Neutrino-less double beta decay
--^{48}Ca and CANDLES--

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Osaka Univ.

Contents

- Double beta decay and Majorana Mass
  - Matter dominated universe and anti-particle
  - ν Majorana mass and double beta decay
- Double beta decay experiments
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- CANDLES detector system
  - –CANDLES I, II, III, VI, Prospects
- Enrichment of ^{48}Ca
  - –Methods of enrichment
  - –Crown ether resin
  - –Other methods

Baryon density in our Universe

$\rho_B \sim 5\text{x}10^{-10}\,\rho_\gamma$

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

Early universe $\rho(B)=\rho(\bar{B}) \sim \rho(\gamma)$

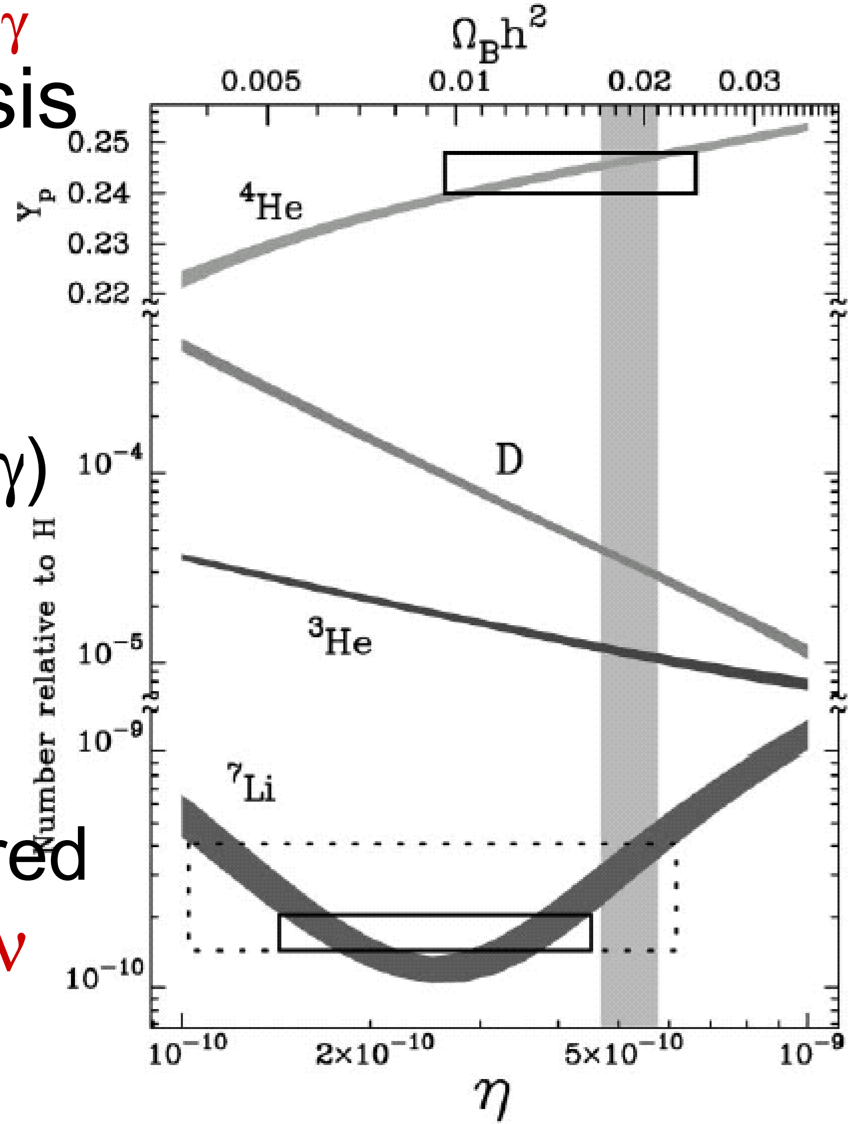
Particle : $10^{10}+5$

Anti-particle : $10^{10}+0$

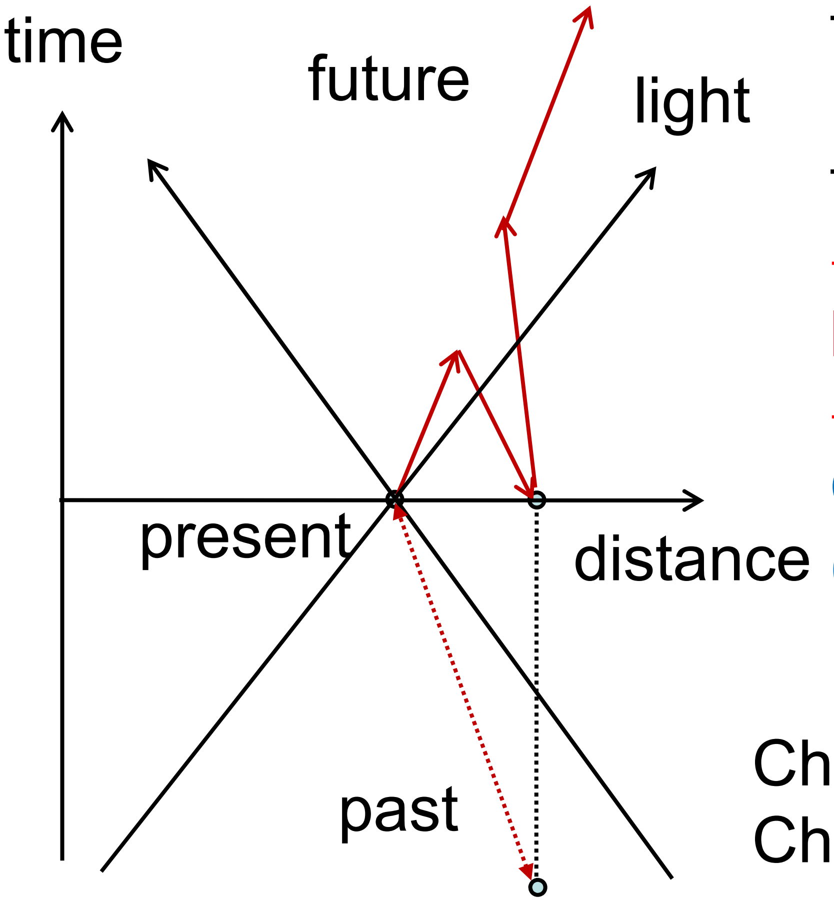
How anti-particles disappeared

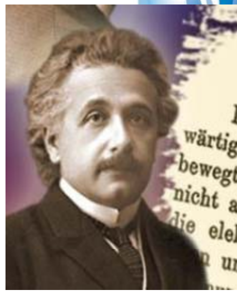
$\rightarrow$ CP + Majorana mass of ν

Double Beta decay



Relativity + uncertainty →anti-particle





- no information is faster than speed of light
- interact with any space-time

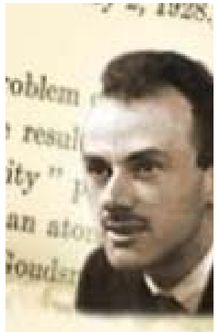
→particle that travels backward in time

→antiparticle

Carries inverse quantity (charge, spin(chirality))

Dirac equation

Feynman



Charge: conserved

Chirality: violated by mass

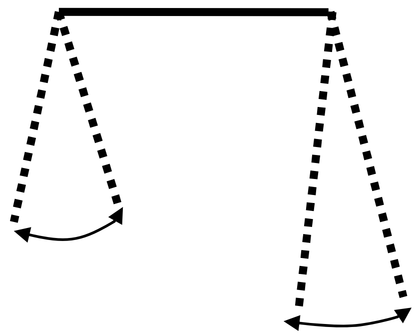
particle ⇔ antiparticle

Majorana particle

Neutrino mass

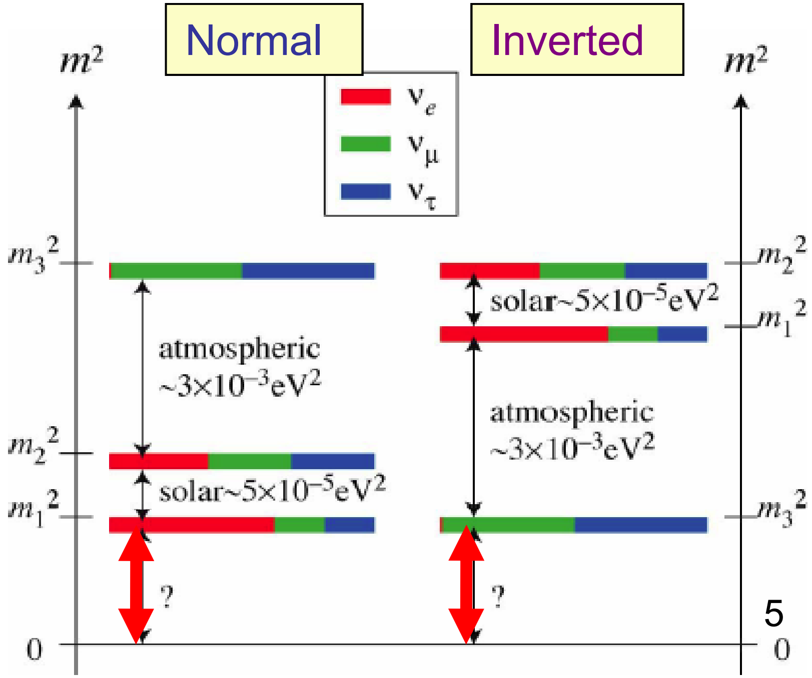
Candles

- Neutrino oscillation is established
  - Δm^2_{12}, Δm^2_{23}, θ_{12}, θ_{23}, (θ_{13})
  - SK, GALLEX-SAGE, SNO, KamLAND
  - T2K, Nova, Double Chooze, Dya Bay, …



- Neutrinos have mass
  - Absolute mass?
  - Majorana particle?

$\Delta m \sim 50$meV
$\Delta m \sim 7$meV



Direct measurement of m_ν

KATRIN => $m_\nu \sim 0.2$ eV

- ^3H β – decay (Q_β: 18.7keV)
- $0\nu\beta\beta$ decay
- CMBR
  - WMAP + SDSS + …

$m_\nu < \sim 0.6$ eV

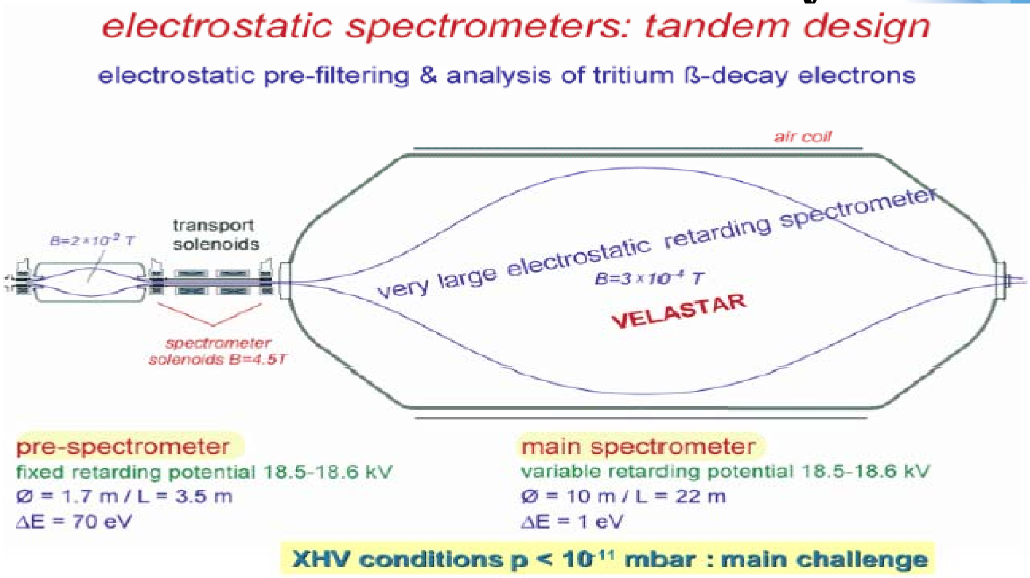
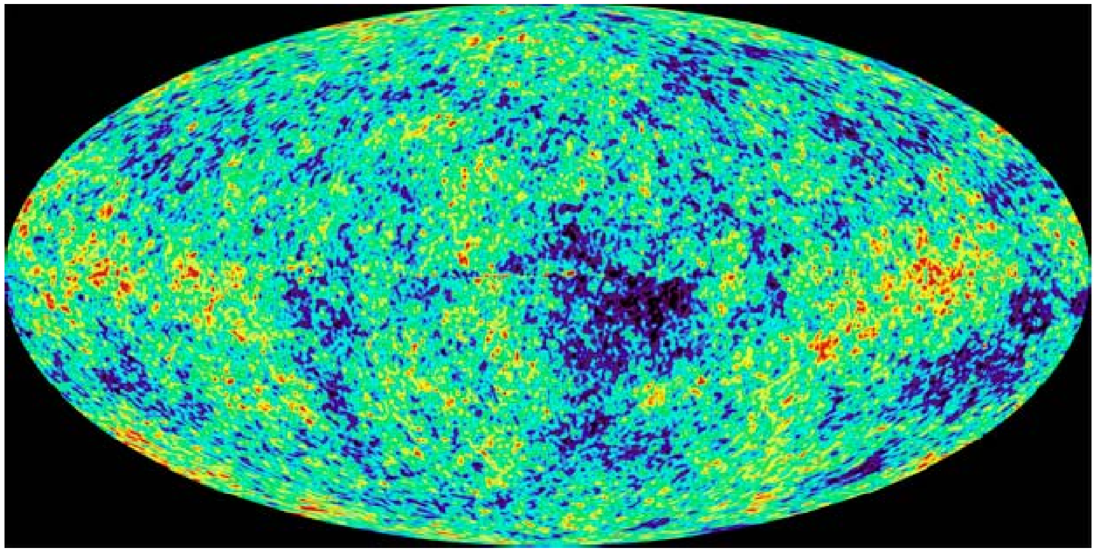


Figure: Pre-Spectrometer and Main Spectrometer



KATRIN Exp.

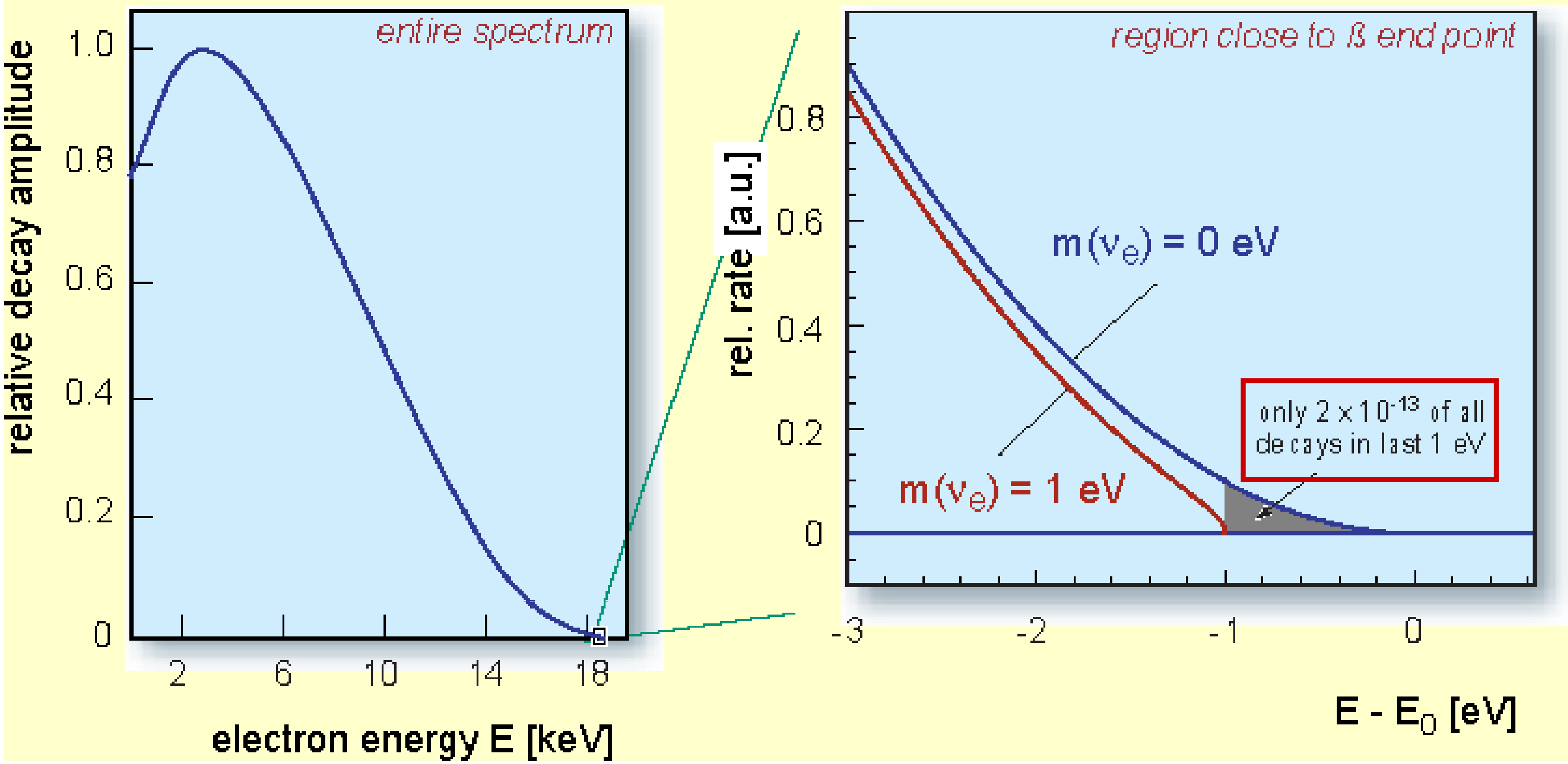
tritium ß-decay and the neutrino rest mass

$$^3H \rightarrow \, ^3He + e^- + \bar{\nu}_e$$

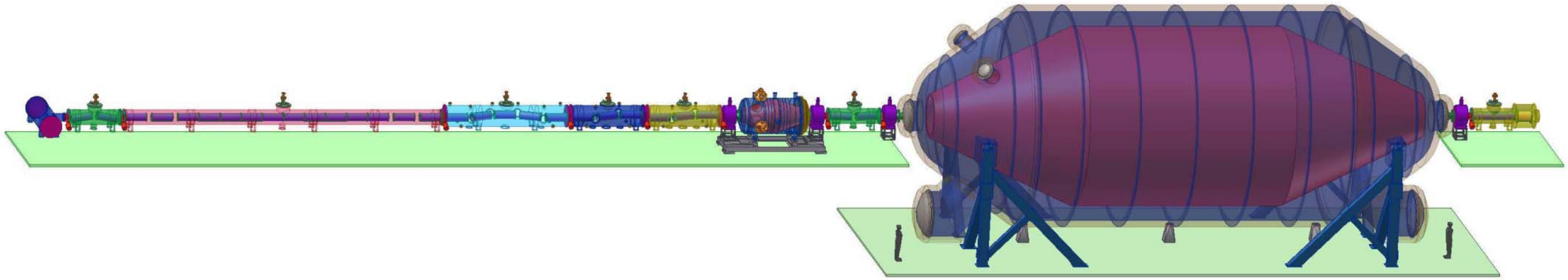
superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV



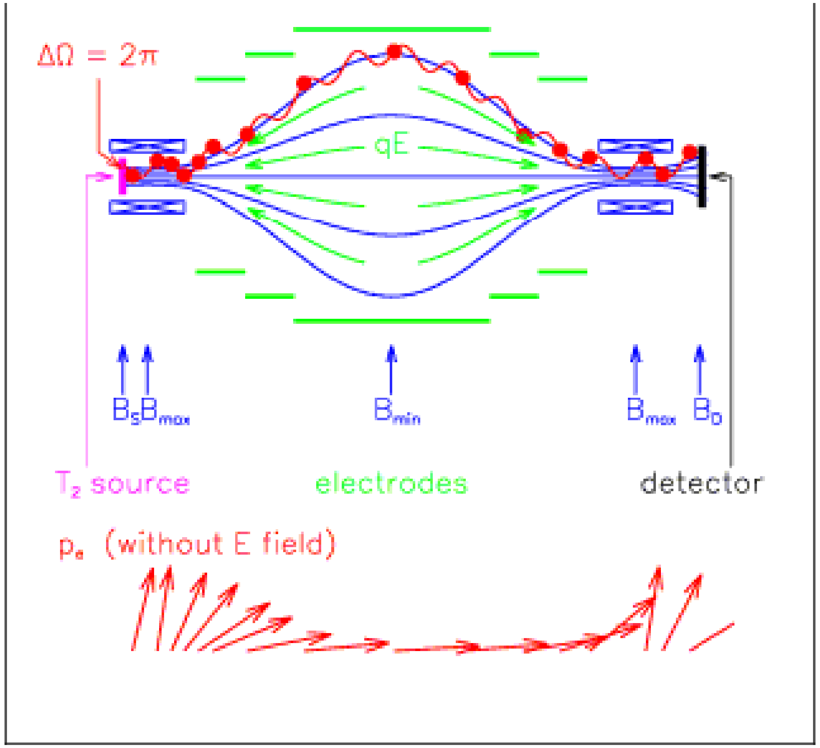
KATRIN Exp.



MAC-E filter

Magnetic Adiabatic Collimation (MAC)

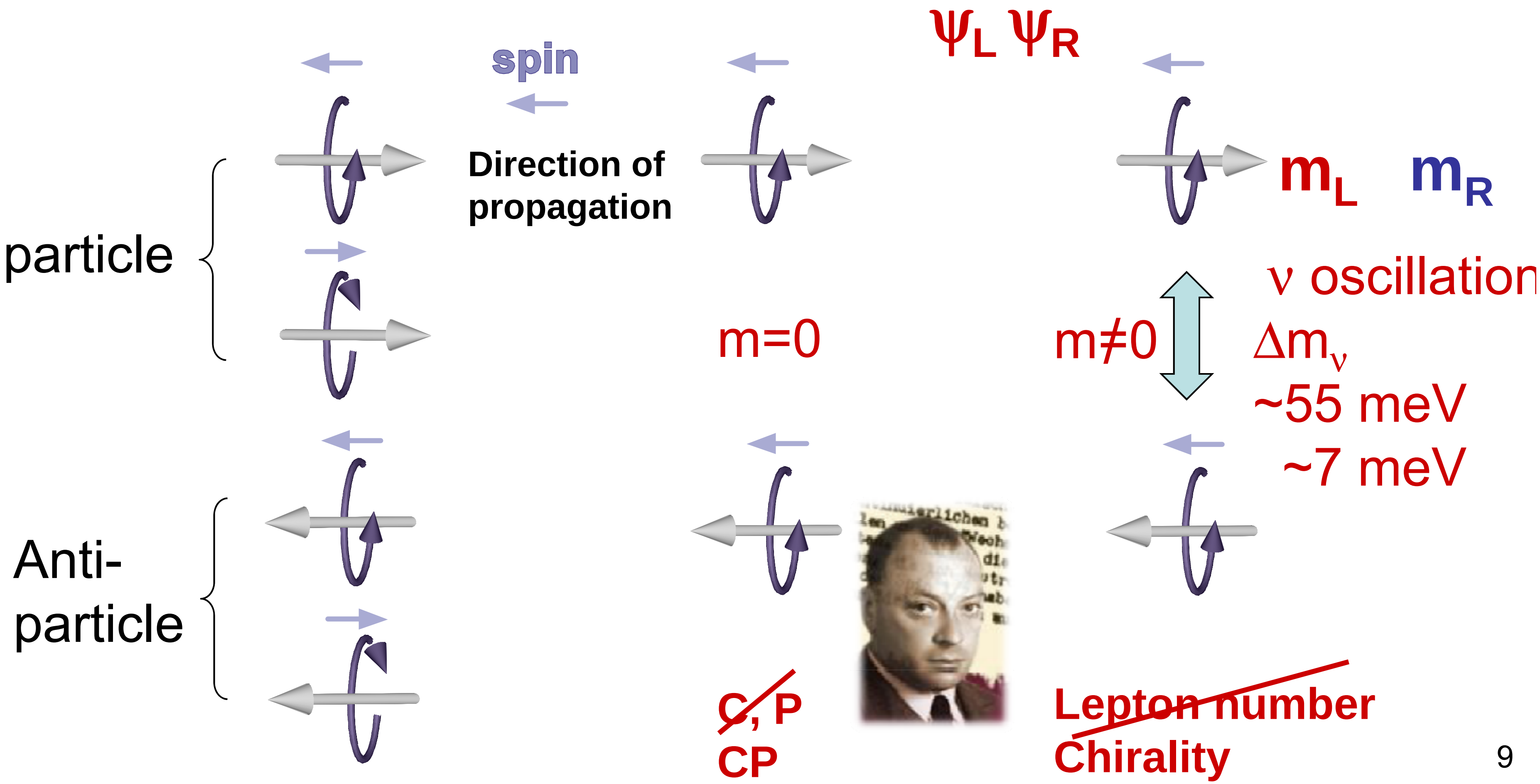
Solid angle 2π



Neutrino type

	Dirac	Weyl	Majorana
• type	Dirac	Weyl	Majorana
• components	4	2	2 x 2

•



ν has to be a Majorana particle

Candles

- Mass term (Dirac)

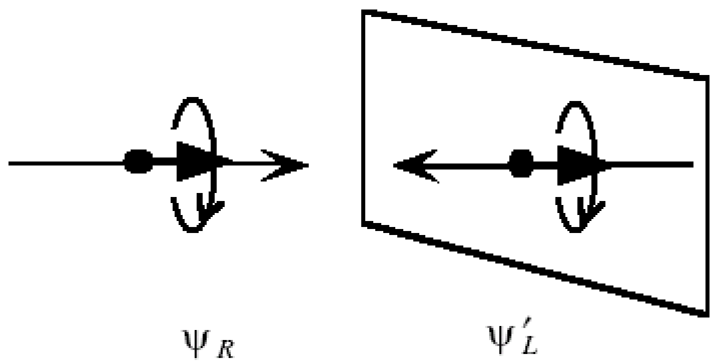
$$\mathcal{L}_D = -m_D \overline{\nu_R^0} \nu_L^0 + \text{ h. c.}$$

- Mass term (Majorana)
  - 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: (Yanagida, Gell-Mann…)
  - Violates lepton number

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

Chirality flip（relativity）

Left handed → right handed (anti-particle)

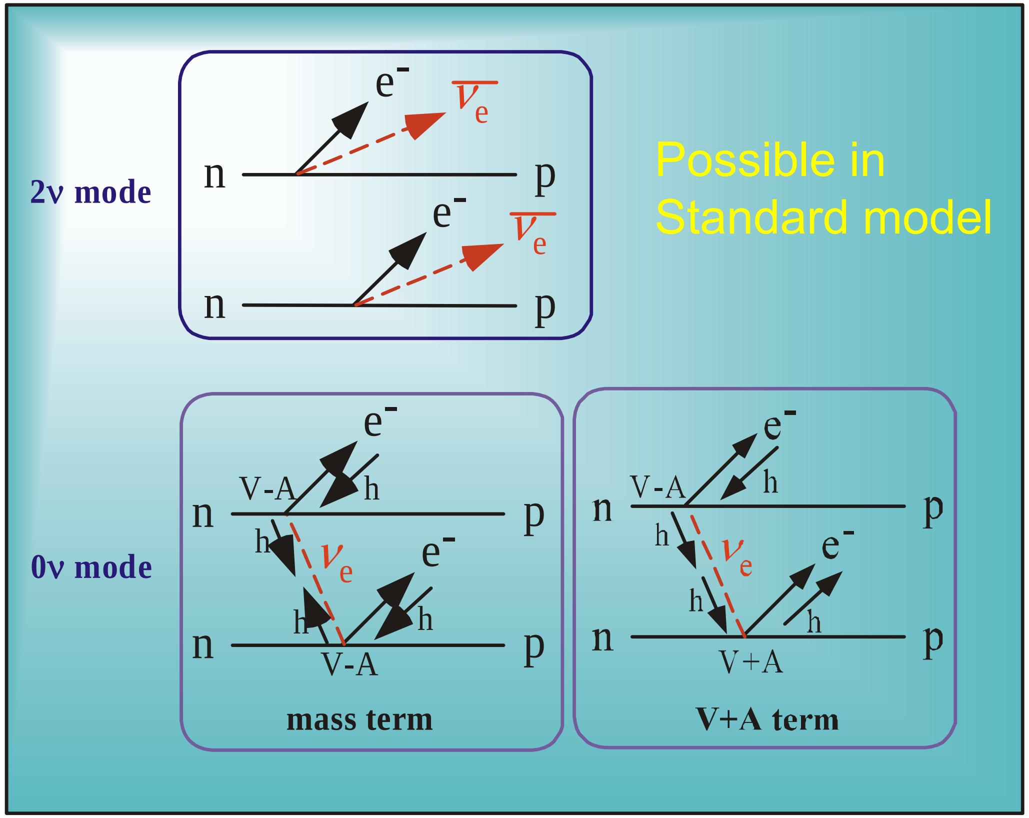


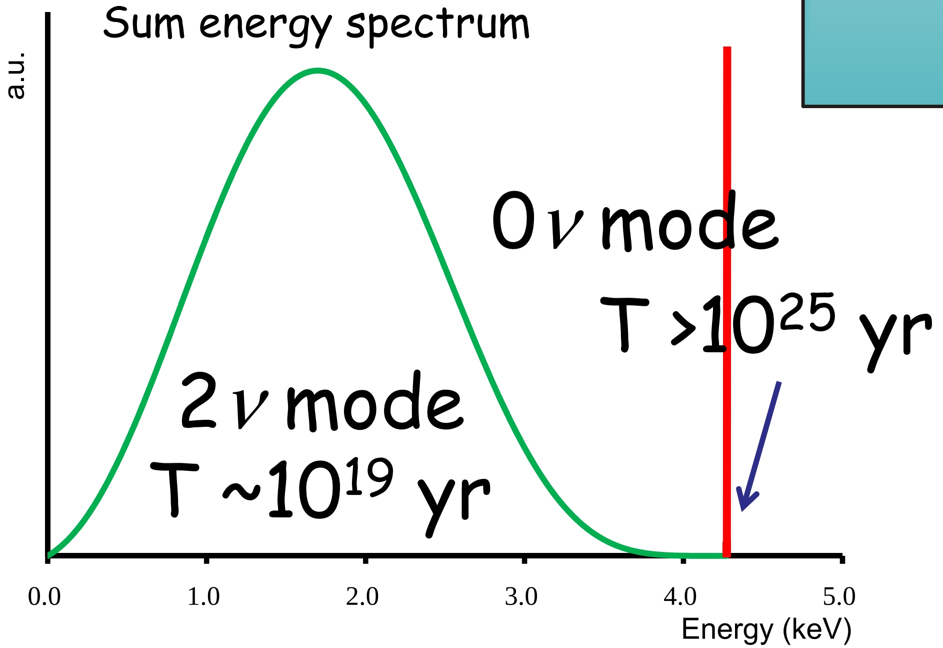
0ν2β decay

Majorana particle

particle⇔anti-particle

- possible only for ν
- matter dominated universe





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

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

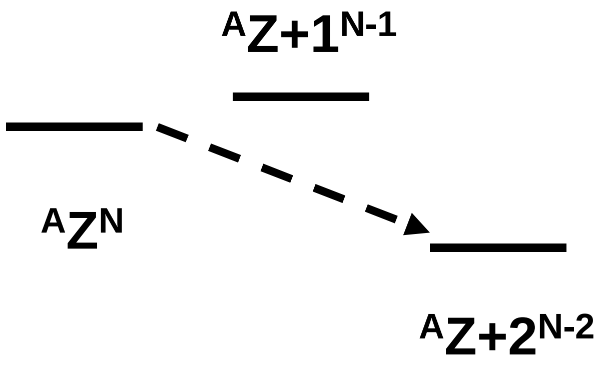
Phase volume — Nuclear matrix element — Effective mass

If $0\nu2\beta$ decay is observed

- Lepton number conservation is violated
  - Particle ⇔ anti-particle
- Neutrinos are Majorana particles
  - Only neutrinos can be Majorana particles
    - Others (quarks and charged leptons): Charge Dirac particles
  - Neutrino mass can be given
- Leptogenesis: Fukugita, Yanagida '86
  - Generates baryon number in our universe

Double beta decay nuclei

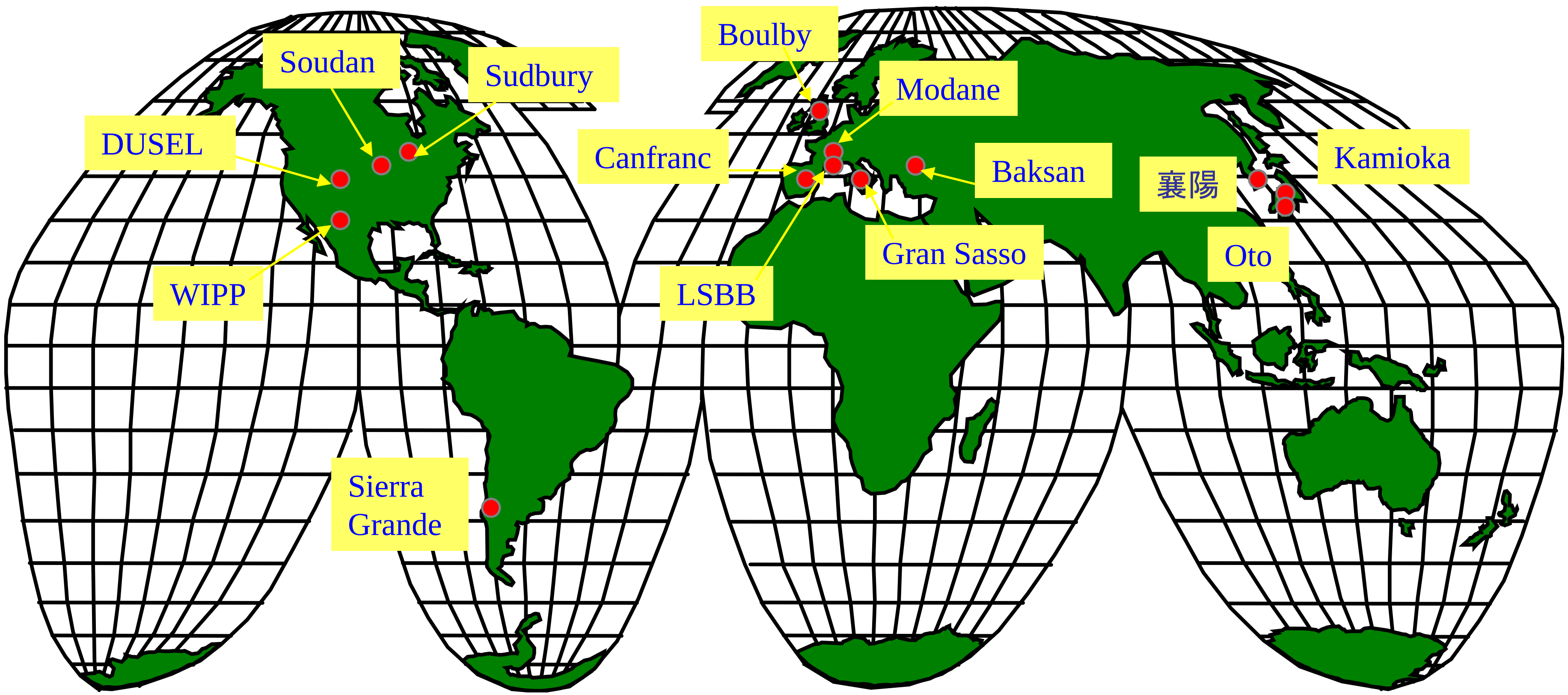
- Nuclei
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo,
  - ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd
  - Positron emitter
- Ultra rare process
  - $10^{20\sim25}$ yr
- Huge natural background sources
  - High sensitive detector
  - Low background circumstance⇔Underground lab.

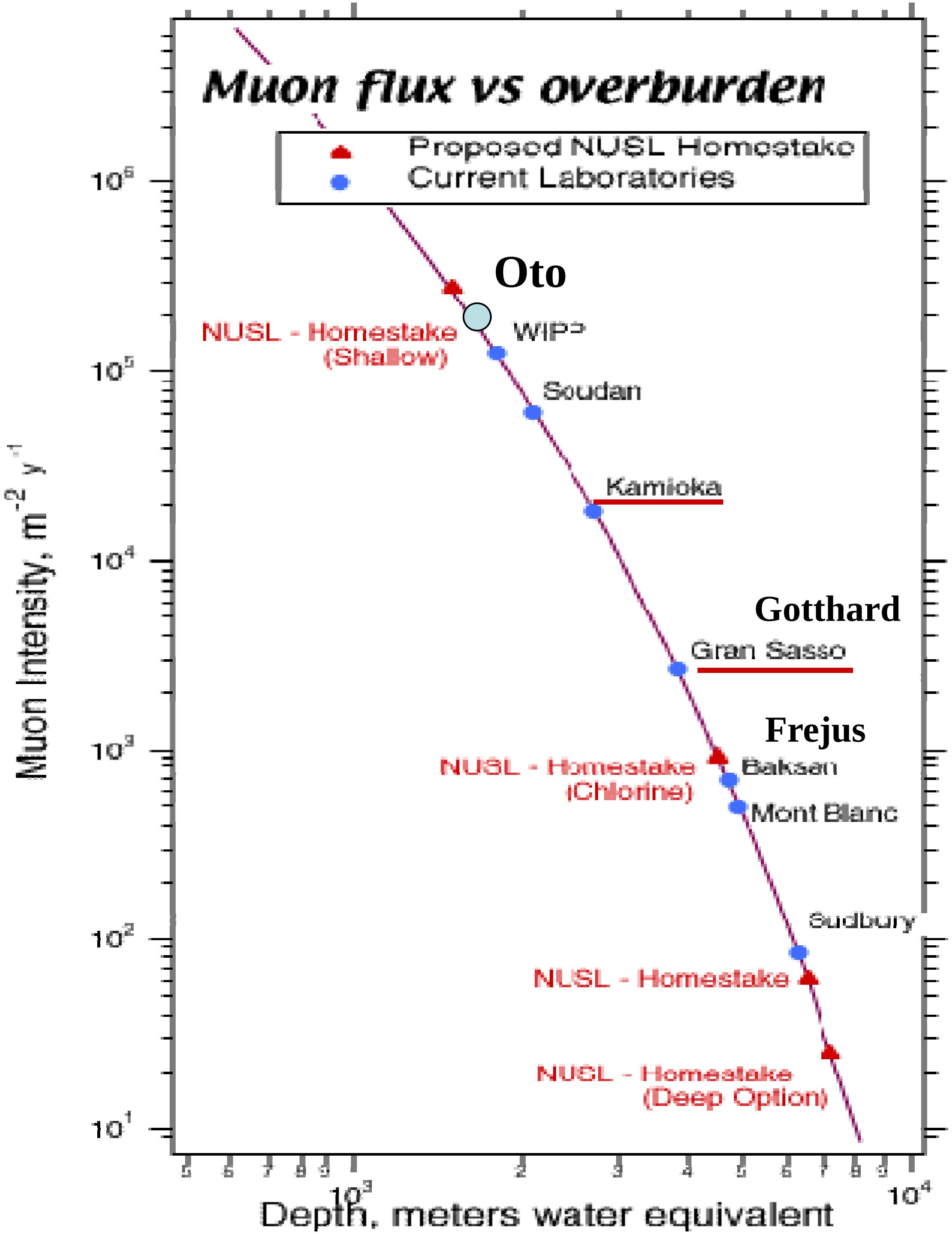


Underground laboraty in the world

Double deta decay
Dark matters

Candles




Muon flux vs overburden
Proposed NUSL Homestake
Current Laboratories
Oto
NUSL - Homestake (Shallow)
WIPP
Soudan
Kamioka
Gotthard
Gran Sasso
Frejus
NUSL - Homestake (Chlorine)
Baksan
Mont Blanc
Sudbury
NUSL - Homestake
NUSL - Homestake (Deep Option)
Muon Intensity, m^{-2} y^{-1}
10^6
10^5
10^4
10^3
10^2
10^1
Depth, meters water equivalent
10^3
10^4

Candles

Detector type

Candles

- Source = detector

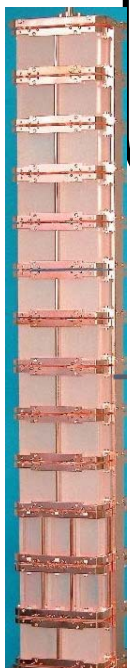
○ ΔE

Semiconductor
- COBRA
- Majorana
- GERDA
- HDM

○ ΔE

Bolometer
- CUORE/CUORICINO

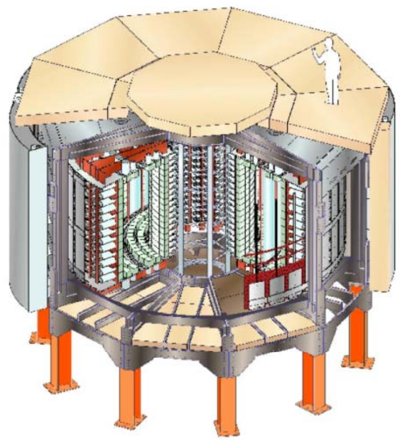
Scintillator
- CANDLES
- KamLAND
- SNO+



- Source ≠ detector

Time Projection, tracking & Drift Chambers
- NEMO/Super-NEMO
- DCBA
- EXO

○ b
× ε

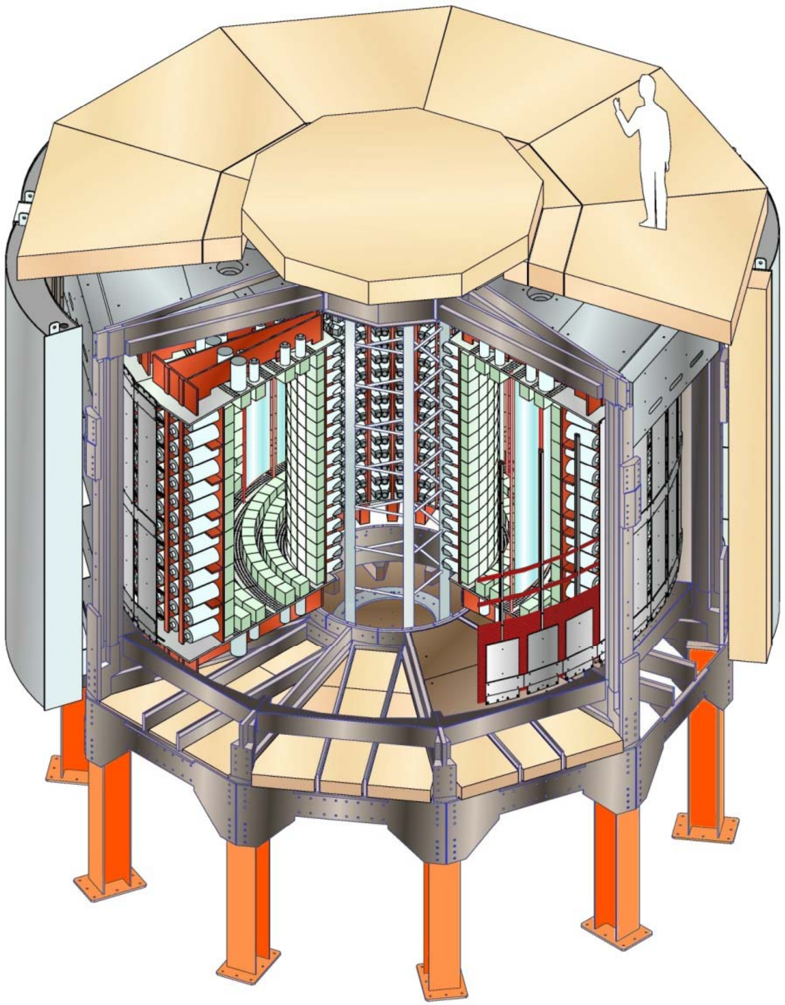


NEMO3 : Neutrino Ettore Majorana Observatory

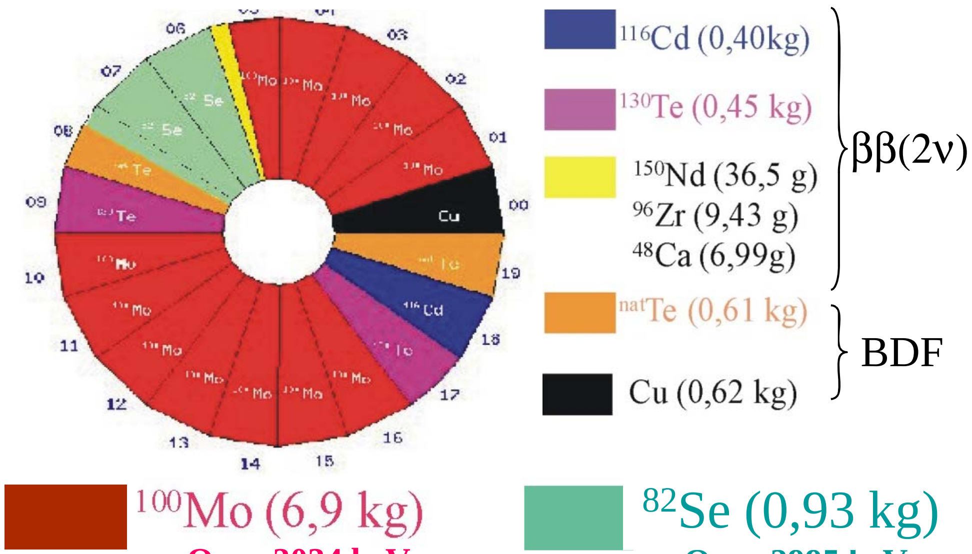
France, United-States, England, Japan, Tcheck Rep., Russia
Started taking data : Feb. 2003, duration : 5 years, Laboratoire Souterrain de Modane (4800 m.w.e)

Candles

Tracking detector (6180 Geiger cells in He+alcohol): Vertex $\sigma_t = 5$ mm, $\sigma_z = 1$ cm
Calorimeter (1940 plastic scintillators – PMTs low radioactivity) FWHM=14% (1 MeV)
Bkg: gamma + neutrons shield, magnetic field, materials low radioactivity



Sources ββ (thickness ~ 60 mg/cm^2)

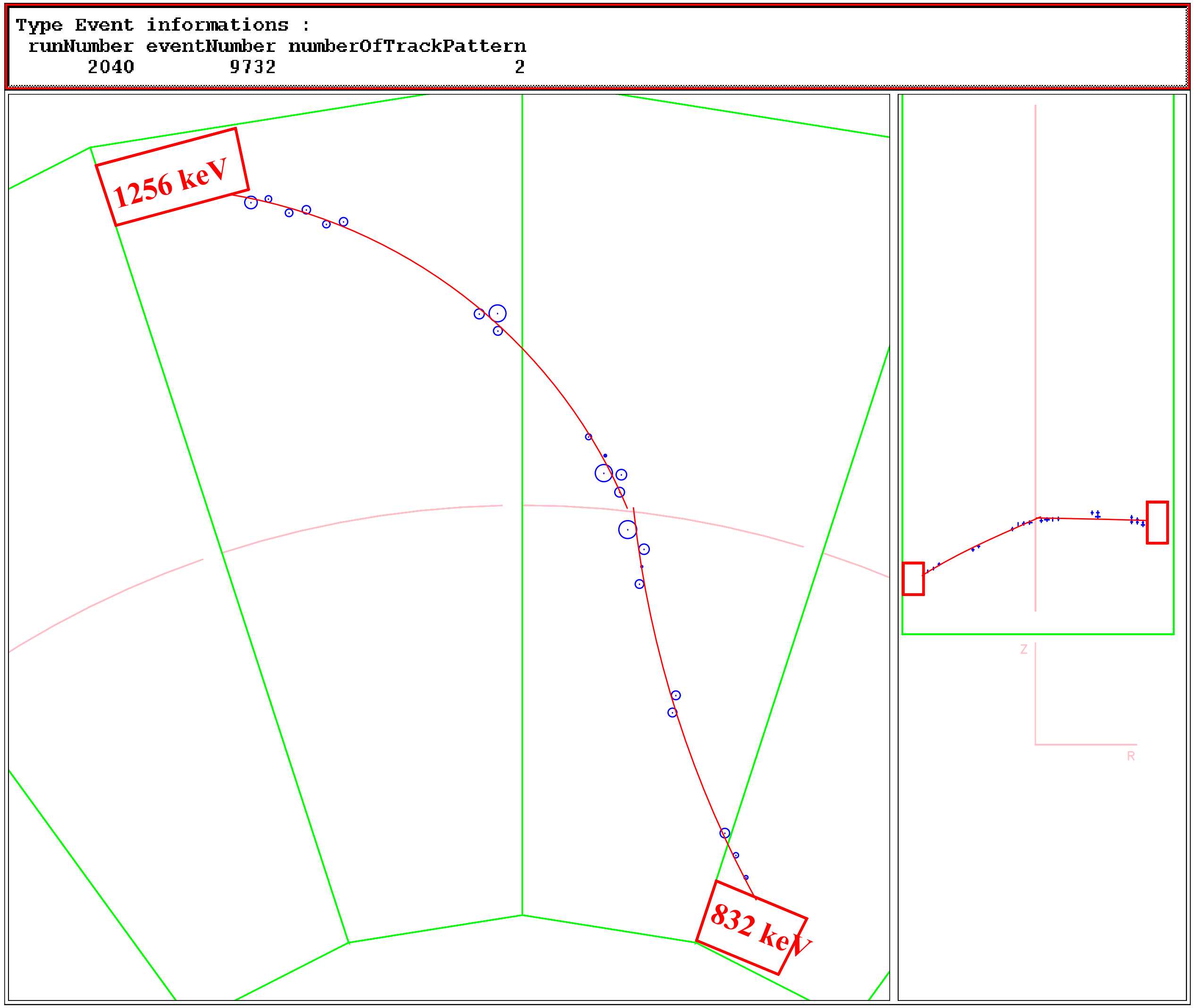


$Q_{\beta\beta}$ = 3034 keV

$Q_{\beta\beta}$ = 2995 keV

^{100}Mo	^{82}Se
N_{Bkg}=0,2 evts y^{-1} kg^{-1}	N_{Bkg}=0,02 evts y^{-1} kg^{-1}
$T^{0\nu}_{1/2}$ > 8. 10^{24} y	$T^{0\nu}_{1/2}$ > 1,5 10^{24} y
<m$_\nu$> < 0,1 – 0,3 eV (90% C.L.)	<m$_\nu$> < 0,45 – 1,2 eV (90% C.L.)

ββ EVENT OBSERVED BY NEMO-3…



E_1+E_2= 2088 keV

(Δt)mes –(Δt)theo = 0.22 ns
(Δvertex)$_\perp$ = 2.1 mm
(Δvertex)$_{//}$ = 5.7 mm

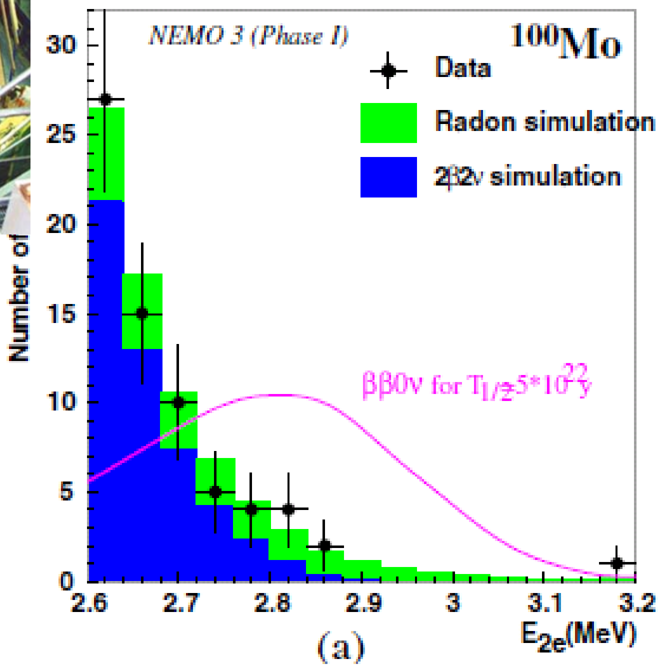
ββ2ν event

Candles

NEMO 3

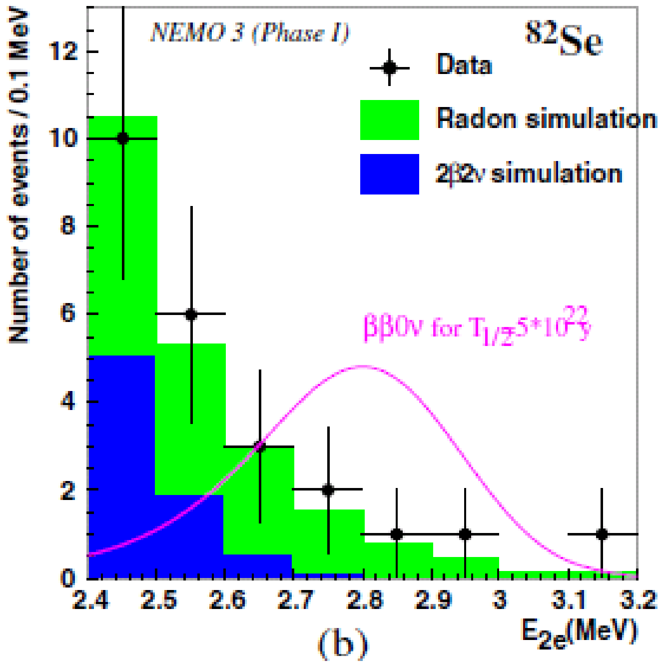
PRL **95,** 182302 (2005)

$> 4.6 \times 10^{23}$ yr



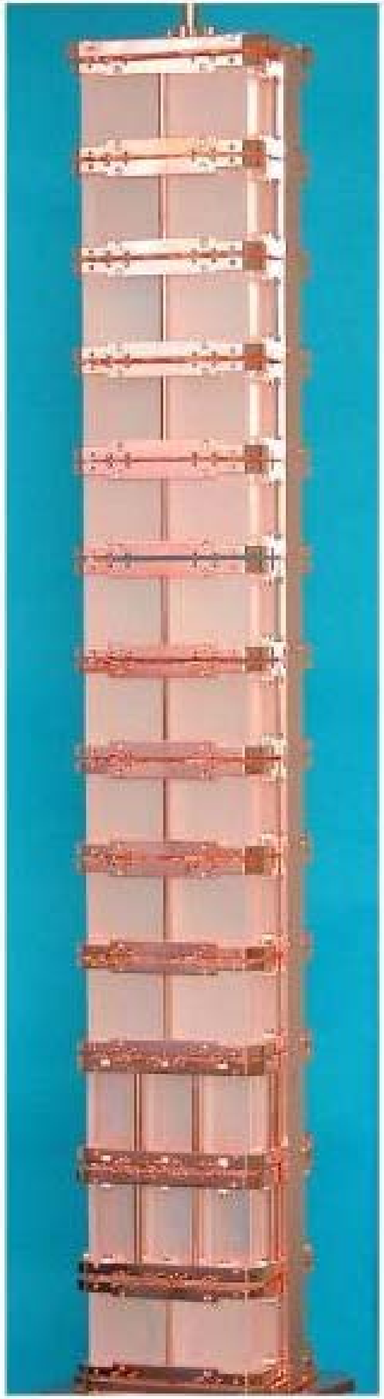
(a)

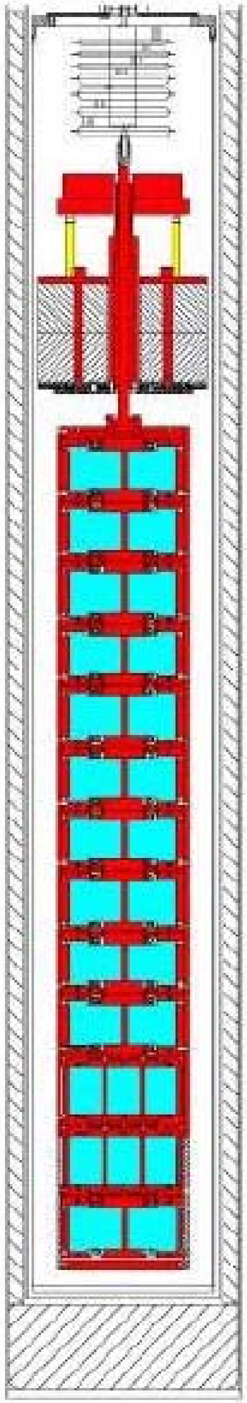
$> 1.0 \times 10^{23}$ yr



(b)

Nuclear matrix elements		^{100}Mo	^{82}Se
Shell model	Caurier 1996 [15]		<4.9
QRPA	Rodin 2005 [16]	<2.7–2.8	<4.1–4.5
QRPA	Simkovic 1999 [17]	<1.0	<3.3
QRPA	Suhonen 2003 [18,19]	<1.1	<2.8–4.2
QRPA	Stoica 2001 [20]	<0.7–1.1	<1.7–3.7

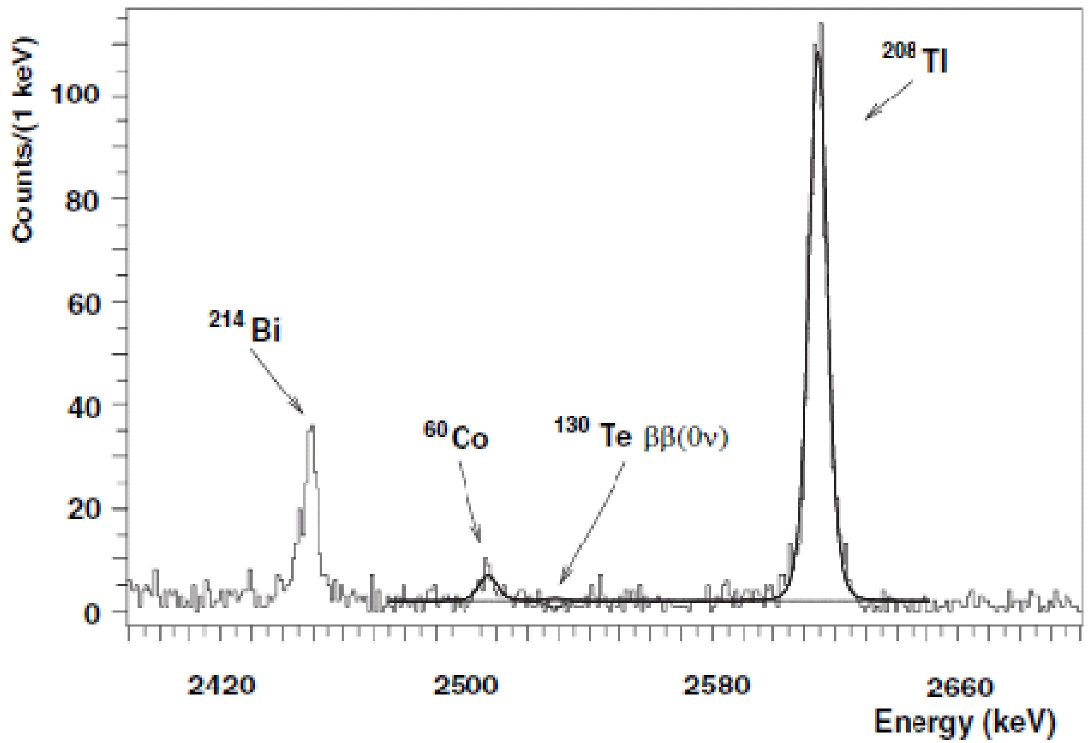




CUORICINO

PRL **95,** 142501 (2005)

Candles



m_ν<0.2-1.05 eV

m_ν<0.21-0.70 eV
TAUP 2009

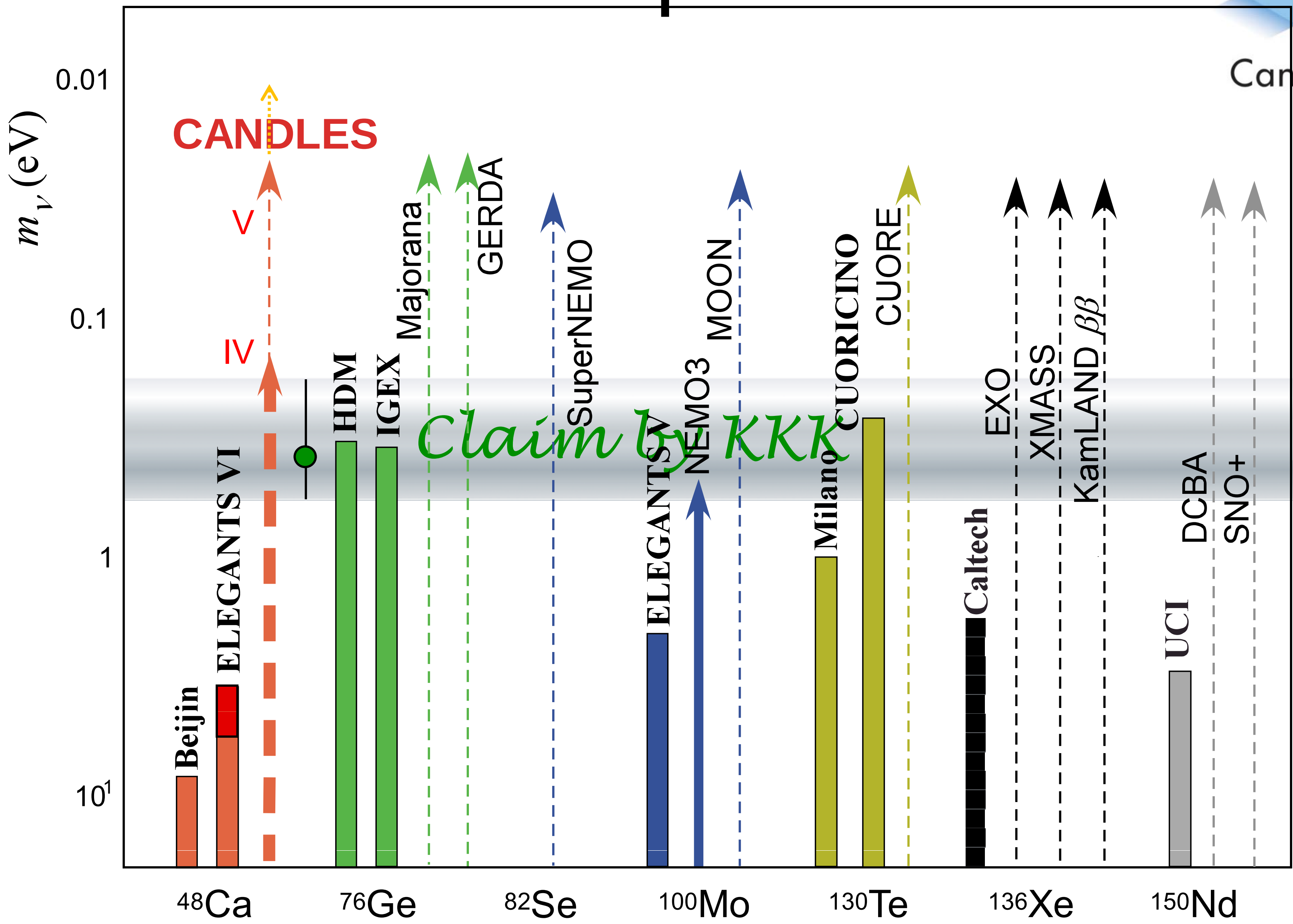
Bolometer TeO_2

Overview of Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

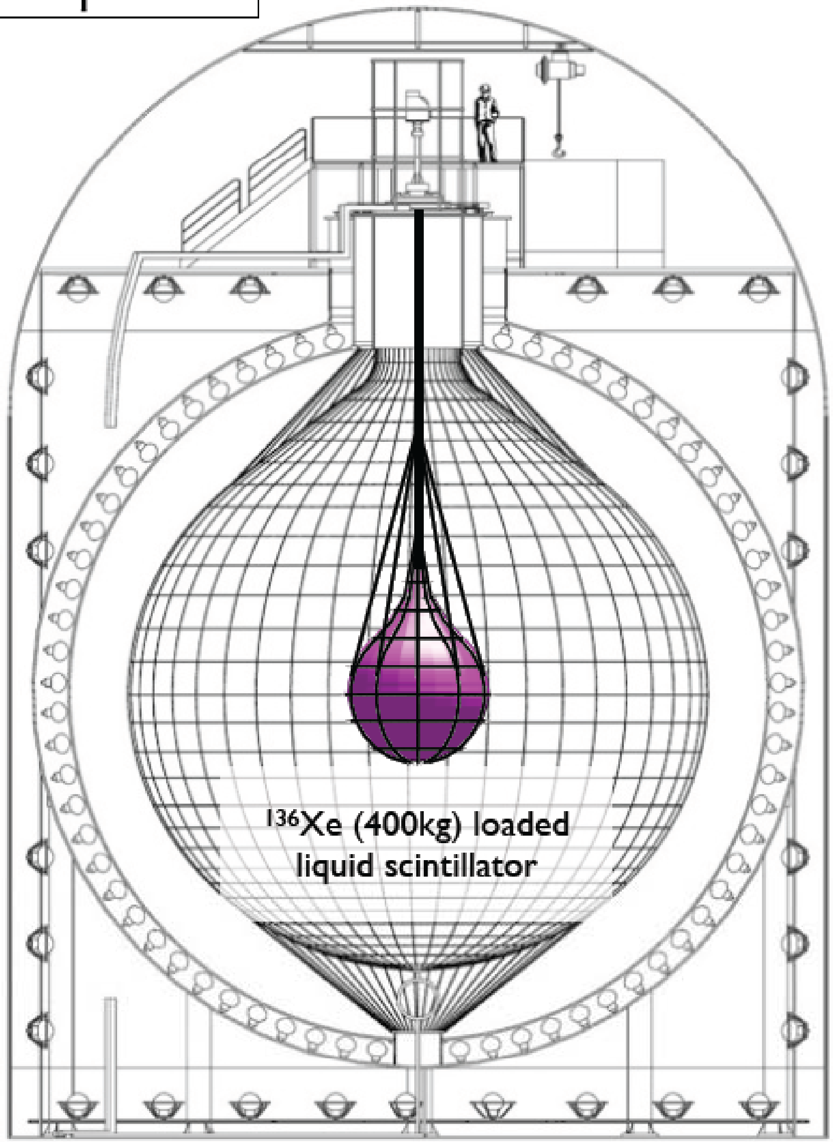
***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

World Experiments



KamLAND with ^{136}Xe

1st phase



starts in FY2011.

KamLAND-ZEN

Merit of using Xe

- isotopic enrichment, purification established
- soluble to LS more than 3 wt%, easily extracted
- slow $2\nu2\beta$ ($T_{1/2}>10^{22}$ years) requires modest energy resolution

Merit of using KamLAND

- ultra low radioactivity environment based on ultra pure LS and 9m radius active shield

U: <3.5x10^{-18} g/g

Th: <5.2x10^{-17} g/g

- no modification to the detector is necessary to accommodate DBD nuclei
- high sensitivity with low cost (1st phase budget secured, 190 kg in hand, 230kg purchase going on)
- reactor and geo- antineutrino observations continue
- high scalability
  capable to contain 10 ton of ^{136}Xe

Studies at Osaka Univ.

Candles

- ELEGANTS III ^{76}Ge (source = det.)
  - Solid state detector
- ELEGANTS V ^{100}Mo (source $\neq$ det.)
  - Plastic scint. + chamber
  - MOON
- ELEGANTS VI **^{48}Ca** (source = det.)
  - CaF_2(Eu) scintillator
- CANDLES **^{48}Ca** (CaF_2 in Liquid scintillator)

Why ^{48}Ca

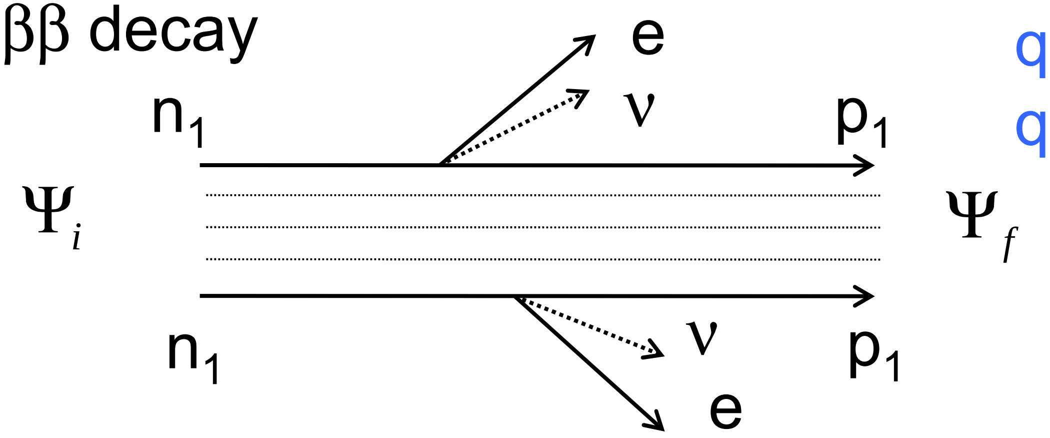
- Highest Q value (4.27 MeV, ^{150}Nd: 3.3 MeV)
  - Large PV, Little BG（γ: 2.6 MeV, β: 3.3 MeV）
- Small natural abundance: 0.187%
  - Isotope separation → expensive (no Gas)
- Next generation
  - $m_\nu \sim T^{-1/2} \sim$ (Det. Mass)$^{-2}$ (no BG)

    $\sim$ (Det. Mass)$^{-4}$（BG limited）

    $$\left(\frac{\Delta EB}{Mt}\right)^{1/4}$$
  - ^{48}Ca (no BG so far)
- Nuclear matrix element ⇒ $\langle m_\nu \rangle$
- If we want to sense normal hierarchy region, only ^{48}Ca + enrichment have a chance.

Nuclear matrix element

2νββ decay



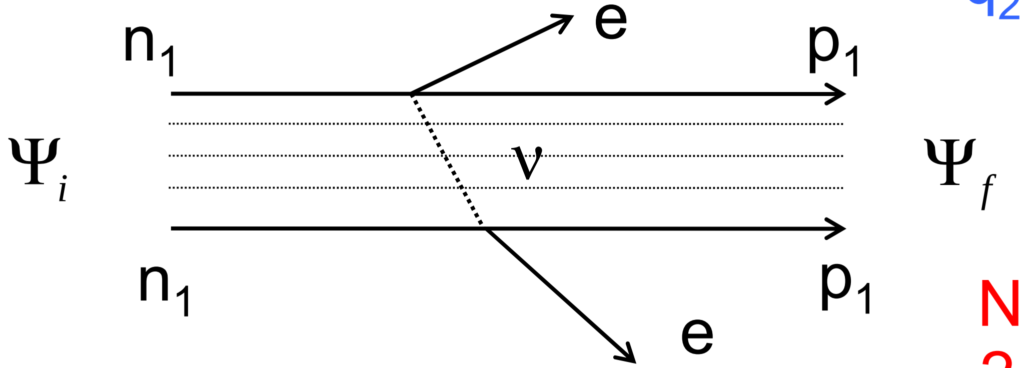
$q_1 \sim 0$
$q_2 \sim 0$

Exp.

$$\int dr \overline{\Psi_f} \Psi_i$$

$F_{2N}(q=0)$

0νββ decay



$q_2 + q_1 \sim 0$
$q_2 - q_1 \sim p_F$

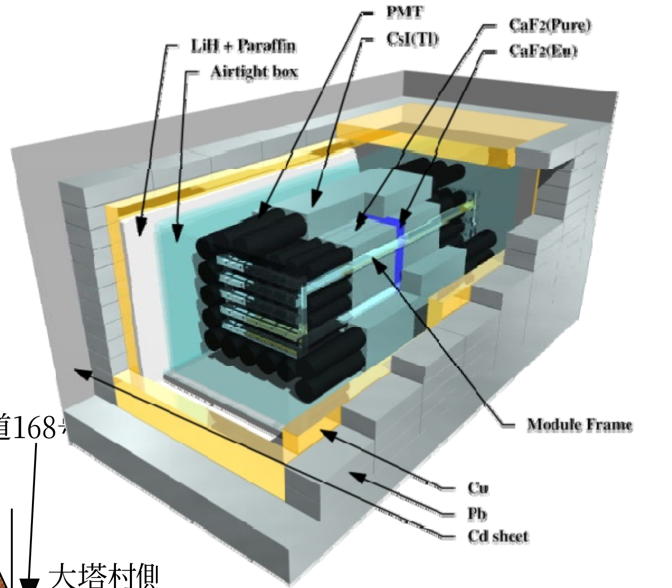
$F_{2N}(q)$

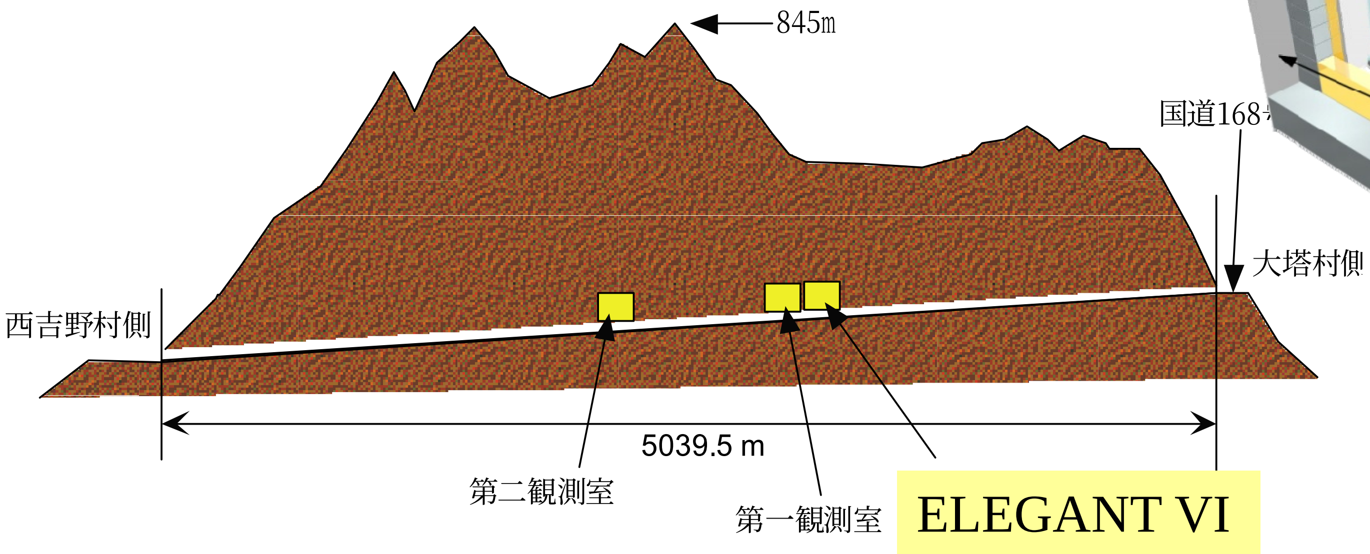
$$\int dr e^{i(q_1 - q_2)(r_1 - r_2)} \overline{\Psi_f} \Psi_i$$

Neutrino potential $1/r \sim A^{-1/3}$
2 nucleon correlation

Oto Cosmo Observatory

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



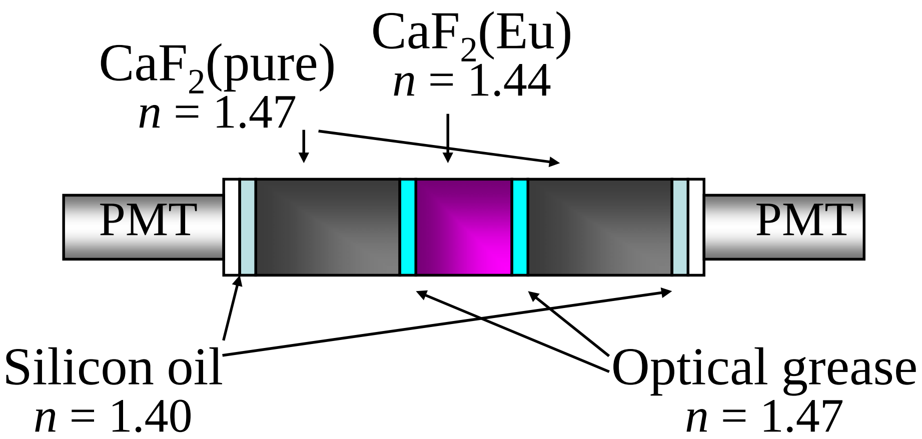


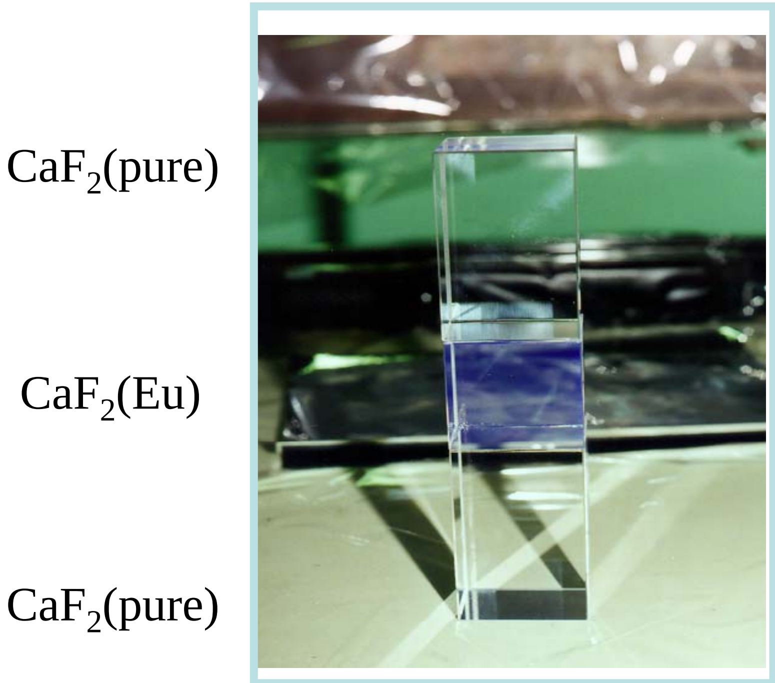
$CaF_2(Eu)$

CaF_2(pure) as { light guide / active shield for PMT side }

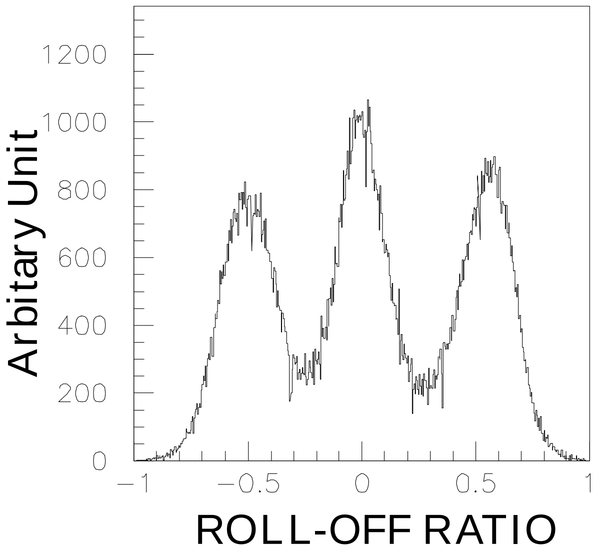
CaF_2(Eu) is not transparent for U.V. light

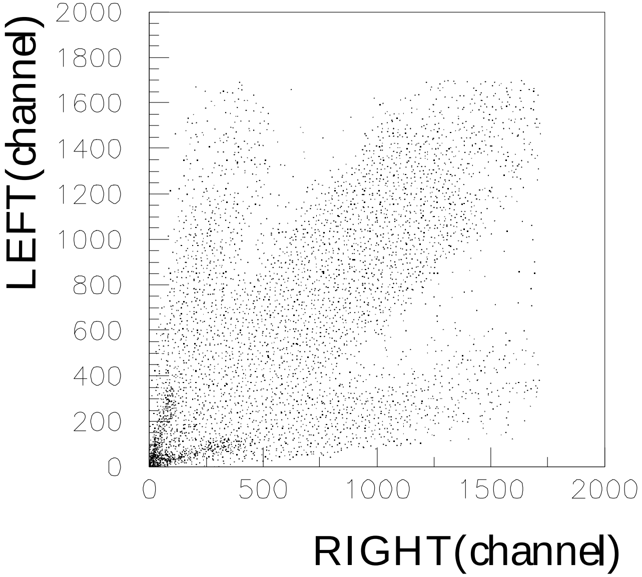
Left - right ratio selects signals from central region





Roll-off ratio





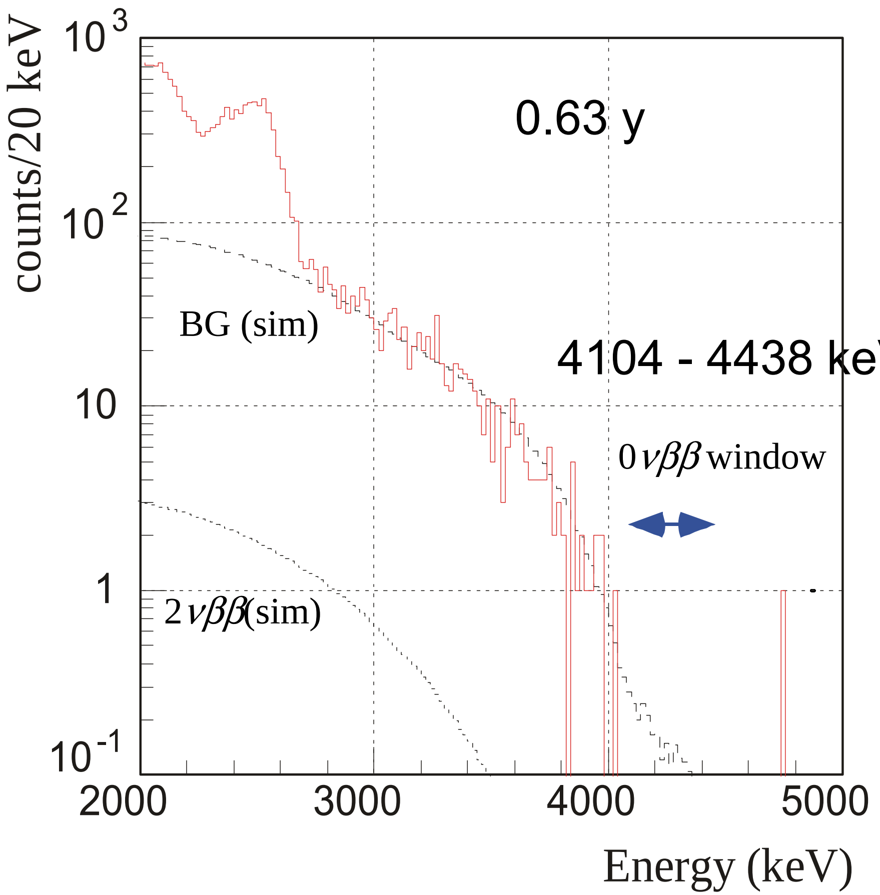
$$R = \frac{V_L - V_R}{V_L + V_R}$$

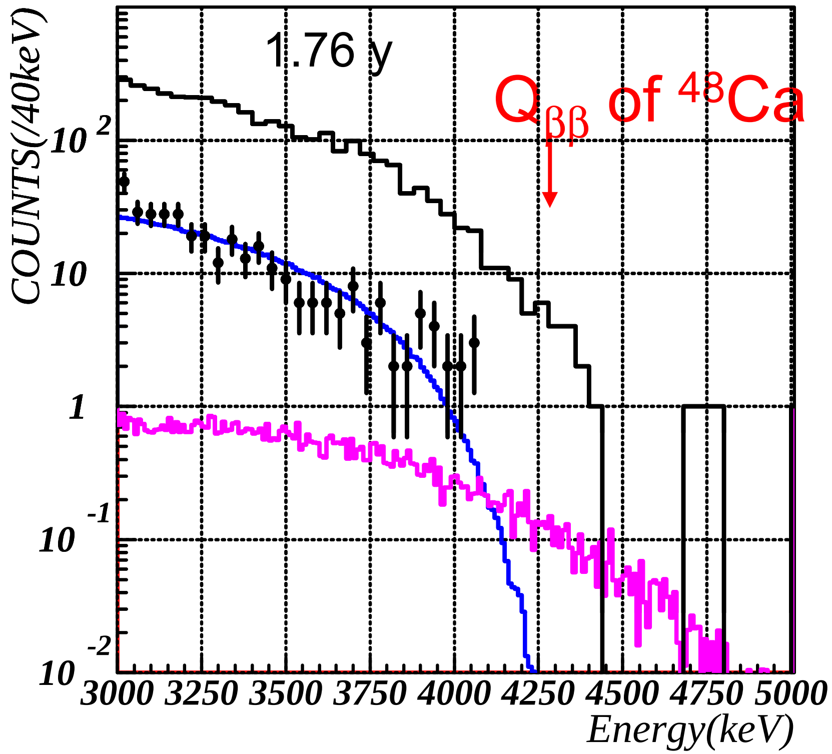
PH(CaF_2(Eu))=
~3 times PH(CaF_2)

^{48}Ca double beta decay by ELEGANT VI

PRC78 058501('08)

Candles





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

NPA 730 '04, 215

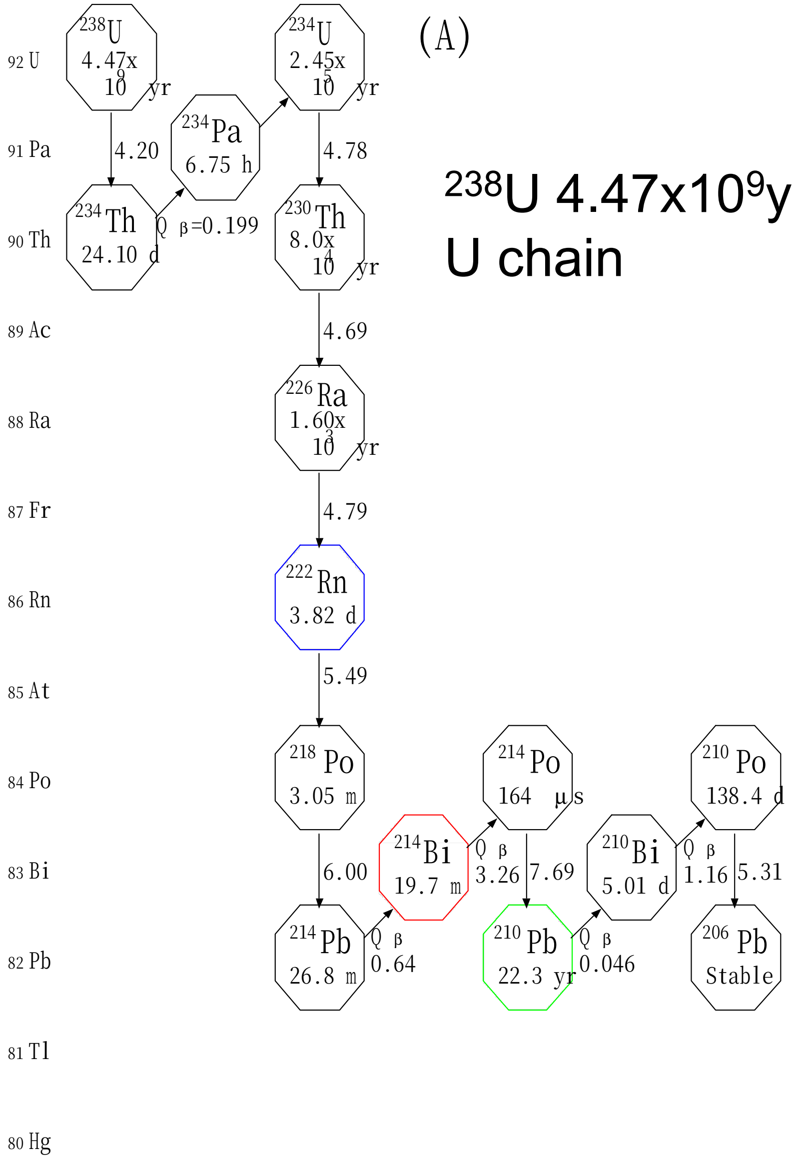
$$T_{1/2}^{0\nu\beta\beta} > 5.8\times10^{22}\ \text{year}\quad (90\%\ \text{C.L.})$$
$$\langle m_\nu \rangle < 3.5 \sim 22\ \text{eV}\quad (90\%\ \text{C.L.})$$

Not limited by backgrounds

But only 6.4g of ^{48}Ca

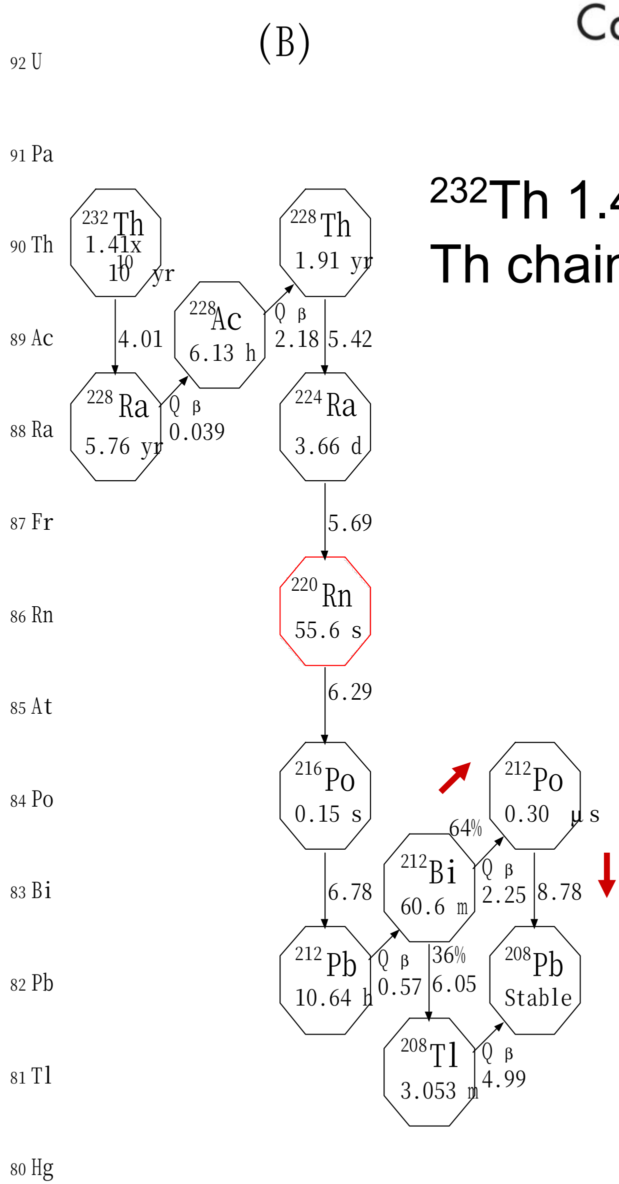
Radioactive Backgrounds

Candles



^{238}U 4.47x10^{9}y

U chain



^{232}Th 1.4x10^{10}y

Th chain

How to sense $m_\nu = 1 \sim 10^{-2}$eV

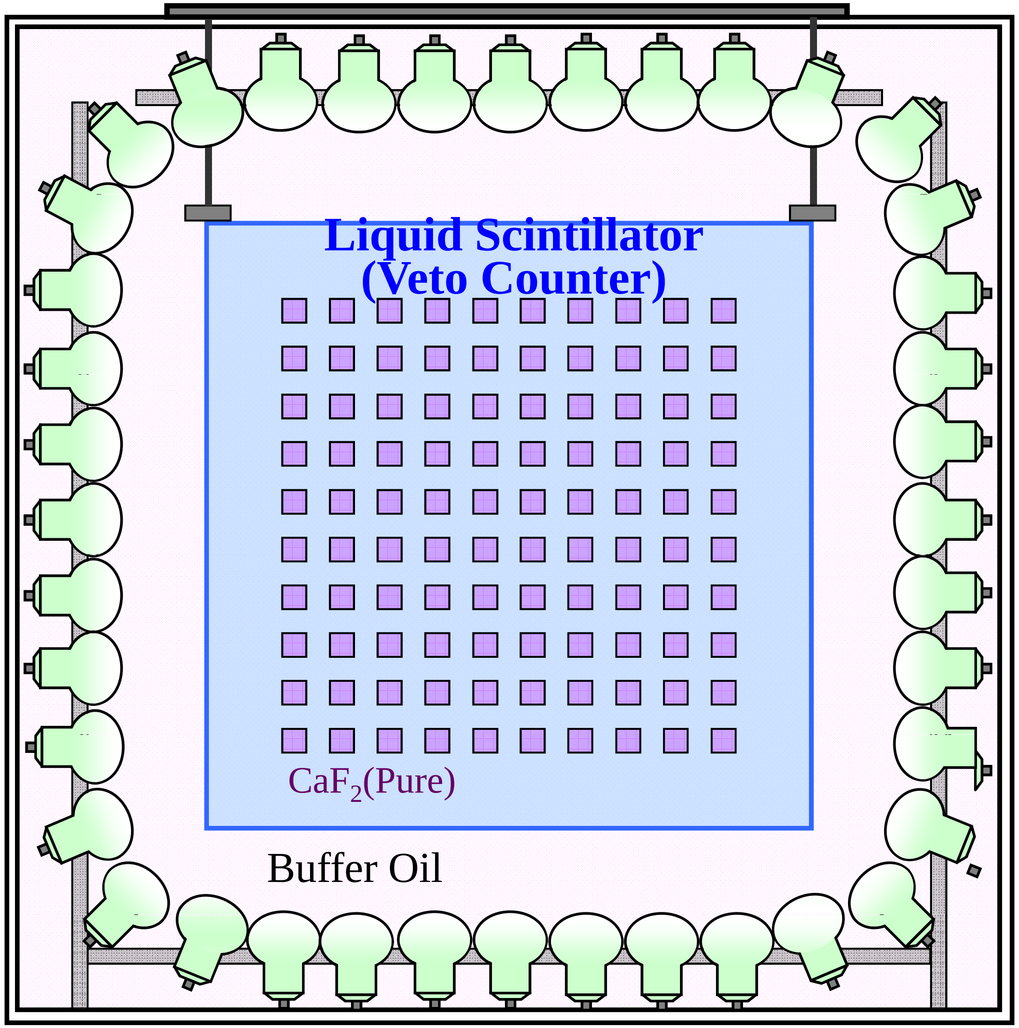
Candles

- 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, 2t, ..
  enrichment
  ^{48}Ca ($Q_{\beta\beta}$=4.27MeV)
- **Liquid Scintillator**
  Wave Length Shifter
  4 π Active Shield
  Passive shield
- **Photomultiplier**
  energy resolution

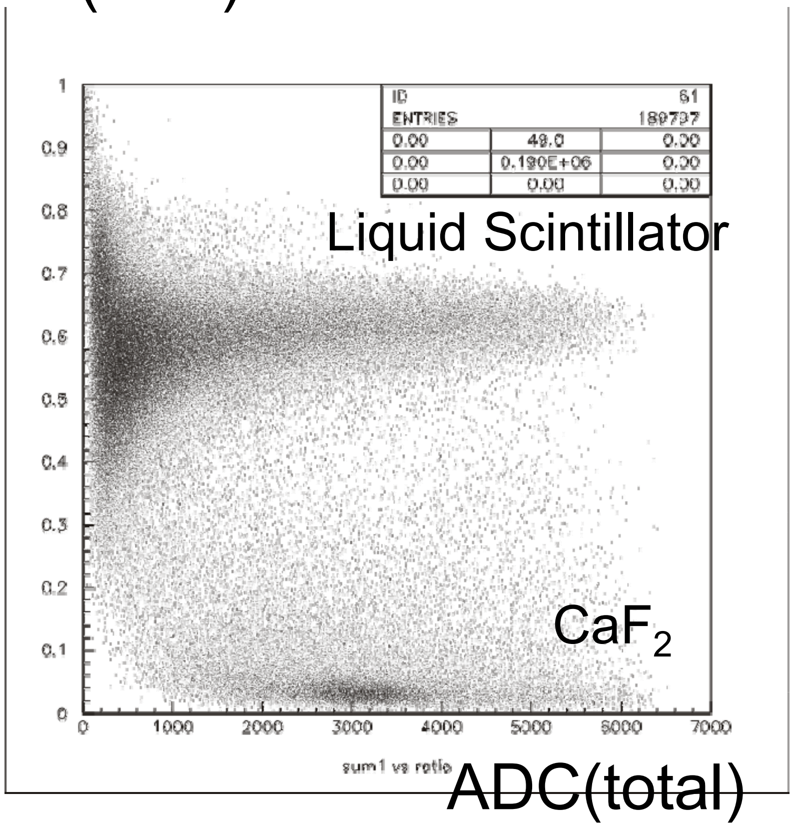
Big detector

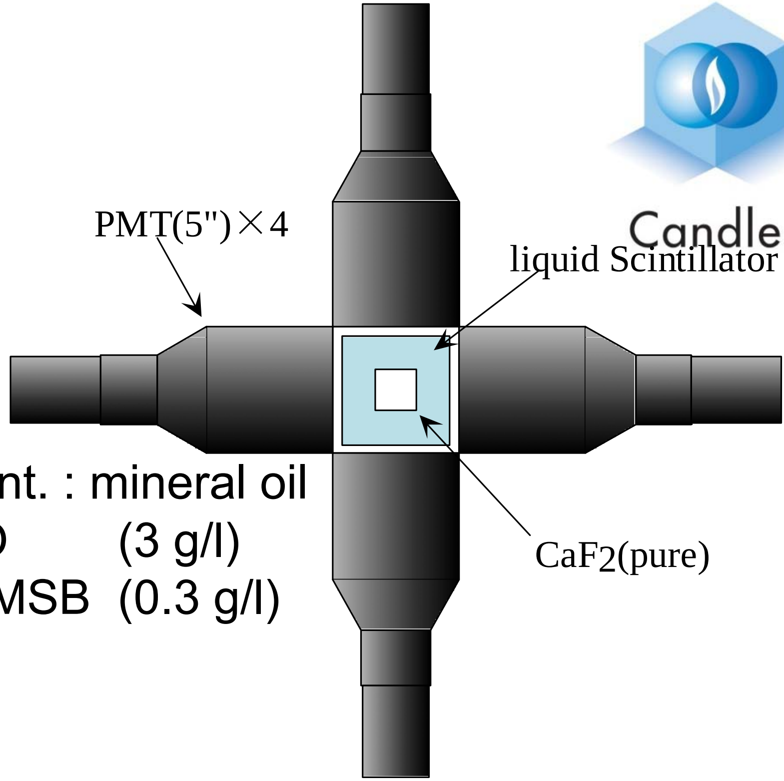
- CaF_2 crystal
  - Best optical lens
  - Long attenuation length
    - 10m (catalog value for visible light)
    - >1m (our measurement for scintillation light)
- Large volume detector
  - 10x10x10 cm^3 x 600 (2t) (CANDLES IV)
  - Increase the number of nuclei (^{48}Ca)

    6.4 g (ELE VI) ~2.5(kg)
  - Enrichment: further increase

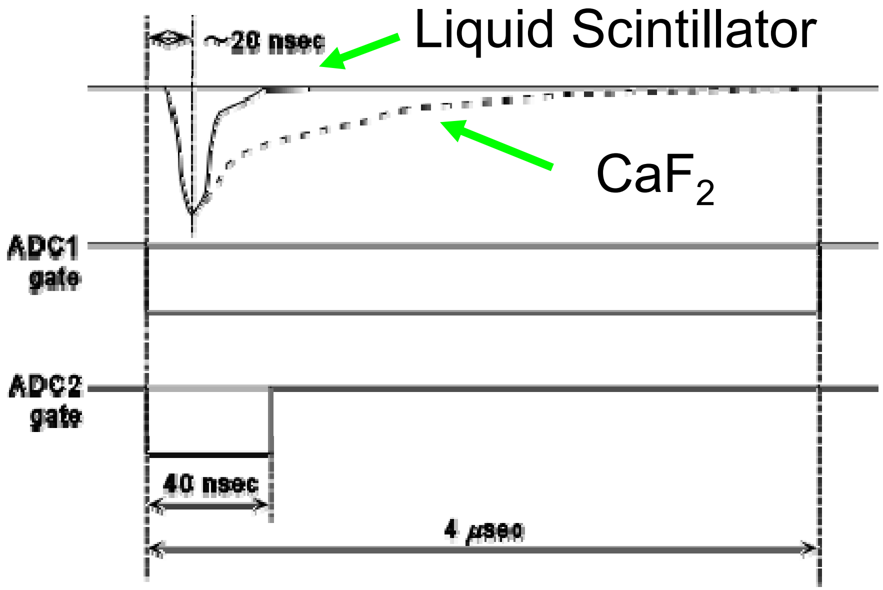
CANDLES I
Background rejection
POP(Proof of Principle)

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





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

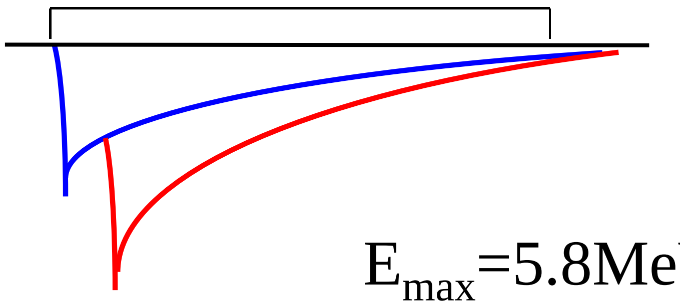


Background @ Q value region

- No natural BG @4.3 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

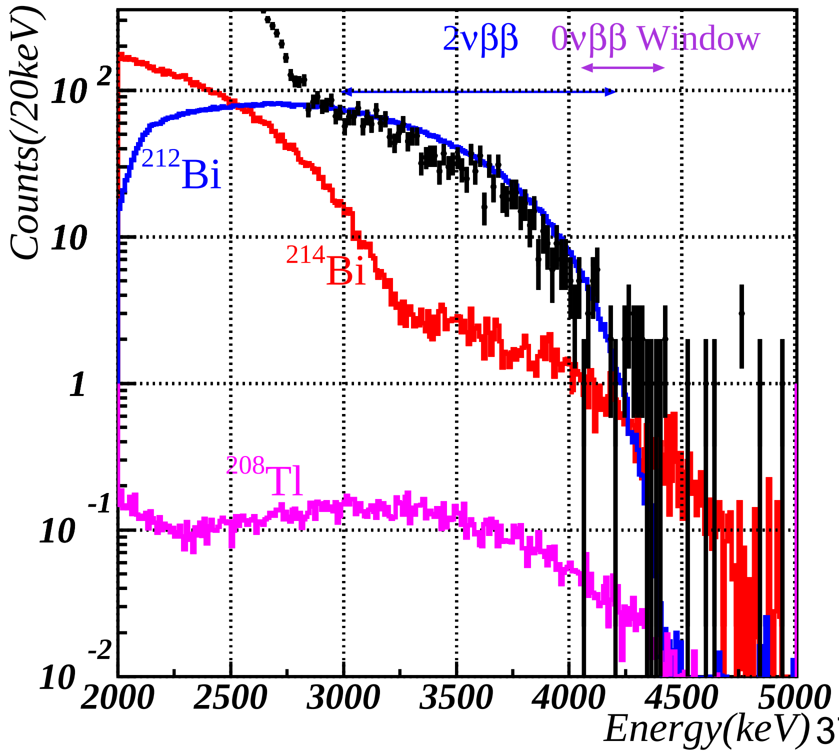
Gate width(4μsec)



β+α

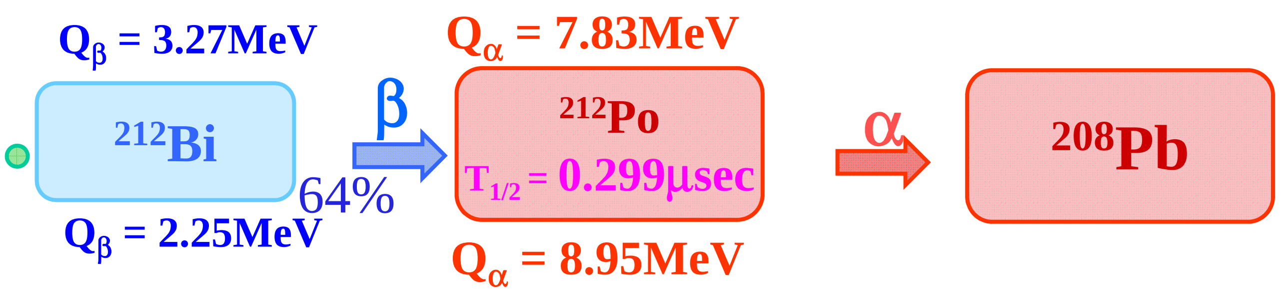
E_{max}=5.8MeV(U)
5.3MeV(Th)

- experimental Data



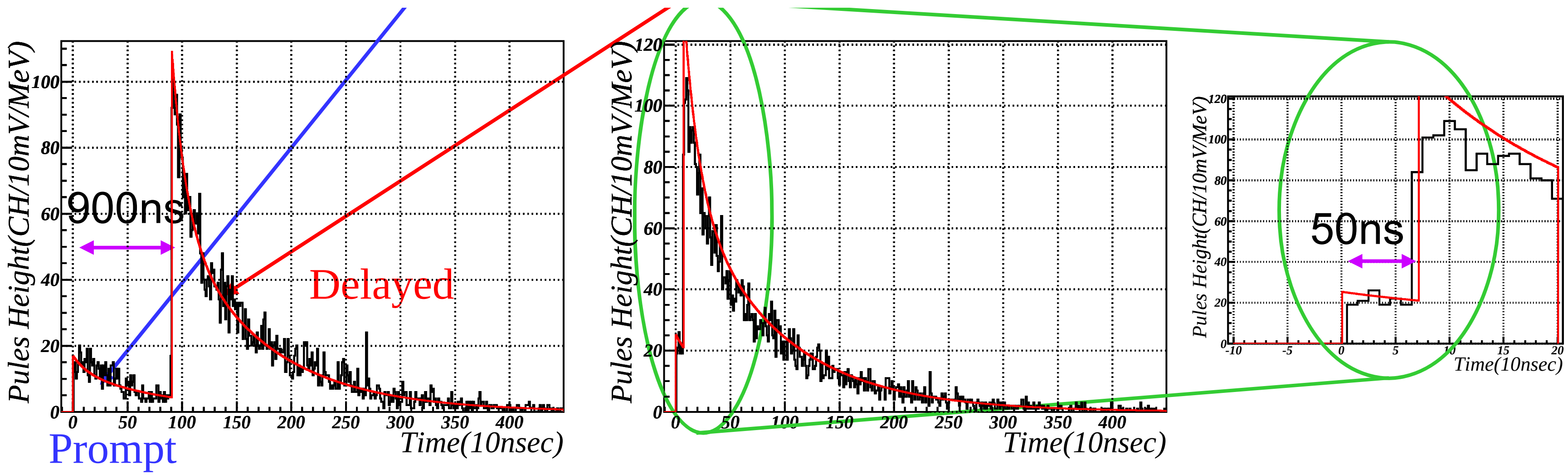
Rejection of Double Pulse

Candles



Th chain

Typical Pulse Shape(100MHz FADC)



Reduction

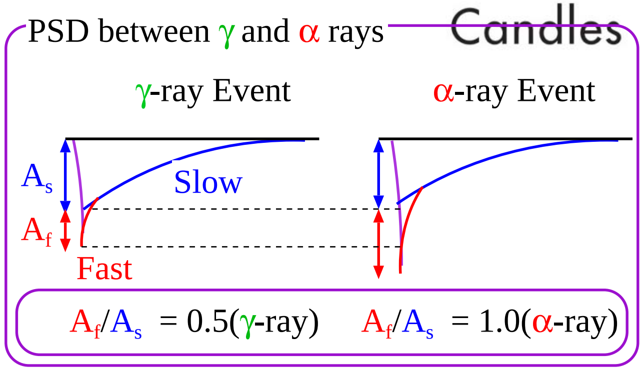
100MHz FADC $\Delta T >$ **30ns(3ch) ; ~3%**

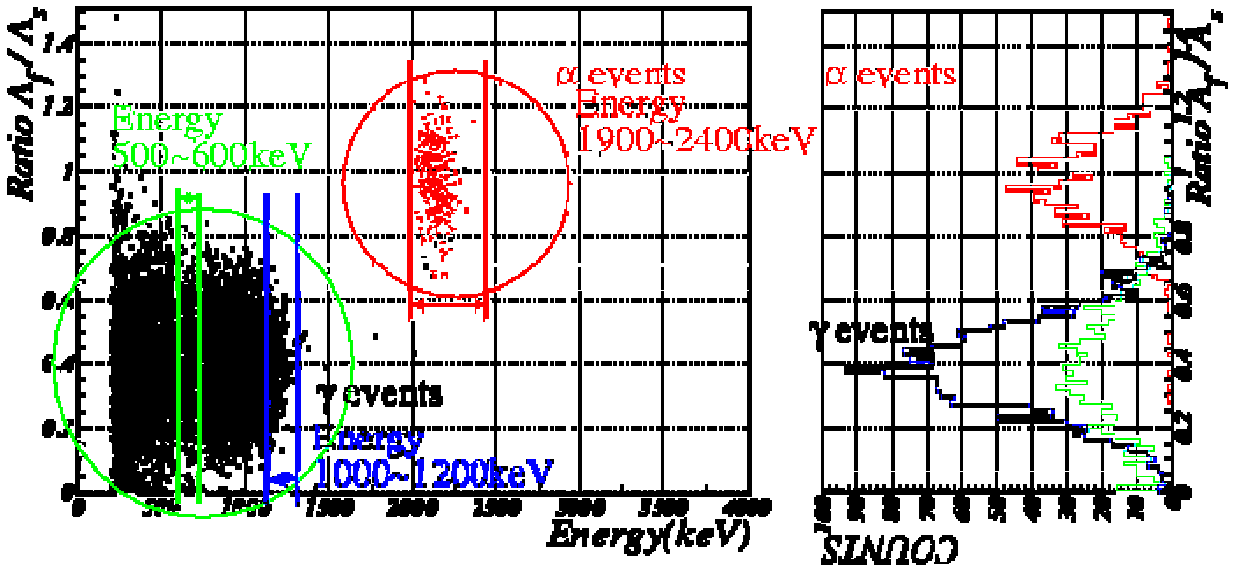
500MHz FADC (under preparation) . . . $\Delta T >$ 5ns ; ~1%

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

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)

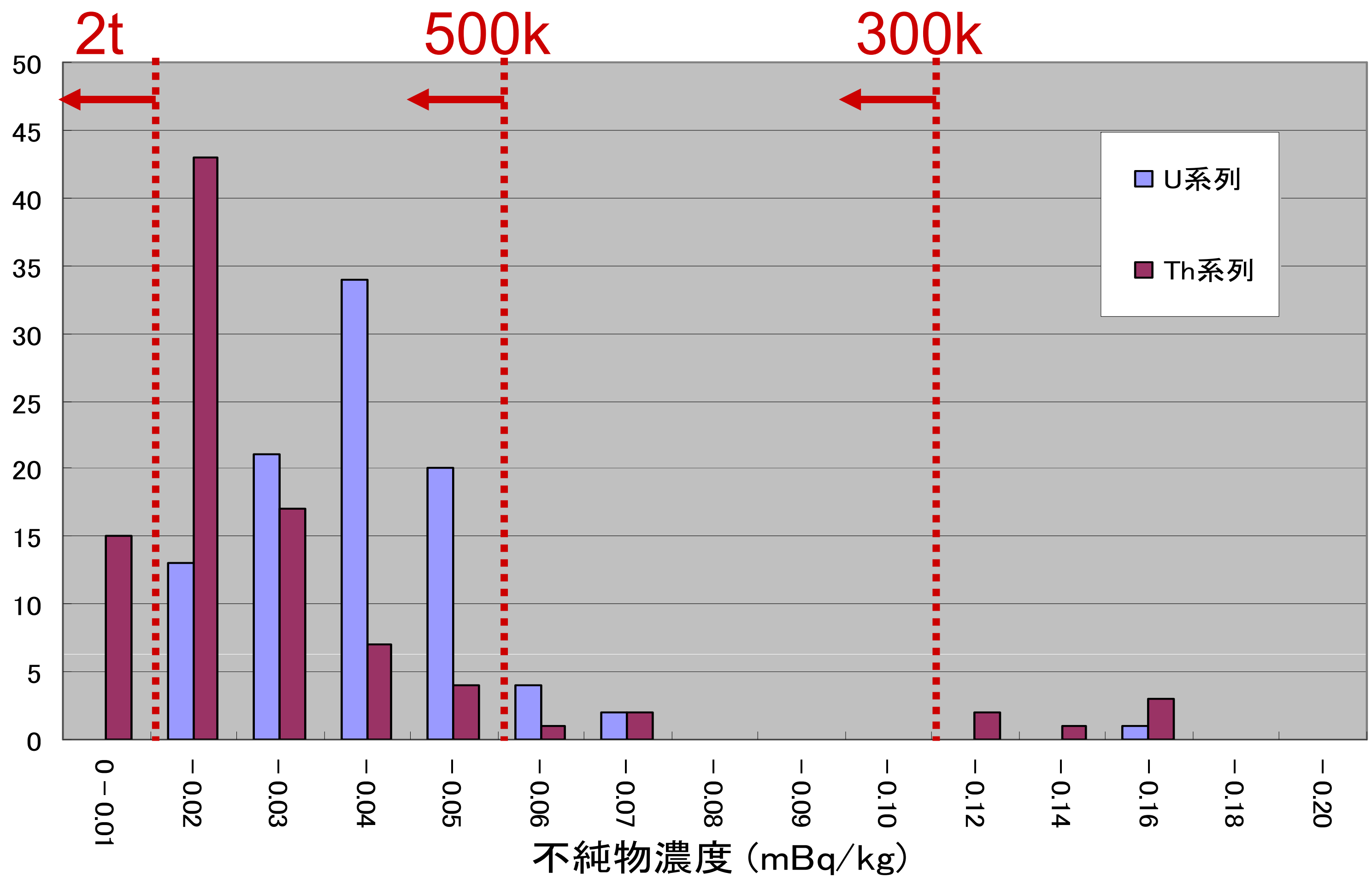
Powder selection

Crystal making

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

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

Radioactive impurities



High resolution CaF_2 crystal

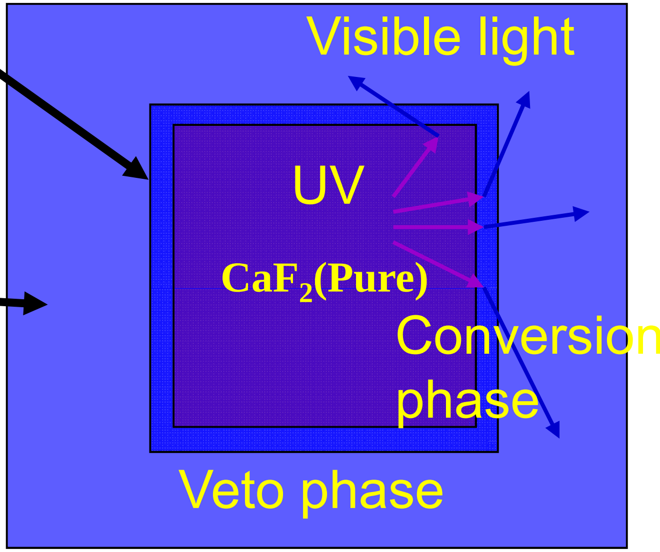
Candles

- Resolution $$\Delta E \sim \frac{1}{\sqrt{N_p}}$$
- Scintillation light
  - ~1/3 of CaF_2(Eu) (quart window PMT)
  - peak emission U.V. (285 nm)

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

Two Phase System

- Conversion Phase
  - M.O(100%)+PPO(0.3g/L)
  - Large conversion eff.
  - good transparency for UV
- Veto Phase
  - Large light output with aromatic solvent (absorb UV)



CaF_2 Emission (~285nm) UV light

⇩

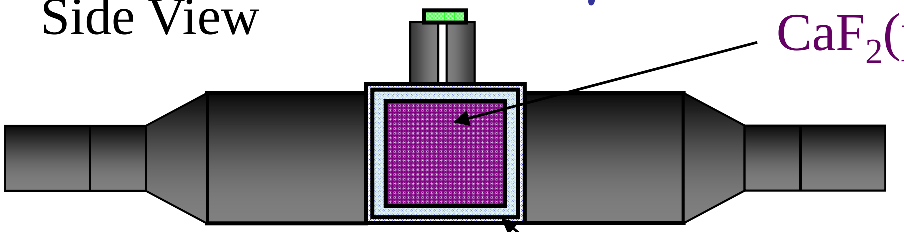
Conversion by WLS(350~400nm) Visible light

⇩ propagate

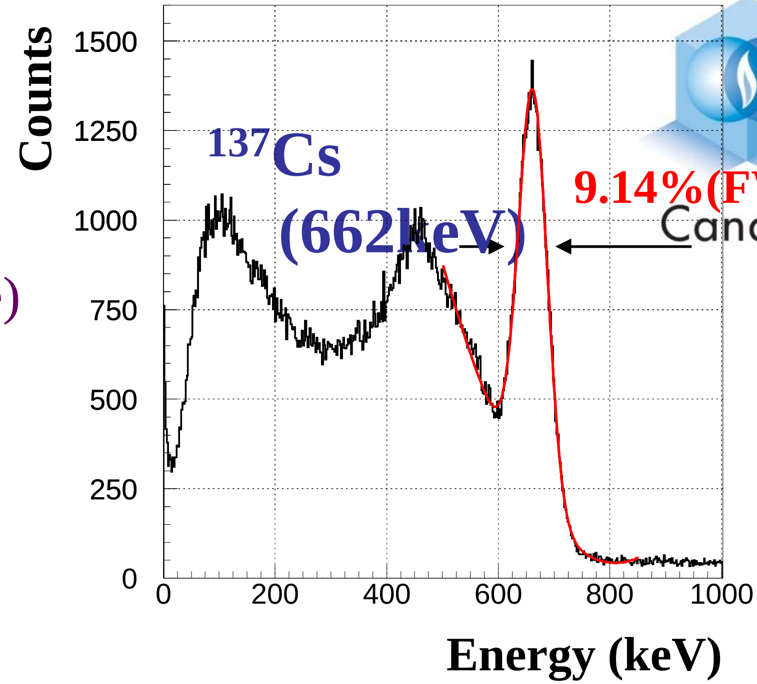
PMT

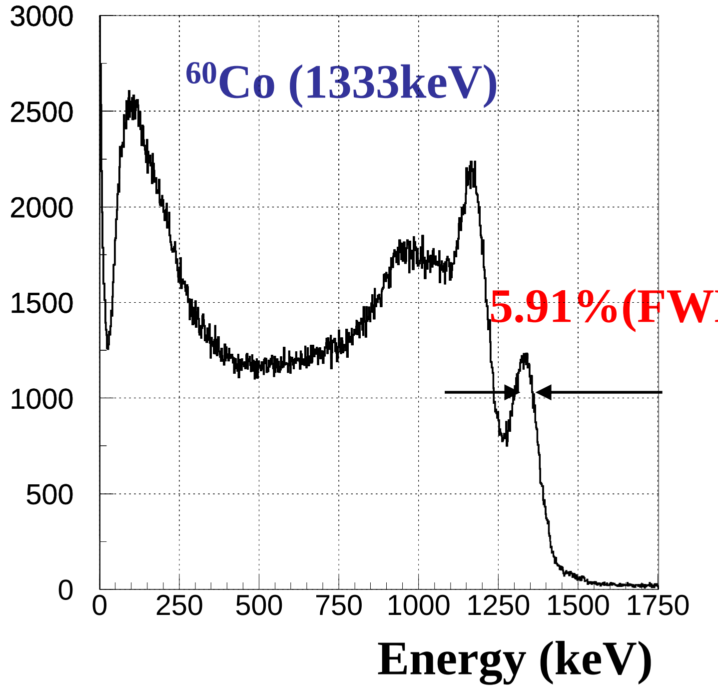
High resolution and
High veto efficiency

Energy resolution



CANDLES I with
10 cm^3 CaF$_2$(pure)

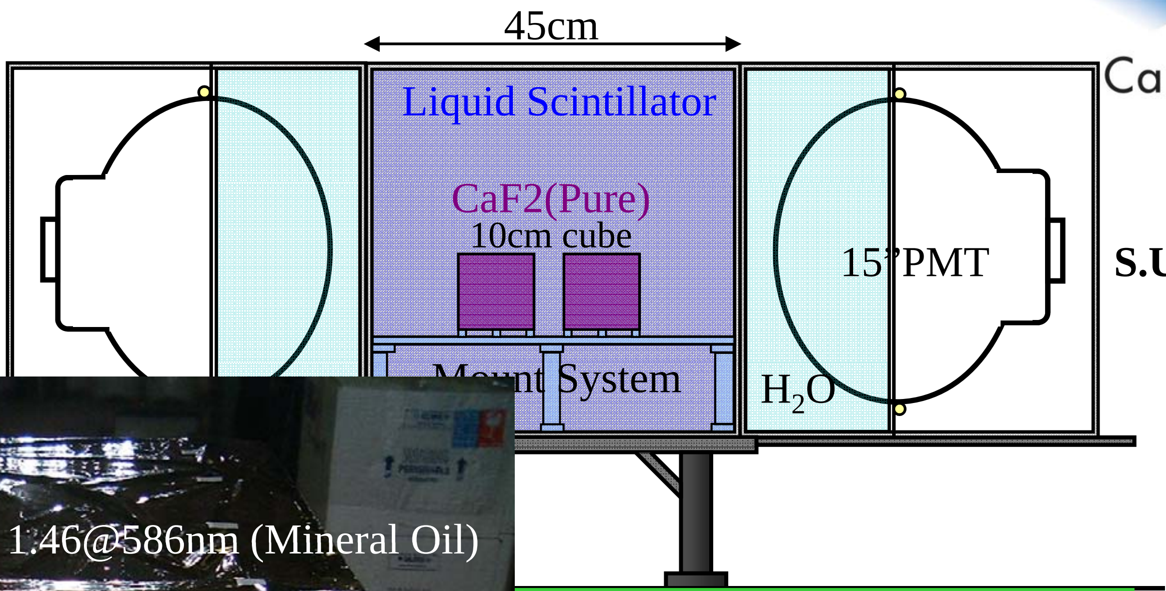




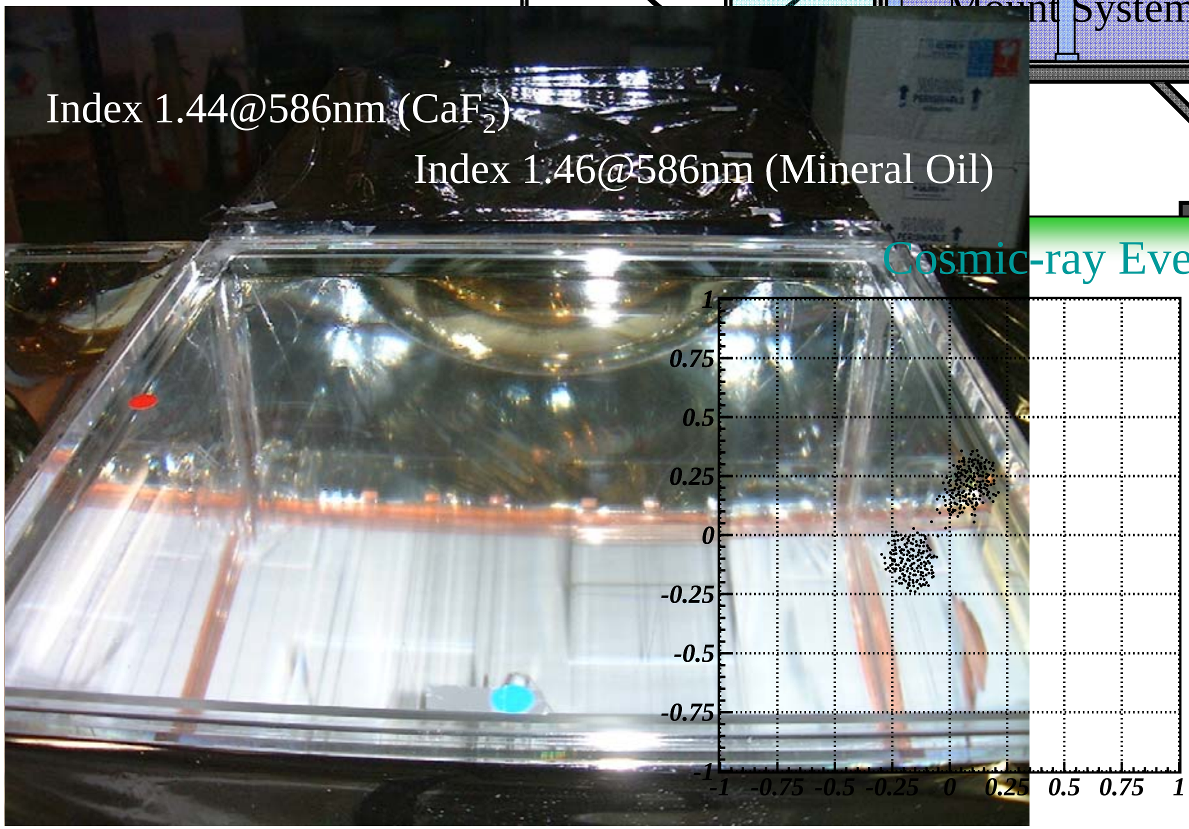
Energy Resolution:
9.1%(FWHM) at 662keV
=3.4% (FWHM) at 4.27MeV
Req. for CANDLES III ; 4.0%

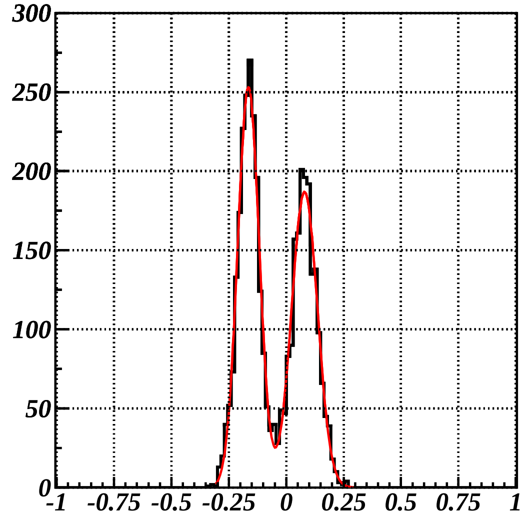
CANDLES-II

- Prototype



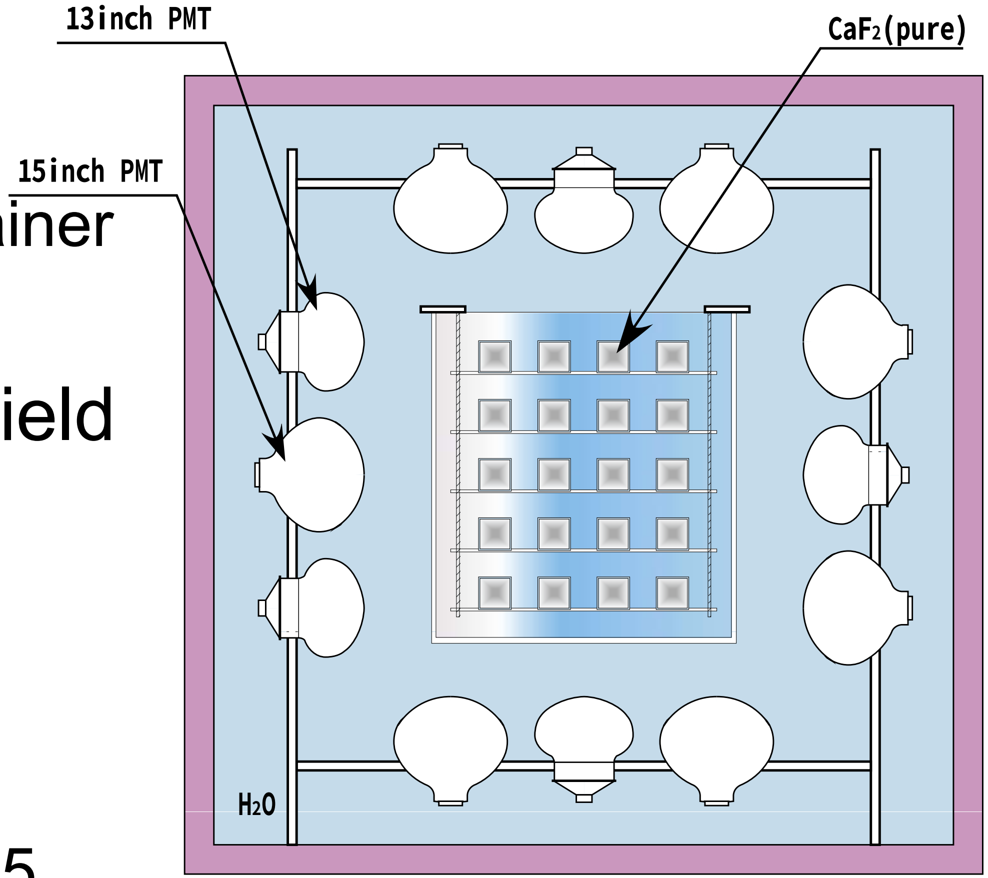
S.Umehara





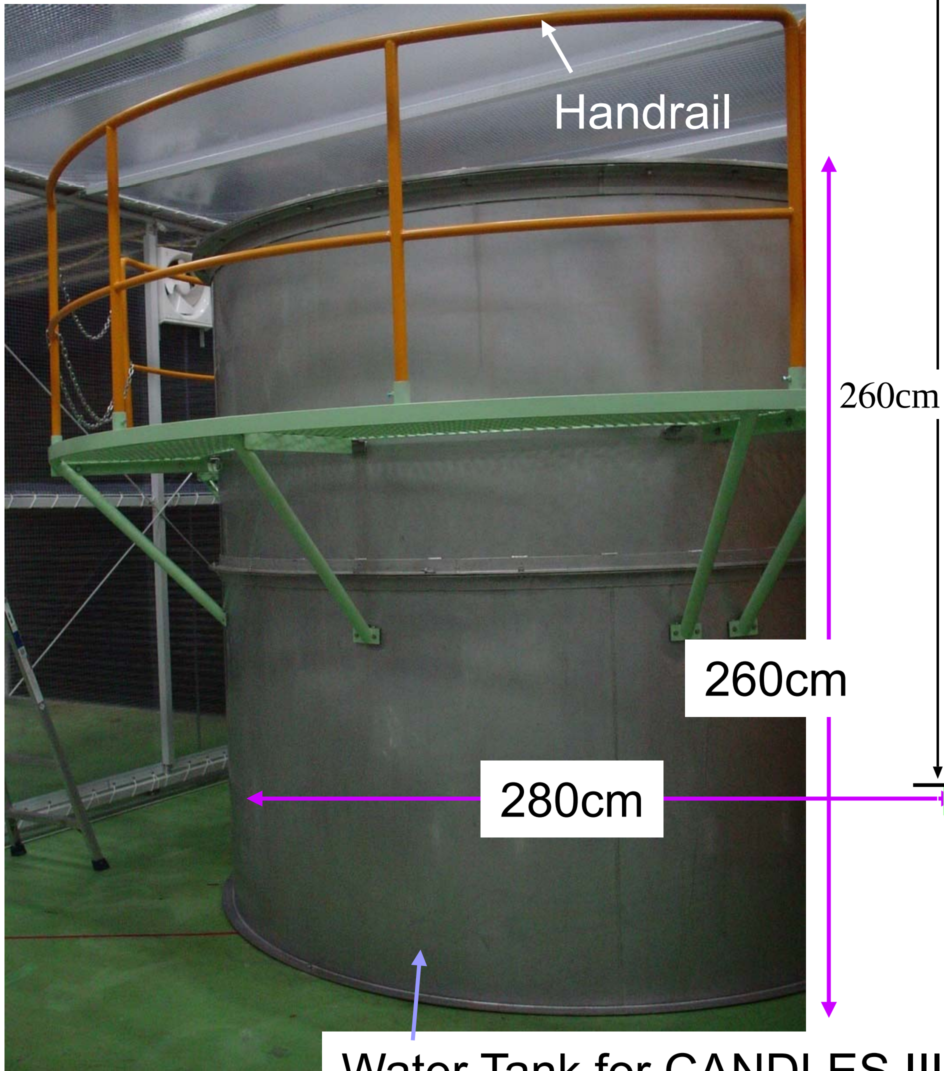
CANDLES III

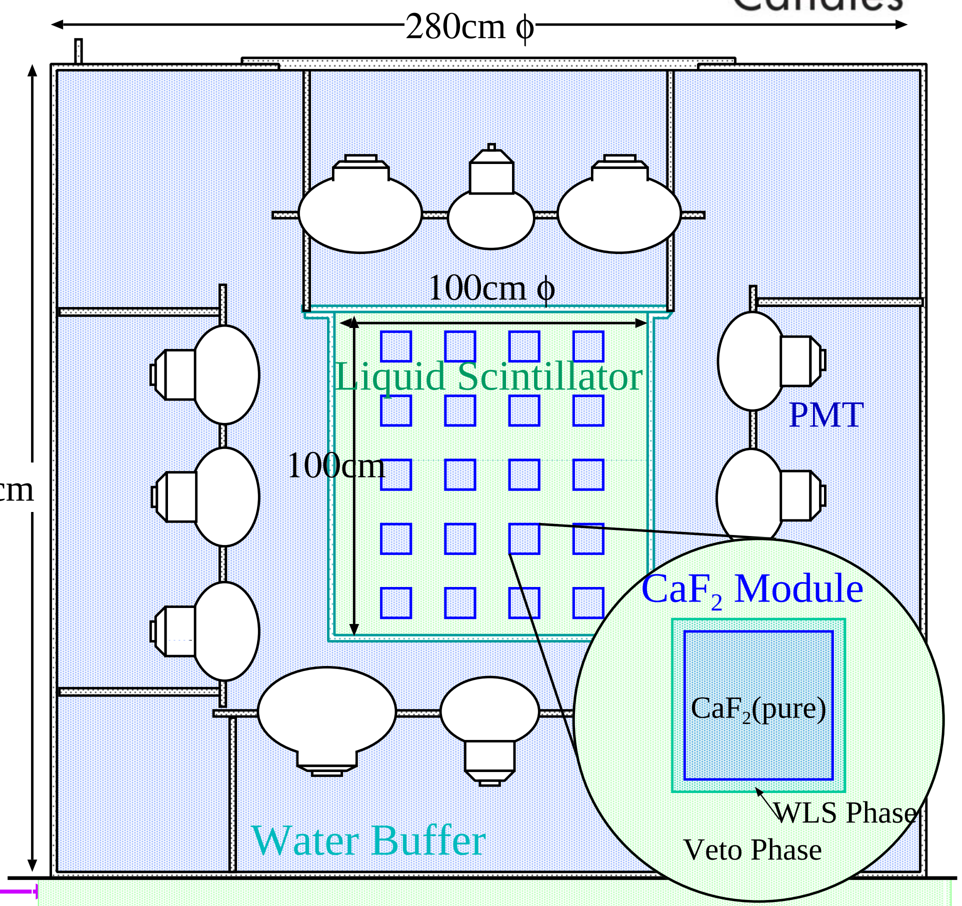
- Construction almost completed @ Osaka Univ.
- CaF_2(pure)
  - 60×10^3 cm^3 ; 191 kg
- Liquid scintillator
  - $^{\phi}1m \times {}^{h}1m$ acrylic container
- Purification system
- H_2O Buffer: passive shield
  - $^{\phi}2800 \times {}^{h}2600$
  - safety regulation
- PMTs
  - 15” PMT (× 8) : R2018
  - 13” PMT (× 32) : R8055



CANDLES III

Outside View

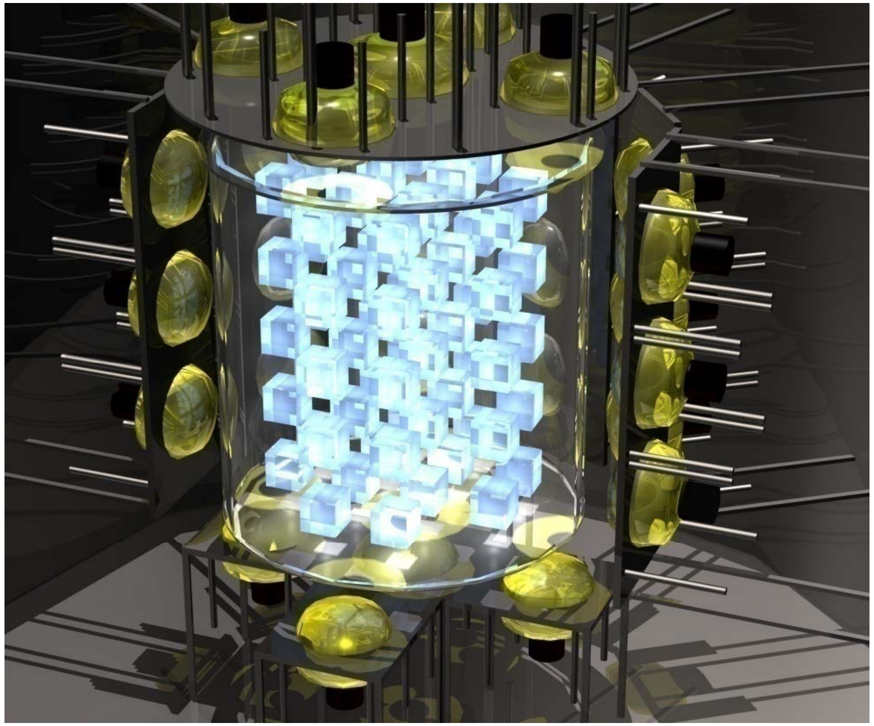




Water Tank for CANDLES III

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

CANDLES III@Osaka

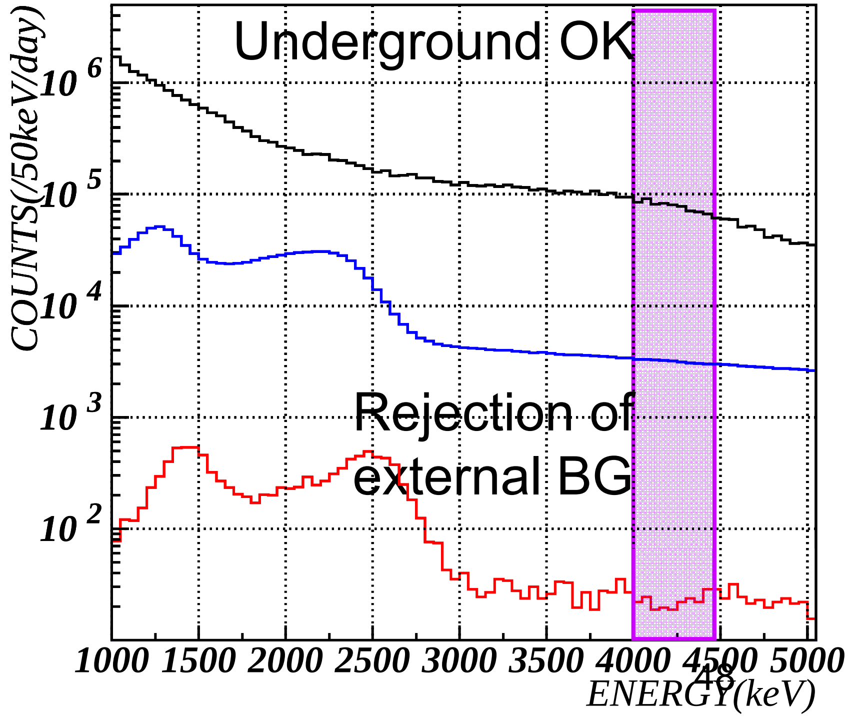


Candles

PMT:
13” × 32
15” × 8

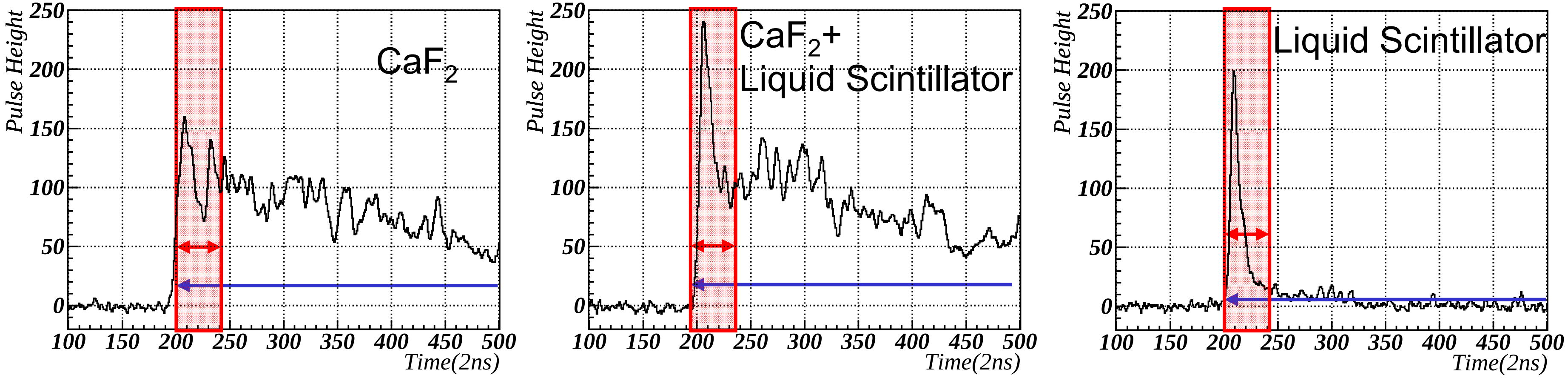
Tank: $^{\phi}2.8 \times {}^{h}2.6$ m

CaF_2: 191 kg
10^3 $cm^3 \times 60$



Rejection of LS Events

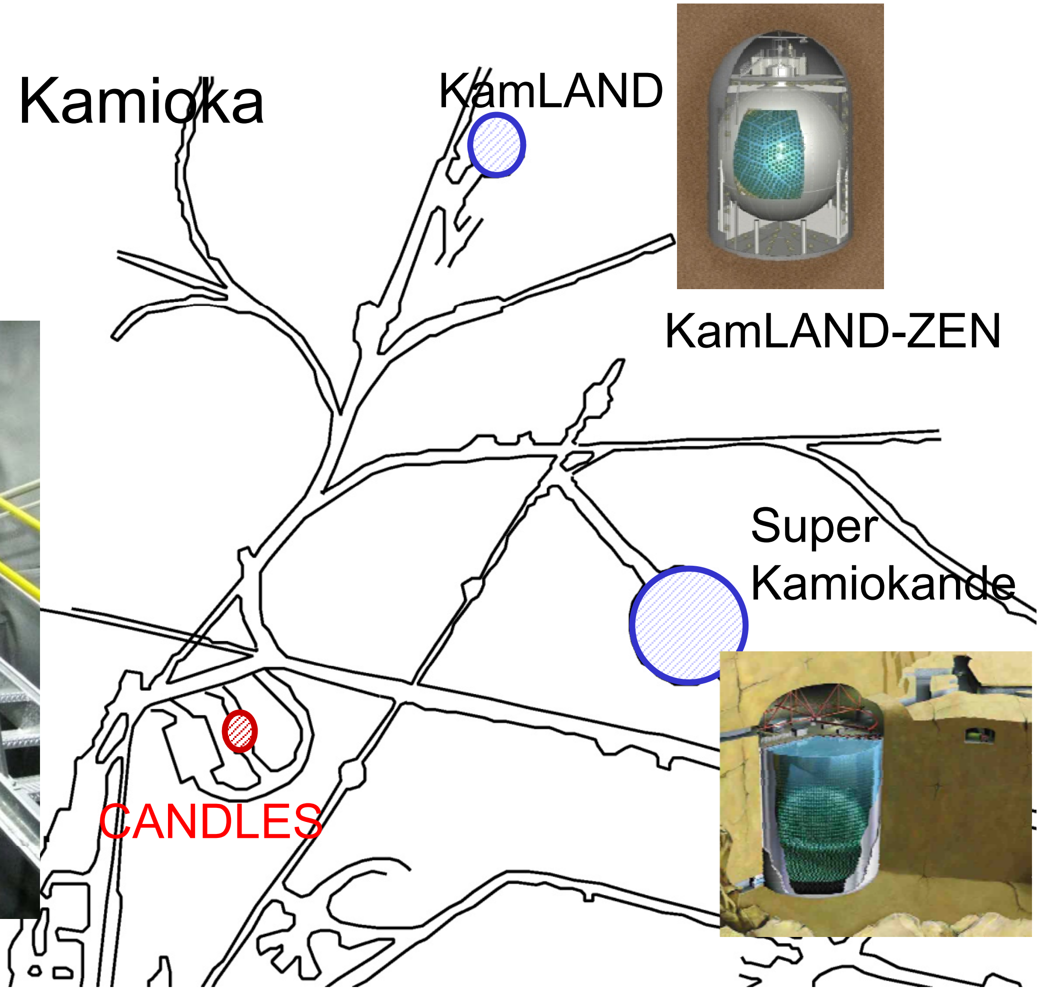
- Rejection by using Pulse shape information
  - Typical Pulse Shapes



$$\text{Charge Ratio} = \frac{\text{charge in partial gate}}{\text{charge in full gate}}$$

CANDLES III（UG）

- Kamioka Experimental hall D
- CANDLES III(UG)
  - 3m φ × 4m h



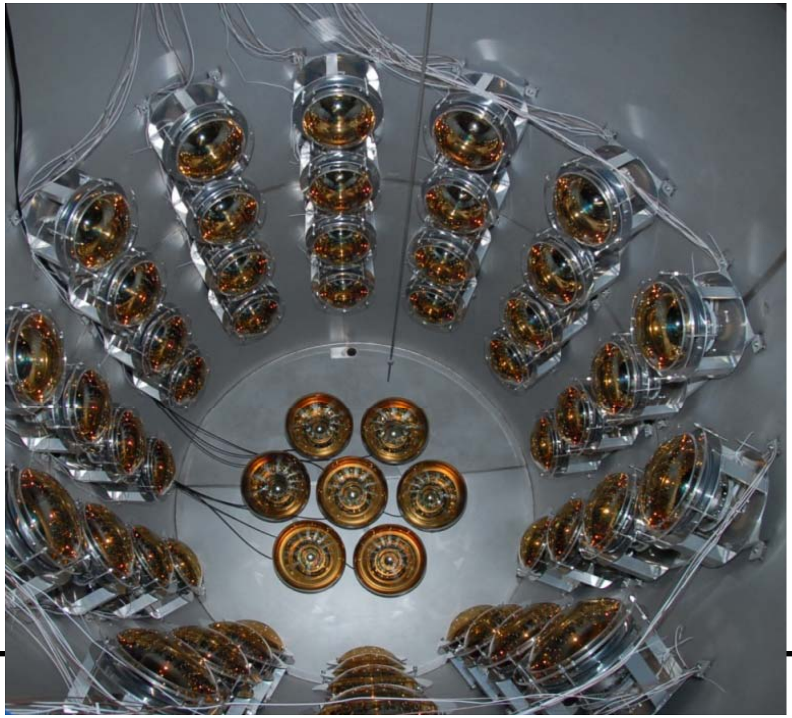
CANDLES III(UG)

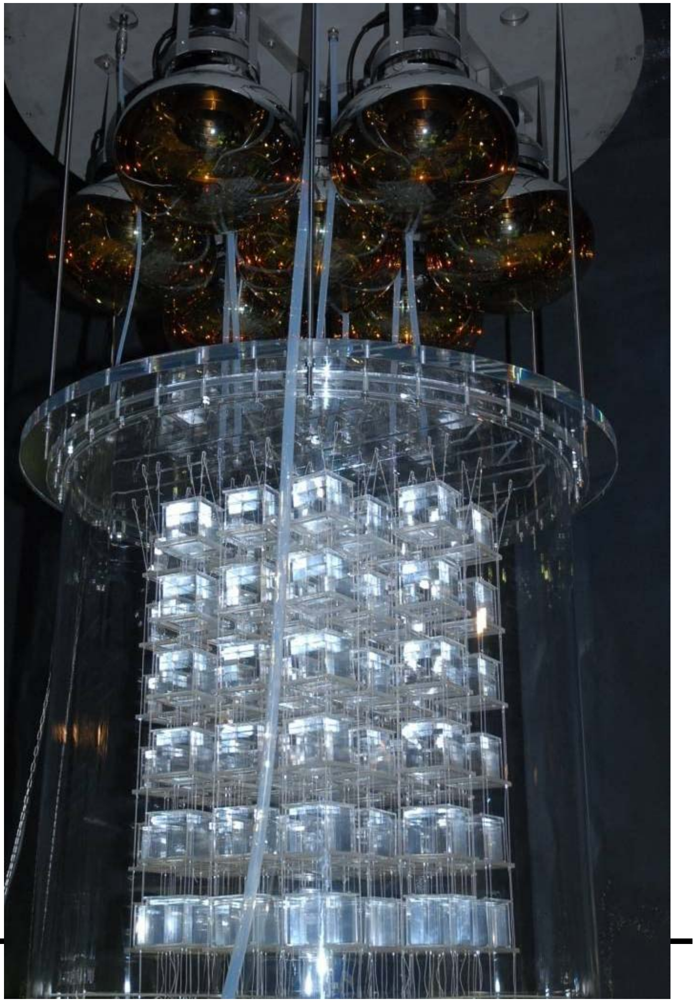
CANDLES III（UG）

- CANDLES III（UG）
  - 62 PMT's
  - 96 CaF_2(305 kg) crystals:

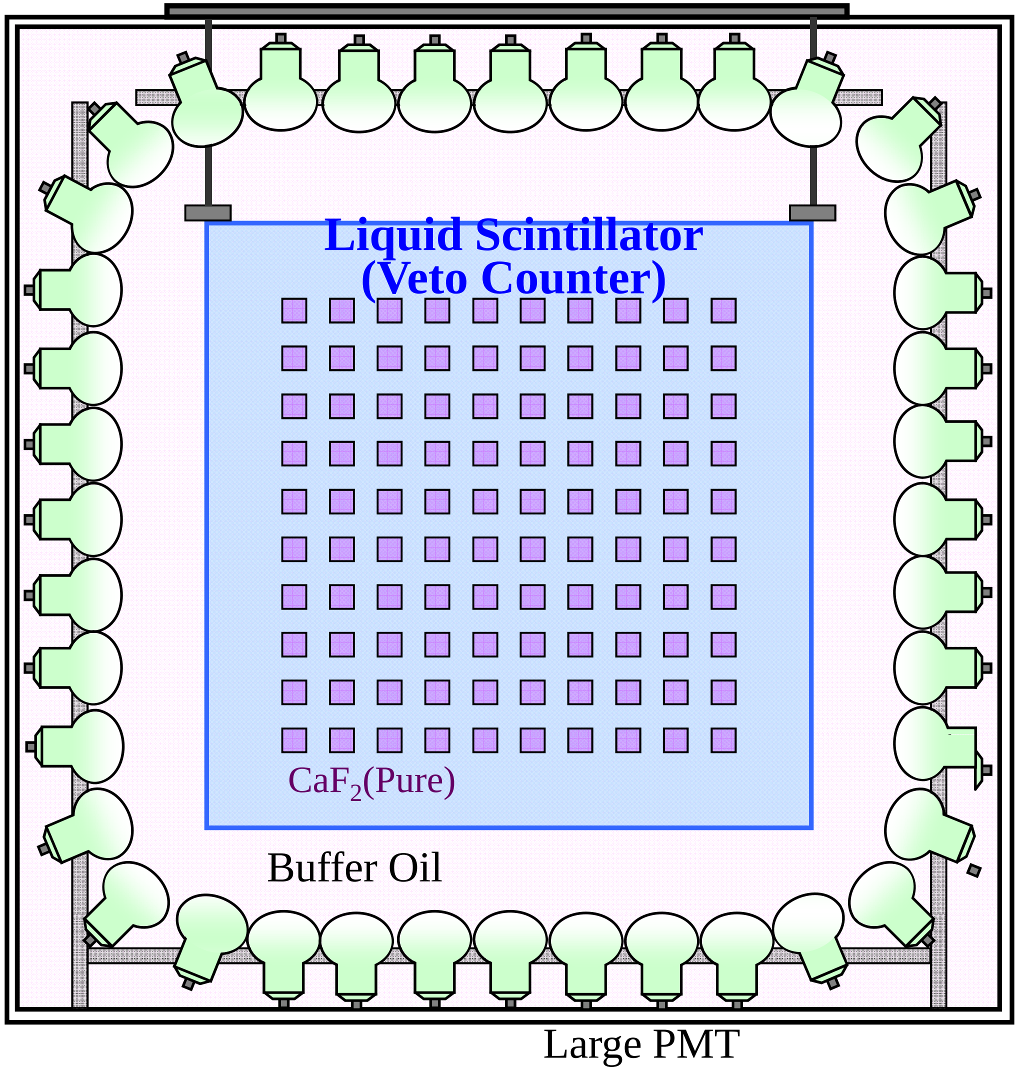
Almost completed

(${CaF_2}$ crystals)





CANDLES IV



$10 \times 10 \times 10\ cm^3\ CaF_2$
(600 cubes) 2 t
liquid scintillator Vessel
(^{48}Ca) 2.5 kg
enrichment

1. BG
    1. BG free CaF_2 crystal
2. Energy resolution
    1. More PMT & gain control

Characteristic of CANDLES

Candles

- BG rate (events/weight)
  - So far the best
    - 2~3 orders
- Scale up:
  - CANDESL IV, V
- Enrichment
  - increase ββ nuclei
  - BG reduction

Target	Project	Abund. (%)	Background rate (counts/kg/year)
^{48}Ca	ELEGANT VI	0.187	0 (measured) 0.075 (expected)
	CANDLES III	0.187	$5x10^{-4}$
	CANDLES IV	0.187	$5x10^{-5}$
^{76}Ge	HDM	~86	0.61
^{130}Te	CUORICINO	33.9	2.4
	CUORE	33.9	0.8 (CUORE-0) 10^{-2}~10^{-3}(Goal)
^{136}Xe	EXO-200	~80	0.1

Mile stone

Candles

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

achieved

- CANDLES IV
  - 600 x10cm^3 ^{48}Ca 2.5kg ~0.2 eV
  - Enrichment 0.2⇒2% ^{48}Ca (90meV⇒50meV)
  - further enrichment ~10meV

Enrichment of ^{48}Ca

Candles

- Issues in a new detector
  - Increase DBD nuclei
  - Reduce BG
- Enrichment
  - Increase DBD = Reduce BG
    - Only established method
  - Most effective ^{48}Ca : 0.19%
    - Up to 500 times improvement
- How?

Nucleus	abundance(%)
$^{48}Ca \rightarrow ^{48}Ti$	0.19
$^{76}Ge \rightarrow ^{76}Se$	7.8
$^{82}Se \rightarrow ^{82}Kr$	9.2
$^{96}Zr \rightarrow ^{96}Mo$	2.8
$^{100}Mo \rightarrow ^{100}Ru$	9.6
$^{116}Cd \rightarrow ^{116}Sn$	7.5
$^{128}Te \rightarrow ^{128}Xe$	31.7
$^{130}Te \rightarrow ^{130}Xe$	34.5
$^{136}Xe \rightarrow ^{136}Ba$	8.9
$^{150}Nd \rightarrow ^{150}Sm$	5.6

Methods of Enrichment

Candles

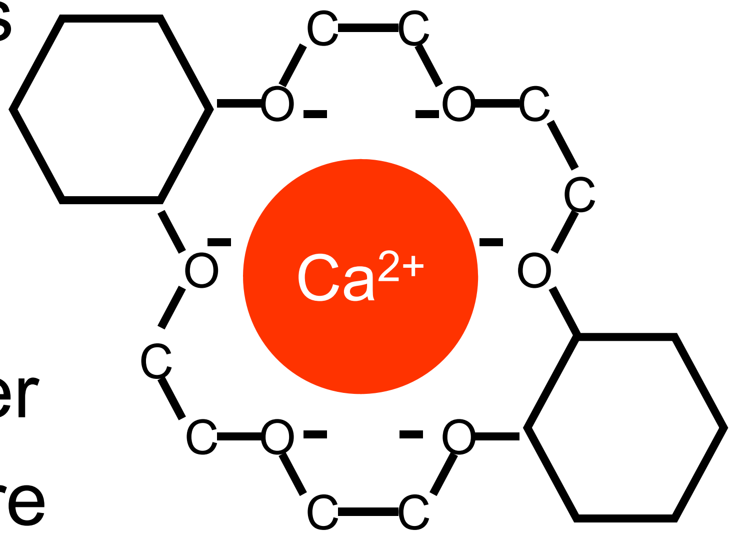
- Centrifuge
  - Gas: UF_6, but no gas for Ca and Nd
- Mass spectrometer

$$\frac{0.00187}{1.9\times10^{-19}\times6.02\times10^{23}}=1.9\times10^{-8}\,mol/\sec$$

  - Sure but Electricity
    - 10kVx1A=10kW; \$0.1/1kWh ⇒15MWh/mol ~1.5M\$/mol (48g): ~10g/1M\$ (0.6mol/year)
  - Ionize, accelerate, bend (magnet), …
- Laser: selective ionization
  - Less acceleration
- Other cost effective methods?

Enrichment of ^{48}Ca by Crown Ether

- Crown ether
  - Cyclic chemical compounds that consist of a ring containing several ether groups.
  - Absorbs Ca ion at the center
  - absorbs lighter Ca ions more
  - Separation coefficient
    - ε~ (3.5~6)x10^{-3} for 18C6



Dicyclohexano
18-crown-6

DC18C6

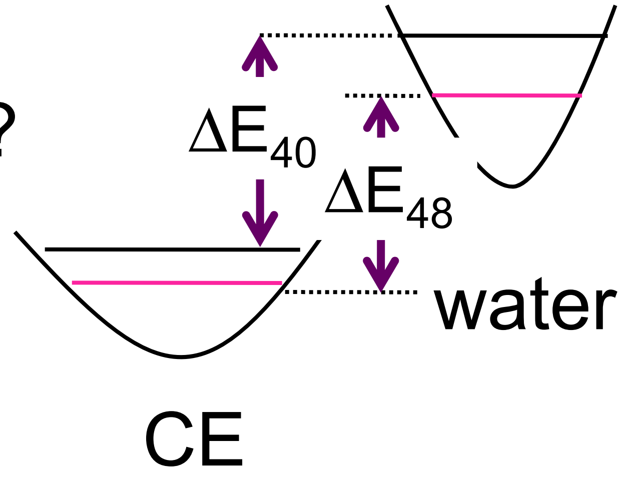
Physics of Enrichment by CE

Candles

- Chemistry: Phenomenological
  - Mechanism of the enrichment?
  - How much can we expect?

$$E_n = \hbar\omega(n + \frac{1}{2})$$

- Energy levels
  - Why CE absorbs lighter isotope?
    - Harmonic oscillator
  - Water: (pH: 10^{-14} mol/ℓ)
    - H_2O: polar molecule: HO pot.
  - Energy difference (ΔE) between water and CE
  - Partition function



Partition function

Candles

- Sum up all states in CE and H_2O with Exp(-E/kT): ^{40}Ca

$$Z^{40} = \left(\sum_{i=0}^{\infty} Exp\left(-\frac{\hbar \omega_{CE}^{40} (i+1/2)}{kT} \right) \right)^3 + \frac{\alpha}{n_W} \left(\sum_{i=0}^{\infty} Exp\left(-\frac{\hbar \omega_{W}^{40} (i+1/2) + \Delta E}{kT} \right) \right)^3$$

  - States in H_2O are normalized by α/n, where α is arbitrary constant and n is concentration.

- Concentration

$$\rho_{CE}^{48} = \left(1 + \frac{\alpha}{n_W} Exp\left(-\frac{3\hbar(\omega_{CE}^{48} - \omega_{W}^{48})}{2kT} \right) \right)^{-1} = \frac{n_W}{n_W + A}$$

  - agrees with exp.

Harmonic oscillator parameter

- Potential depth: U=α 344 eV, α: reduction factor
- $\hbar\omega$ $$\frac{U}{2}\left(\frac{\delta r}{R}\right)^2 = \frac{1}{2}M(\omega\delta r)^2 \qquad \hbar\omega = \alpha 0.19 eV$$
- $\Delta\hbar\omega$ $$\Delta\hbar\omega_{mass} = \hbar\omega\frac{\sqrt{k/M_{40}} - \sqrt{k/M_{48}}}{\sqrt{k/M_{40}}} = \hbar\omega \times 0.087$$ $$\Delta\hbar\omega_{tot} = \Delta\hbar\omega_{mass}\left(\frac{R_W - R_{CE}}{R_W}\right)$$
- Radius 4.7(H_2O), 5(15C5), 6(18C6), 7(21C7)
- 1.1meV, 4.6meV, 8.1meV
- α~0.011 ε 0.00075, 0.0031, 0.0055

Experiment by CE resin

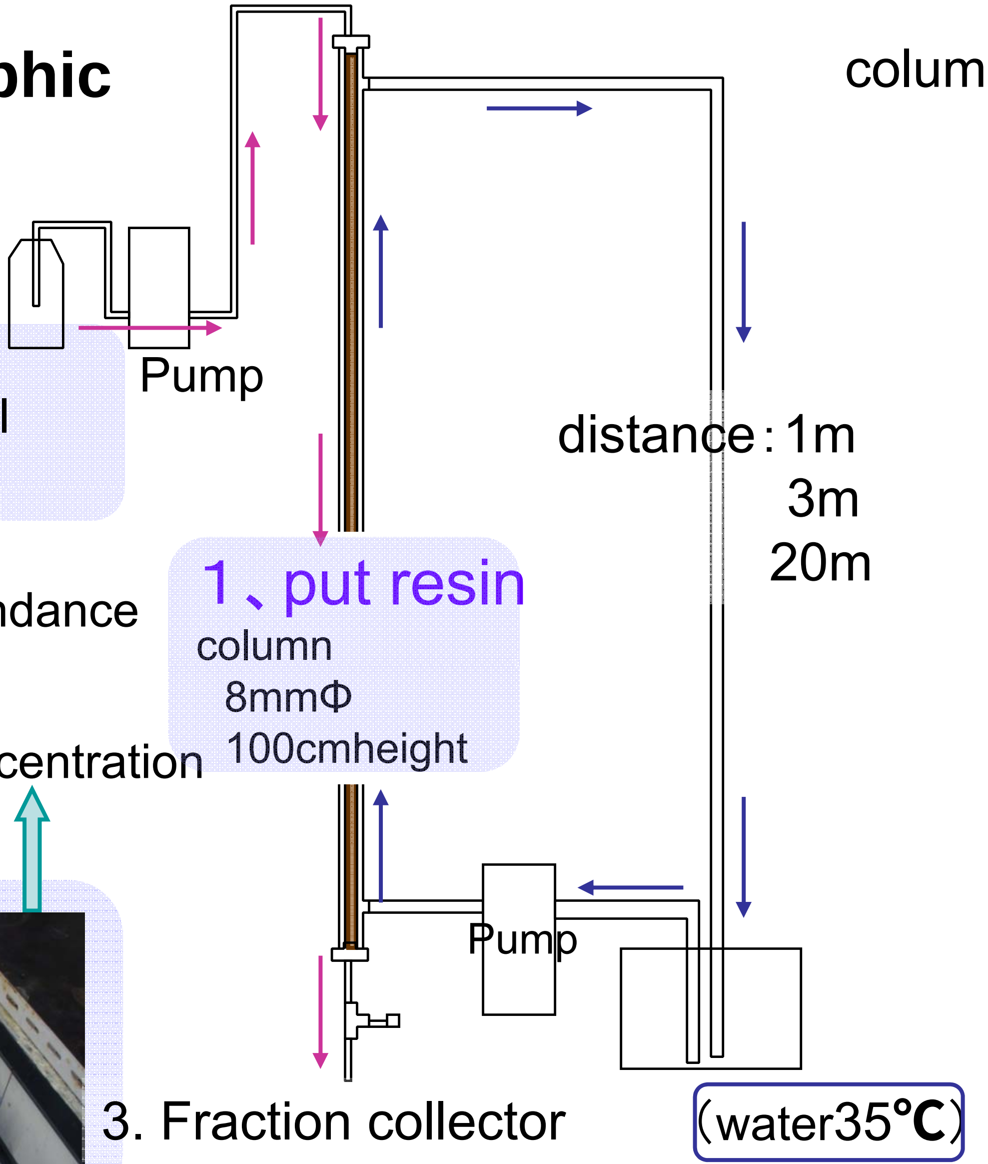
- **Chromatographic method （migration）**

2、Ca solution
0.09M $CaCl_2$+9M HCl
0.34ml/min

5、measure abundance

4、measure concentration

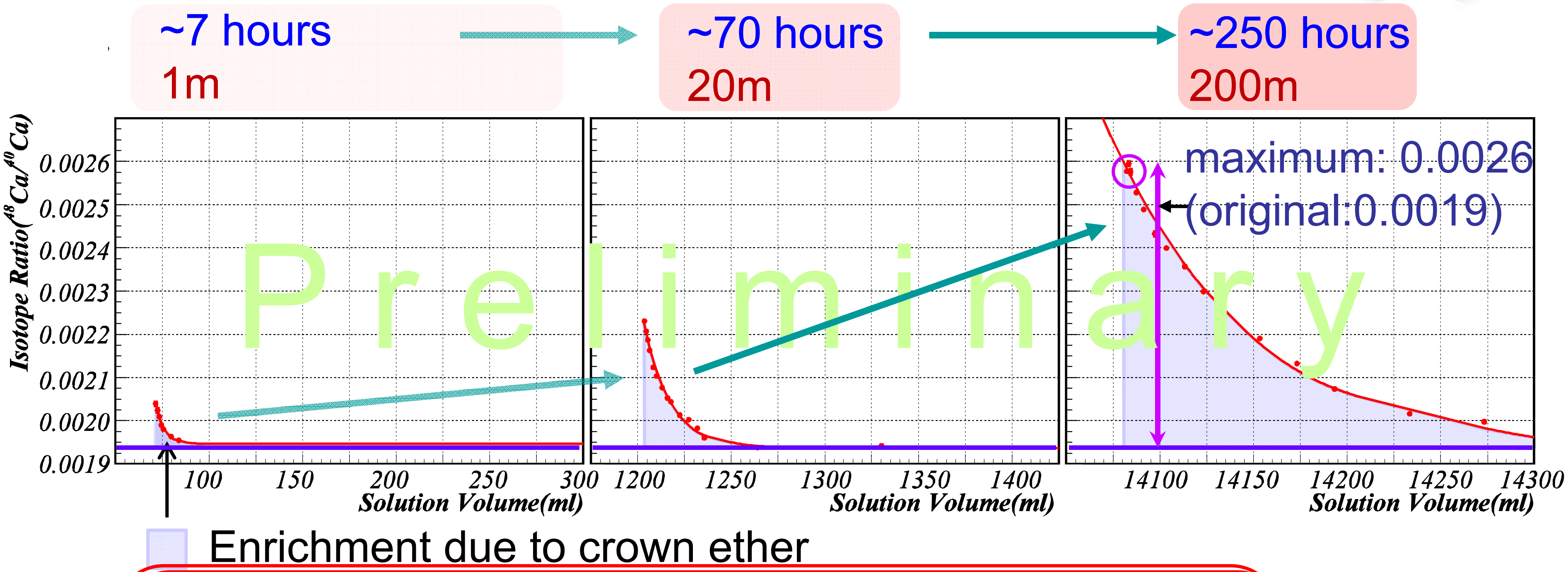
1、put resin
column
8mmΦ
100cmheight



3. Fraction collector

column

Enrichment for long migration



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

Enrichment by CE

- Separation coefficient
  - ε=0.003~0.006 (18C6)
  - CE size dependence
    - 15C5: ε=0.00075, 18C6 ε=0.003~0.006
    - 21C7: ε: ~ 0.01 (need exp.)
- Current condition: scalable
  - 1m, 3m, 20m, 200m ⇒ km
  - 8mmϕ tube: 10^4 (80cm) CE 3t
    - 2%(10x0.19%) and 100 kg:1 year migration
- Further improvement: more enrichment

Other methods

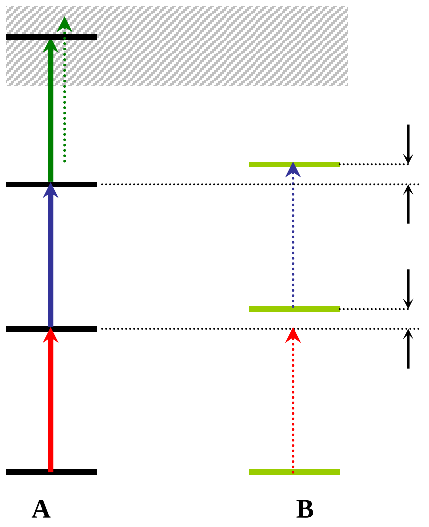
Candles

- Laser enrichment
  - Plant was once built for U but terminated.
  - Efficiency of laser was improved substantially.
  - Ca is easier then U in principle.
  - KAERI had agreement with NEMO group
    - enrichment of kg order 48Ca.
- Electro-migration
  - Essentially easy method.
  - Increase of electric field without increase of power loss.

Laser enrichment

general (U etc.)

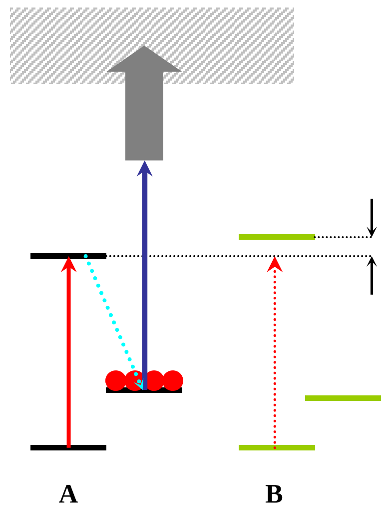
Autoionization



<3-step photoionization>

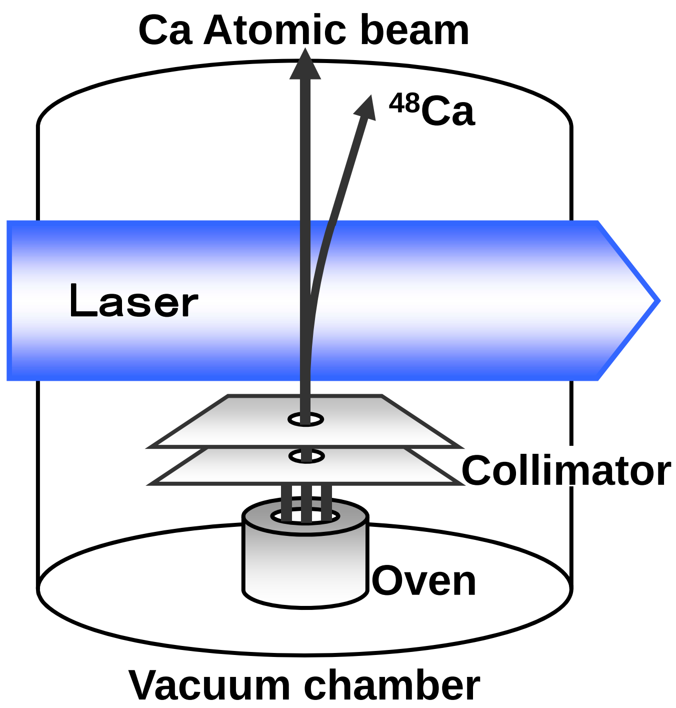
KAERI

Autoionization (or to continuum)



<ISOP followed by photoionization>

R&D agreement
with NEMO



Laser separation by Radiation pressure Niki (Fukui U.)

CANLDES

Candles

- CANDLES IV
  - 2t: 2.5 kg ^{48}Ca
- Enrichment (CE resin)
  - 2% 100kg(CaF_2)/year ⇒1.3(^{48}Ca)kg /year
  - Further study of parameters
    - Enrichment of 5% or more
  - Other methods (Laser, electro-migration) (2 years)
- $<m_\nu>$~90meV, 50 meV(improvement),
- 10 meV (energy resolution: bolometer) but CaF_2 is necessary

Current parameter