CANDLES for the study of double beta decay of ^{48}Ca and its enrichment

T. Kishimoto

RCNP

Osaka Univ.

Present to near future of RCNP

- Cyclotron accelerator facility: Hatanaka
- LEPS facility: hadron physics: Nakano

- Research center for subatomic science (present)
  - How matter (mass) was synthesized
    - LEPS2: Hadron physics (GeV photon)
    - MUSIC: Lepton Flavor mixing (muon)
    - CANDLES: Double beta decay (Lepton number violation)
  - Collaboration with J-PARC, RIKEN, Tohoku,…, China and other countries. Asian accelerator science school

- Higher Intensity for cyclotron facility (near future)
  - Neutron EDM, Muon, BNCT

Baryon density in our Universe

Candles

- Big bang nucleosynthesis
  - ^{4}He, D, ^{3}He, ^{7}Li
  - Baryon density

$$\rho_B \sim 10^{-10}\,\rho_\gamma$$

If particle number is conserved,

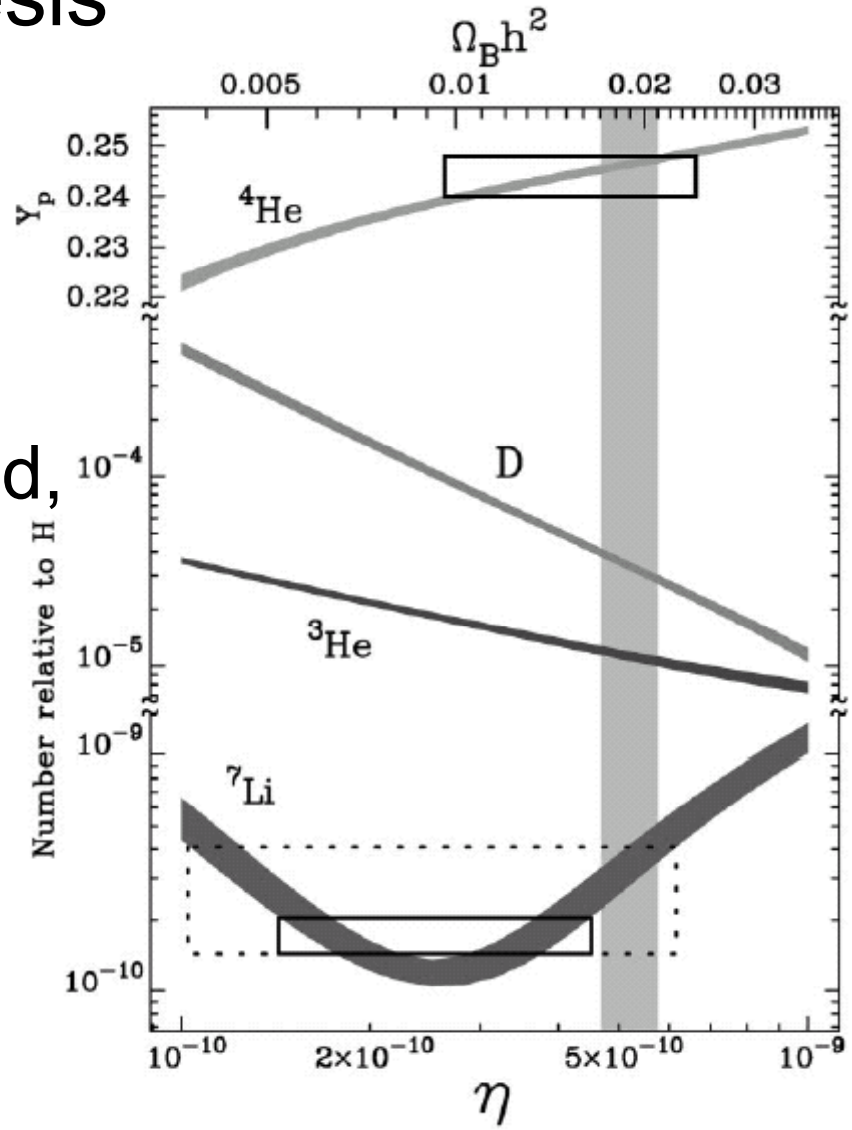
Particle : 1,000,000,001

Anti-particle : 1,000,000,000

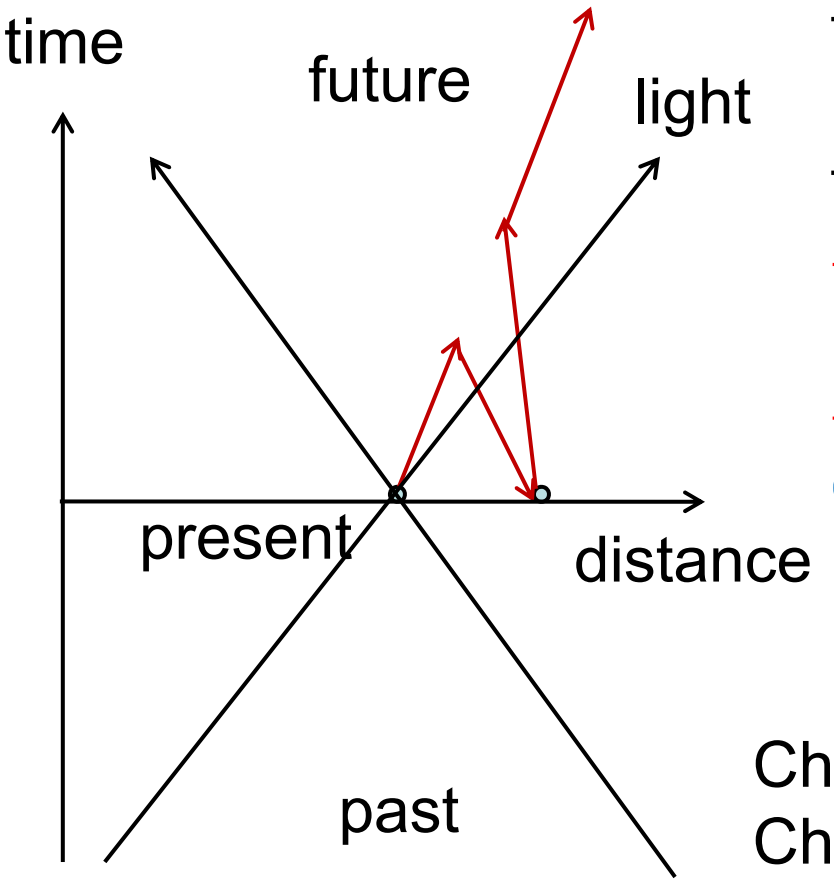
Matter dominated Univ.

→~~CP~~ + ~~particle #~~

→Double Deta decay



Relativity + uncertainty →anti-particle



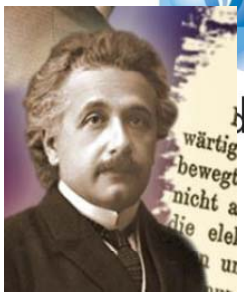
・no information is faster than speed of light

・interact with any space-time

→particle that travels backward in time

→antiparticle

Carries inverse quantity (charge spin(chirality))



Dirac equation

Feynman

Charge: conserved

Chirality: violated by mass

particle ⇔ antiparticle

Majorana particle

ν has to be a Majorana particle

Candles

- Mass term (Dirac)

$$\mathcal{L}_D = -m_D \overline{\nu_R^0} \nu_L^0 + \text{ h. c.}$$

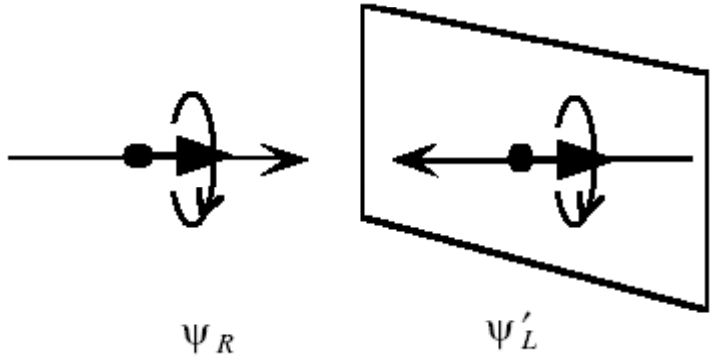
- Mass term (Majorana)

$$\mathcal{L}_{m_L} = -\frac{m_L}{2} \overline{(\nu_L^0)^c} \nu_L^0 + \text{ h. c.}$$

  - Only Left (right) handed mass term can be made
  - Left and right can have different mass
  - We know only left-handed neutrino
  - Heavy right-handed ν （see-saw mechanism）
  - Violates lepton number

Chirality flip（relativity）

Left handed → right handed (anti-particle)



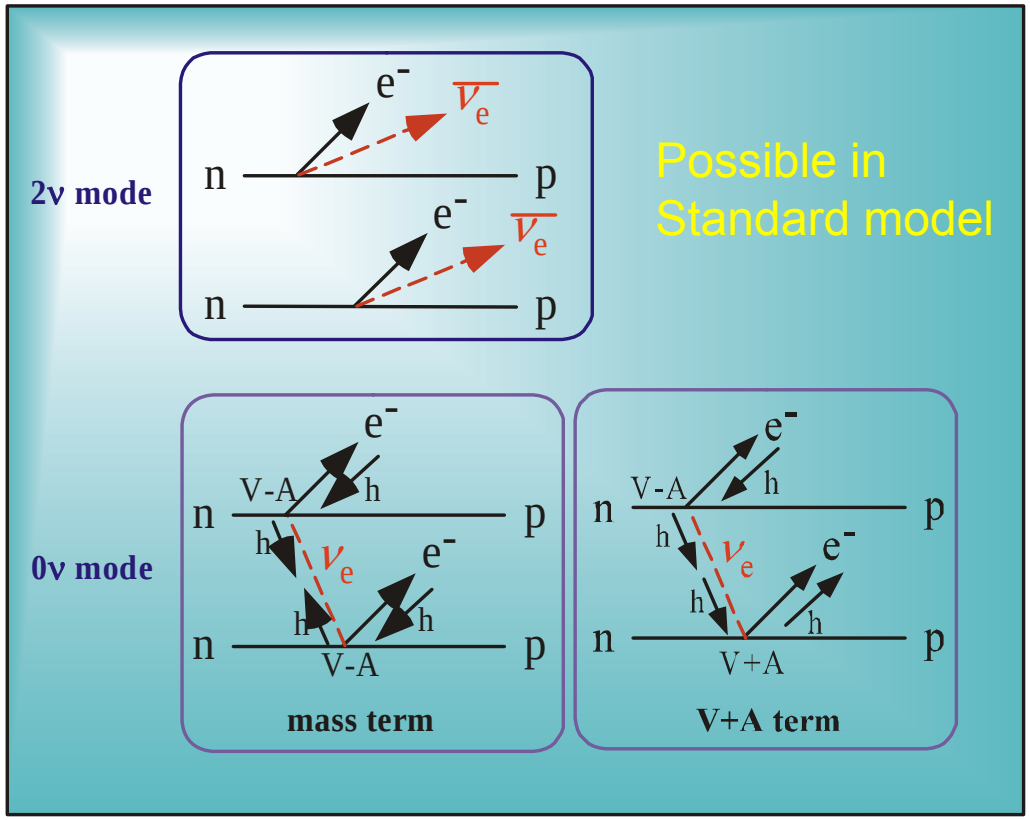
Leptogenesis

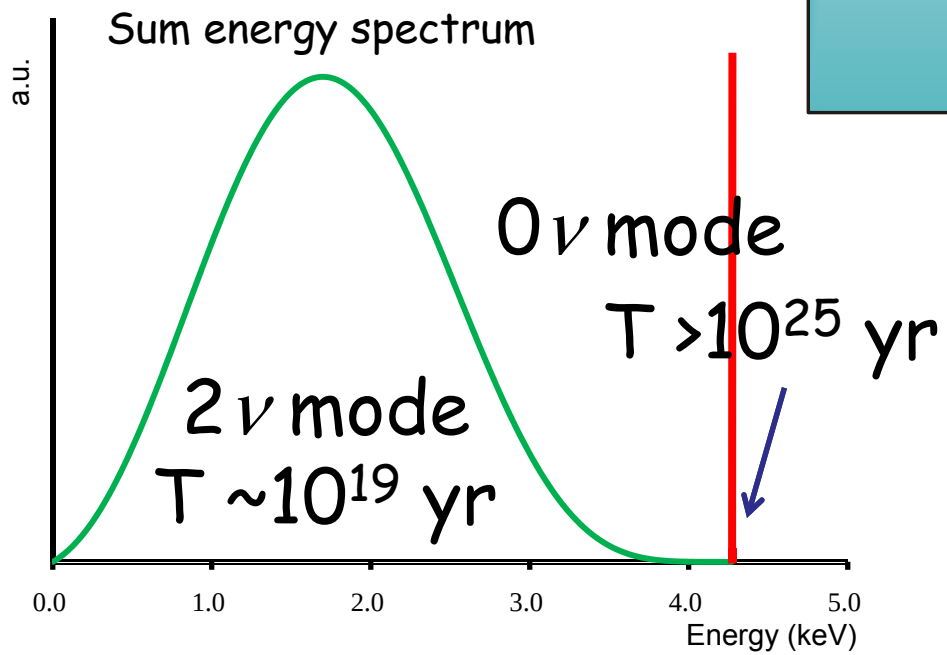
0ν2β decay

Majorana particle

particle⇔anti-particle

- possible only for ν
- matter dominated universe





$$|T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)|^{-1}$$

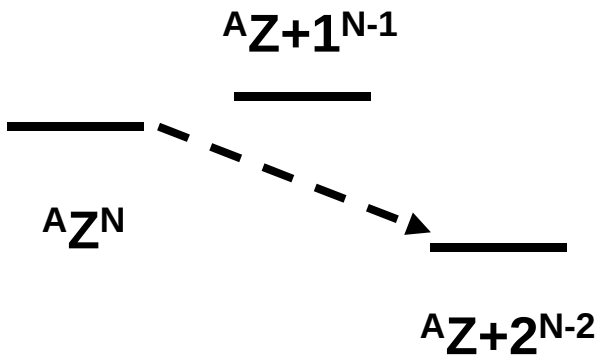
$$= G^{0\nu} \, |M^{0\nu}_{NM}|^2 \, \langle m_\nu \rangle^2 + ...$$

Phase volume | Nuclear matrix element | Effective mass

Double beta decay nuclei

Candles

- Nuclei
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo,
  - ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd
  - Positron emitter
- Ultra rare process
  - $10^{20\sim25}$ yr
- Huge natural background sources
  - High sensitive detector
  - Low background circumstance⇔Underground lab.



So many experiments and laboratories in the world

Why ^{48}Ca

Candles

- Highest Q value (4.27 MeV, ^{150}Nd: 3.3 MeV)
  - Large PV, Little BG（γ: 2.6 MeV, β: 3.3 MeV）
- Small natural abundance: 0.187%
  - Isotope separation → expensive (no Gas)
- Next generation
  - $M_\nu \sim T^{-1/2} \sim$ Det. Mass^{-2} (no BG)

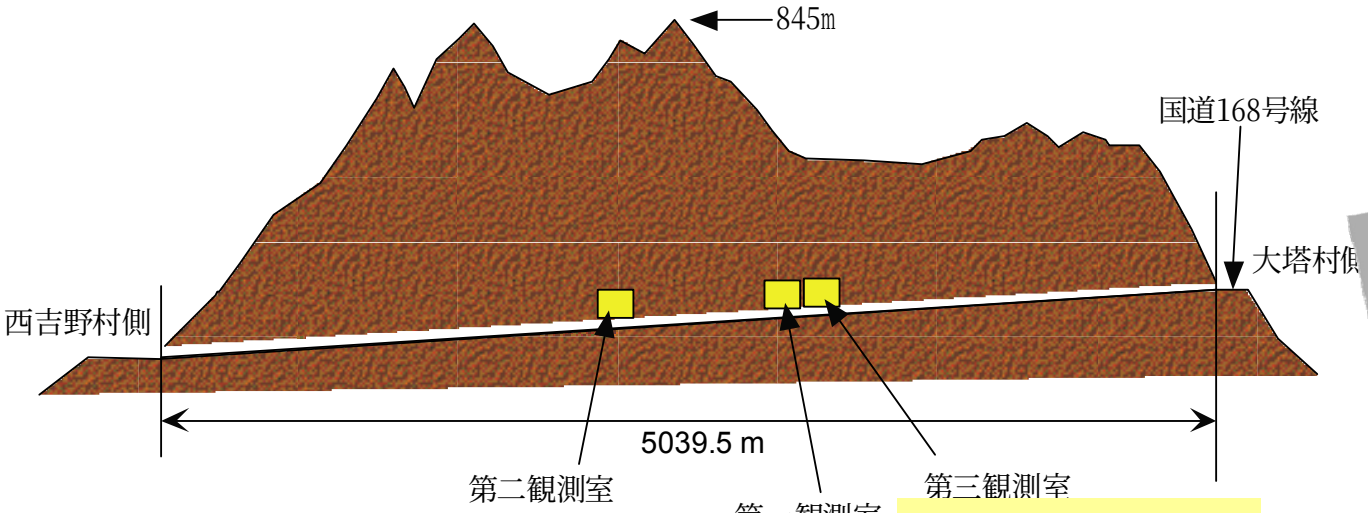
    $\sim$ Det. Mass^{-4}（BG limited）
  - ^{48}Ca (no BG so far)
- Reliable nuclear matrix element ⇒ $\langle m_\nu \rangle$
- If we want to sense normal hierarchy region, only ^{48}Ca + enrichment have a chance.

Oto Cosmo Observatory

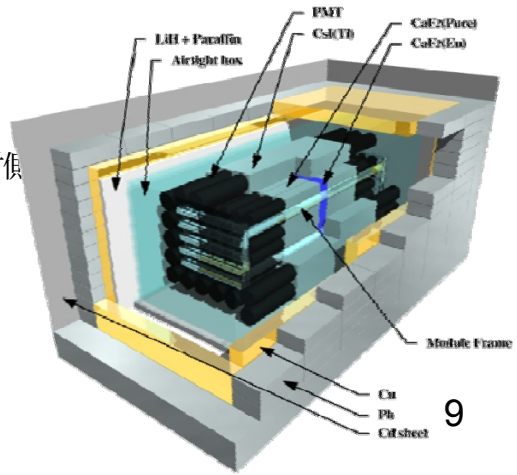
A tunnel constructed for a railroad but never used. It is 60km south from Osaka

$$T_{1/2}^{0\nu\beta\beta} > 1.4\times10^{22}\ \text{year}\quad (90\,\%\ \text{C.L.})$$
$$\langle m_\nu \rangle < 7.2 \sim 44.7\ \text{eV}\quad (90\,\%\ \text{C.L.})$$

NPA 730 ’04, 215



ELEGANT VI



^{48}Ca double beta decay by ELEGANT VI @ Oto

NPA 730 ’04, 215

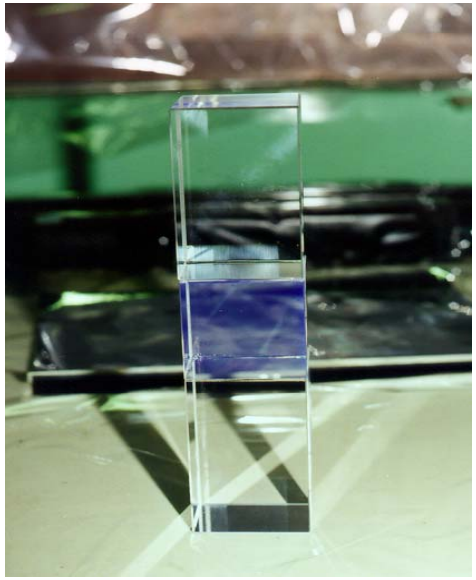
PRC78 058501(‘08)

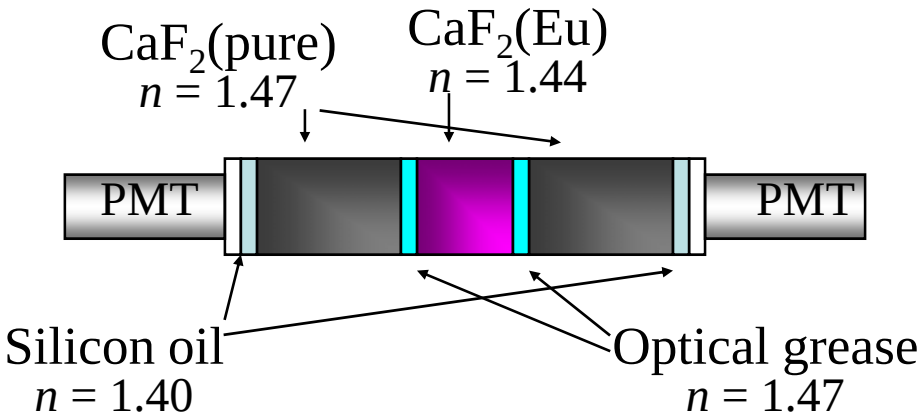
Candles

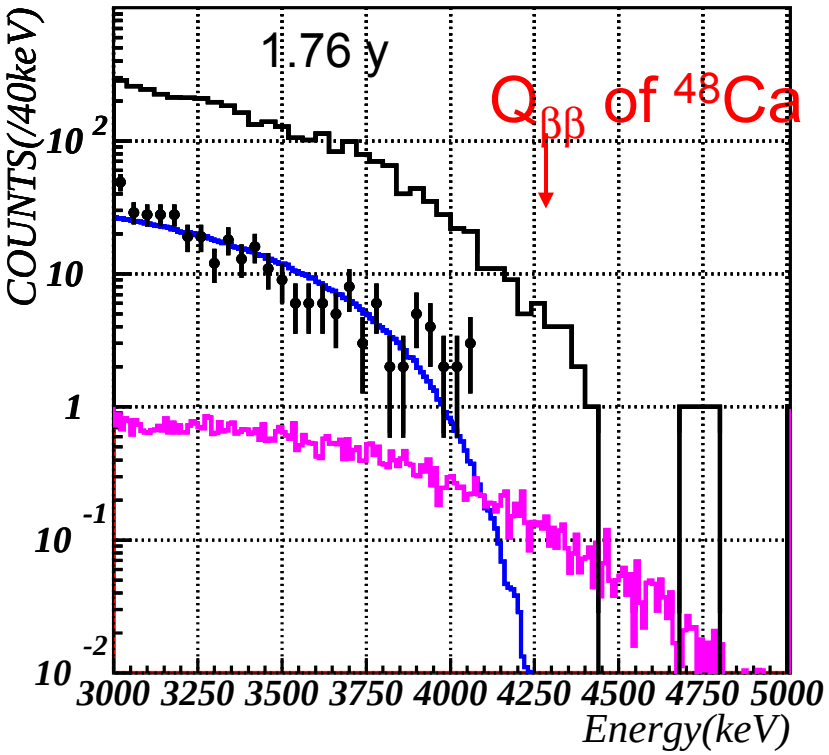
CaF_2(pure)

CaF_2(Eu)

CaF_2(pure)







$$T_{1/2}^{0\nu\beta\beta} > 5.8\times10^{22}\ \text{year}\quad (90\,\%\ \text{C.L.})$$

$$\langle m_\nu \rangle < 3.5 \sim 22\ \text{eV}\quad (90\,\%\ \text{C.L.})$$

Not limited by backgrounds

But only 6.4g of ^{48}Ca

How to sense m_ν=1~10^{-2}eV

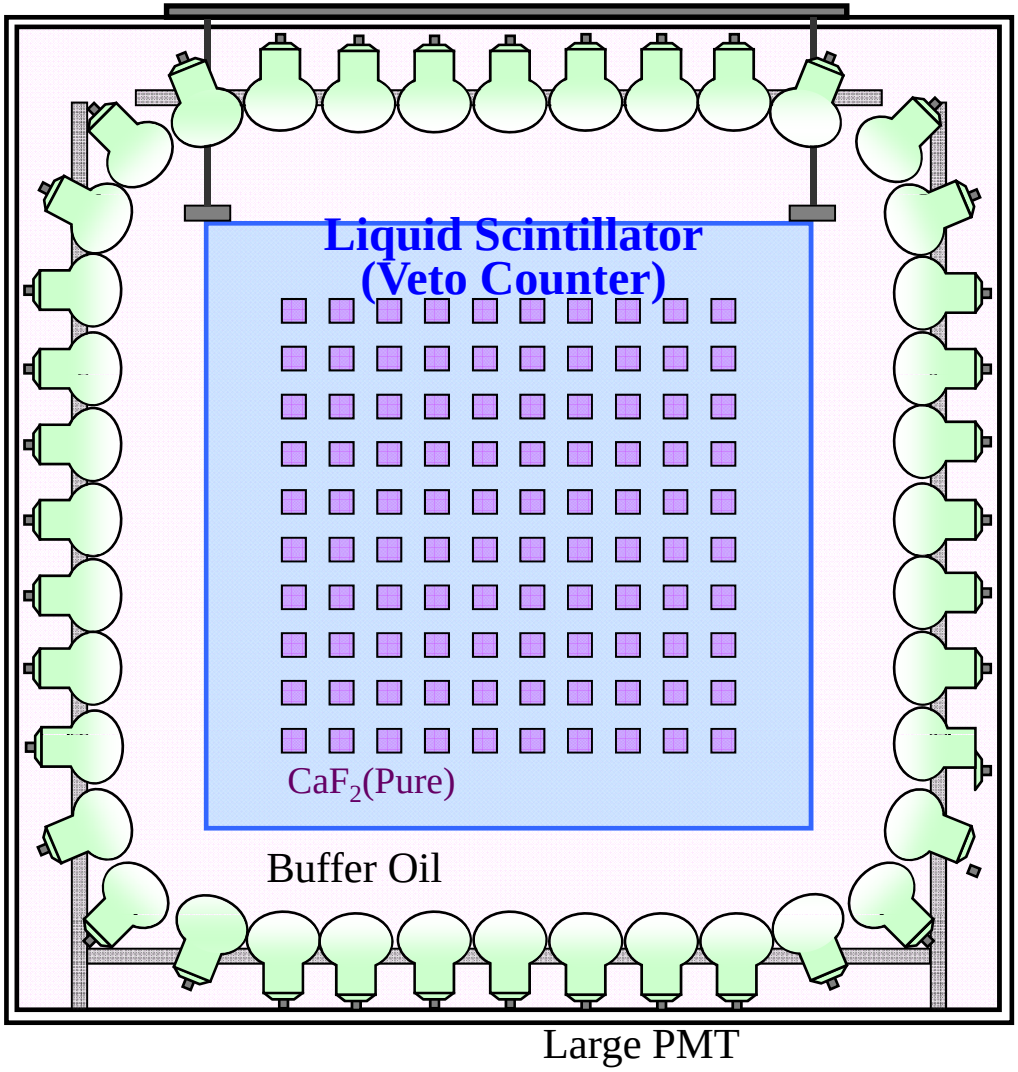
Candles

- Big detector
  - Huge amount of materials
- Low radioactive background
  - Active shield
  - Passive shield
  - Low background material
  - BG rejection by signal processing
- High resolution
  - Backgrounds from $2\nu\beta\beta$ decay

- **CANDLES** is our solution

CANDLES

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

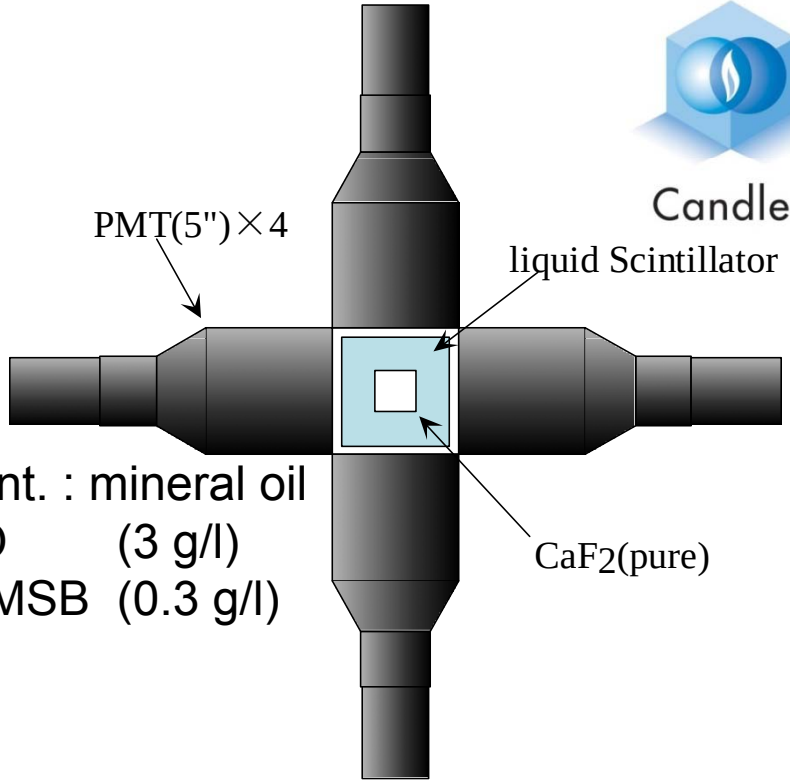


- **CaF_2(Pure)**
  200kg, 300kg, 3t, enrichment
  ^{48}Ca ($Q_{\beta\beta}$=4.27MeV)
- **Liquid Scintillator**
  Wave Length Shifter
  4 π Active Shield
  Passive shield
- **Photomultiplier**
  energy resolution

CANDLES I

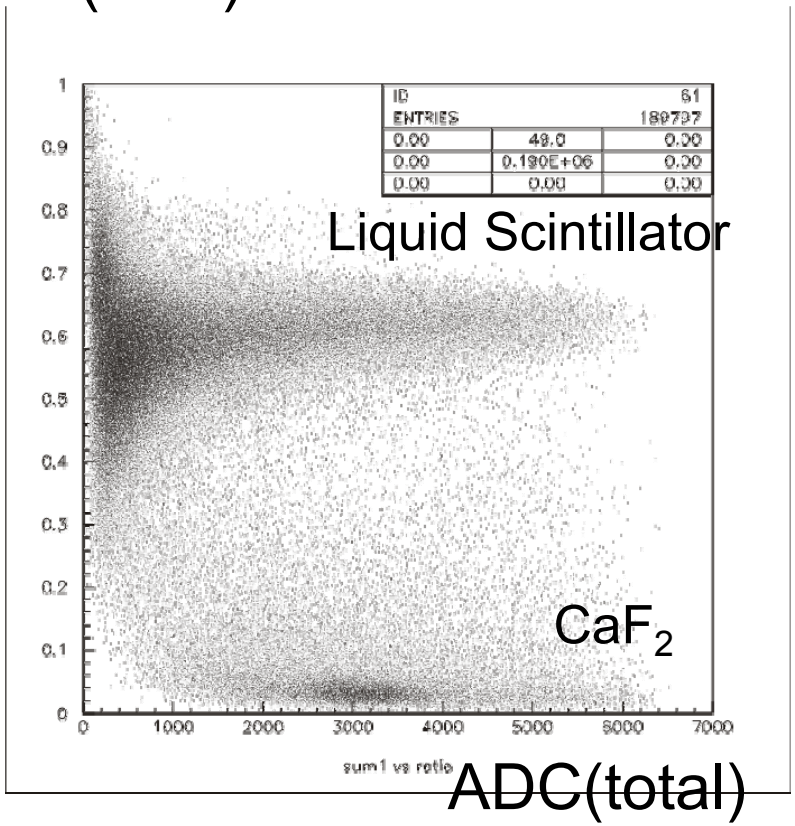
Background rejection

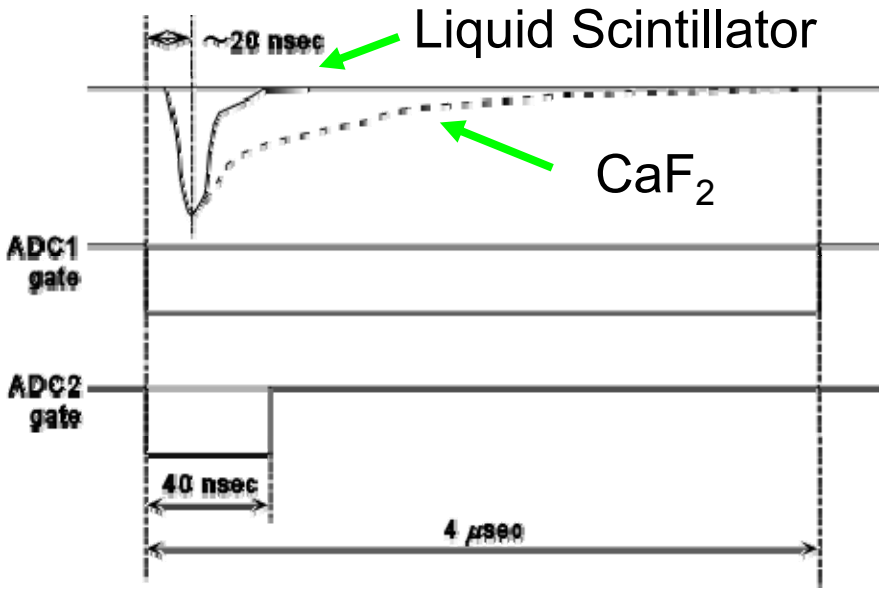
POP(Proof of Principle)



liq. scint. : mineral oil
+ DPO (3 g/l)
+ Bis-MSB (0.3 g/l)

$$\frac{\text{ADC(fast)}}{\text{ADC(total)}}$$

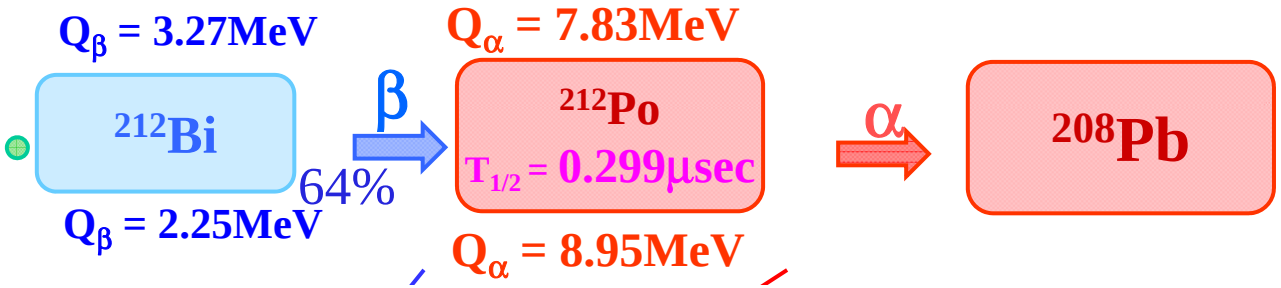




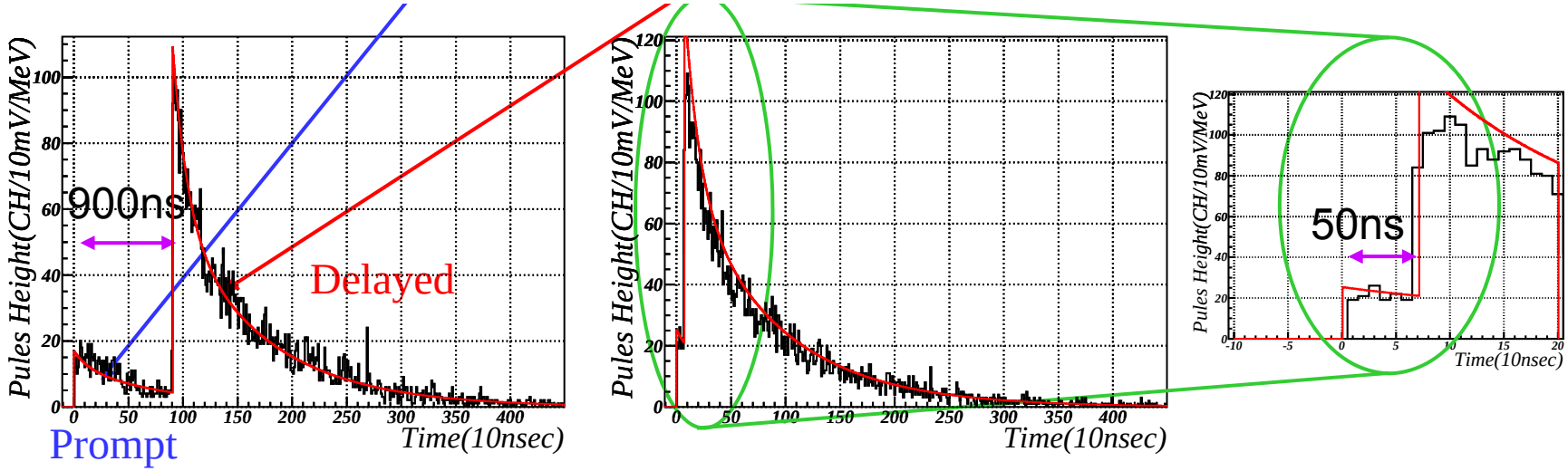
Rejection of Double Pulse

Candles

Sum energy ~ Q value



Typical Pulse Shape(100MHz FADC)



Reduction

100MHz FADC $\Delta T >$ **30ns(3ch) ; ~3%**

500MHz FADC (under preparation) . . . $\Delta T >$ **5ns ; ~1%**

Development of Low Background CaF_2 Crystals

Candles

CaF2(Eu) in ELEGANT VI
U-chain(214Bi) : 1100μBq/kg
Th-chain(220Rn) : 98μBq/kg

- Where is the crystals contaminated?

Raw Materials $CaCO_3$, HF → **CaF_2 Powder** → **Fused CaF_2** → **CaF_2 Crystal**

Radioactivities in CaF_2 Powder (HPGe measurement) ↔ Radioactivities in CaF_2(pure) Crystal (α-ray measurement)

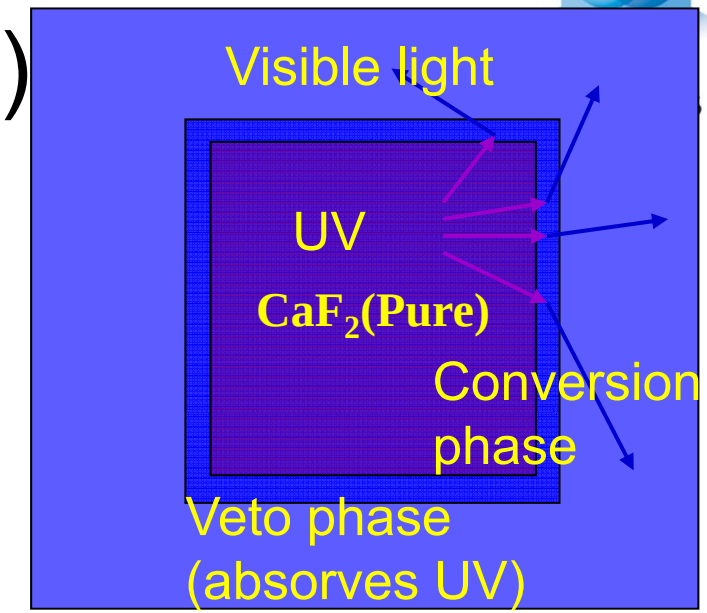
↓

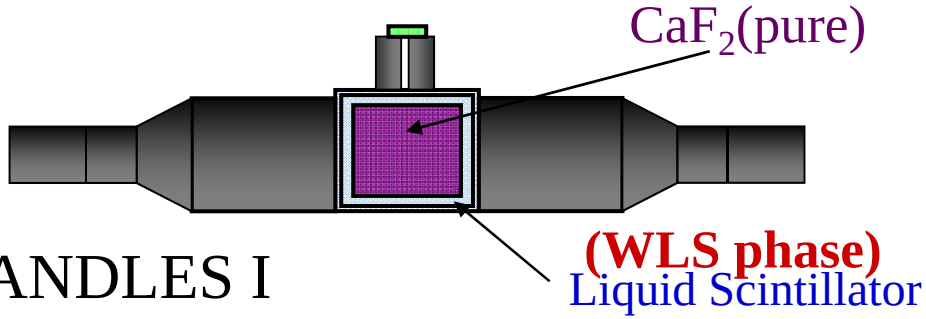
Powder selection
Crystal making

U-chain(^{214}Bi) ~41μBq/kg . . . 1/25 of Previous Crystals
Th-chain(^{220}Rn) ~21μBq/kg . . . 1/5 of Previous Crystals

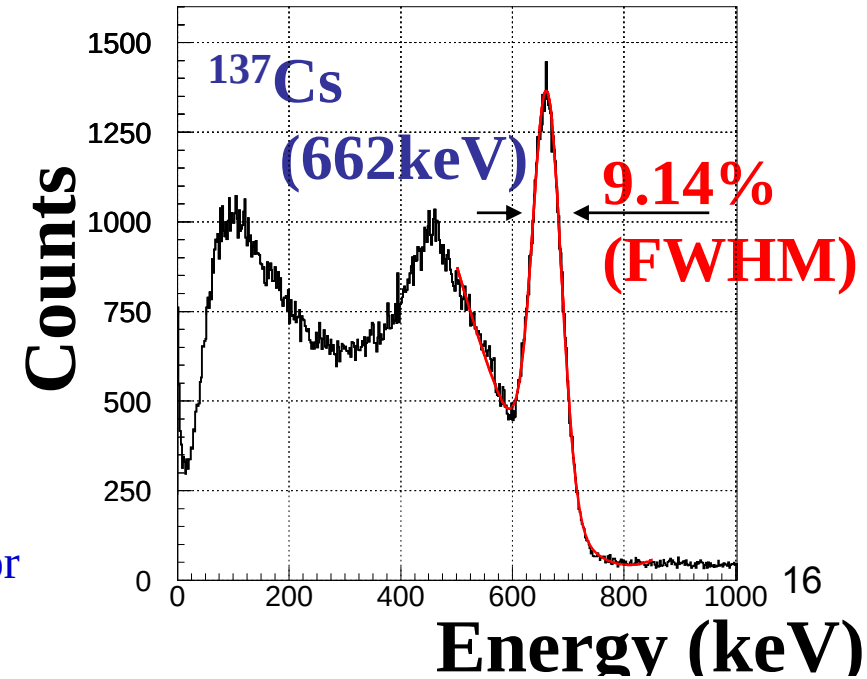
Energy resolution and BG rejection (2 phase system)

- BG from 2νββ
- Energy resolution
- CaF_2 : UV
  - ~~PMT~~
- 2 phase system

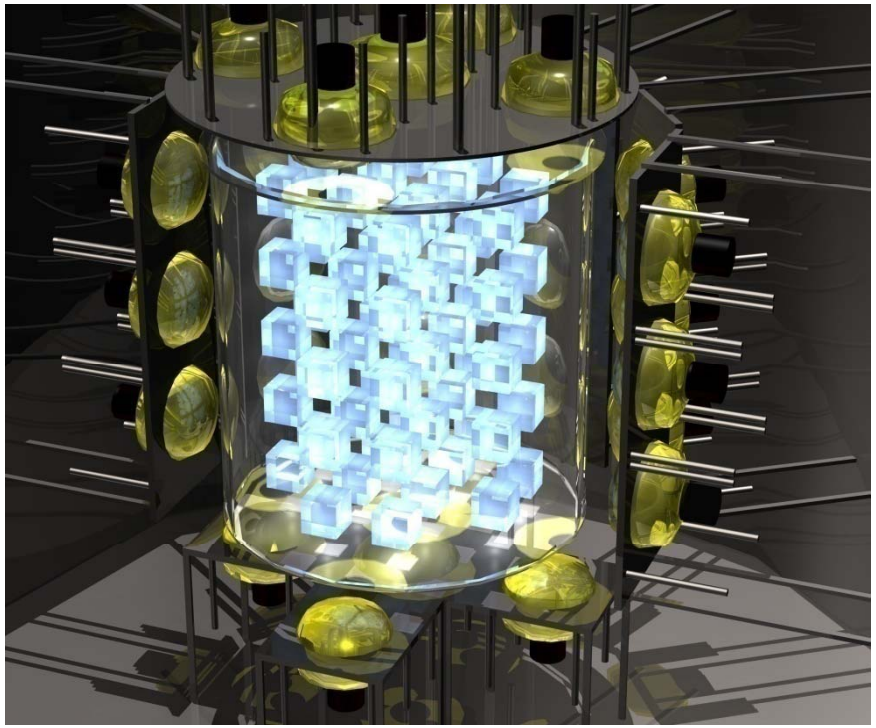




CANDLES I



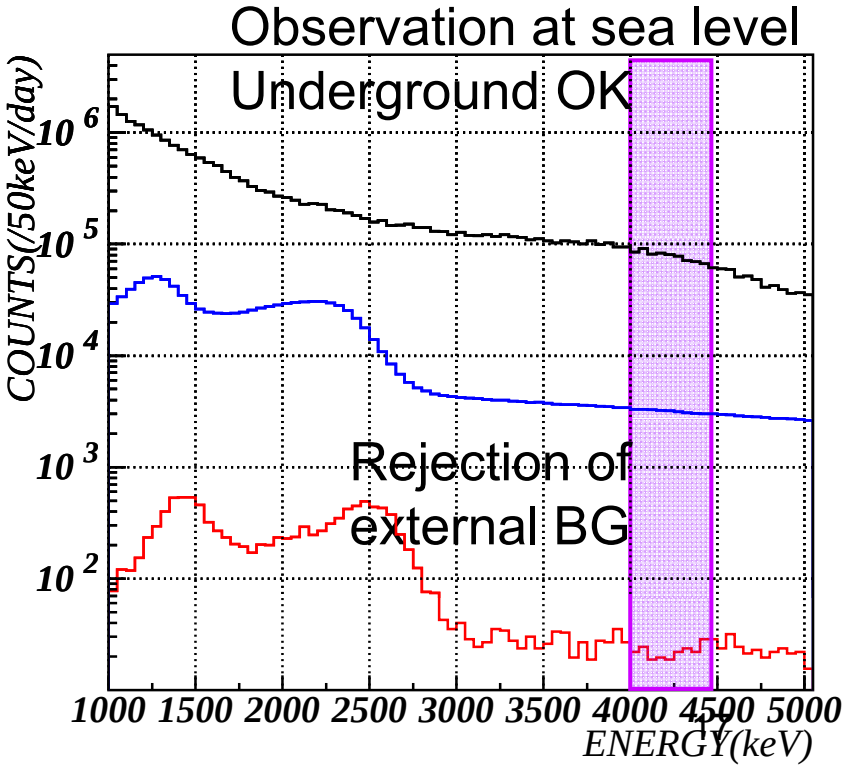
CANDLES III@Osaka



PMT:
13” × 32
15” × 8

Tank: Φ2.8 × h2.6 m

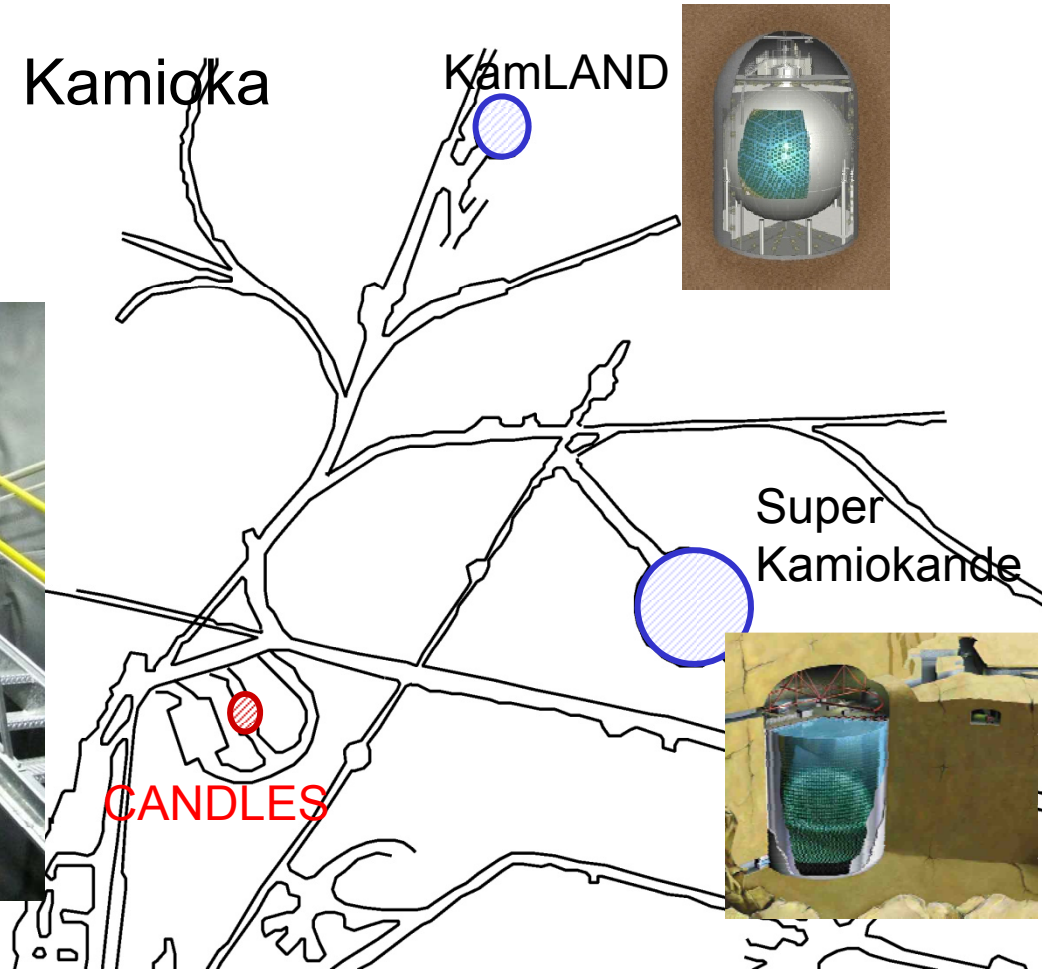
CaF_2: 191 kg
10^3 cm^3 × 60



CANDLES III（UG）

- Kamioka Experimental hall D
- CANDLES III(UG)
  - 3m $\phi \times$ 4m h

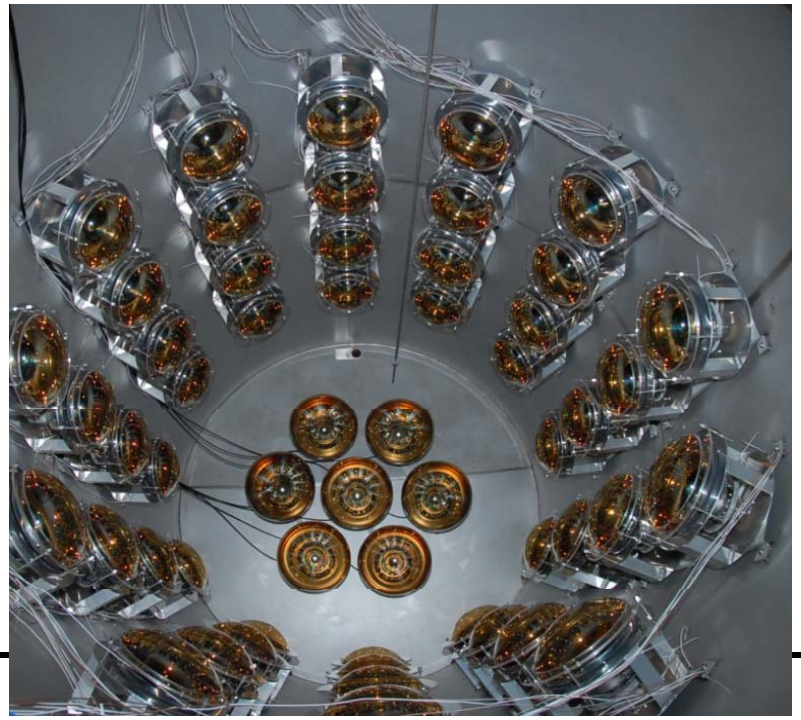
CANDLES III(UG)



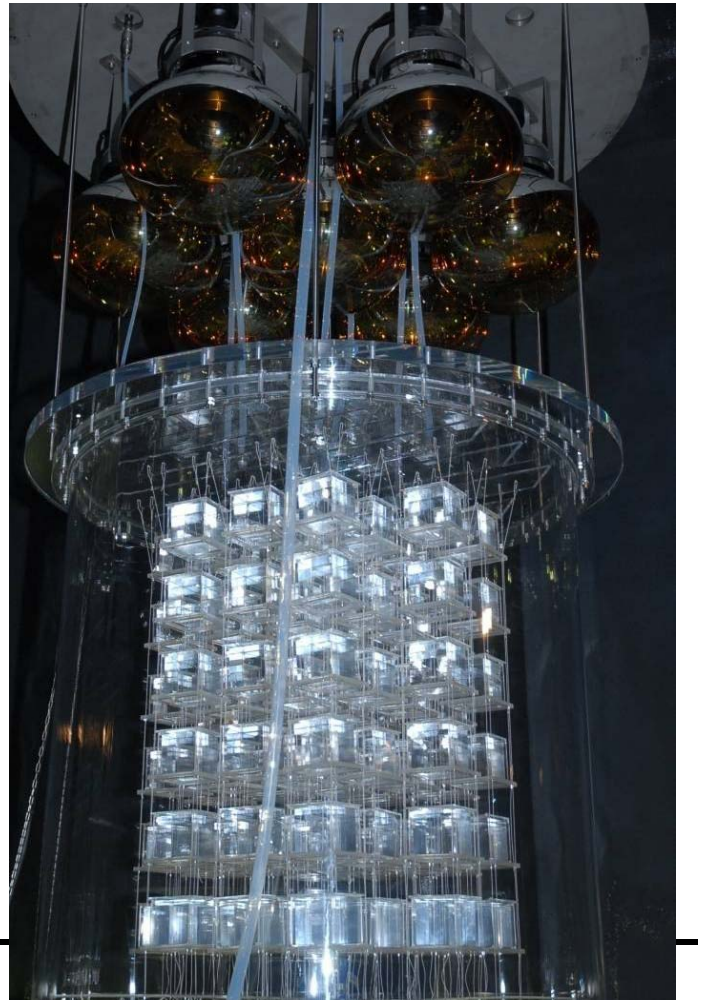
CANDLES III（UG）

- CANDLES III（UG）
  - 62 PMT's
  - 96 CaF_2(pure) crystals

Almost completed



(CaF_2 crystals)



Mile stone

Candles

- ELEGANTS VI
  - Best ^{48}Ca $0\nu\beta\beta$ limit
- CANDLES I, II
- CANDLES III+ III(UG)
  - 100 x10cm^3 CaF_2 (~30 μBq/kg) ~0.5 eV
  - Start running in this November.

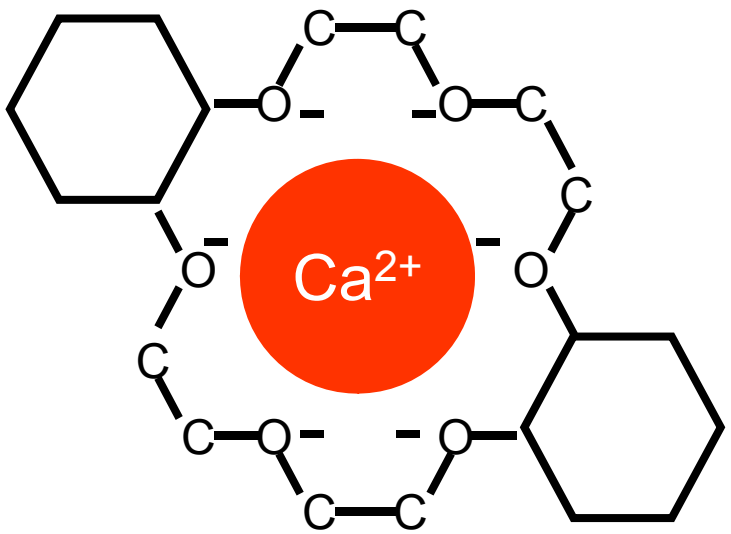
achieved

- CANDLES IV
  - 3t CaF_2 (3.5 kg ^{48}Ca) (~3 μBq/kg) ~0.1 eV
- CANDLES V
  - Enrichment and 0.3~1t of ^{48}Ca ($m_\nu \simeq 10$meV)

Enrichment of ^{48}Ca

- Increase ββ nuclei
- BG reduction
- Crown ether
  - Sep. coeff. $\varepsilon \sim (3.5 \pm 0.5) \times 10^{-3}$
  - Crown ether resin

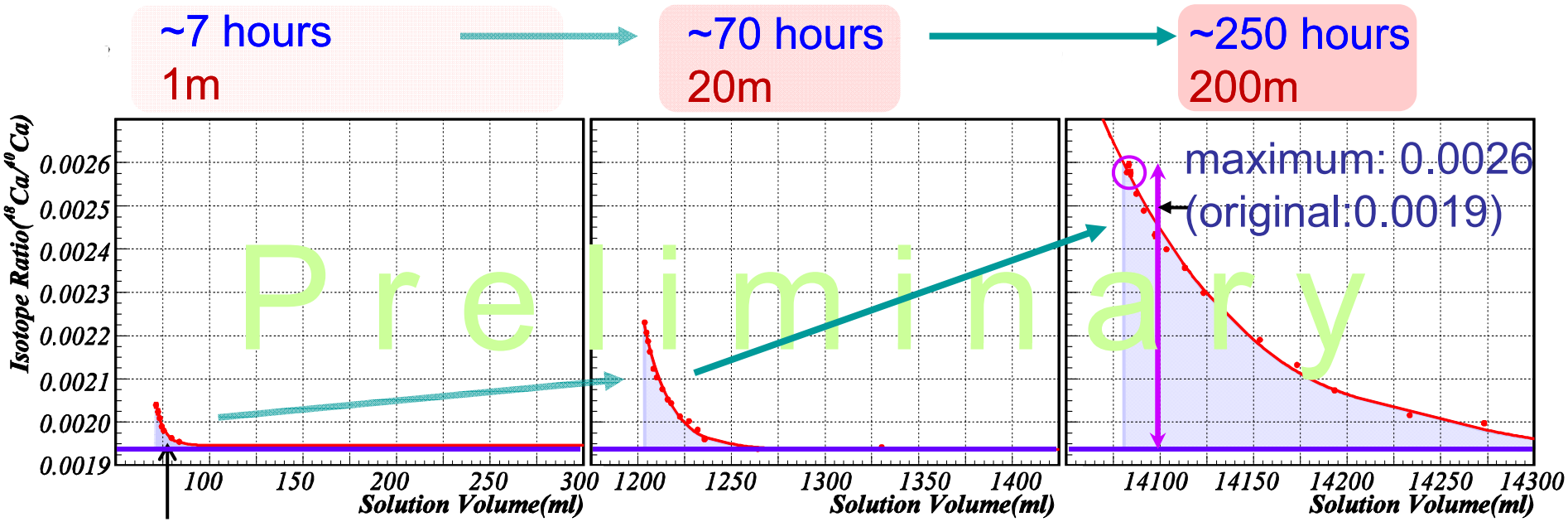
^{48}Ca : 0.2% => 5~10 %



Dicyclohexano
18-crown-6

DC18C6

Enrichment for long migration



Enrichment due to crown ether

- long migration length
- higher enrichment and larger amount
  ~7時間(1m) → ~250時間 (200m)
  amount: ×17, enrichment: ×8

Summary

Candles

- Double beta decay will change our understanding on particle and anti-particle and our universe.
- CANDLES has potential to see signals.
- Enrichment of ^{48}Ca is key R&D item.
  - Crown ether (CE) resin is under R&D.
  - China is the largest supplier of CE.
- Collaborators are welcome particularly from China, where underground science is under preparation.

Candles

Thank you.