Study of ^{48}Ca Double Beta Decay by CANDLES

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Osaka Univ.

Neutrino has to be a Majorana particle

Candles

- Dirac mass term

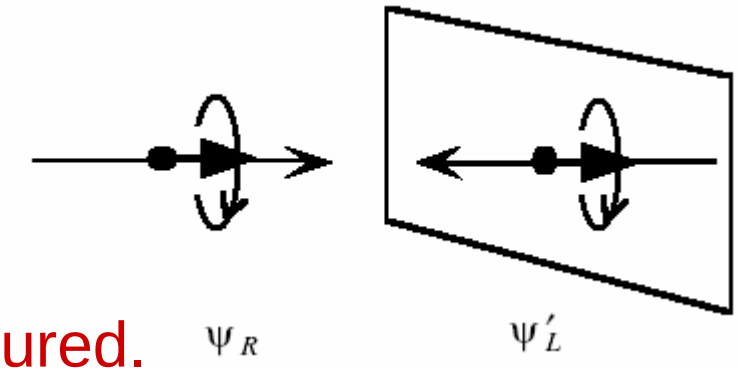
$$\mathcal{L}_D = -m_D \overline{\nu_R^0} \nu_L^0 + \text{ h. c.}$$

- Majorana mass term

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

  - ν_L and ν_R could have different mass
  - We have only ν_L
  - ν_R is very massive
  - Lepton number violation
  - See-saw mechanism

Special Relativity:
Helicity flip ⇔ mass



Double beta decay has to be measured.

Majorana's neutrinos

- Today, Majorana is particularly well known for his ideas about neutrinos. Bruno Pontecorvo, the "father" of neutrino oscillations, recalls the origin of Majorana neutrinos in the following way: Dirac discovers his famous equation describing the evolution of the electron; Majorana goes to Fermi to point out a fundamental detail: " I have found a representation where all Dirac γ matrices are real. In this representation it is possible to have a real spinor that describes a particle identical to its antiparticle."

CERN courior, 2006

Dirac : anti-particle
Majorana : left-handed

Why ^{48}Ca

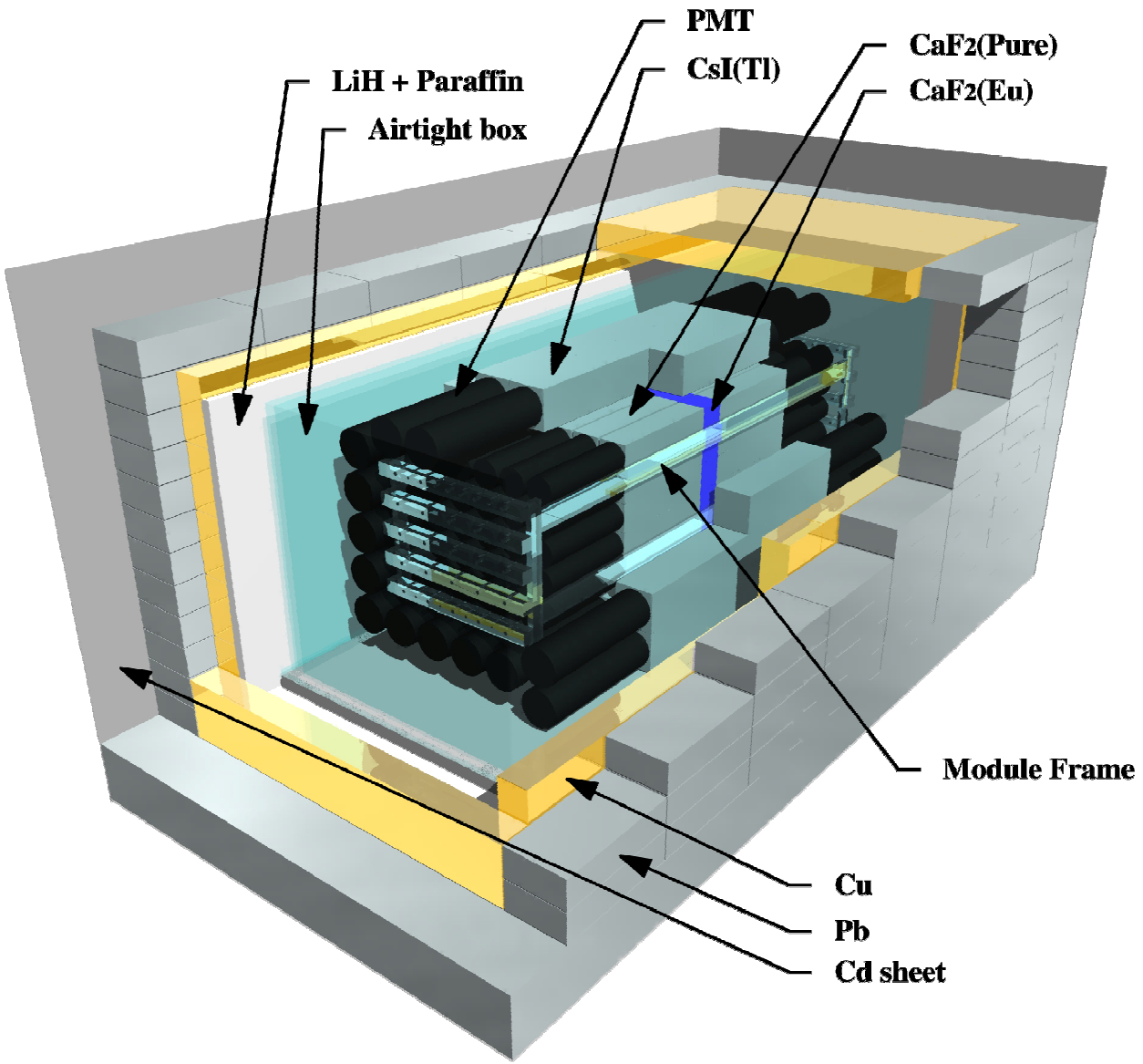
- Highest Q value (4.27 MeV)
  - next largest ^{150}Nd (3.3 MeV)
  - Large phase space factor
  - Little BG（natural radioactivity γ: 2.6 MeV, β: 3.3 MeV）
- Natural abundance: 0.187%
  - Isotope separation: expensive (no Gas)
  - Early studies (recent studies use separated isotope)
- Next generation
  - $M_\nu \sim T^{-1/2} \sim M^{-2}$ (no BG)

    $\sim M^{-4}$（BG limited）
  - ^{48}Ca (no BG)

$$\langle m_\nu \rangle < 7.2 \sim 44.7\ \mathrm{eV}\ \ (90\,\%\ \ \mathrm{C.L.})$$

NPA 730 '04, 215

ELEGANT VI



Candles

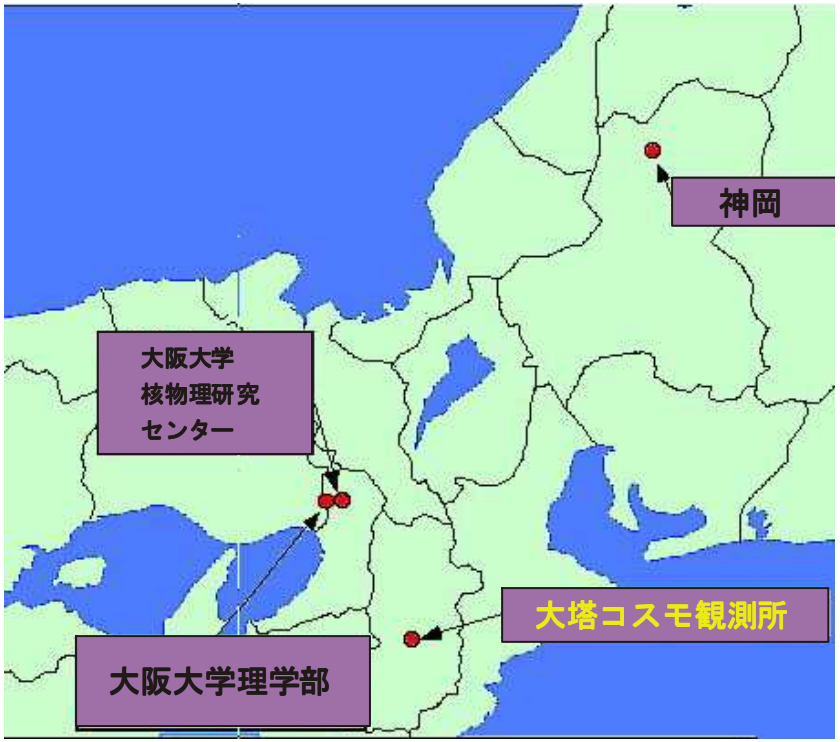
shields

- γ
  - Cupper lead
- neutron
  - paraffin
  - LiH, Cd
- Radon
  - air-tight box

Acitve shields

- CsI
- roll off ratio

Oto Cosmo Observatory

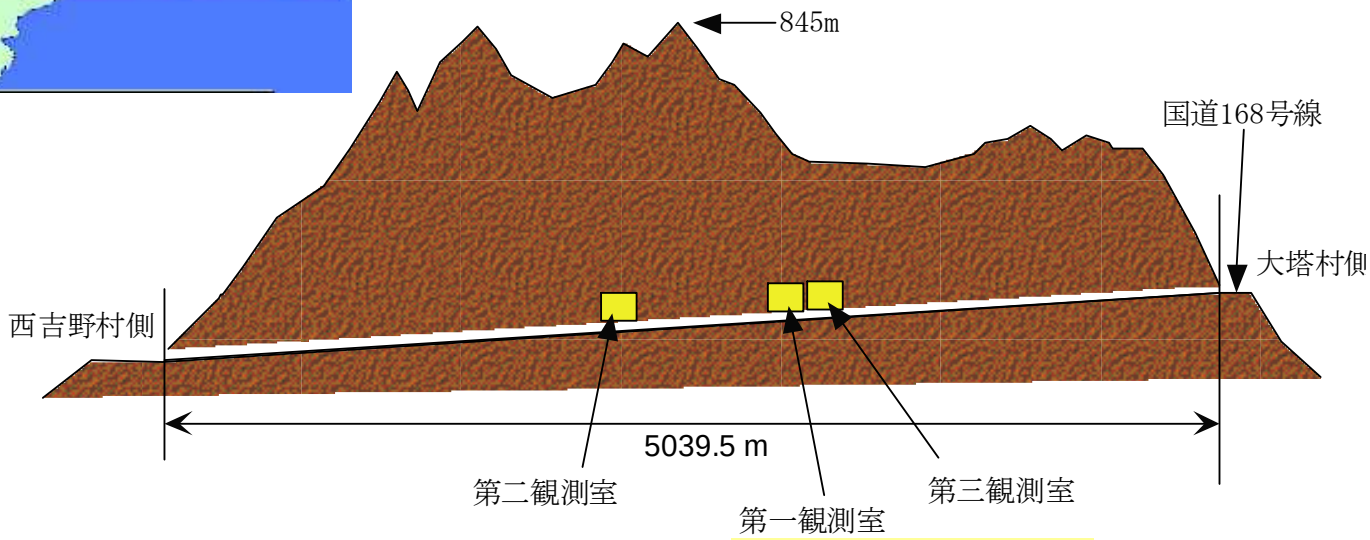


Candles

tunnel constructed for railroad (but not used)

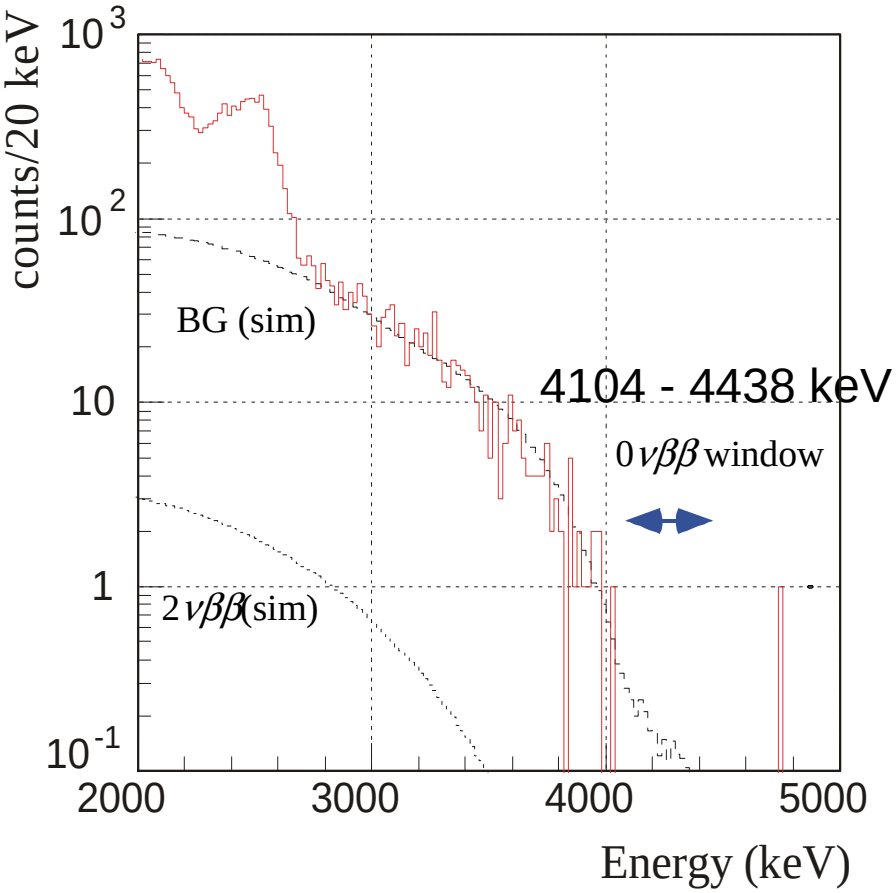
470m (1.3 km water equivalent) shield

旧国鉄の五新線（奈良県五條市～和歌山県新宮市）用の鉄道トンネルだが、結局線路は敷かれず。



ELEGANT VI

Double Beta Decay of ^{48}Ca Studied by ELEGANT VI



0.63 y

$T_{1/2}^{0\nu\beta\beta} > 4.5\times10^{22}$ year (68 % C.L.)

$> 1.4\times10^{22}$ year (90 % C.L.)

World best value

$\langle m_\nu \rangle < 7.2 \sim 44.7$ eV (90 % C.L.)

NPA 730 '04, 215

$T_{1/2}^{0\nu} > 9.5\times10^{21}$ years (76% C.L.) Beijing

$> 1.5\times10^{21}$ years (90% C.L.) TGV

Not limited by backgrounds

Backgrounds are known

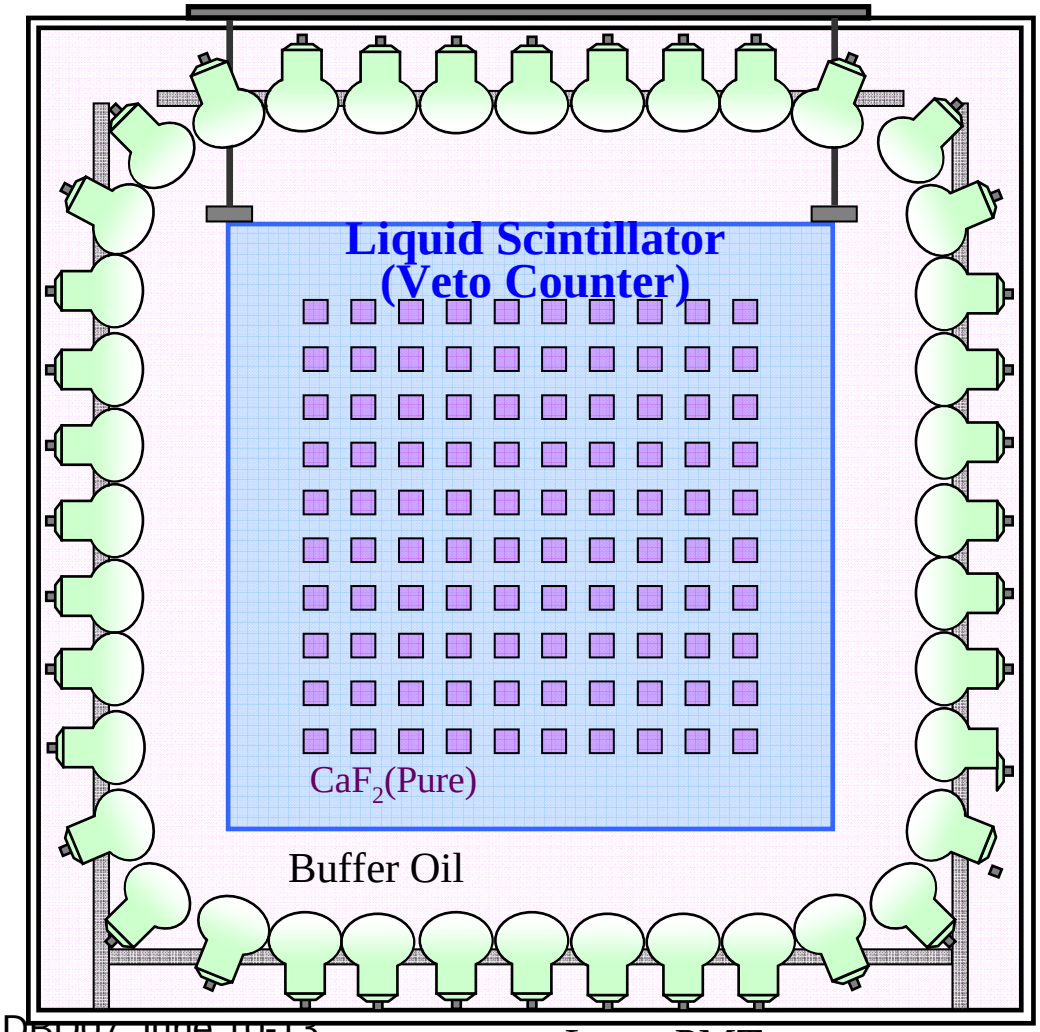
How to sense $m_\nu = 10^{-(1\sim2)}$eV

- 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, 6t,100t**
  - ^{48}Ca (200g, 300g, 6kg, 100kg)
- **Liquid Scintillator**
  - Wave Length Shifter
  - 4 π Active Shield
  - Passive shield
- **Photomultiplier**
  - energy resolution

CaF_2 crystal

- Big detector
  - Best optical lens
  - Long attenuation length
    - 10m (catalog value for visible light)
    - >1m (our measurement for scintillation light)
- CANDLES IV
  - 15x15x15 cm^3 x 600 (6t)
  - Increase the number of nuclei (^{48}Ca)

6.4 g (ELE VI) ~6(kg)

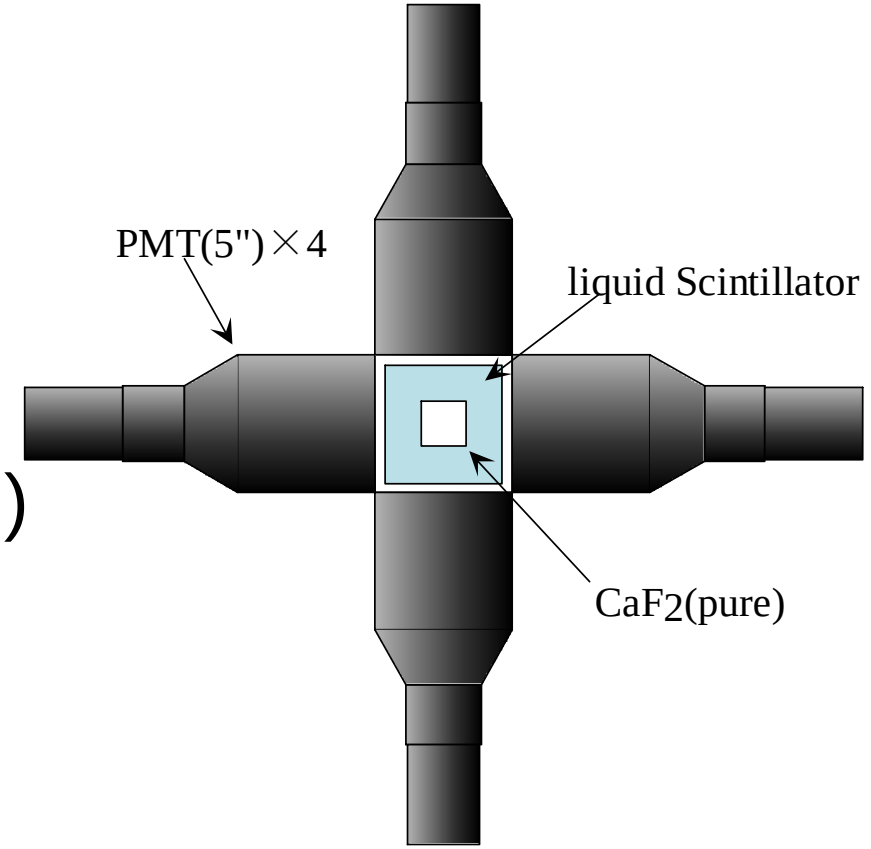
$$8.1\times10^{22}\ \text{atoms} \Rightarrow \sim 10^{26}\ \text{atoms}$$

CANDLES I

Candles

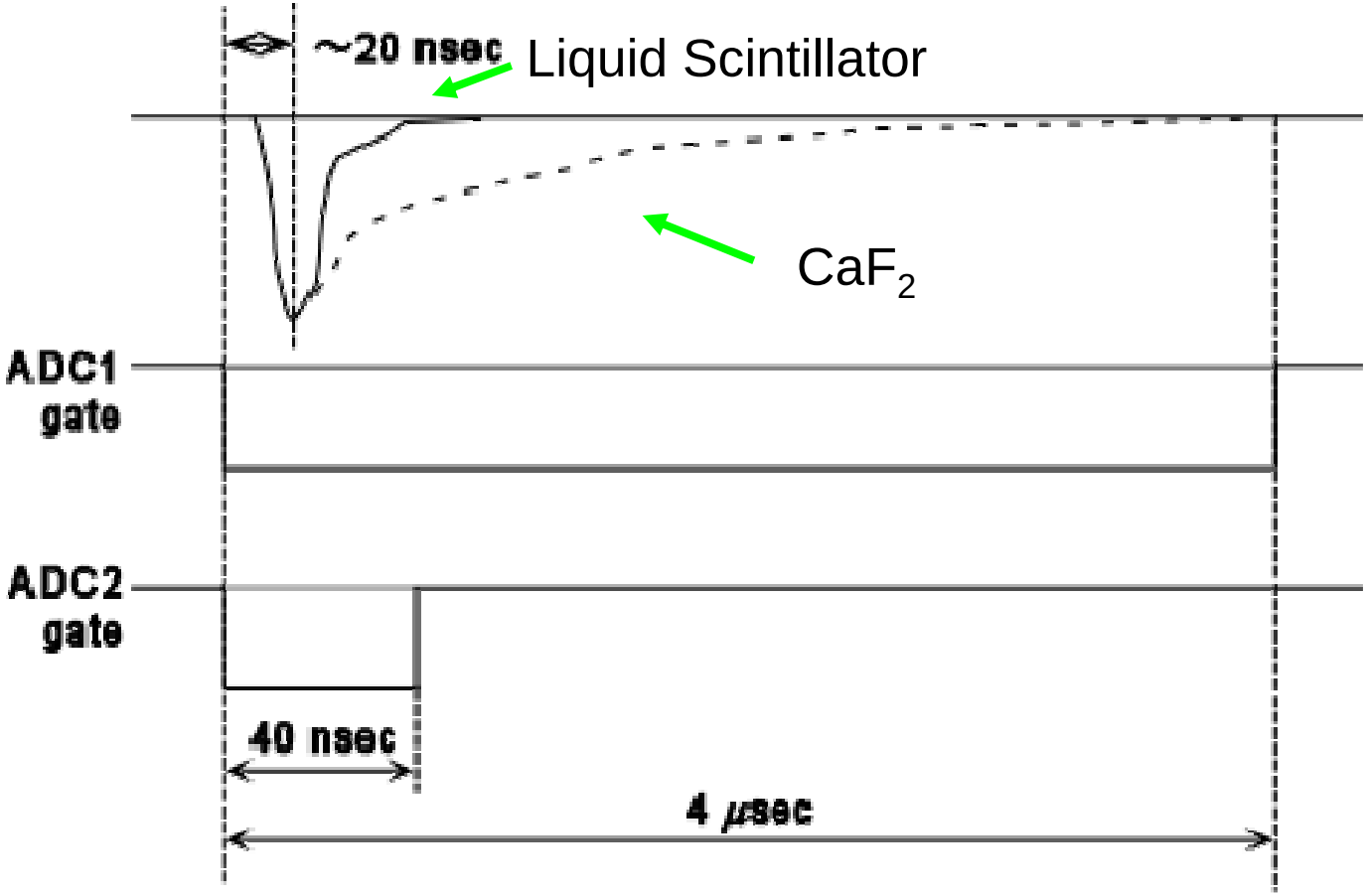
POP (Proof of Principle) Detector

CaF_2(pure) crystal
in liquid scintillator
(with w.l. shifter)
viewed by 4 PMTs (5 inch)



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

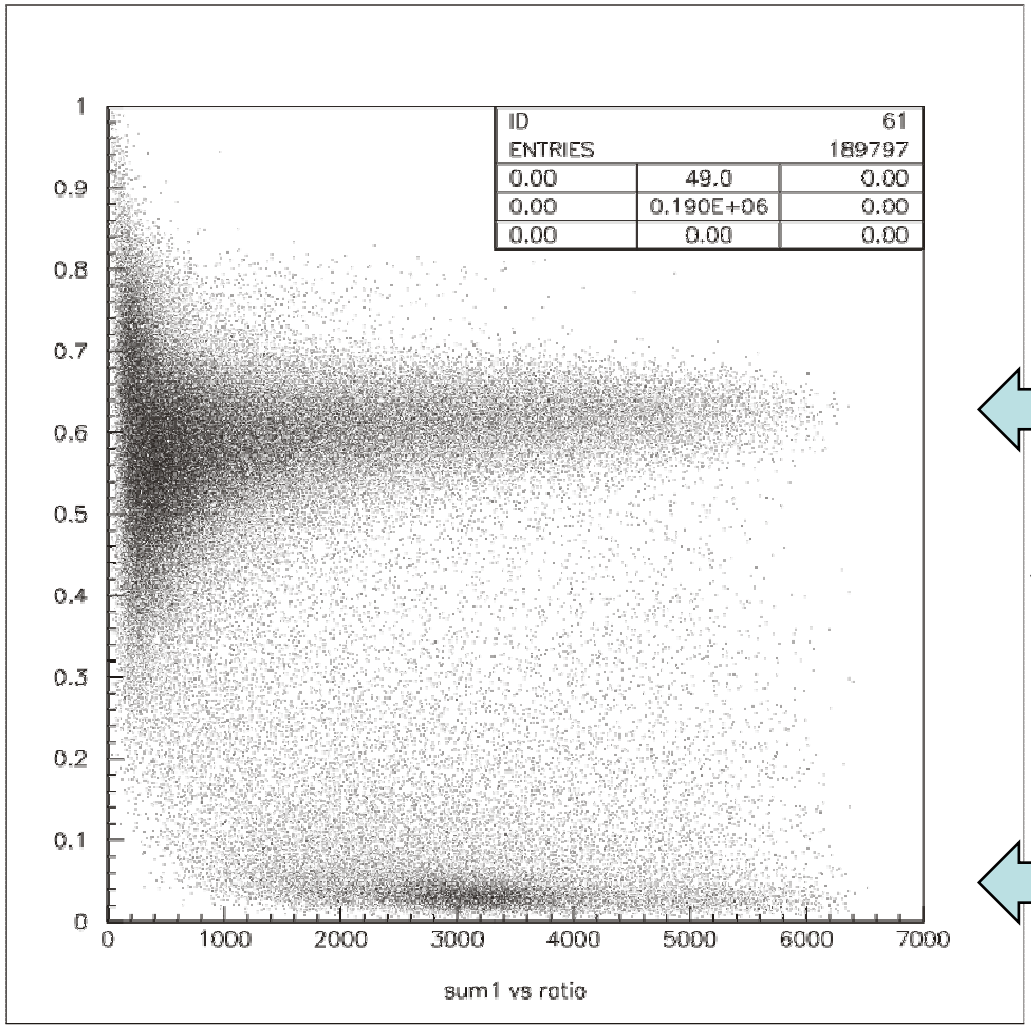
Signal discrimination



Decay time
Liq. Scinti
~10 nsec
CaF_2
~1 μsec

ADC(fast)/ADC(total) { ~1 liquid scintillator
~0.04 CaF_2

Signal discrimination



ADC(fast)/ADC(total)

ADC(total)

^{57}Co source

Signal from Liquid scintillator

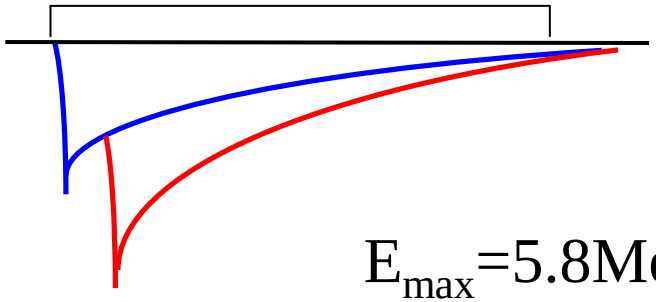
CaF_2

Background @ Q value region

- No natural BG @ ~4 MeV
  - Maximum energy
    - γ~ 2.6 MeV, β~3.3 MeV, α~2.5 MeV(quench~0.3)
  - Successive decay of α β γ
    - ~1μsec decay time

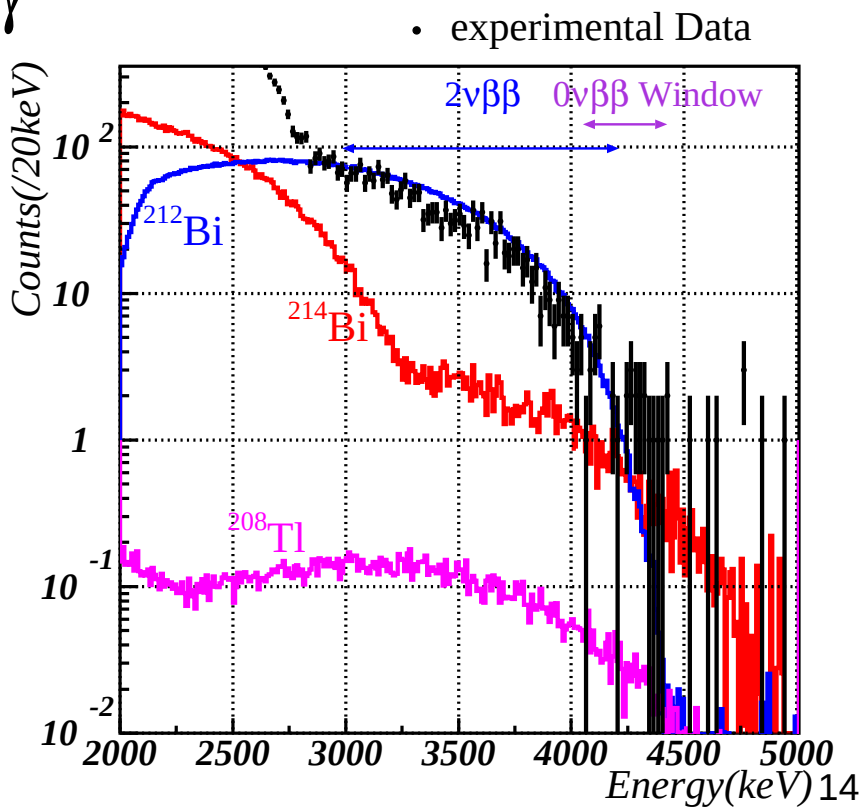
Pulse shape

Gate width(4μsec)

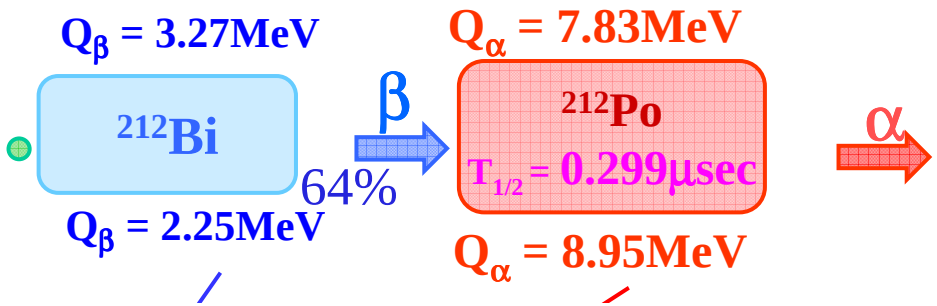


β+α

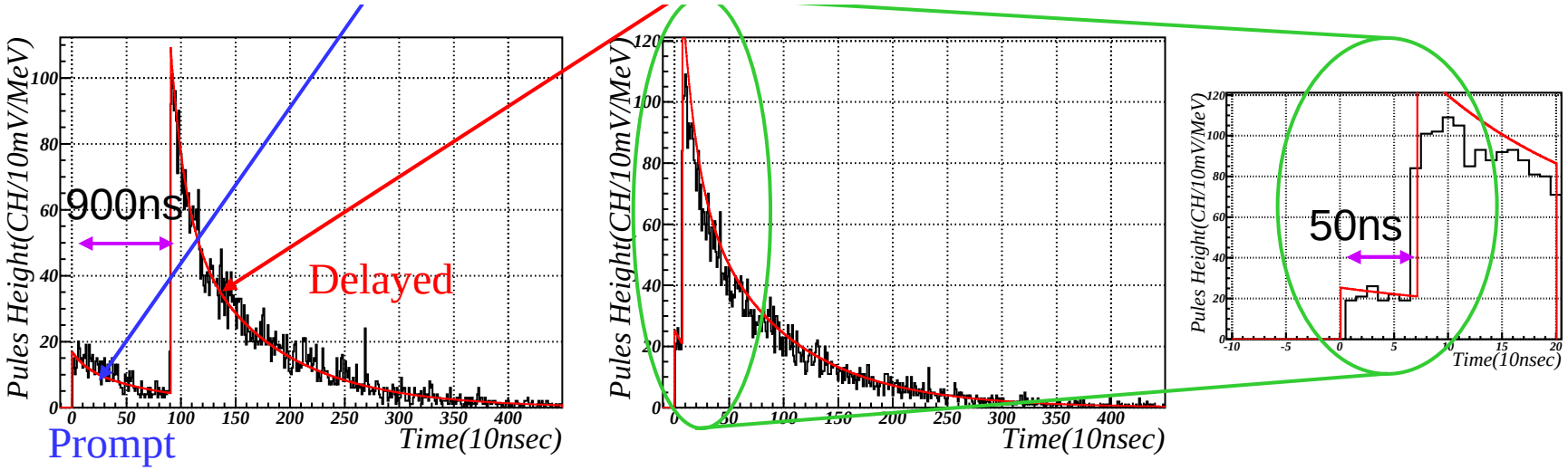
E_{max}=5.8MeV(U)
5.3MeV(Th)



Rejection of Double Pulse



Typical Pulse Shape(100MHz FADC)



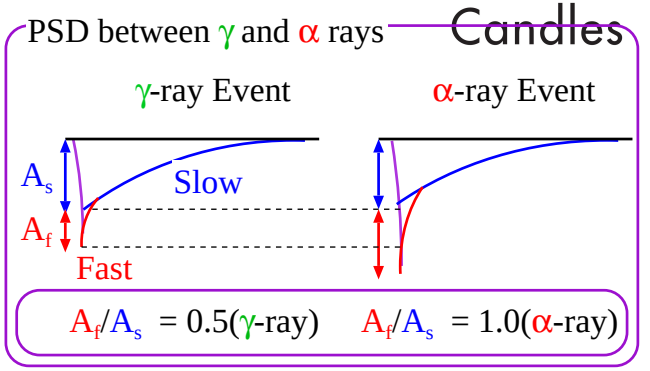
Reduction

100MHz FADC $\Delta T >$ **30ns(3ch) ; ~5%**

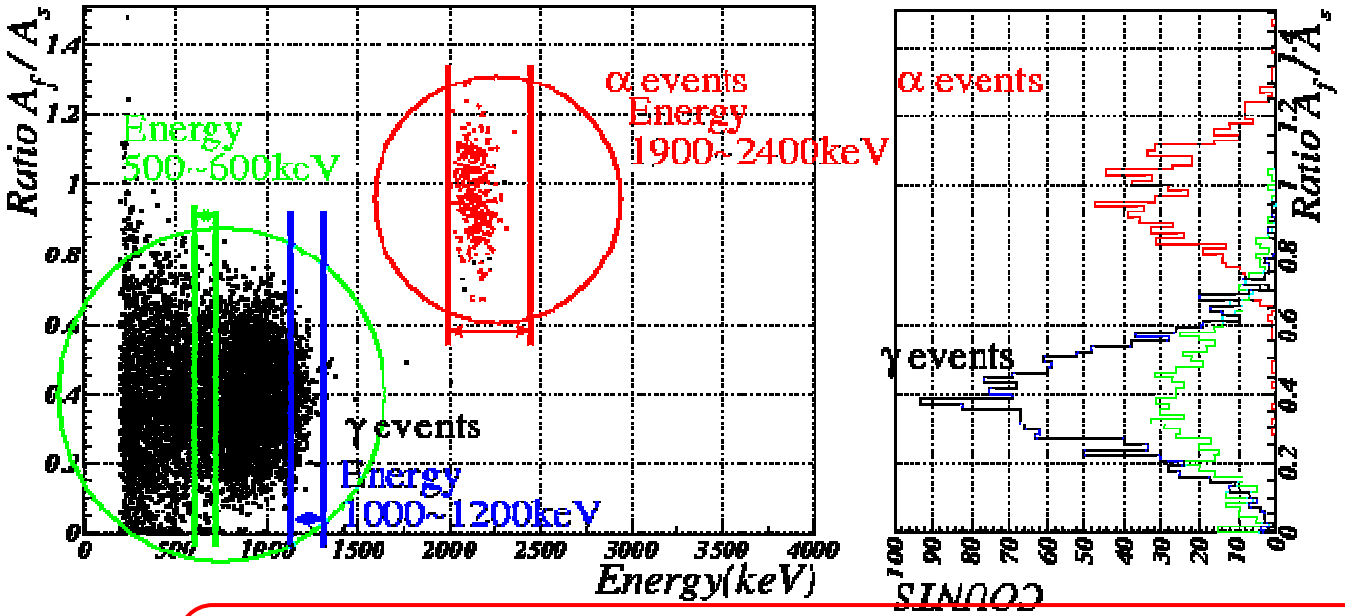
500MHz FADC (under preparation) . . . $\Delta T >$ **5ns ; ~1%**

Pulse Shape Discrimination

Difference in decay time
between α and γ rays



- **PSD (Event by Event)**
  - **FADC (100MHz)**
  - ***A*$_{fast}$*/A*$_{slow}$ (Fast and slow component)**



Discrimination between α and γ(β) Events

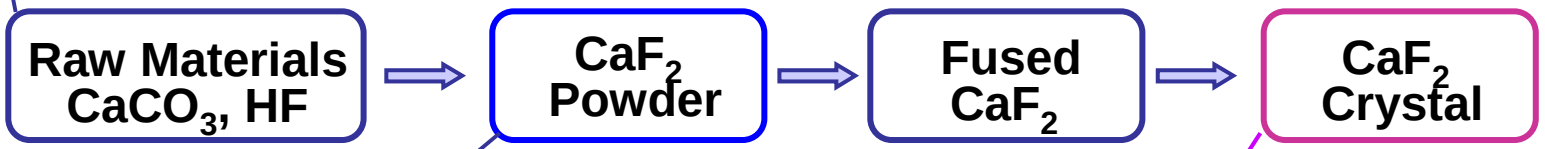
Background Reduction ~ 0.3%

Development of High Purity CaF_2 Crystals

Candles

CaF_2(Eu) in ELEGANT VI
U-chain(^{214}Bi) :1100 μBq/kg
Th-chain(^{220}Rn) : 98 μBq/kg

U and Th (ICP-MS)



Radioactivities in CaF_2 Powder (HPGe measurement) ⟷ Radioactivities in CaF_2(pure) Crystal (β–α delayed coincidence)

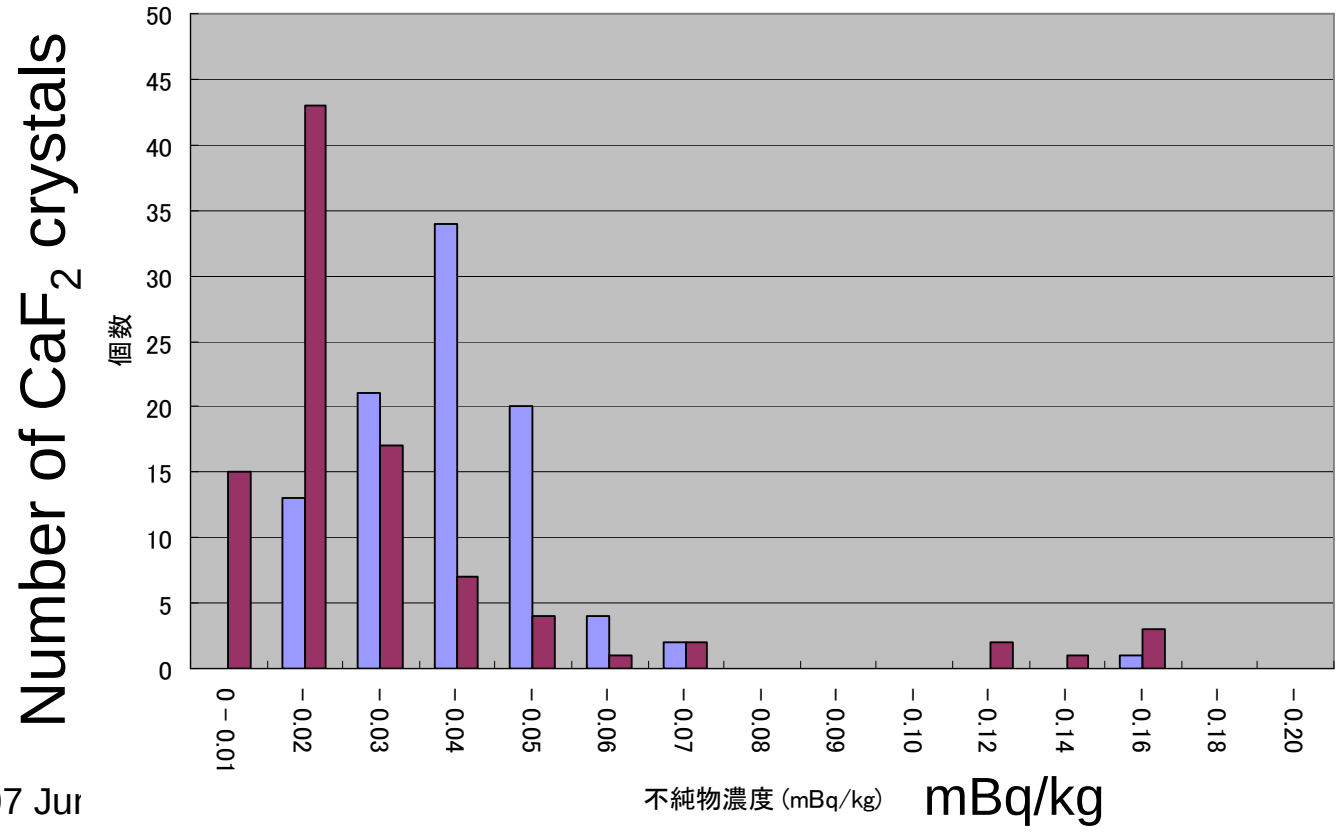
Powder selection
Crystal growing

96 crystals

U-chain(^{214}Bi) ~36 μBq/kg …1/30 of Previous Crystals
Th-chain(^{220}Rn) ~28 μBq/kg …1/3 of Previous Crystals

Radioactivities in CaF_2

- β–α, α–α delayed coincidence
- @ Oto Cosmo observatory



95 crystals

U~36μBq/kg
14 (best)

Th~20μBq/kg
6 (best)

Energy resolution of CaF_2

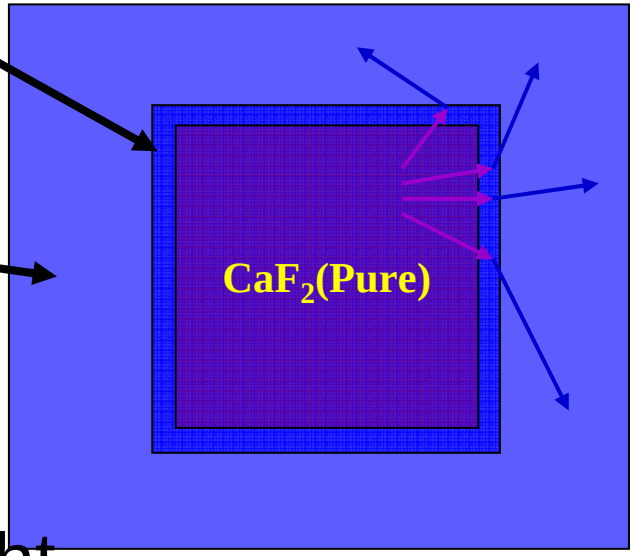
- Energy Resolution $\Delta E \sim \frac{1}{\sqrt{N_p}}$
- Scintillation light
  - ~0.5 of CaF_2(Eu) (quart window PMT)
  - peak emission U.V. (285 nm)

- Increase # of photons
  - Wavelength shifter
  - UV ⟹ visible light

Two Phase System

Concept of Method

- Conversion Phase
  - Large conversion eff.
  - good transparency for UV
- Veto Phase
  - Large light output with aromatic solvent



CaF_2 Emission (~285nm) — UV light

⇩

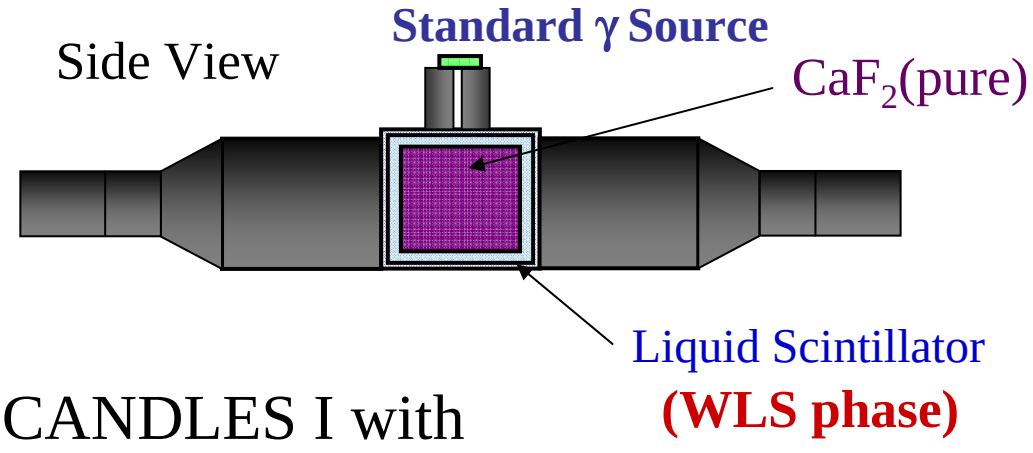
Conversion by WLS(350~400nm) — Visible light

⇩ propagate

PMT

High resolution and
High veto efficiency

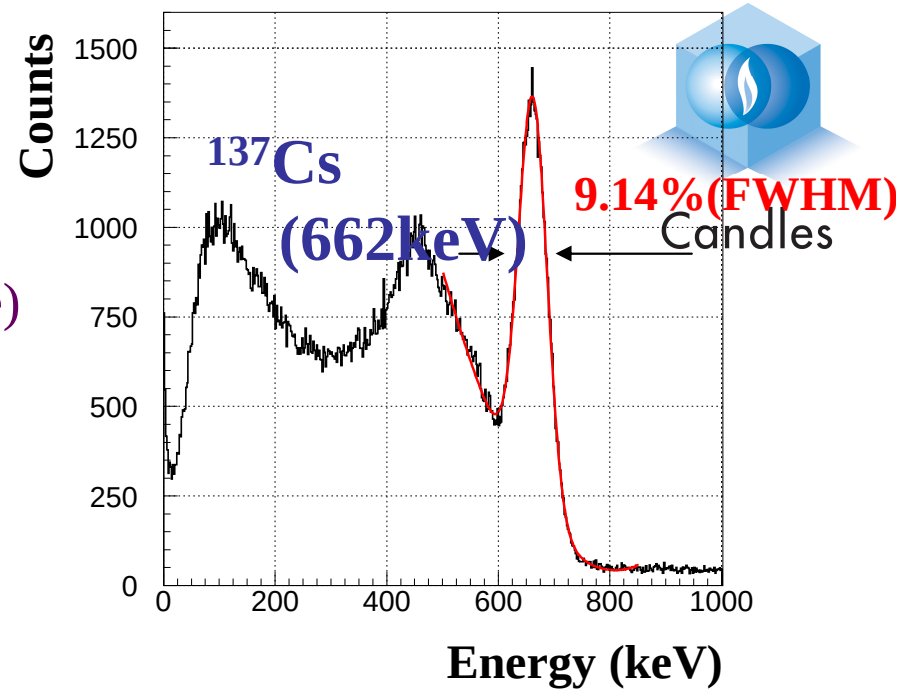
Energy resolution

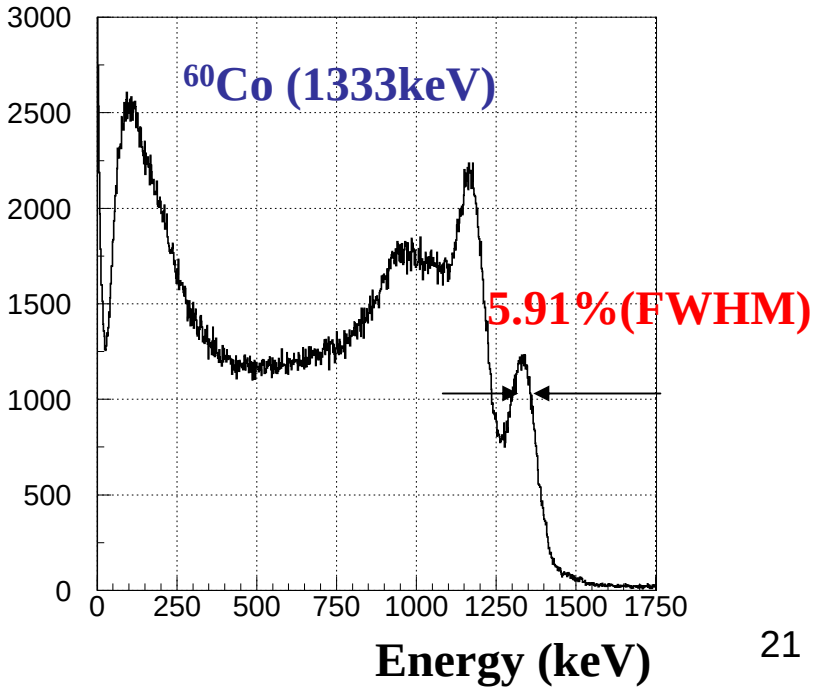


CANDLES I with
10 cm^3 CaF_2(pure)

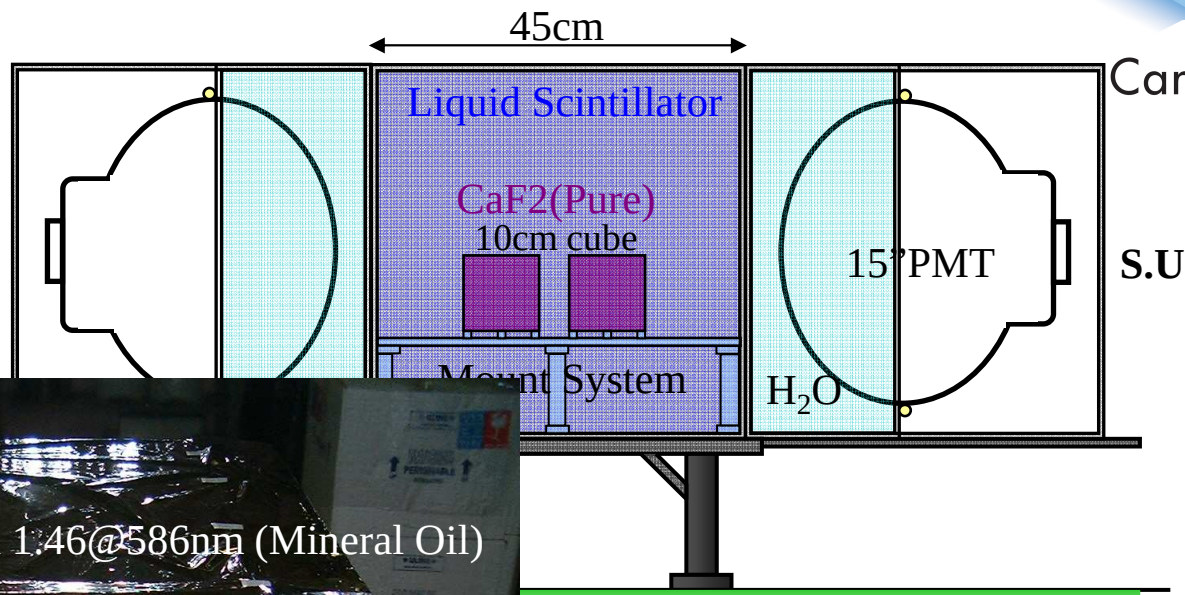
~1 ph/keV

Energy Resolution:
9.1%(FWHM) at 662keV
=3.4% (FWHM) at 4.27MeV
Req. for CANDLES III ; 4.0%





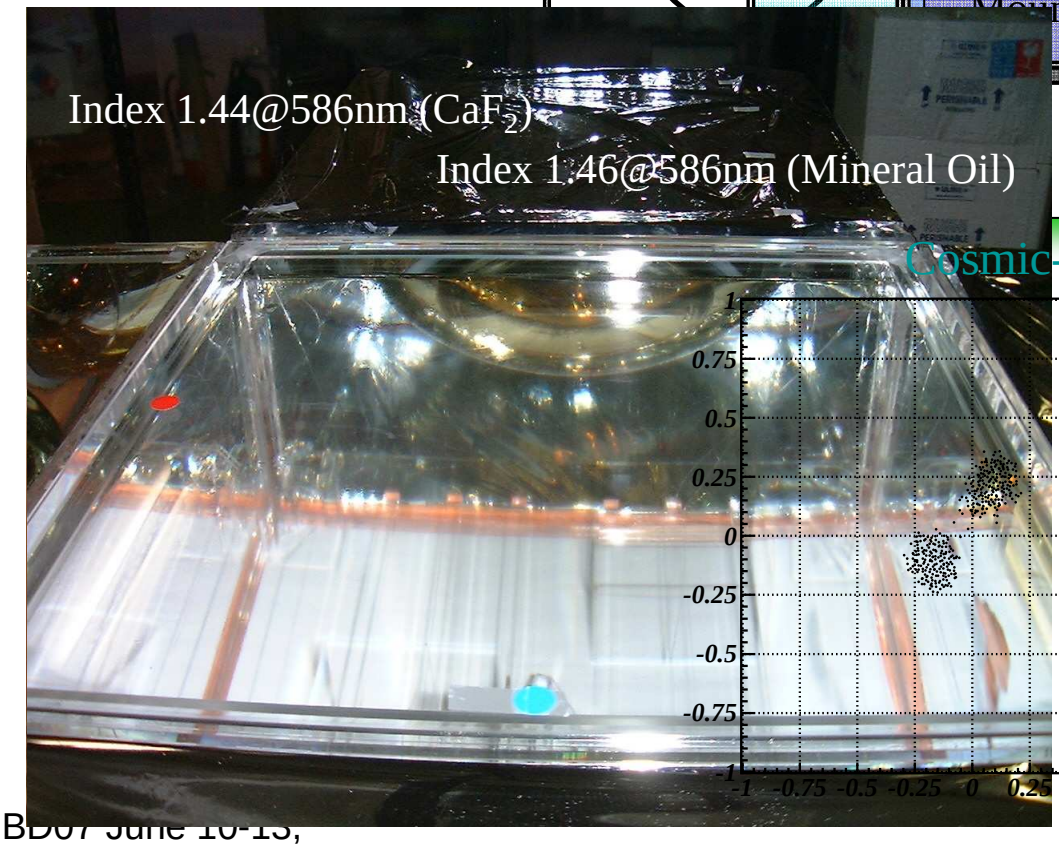
CANDLES-II



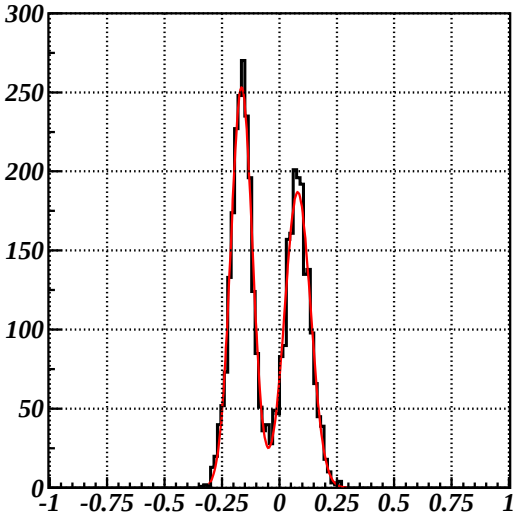
Candles

S.Umehara

- Prototype

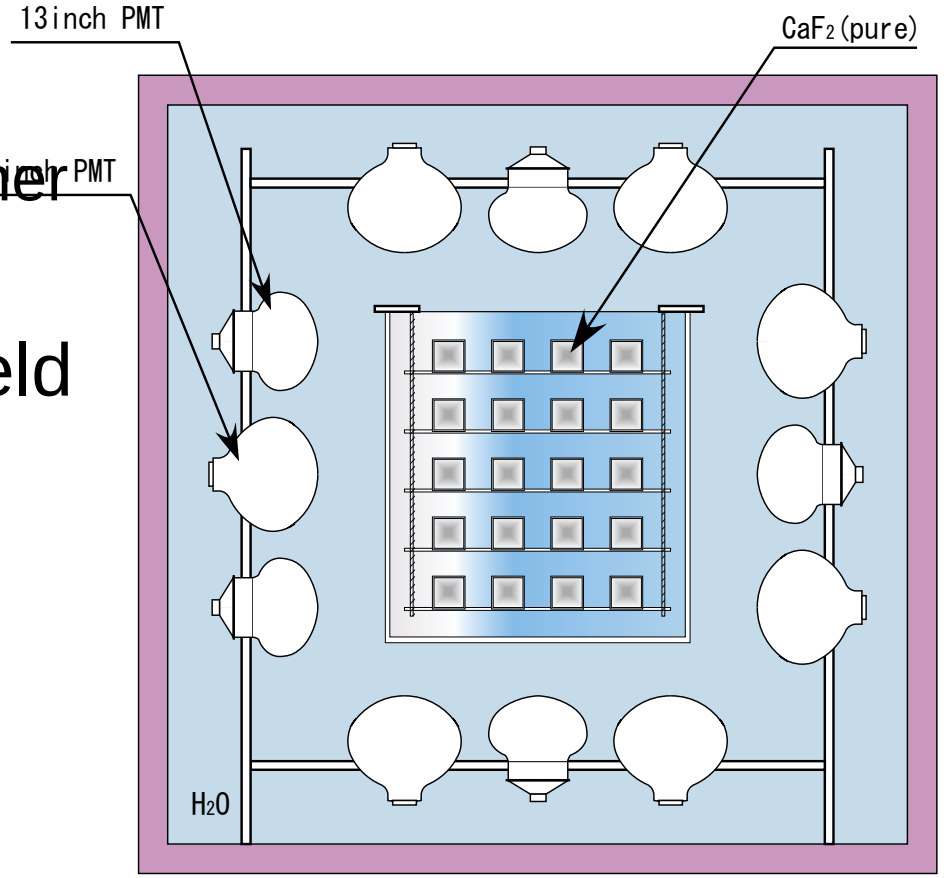


Cosmic-ray Events (High Energy)

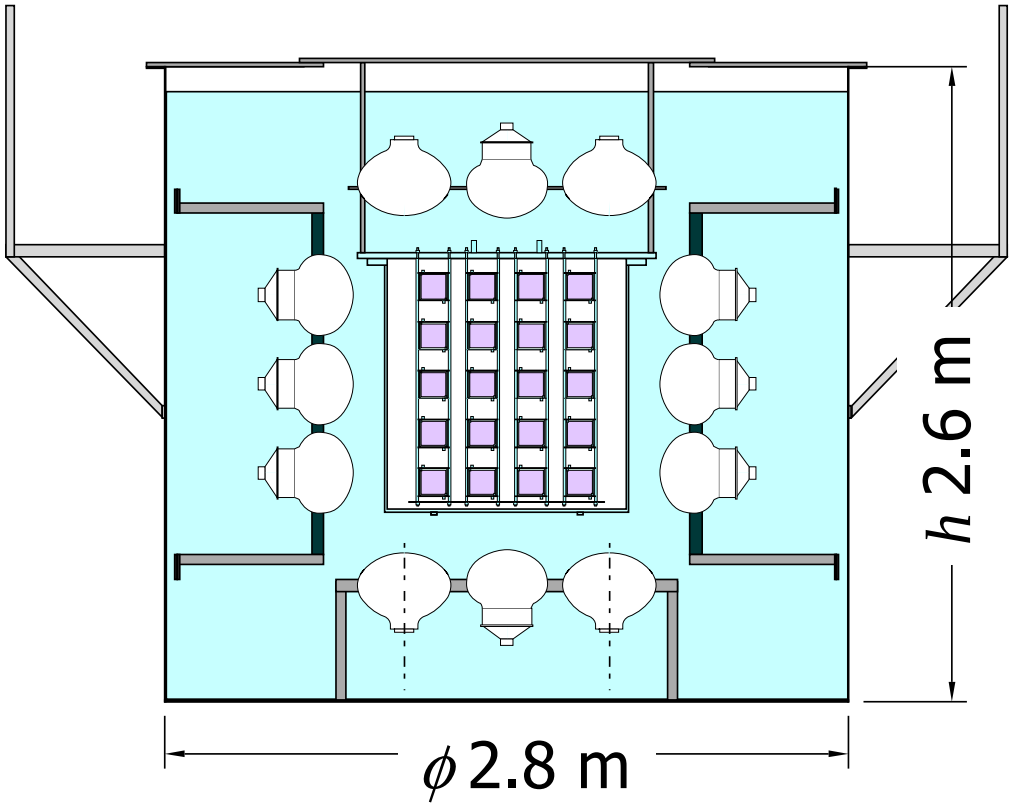


CANDLES III

- Construction almost completed @ Osaka Univ.
- CaF_2(pure)
  - 60×10^3 cm^3 ; 191 kg
- Liquid scintillator
  - ϕ1m × h1m acrylic container
- Purification system
- H_2O Buffer: passive shield
  - ϕ2800 × h2600
  - safety regulation
- PMTs
  - 15” PMT (×8) : R2018
  - 13” PMT (×32) : R8055

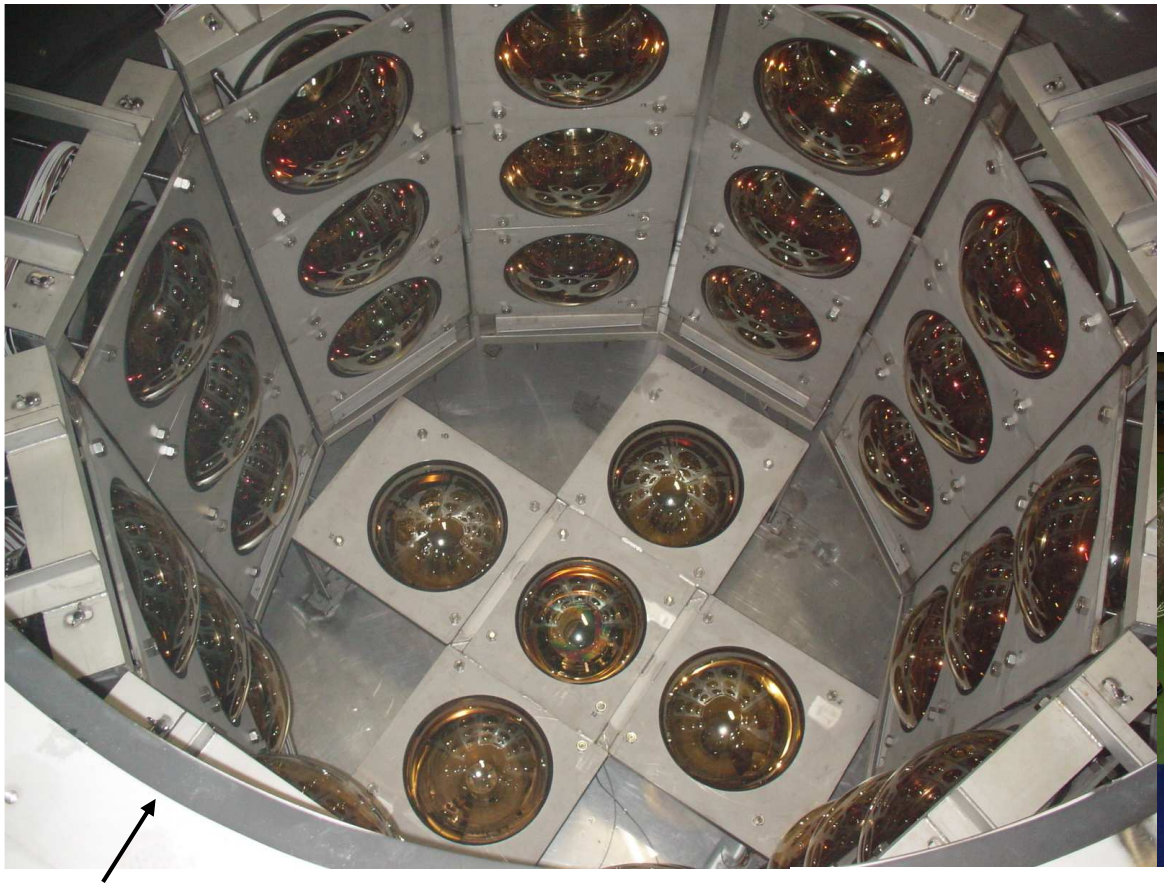


CANDLES III (prototype)



CANDLES III

Inside View



40 PMTs Version
And 60 PMTs Version . . . Funded

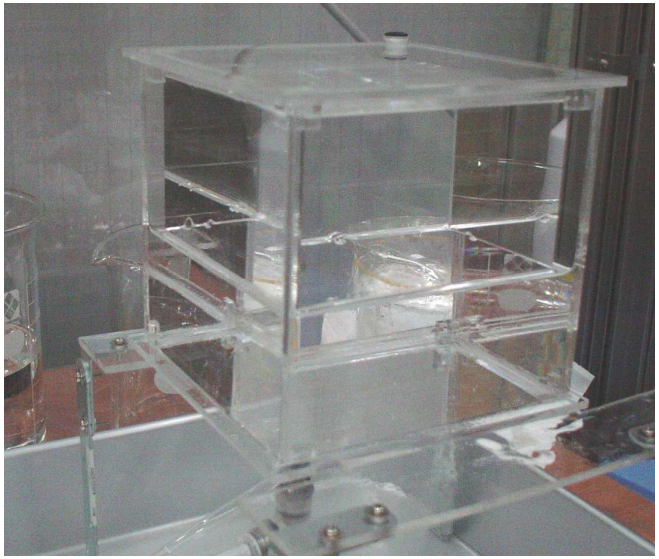
Photomultiplier Tube(13inch)

Tank for Liquid Scintillator
(Acrylic Case)

CaF_2 module

Candles

- CaF_2 + conversion phase + acrylic case



half filled

filled

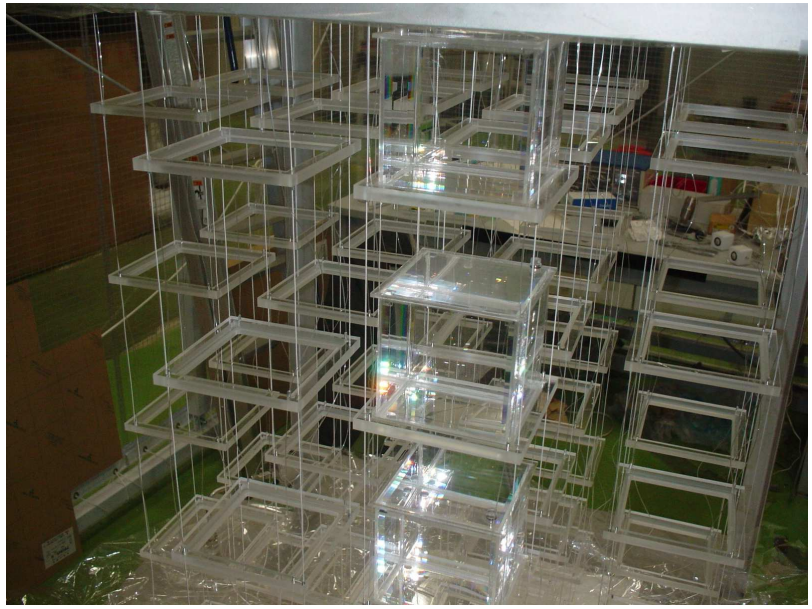
Index 1.44@586nm (CaF_2)

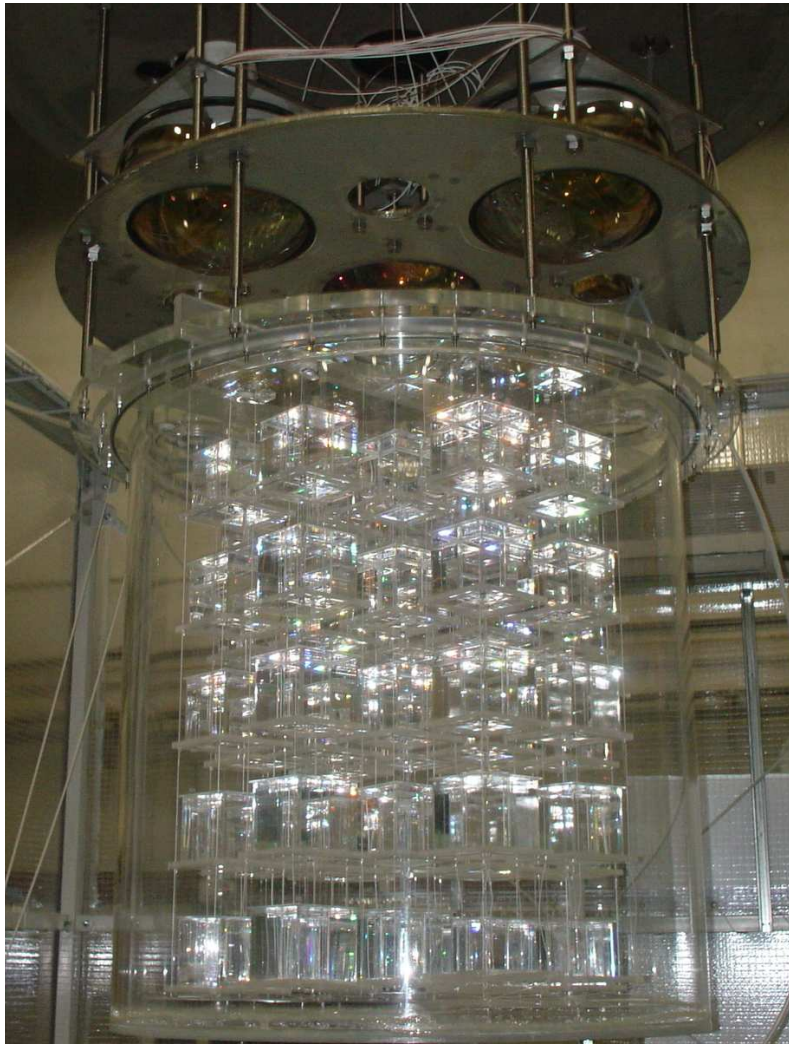
Index 1.46@586nm (Mineral Oil)

LS tank

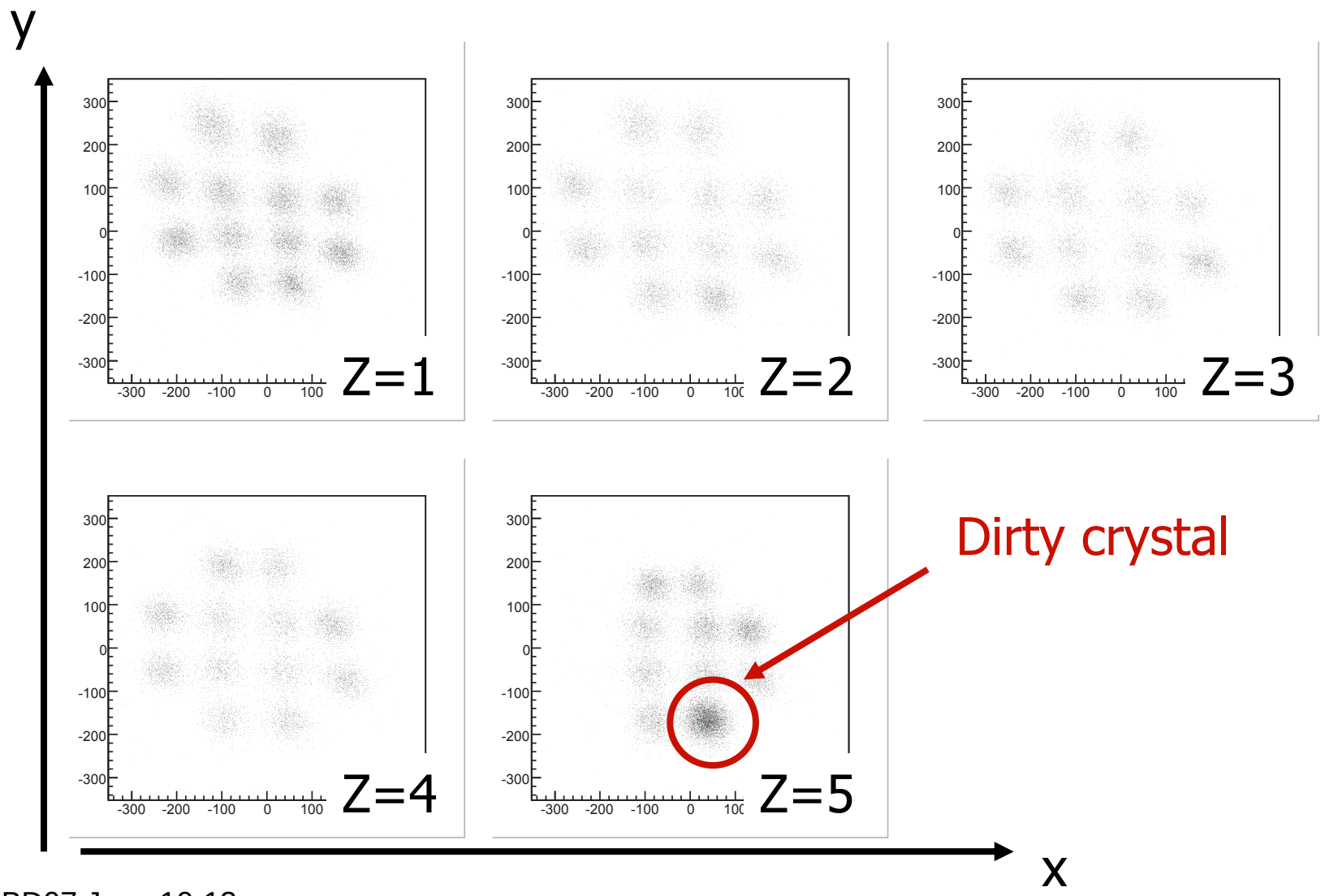
Candles

- 58 CaF_2 modules installed





Calibration just started



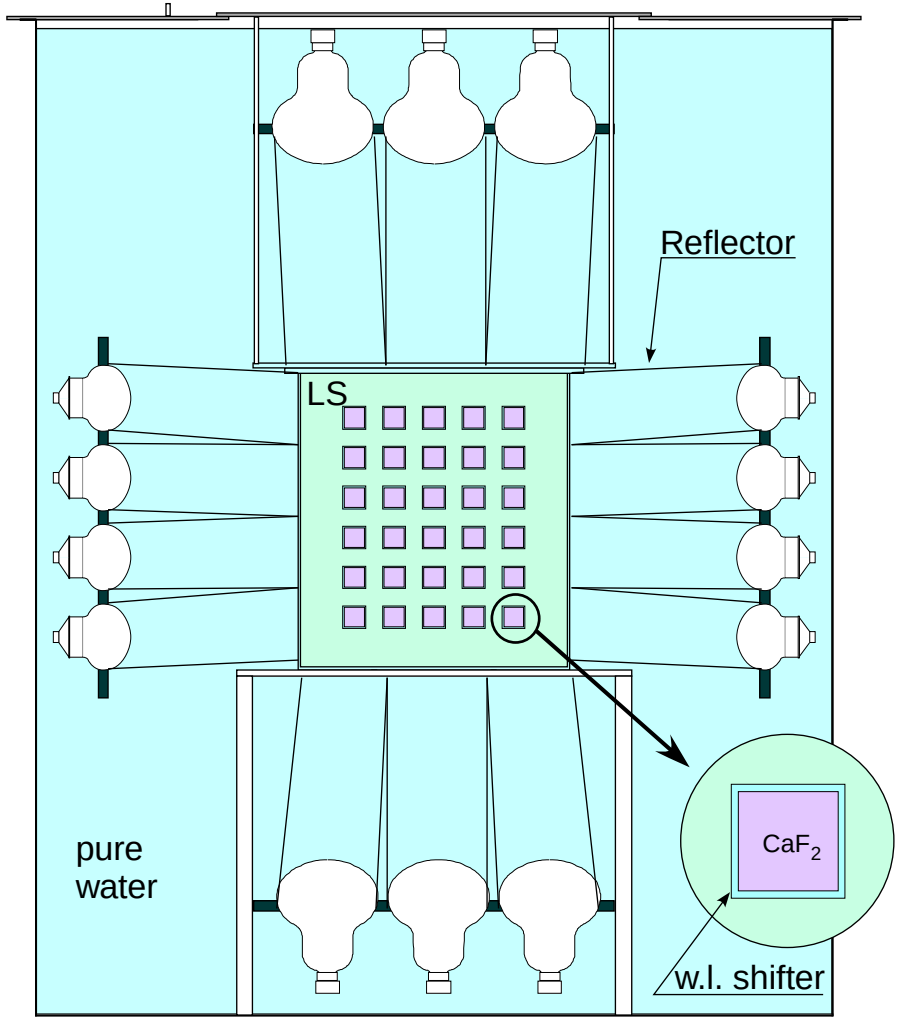
CANDLES III(U.G.)

san-chika

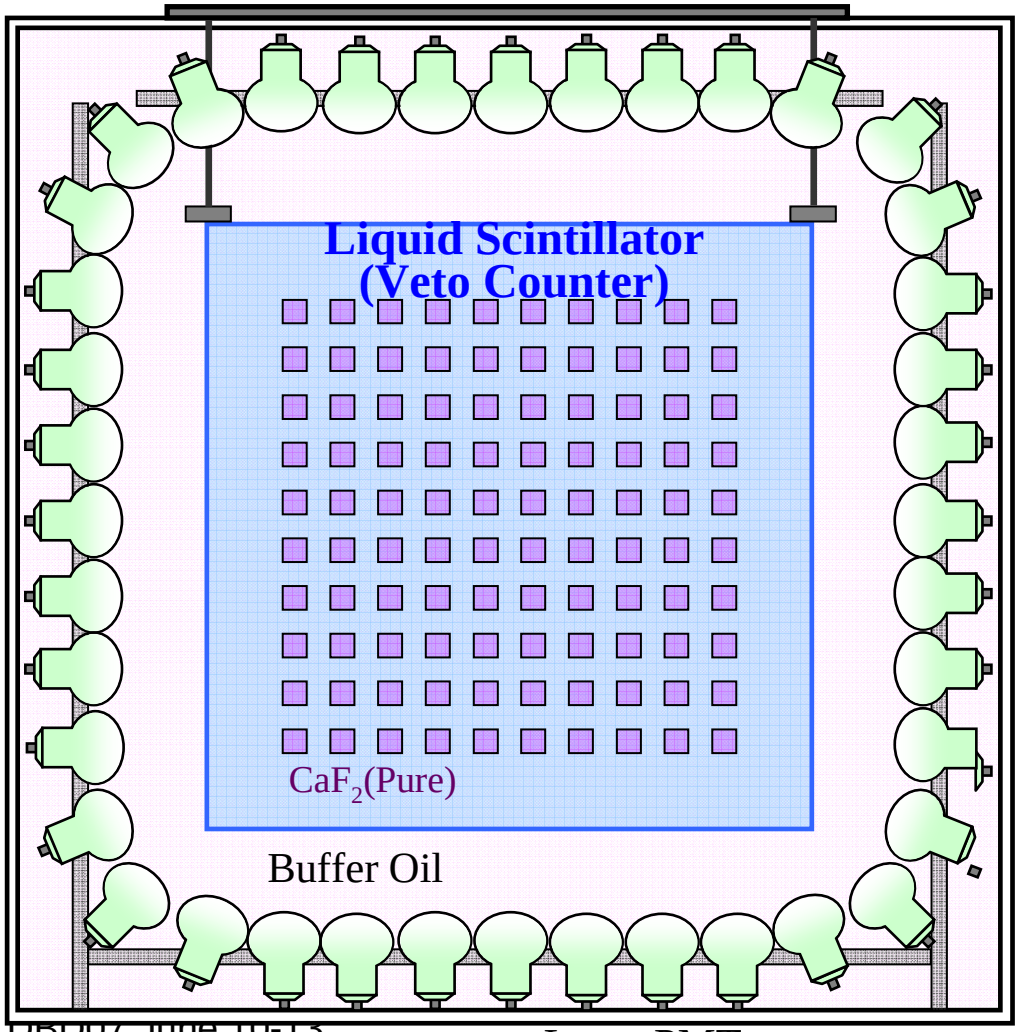
- CaF_2(pure)
  - 10^3 cm^3 × 96 crystals; 305 kg
- Liquid scintillator
  - two phase system
  - Purification system
- H_2O Buffer
  - passive shield
- PMTs
  - 17” PMT (×14) : R7250
  - 13” PMT (×56) : R8055
  - mirror type reflector
- photon trans. simulation

  ⇨ energy res. ~3.5 % @ $Q_{\beta\beta}$

- Kamioka underground lab.



CANDLES IV



$10 \times 10 \times 10$ cm^3 CaF_2 (1000 cubes) 3.2 t liquid scintillator Vessel (^{48}Ca) 3.2 kg

1. BG (~10μBq/kg Th)
    1. Needs R&D
    2. Current best ~6μBq/kg
2. Energy resolution
    1. Photo coverage

Mile stone

- ELEGANTS VI
  - running with new BG rejection (2ν)
- CANDLES I, II
- CANDLES III
  - 10cm^3 cube (100 crystals) ~0.5 eV
  - BG of CaF_2 ~30 μBq/kg (<100 μBq/kg) Achieved

- CANDLES III(UG) Kamioka
- CANDLES IV
  - 10cm^3 cube (1000 crystals) 3.2t
  - BG of CaF_2 ~10 μBq/kg for 0.2 eV
  - Kamioka

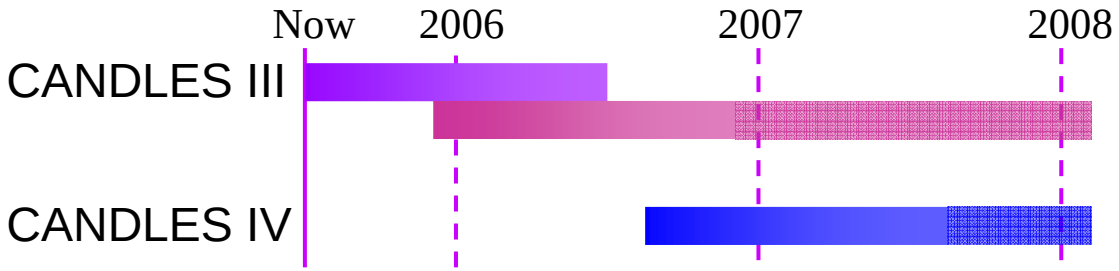
Future

- CANDLES V to sense 30 meV region
  - ~100 ton CaF_2
  - Can be installed in
    - Kamland
    - SNO

    } Vessel and PMT's
- Isotope separation
  - Available: ^{76}Ge, ^{100}Mo, ^{128}Te
  - exception: ^{48}Ca(Hazama), ^{150}Nd (Ohsumi)
    - R&D
      - Crown ether, centrifuge, others
    - If 2%: 10 meV region

Sensitivity of CANDLES Series

	CANDLES III	CANDLES IV	CANDLES V
Crystal	3.2kg × 60 crystals		
Total Mass	191kg	6.4 ton	100 ton
Energy Resolution	4.0%(Req.)	3.5%(Req.)	3.2%(Req.)
^{214}Bi(μBq/kg)	50	10	1
^{212}Bi(μBq/kg)	20	1	0.1
2νββ	0.01	0.10	1.33
^{214}Bi	0.01	0.03	0.05
^{212}Bi	0.07	0.10	0.15
^{208}Tl	0.04	0.06	0.10
Expected BG	0.14/year	0.29/year	1.63/year
Measuring Time	5 years	6	7
<mν>	0.56 eV	0.10	0.03



Performance @ sea Level Lab.
Measurement
@ Underground Lab.
Construction start