CANDLES for the Study of ^{48}Ca double beta decay and its future prospect

T. Kishimoto
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CANDLES Collaboration

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Tsukuba University
飯田崇史
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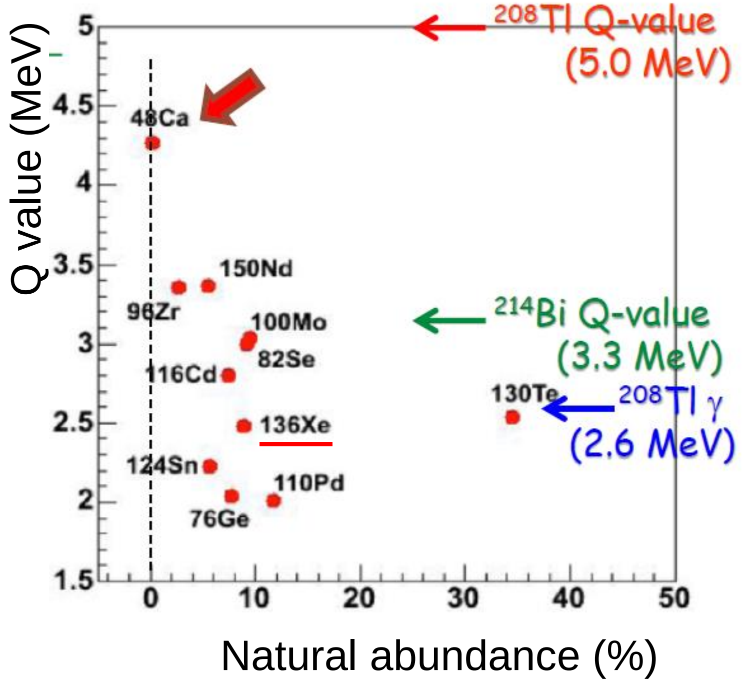
大隅秀晃
The Wakasa wan Energy Research Center
鈴木耕拓

Why ^{48}Ca

- Highest Q value
  - 4.27 MeV, (^{150}Nd: 3.3 MeV)
  - Least BG（γ: 2.6 MeV, β: 3.3 MeV）
  - Large phase space factor
- Small natural abundance:
  - 0.187%
  - Separated isotope → expensive
- Next generation
  - $<m_\nu> \sim T^{-1/2} \sim M^{-1/2}$ (no BG) M: mass
    $\sim M^{-1/4}$（BG limited）
  - Enrichment:　mass＋S/N：　500 times
  - High resolution：bolometer（crystal）
- Beyond inverted hierarchy
  - ^{48}Ca + enrichment + bolometer



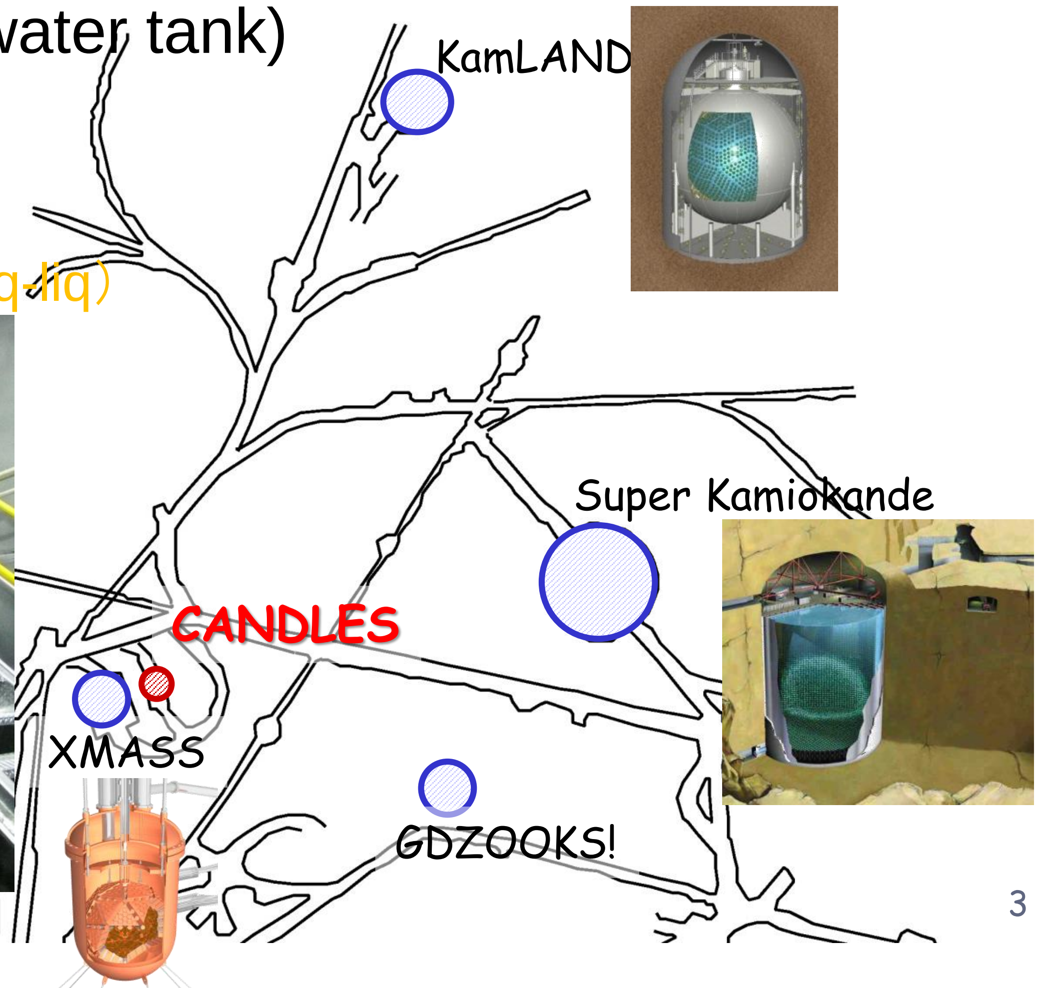
CANDLES

Nuclear matrix element
→ neutrino mass

CANDLES III @ Kamioka

- CANDLES III
  - Site: Kamioka U.G.L. ~1000 m
  - Size: 3mΦ × 4mh (water tank)
  - Liquid scintillator
    - Reservoir tank
    - Purification system（liq-liq）

Kamioka Lab. Map

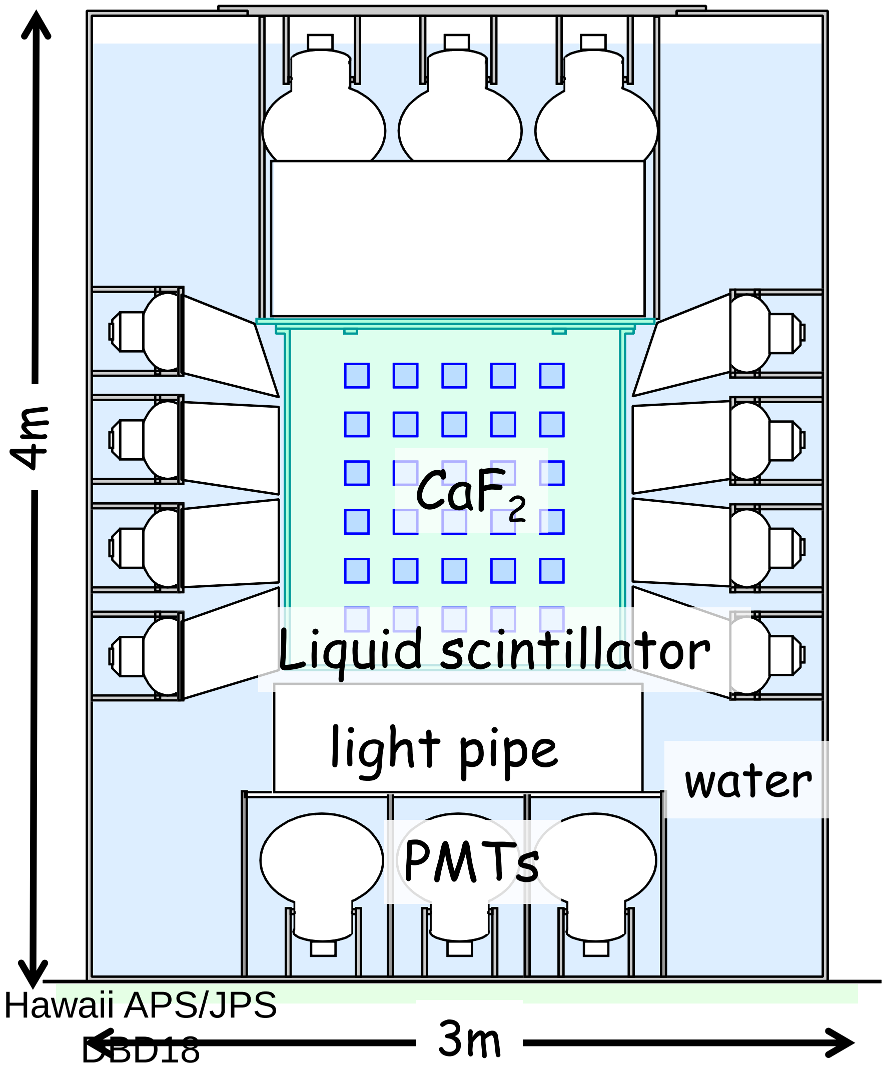


CANDLES III(UG)

CANDLES at Kamioka underground laboratory

Candles

- CANDLES III



- **CaF_2 scintillator (CaF_2(pure))**
  305 kg (96 × 3.2kg)
  τ ~ 1μsec
- **liquid scintillator (LS)**
  4π active veto
  $2m^3$
  τ ~ a few 10nsec
- **PMT's**
  13inch PMT × 48
  20inch PMT × 14
- **light pipe**
  light collection : energy resolution
- Veto

Pulse shape difference
CaF_2(pure) : ~1μsec
Liquid scintillator : a few 10 nsec

CANDLES III(UG)

CANDLES at Kamioka underground laboratory

Candles

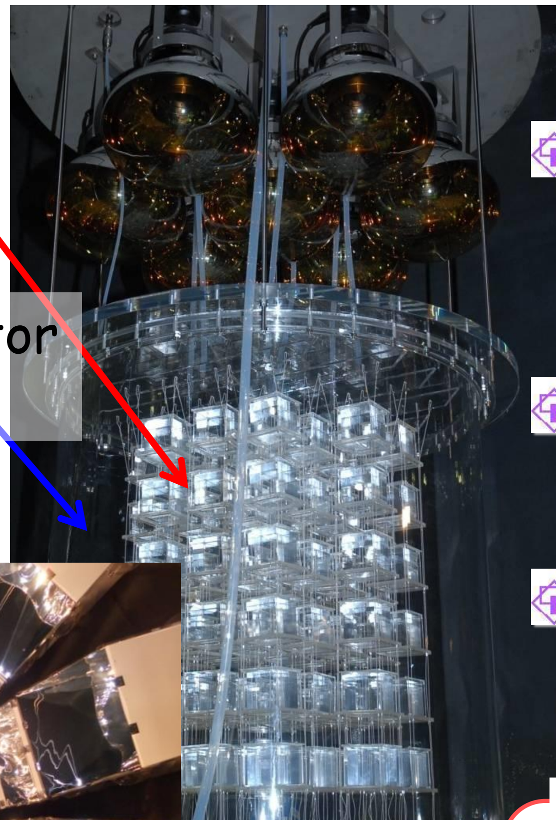
CANDLES III

CaF_2 (305kg)

Liquid scintillator tank($2m^3$)

PMT

Light pipe



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  - light collection : energy resolution
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Pulse shape difference

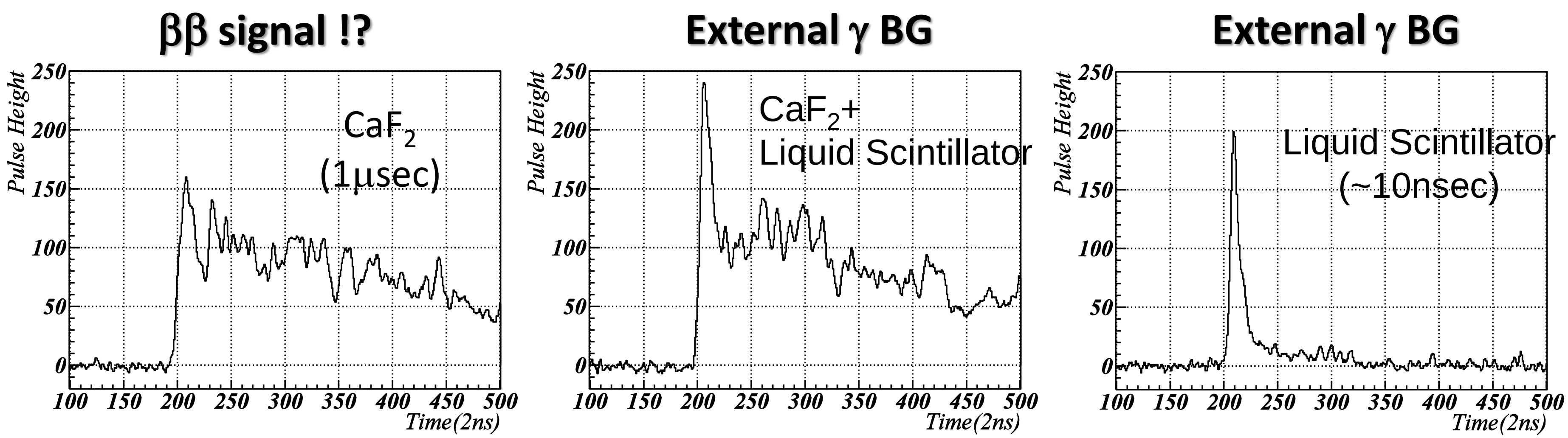
CaF_2(pure)	: ~1μsec
Liquid scintillator	: a few 10 nsec

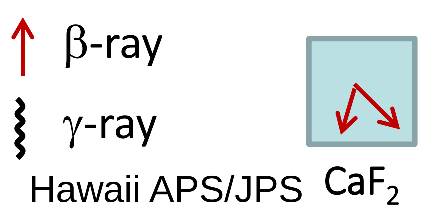
4π active veto by Liquid scintillator (LS)

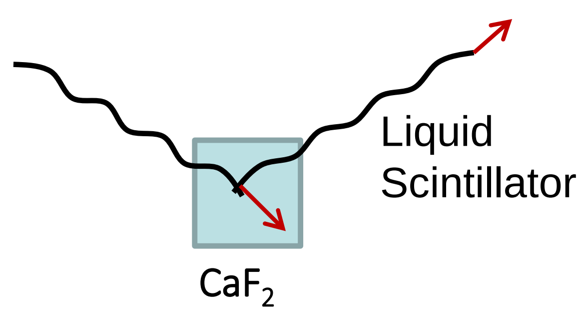
- Rejection of external γ–ray background

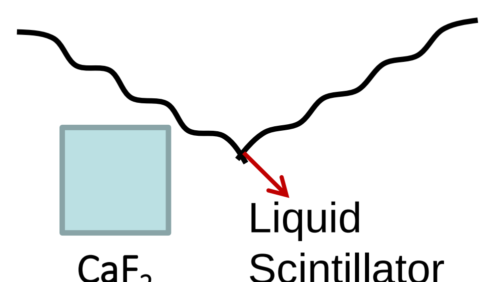
Candles

- Pulse shape information by 500 MHz Flash ADC.
- Distinguish event type by offline pulse shape analysis taking advantage of different decay time.





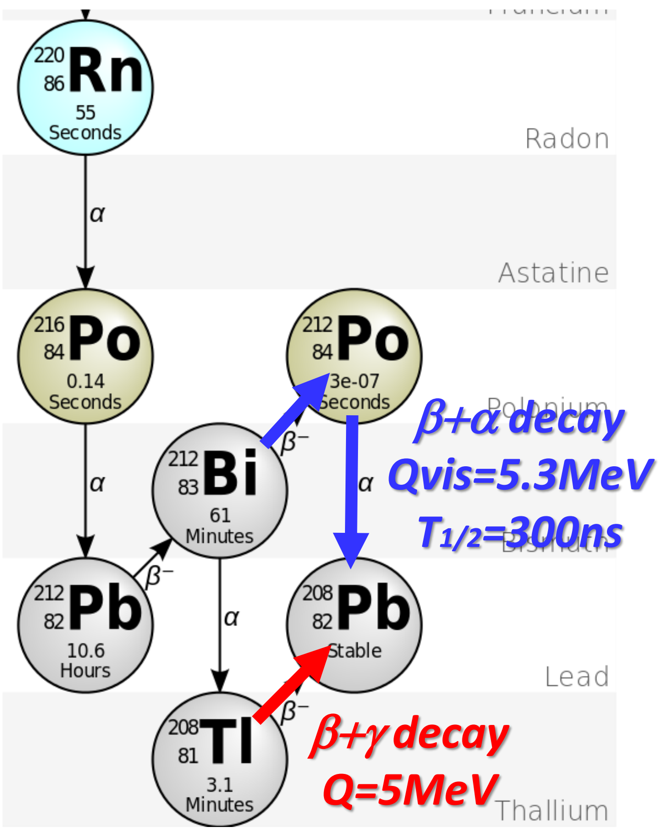




Internal backgrounds and reduction

Candles

- External BGs were reduced by LS active shild.
- Remaining BGs originate from internal radioactivity of Th chain (^{208}Tl and ^{212}Bi-^{212}Po).
- 2νββ is not serious BG in current sensitivity. (it will be major BG after ^{48}Ca enrichment)
- We reject remaining BGs by analysis.



Rejection of Double Pulse

Candles

$Q_\beta = 3.27MeV$

^{212}Bi → β 64% → ^{212}Po ($T_{1/2} = 0.299\mu sec$) → α → ^{208}Pb

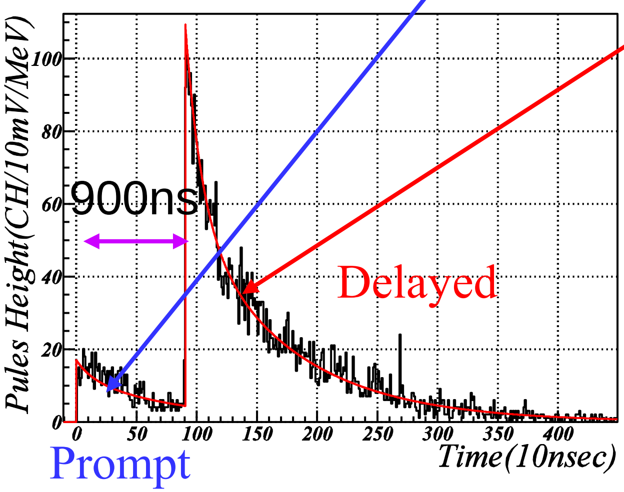
$Q_\beta = 2.25MeV$

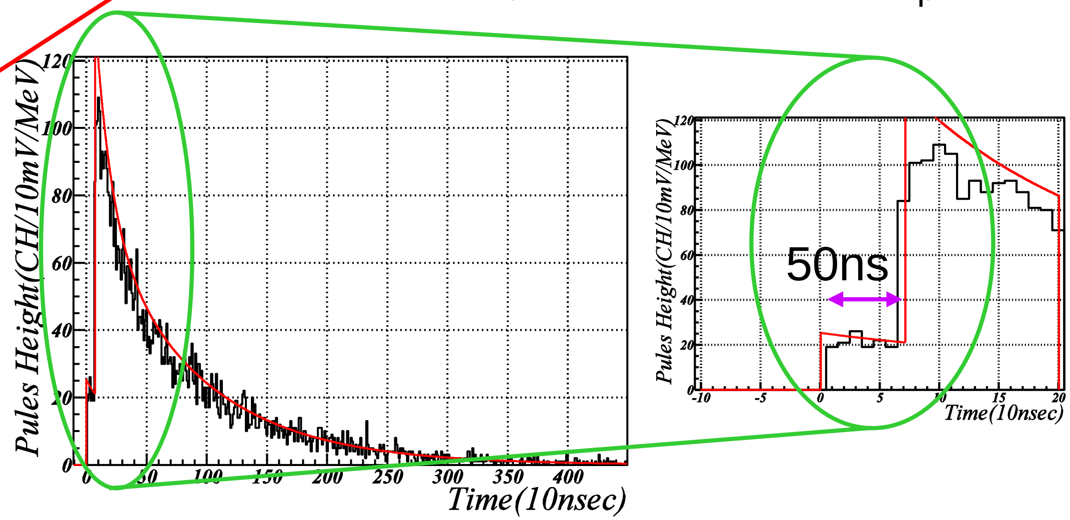
$Q_\alpha = 7.83MeV$

$Q_\alpha = 8.95MeV$

BG in $Q_{\beta\beta}$ region: Sum E
E_α(1/3 Quench) +$E_\beta \simeq$5.3 MeV

Typical Pulse Shape





Reduction

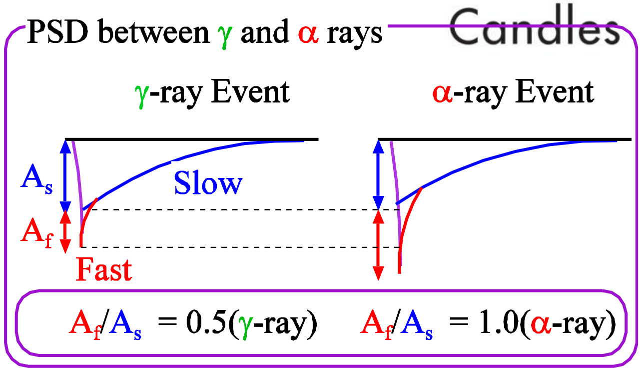
100MHz FADC (old) ΔT > 30ns(3ch) ; ~5%

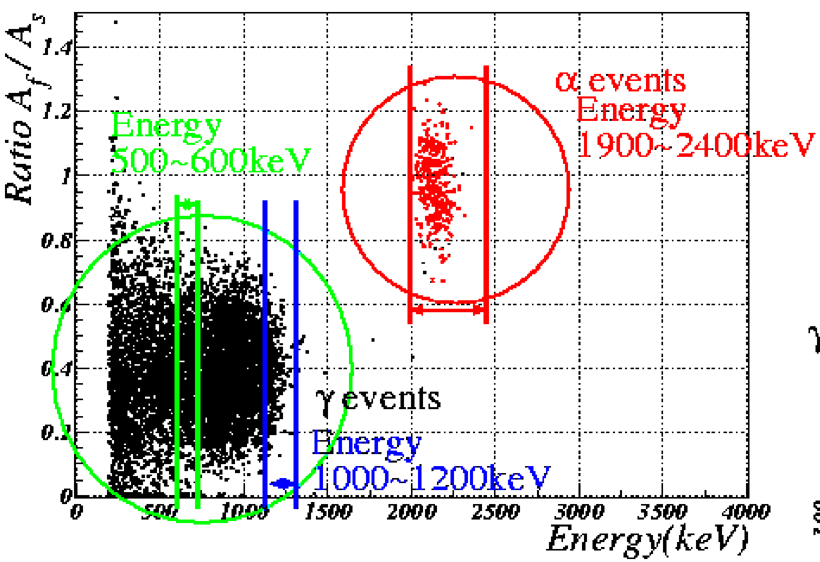
500MHz FADC . . . ΔT > 10ns ; ~2%

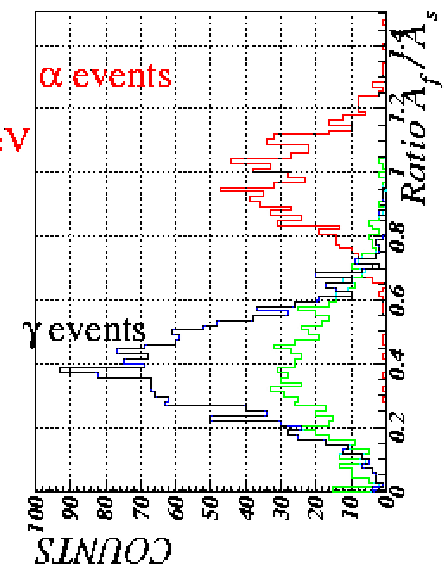
Pulse Shape Discrimination

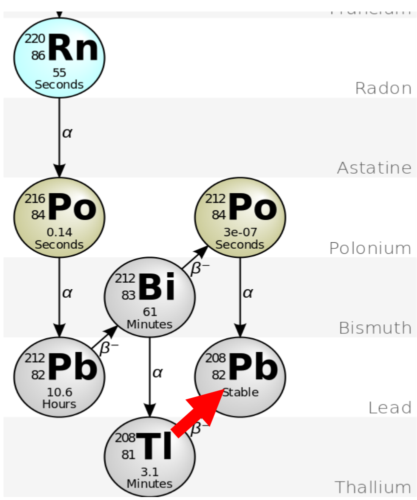
Difference in decay time
between α and γ rays

- **PSD (Event by Event)**
  - **FADC**
  - ***A_{fast}/A_{slow}*** **(Fast and slow component)**





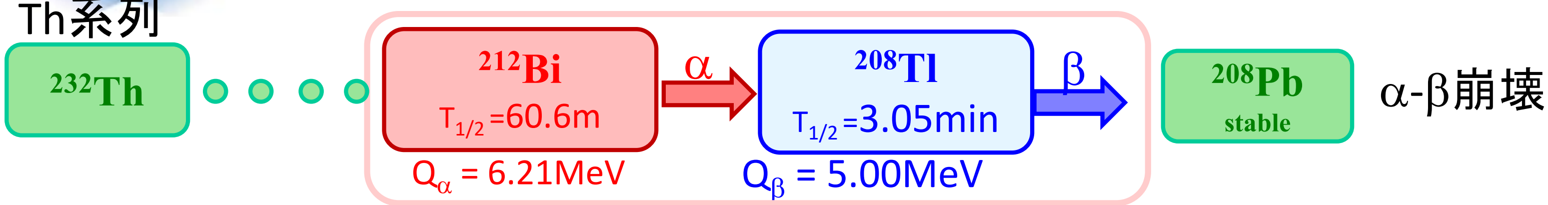




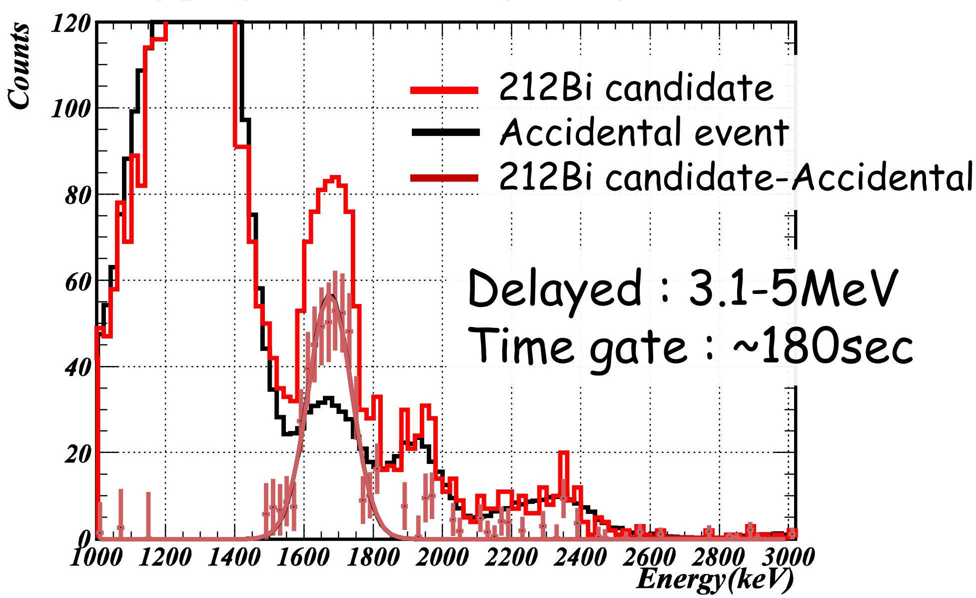
Discrimination between α and γ(β) Events

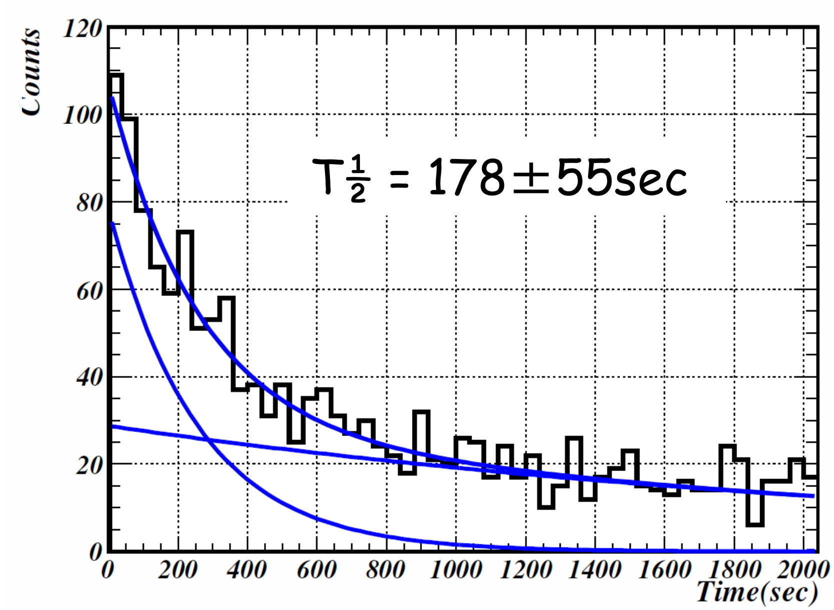
Background Reduction ~ 0.3%

^{208}Tl event cut



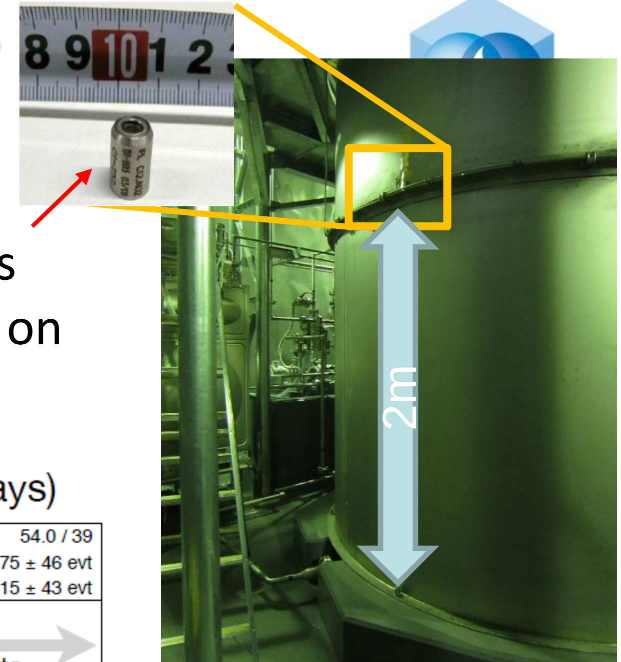
Eneryg spectrum of prompt events



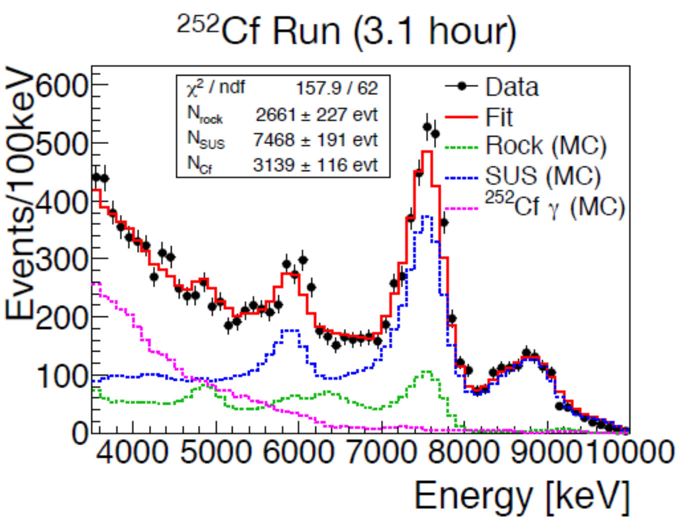


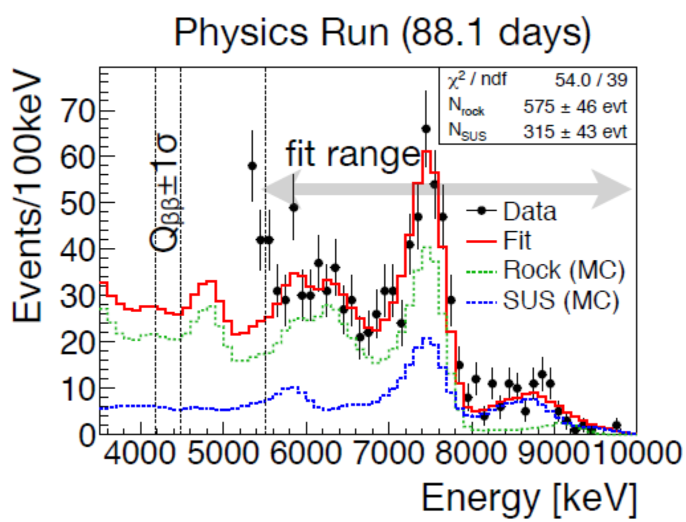
1. Find parent ^{212}Bi α-decay candidate by pulse shape analysis.
2. Apply 12min veto from ^{212}Bi candidate in the same crystal.

External backgrounds
-- Neutron source run --



- To confirm our assumption that high E gamma ray BG's are from (n, γ) reactions, ^{252}Cf neutron source was set on the detector and data were taken.



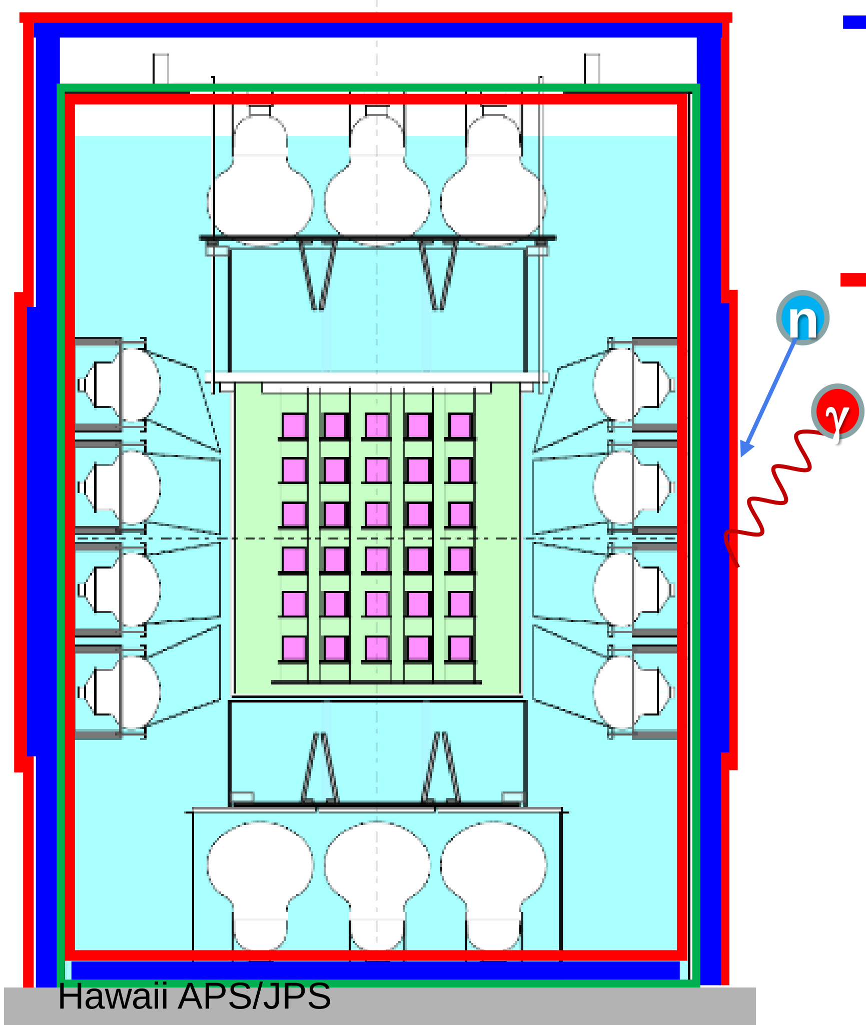


- Spectra for neutron source run and physics run are consistent.
- MC simulation of (n,γ) can well reproduce the BG spectrum.

→ ***We identified main BG as (n,γ) !!***

Shield for (n,γ) background reduction

CANDLES shield overview



- **CANDLES tank** (green)
- **Pb shield (7-12cm)** (blue)
  Reduce γ-ray from surrounding rock
  Effect of Pb (n,γ) is one order smaller than that of stainless tank
- **Boron sheet (4-5mm)** (red)
  Reduce n captured by stainless tank

- (n,γ) BGs in CANDLES is expected to become **1/80** by MC.
- Expected number of backgrounds after shield installation:

  Rock : 0.34±0.14 event/year
  Tank : 0.4±0.2 event/year

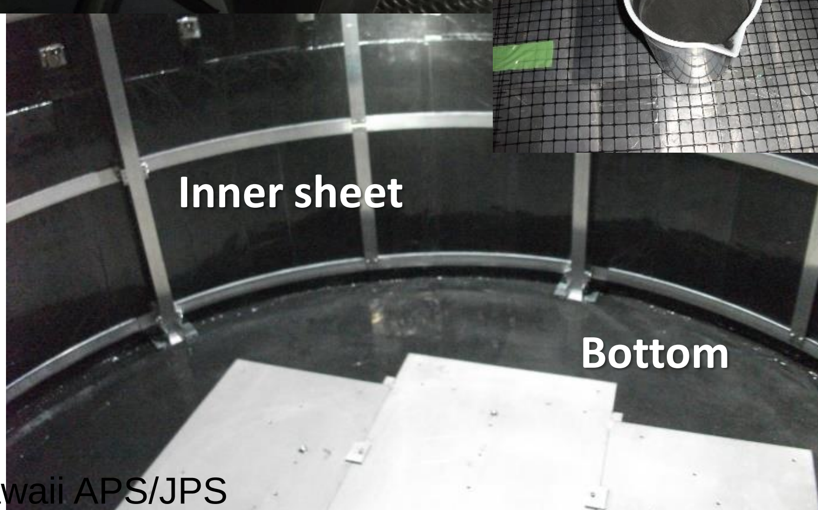
Pb shield construction

- **Pb shield construction was started from March 2015.**
- **All the collaborators worked very hard!**

B shield construction

Candles

- **Neutron shield (B sheet) installation.**



B_4C 40wt%
Silicone rubber
(*B sheet*)

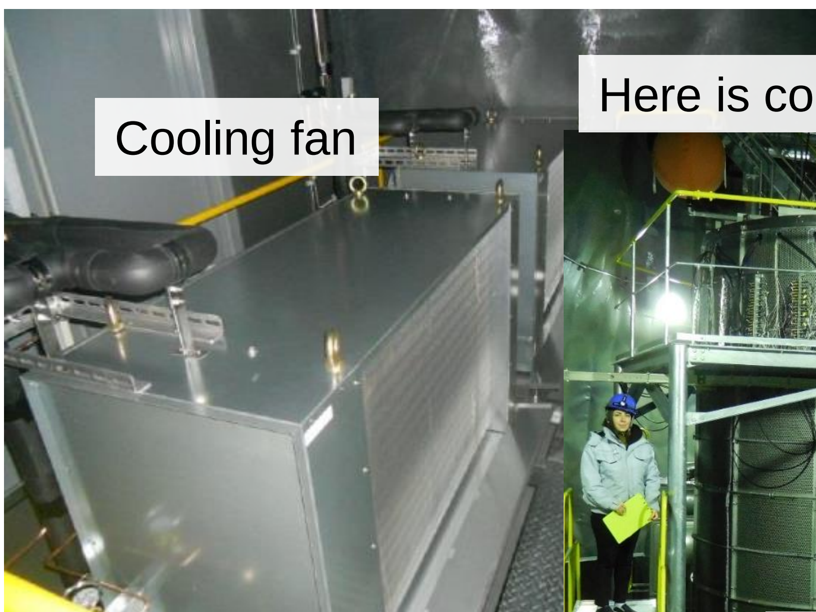
4-5mm thickness.
Covered $100m^2$ area

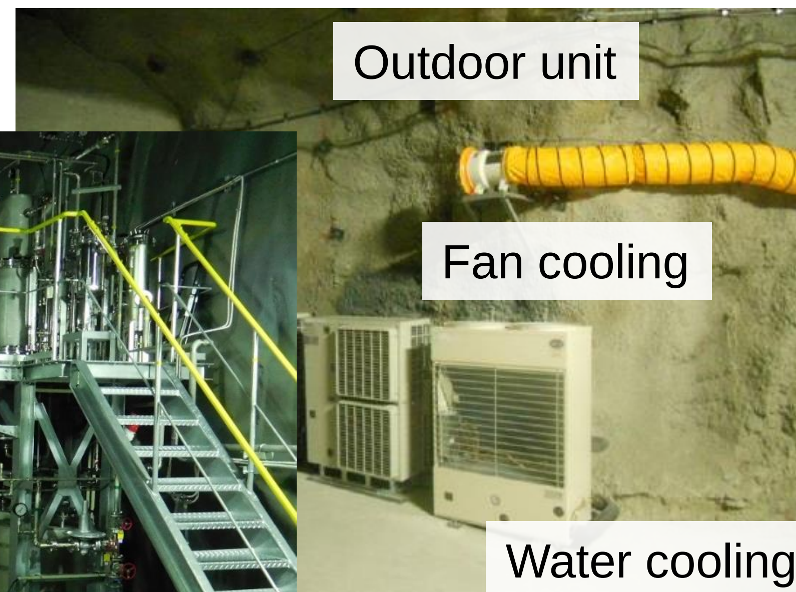
- **For bottom B shield, liquid type was poured on top of the Pb.**
- **This is for both shielding neutron and waterproofing the bottom Pb blocks.**
- **B and Pb elution into water have been checked periodically after water filling.**

Cooling system of the hall

- Cooling
  - CaF_2 have higher gain by cooling (~40% by 20℃ to 0)
  - Experimental hall
    - Room temperature: 2℃、crystal: 3℃、±0.1℃ } 1.4
  - ＋cancelation magnetic (Earth's mag. F) } 1.3

=1.8



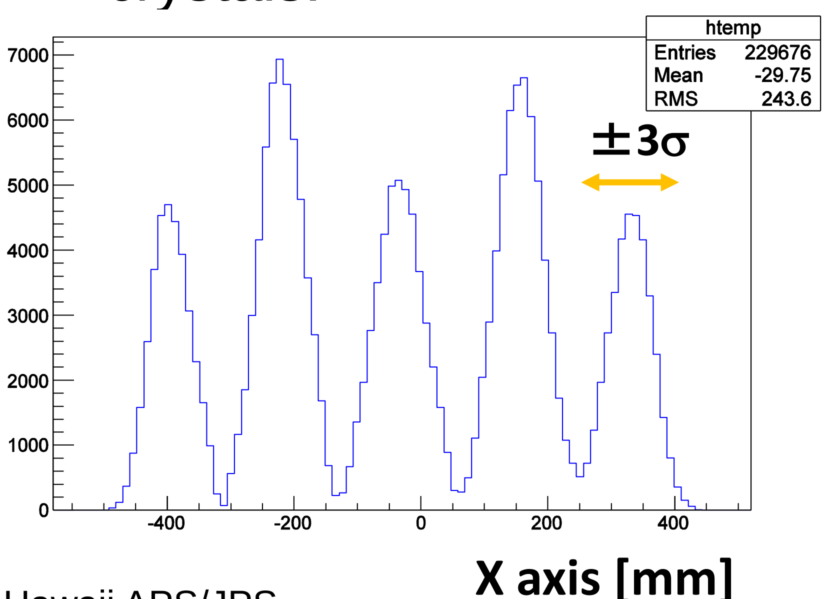


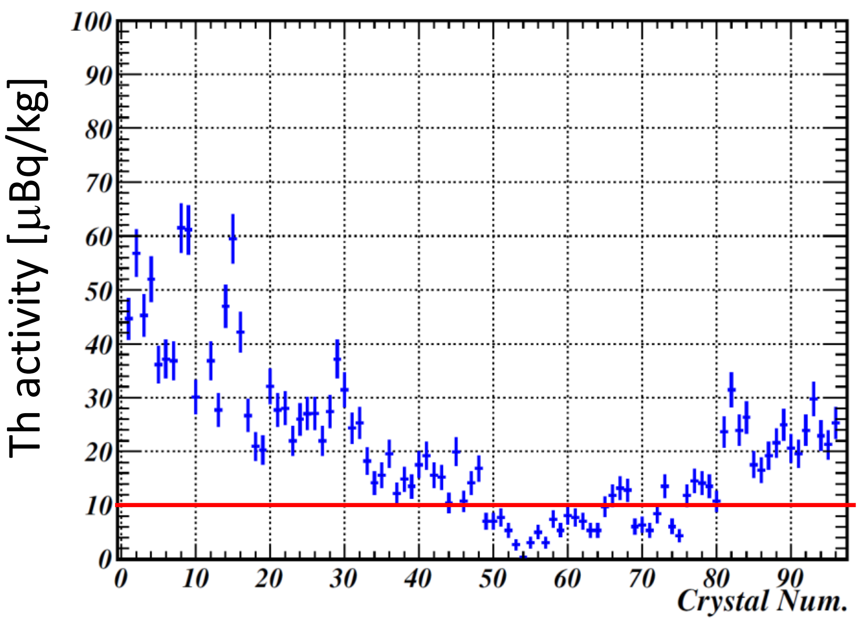
Position reconstruction and crystal selection

- Position of each event is reconstructed by weighted mean of observed charge in each PMT.

$$\frac{\sum Npe(i) \times \overrightarrow{PMT(i)}}{\sum Npe(i)}$$

- Crystal separation is ~7σ peak to peak.
- Crystal selection criteria is within 3σ from the peak.
- 27 clean crystals (Th contamination < 10 μBq/kg) out of 96 crystals are selected and the results are compared to all crystals.





Energy Spectra & Event Selecti

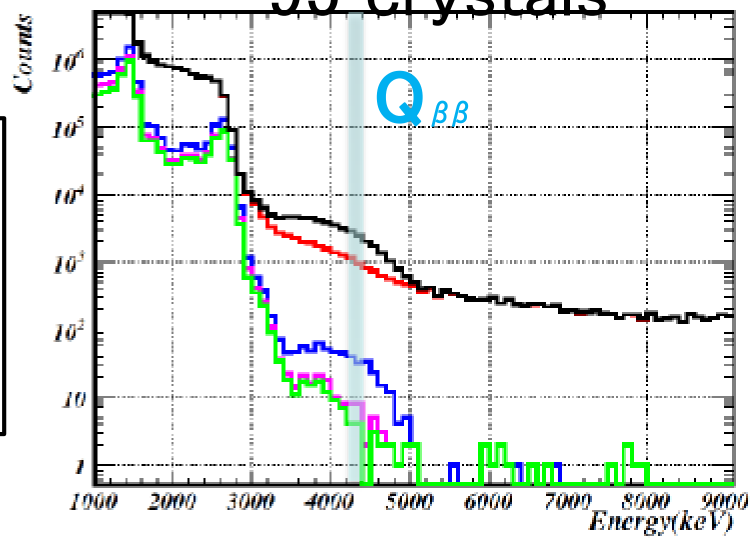
Preliminary

Candles

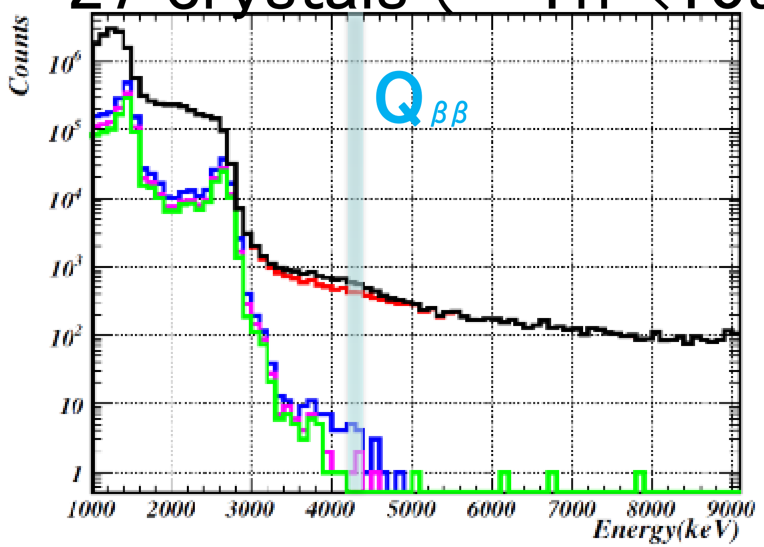
LiveTime : 131 days

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

95 crystals



27 crystals (^{232}Th <10uBq



# event	95 crystals			27 crystals		
	Qββ	4-5MeV	5.5-6.5MeV	Qββ	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

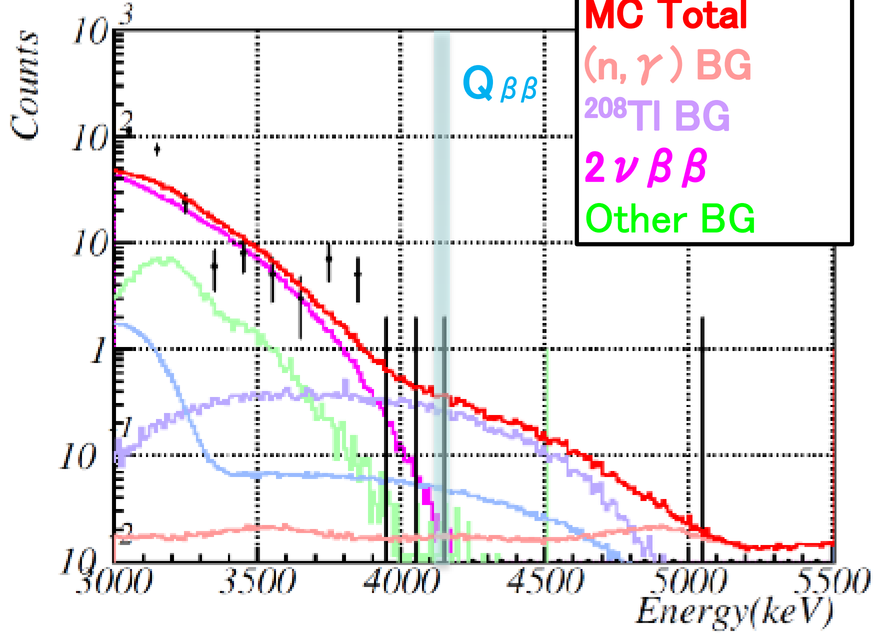
☑ No event in high purity crystals is confirmed.

Results

Preliminary

	95 CaF2	27 CaF2
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 CaF2



$\chi^2{}_\beta$<1.5, −3σ<SI<1σ
−2σ<position cut<2σ
Pileup cut > 20ns
^{208}Tl cut
−1σ<0νββ window<2σ

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

CANDLES is now giving the best lifetime limit!
- **further measurement**
- **developments for future**

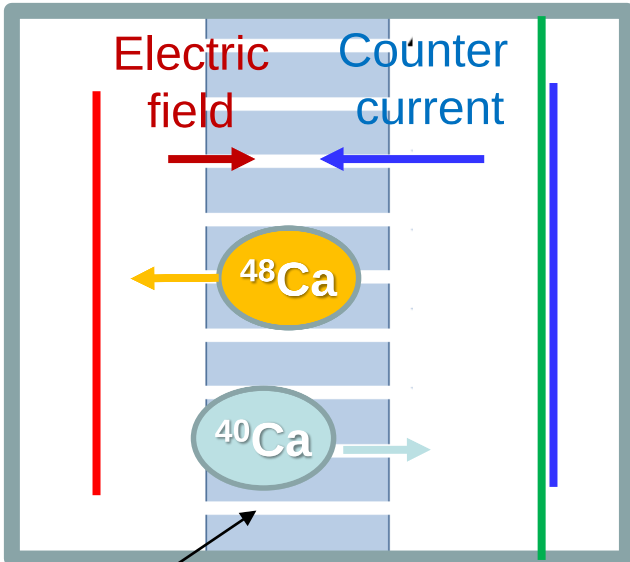
PANIC2017

^{48}Ca enrichment

- Natural abundance of ^{48}Ca is 0.187%.
- ^{48}Ca has a room of 500 times improvement (S & S/N) by enrichment
- Commercial ^{48}Ca → too expensive (M$/10g but kg-ton)
- Enrichment is crucial for large volume ^{48}Ca DBD search.
- Challenges in CANDLES:
  - Crown ether resin + chromatography
    - 1.3 times
  - Crown ether + micro reactor
  - Laser separation
  - **Multi-channel counter current electrophoresis (MCCCE)**

Multi-channel counter current electrophoresis

Candles



Ion exchange membrane

BN plate 10 mm thick
0.8mmΦ, every 4 mm

- Separation using difference of migration speed between ^{40}Ca / ^{48}Ca.
- High power + effective heat removal
  - Migration path: thermal conductor and insulator (BN)
- Pulsed flow to get uniform flow speed

$$R(MCCCE) = \frac{43Ca/48Ca(MCCCE)}{43Ca/48Ca(natural)}$$

Enrichment
(48/43): 3.08
(48/40): 6

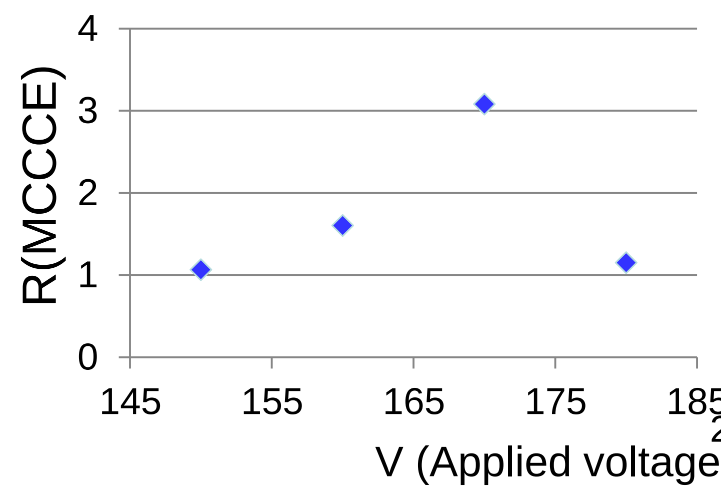
BN; Insulator but high thermal conductivity

PTEP

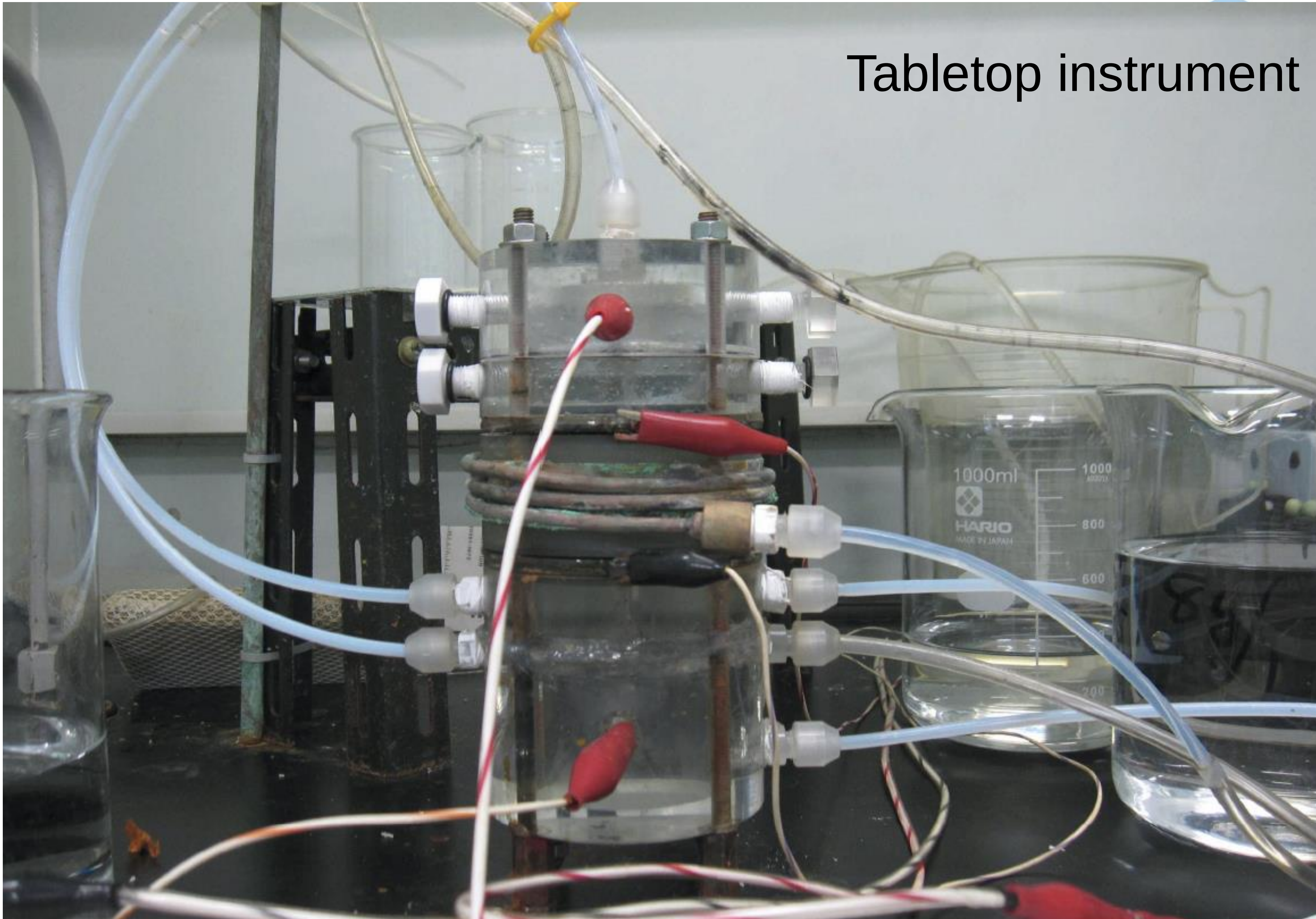
Prog. Theor. Exp. Phys. **2015**, 033D03 (10 pages)
DOI: 10.1093/ptep/ptv020

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

T. Kishimoto[1,2,*], K. Matsuoka[2], T. Fukumoto[3], and S. Umehara[2]



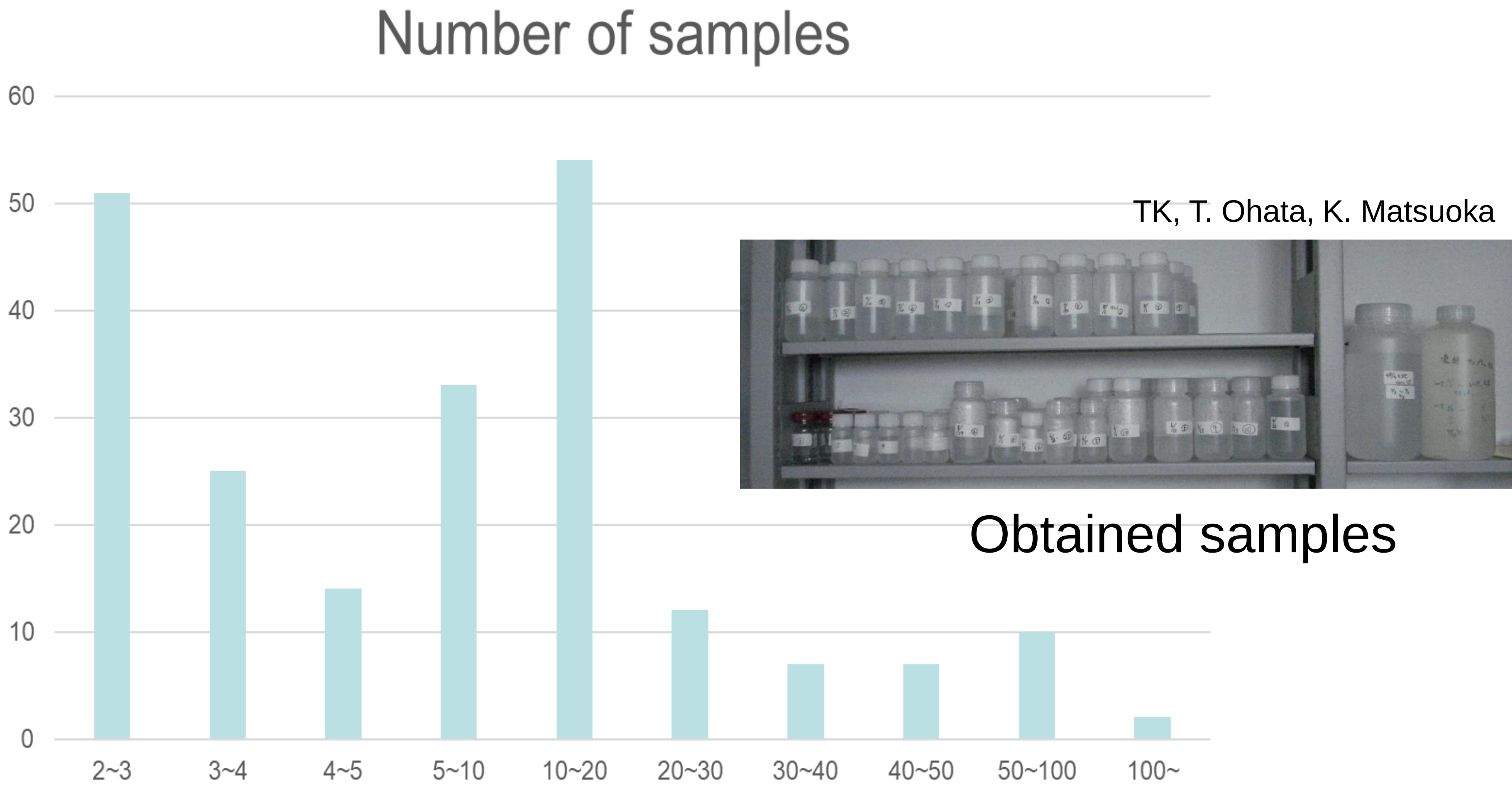
Tabletop instrument



history

- 2015: 10mm BN ~3 $^{48}Ca/^{43}Ca$, (6 $^{48}Ca/^{40}Ca$) PTEP
  - then faced difficulty
- 2017 year end
  - After 2 years struggle, results become reproducible
- 2018 February: ~10 times
- 2018 April: modification to give uniform T and E
  - ~a few 10's times
  - May: ~ 100 times
- Condition
  - BN 20 mm

Highly enriched samples



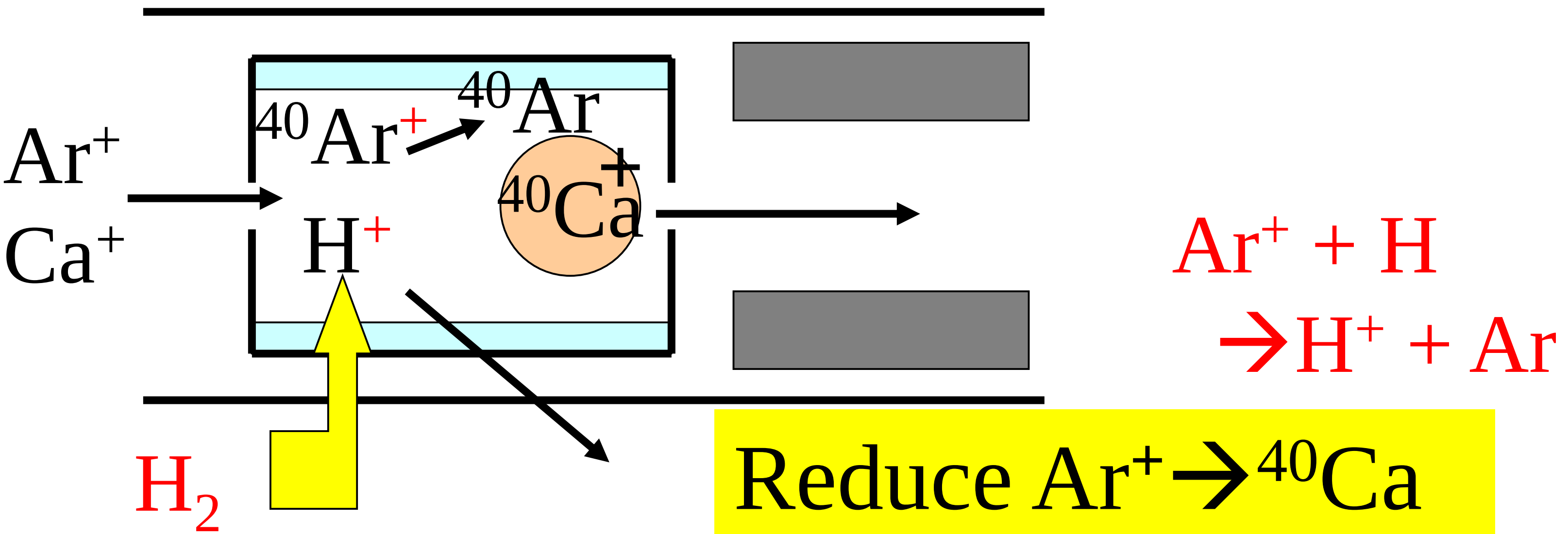
$^{48}Ca/^{43}Ca$ (Enrichment/natural)

TK, T. Ohata, K. Matsuoka

Obtained samples

$^{48}Ca/^{40}Ca$ ratio

- $^{48}Ca/^{43}Ca$ is so high then $^{48}Ca/^{40}Ca$?
  - We usually measure $^{48}Ca/^{43}Ca$, since no interference
  - Similar nat. ab. ^{48}Ca: 0.187%, ^{43}Ca: 0.135%
- ^{40}Ar forbids ^{40}Ca measurement in ICP-MS
  - Reaction(collision)-cell ICP-MS + reaction-gas (H_2, He, NH_3)

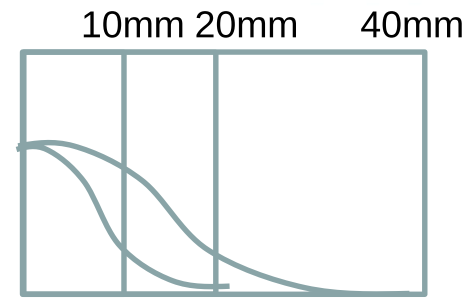


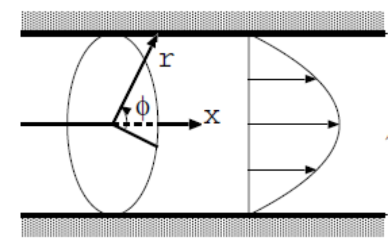
Enrichment

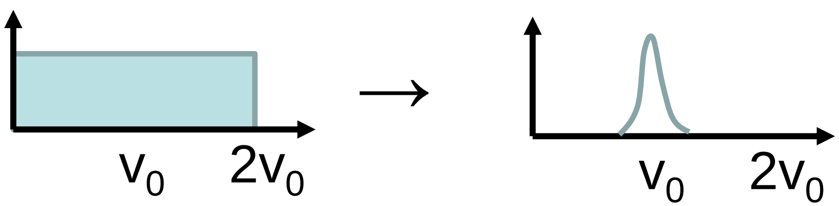
- Migration distance $l = \mu E t$
  - μ : mobility difference $\Delta\mu = \mu(^{40}Ca) - \mu(^{48}Ca)$
  - Separation $\Delta\ell = \Delta\mu E t$
- Diffusion: deteriorate separation
  - Diffusion constant : D $\sigma = \sqrt{2Dt}$
- Enrichment $\frac{\sigma}{\Delta\ell} \propto \frac{1}{E\sqrt{t}} \propto \frac{1}{E\sqrt{\ell}}$ increase of E t (ℓ)
- Yield ~5% (concentration) $Y = \frac{\Delta v}{v} \sim 5\% \sim \frac{\Delta\mu}{\mu}$
  - Migration speed difference ~ 5%
  - Long Migration distance ~ 20/0.05 ~ 400 mm
  - Enrichment and yields are consistent

Enrichment

- Enrichment → Reduction of ^{40}Ca
  - 10mm BN 1/6 → σ~10mm
  - 20mm BN 1/80 → σ~9mm
  - Width
    - σ~1mm: thermal diffusion (too small)
    - Hagen-Poiseuille flow → pulsed flow







$$\sigma = \frac{400}{\sqrt{12}} \sim 115mm \qquad \sigma = \frac{2}{\sqrt{12}}\sqrt{200} \sim 8mm$$

Next step

- 40mm BN 1/1000 → σ~13mm
  - More than 99% enrichment is possible
  - Practical goal 80% or more enough for DBD

$$\sigma = \sqrt{BN_{thickness}}$$

80%

Production of enriched ^{48}Ca

- Current system
  - 16% ($^{48}Ca/^{40}Ca$)
  - 12 cm^2, 0.01 N → 0.1mg/day
- Next system
  - 80% or more
  - 1.2m^2, 0.03 N → 0.3g/day → 100g/year
  - Tons; require plant → further needs
    - Our field
    - Other fields (beam, medical use,..)

    } plant
  - CANDLES works for 80%

Development for CaF_2 Scintillating Bolometer:

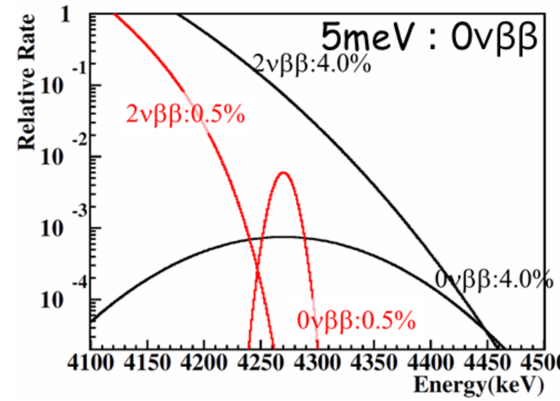
- Sei Yoshida, ….

- Collaborative research with Korean colleague
  Yong-Hamb Kim (IBS & KRISS)
  Minkyu Lee (KRISS)
  Inwook Kim
  Do-Hyoung Kwon
  Hyejin Lee
  Hye-Lim Kim

Background Candidates for CaF_2

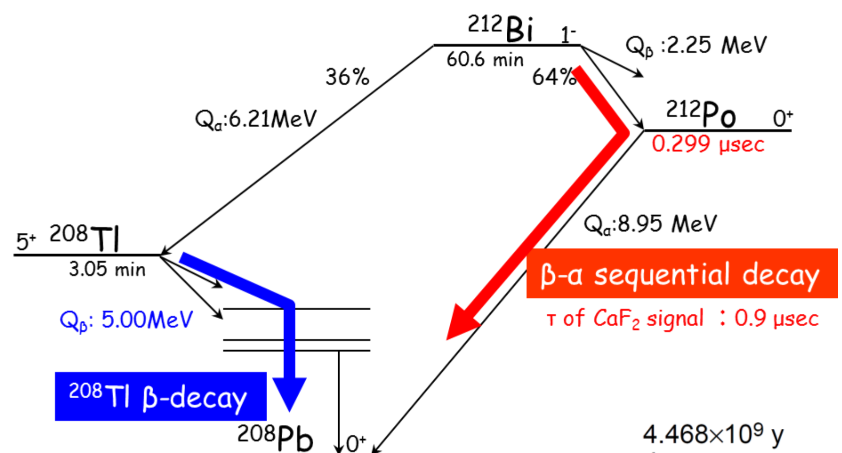
- Tail of $2\nu\beta\beta$ spectrum
  - Improving energy resolution

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

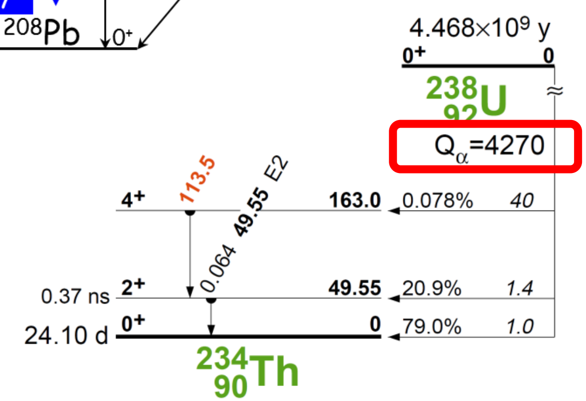
Possible to further reduce
the BG by developing Bolometer



- 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

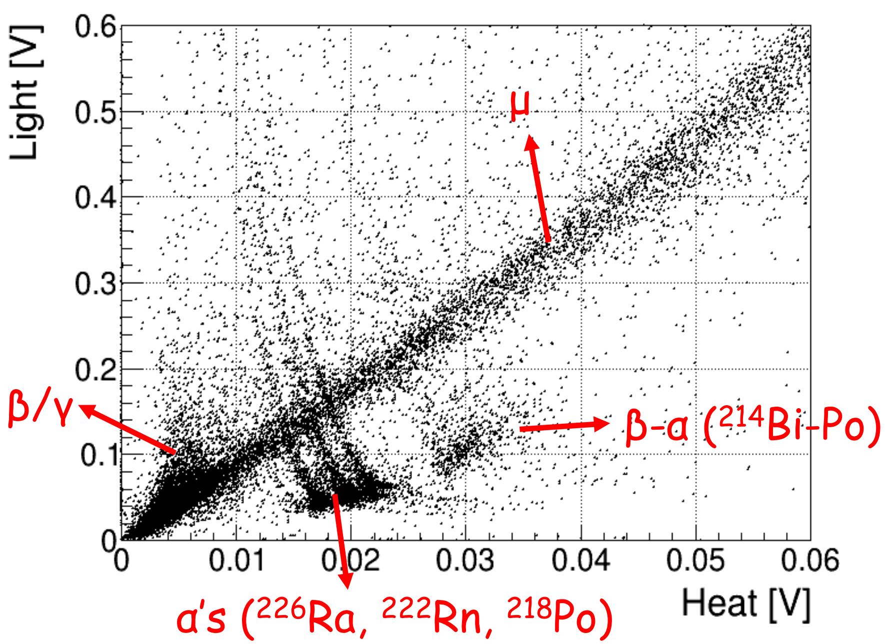


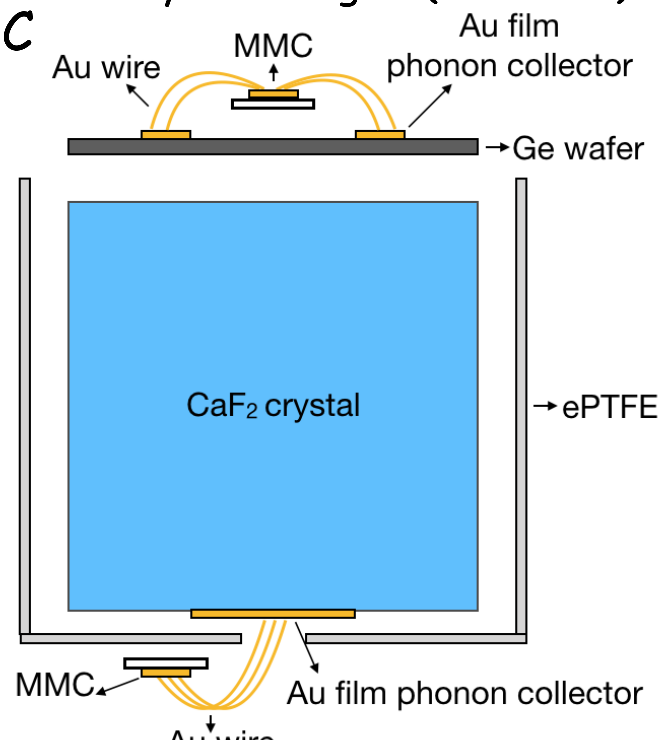
→ **Developing CaF_2 Scintillating Bolometer**

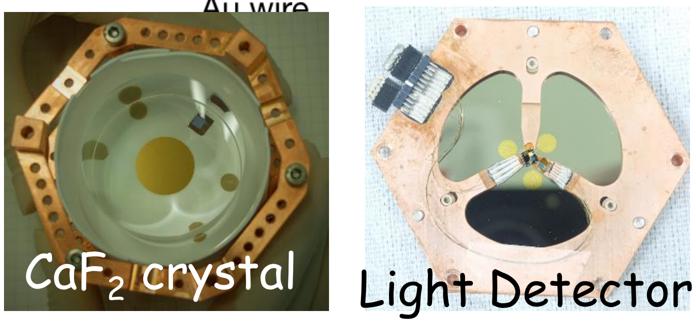
CaF_2(pure) Scintillating Bolometer

Poster by Xiaolong Li (Osaka U.)

- First Challenge using CaF_2(pure) and MMC
  - Crystal: CaF_2(pure)
    - Volume: 300g (5cmφ × 5cm)
    - Emission peak : 280nm
    - Light output: 25,000 photons/MeV





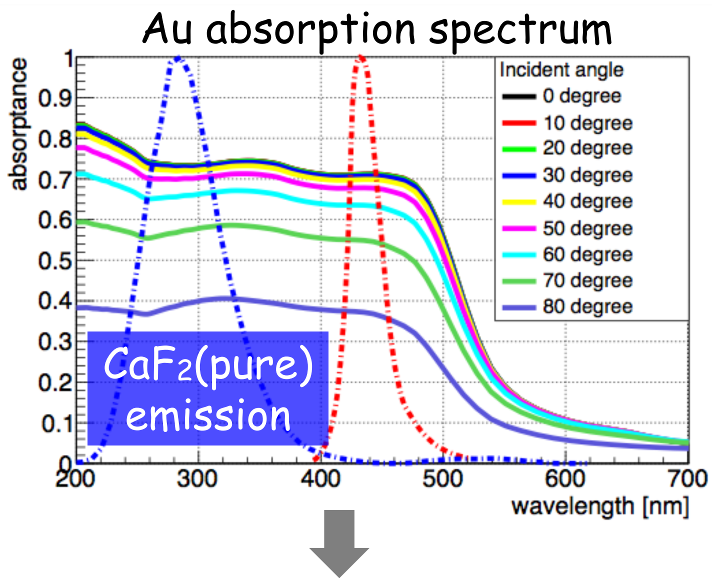


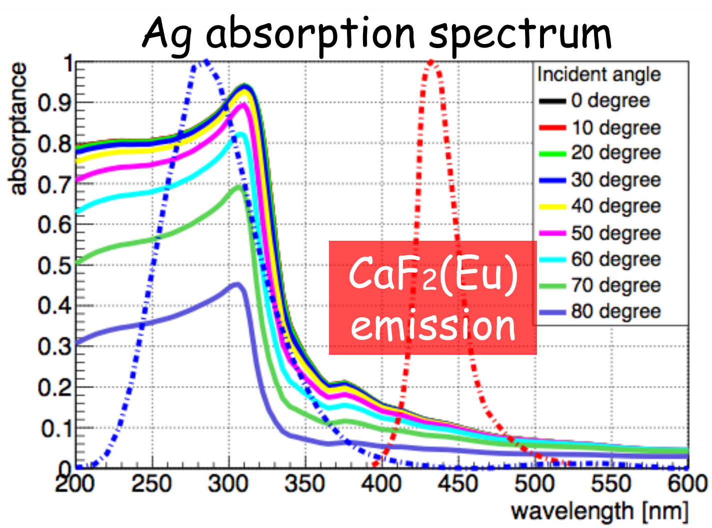
- Problem
  - UV scintillation of CaF_2 is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ➔ make worse E-resolution.

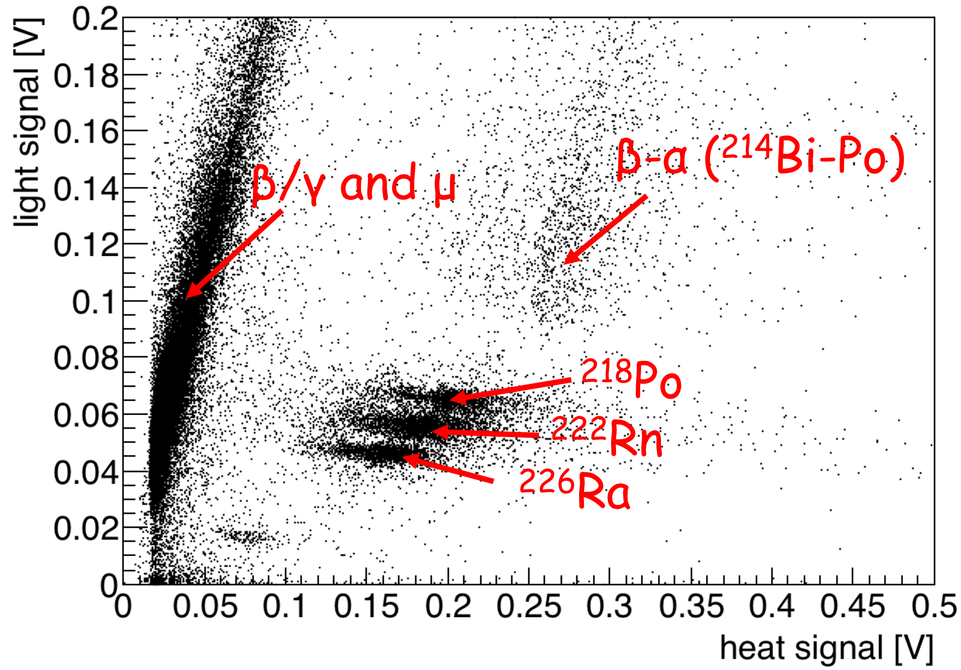
CaF2(Eu) scintillating Bolometer

Poster by Xiaolong Li (Osaka U.)

- New trial to overcome UV absorption
  - CaF_2(Eu) +Ag-deposit instead of CaF_2(pure) + Ag-deposit







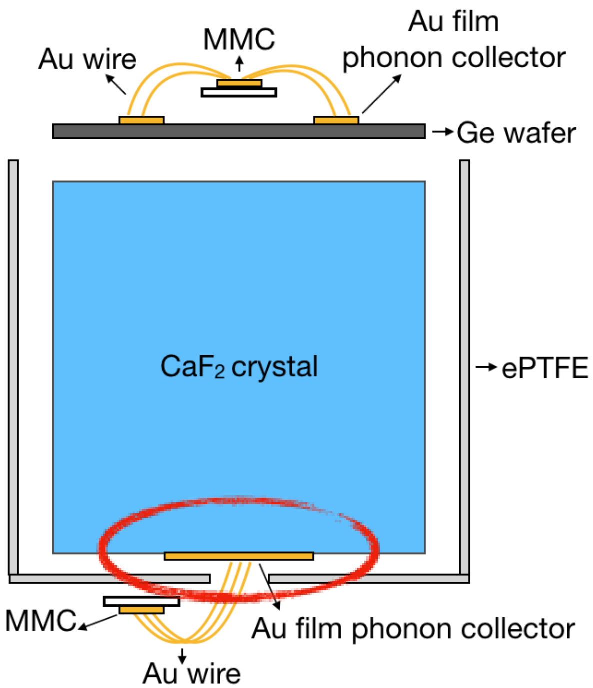
- ✓ Improved light signal properties.
- ✓ In the heat channel, peaks of α's are widely spread. (due to position dependence)
- ✓ Due to doping Eu ?

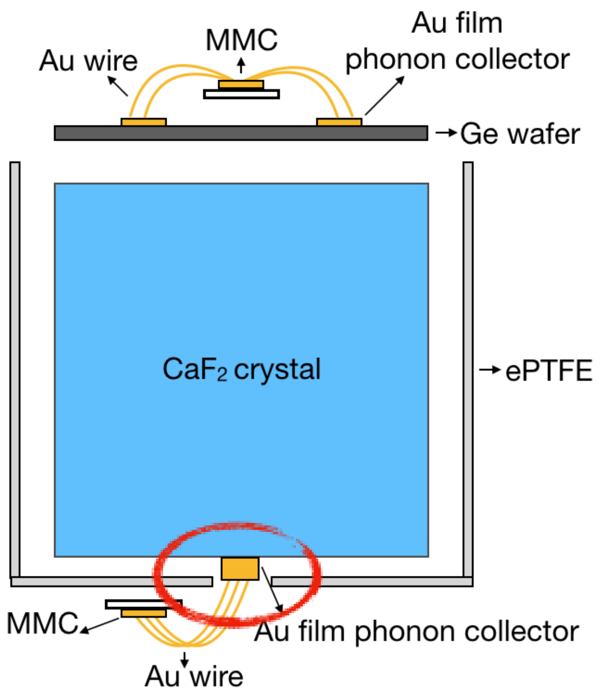
Prospects for the development

Poster by Xiaolong Li (Osaka U.)

- Improving E-resolution of CaF_2(pure) scintillating bolometer
  - Radio-pure CaF_2(pure) crystal had been developed.
  - Doping Eu may affect phonon propagation in CaF_2 crystal.

- New trial in the next step
  - CaF_2(pure) crystal with smaller but thicker Au-deposit phonon collector.
    - Smaller → reducing scintillation absorption effect
    - Thicker → increasing the strong electron-phonon interaction.





CANDLES project

Candles

- CANDLES:
  - CANDLES III(UG): current detector
    - CaF_2 crystals with low BG
    - High resolution

Background free measurement

- Future prospect
  - Enrichment ^{48}Ca
    - MCCCE method for tons
    - CANDLES will work
  - Bolometer
    - CaF_2 Scintillating Bolometer

CANDLES
to normal hierarchy
Still lot to do
Promising

Thank you !!