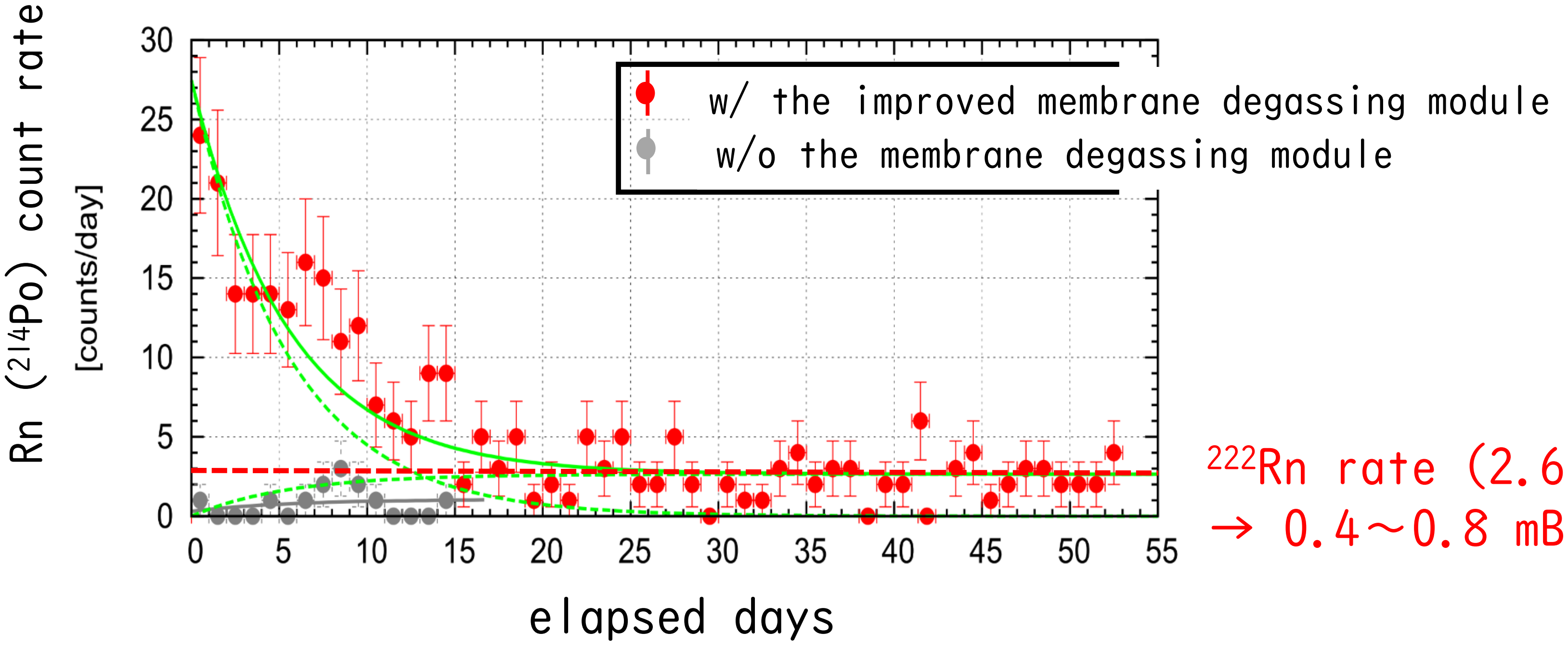




- The membrane degassing module is the main background source.
- Housing changed from resin to stainless steel.

Continuous measurement of ^{222}Rn in $Gd_2(SO_4)_3$ water

- We achieved **the required background level of <1 mBq/m³**.
  - 10x improvement from the past design.



^{222}Rn rate (2.65±0.41 counts/day)
→ 0.4〜0.8 mBq/m³

- Four detectors are started operation in SK-Gd & XENONnT.

Automation of high-sensitivity ^{222}Rn measurement in $Gd_2(SO_4)_3$ water

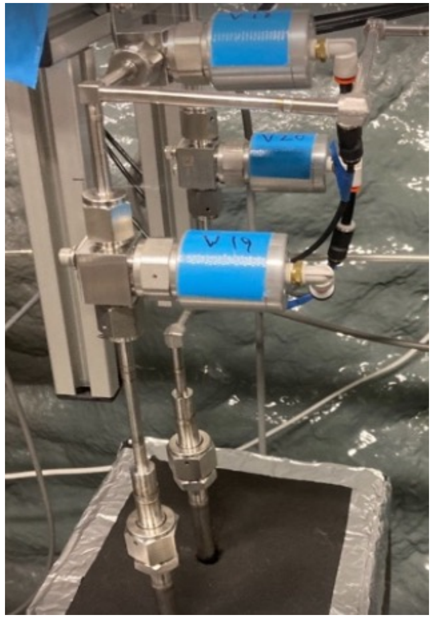
- High-sensitivity measurement method
  - After adsorbing ^{222}Rn onto activated carbon cooled to −75℃, the activated carbon is heated to 150℃ to release ^{222}Rn.
  - Then, ^{222}Rn is measured using a low-background radon detector.
- Problems with the conventional method
  - Complex valve operations had to be performed manually.
  - It was necessary to attach and detach the refrigerator and heater when cooling and heating the activated carbon.
- Goal
  - Automation of work with **remote valves, temperature controller,** and **operation panel.**

Automation of high-sensitivity ^{222}Rn measurement in $Gd_2(SO_4)_3$ water

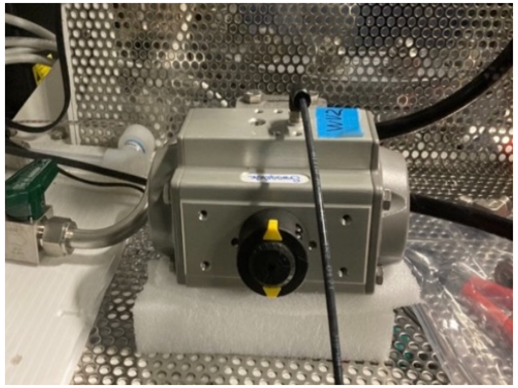
- Newly introduced equipment

Remote valves

for pure air

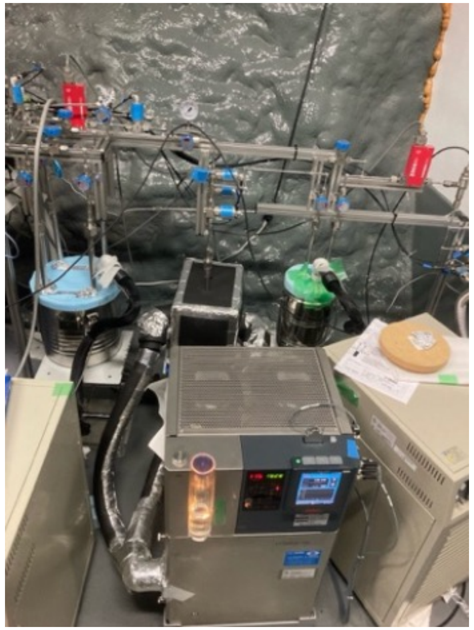


for $Gd_2(SO_4)_3$ water



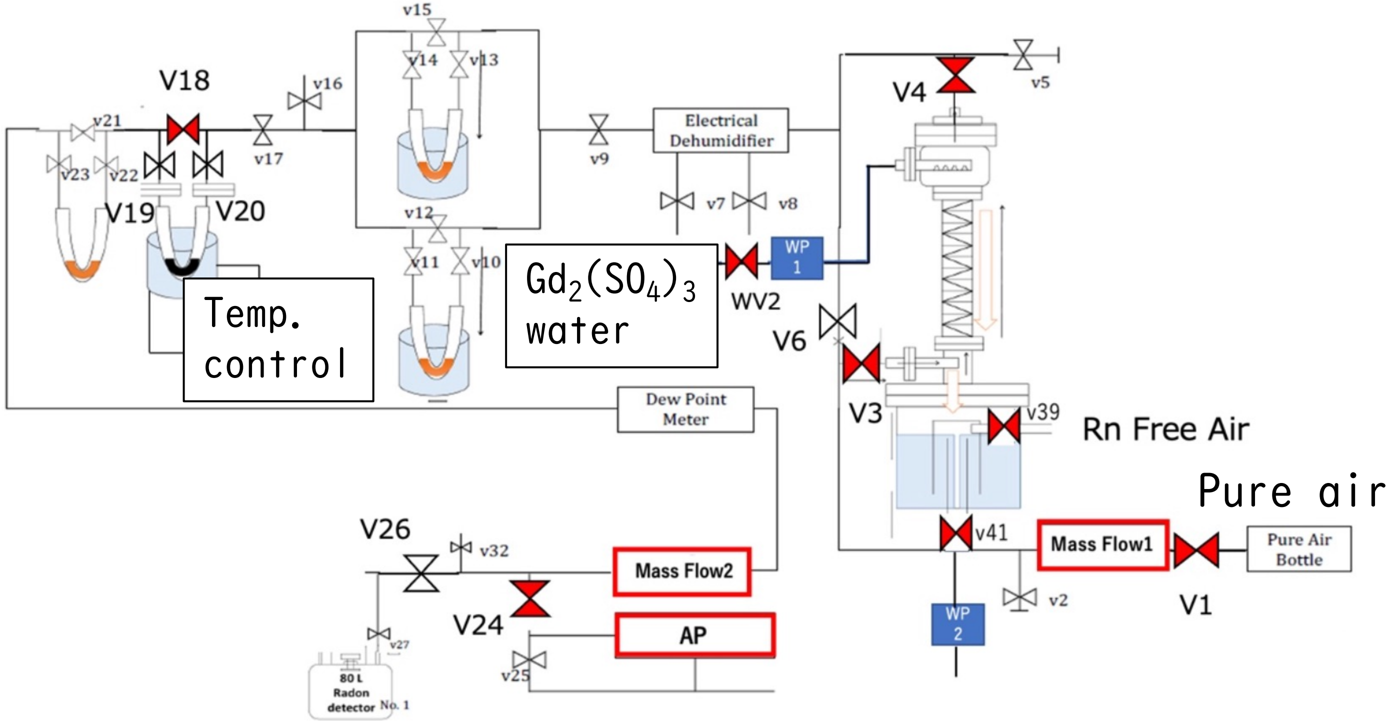
Temp. controller

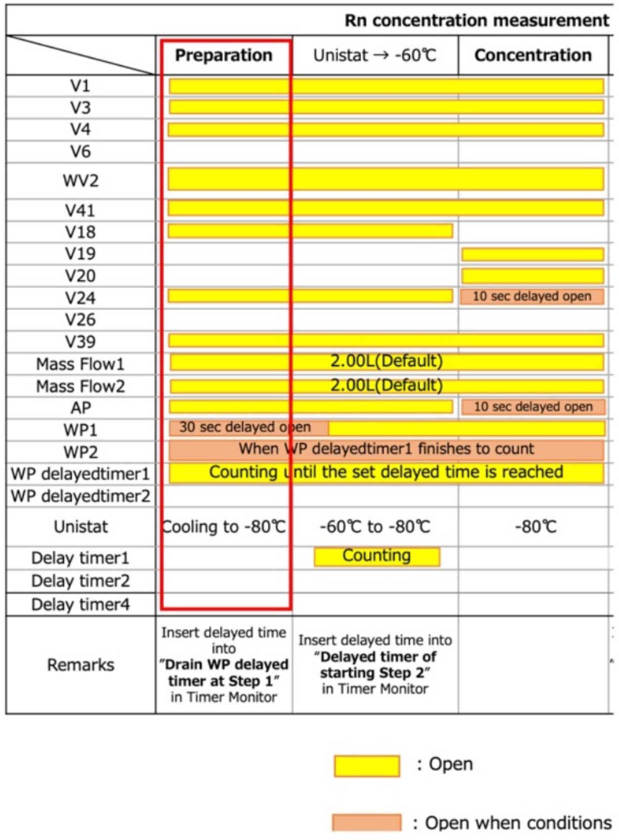
−75°C to 150°C



Operation panel

Automation of high-sensitivity ^{222}Rn measurement in $Gd_2(SO_4)_3$ water





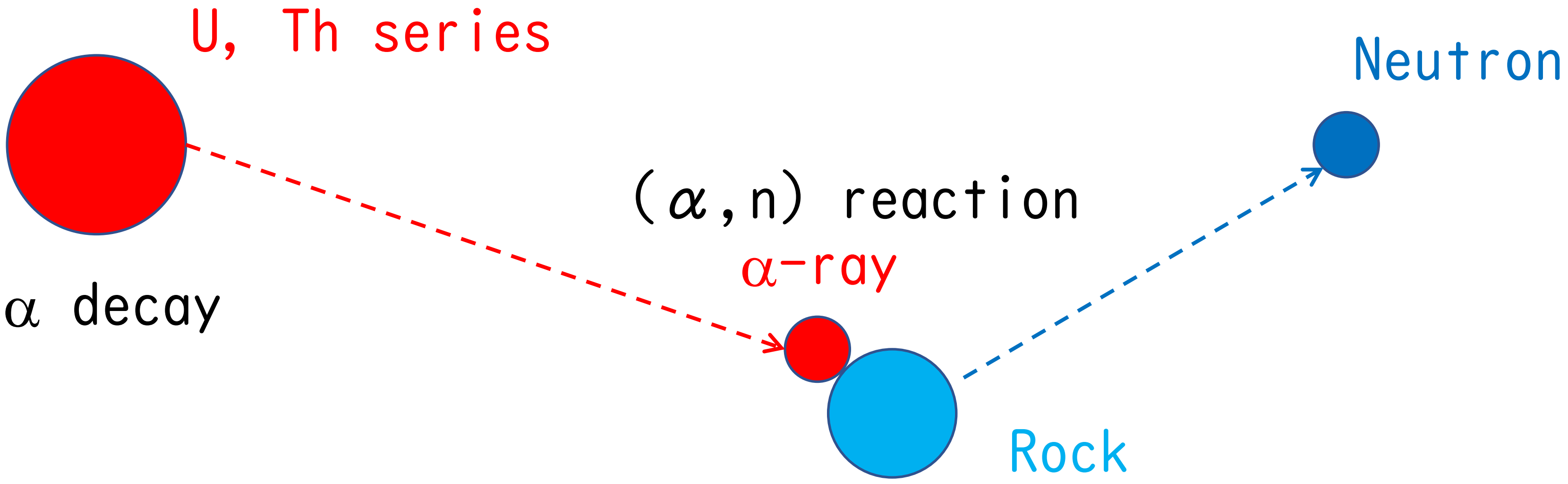
We have **successfully automated the work.**

The system will start operation in SK-Gd.

Environmental neutron measurements in the underground

The primary sources of environmental neutrons in the underground

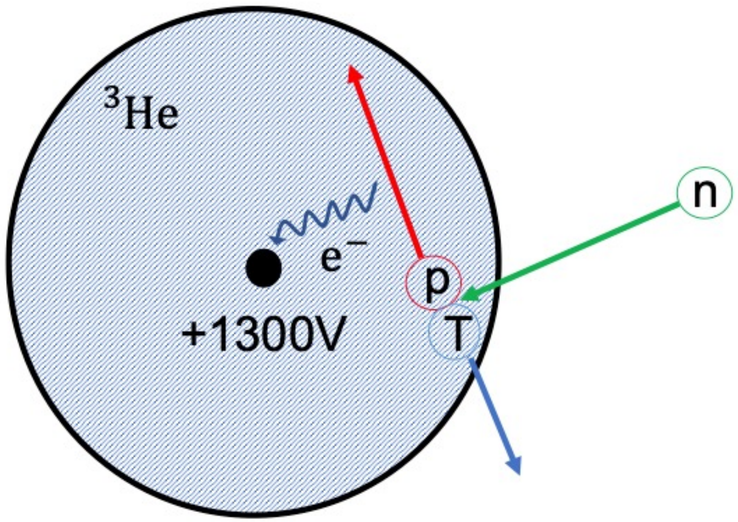
- (α,n) reaction between rock and α-rays generated by the decay of the U and Th series contained therein.

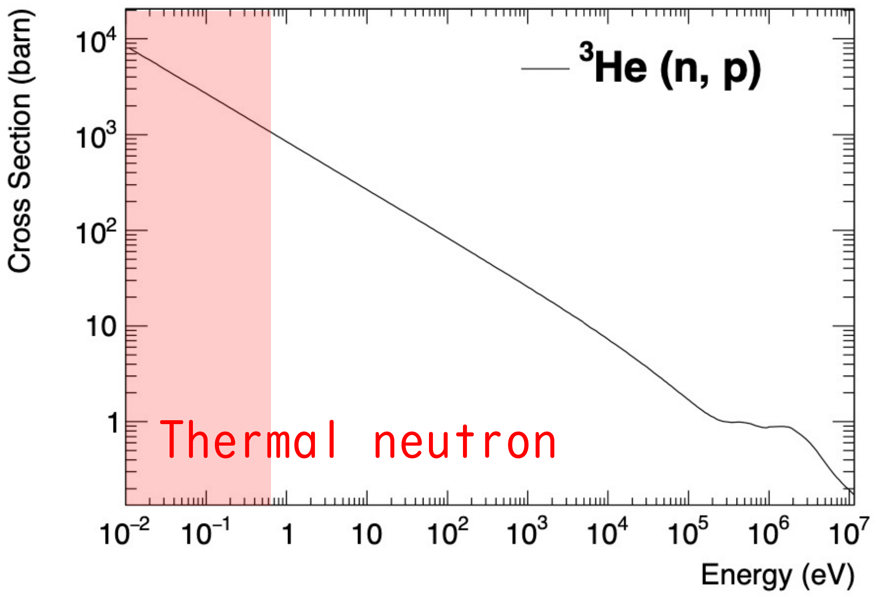


^{3}He proportional counter

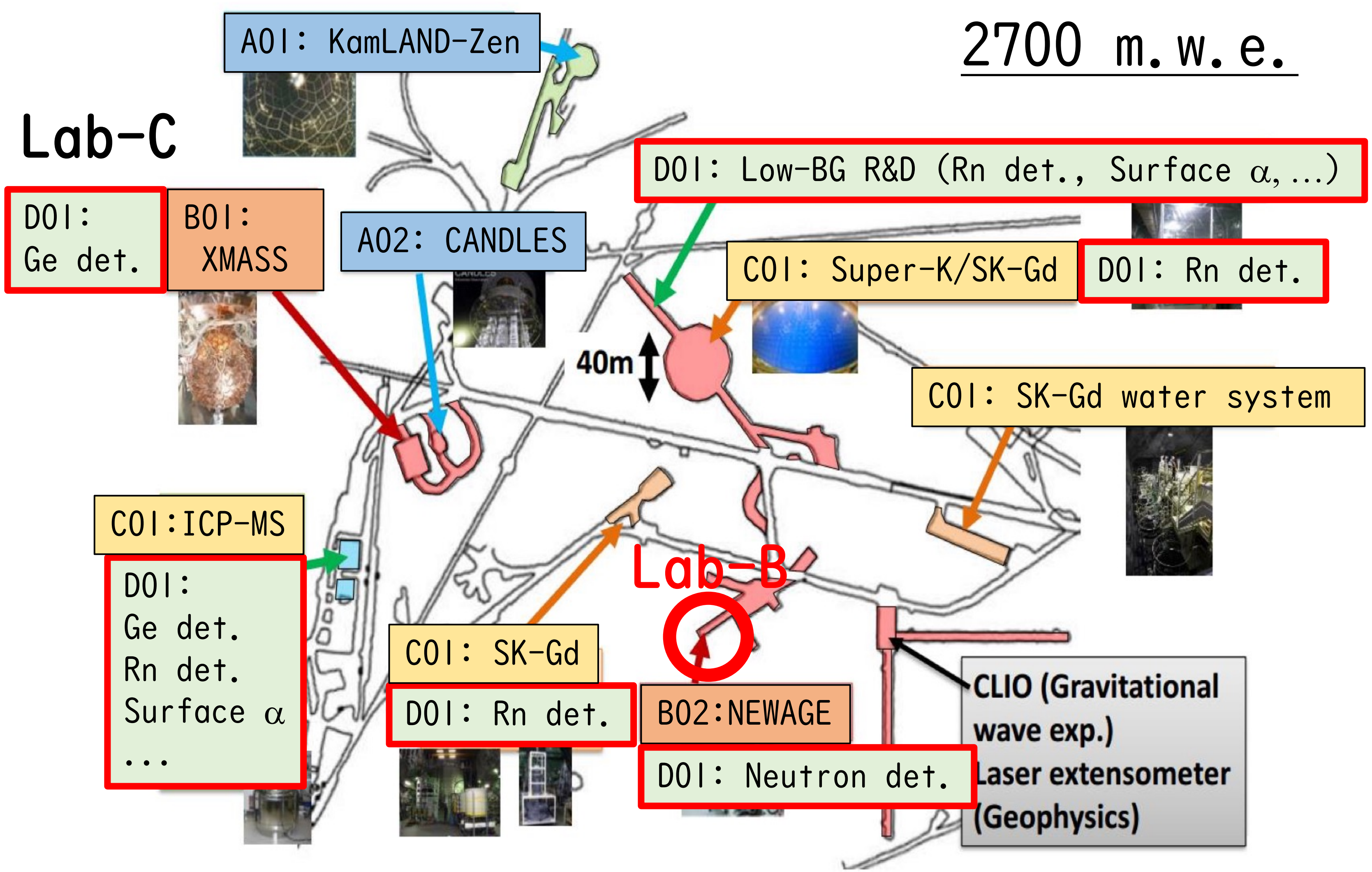
^3He proportional counter

- $^3He + n \rightarrow p + T + 0.765$ MeV
- High sensitivity to thermal neutrons
- Fast neutrons are measured after decelerating using a moderator (such as polyethylene).

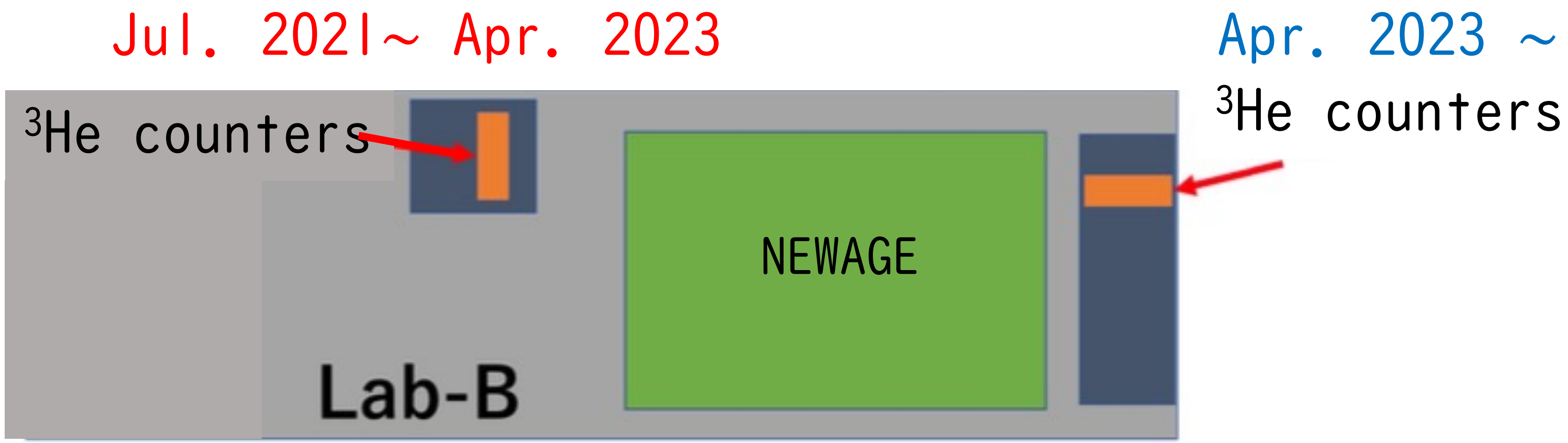




Environmental neutron measurement in Lab-B



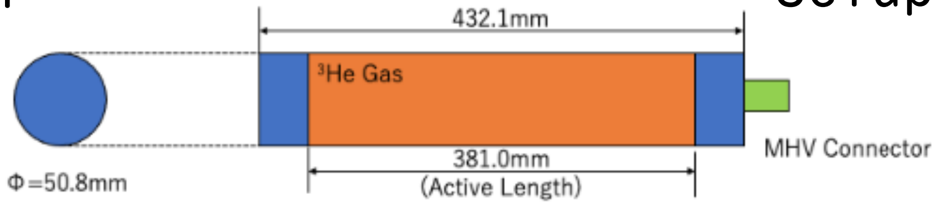
Two ^{3}He proportional counters in Lab-B



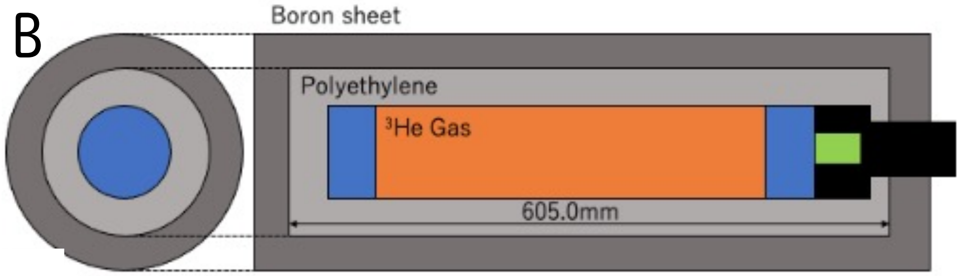
Environmental neutron measurement in Lab-B with two ^{3}He proportional counters

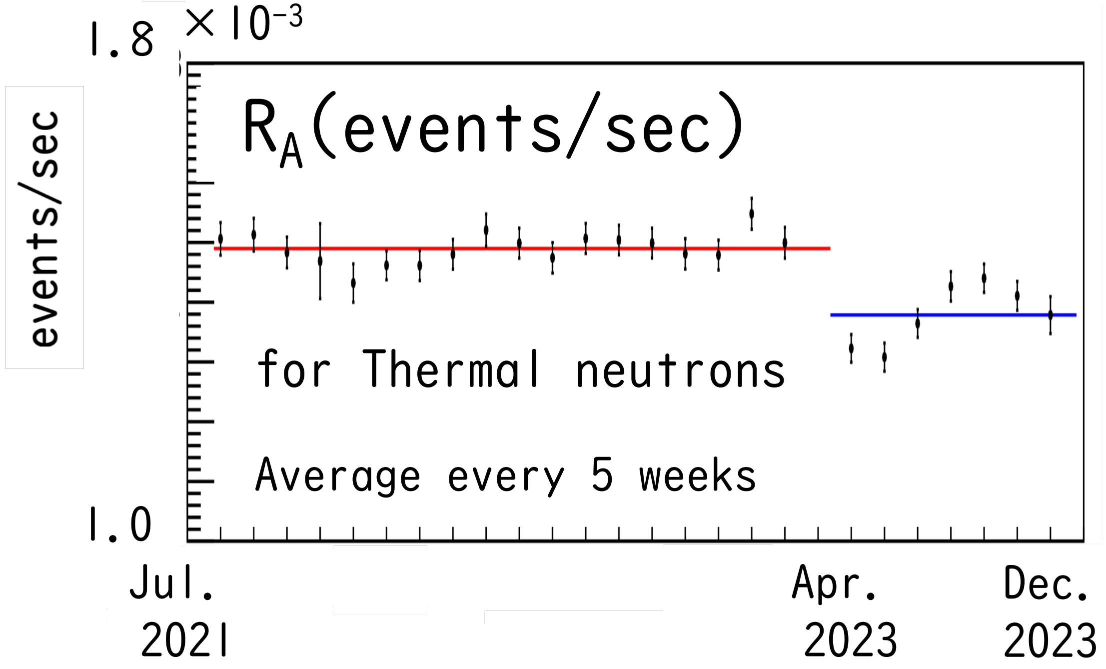
- Jul. 2021 ~ Apr. 2023, Apr. 2023 ~

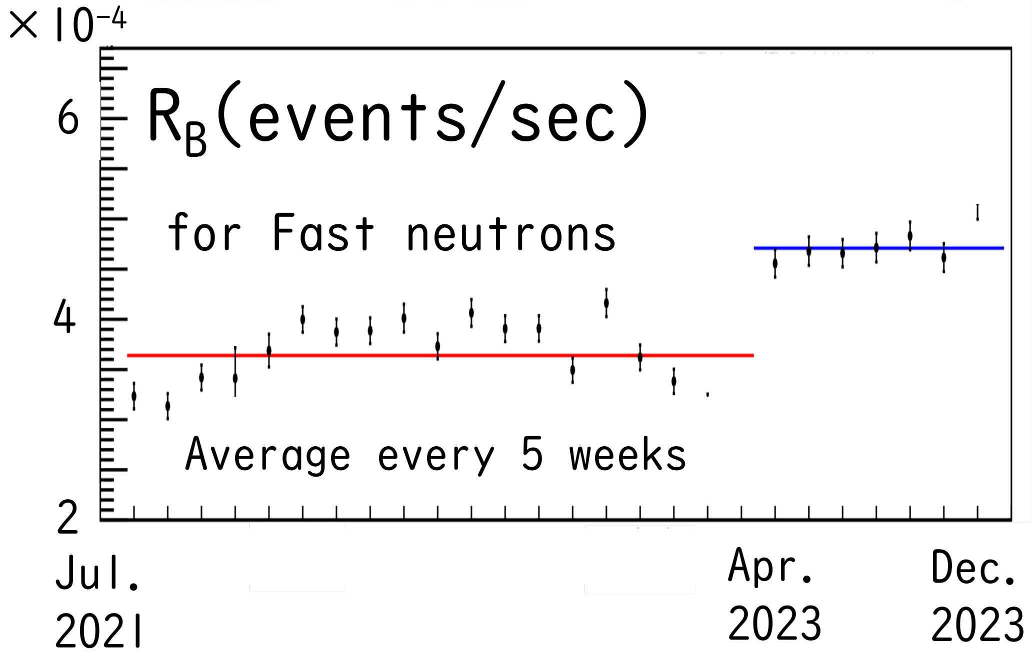
Setup A



Setup B







Correlation between Lab-B neutron flux and environmental parameters

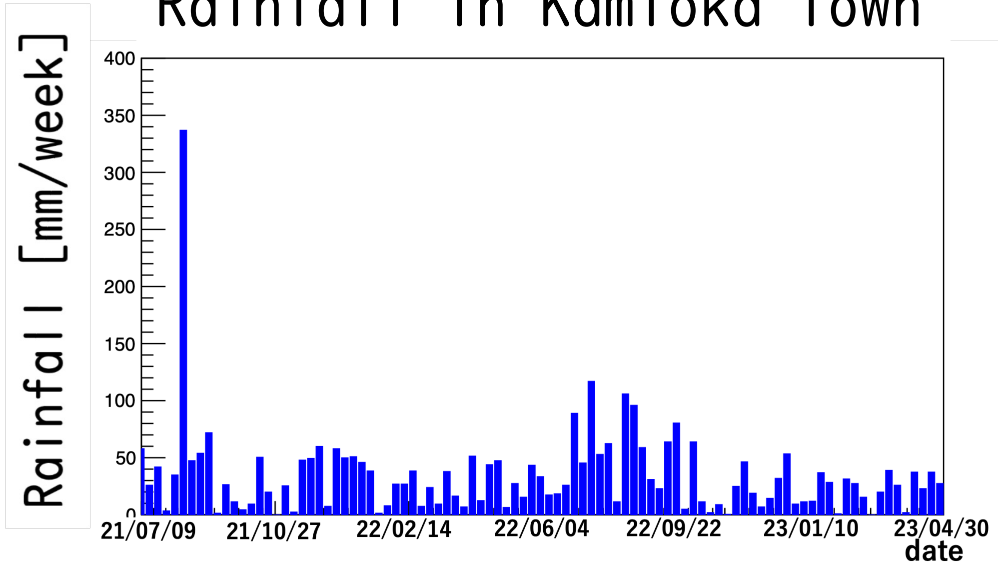
We investigated the correlation between Lab-B neutron flux and environmental parameters from Jul. 2021 to Apr. 2023.

1. Rainfall
2. Rn concentration in the mine-tunnel air
3. Humidity in the mine-tunnel air

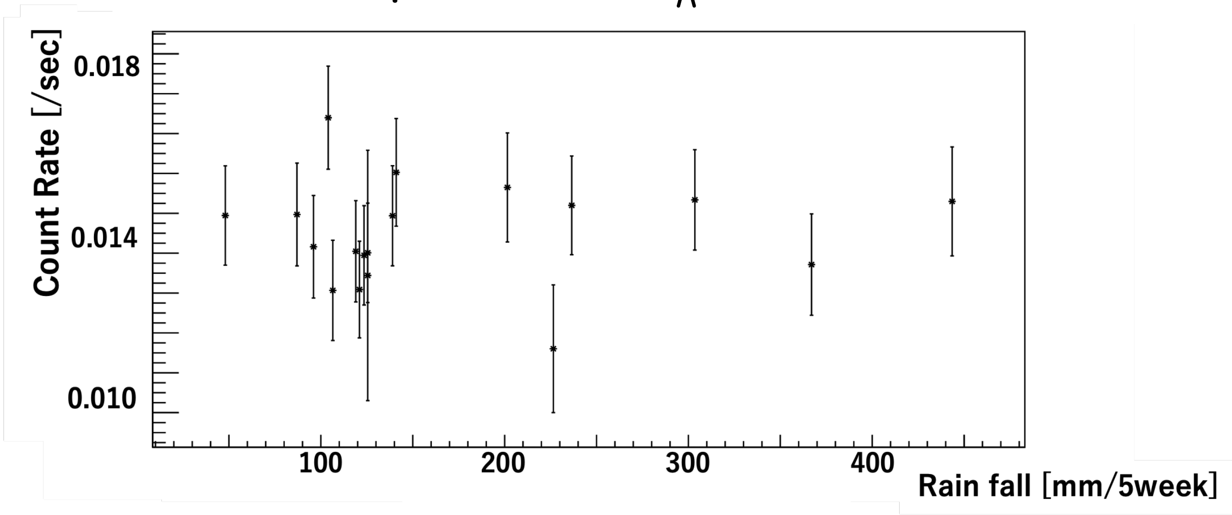
Correlation with Rainfall

- Using rainfall data observed in Kamioka Town (~12 km from the Kamioka underground laboratory.)

Rainfall in Kamioka Town



Scatter plot of R_A and rainfall

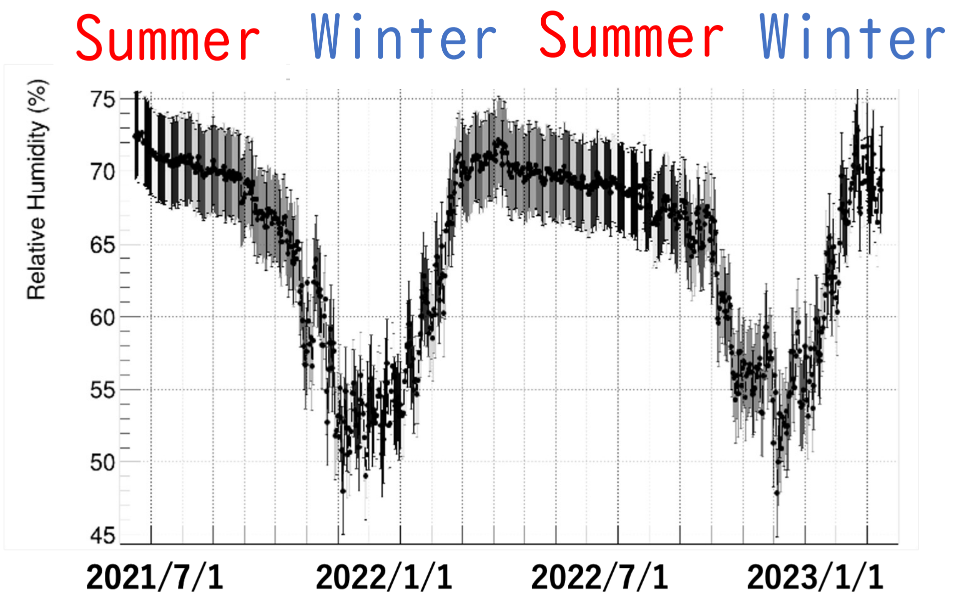


	R_A	R_B	R_A/R_B
correlation coefficient	0.17	0.12	-0.08

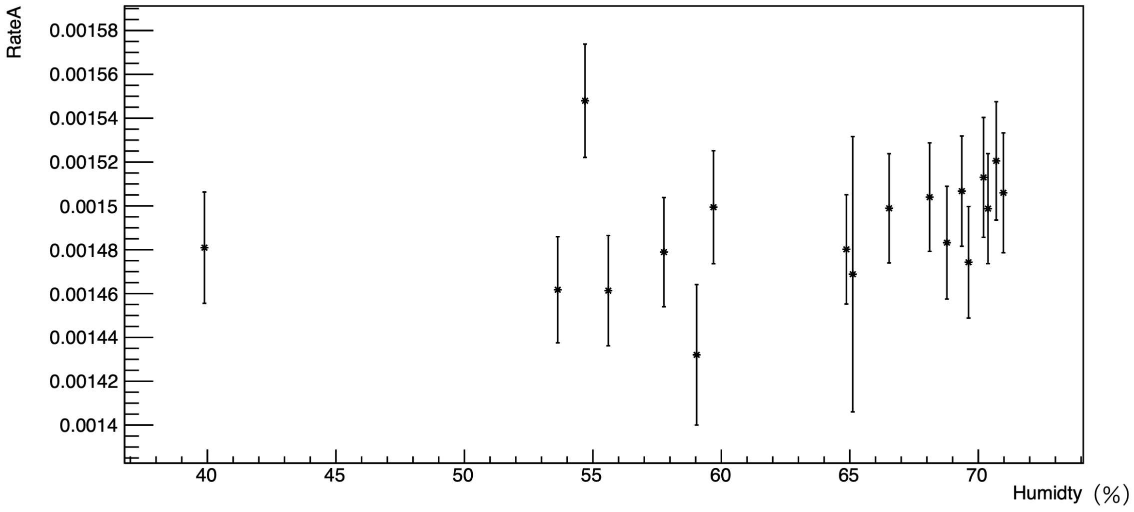
No correlation

Correlation with Humidity in the mine-tunnel air

Humidity in the mine-tunnel air



Scatter plot of R_A and Humidity



	R_A	R_B	R_A/R_B
correlation coefficient	0.28	-0.27	0.28

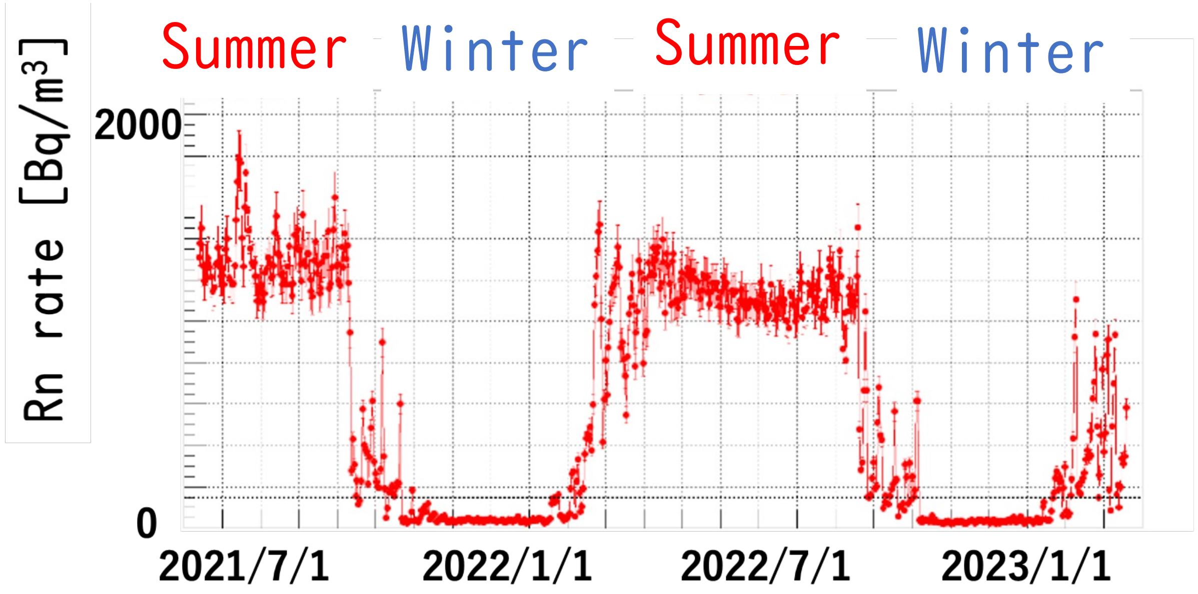
R_A: Weak positive

R_B: Weak negative

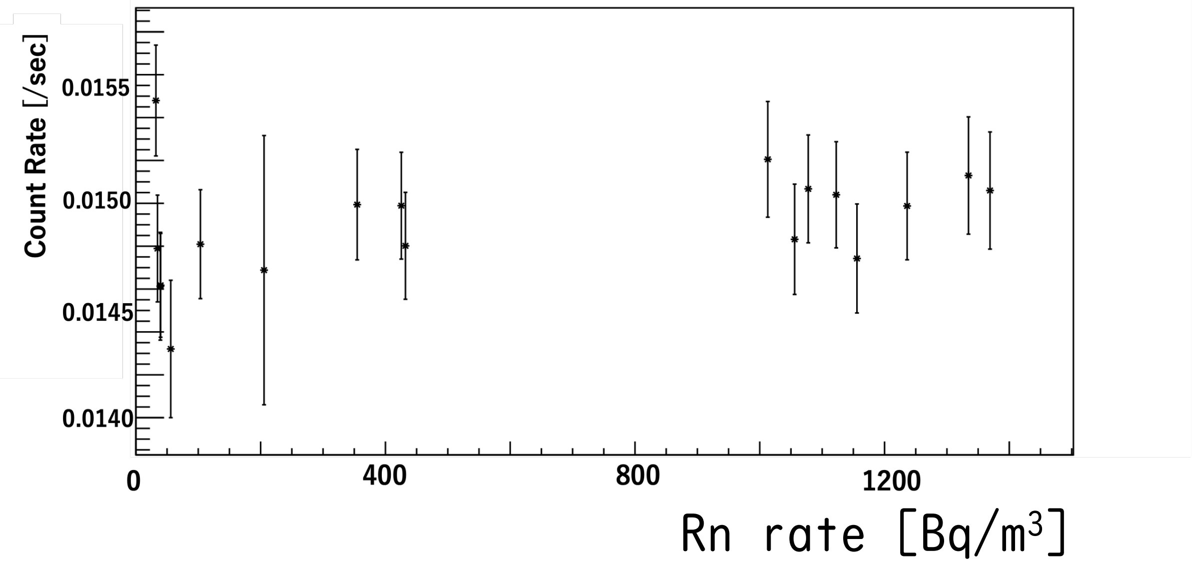
R_A/R_B: Weak positive

Correlation with the Rn rate in the mine-tunnel air

Rn rate in the mine-tunnel air



Scatter plot of R_A and Rn rate



	R_A	R_B	R_A/R_B
correlation coefficient	0.41	-0.11	0.19

R_A: Medium positive

R_B: No correlation

R_A/R_B: No correlation

Summary of long-term environmental neutron measurement in the underground

- Conclusion
  - No correlation with rainfall
  - **Weak correlation with humidity in the mine-tunnel air**
  - **Medium correlation with Rn rate in the mine-tunnel air**

- ToDo
  - Will verify the effects of humidity and Rn rate in the mine-tunnel through simulation

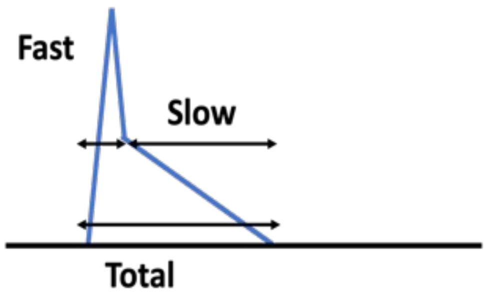
Liquid scintillator neutron detector

* Saint-Gobain BC501A

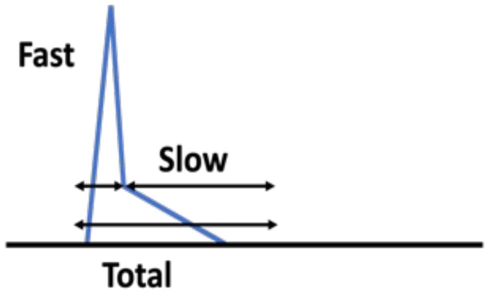
Liquid scintillator* neutron detector

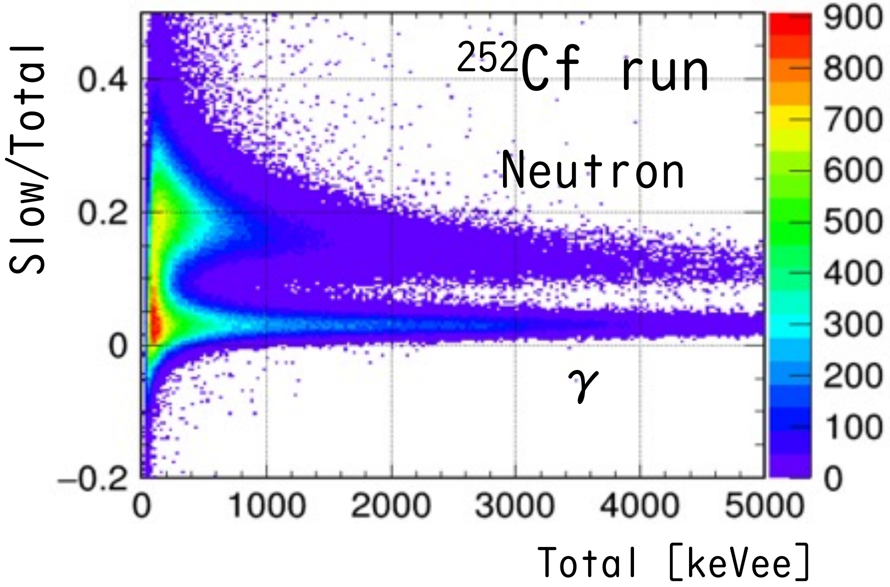
- Neutrons are detected through the scattered protons.
- γ-rays and electrons can be removed by pulse-shape discrimination, but α-rays are difficult to remove.

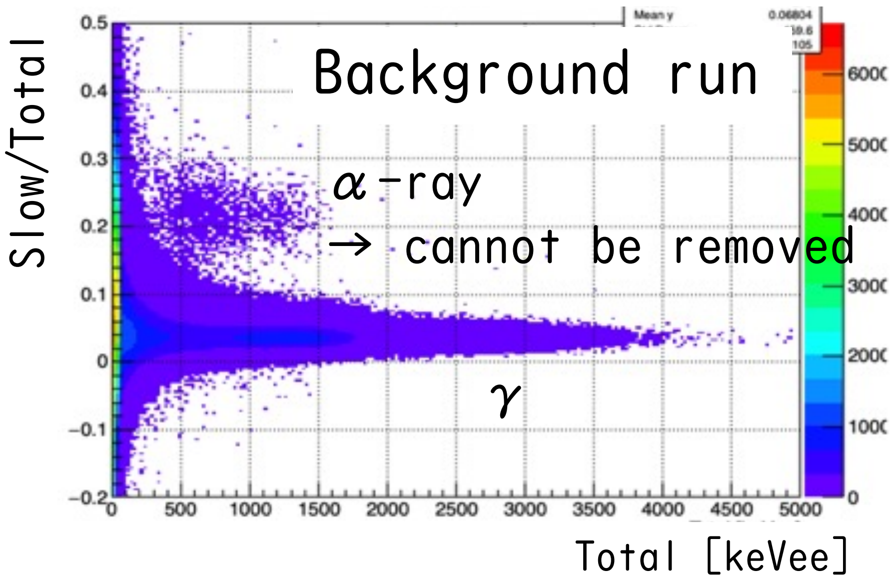
Nuclear event
(Neutron & α)



Electron event
(γ & β)

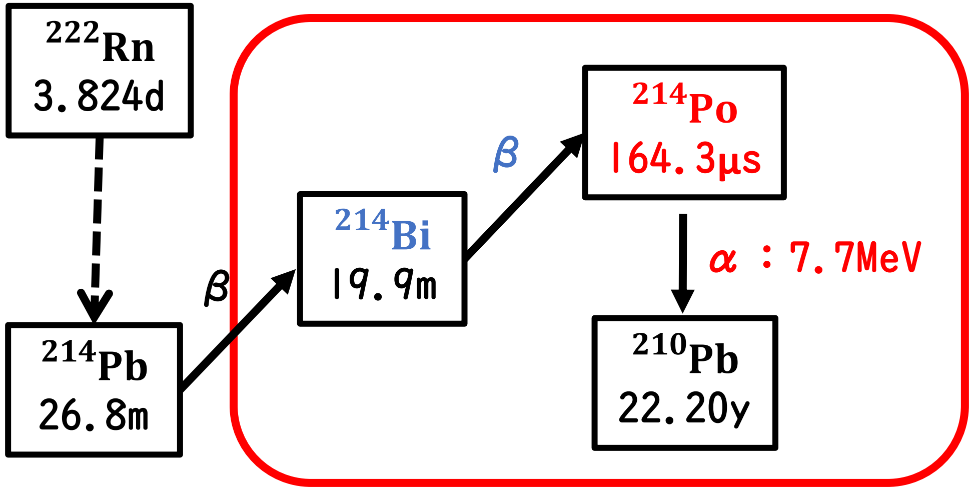






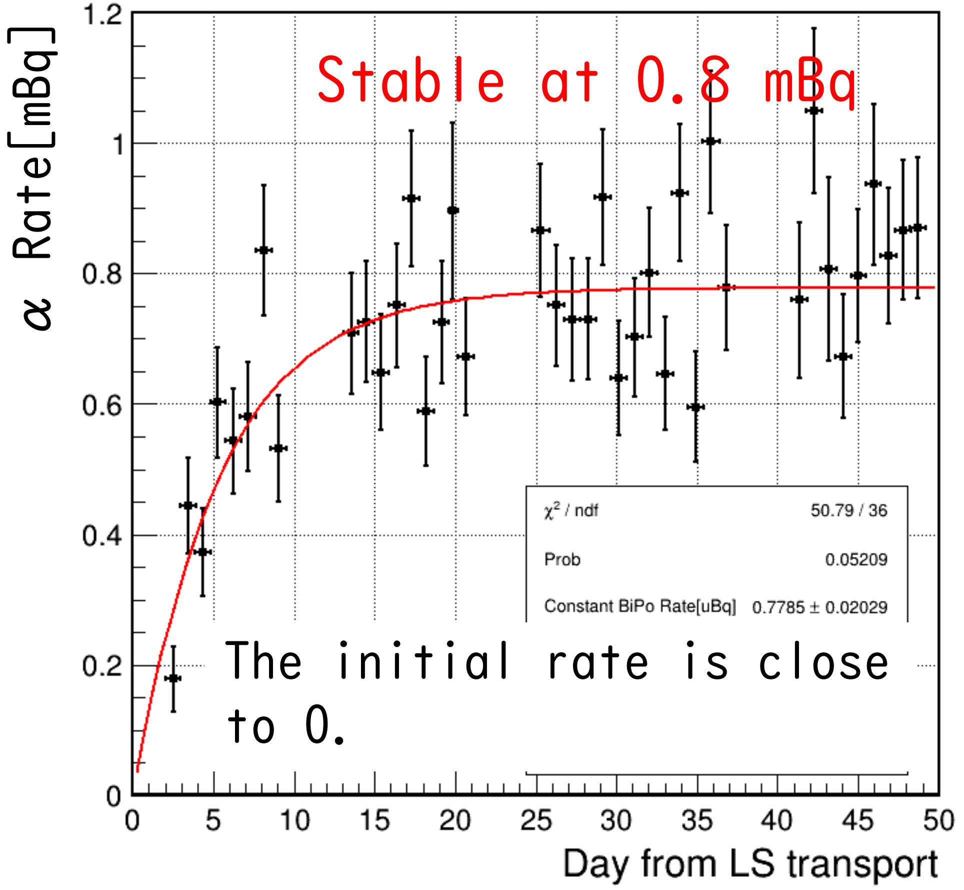
α-ray background of liquid scintillator detector

- Evaluate α-ray BG by delayed-coincidence of ^{214}Bi–^{214}Po



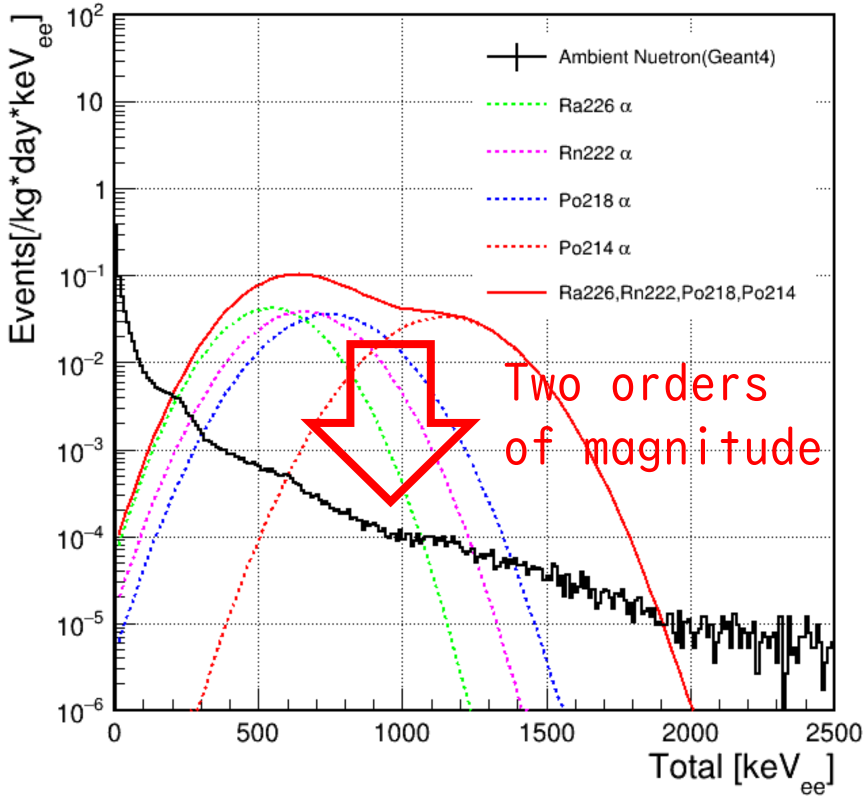
Since the half-life of ^{214}Po is short, ^{214}Bi–^{214}Po can be selected by Δt.

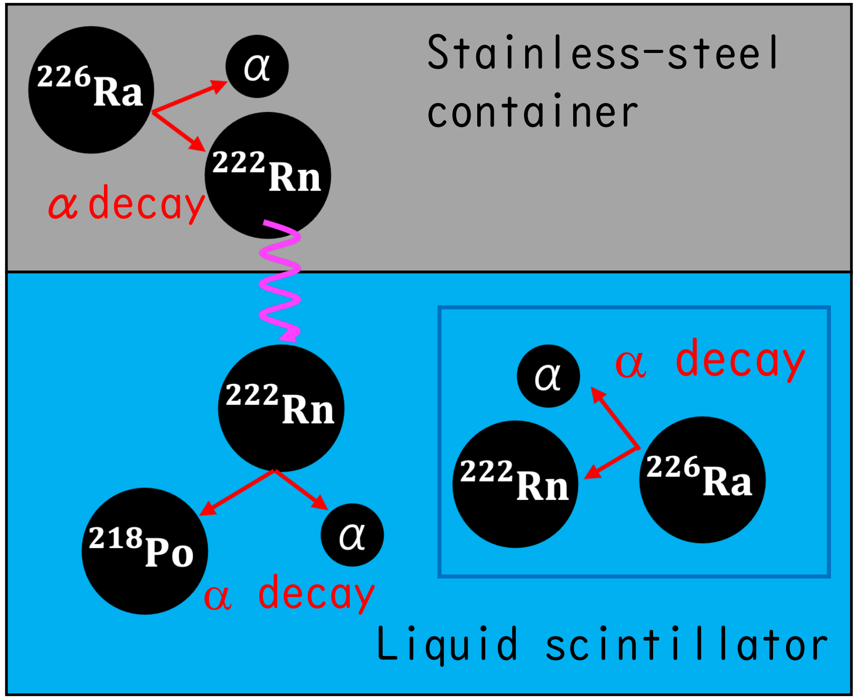
Bi-Po α-ray rate



α-ray background of liquid scintillator detector

expected neutron signal &
α α-ray background (0.8mBq)

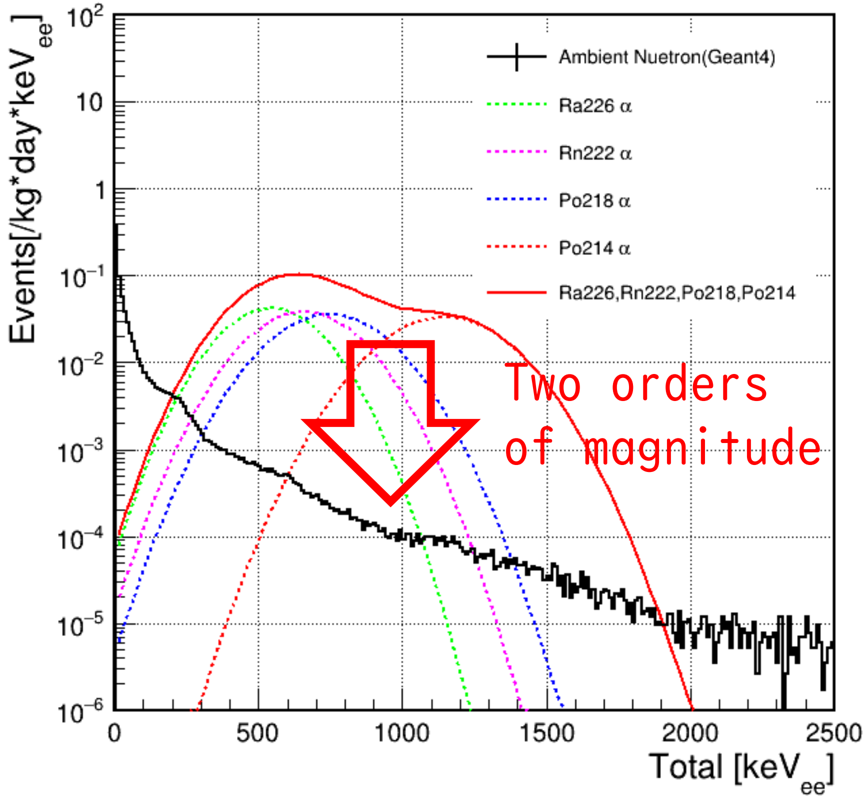




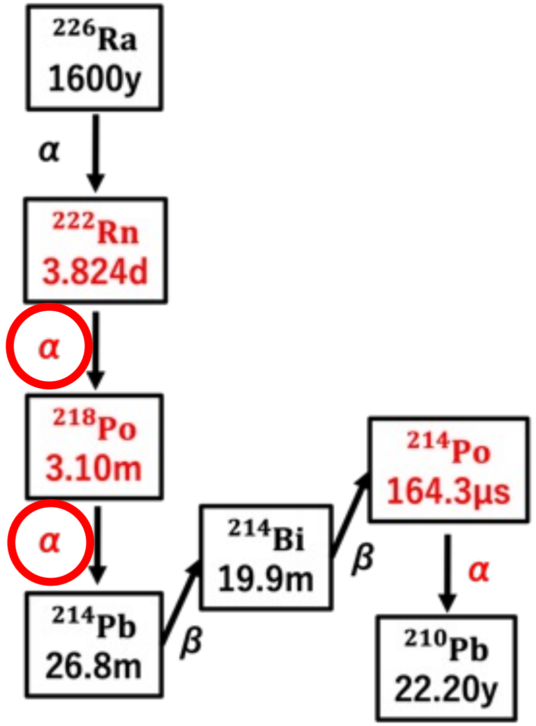
- Reduction by detector improvement (x 1/10)
  - Additional purification of liquid scintillator
  - Surface treatment of stainless-steel containers
  - ^{222}Rn reduction by periodic N_2 bubbling

α-ray background of liquid scintillator detector

expected neutron signal &
α α-ray background (0.8mBq)



- Reduction through analysis (x 1/10)
  - Tag the α-rays from ^{222}Rn and ^{218}Po with delayed coincidence measurement.



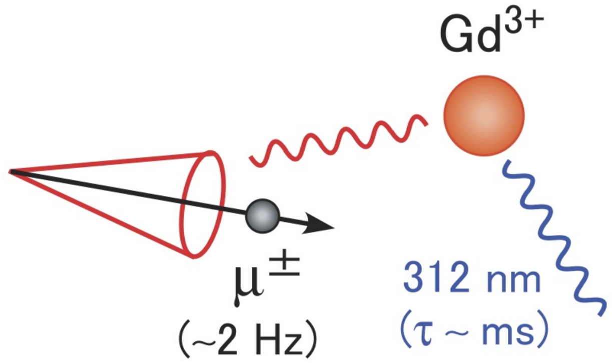
Assuming ^{222}Rn rate = 0.08 mBq

Time window	500 sec
Signal efficiency	41.2%
α-ray reduction	94.4%

Laser-induced luminescence spectroscopy for Gd^{3+}

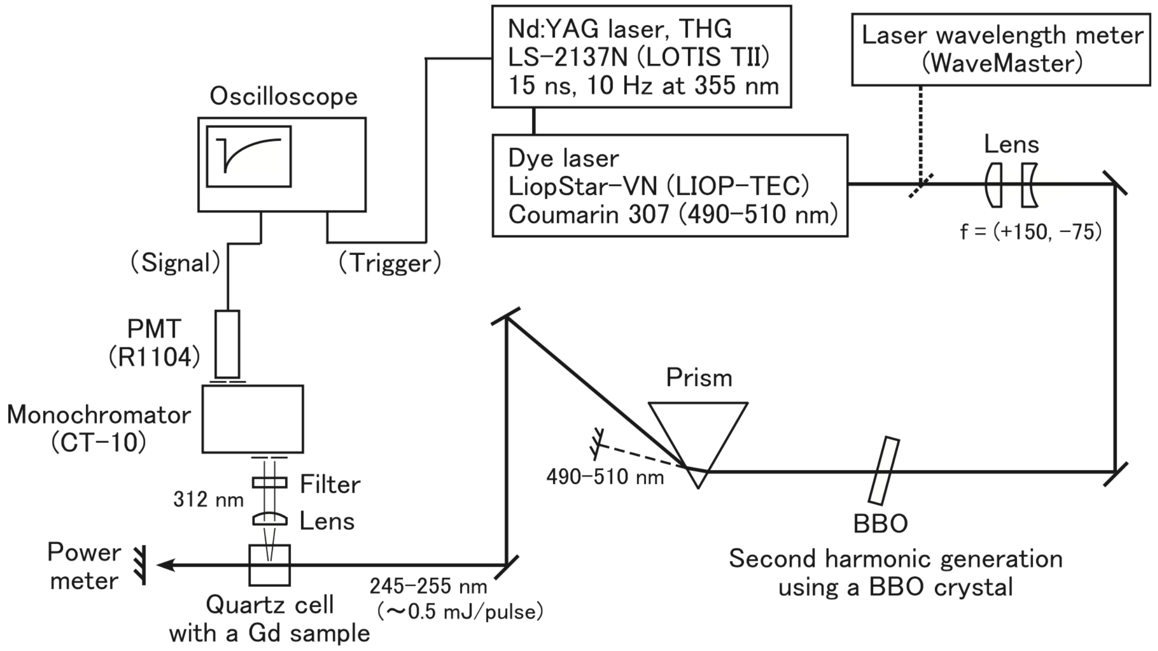
Laser-induced luminescence spectroscopy for Gd^{3+}

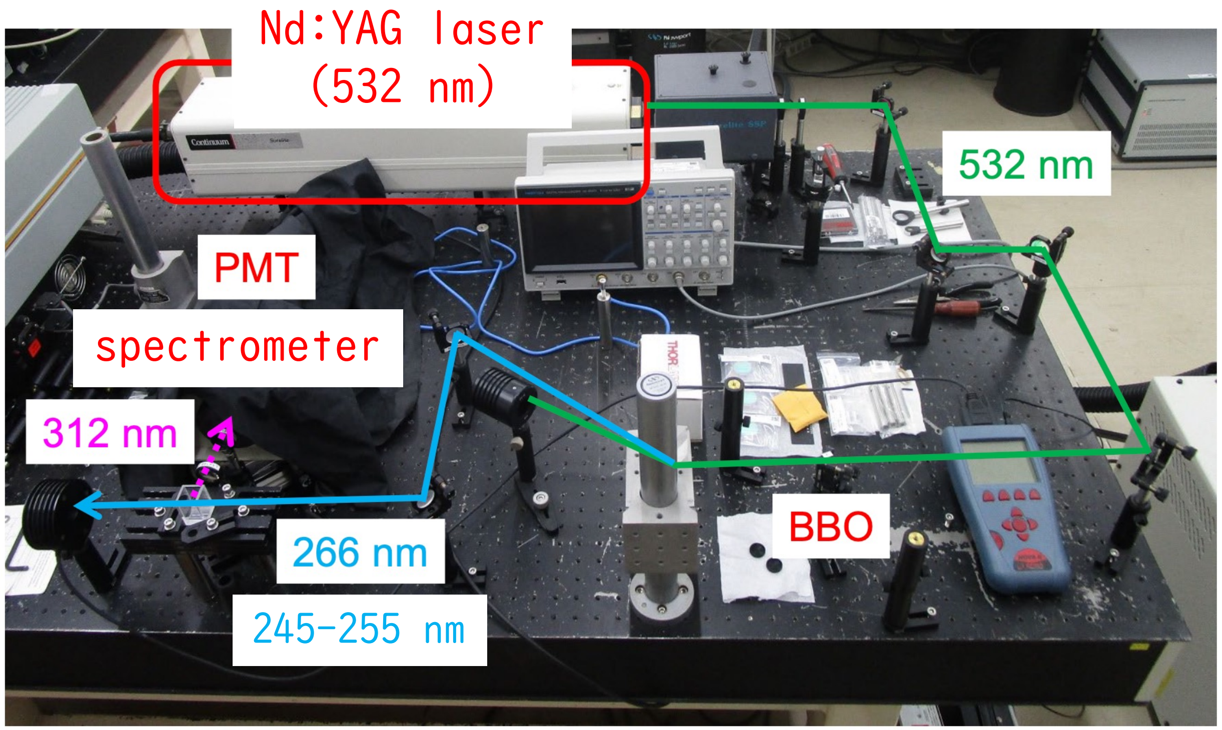
- Gd^{3+} luminescence is a phenomenon in which Gd^{3+} is excited by a photon and emits a 312 nm photon after O(1) msec.
- In SK-Gd, Gd^{3+} luminescence due to a Cerenkov photon could become a background, but there was no detailed measurement of Gd^{3+} luminescence in $Gd_2(SO_4)_3$ water.
- We investigated the emission characteristics of Gd^{3+} with laser-induced luminescence spectroscopy.



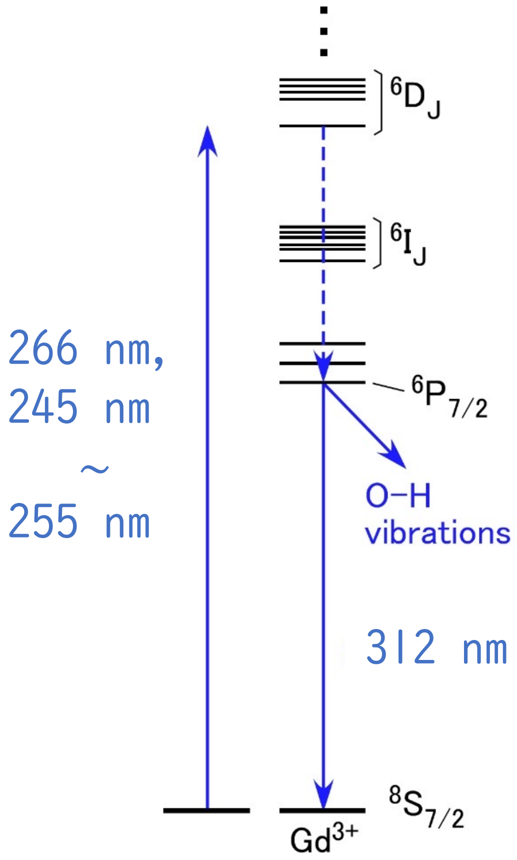
Laser-induced luminescence spectroscopy for Gd^{3+}

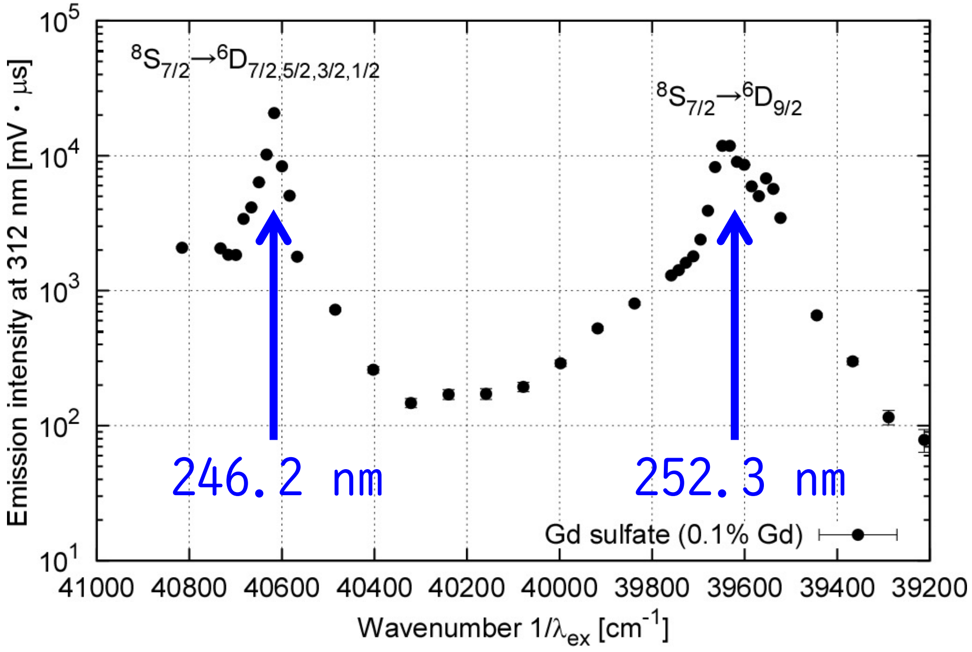
266 & 245-255 nm laser is irradiated to the cell w/ $Gd_2(SO_4)_3$ water, and 312 nm photons emitted from the cell are observed with a PMT.





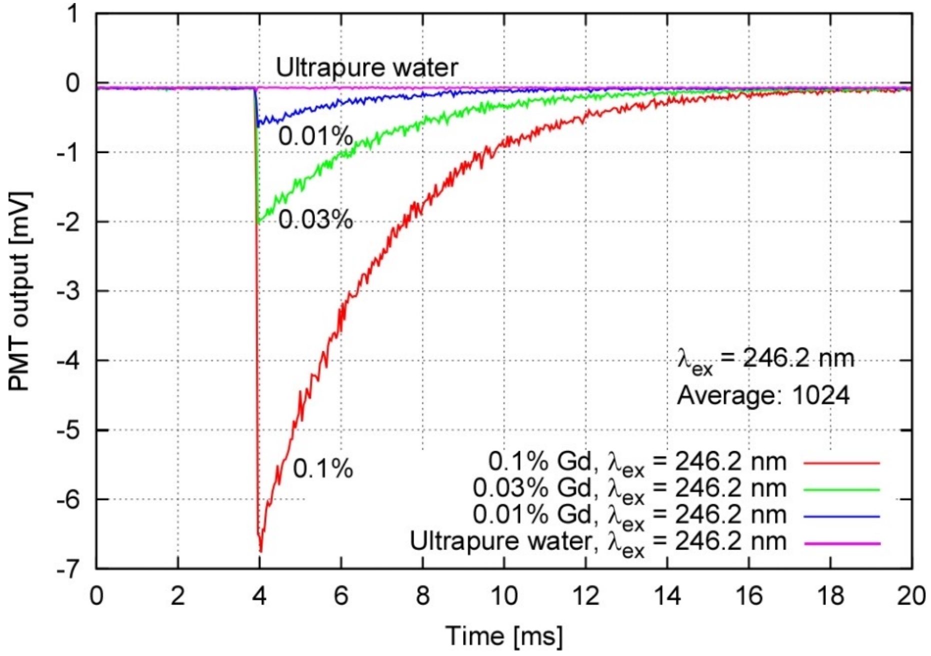
Laser-induced luminescence spectroscopy for Gd^{3+}





Luminescence increases by two orders of magnitude at resonant wavelength (246.2 nm & 252.3 nm)

246.2 nm laser pulse

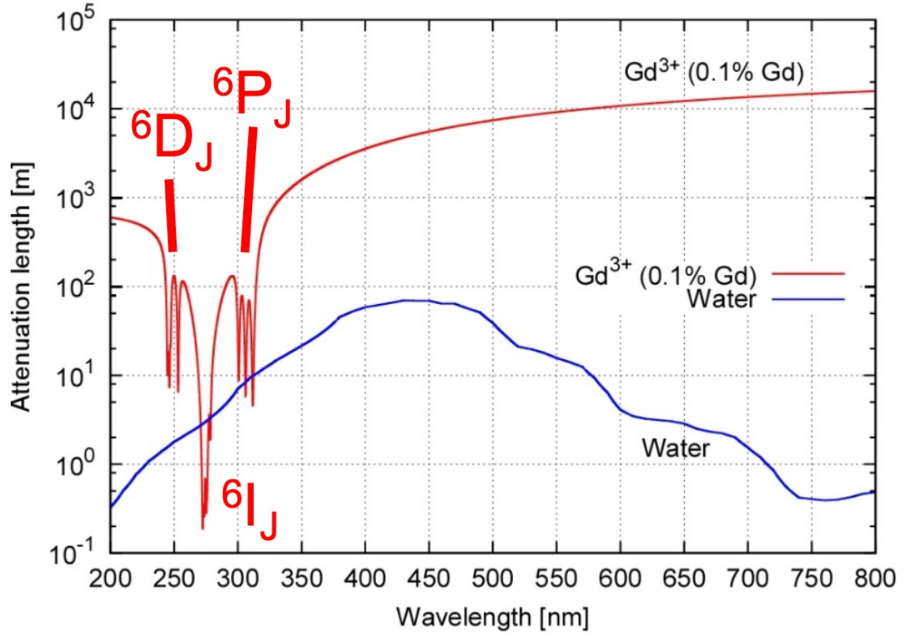


Emission lifetime ~ 3 ms

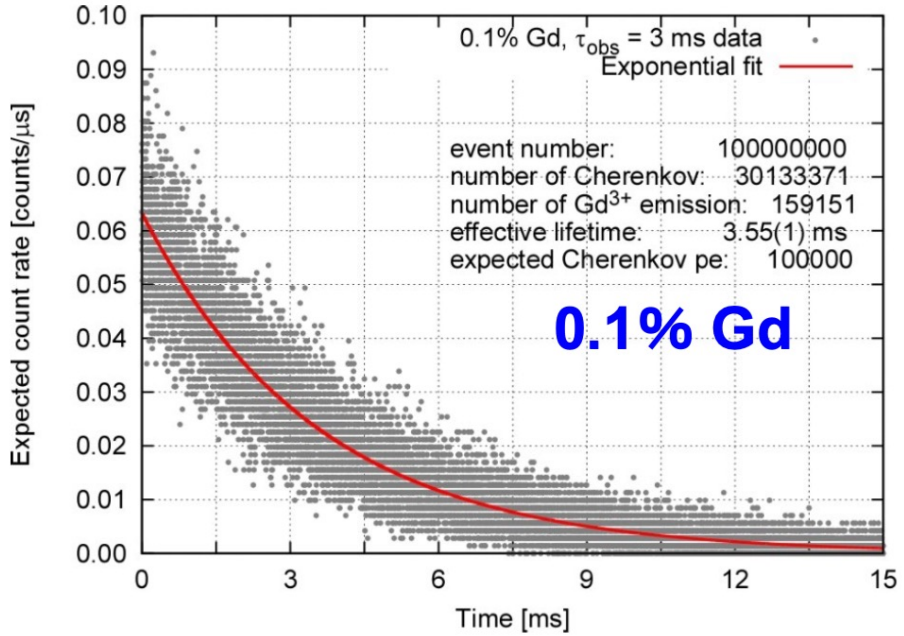
Impact of Gd^{3+} luminescence on SK-Gd

A simulation study was performed with SK-Gd geometry.

Attenuation length of Gd^{3+}



Expected count rate at SK-Gd



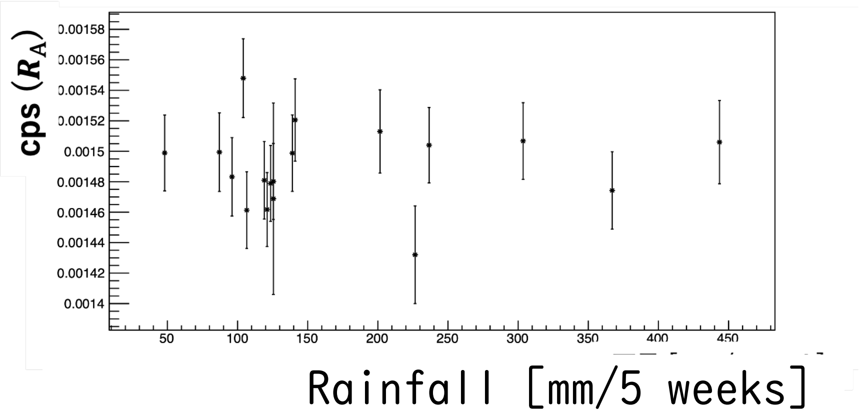
The expected count rate at SK-Gd is < 0.1 counts/μs; therefore, the impact on SK-Gd is small.

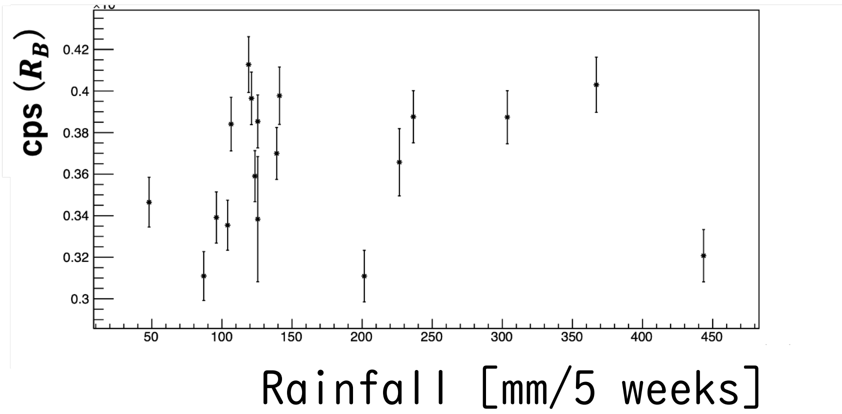
Summary

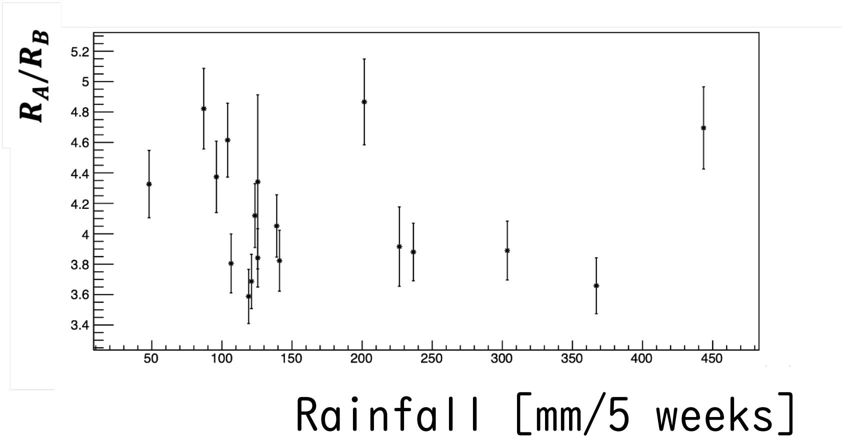
- Material screenings with HPGe detectors
  - An ultra-low BG HPGe detector with **the world's highest level of sensitivity** was developed.
- Rn assay in $Gd_2(SO_4)_3$ water
  - **The required background level of <1 mBq/m^3** is achieved.
- Environmental neutron measurements in the underground
  - **Weak correlations with humidity** in the mine-tunnel air.
  - **Medium correlation with Rn rate** in the mine-tunnel air.
- Laser-induced emission spectroscopy for Gd^{3+}
  - **The effect on SK-Gd is small.**

Backup

Neutron flux % rainfall

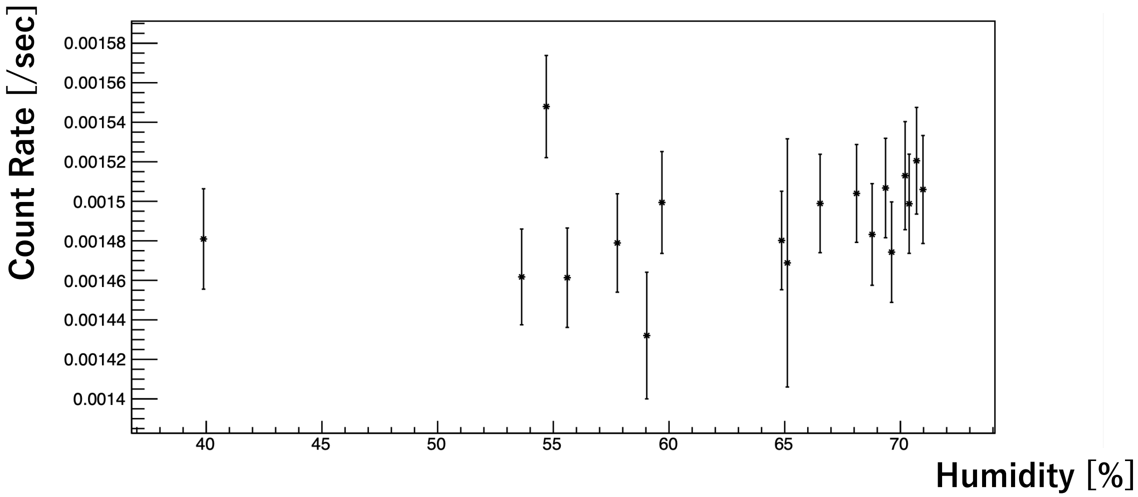


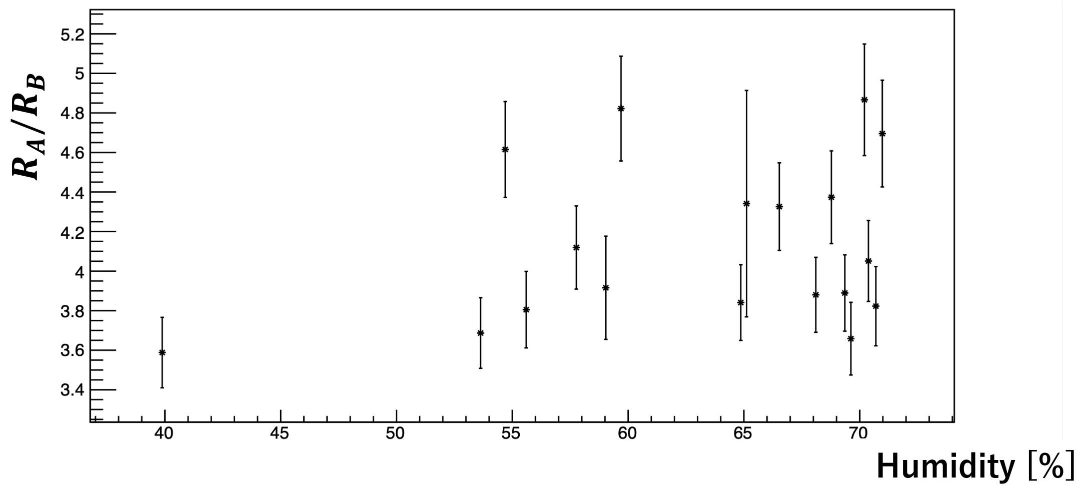


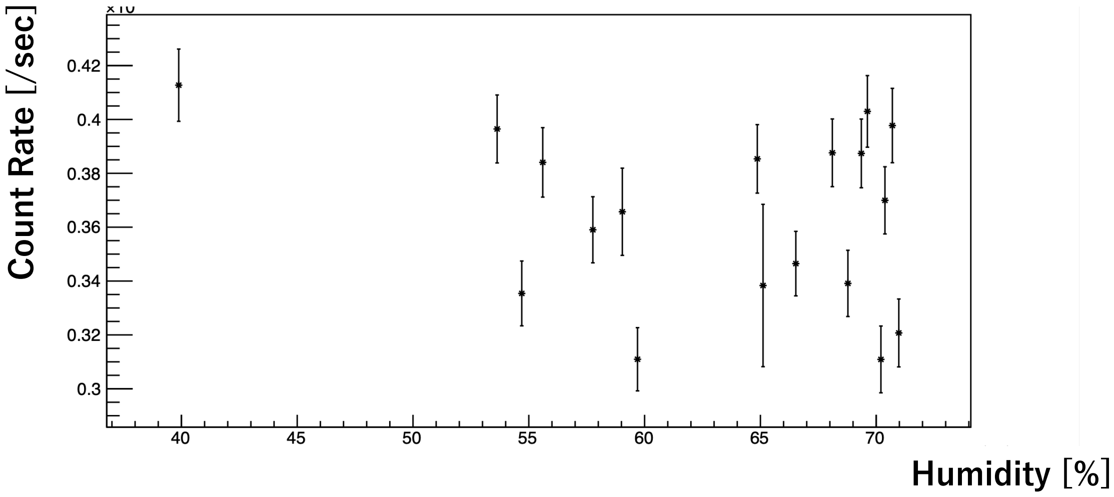


	R_A	R_B	R_A/R_B
correlation coefficient	0.17	0.12	-0.08

Neutron flux % Humidity

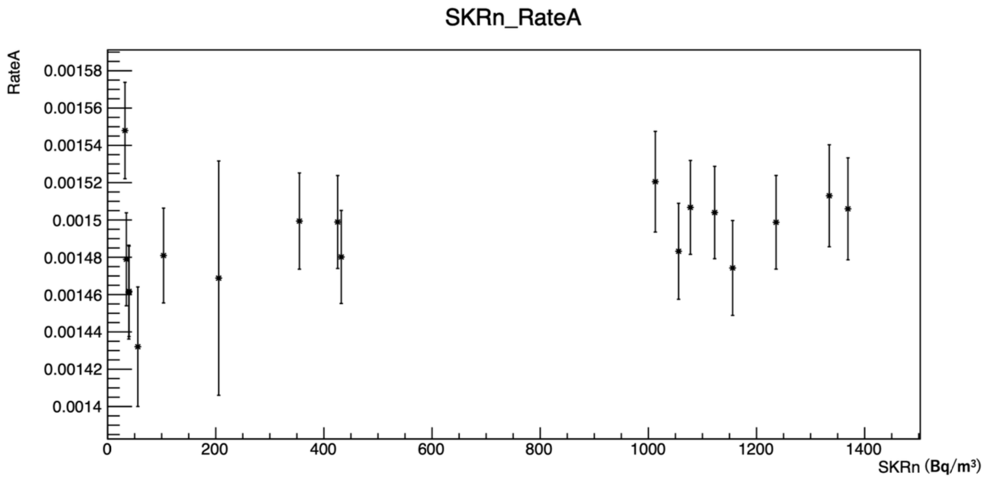


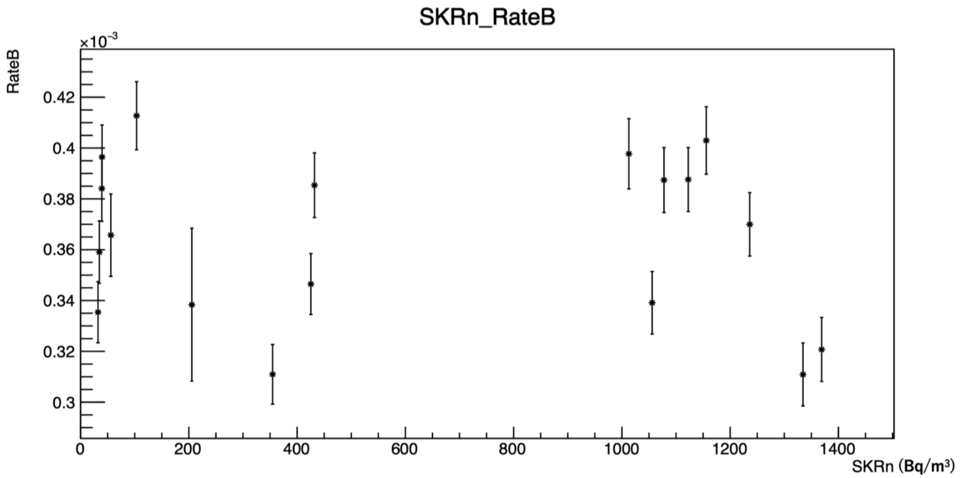


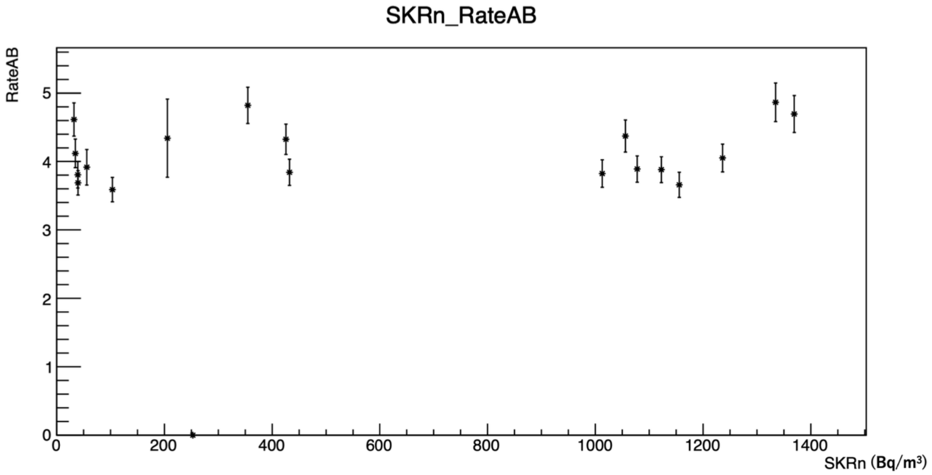


	R_A	R_B	R_A/R_B
correlation coefficient	0.28	-0.27	0.28

Neutron flux % Rn rate





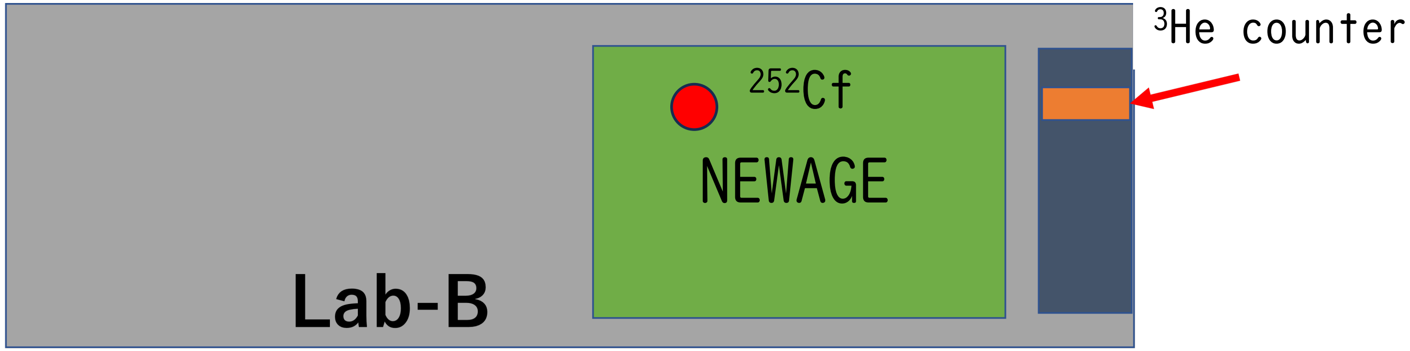


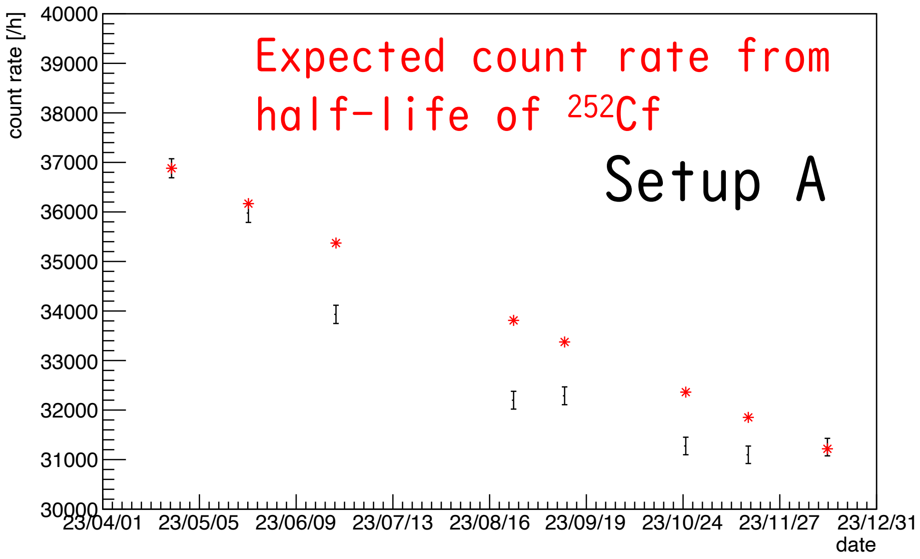
	R_A	R_B	R_A/R_B
correlation coefficient	0.41	-0.11	0.19

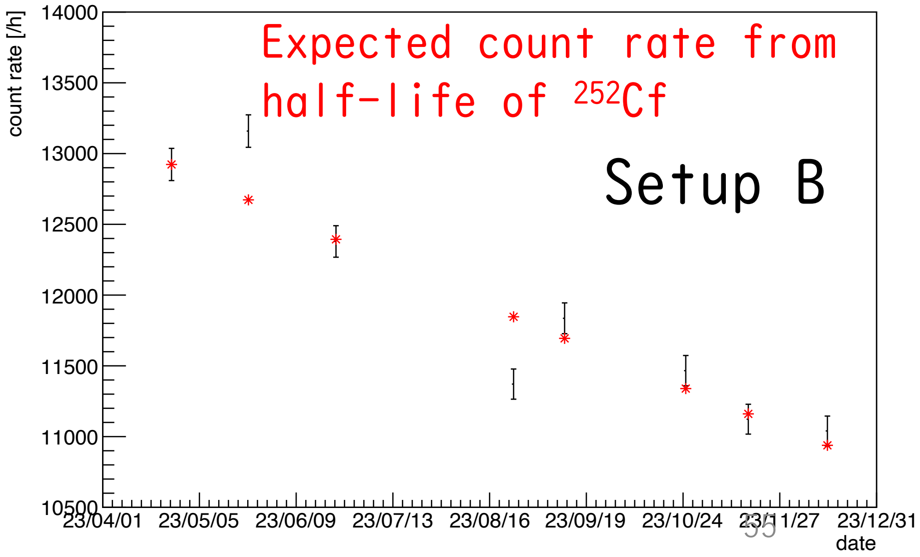
Calibration of ^{3}He proportional counter

Check if the sensitivity of ^{3}He proportional counter is stable.

- Started on Apr. 2023
- Irradiation with neutrons from ^{252}Cf for 1 hour
- Conducted approximately once a month





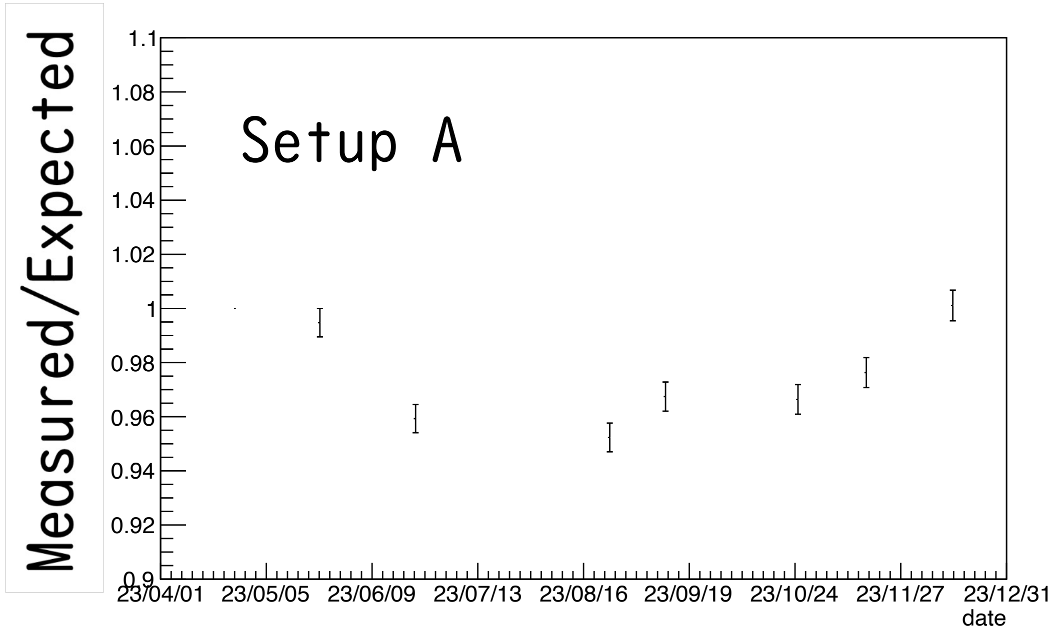


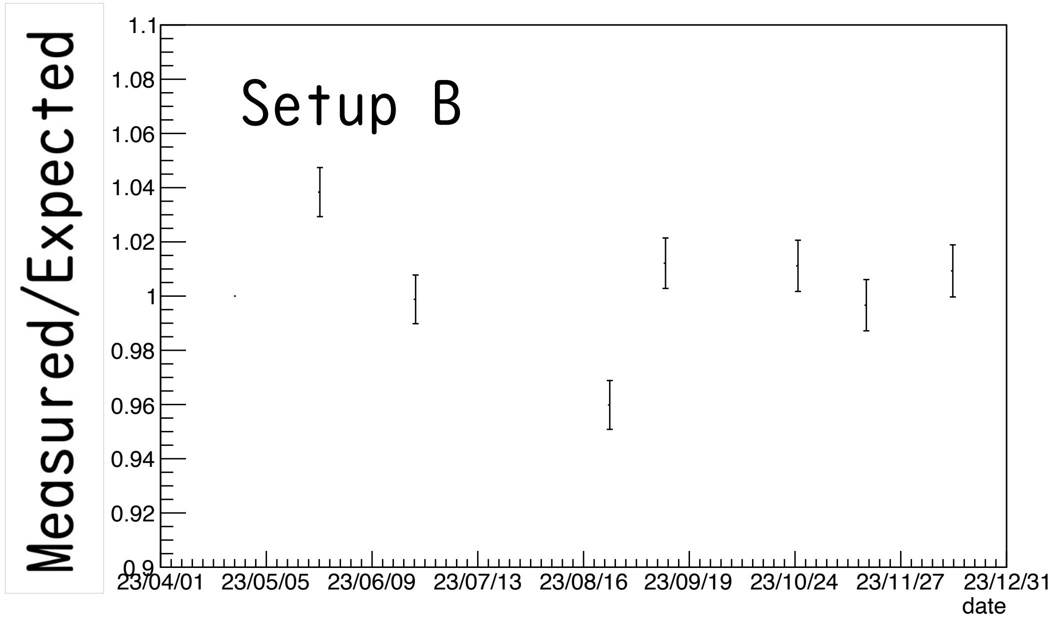
Calibration of ^{3}He proportional counter

The deviation from the expected rate is
- Setup A: −5% ~ 0%
- Setup B: −4% ~ +4%

We are currently investigating the cause of the discrepancy from the expected value.
- It has been confirmed that the gain has stayed the same.

Large statistical error
- Considering increasing calibration time





Coefficient Interval	Correlation
0.00 – 0.199	Very Weak
0.20 – 0.399	Weak
0.40 – 0.599	Medium
0.60 – 0.799	Strong
0.80 – 1.000	Very Strong