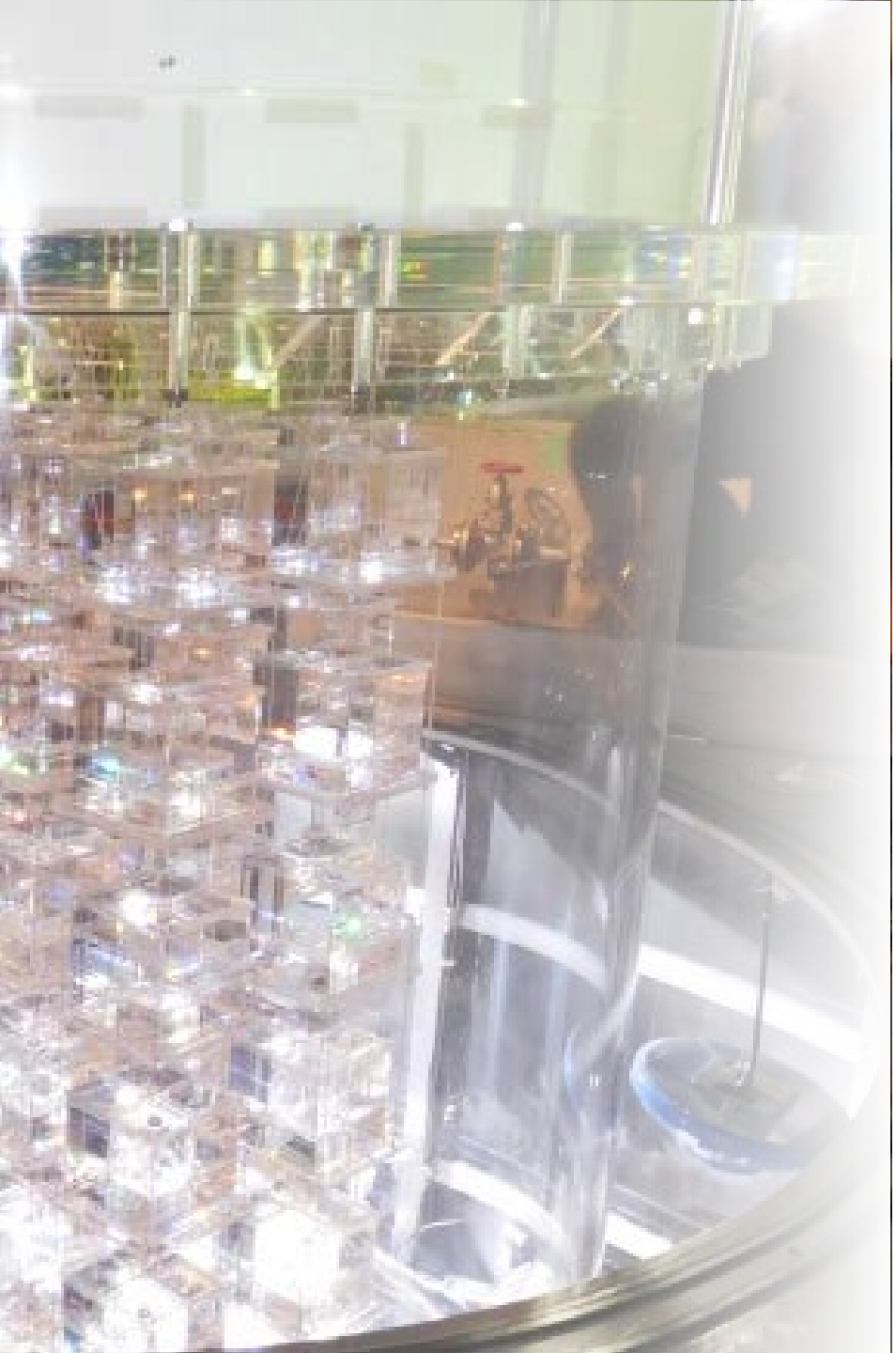


Neutrino-less Double Beta Decay study in CANDLES experiment

2017/Sep/02
PANIC2017 @ CNCC Beijing

Takemoto Yasuhiro
Osaka University RCNP
for the
CANDLES Collaboration

CANDLES Collaboration (~30 members)

Osaka Univ.

Osaka RCNP

Fukui Univ.

Tokushima Univ.

Osaka Sangyo Univ.

Tsukuba Univ.

Saga Univ.

Wakasa Energy Center

Outline of the Talk

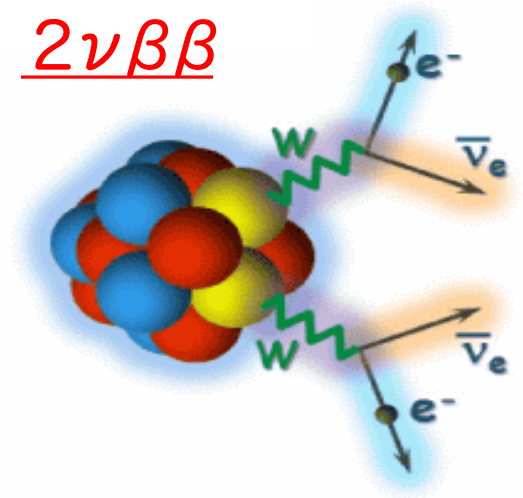
- Double Beta Experiment

- CANDLES Experiment
  - Background
  - Detector Upgrade
  - Current Limit

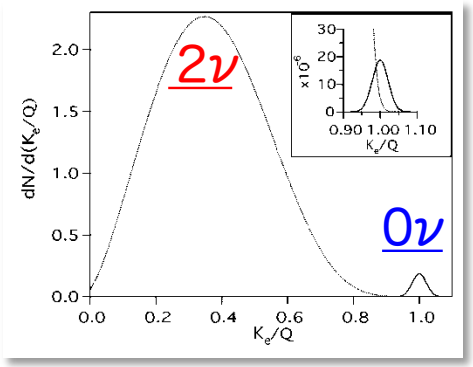
- R&D for Next/Future CANDLES

Double Beta Decay experiment

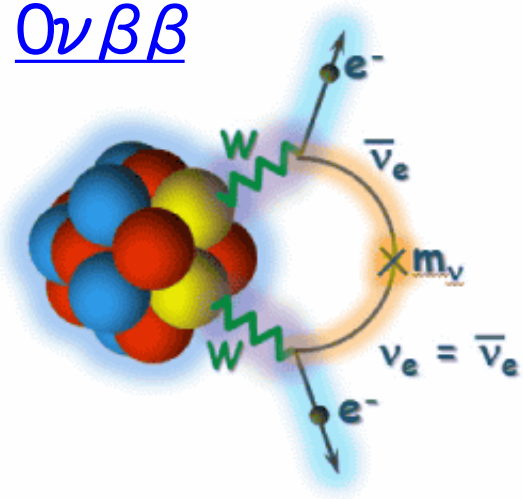
$2\nu\beta\beta$



Ann.Rev.Nucl.Part.Sci.52:115



$0\nu\beta\beta$

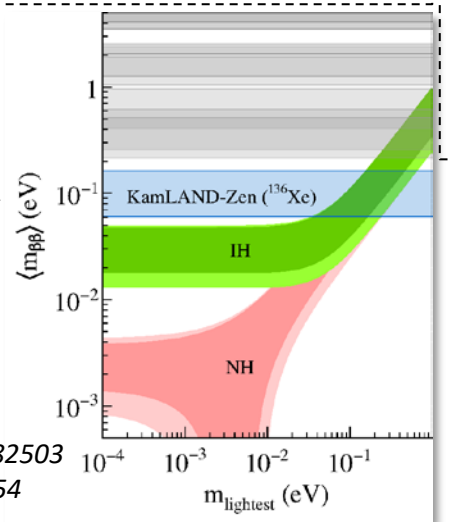


Continuous vs. *Monochro.*

- ✓ rare but under standard model
- ✓ measured with >10 Isotopes
  - ✓ ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, ^{48}Ca...
- ✓ $T_{1/2}$: 10^{18} ~ 10^{20} yr

- ✓ extremely rare beyond standard model
  - ✓ Majorana particle ($\nu = \bar{\nu}$)
  - ✓ lepton number violation ⇒ leptogenesis
  - ✓ neutrino mass ⇒ hierarchy
- ☐ under measurement with
  - ✓ ^{136}Xe, ^{76}Ge, ^{130}Te, ^{48}Ca...
- ☐ $T_{1/2}$: ≧10^{26} yr (KL-Zen, GERDA)

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



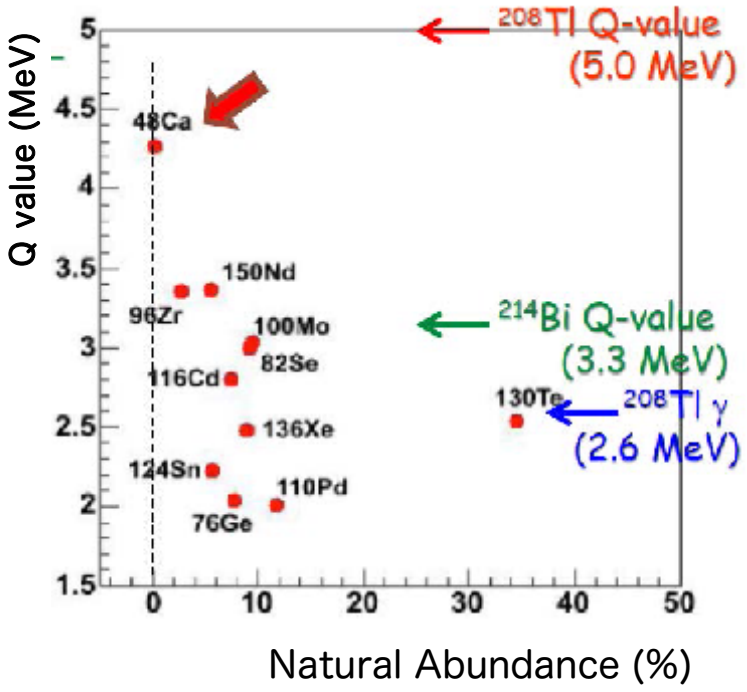
Phys.Rev.Lett.117,082503
+ Eur.Phys.J.C71 1754

<u>milestones</u> for neutrino mass hierarchy
- *~60meV* : degenerated ?
- *~20meV* : inverted ?
- ~meV : normal ?

$0\nu\beta\beta$ experiment w/ ^{48}Ca

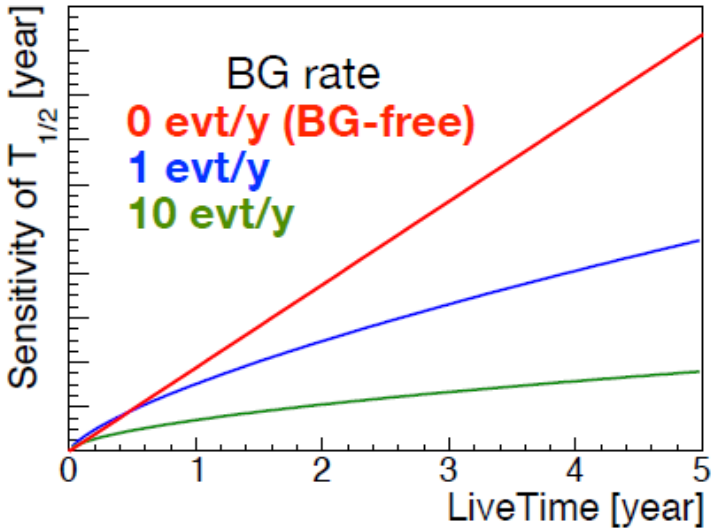
$^{48}CaF_2$ crystal as target $0\nu\beta\beta$

- Max $Q_{\beta\beta}$ @ 4.271MeV
  - ≧ ^{238}U, ^{232}Th, ^{40}K...
    - except Internal ^{208}Tl ($\beta+\gamma$)
  - ~ 0 BG @ $Q_{\beta\beta}$
  - powerful in next generation
    - $\langle m_\nu \rangle \sim T^{-1/2} \sim M^{-1/2}$
    - c.f. $\sim M^{-1/4}$ (BG limit)
  - Large phase space factor



- Low natural abundance (0.187%)
  - separated isotope is expensive (M$/10g)
  - independent enrichment is required

- high E res. (<1%) at low temp.
  - inevitable for 2ν vs 0ν
  - bolometer technique is required



CANDLES III experiment

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

①

②

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

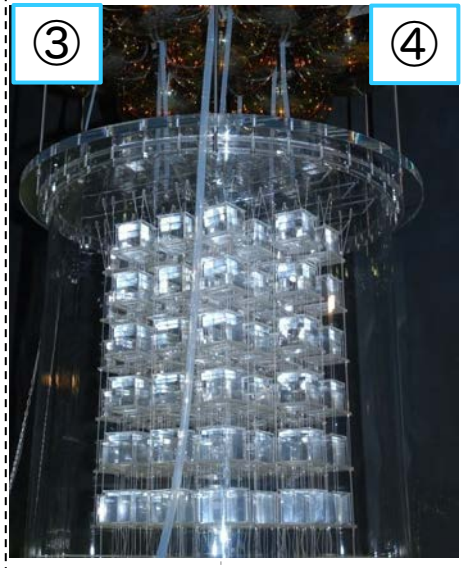
① pure water (4x3mϕ)
- passive shield

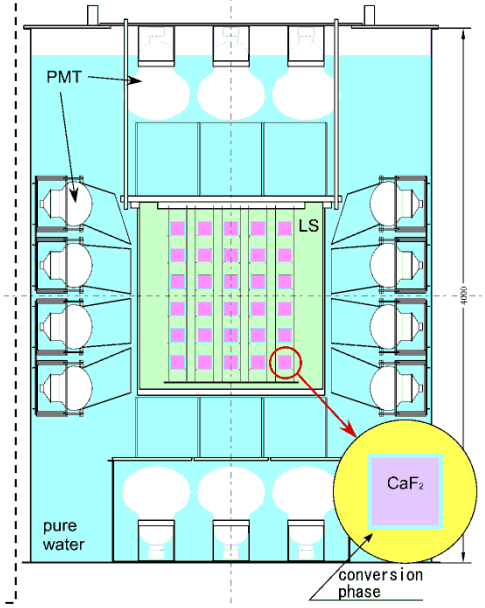
② PMT + light guide
- 10” (R7081) x12
- 13” (R8085) x36
- 20” (R7250) x14
- guide : ~93% ref @420nm

③ 2.1m^3 LS
- 4π active shield
- ~10ns pulse

④ CaF_2 (pure) module x 96
: 305kg (350g ^{48}Ca)
WLS : 280⇒420nm
- ~1μs pulse ⇒ PSD

③ ④

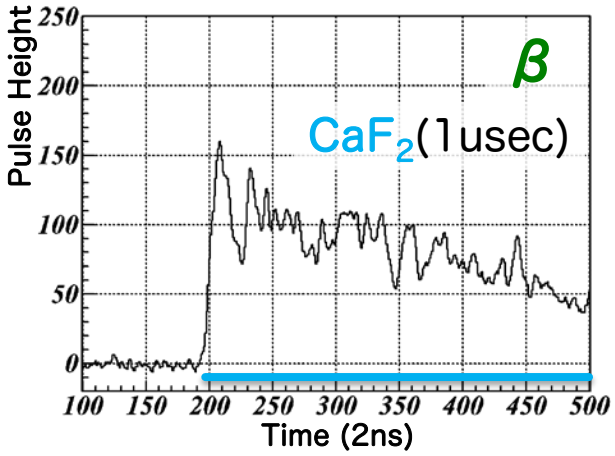


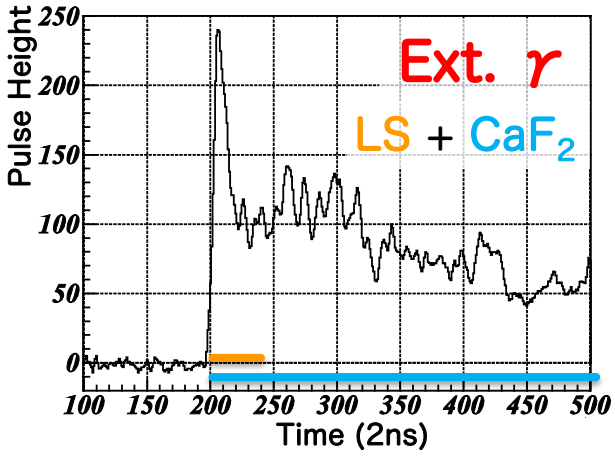


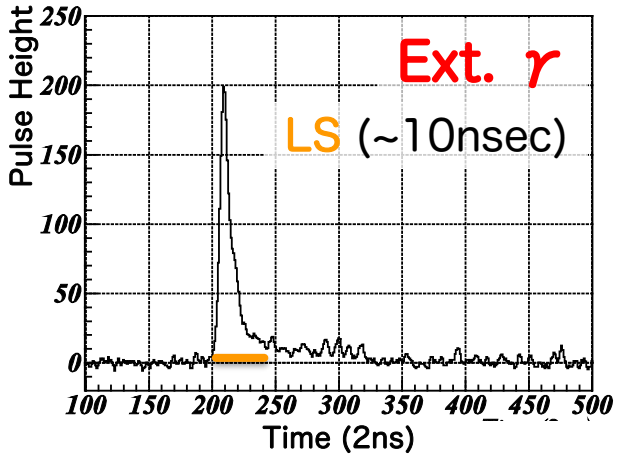
Signal in 4π active shield (Liquid Scintillator : LS)

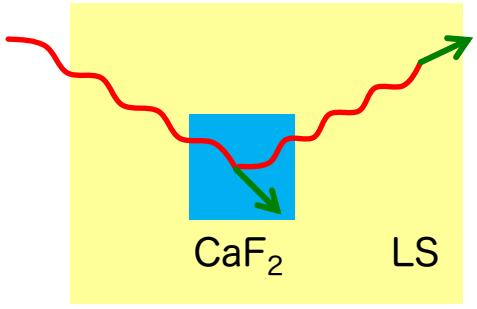
Rejection of external γ events with LS

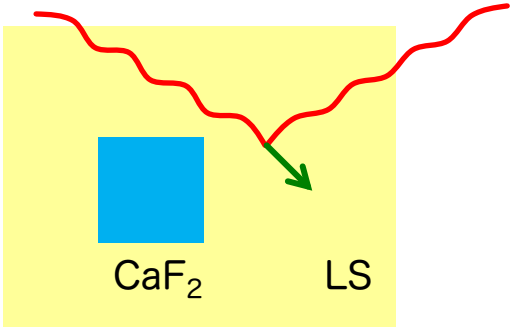
- Event discrimination by offline pulse shape analysis
  - Distinctive time constant : CaF_2(1usec) vs. LS (~10nsec)
- 500MHz Flash ADC provides fine structure





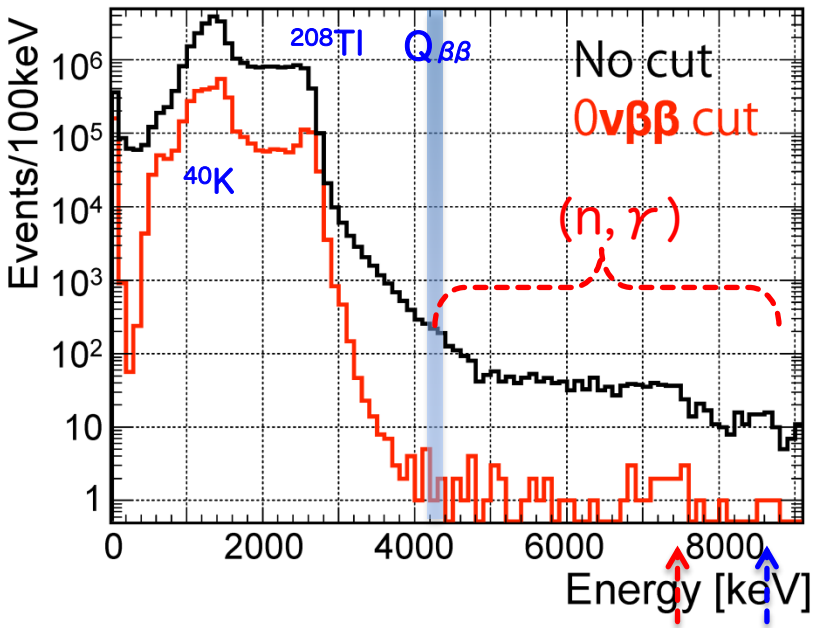


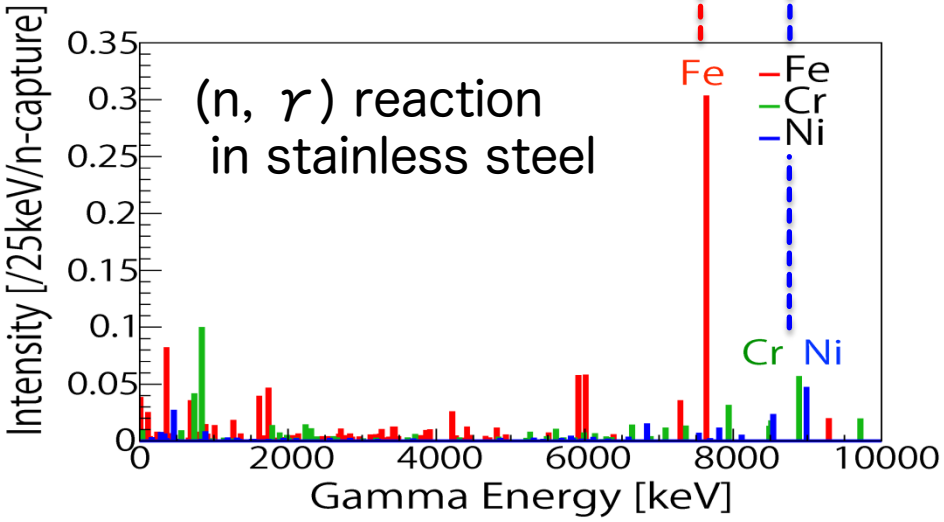




Background Spectrum in CANDLES III (2015)

26 crystal data (least ^{232}Th)



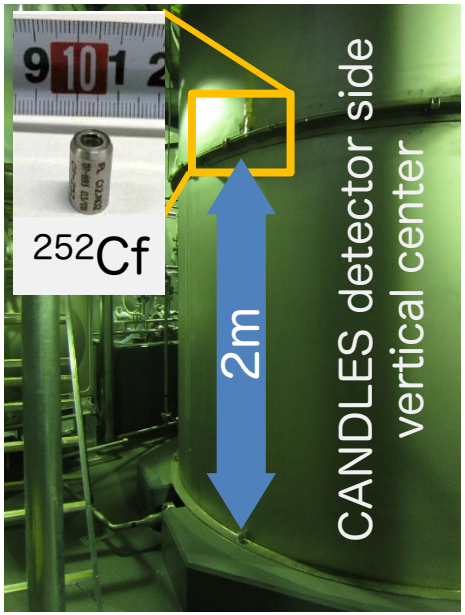


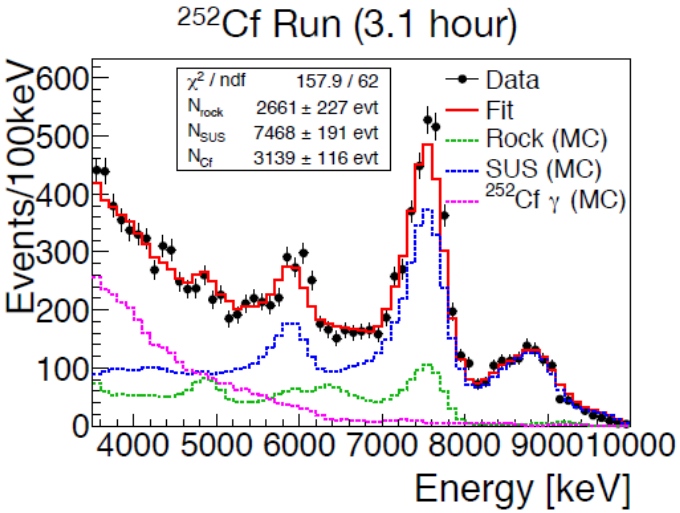
Live Time	60.3 d
Exposure (^{48}Ca)	5.73 kg・d
Events in ROI	6
Expected BG	(n, γ) : 3.4± 0.4 ^{208}Tl : ~1
Sensitivity ($T_{1/2}$)	0.8 x 10^{22} yr

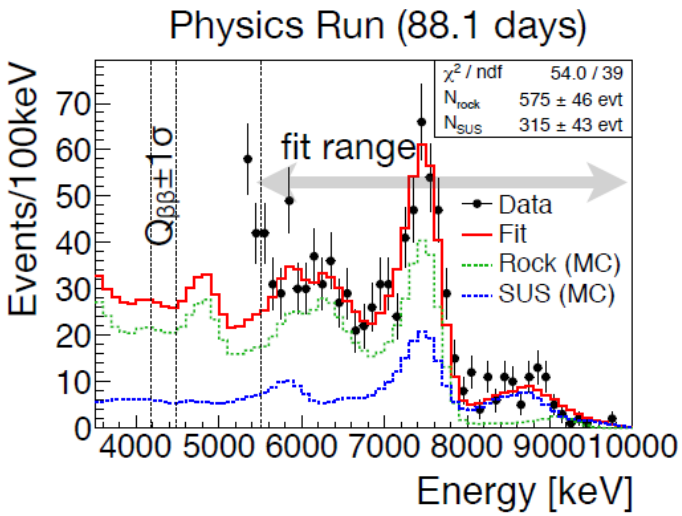
- high E BG remains after LS cut
- BG peaks ~ 7.5MeV
- seems to be produced from neutron capture on surrounding materials
  - rock n ⇒ rock γ ⇒ CaF_2
  - rock n ⇒ SUS tank γ ⇒ CaF_2

Understand (n, γ) with ^{252}Cf & MC

^{252}Cf : put neutron source
on the SUS tank side or on the rock side
MC : detector simulation for (n, γ) reaction
in the stainless tank and in the rock



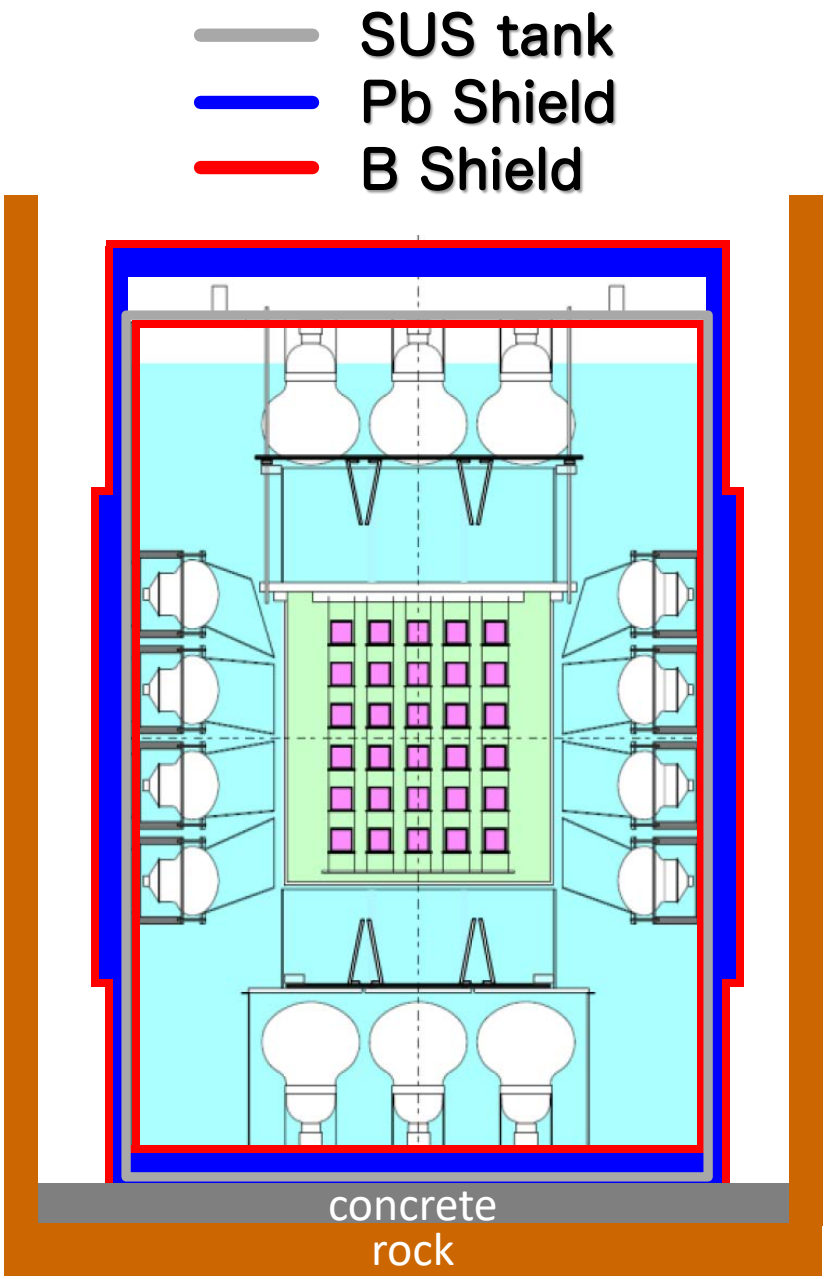




☑High E peaks are identified with ^{252}Cf data.
☑(n, γ) MC in rock and stainless tank well reproduced the real data.

⇒ ☑ main BG is identified and understood as (n, γ) reaction
76 ± 9 (stat.) events/yr/96 crystals

Detector Upgrade : neutron & gamma Shield



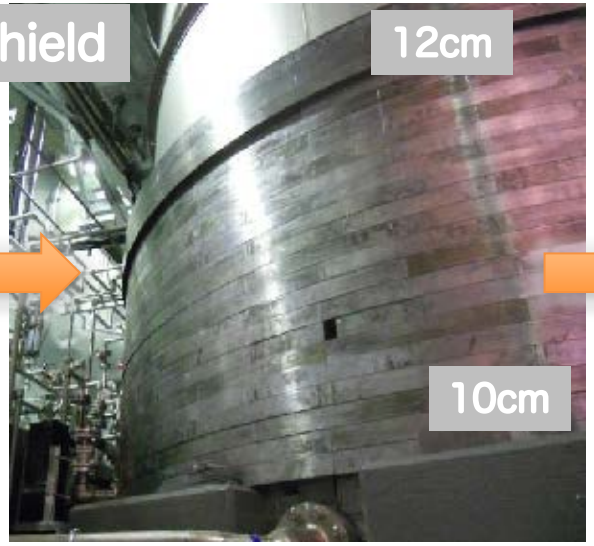
‣Target : ~1 event/yr/96crystals

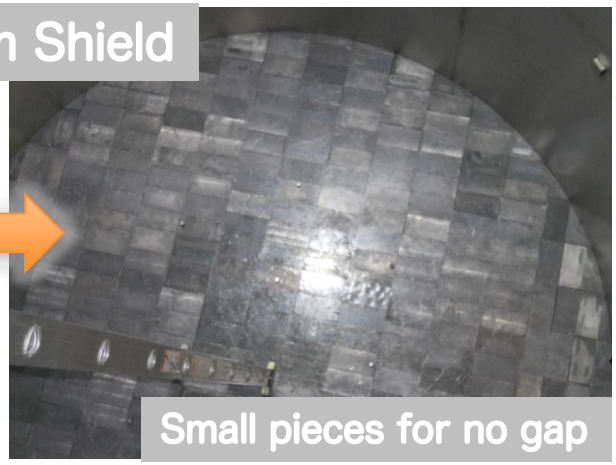
- **Pb Shield** : γ shield (~1/120)
  (n,γ) @ Pb = O(10^{-1}) of @ SUS
  Top (7cm)
  Bottom (10cm) inside tank
  Side (10cm) + Barrel (12cm)

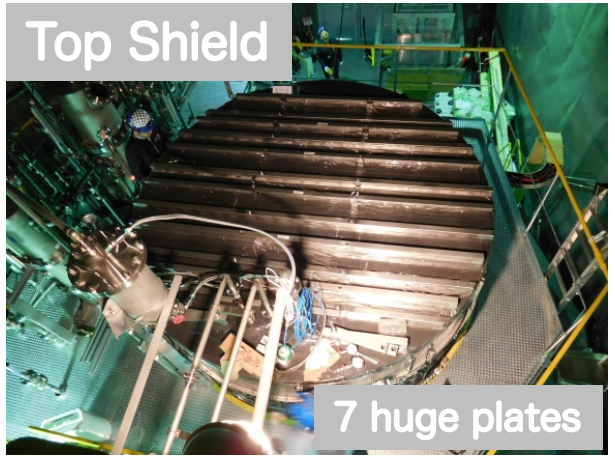
- **B Shield** : n shield for SUS (~1/30)
  Top, Side (5mm 40wt% B_4C sheet)
  outside Pb, inside SUS
  Bottom (liquid type) inside SUS

- (n,γ) BGs in CANDLES is estimated by MC to become ~1/80.
  Rock : 0.34±0.14 event/yr
  Tank : 0.4±0.2 event/yr

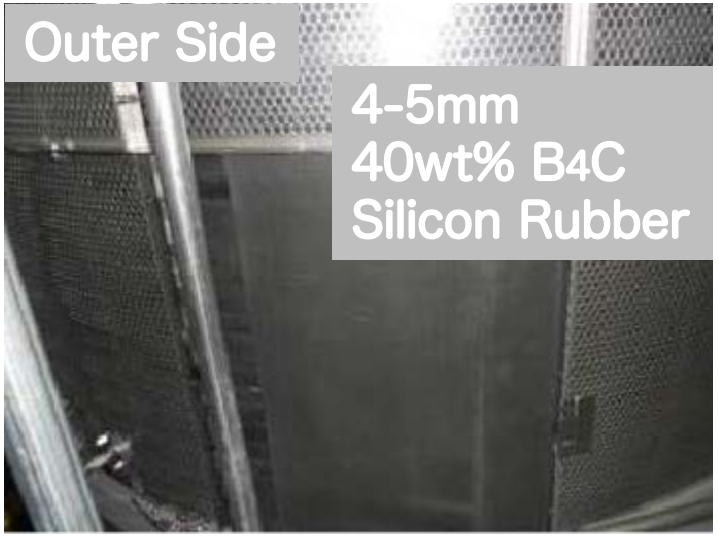
Pb Shield Construction

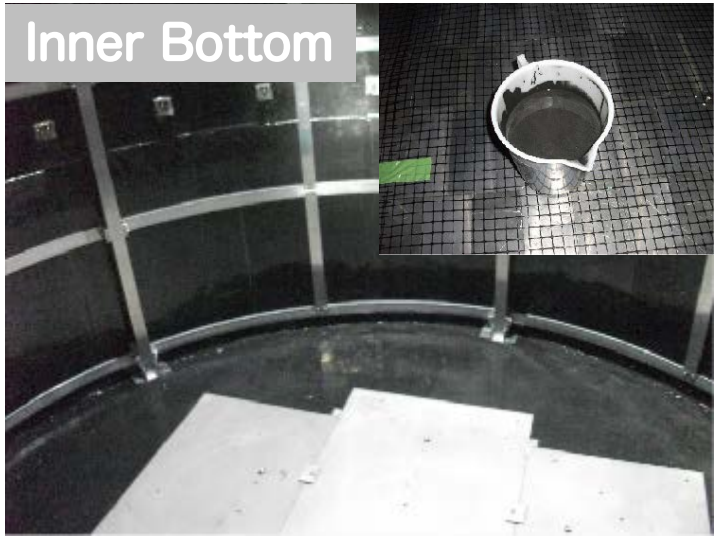






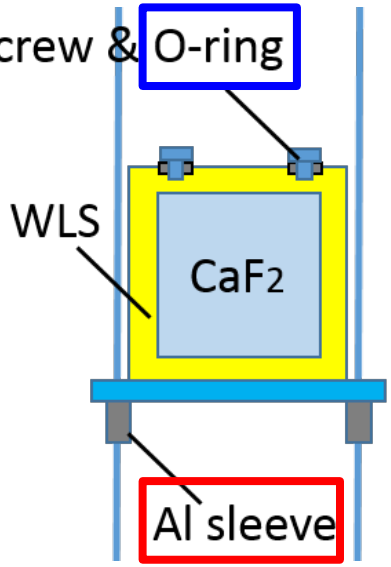
B Shield Construction



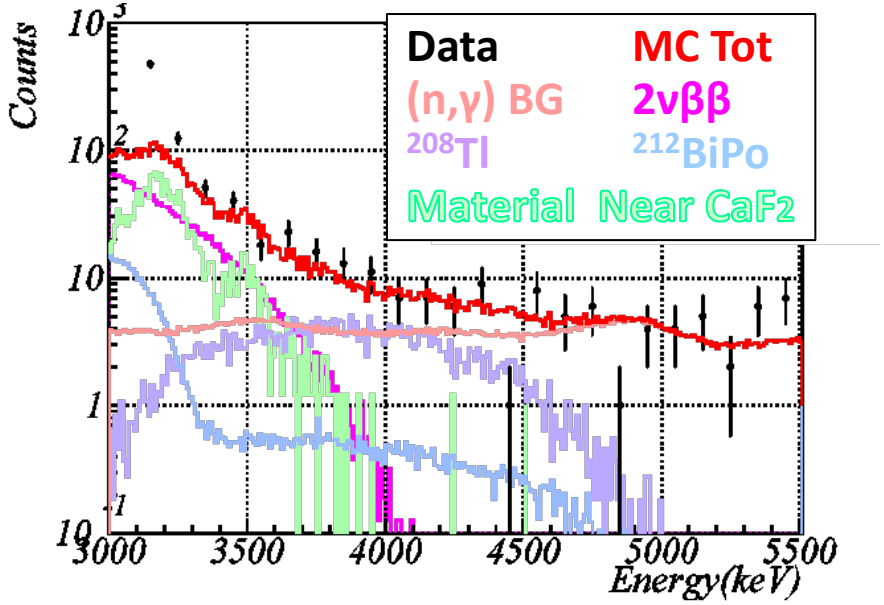


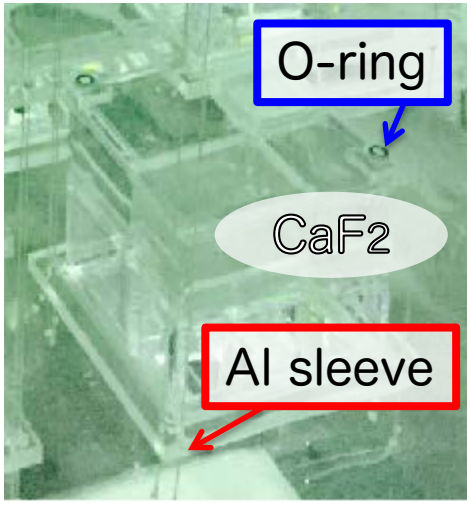
- Liquid B compound was poured on top of Pb shield for inner bottom shield.
- This is for both shielding neutron and waterproofing the bottom Pb blocks.
- No B and Pb elution into water have been confirmed by monthly water ICP-MS/OES examination.

Low BG material selection for near CaF_2



BG spectrum before new shield

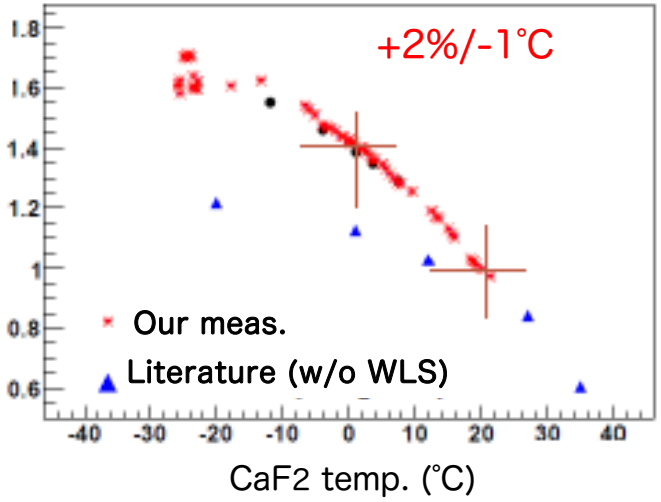




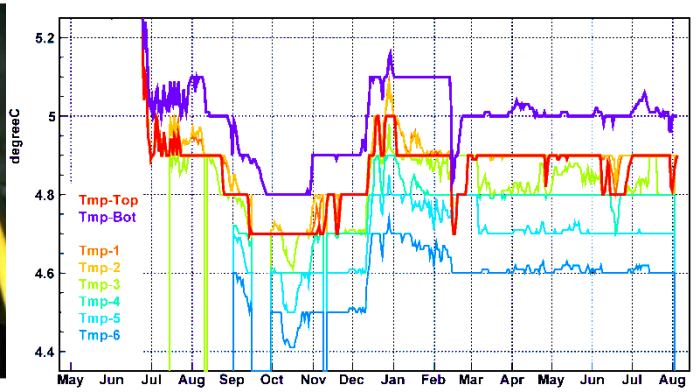
- Radioassay with Ge detector
  ⇒ Al sleeve and O-ring are dirty
- Replacement by cleaner ones
  ⇒ ^{232}Th for Al sleeve 0.4⇒0.1mBq/crystal
- Less than half background
  @ 3-3.5MeV region is expected.

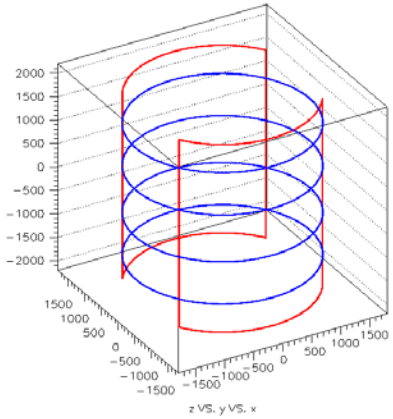
Detector Cooling & Geomag. Compensation

CaF2 Light Yield

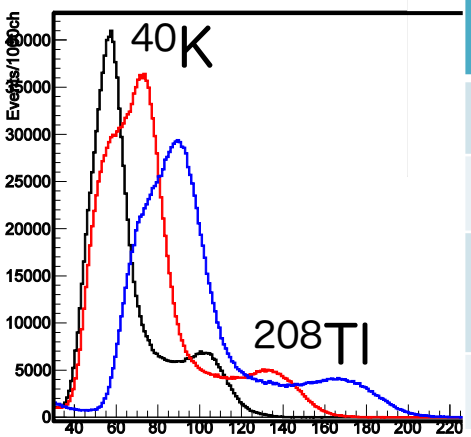


- CaF2 light yield increases when chilled +2%/-1℃
- Cooling system (cool room ⇒ detector) was installed.
- Under stable control with +24% light yield
  (room 17.5⇒2.0±0.8℃, water 17.0⇒4.9±0.1℃)





Geomagnetic compensation coil for large PMT was also installed.



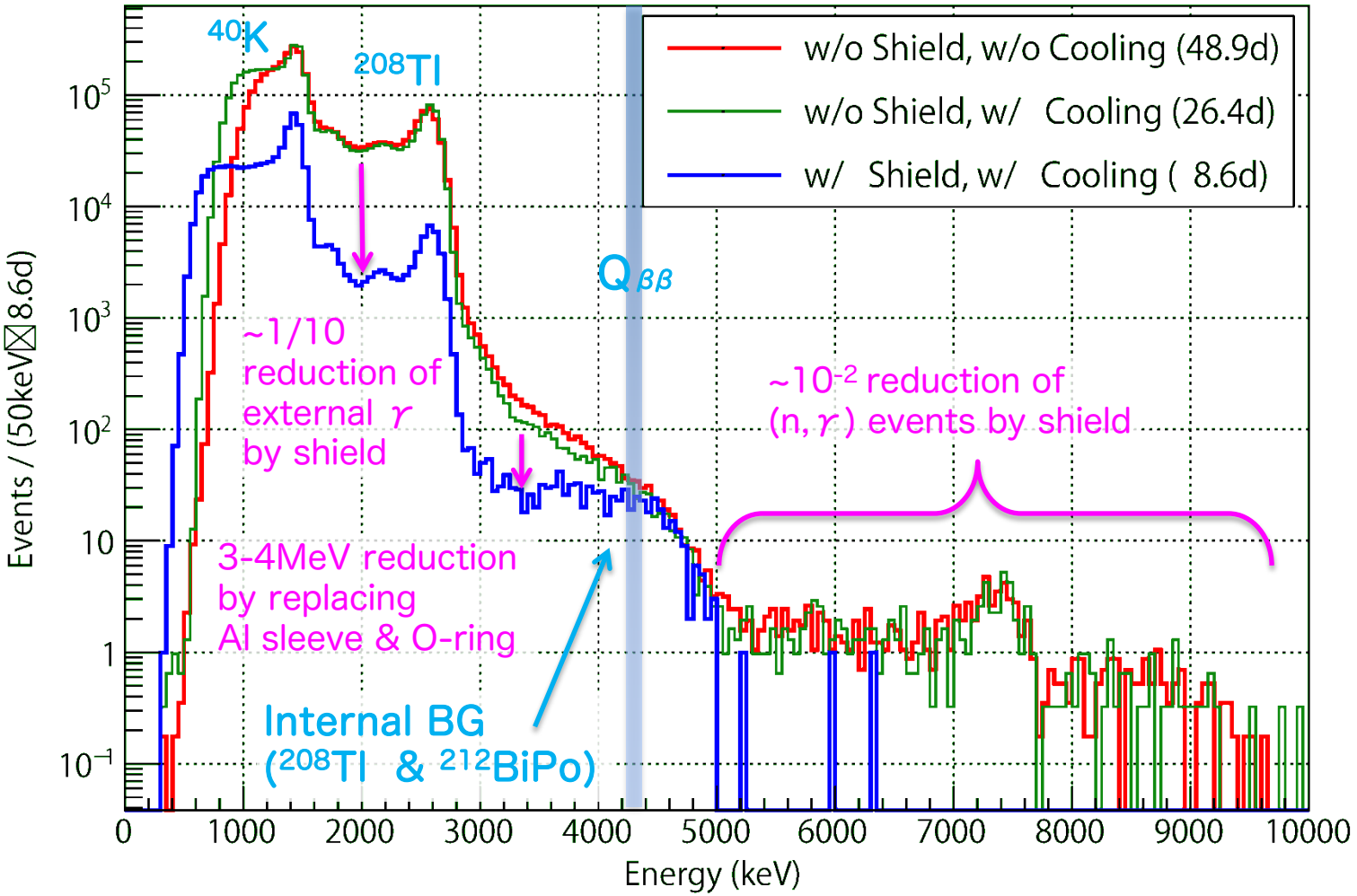
Total ADC count

	^{88}Y (1.8MeV) Resolution
Original	4.8%
+Coil	4.2%
+Cool (4.0℃)	3.6%
now	4.1%

Resolution progress by upgrade is confirmed.

Background after Detector Upgrade

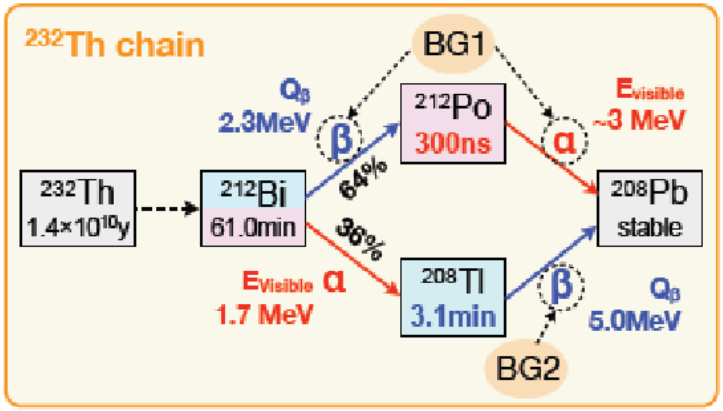
BG measurement w/ Pb+B shield, low BG material, Cooling, Coil



- 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

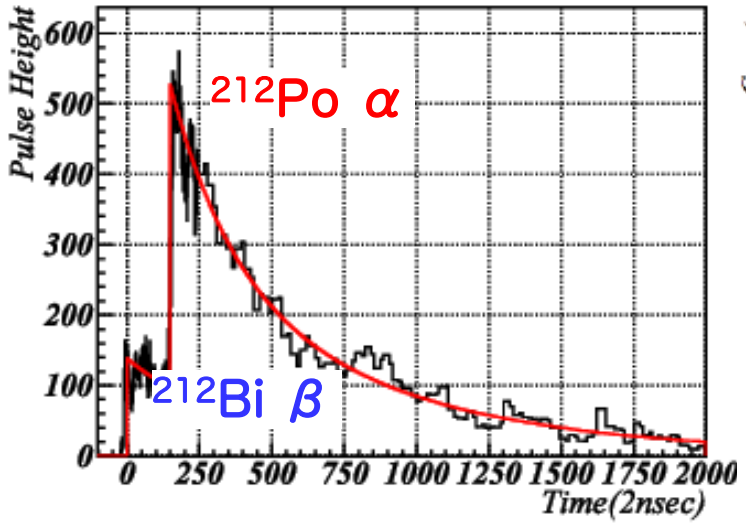
Internal BG in CANDLES : ^{232}Th daughters



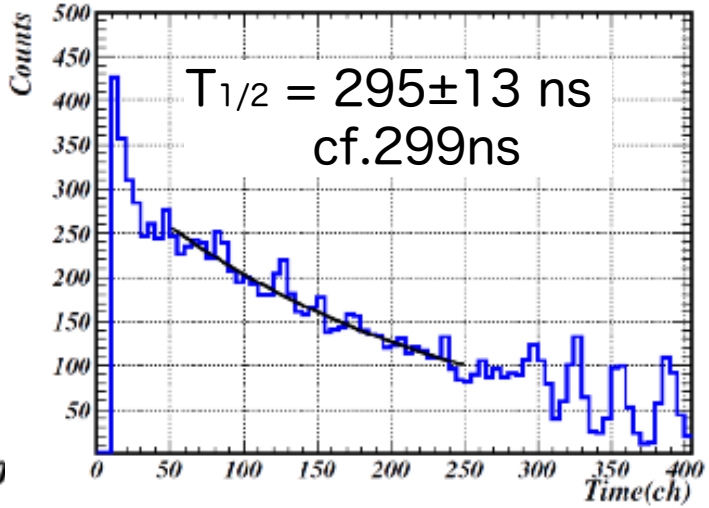
BG1: ^{212}BiPo sequential decay

- Total Max 5.3 MeV ⇒ $0\nu\beta\beta$ BG
- Pileup in one event window (4usec)
- Pulse Shape Analysis removes this.

Typical BiPo Waveform

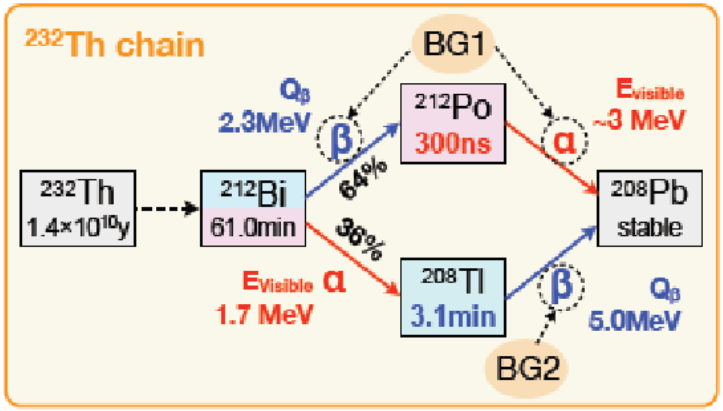


Time Interval of ^{212}BiPo



Pileup identification with ΔT > 20ns ⇒ 95% rejection efficiency.
Remaining 5% contribution is currently negligible.

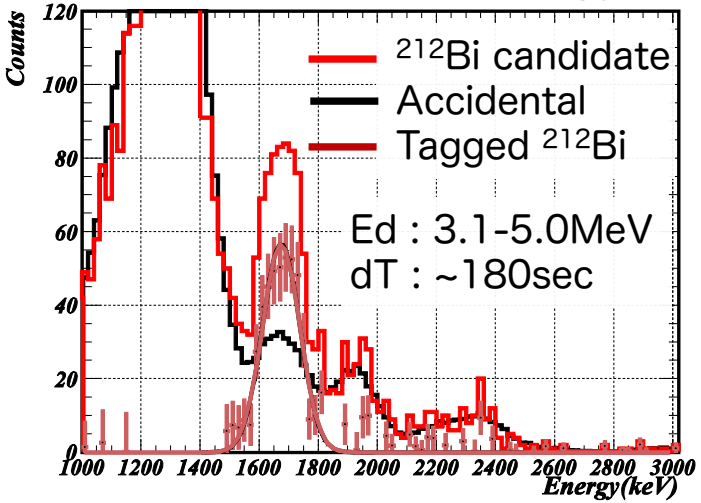
Internal BG in CANDLES : ^{232}Th daughters



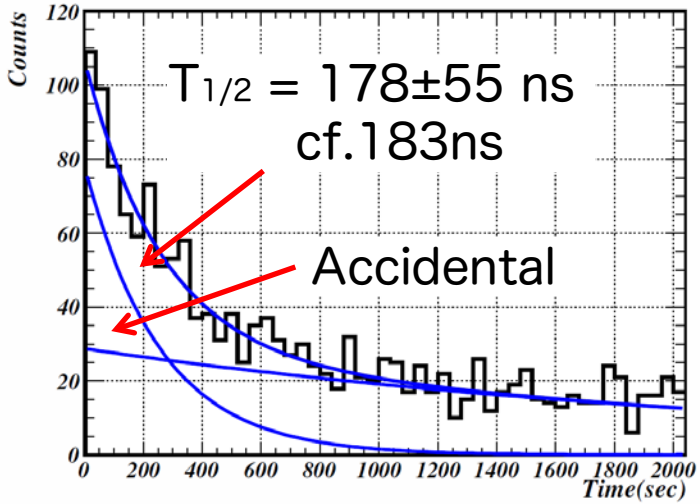
BG2: ^{208}Tl ($\beta+\gamma$)

- Total Max 5.0 MeV ⇒ $0\nu\beta\beta$ BG
- Event tagging with ^{212}Bi
  - Find parent ^{212}Bi α candidate by PSD.
  - Veto ^{208}Tl in 12min for same crystal

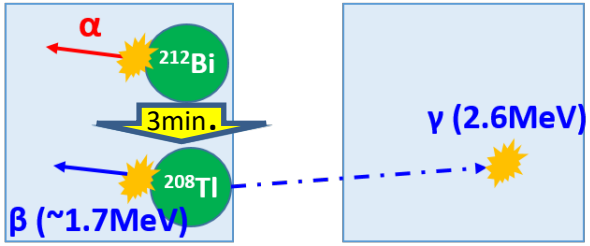
Prompt ^{212}Bi energy



Time Interval of ^{208}Tl



- current rejection eff. ~75%, acceptance~83%
- detection of Multi-crystal hit by escaped γ is under study.



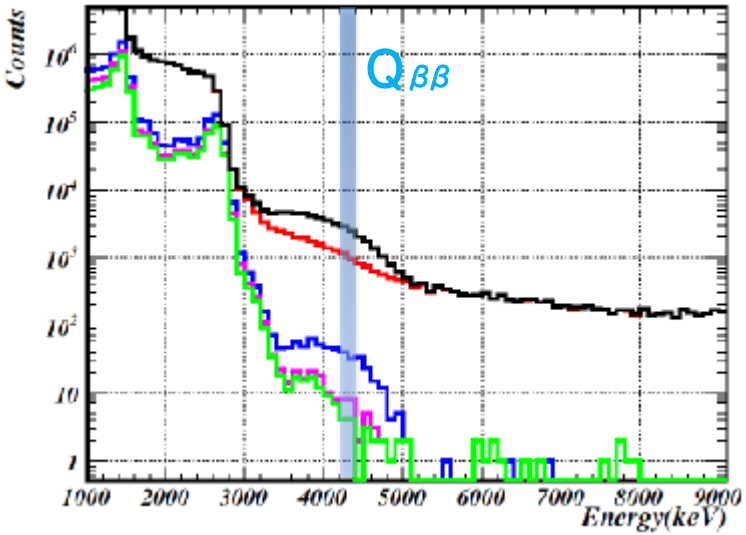
Energy Spectra & Event Selection

Preliminary

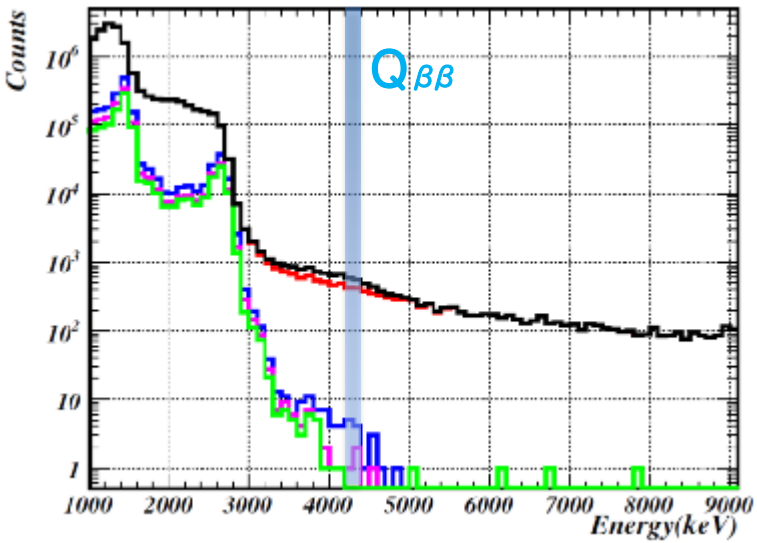
LiveTime : 131 days

Exp. Data
^{212}BiPo Cut
LS Cut
^{208}Tl Cut
Position Cut

95 crystals



27 crystals (^{232}Th <10uBq/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}Tl Cut	19	49	6	3	6	1
Position Cut	10	34	6	0	2	1

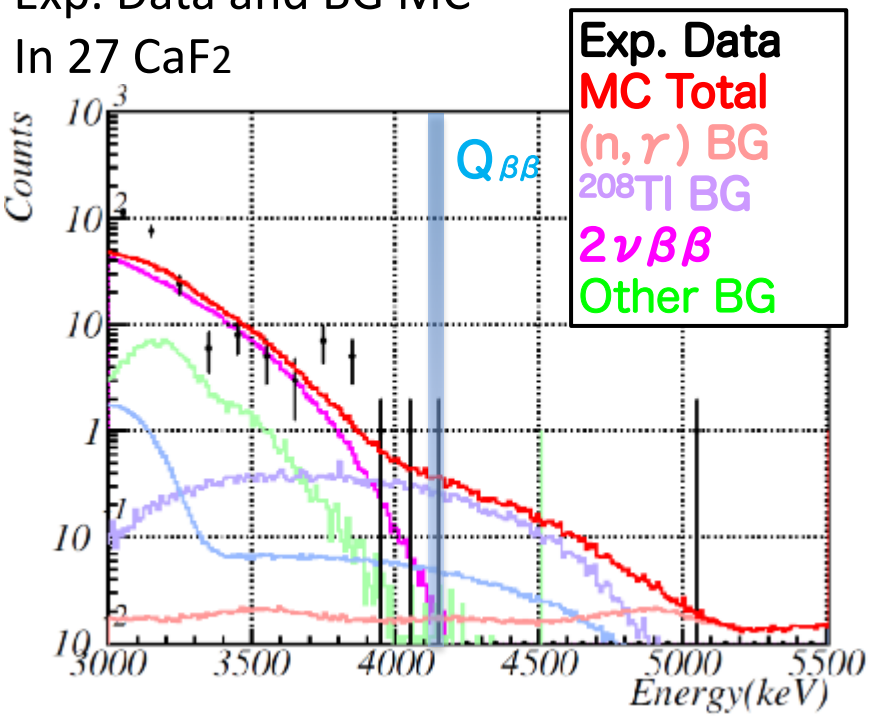
☑ No event in high purity crystals is confirmed.

Results

Preliminary

	95 CaF_2	27 CaF_2
Livetime	131	
$0\nu\beta\beta$ eff.	0.39 ± 0.06	
Event in ROI	10	0
Expected BG	~11	~1.2
$T^{1/2}_{0\nu\beta\beta}$ ^{48}Ca (yr)	>3.8x10^{22}	> 6.2x10^{22}
Sensitivity (yr)	6.2x10^{22}	3.6x10^{22}

Exp. Data and BG MC
In 27 CaF_2



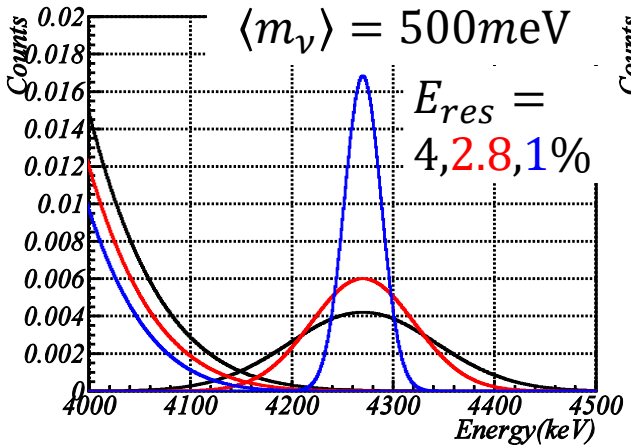
* ELEGANT IV
Exposure : 4947kg・d (2yr<)
$0\nu\beta\beta$ eff. : 0.53
$T^{1/2}_{0\nu\beta\beta}$ ^{48}Ca : 5.8x10^{22} yr

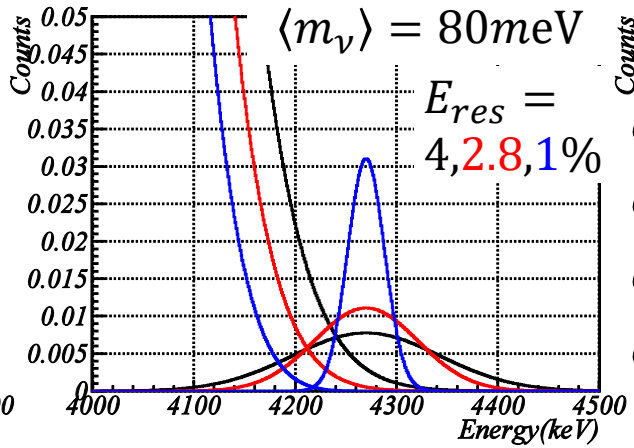
χ^2_β<1.5, -3σ<SI<1σ
-2σ<position cut<2σ
Pileup cut > 20ns
^{208}Tl cut
-1σ<$0\nu\beta\beta$ window<2σ

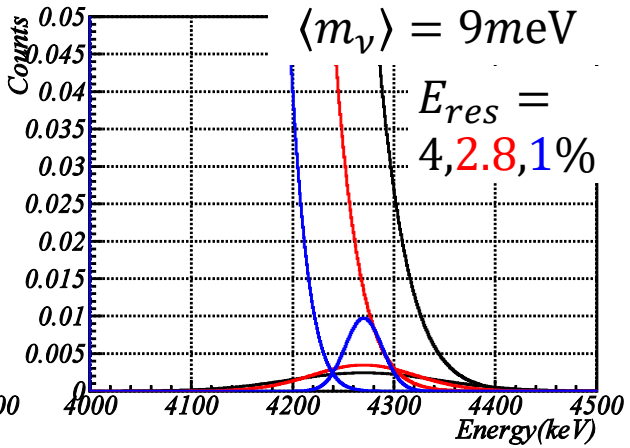
CANDLES is now exploring the forefront $T^{1/2}_{0\nu\beta\beta}$ in ^{48}Ca !

Future CANDLES

	CANDLES III+	CANDLES IV	CANDLES V
Crystal CaF_2 / ^{48}Ca	0.187% 305 kg / 0.35 kg	2% 2000 kg / 25 kg	50% 2000 kg / 610 kg
Energy Res.	6%	2.8% (required)	1.0% (required)
$\langle m_\nu \rangle$ sensitivity	500 meV	80 meV	9 meV
Feature	Cooling CaF_2 Low BG	Cooling CaF_2 Low BG Massive ^{48}Ca DH ⇒ IH	Massive ^{48}Ca Bolometer IH ⇒ NH



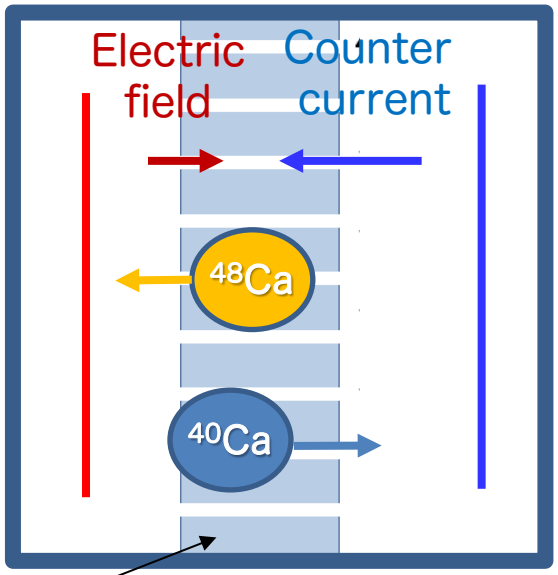




both Enrichment & Bolometer techniques are necessary
for future CANDLES

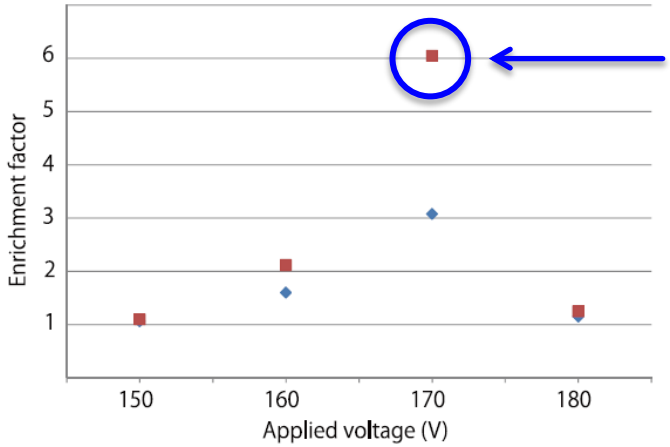
R&D : ^{48}Ca enrichment : MCCCE

- Multi-channel counter current electrophoresis



Boron Nitride plate
80mmϕx10mm,
x69 0.8mmϕ channel

- Separation using difference of migration speed between ^{40}Ca / ^{48}Ca.
- Principle was demonstrated.



Enrichment Factor (48/40): 6.1

- Reproducibility has been increased.
- Further study on parameter optimization for
  - High enrichment
  - Large amount

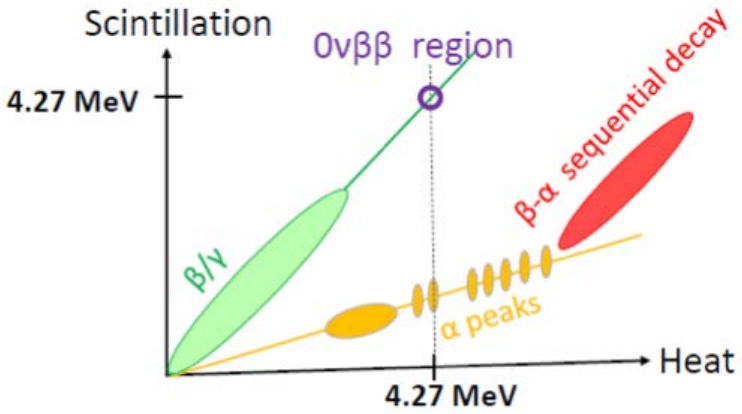
- Parallel R&D on crown-ether + micro-reactor, crown-ether resin + chromatography, laser isotope separation.

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

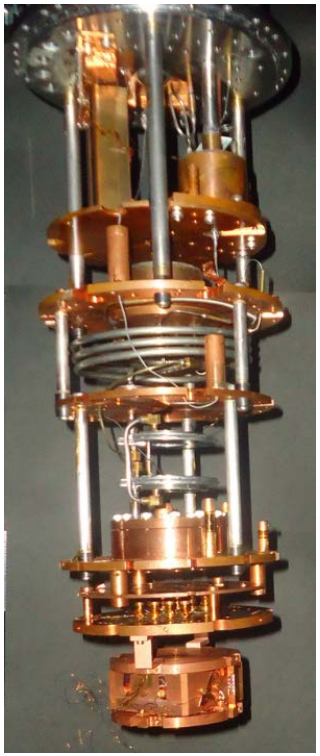
Calcium isotope enrichment by means of multi-channel counter-current electrophoresis for the study of particle and nuclear physics

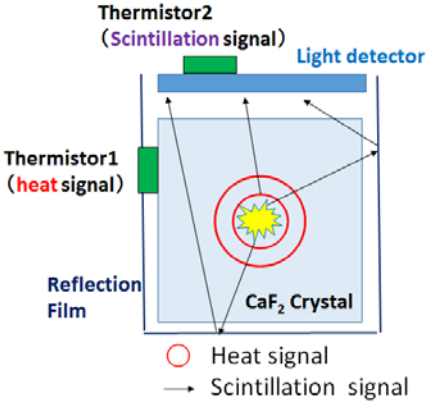
R&D : Scintillating Bolometer

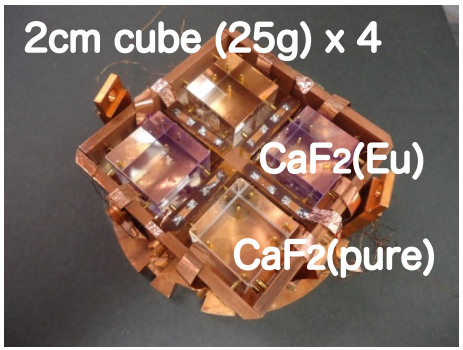
- $2\nu\beta\beta$ is an inevitable BG for explorer IH, NH.
- Better energy resolution is necessary.
  Scintillator → Bolometer
- ^{238}U α 4.27MeV will be BG.
- Simultaneous measurement of heat and scintillation enables to identify the PID(α/β)
  ⇒ Scintillating Bolometer
- The technique was already established.
  CRESST-II (CaWO4), Lucifer, AMoRE



143mK rise @ 10mK







Dilution refrigerator

- Dilution refrigerator, developed for the dark matter search with LiF.
- Cooling power is 2μW @ 20mK

Cooling Test

- LN_2 pre-cooling (77K)
- LHe pre-cooling (4K)
- 1K pot decompressing cooling (1K)
- $^3He/^4He$ mixed gas circulation (10mK)
- Detect Heat Signal

on going done

Other Preparation

- Ge wafer for light detector prepared
- 10cm Pb + 5cm Cu shield ready.

Summary

- CANDLES : $0\nu\beta\beta$ search by ^{48}Ca (350g) / CaF_2 (305kg)
  - highest Q (4.3MeV), potential 0 BG observation, important for IH/NH

- Detector upgrade in 2015-2016
  - Additional passive shield against largest BG : (n, γ)
    - Pb : 7 or 12 cm, B : 5mm ➔➔ 10^{-2} reduction
  - Low BG material replacement
  - Detector cooling & Geomagnetic Compensation coil
    - 17℃ ⇒ 4.9℃ ➔➔ +47% light yield

- Remaining BG : ^{208}Tl inside CaF_2
  - Further analytical rejection study is on going

- Preliminary $T_{0\nu\beta\beta}^{1/2}$ limit on ^{48}Ca : 6.2×10^{22} yr (sensitivity 3.6×10^{22} yr)

  (ELEGANT IV > 5.8×10^{22} yr)

  > 3.5 exposure already, and continue to explore the forefront.

- Future CANDLES
  - ^{48}Ca enrichment with MCCCE method, Scintillating Bolometer under study