Performance of Upgraded Shielding System in CANDLES

Kyohei Nakajima (University of Fukui)
for the CANDLES collaboration

Low Radioactivity Techniques 2017
Ewa Womans University, Seoul, Korea
May.25, 2017

Contents

- The CANDLES experiment
- Shielding system for (n,γ) background
- Background before/after shielding
- Summary

Collaboration meeting photo in Oct. 2016

CANDLES Collaboration
(~30 people from 5 Institutes)

- Osaka University
- University of Fukui
- University of Tokushima
- Osaka Sangyo University
- University of Tsukuba

CANDLES

CAlcium fluoride for the study of **N**eutrinos and **D**ark matters by **L**ow **E**nergy **S**pectrometer

- **CANDLES**: Double beta decay experiment with ^{48}Ca
  - **Advantage**: Highest Q-value (4.27 MeV)
    - cf. Next highest: ^{150}Nd (3.37 MeV)
  - **Disadvantage**: Low natural abundance, 0.187%
    - Enrichment technique is under development.

Half life limit of neutrinoless double beta decay ($0\nu\beta\beta$)

- **World best limit: $T_{1/2} > 1.1\times10^{26}$ year (^{136}Xe; KamLAND, 2016)**
- **Best limit with ^{48}Ca: $T_{1/2} > 5.8\times10^{22}$ year (ELEGANT VI, 2008)**
  - **cf. CANDLES (2015): $T_{1/2} > 0.8\times10^{22}$ year**
    - Limited by high energy γ-rays from (n,γ) reaction; (n,γ) BG
    - Under development for the future research

✓Enrichment (^{48}Ca: 0.2% → ?%): T. Kishimoto (attendee)

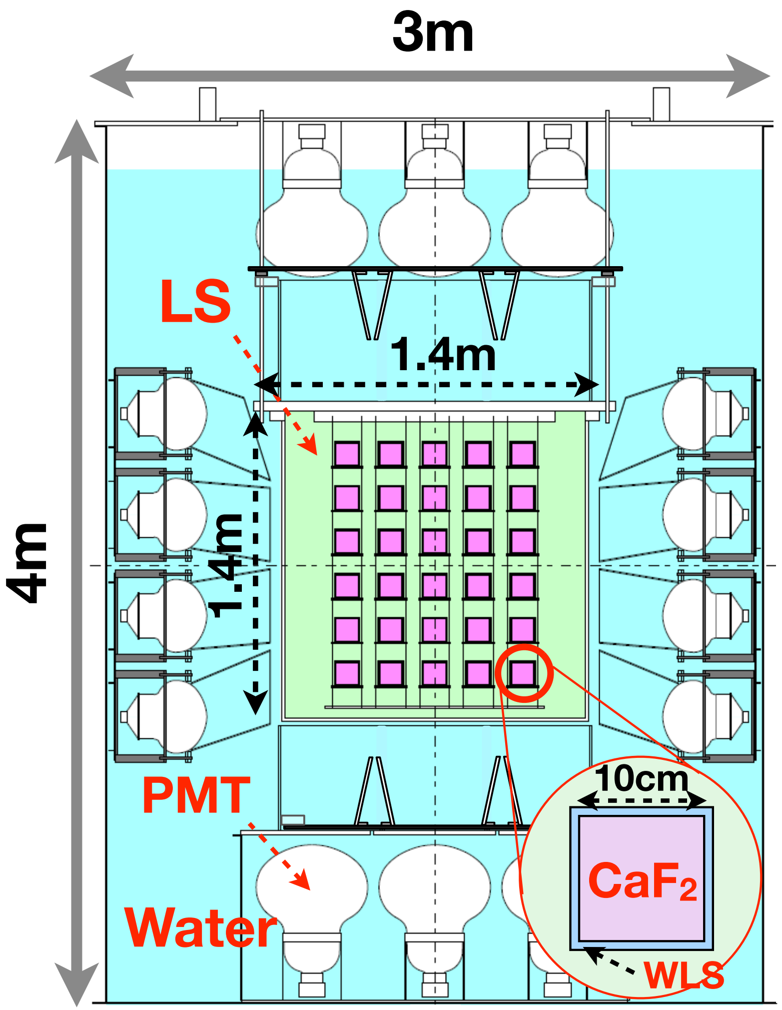
✓CaF_2 bolometer (σ: 2% → ~0.3% at 4.27 MeV): X. Li (attendee)

CANDLES III (U.G.) Detector

Under Ground

CANDLES Detector

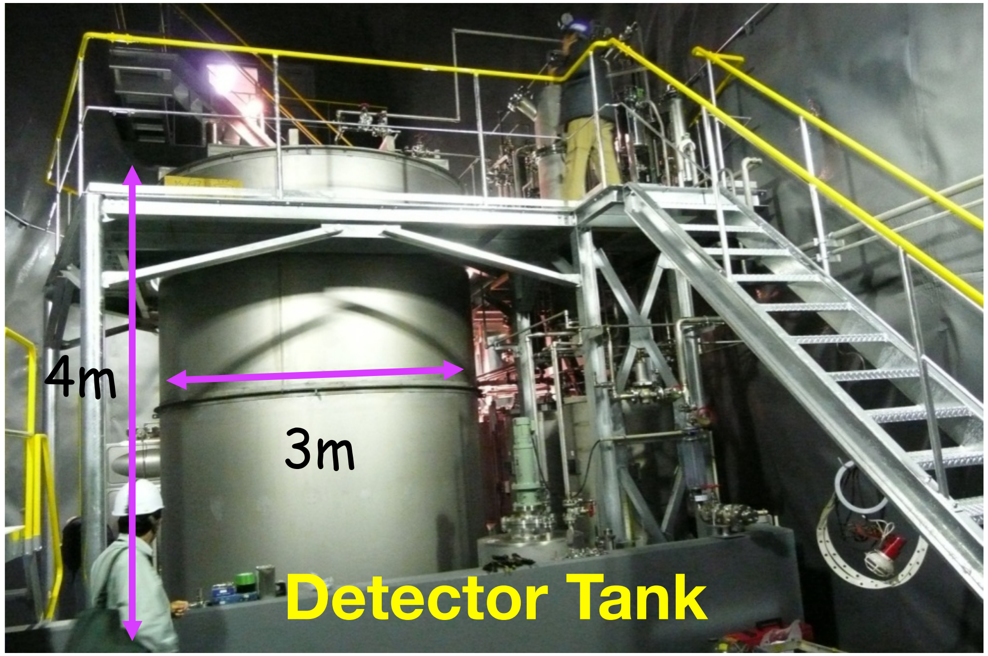
@ Kamioka (2700 m.w.e.)

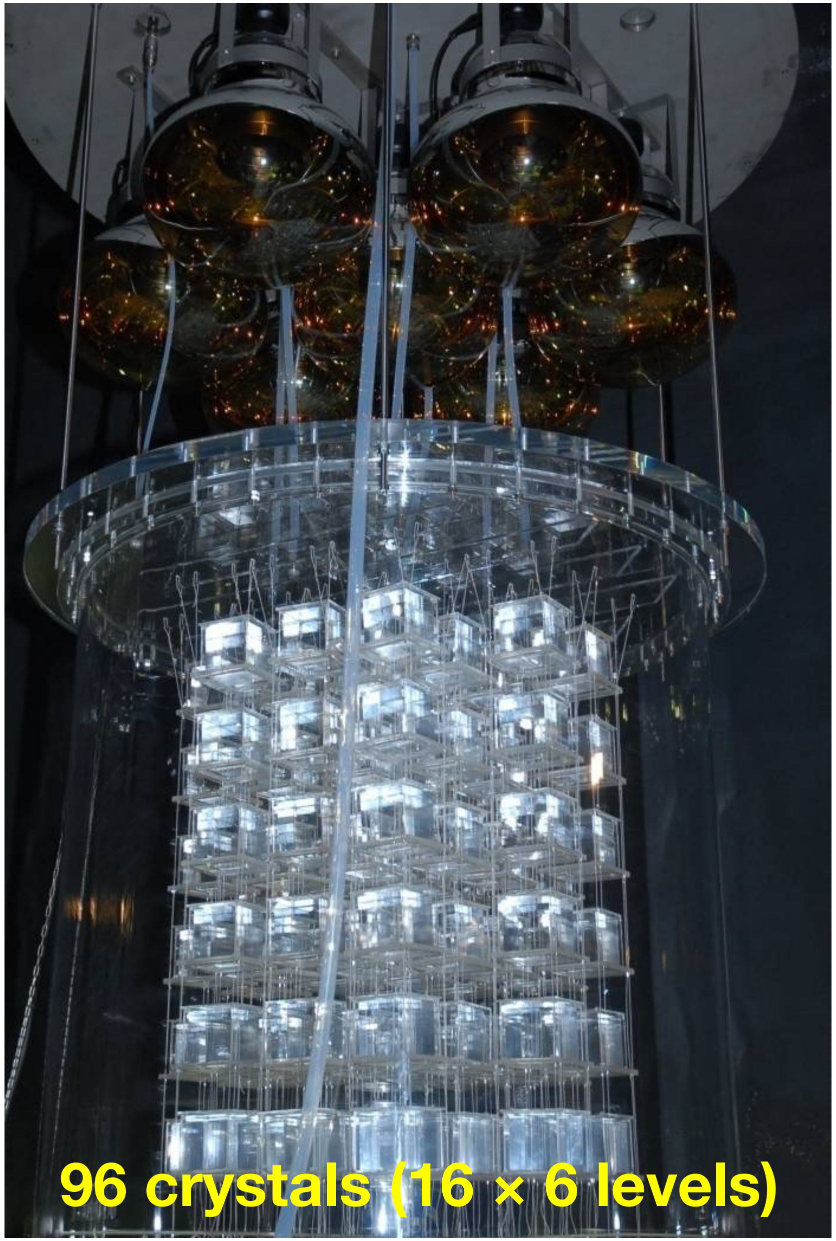


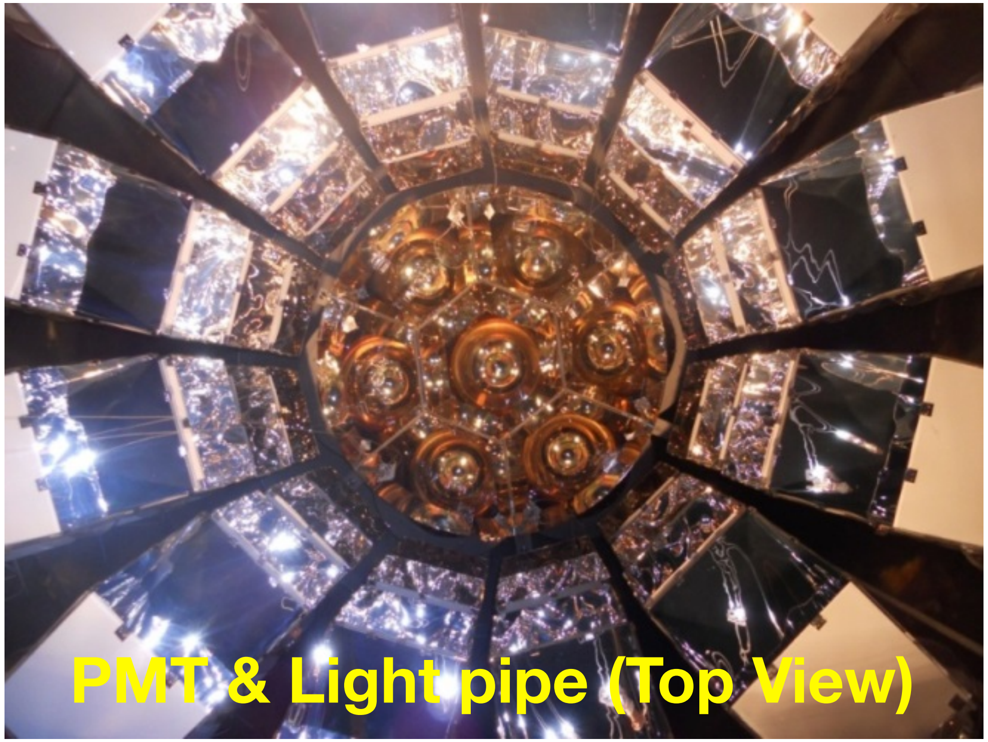
Detector components (from inside)

- **CaF_2 module**
  - $10 \times 10 \times 10$ cm^3 × 96 crystals (305 kg)
    - ^{48}Ca ~350 g (~0.2% nat.)
  - Wave length shifter (WLS)
    - 280 (CaF_2) → 420 nm (PMT-sensitive)
- **Liquid scintillator (LS)**
  - Active veto (for internal/external γ-rays)
- **Pure water**
  - Passive shield (for external radiations)
- **62 PMTs**
  - 13 inch PMT × 48, Side
  - 20 inch PMT × 14, Top/Bottom
  - Light pipe: reflection ~ 93% @ 420 nm

Detector Photographs

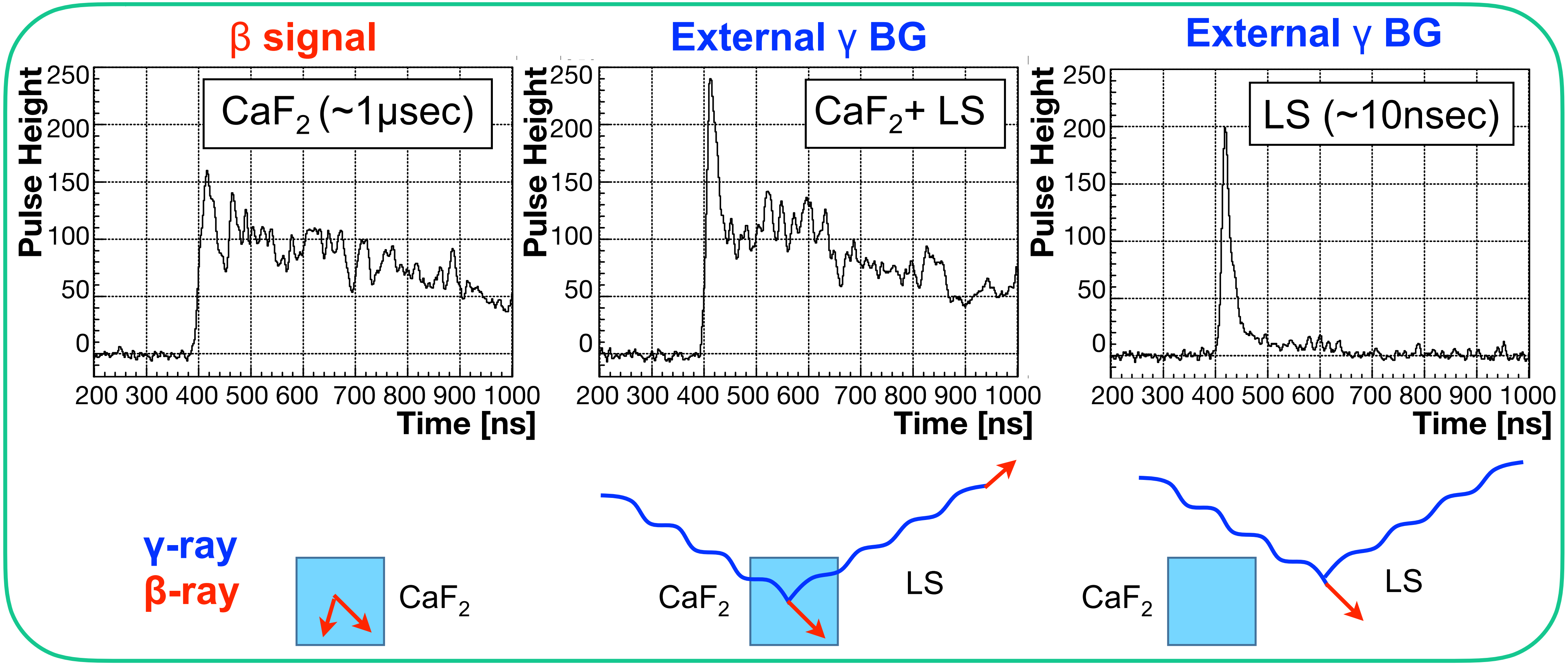






4π Active Shield by Liquid Scintillator (LS)

- **Reject external γ-ray background**
  - Distinguish event type by pulse shape in offline analysis
    - Different time constant of pulse shape between CaF_2 and LS
      CaF_2: ~1 μs, LS: ~10 ns

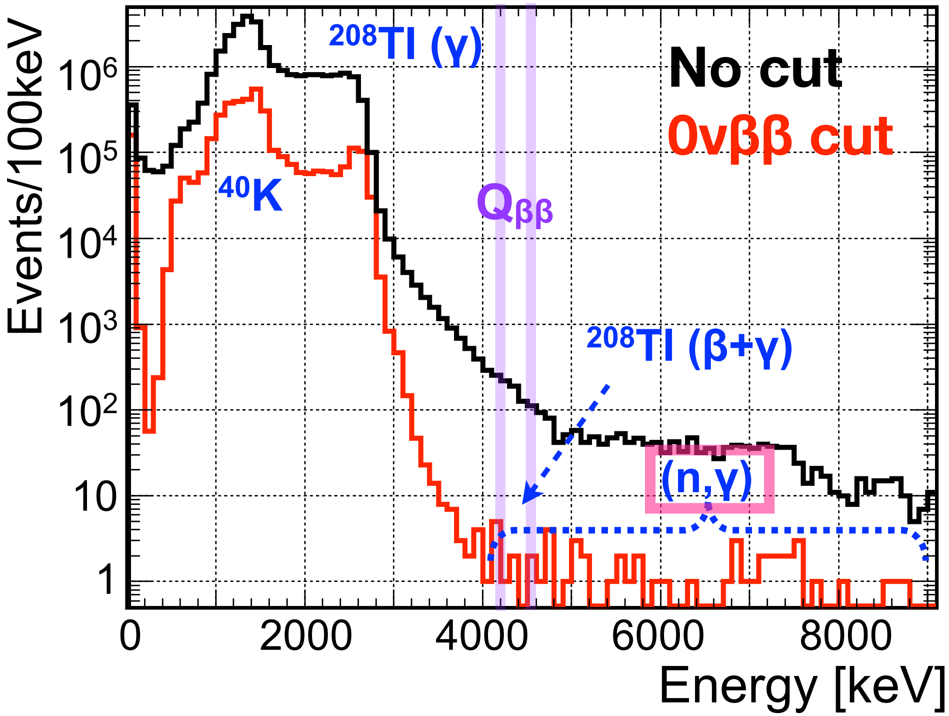


✓ **Energy deposit in LS < a few % in total → Find β signals in CaF_2**

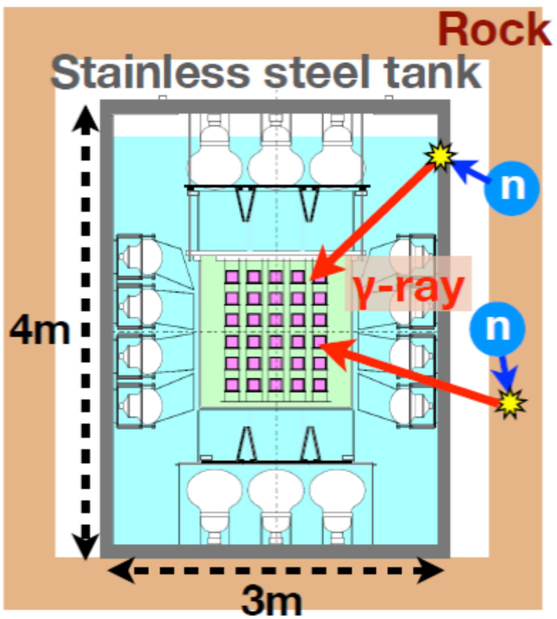
Background Result (2015)

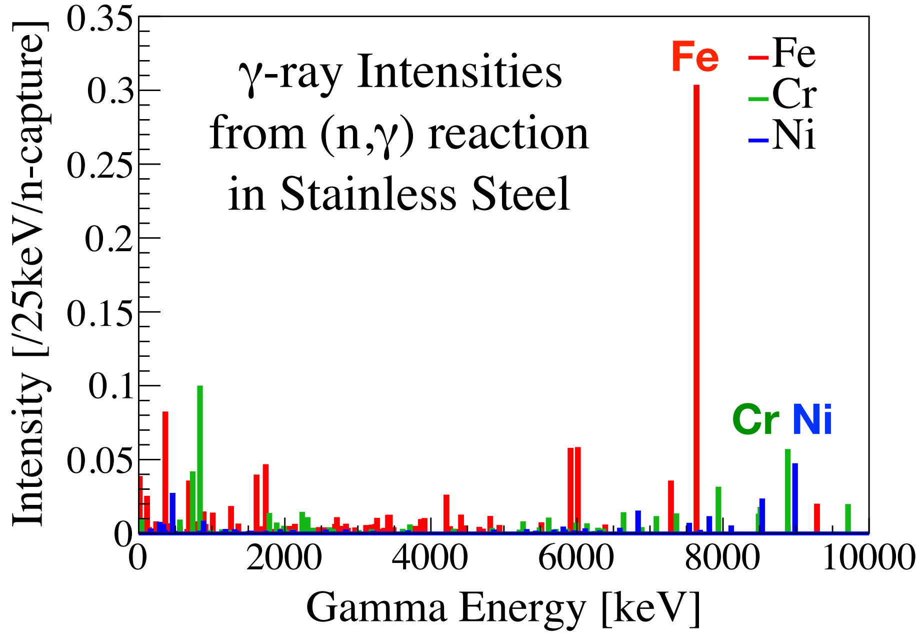
CANDLES (2015)
(with 26 ^{232}Th-least crystals)

Date	2013/6 - 2013/9
LiveTime	60.3 days
Exposure (^{48}Ca)	5.73 kg•days
Number of events	**6**
Expected BG	**(n,γ): 3.4±0.4** **^{208}Tl: ~1**
Sensitivity ($T_{1/2}$)	0.8×10^{22} year



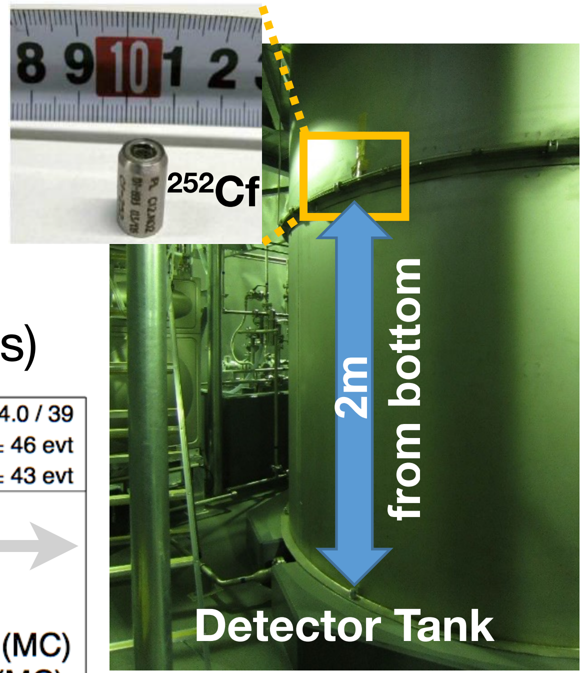
Schematic View of (n,γ) Reaction



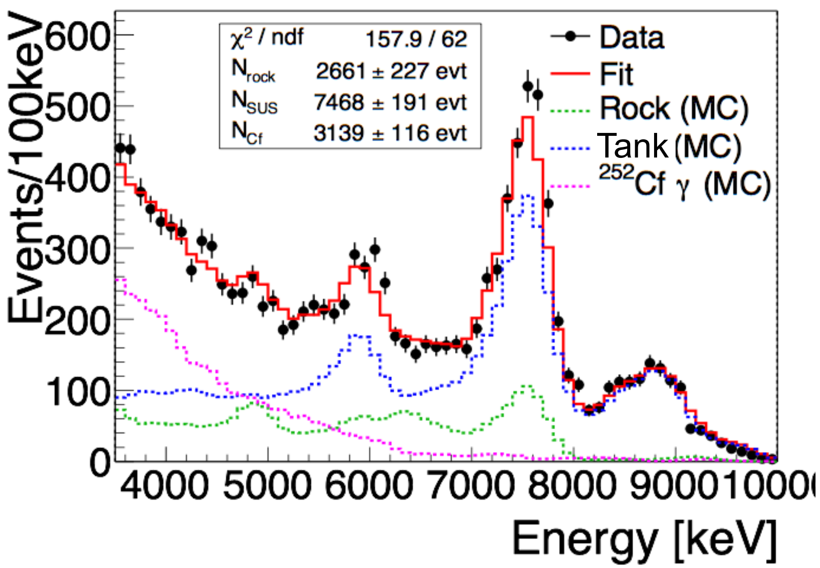


Understanding of (n,γ) Background

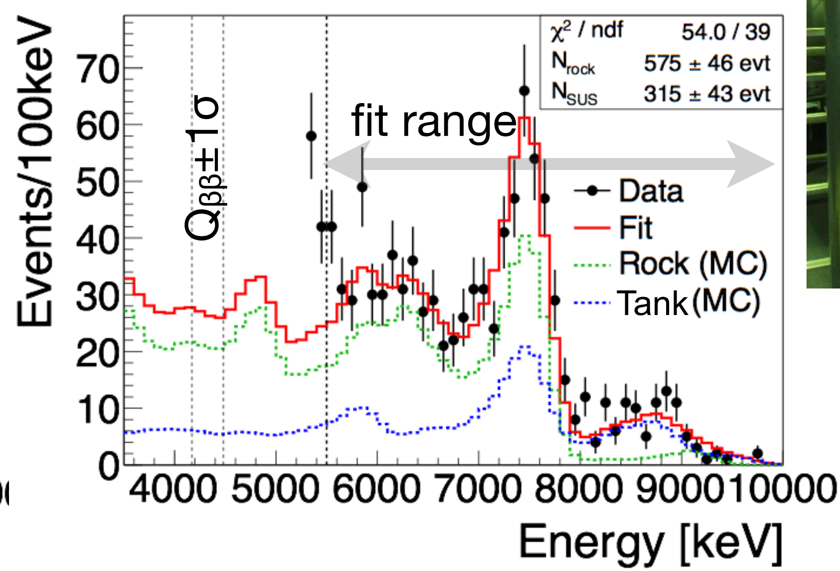
- **Data**: set ^{252}Cf neutron source outside of the tank
- **MC**: perform detector simulation for (n,γ) reactions in rock and tank



Neutron Run (3.1 hours)



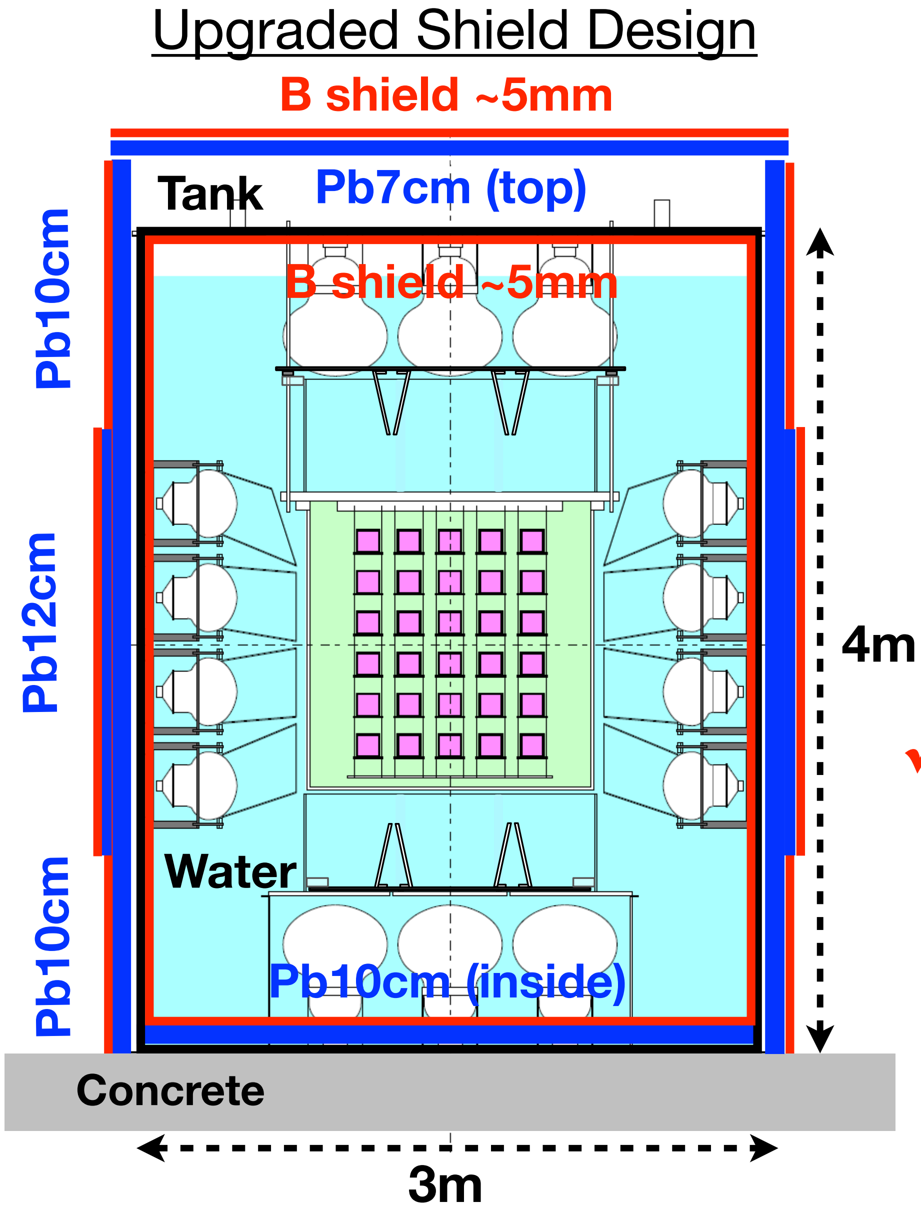
Physics Run (88.1 days)



✓ **Consistent spectra between neutron source run and physics run**
✓ **Reproduce observed spectra by MC simulation of (n,γ) reaction**
- **(n,γ) BG: 76±9(stat.) events/year/96crystals**

Shield for (n,γ) Background

- **Reduce (n,γ) events by additional passive shield**
  - **Goal: ~1 events/year/96crystals (~1/80 level)**

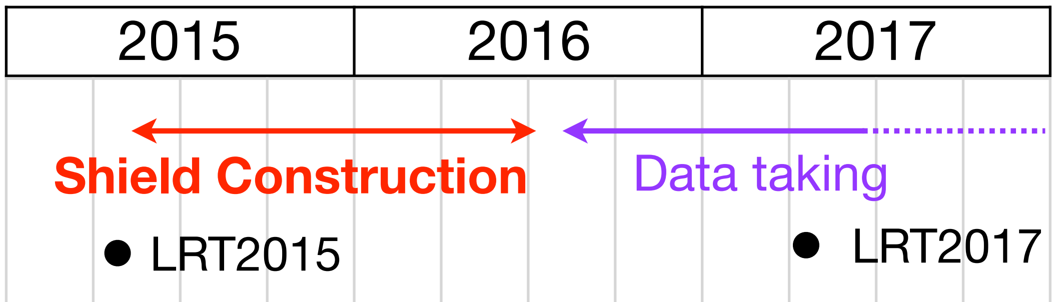


CANDLES tank

Pb shield (7-12cm)
- for γ-rays from surrounding rock
- Bottom shield inside of the tank

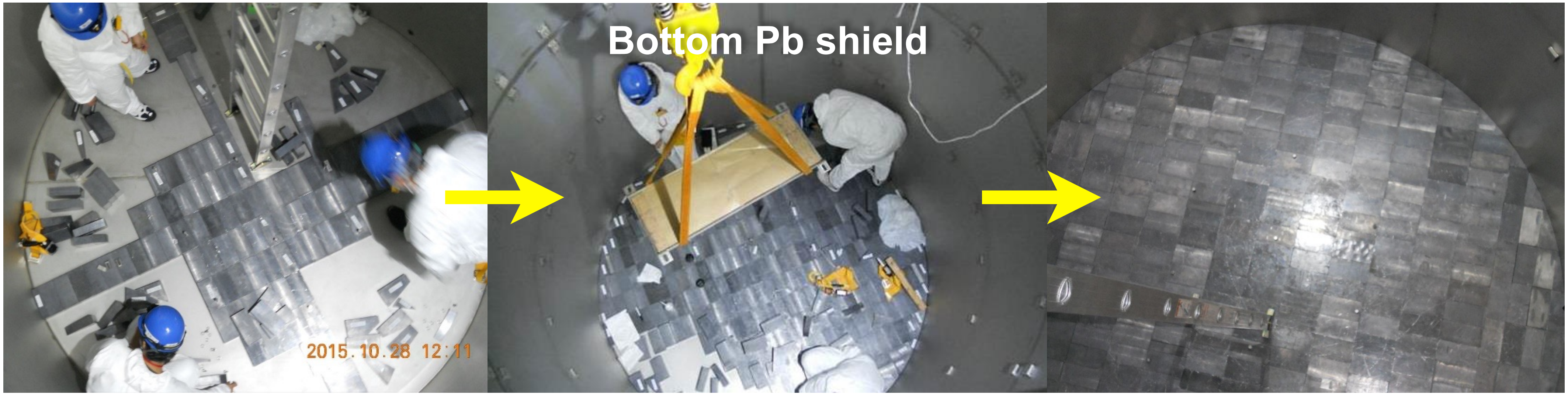
Boron sheet (~5mm)
- for neutron captures on tank
- Rubber sheet contained 40wt% B_4C
- Inside and outside of the tank
- Use liquid type at inner bottom

✓MC Estimation: ~0.7 (±50%) events/year



Pb Shield Construction

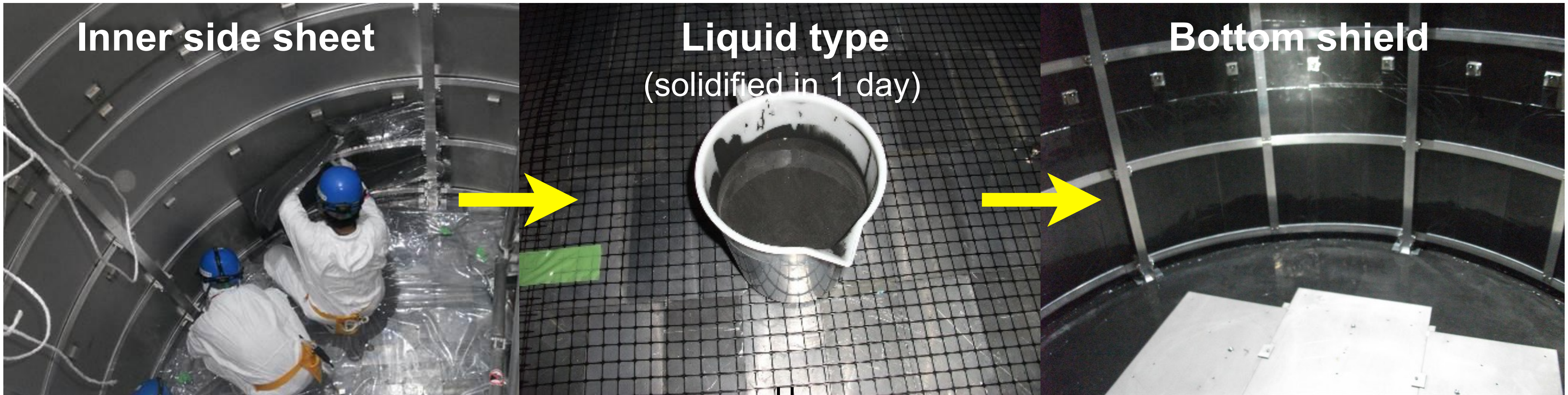
- Pb shield construction started from Mar. 2015



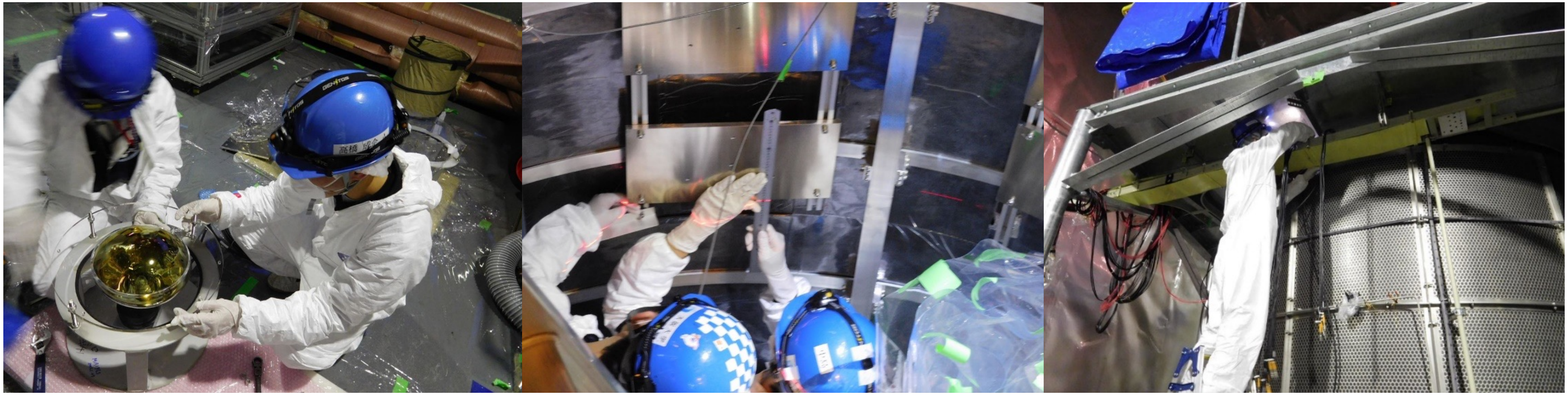
Cover bottom Pb blocks by liquefied B shield

Boron Shield Construction

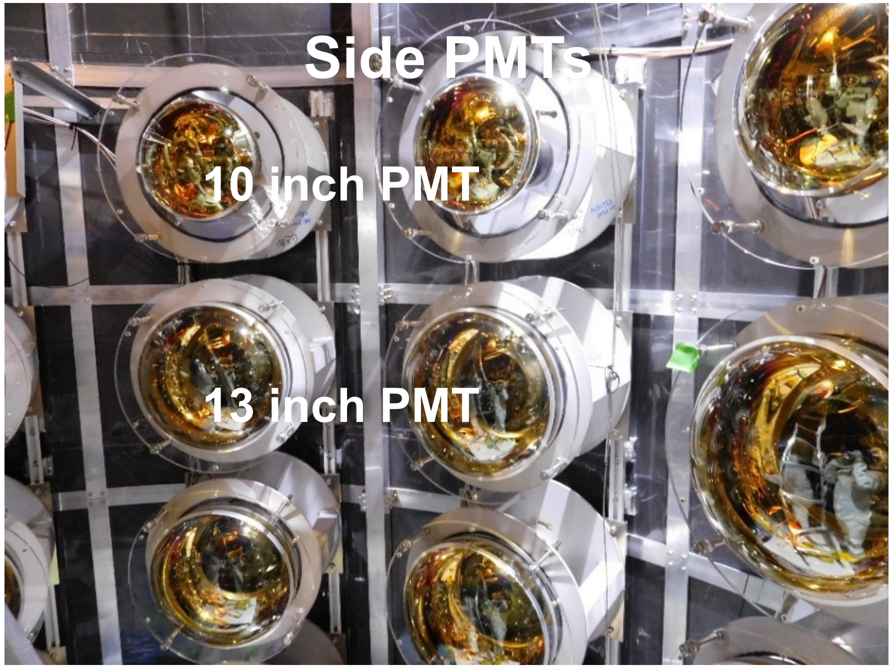
- Pour liquid type B shield at bottom
  - for neutron shielding and waterproofing bottom Pb blocks
- Check B and Pb elution into water periodically after water filling

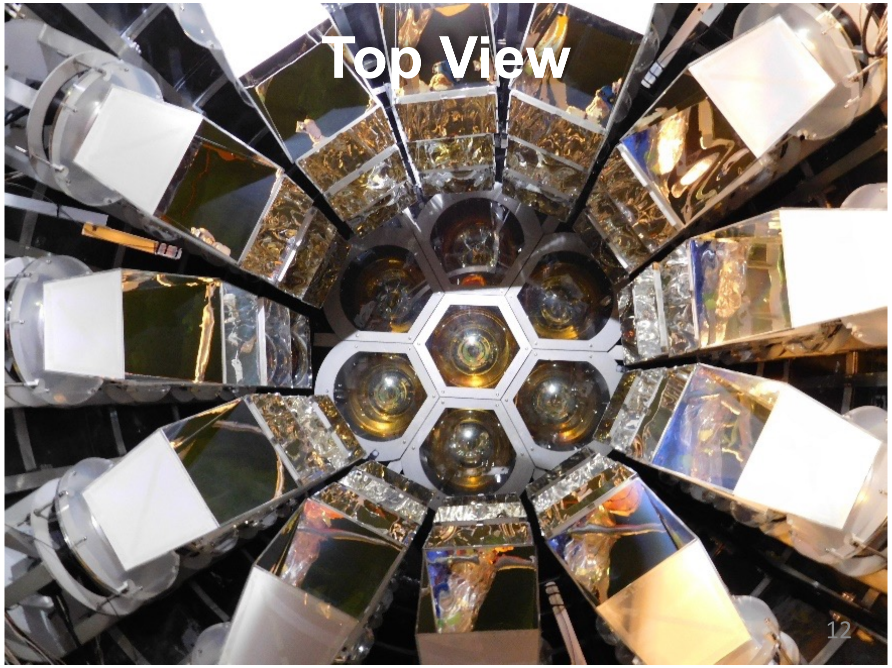


PMT Reinstallation



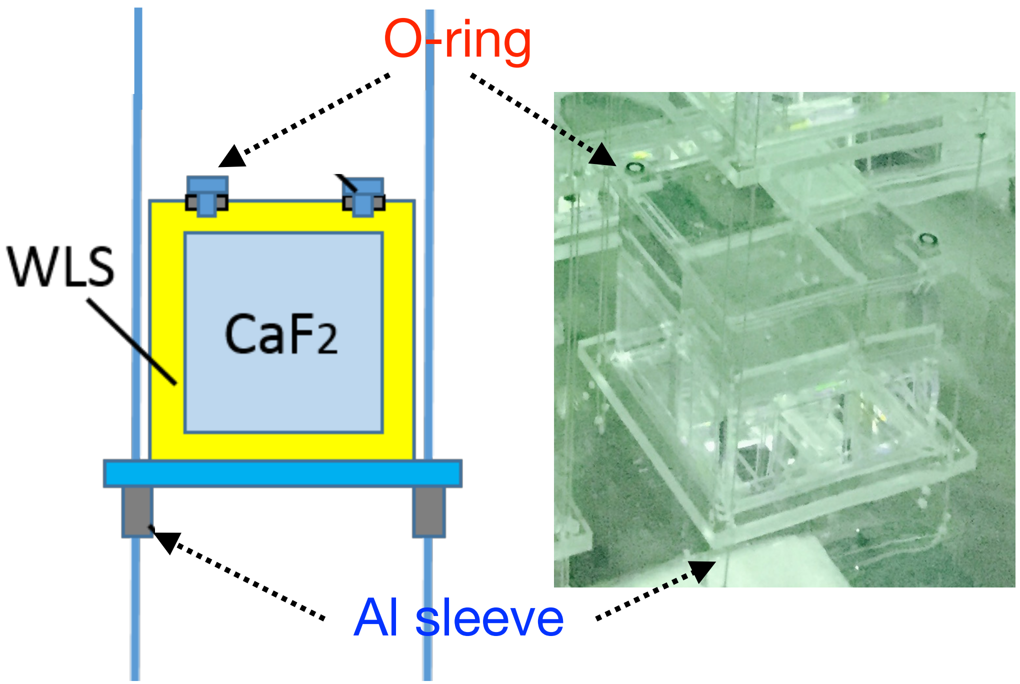
- Twelve 10inch PMTs (faster response) are installed for performance study.





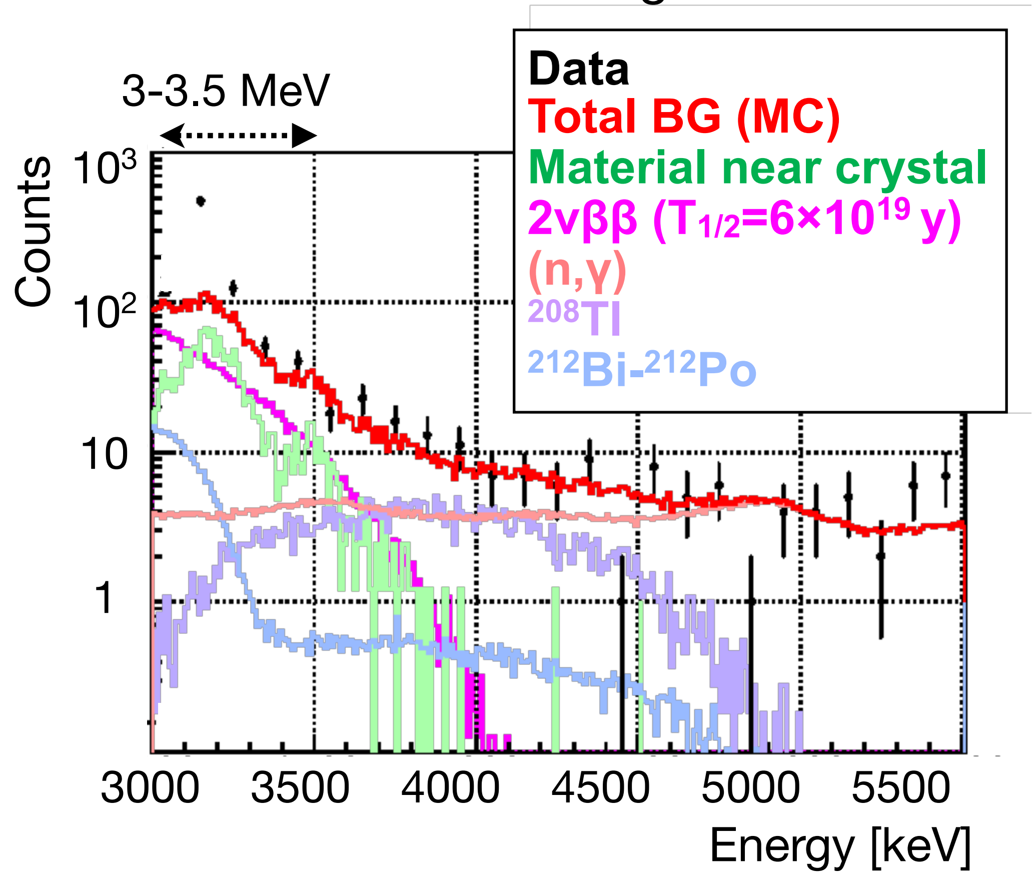
Material Replacement near CaF_2 Crystals

- Measured radioactivity in materials with Ge detector
  → "Al sleeve" and "O-ring" are dirty
- Replaced them with clearer ones during shield construction
- Expect half background in 3-3.5 MeV region



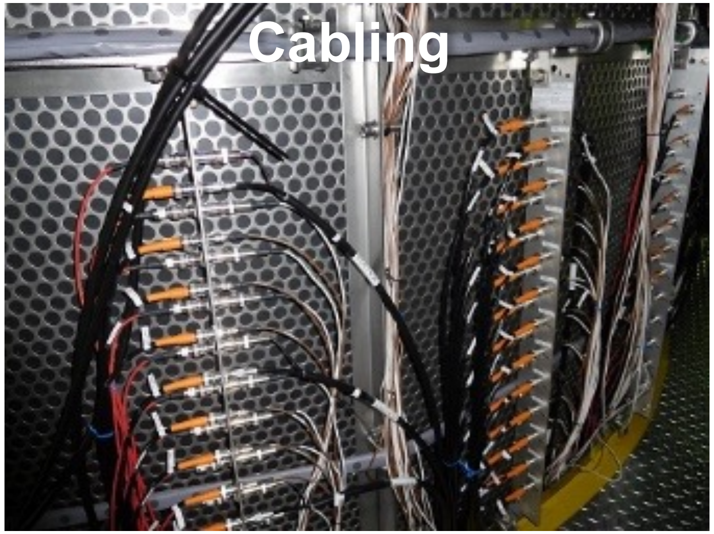
Al sleeve (^{232}Th)
before: ~0.4 mBq/crystal
after: ~0.1 mBq/crystal

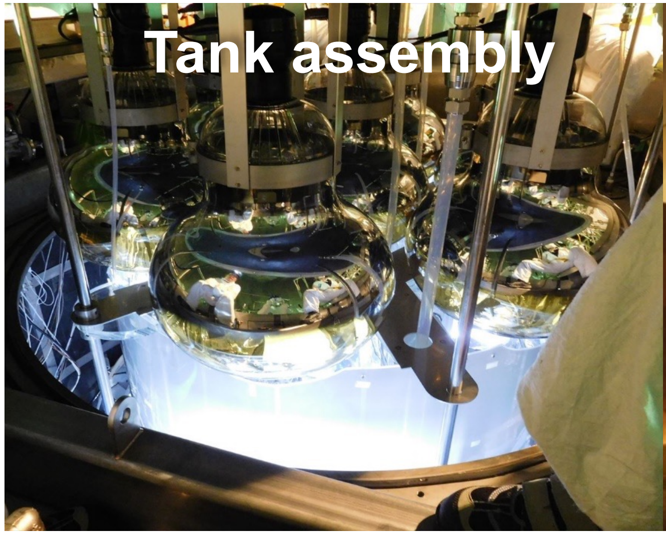
Observed spectrum with Simulated spectra before shielding



Completion of Shield Construction


Close detector after top Pb installation

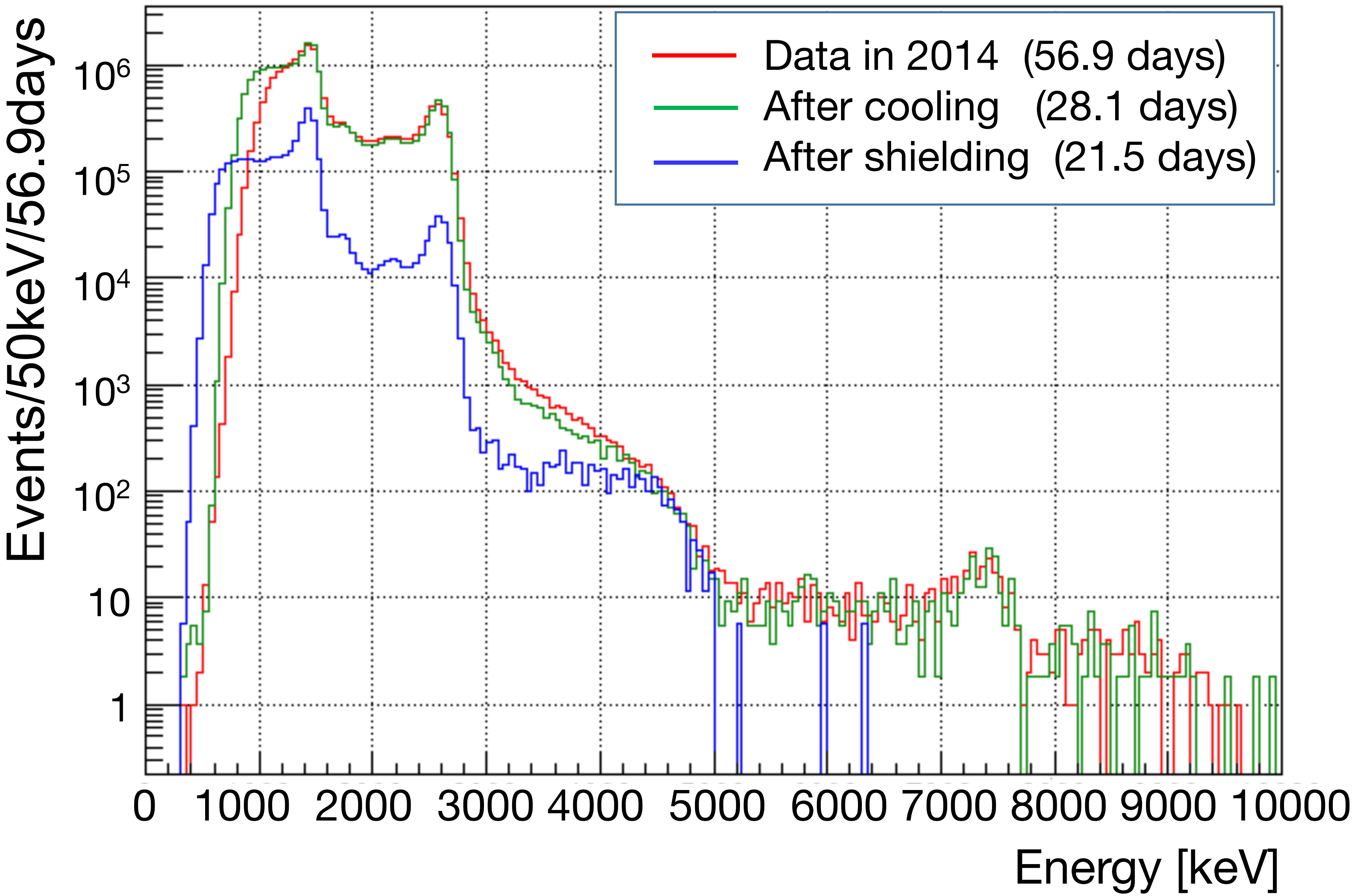

Cabling


Tank assembly


Collaboration meeting @Toyama

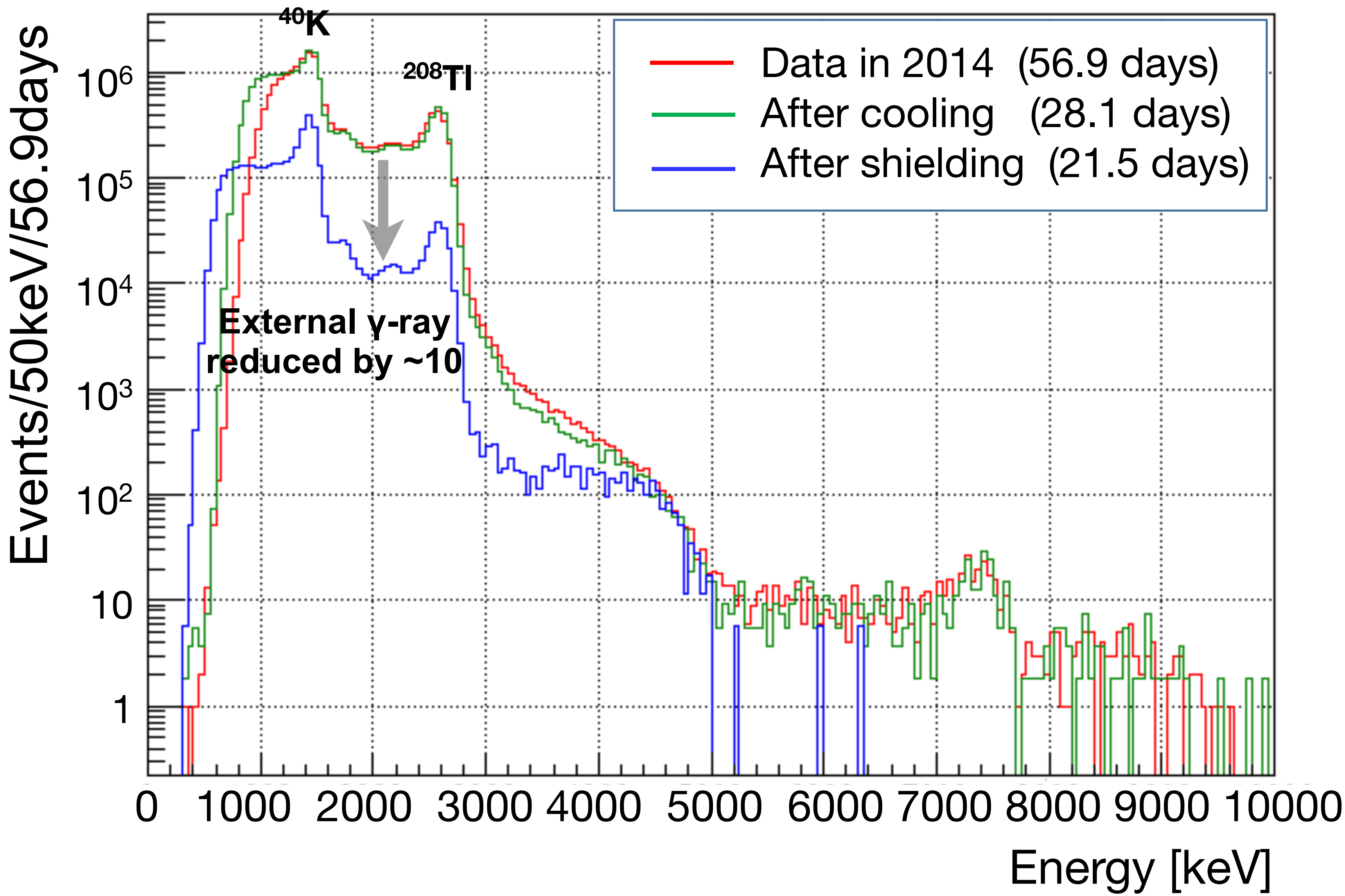
Construction finished in May 2016

Energy Spectra before/after Shielding



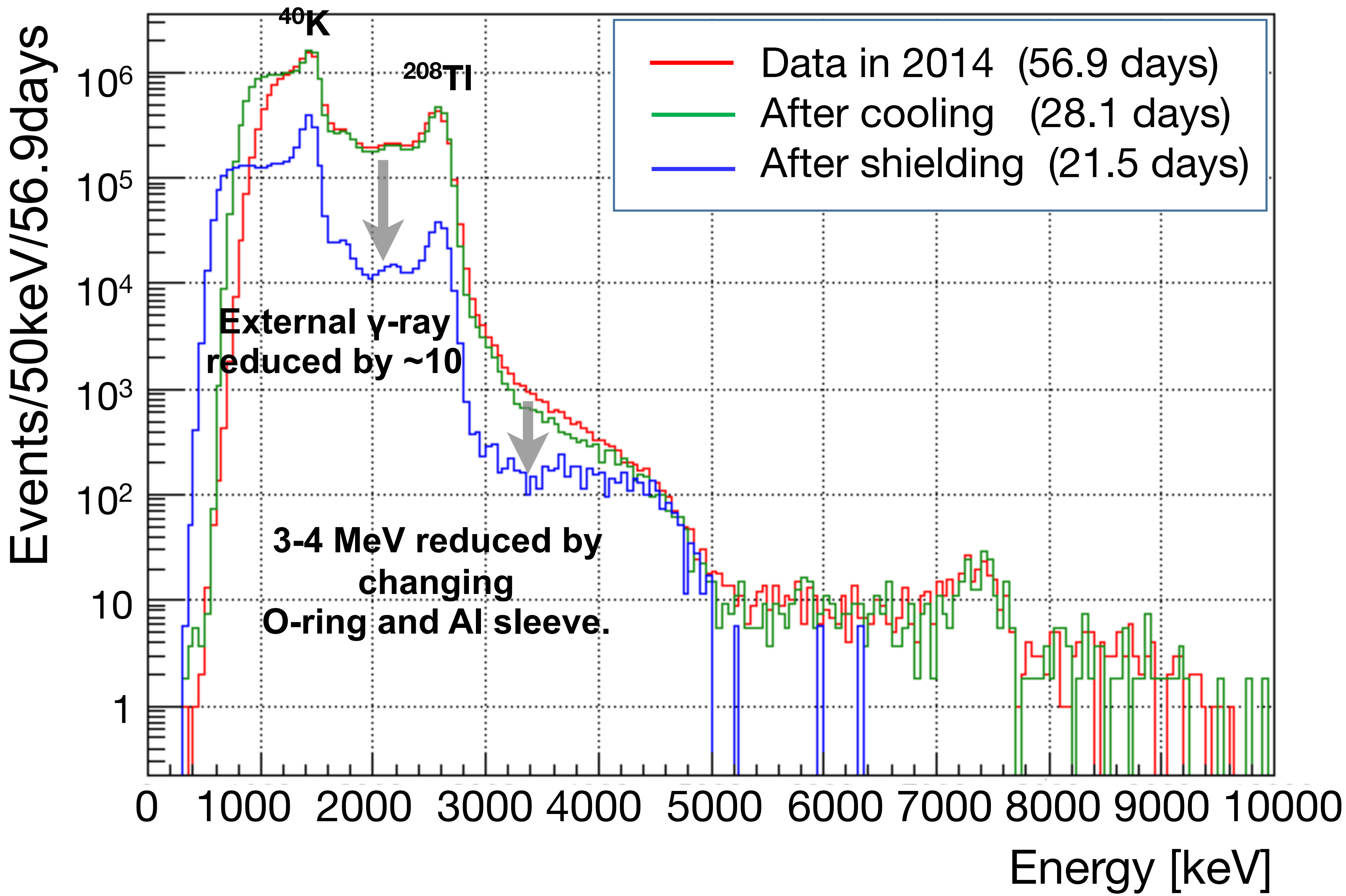
※ Apply loose LS cut (PSD but) and no ^{208}Tl veto

Energy Spectra before/after Shielding



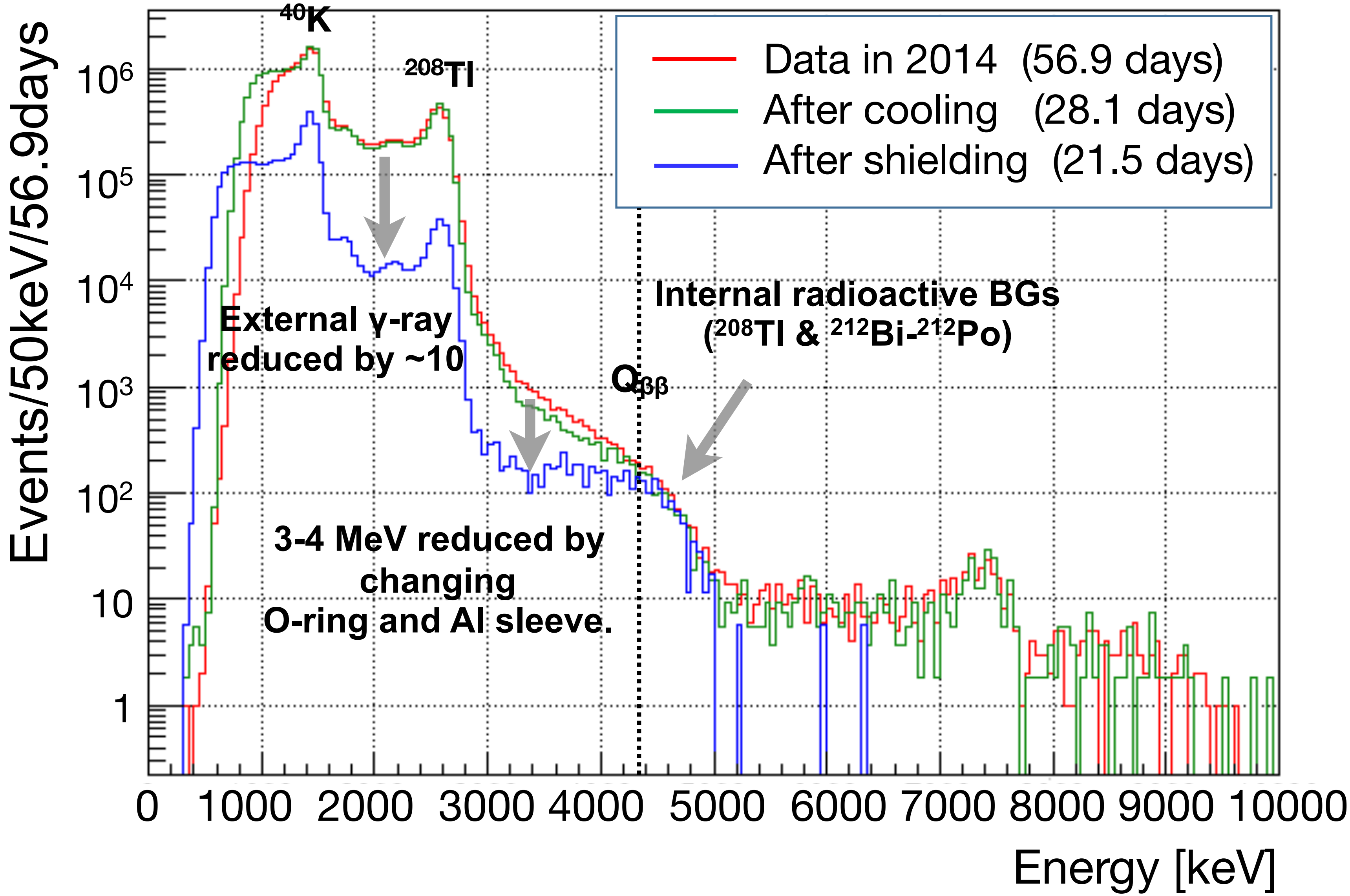
※ Apply loose LS cut (PSD but) and no ^{208}Tl veto

Energy Spectra before/after Shielding



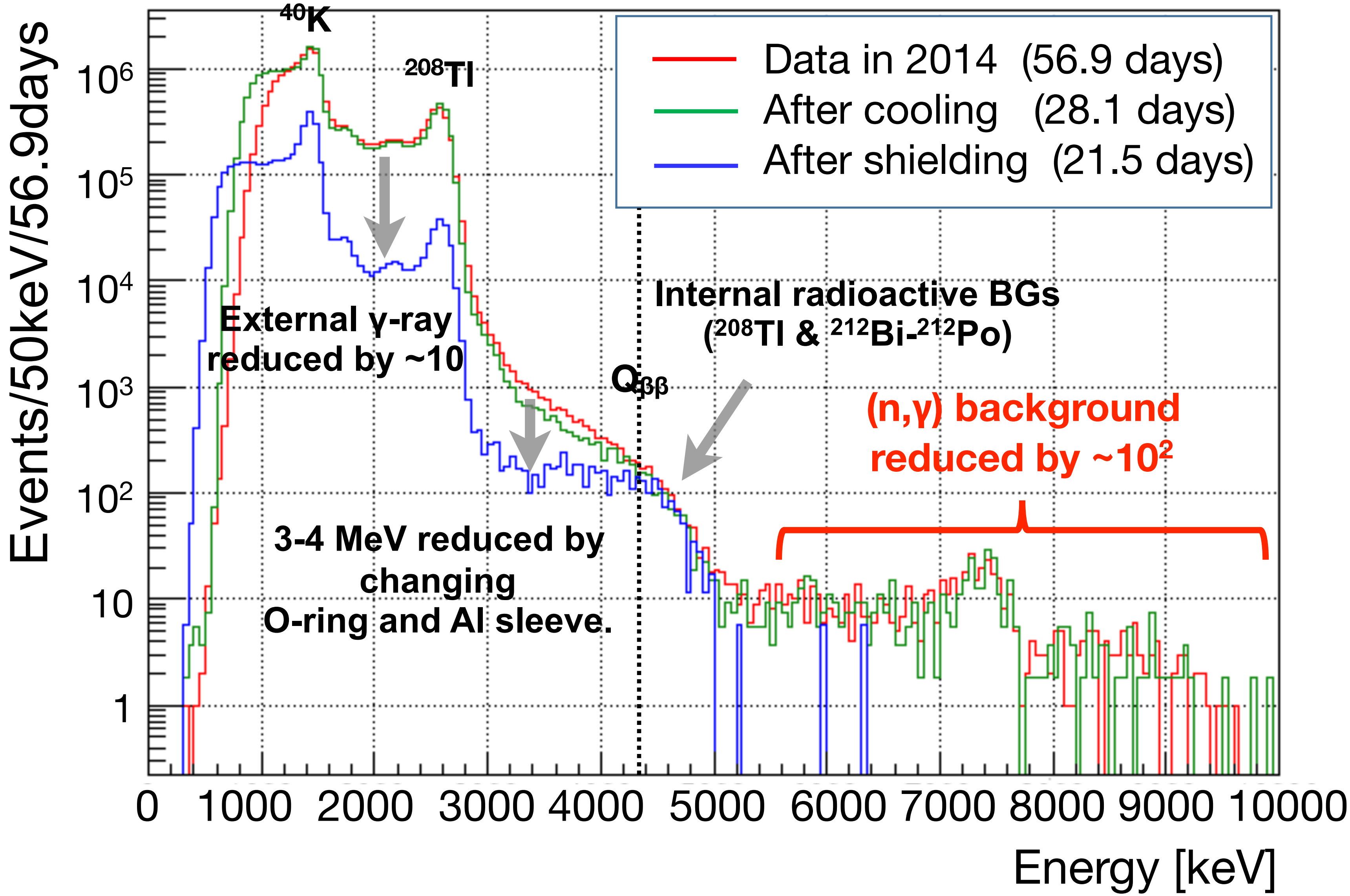
※ Apply loose LS cut (PSD but) and no ^{208}Tl veto

Energy Spectra before/after Shielding



※ Apply loose LS cut (PSD but) and no ^{208}Tl veto

Energy Spectra before/after Shielding

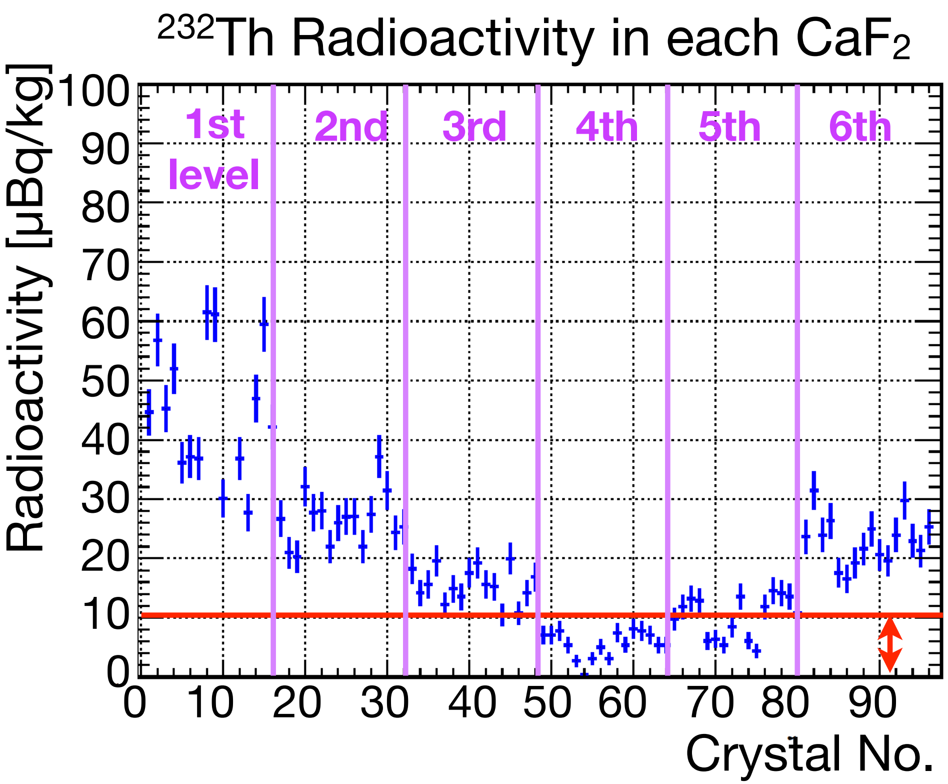


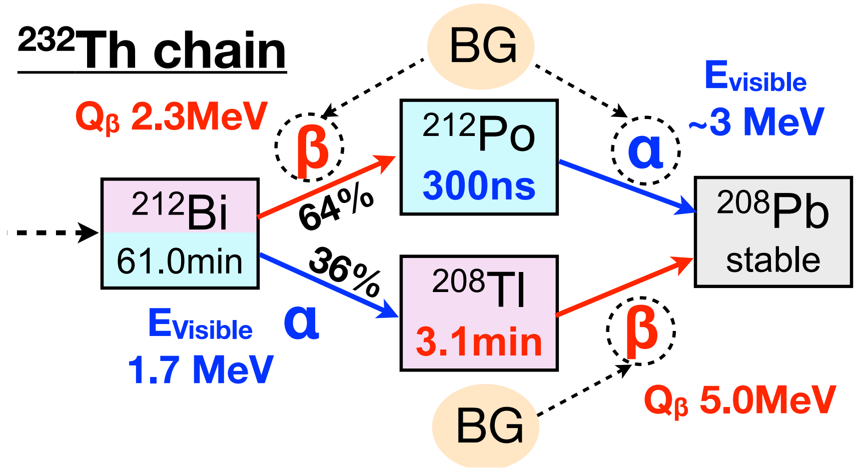
※ Apply loose LS cut (PSD but) and no ^{208}Tl veto

Remaining Backgrounds

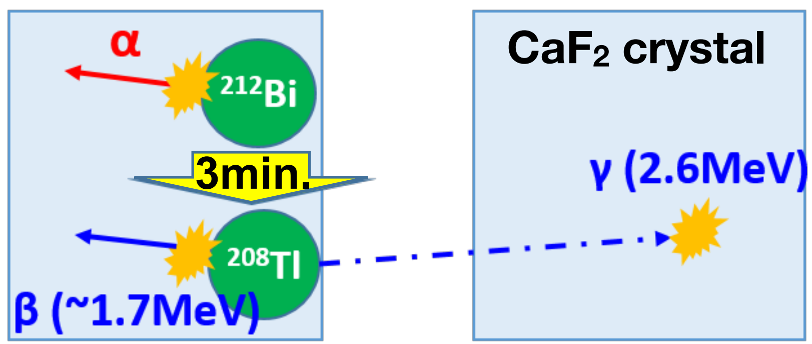
- Largest BG: ^{208}Tl from ^{232}Th chain in CaF_2
  - Reject ^{208}Tl by applying veto time after ^{212}Bi (α-rays)
    - Single crystal veto or Multi crystal veto
  - Two ways of crystal selection
    - All crystals or ^{232}Th-least 27 crystals (< 10 μBq/kg)

✓ Crystal set according to ^{232}Th radioactivity

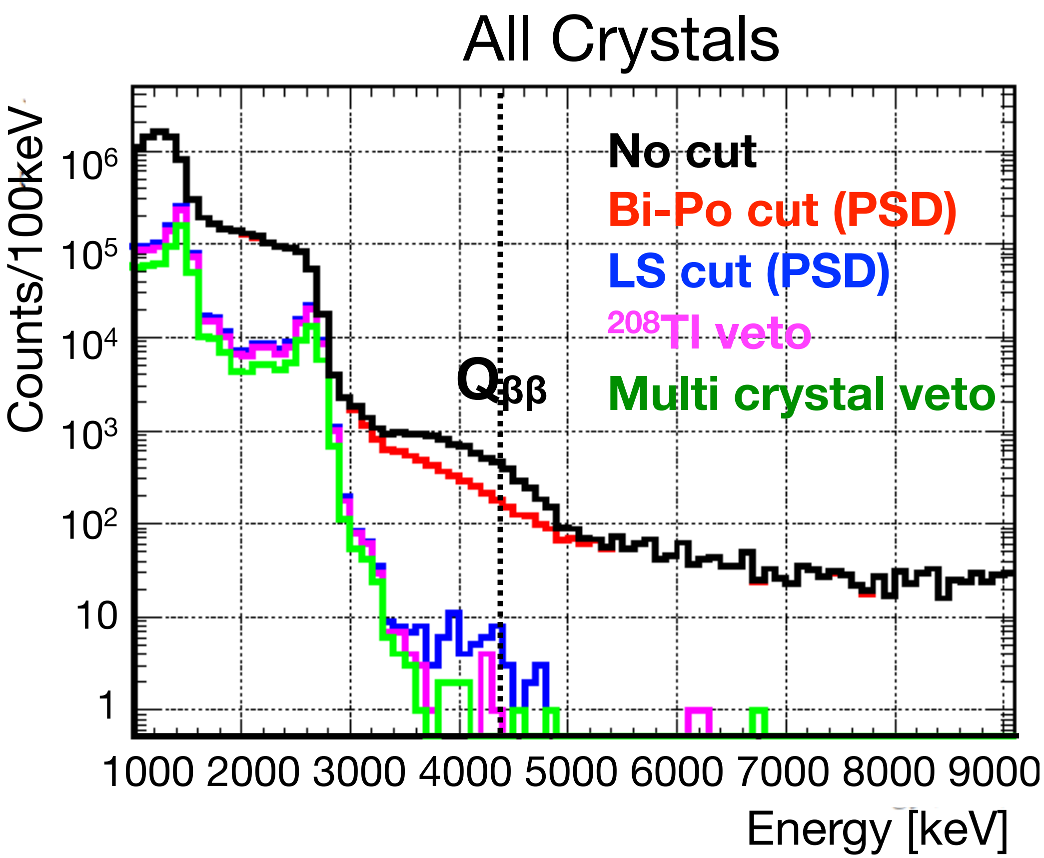


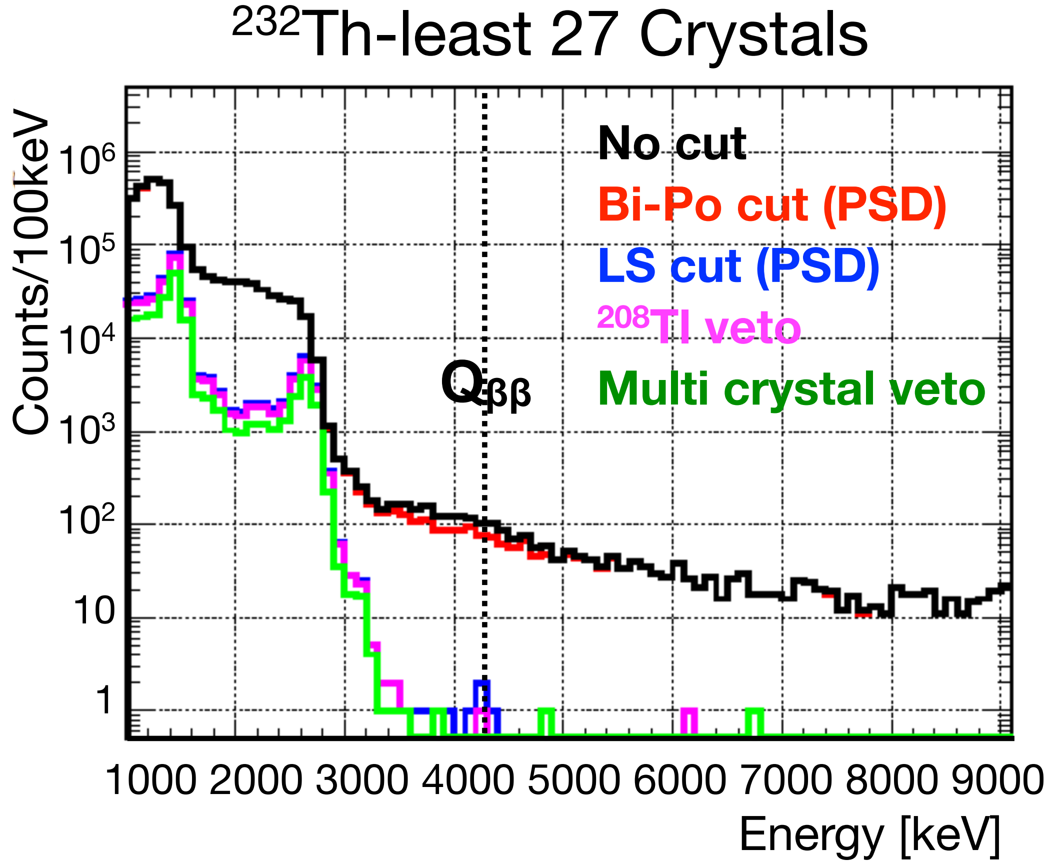


Schematic view of Multi-hit event



Energy Spectrum after Shielding (21.5 days)





	All crystals	27 crystals
Number of events	0	0
Expected ^{208}Tl	1.4	0.14
Expected (n,γ)	0.04	0.01
Signal Efficiency	0.30	0.30
Sensitivity at 1year	0.9×10^{23} year	0.5×10^{23} year

- Data set: 21.5 days
- $Q_{\beta\beta}$ $_{-1\sigma}^{+2\sigma}$: 4170-4480 keV

cf. 0.6×10^{23} year (ELEGANT VI)

Summary

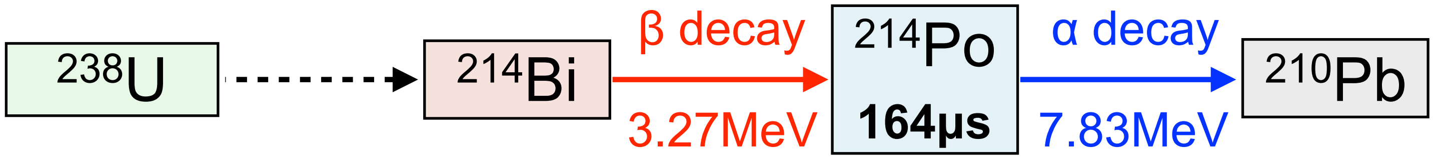
- CANDLES is a double beta decay experiment with ^{48}Ca.
  - $Q_{\beta\beta}$ = 4.27 MeV, 0.2% natural abundance
- Before shielding: largest background was γ-rays from (n,γ) reaction.
- Installed additional passive shield in 2015-2016.
  - Pb shield: 7~12 cm, B shield: ~5 mm
- After shielding: (n,γ) background reduced by ~1/100
  - Next largest background: ^{208}Tl from ^{232}Th in CaF_2
    - Further effort for analytical rejection method is necessary.
- Sensitivity at 1 year: (0.5~1) × 10^{23} year
- Analysis is going on with almost 1-year data set.

BackUp

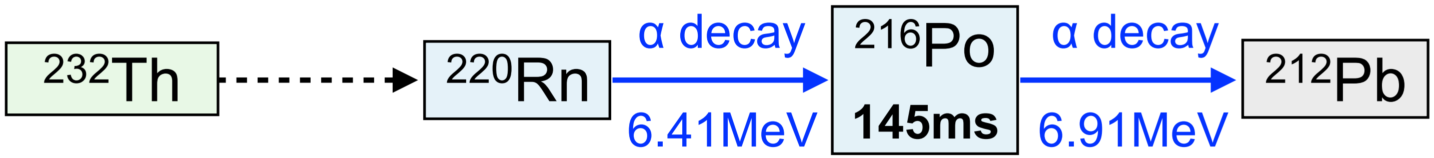
Radioactive Impurities in CaF_2

- **CANDLES developed low contaminated CaF_2 by powder selection.**
- Radioactivities in CaF_2 crystals can be measured by delayed coincidence assuming radioactive equilibrium.

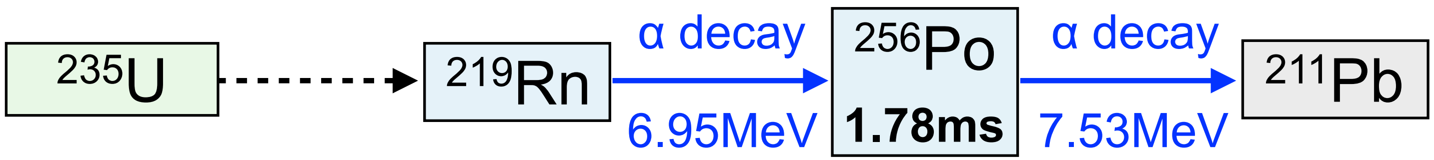
- **^{238}U: ~36 μBq/kg** (= 9.9 decays/day/crystal)



- **^{232}Th: ~21 μBq/kg** (= 5.8 decays/day/crystal) ⟵ BG



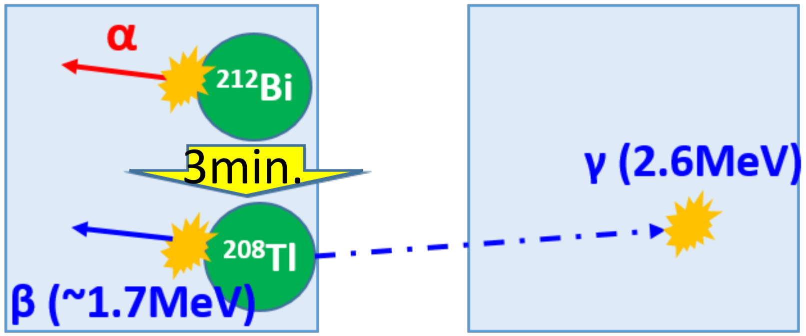
- **^{235}U: ~16 μBq/kg** (= 4.4 decays/day/crystal)



- These α-rays can be used for energy and PSD studies.
- α-ray peaks are observed around 1.5~3 MeV due to quench.

^{208}Tl Analysis (Multi crystal veto)

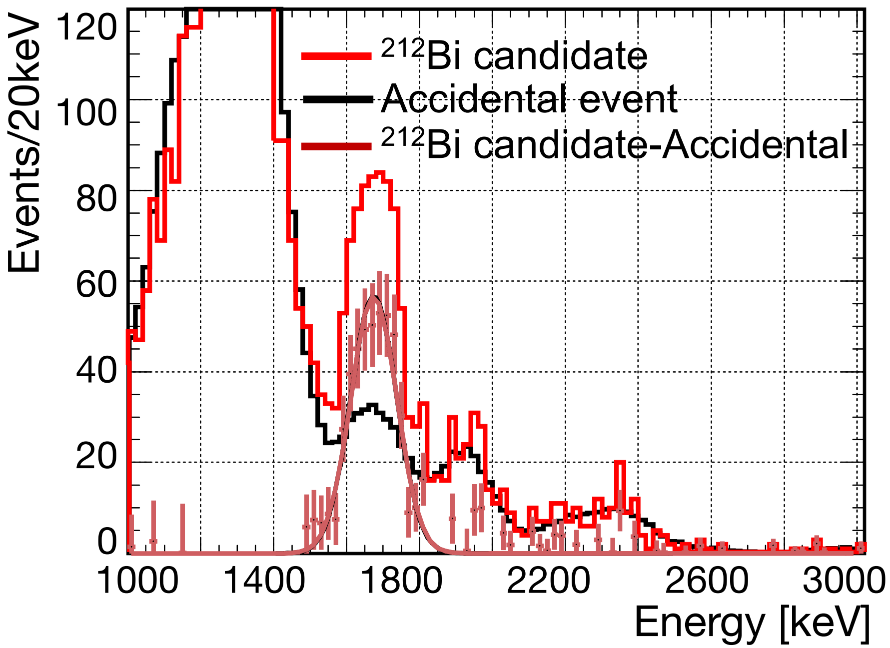
Schematic view of ^{208}Tl multi-hit event



Flow of multi-hit event

1. ^{212}Bi nucleus undergo alpha decay.
2. After ~3min, ^{208}Tl undergo β+γ decay.
3. γ-ray goes outside and is detected in different crystal.
4. In this case, α and β are reconstructed in different crystal due to deposit energy.

^{212}Bi Spectrum (prompt signals in ^{212}Bi-^{208}Tl coincidence)

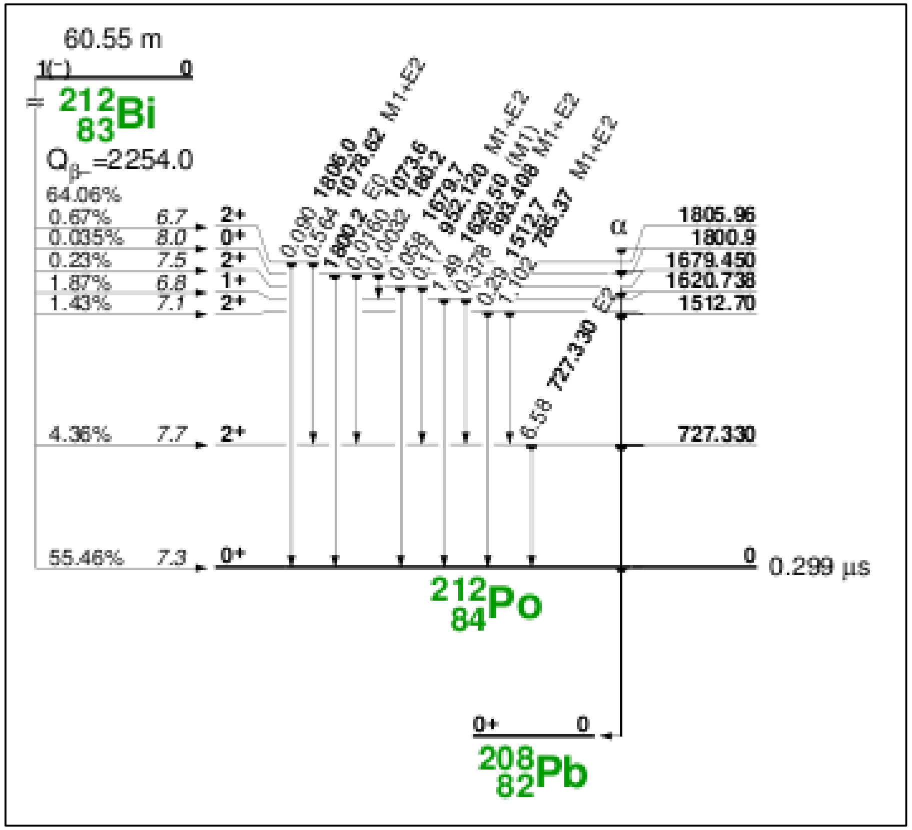


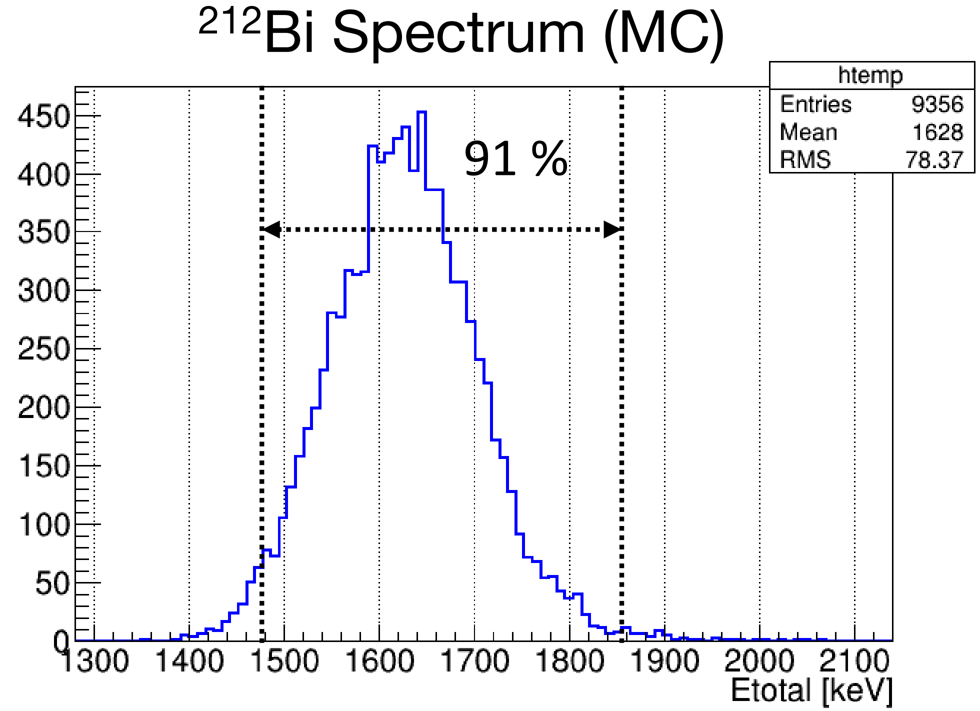
- Better to apply veto time for neighboring crystals (**Multi crystal veto**)

  → Worse signal efficiency due to many accidentals

  - Accidental rate reduced after shielding
- We are studying and improving cut method.

^{208}Tl Analysis

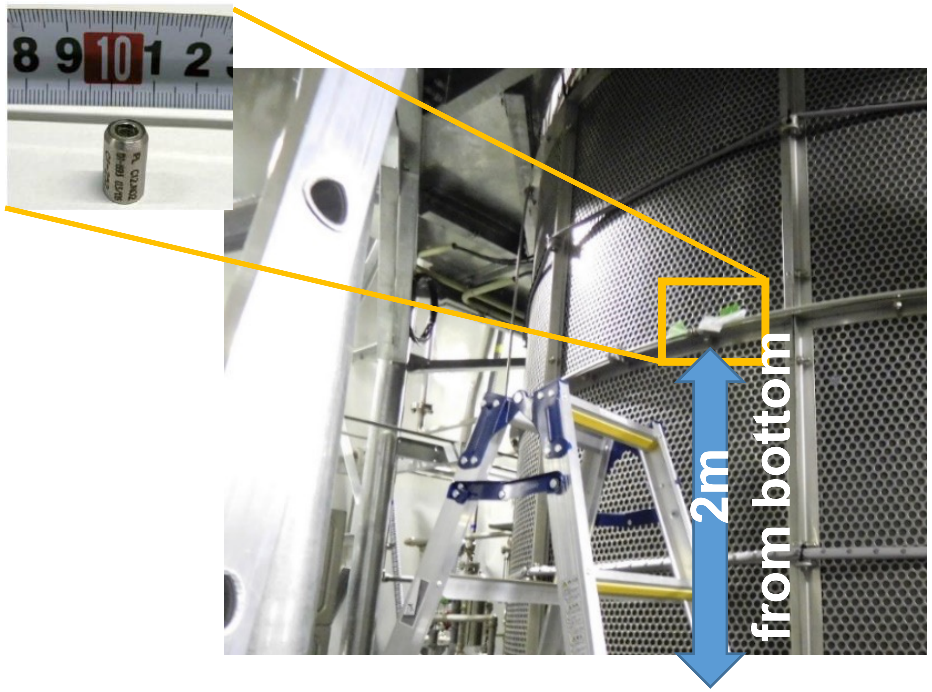




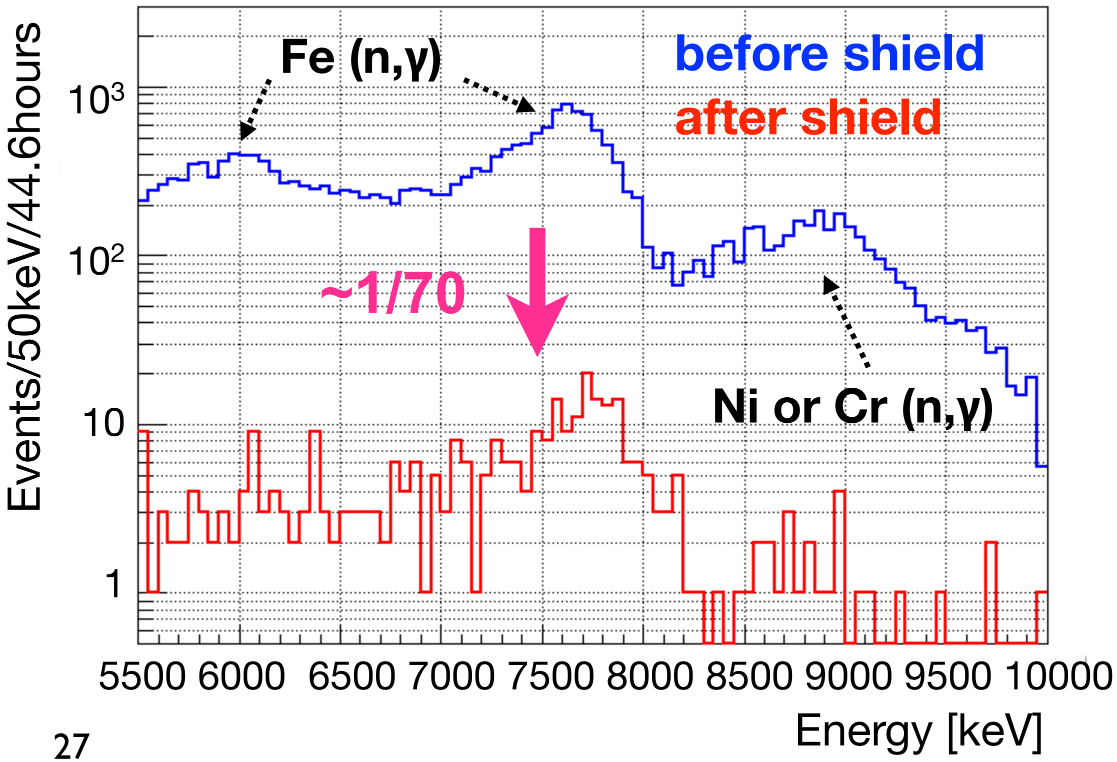
	Cut condition	Eff.	Rejection Eff (only single hit event)
208Tl veto	Energy + Crystal cut	91%	~ 87%
	Alpha selection (PSD)	98%	
	Veto time (18 min)	98%	

(n,γ) Background after Shielding

- Take data with neutron source (^{252}Cf) again
- Reduction of (n,γ) background: ~1/70
  - Similar to the MC expectation
  - Since reduction for fast neutron is worse than for thermal neutron, reduction factor is not exactly same as expected.



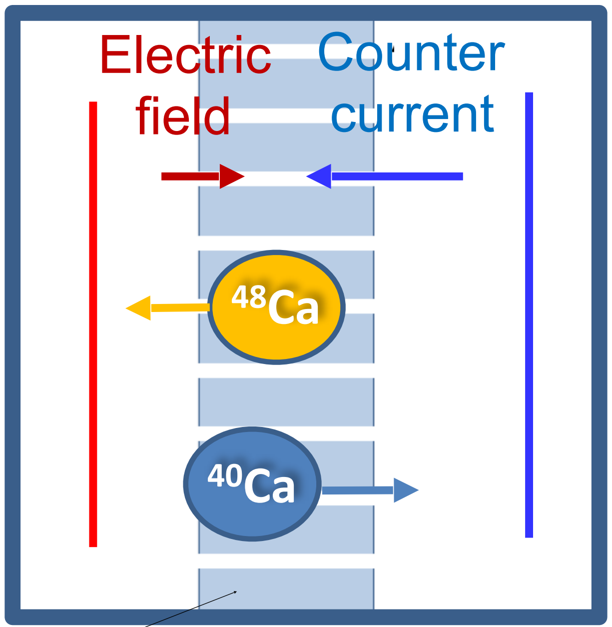
Observed Spectrum in Neutron Source Run



^{48}Ca Enrichment

- Natural abundance of ^{48}Ca is 0.187%.
- Commercial ^{48}Ca is too expensive (M$/10g but kg-ton)
- Developing enrich technique of ^{48}Ca is crucial for large volume DBD search.
- Challenges in CANDLES:
  - Crown ether resin + chromatography (Osaka, TIT…)
    - 1.3 times and cost down → *Journal of Chromatography A Volume 1415, 9 October 2015, Pages 67*
  - Crown ether + micro reactor (Osaka sangyo)
  - Laser separation (Fukui)
    - Good separation but smaller productivity
  - Multi-channel counter current electrophoresis (Osaka)

Multi-channel counter current electrophoresis



BN plate 10 mm thick
0.8mmΦ, every 4 mm

- Separation using difference of migration speed between ^{40}Ca / ^{48}Ca.
- Principle was demonstrated.
- Further study on parameter optimization

High enrichment
Large amount

$$R(MCCCE) = \frac{43Ca/48Ca(MCCCE)}{43Ca/48Ca(natural)}$$

Enrichment
(43/40): 3.08
(48/40): 6

PTEP
Prog. Theor. Exp. Phys. **2015**, 033D03 (10 pages)
DOI: 10.1093/ptep/ptv020

Calcium isotope enrichment by means of multi-channel counter-current electrophoresis for the study of particle and nuclear physics

T. Kishimoto[1,2,*], K. Matsuoka[2], T. Fukumoto[3], and S. Umehara[2]