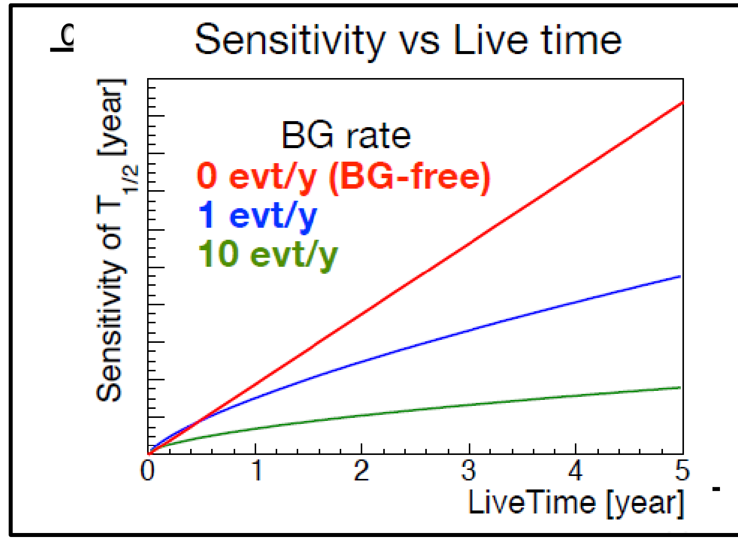
CANDLES
Project for the study of neutrino-less double beta decay of ^{48}Ca

Sei Yoshida
Department of Physics, Osaka Univ.

Revealing the history of the universe with underground particle and nuclear research
the University of Tokyo
May 11th, 2016

^{48}Ca for ββ Isotope

- ^{48}Ca isotope
  - Highest Q-value (4.27MeV)
    - ➔ Large phase space factor
    - ➔ Low background
      - γ-ray ; 2.6 MeV (^{208}Tl)
      - β-ray ; 3.3 MeV (^{214}Bi)



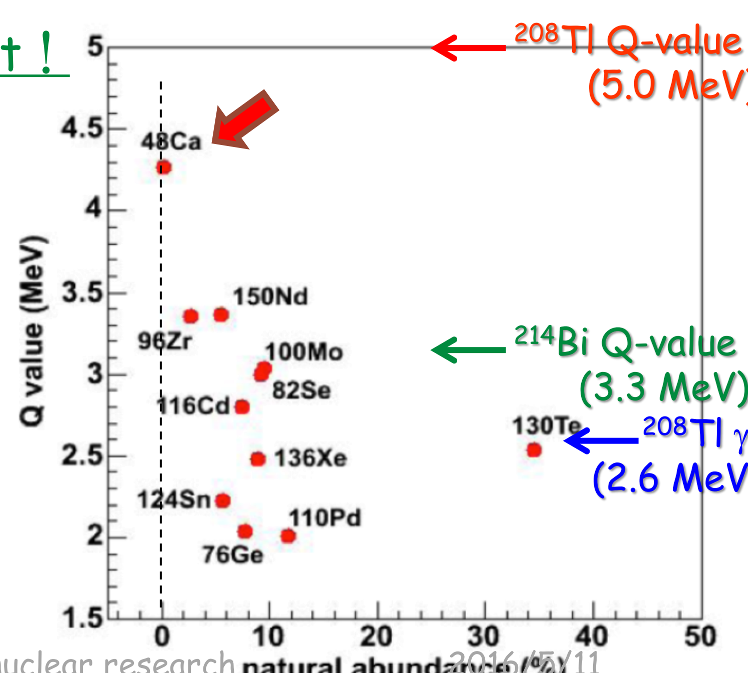
  - Chance to realize the Background Free Measurement !

$$\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (1/ M \cdot T_{live})^{1/2}$$

  - Small natural abundance (0.187 %)

However,

  - Chance to improve the sensitivity by the enrichment without scale-up.
  - Low risk to increase BG origins

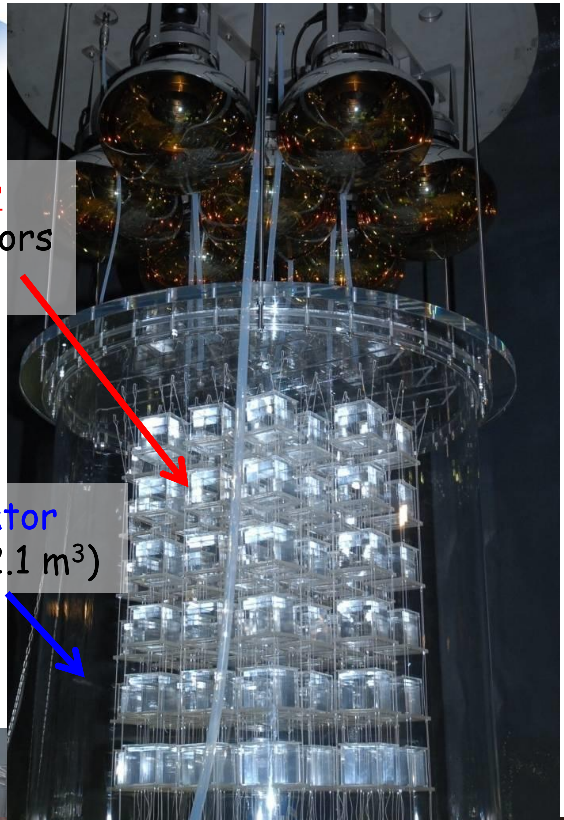


CANDLES Project

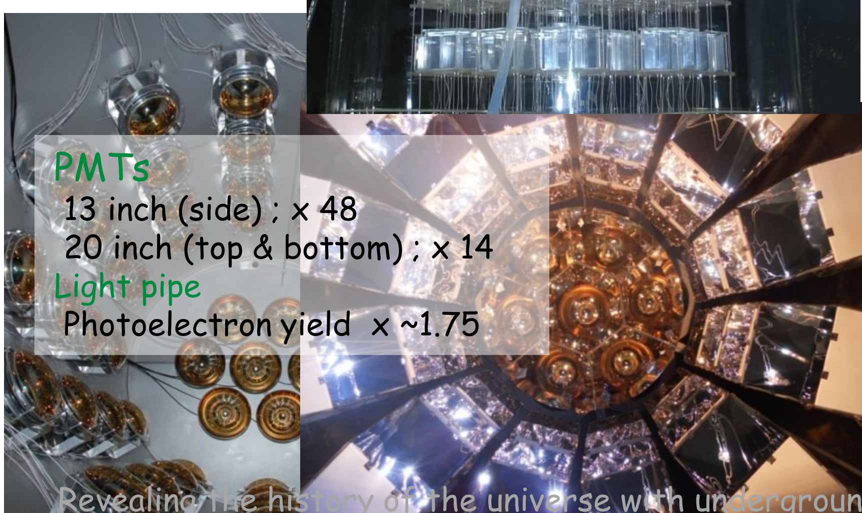
The Project to search for $0\nu\beta\beta$ decay of ^{48}Ca,

CANDLES III Detector

Main detector
CaF_2 scintillators
(305kg)



Liquid scintillator
acrylic tank (2.1 m^3)



- CaF_2 Module
  - CaF_2(Pure) ; 96 Crystal → 305 kg
  - WLS Phase ; 280 nm → 420 nm
    - Thickness ; 5 mm
    - Composition ; Mineral Oil＋bis-MSB (0.1 g/L)
- Liquid Scintillator (LS) **4π Active shield**
  - 1.37 m ϕ x 1.4 m height
  - Volume ; 2.1 m^3 (1.65 ton)
  - Composition
    - Solvent ; Mineral Oil(80%)+PC(20%)
    - Solutes (WLS's) ; PPO (1.0g/L) + bis-MSB (0.1g/L)
- Acrylic Tank
  - Container for LS
- Water Buffer
  - Pure Water ➔ Passive Shield
    (Pre,Final-filter, Chacoal-filter, UV-lamp, Ion-Exchanger)
  - Distance PMT – LS ; 50 cm
- PMTs + Light pipe
  - 13 inch (Side) ; x 48
  - 20 inch (Top and Bottom) ; x 14
  - Reflector Film : reflectivity ~93% @ 420nm

Pulse Shape Discrimination

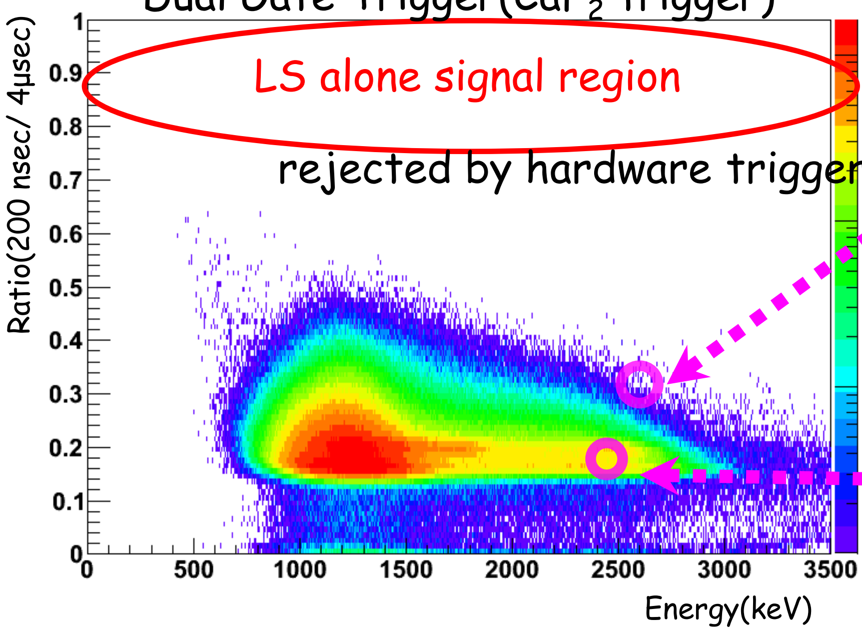
4π Active shield

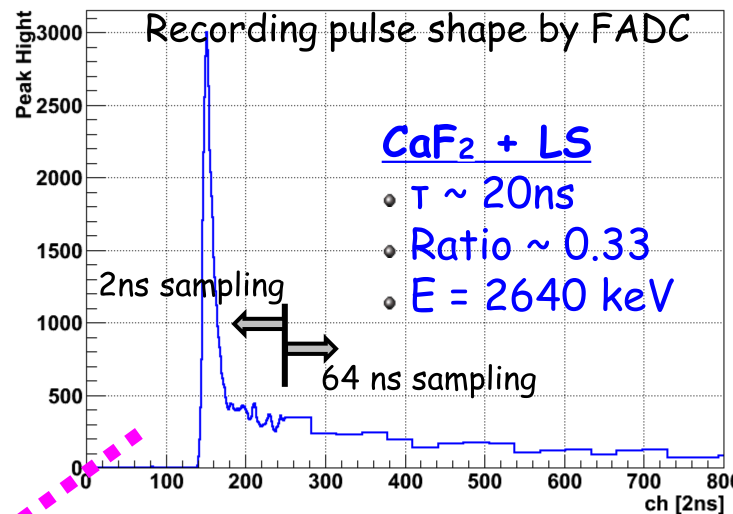
- Scintillator ID (CaF_2 and LS signals)

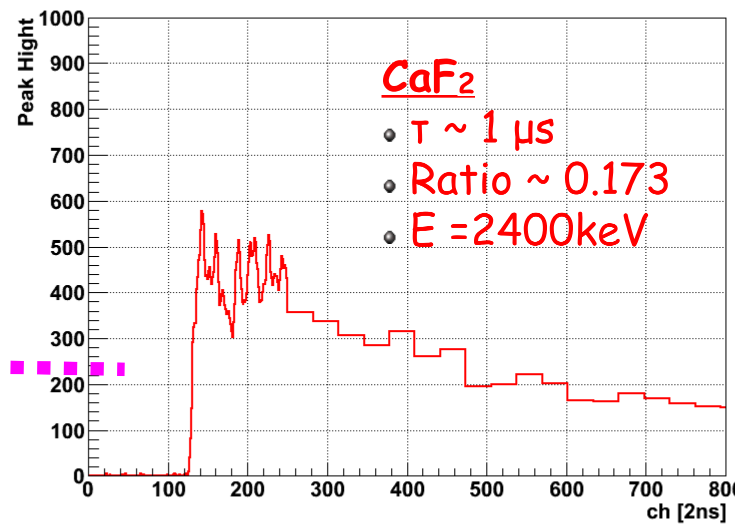
Difference of scintillation time constant

- CaF_2 ; ~ 1000 nsec
- LS ; a few 10 nsec

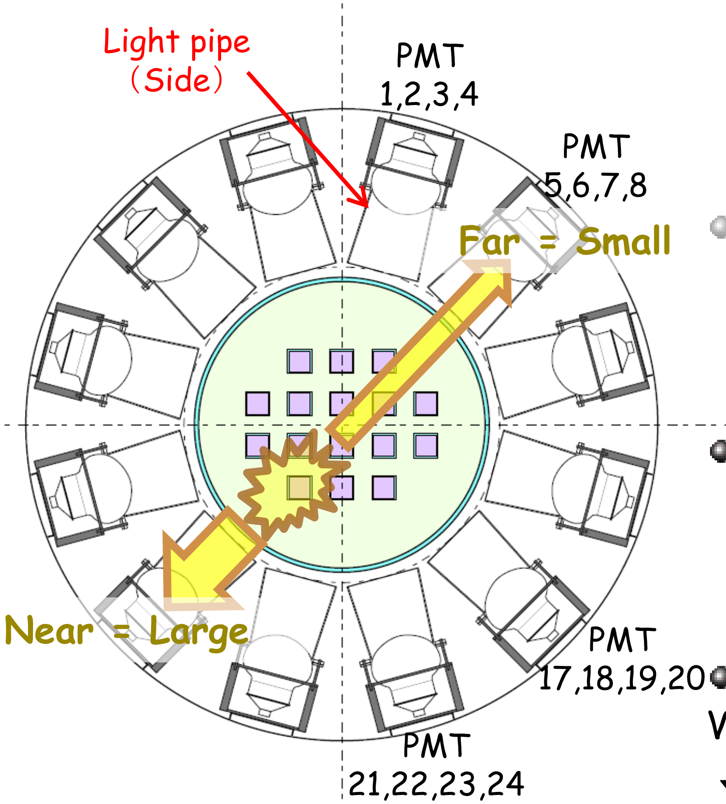
$$\text{Ratio} = \frac{\text{Prompt pulse (0:200nsec)}}{\text{Total Pulse}}$$







Event Reconstruction



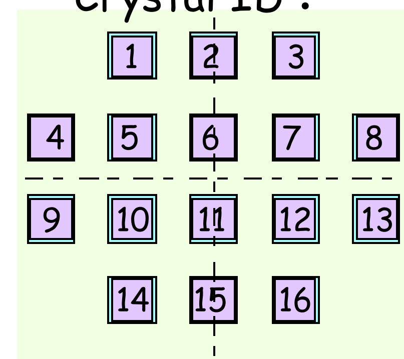
Top View

- CaF_2 Module Configuration
  - 16 x 6 layers = 96 crystals
  - Calibration Crystal (C11) ; Top layer
    Contaminated Crystal (U, Th amounts ~ x 1000) to investigate detector performance.
- PMTs
  - 13 inch : 12 x 4 layers
  - 20 inch : Top & Bottom 7 each
    62 PMTs in total
- Energy
  - Number of Photoelectrons
  - Regular calibration using ^{88}Y
- Position

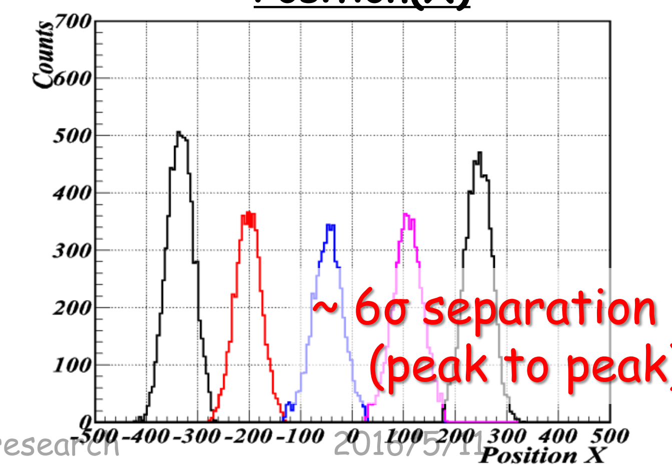
Weighted Mean =

$$\frac{\sum PMT(i) \cdot NPE \times \overrightarrow{PMT(i)}}{NPE\ Total}$$

Crystal ID :



Position(X)



Background Candidates

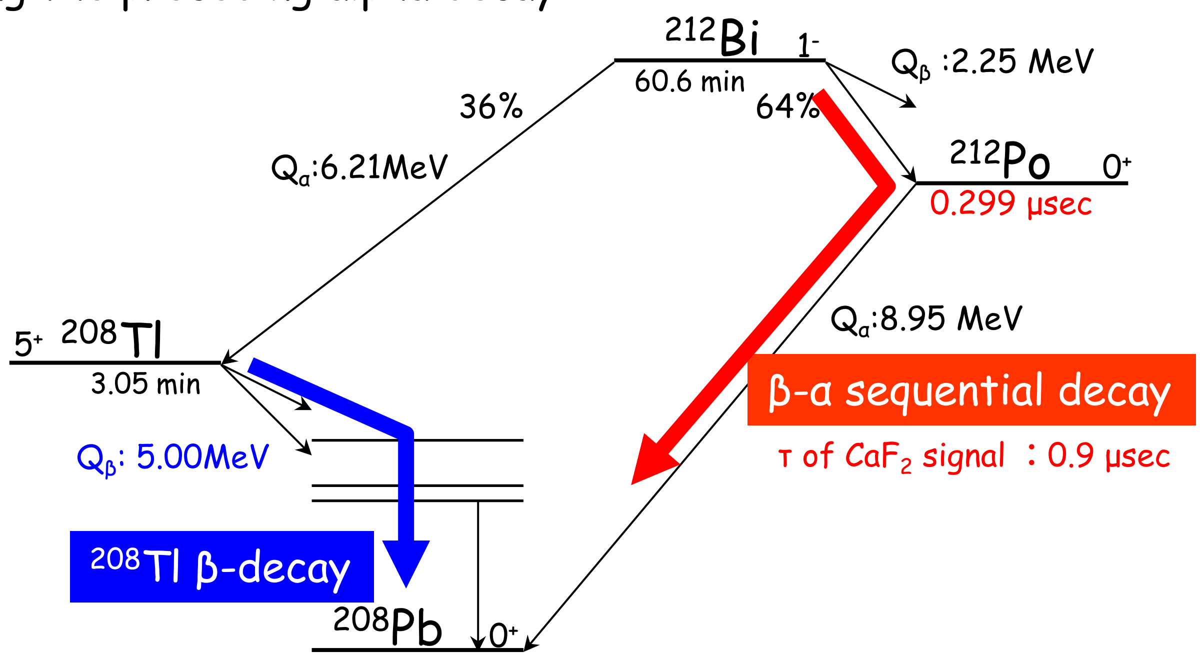
- 2νββ decay event (unavoidable background)
  - ➔ Improve E-resolution

- Natural radioactivities in CaF_2 crystal

  β-α Sequential Pulse
  - Reduction by pulse shape analysis

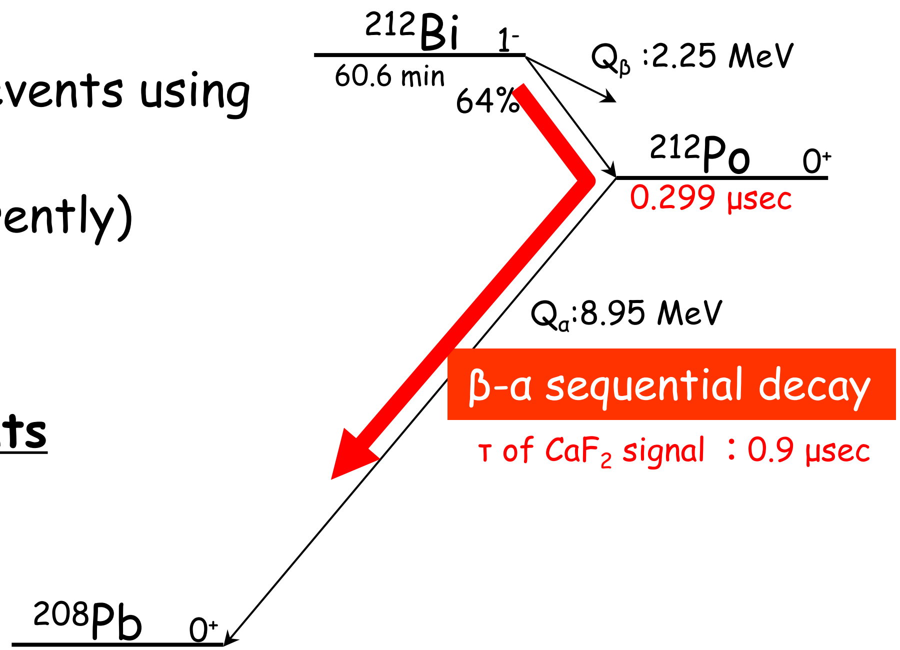
  ^{208}Tl Decay
  - Reduction by tagging the preceding alpha decay

- Neutron induced BG



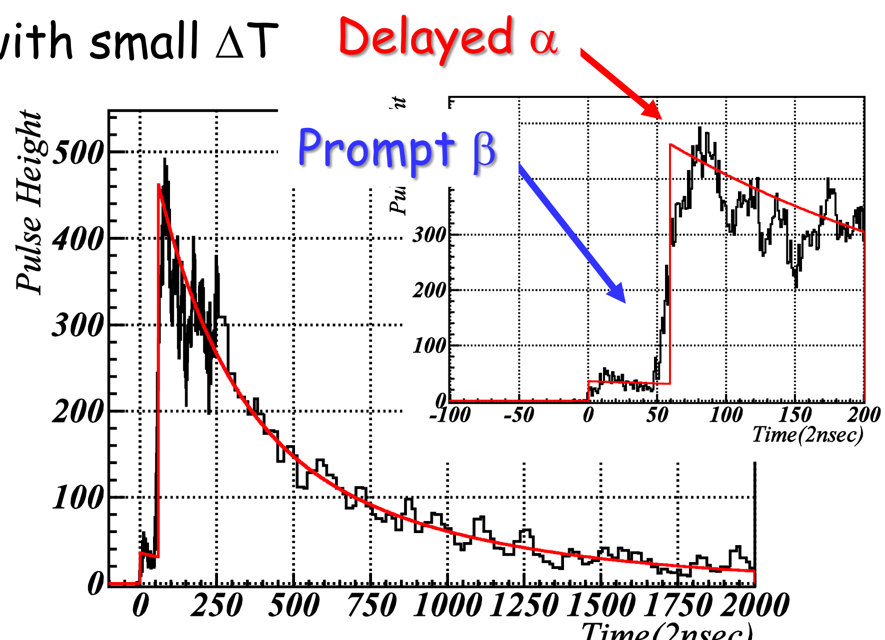
Background Rejection (1)

- <u>Sequential Event Rejection</u>
  - We can identify the sequential events using pulse shape.
  - Rejection efficiency > 95% (currently)



<u>Typical pulse shape of sequential events</u>

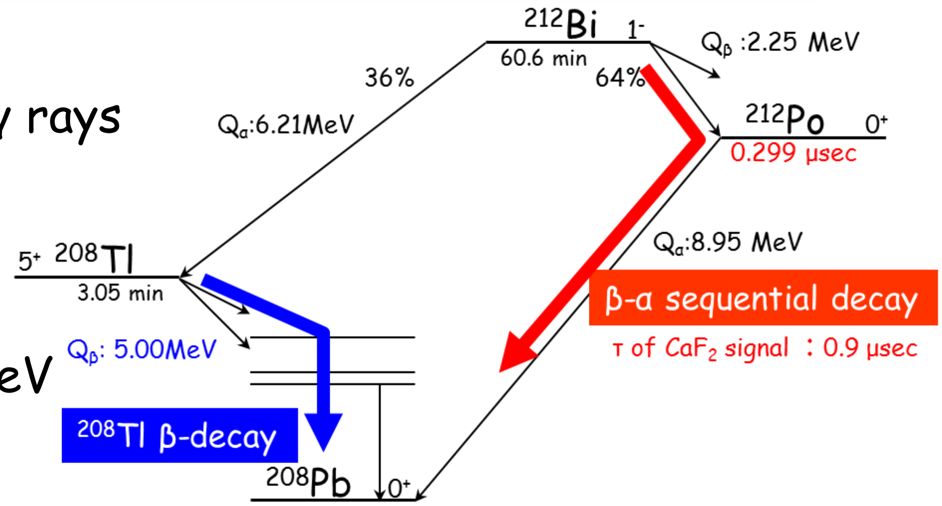
with small ΔT

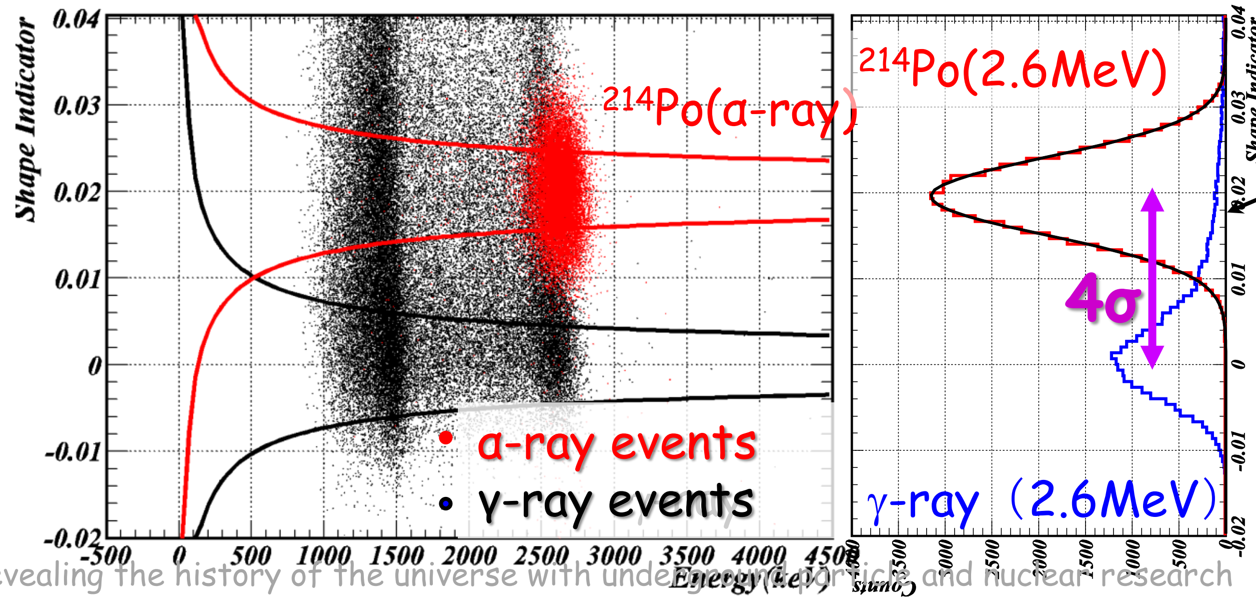


Sum-up signal of 62 PMT

Background Rejection (2)

- Pile-up event & ^{208}Tl Rejection
  - Particle identification between α/γ rays
    - rejection of β-α pile-up events
    - identification of prompt ^{212}Bi event
  - 97 % rejection efficiency at 2.6MeV
    (γ ray:3%)
    ➔ 97% (β+α) at 4.27MeV





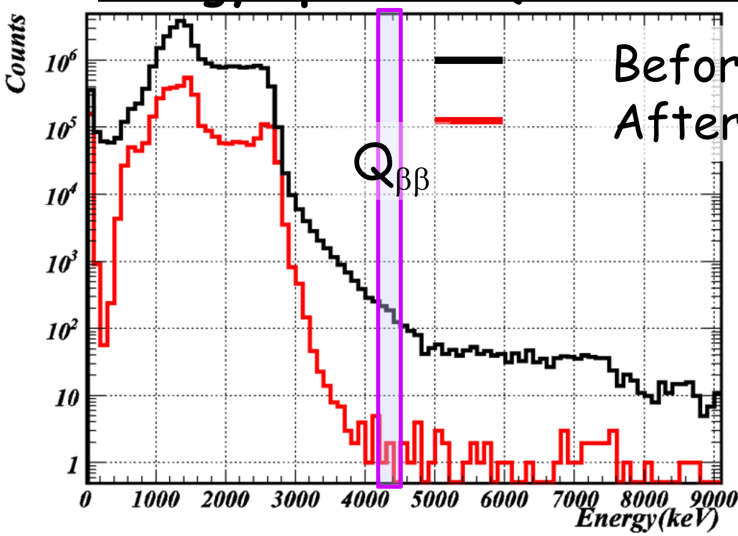
CaF$_2$ γ
+small LS signal

ref：Shape Indicator
(PRC67(2003) 014310)

Energy Spectrum

- Measurement : Physics run in CANDLES-III (2014)

Energy spectrum (~8 weeks)



Before event selection
After event selection (BG rejection)

	Pilot run data
Measurement time	4987 kg・days
Number of events	6
Expected BG	~1 (CaF_2 crystal) 3.4(γ-rays)
Sensitivity	0.8×10^{22} year

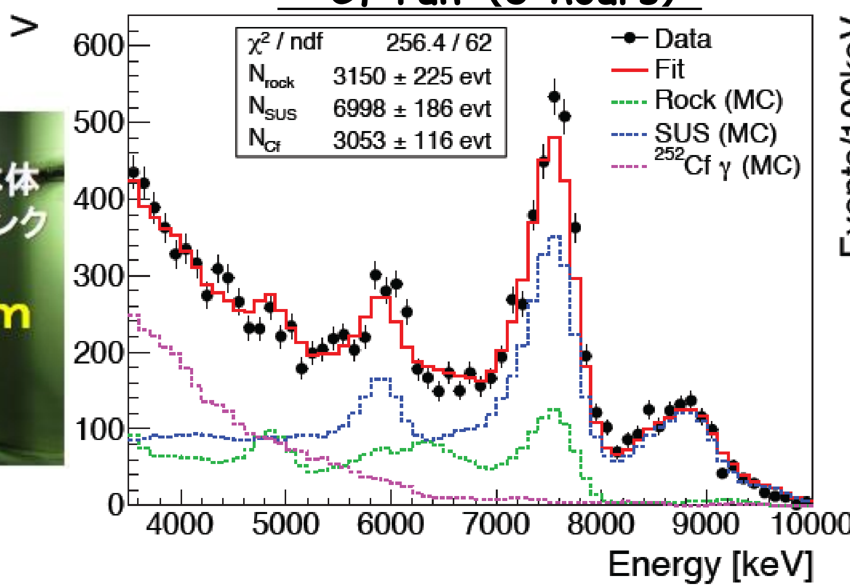
- Current detector sensitivity (8 weeks) : 0.8×10^{22}year
- We will install shield system for γ-rays(neutron origin) and continue the measurement.

➔ Detector sensitivity:0.5eV

Background @ High energy region

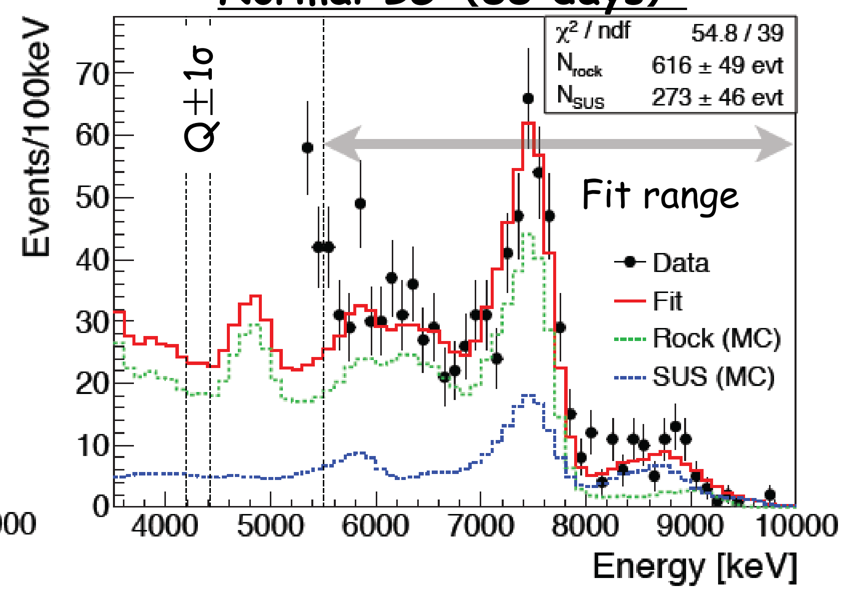
- Neutron source run (^{252}Cf)
  - 1 hour of source run = 1 year of physics run
  - Energy spectrum obtained is well reproduced by MC of neutron capture γ-ray.
- (n,γ) BG in 0νββ window is evaluated from MC spectrum.
  - Rock/SUS = 3.6±0.7 in $Q_{\beta\beta}\pm1\sigma$
  - (n,γ) BG: 3.4±0.4(stat.) evt/26crystals/60days (Run data, 3±1 evt)
  - Currently, most serious background component in CANDLES

^{252}Cf run (3 hours)



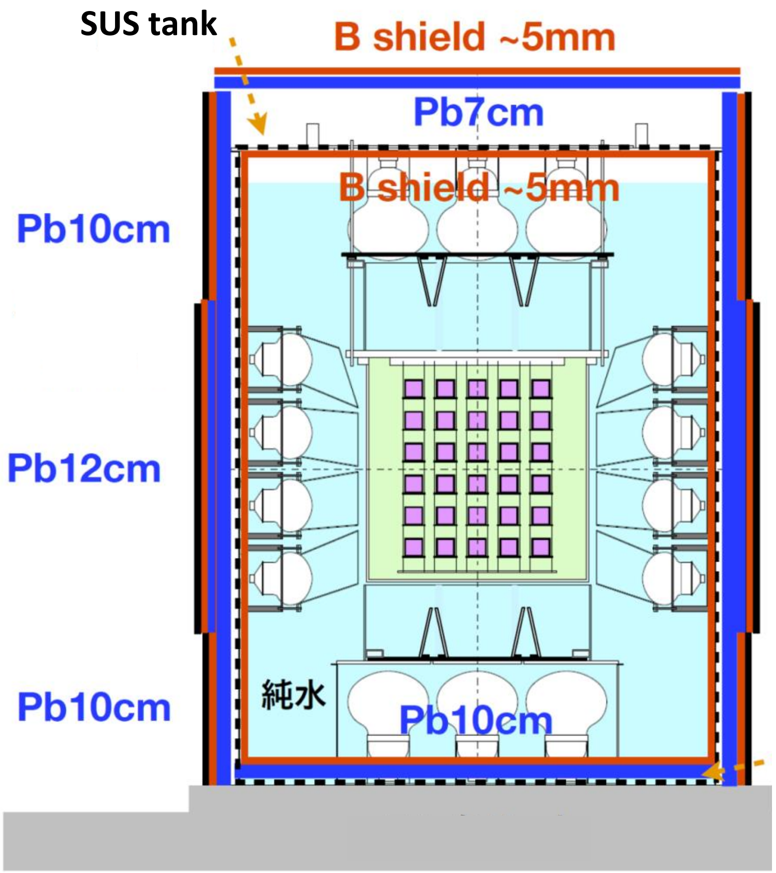
Loose event selection cut !

Normal BG (88 days)



Shield for neutron induced γ-rays

- Toward "Background Free Measurement"
  - We designed the shield by MC simulation, and had finished the construction.



- **Pb bricks**
  - 7 ~ 12cm in thickness
  - Reduce (n,γ) BG from rock.
  - Pb(n,γ) event rate is an order of magnitude smaller than that of stainless steel tank.
  - γ-ray from rock decrease by factor of **1/180**
- **Boron sheet**
  - B_4C loaded silicone rubber sheet: ~ 5 mm in thickness
  - Reduce thermal neutron to avoid (n,γ) reaction in water tank.
  - N-capture events decrease by factor of **1/40**
- Number of BG after shield installation estimated by MC

  Rock : 0.34±0.14 event/year

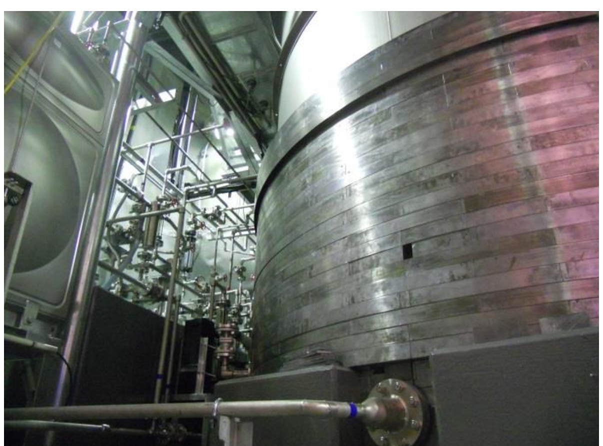
  Tank : 0.4±0.2 event/year

$T_{1/2}$ > 10^{23} year is expected with one year data !

CANDLES shield system

- Construction was finished till February 2016



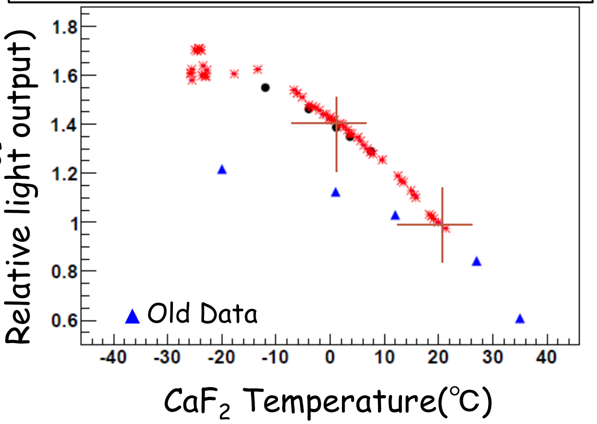



Detector Improvement Cooling system

- Installation of the Cooling system
  - CaF_2 light output depends on its temperature.
  - Gain ~ +2% / ℃ (down to -20 ℃)
  - **To increase the light yield**, the experimental room is cooled down to 2 ℃ (~ 4 ℃ at detector center)
  - **To stabilize** the temperatureat the detector center within 0.1 ℃ (0.2% of gain).

    ➔ Check gain stability using ^{208}Tl γ-ray peak

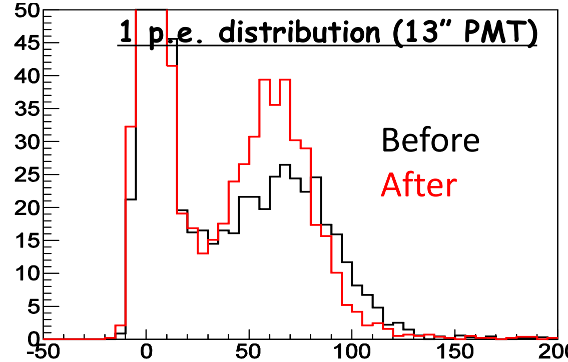
Temp. Dependence of Light Output



CANDLES cooling system

Detector Improvement Cancellation Coil

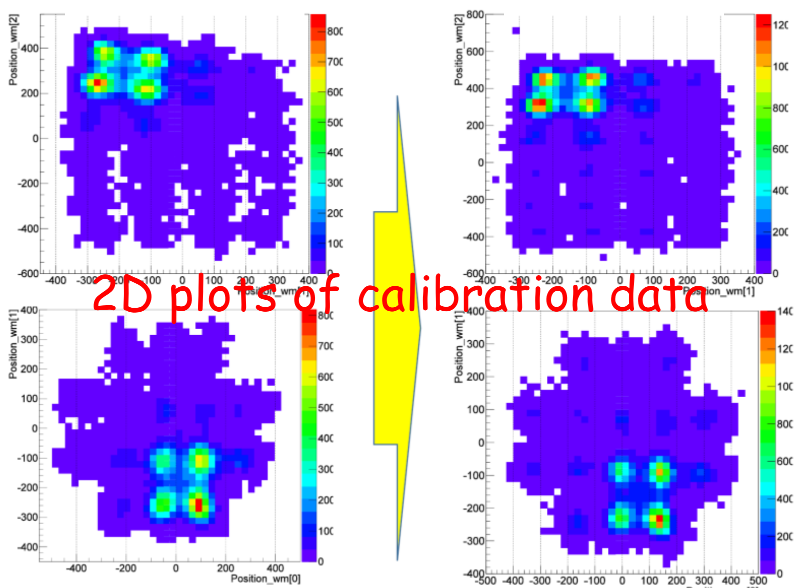
- Installation Magnetic cancellation coil
  - We are using large diameter PMTs (13 and 20 inch's) . It is well-known to deteriorate the performance.
  - Winded coil surrounding the water tank
    ~1.5A current to cancel geomagnetic field.
  - Better p.e. collection efficiency of PMT dynode.



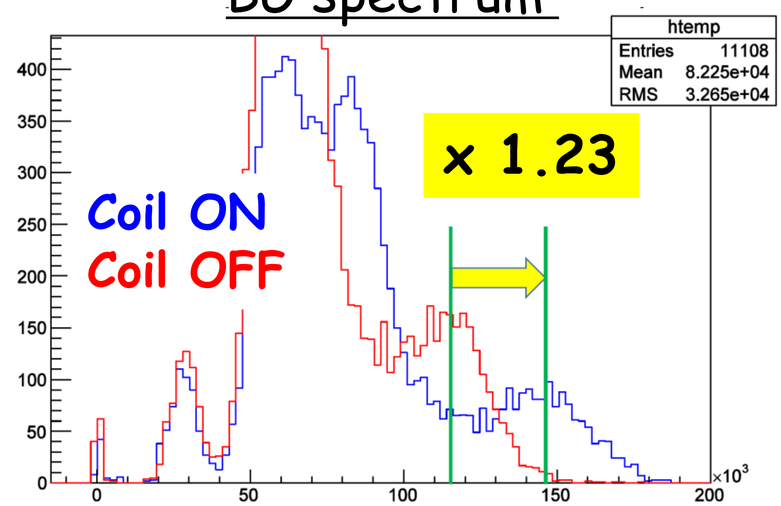
Position Reconstruction

Coil OFF

Coil ON



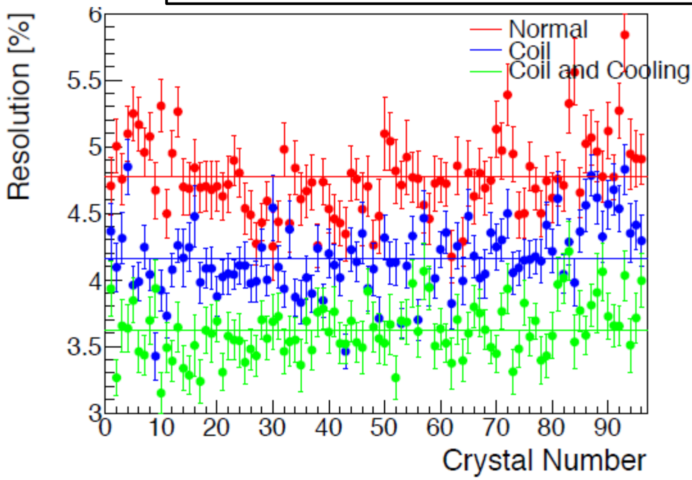
BG spectrum



Detector Improvement

- Light yield has been increased by the detector upgrades

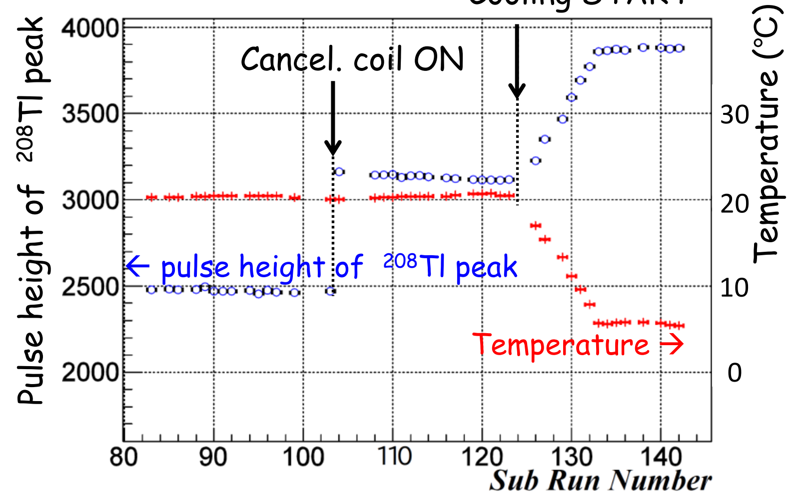
Obtained from ^{88}Y source calibration



Average on 96 CaF_2 crystals

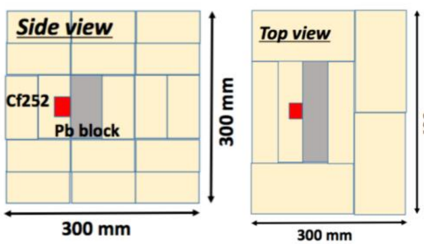
	Relative light yield	Resolution (σ) at 1.8MeV
Before	1	4.8%
Coil ON	1.23	4.2%
Cooling	1.58	3.6%

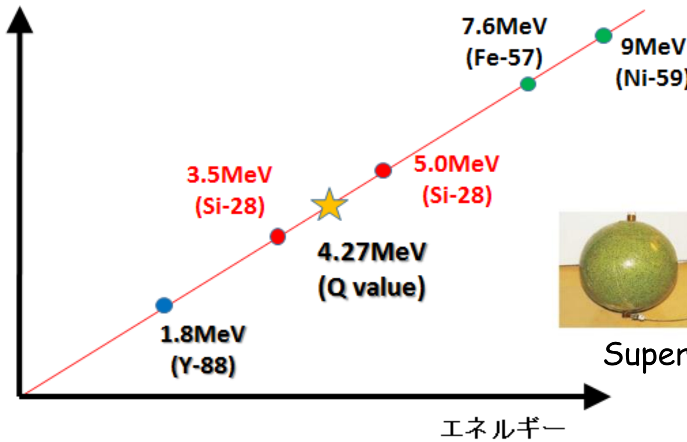
- Cooling system works for stable temperature control.
- Gain increase and energy scale stability is also checked using 2.6MeV γ-ray peak of ^{208}Tl.

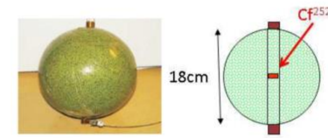


Energy calibration (n,γ) reaction

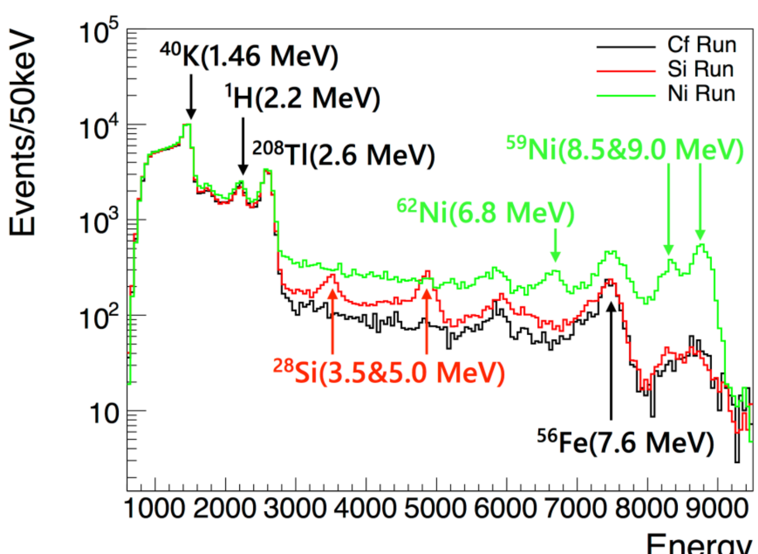
- New tool development for energy calibration near Q-value.
  - ^{28}Si(n,γ) reaction emits 3.5 MeV and 5.0 MeV γ-rays.
  - Si loaded polyethylene bricks are made and ^{252}Cf neutron source is placed at the center of the bricks.

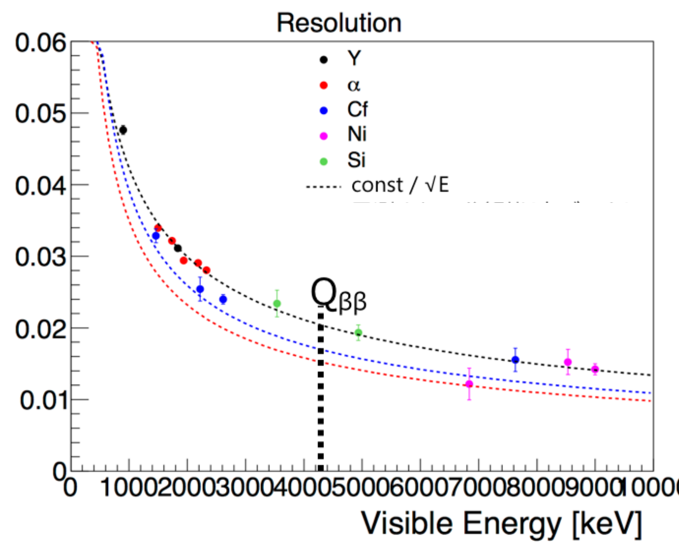






Super-K Ni ball



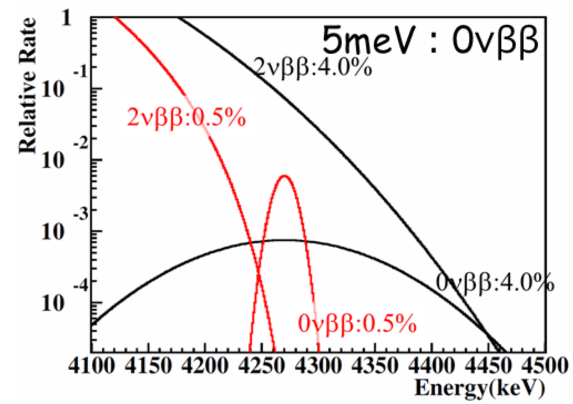


R&D for Future

Development in Future

- Sensitivity of CANDLES

	CANDLES III	Next CANDLES	
Crystal	3.2kg × 96 crystals	2% ^{48}Ca	50% ^{48}Ca
Total Mass	305kg (350g)	2 ton (25kg)	2 ton(610kg)
Energy Resolution	(4.0%)	2.8%(Req.)	0.5%(Req.)
$2\nu\beta\beta$	0.01	0.1	0.01
^{212}Bi, ^{208}Tl	0.26	~0.1	~0.01
Expected BG	0.27/year	< 0.7/3year	< 0.2/9year
$\langle m_\nu \rangle$	0.5 eV	0.08	0.009
	Current system	~2% enriched ^{48}Ca and cooling system	



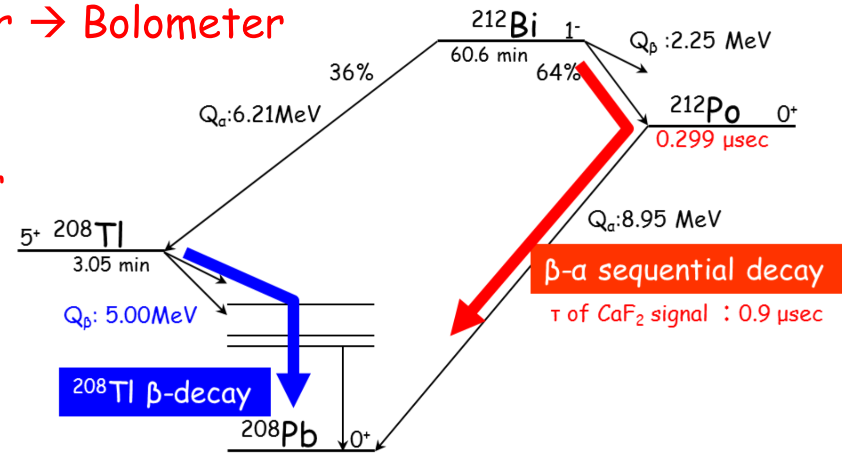
- Exploring Inverted hierarchy → Normal hierarchy region
  - Required two improvements
    - Realizing highly enriched ^{48}CaF, and ton-scale detector . <u>The enrichment technique is beeing developed, and is established for the small amount of Calcium. The technique is promising, we are on the stage of stable driving.</u>
    - Much better energy resolution (to avoid $2\nu\beta\beta$ background events)

- Impossible to further improve the energy resolution of CaF_2 scintillator

  ➔ Development of $^{48}CaXX$ bolometer

Background Candidates in Bolometer

- Tail of 2νββ spectrum
  - Improving energy resolution ; scintillator → Bolometer
- ^{48}CaXX internal radioactivities
  - Th-chain（β-α sequential decays） → Bolometer
  - Th-chain（^{208}Tl）
    → Segmentation, Multi-crystal
  - Environmental neutrons
    - Improving resolution ＋Multi-crystal



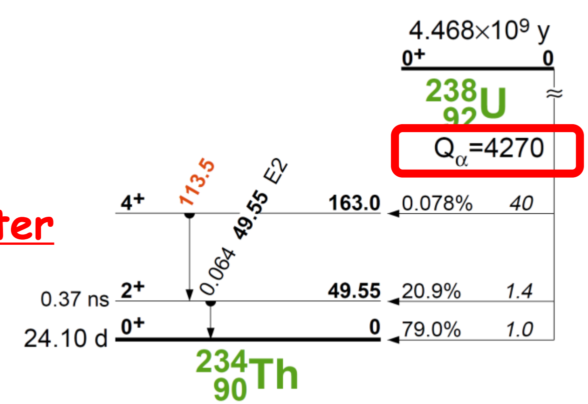
Possible to further reduce the BG by developing Bolometer

- But… new BG candidate
  - Q value of ^{48}Ca : 4267.98(32) keV @ arXiv:1308.3815
  - Q-value of ^{238}U (α-decay) ： 4270 keV

Impossible to avoid

➔ required particle ID

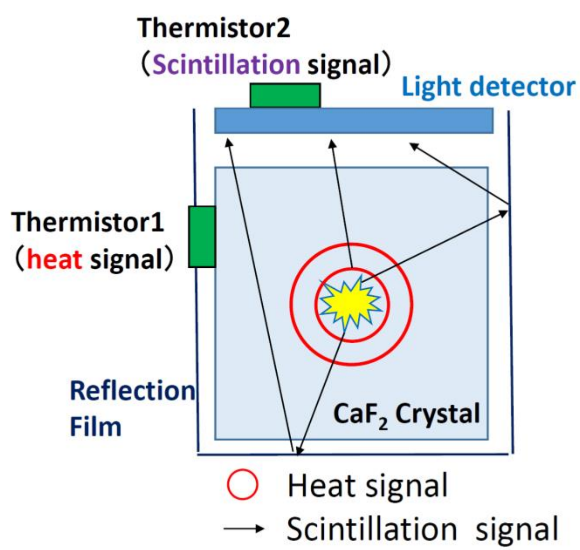
➔ <u>Developing CaF_2 Scintillating Bolometer</u>

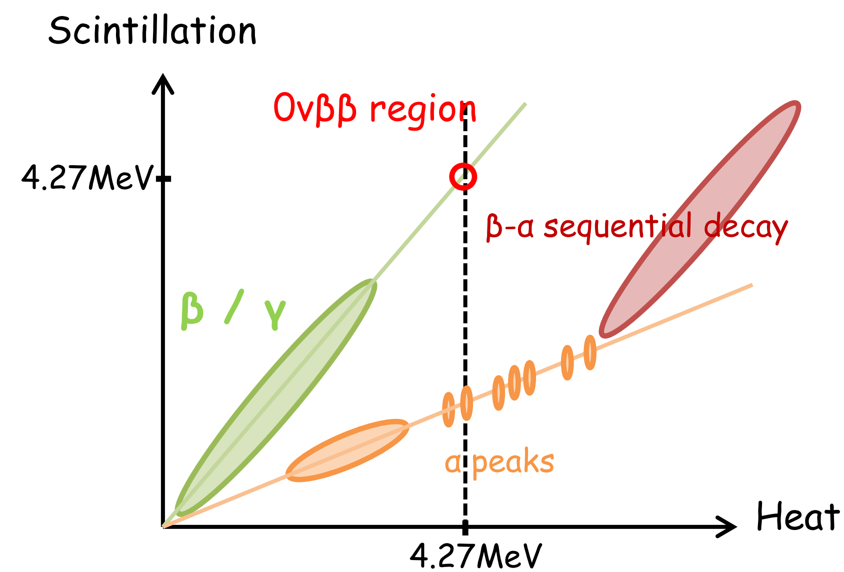


Scintillating Bolometer

- The technique (scintillating bolometer) was already established,
  - CRESST-II ($CaWO_4$), Lucifer, AMoRE
  - CaF_2(Eu) scintillating bolometer was also demonstrated by Milano group.

    Ref; NIMA386 (1997) 453, small size (~ 0.3 g) of CaF_2(Eu)





- Simultaneous measurement both heat and scintillation enables to identify the particle types (α/β particle ID)
- It is possible to reject alpha decay events of ^{238}U
  - Q-value; 4.27MeV = Q-value of ^{48}Ca 0νββ

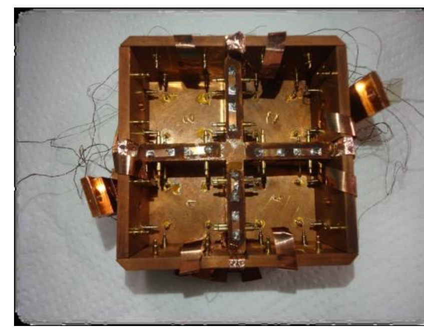
    ➔ ***Chance to achieve "BG free measurement"***

Current status of Development

- Dilution refrigerator
  - We will use the dilution refrigerator which was developed for the dark matter search by LiF by the Univ. of Tokyo group, and was customized to low BG measurement.
  - Preparing the operation.

    Under leak hunting in the ^{3}He-^{4}He circulation line.

- Target
  - 2cm cube of CaF_2 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.
- Schedule (Challenging)



Schedule

2017

Jun. Achieve low temperature (~few K)
Jul. Achieve ultra low temperature (~10 mK)
Sep. Detect the heat signal
Dec. Add a light detector to bolometer and achieve the simultaneous detection of heat and light signals

2018

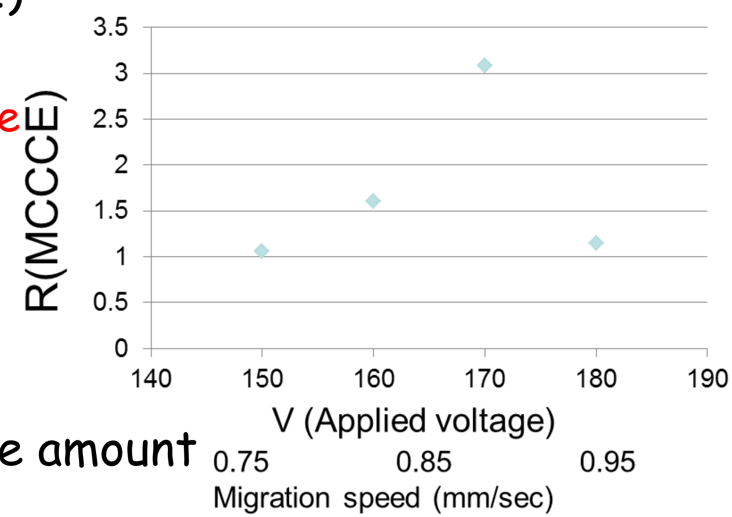
Mar. Increasing crystal's size and number

Enrichment of ^{48}Ca : MCCCE

- Electrophoresis
  - Migration speed is different between ^{40}Ca/^{48}Ca → Isotope separation
  - Capillary Electrophoresis
    - Small diameter ➔ High power density
    - Small amount , Good separation in short time
  - Counter Current Electrophoresis (CCE)
    - Large diameter ➔ Low power density
    - Large amount, Low separation in long time
  - In order to overcome,
    ➔ Multi-channel CCE
  - Principle was demonstrated,

currently stable driving and toward large amount

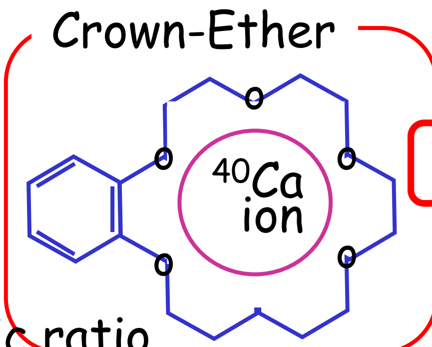
$$R(MCCCE) = \frac{43Ca/48Ca(MCCCE)}{43Ca/48Ca(natural)}$$

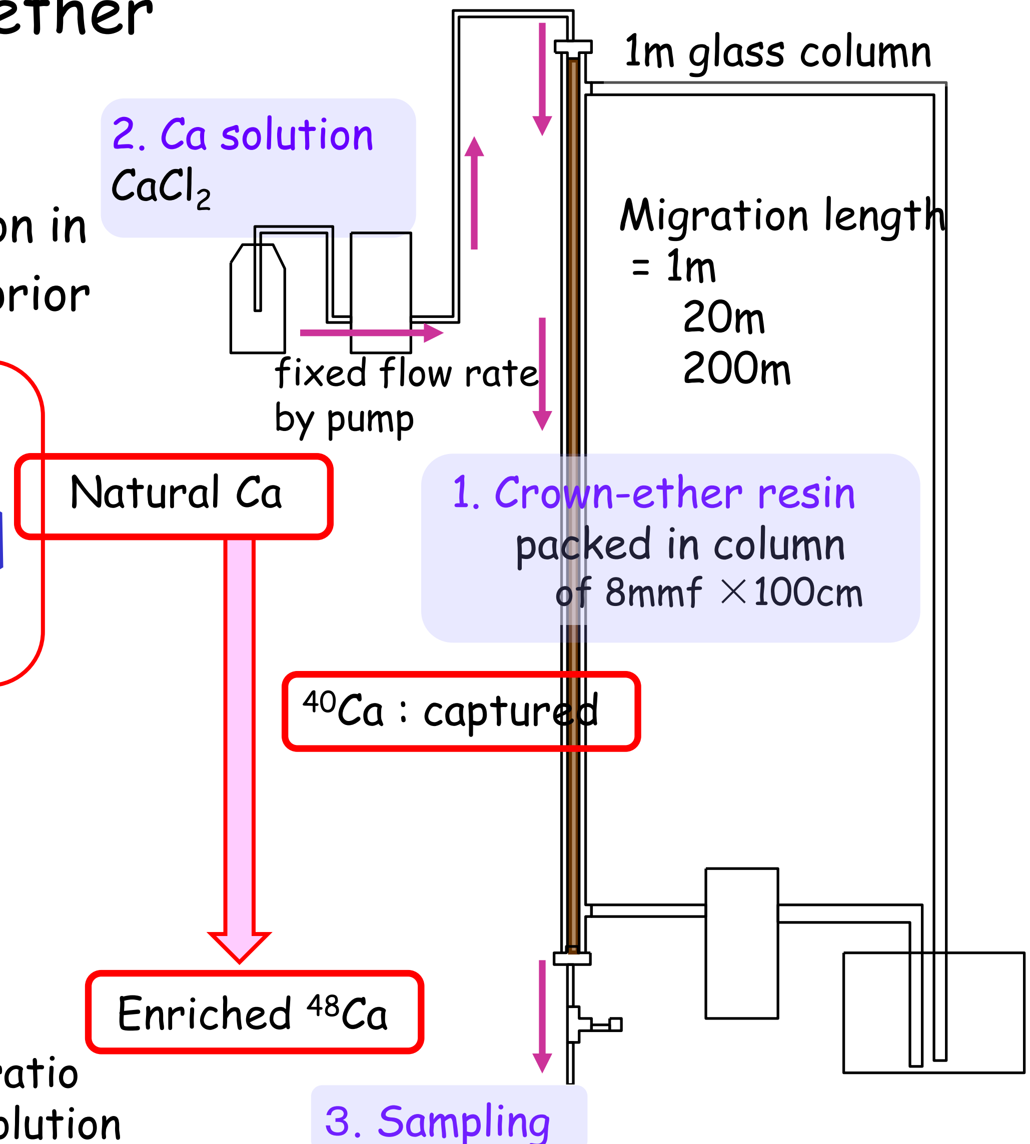


Enrichment
(43/40): 3.08 ➔ (48/40): ~ 6

R&D ; Enrichment of ^{48}Ca

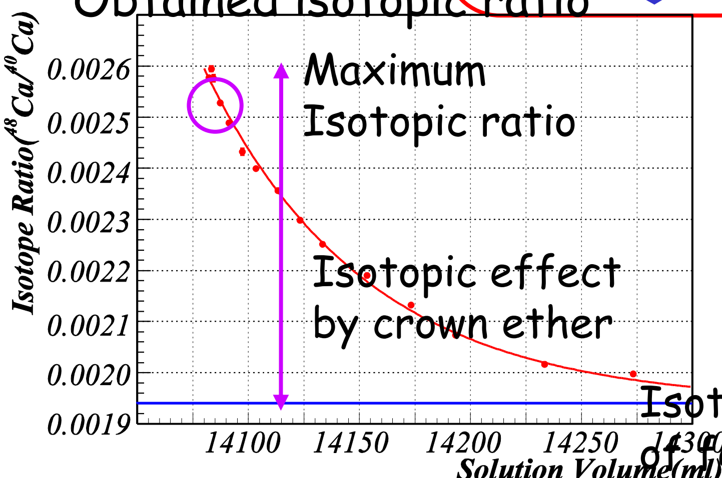
- Enrichment by crown-ether
  - Crown-ether rings adsorb Calcium ions
  - For calcium, ^{40}Ca adsorption in crown-ether is slightly prior





Result

Obtained isotopic ratio



- Cost of crown-ether resin is much improved recently.

Summary

- CANDLES is the project to search for 0νββ decay of ^{48}Ca.
- Measurement of 0νββ decay of ^{48}Ca has a great chance to achieve "Background Free Measurement", the key characteristic to perform sensitive 0νββ search .
- CANDLES-III detector is currently operated in the underground lab. at Kamioka mine.
    - The basic performance is now under investigation, especially about background profile, and its rejection capability.
    - We are continuously upgrading the detector to achieve the BG free condition.
- ^{48}Ca has a large potential sensitivity when we established the enrichment technique of ^{48}Ca (not mentioned in datail).
- For further improvement of the sensitivity, we are starting to develop the scintillating bolometer of CaF_2. This R&D will be a key technique to explore the normal hierarchy region.

CANDLES Collaboration

- ***Department of Physics, Osaka University***
  T. Kishimoto, S. Yoshida, H. Kakubata, Wang Wei, V. T. T. Trang, C. Wei Min, T. Maeda, T. Ohata, K. Tetsuno, T. Uehara, X. Lee, B.T. Khai, M. Shokati, T. Batpurev, K. Akutagawa, S. Katagiri, N. Yotsunaga, K. Kanagawa, M. Tsuzuki
- ***Research Center for Nuclear Physics, Osaka University***
  M. Nomachi, S. Ajimura, S. Umehara, T. Iida, Y. Takemoto, K. Matsuoka, Y. Takihira
- ***Guraduate School of Engineering, University of Fukui***
  Y. Tamagawa, I. Ogawa, K. Nakajima, S. Noshiro, A. Masuda, K. Morishita, M. Washino, F. Doukaku, T. Hiyama, K. Teranishi, N. Takahashi
- ***Faculty of Integrated Arts and Science, University of Tokushima***
  K. Fushimi, K. Mori
- ***Osaka Sangyo University***
  R. Hazama, N. Nakatani
- ***Saga University***
  H. Ohsimi

Candle

Thank you.