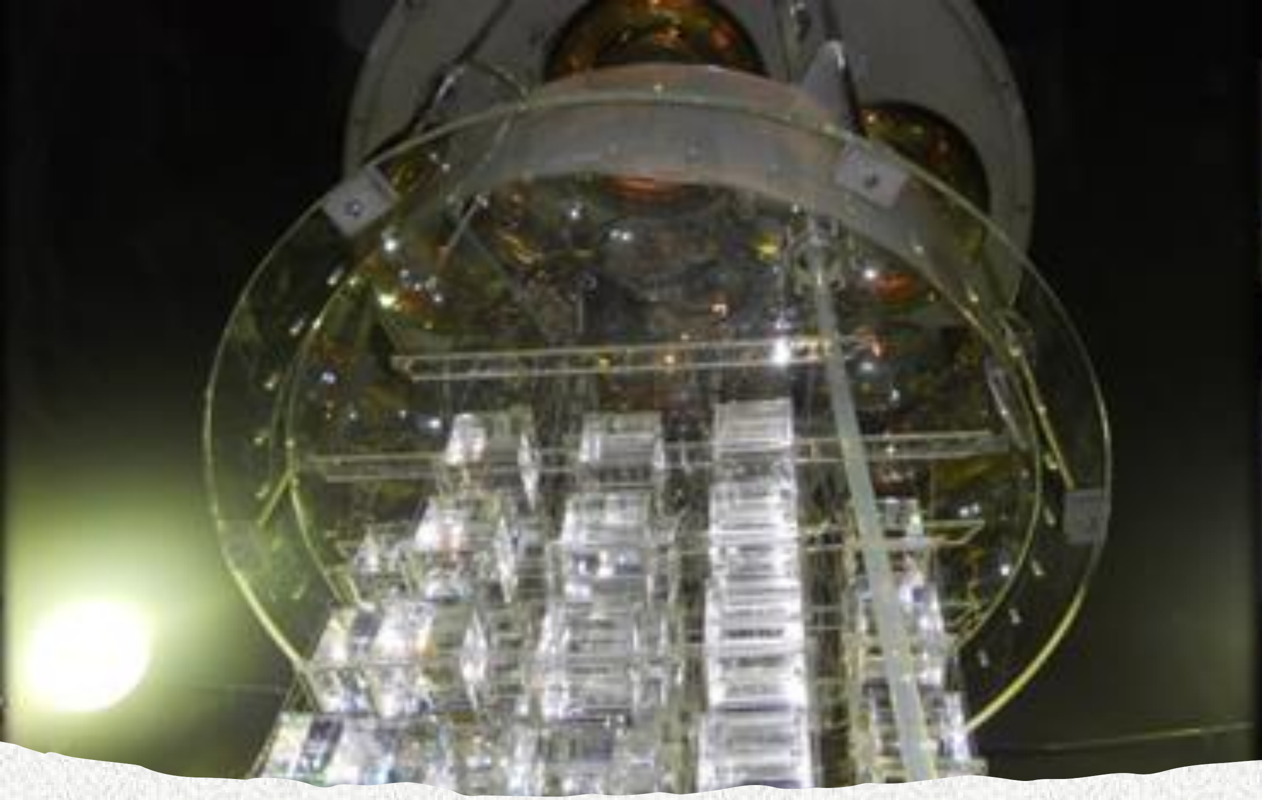


– CANDLES –

An experimental approach to search for $0\nu\beta\beta$ of ^{48}Ca

Kavli IPMU Postdoc Colloquium Series

Oct. 8th, 2021

Bui Tuan Khai

The massive neutrino

- Nobel prize in Physics 2015 awarded

  for Prof. Takaaki Kajita (Super-K, JP)

and Prof. Arthur. B. McDonald (SNO, CA)

⇒discovery of **neutrino oscillations**

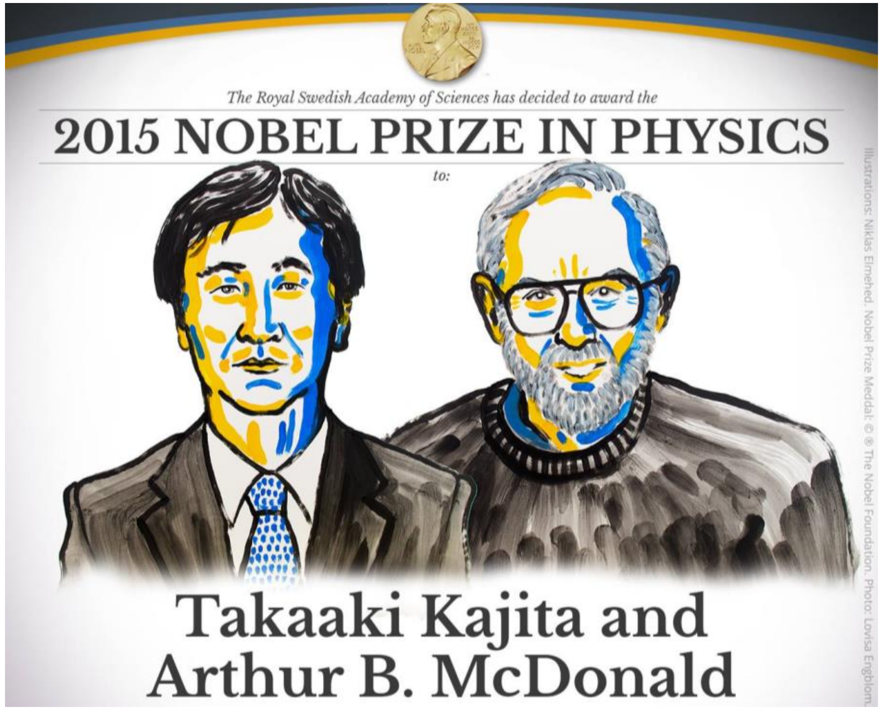
⇒show **neutrinos have mass**

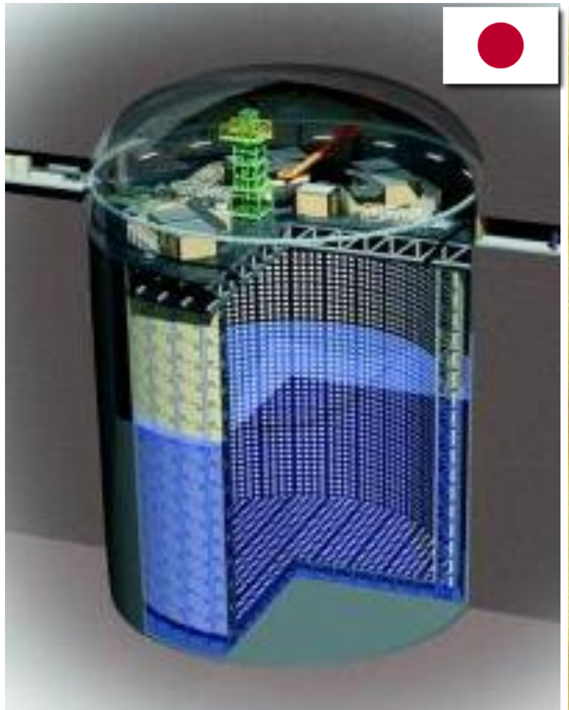
⇒Some unknown questions:

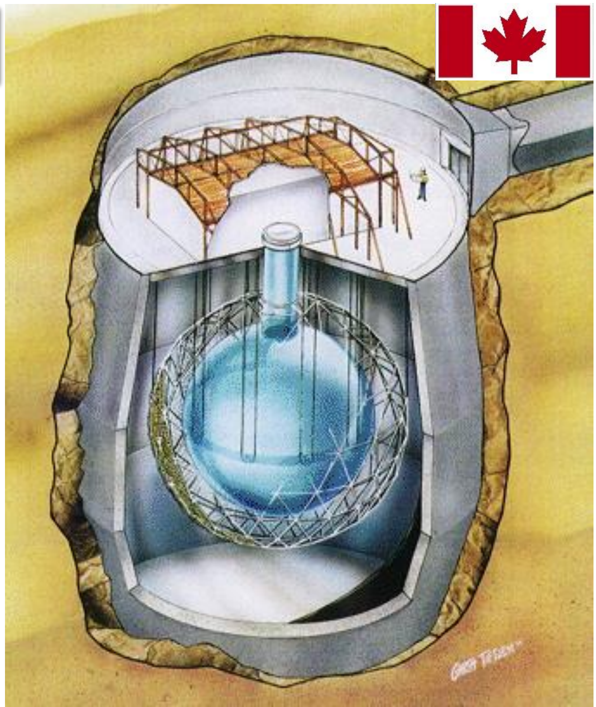
  - absolute neutrino mass?
  - Neutrino: Majorana ($\nu=\bar{\nu}$) or Dirac($\nu\neq\bar{\nu}$)?

matter – antimatter asymmetry?

⇒ Neutrino-less double beta decay is an excellent tool



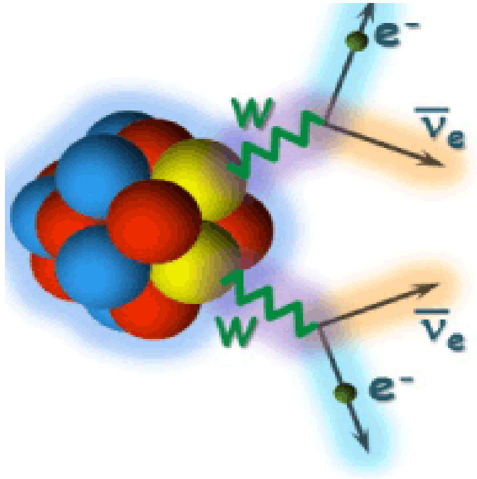


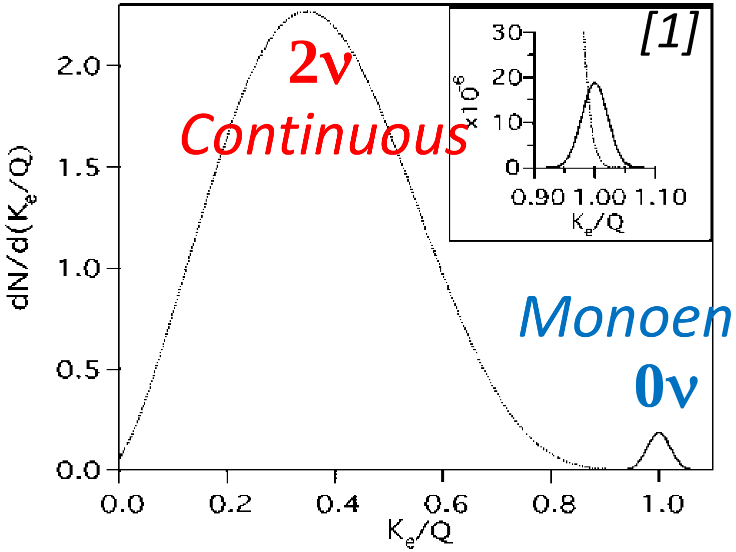


Double Beta Decay (DBD)

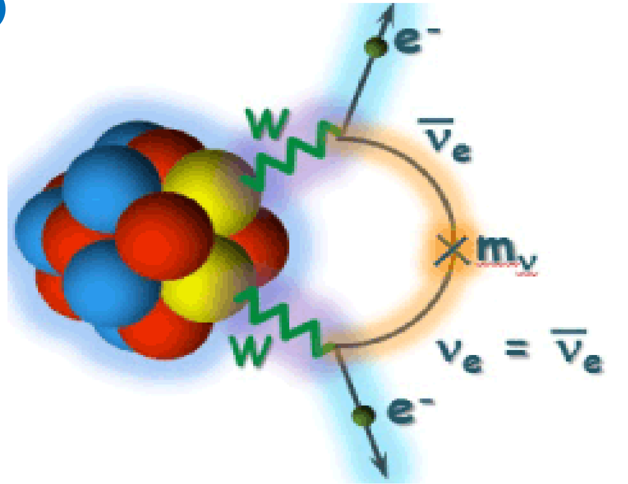
[1] Ann.Rev.Nucl.Part.Sci.52:115

2νββ





0νββ



- Obtained in >10 isotopes
- $T^{2\nu}_{1/2}$ = 10^{18}~10^{20} yr
- Rare, under standard model (SM)

- No observation
- $T^{0\nu}_{1/2}$ > 10^{26} yr (KamLAND-Zen)
- Extremely rare!

❖ <u>Physics of **0νββ decay**</u>:

➢ Neutrino mass from the $\mathbf{T^{0\nu}_{1/2}}$

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|\langle m_{\beta\beta}\rangle^2/m_e^2\right||M^{0\nu}|^2$$

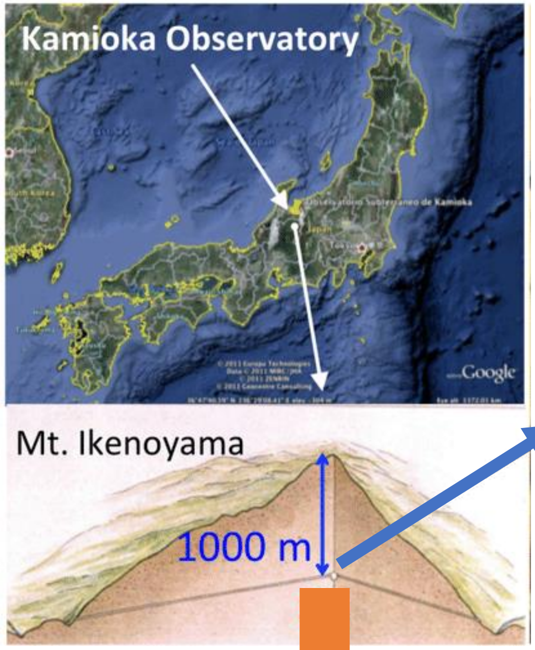
➢ Nature of neutrino: Majorana or Dirac?

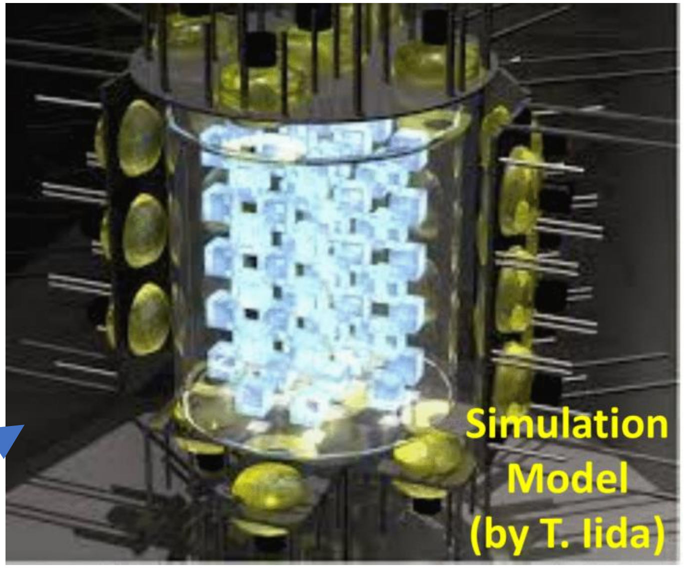
➢ Lepton number not conserved (ΔL=2)

⇒ New physics beyond SM

CANDLES experiment

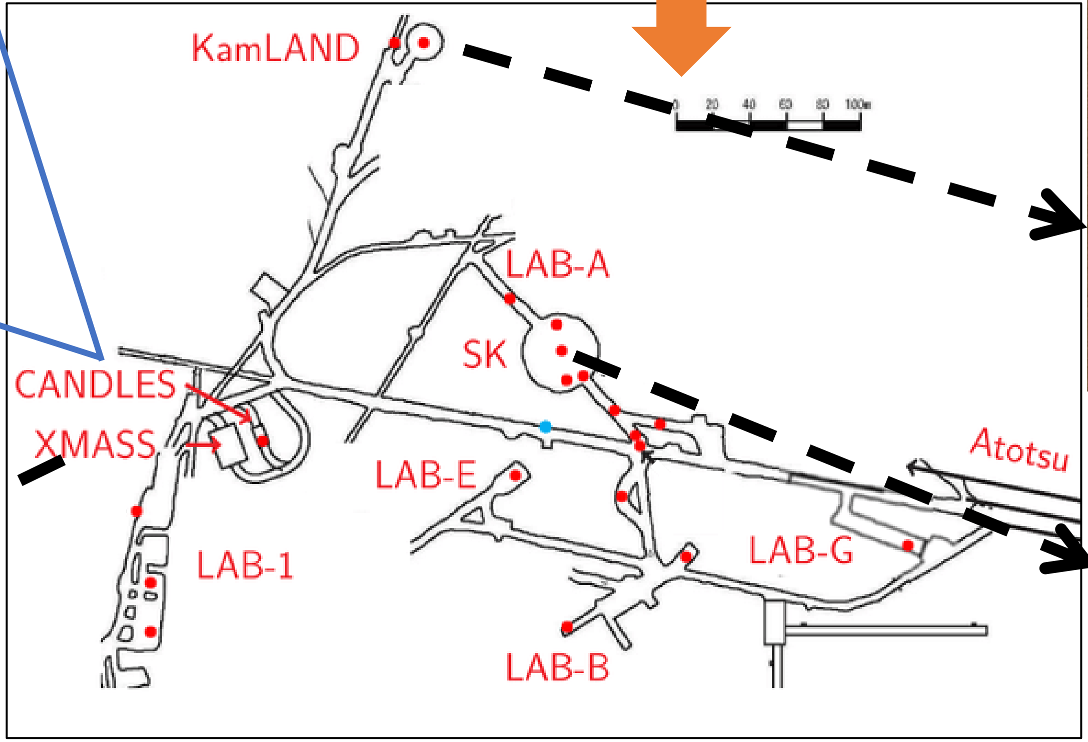
- To observe $0\nu\beta\beta$ of ^{48}Ca
- Set up @ Kamioka (2700m.w.e depth)

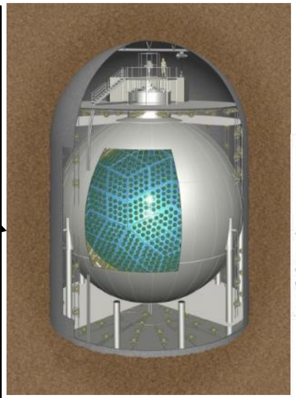




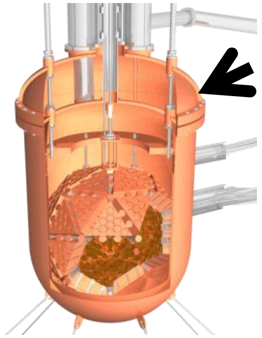
CANDLES

CAlcium fluoride for studies of **N**eutrino and **D**ark matters by **L**ow **E**nergy **S**pectrometer





Kam LAND



Dark Matter Search

0νββ experiment with ^{48}Ca

✓ **Highest $Q_{\beta\beta}$ 4.27 MeV**

- Large phase space factor
- Far from BKG (γ: 2.6 MeV; β: 3.3 MeV)

⇒**Aim for background-free measurement**

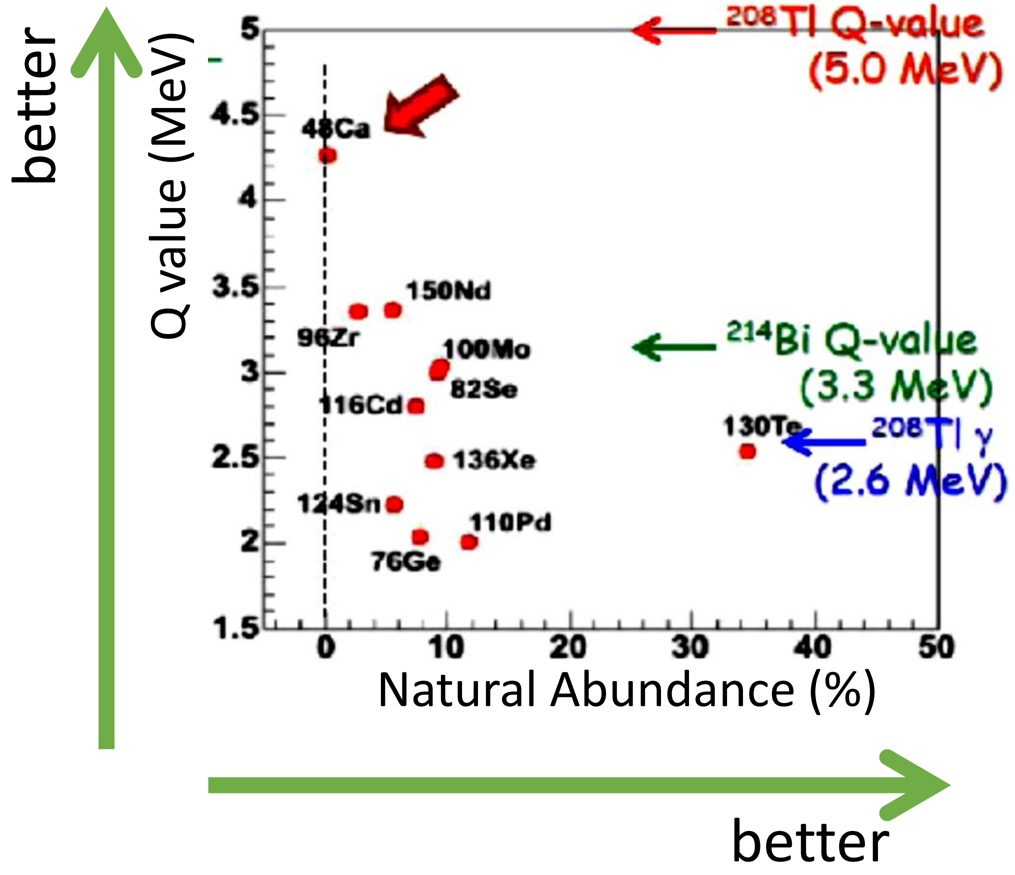
☒ **Low abundance**

- Natural abundance: <0.2 %
- Separate isotopes: expensive

⇒**Cost-effective enrichment**

❑**Energy Resolution** $T_{1/2}^{0\nu} \propto (N_{BKG} \cdot \Delta E)^{-1/2}$

⇒ Improve sensitivity



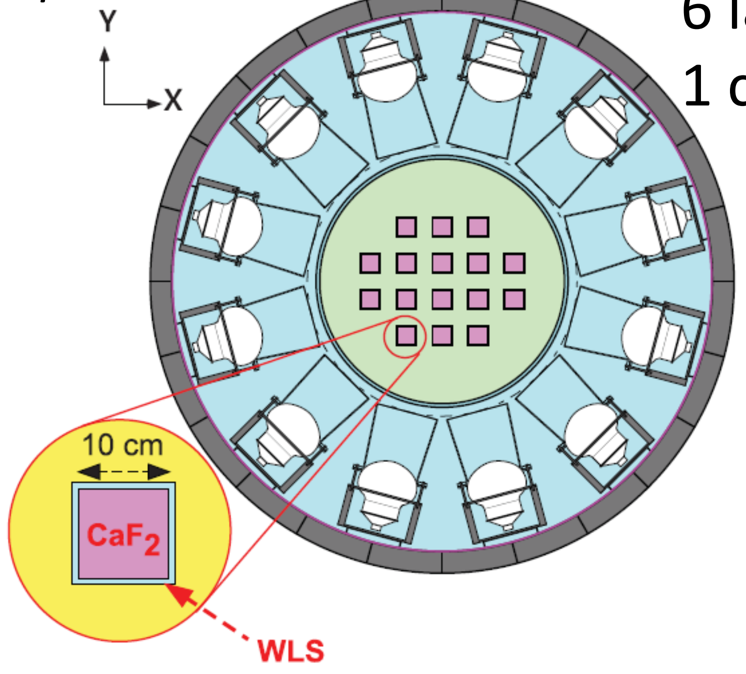
❖To improve sensitivity for 0νββ in CANDLES:

- Enrichment (~600kg ^{48}Ca)
- High resolution (bolometer)
- Low background

CANDLES experiment

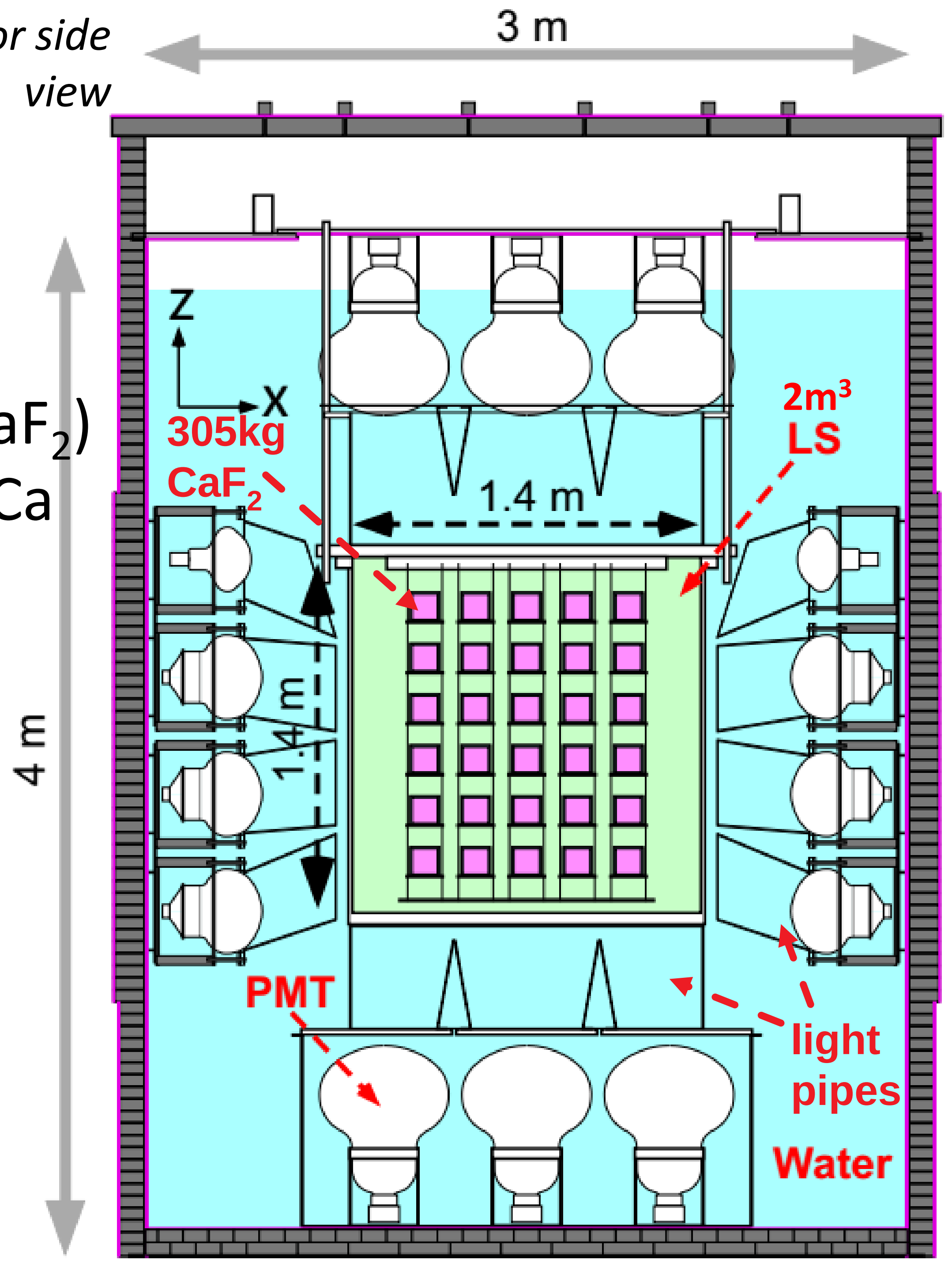
- To observe $0\nu\beta\beta$ of ^{48}Ca
- Set up @ Kamioka (2700m.w.e depth)
- CANDLES consists of:
  - 96 $^{nat.}CaF_2$ cubes: detector+source $\Rightarrow$ 350g ^{48}Ca (305kg CaF_2)

top view



6 layers x 16 crystals/layer
1 crystal: 10cm cube

Detector side view



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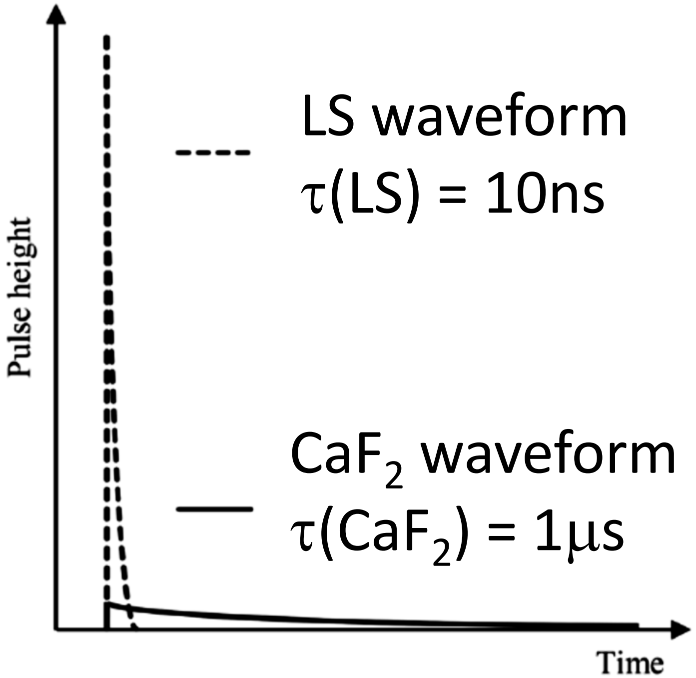

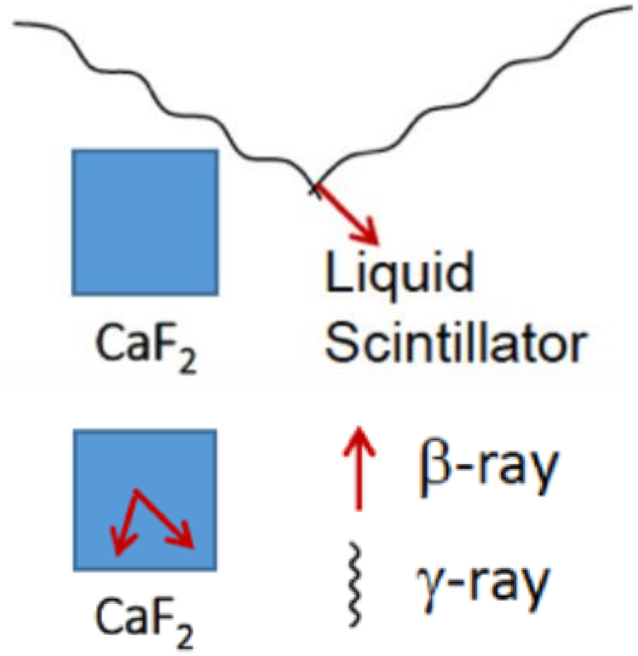

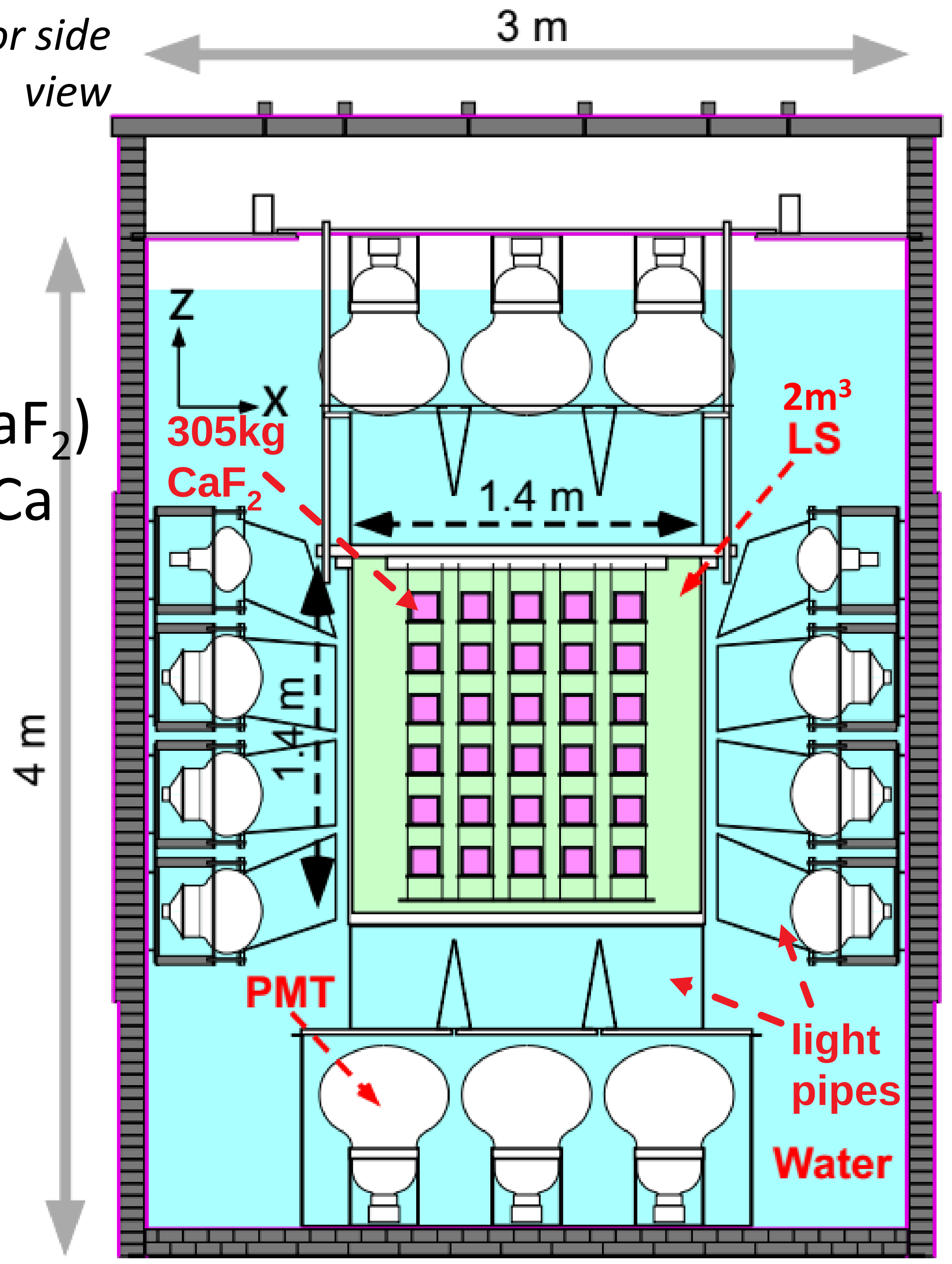

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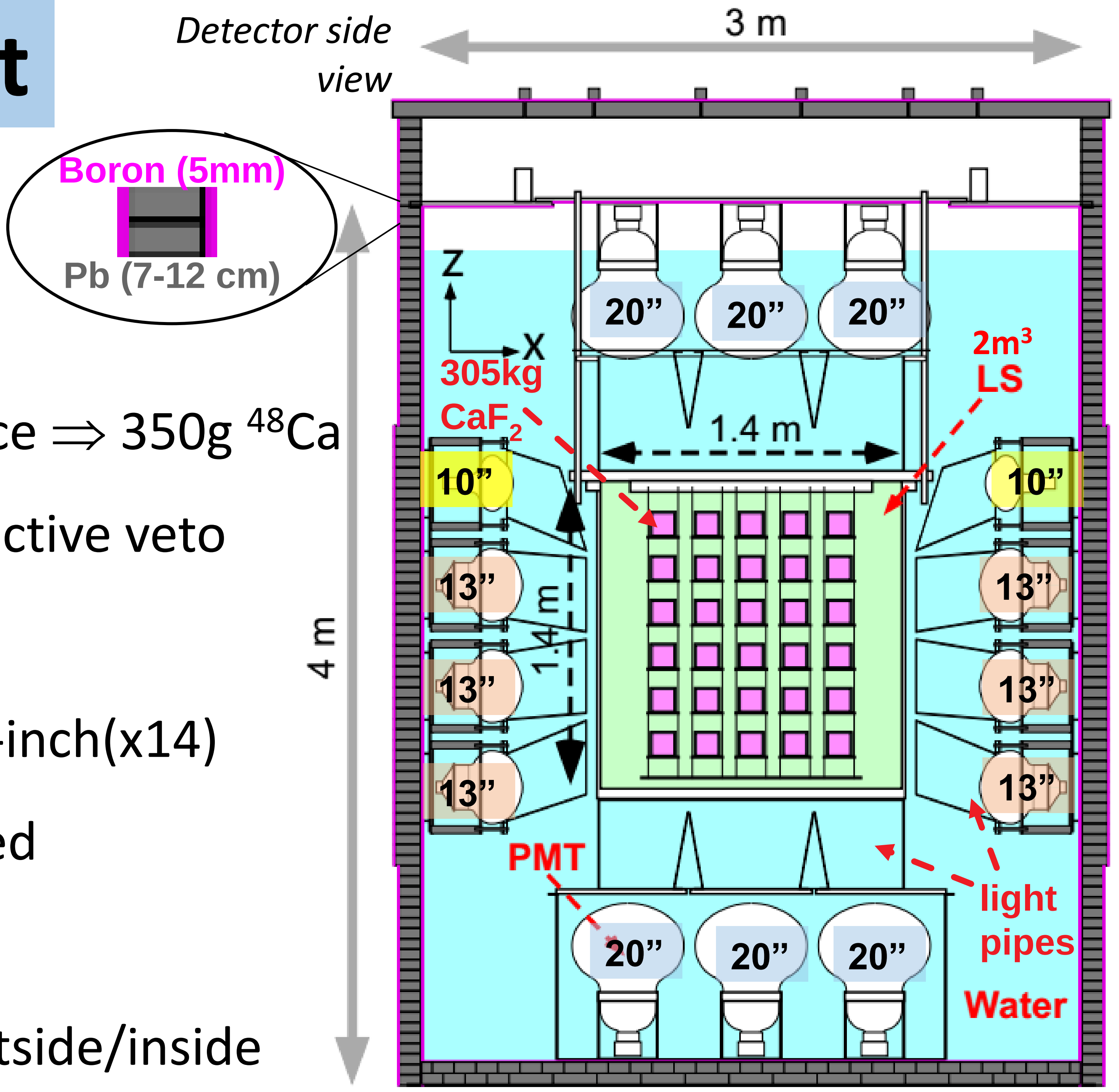
  - 96 $^{nat.}CaF_2$ cubes: detector+source ⇒ 350g ^{48}Ca
  - Liquid scintillator (LS): $2m^3$, 4π active veto
  - 62 PMTs surrounding:
    - 10-inch(x12), 13-inch(x36), 20-inch(x14)
    - each PMT waveform is recorded
  - Water passive shield $4m^h \times 3m^\phi$
  - Passive shielding (Pb+Boron) outside/inside



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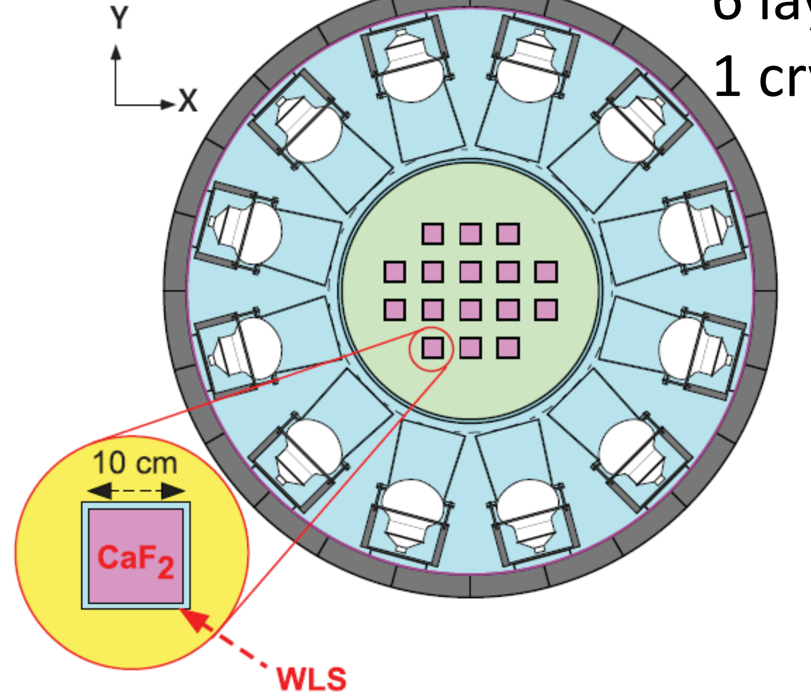
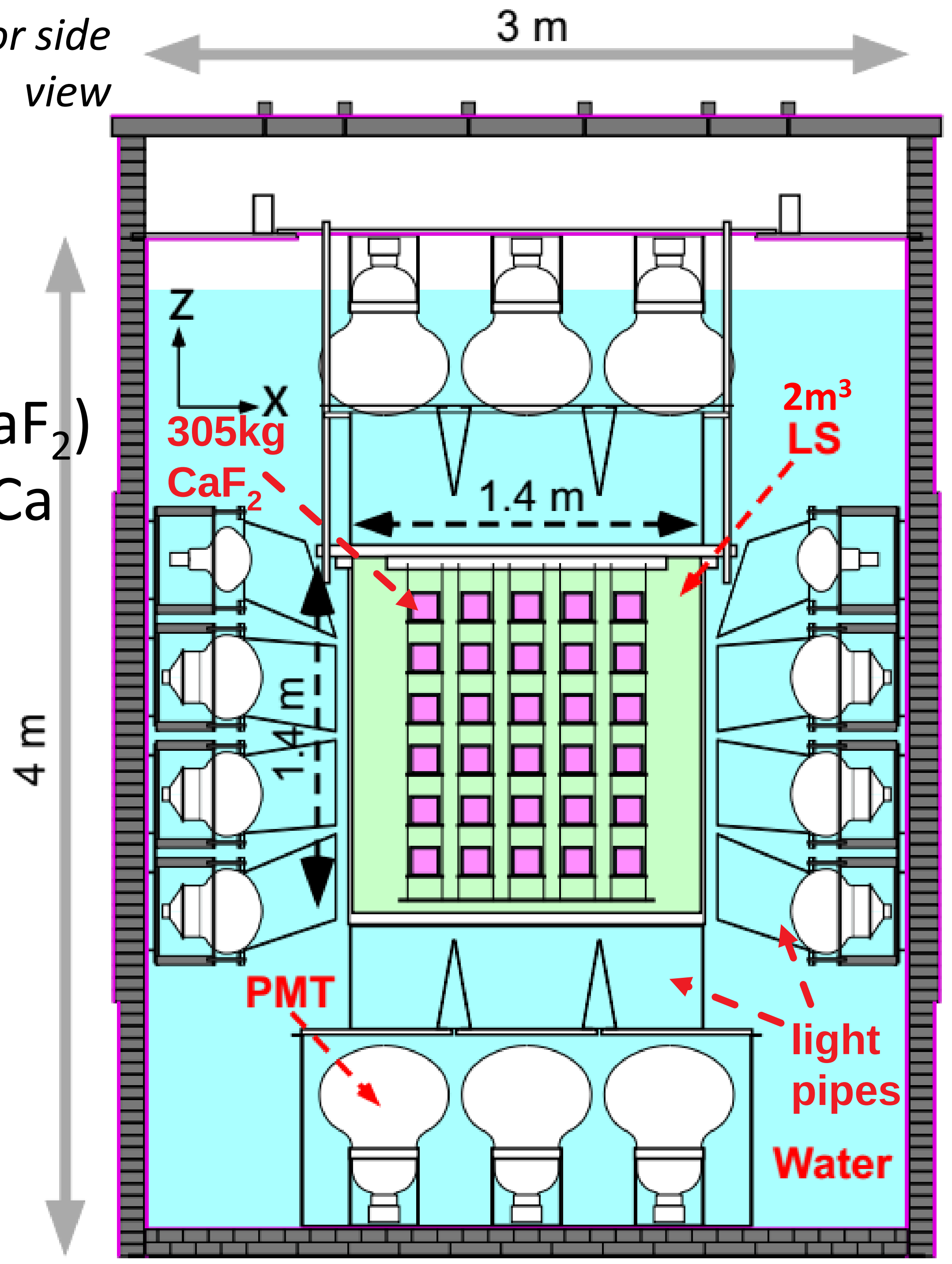
top view



6 layers x 16 crystals/layer
1 crystal: 10cm cube

Detector side view



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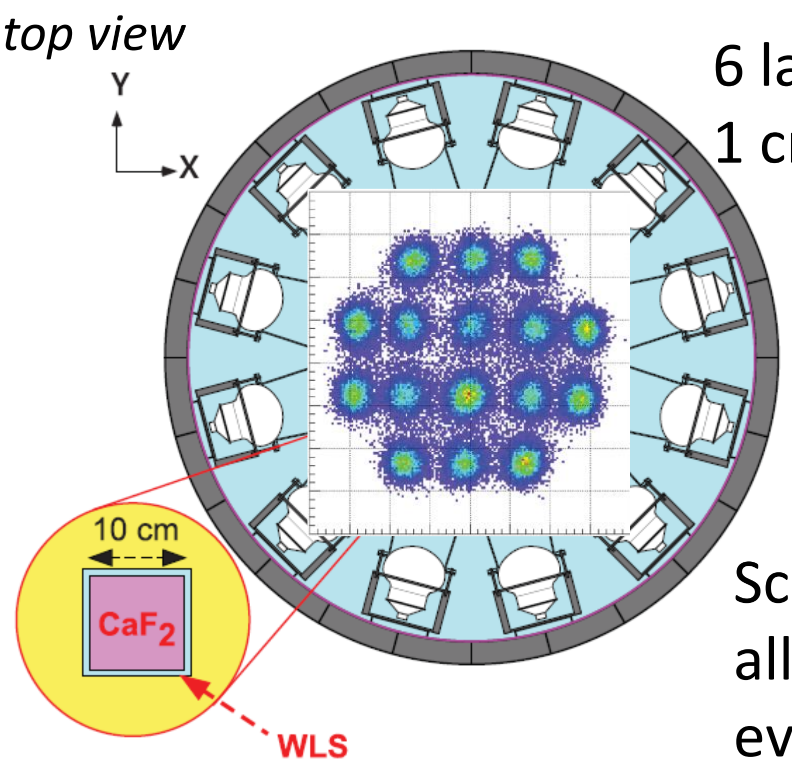
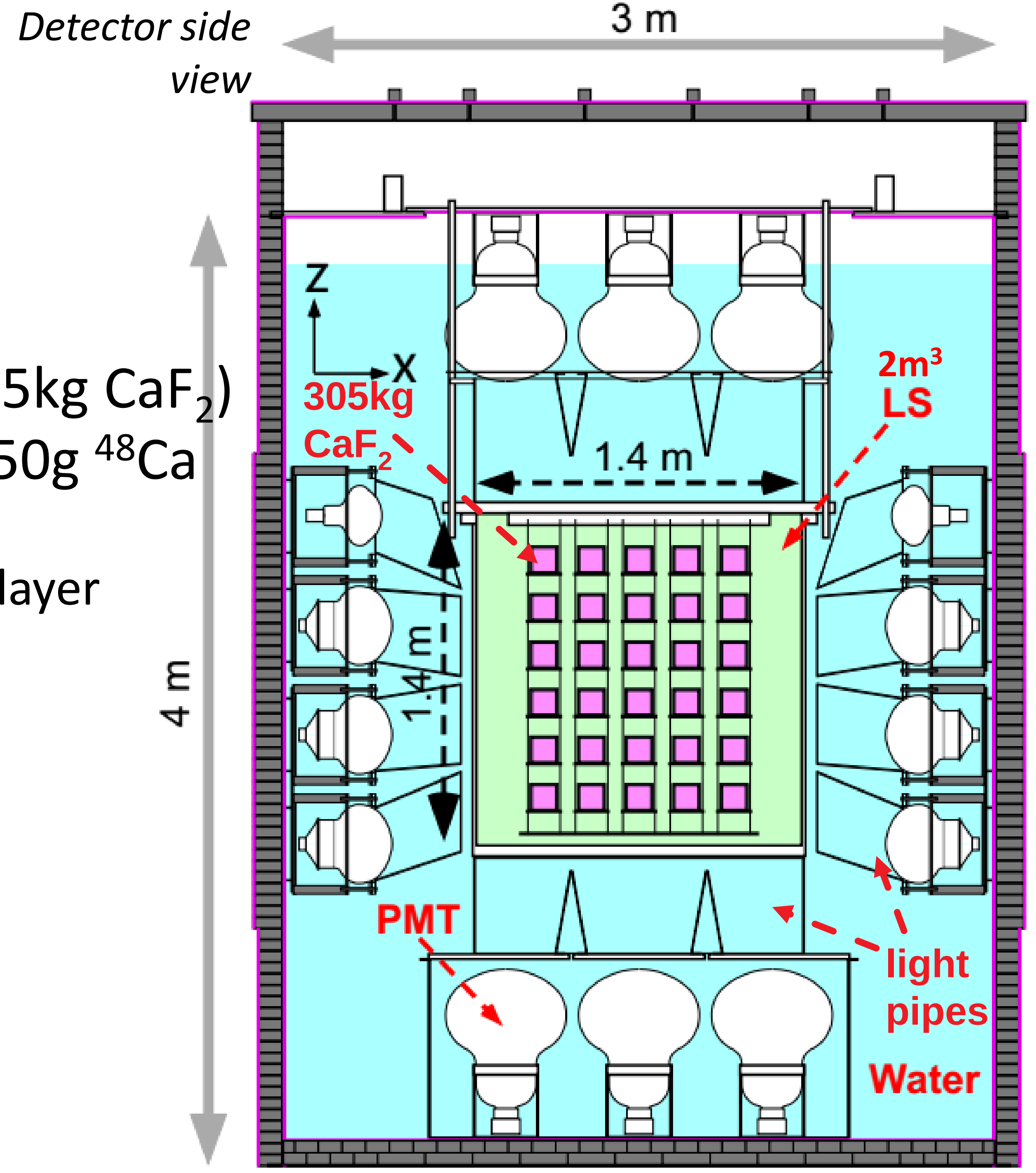


Scintillation photons allow to reconstruct event position

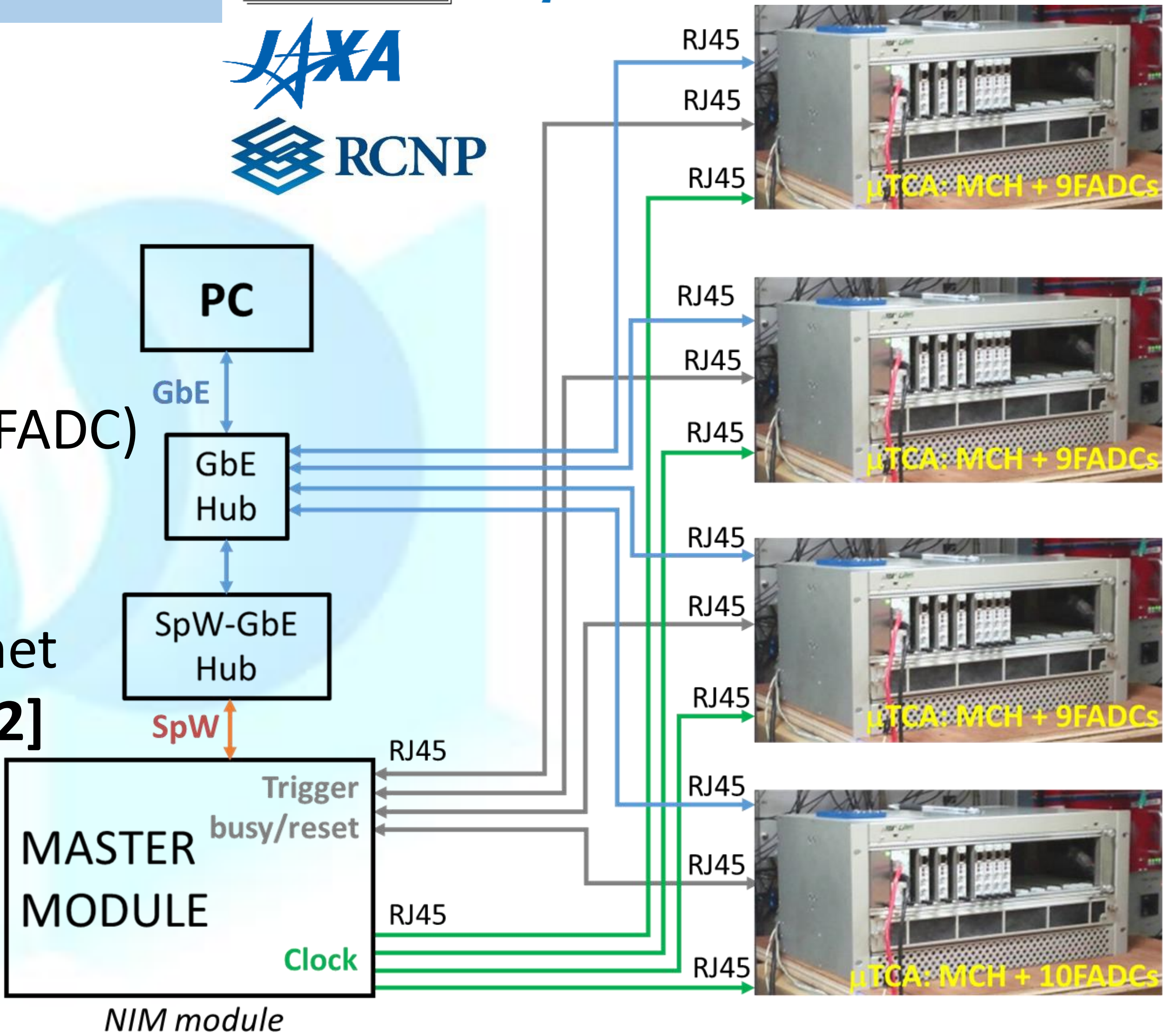


DAQ system in CANDLES

Developed by SHIMAFUJI JAXA RCNP

μTCA® DAQ system

- Using **500MHz-8bit-8buffers** FADCs
- Record ~9μsec waveform:
  - ➢First 768 ns, record 2ns/sample
  - ➢Latter sum every 64ns
- 74 FADC channels: divided in 4 crates
- Each crate: 1 MCH + 9or10 FADCs (2Chs/FADC)
- Master Module: synchronize modules
- Main trigger: CaF_2-like events **[1]**
- PC ↔ FADC: SpaceWire ↔ GigabitEthernet
- Software framework: DAQ-Middleware **[2]**



DAQ performance in daily data taking**[3]**:

- Data size: ~50kB/event

⇒@current trigger rate of 10cps, negligible dead-time($<10^{-6}$)

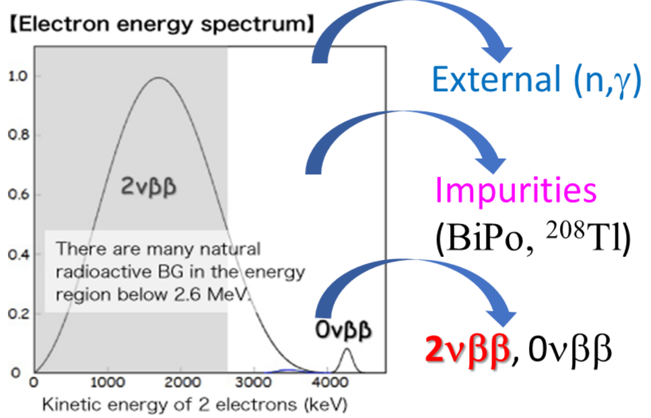
⇒Max speed 100cps (5MB/s)

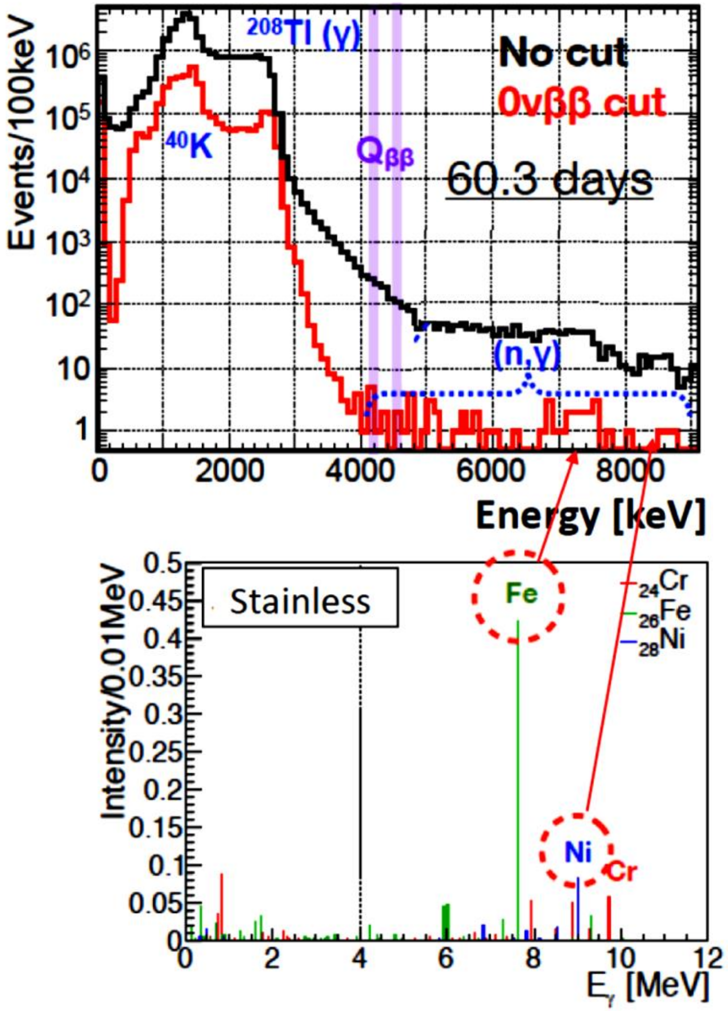
[1] T. Maeda et al. IEEE TNS 62:1128
[2] K. Suzuki et al. IEEE TNS 62:1122
[3]B. T. Khai et al. IEEE TNS 66 1174

Background in CANDLES

❖ Background at $Q_{\beta\beta}$ of ^{48}Ca:

o External (n,γ): passive shielding (Pb, B)





- Even after LS cut, there exist background in high energy region above 4MeV.
- BG spectrum has peak around 7.5MeV
- This BG seem to be produced from (n,γ) on surrounding material.

⇒ Confirm with MC and ^{252}Cf measurement

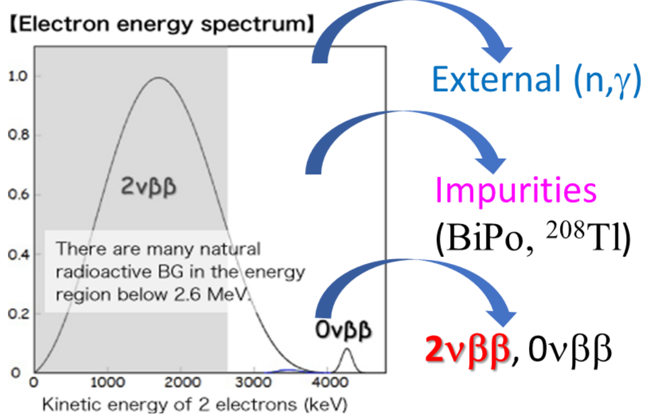
⇒ Reduce by installing passive shield (Pb,B)

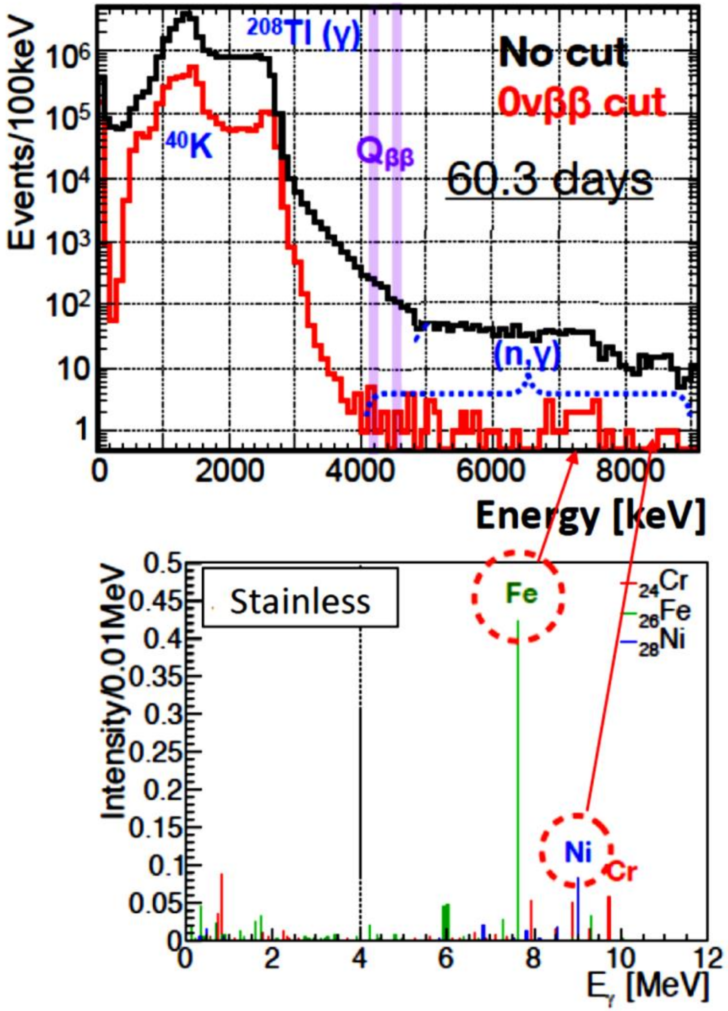
⇒ The (n,γ) background is reduced ~1/100 times after shielding

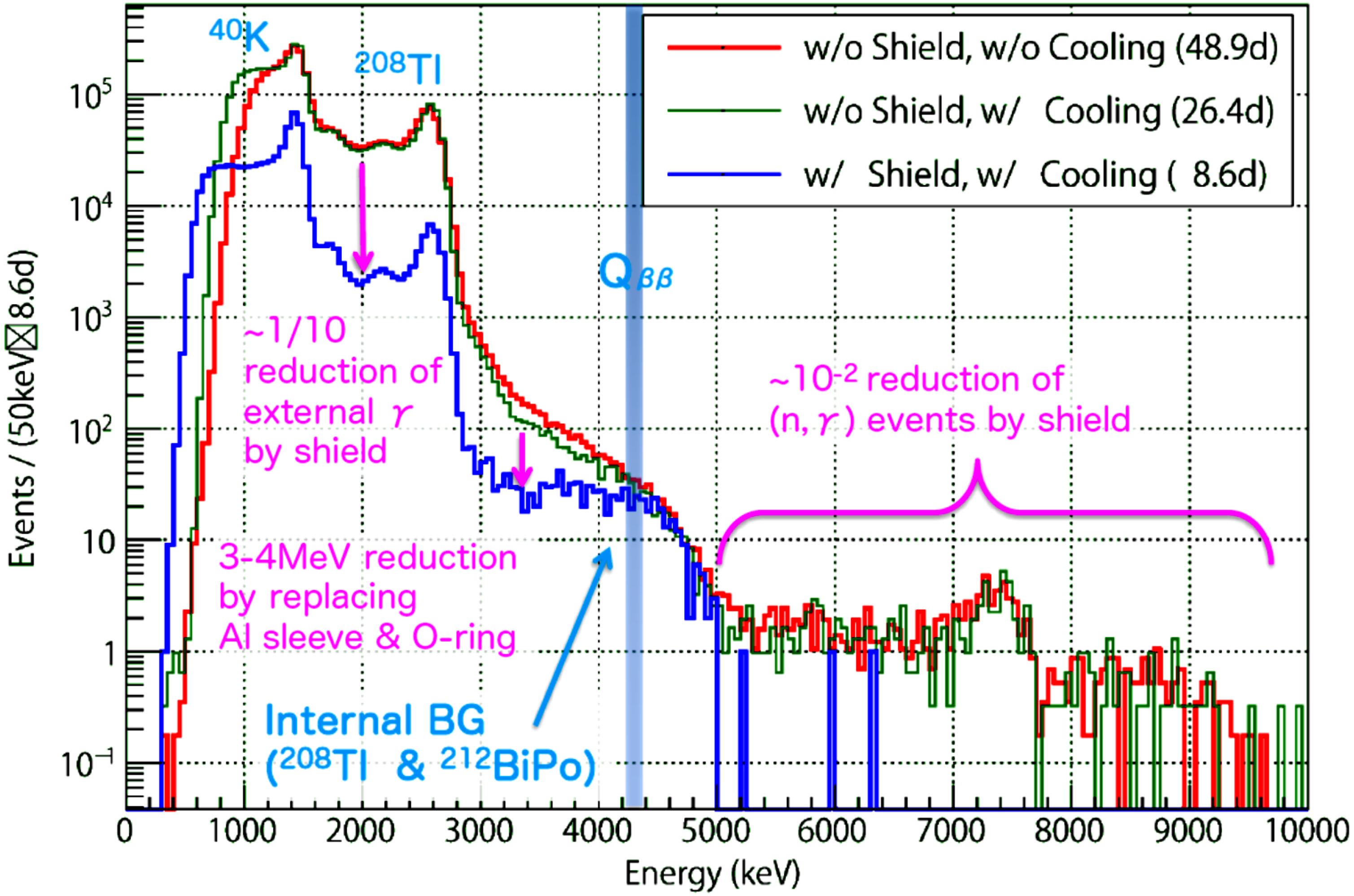
Background in CANDLES

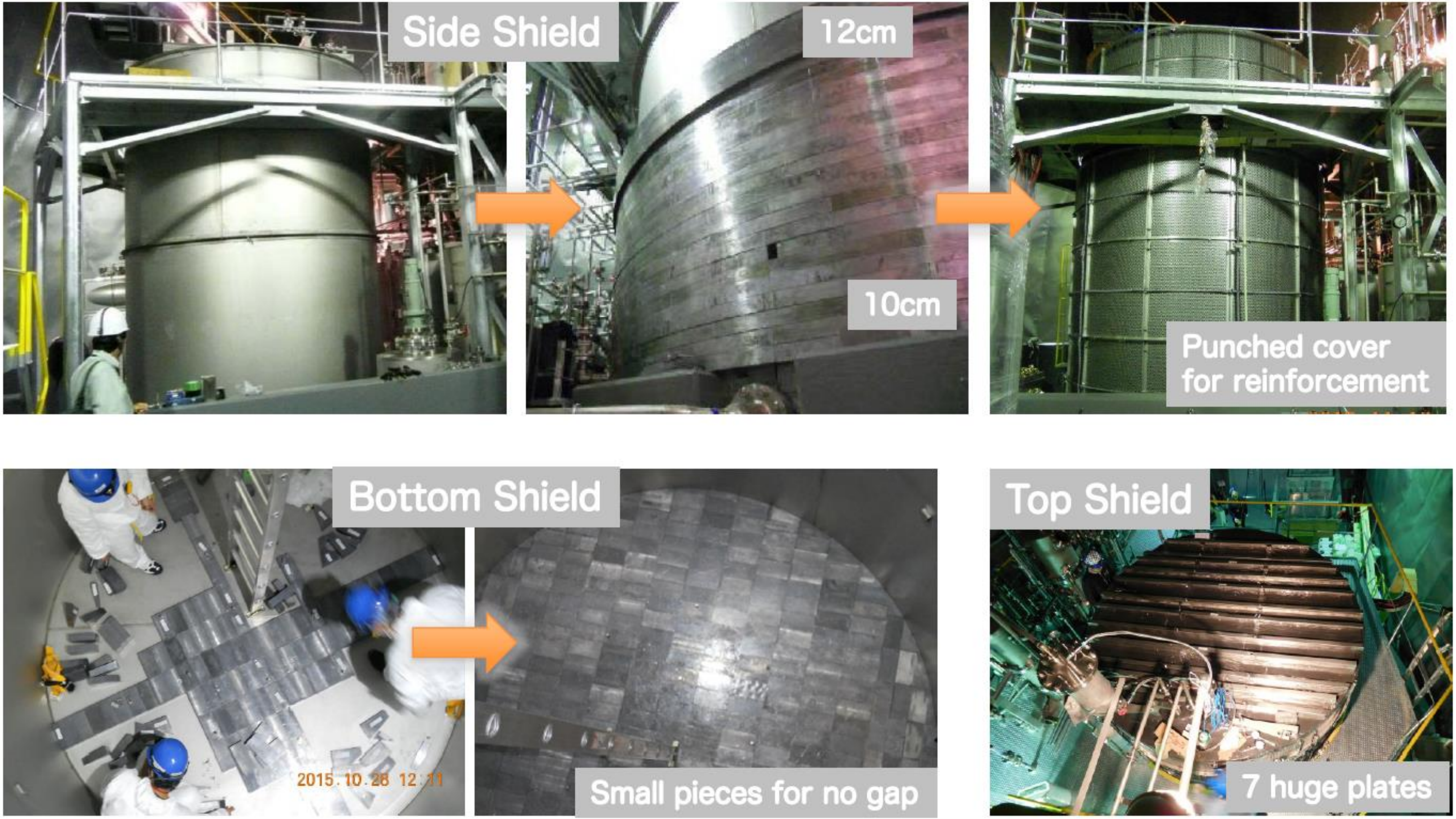
❖ Background at $Q_{\beta\beta}$ of ^{48}Ca:

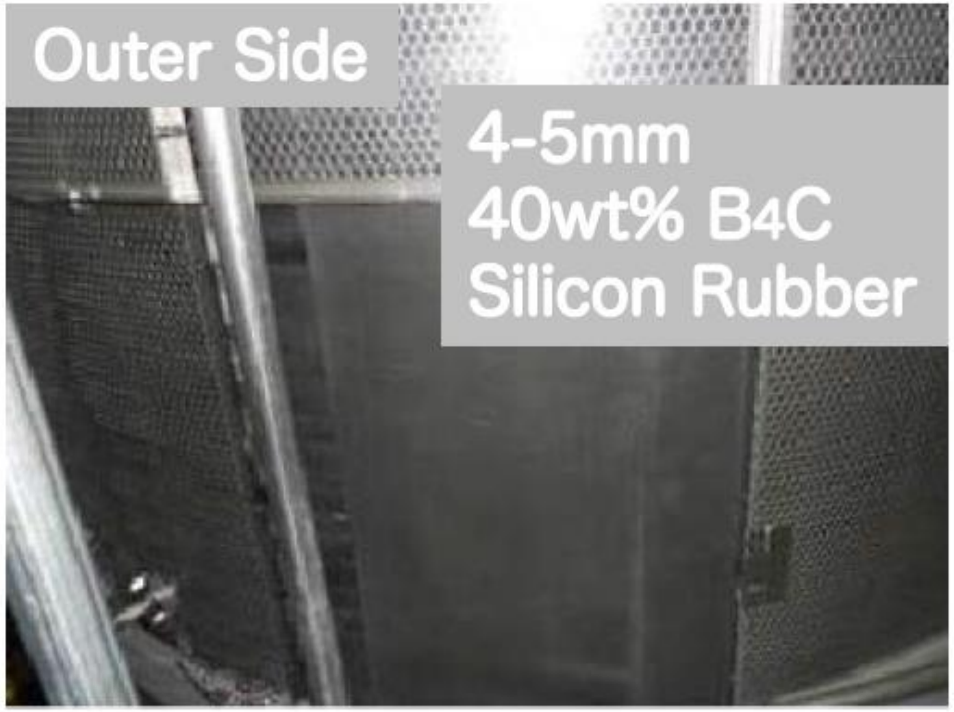
o External (n,γ): passive shielding (Pb, B)

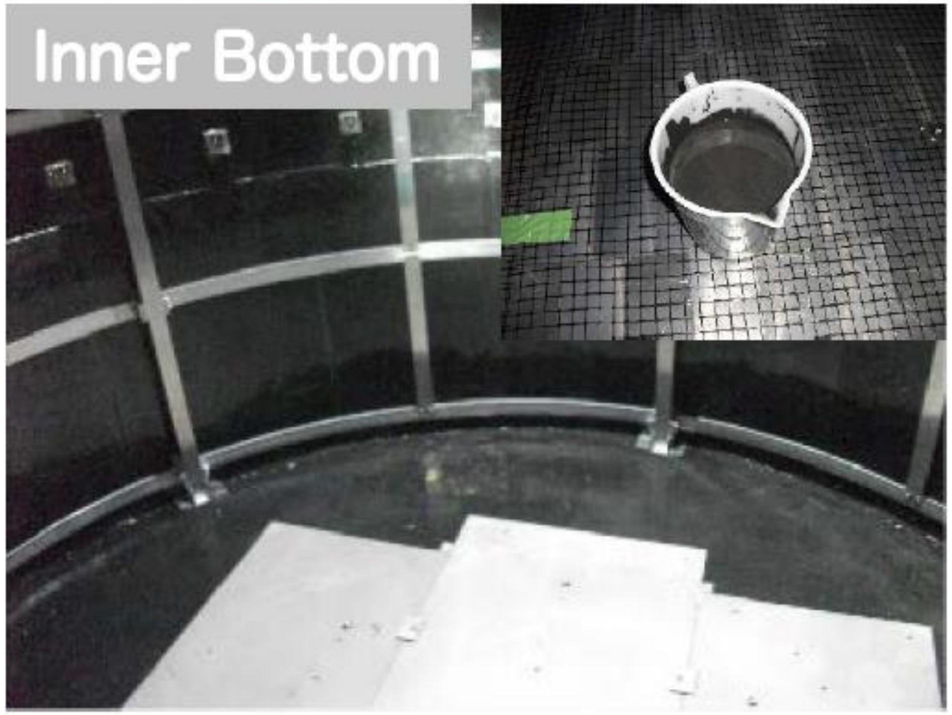







Side Shield
12cm
10cm
Punched cover
for reinforcement
Bottom Shield
2015.10.28 12:11
Small pieces for no gap
Top Shield
7 huge plates





B Shielding Construction

- Top and surrounding: silicon rubber sheet
- Inner bottom: liquid type
- Check if Pb or B contaminated in water

$\Rightarrow$ Take water sample for ICPMS examination

$\Rightarrow$ No contamination

Background in CANDLES

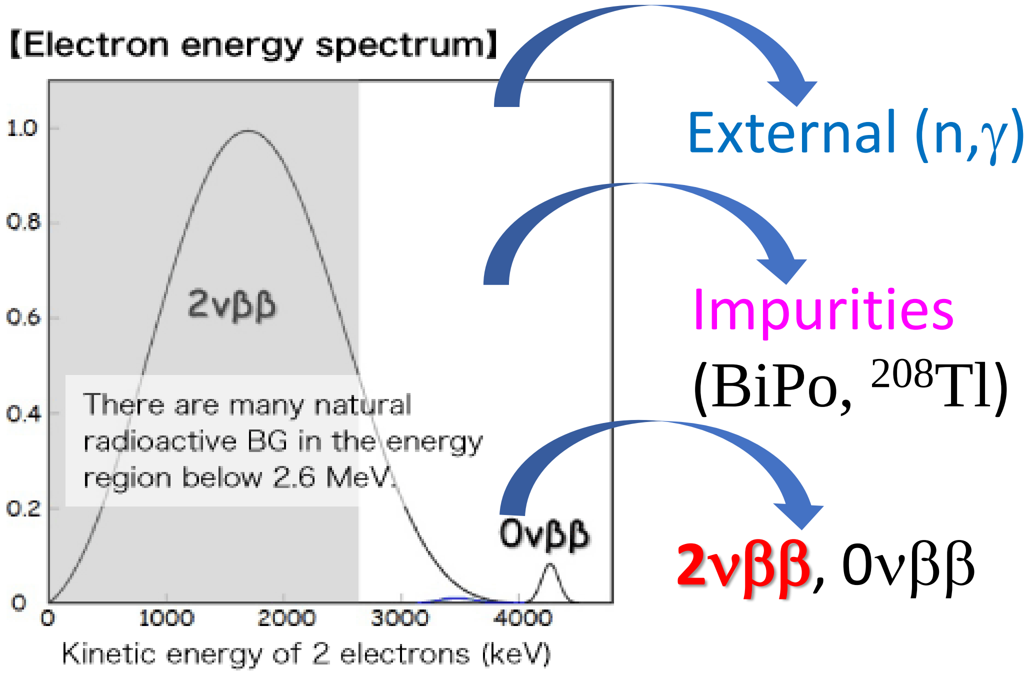
❖ Background at $Q_{\beta\beta}$ of ^{48}Ca:

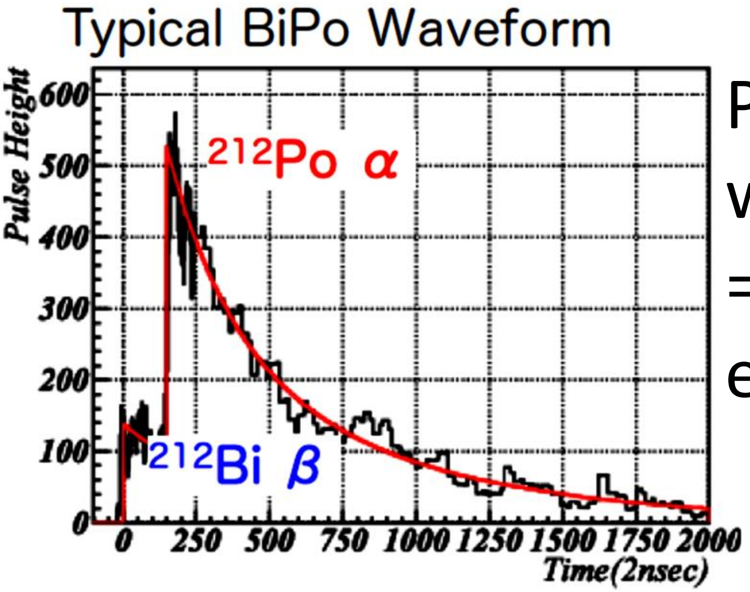
○ External (n,γ): passive shielding (Pb,B)

○ Impurities background:

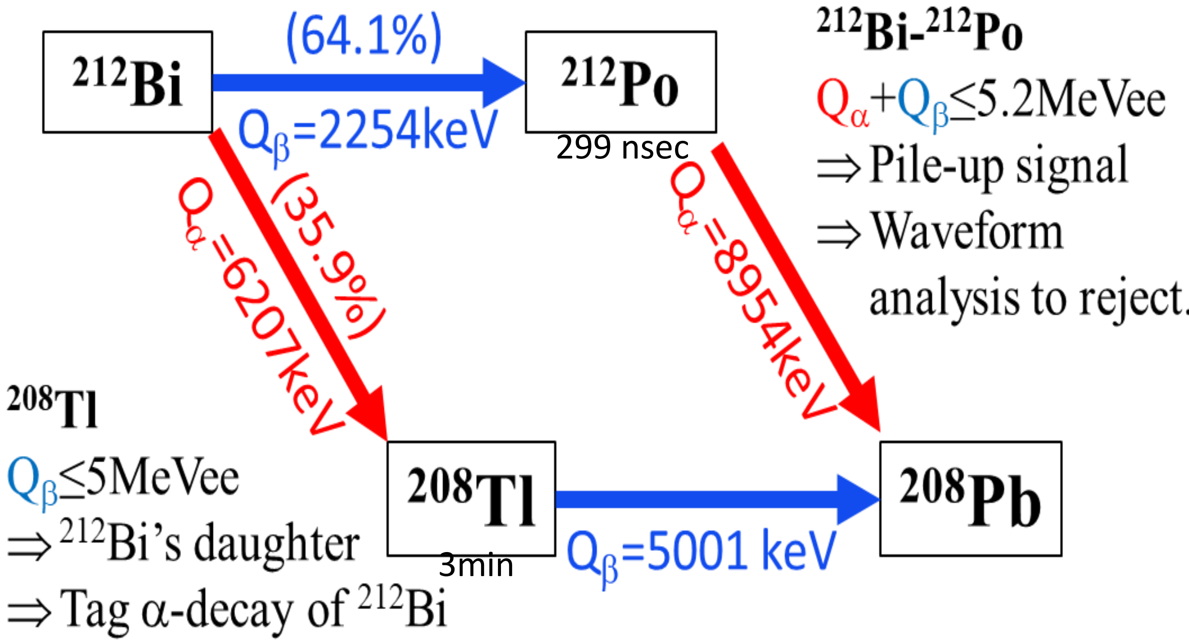
▪ $^{212}Bi^{212}Po$ sequential decay: pile-up

⇒Waveform analysis





Pileup identification with ΔT > 20ns ⇒ 99% rejection efficiency



Background in CANDLES

❖ Background at $Q_{\beta\beta}$ of ^{48}Ca:

○ External (n,γ): passive shielding (Pb,B)

○ Impurities background:

- $^{212}Bi^{212}Po$ sequential decay: pile-up

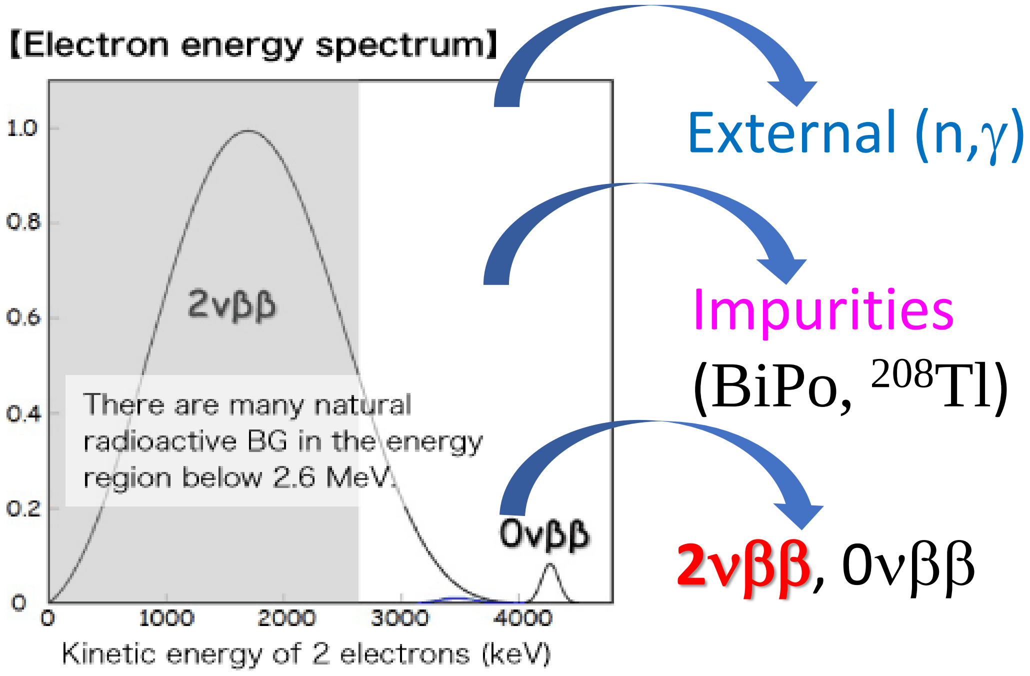
⇒Waveform analysis

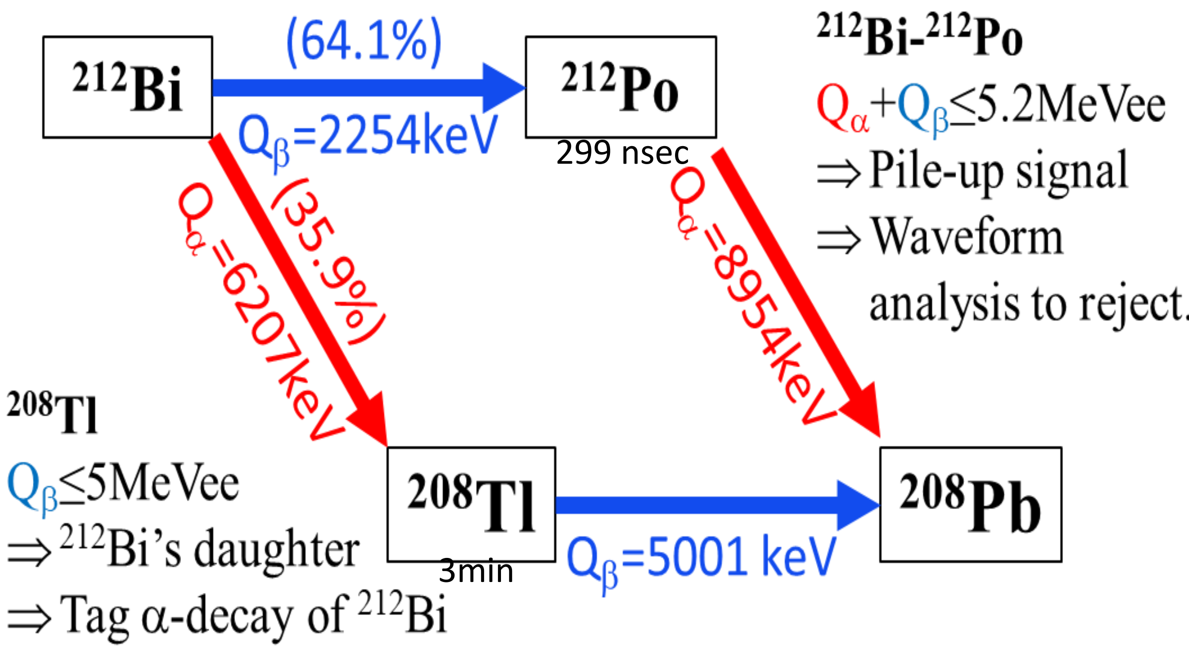
- ^{208}Tl β-decay: remove by tagging preceding α-decay

⇒ tagging efficiency (DAQ + Analysis)

⇒negligible deadtime DAQ in Physics Run

⇒Rejection efficiency: 89%





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❖Background at $Q_{\beta\beta}$ of ^{48}Ca:

○External (n,γ): passive shielding (Pb,B)

○Impurities background:

- $^{212}Bi^{212}Po$ sequential decay: pile-up

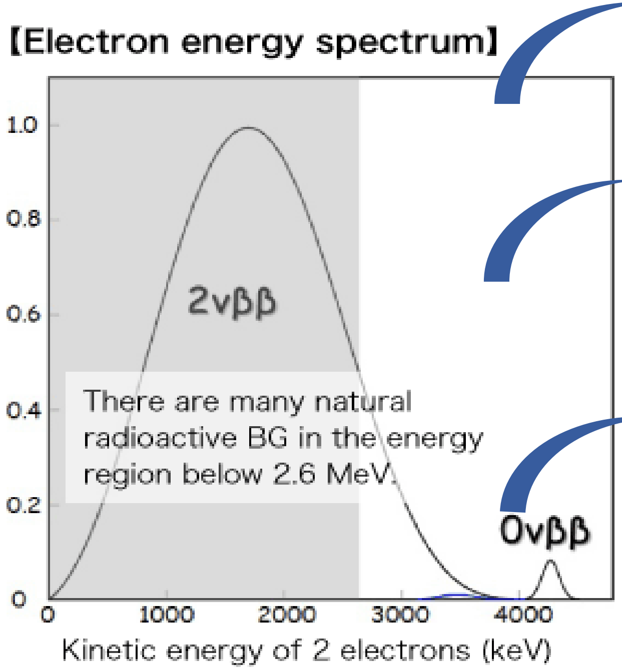
⇒Waveform analysis

- ^{208}Tl β-decay: remove by tagging preceding α-decay

⇒ tagging efficiency (DAQ + Analysis)

○2νββ: irreducible background

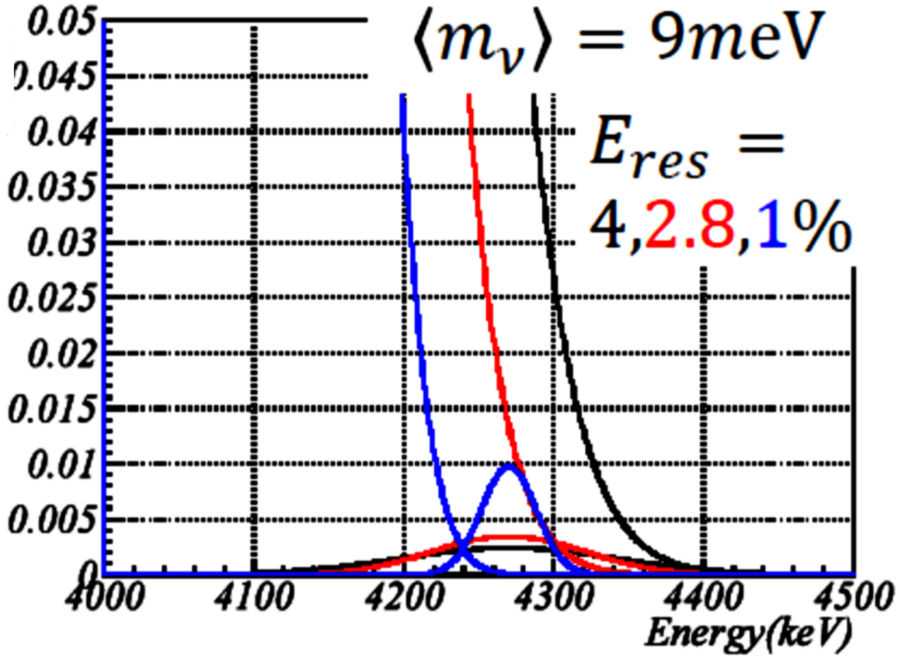
⇒improve resolution, under study



External (n,γ)

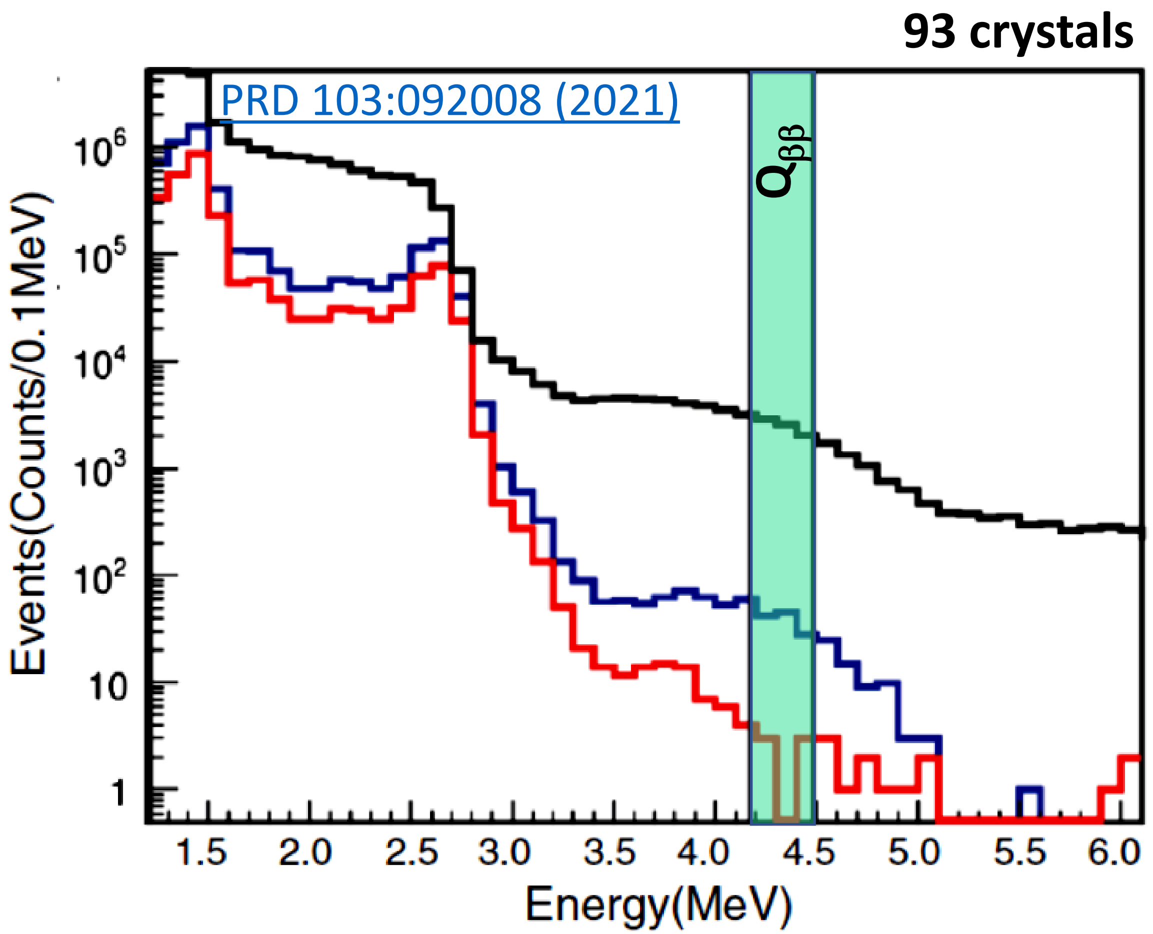
Impurities (BiPo, ^{208}Tl)

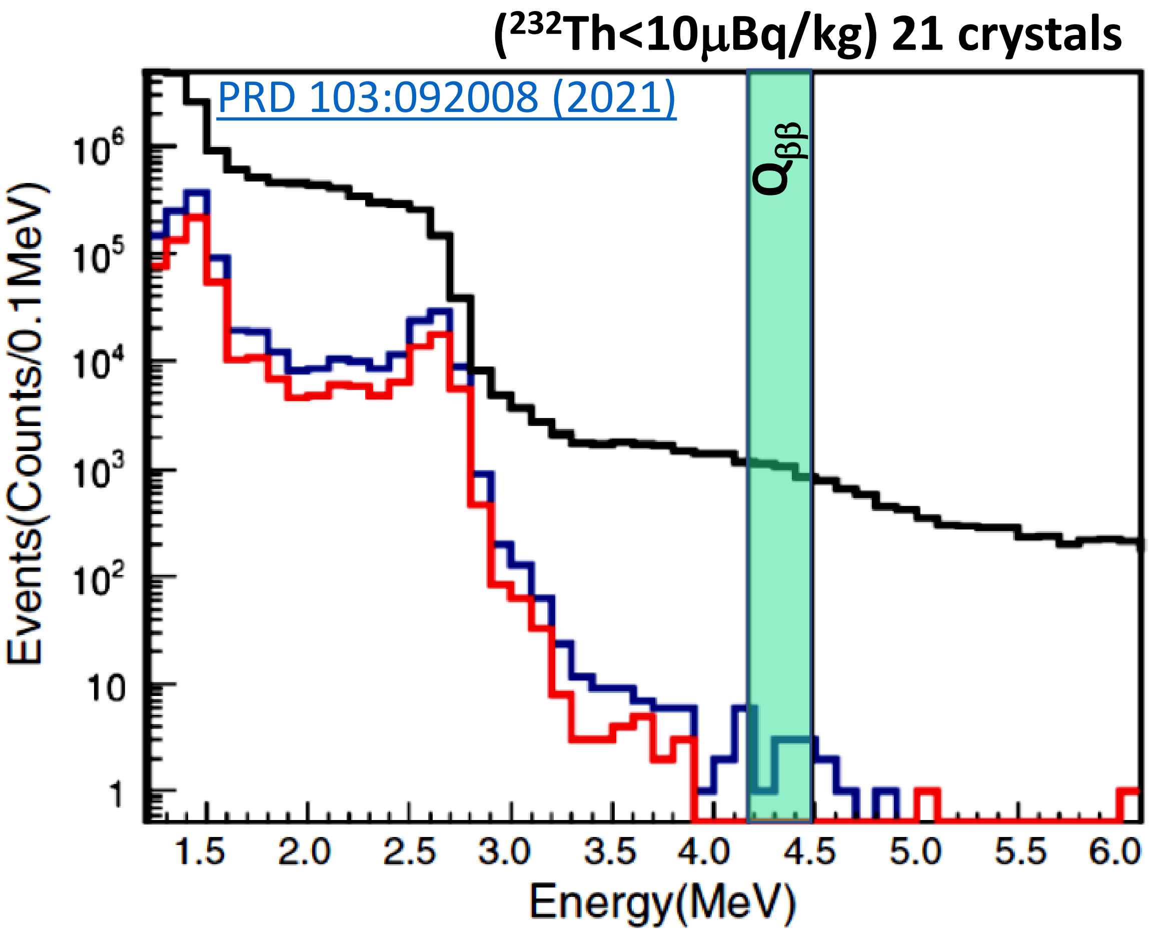
2νββ, 0νββ



Energy spectra & Event selection

Live time: 130.4 days





- Raw events
- Remove β+LS & BiPo BKG
- Remove ^{208}Tl & crystal select

With 21 high purity $^{nat.}CaF_2$ crystals:

$(T^{0\nu}_{1/2})$>5.6×10^{22}years (90% C.L.)

$\langle m_{\beta\beta}\rangle$ < 2.9 – 16 eV (90% C.L.)

Energy spectra & Event selection

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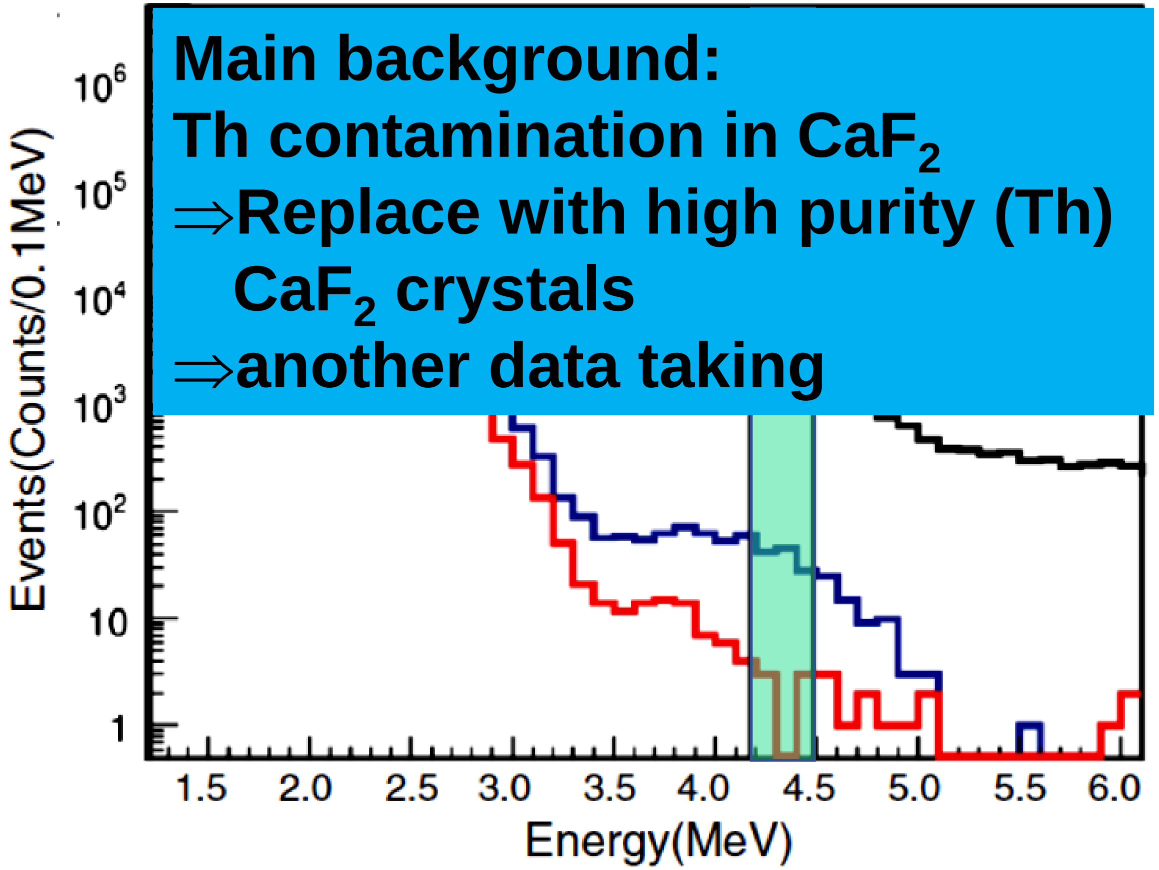

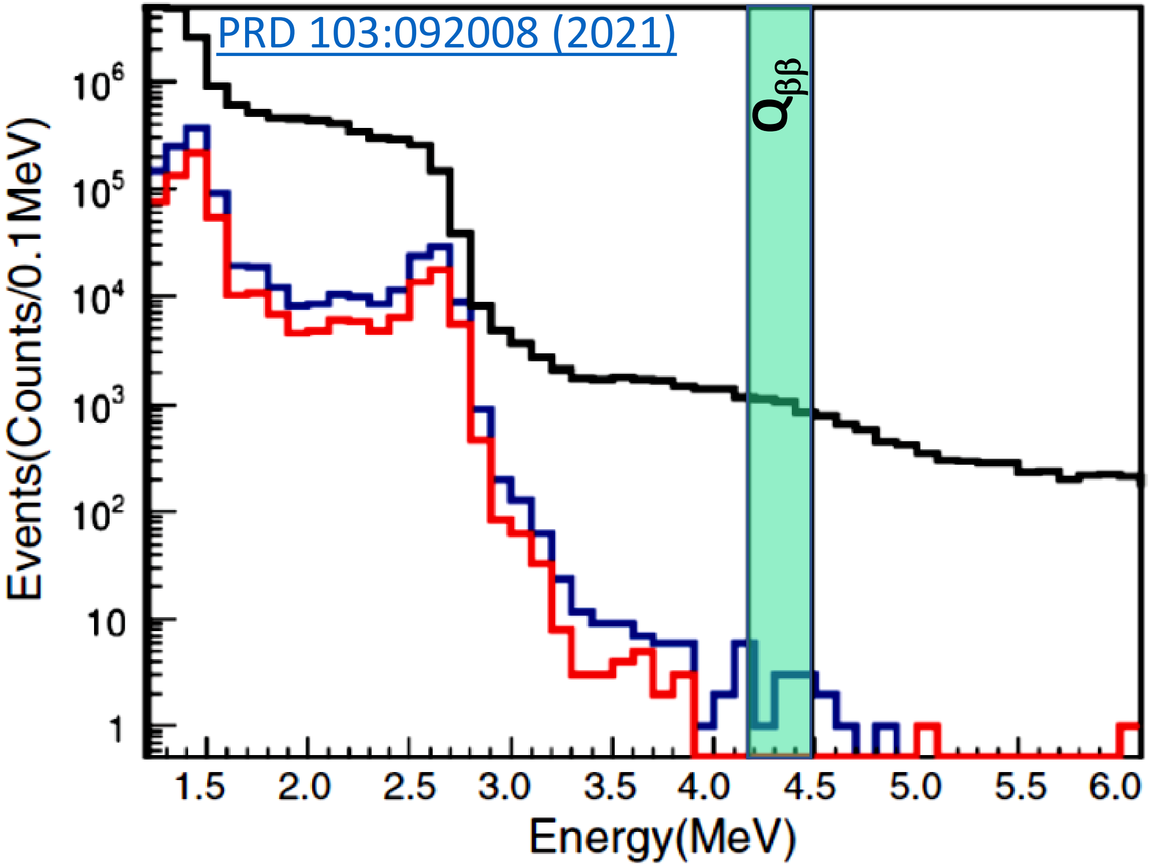

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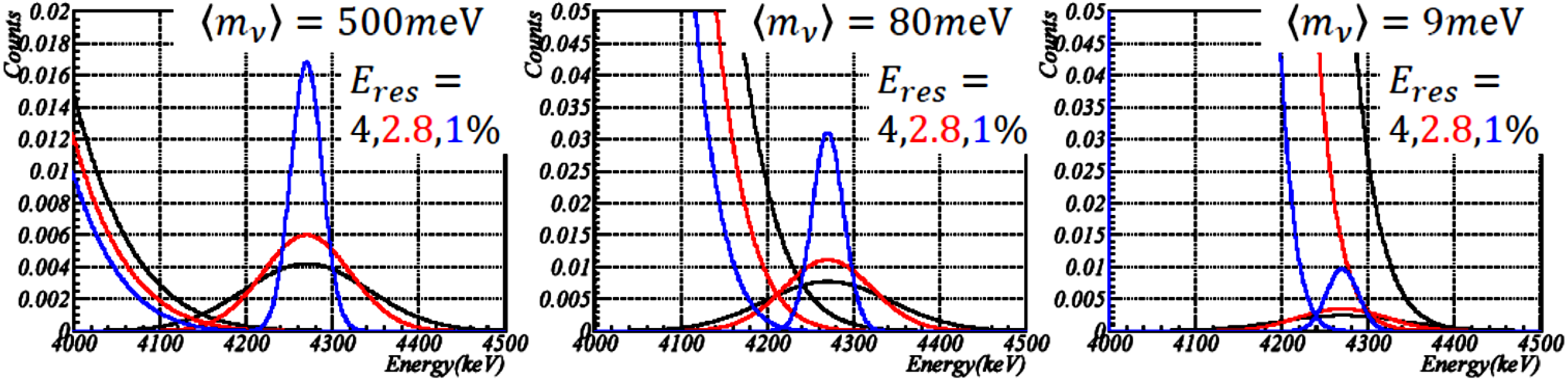
$\langle m_{\beta\beta}\rangle$ < 2.9 – 16 eV (90% C.L.)

CANDLES: current and future

	CANDLES III+	CANDLES IV	CANDLES V
Crystal CaF_2 / ^{48}Ca	0.187% (nat.) 305 kg / 0.35 kg	**2%** 2000 kg / 25 kg	**50%** 2000 kg / 610 kg
Energy Res.	6%	**2.8%** (required)	**1.0%** (required)
$<m_\nu>$ sensitivity	500 meV	**80 meV**	**9 meV**
Feature	Low BG No enrichment	Low BG 2% enrich ^{48}Ca Cooling CaF_2	Low BG 50% enrich ^{48}Ca Bolometer (**~10 mK**)



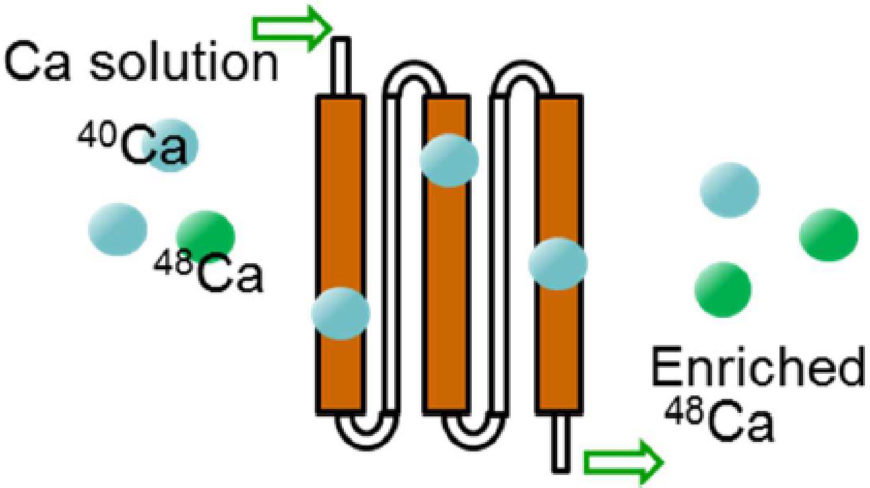
R&D for next step: Enrichment of ^{48}Ca

- ^{48}Ca
  - Natural abundance is low： 0.19%

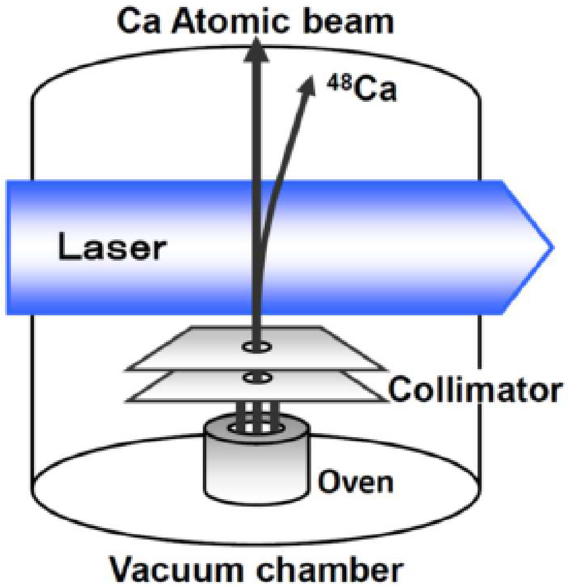
  ⇒ We can improve the detector sensitivity by enrichment
  - But enrichment of ^{48}Ca is difficult
- New enrichment techniques
  - Crown-ether, laser enrichment, Electrophoresis

  ⇒ Aim for: massive & cost-effective production

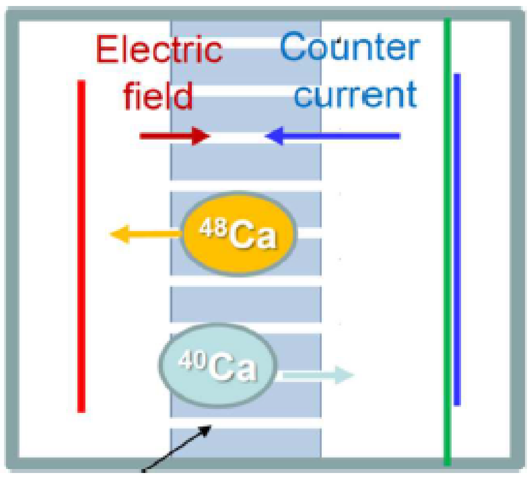
Chemical enrichment by crown-ether



Laser enrichment



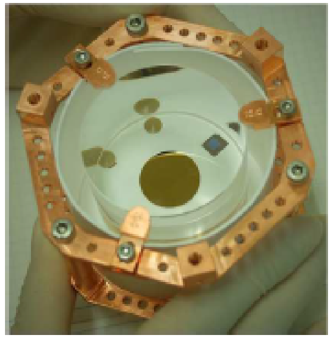
Electrophoresis

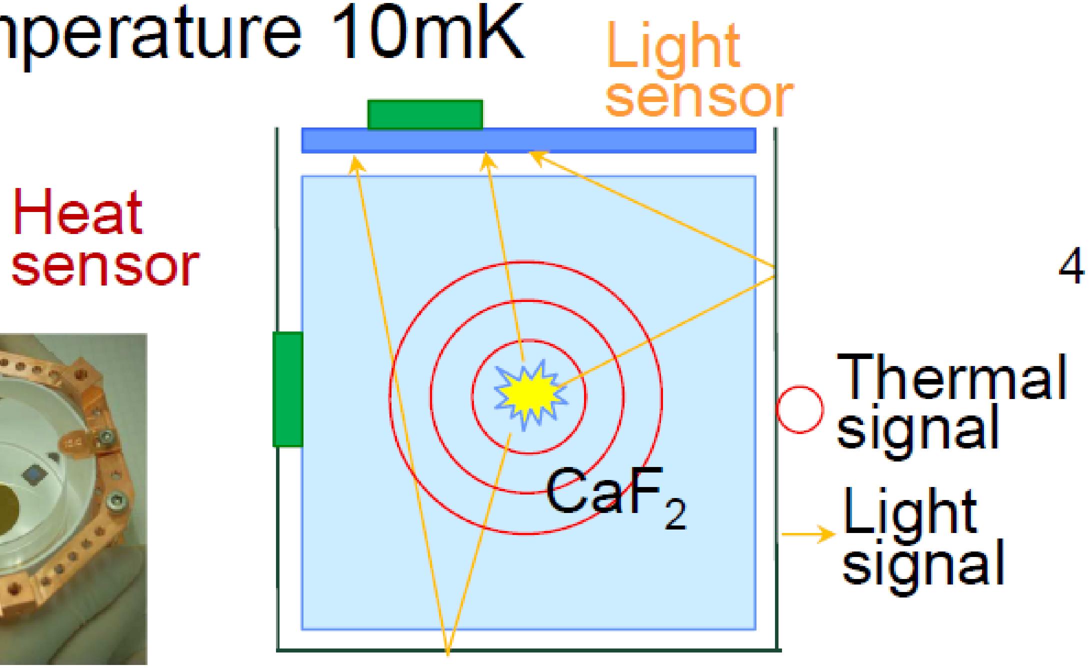


R&D for next step: Scintillating Bolometer

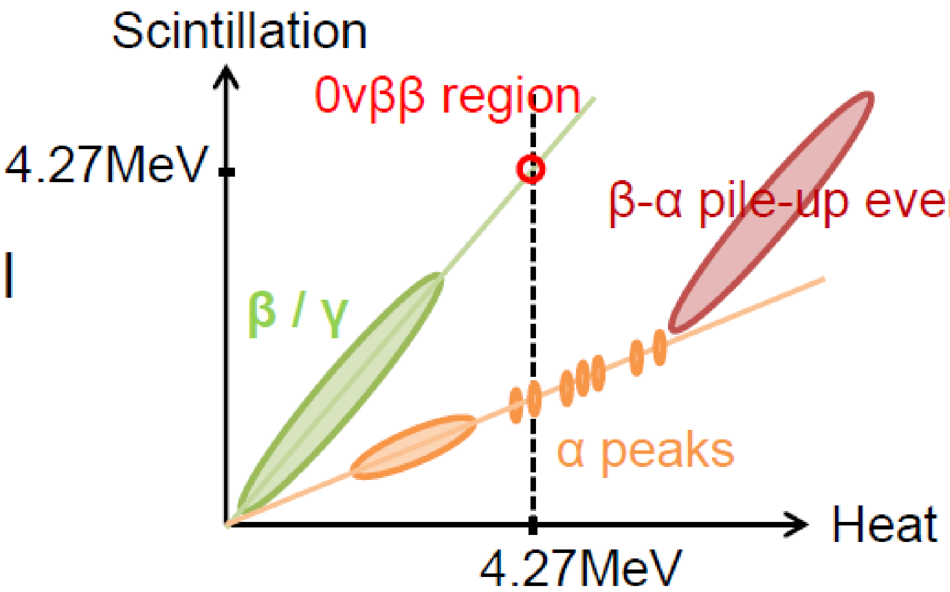
- Expected BG: 2νββ events, α-rays
- bolometer: good energy resolution (COURE, AMORE)
  - For reduction of BG affects from 2νββ events
- Scintillating bolometer: good particle identification ability
  - For reduction of BG affects from α-ray

Scintillating bolometer at low temperature 10mK





Particle identification by scintillating bolometer



SUMMARY

- **CANDLES**:
  - searching for $0\nu\beta\beta$ of ^{48}Ca ($Q_{\beta\beta}$=4.27MeV) at Kamioka
  - Low background technique is very important
  - Obtained $T_{1/2}^{0\nu}$ limit 5.6×10^{22}years, LT=130.4 days
  - This is comparable with most stringent limit of $T_{1/2}^{0\nu}$ by obtained by ELEGANT VI (5.8×10^{22}years, LT>2years)
- **Future**:
  - High purity CaF_2 crystals
  - Enrichment of ^{48}Ca: $^{48}CaF_2$ crystals
  - CaF_2 scintillating bolometer

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer

35 members, 7 institutes
6 members, 2 institutes

Institute for Basic Science
KRISS Korea Research Institute of Standards and Science

← More info

Some publications

[0νββ] PRD 103:092008
[0νββ] PRC 78:058501
[0νββ] Nucl. Phys. A 730:215

[DAQ] IEEE TNS 66:1174
[DAQ] IEEE TNS 62:1122
[DAQ] IEEE TNS 62:1128

[Detector] NIMA 986:164727
[Detector] Astropart. Phys.100:54
[Detector] NIMA 705:1
[Detector] NIMA 601:282
[Detector] IEEE TNS 68:368

[Enrich] J. Nucl. Sci. Tech. 55:1473
[Enrich] Austin Chromatogr. 3:1040
[Enrich] J. Chroma. 1415:67
[Enrich] PTEP 2015:053C03
[Enrich] PTEP 2015:033D03

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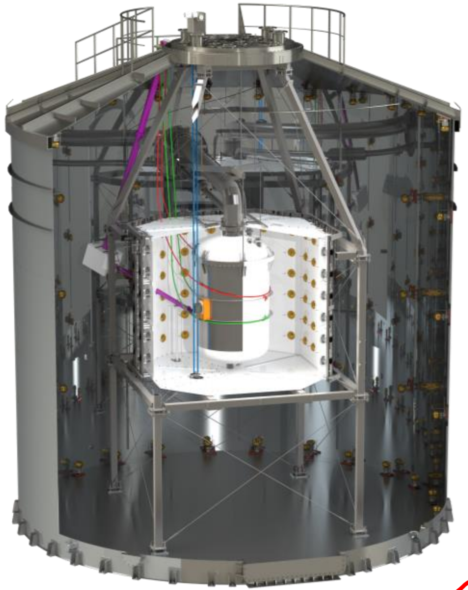
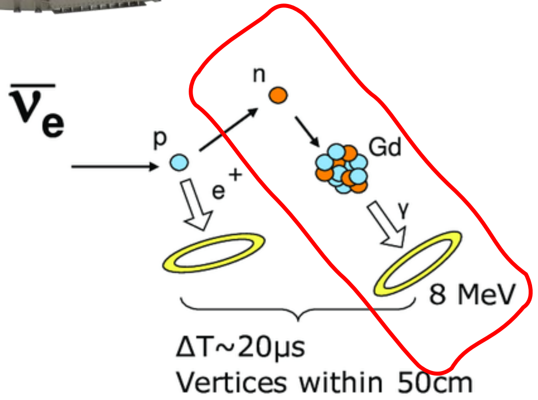
CANDLES, a journey with great people and a lot of fun.

XENON



NEW JOURNEY

KAVLI IPMU



Super-K and EGADS technology

Gd Water Cherenkov for neutrino study

First time used as neutron Veto !!!