Current status and future prospects of the CANDLES experiment

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Contents

- Double beta decay
  - ^{48}Ca measurement
- CANDLES projects
  - CANDLES III : Current operating detector system
    - First result for 130 days with BG free
    - New analyses for further background rejection
  - Next detector system
    - ^{48}Ca enrichment
    - Scintillating bolometer
- Summary

Requirement of DBD experiment

- Sensitivity for $\langle m_{\beta\beta} \rangle$
  - $\langle m_{\beta\beta} \rangle^2 \propto \dfrac{1}{T_{1/2}^{0\nu\beta\beta} G_{0\nu} |M_{0\nu}|^2}$

$\langle m_{\beta\beta} \rangle$: Majorana neutrino mass

$T_{1/2}^{0\nu\beta\beta}$: half-life

$G_{0\nu}$: phase space factor

$M_{0\nu}$:nuclear matrix element

- Requirement for experiment
  - large target mass & low background
    - $T_{1/2}^{0\nu\beta\beta} \propto \sqrt{M_{detector}}$:with background

      $\propto M_{detector}$:without background

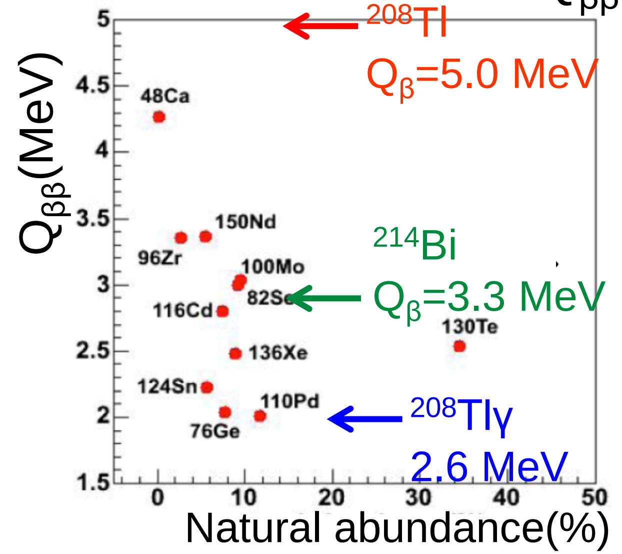
    * background free measurement

    = effective for high sensitivity

Double beta decay of ^{48}Ca

- Why ^{48}Ca ? : advantage of ^{48}Ca
  - higher $Q_{\beta\beta}$ value (4.27MeV) . . .
    →low background
    because Q $_{\beta\beta}$ value is higher than BG
    E_{max}=2.6MeV(^{208}Tl, γ-ray)
    3.3MeV(^{214}Bi,β-ray)
  - But small natural abundance 0.19%

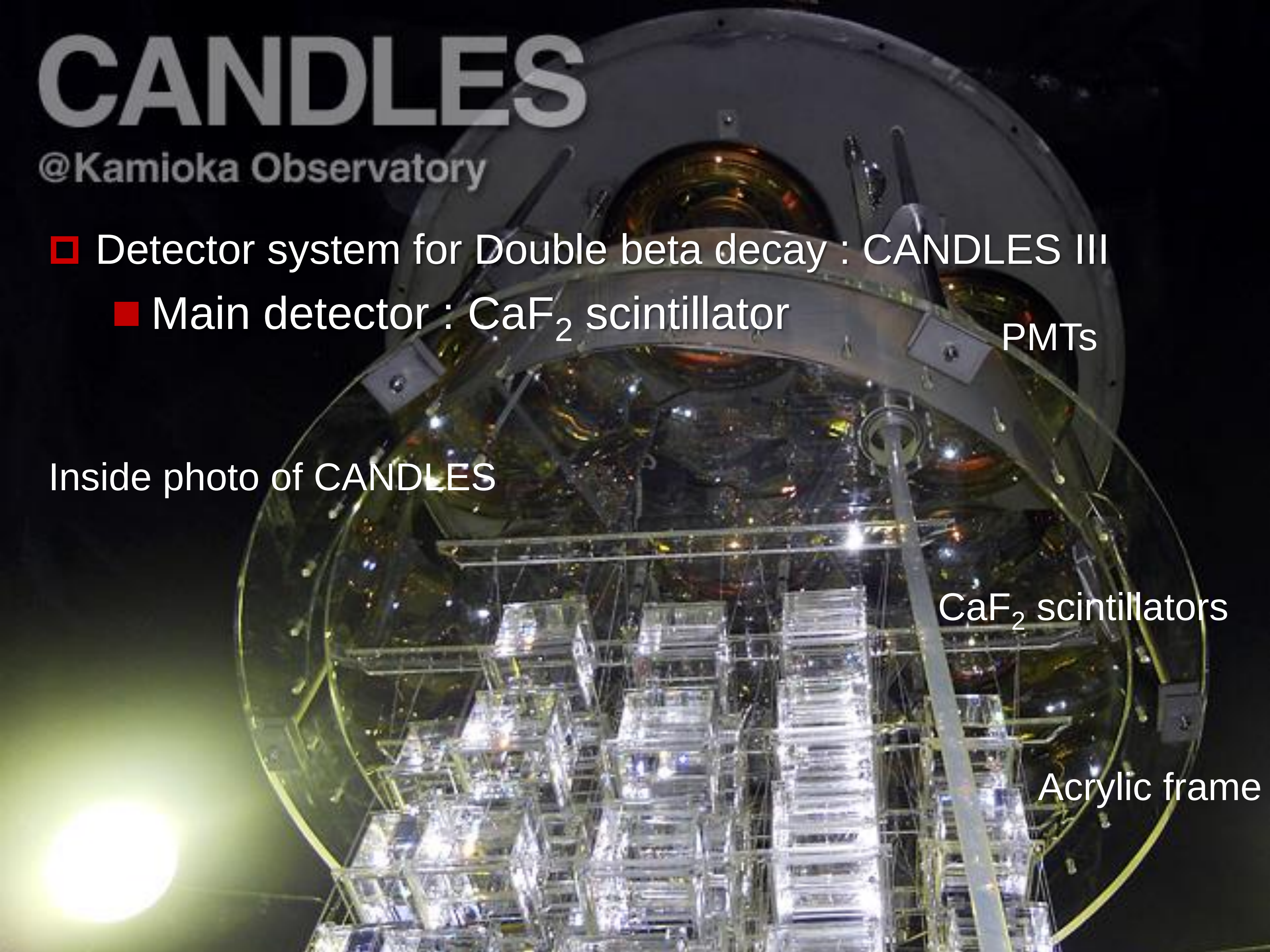
Natural abundance vs $Q_{\beta\beta}$



- Double beta decay of ^{48}Ca by using CaF_2
  - CANDLES system
    - CANDLES III : current detector system
    - Next techniques : Enrichment + scintillating bolometer for new detector system

CANDLES
@Kamioka Observatory

- Detector system for Double beta decay : CANDLES III
  - Main detector : CaF_2 scintillator



Kamioka underground laboratory

http://gwcenter.icrr.u-tokyo.ac.jp/wp-content/uploads/2011/02/LCGT.jpg

Kamioka mine for zinc and lead

↓

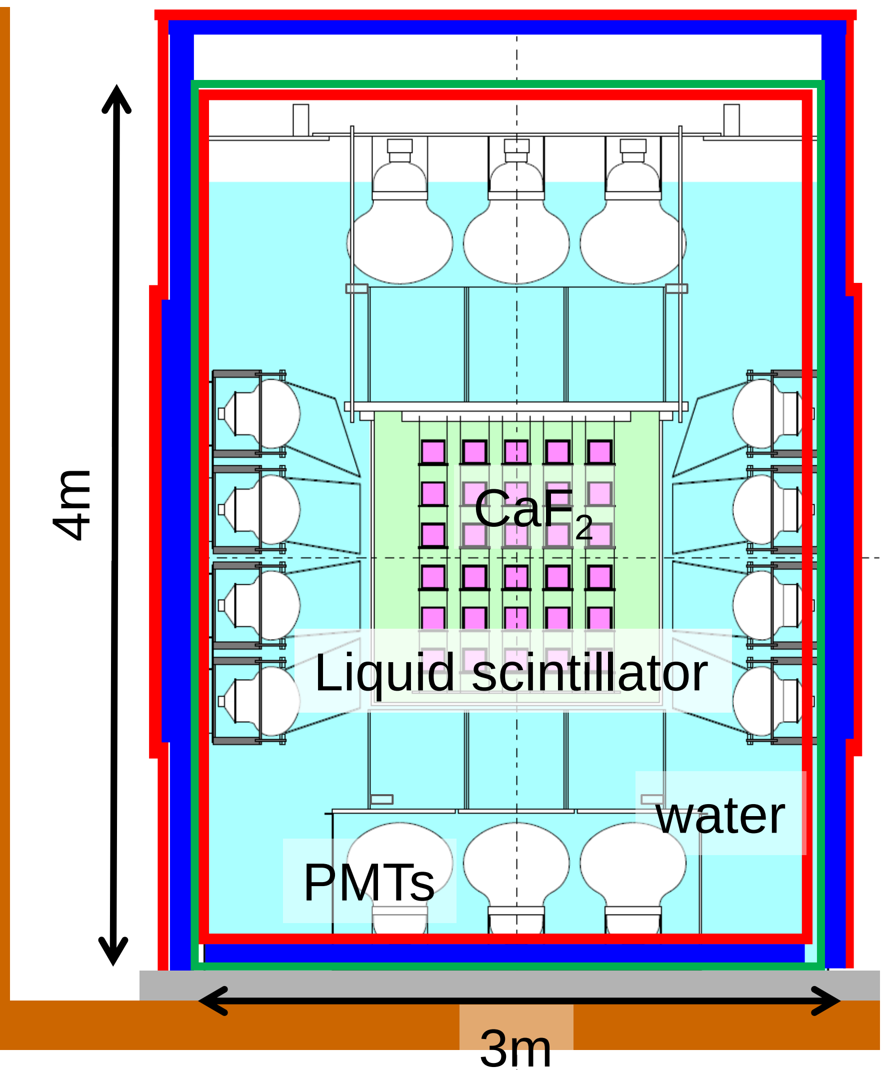
Kamioka Lab for underground sciences

- 1000 m.w.e. depth
- 400 km away from Oaska

CANDLES : double beta decay
KamLAND : neutrino & double beta decay
Super Kamiokande : neutrino
NewAGE : dark matter
KAGRA : gravitational wave

CANDLES III

Ref : K. Nakajima et al, Astroparticle Phys, 100, (2018), 54-60
Ref : T. Iida et al, Nucl. Inst. Meth. A986, (2021), 164727



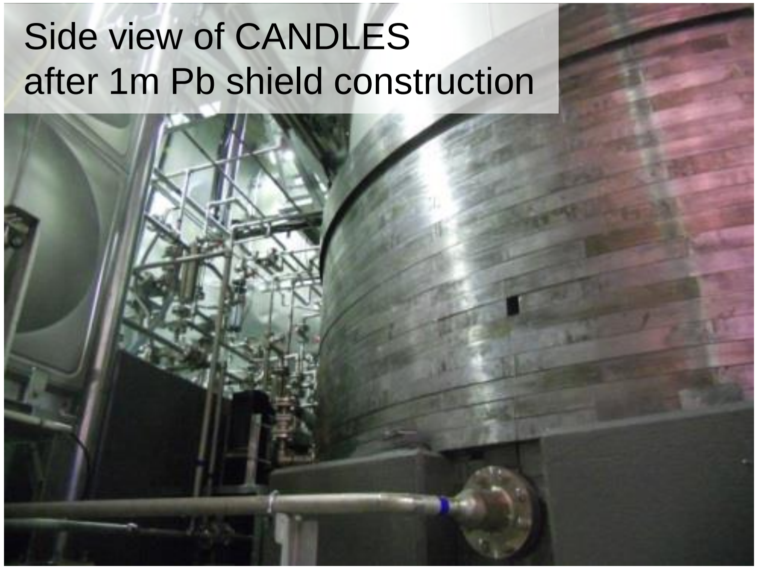
- CaF_2 scintillator (CaF_2 (pure))
  - 305kg (96modules × 3.2kg)
  - ^{48}Ca : 350g
- Liquid scintillator (LS)
  - 4π active shield(2m^3)
- 62 Large photomultiplier tube
- Shielding system
  - Pb : 10-12cm
  - B_4C sheet : 5mm

CANDLES tank(stainless steel)
Pb（γ-ray shield）
B sheet（neutron shield）

Shield construction

- Shielding system
  - Pb shield, B_4C sheet

Pb total mass : ~50ton



setting Pb bricks
in the main tank

Result

Result of measurement for 130days

Result with 21 high purity CaF_2

	result
0vββ efficiency	0.36(21CaF_2)
Num. of eve.(exp)	0
Expected BG	1.02
Half life of ^{48}Ca	>5.6×10^{22}year
Sensitivity	2.8×10^{22}year

Ref : Phys. Rev. D103, (2021), 092008

＊comparable to most stringent limit of ^{48}Ca

ELEGANT VI

measurement time : 4947kg・day(2 years <)

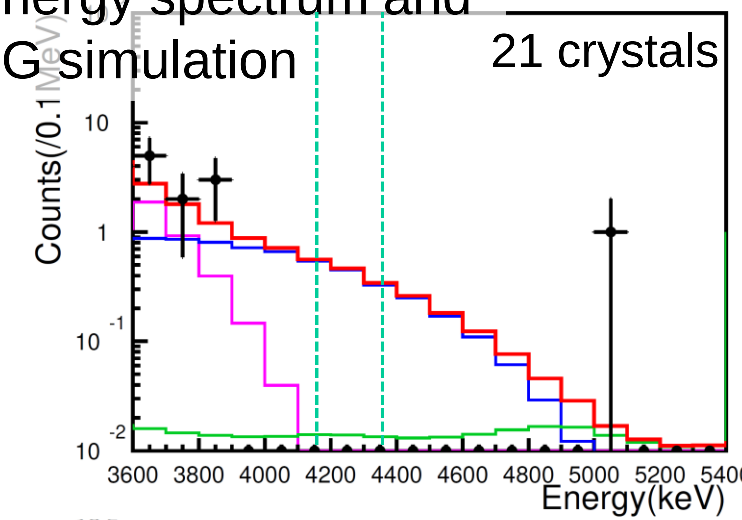
half life limit : 5.8×10^{22} year

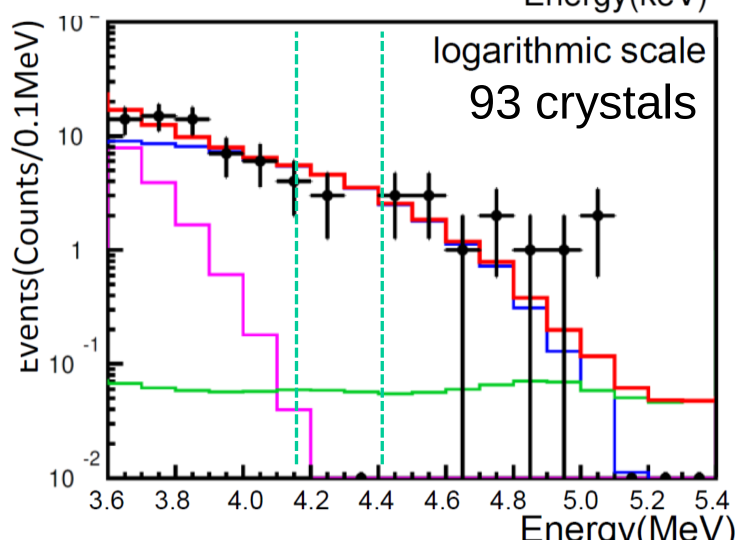
*Achieved background rate

- < 10^{-3} events/keV/year/(kg of ^{nat}Ca)
- comparable to lowest background level

● experimental data
simulation(total)
γ-ray from N capture
contamination in CaF_2 (^{208}Tl and ^{212}BiPo)
2νββ

Energy spectrum and BG simulation

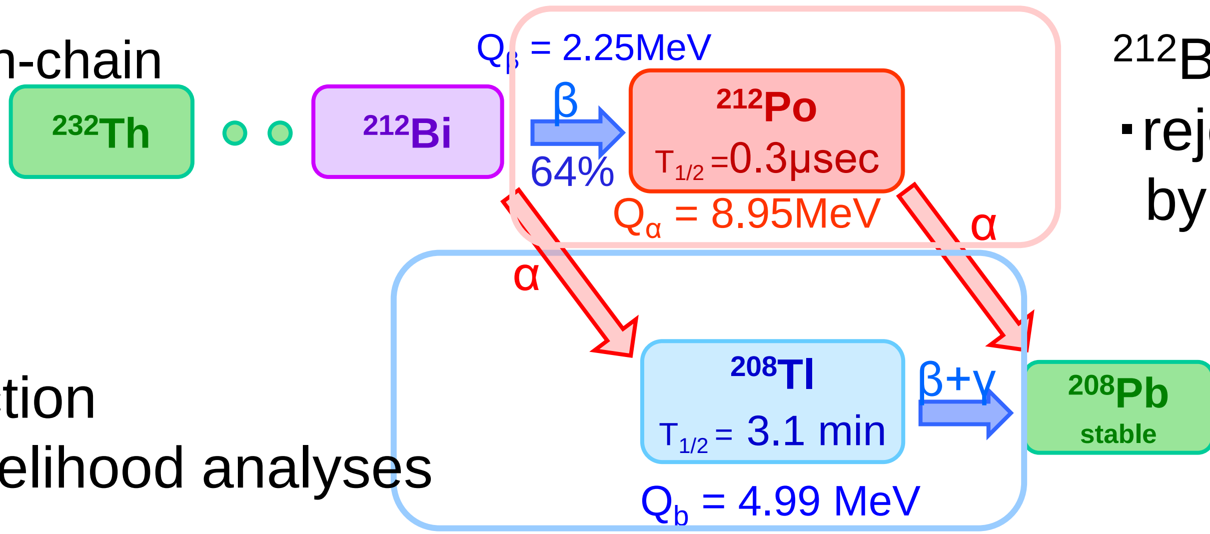




Improvement of Analyses

- For background free measurement
  - Measurement time : 130 days + 652 days
  - Improved analyses for background rejection
    - $^{212}Bi^{212}Po$(pile up events) rejection : finished
      - by rise shape observation of pulse shape
    - ^{208}Tl rejection : in progress
      - by identification of prompt ^{212}Bi α decay

Th-chain



$^{212}Bi^{212}Po$
・rejection
by machine leaning

^{208}Tl
・rejection
by likelihood analyses

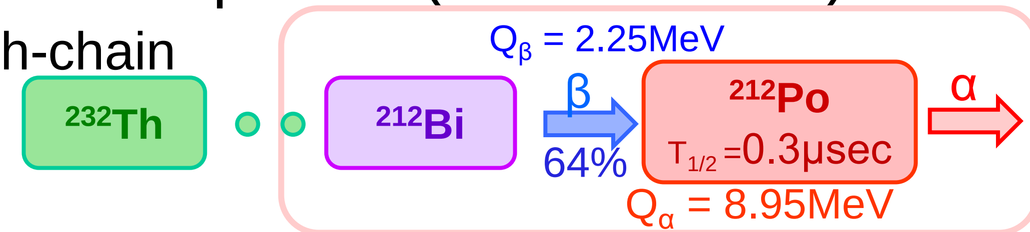
^{212}Bi^{212}Po rejection by CNN

T. Batpurev(D thesis)
T. Sakai(M thesis)

- Pile up event(Double Pulse) : ^{212}Bi→^{212}Po

Poster presentation by R. Sirai

Th-chain

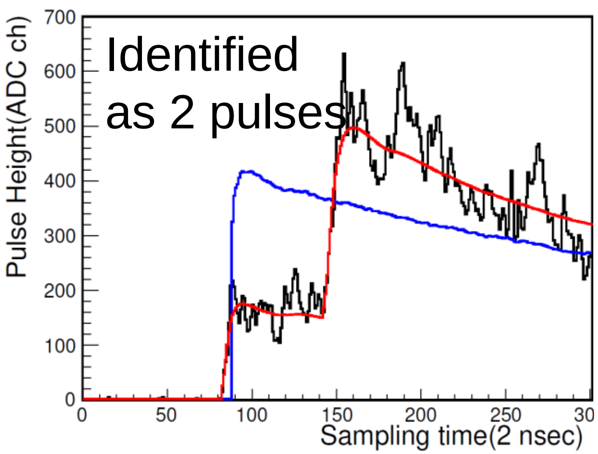


Rej. efficiency by fitting ~ 95 %

- Rejection by "Fitting" and "Machine learning method"

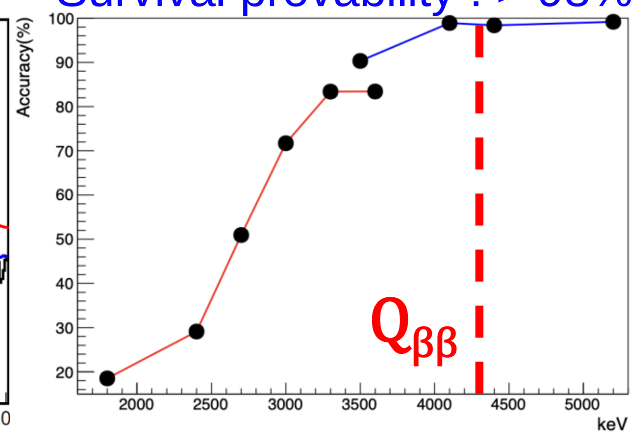
Typical pulse shape with long Δt(~100nsec)

fitting as 2 pulse function (red)
as 1 pulse function (blue)

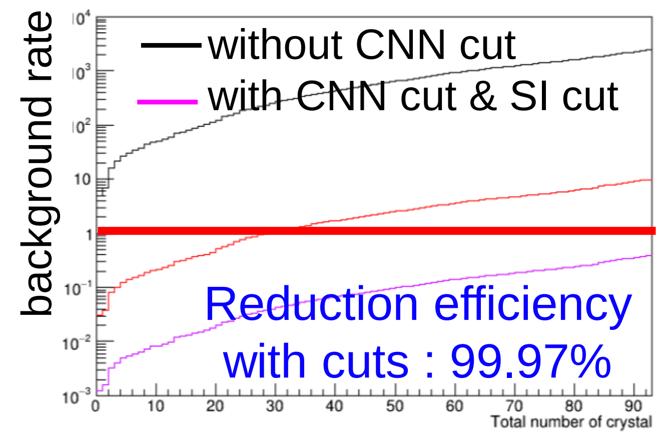


Survival probability for ββ events with cut by machine learning

Survival provability : > 98%



Rejection efficiency for short Δt events in 4.2-4.4 MeV 0νββ region



For 0νββ energy region :
Rejection effi. of ^{212}Bi^{212}Po >99.9%、survival probability for 0νββ>98%

^{208}Tl rejection : past analysis

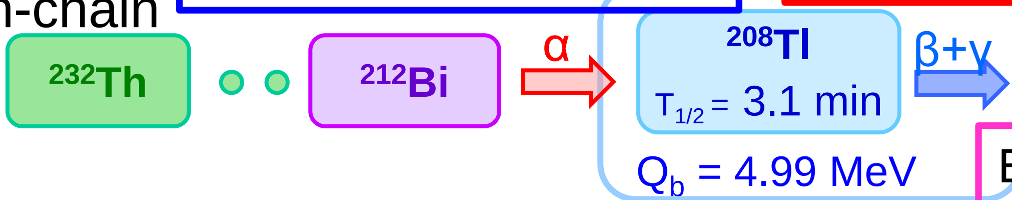
- rejection : identification of prompt ^{212}Bi

Already applied

Pulse shape : α-ray like

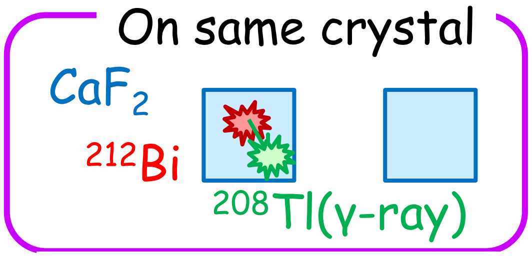
Time correlation : within short Δt

Th-chain

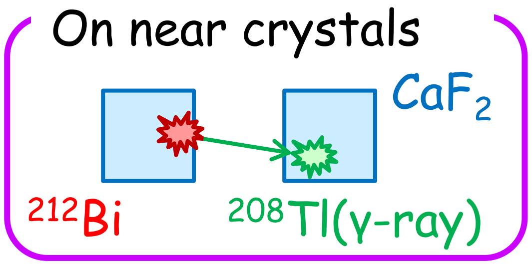


Event position : (required)
^{208}Tl and ^{212}Bi events on same CaF_2

Patterns of event position

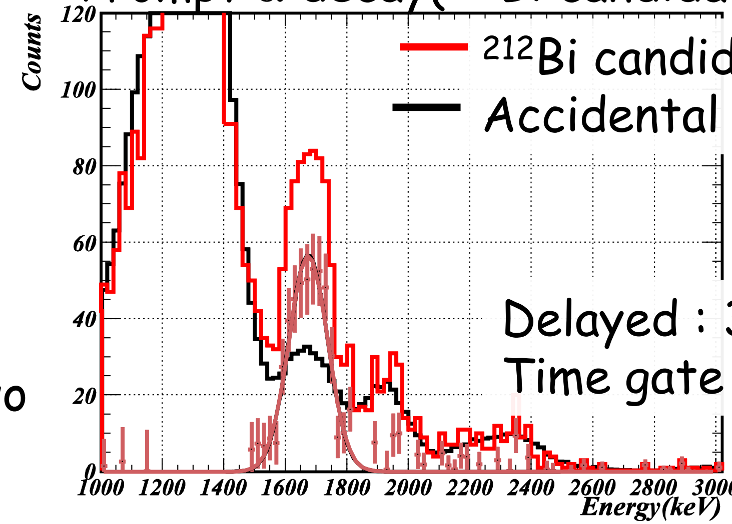


Rejected



Not rejected
"Multi-hit" on two CaF_2 crystals

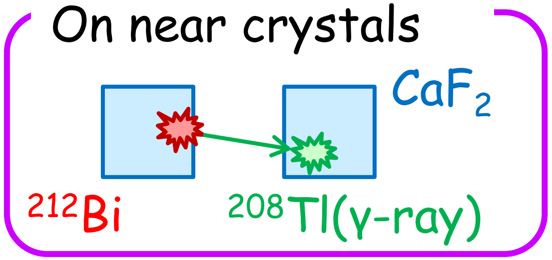
Prompt α decay(^{212}Bi candidate)



We can identify ^{212}Bi and ^{208}Tl events on same crystal. : ~78%
Next : we try to identify ^{212}Bi and ^{208}Tl on near crystals.

G. Miyoshi(M thesis)

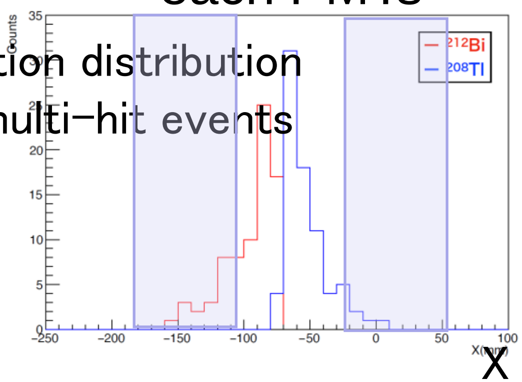
Position distribution of ^{208}Tl



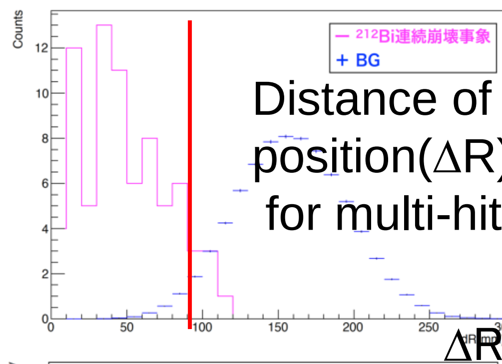
"Multi-hit" on two CaF_2 crystals

- Identification by using distance of ^{212}Bi^{208}Tl event position
  - ^{208}Tl event position simulation by using photoelectron distribution for each PMTs

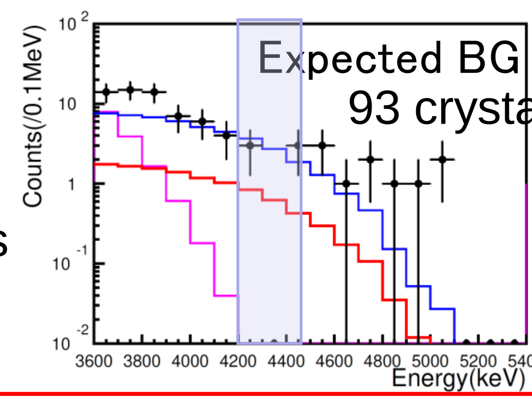
Position distribution for multi-hit events



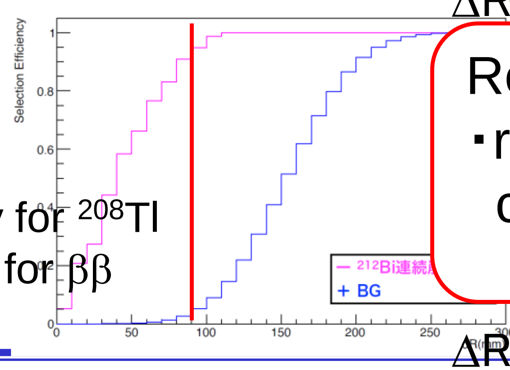
Distance of event position(ΔR) for multi-hit events



Expected BG 93 crystals



Rejection efficiency for multi-hit events



Rejection efficiency for ^{208}Tl

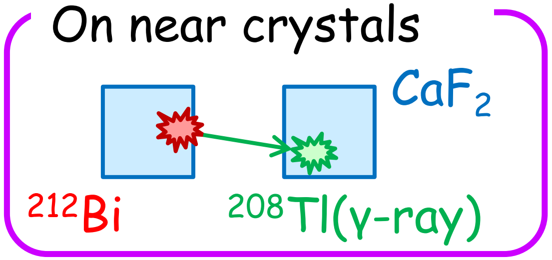
Survival provability for ββ

Rejection by ^{208}Tl multi-hit events

- rejection efficiency >95 %
  cut point:90mm
  (survival provability > 95%)

G. Miyoshi(M thesis)

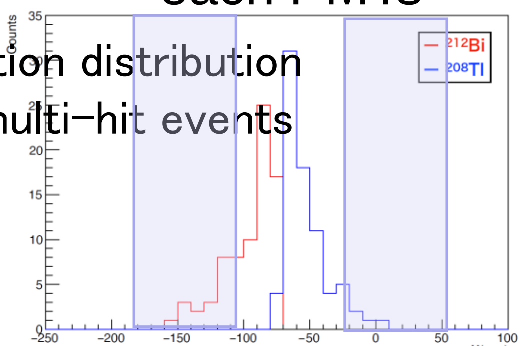
Position distribution of ^{208}Tl



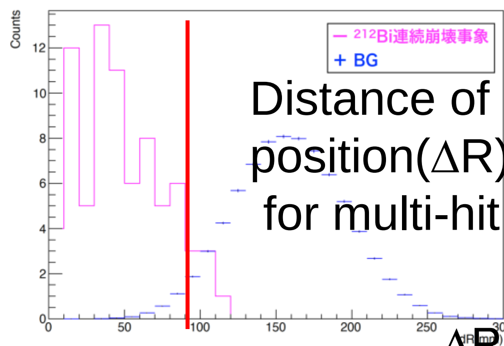
"Multi-hit" on two CaF_2 crystals

- Identification by using distance of ^{212}Bi^{208}Tl event position
  - ^{208}Tl event position simulation by using photoelectron distribution for each PMTs

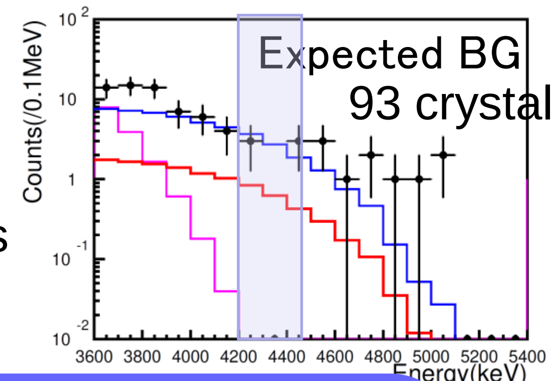
Position distribution for multi-hit events



Distance of event position(ΔR) for multi-hit events



Expected BG 93 crystals



events

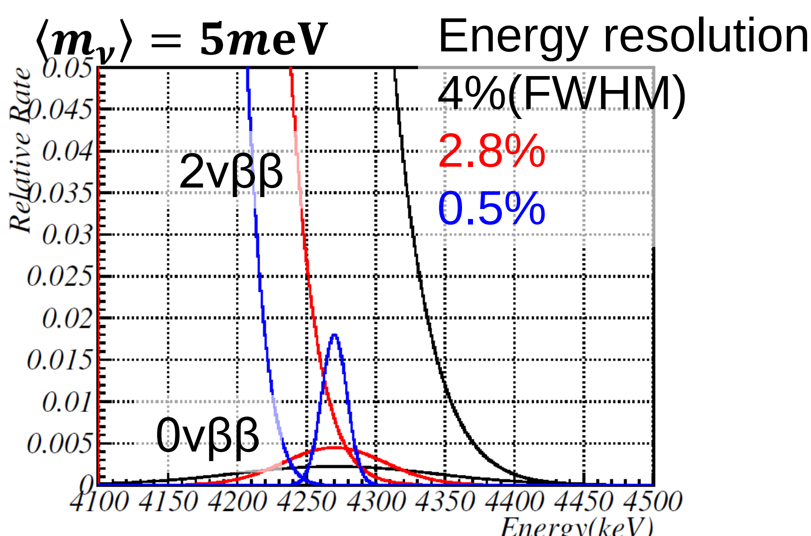
%)

By using
the position information between ^{212}Bi and ^{208}Tl
pulse shape information of ^{212}Bi
we will achieve lower background rate as BG free
will obtain more stringent ^{48}Ca half-life limit.

Future CANDLES

- Next step of double beta decay measurement

	CANDLES III	Next detector system
^{48}Ca Abundance	0.187%	50%
^{48}Ca Weight	0.35 kg	600 kg ~
Energy Resolution	6%	1.0% (required)
$\langle m_\nu \rangle$ sensitivity	500meV	~5 meV
Feature	Cooling CaF_2 Low BG	Enrichment of ^{48}Ca Scintillating bolometer



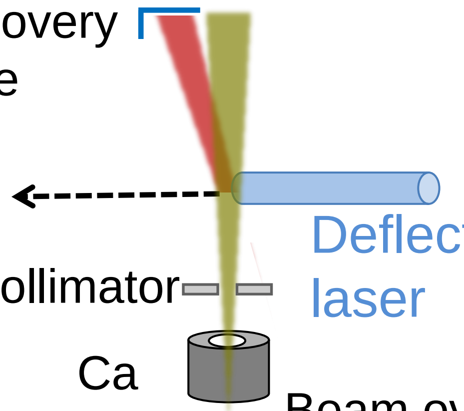
- Large amount of ^{48}Ca
  - For high sensitivity : increase by enrichment ← limited by small mass of ^{48}Ca
- Higher energy resolution
  - To reduce 2νββ events

Fukui Univ.: H.Niki, I.Ogawa

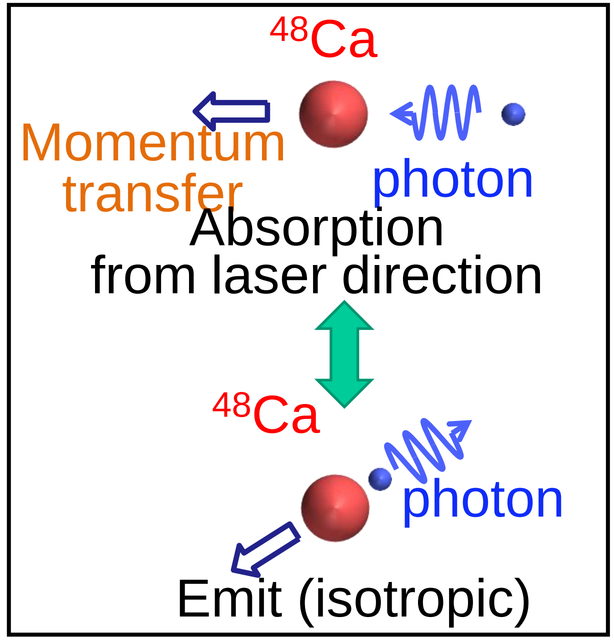
Next detector system：enrichment

- introduction of laser isotopic separation(LIS)

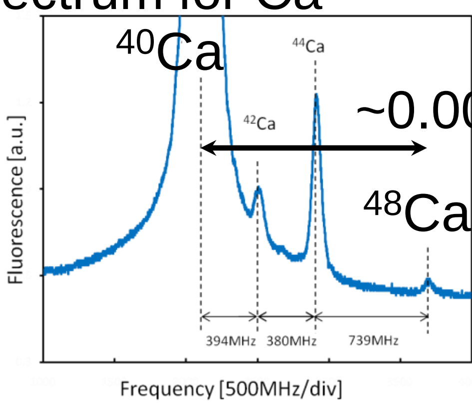
Setup



Deflection method

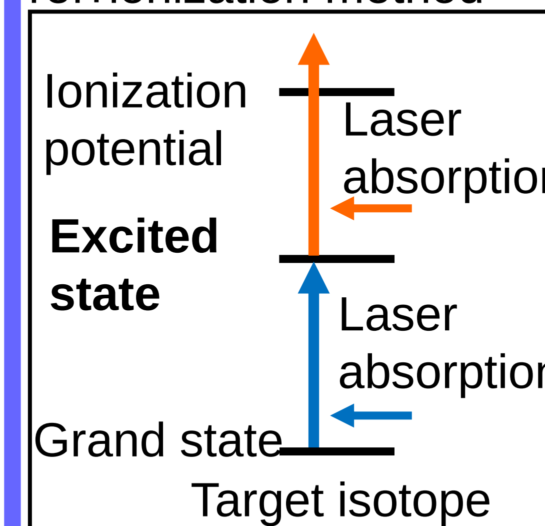


Absorption wavelength spectrum for Ca



Important point
- blue laser with narrow linewidth

ref：ionization method

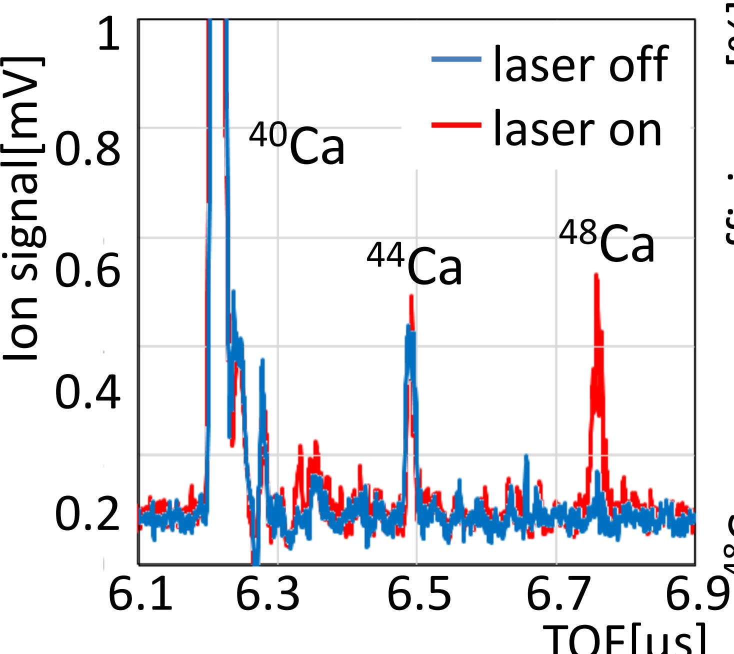


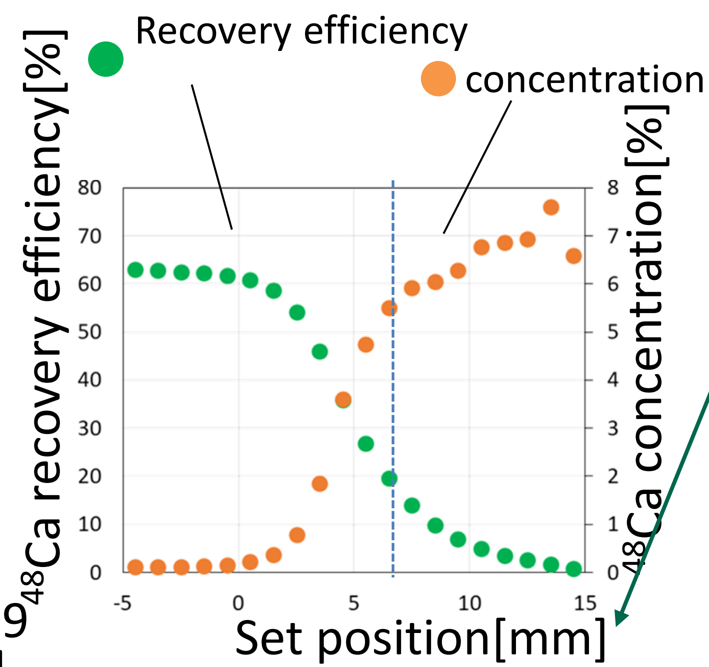
Two laser for enrichment
- for excitation
- for ionization

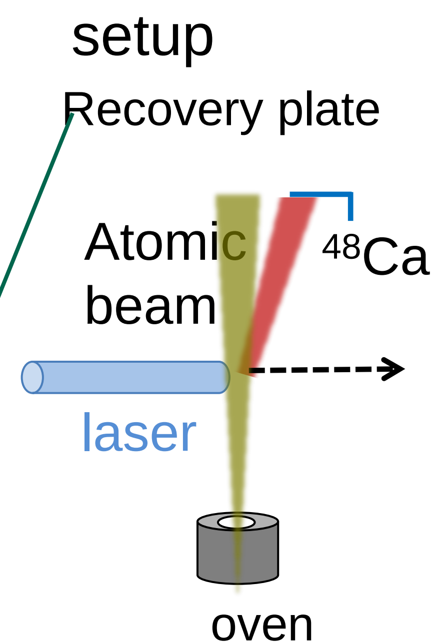
Laser isotopic separation

Ref :K. Matsuoka et al, J. of Phys. : Conf. Ser. 1468, (2020), 012199
Ref : Presentation by I. Ogawa in SPLG2021

- Separation effect





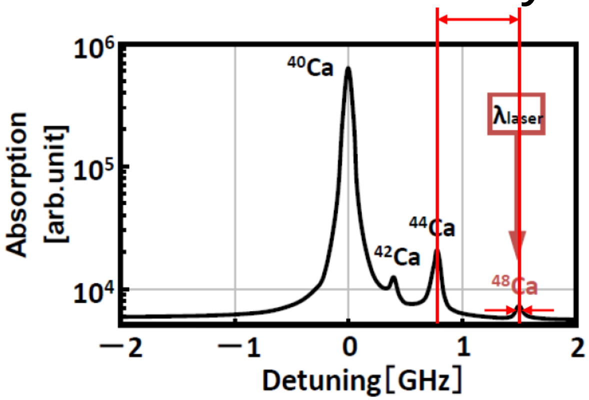


When Recovery plate is set at 6.5mm･･･
Recovery effi. 19.6% concentration 5.5%

- For high-concentration･high-recovery effi.
  - Large deflection → mass production
    - optimize irradiation system for deflection laser
    - High intensity blue laser

Requirement for blue laser

- Narrow linewidth and Stability of wavelength



Absorption spectrum of Ca at 423nm

Isotope shift : ~ 800 MHz

Natural width : ~34MHz

  - Target of laser frequency stability for production
    - 2MHz rms → 422.792xxxxx ± 0.0000006 nm
- Laser power for ^{48}Ca production
  - Number of photons absorbed by 1 atom : 1,000 photon
  - >1 kW of laser power for production 1kg/year ^{48}Ca
    - (base power)100 mW → (FY2023)2 W →(future) 2 kW → 300 kW

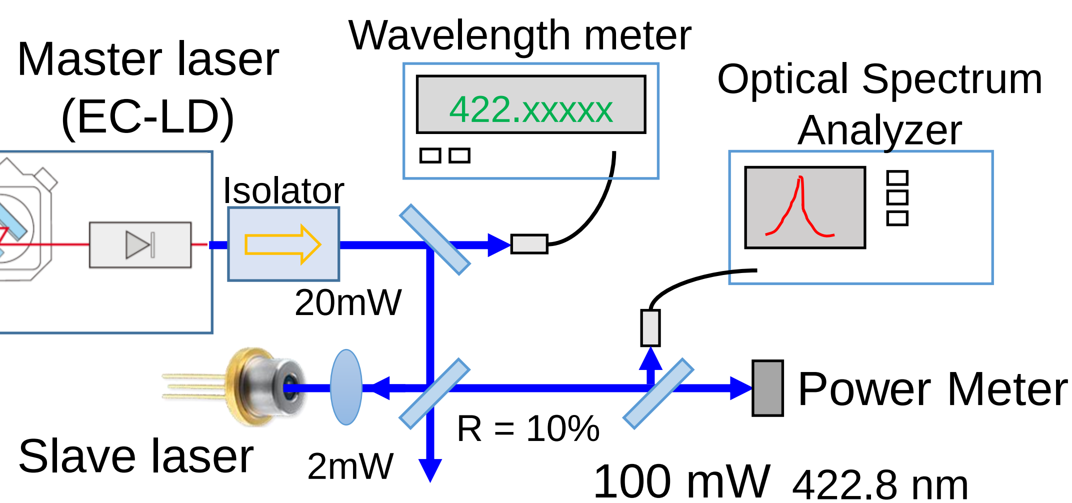
First step for demonstration
: 2 W laser with 0.0006 pm width

High intensity blue laser with narrow linewidth

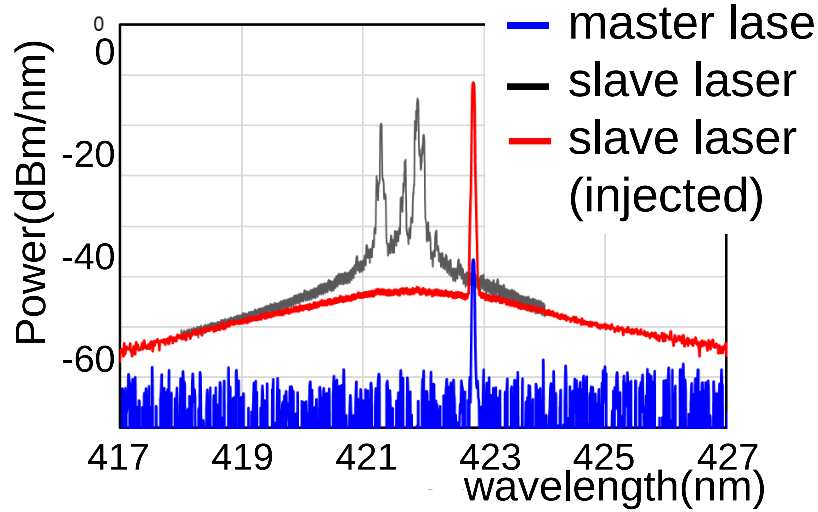
S. Tokita(ICR, Kyoto)
& N. Miyanaga(ILT)

- Experiment of injection locking
  - Master laser with controlled wavelength : seed laser
  - Slave lasers for summing up laser power

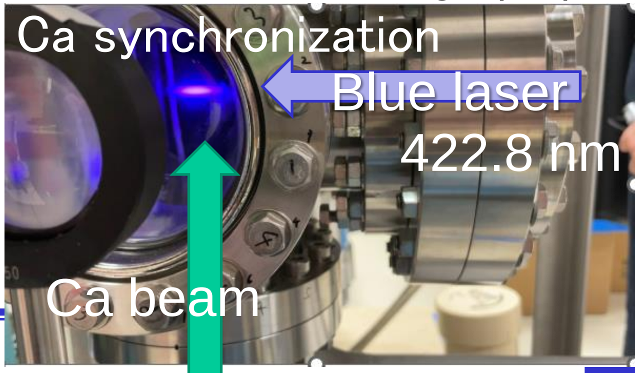
Experimental Setup



Wavelength of lasers



Controlled wavelength of slave laser
by temperature & current



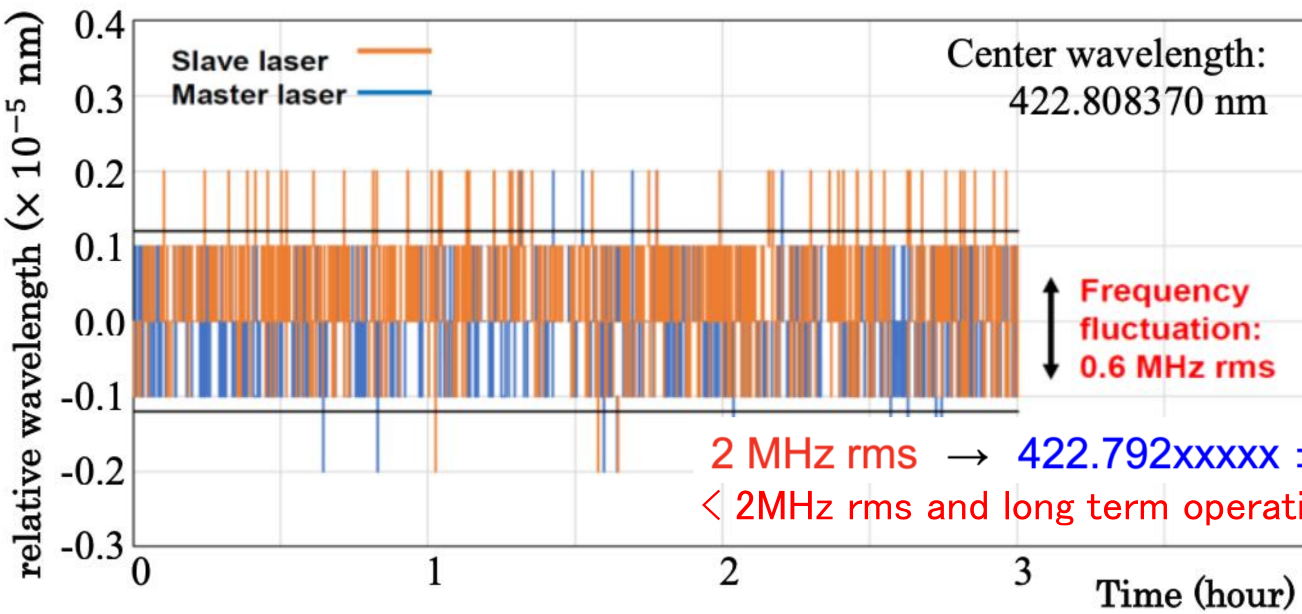
Injection locked system :OK
Next : stabilization of wavelength

Blue laser : stabilization

S. Tokita(ICR, Kyoto)
& N. Miyanaga(ILT)

- Test for laser stabilization
  - Stabilization by PDH method
    - Control signal : sent to each slave laser
    - Wavelength : adjusted by temperature control

Experiment of wavelength stabilization



2 MHz rms → 422.792xxxxx ±0.0000006 nm

< 2MHz rms and long term operation was obtained

The laser wavelength was stabilized in 2 x 10^{-5} nm width

LIS system for ^{48}Ca production

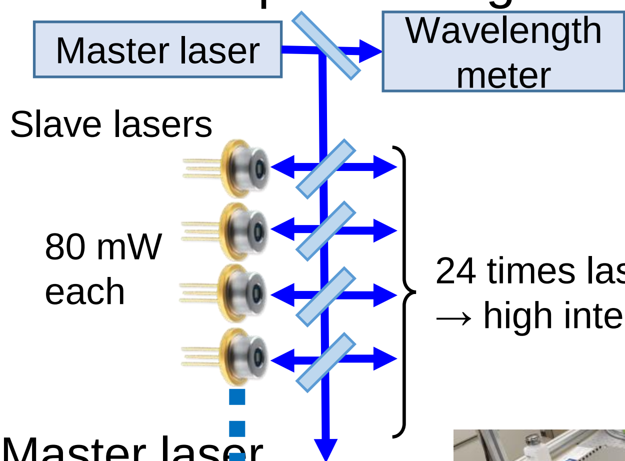
RCNP, Osaka Univ.
ICR, Kyoto Univ.
Fukui Univ.

- 2W laser array and LIS chamber

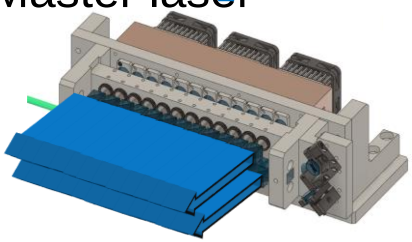
Poster presentation by R. Anawat

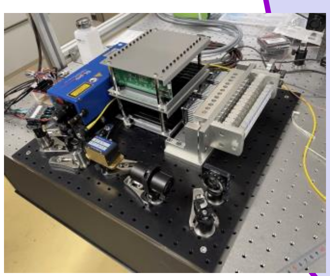
Multiple laser array for 2W laser

Conceptual design



Master laser

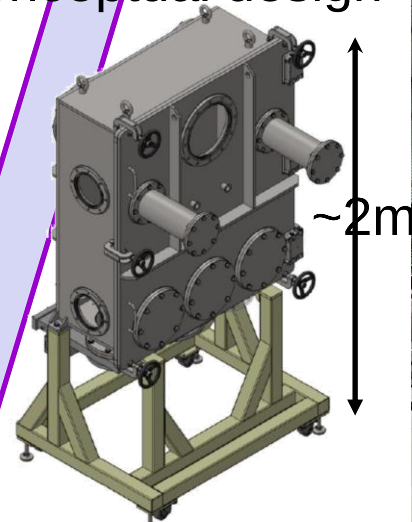


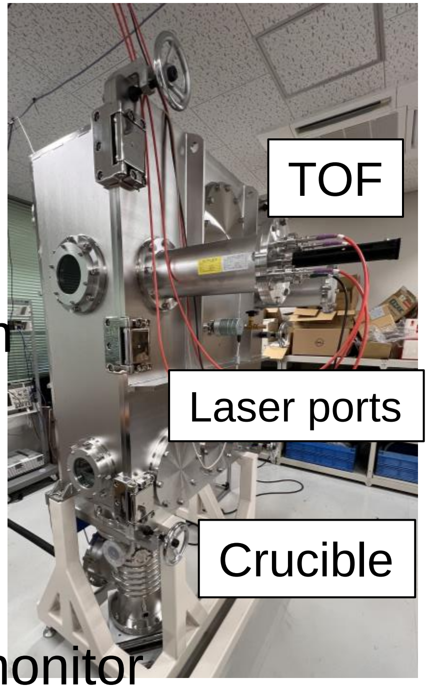


80 mW x 24 = 2 W under construction

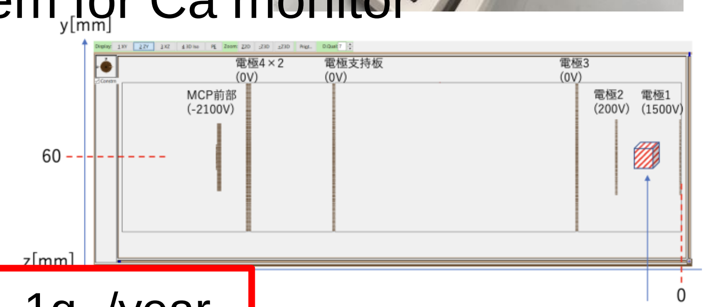
Main chamber

Conceptual design





TOF system for Ca monitor

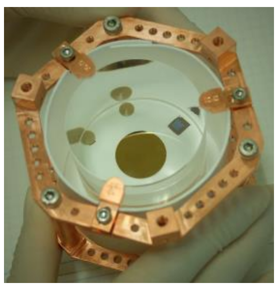


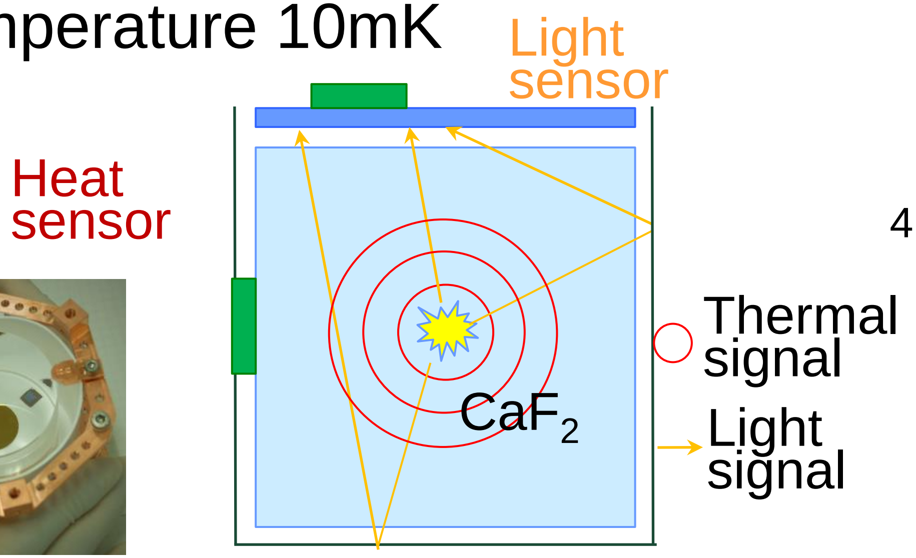
Correspond to production rate of ~1g~/year

We will start pilot operation in this fiscal year

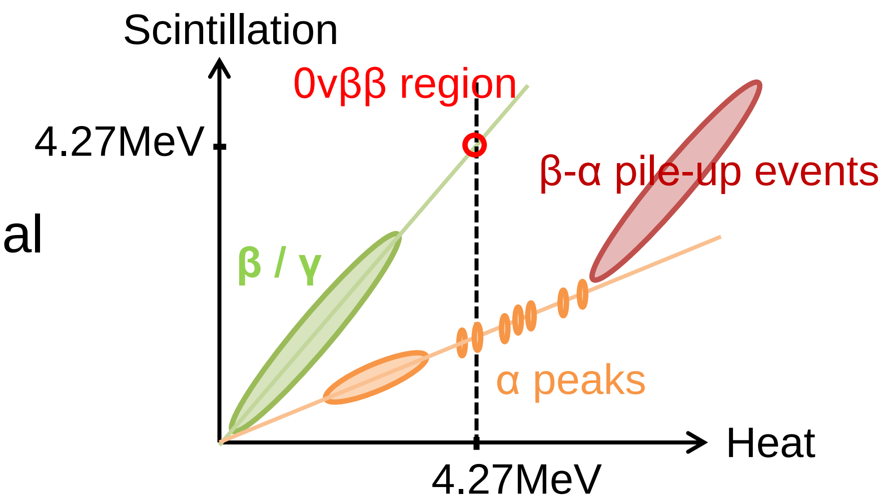
Next detector system：scintillating bolometer

Scintillating bolometer at low temperature 10mK





Particle identification by scintillating bolometer



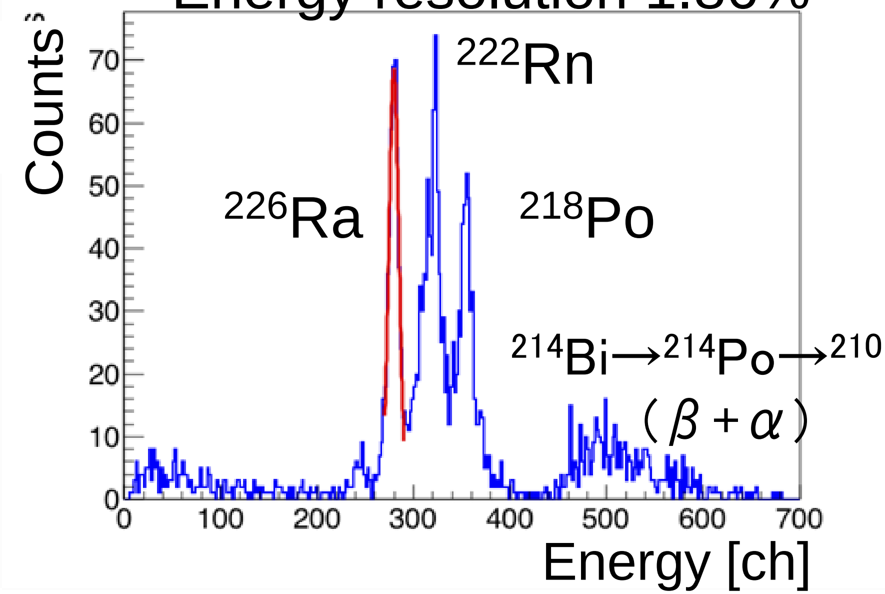
- Expected BG：2νββ events, α-rays
- bolometer：good energy resolution
  - For reduction of BG affects from 2νββ events
- Scintillating bolometer：good PI ability
  - For reduction of BG affects from α-ray

IBS Kim Yong-Hamb
AMoRE sub group
CANDLES sub group

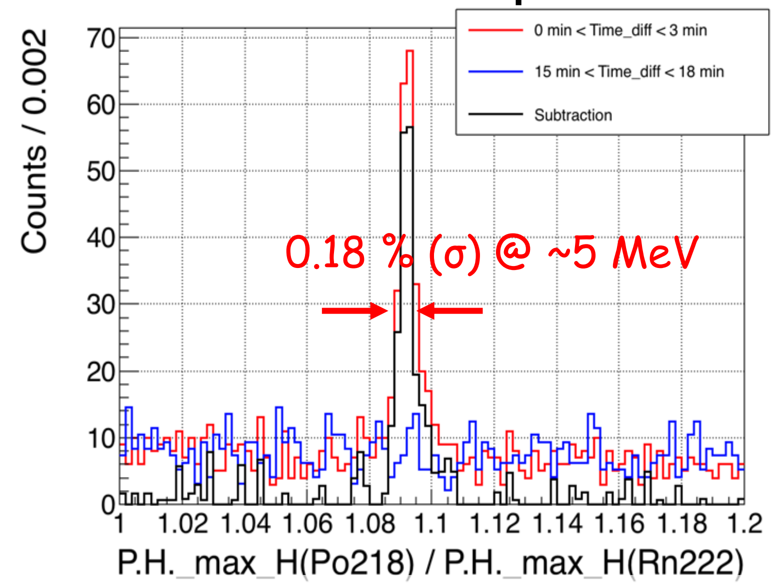
Scintillating bolometer

Energy spectrum of α-events

Energy resolution 1.86%

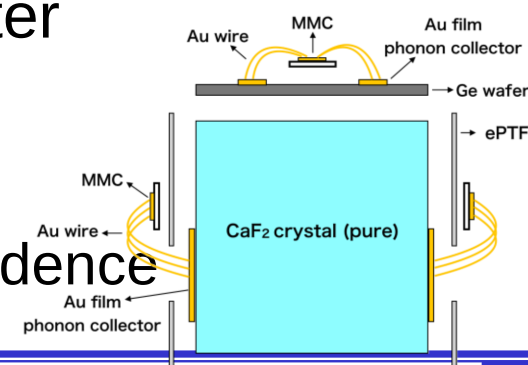


Energy ratio between two events at the same position



$^{222}Rn \rightarrow ^{218}Po(3min) \rightarrow ^{214}Pb$

- First result of CaF_2(pure) scintillating bolometer
  - Energy resolution(σ):1.86±0.11%
    - But not best by position dependence
  - Additional sensor for removing position dependence



Ref :K. Tetsuno et al, J. of Phys. : Conf. Ser. 1468(2020)012132

Summary

- CANDLES project
  - CANDLES III : in Kamioka laboratory
    - We installed the shielding system.
      BG from neutron capture is reduced by ~1/100
    - Obtained half-life limit : $>5.6 \times 10^{22}$ year
      - New result for 778 days will be reported with new background rejection analyses
        - ^{212}BiPo rejection by CNN analysis
        - ^{208}Tl rejection
  - Next detector system → to search for < 10meV region
    - We will apply ;
      - Enrichment of ^{48}Ca : $^{48}CaF_2$
        - Now on stage of “cost effective” mass production
      - CaF_2 scintillating bolometer