Current status and prospect of the CANDLES experiment

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- ^{48}Ca double beta decay
- 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 $\langle m_{\beta\beta} \rangle$
  - $\langle m_{\beta\beta} \rangle^2 \propto \frac{1}{T_{1/2}^{0\nu\beta\beta} G_{0\nu} |M_{0\nu}|^2}$

$\langle m_{\beta\beta} \rangle$: 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

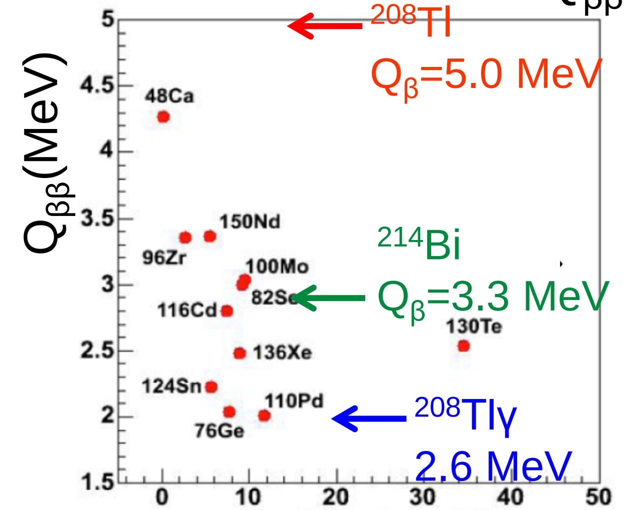
  * background free measurement

  = effective for high-sensitive measurement

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%
- 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

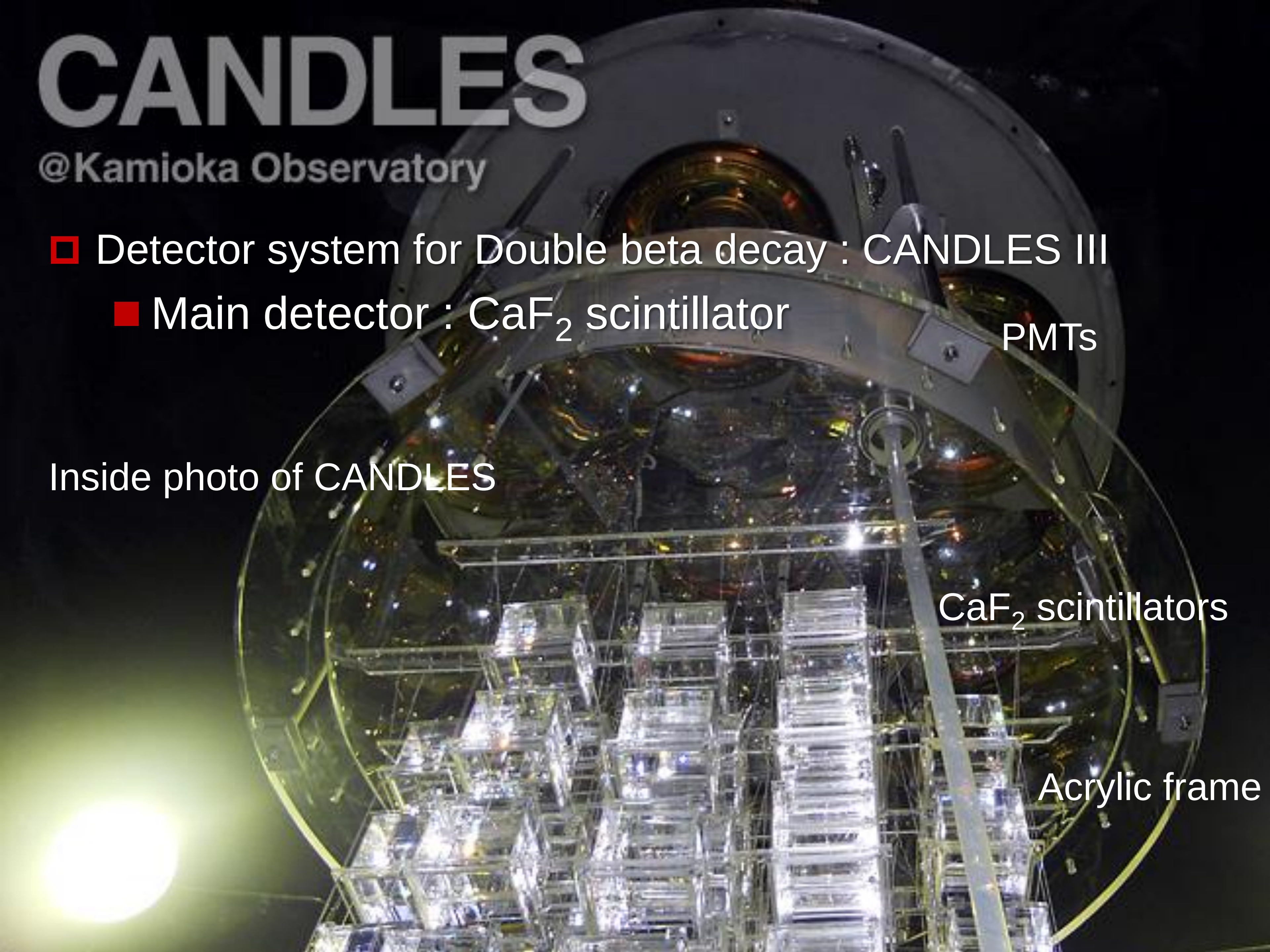
Natural abundance vs $Q_{\beta\beta}$



CANDLES

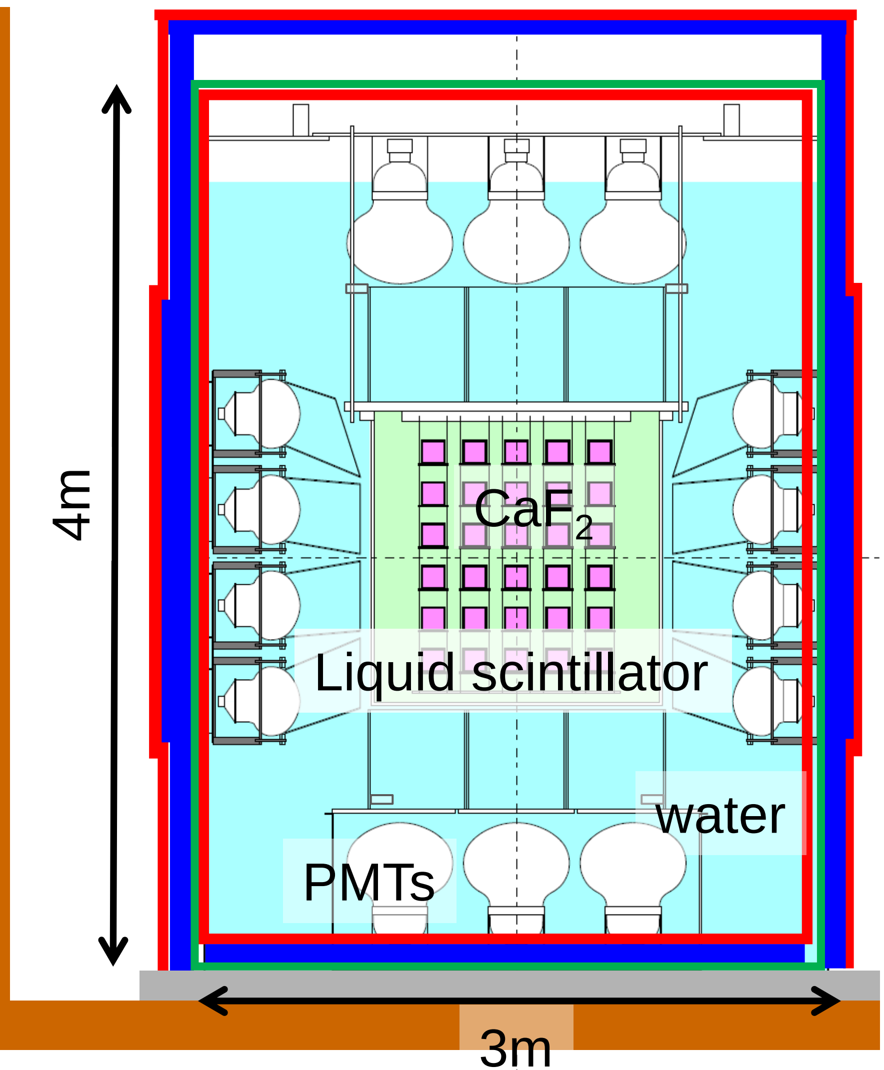
@Kamioka Observatory

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

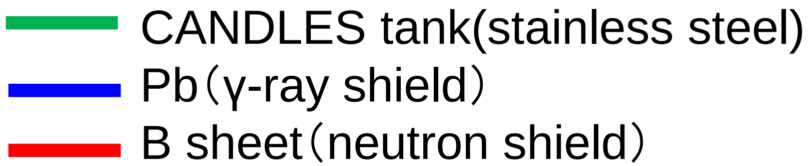


CANDLES III

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



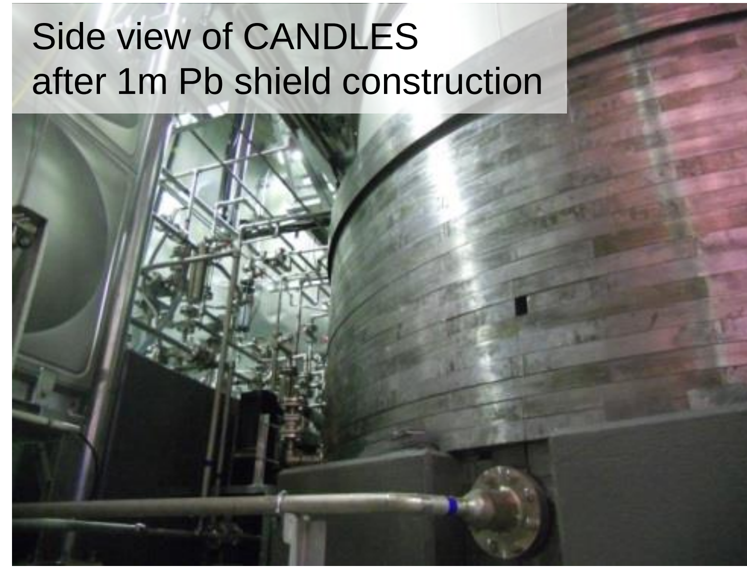
- CaF_2 scintillator (CaF_2 (pure))
  - 305kg (96modules × 3.2kg)
  - ^{48}Ca : 350g
- Liquid scintillator (LS)
  - 4π active shield($2m^3$)
- 62 Large photomultiplier tube
- Shielding system
  - Pb : 10-12cm
  - B_4C sheet : 5mm



Shield construction

- Shielding system
  - Pb shield, B_4C sheet

total mass of lead : ~50ton



setting Pb bricks
in the main tank

Result

Result of measurement for 130days

Result with 21 high purity CaF_2

	result
0νββ 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

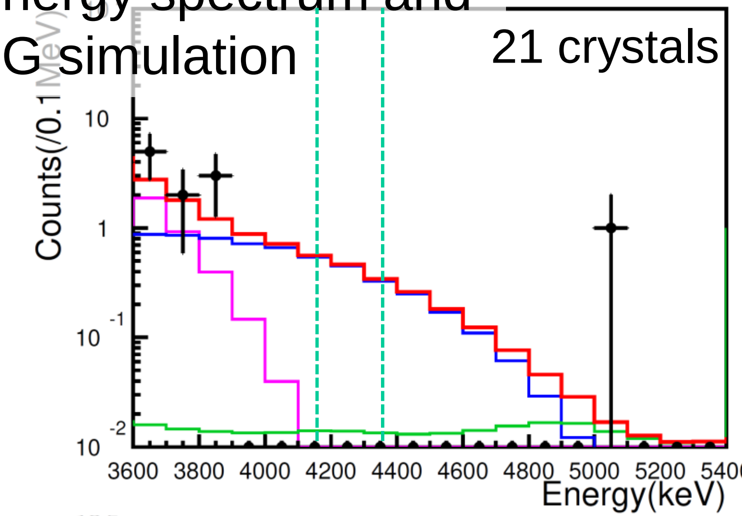
Ref : Phys. Rev. D103, (2021), 092008

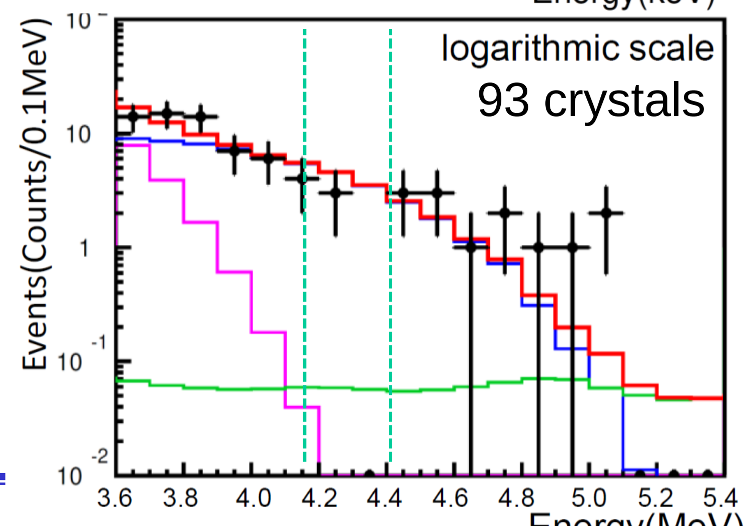
＊comparable to most stringent limit of ^{48}Ca
ELEGANT VI
measurement time : 4947kg・day(2 years <)
half life limit : 5.8×10^{22} year

*Achieved background rate
・< 10^{-3} events/keV/year/(kg of ^{nat}Ca)
・comparable to lowest background level
*for further improvement, BG reduction analysis

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

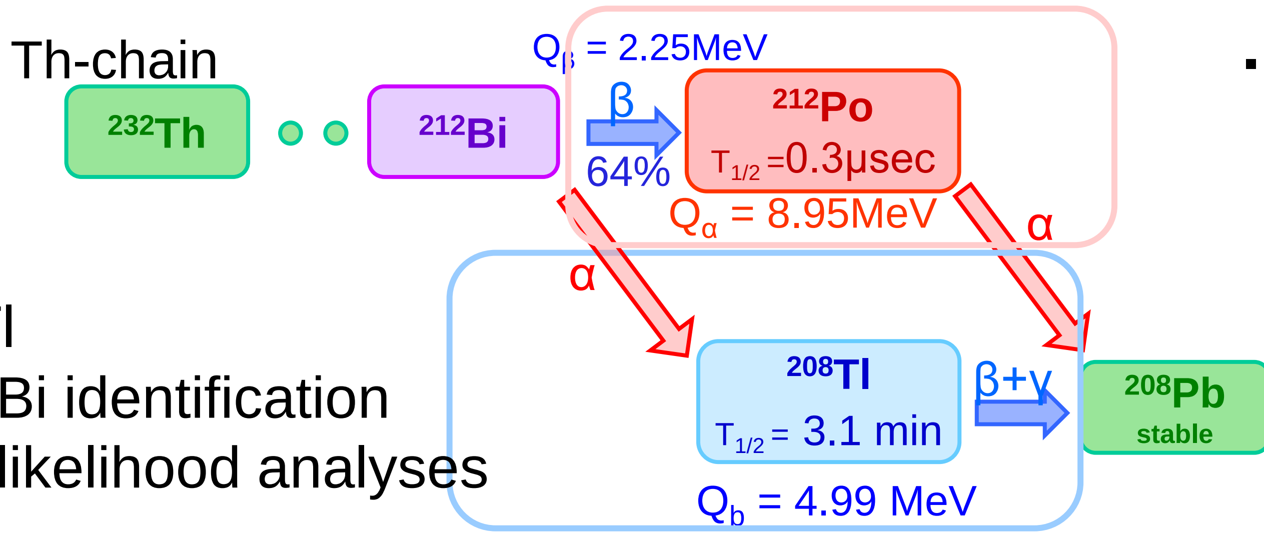
Energy spectrum and BG simulation





Improvement of Analyses

- For background free measurement
  - Measurement time : 130 days + 652 days
    - Current analysis : not achieve background free measurement
  - Improved analyses for background rejection
    - $^{212}Bi^{212}Po$(pile up events) rejection : machine leaning
      - for rise shape observation of pulse shape
    - ^{208}Tl rejection : likelihood analysis
      - for identification of prompt ^{212}Bi α decay

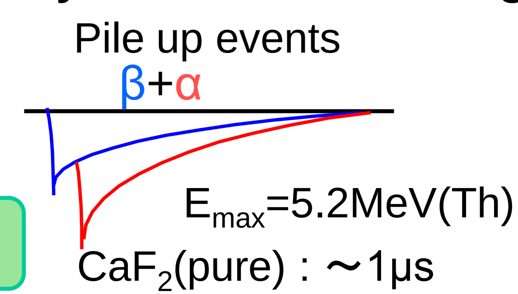


^{208}Tl

▪^{212}Bi identification
by likelihood analyses

$^{212}Bi^{212}Po$

▪rejection
by machine leaning

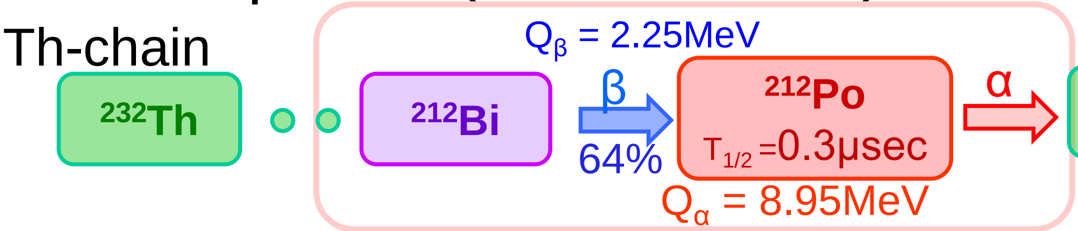


$^{212}Bi^{212}Po$ rejection by CNN

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

Poster presentation by R. Sirai

- Pile up event(Double Pulse) : $^{212}Bi \rightarrow ^{212}Po$



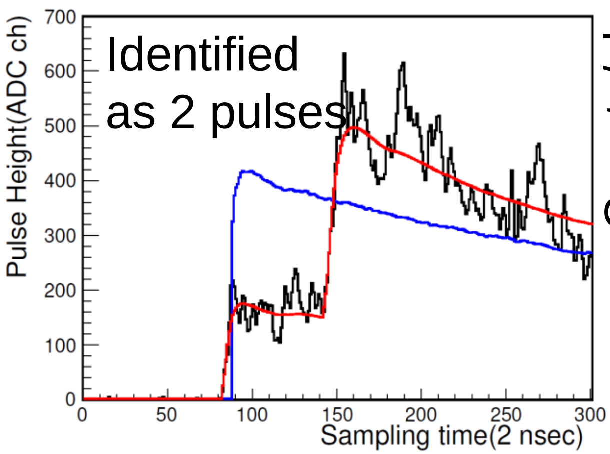
Rej. efficiency by fitting ~ 95 %

- Rejection by "Fitting" & "Machine learning method(CNN)"

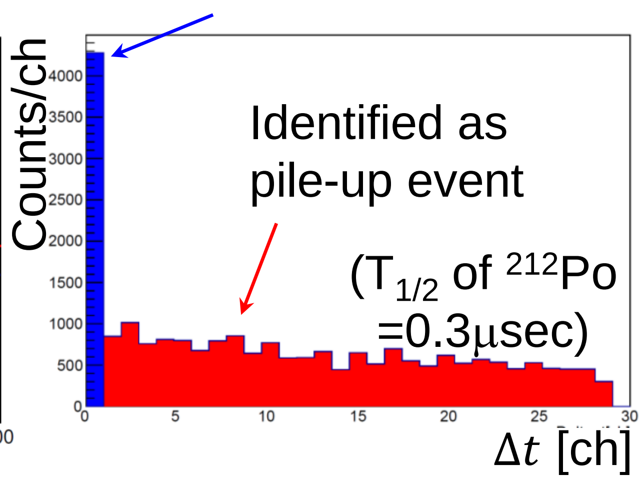
Typical pulse shape with long Δt(~100nsec)

fitting as 2 pulse function

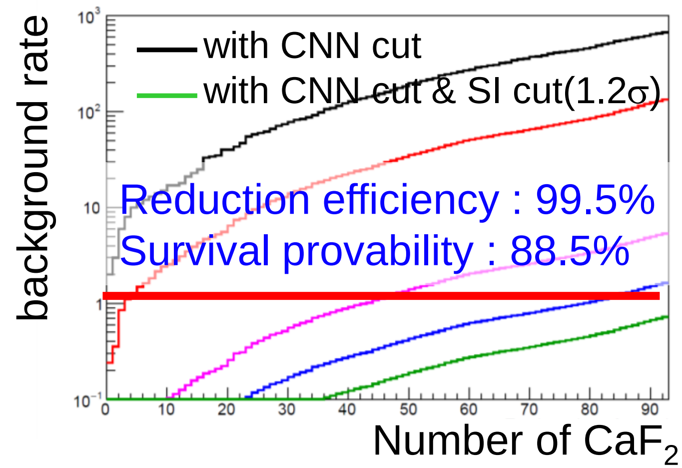
as 1 pulse function



Δt distribution by CNN



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



For 0νββ energy region：
Rejection effi. of $^{212}Bi^{212}Po$ >99.5%、survival probability for 0νββ 89.5%

^{208}Tl rejection : past analysis

- rejection : identification of prompt ^{212}Bi

Already applied

Pulse shape : α-ray like

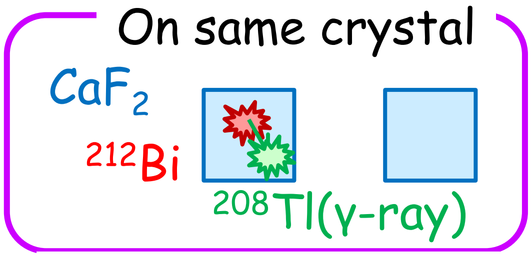
Time correlation : within short Δt

Th-chain

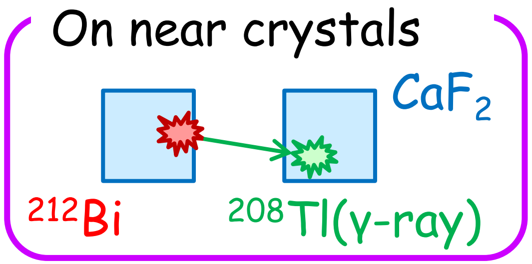
^{232}Th ● ● ^{212}Bi —α→ ^{208}Tl ($T_{1/2}$ = 3.1 min, Q_b = 4.99 MeV) —β+γ→ ^{208}Pb stable

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

Patterns of event position

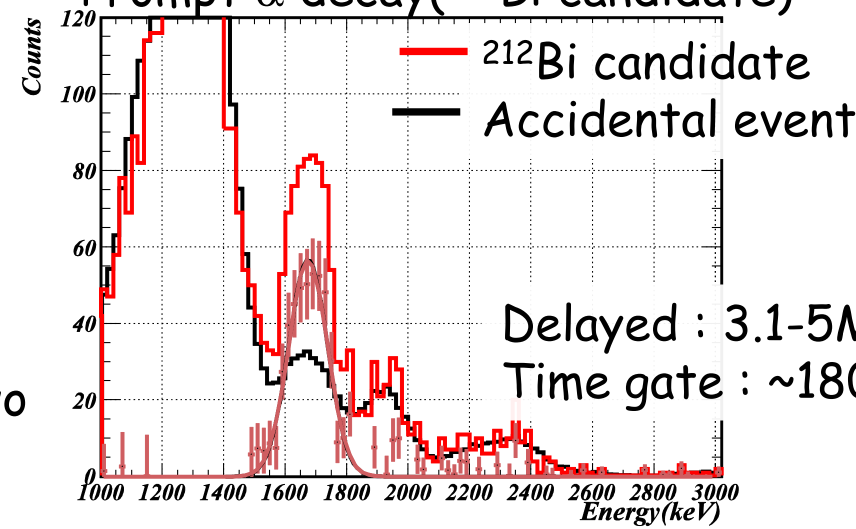


Reject



Not reject
"Multi-hit" on two CaF_2 crystals

Prompt α decay(^{212}Bi candidate)



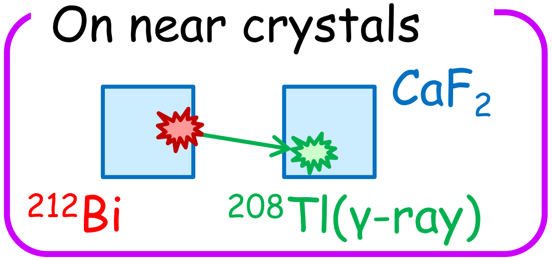
Delayed : 3.1-5MeV
Time gate : ~180sec

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

G. Miyoshi(M thesis)

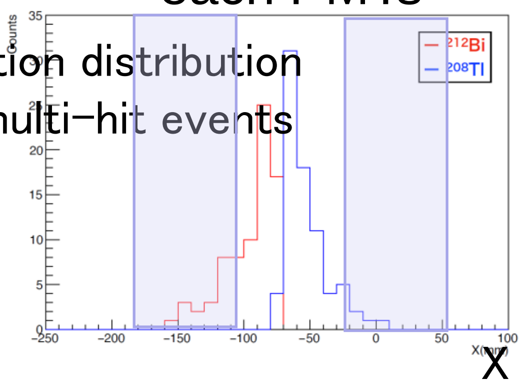
Position distribution of ^{208}Tl

"Multi-hit" on two CaF_2 crystals

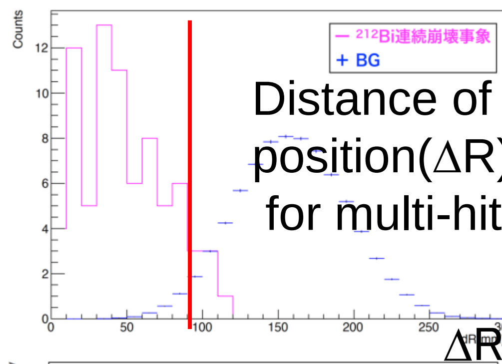


Distance between ^{208}Tl and ^{212}Bi : small
→position information

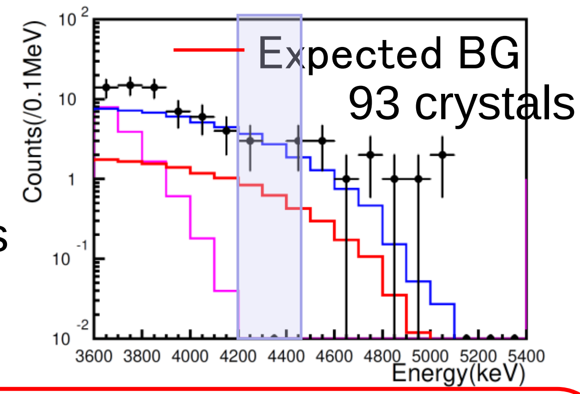
- Identification by using distance of ^{212}Bi^{208}Tl event position
  - ^{208}Tl event position simulation by using photoelectron distribution for each PMTs



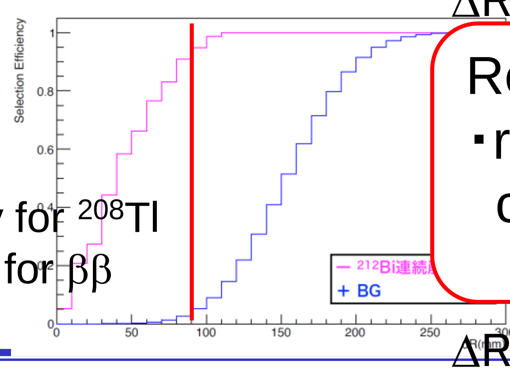
Position distribution for multi-hit events



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



Rejection efficiency for multi-hit events

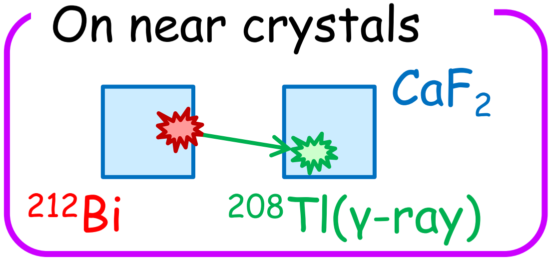


Rejection efficiency for ^{208}Tl (magenta line)
Survival provability for ββ (blue line)

Rejection by ^{208}Tl multi-hit events
- rejection efficiency >95 %
  cut point:90mm
  (survival provability > 95%)

G. Miyoshi(M thesis)

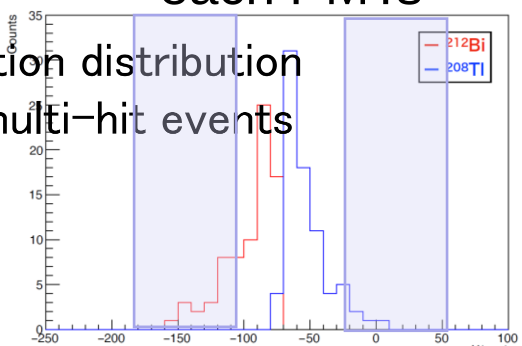
Position distribution of ^{208}Tl



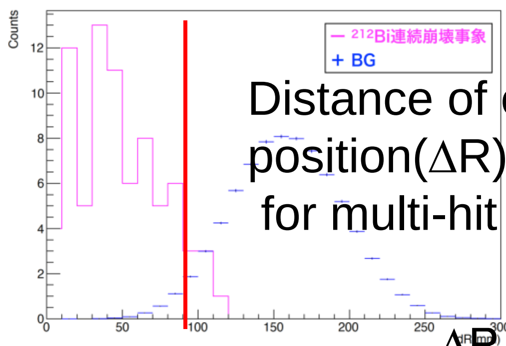
"Multi-hit" on two CaF_2 crystals

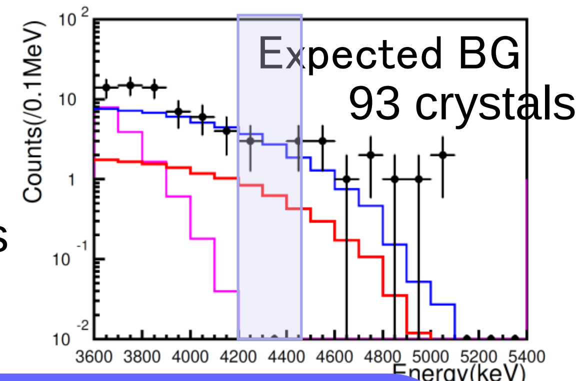
- Identification by using distance of ^{212}Bi^{208}Tl event position
  - ^{208}Tl event position simulation by using photoelectron distribution for each PMTs

Position distribution for multi-hit events



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



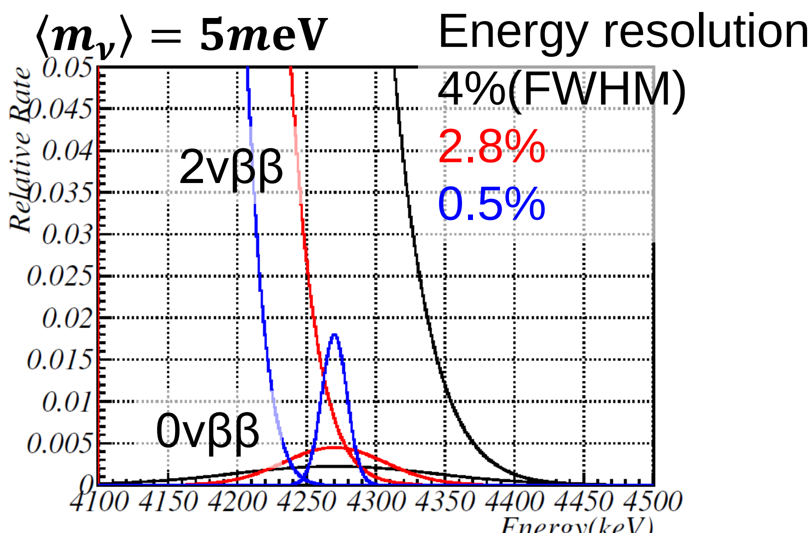


By using
  the position information between ^{212}Bi and ^{208}Tl
  pulse shape information of ^{212}Bi
we will achieve lower background rate as BG free
  will obtain more stringent ^{48}Ca half-life limit.

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



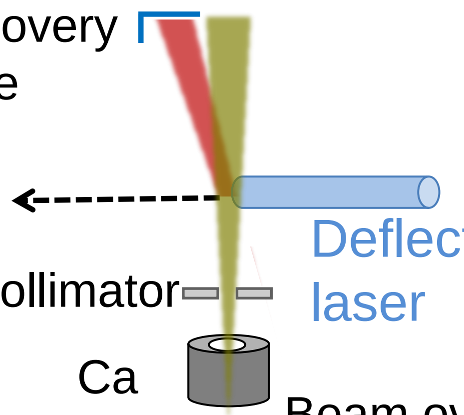
- Large amount of ^{48}Ca
  - increase by enrichment
    ← limited by small mass of ^{48}Ca
  - → increase without scale-up
- Higher energy resolution
  - To reduce 2νββ events

Fukui Univ.: H.Niki, I.Ogawa

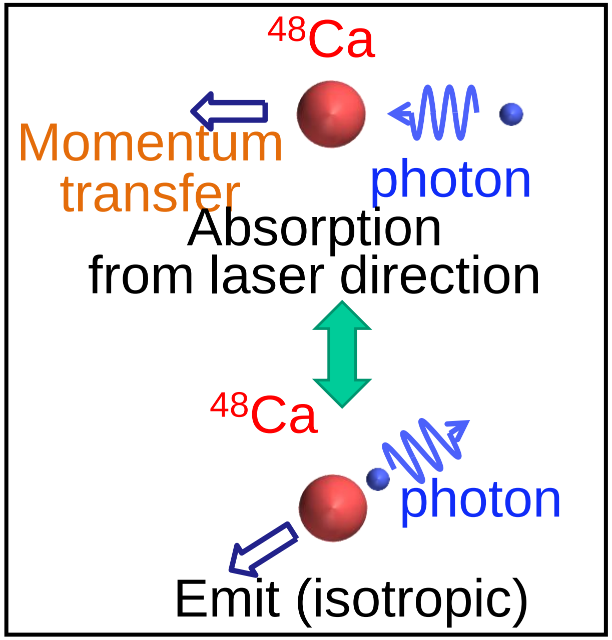
Next detector system：enrichment

- introduction of laser isotopic separation(LIS)

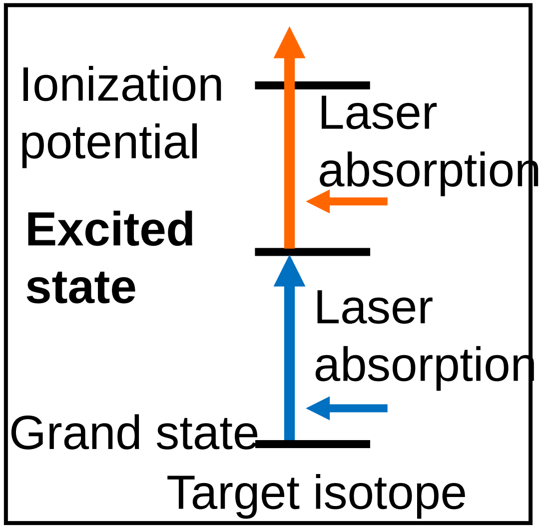
Setup



Deflection method

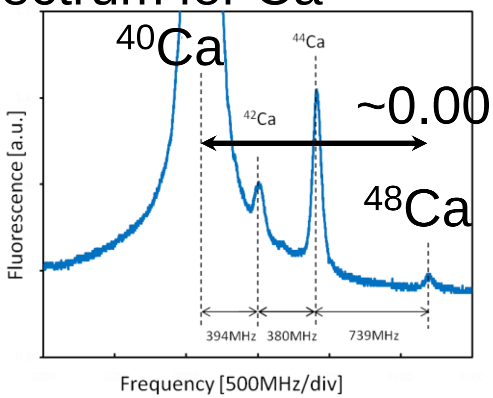


ref：ionization method



Two laser for enrichment
- for excitation
- for ionization

Absorption wavelength spectrum for Ca

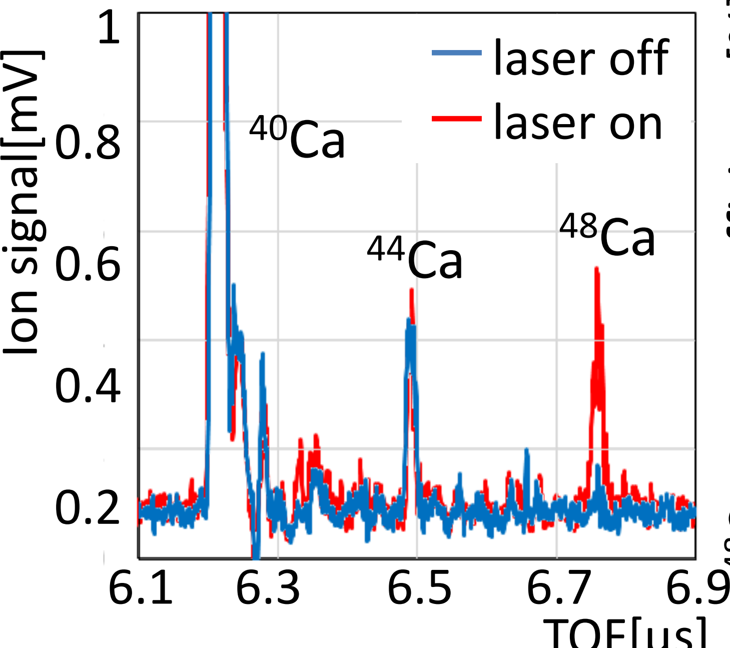


Important point
- blue laser with narrow linewidth

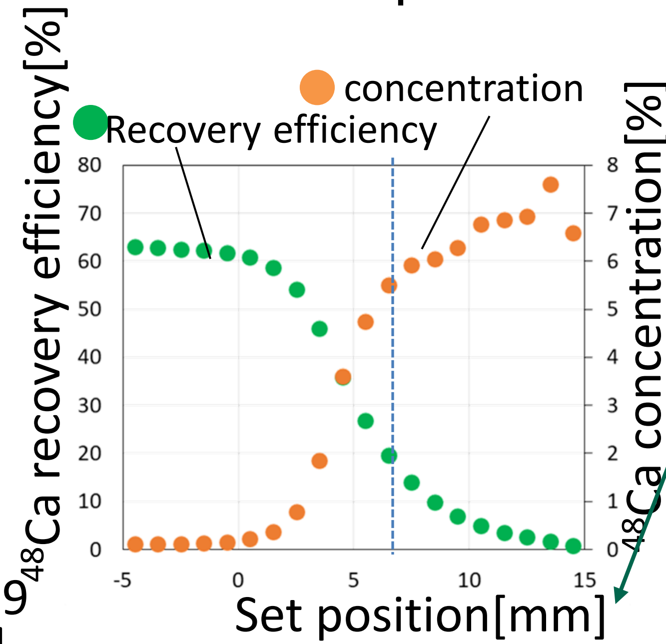
Laser isotopic separation

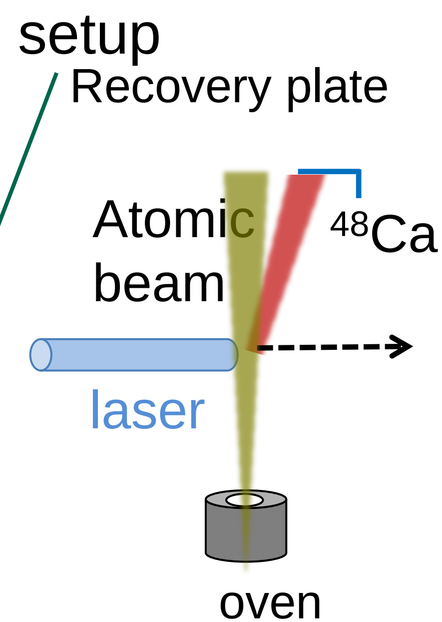
Ref :K. Matsuoka et al, J. of Phys. : Conf. Ser. 1468, (2020), 012199
Ref : Presentation by I. Ogawa in SPLG2021

☐ Separation effect



Position dependence of LIS effect





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

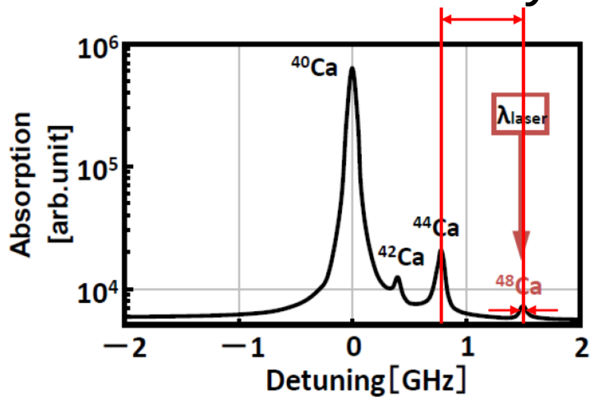
☐ For high-concentration・high-recovery effi.

- Large deflection → mass production
  - optimize irradiation system for deflection laser
  - Construct high intensity blue laser

Requirement for blue laser

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

- 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

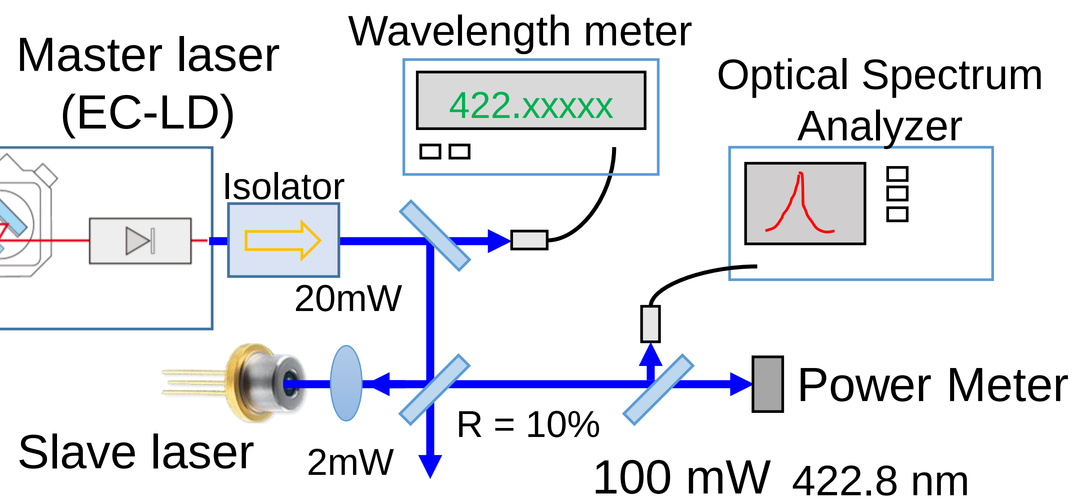
First step for demonstration
: 2 W laser with 0.0006 pm width
by using 100 mW lasers

High intensity blue laser with narrow linewidth

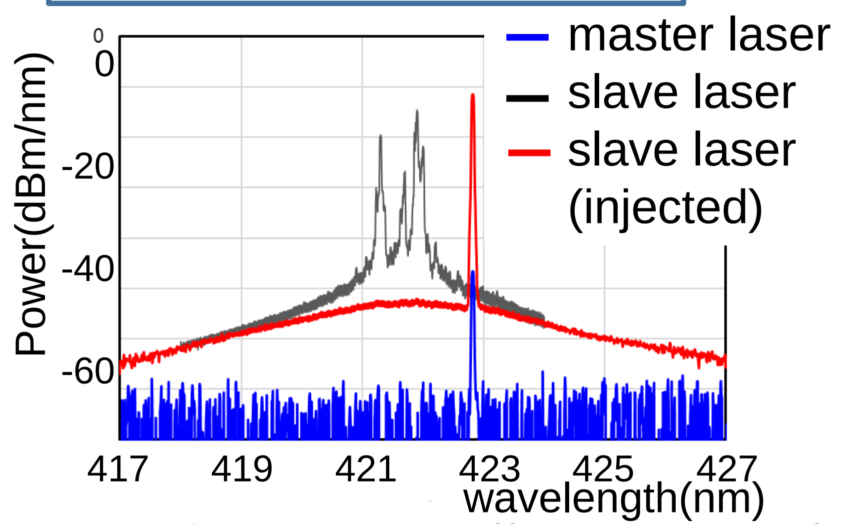
S. Tokita(ICR, Kyoto) & N. Miyanaga(ILT)

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

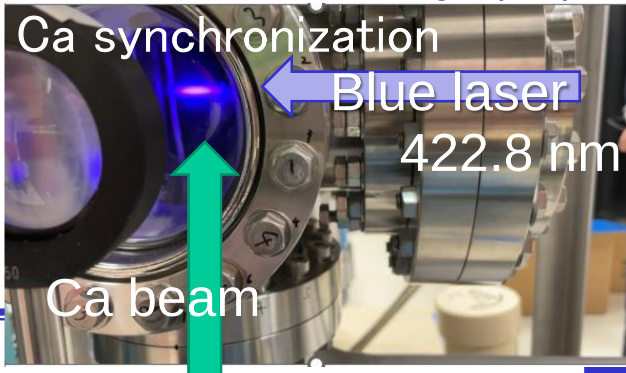
Experimental Setup



Wavelength of lasers



Controlled wavelength of slave laser
by temperature & current



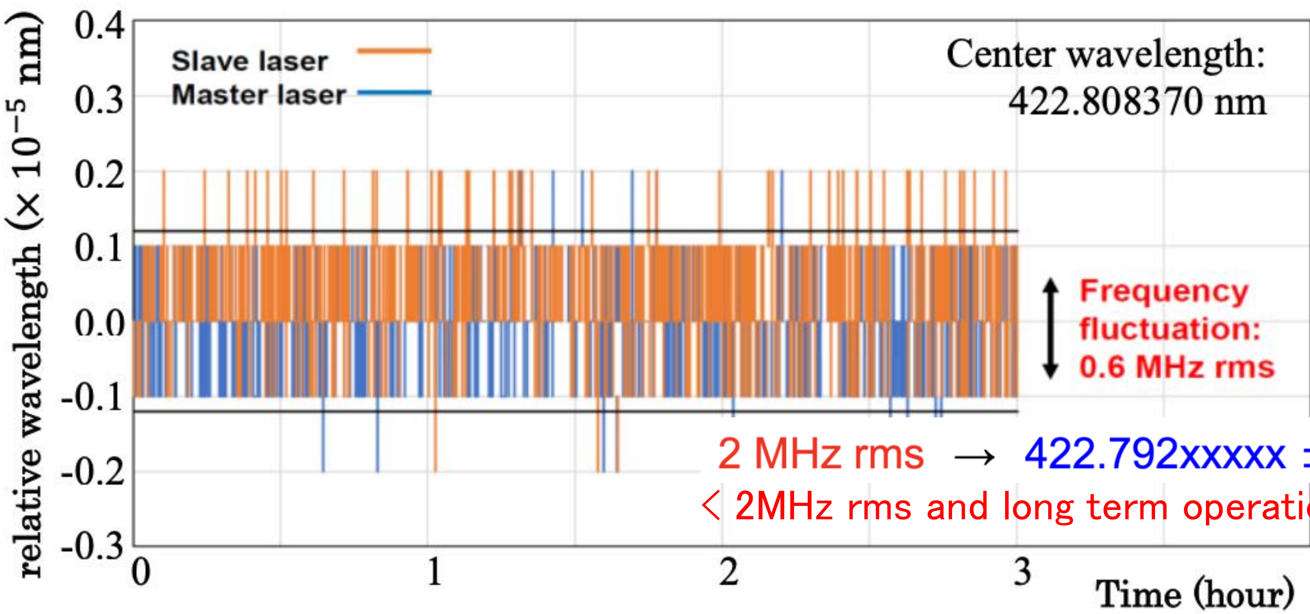
Injection locked system :OK
Next : stabilization of wavelength

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



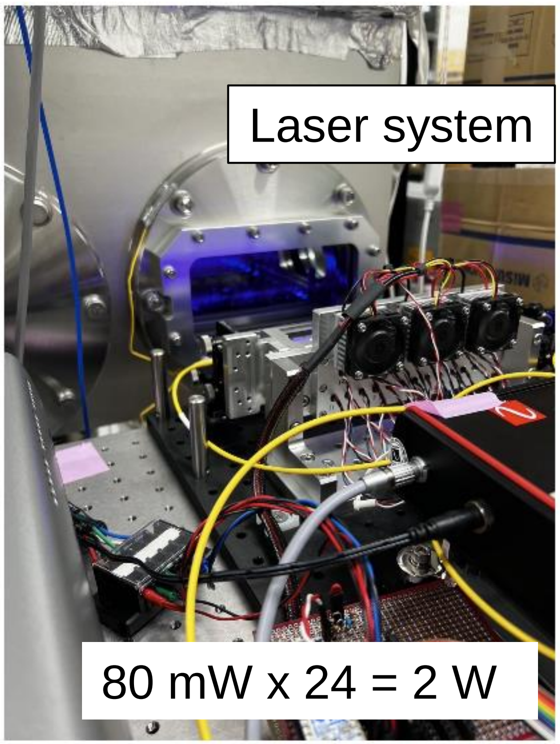
2 MHz rms → 422.792xxxxx ±0.0000006 nm
< 2MHz rms and long term operation was obtained

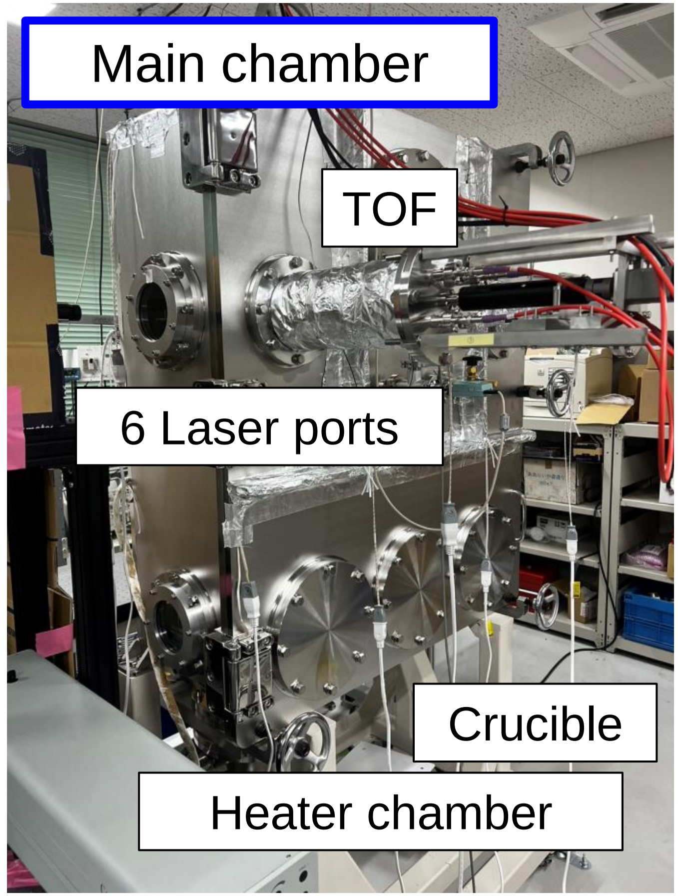
The laser wavelength was stabilized in 0.2 x 10^{-5} nm width

LIS system : Main Chamber

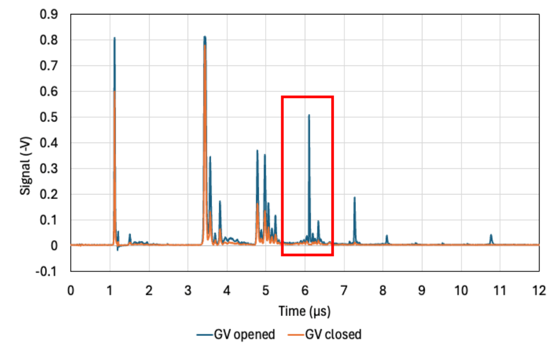
Poster presentation by R. Anawat

- Design and Construction of Basic System

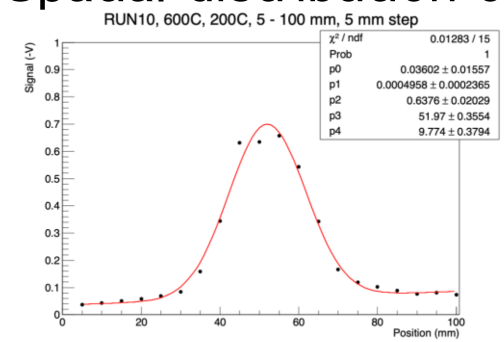




Ca monitor(TOF system)



Spatial distribution of Ca



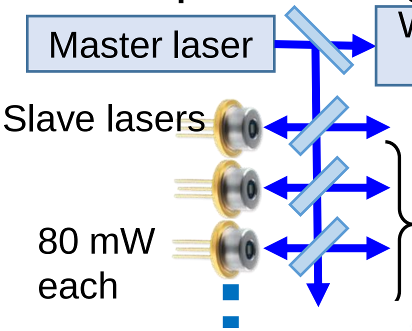
Main chamber : 6 laser irradiation ports & 3 heater chambers(Max mol/year)
Current status : minimum operation(1 laser & 1 chamber)
for design check & modification

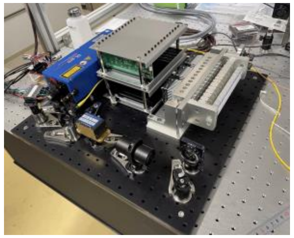
Summary of LIS system

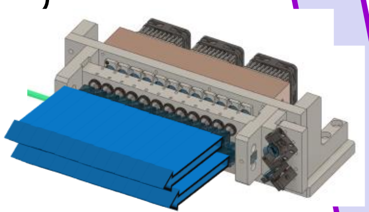
RCNP, Osaka Univ.
ICR, Kyoto Univ.
Fukui Univ.

Multiple laser array

Conceptual design





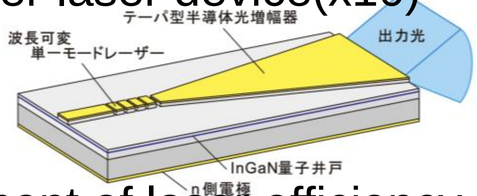


80 mW x 24 = 2 W

Construction of basic system

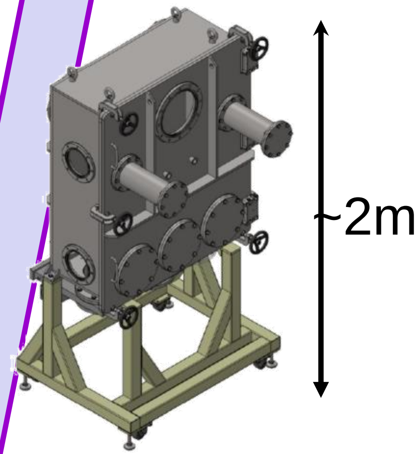
Next step

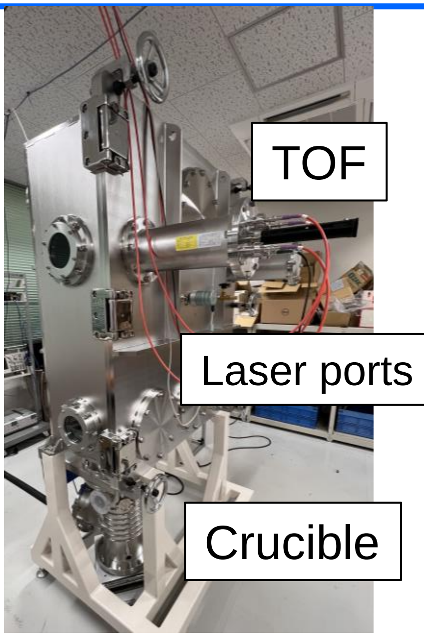
High power laser device(x10)

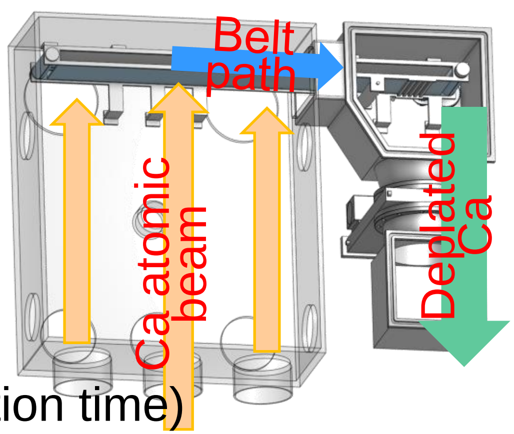


Improvement of laser efficiency
(production rate/laser power W)

Main chamber





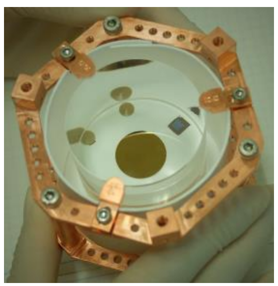


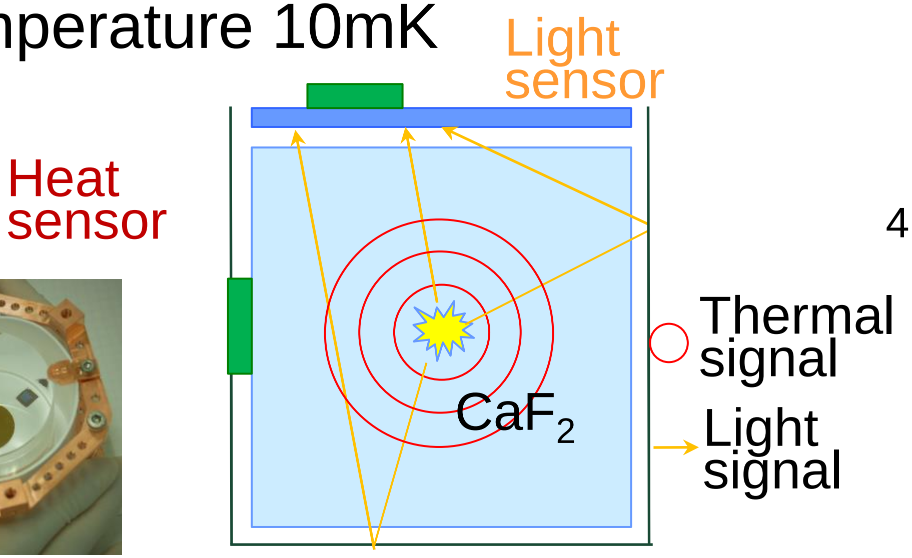
Correction system
(increasing of operation time)

To increase production rate(x10～)

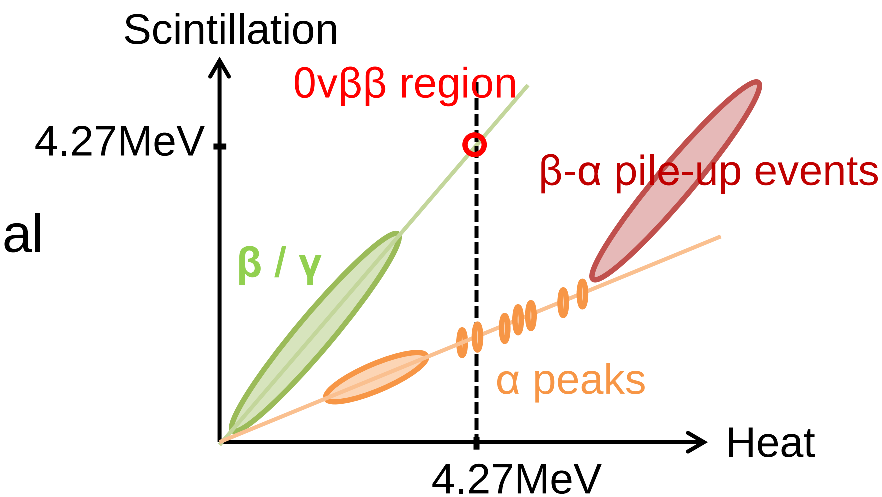
Next detector system：scintillating bolometer

Scintillating bolometer at low temperature 10mK





Particle identification by scintillating bolometer



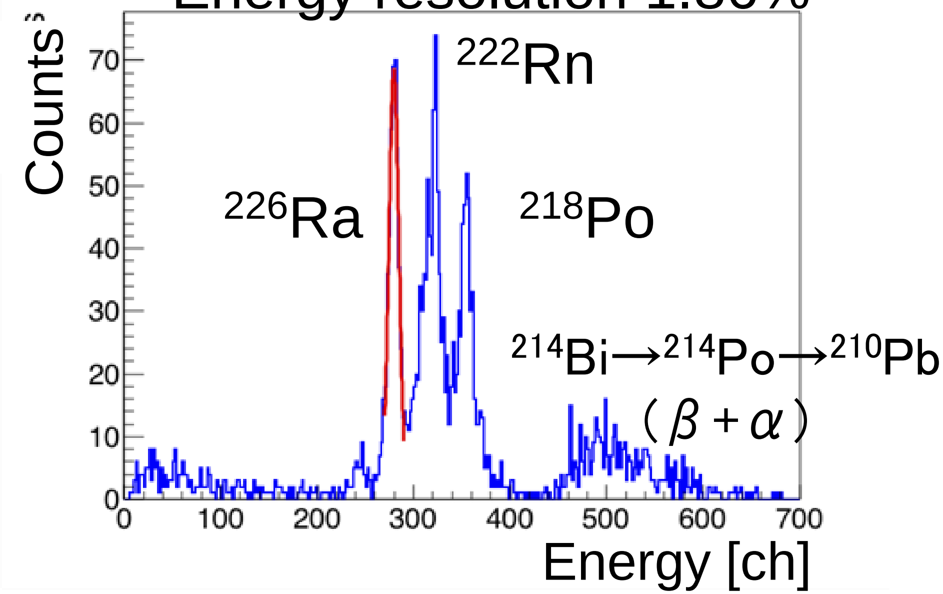
- Expected BG： 2νββ events, α-rays
- bolometer：good energy resolution
  - For reduction of BG affects from 2νββ events
- Scintillating bolometer：good PI ability
  - For reduction of BG affects from α-ray

Scintillating bolometer

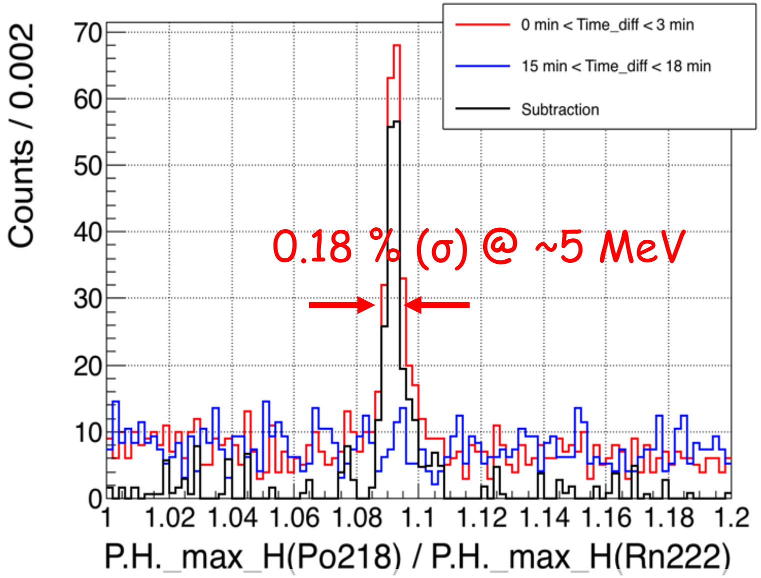
IBS Kim Yong-Hamb
AMoRE sub group
CANDLES sub group

Presentation
By S. Yoshida

Energy spectrum of α-events
Energy resolution 1.86%

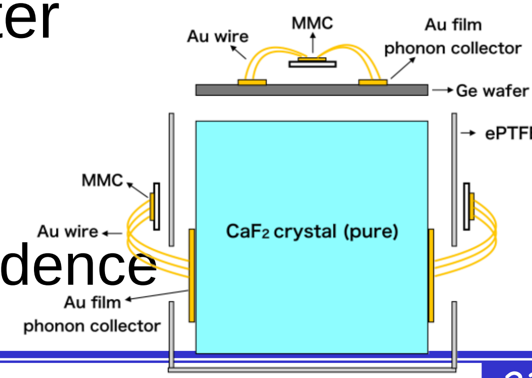


Energy ratio between two events at the same position



^{222}Rn→^{218}Po(3min)→^{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



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 × 10^{22} year
      - background rejection analyses for 778 days data
        - ^{212}BiPo rejection by CNN analysis
        - ^{208}Tl rejection by likelihood
  - 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