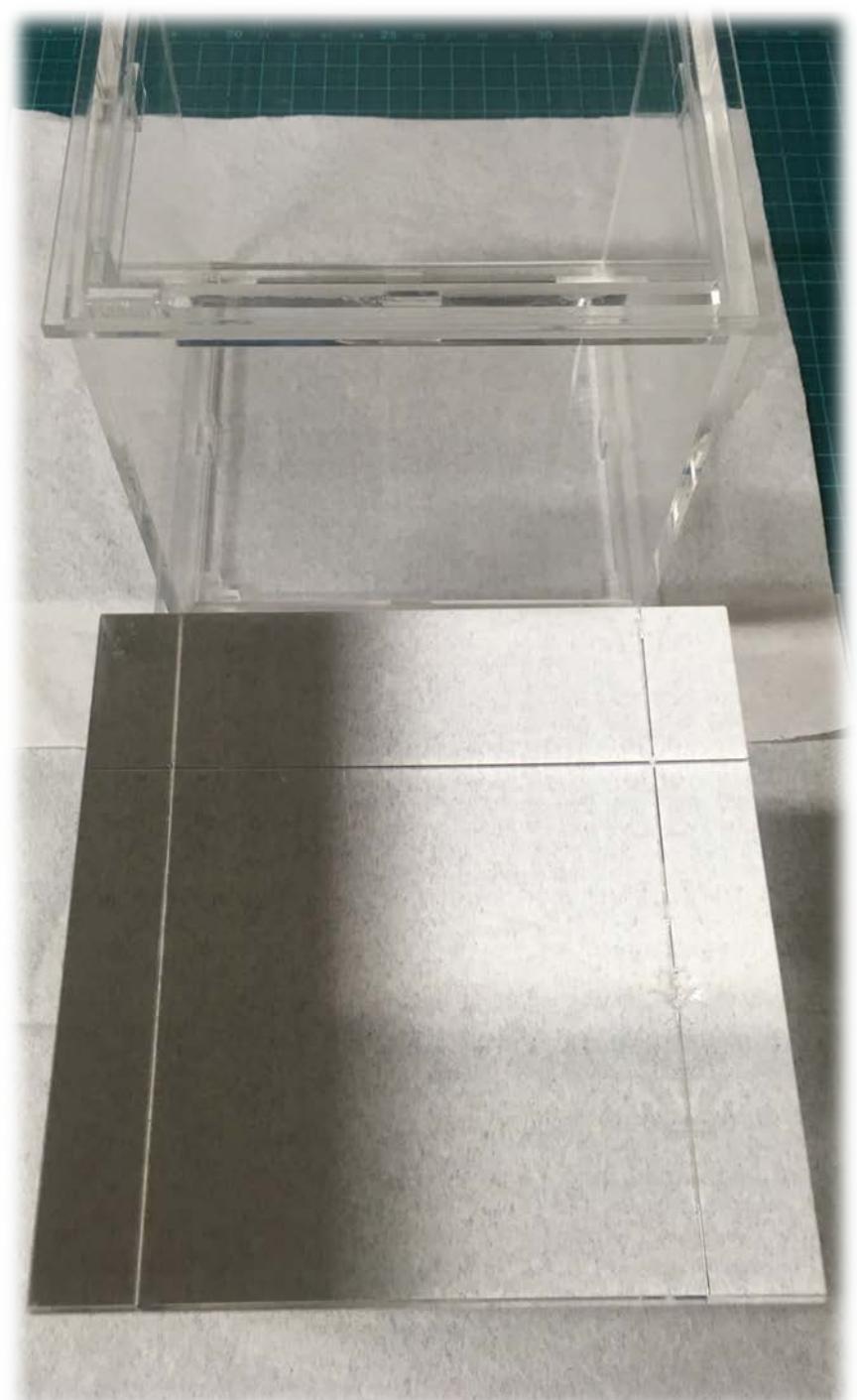




# CANDLES project to search for neutrino-less double beta decay of $^{48}\text{Ca}$



Yasuhiro Takemoto  
for CANDLES collaboration  
Osaka Univ. RCNP



# CANDLES Collaboration



Osaka  
Univ.



Osaka  
RCNP



Univ. of  
Fukui



Tokushima  
Univ.



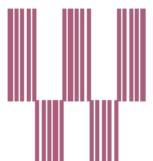
Osaka  
Sangyo  
Univ.



Tsukuba  
Univ.



Saga  
Univ.



Wakasa  
Energy  
Center



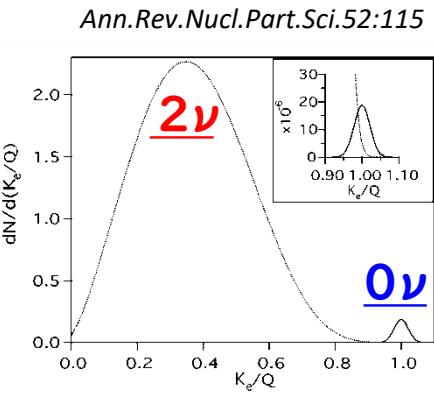
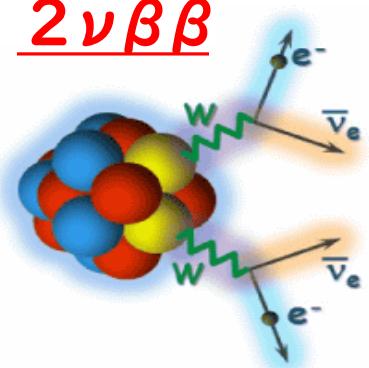
# Outline

- Double Beta Decay of  $^{48}\text{Ca}$
- CANDLES experiment
  - Upgrades on Detector
  - Running Status
  - Current Limit
- R&D for Next/Future CANDLES



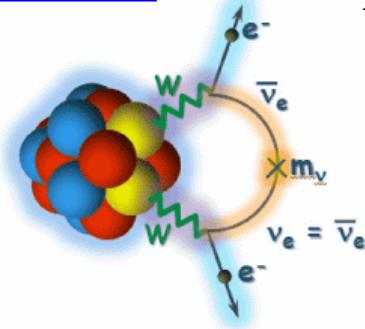
# Double Beta Decay of $^{48}\text{Ca}$

$2\nu\beta\beta$

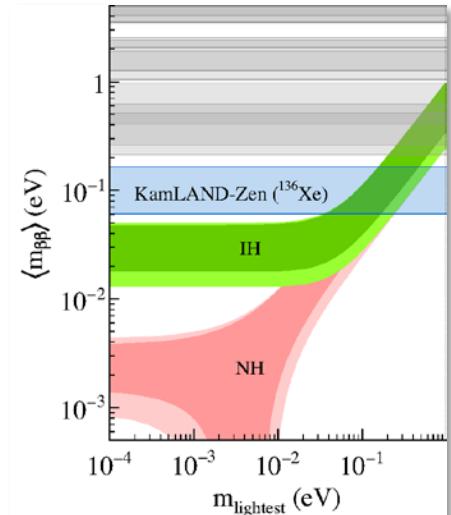


Continuous vs. Monochro.

$0\nu\beta\beta$



$$T_{1/2}^{0\nu} = [G_{0\nu}|M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2]^{-1}$$



Phys. Rev. Lett. 117, 082503  
+ Eur. Phys. J. C71 1754

## Neutrinoless Double Beta Decay $0\nu\beta\beta$

- ✓ extremely rare beyond standard model
  - ✓ Majorana particle ( $\nu = \bar{\nu}$ )
  - ✓ lepton number violation  $\Rightarrow$  leptogenesis
  - ✓ effective neutrino mass & mass hierarchy
- $T_{1/2} : \geq 10^{26} \text{ yr}$  (KL-Zen, GERDA)

## $^{48}\text{CaF}_2$ crystal as $0\nu\beta\beta$ target

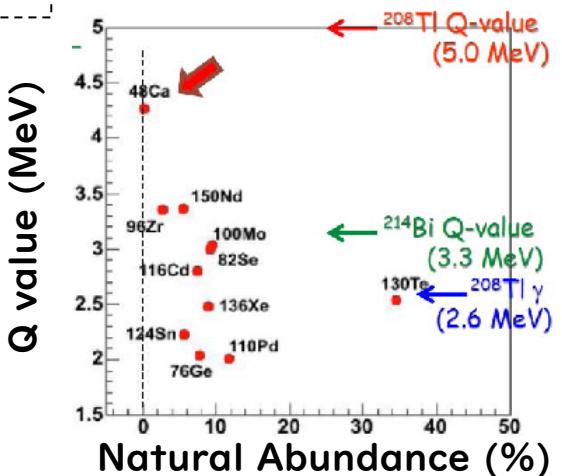
Pros : Max  $Q_{\beta\beta}$  @ 4.271 MeV

$\geq 238\text{U}, 232\text{Th}, 40\text{K}...$

$\Rightarrow \sim 0 \text{ BG}$  @  $Q_{\beta\beta}$

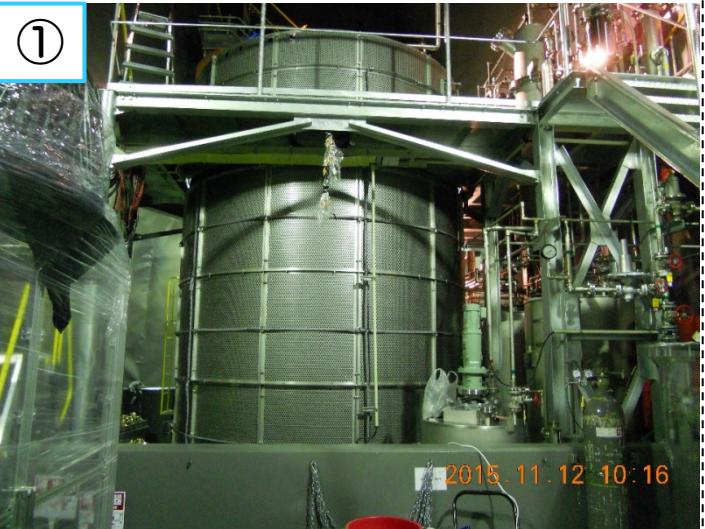
: Large NME, small uncertainty  
 $\Rightarrow$  higher sensitivity to  $m_{\beta\beta}$

Cons : Low natural abundance (0.187%)



# CANDLES III experiment

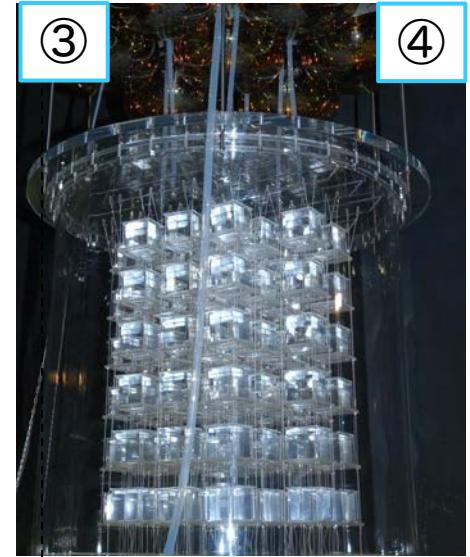
Calcium Fluoride for Studies of Neutrino and Dark Matters by Low Energy Spectrometer



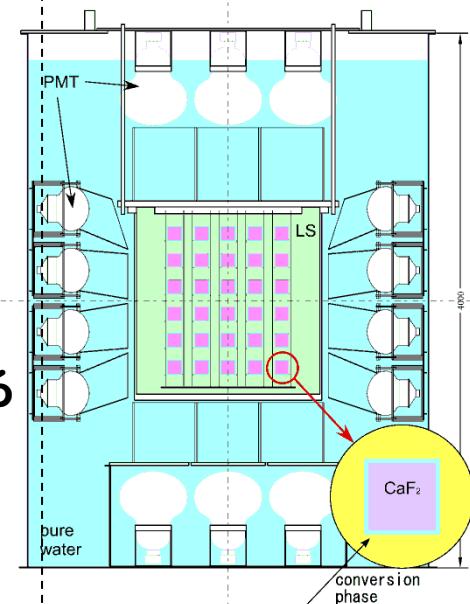
@ Kamioka-mine (UG)  
1 km overburden ( $10^{-5} \mu$ )



- ① pure water (4x3m  $\phi$ )
  - passive shield
- ② PMT
  - 10" (R7081) x12
  - 13" (R8085) x36
  - 20" (R7250) x14
  - Light guide : ~93% ref @420nm

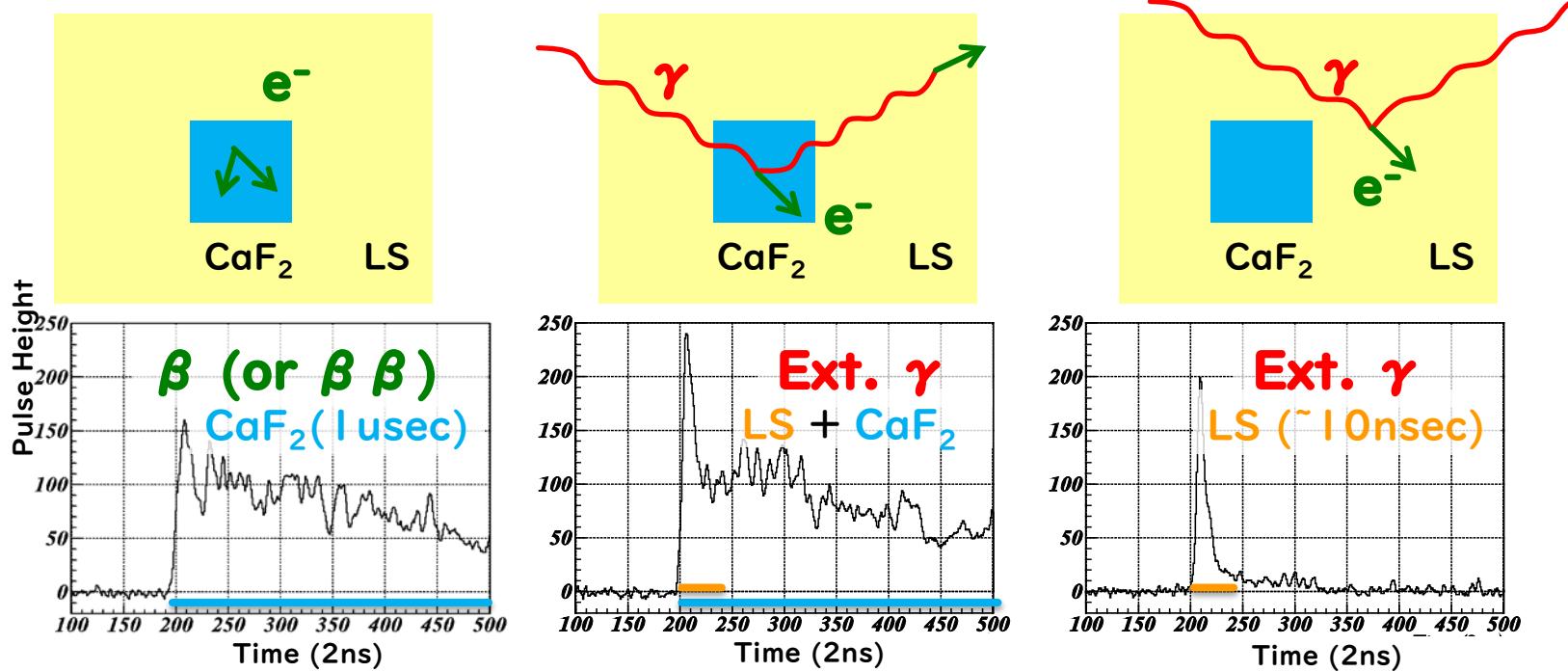


- ③ 2.1 m<sup>3</sup> LS
  - $4\pi$  active shield
  - ~10ns pulse
- ④ CaF<sub>2</sub> (pure) module x 96 : 305kg (350g <sup>48</sup>Ca)  
WLS : 280⇒420nm
  - ~1 μs pulse ⇒ PSD



# BG Reduction Scheme

## Typical Light Emission & Waveform

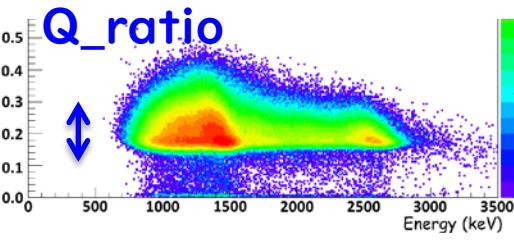
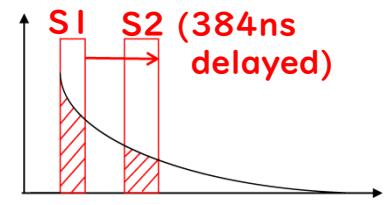
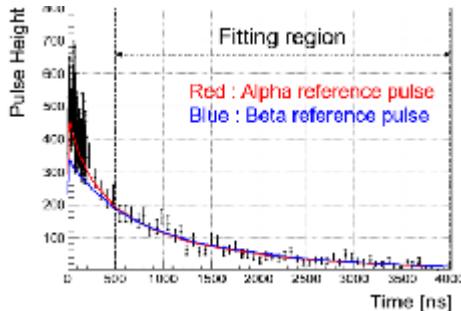


## Rejection of external $\gamma$ events with LS

- **Dual-Gated Trigger** : Hit in S1 & S2
- **Q\_ratio cut** : Q200ns / Q4us

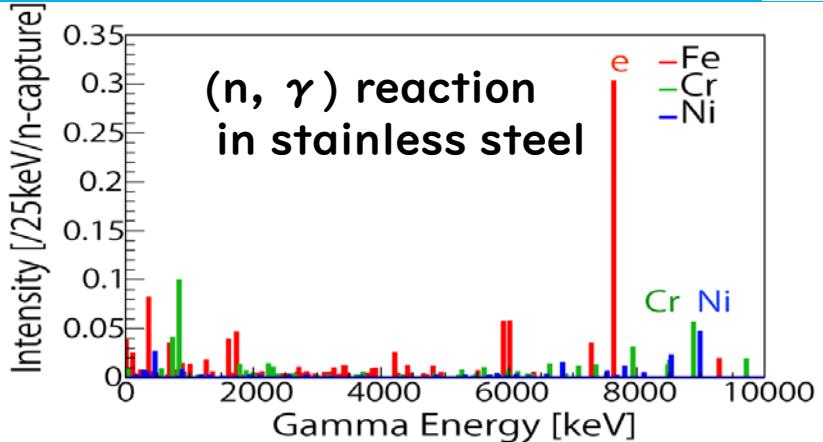
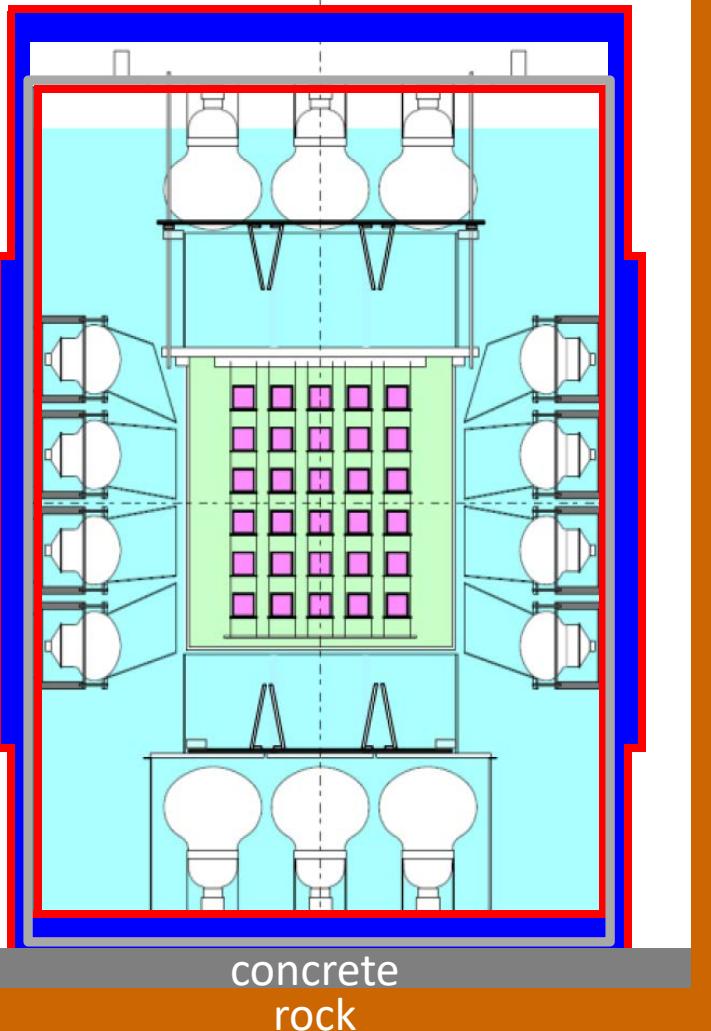
## $\alpha$ / $\beta$ / $\beta$ + LS discrimination

- Event by event fit to reference  $\alpha$ ,  $\beta$  waveform



# Upgrades on Current Data

- SS (stainless steel) tank
- Pb Shield
- B Shield



- High E BGs were estimated as ( $n, \gamma$ ) reaction in **rock**, SS tank

## Suppression with passive shield

- **Pb Shield** :  $\gamma$  shield ( $\sim 1/120$ )  
 $(n, \gamma)$  @ Pb =  $O(10^{-1})$  of @ SS
- **B Shield** : n shield for SS ( $\sim 1/30$ )  
 Top, Side (5mm 40wt% B<sub>4</sub>C sheet)

( $n, \gamma$ ) BGs are estimated by MC  
 to become  $\sim 1/80$ .

Rock :  $0.34 \pm 0.14$  event/yr  
 Tank :  $0.4 \pm 0.2$  event/yr

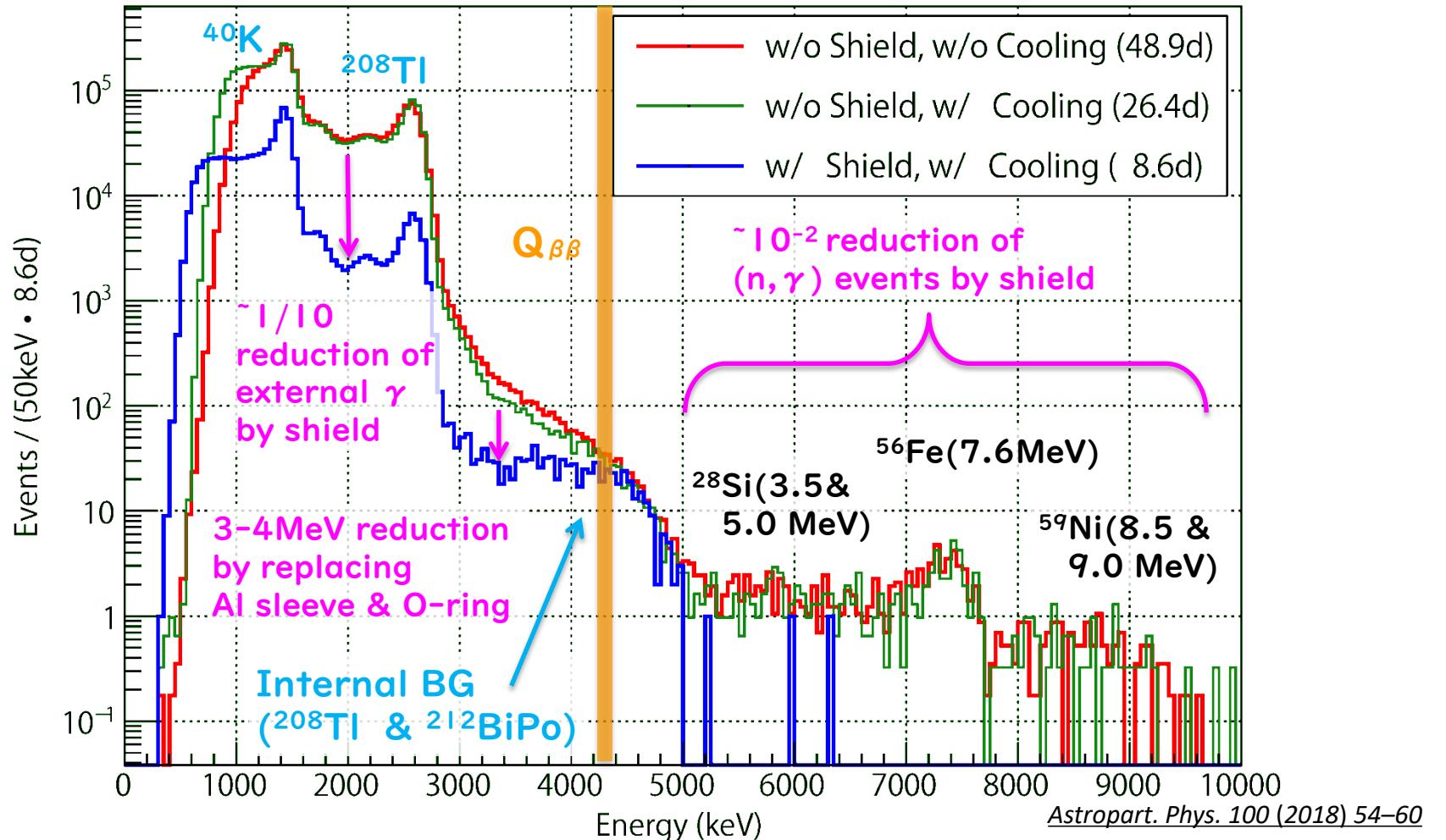
# Pb, B Shield Construction



- **Pb Shield** : Top (7cm) outside, Bottom (10cm) inside  
Side (10cm) + Barrel (12cm)
- **B Shield** : Top, Side (4mm 40wt% B<sub>4</sub>C sheet) outside Pb, inside SS Tank  
Bottom (liquid type) inside SS Tank

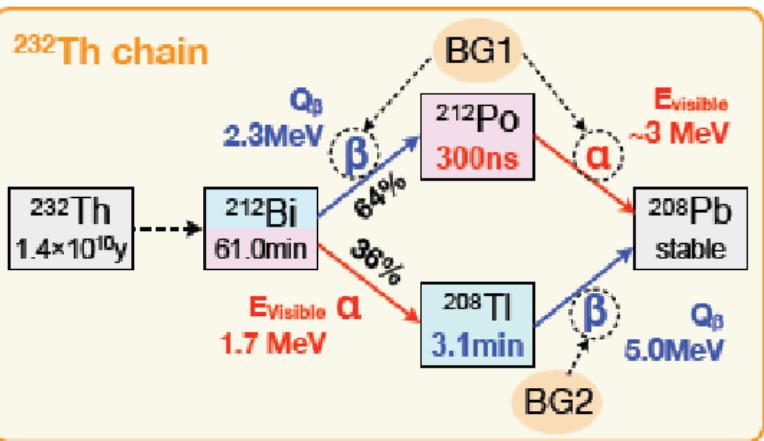
# Confirmation of Upgrades

BG measurement w/ Pb+B shield, low BG material, Cooling ( $\sim 4.9^\circ\text{C}$ ), Coil

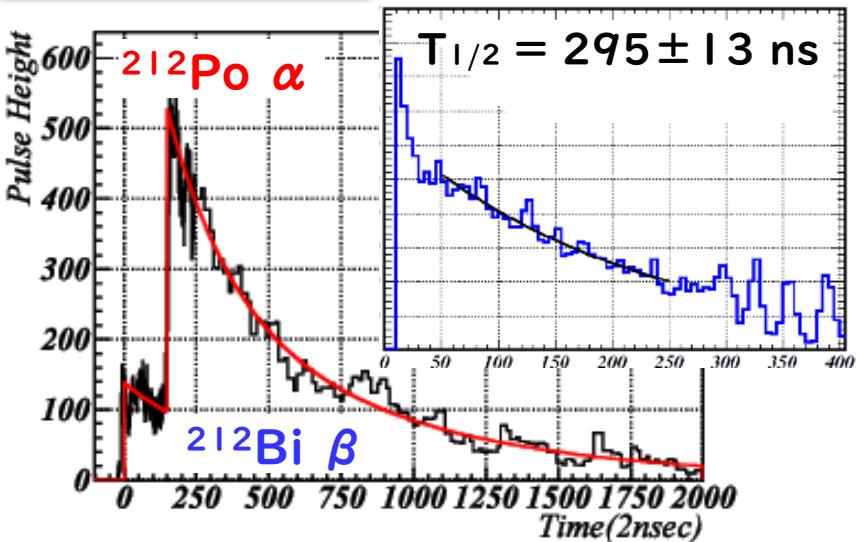


- All upgrades successfully reduced BG by designed magnitude !
  - Analytical internal BG reduction is next key for current CANDLES
- \* only loose LS cut is applied on this plot

# Internal BGs : $^{232}\text{Th}$ daughters



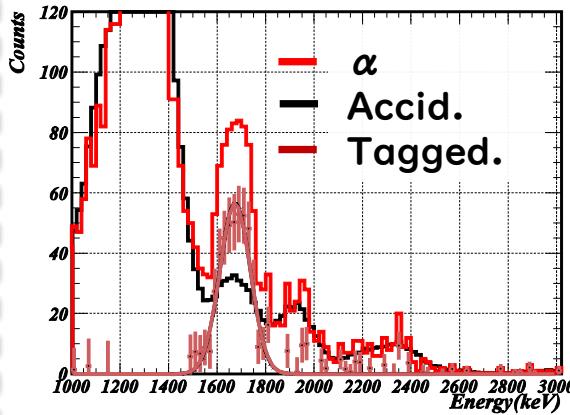
BG1 :  $^{212}\text{BiPo}$



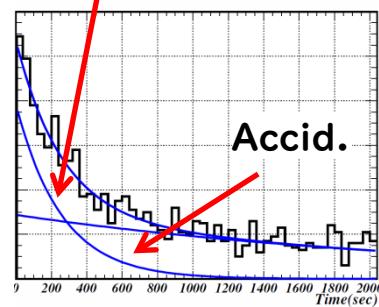
Pileup identify w/  $\Delta T > 20\text{ns}$   
Remaining 5% is currently negligible.

BG2 :  $^{208}\text{Tl}$

- $^{212}\text{Bi} \alpha$  tagging



$$T_{1/2} = 178 \pm 55 \text{ ns}$$

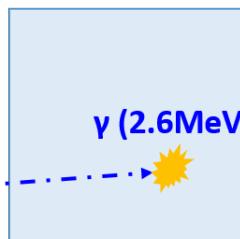
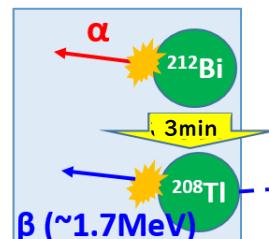


- $^{208}\text{Tl}$  veto

$^{212}\text{Bi} \alpha$  PSD tag

12min  $\beta$  veto  
in the same  $\text{CaF}_2$

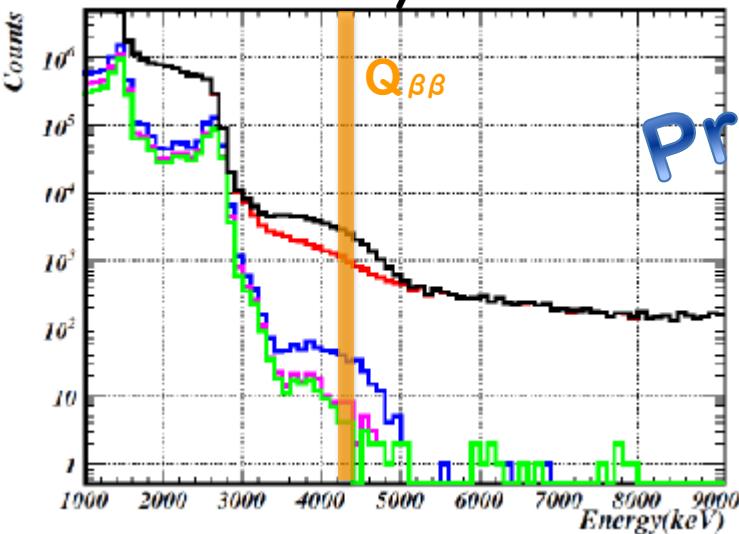
- rejection eff. ~75%, accep. ~83%
- Multi- $\text{CaF}_2$  hit by escaped  $\gamma$  is under study.



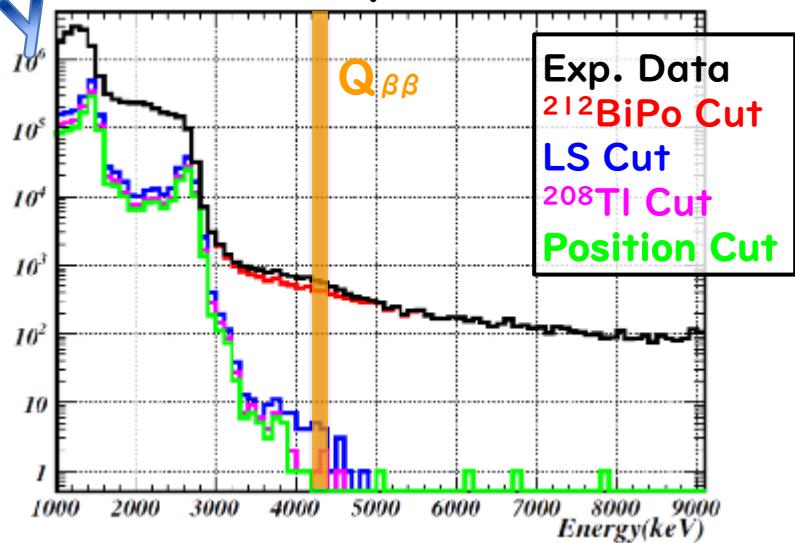
# Data & Event Selection

Live-Time : 131 days ('16/06-12), +47% L.Y. w/ chilling 17  $\Rightarrow$  4.9°C,  
+ geo-mag. compensation coil  $\Rightarrow\Rightarrow$  4.1% Eres@ $^{88}\text{Y}$

95 crystals



27 crystals



Preliminary

$(^{232}\text{Th} < 10\text{uBq/kg})$

# event	95 crystals			27 crystals		
	Q $\beta\beta$	4-5MeV	5.5-6.5MeV	Q $\beta\beta$	4-5MeV	5.5-6.5MeV
LS Cut	115	257	8	12	23	1
$^{208}\text{Tl Cut}$	19	49	6	3	6	1
Position Cut	10	34	6	0	2	1

No event in high purity crystals is confirmed.

# Current Limit on $T_{0\nu\beta\beta}^{1/2}$ $^{48}\text{Ca}$

## Preliminary

	95 CaF <sub>2</sub>	27 CaF <sub>2</sub>
Livetime (yr)		131
$0\nu\beta\beta$ eff.		$0.39 \pm 0.06$
Event in ROI	10	0
Expected BG	~11	~1.2
$T_{0\nu\beta\beta}^{1/2}$ $^{48}\text{Ca}$ (yr)	$>3.8 \times 10^{22}$	$>6.2 \times 10^{22}$
Sensitivity (yr)	$6.2 \times 10^{22}$	$3.6 \times 10^{22}$

\* ELEGANT IV

Exposure :  $4947\text{kg} \cdot \text{d}$  (2yr <

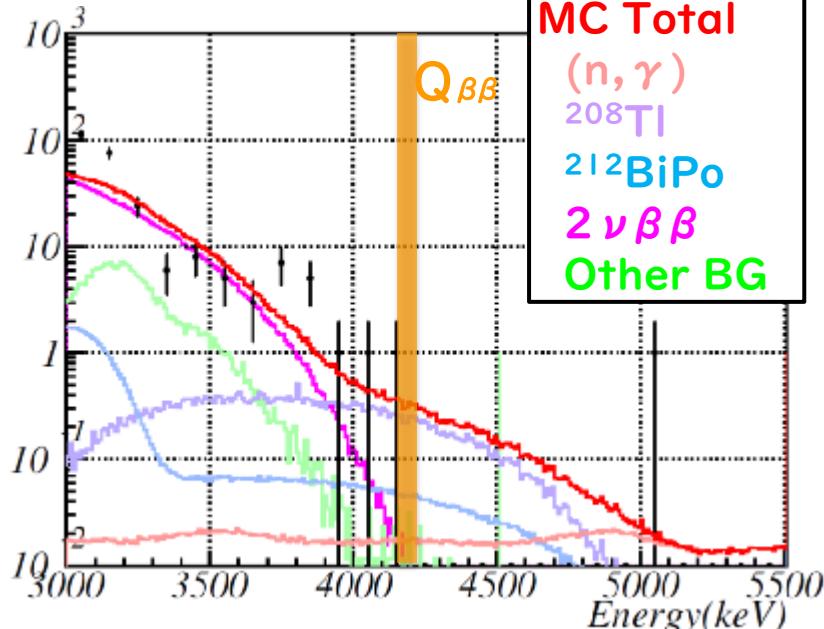
$0\nu\beta\beta$  eff. : 0.53

$T_{0\nu\beta\beta}^{1/2}$   $^{48}\text{Ca}$  :  $5.8 \times 10^{22}$  yr

CANDLES continues to explore  
the forefront  $T_{0\nu\beta\beta}^{1/2}$  in  $^{48}\text{Ca}$  !

⇒ Further continuous data taking to study energy uncertainty  
due to baseline drift within 1 FADC value

Exp. Data and BG MC  
In 27 CaF<sub>2</sub>

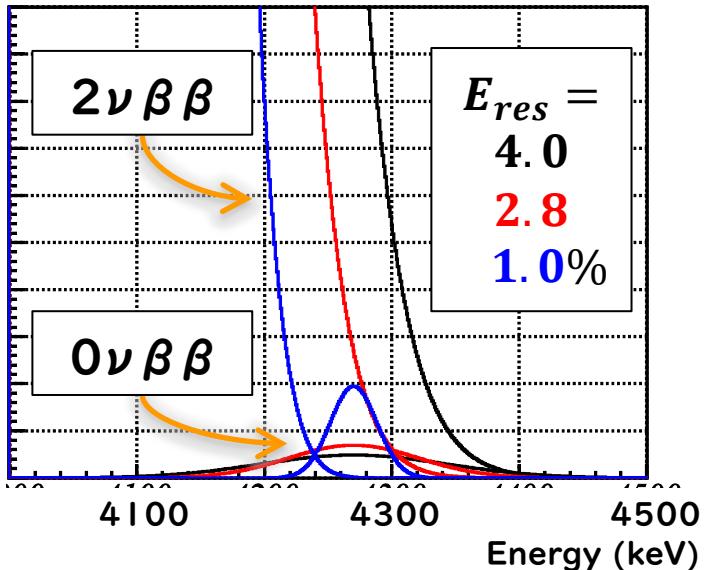


$\chi^2_\beta < 1.5$ ,  $-3\sigma < \text{SI} < 1\sigma$   
 $-2\sigma < \text{position cut} < 2\sigma$   
 Pileup cut  $> 20\text{ns}$   
 $^{208}\text{TI}$  cut  
 $-1\sigma < 0\nu\beta\beta$  window  $< 2\sigma$

# Future CANDLES

	CANDLES III+	CANDLES IV	CANDLES V
$^{48}\text{Ca}$ Abundance	0.187%	2%	50%
$^{48}\text{Ca}$ Weight	0.35 kg	25 kg	~600 kg
Energy Res.	6%	2.8% (required)	1.0% (required)
$\langle m_\nu \rangle$ sensitivity	500 meV	80 meV	9 meV
Feature	Cooling CaF <sub>2</sub> Low BG	+ Massive $^{48}\text{Ca}$ + Much low BG <i>DH <math>\Rightarrow</math> IH</i>	++ Massive $^{48}\text{Ca}$ <b>Scint. Bolometer</b> <i>IH <math>\Rightarrow</math> NH</i>

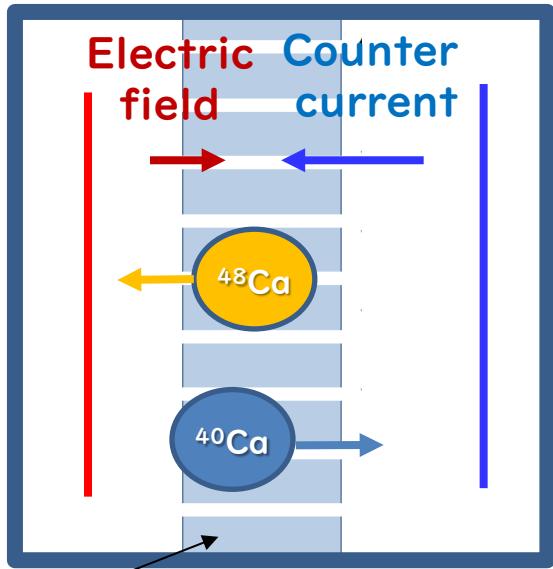
$$\langle m_\nu \rangle = 9 \text{ meV}$$



- Variety of  $^{208}\text{TI}$ . Among crystals
  - stable purity control
  - higher purity crystal
- Small number of target nuclei
  - high & large amount enrichment
- Inevitable  $2\nu\beta\beta$  background
  - much higher energy resolution
  - scintillator  $\Rightarrow$  bolometer

# Enrichment of $^{48}\text{Ca}$

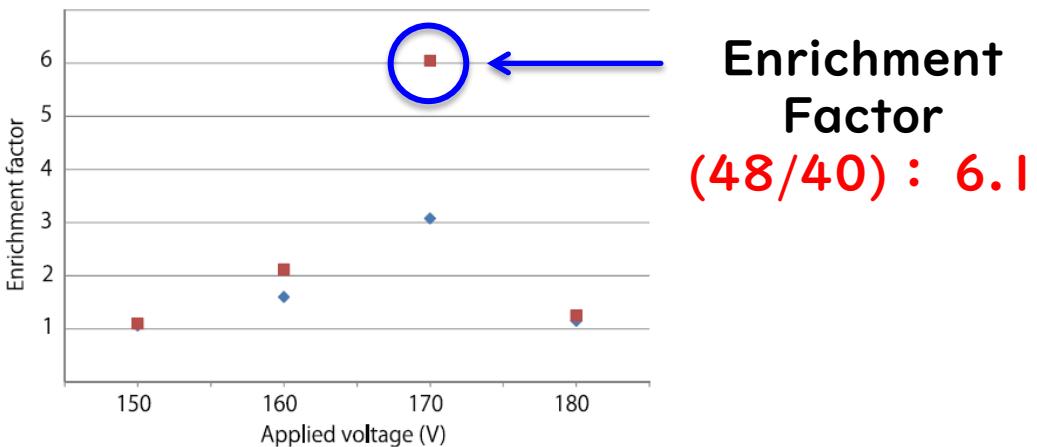
- Multi-channel counter current electrophoresis (MCCCE)



Boron Nitride plate  
 $80\text{mm} \phi \times 10\text{mm}$ ,  
 $\times 69$   $0.8\text{mm} \phi$  channel



- Migration speed diff. btw.  $^{40}\text{Ca}$  /  $^{48}\text{Ca}$ .
- Principle was demonstrated.

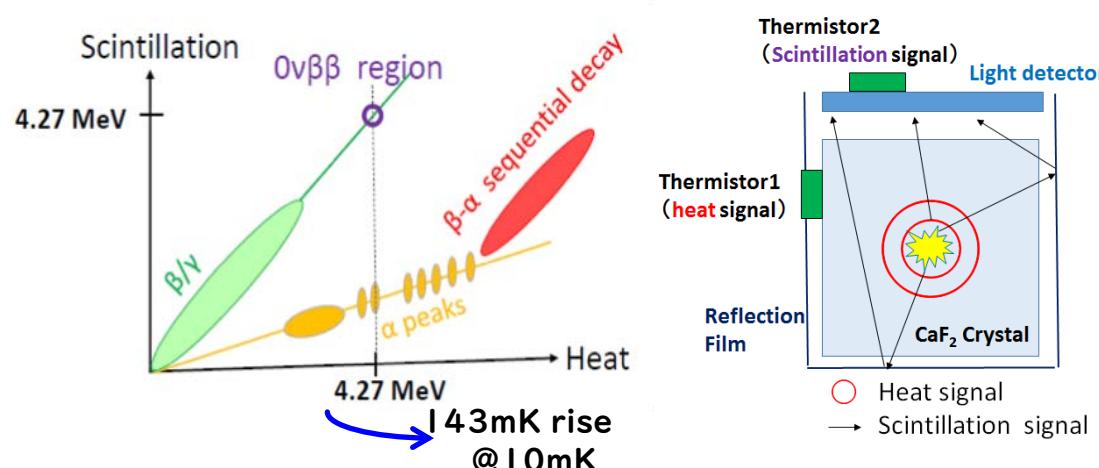


- Much higher enrichment & reproducibility w/ different parameter configuration
- Large amount enrichment

- Parallel R&D on
  - crown-ether + micro-reactor
  - crown-ether resin + chromatography
  - laser isotope separation.

# Scintillating Bolometer

- 1% or less Energy res. for IH.  
**Scintillator → Bolometer**
- Simul. meas. of heat and scinti.  
to discriminate  $\beta$  /  $\alpha$   
( $^{238}\text{U}$   $\alpha$  4.27MeV  $\sim Q_{0\nu\beta\beta}$ )  
⇒ **Scintillating Bolometer**
- Established technique.  
CRESST-II, Lucifer, AMoRE



## Detector :

Ge wafer + NTDGe thermistor +  
PTFE reflector  
CaF<sub>2</sub> (Eu) + CaF<sub>2</sub>(pure)

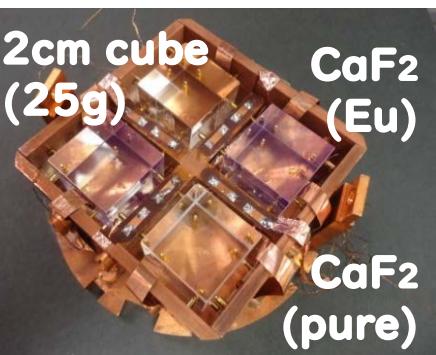
## Dilution refrigerator @ Osaka

Developed for DM search with LiF.  
Cooling power is  $2 \mu\text{W}$  @ 20mK

- Long time operation at 500mK
- Struggling to 10mK ( $^3\text{He}/^4\text{He}$  mixed gas)

⇒ **New refrigerator to accelerate : Triton300**

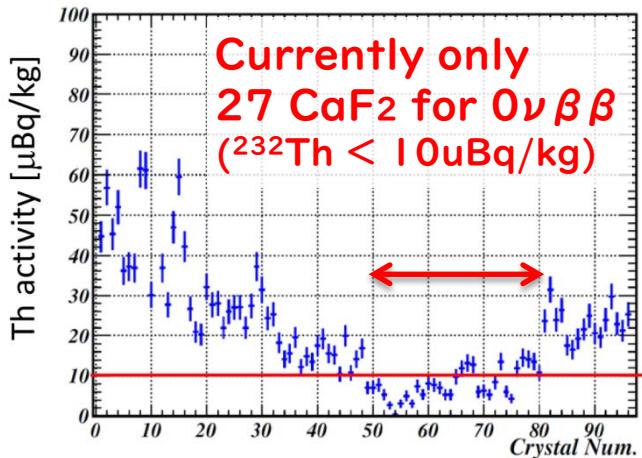
<10mK control,  $>6 \mu\text{W}$  @ 20mK



□ soon assembled

# Toward High Purity

## To Lower RI in CaF<sub>2</sub>



- Same best purity repetition to increase mass
  - Collabo. w/ a material provider
  - Under RI evaluation of sample crystals
- Higher purity crystal production for future large amount crystals
  - Collabo. w/ another material provider
  - Under evaluation of material powder by Ge



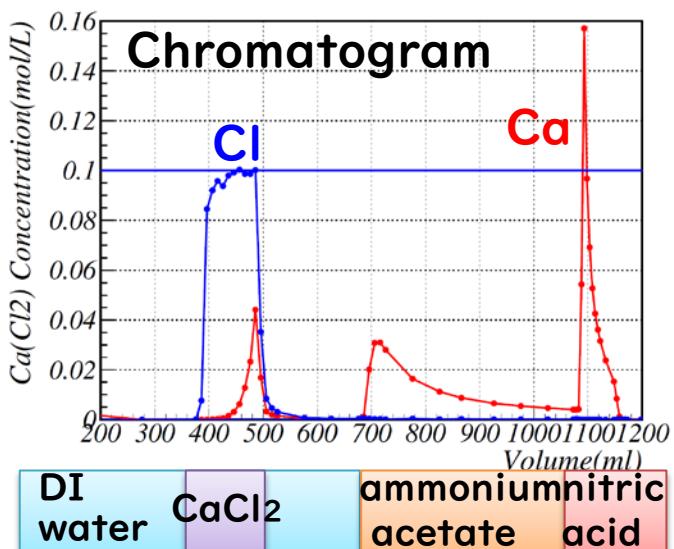
## By study for CaF<sub>2</sub> crystal from CaCl<sub>2</sub>

- Enrichment is mainly done in CaCl<sub>2</sub>
- For crystalize, CaF<sub>2</sub> is required
- ⇒ Replace CaCl<sub>2</sub> to CaF<sub>2</sub>

- confirmation of Cl separation
- re-bonding to F
- introduce “displacement chromatography” to reduce U/Th



11 cm column



# Summary

- CANDLES :  $0\nu\beta\beta$  search by  $^{48}\text{Ca}$  (350g) /  $\text{CaF}_2$  (305kg)
  - highest Q (4.3MeV), potential 0 BG observation, important for IH/NH
- Detector upgrade in 2015-2016
  - Passive Pb, B shield against largest BG :  $(n, \gamma)$  :  $10^{-2}$  reduction
  - Detector cooling & Geomagnetic Compensation coil
    - ◆  $17^\circ\text{C} \Rightarrow 4.9^\circ\text{C}$  → +47% light yield
- Preliminary  $T_{0\nu\beta\beta}^{1/2}$  limit on  $^{48}\text{Ca}$  :  $6.2 \times 10^{22}$  yr in 131 days
  - (sensitivity  $3.6 \times 10^{22}$  yr)
  - (ELEGANT IV  $> 5.8 \times 10^{22}$  yr)
  - > 5.5 exposure already, and continue to explore the forefront.
- Future CANDLES for larger  $^{48}\text{Ca}$  mass, better Eres, purer  $\text{CaF}_2$ 
  - $^{48}\text{Ca}$  enrichment with MCCCE, Clown Ether, Laser Separation
  - Scintillating Bolometer study, accelerated with new DR
  - purer  $\text{CaF}_2$  selection and  $\text{CaCl}_2 \Rightarrow \text{CaF}_2$  production

고맙습니다 !  
Thank you !



## CANDLES project to search for neutrino-less double beta decay of $^{48}\text{Ca}$

*Saturday, 7 July 2018 10:15 (15)*

Neutrino-less double beta decay( $0\nu\beta\beta$ ) is acquiring great interest after the confirmation of neutrino oscillation which demonstrated nonzero neutrino mass.

Measurement of  $0\nu\beta\beta$  provides a test for the Majorana nature of neutrinos and gives an absolute scale of the effective neutrino mass.

In order to search for  $0\nu\beta\beta$  of  $^{48}\text{Ca}$ , we proposed CANDLES project and a detector system by using  $\text{CaF}_2$ (pure).

The CANDLES III system, which is one of the CANDLES project, aims at a high sensitive measurement by a characteristic detector system.

The system realizes a complete  $4\pi$  active shield by immersion of the  $\text{CaF}_2$  scintillators in liquid scintillator.

The active shield leads to a low background condition for the measurement.

Now we have developed the CANDLES III system, which contained 350 g of  $^{48}\text{Ca}$  at the Kamioka underground laboratory.

In 2016, we have installed a shielding system in the CANDLES III system to reduce background events by the high energy  $\gamma$ -rays, which were emitted from neutron capture reaction on surround materials.

By the system, we reduced the background events from neutron capture by two orders of magnitude.

After this upgrade, we started a double beta decay measurement and obtained result.

Furthermore, we started development of next detector system.

In this system, we will use a  $\text{CaF}_2$  scintillating bolometer and enriched  $^{48}\text{Ca}$ .

In this paper, we will report result of  $^{48}\text{Ca}$  double beta decay measurement by using the CANDLES III system and current status of the  $\text{CaF}_2$  scintillating bolometer and enrichment of  $^{48}\text{Ca}$ .

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**Presenter(s) :** TAKEMOTO, Yasuhiro (Osaka University)

**Session Classification :** Neutrino Physics

**Track Classification :** Neutrino Physics