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

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CANDLES Collaboration

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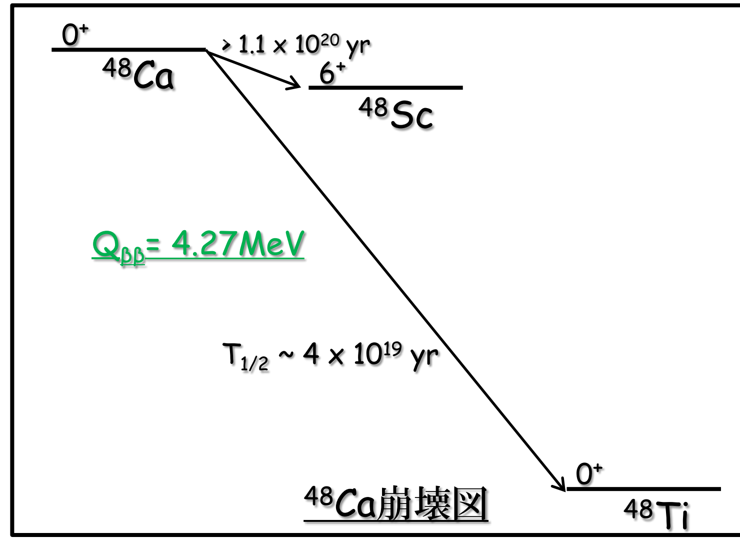
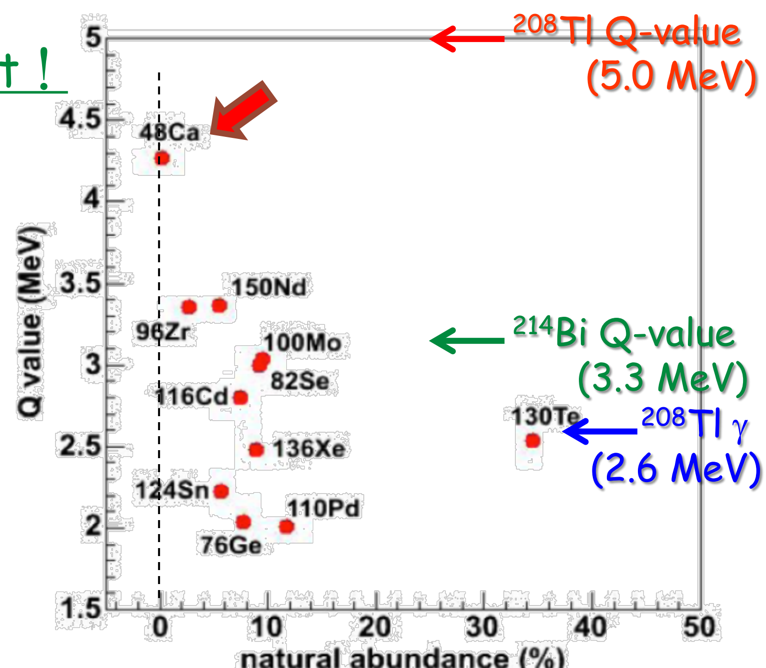
^{48}Ca for ββ Isotope

- ^{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)



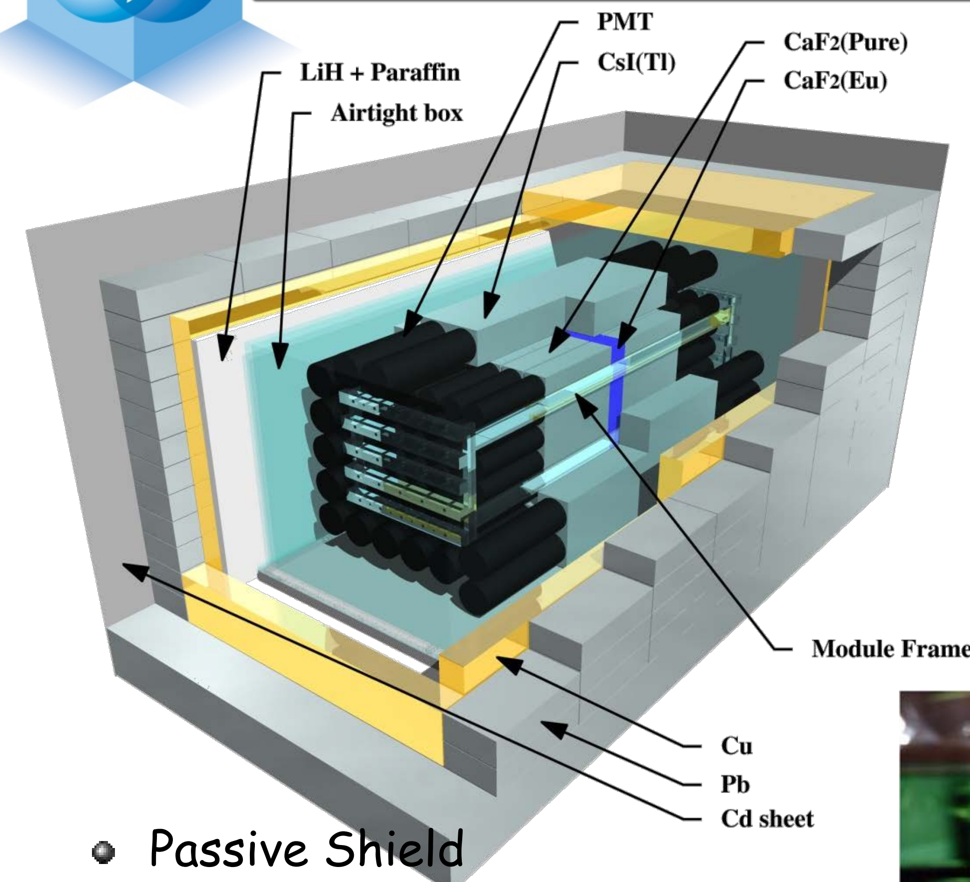
  - Chance to realize the Background Free Measurement !

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



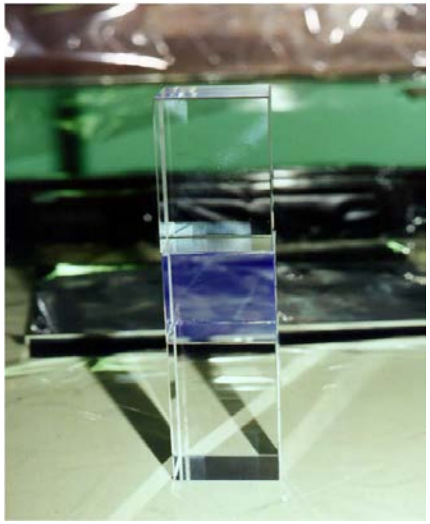
  - Small natural abundance (0.187 %)
- However,
  - Chance to improve the sensitivity by the enrichment without scale-up.
  - Low risk to increase BG origins

ELEGANT VI Detector Array



- Large mass
  - Scintillator 45×45×45 cm^3
    6.4 g of ^{48}Ca, ~3.5 kg ^{19}F
- Low Background
  - high purity crystal
  - least material : non hygroscopic
  - **4π active shield**
    - CaF_2(Eu)+CaF_2(pure)
      roll-off ratio
    - segmentation
    - CsI(Tl) veto detector

- Passive Shield
  - OFHC Cu(5 cm), Pb(10 cm)
  - air-tight box + N_2 gas purge
    Rn in the air
  - LiH + paraffin(15 mm)
    Cd sheet(0.6 mm)
    H_3BO_3+H_2O tank



CaF_2(pure)
UV emission (~285nm)

CaF_2(Eu)
Visible light emission
Non-transparent ag. UV

CaF_2(pure)

Result of ELE-VI

- No events were observed in 0νββ energy window.

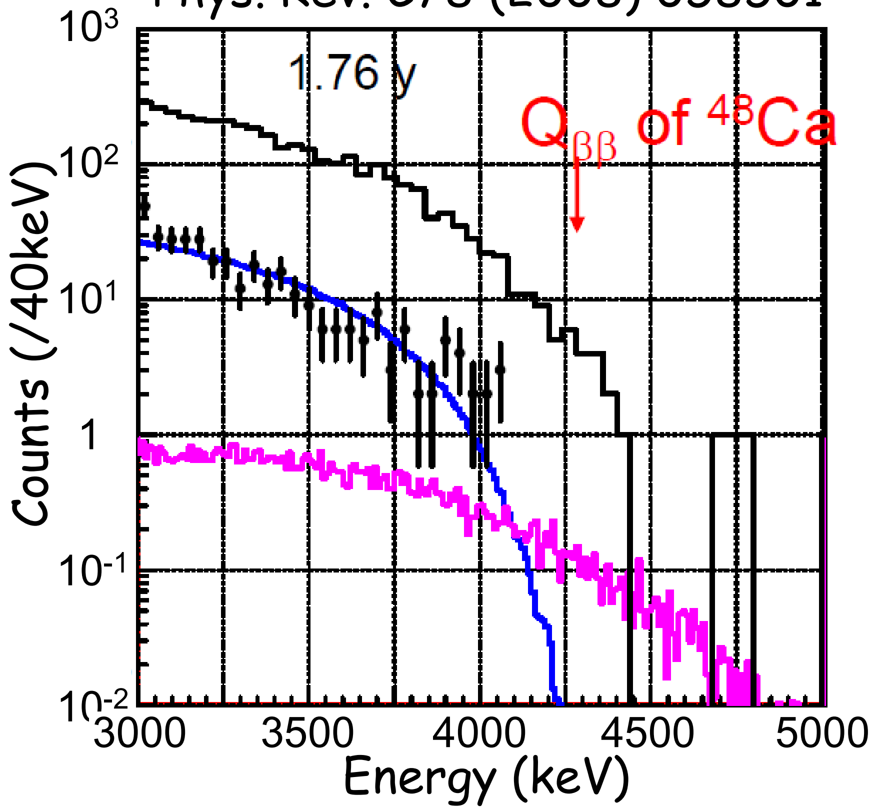
  "Background Free Measurement"

- 0νββ half-life of ^{48}Ca : most stringent

$$T_{1/2}^{0\nu\beta\beta} > 5.8\times10^{22}\ \text{year}\quad (90\,\%\ \text{C.L.})$$

$$\langle m_\nu \rangle < 3.5 \sim 22\,\text{eV}\quad (90\,\%\ \text{C.L.})$$

Phys. Rev. C78 (2008) 058501



- 4π active shield was effectively worked to achieve "Background Free Measurement".

- Sensitivity was not limited by Background. For further sensitivity, we need a large amount of ^{48}Ca

➔ CANDLES

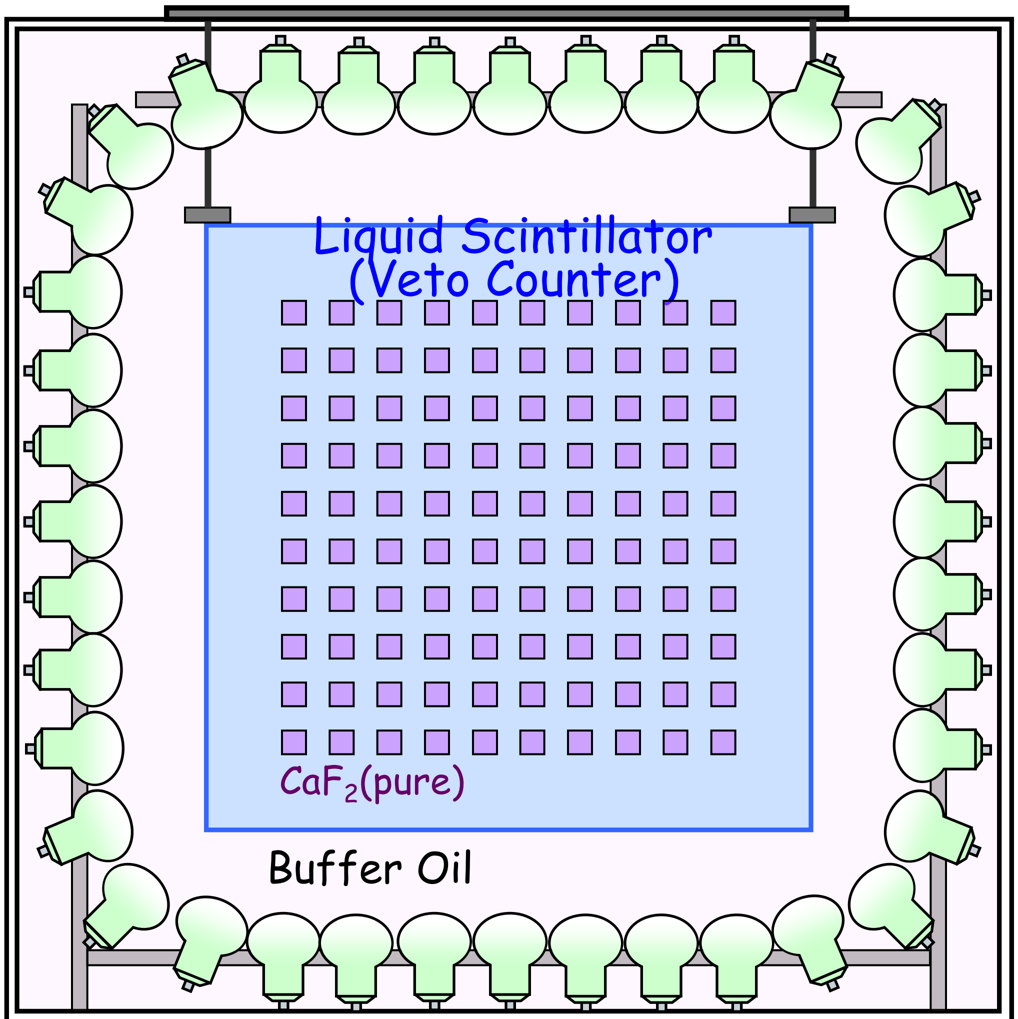
CANDLES Project

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

Conceptual Design of CANDLES

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matrters by Low Energy Spectrometer



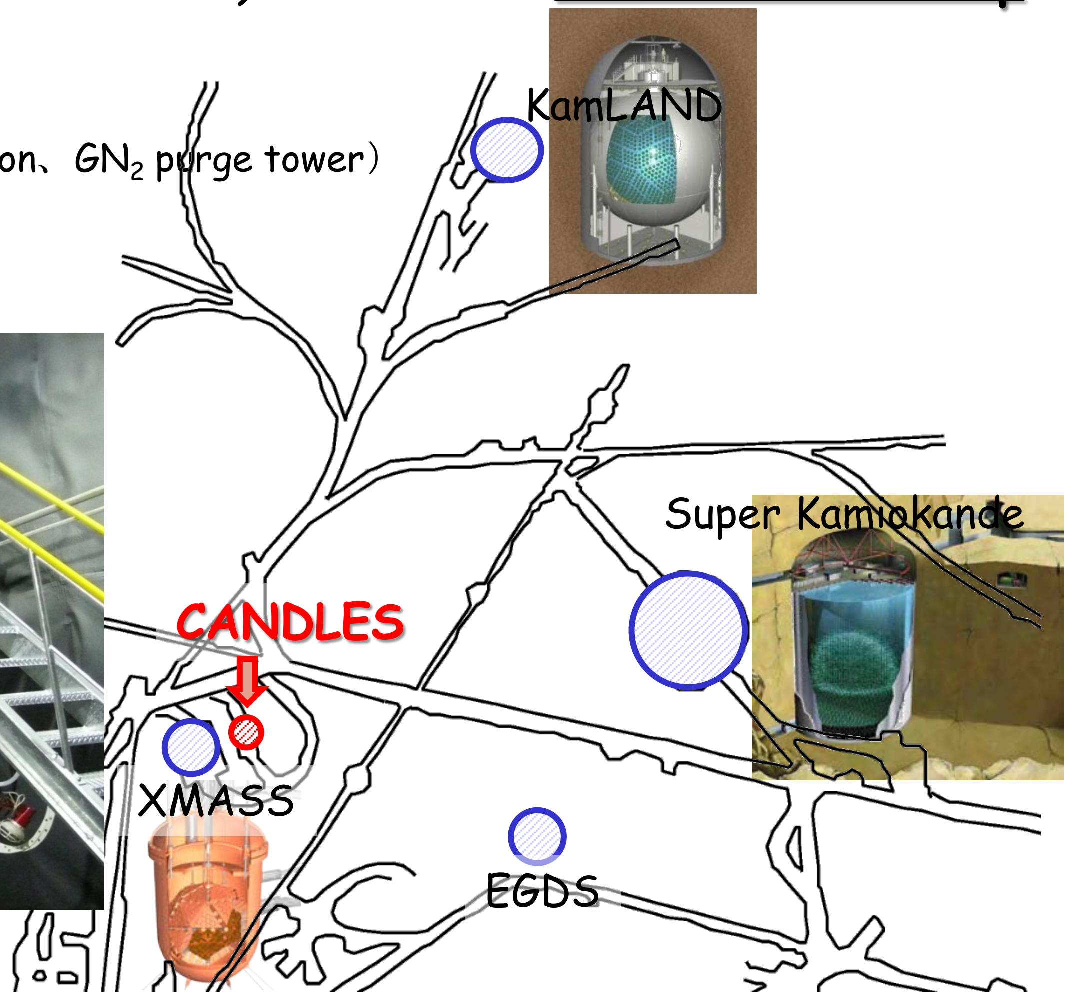
- CaF_2(pure) scintillator
  - ^{48}Ca ; $0\nu\beta\beta$ isotope
  - Transparent, Ultra-pure crystal
  - Long attenuation length (>10m@350nm)
  - $\beta\beta$ decay source = detector → Good detection ε
  - Low cost
  - Low-Z nucleus → less sensitive γ-ray BG
- Liquid scintillator
  - 4π active shielding
  - Large volume
  - High purity, transparent
  - WLS(Wave length shifter)
    - CaF_2(pure) Emission ; 280 nm
    - PMT Q.E. ; max. @ 400 nm
- Large PMT
  - Simultaneous measurement with CaF_2 & LS
  - Identified by pulse shape of scintillation light
    - CaF_2 ; time constant ~ 1000 nsec
    - LS ; a few 10 nsec

→ Large Volume Detector

CANDLES III @ Kamioka

- **CANDLES III**
  - Site: Kamioka mine ~1000 m depth
  - Detector: 3m$^{\phi}$ × 4m ^{h} (Water tank)
  - Liquid Scintillator
    - Reserver tank
    - Purif. system（L-L Extraction、GN_2 purge tower）

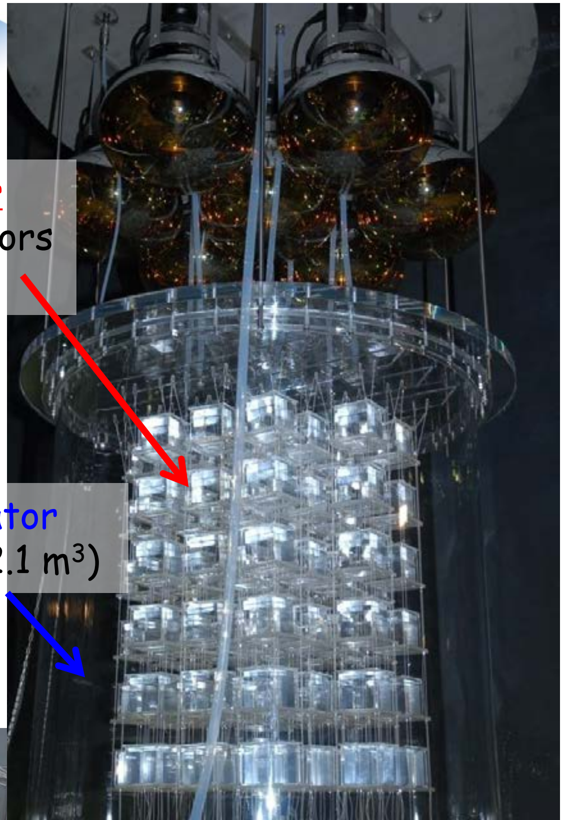
Kamioka Lab. Map

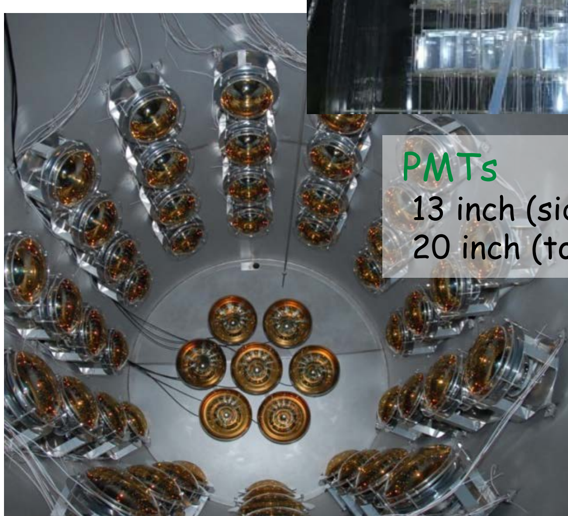


CANDLES III Detector

Main detector
CaF_2 scintillators
(305kg)

Liquid scintillator
acrylic tank (2.1 m^3)



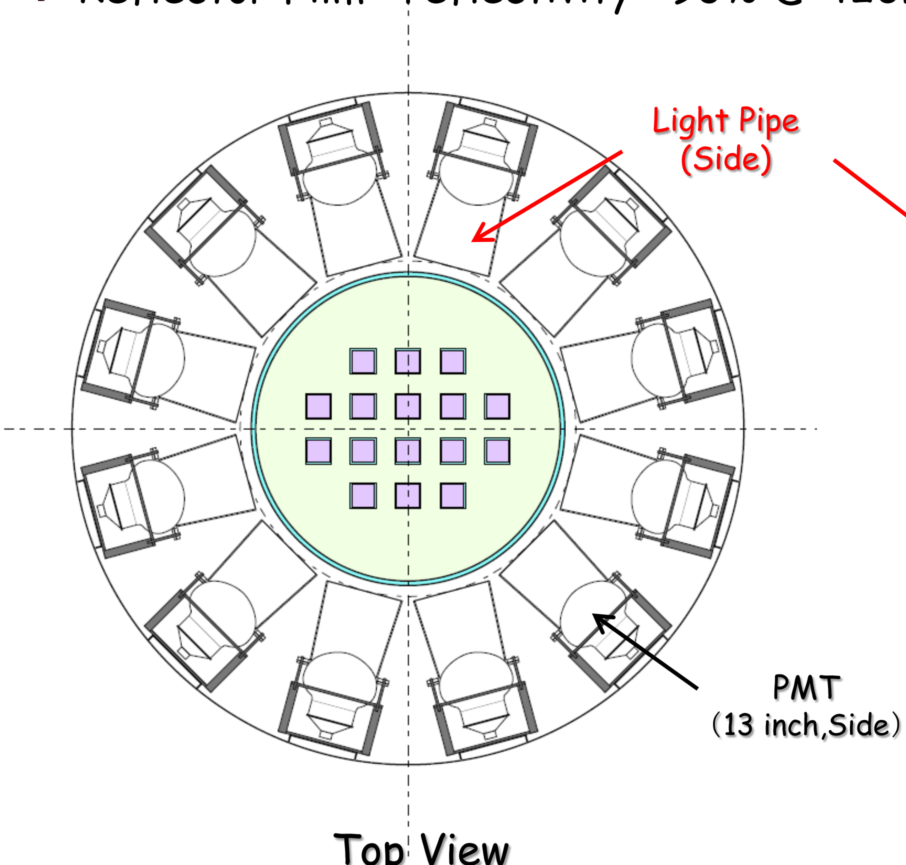


PMTs
13 inch (side) ; x 48
20 inch (top & bottom) ; x 14

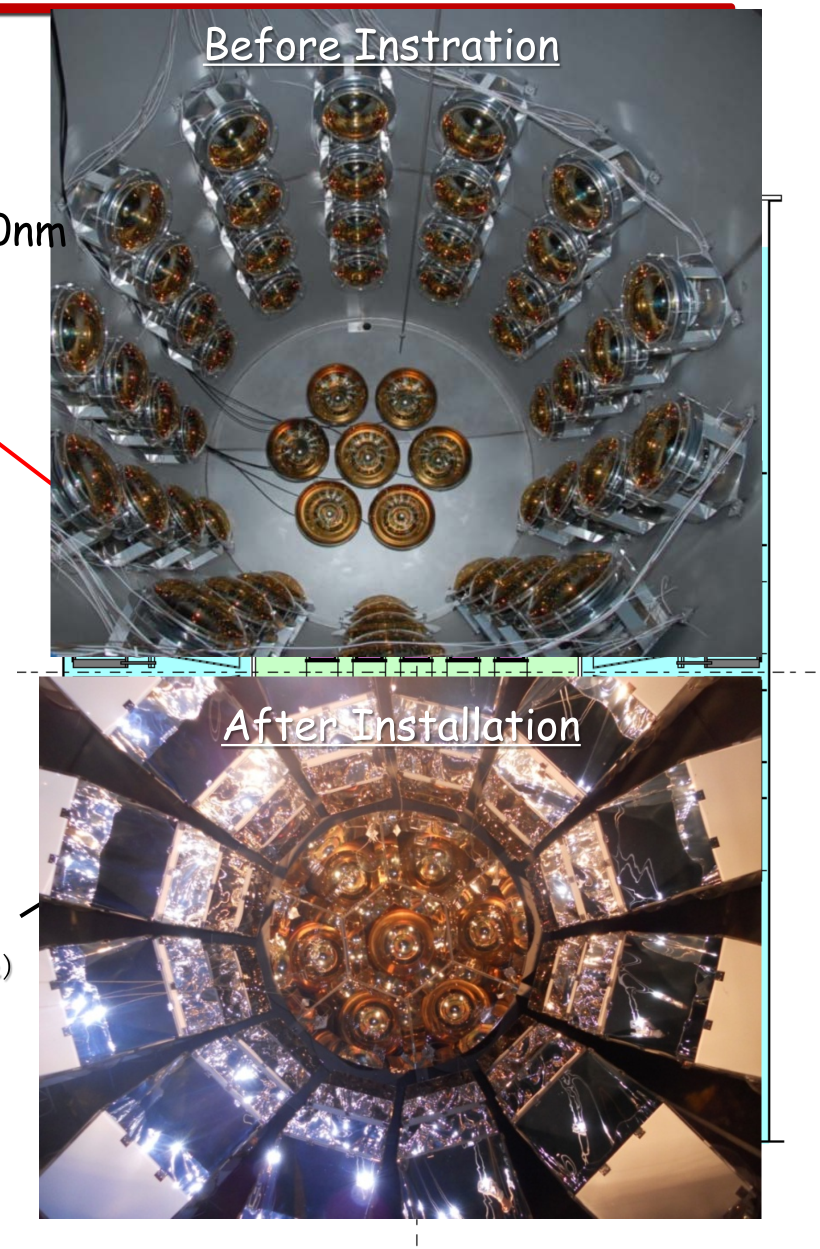
- CaF_2 Module
  - CaF_2(Pure) ; 96 Crystal → 305 kg
  - WLS Phase ; 280 nm → 420 nm
    - Thickness ; 5 mm
    - Composition ; Mineral Oil＋bis-MSB (0.1 g/L)
- Liquid Scintillator (LS)
  - 1.4 m ϕ x 1.4 m H
  - Volume ; 2.1 m^3 (1.65 ton)
  - Composition
    - Solvent ; Mineral Oil(80%)+PC(20%)
    - 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
  - 13 inch (Side) ; x 48
  - 20 inch (Top and Bottom) ; x 14

Light Propagation to PMT

- To improve energy resolution
  - Guide scintillation light to PMTs
  - Reflector Film : reflectivity ~93% @ 420nm



Top View



Pulse Shape Discrimination

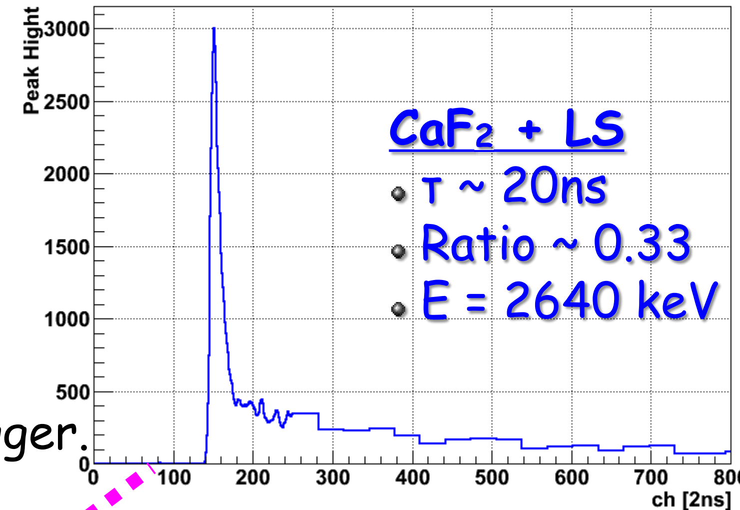
- Pulse shape discrimination between CaF_2 and LS signals

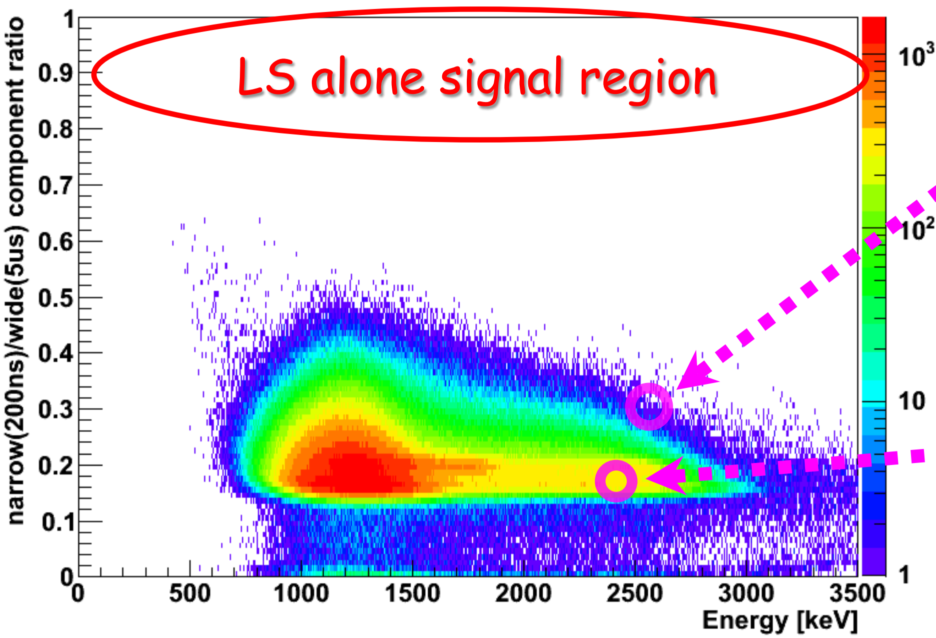
Difference of scintillation time constant

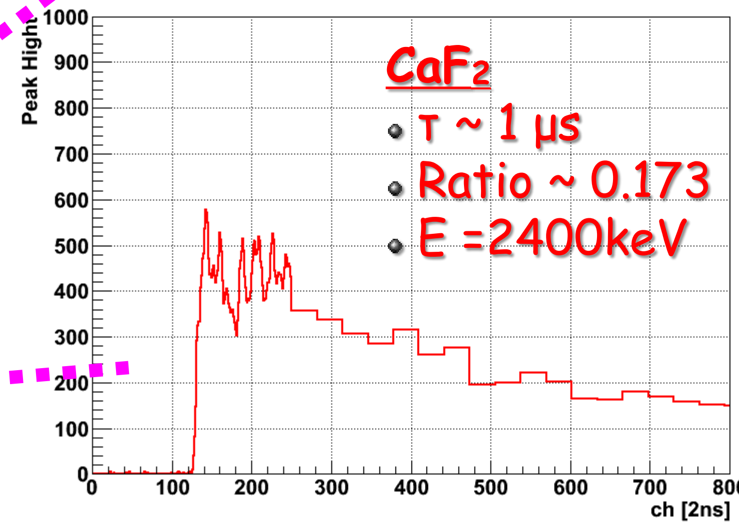
- CaF_2 ; ~ 1000 nsec
- LS ; a few 10 nsec

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

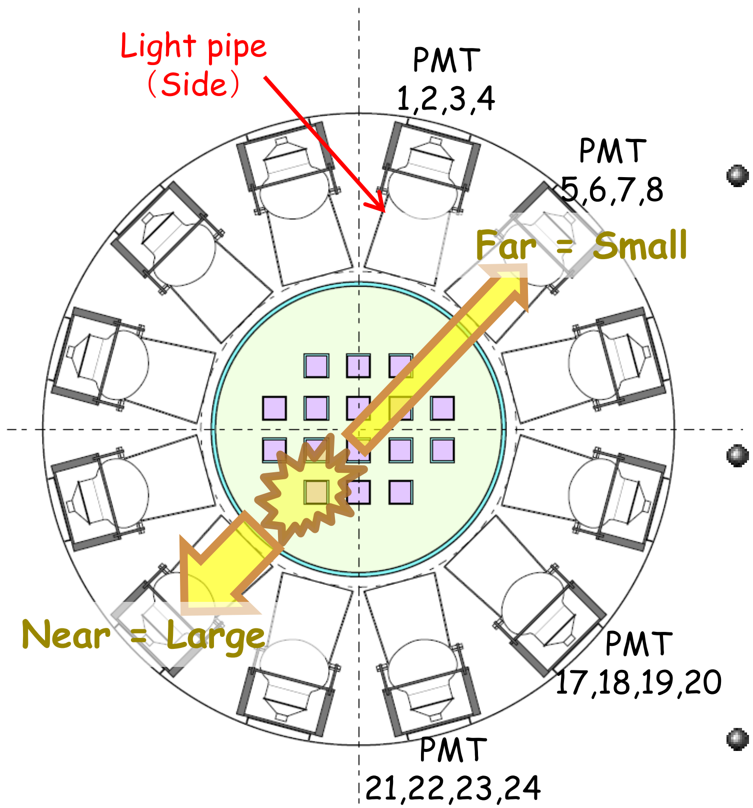
LS alone signals is rejected by hardware trigger.







Event Reconstruction



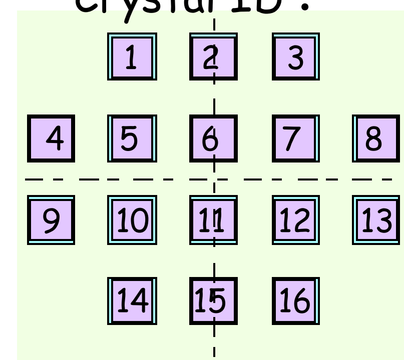
Top View

- CaF_2 Module Configuration
  - 16 x 6 layers = 96 crystals
  - Calibration Crystal (C94) ; Lowest layer⑭

    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

Crystal ID :

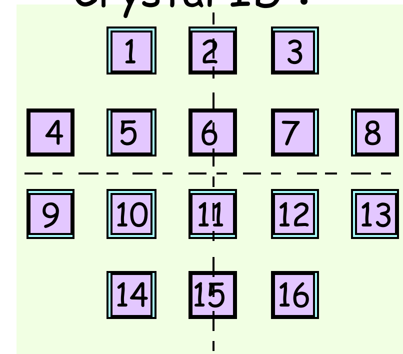


- Energy
  - Number of Photoelectrons
  - Regular calibration using ^{88}Y
- Position
  - Weighted Mean = $\dfrac{\sum PMT(i) \cdot NPE \times \overrightarrow{PMT(i)}}{NPE\ Total}$

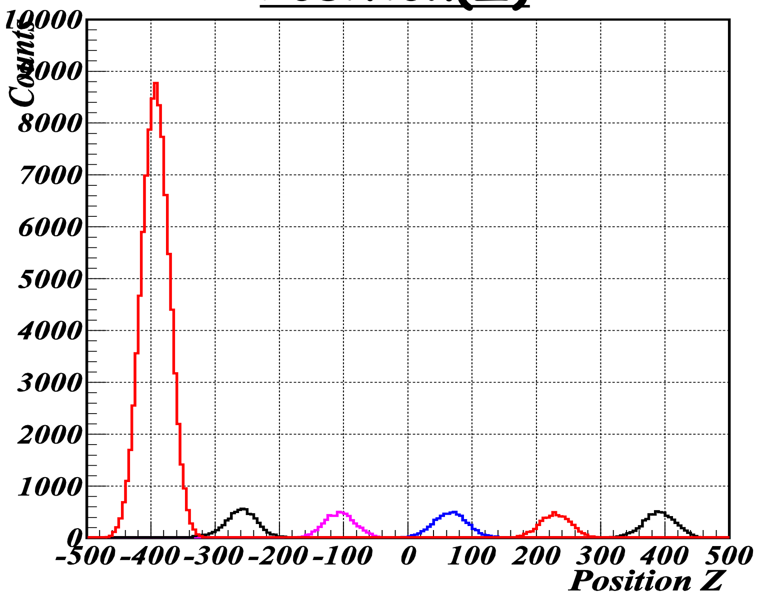
Position Reconstruction

- Position Reconstruction
  - Select events with CaF_2 pulse shapes
  - 95 high-purity crystals and 1 contaminated (calibration) crystal
- ~6σ separation
- Single-site & multi-site events of γ-rays : R&D

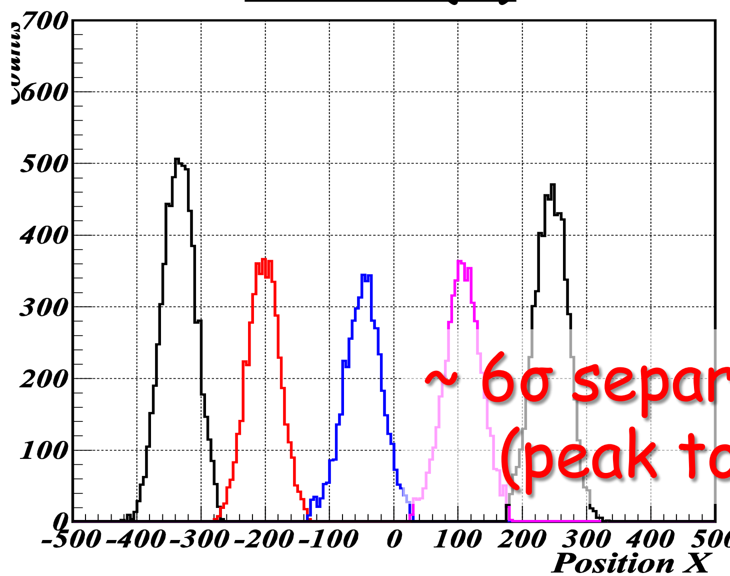
Crystal ID :



Position(Z)



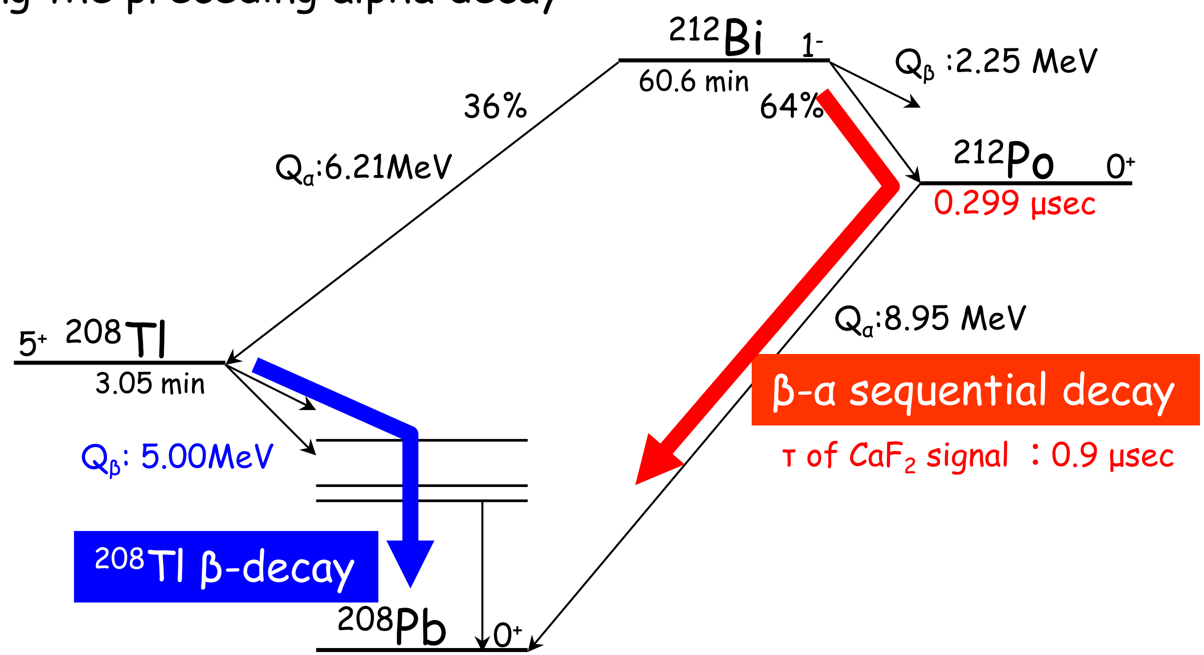
Position(X)



~ 6σ separation (peak to peak)

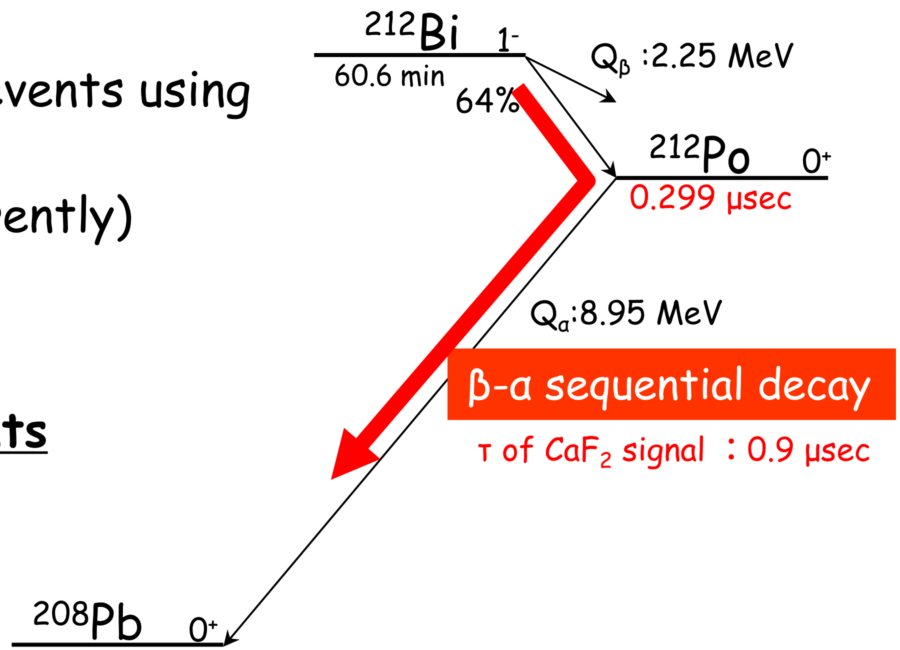
Background Candidates

- 2νββ decay event (unavoidable background)
  - ➔ Improve E-resolution
- Natural radioactivities in CaF_2 crystal
  - Sequential Pulse
    - Reduction by Pulse Shape Analysis
  - ^{208}Tl Decay
    - Reduction by tagging the preceding alpha decay
- Neutron induced BG



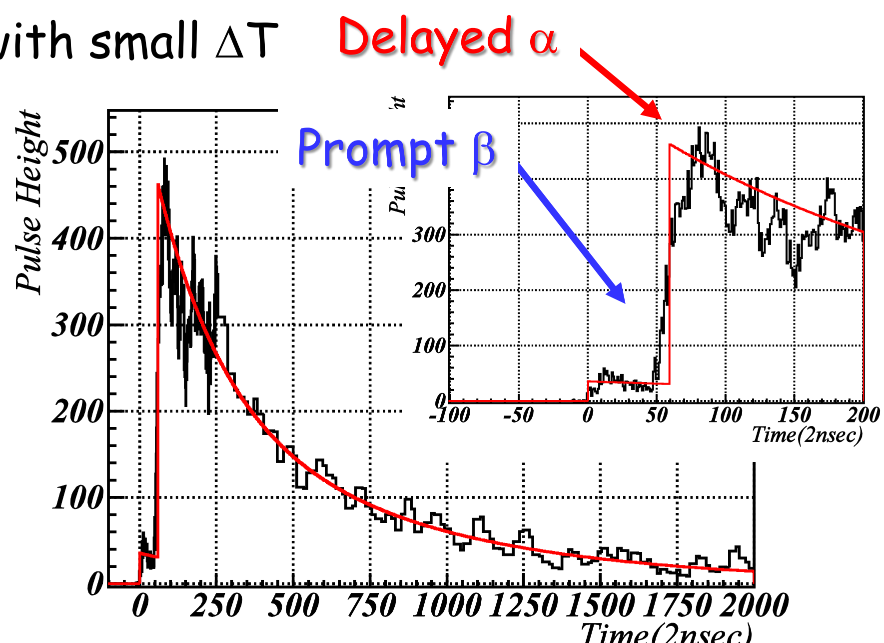
Background Rejection (1)

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



Typical pulse shape of sequential events

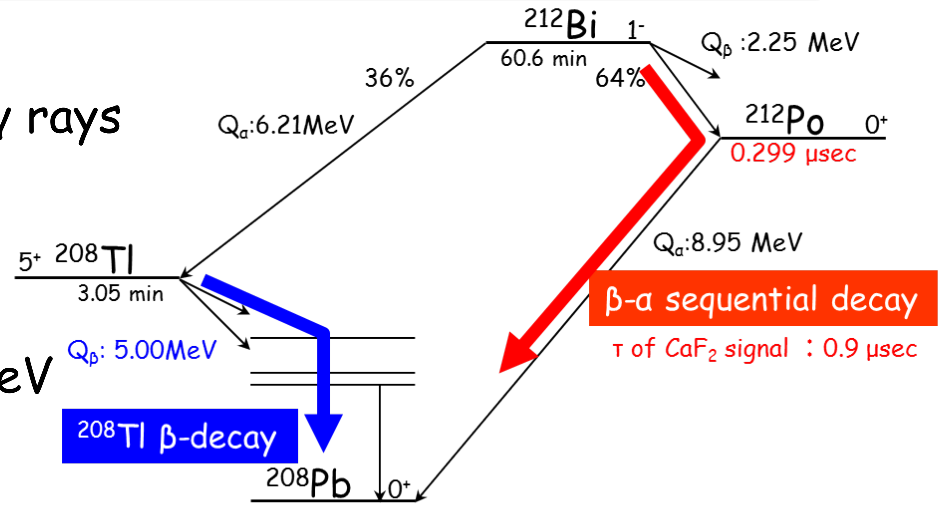
with small ΔT

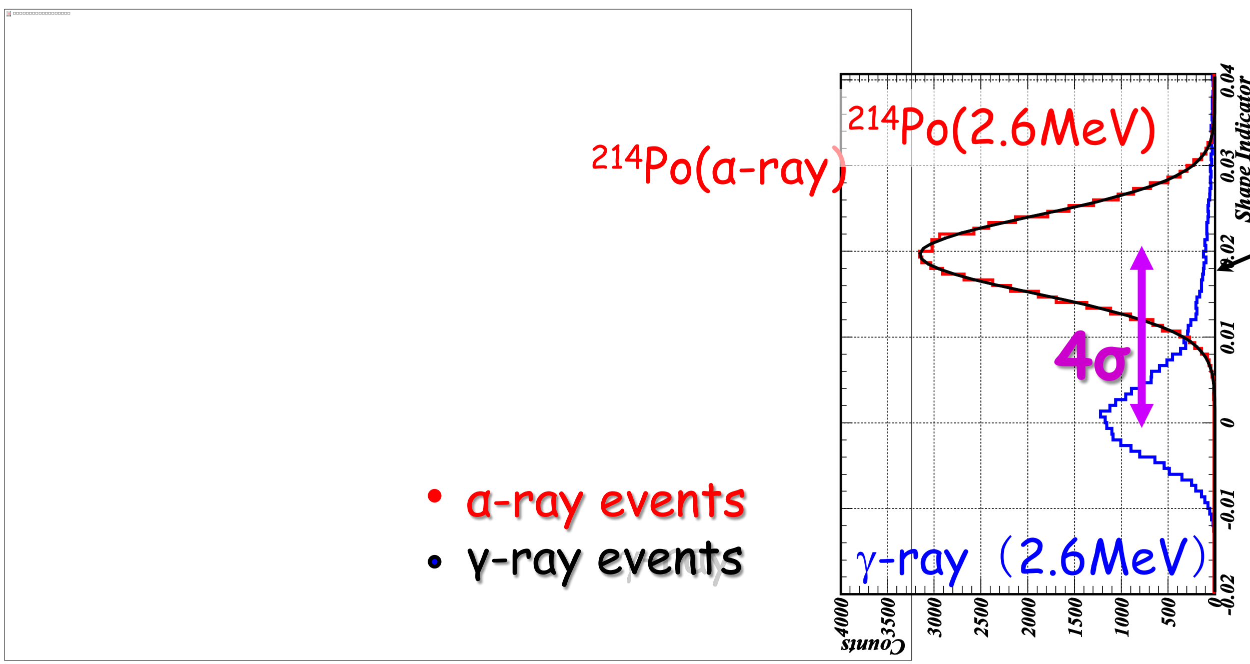


Sum-up signal of 62 PMT

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



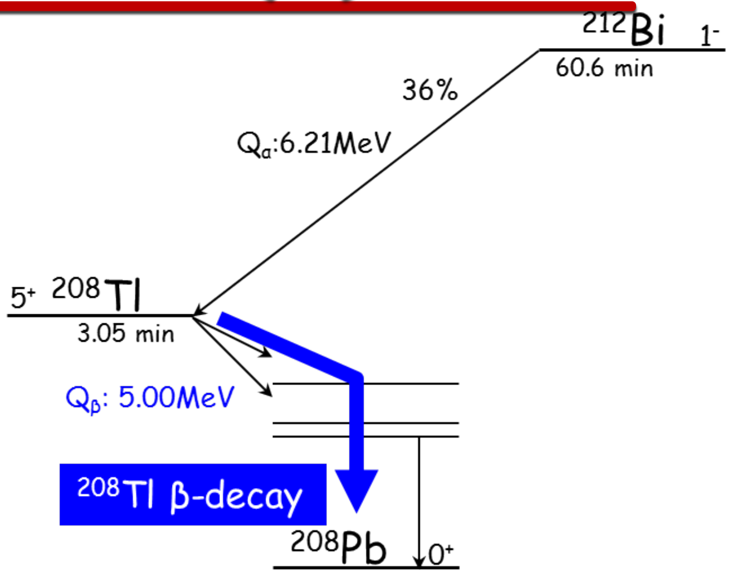


CaF_2 γ
+small LS signal

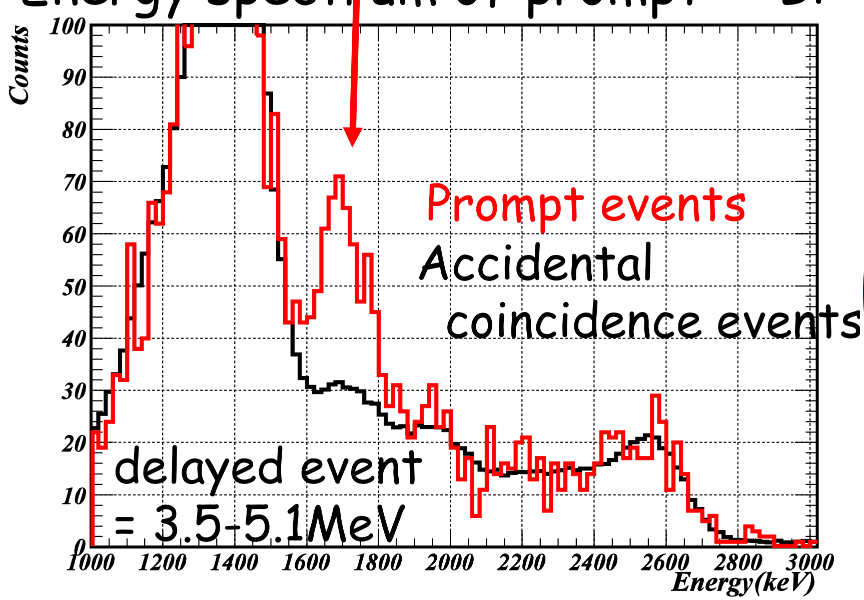
ref：Shape Indicator
(PRC67(2003) 014310)

Background Rejection (3)

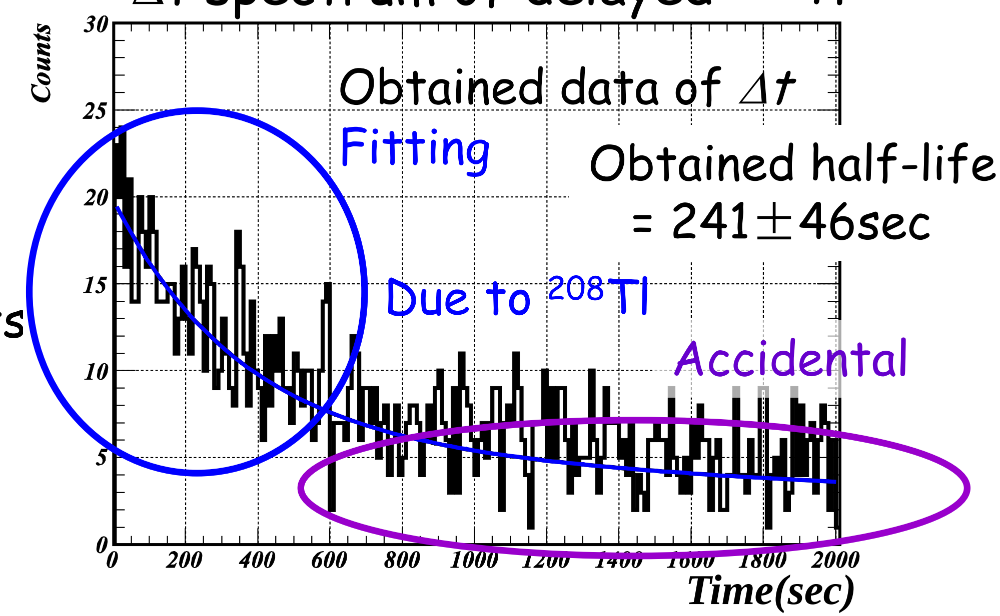
- $^{212}Bi \rightarrow ^{208}Tl \rightarrow ^{208}Pb$ decay
  - We can identify the prompt α decay of ^{212}Bi using PSD.
  - We set the veto window (~15 min.) after detecting ^{212}Bi-α signal.
  - We improved the rejection efficiency by DAQ upgrade etc.



Energy spectrum of prompt ^{212}Bi



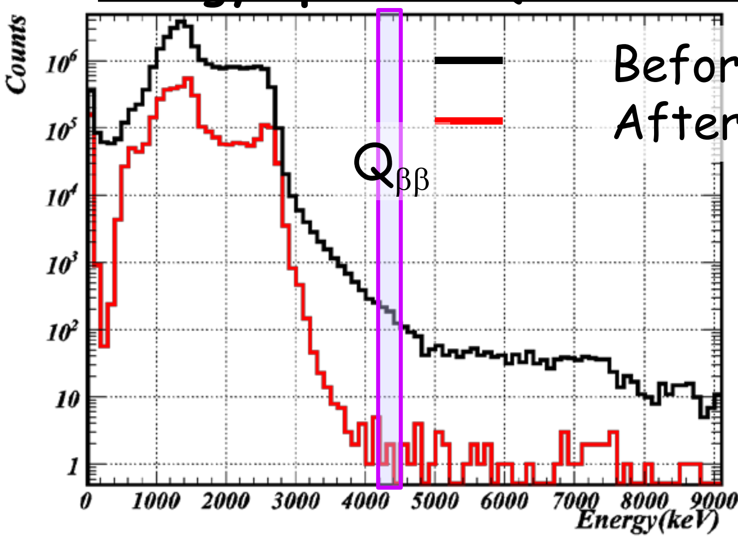
Δt spectrum of delayed ^{208}Tl



Energy Spectrum

- Measurement : Current physics run in CANDLES-III

Energy spectrum (~8 weeks)



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

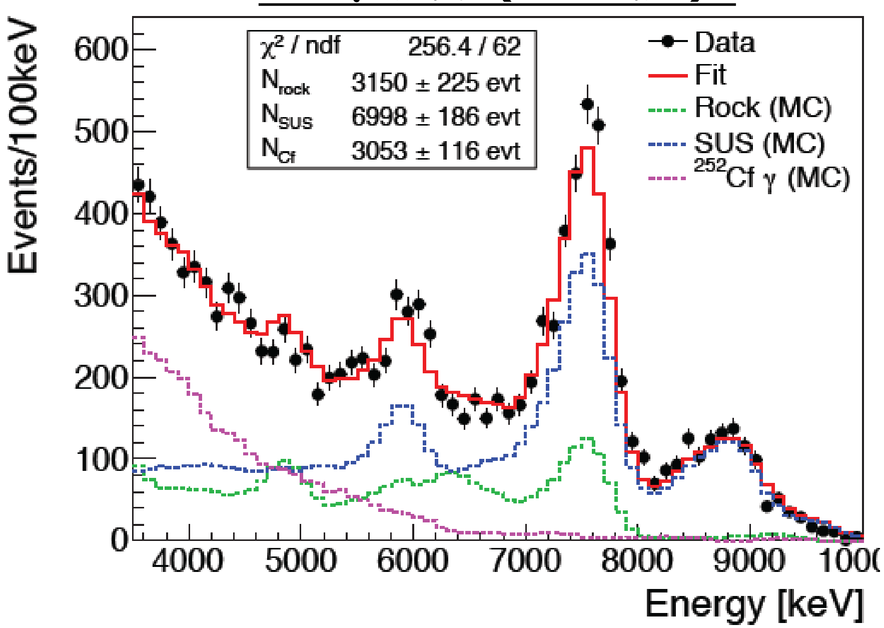
  ➔ Detector sensitivity:0.5eV

Background @ High energy region

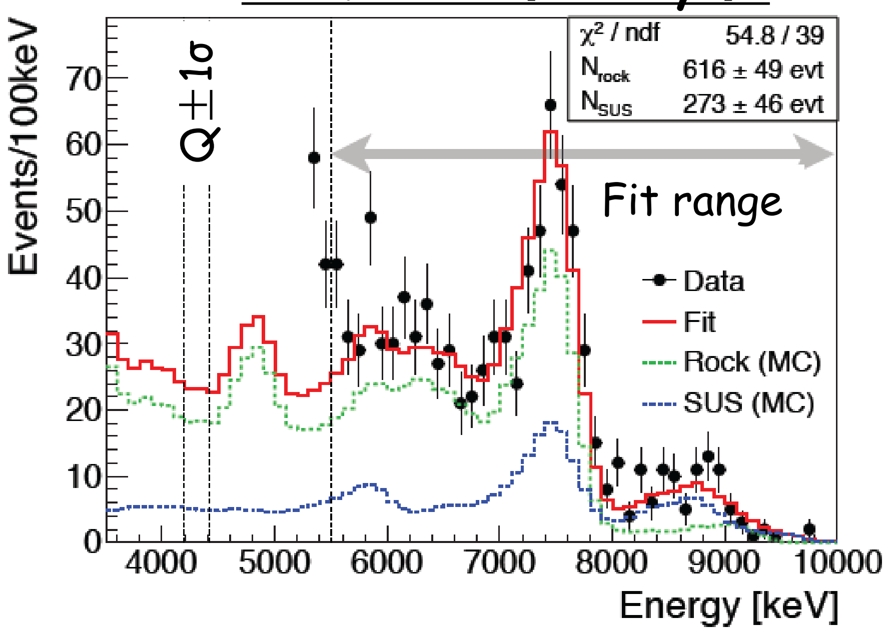
- Neutron source run (^{252}Cf)
  - 1 hour of source run = 1 year of physics run
- Detector simulation of (n,γ)
  - Generate γ-rays uniformly in tank or rock according to γ-ray spectrum of (n,γ) reaction

Loose event selection cut !

^{252}Cf run (3 hours)



Normal BG (88 days)



Background @ High energy region

- Obtained spectra are well reproduced by MC simulations.
  - Various cut efficiencies for $0\nu\beta\beta$ analysis can be checked with source run.

- (n,γ) BG in $0\nu\beta\beta$ window is evaluated from MC spectrum.
  - Rock/SUS = 3.6 ± 0.7 in $Q_{\beta\beta} \pm 1\sigma$
  - (n,γ) BG: 3.4 ± 0.4(stat.) evt/26crystals/60days
    (consistent with estimation from data, 3 ± 1 evt)
  - Currently, largest background component in CANDLES

- Toward "Background Free Measurement"
  - We are now designing the shield by MC simulation.
  - We will install
    - Pb shield : for (n,γ) BG from rocks in the mine
    - B or Cd sheet: ~ a millimeter in thickness : for neutron BG, to avoid (n,γ) reaction in SUS water tank

Further Improvement

- Recent upgrading detector system
- R&D's

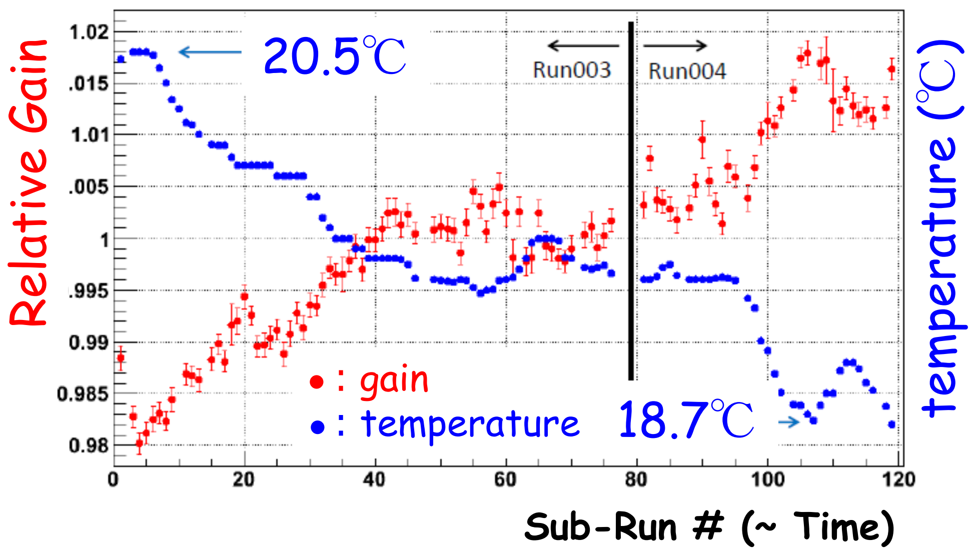
Gain Correction by Temperature

- **Gain Correction**
  - Energy scale was checked in pilot run by using highly contaminated crystal.
  - CaF_2 light output depends on its temperature.
  - Gain ~ +2% / deg.C

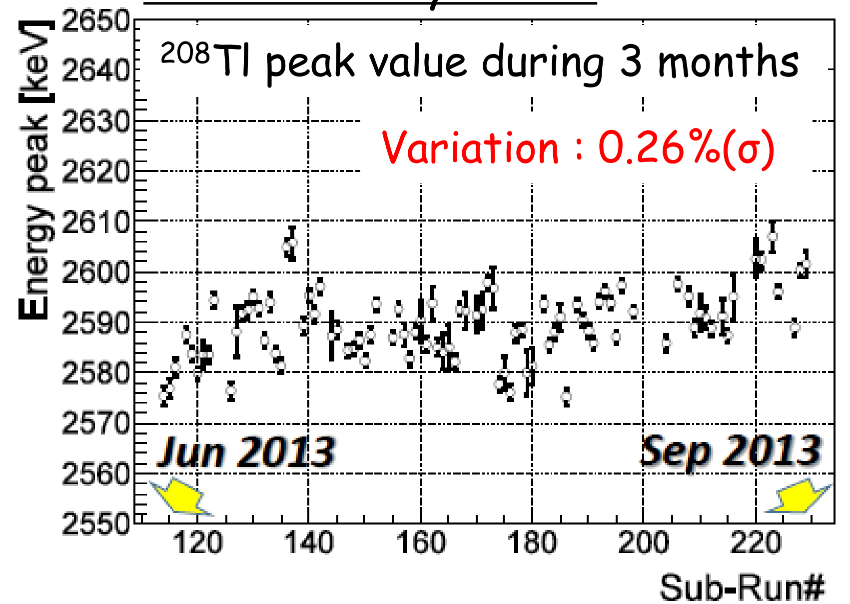
    ➔ Check gain stability using ^{208}Tl γ-ray peak (physics run).

    Gain variation : 0.26%(σ)
  - <u>This satisfied our current requirement !</u>

<u>Detector Temp. .vs. Gain (BG peak)</u>



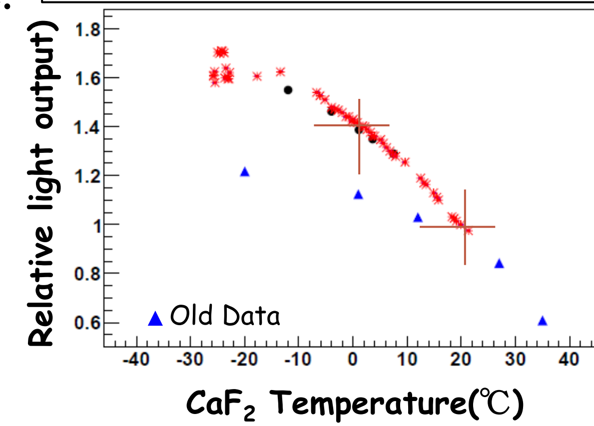
<u>Gain Stability Check</u>



Detector Cooling System

- Light Output of CaF_2 Scintillator
  - CaF_2 light output is proportionally increasing down to -20 ℃.
  - This effect was confirmed by CaF_2 module.

Temp. Dependence of Light Output



- Installation of the cooling system.
  - We cooled the experimental room, down to 2 Celsius deg. to stabilize the temperature at the detector center within 0.1 deg.C (0.2% of gain).

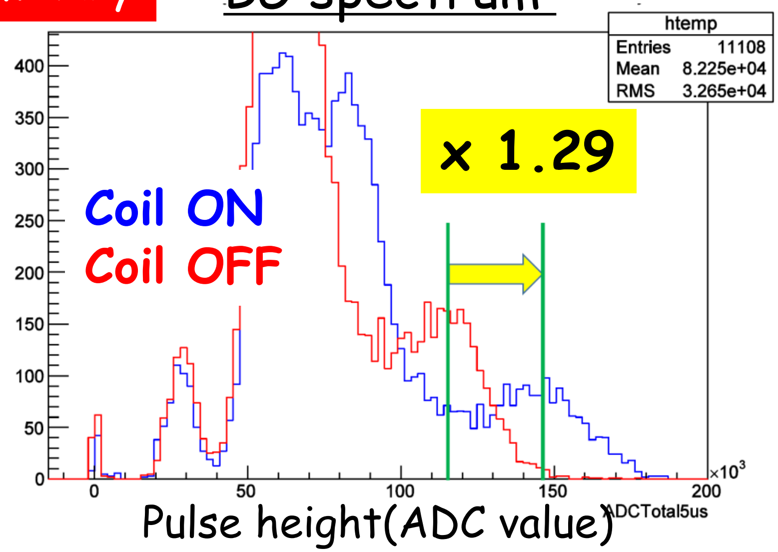
    ➔ 35% increase of gain
  - The system was installed in March 2014. The test operation was "almost" successfully done.
  - The heat exhaust outside of the room is currently improving.
  - We will start to operate the cooling system in this month.

Upgrading CAN-III Detector

- Installation of the "Geomagnetic cancellation coil"
  - We are using large diameter PMTs (13 and 20 inch's)
  - Well-known that performance deterioration
  - Photoelectron collection is improved to be ~ 30%.

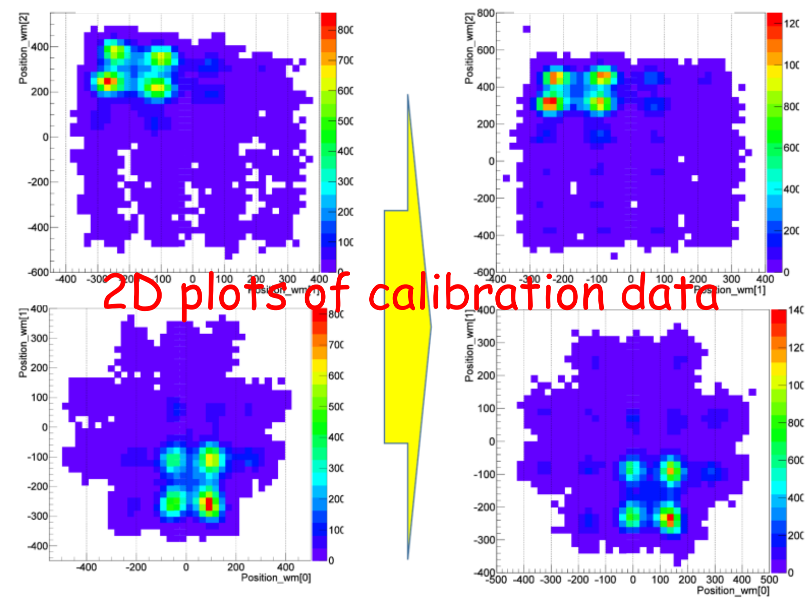
Preliminary

BG spectrum



Position Reconstruction

Coil OFF Coil ON

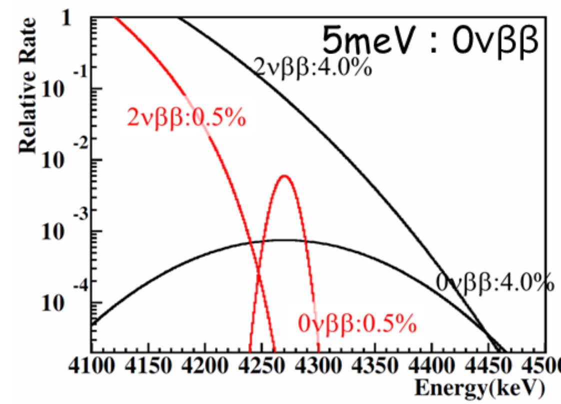


- Energy resolution is expected to be improved ~30%.
  ➔ achieve ~ 4% (FWHM) @ Q-value

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.)
2νββ	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	

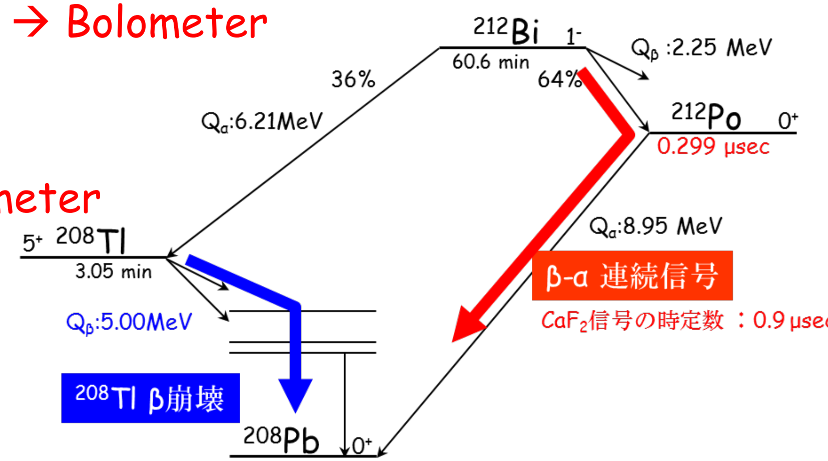


- Exploring Inverted hierarchy → Normal hierarchy region
  - Required two improvements
    - Realizing highly enriched ^{48}CaF, and ton-scale detector . The enrichment technique is established for the small amount of Calcium, up to ~2% (x 10 enrichment of natural abundance). The method is promising, we are on the stage of mass production.
    - Much better energy resolution (to avoid 2νββ 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



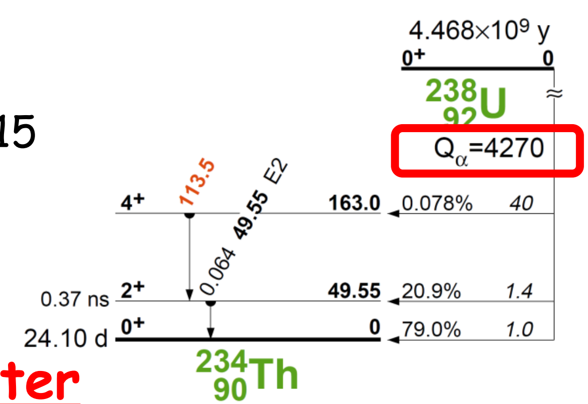
Possible to further reduce the BG by developing Bolometer

- 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

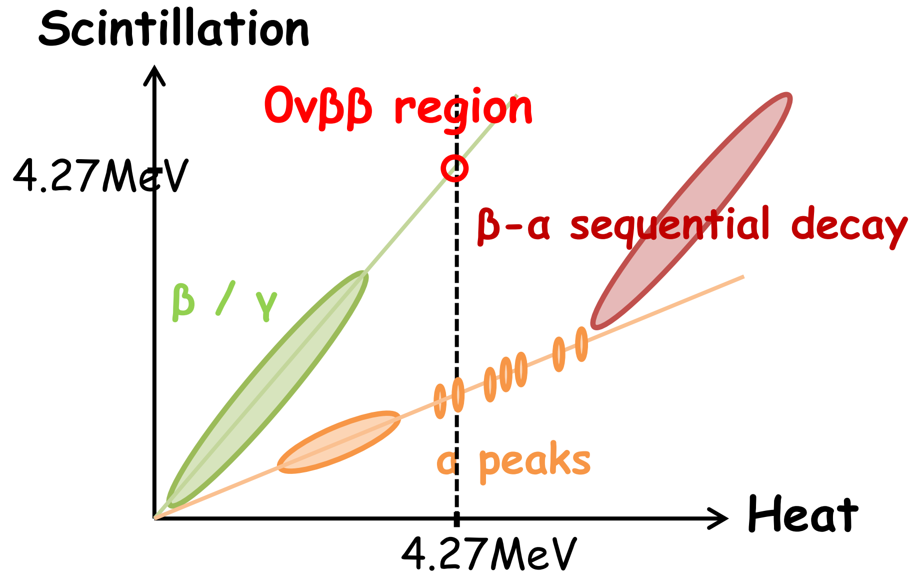
➔ required particle ID

➔ <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 48Ca 0νββ

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

Development of Scinti. Bolometer

- This R&D program was funded in Grant-in-Aid for Scientific Research on Innovative Areas "Revealing the history of the universe with underground particle and nuclear research"

- We are now preparing the operation of dilution refrigerator at sea level laboratory.

- We expects to have the help of the experience of LiF bolometer of the U. of Tokyo group. Someone who worked in Tokyo LiF group are involved in the "Innovative Areas Project".

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 would establish the enrichment technique of large amount 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.

Thank you.