Low background DBD search in CANDLES

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for the CANDLES collaboration

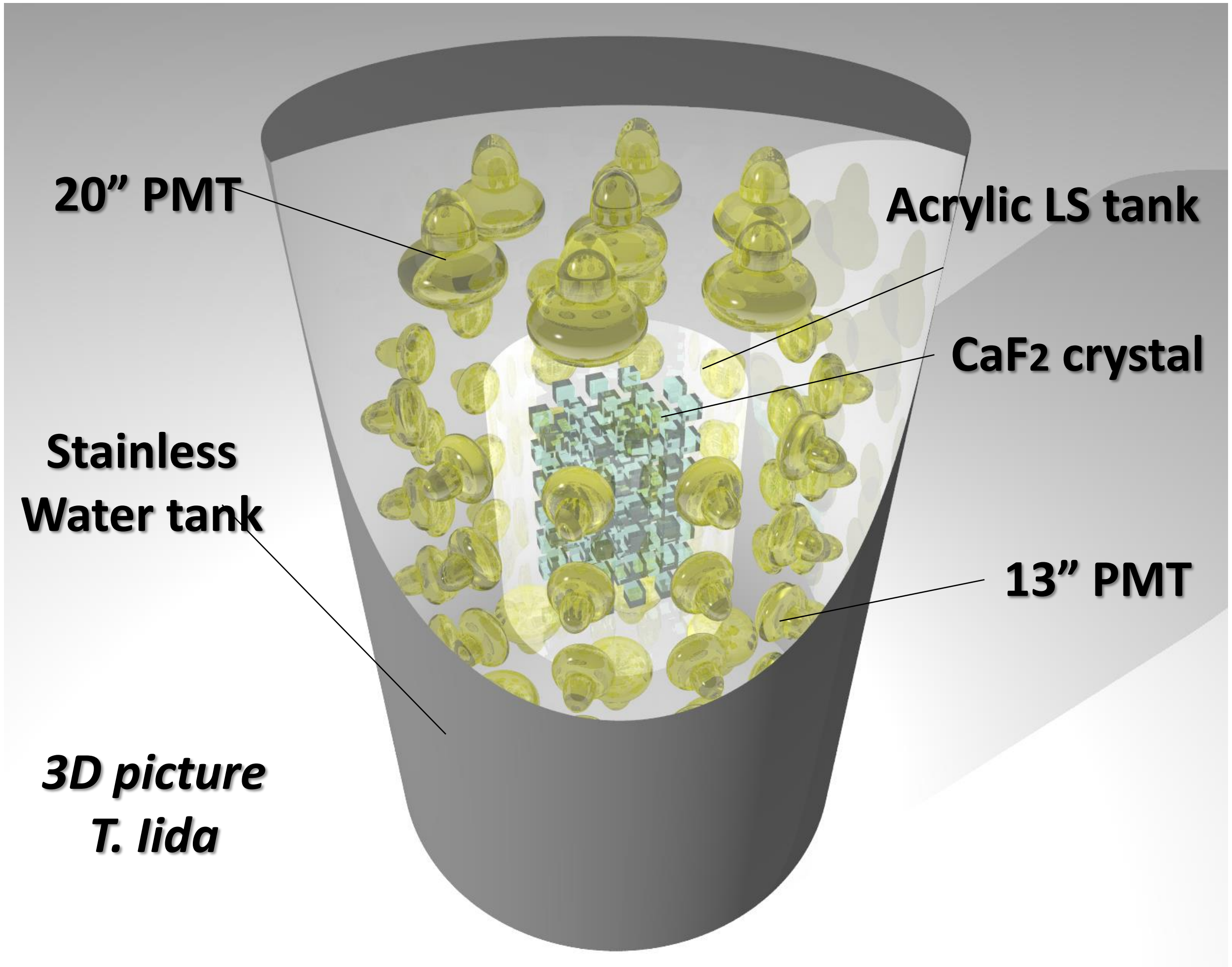
2016 Nov. 8th
DBD16 @Osaka University

Outline

- The CANDLES experiment
- Progress from the last DBD
- Background and its reduction
- Sensitivity for $0\nu\beta\beta$
- Future R&D
- Summary

Welcome to Osaka!

The CANDLES experiment



Collaborating Institutions

大阪大学 OSAKA UNIVERSITY
RCNP 大阪大学 核物理研究センター
国立大学法人 福井大学 UNIVERSITY OF FUKUI
徳 島 大 学 The University of Tokushima
大阪産業大学 OSAKA SANGYO UNIVERSITY
SAGA UNIVERSITY 国立大学法人 佐賀大学

CAlcium fluoride for studies of **N**eutrino and **D**ark matters by **L**ow **E**nergy **S**pectrometer

Double beta decay sensitivity

○KamLAND

$0\nu\beta\beta$ search with ^{136}Xe

World best limit on $0\nu\beta\beta$

$T_{1/2} > 1.1 \times 10^{26}$ [year]

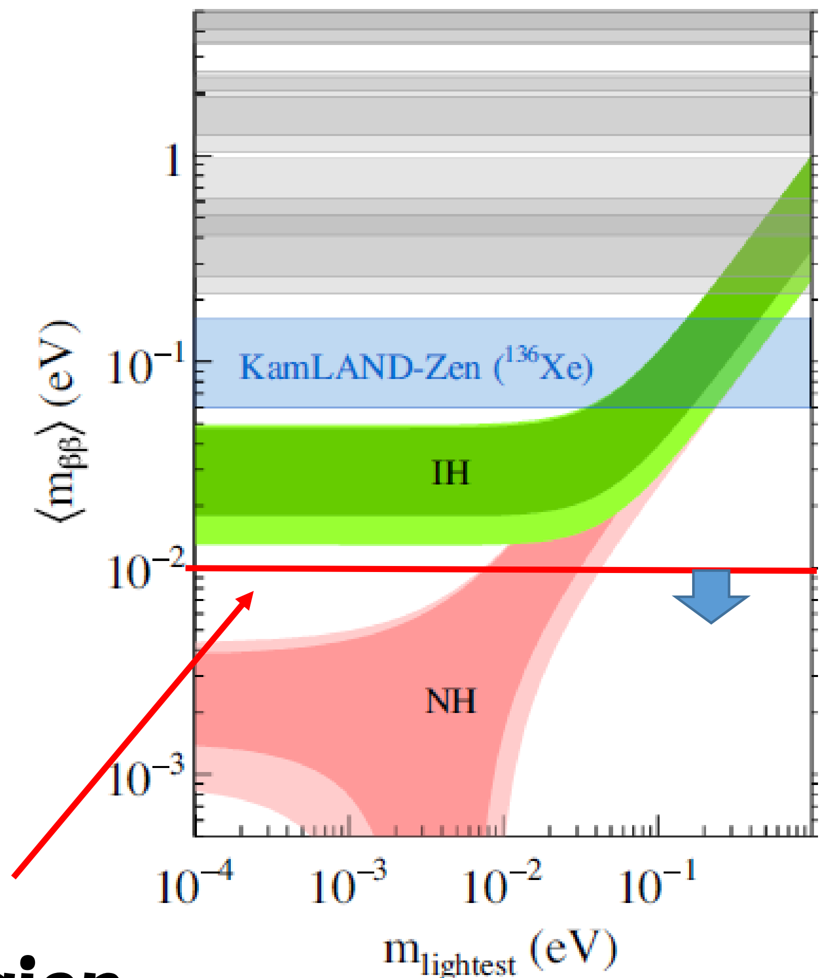
→ $m_{\beta\beta} < 61 - 165$ meV

○CANDLES

$0\nu\beta\beta$ search with ^{48}Ca

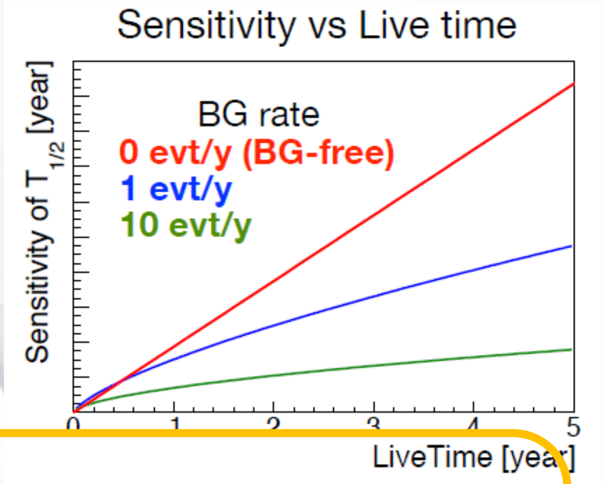
Current sensitivity on $0\nu\beta\beta$

$T_{1/2} \sim 10^{22}$ [year]



Aim for below IH region by making a breakthrough in future!!

What's breakthrough?



Since $0\nu\beta\beta$ is very rare signal, we need to achieve stringent conditions.

- **Low background level**

  Q-value of ^{48}Ca (4.27MeV) is highest among all the $0\nu\beta\beta$ candidates and therefore low background (BG) level is naturally possible.
  In addition, active veto by LS and additional shield can reduce more BGs.

- **Good energy resolution**

  Mainly focus on BG today!!

  For separating $0\nu\beta\beta$ and $2\nu\beta\beta$.
  Current energy resolution is $\sigma\sim2\%$ @4.27MeV.
  Plan to develop "CaF2 Bolometer" ($\sigma\sim0.3\%$) for future.

- **Large volume**

  Natural abundance of ^{48}Ca is 0.2%.
  Developing "^{48}Ca enrichment technique".
  Now we've achieved enrichment with factor of 6 by MCCCE※ method.

※ T. Kishimoto et al., Prog. Theor. Exp. Phys. 033D03 (2015)

The CANDLES-III (U.G.) detector

Experiment is located in Kamioka, Japan.

- **CaF_2 (pure) scintillator （τ ～1μsec）**

  10×10×10 cm^3×96 crystals（300 kg）
- **2m^3 Liquid scintillator（τ ～10nsec）**

Active veto using different time constant!!

- **Cylindrical water tank (φ3m×h4m)**
- **62 Photomultipliers（PMT）**

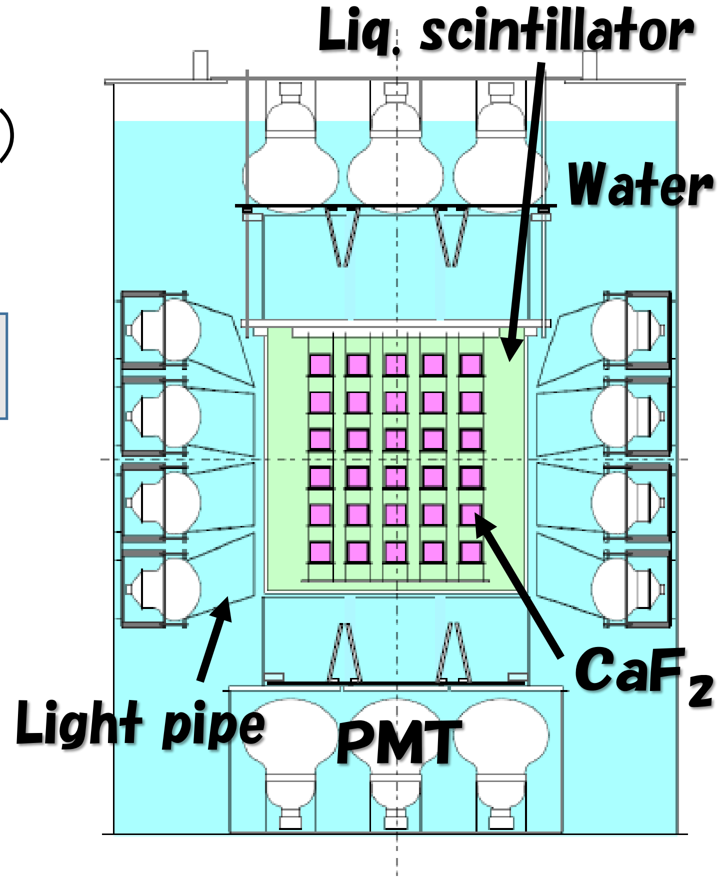
  13 inch PMT（R8055） ×48

  20 inch PMT（R7250） ×14

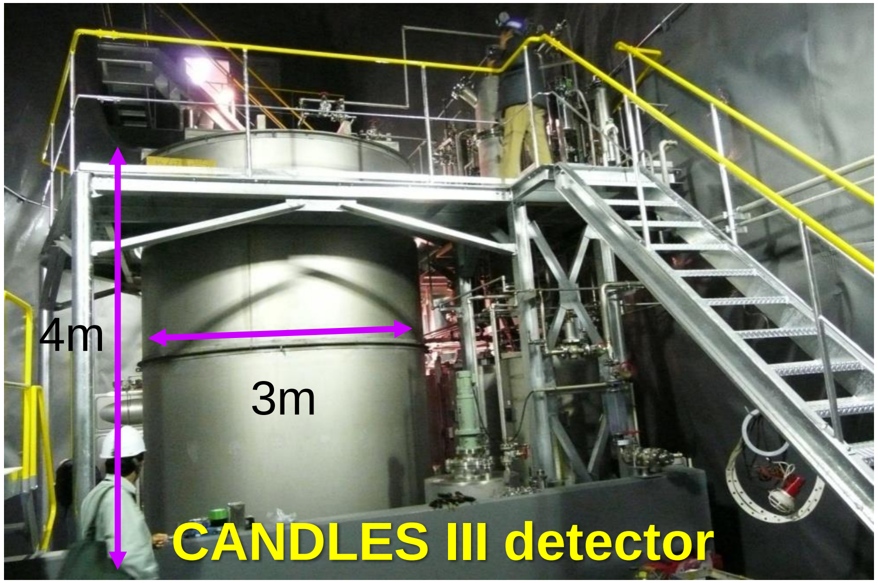
- **Light collection system**

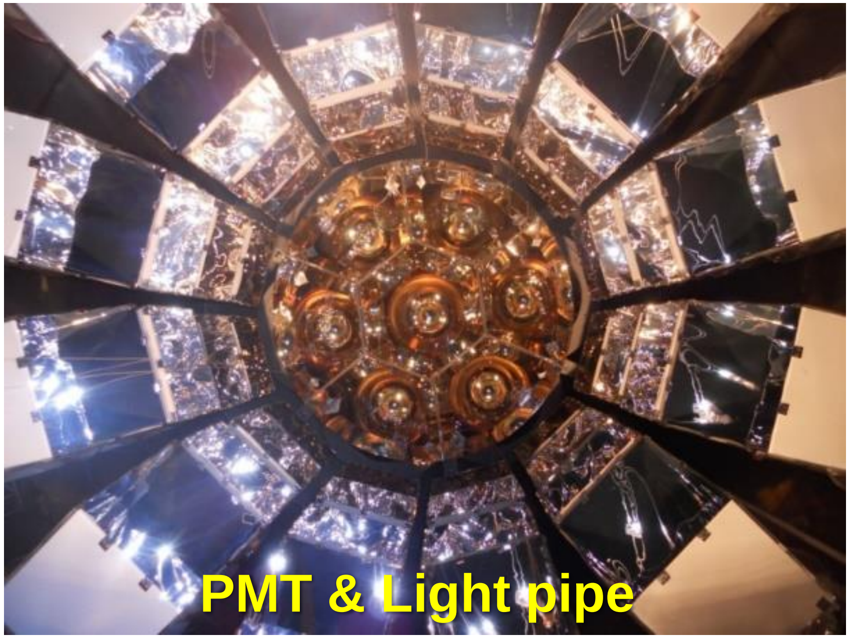
  Al sheet：Reflectance *~93% @ 420nm*

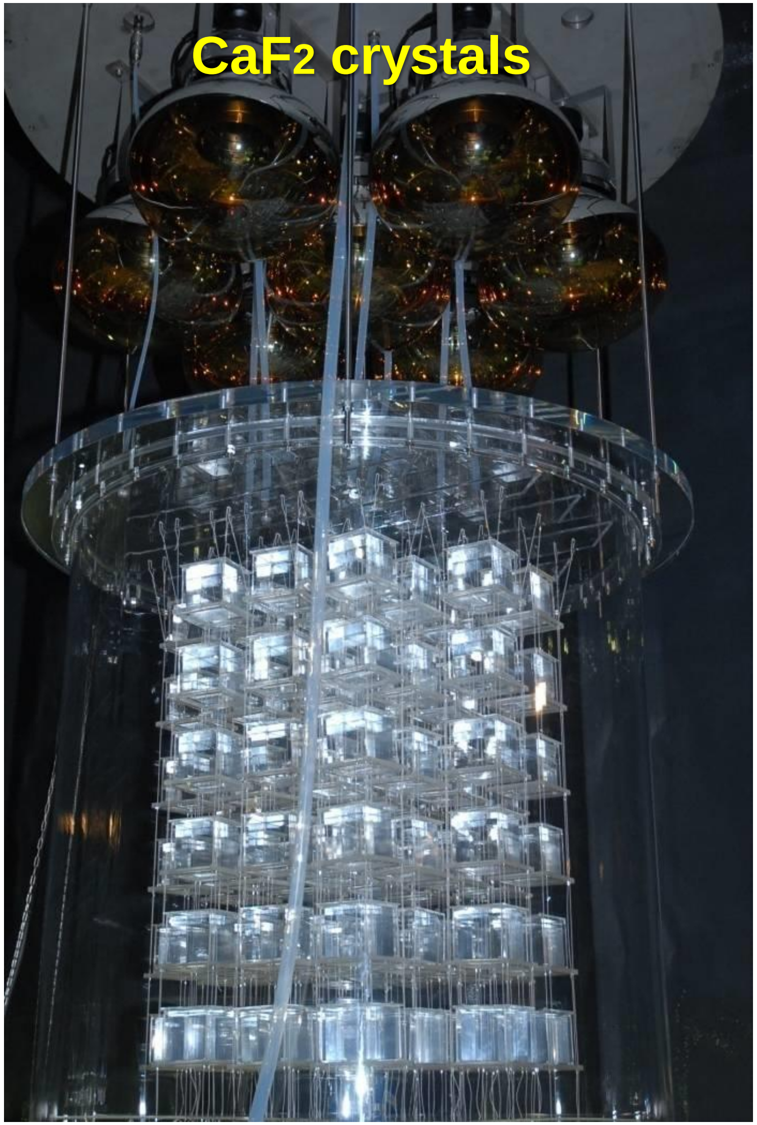
○Schematic view



The CANDLES (U.G) detector in Kamioka observatory





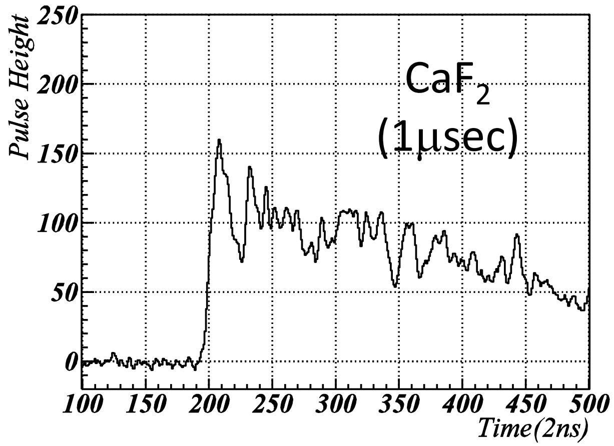


4π active veto by Liquid scintillator (LS)

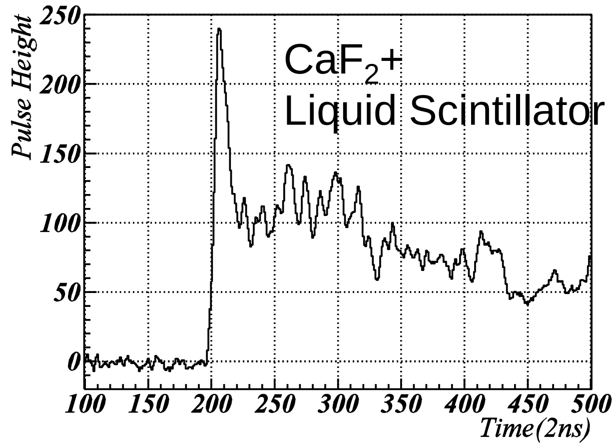
- Rejection of external γ–ray background

- Pulse shape information by 500 MHz Flash ADC.
- Distinguish event type by offline pulse shape analysis taking advantage of different decay time.
- Detail of analysis method is explained later.

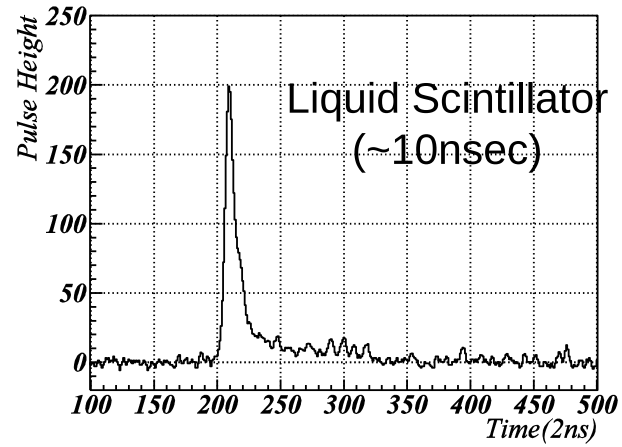
ββ signal !?

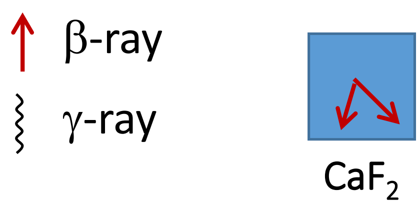


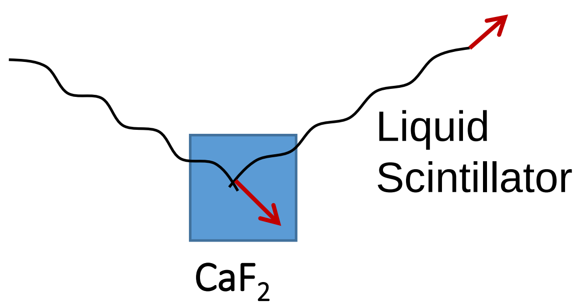
External γ BG

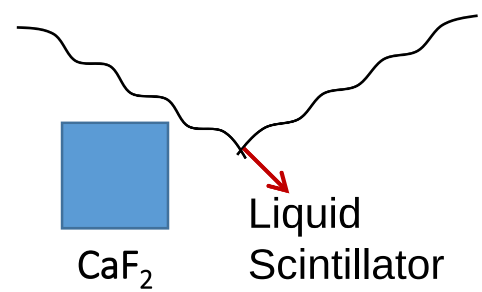


External γ BG

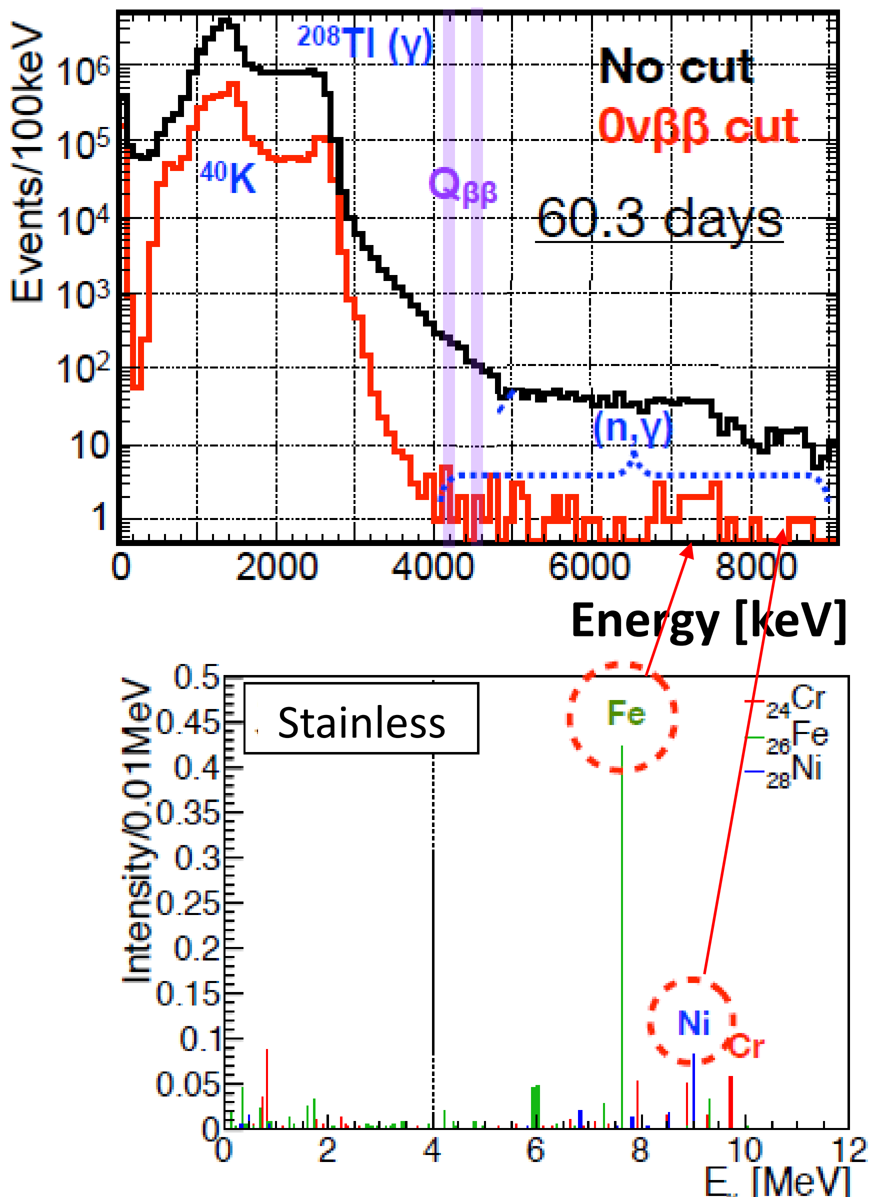






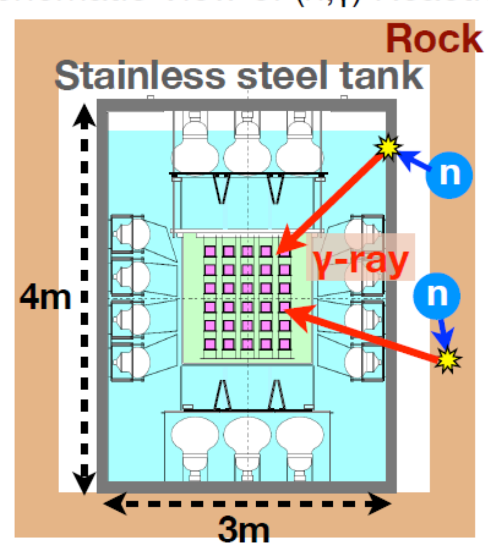


Background spectrum in CANDLES



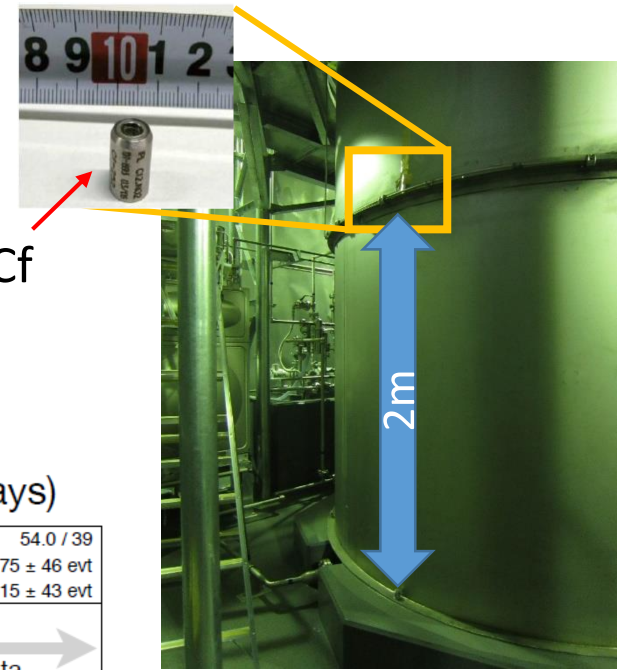
- Even after LS cut, there exist background in high energy region above 4MeV.
- BG spectrum has peak around 7.5MeV.
- This BGs seem to be produced from neutron capture on surrounding material → (n,γ).

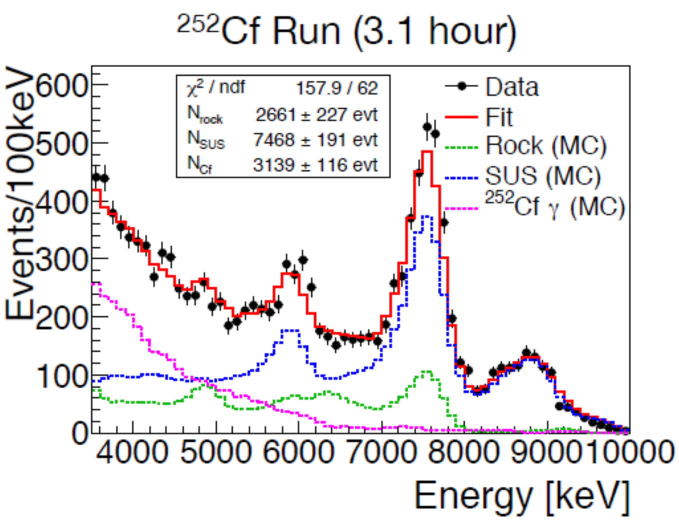
Schematic View of (n,γ) Reaction

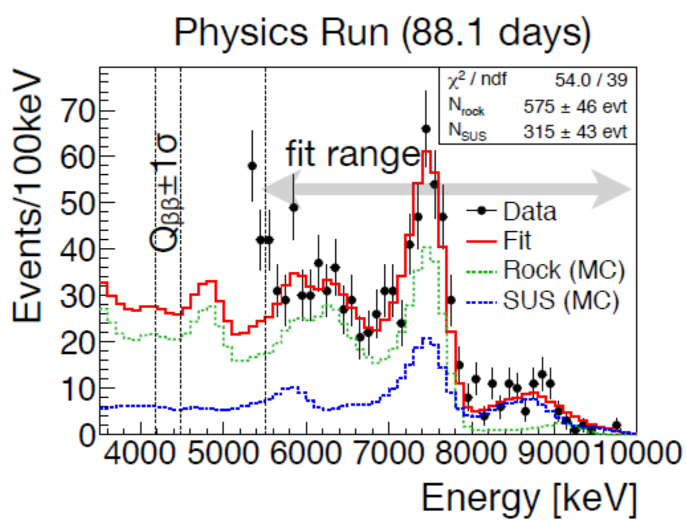


Neutron source run

- In order to confirm that our assumption is correct, ^{252}Cf neutron source was set on the detector and data was taken in 2014.





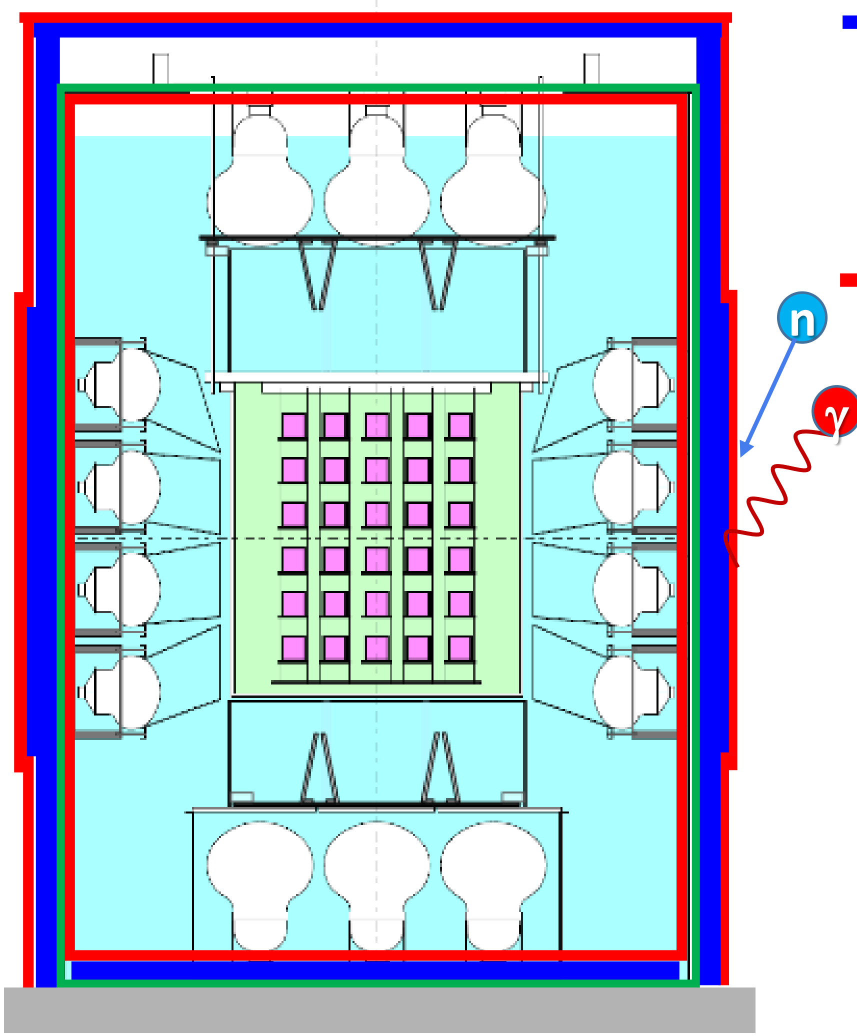


- Spectra for neutron source run and physics run are consistent.
- MC simulation of (n,γ) can well reproduce the BG spectrum.

We identified main BG as (n,γ) !!

Shield for (n,γ) background reduction

CANDLES shield overview



CANDLES tank

Pb shield (7-12cm)

Reduce γ-ray from surrounding rock
Effect of Pb (n,γ) is one order smaller than that of stainless tank

Boron sheet (4-5mm)

Reduce n captured by stainless tank

- (n,γ) BGs in CANDLES is expected to become **1/80** by MC.
- Expected number of backgrounds after shield installation:

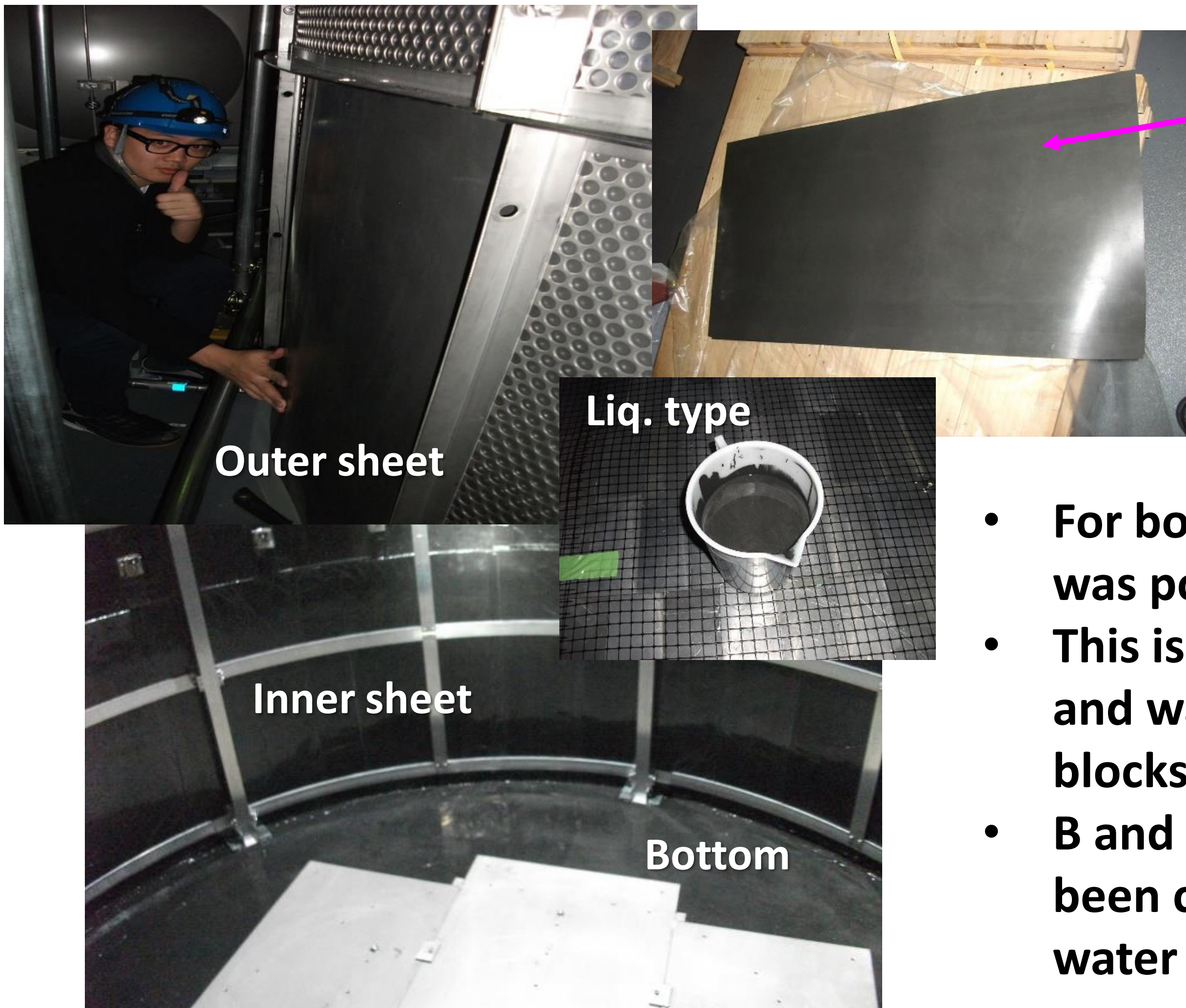
  Rock : 0.34±0.14 event/year
  Tank : 0.4±0.2 event/year

Pb shield construction

- **Pb shield construction was started from March 2015.**
- **All the collaborators worked very hard!**
  I used even professors like a horse ;)

B shield construction

- **Neutron shield (B sheet) installation.**



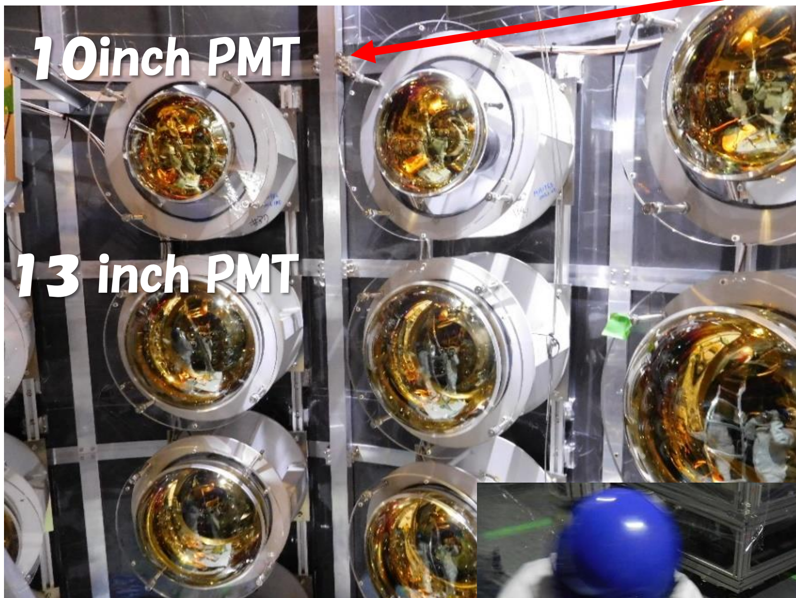
B_4C 40wt%
Silicone rubber
(*B sheet*)

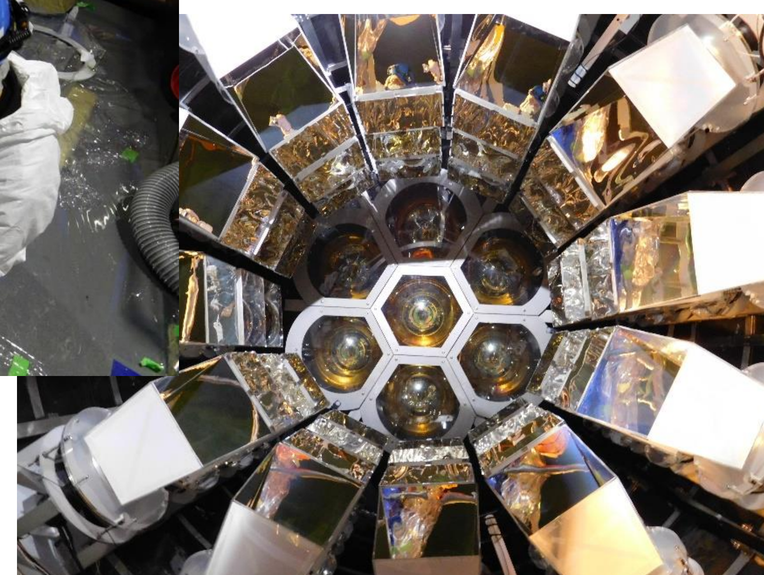
4-5mm thickness.
Covered 100m^2 area

- **For bottom B shield, liquid type was poured on top of the Pb.**
- **This is for both shielding neutron and waterproofing the bottom Pb blocks.**
- **B and Pb elution into water have been checked periodically after water filling.**

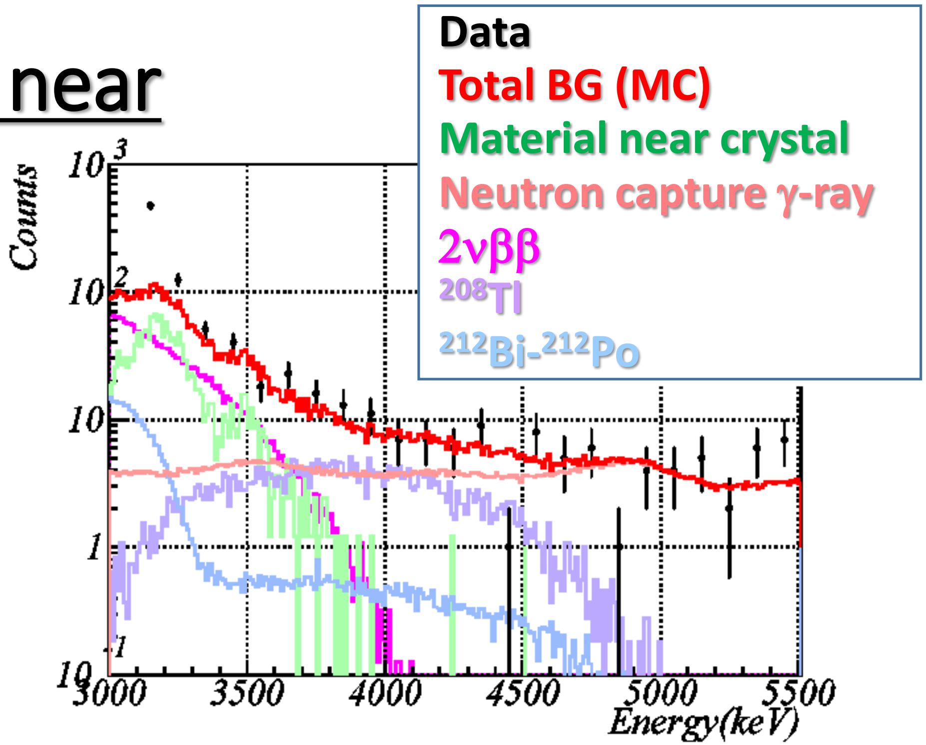
PMT reinstallation

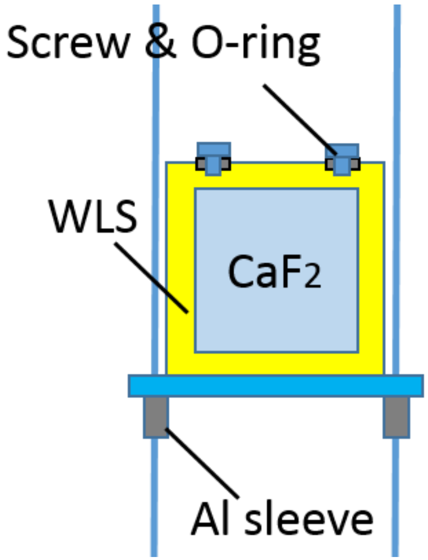
Fast time response.
Twelve 10inch PMTs are installed for performance study.



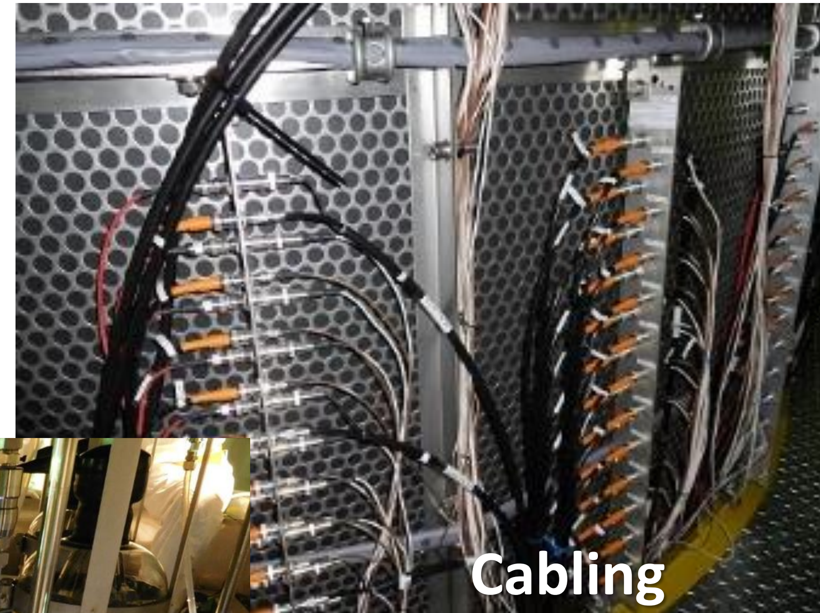


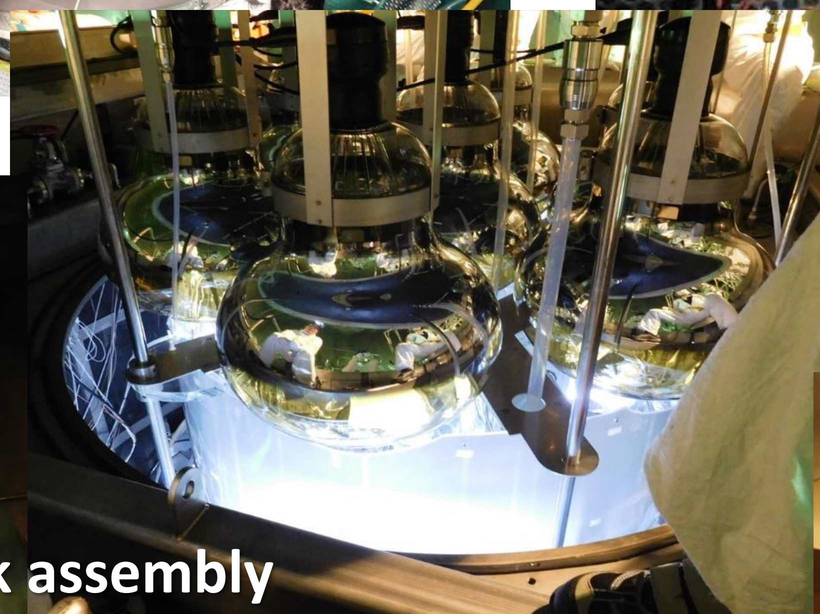
Material change near CaF2 crystal

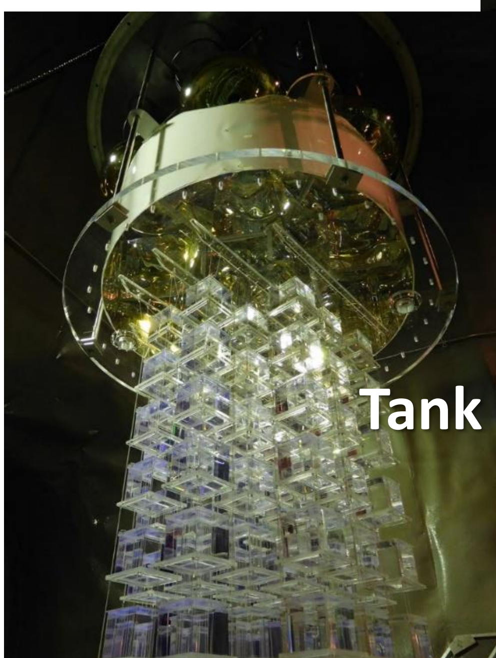




- Radioactivity measurement with Ge detector indicated that “Al sleeve” and “O-ring” are dirty.
- We replaced them with new ones which are expected to be cleaner during shield construction.
- BG in 3 – 3.5 MeV is expected to decrease about less than half.



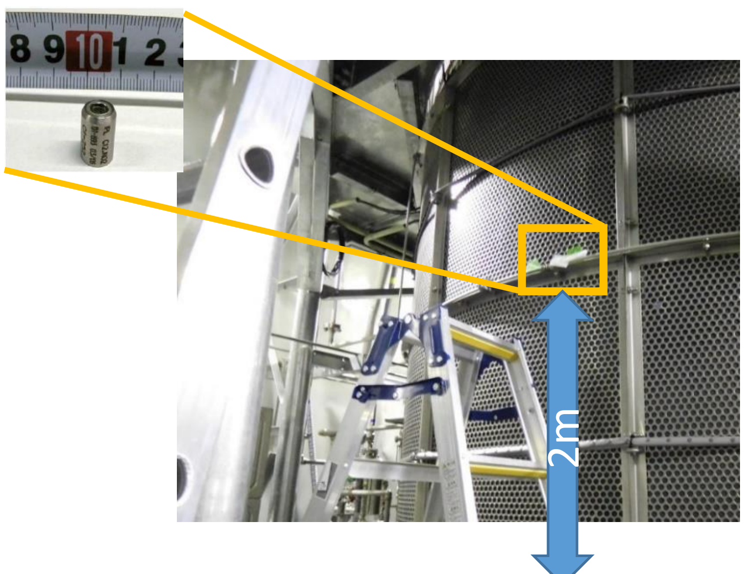


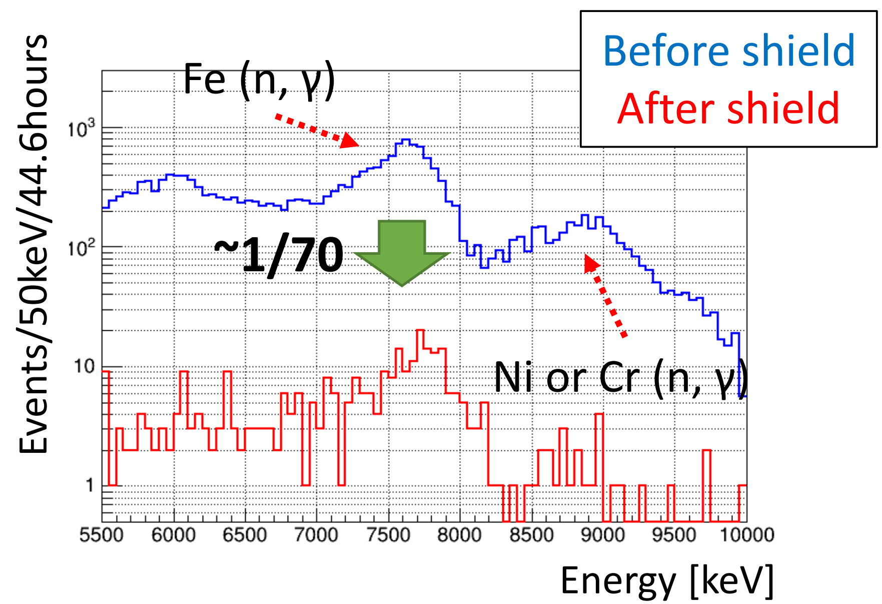


Construction finished in May 2016 !!

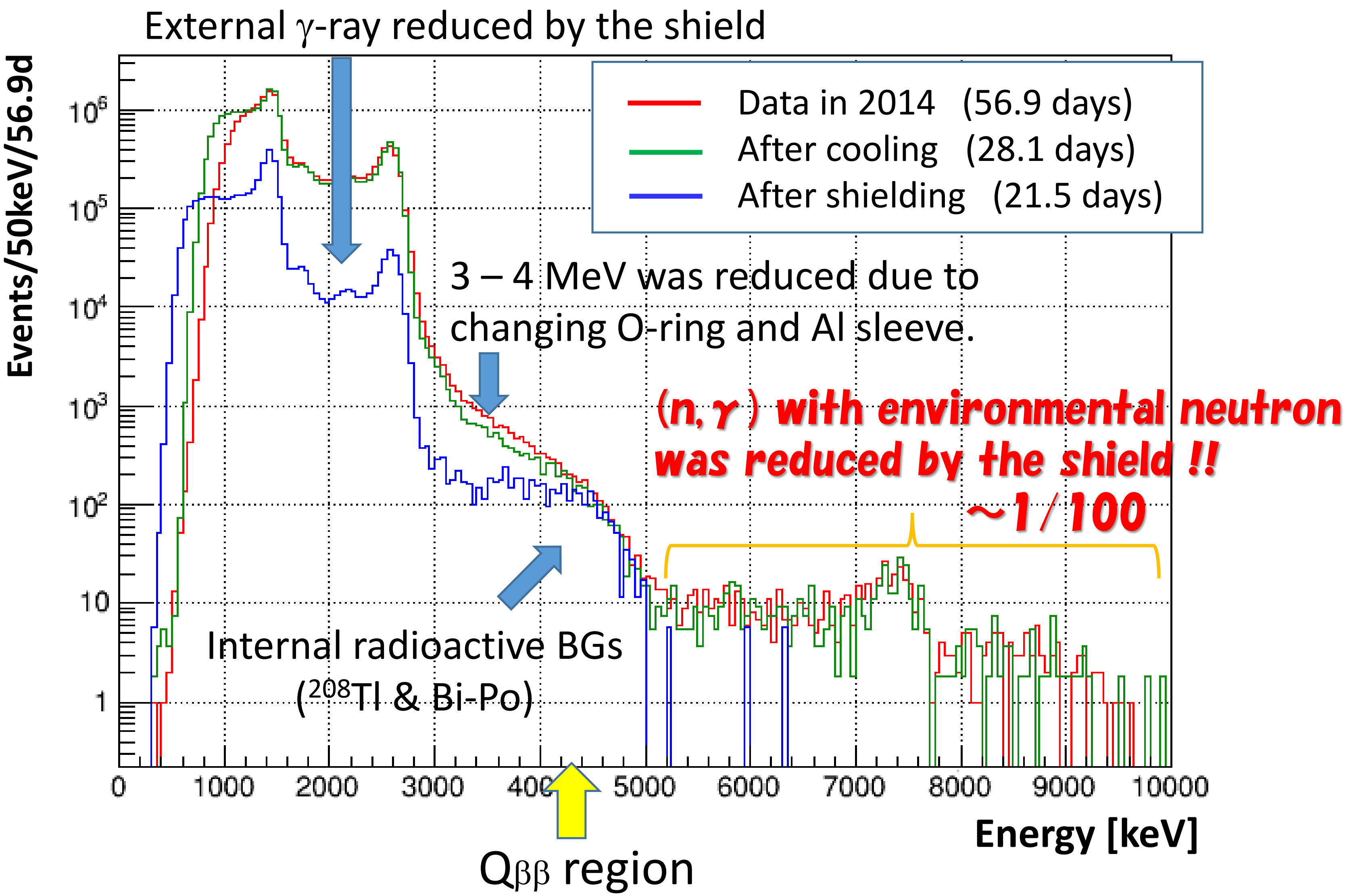
Neutron source run again!

- New ^{252}Cf source data was taken in June 7th – 14th in order to check performance of the shield with same setup.
- To compare with high statistics, loose LS cut was applied.
- (n,γ) with ^{252}Cf was decreased by ~1/70!!
- This reduction is similar to we expected from MC.
- Since reduction for fast neutron is worse than for thermal neutron, reduction factor is not exactly same as expected.



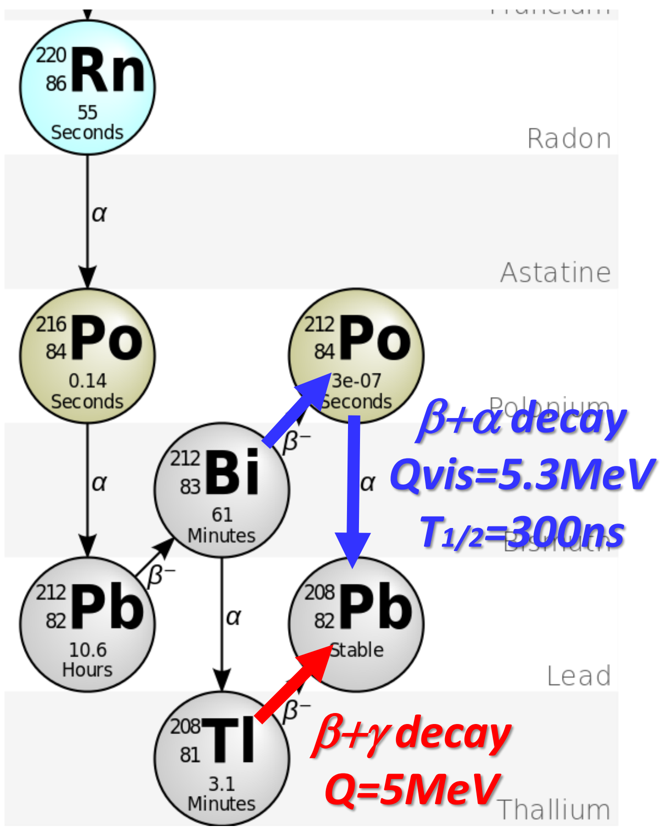


Energy spectra of physics run after loose LS cut



Remaining backgrounds and reduction

- After shielding external BGs were reduced about two order.
- Remaining BGs is originating from internal radioactivity of Th chain (^{208}Tl and ^{212}Bi-^{212}Po).
- $2\nu\beta\beta$ is not serious BG in current sensitivity. (it will be major BG after 48Ca enrichment)
- We reject remaining BGs by analysis.

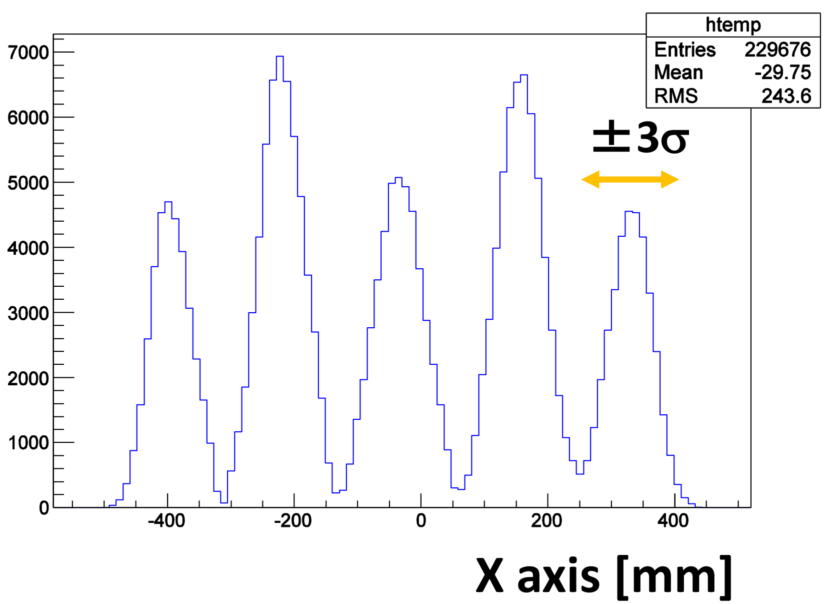


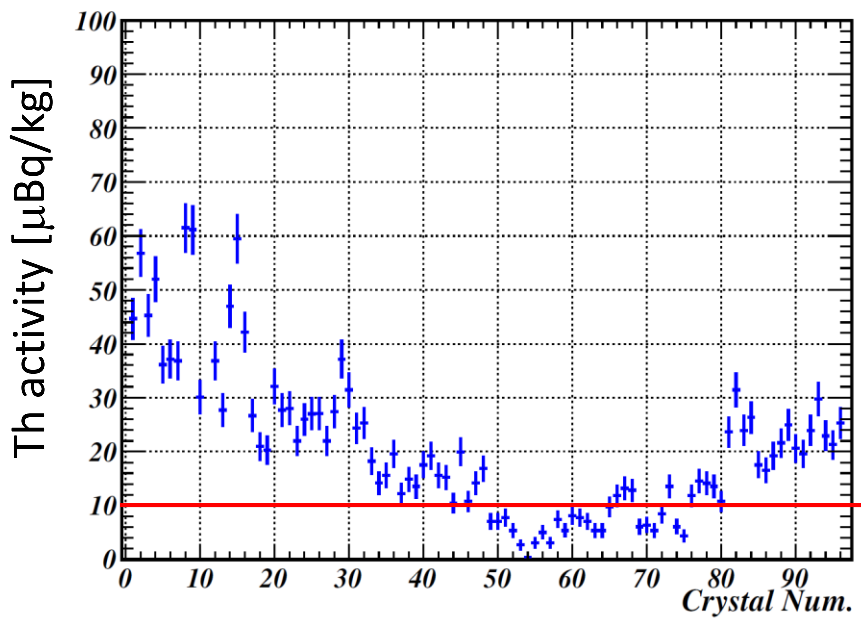
Position reconstruction and crystal selection

- Position of each event is reconstructed by weighted mean of observed charge in each PMT.

$$\frac{\sum Npe(i) \times \overrightarrow{PMT(i)}}{\sum Npe(i)}$$

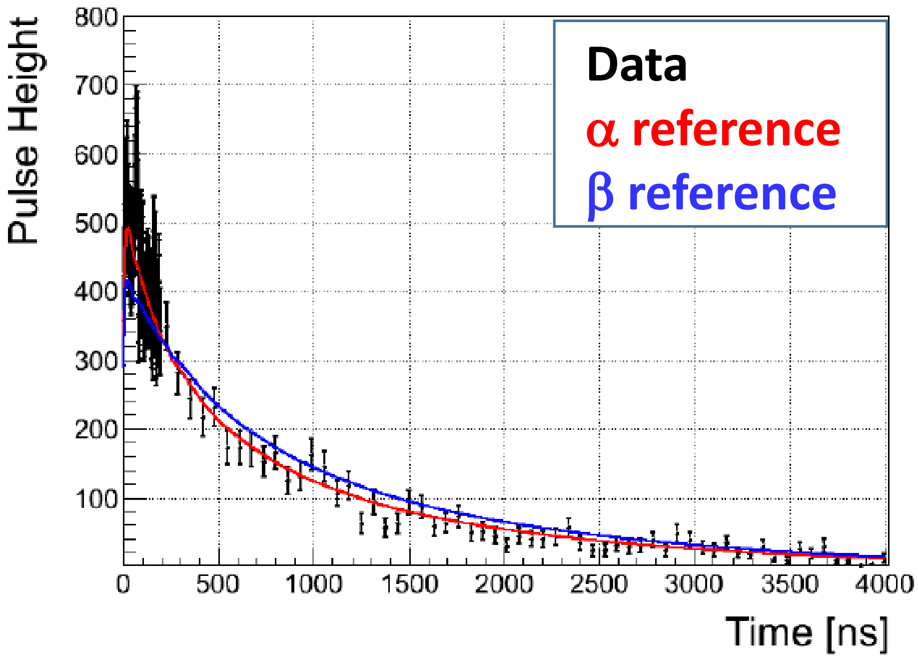
- Crystal separation is ~7σ peak to peak.
- Crystal selection criteria is within 3σ from the peak.
- 27 clean crystals (Th contamination < 10 μBq/kg) out of 96 crystals are selected and the results are compared to all crystals.

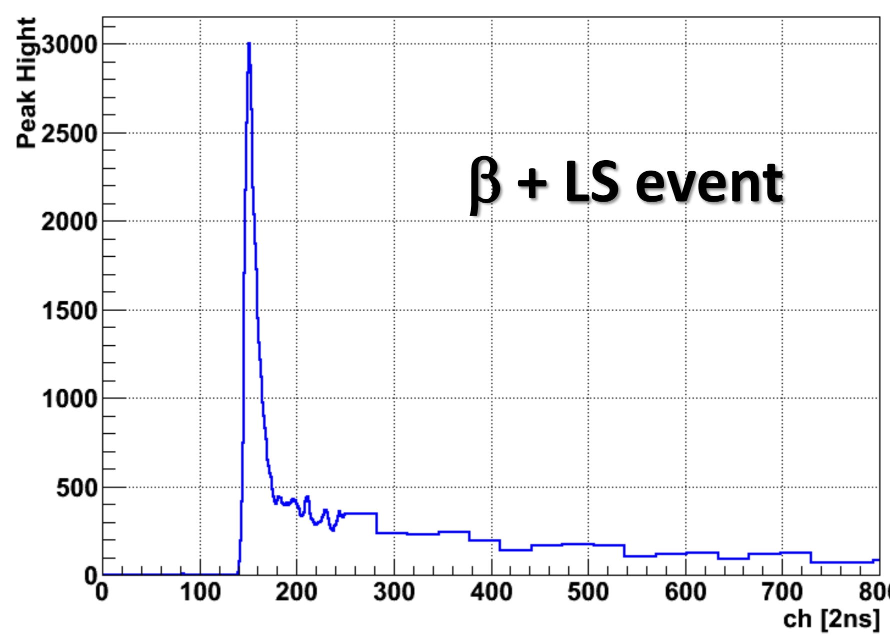




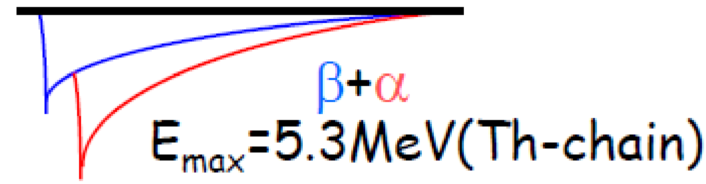
Pulse shape discrimination

- Pulse shape α/β are different in CaF2 scintillator and LS has also very different shape.
- Make reference pulse for each event type (α / β / LS).
- Chi2 fitting each reference pulse to the data and identify which event type is most likely event by event.

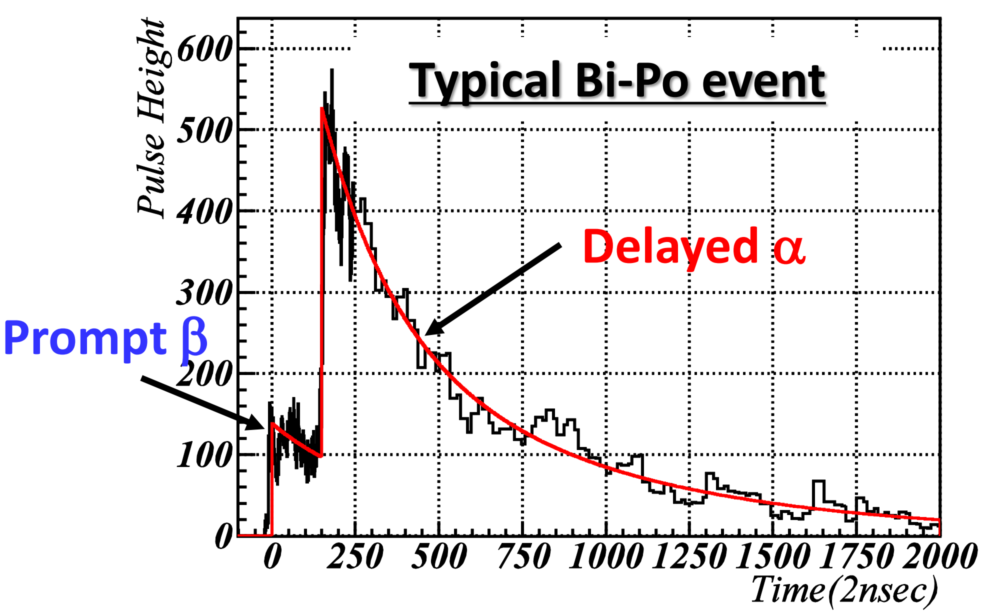


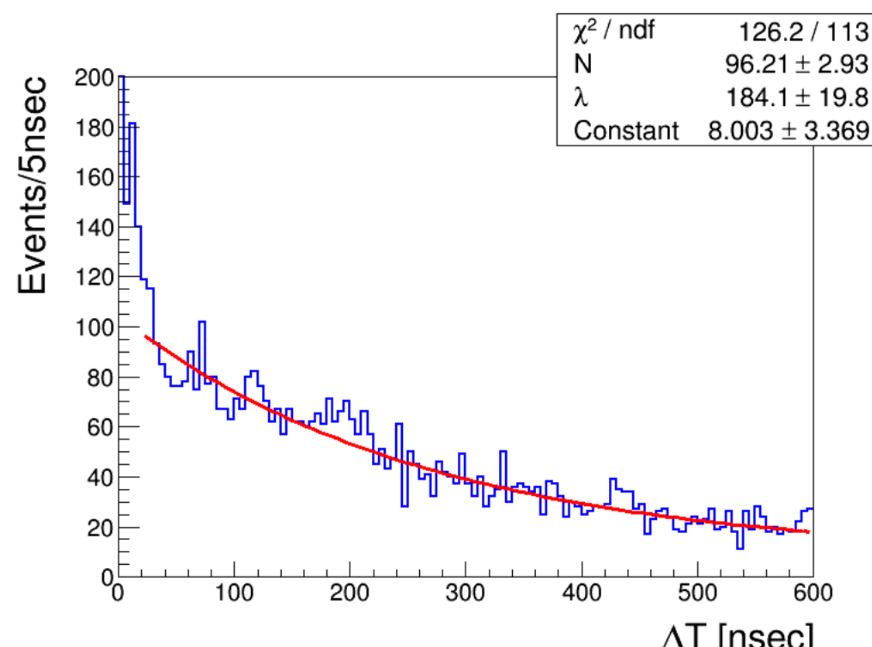


Bi-Po event cut

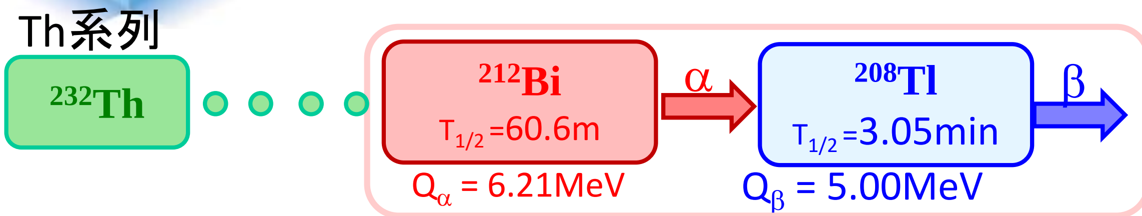


- ^{212}Bi-^{212}Po sequential decay has enough short half-life ($T_{1/2}$=300ns) to be included in one event (4 μsec).
- It can be a BG in $Q_{\beta\beta}$ region since its total visible energy is 5.3 MeV at maximum.
- Pulse shape analysis can remove this background and effect to $0\nu\beta\beta$ search is negligibly small for now.



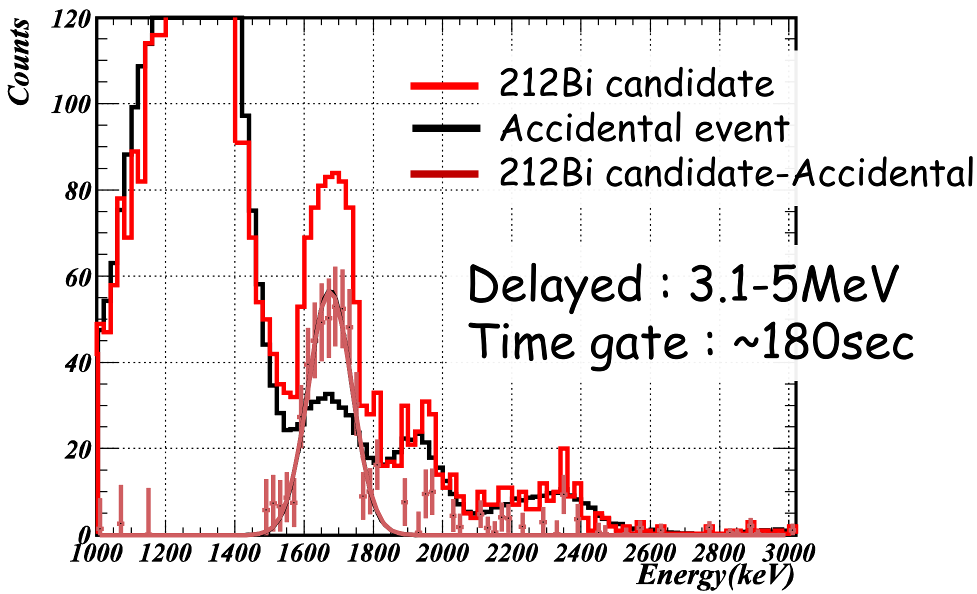


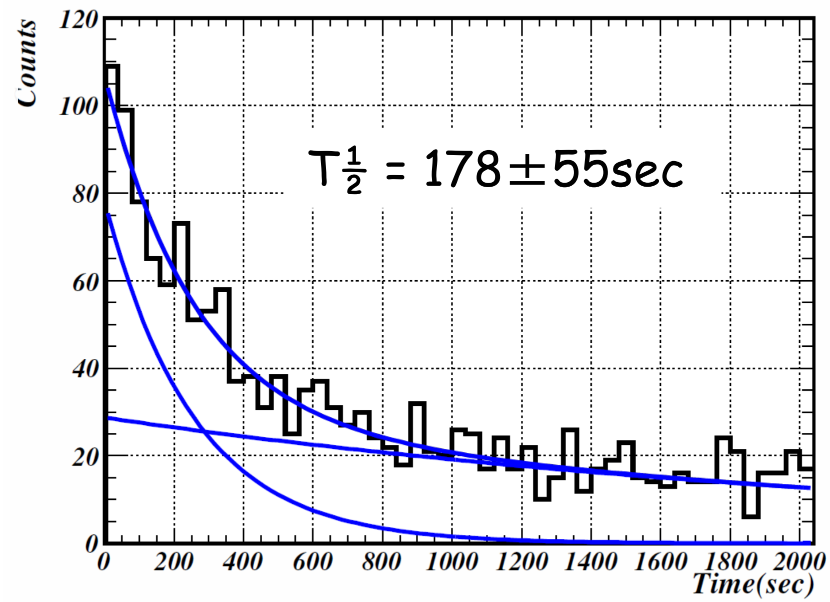
208Tl event cut



α-β崩壊

Eneryg spectrum of prompt events

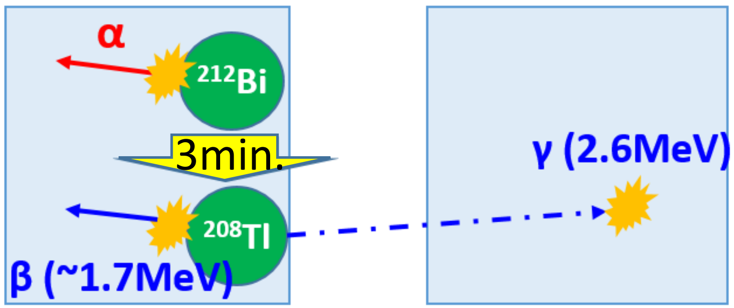




1. Find parent 212Bi α-decay candidate by pulse shape analysis.
2. Apply 12min veto from 212Bi candidate in the same crystal.

^{208}Tl multi-hit event cut

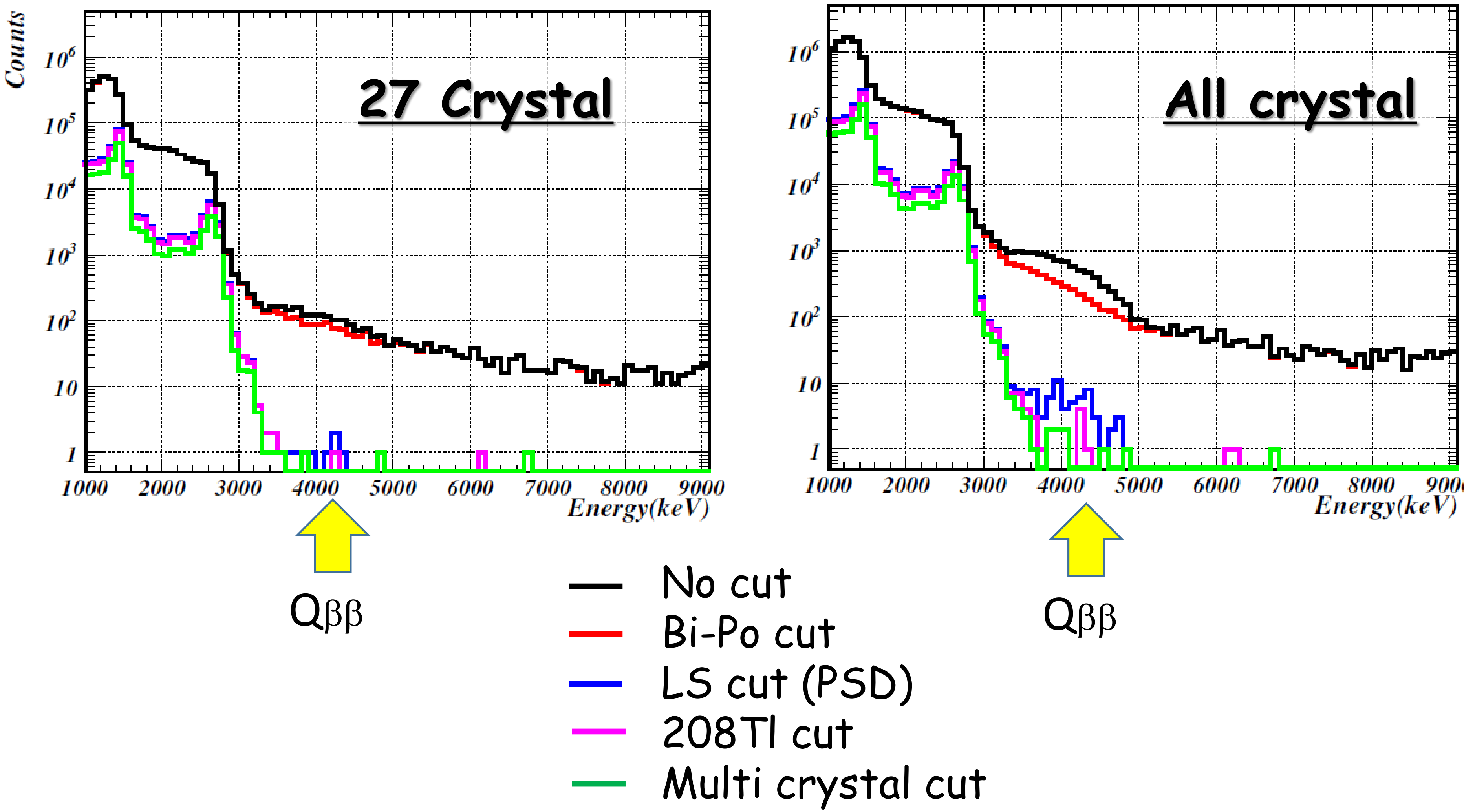
^{208}Tl multi-hit event



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

- In order to remove multi-hit event as well as single hit, we tried to apply veto not only for the same crystal, but also for the neighboring crystals.
- Although this cut is powerful to remove ^{208}Tl BG, signal efficiency become worse due to many accidental coincidence.
- Now we are under studying and improving cut method.

Energy spectrum at each reduction



Sensitivity for $0\nu\beta\beta$ in 1 year

Sensitivity is calculated from expected BGs.

Data set : 21.5 days after shielding
$Q_{\beta\beta}$ region: 4170 - 4480 keV ($Q_{\beta\beta}$ -1σ $+2\sigma$)

	Without multi-hit cut		With multi-hit cut	
	27 crystals	All crystals	27 crystals	All crystals
# of ev @$Q_{\beta\beta}$	1	5	0	0
Expected ^{208}Tl	0.22	2.2	0.14	1.4
Expected (n.γ)	0.01	0.04	0.01	0.04
Sig. eff.	0.46		0.30	
Sensitivity @1y	0.7×10^{23} [y]	1.0×10^{23} [y]	0.5×10^{23} [y]	0.9×10^{23} [y]

Sensitivity of CANDLES for $0\nu\beta\beta$ after 1 year is
$0.5 - 1.0 \times 10^{23}$ [year]

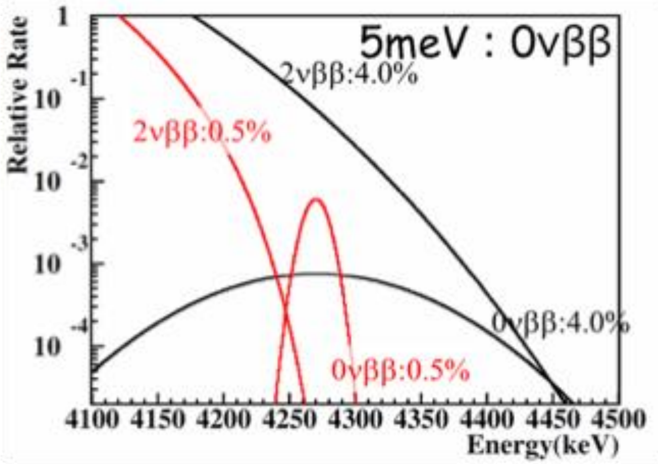
R&D for future

✓Scintillating bolometer for low BG

✓^{48}Ca enrichment for large target volume

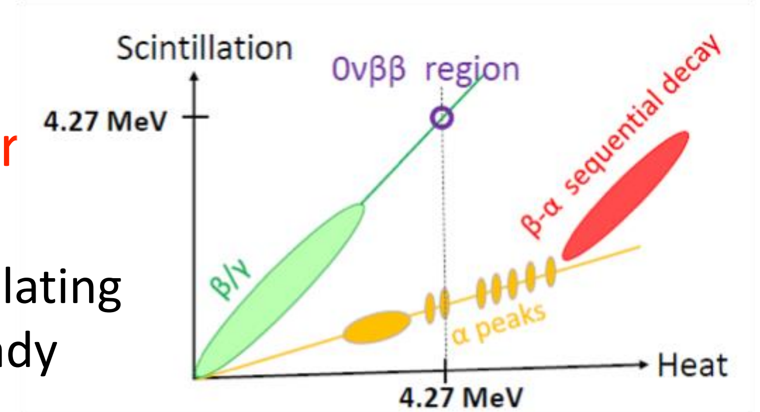
Bolometer development

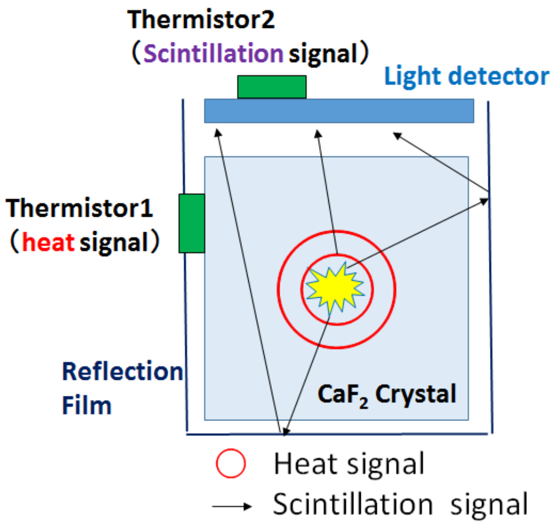
- Now ^{208}Tl is dominant BG and $2\nu\beta\beta$ is almost negligible in the current sensitivity.
- However, $2\nu\beta\beta$ will become main enemy for future after ^{48}Ca enrichment.
- Better energy resolution is necessary.
  Scintillator → Bolometer
- New BG appear in bolometer.



^{48}Ca $Q_{\beta\beta}$: 4268 keV / ^{238}U Q_{α} : 4270 keV

Need particle ID → Scintillating bolometer



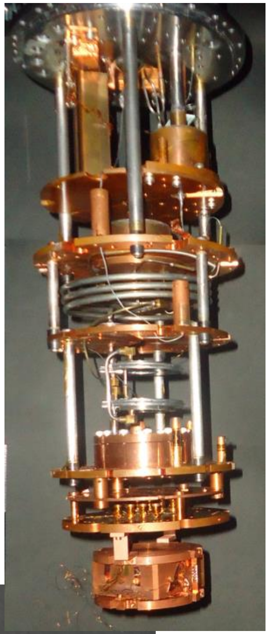


The technique of scintillating bolometer was already established.

→ CRESST-II (CaWO4), Lucifer, AMoRE

- Simultaneous measurement both heat and scintillation enables to identify the particle types (α/β particle ID) .

Bolometer development

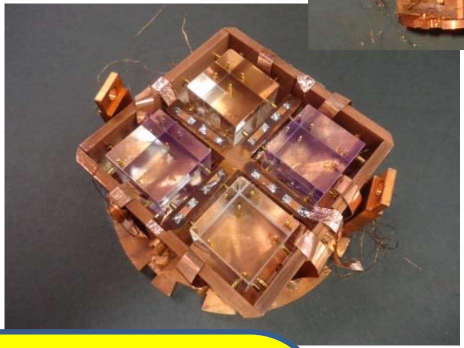


Dilution refrigerator

- We will use the dilution refrigerator which was developed for the dark matter search with LiF by the Univ. of Tokyo, and was customized to low BG measurement.
- Cooling power is 2μW @ 20mK

Target

- 2cm cube of CaF2 crystal (25 g) in the initial stage.
- Temperature rise at Q-value is 1.43×10-1 K at 10 mK.
- Neutron Transmutation Doped Germanium(NTD-Ge) thermistors borrowed from the Univ. of Tokyo.



Please see Tetsuno's poster

Schedule

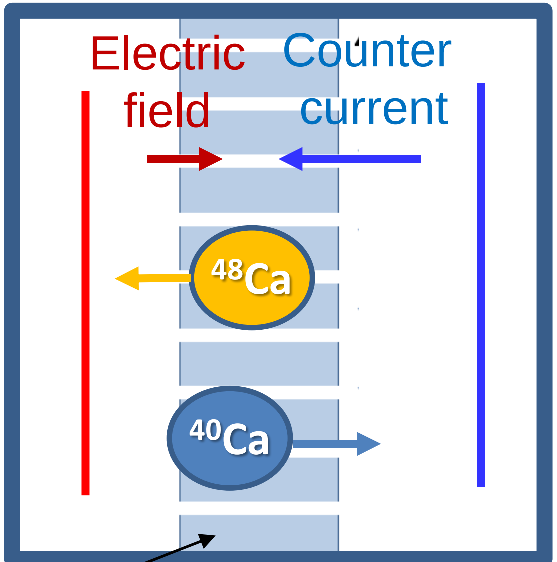
2016
- Achieve low temperature (~a few K) ***Done!!***
- Achieve ultra low temperature (~10mK)
- Detect heat signal

2017
- Add a light detector to bolometer and achieve the simultaneous detection of heat and light signals
- Increase crystal size and number

^{48}Ca enrichment

- Natural abundance of ^{48}Ca is 0.187%.
- Commercial ^{48}Ca → 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 for,,,

High enrichment
Large amount

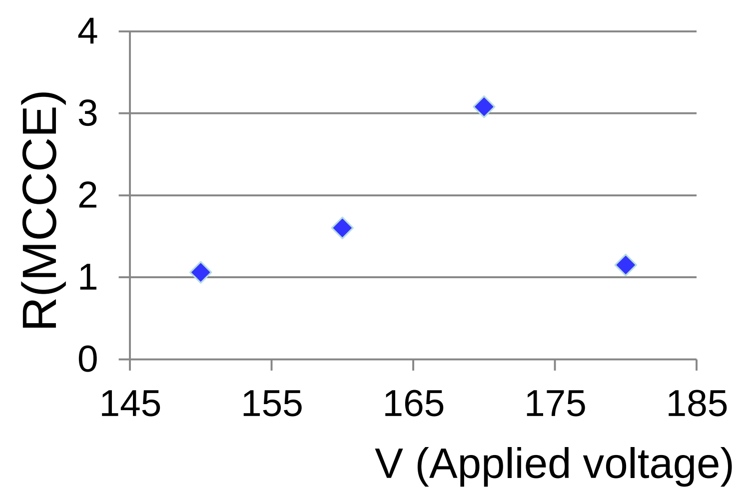
$$R(MCCCE) = \frac{43Ca/48Ca(MCCCE)}{43Ca/48Ca(natural)}$$

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]



Summary

- **CANDLES** is a project to search for double beta decay of ^{48}Ca using 300kg CaF2 scintillator, running in Kamioka underground lab..
- Using ^{48}Ca has a great chance to achieve **"Background Free Measurement"**, one of the key to perform sensitive $0\nu\beta\beta$ search.
- Additional shield consisting of Pb/B was installed in 2015-2016 and data taking restarted from this May.
- The (n,γ) background was reduced by almost two order of magnitude.
- ***Sensitivity of $0\nu\beta\beta$ is $0.5-1.0\times10^{23}$ [year]***
- We are now trying to improve analysis method for achieving better sensitivity.
- Future R&D is also ongoing.

New collaborative institute and Postdoc are now wanted!!

Backup slide

Thank you !!

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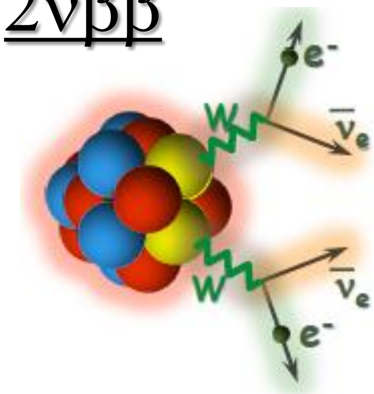
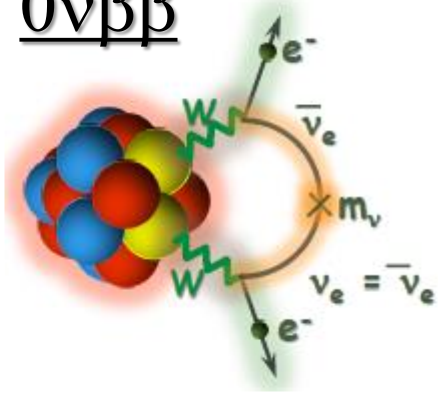
Double beta decay

2νββ



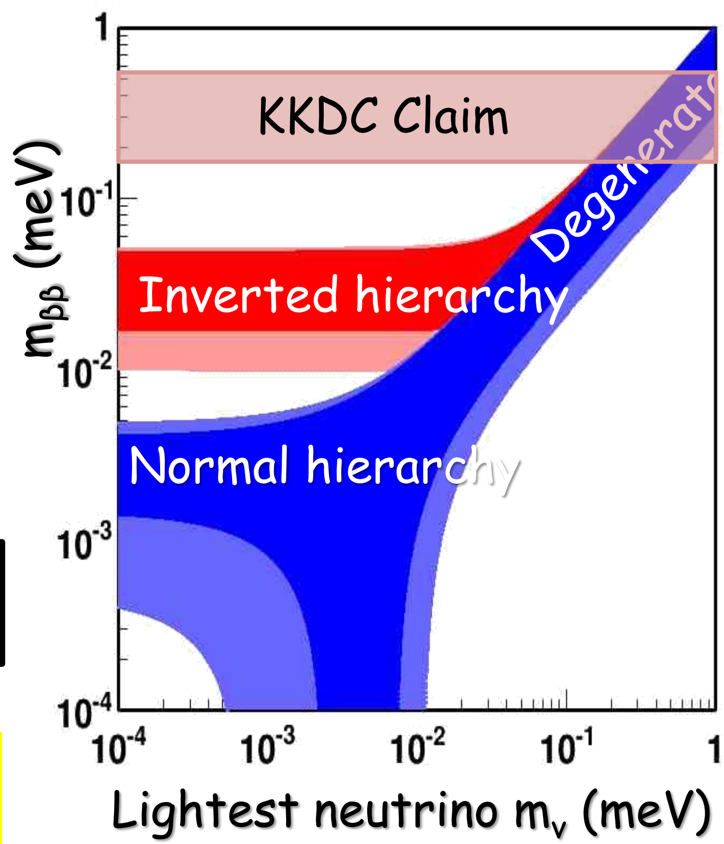
- Standard model
- Already observed in some nuclei
- $T_{1/2}$: 10^{18} ~ 10^{20} yr

0νββ



- Beyond the SM
- Proof of **Majorana neutrino**
- $T_{1/2}$: > 10^{25} yr

Constraint of ν mass from oscillation experiments



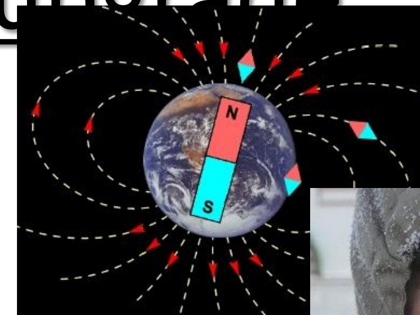
0νββ half-life : $$\frac{1}{T_{1/2}} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

◎If Majorana neutrino…

Light neutrino mass（See-Saw mechanism）

Matter dominated universe（Leptogenesis）

Recent detector upgrade



2014

Magnetic cancellation coil installation
Detector cooling system installation

For better energy resolution!!

DBD14 @Hawaii

Data taking

2015

Gamma and neutron shield construction

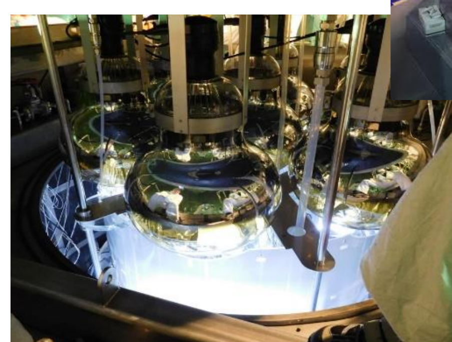
For lowering background level!

2016

Preparation for next run

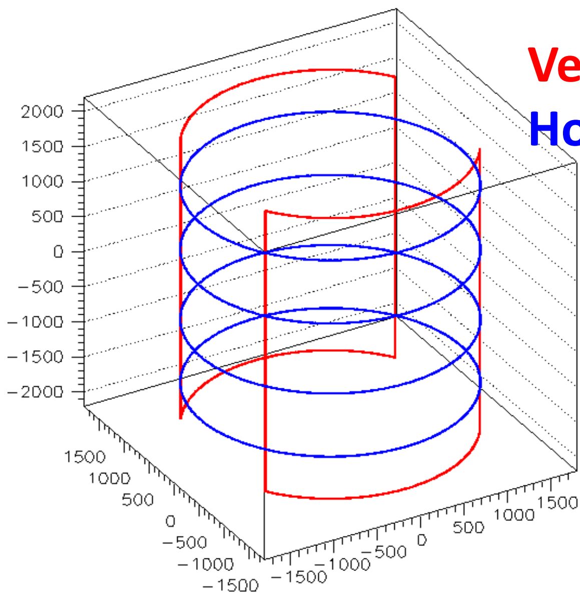
Data taking

DBD16 @Osaka

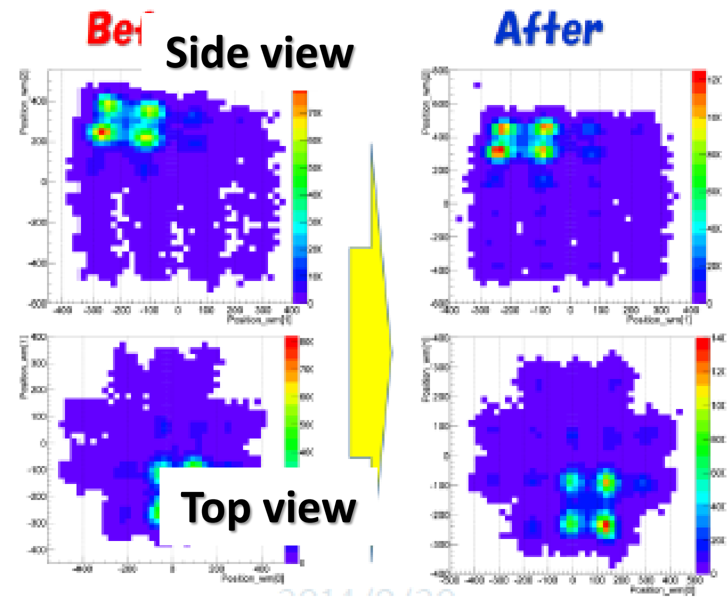


Magnetic cancellation coil

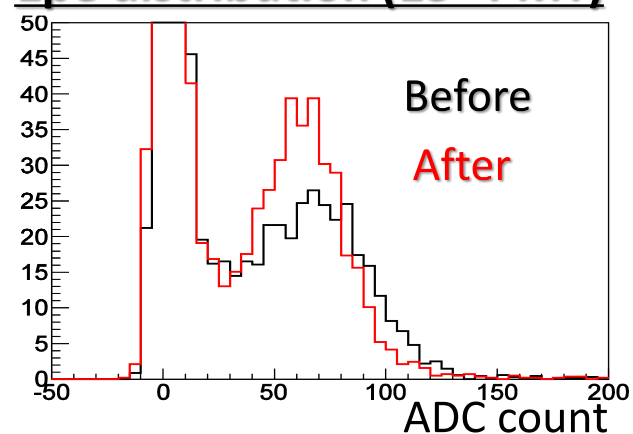
- **Winded coil surrounding the water tank and apply ~1.5A current to cancel geomagnetic field.**
- **Better p.e. collection efficiency of PMT dynode is expected.**



Reconstructed position



1pe distribution (13" PMT)

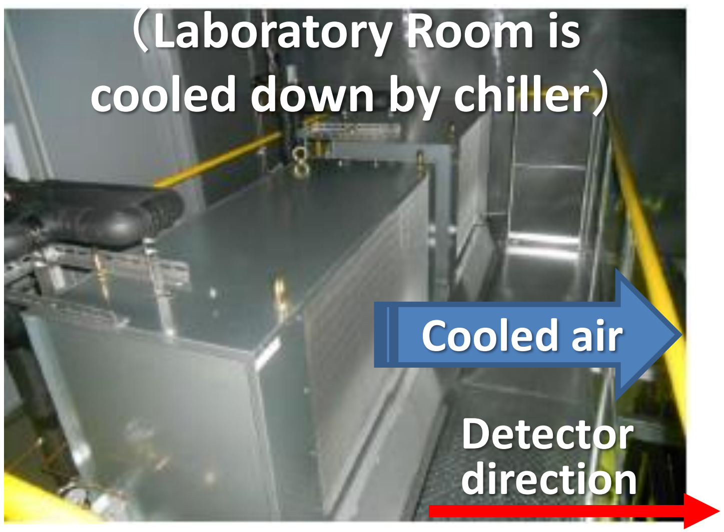


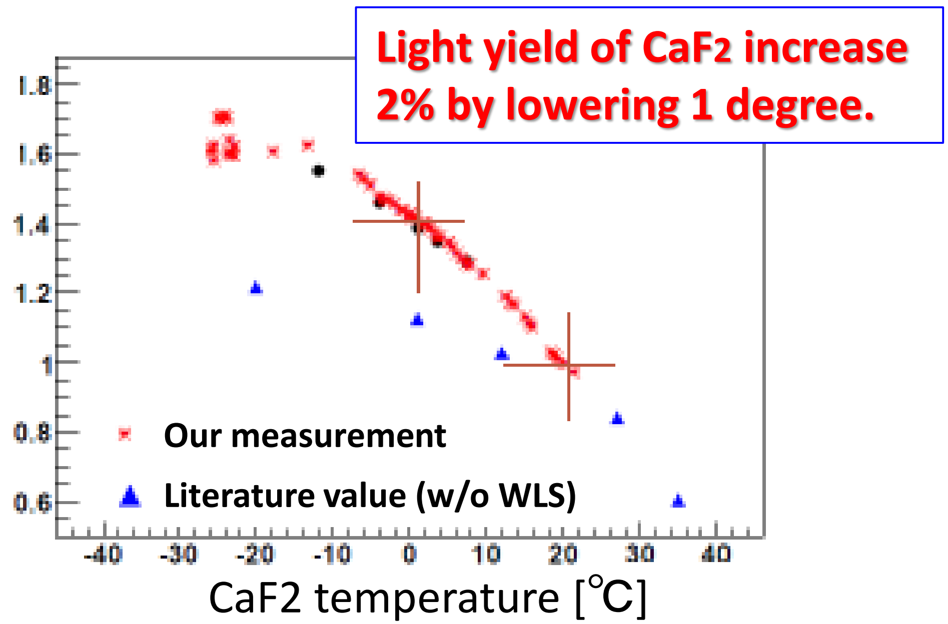
1. **Light yield increased (later)**
2. **Position distortion improved**
3. **1pe distribution improved**

Cooling system

- **Cooling system** was installed and tested in middle of 2014.
- **Data was taken with low temperature** in the end of 2014.

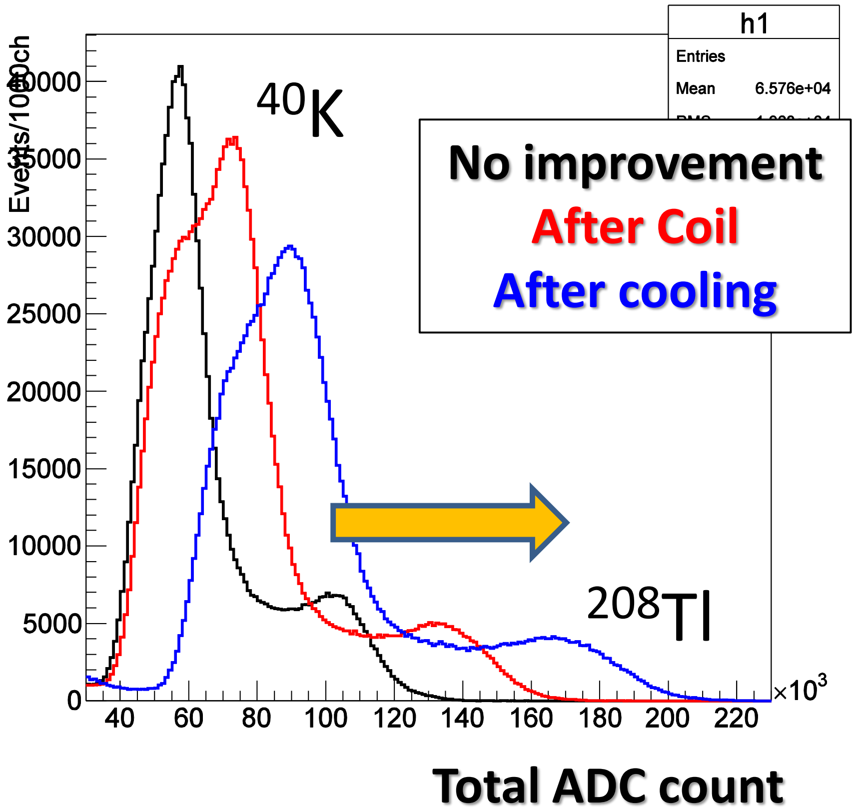
CANDLES cooling system





- ✓ **Room temp. → 2℃, Water temp. → 4.3℃**
- ✓ Test data was successfully collected with very good stability (±0.1℃) during ~1 month.

Light yield increase



- Light yield has been increased by the detector upgrades.

	Relative light yield	Resolution
Before	1	σ = 4.8%
Coil	1.23	σ = 4.2%
Cool	1.58	σ = 3.6%

Obtained from ^{88}Y source calibration

After improvements, ~1000 [p.e./MeV] is achieved