二重β崩壊検出のためのCANDLESの開発

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for the CANDLES collaborations

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6. Goal of CANDLES system

Physics motivation of double beta decay

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1-1. Introduction

Neutrino oscillation ➡ mixing angle, Δm^2

- **Absolute mass of neutrino? & Mass pattern?**

- Why neutrinos are so light ?
- Is there heavy neutrino ? **Dirac or Majorana ?**

- Matter-antimatter asymmetry in Universe.

Is lepton number violated ?

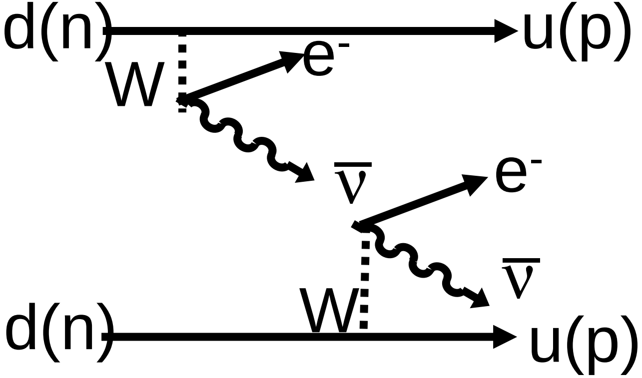
Most sensitive prove

neutrinoless double beta decay

New physics beyond the Standard Model !!

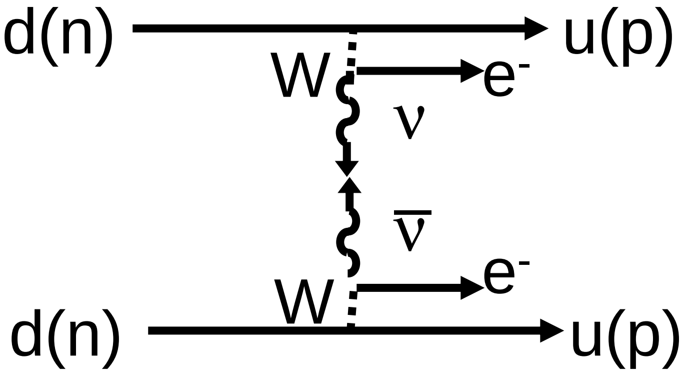
1-2. Double beta decay

- **2νββ decay**



Allowed by SM.

- **0νββ decay**

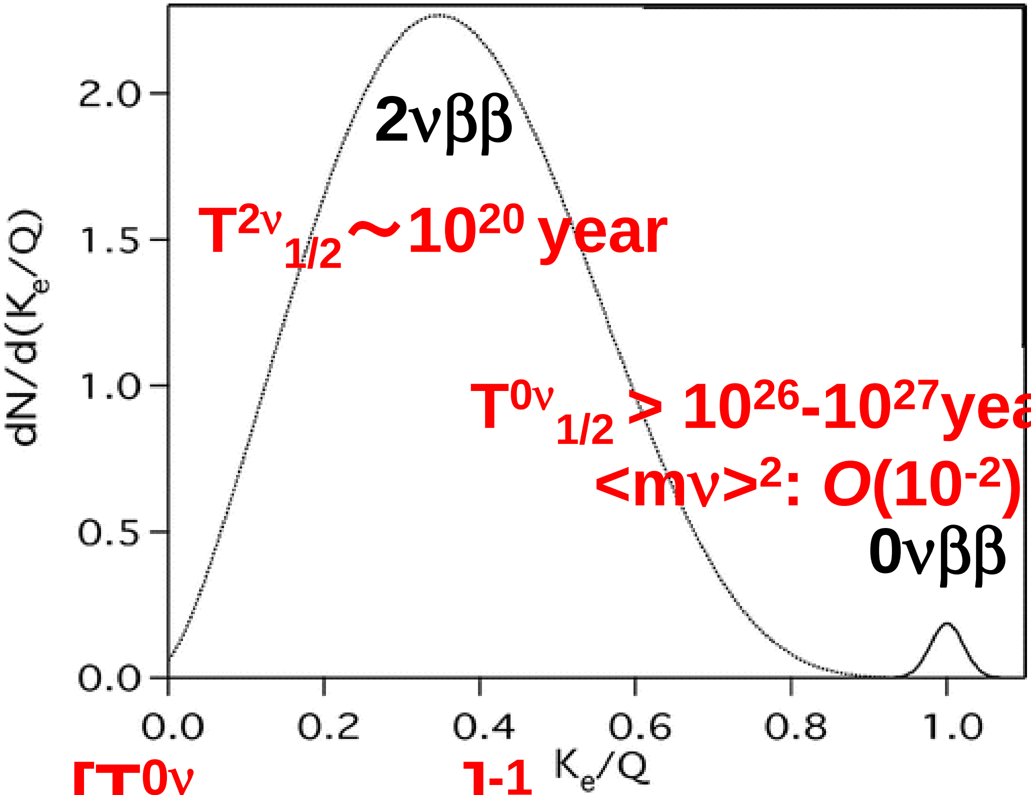


$\nu = \bar{\nu}$: majorana

(N, A) ->(N+2, A) + $2e^-$

Violating lepton number

Sum of electron kinetic energies spectra



$T^{2\nu}_{1/2}$ ~ 10^{20} year

$T^{0\nu}_{1/2}$ > 10^{26}-10^{27}year

$\langle m\nu\rangle^2$: $O(10^{-2})$ eV

$$[T^{0\nu}_{1/2(0+\text{->}0+)}]^{-1} = G^{0\nu}_{(Eo,Z)}|M_{0\nu}|^2\langle m\nu\rangle^2$$

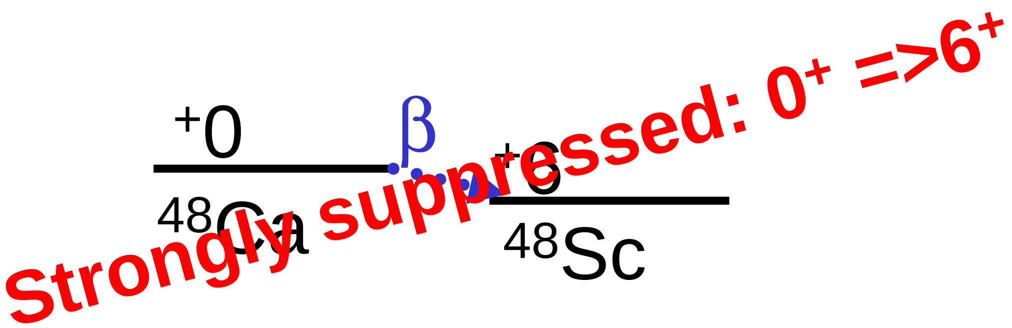
$G^{0\nu}_{(Eo,Z)}$: phase-space integral

$M_{0\nu}$: nuclear matrix element

Effective neutrino mass

1-3. Double beta decay

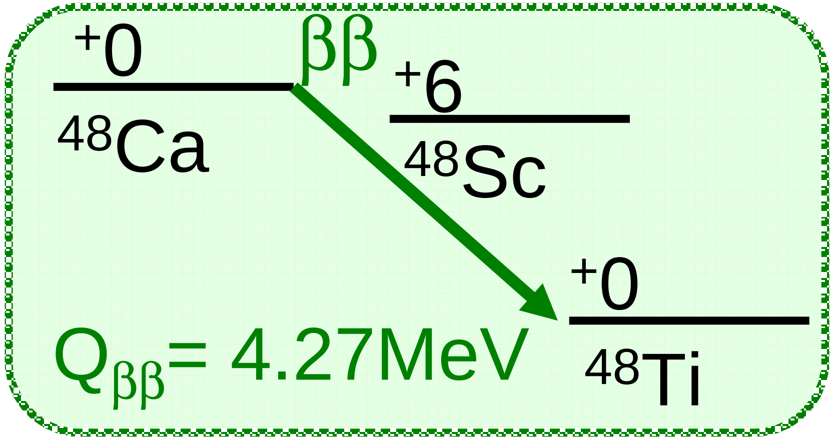
^{48}Ca,^{76}Ge,^{87}Se,^{96}Zr,^{100}Mo, ^{116}Cd,
^{128}Te,^{130}Te ,^{136}Xe ,^{150}Nd.



$^{+}0$ β $^{+}6$

^{48}Ca ^{48}Sc

Strongly suppressed: $0^{+} \Rightarrow 6^{+}$



$^{+}0$ ββ $^{+}6$

^{48}Ca ^{48}Sc

$^{+}0$

^{48}Ti

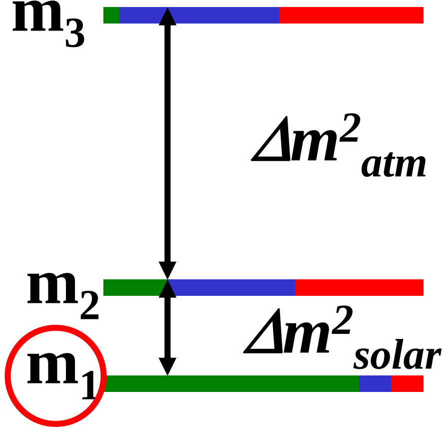
$Q_{\beta\beta}$= 4.27MeV

1-4. Effective mass vs minimum mass

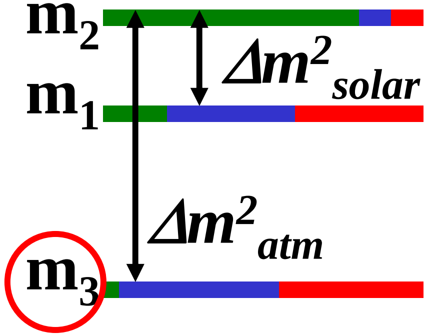
$$\langle m_\nu \rangle = \left| \sum_i \left| U_{ei} \right|^2 m_{\nu_i} e^{i\alpha_i} \right|$$

(U$_{ei}$: mixing matrix, α_i: Majorana phases)

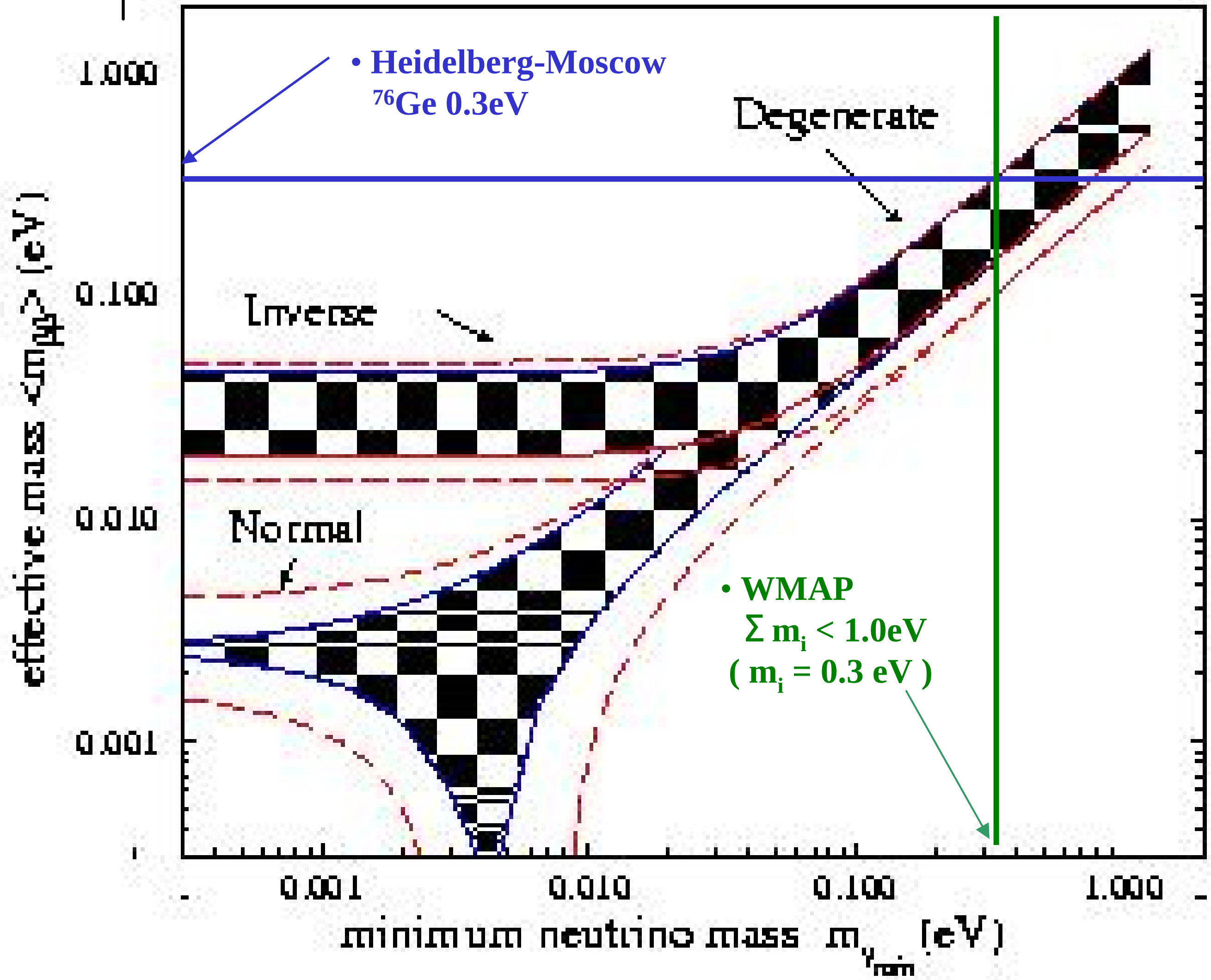
Normal Hierarchy



Inverted Hierarchy



Flavor: e mu tau



- **Heidelberg-Moscow**
  ^{76}Ge 0.3eV

- **WMAP**
  $\Sigma m_i < 1.0$eV
  ($m_i = 0.3$ eV)

http://www.aps.org/neutrino

Double beta decay in the world

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2-1. Current situation in experimental DBD

Isotope	Exposure (kmole-y)	BG (counts)	$T0^{\nu\beta\beta}_{1/2}$ (year)	$<m_{\beta\beta}>$ (eV)	Collaboration (Inclusive/ Exclusive)
^{48}Ca	**$5x10^{-5}$**	**0**	**$> 1.4 \text{ x } 10^{22}$**	**< 7.2-44.7**	**ELEGANT VI (In)**
^{76}Ge	0.943	**61**	$= 1.2 \text{ x } 10^{25}$	= 0.44	Heidelberg-Moscow (In)
^{76}Ge	0.117	**3.5**	$> 1.6 \text{ x } 10^{25}$	< 0.33-1.35	IGEX (In)
^{82}Se	$7x10^{-5}$	0	$> 2.7 \text{ x } 10^{22}$ *	< 5.0	UCI (Ex)
^{100}Mo	$5x10^{-4}$	4	$> 5.5 \text{ x } 10^{22}$	< 2.1	ELEGANT V (Ex)
^{116}Cd	$1x10^{-3}$	14	$> 1.7 \text{ x } 10^{23}$	< 1.7	
^{128}Te	Geochem.	NA	$> 7.7 \text{ x } 10^{24}$	< 1.1-1.5	(In)
^{130}Te	0.0025	**5**	$> 5.5 \text{ x } 10^{23}$	< 0.37-1.9	CUORICINO (In)
^{136}Xe	$7x10^{-3}$	16	$> 4.4 \text{ x } 10^{23}$	< 1.8-5.2	Gotthard (Ex)
^{150}Nd	$6x10^{-5}$	0	$> 1.2 \text{ x } 10^{21}$	< 3.0	UCI (Ex)

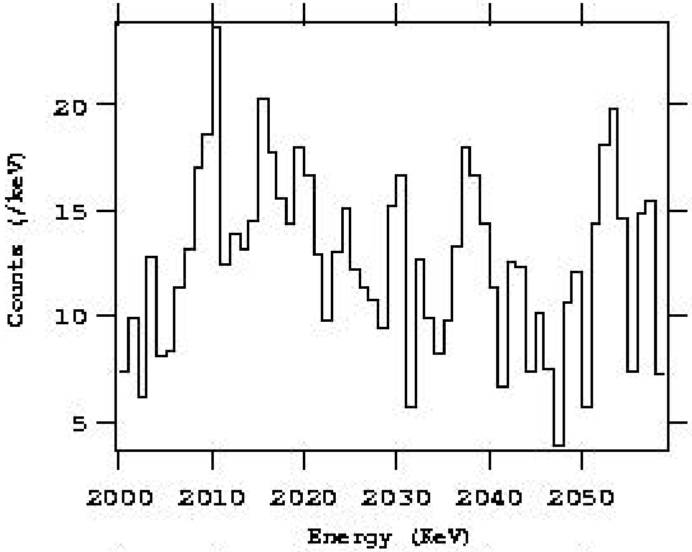
*: 68%CL

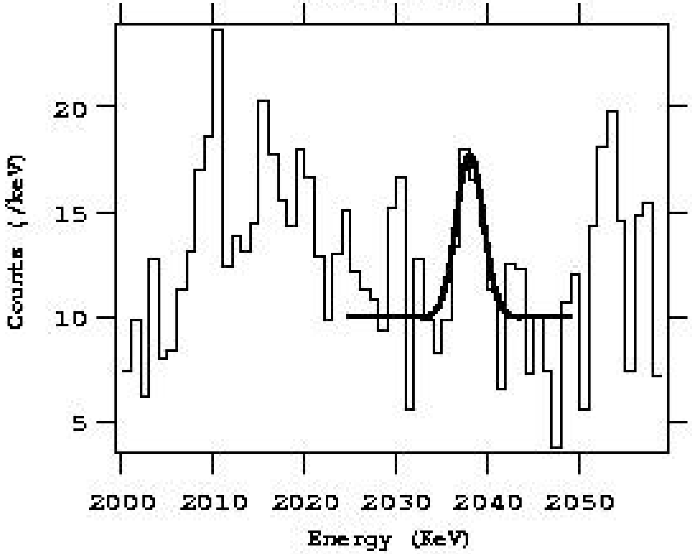
Uncertainty in $|M_{0\nu}|$

http://www.aps.org/neutrino

2-2. Heidelberg-Moscow (Enriched ^{76}Ge detector)

^{76}Ge 11kg @ Laboratori Nazionali del Gran Sasso





$\Delta E_{(FWHM)}$ @2040keV ∼4 keV

$T_{1/2}^{0\nu}$ = 1.2x10^{23}years for ^{76}Ge(∼71.7kg yr) **<mν> = 0.1 – 0.9eV**

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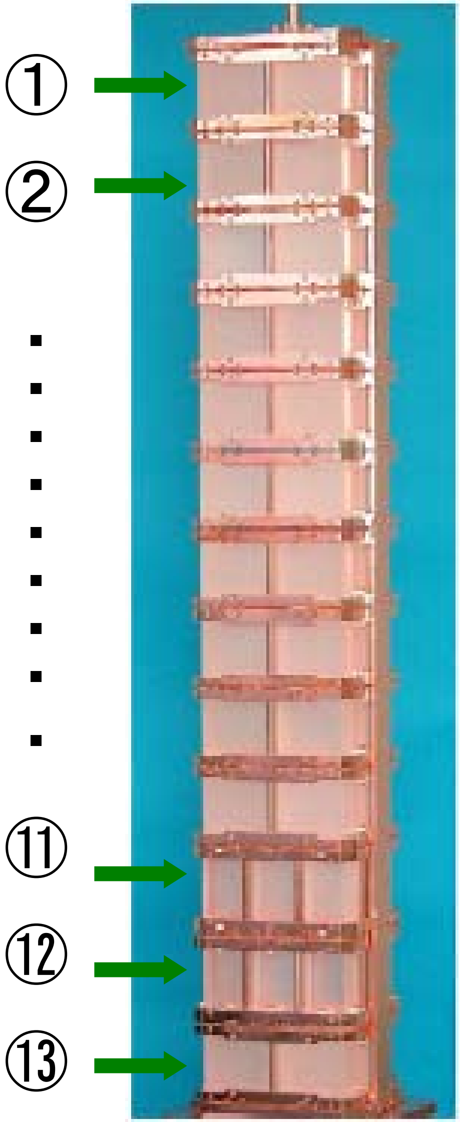
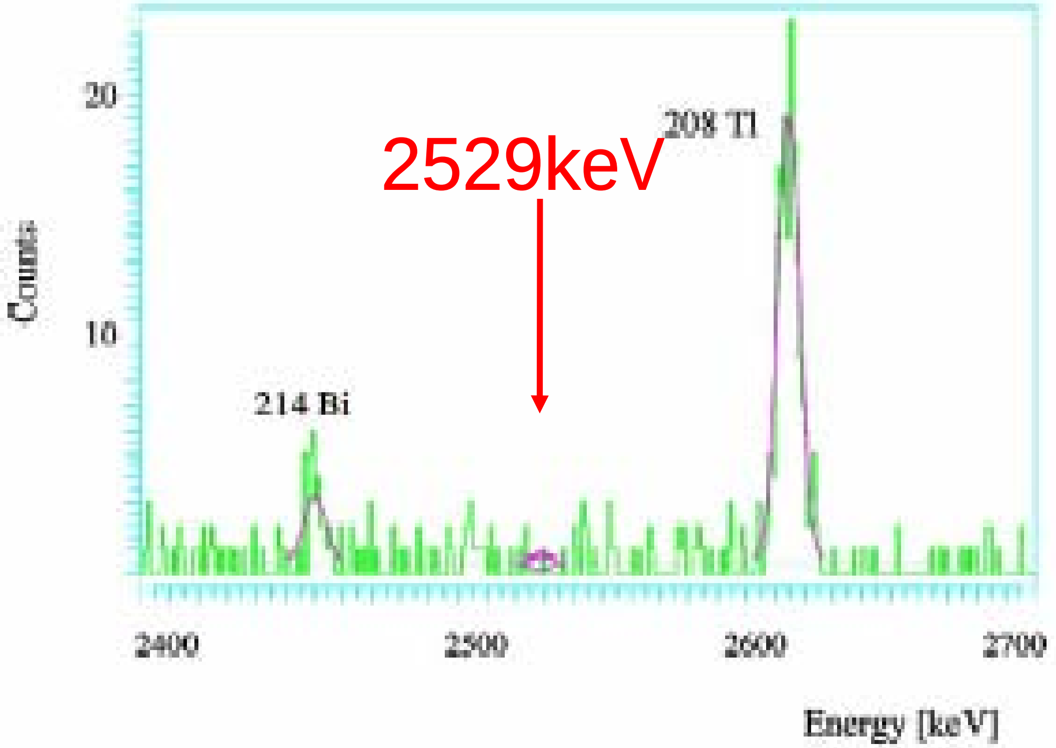
2-3. CUORICINO (Cryogenic Bolometor)

TeO_3 340g @ Laboratori Nazionali del Gran Sasso





ig. 4. Sum of the spectra of the 5 × 5 × 5 cm³ and 3 × 3 × 6 cm³ crystals in the region of neutrinoless double beta decay.

$\Delta E_{(FWHM)}$ @2529keV ∼7keV : 5x5x5 cm^3

$T_{1/2}^{0\nu} > 5.5\mathrm{x}10^{23}$years for ^{130}Te(∼30kg) <mν> < 0.37 – 1.9eV

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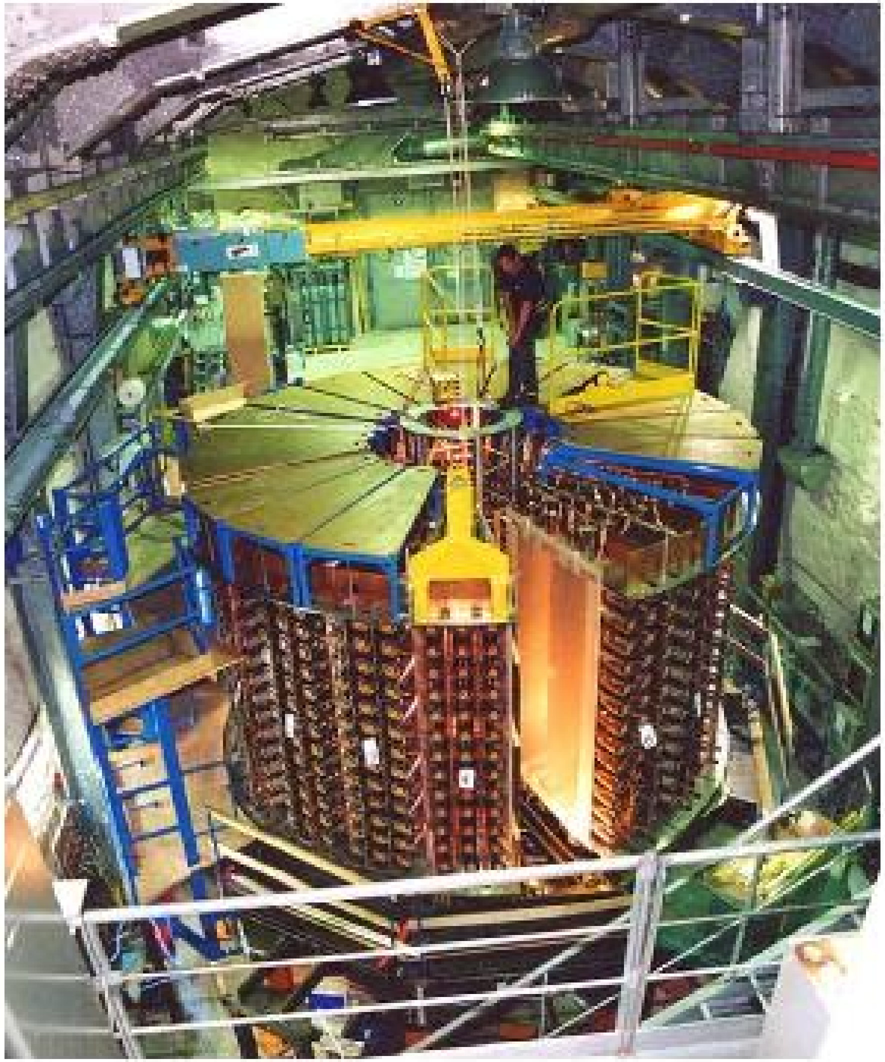
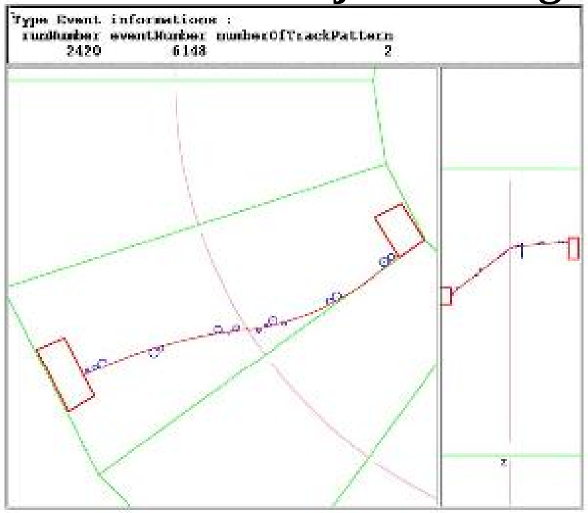
2-4. NEMO-3 detector (Tracking device & calorimeter)

Frejus Underground Lab.





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Type Event informations :
 runNumber eventNumber numberOfTrackPattern
     2420        6148                    2
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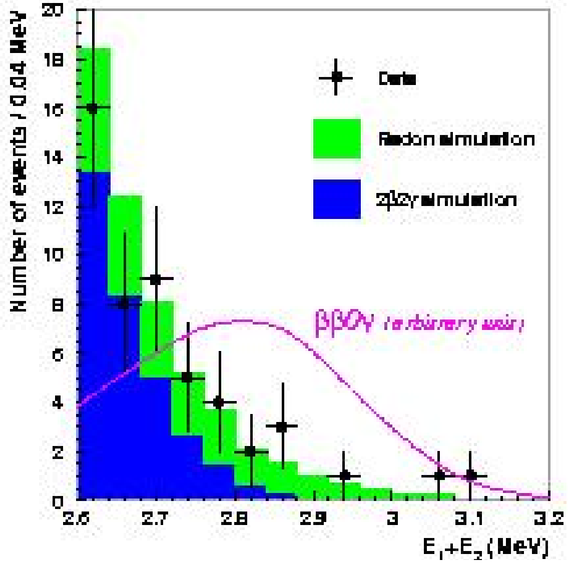


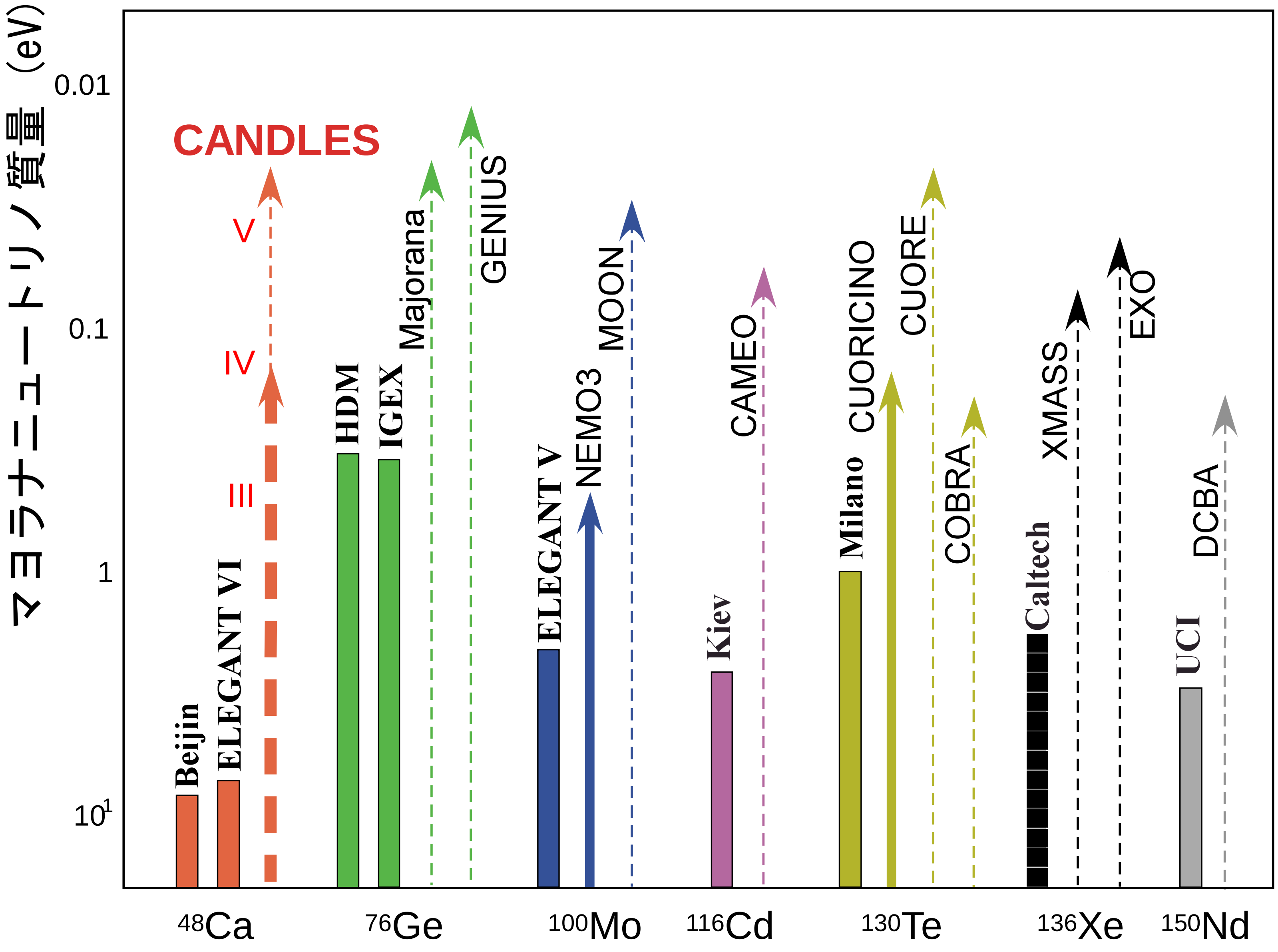
^{100}Mo

Expected BG @2.8-3.2MeV = 7.0 ±1.7 counts/kg/year **8 events observed**

$T_{1/2}^{0\nu}$ > 3.5x10^{23}years for ^{100}Mo(～7kg) **<mν> < 0.7 – 1.2eV**

hep-ex/0412012

2-5. Present status & future experiment



Double beta decay of ^{48}Ca

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3-1. Double beta decay of ^{48}Ca

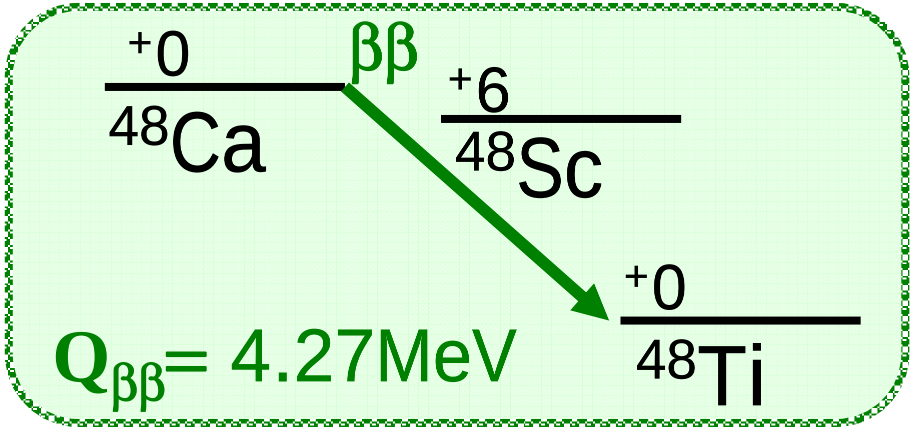
- CaF$_2$ scintillation detector

  Source= Detector

  : High Detection Efficiency

- Largest Q$_{\beta\beta}$ value

  : Low background

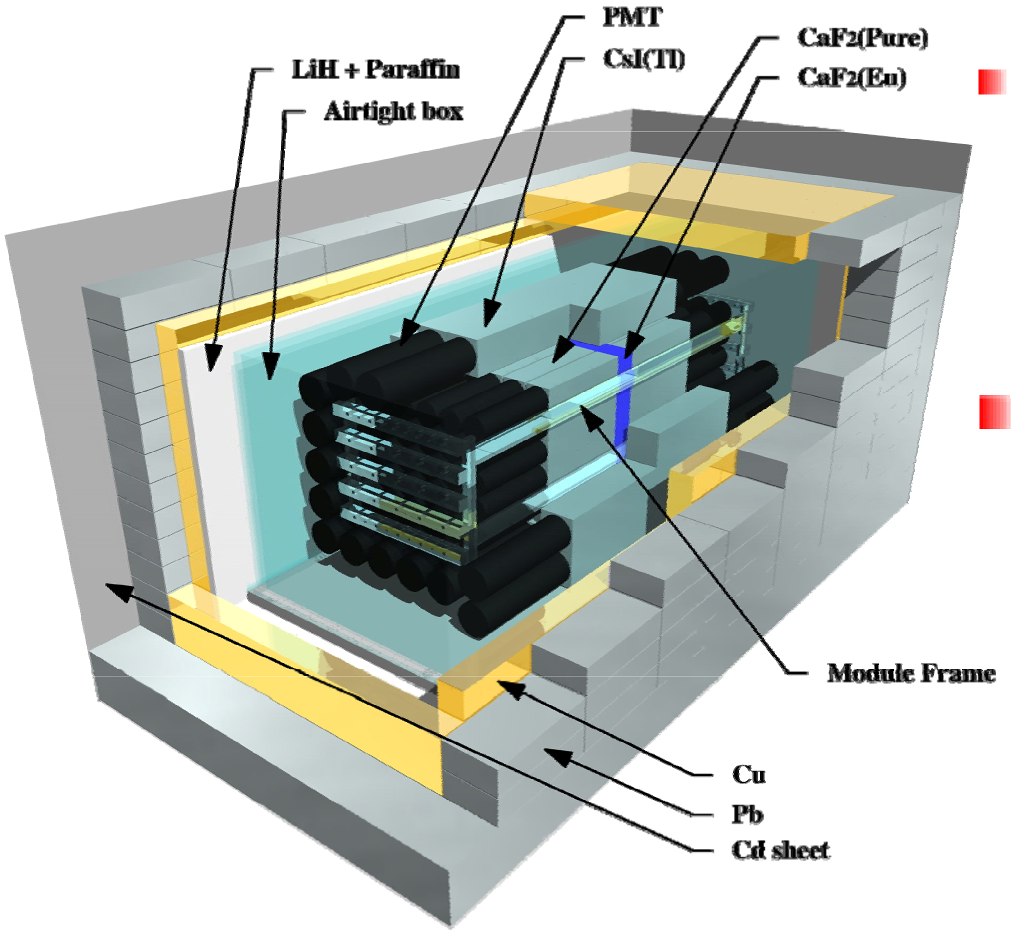


$Q_{\beta\beta}$= 4.27MeV

^{48}Ca abundance (0.187%)

3-2. ELEGANT VI

ELEctron GAmma ray Neutrino Telescope



- **Detector & Source**

  : **CaF_2 (Eu)**

  45x45x45 mm^3, 23crystals 6.7kg

- 4π active shield

  : **CaF_2(pure)**:active L.G.

  45x45x200 mm^3, 48crystals

  : **CsI(Tl)**

  65x65x250mm^3, 38modules

- Passive shield for neutron

  : LiH+paraffin 15mm

  : Cd sheet 0.6mm

  : H_3BO_3+H_2O tank

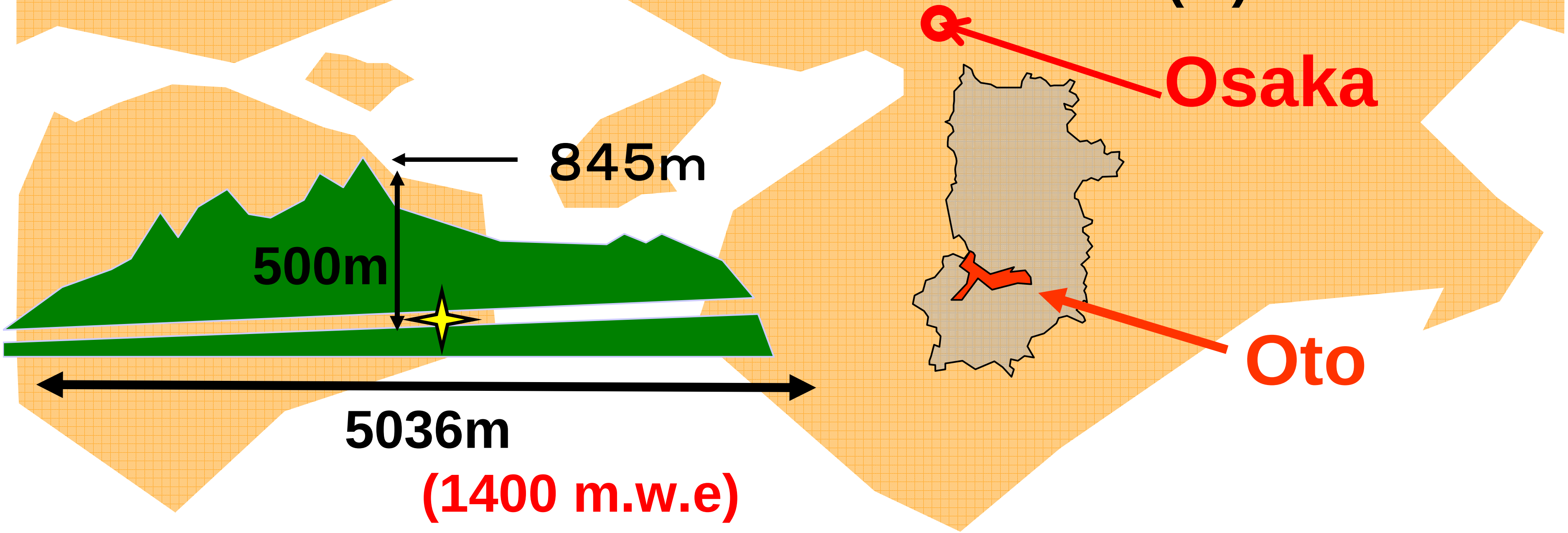
- Passive shield for γ ray

  : OFHC Cu 5cm

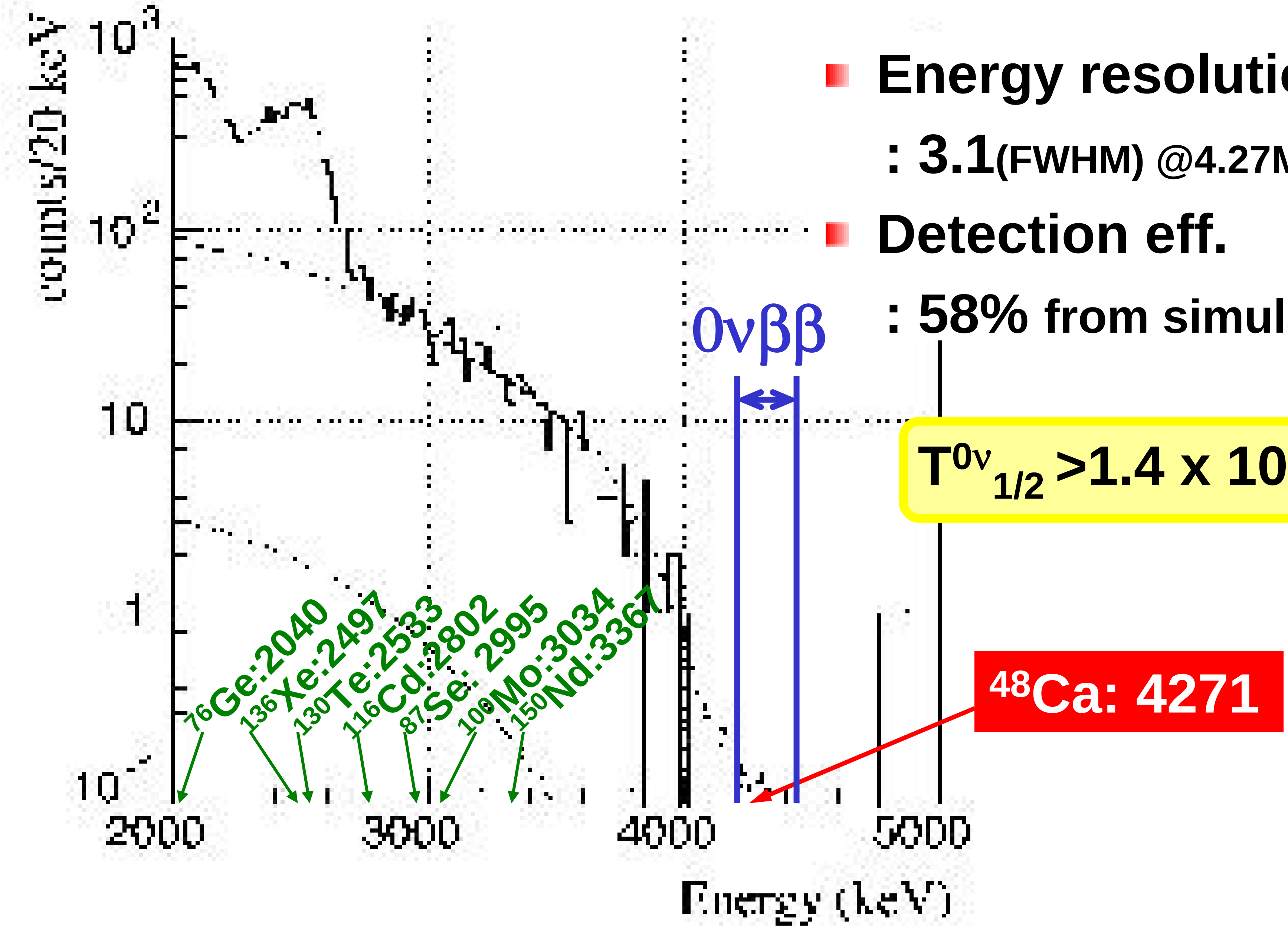
  : Pb 10cm

3-3. Oto Cosmo Observatory

- Low background measurement
  - Cosmic ray : $4\times10^{-7}/\mathrm{cm}^2\cdot\mathrm{sec}$ (1/100,000)
  - Neutron : $4\times10^{-5}/\mathrm{cm}^2\cdot\mathrm{sec}$ (1/100)
  - Radon : $10\mathrm{Bq/m}^3$ (equal out of the tunnel)
- ELEGANT VI : Double beta decay of ^{48}Ca
  : Dark matter search with ^{19}F
- ELEGANT V : Dark matter search with NaI(Tl)



3-4. BG free measurement @ ELE-VI



- **Energy resolution**
  : 3.1(FWHM) @4.27MeV
- **Detection eff.**
  : 58% from simulation

$T^{0\nu}_{1/2}$ >1.4 x 10^{22} y

NPA730(2004)215

CANDLES system

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4-1. Improvement of sensitivity

- ELEGANT VI (6.6g of ^{48}Ca)@Oto

  4π active shield + Largest $Q_{\beta\beta}$ value

BG free measurement

- Increase the number of ^{48}Ca nuclei (Order of kg)

  Large volume detector → **CANDLES**

CAlcium fluoride for studies of **N**eutorino

and **D**ark matter by **L**ow **E**nergy **S**pectrometer

  - 4π active shield + largest $Q_{\beta\beta}$ value

Huge volume detector !!

4-2. CANDLES system

CAlcium fluoride for studies of Neutorino and Dark matter by Low Energy Spectrometer

- Undoped CaF_2 scintillator

  : Long attenuation length

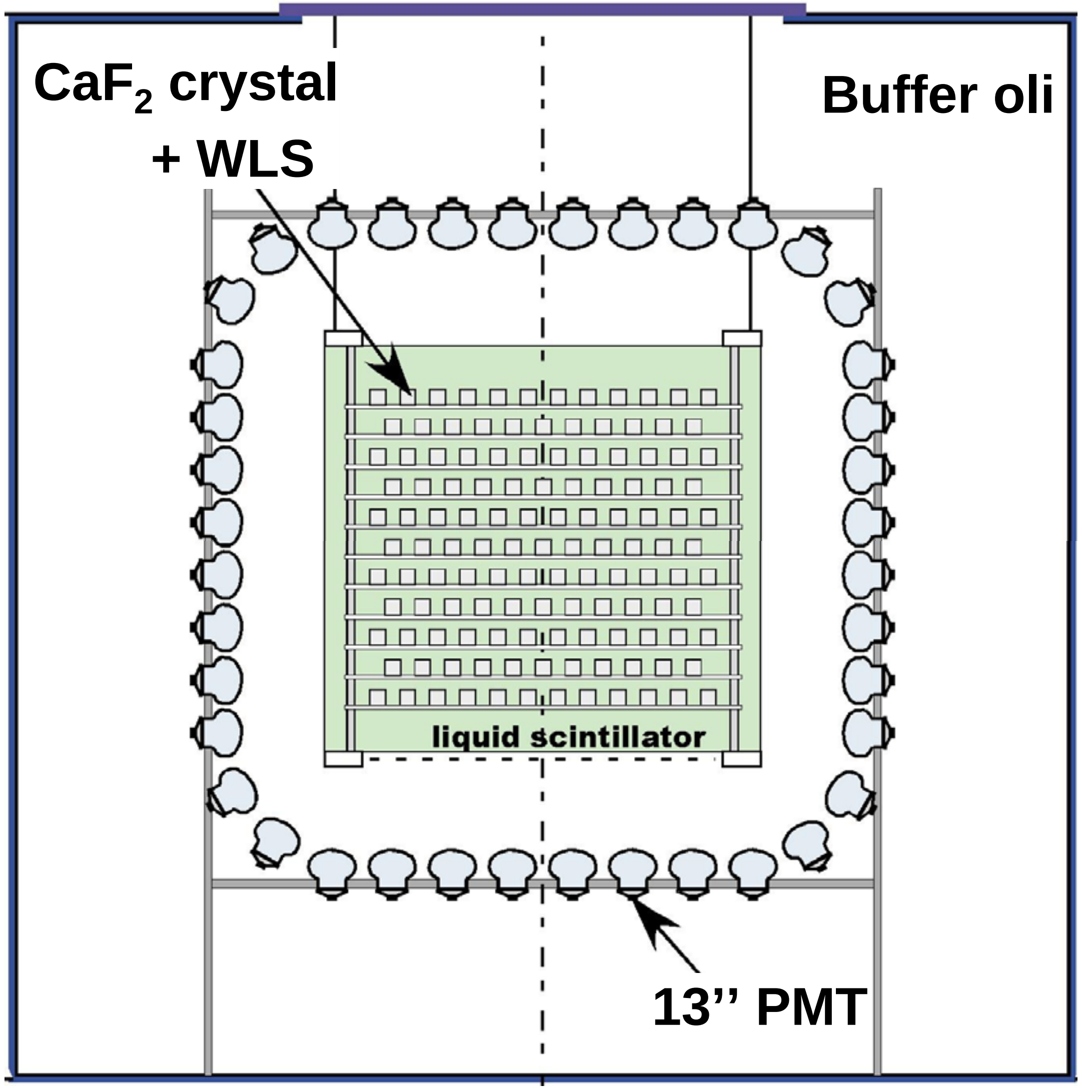
- Liquid scintillator

  : 4π active shield

Decay time of signal

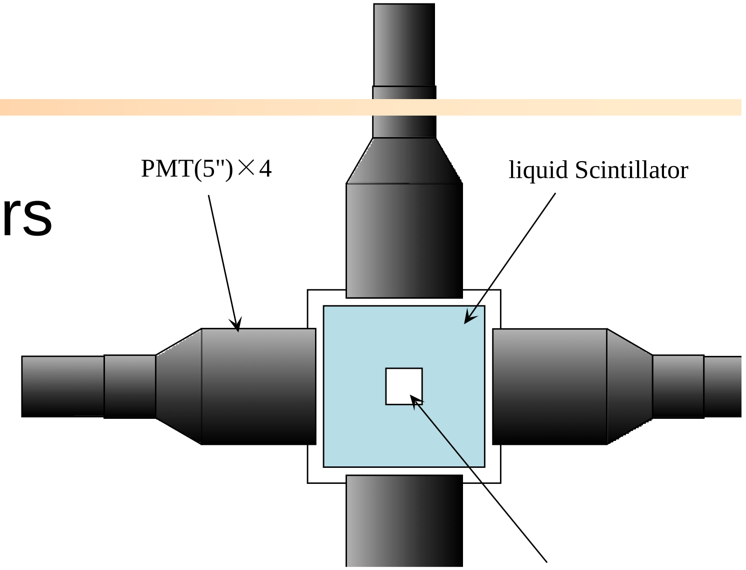
900nsec : CaF_2(pure)

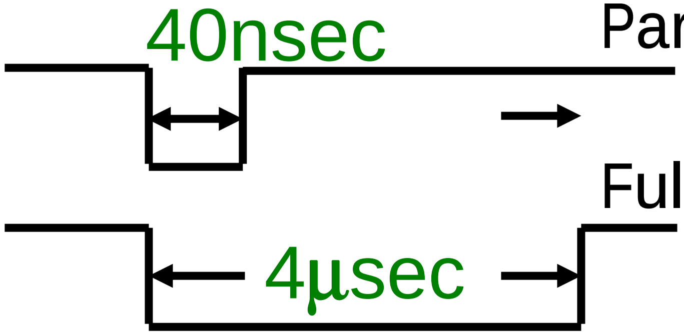
A few 10nsec : Liq. Scinti.

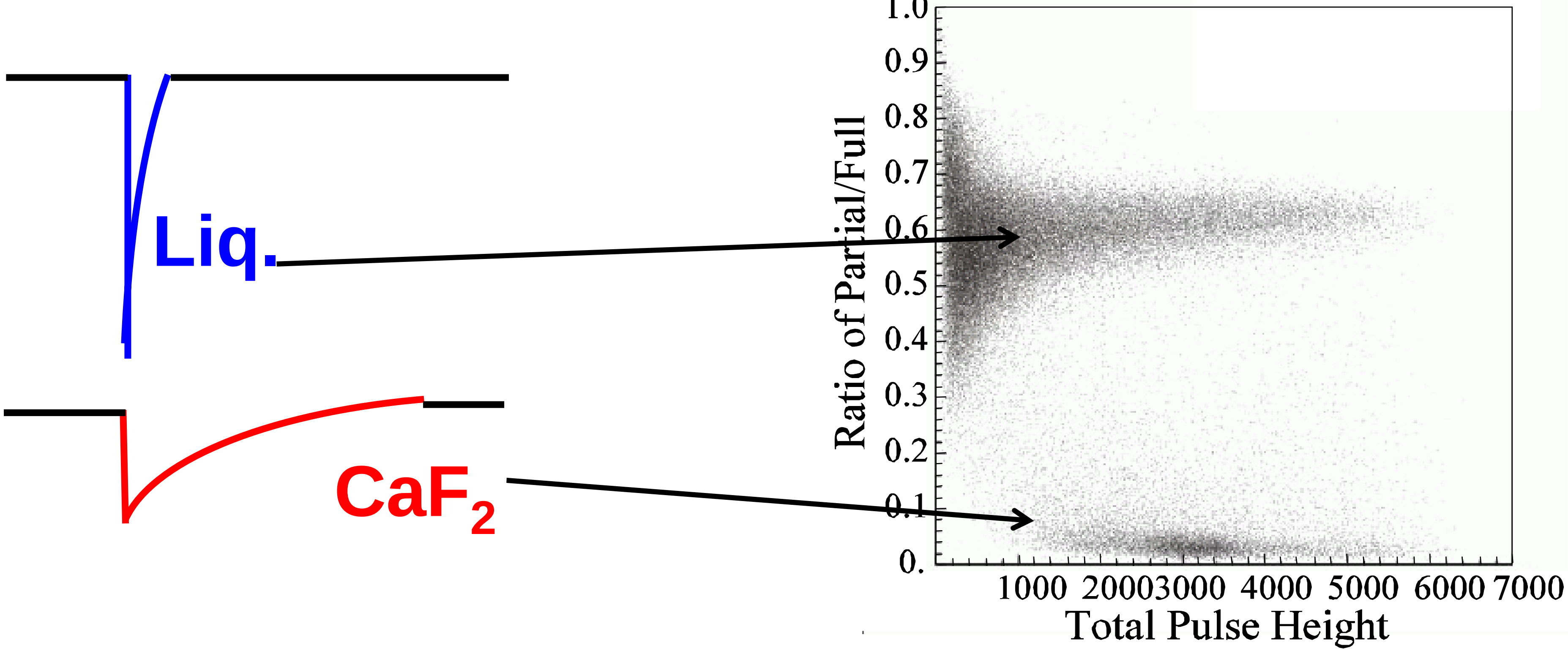


4-3. Dual gate Discrimination

PSD between CaF$_2$ and Liquid Scintillators







4-4. Progress of CANDLES

- CANDLES I
  - Light collection efficiency : Optimization of mixture
  - BG rejection : Pulse shape discrimination

    Liq./CaF_2, α/γ , double pulse

- CANDLES III 60crystals x 3.2kg = 191kg
  - Under Construction

- R&D study
  - Reduction of radioactive impurities in CaF_2 crystal
  - Enrichment ^{48}Ca

BG rejection
Pulse shape discrimination

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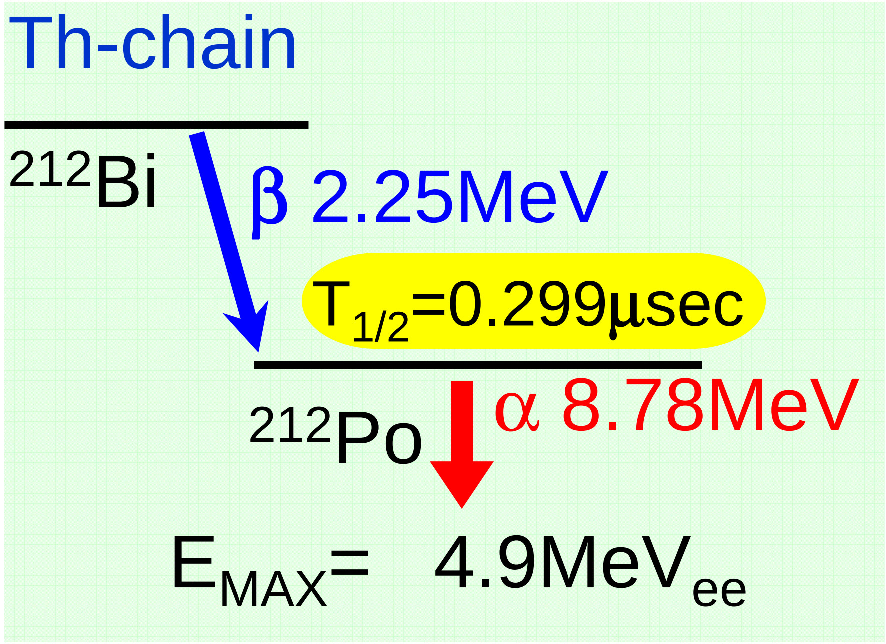
5-1. Background



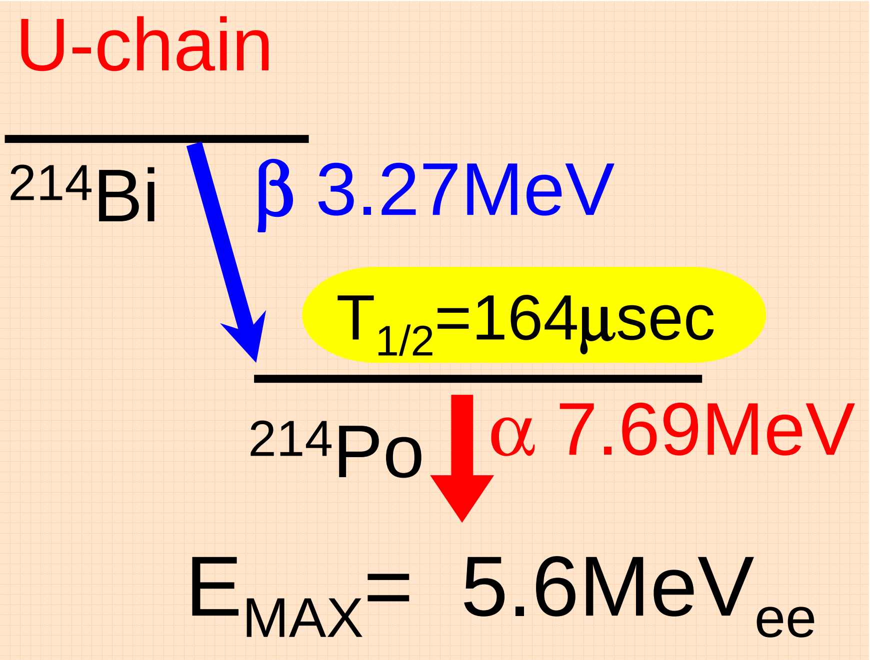
Th-chain

$^{212}\mathrm{Bi}$ β 2.25MeV

$T_{1/2}=0.299\mu\mathrm{sec}$

$^{212}\mathrm{Po}$ α 8.78MeV

$E_{MAX}=$ 4.9MeV$_{ee}$



U-chain

$^{214}\mathrm{Bi}$ β 3.27MeV

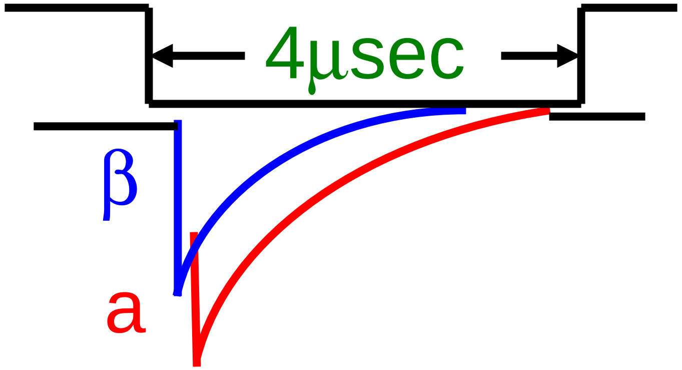
$T_{1/2}=164\mu\mathrm{sec}$

$^{214}\mathrm{Po}$ α 7.69MeV

$E_{MAX}=$ 5.6MeV$_{ee}$

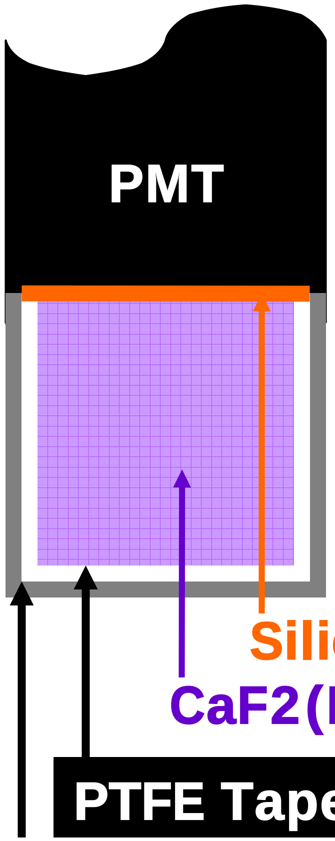
Ee= f × Eα (f = 0.30)

ADC Gate



α/γ & double pulse rejection

5-2. Set Up (α/γ discrimination)



2”PMT(R2256)
(Quartz Glass)

Silicon Oil(KF96H)

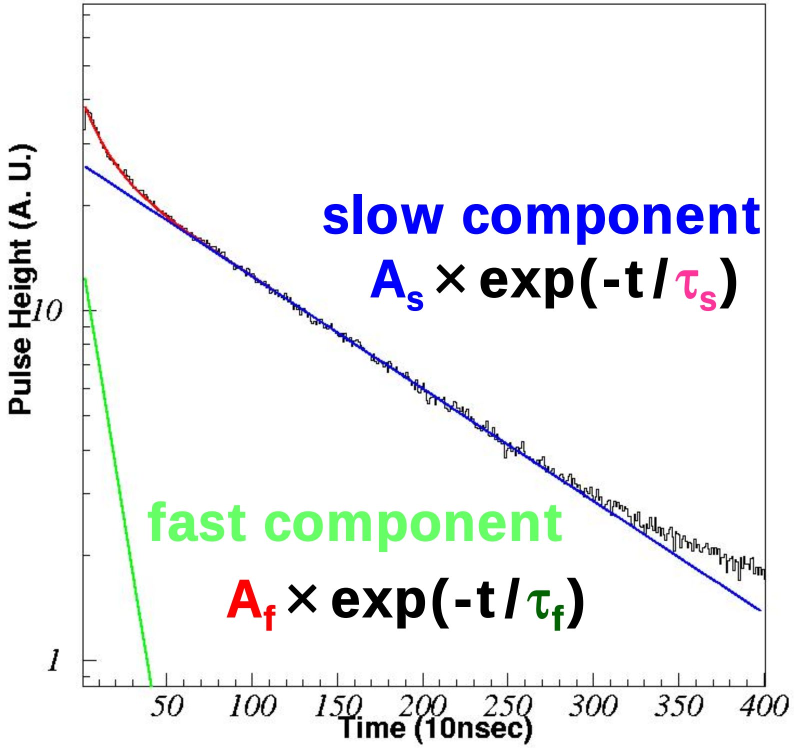
CaF2(Pure) ; 300mBq/kg; $45 \times 45 \times 45\text{mm}^3$

PTFE Tape Reflector(BC642)

Aluminum Foil

5-3. Reference Pulse

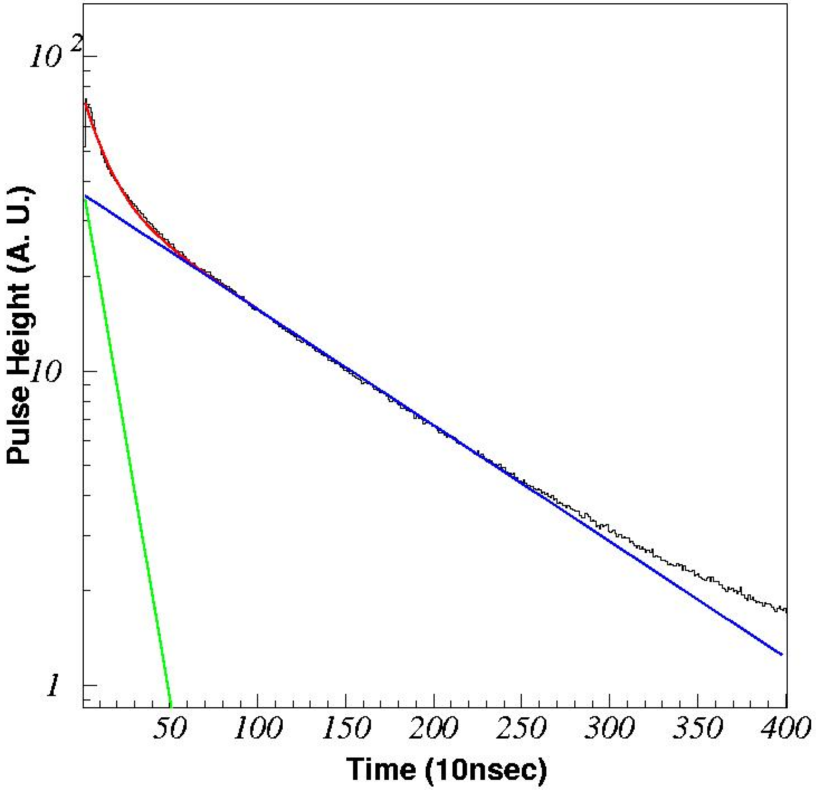
^{60}Co
Gamma :1000-1200keV



slow component
$A_s \times \exp(-t/\tau_s)$

fast component
$A_f \times \exp(-t/\tau_f)$

結晶内部の放射線不純物
Alpha :1624-1736keV



	A_f	τ_f(nsec)	A_s	τ_s(nsec)
α	40.8±0.1	131.7±0.7	36.7±0.05	1177±1
γ	14.2±0.2	144.6±4	26.2±0.1	1355±4

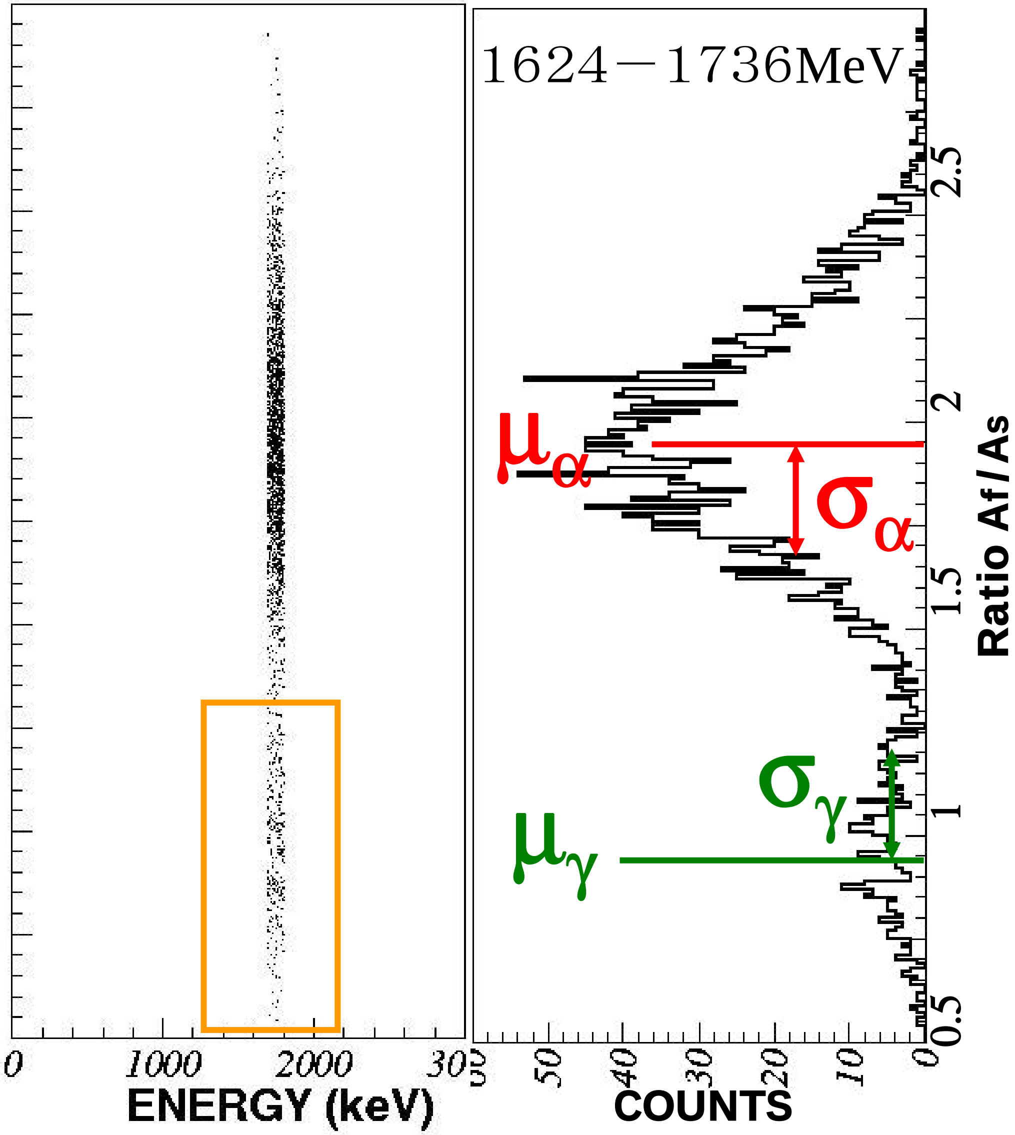
$A_f = A_s$
$A_f < A_s$

5-4. Pulse Shape Discrimination

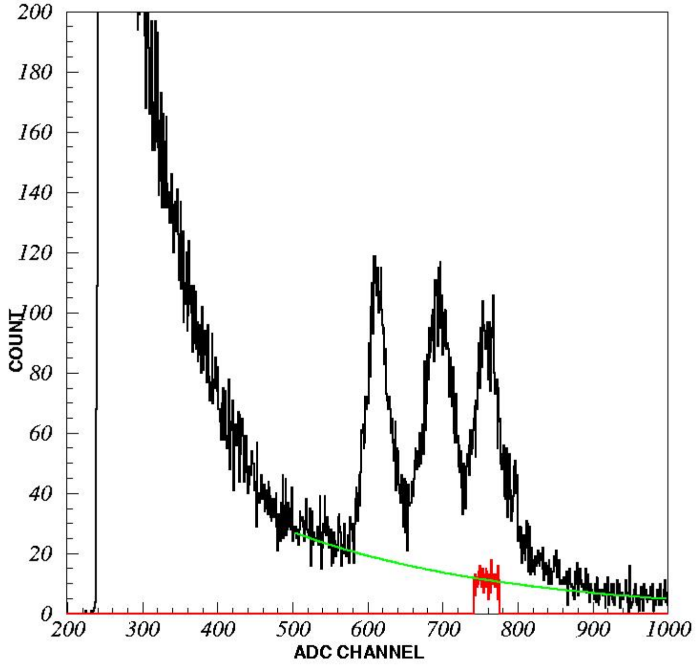
$$A_s \times \exp(-\,t/\tau_s) + A_f \times \exp(-\,t/\tau_f)$$

Free parameter

Fixed from Reference Pulse



$$\frac{\sigma_\alpha+\sigma_\gamma}{\mu_\alpha-\mu_\gamma}=0.51$$



Goal of CANDLES system

6-1. Sensitivities of CANDLES

- **CANDLES III** → $\langle m\nu \rangle$: 0.56eV
  - CaF_2: 60crystals x 3.2kg 191kg
  - E-Resolution: 4%@4.27MeV
  - Measurement time: 5year
- **CANDLES IV** → $\langle m\nu \rangle$: 0.11eV
  - CaF_2: 1000crystals x 3.2kg 3.2ton
  - E-Resolution: 3.5%@4.27MeV
  - Measurement time: 10year
- **CANDLES V** → $\langle m\nu \rangle$: 0.04eV
  - Enrichment of ^{48}Ca 0.187% => 2%

    or Scale up detector (40ton) & BG reduction
  - Measurement time: 10year

Summary

- **0νββ decay**

  Lepton number violation

  Majorana

  absolute mass of neutrino

Very HOT

- BG free measurement @ ELE-VI **successful**

  Increase the number of ^{48}Ca nuclei → **CANDLES**

- Performance of CANDLES system
  - Light collection efficiency : **good**
  - Pulse shape discrimination

    Liq./CaF$_2$, double pulse, α/γ : **good**

- CANDLES III (Sensitivity $\langle m_n \rangle$: 0.56eV) **Under Construction**

Future prospect CANDLES V → $\langle m_\nu \rangle$: 0.04eV

Thank you for your attention !!