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

T. Kishimoto

Osaka Univ.

Contents

- Double beta decay and Majorana Mass
- Double beta decay of ^{48}Ca
  - –ELEGANTS VI
- How to sense 1~10^{-2} eV region
- CANDLES
  - –Concept
  - –CANDLES I, II, III, VI, V
- Prospect (Mile Stone)

Neutrino has to be Majorana particle

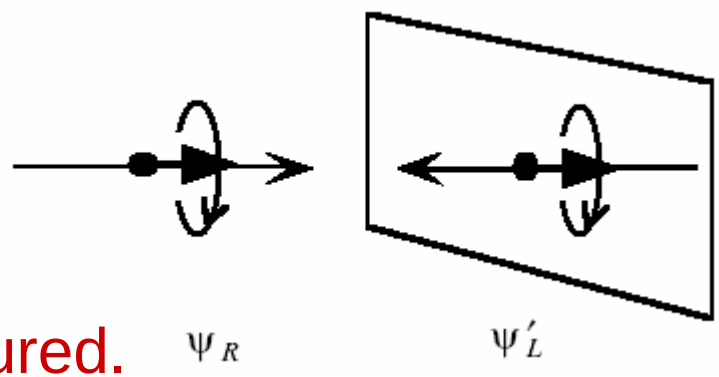
- Dirac mass term

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

- Majorana mass term
  - Left-handed and right-handed particle could have different mass
  - We have only left handed neutrino.
  - Heavy right-handed neutrino
  - Lepton number violation

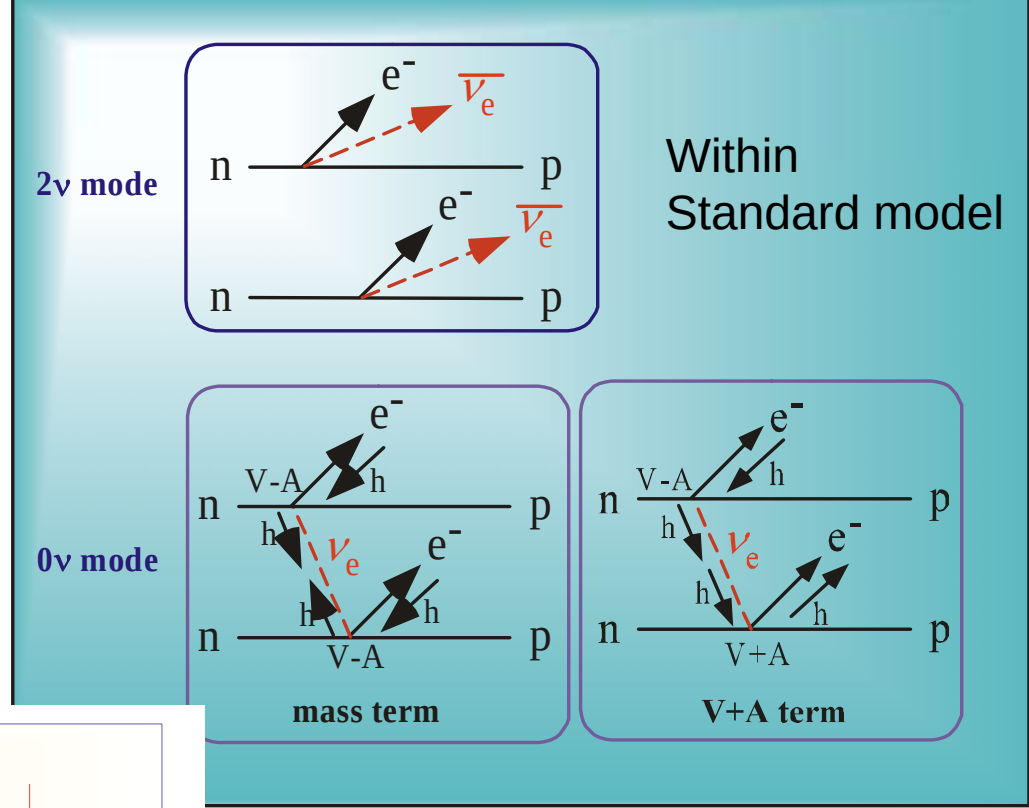
$$\mathcal{L}_{m_L} = -\frac{m_L}{2} \overline{(\nu_L^0)^c} \nu_L^0 + \text{ h. c.}$$

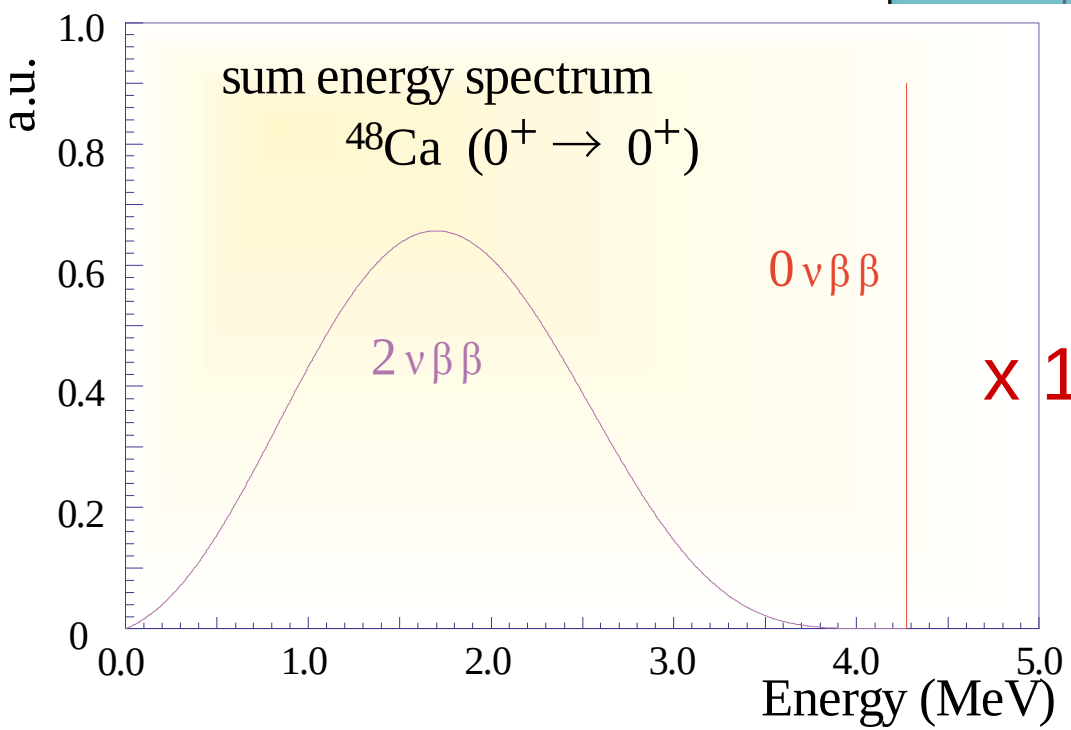
Relativity: Helicity flip mass



Double beta decay has to be measured.

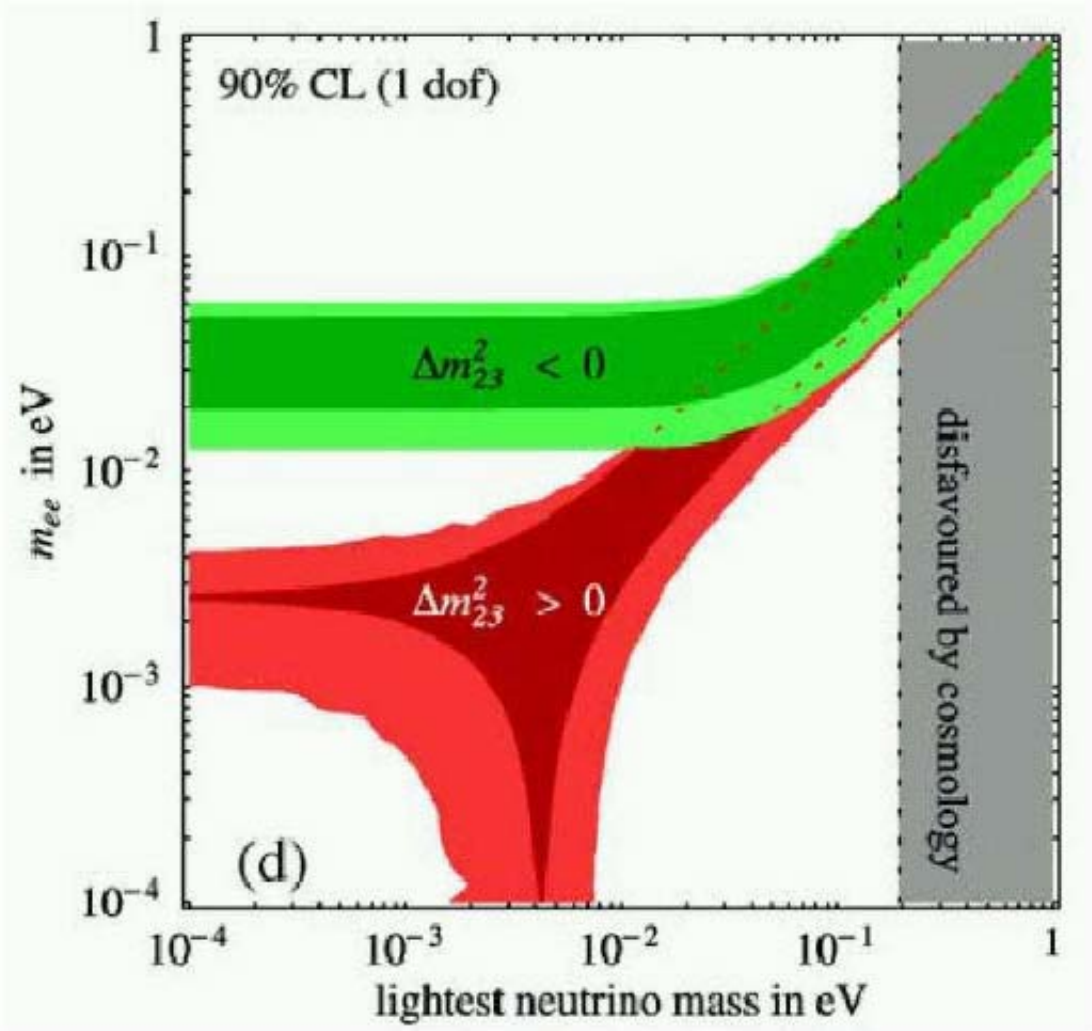
Double beta decay





x $10^{-5\sim6}$

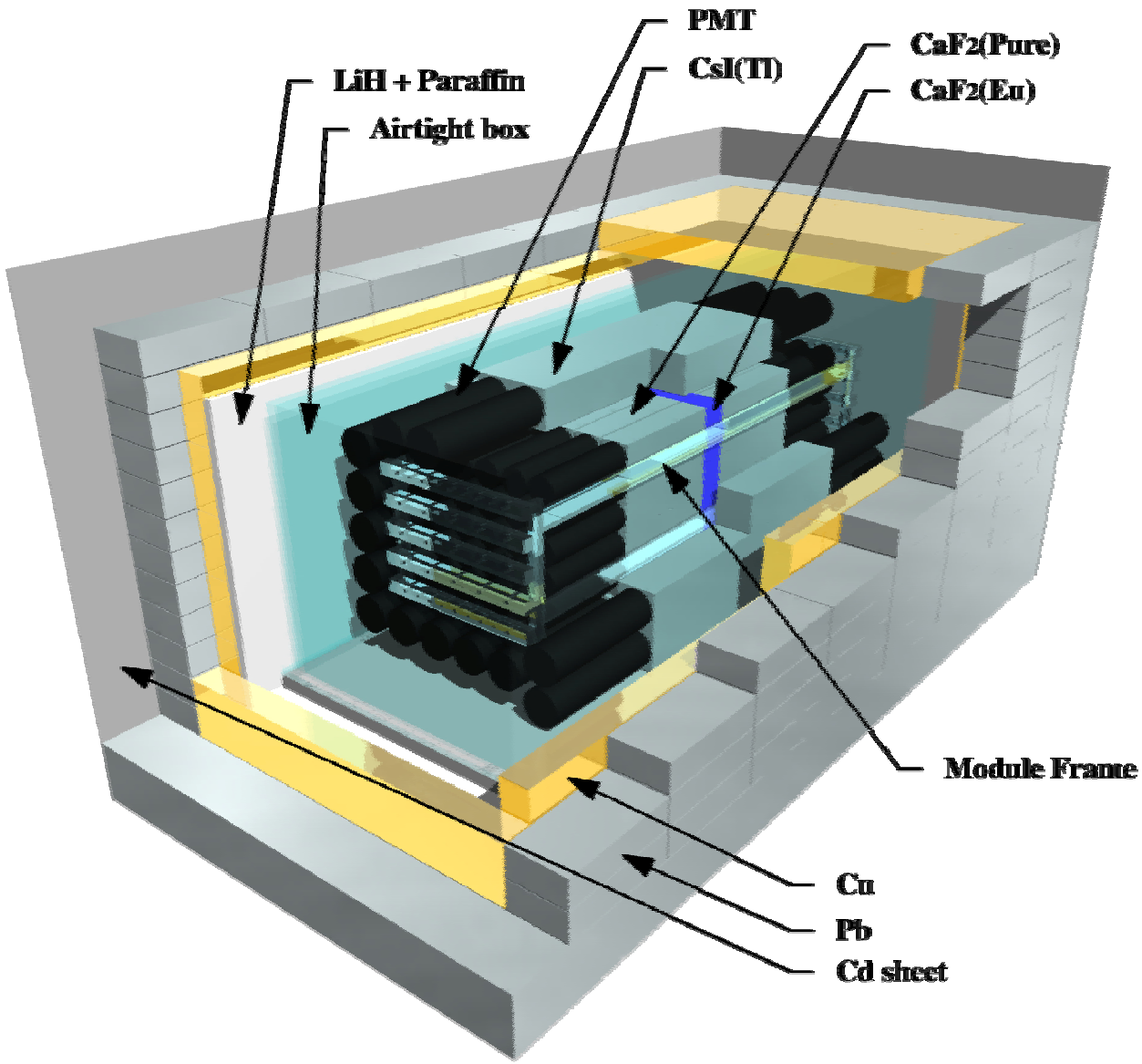
Current understanding



Double beta decay of ^{48}Ca

- Largest Q value (4.27 MeV)
  - next largest ^{150}Nd (3.3 MeV)
  - Large phase space factor
  - Least background (γ: 2.6 MeV, β: 3.3 MeV)
- Natural abundance → 0.187%
  - Enrichment → (no Gas); Hazama
  - Small amount ~10g
- Next generation
  - $M_\nu \propto 1/T^2 \propto$ M^2 if background free
  - $M_\nu \propto 1/T^2 \propto$ M^4 if background limited
- ^{76}Ge experiment (already seen backgrounds)
- ^{48}Ca (no backgrounds seen) large Q value

ELEGANT VI


PMT
CsI(Tl)
CaF2(Pure)
CaF2(Eu)
LiH + Paraffin
Airtight box
Module Frame
Cu
Pb
Cd sheet

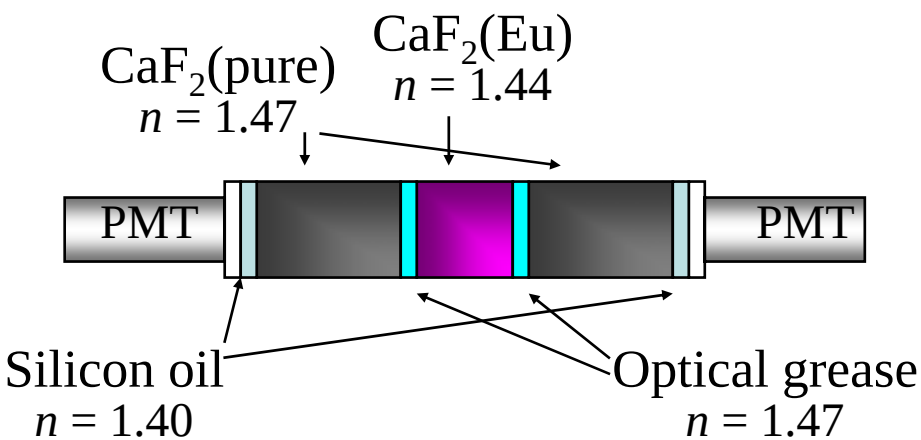
ELEGANTS VI

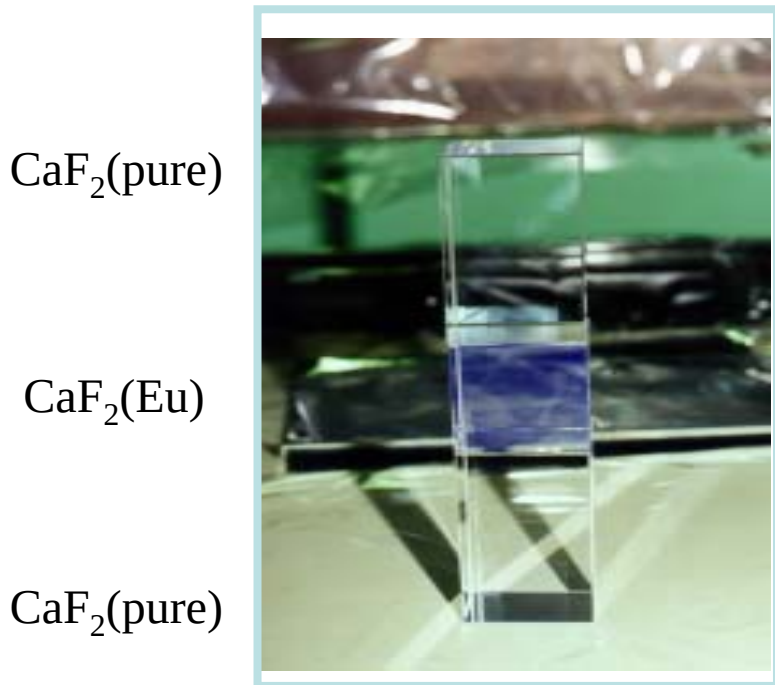
- CaF_2(Eu)
  - Size 45x45x45 mm^3 x 25(23)
    - ~6.42 g ^{48}Ca
- passive shield
  - OFHC Cu, Pb (γ)
  - air-tight box + N_2 gas purge (Rn)
  - LiH + paraffin, Cd sheet, H_3BO_3+H_2O tank (n)
- 4π active shield
  - CaF_2(Eu)+CaF_2(pure)
    - roll-off ratio (PMT side shield)
  - Segmentation (single hit)
  - CsI(Tl) veto detector

Roll-off ratio (4π active shield)

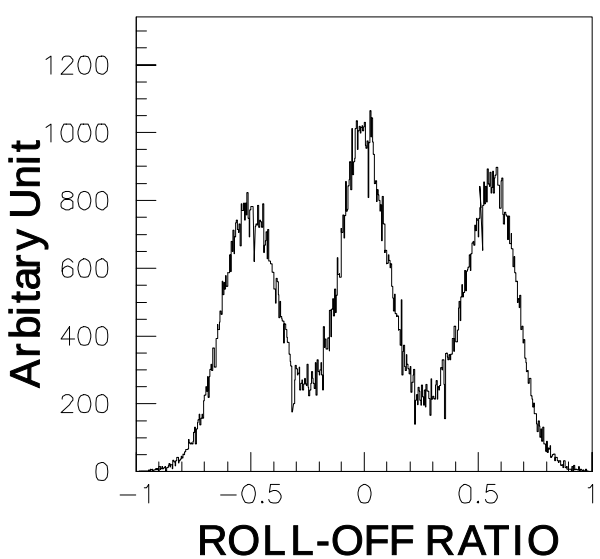
CaF_2(pure) as { light guide
active shield against PMT

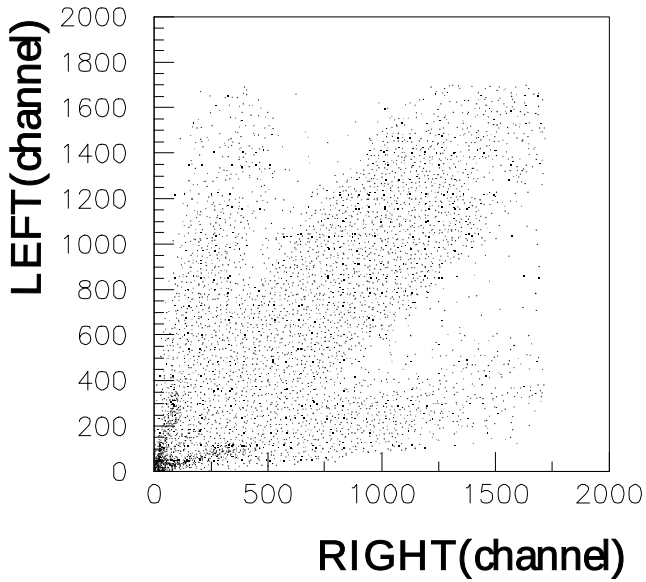
CaF_2(Eu) is not transparent for U.V. light





Roll-off ratio





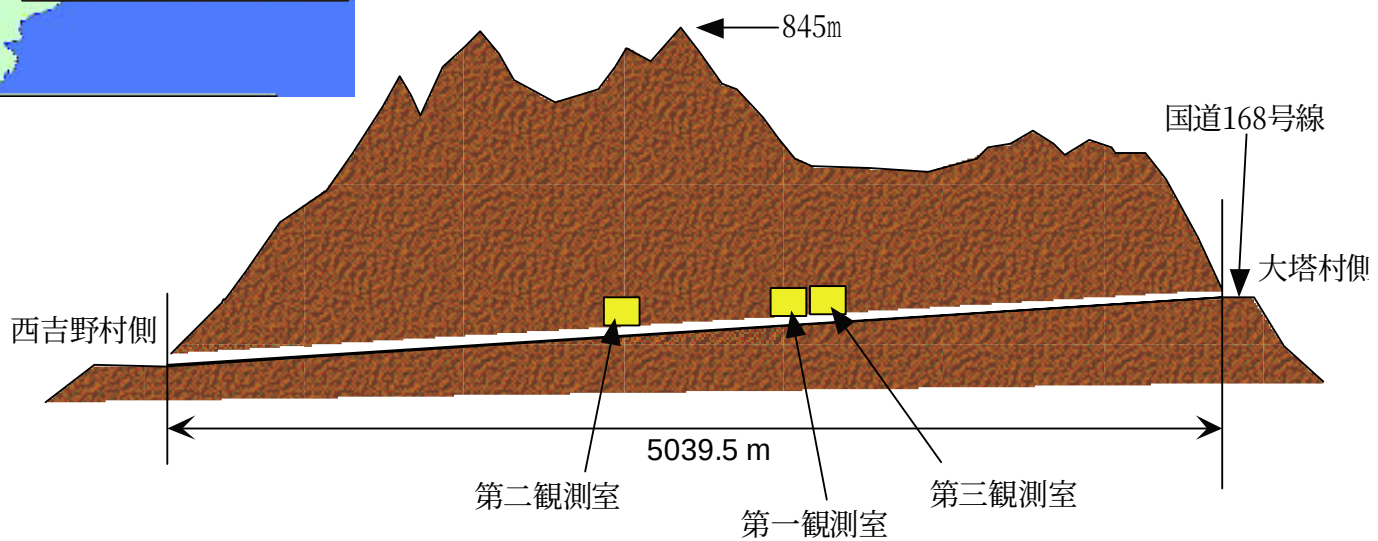
$$R = \frac{V_L - V_R}{V_L + V_R}$$

Oto Cosmo Observatory

tunnel constructed for railroad (but not used)

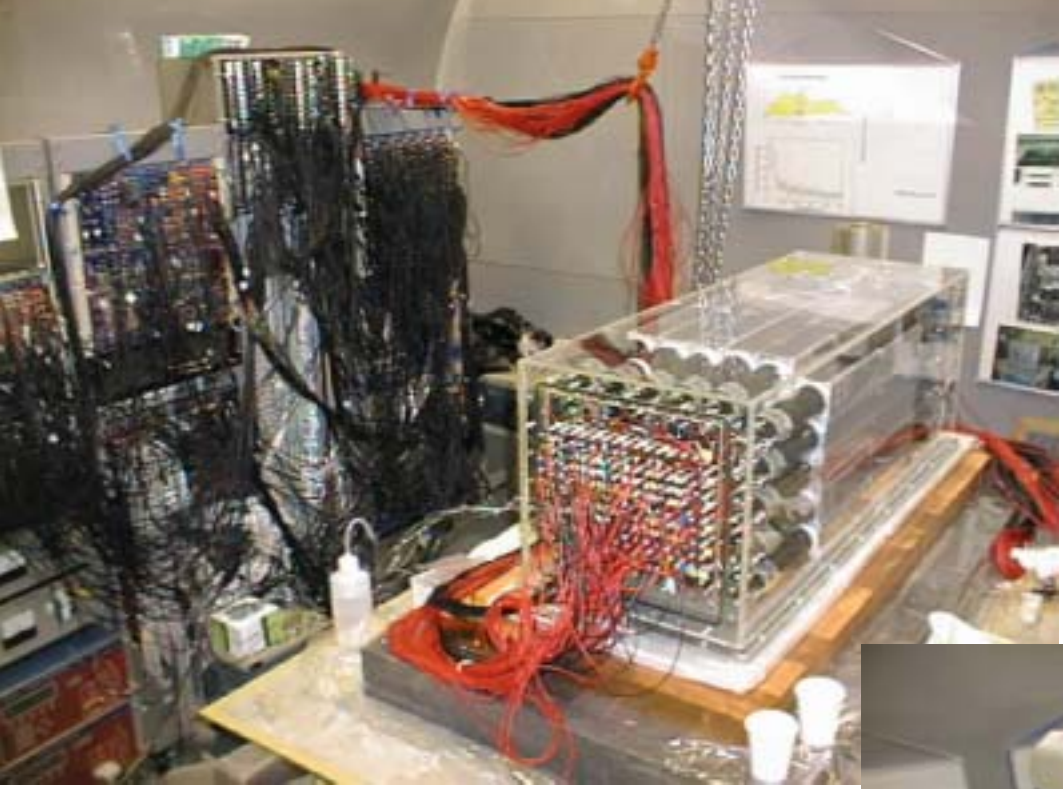
470m (1.3 km water equivalent) shield

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。

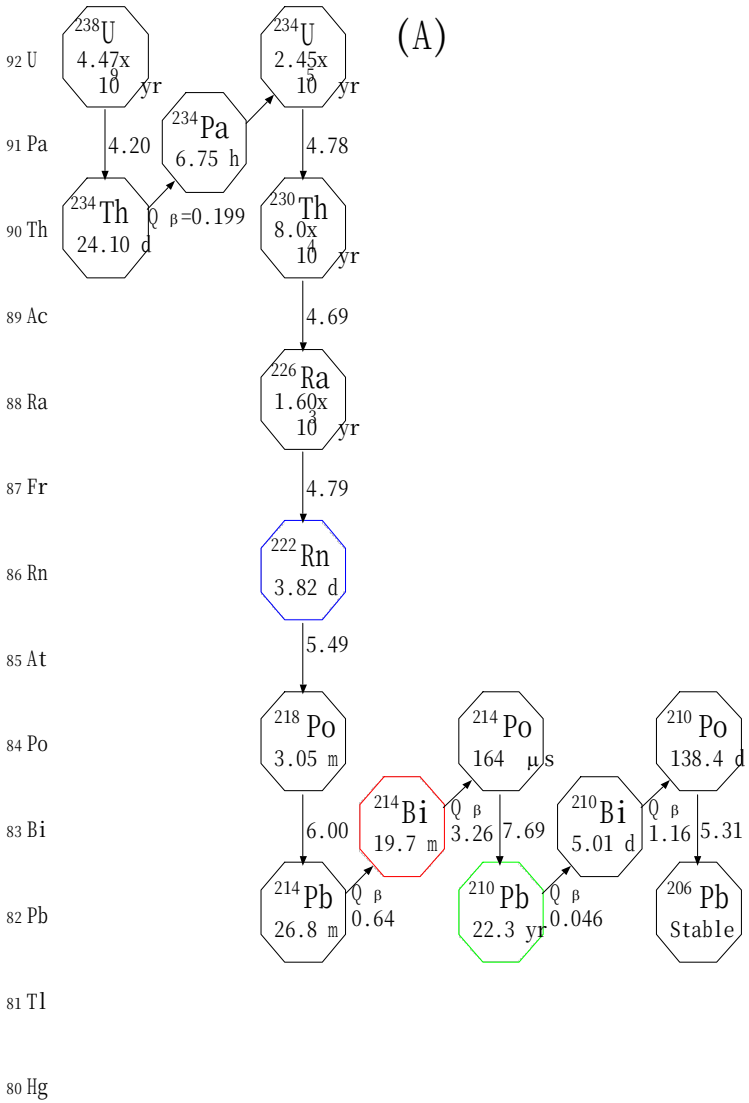


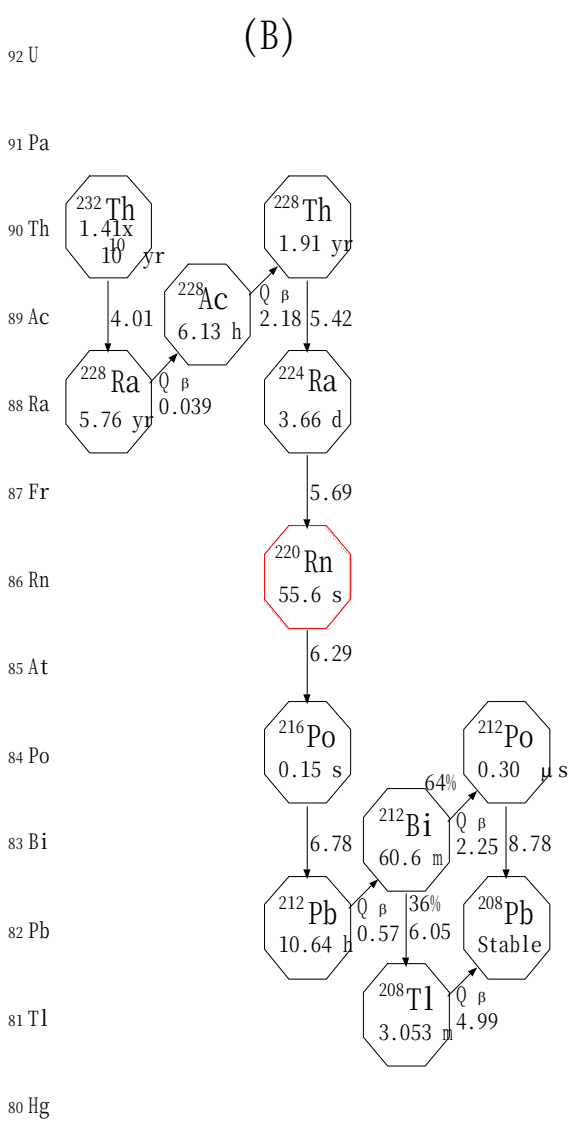
ELEGANT VI

Under ground laboratory



Radioactive Backgrounds





Radioactive Contamination

- U-series
  - hardware (second) trigger
  - time window : 9 – 499 μsec.

$$^{214}\mathrm{Bi} \xrightarrow{E_\beta=3270} {}^{214}\mathrm{Po} \xrightarrow{E_\alpha=7687} {}^{210}\mathrm{Pb}$$

$$(164.3\,\mu\mathrm{sec})$$

- Ac-series

$$^{219}\mathrm{Rn} \xrightarrow{E_\alpha=6819} {}^{215}\mathrm{Po} \xrightarrow{E_\alpha=7386} {}^{211}\mathrm{Pb}$$

$$(1.781\,\mathrm{msec})$$

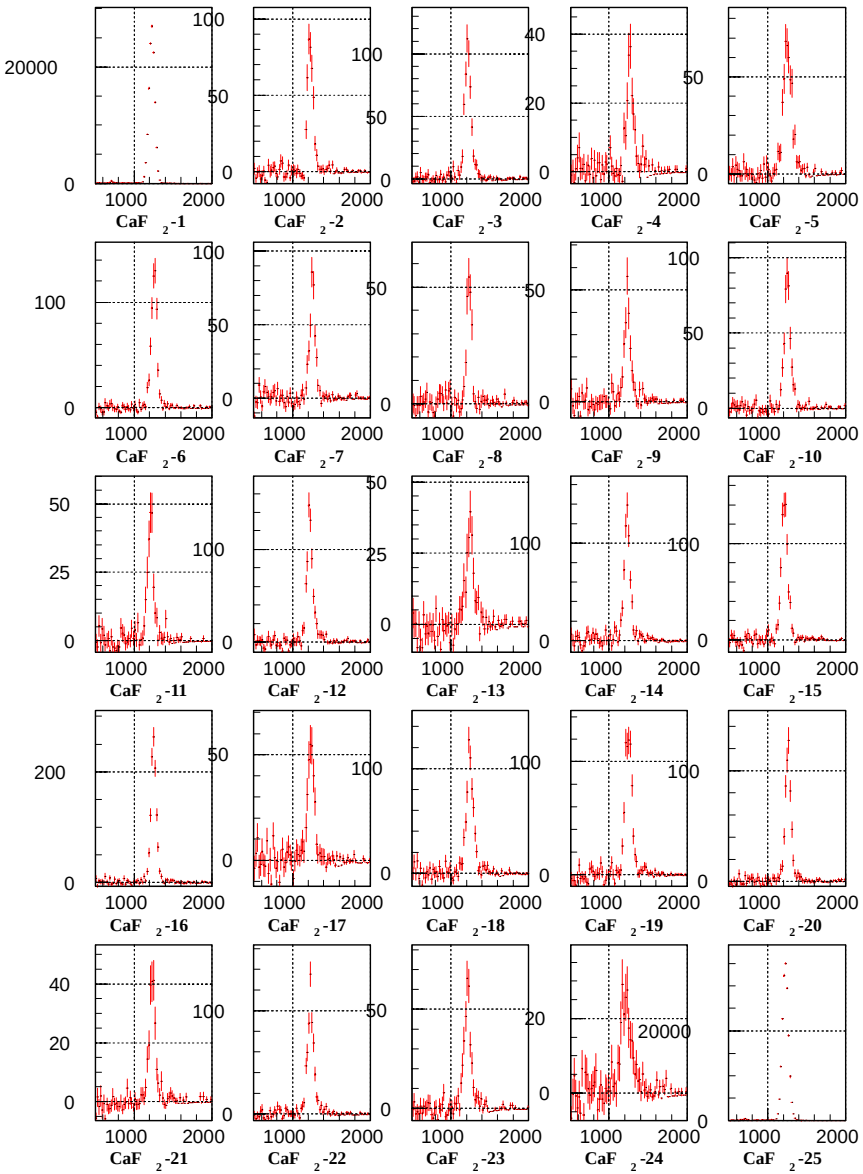
- Th-series
  - time window : 0.05 – 1.0 (0.5) sec.

$$^{220}\mathrm{Rn} \xrightarrow{E_\alpha=6288} {}^{216}\mathrm{Po} \xrightarrow{E_\alpha=6779} {}^{212}\mathrm{Pb}$$

$$(0.145\,\mathrm{sec})$$

$^{220}\mathrm{Rn} \xrightarrow{E_\alpha = 6288} {}^{216}\mathrm{Po} \xrightarrow{E_\alpha = 6779} {}^{212}\mathrm{Pb}$

(0.145 sec) time window : 0.05-1.0 sec



Average contamination

(#2 — #24)

U – series

1.11×10^{-3} Bq/kg

Ac – series

3.84×10^{-4} Bq/kg

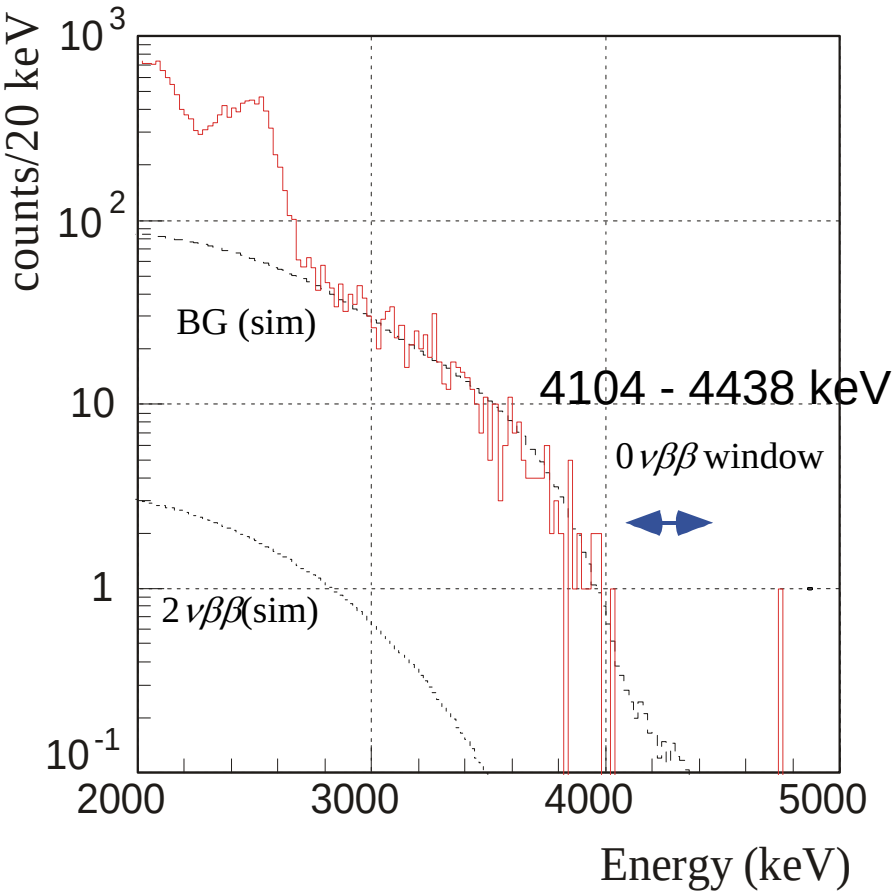
Th – series

1.09×10^{-4} Bq/kg

U: 1.25×10^{-5} Bq= 1 ppt

Th: 0.1 mBq=24.6 ppt

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



0.63 y

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

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

World best value

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

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

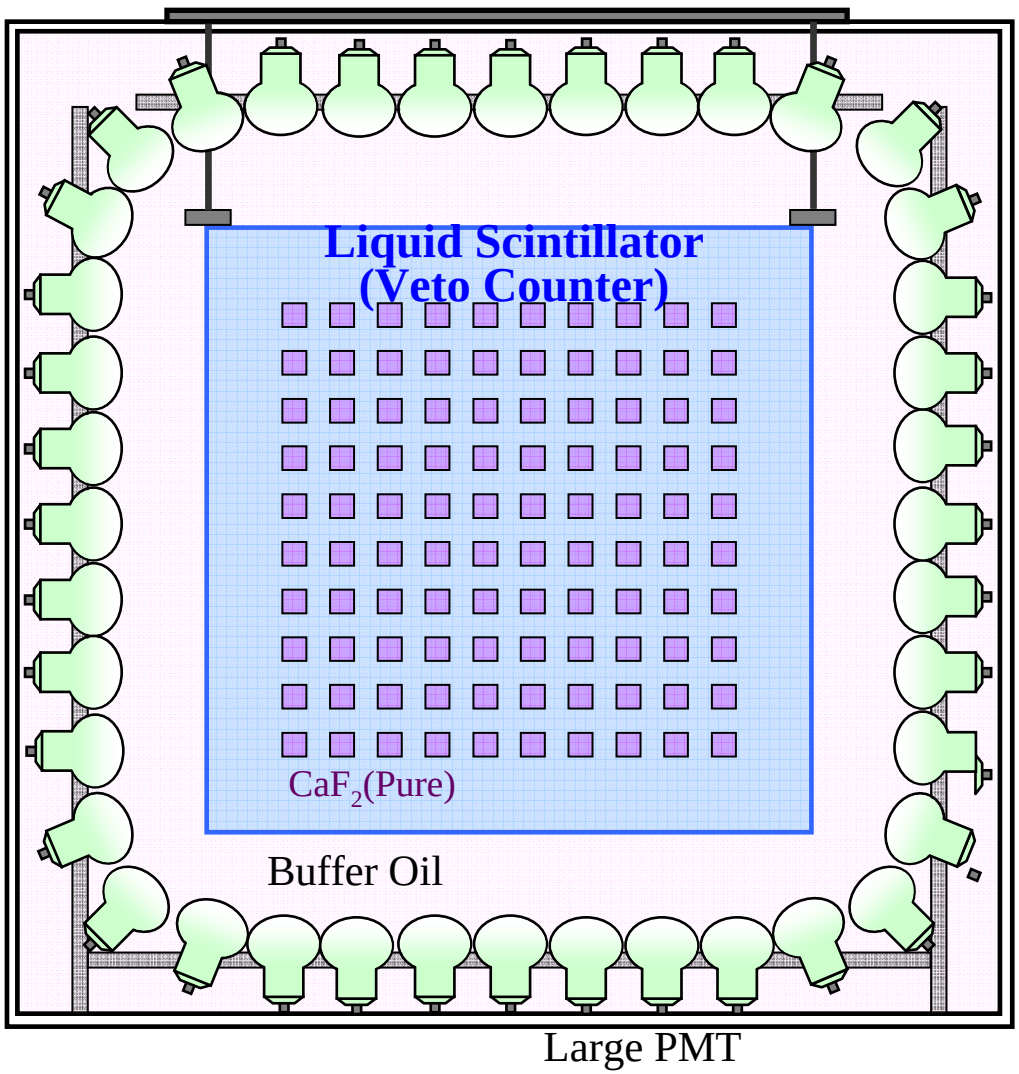
How to sense m_ν=1~10^{-2}eV

- 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, 400kg, 6t,100t
  - ^{48}Ca ($Q_{\beta\beta}$=4.27MeV)
- **Liquid Scintillator**
  - Wave Length Shifter
  - 4 π Active Shield
  - Passive shield
- **Photomultiplier**
  - energy resolution

Big detector

- CaF_2 crystal
  - Best optical lens
  - Long attenuation length
    - 10m (catalog value for visible light)
    - >1m (our measurement for scintillation light)
- Large volume detector
  - 10x10x10 cm^3 x 600 (6t) (CANDLES IV)
  - Increase the number of nuclei (^{48}Ca)

6.4 g (ELE VI) ~6(kg)

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

Low Radioactive Background

Active shield (Liquid Scintillator)

- 4π active shield

  decay time of the signal

  - ~1 μsec CaF_2
  - ~10 nsec liquid scintillator

- passive shield
  - Large volume with Low radio activity
  - U/Th ~0.1ppt, K ~1ppt
  - purification system (U,Th,K,Rn,…)

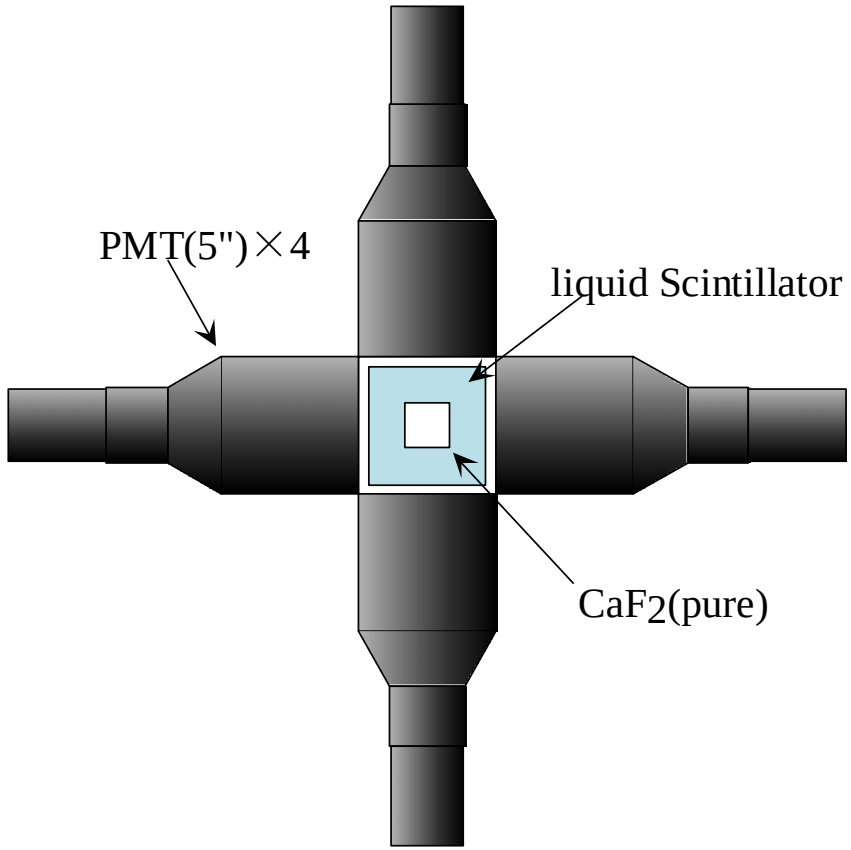
    KamLAND, BOREXINO

CANDLES I

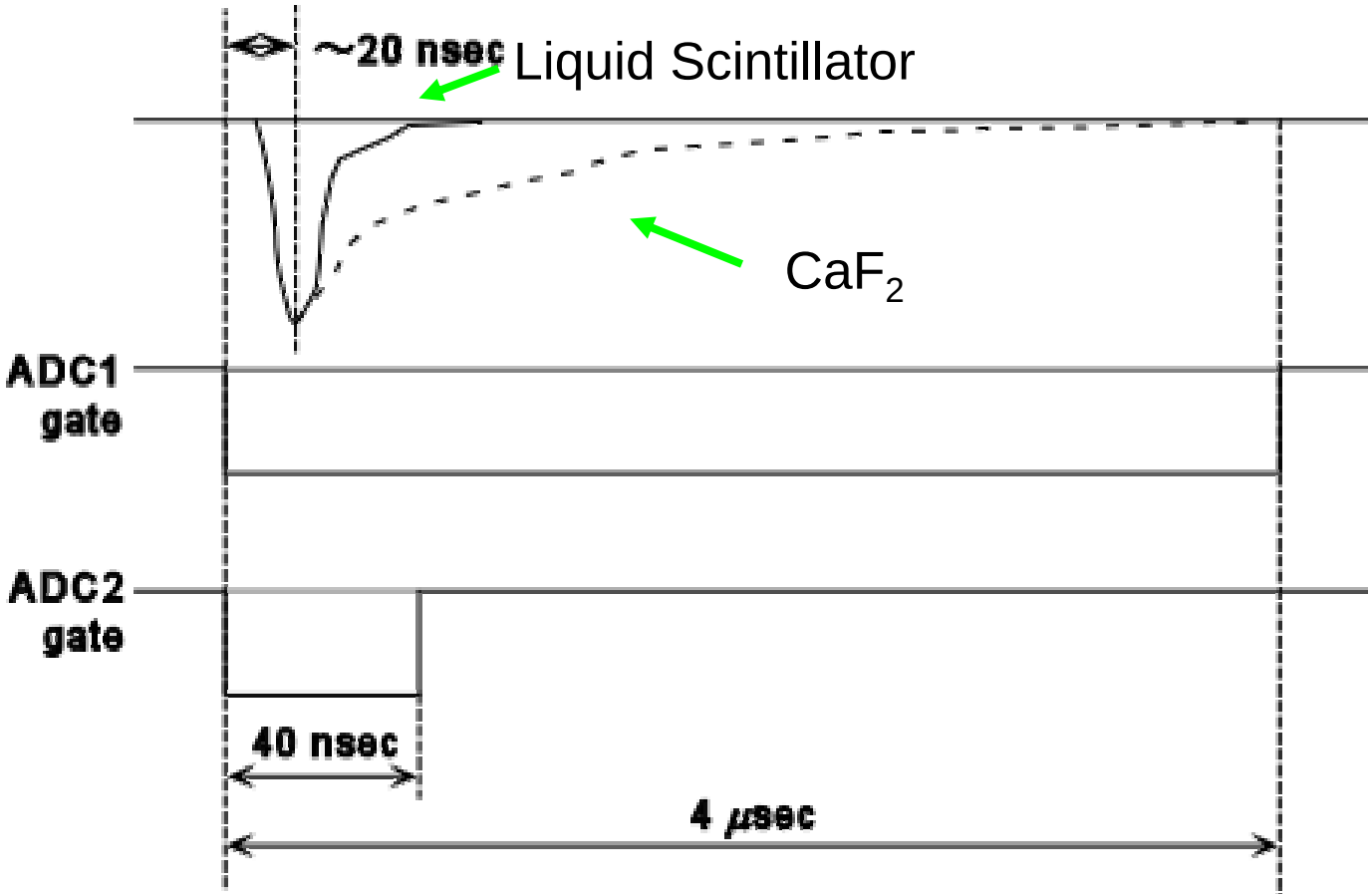
POP (Proof of Principle) Detector

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)

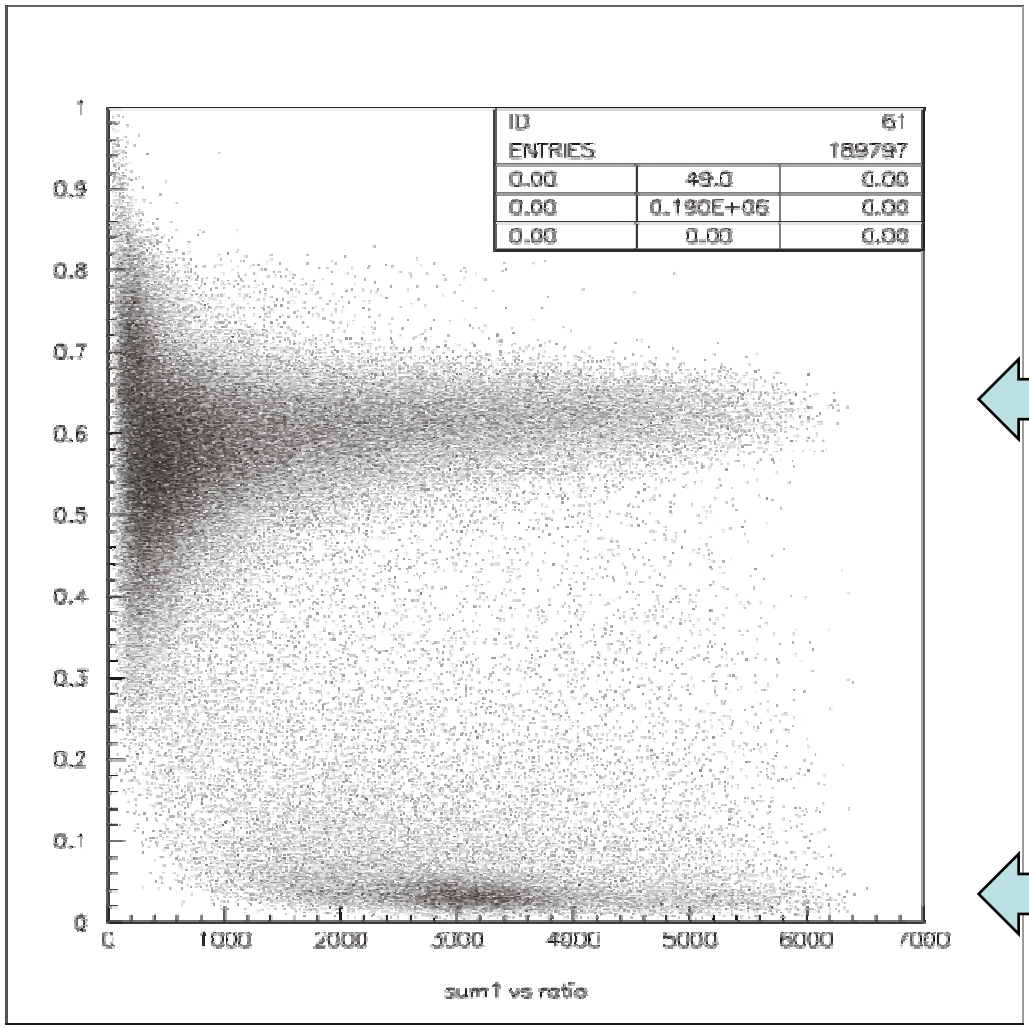


Signal discrimination



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

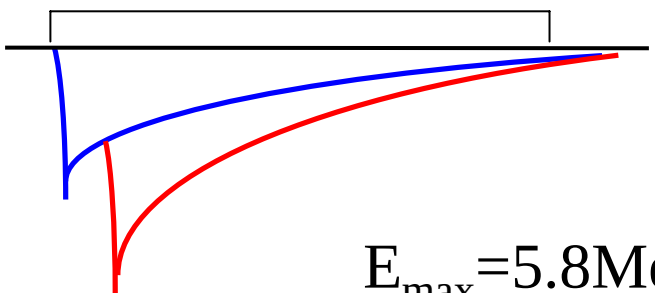
CaF_2

Low background material

- Backgrounds @ ~4 MeV
  - Maximum energy
    - γ~ 2.6 MeV, β~3.3 MeV, α(max)~2.5 MeV(quench)
  - Successive decay of α β γ
    - ~1μsec decay time

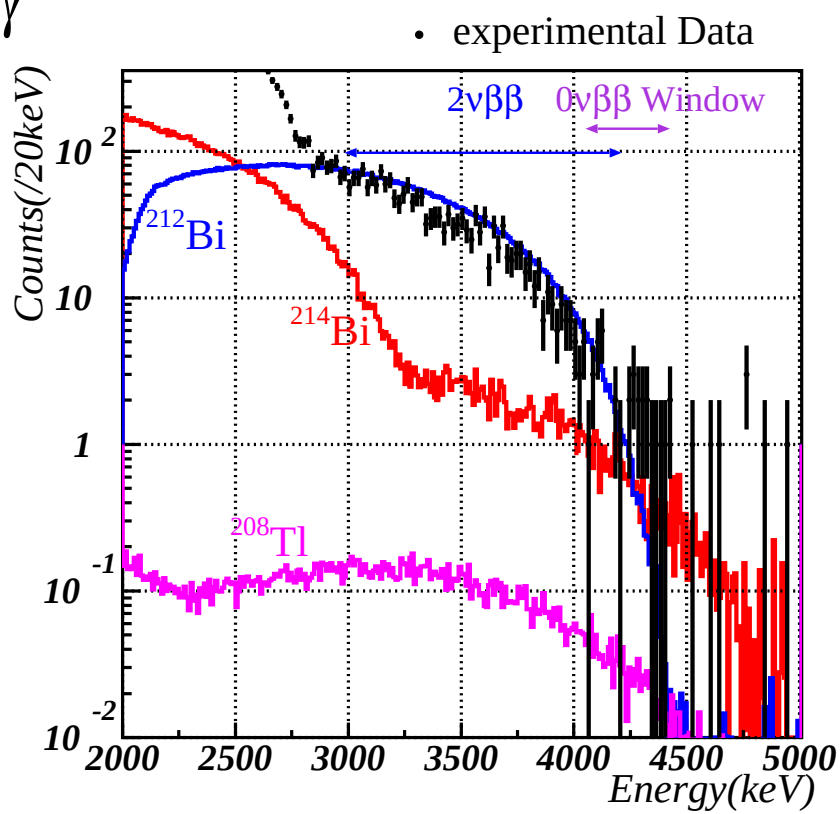
Pulse shape

Gate width(4μsec)

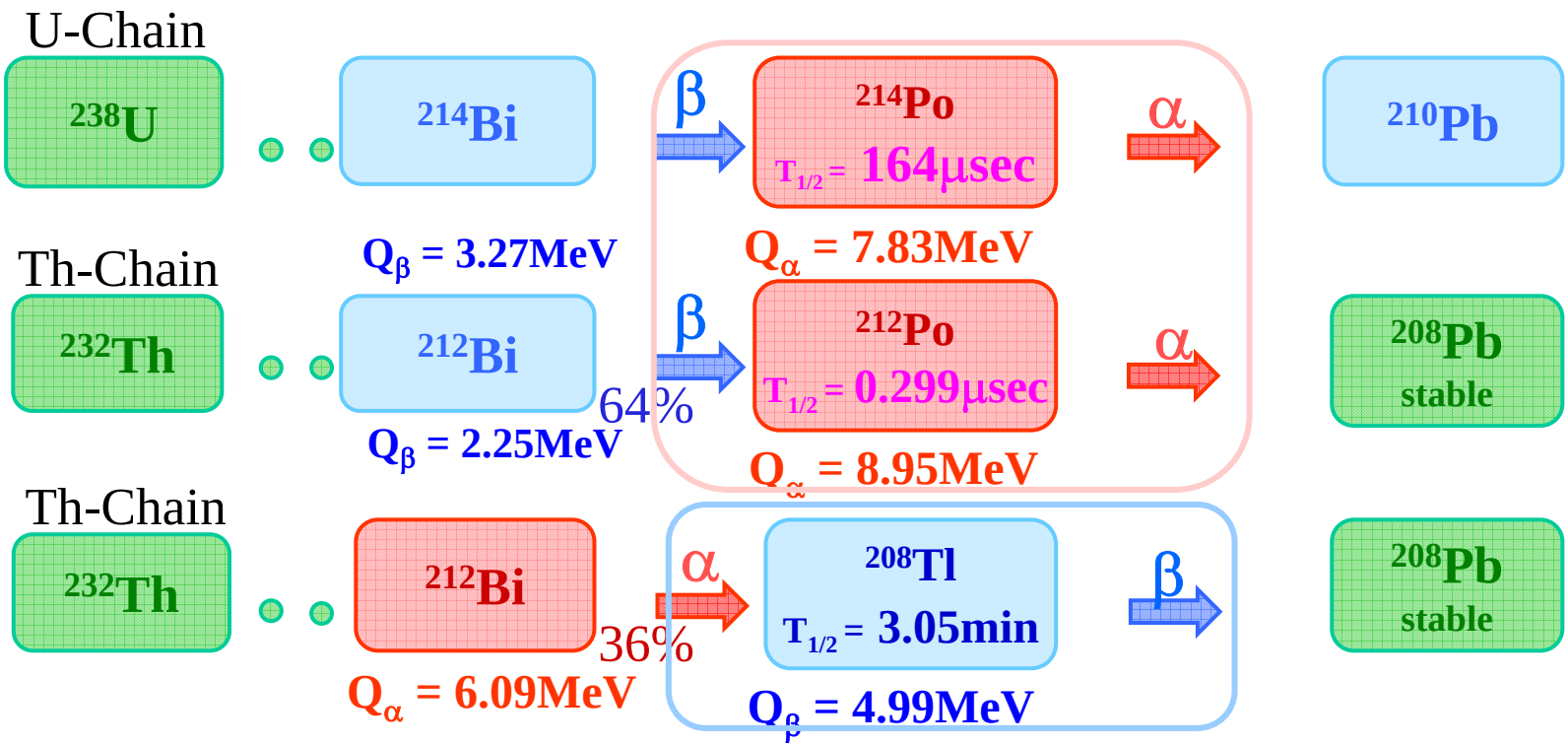


β+α

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



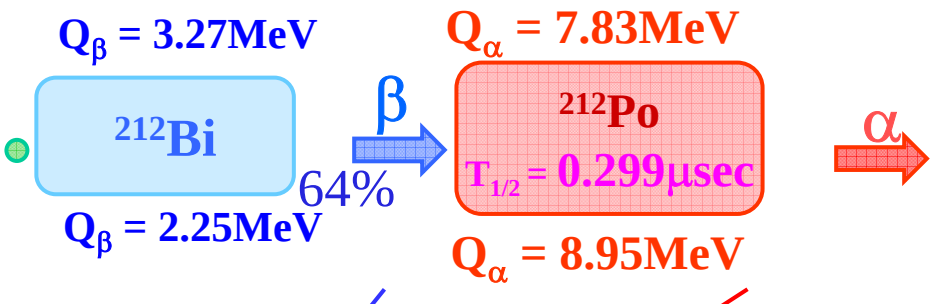
Backgrounds



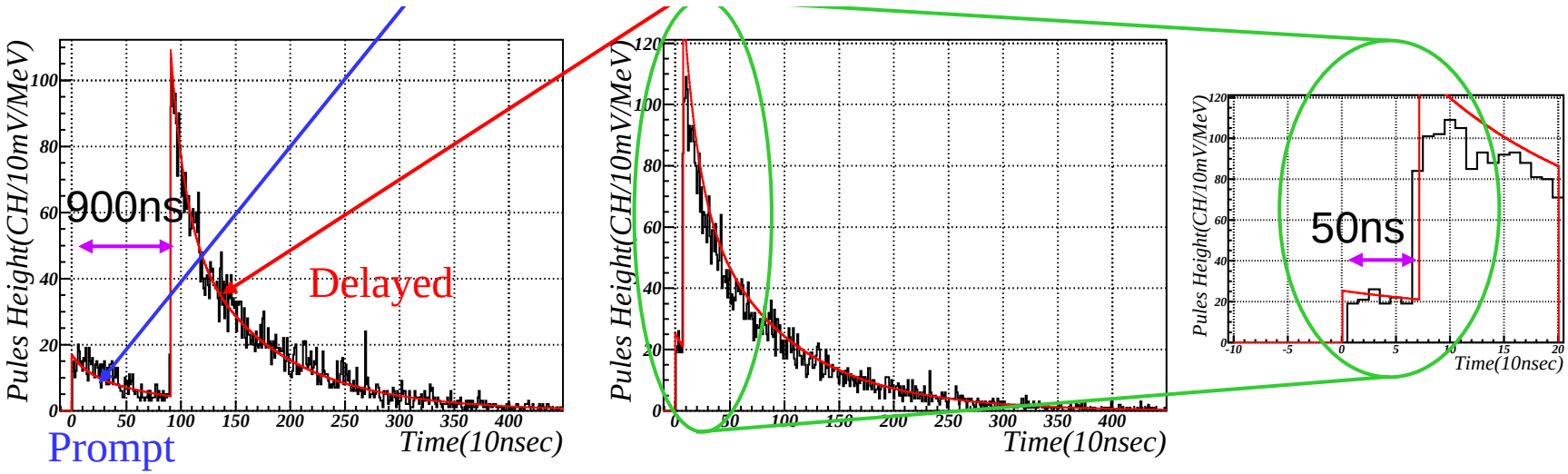
Rejection . . .

- High Purity CaF_2(pure) Crystal
- Rejection of double pulse
- Pulse Shape Discrimination between α and γ rays
- Space-Time Correlation Cut . . . For ^{208}Tl Rejection

Rejection of Double Pulse



Typical Pulse Shape(100MHz FADC)



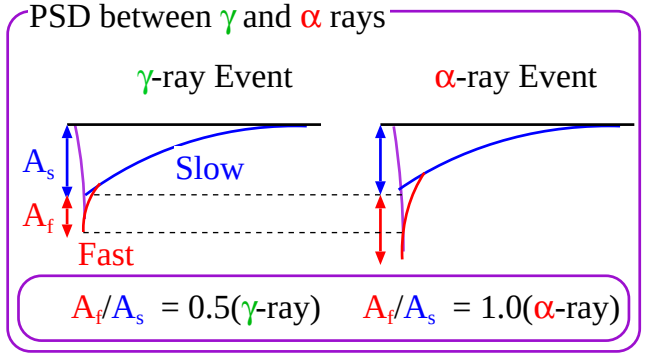
Reduction

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

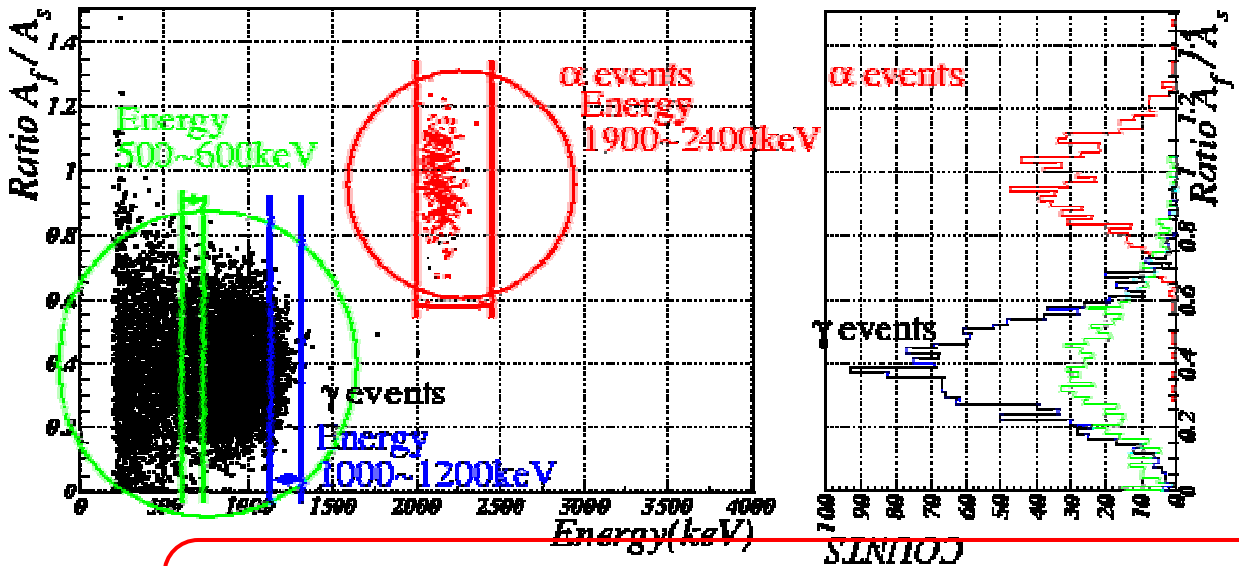
500MHz FADC (under preparation) . . . $\Delta T >$ **5ns ; ~1%**

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)**



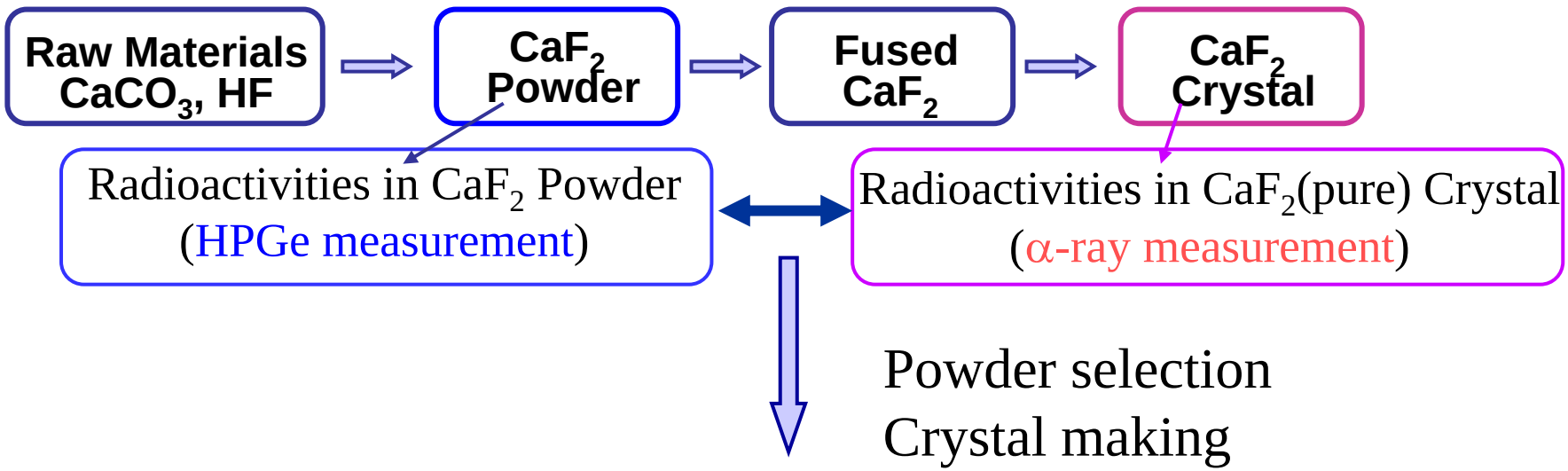
Discrimination between α and γ(β) Events

Background Reduction ~ 0.3%

Development of Low Background CaF_2 Crystals

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

- Where do is the crystals contaminated?



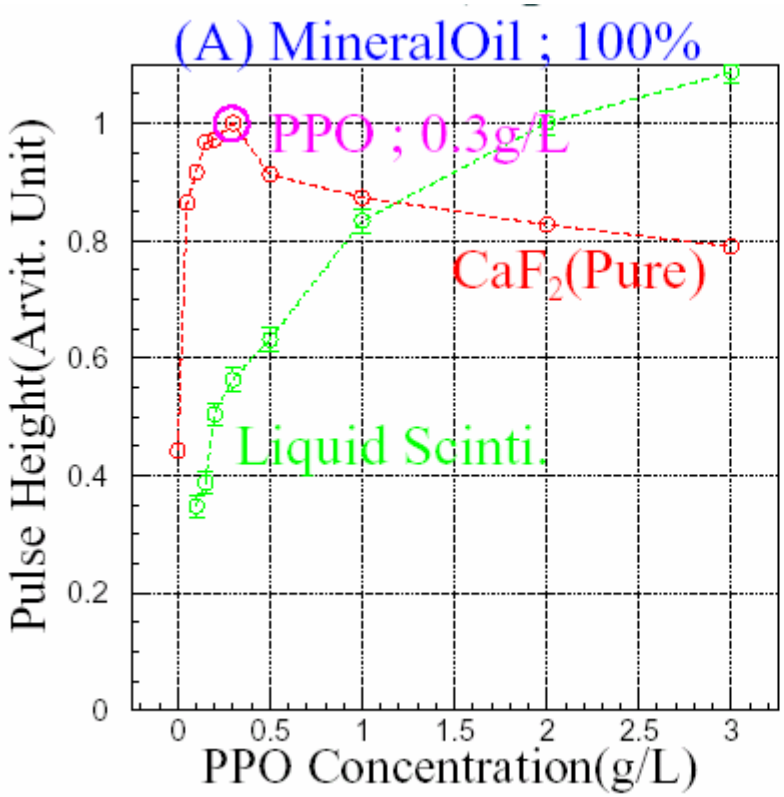
U-chain(^{214}Bi) ~41μBq/kg . . . 1/25 of Previous Crystals
Th-chain(^{220}Rn) ~21μBq/kg . . . 1/5 of Previous Crystals

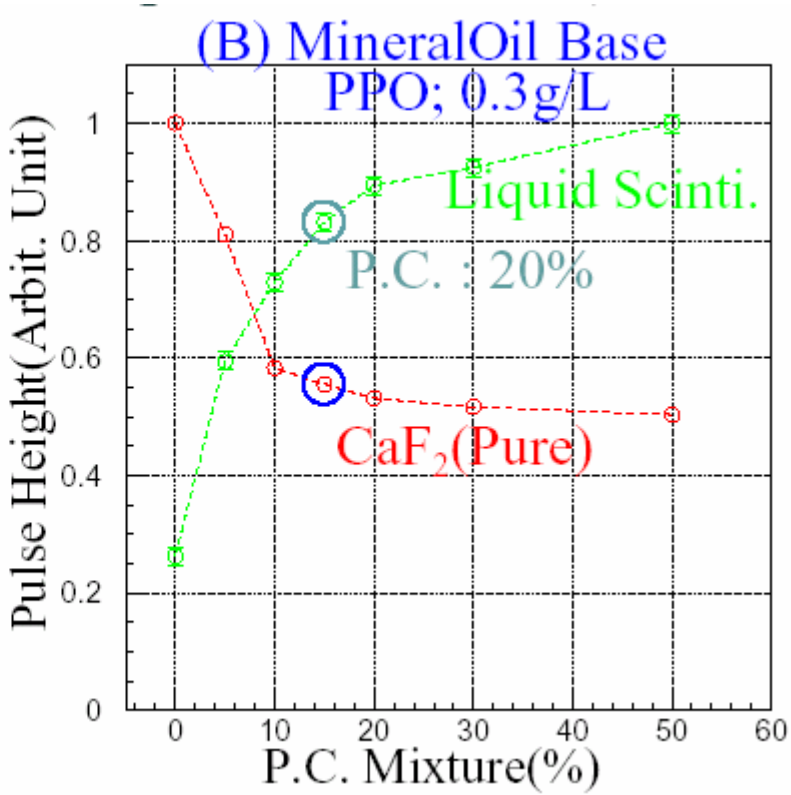
High resolution CaF_2 crystal

- Resolution $\Delta E \sim \frac{1}{\sqrt{N_p}}$
- Scintillation light
  - ~1/2 of CaF_2(Eu) (quart window PMT)
  - peak emission U.V. (285 nm)

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

Wavelength shifter





CaF_2 UV light

Maximum light output @ 0.3g/l PPO

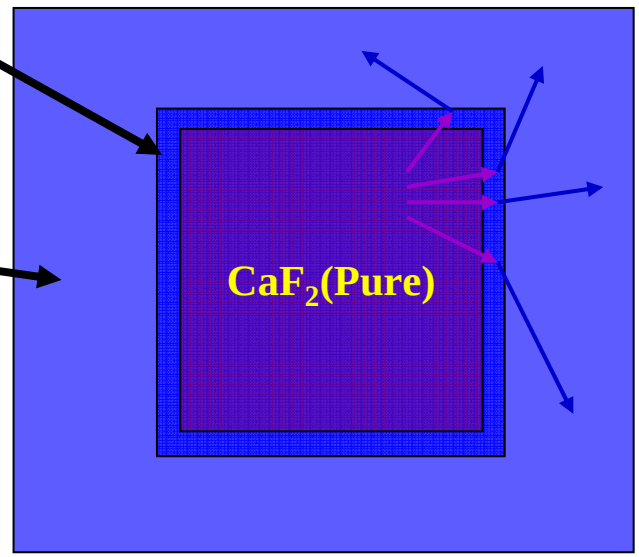
Pseudocumene reduces it.

→Two phase

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)

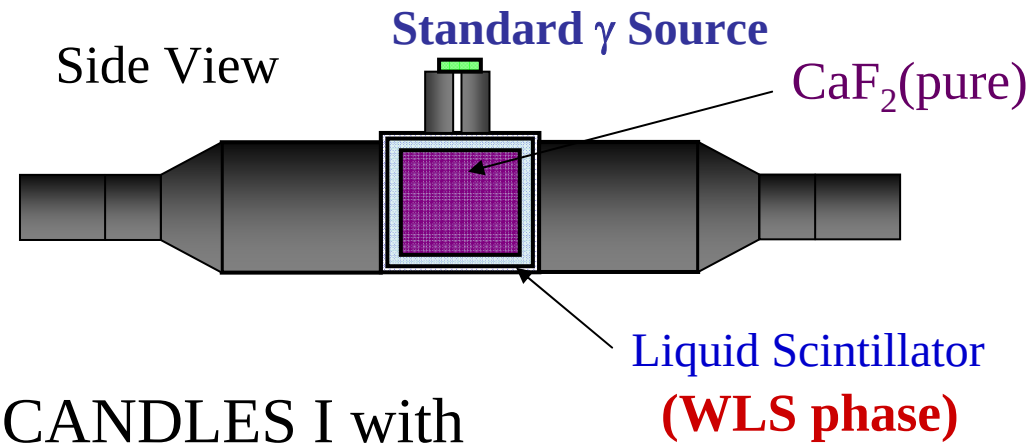
⇩

Conversion by WLS(350~400nm)

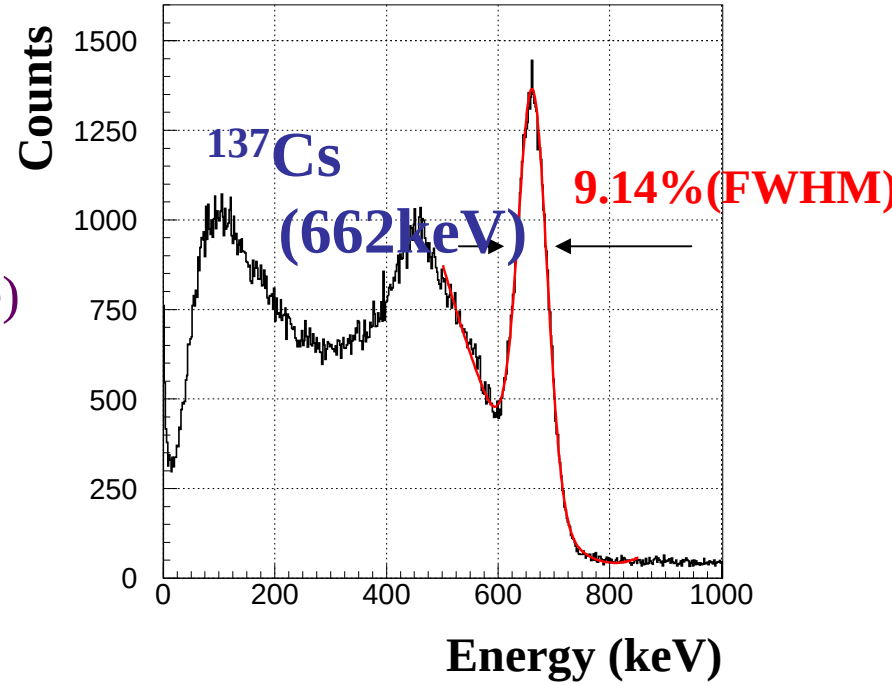
⇩ propagate

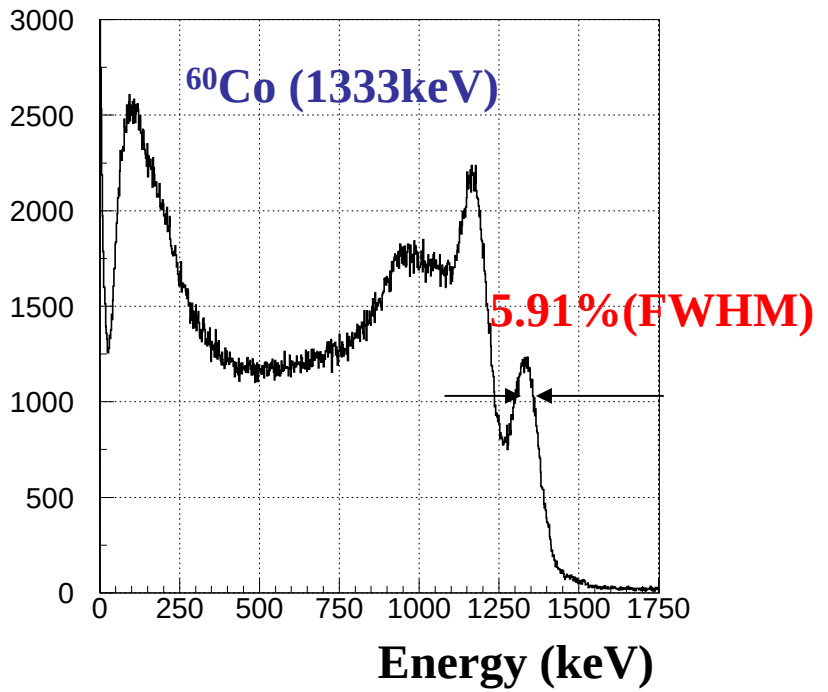
PMT

Performance



CANDLES I with
10 cm^3 CaF_2(pure)

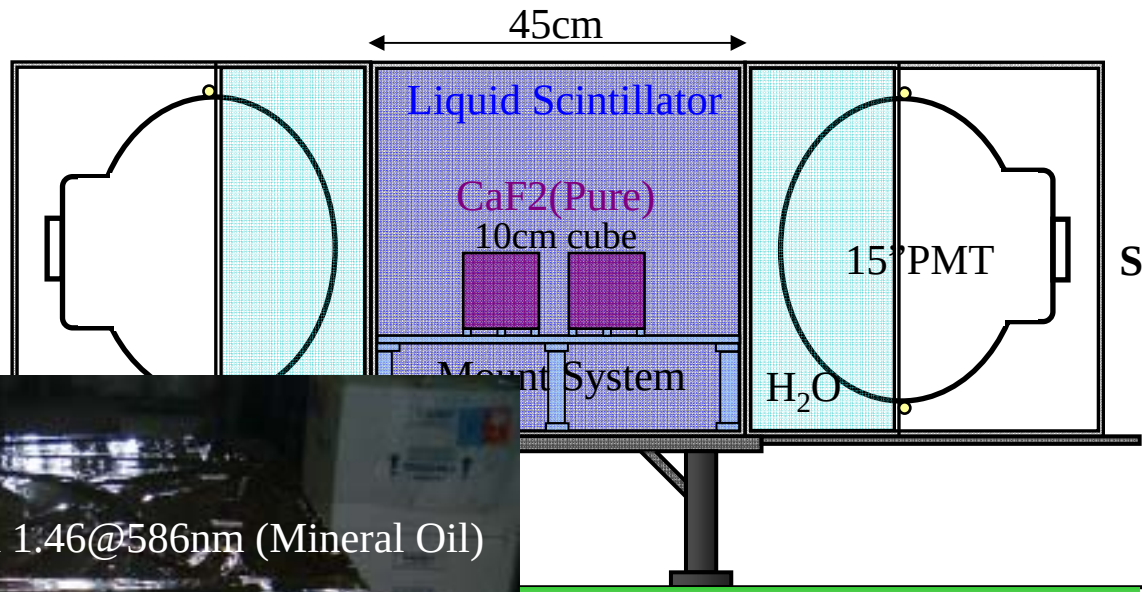




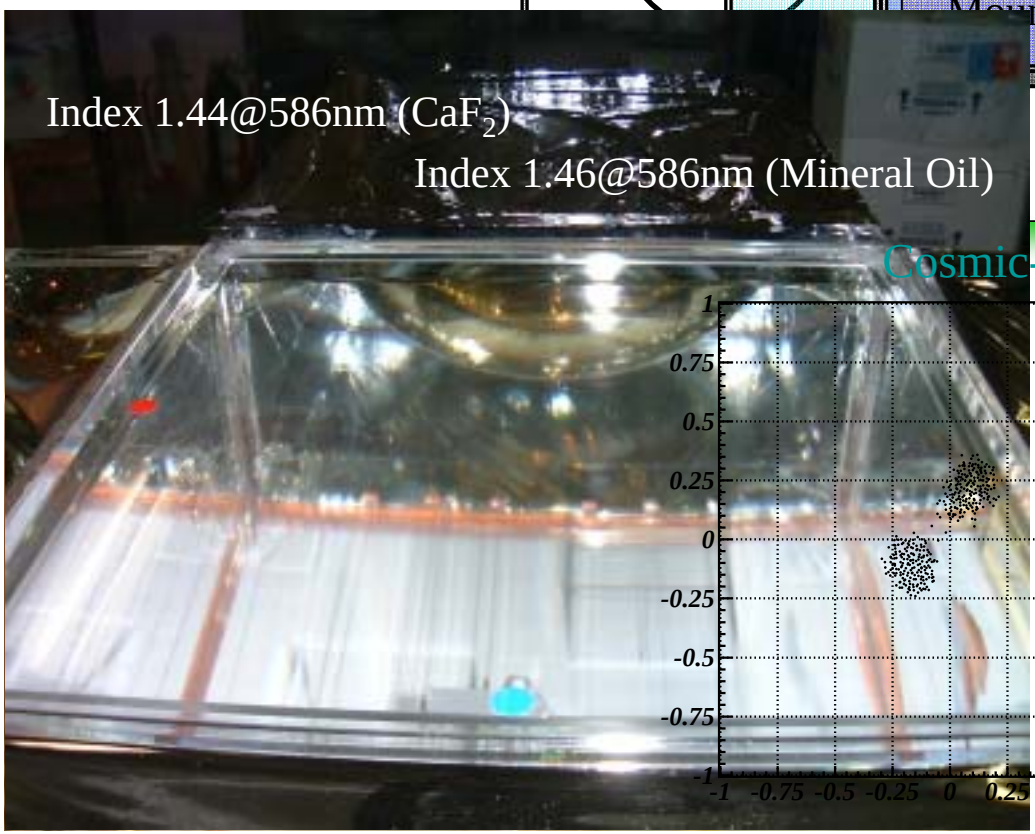
Energy Resolution:
9.1%(FWHM) at 662keV
=3.4% (FWHM) at 4.27MeV
Req. for CANDLES III ; 4.0%

CANDLES-II

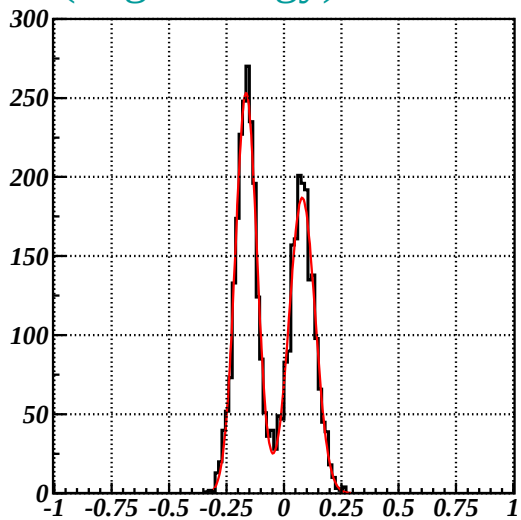
- Prototype



S.Umehara



Cosmic-ray Events (High Energy)

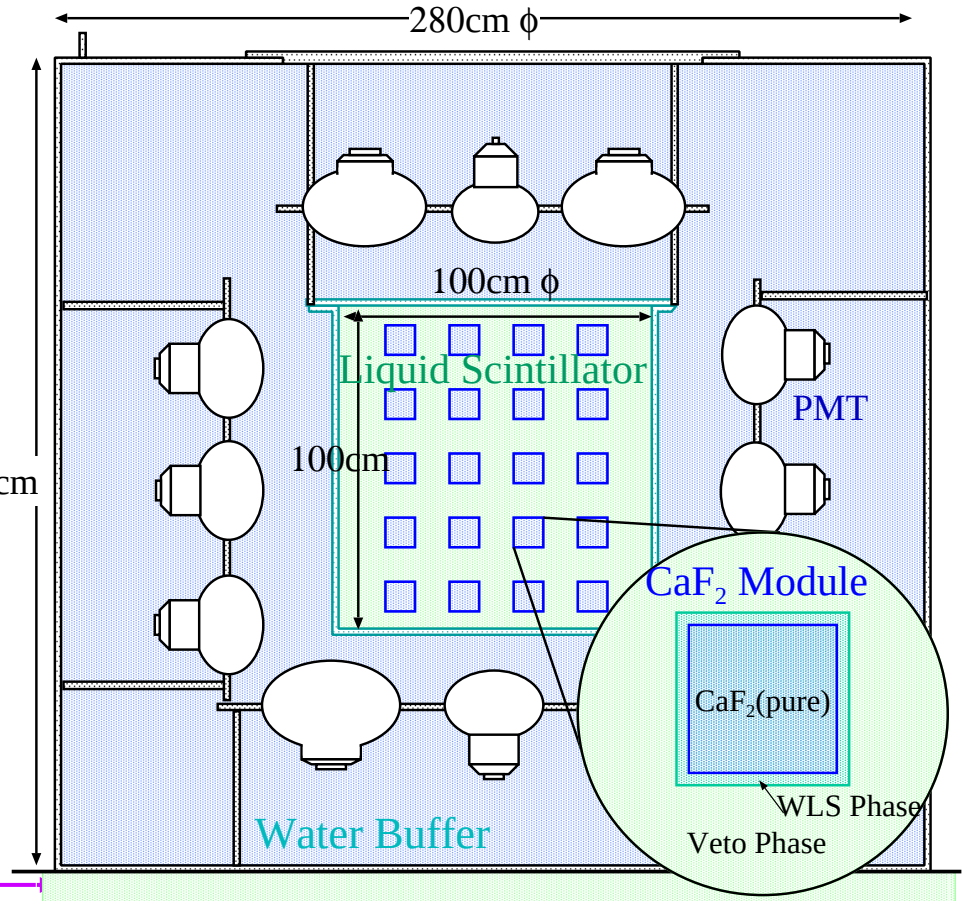


CANDLES III

- Construction almost completed @ Osaka Univ.
- CaF_2(pure)
  - 10^3 cm^3 ✕ 60 crystal; 191 kg
  - ~400 kg @ underground lab.
- Liquid scintillator
  - ϕ1000✕h1000 acrylic container
- Purification system (Ogawa)
- H_2O Buffer passive shield
  - ϕ2800✕h2600
  - safety regulation
- PMTs
  - 15” PMT (✕8) : R2018
  - 13” PMT (✕32) : R8055

CANDLES III

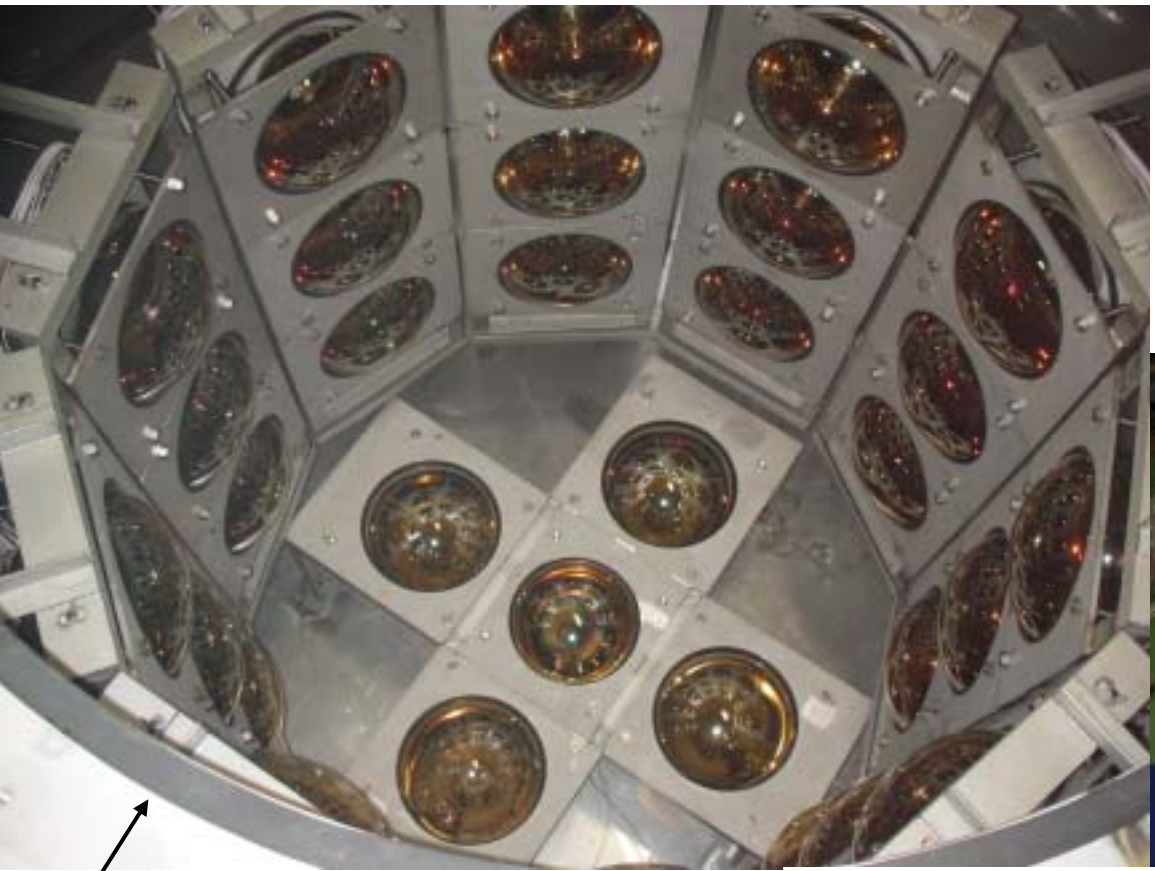
Outside View



CaF_2(pure) : 10×10×10cm^3
60 Crystals (191kg)

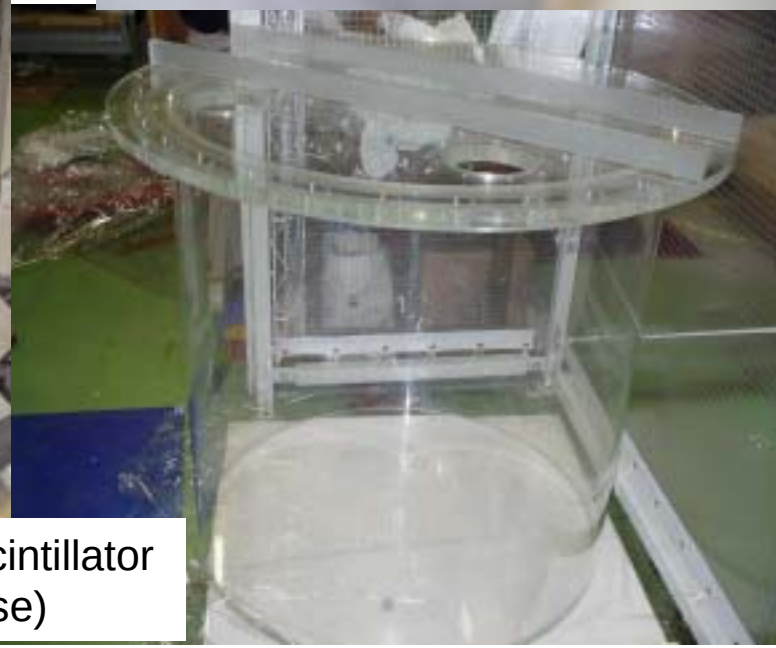
CANDLES III

Inside View



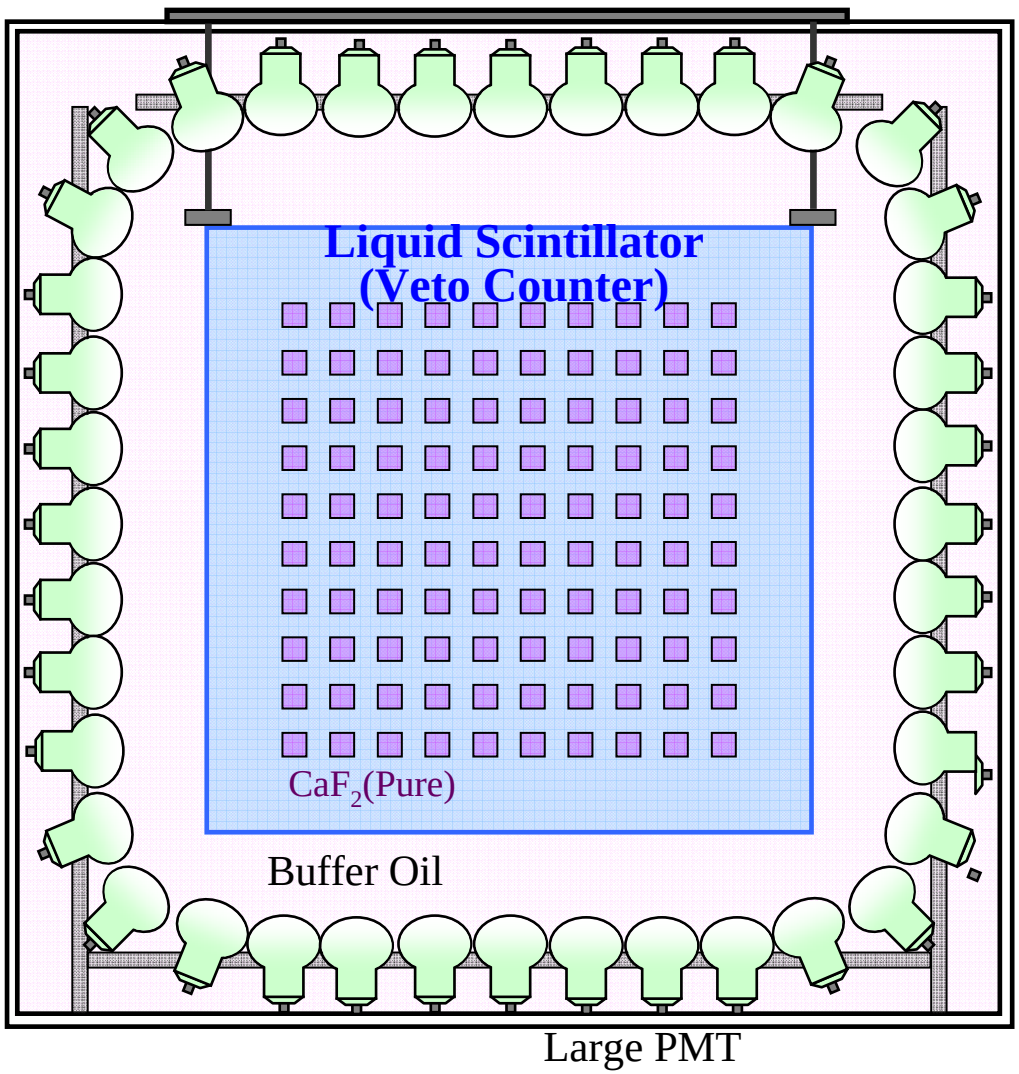
40 PMTs Version
And 60 PMTs Version . . . Funded

Photomultiplier Tube(13inch)



Tank for Liquid Scintillator
(Acrylic Case)

CANDLES IV

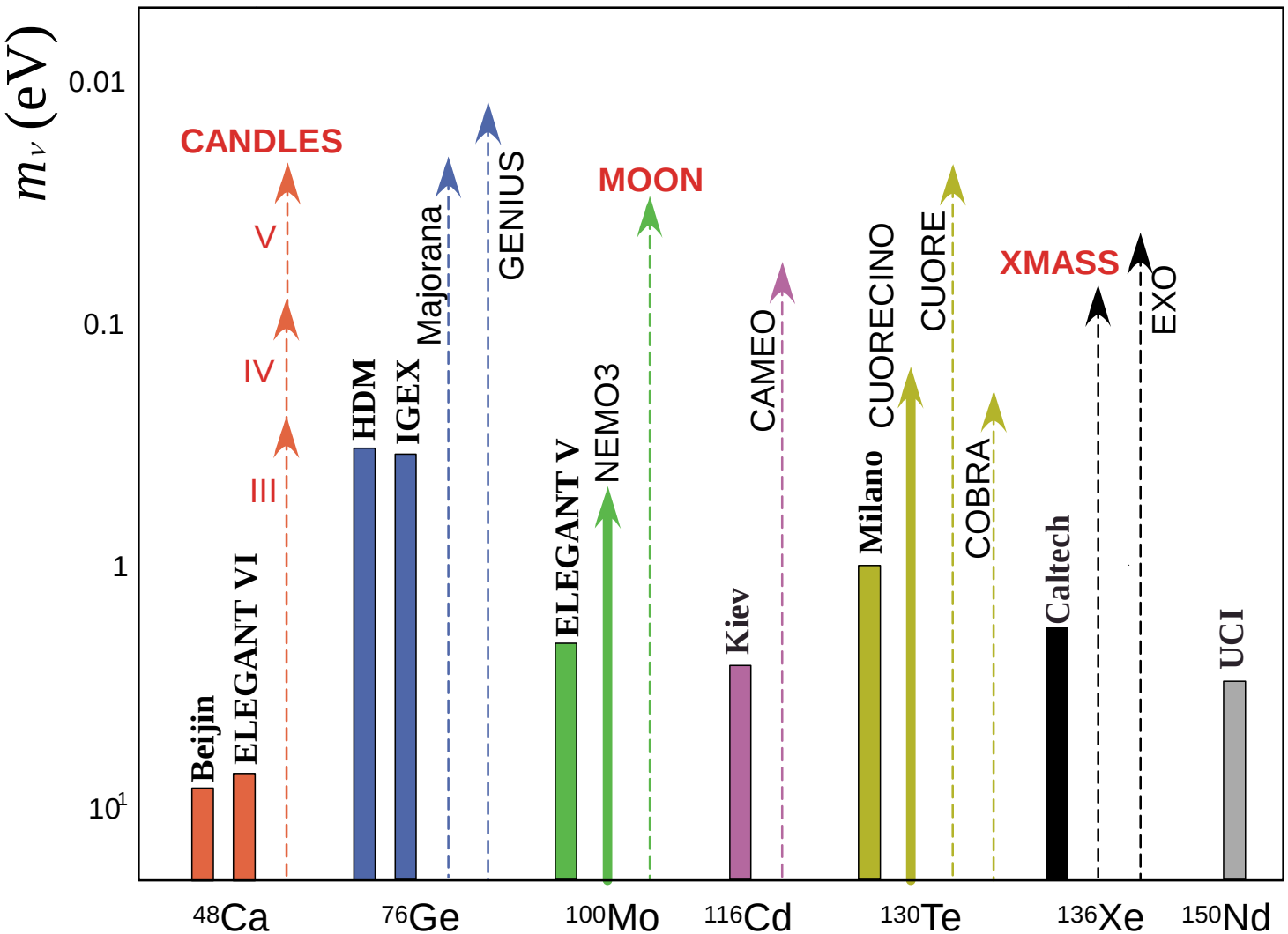


$15 \times 15 \times 15$ cm^3 CaF_2 (600 cubes) 6.4 t

liquid scintillator Vessel (^{48}Ca) 6.4 kg

1. BG
    1. Needs R&D
2. Energy resolution
    1. Buy PMT & gain adjust

CANDLES and world projects



Mile stone

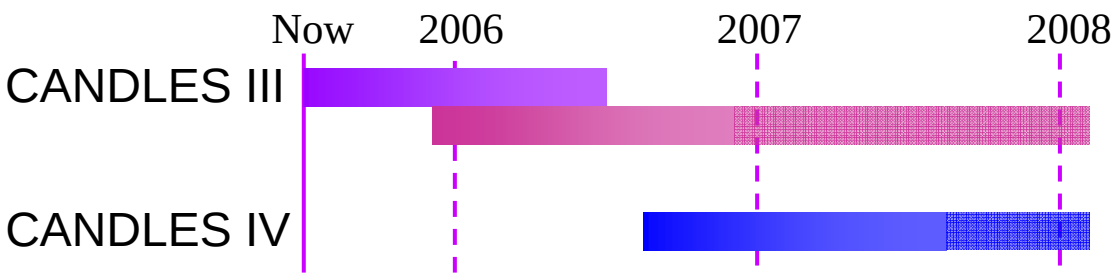
- ELEGANTS VI
  - running with new BG rejection (2ν)
- CANDLES I, II, POP
- CANDLES III (under construction @ our lab.)
  - CaF2($10cm^3$) 200kg:sea level, 400 kg; UG lab.
  - ~30 μBq/kg for ~0.5 eV

achieved

- CANDLES IV
  - $15cm^3$ cube (600 crystals) 6.4t; Kamioka
  - ~3 μBq/kg for ~0.1 eV in 6 years
- CANDLES V
  - 100t; SNO or Kamland or … for ~30meV in 7years

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

Prospects

- If the detector to sense 0.03 eV is ever built,
  - Majorana neutrino
  - Neutrino mass
- Next generation detector
  - Much bigger
    - CANDLEC IV (6.4t)
  - Further bigger
    - CANDLES V (100t)
    - SNO, Kamland
- Further option: Enrichment