CANDLES

-- Study of ^{48}Ca double beta decay --

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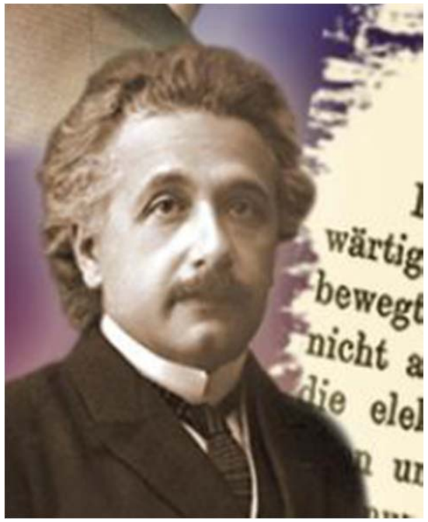
Contents

Candles

- Double beta decay and Majorana neutrino
  - Anti-particle
  - Majorana neutrino and double beta decay
- Why ^{48}Ca
- CANDLES detector
  - Concept
  - CANDLES I, II, III, VI, V
- Prospect
  - Enrichment of ^{48}Ca
  - Bolometer

Anti-particle

- Special relativity
  - Light velocity: constant
  - No information is faster than light
  - Any motion is relative



Einstein

- Quantum mechanics
  - Particle ⇔ Wave
  - Uncertainty principle

Bohr
Copenhagen

Relativistic quantum mechanics
-- Dirac equation --

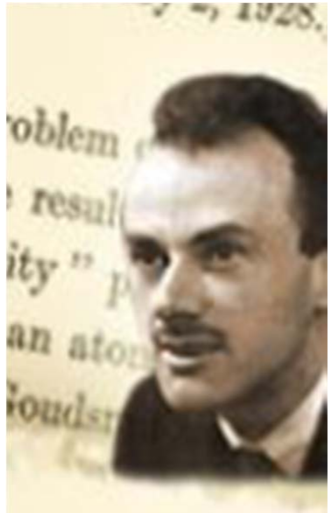
- Relativity and quantum mechanics

$$E = \sqrt{p^2 + m^2}$$

$$(E) = H = \alpha p + \beta m$$

Matrix
removes $\sqrt{\ }$
linear eq.

- Predicts anti-particle



Dirac

Positron as an anti-particle of an Electron

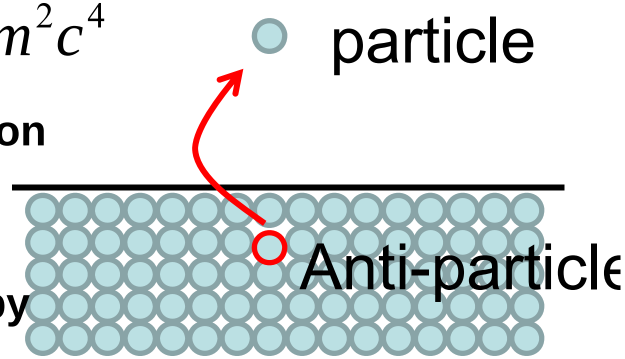
$$E^2 = p^2c^2 + m^2c^4$$

Every fermion has its anti-particle.

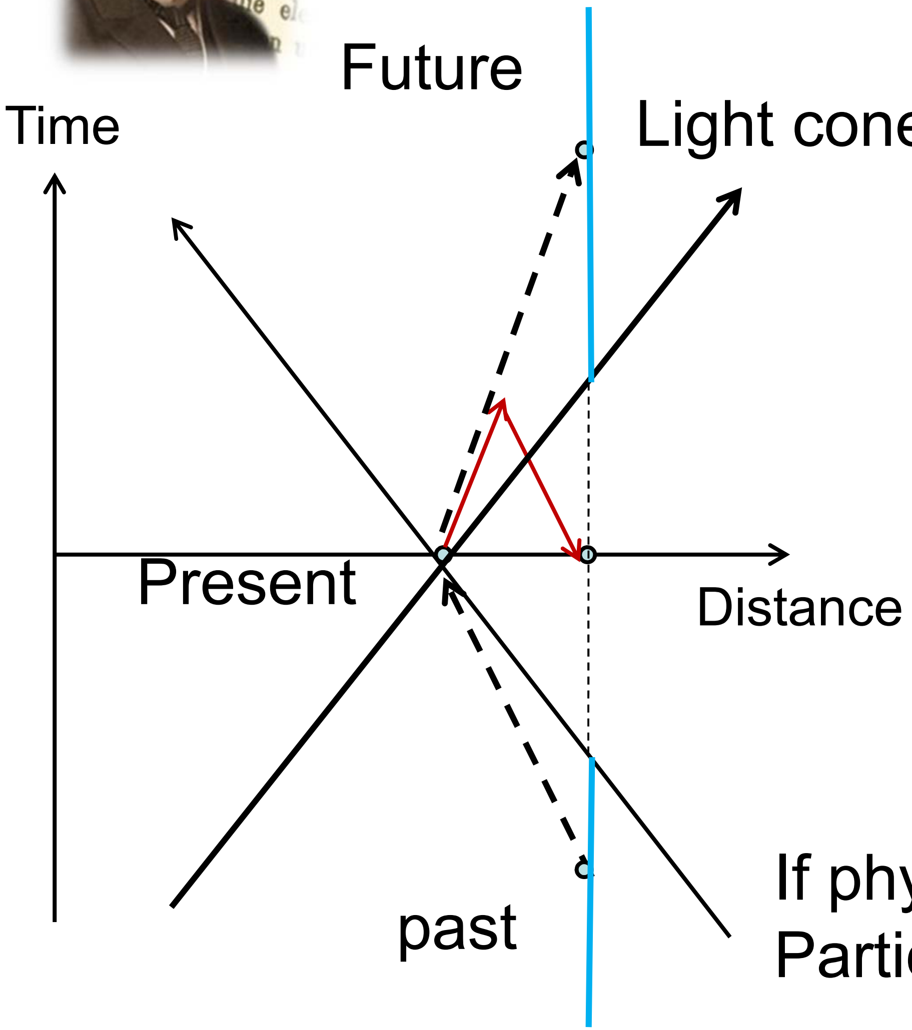
Pair creation or annihilation
Particle number is conserved

Klein-Gordon equation

Dirac sea Occupied by Frmions



Relativity + uncertainty principle →antiparticle



- uncertainty principle allows interaction between any points in space-time (relativity forbids)

→a particle travelling backwards in time ⇒ anti-particle

Carries inverse quantity (charge, spin(chirality))

Feynman

If physical quantity is reversed

Particle ⇔ Anti-particle is possible

Majorana neutrino

Candles

- 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 courier 2006

Majorana neutrino:
Dirac eq.
Another sol.

Universe is matter dominated

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

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

If particle number is conserved,

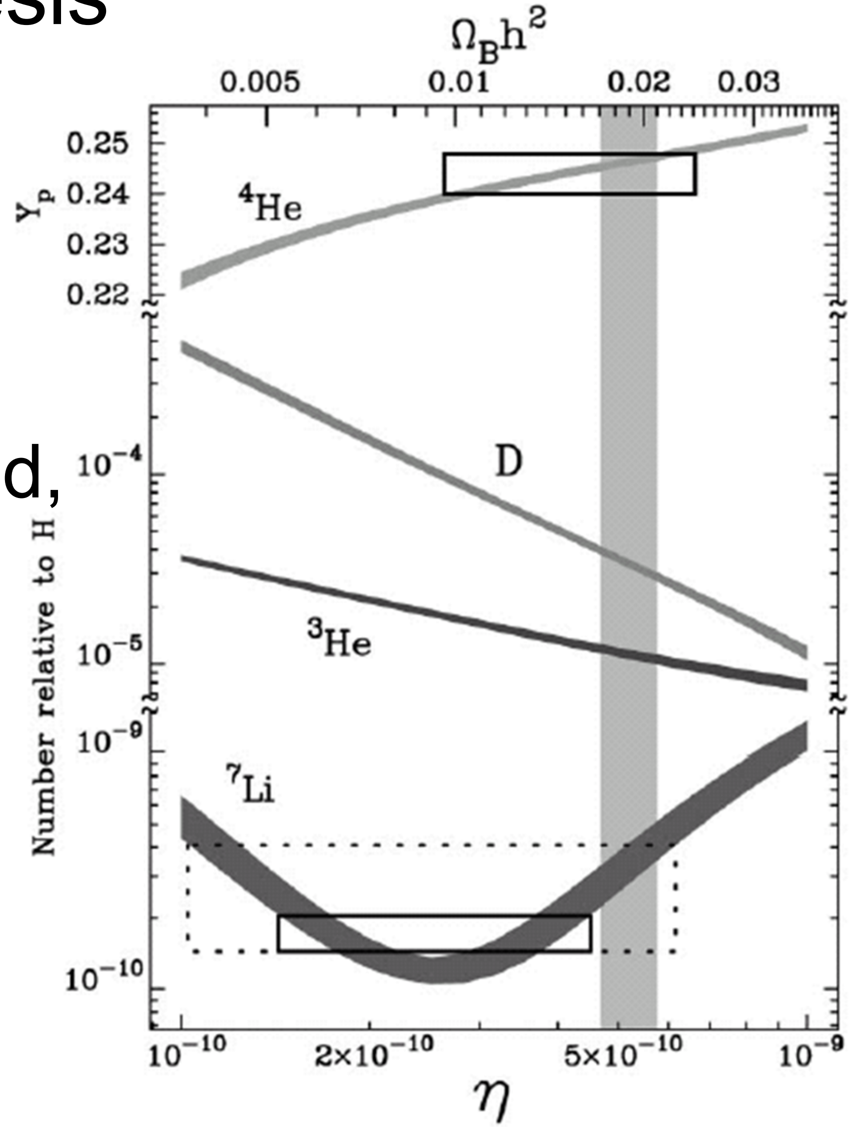
Particle : 10,000,000,001

Anti-particle : 10,000,000,000

Matter dominated Univ.

→~~CP~~ + ~~particle #~~

→Double Beta decay

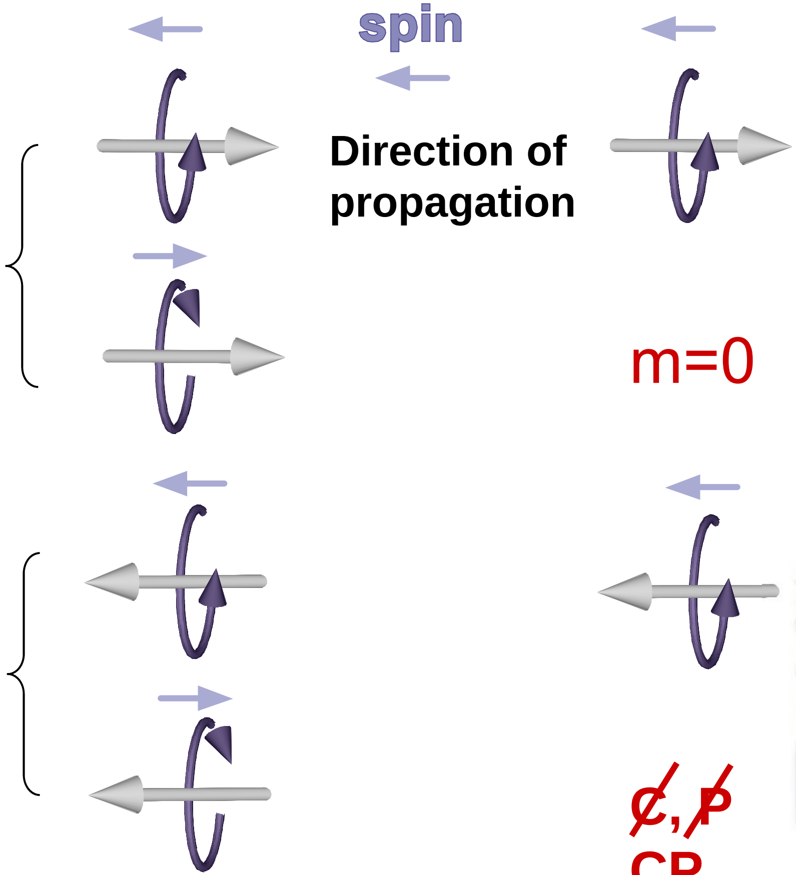


Neutrino type

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

•

ψ_L ψ_R



m_L m_R

m=0

m≠0

ν oscillation

Δm_ν

~50 meV

~9 meV

$\nu = \bar{\nu}$

$\not{C}$, $\not{P}$

CP

~~Lepton number~~

Chirality

ニュートリノ振動

arXiv:1205.4018v4 [hep-ph] 24 Oct., 2012
Global status of neutrino oscillation parameters after Neutrino-2012
D. V. Forero, M. Tórtola, and J. W. F. Valle

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- Neutrinos have mass; Parameters

parameter	best fit	1σ range	2σ range	3σ range
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.62	7.43–7.81	7.27–8.01	7.12–8.20
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$	2.55 2.43	2.46 – 2.61 2.37 – 2.50	2.38 – 2.68 2.29 – 2.58	2.31 – 2.74 2.21 – 2.64
$\sin^2\theta_{12}$	0.320	0.303–0.336	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400-0.461 & 0.573–0.635 0.569–0.626	0.38–0.66 0.39–0.65	0.36–0.68 0.37–0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276	0.019–0.030 0.020–0.030	0.017–0.033
δ	0.80π -0.03π	$0-2\pi$	$0-2\pi$	$0-2\pi$

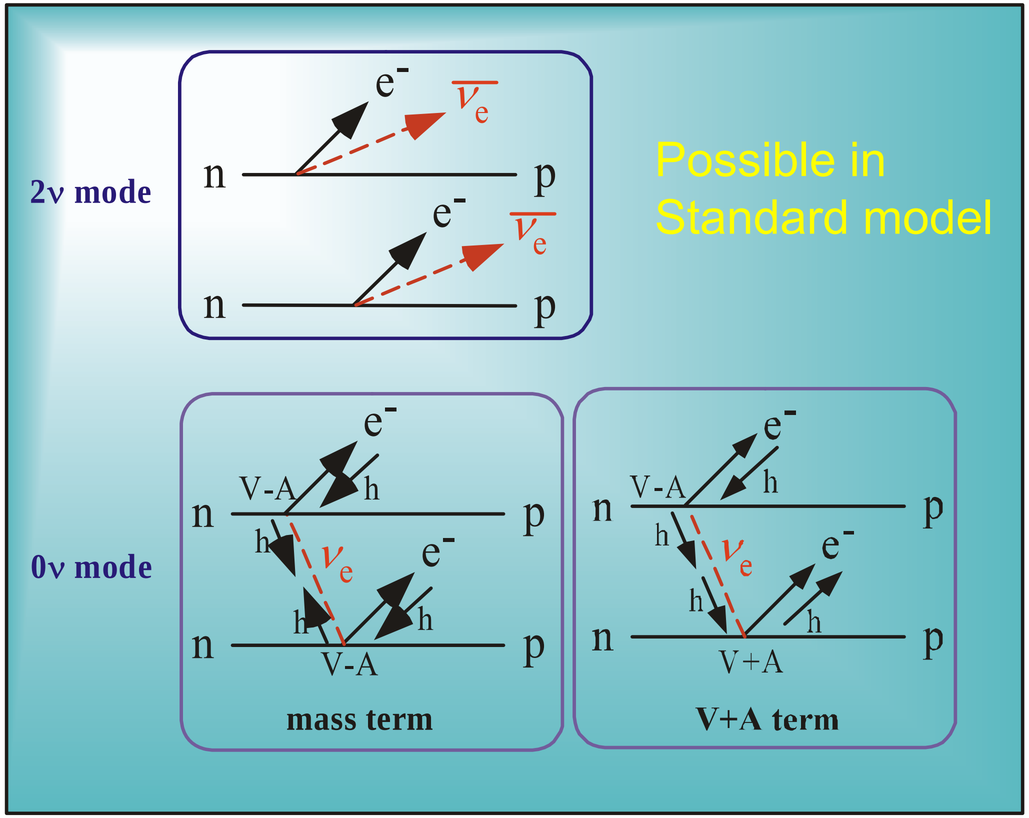
Δm_{13}^2, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, δ は上段の数字が順階層、下段が逆階層
Absolute neutrino mass?

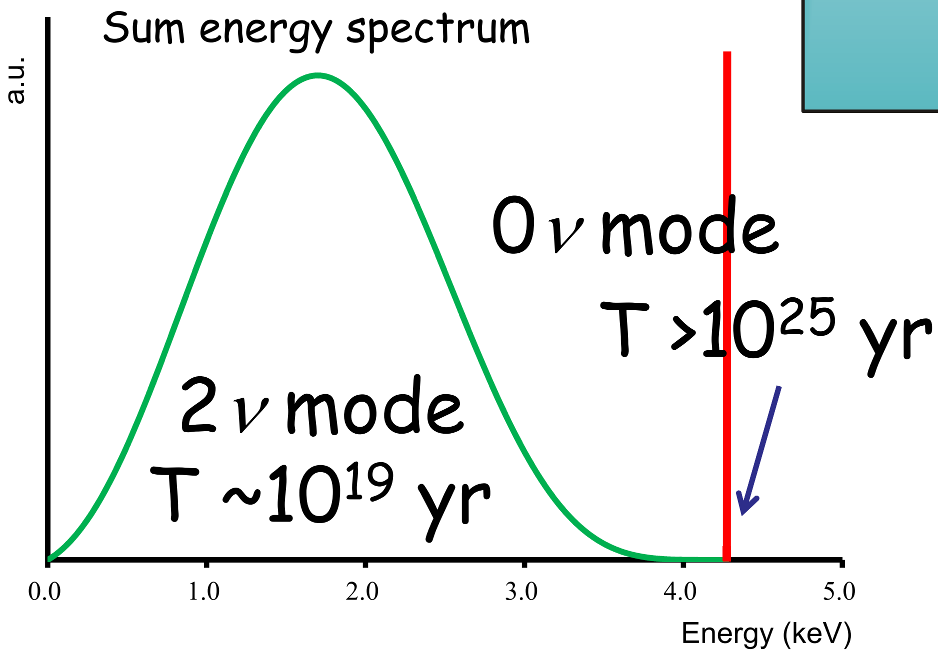
0ν2β decay

Majorana particle

particle⇔anti-particle

- possible only for ν
- matter dominated universe





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

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

Phase volume — Nuclear matrix element — Effective mass

ν has to be a Majorana particle

Candles

- Mass term (Dirac)

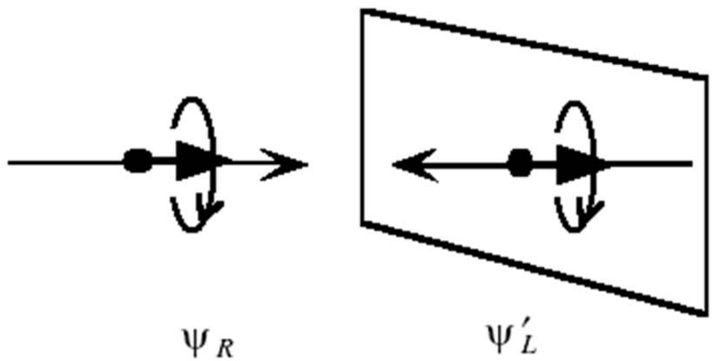
$$\mathcal{L}_D = -m_D \overline{\nu_R^0} \nu_L^0 + \text{h. c.}$$

- 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 mechanism）
  - Violates lepton number
  - Leptogeneysis

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

Chirality flip（relativity）

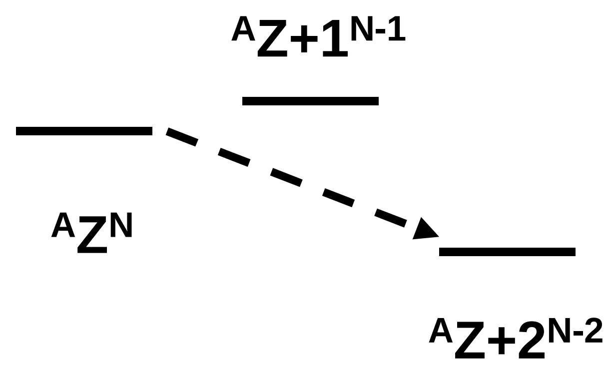
Left handed → right handed (anti-particle)



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.



Detector type

Candles

- Source = detector

○ ΔE

Semiconductor
COBRA
Majorana
GERDA

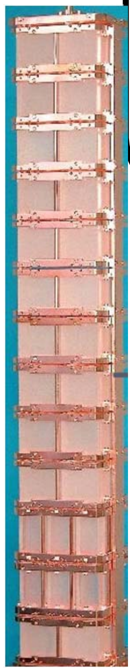
○ ΔE

Bolometer
CUORE/CUORICINO

ΔE

Scintillator
CANDLES
KamLAND
SNO+

b
○ ε

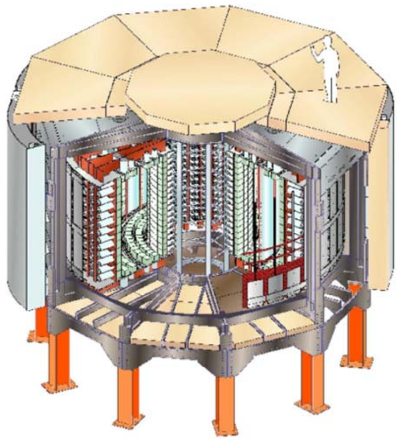


- Source ≠ detector

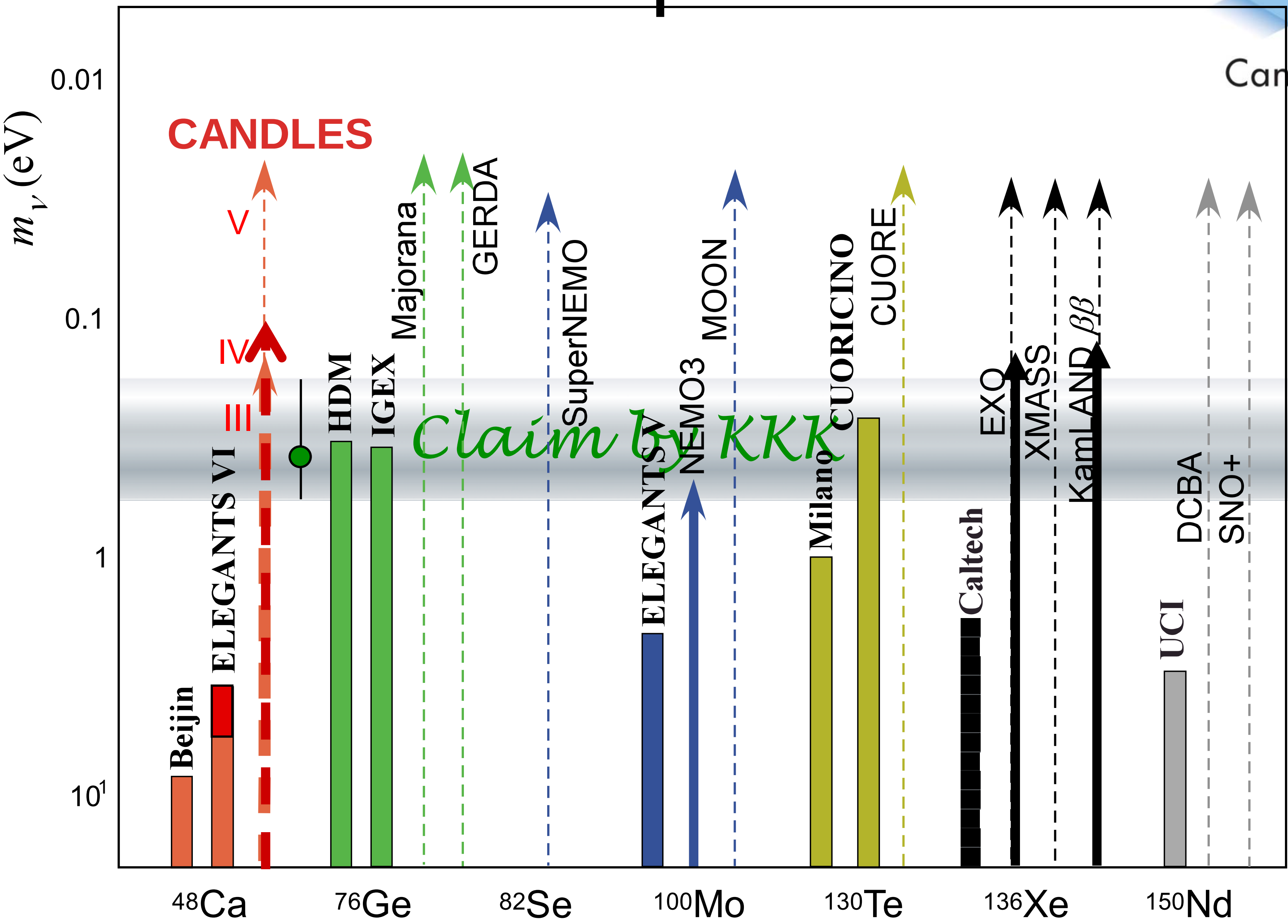
ΔE

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

○ b
× ε

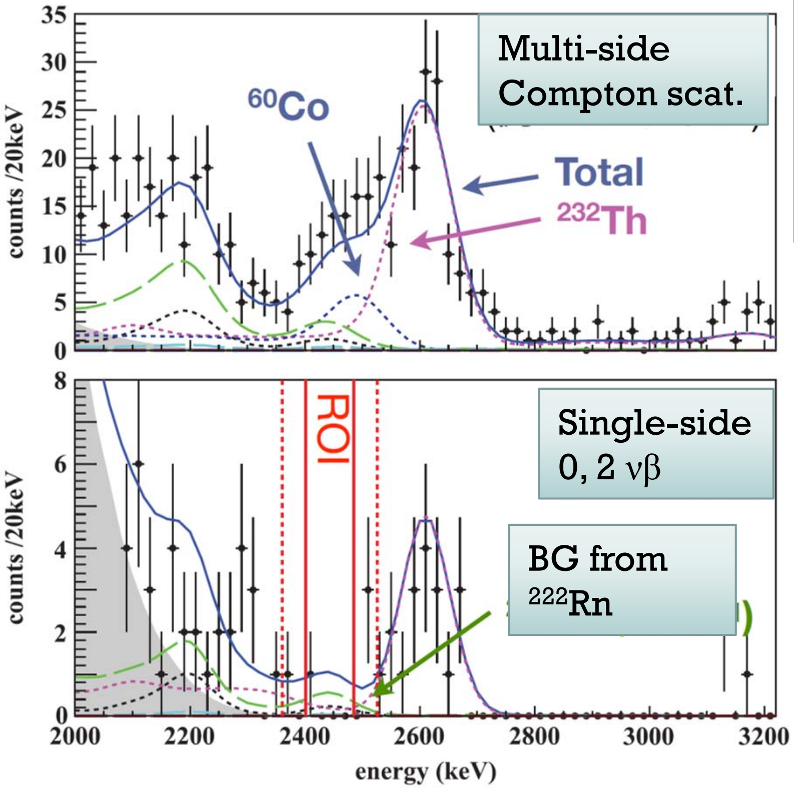


World Experiments



First Result of EXO-200

- Nov. 2011: ^{136}Xe $2\nu\beta\beta$ (Ackerman et al. PRL107, 212501)
  - $T_{1/2}$ = (2.11 ± 0.04 stat. ± 0.21 syst.) × 10^{21} year
- July 2012: $0\nu\beta\beta$ (M. Auger et al., PRL109, 032505)
  - $T^{0\nu\beta\beta} > 1.6 \times 10^{25}$ year (90% C.L.), $\langle m_{\beta\beta} \rangle$ < 140-380 meV (90% C.L.)



- ^{136}Xe
  - Live time: 120.7 days
  - Active 136Xe mass: 79.4 kg
  - Exposure: 26.2 kg•yr
    (ref. 89.5 forKamLAND-Zen)

	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background index b ($kg^{-1}yr^{-1}keV^{-1}$)	$1.5\cdot10^{-3}$ ± 0.1		$1.4\cdot10^{-3}$ ± 0.1	

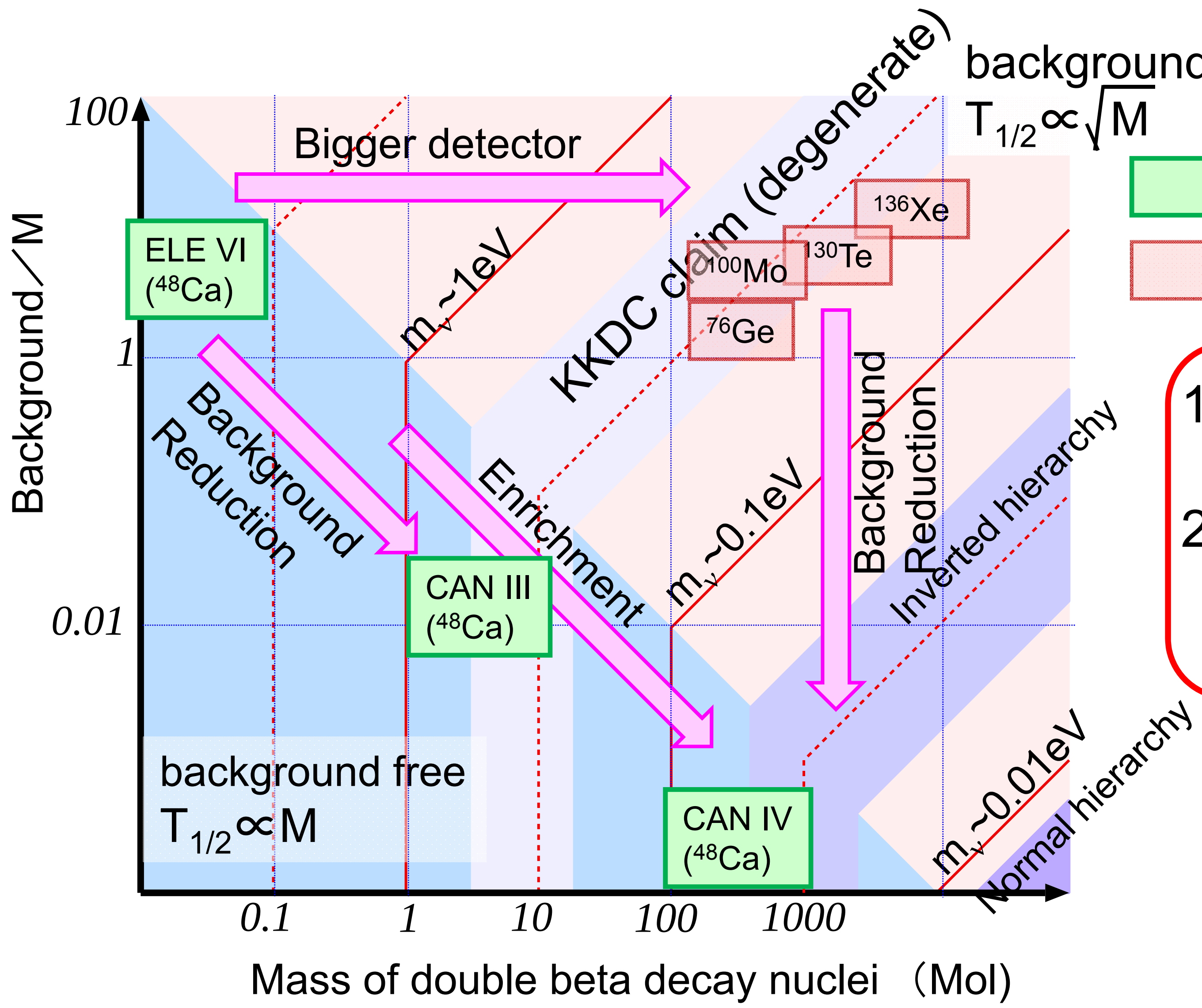
Kamland-Zen gives similar limit

Why ^{48}Ca

Candles

- Highest Q value (4.27 MeV, ^{150}Nd: 3.3 MeV)
  - Large phase space factor
  - Little BG (γ: 2.6 MeV, β: 3.3 MeV)
- Natural abundance → 0.187%
  - Isotope separation → expensive (no Gas)
- Next generation
  - $M_\nu \sim T^{-1/2} \sim M^{-2}$ (no BG)
    $\sim M^{-4}$ (BG limited)
  - ^{48}Ca (no BG so far)
- If we want to sense normal hierarchy region, only ^{48}Ca + enrichment has a chance.

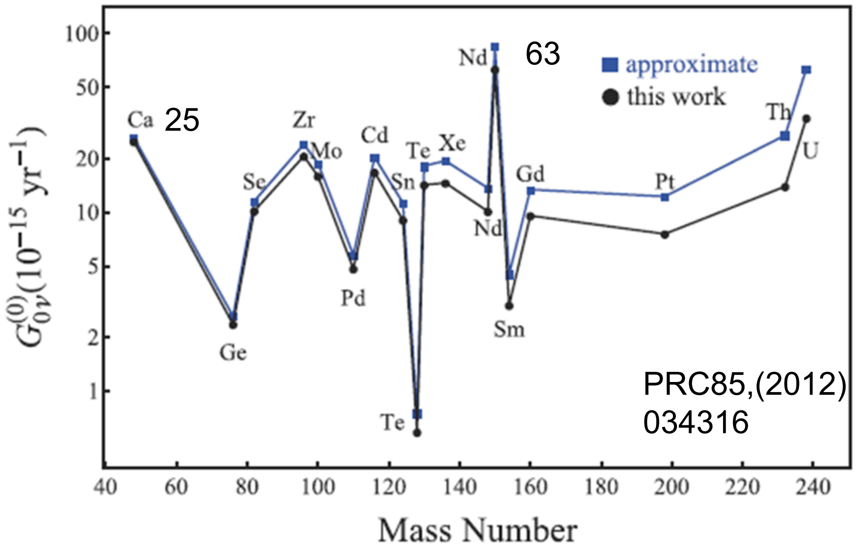
Our strategy



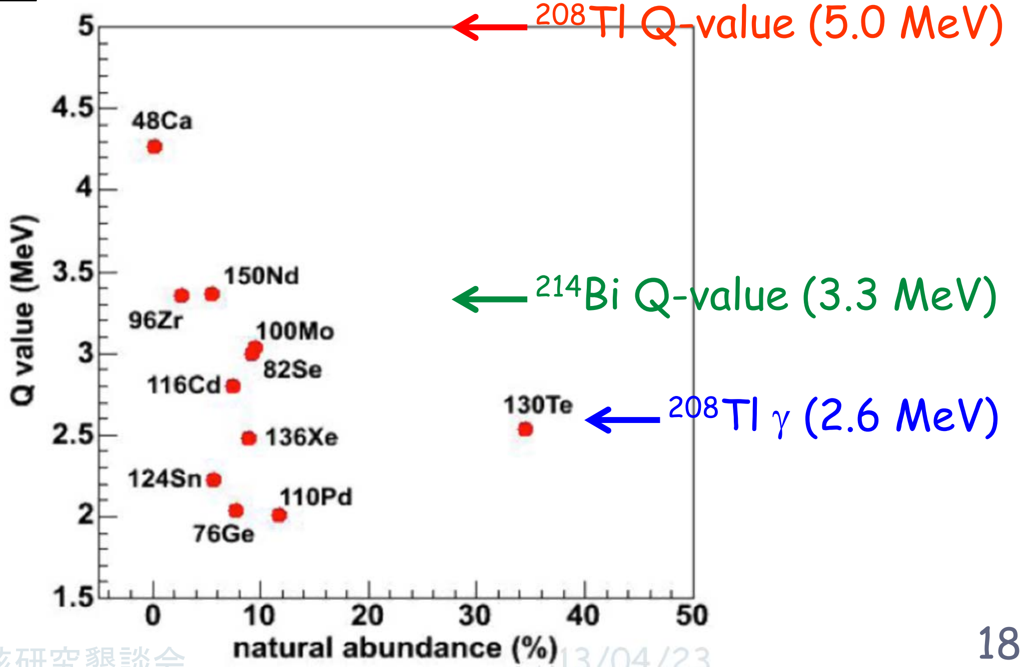
1. Achieve BG free measurement
2. Scale up
   Enrichment
   Improve S/N

ββ核種の選択

- Phase Space Factor
  - $Q^5F(z)$
  - ^{150}Nd ~ Large



- Q値
  - 自然界のBackground源
  - 2.6(γ), 3.3(β)MeVとの差
  - ^{48}Ca, ^{150}Nd, ^{96}Zr 3.3MeV以上

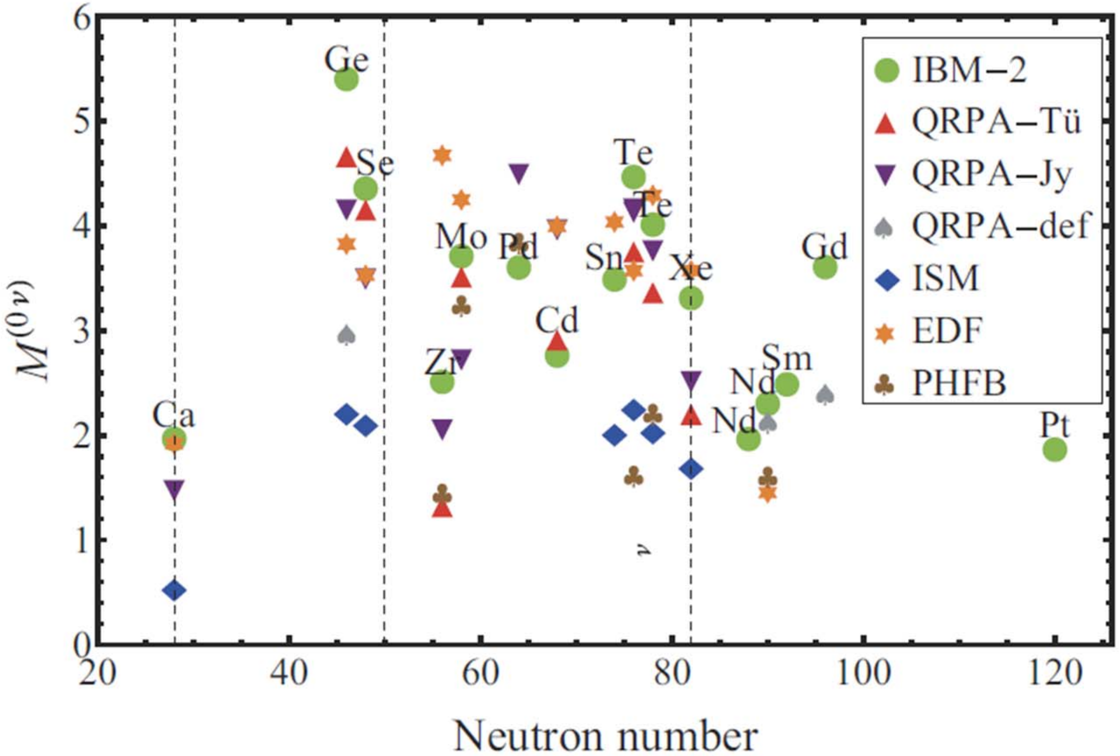


- 自然存在比/濃縮
  - 濃縮の可否、難易度
  - ^{130}Te ; ~ 34%
  - ^{136}Xe ; 濃縮容易
  - ^{100}Mo, ^{82}Se, ^{76}Ge, ^{116}Cd ; 濃縮OK

核行列要素 (NME)

- 理論的なモデル計算
  - 不定性；~ a few 倍 （rate で1桁も有り得る）
  - モデル依存
  - 2νββ崩壊の半減期測定 → モデル計算の妥当性？（最適化）

→ 複数の核種での測定不可欠

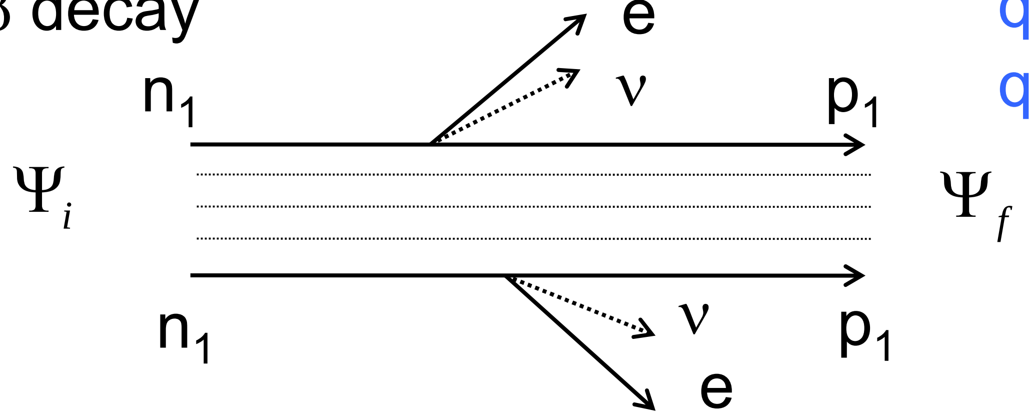


J. Barea, *et al.*,
PRC 87 (2013) 014315

IBM
Interacting Boson Model
^{48}Caで比較的大きな値

Nuclear matrix element

2νββ decay

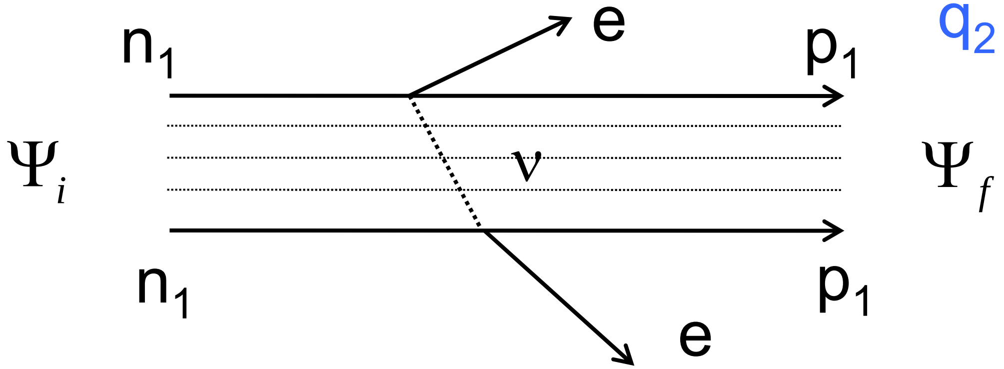


$q_1 \sim 0$ 中性子のwf→陽子のwf

$q_2 \sim 0$ 基底状態同士結べる？

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

0νββ decay



$q_2 + q_1 \sim 0$ 中性子間の相対運動

$q_2 - q_1 \sim any$ →陽子間の相対運動

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

$1/r \sim A^{-1/3}$

$p_F \sim 300\,\mathrm{MeV/c}$

ニュートリノ交換

2核子相対運動量

β崩壊の核行列要素

- 中性子→陽子：アイソスピン昇降演算子
- フェルミ遷移 $S_L = s_\nu + s_e = 0$

$$\int dr \overline{\Psi_f} \sum_j \tau_j \Psi_i = \int dr \overline{\Psi_f} T_j \Psi_i$$

アイソスピン：変化せず
T_i=T_f: IAS（陽子・中性子入替）

- ガモフ・テラー（GT）遷移 $S_L = s_\nu + s_e = 1$

$$\int dr \overline{\Psi_f} \sum_j \sigma_j \tau_j \Psi_i$$

アイソスピン：可変
主に励起状態へ

$^{48}Ca \rightarrow {}^{48}Ti$, ΔT=2: GT 遷移
閉殻では NME=0: lowest order

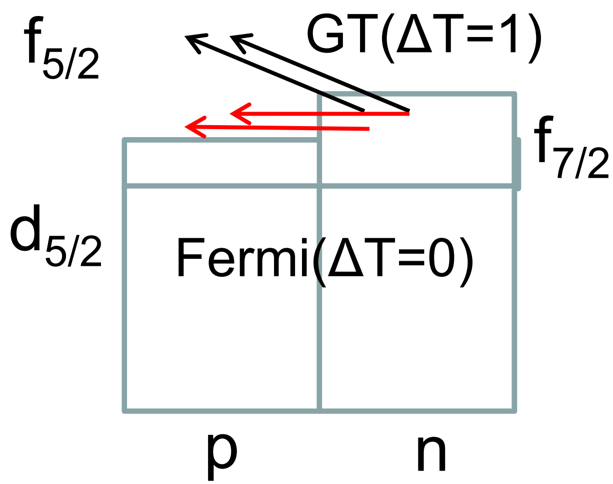
Nuclear Matrix element

$$M'^{0\nu} = \left(\frac{g_A}{1.25}\right)^2 \langle f| - \frac{M_F^{0\nu}}{g_A^2} + M_{GT}^{0\nu} + M_T^{0\nu} |i\rangle$$

GT: usually considered
Fermi: none if isospin holds
Tensor: small

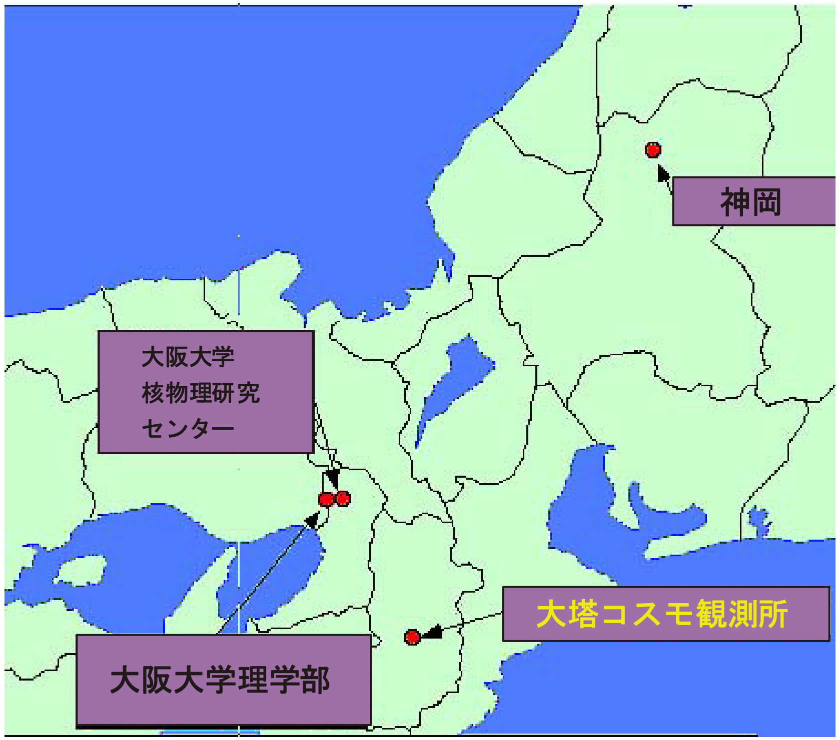
- ^{48}Ca　　Ab initio cal. (shell model)
  - lowest order = 0
    - GT: $n(f_{7/2}) \rightarrow p(f_{5/2})$ no GS
    - Fermi: $n(f_{7/2}) \rightarrow p(f_{7/2})$ IAS
  - In reality：2νββ観測

殻模型計算は出発点



核行列要素（NME）

- 殻模型
  - 2重閉殻(doubly closed shell)ではNMEは0から出発し小さ目。開殻(open shell)ではNMEが大き目。しかし、2vββ崩壊のNMEには、そういう規則性が無い。
  - 計算精度向上:パラメーター調整、干渉性
- その他の模型
  - 重い核のNME計算には模型が必要。精度を上げるとモデルの限界が見える。（配位混合、変形･･）
- ^{48}Caもそれなりに大きい（殻模型以外）



Oto Cosmo Observatory

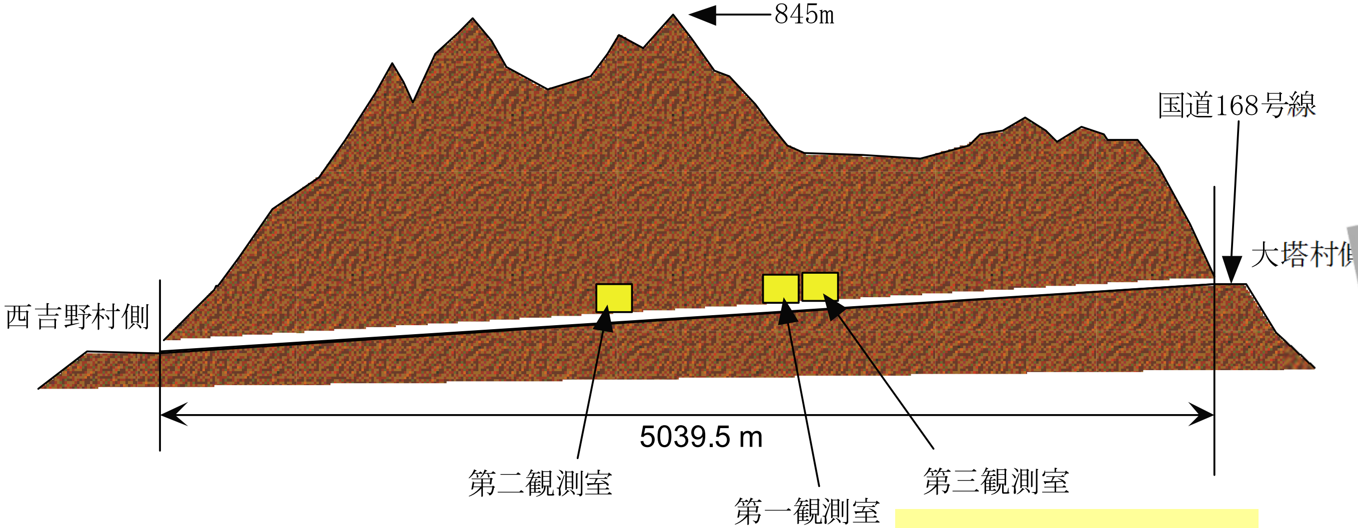
Candles

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

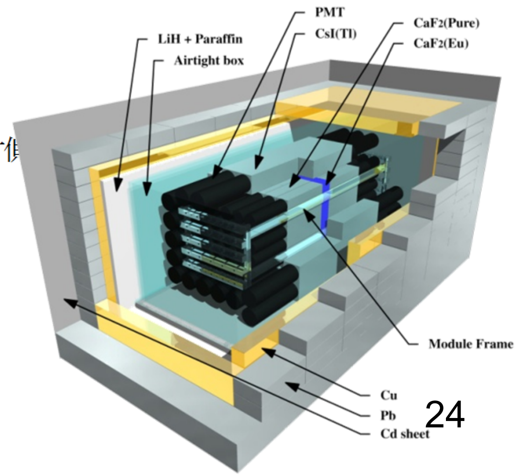
$$T_{1/2}^{0\nu\beta\beta} > 1.4\times 10^{22} \text{ year} \quad (90\% \text{ C.L.})$$

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

NPA 730 '04, 215



ELEGANT VI



^{48}Ca double beta decay by ELEGANT VI

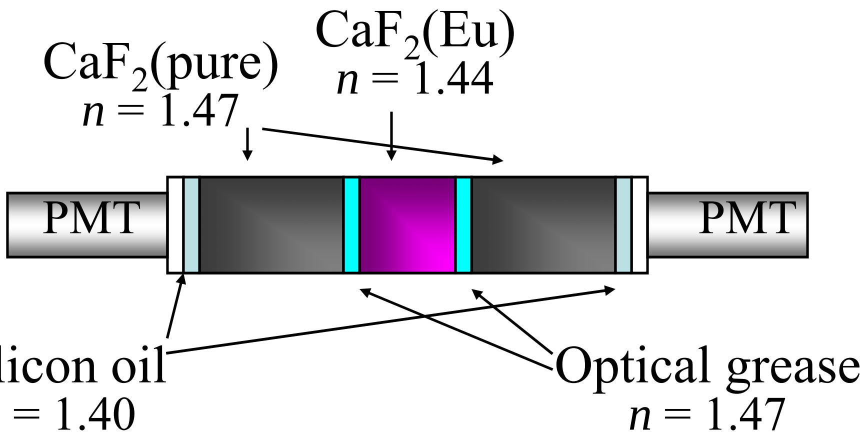
PRC78 058501('08)

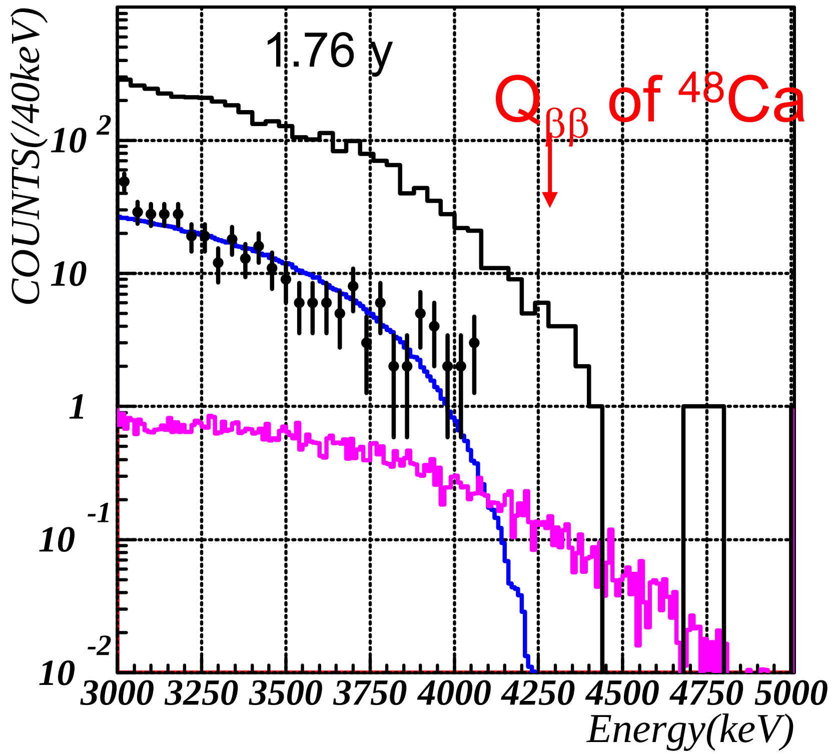
Candles

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

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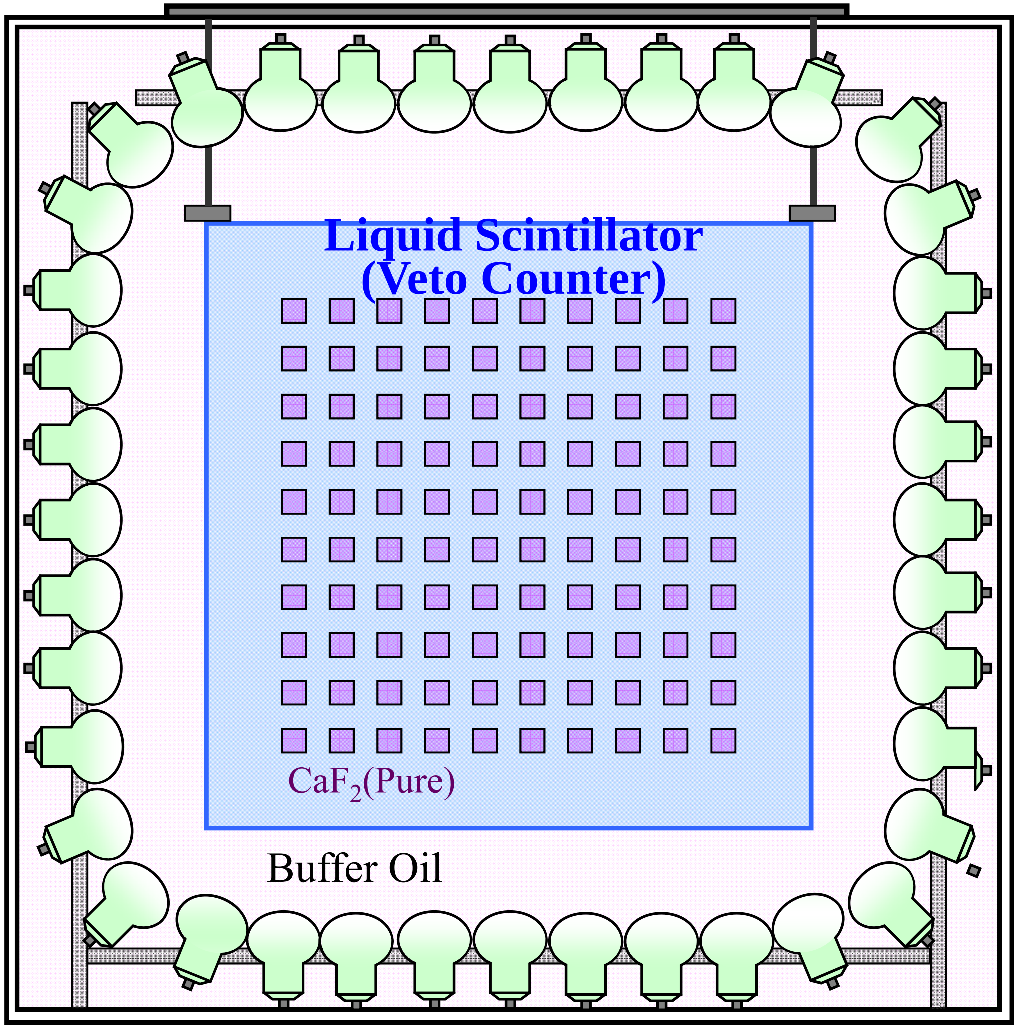
- Big detector
  - Huge amount of materials
- Low radioactive background
  - Active shield
  - Passive shield
  - Low background material
  - BG rejection by signal processing
- High resolution
  - Backgrounds from 2νββ decay

- **CANDLES** is our solution

CANDLES

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



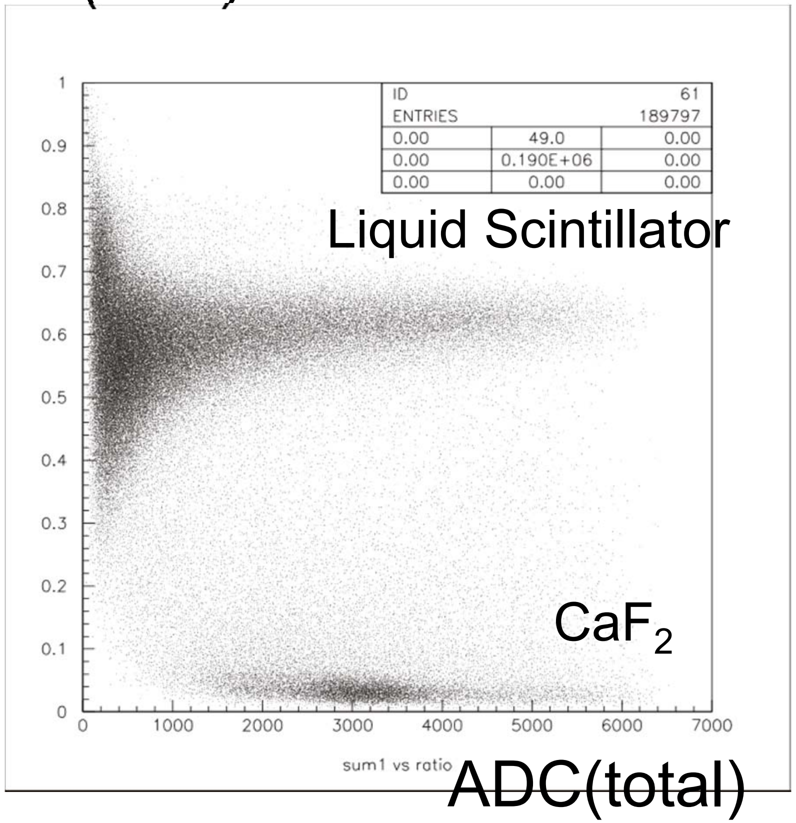
- **CaF_2(Pure)**
  200kg, 300kg, 3t,100t
  ^{48}Ca ($Q_{\beta\beta}$=4.27MeV)
- **Liquid Scintillator**
  Wave Length Shifter
  4 π Active Shield
  Passive shield
- **Photomultiplier**
  energy resolution

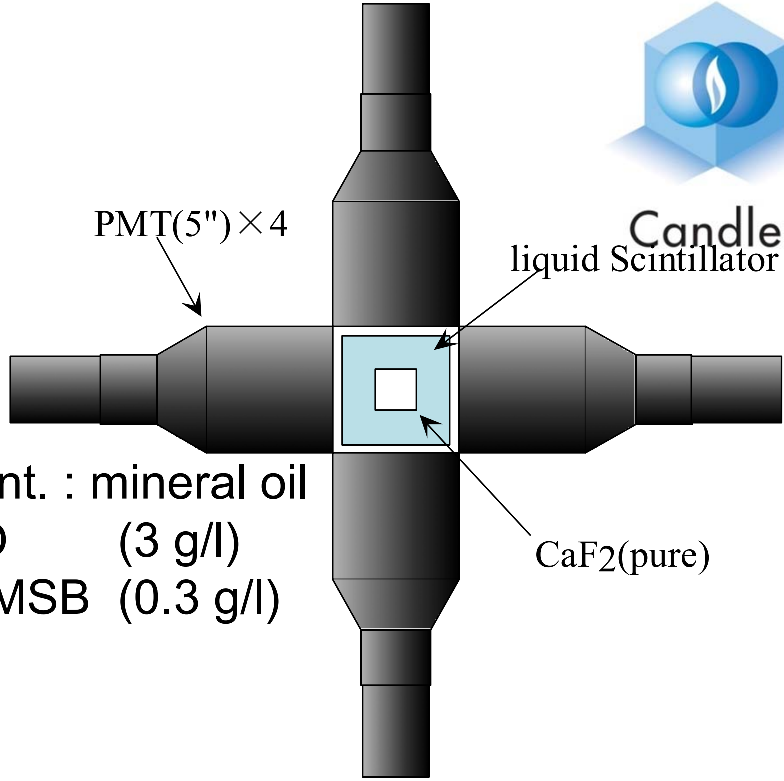
CANDLES I

Background rejection

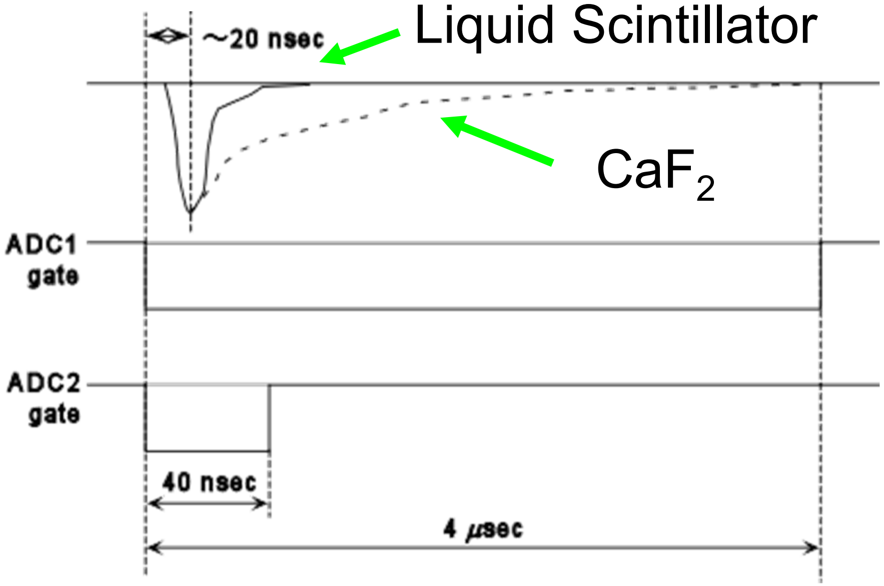
POP(Proof of Principle)

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





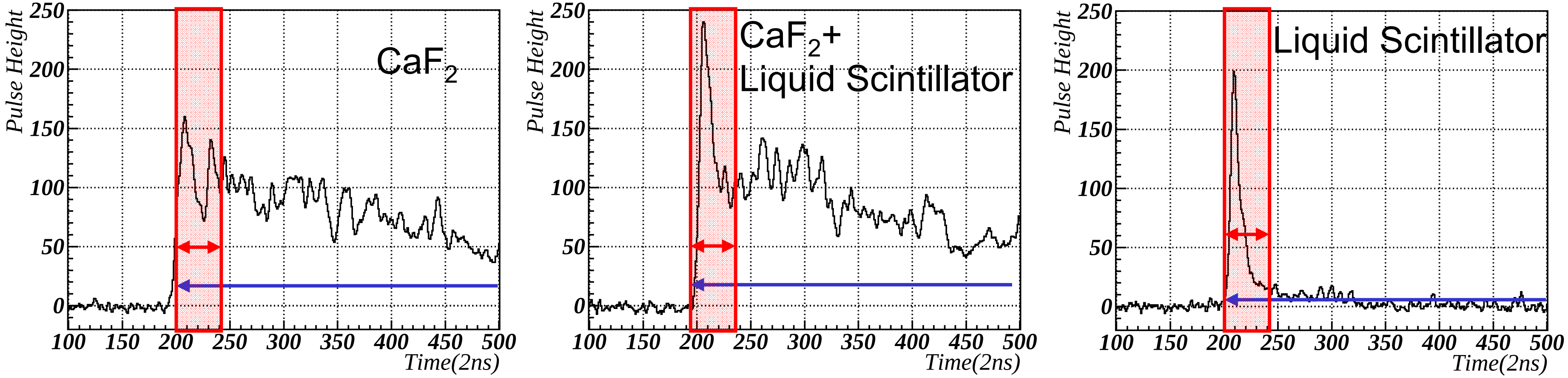
liq. scint. : mineral oil
+ DPO (3 g/l)
+ Bis-MSB (0.3 g/l)



Rejection of LS Events

Candles

- Rejection by using Pulse shape information by 500 MHz Flash ADC
  - Typical Pulse Shapes

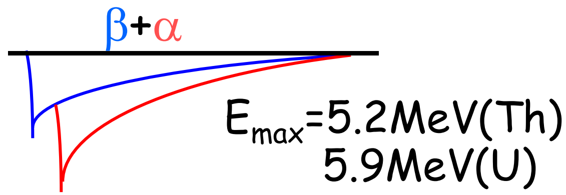


$$\text{Charge Ratio} = \frac{\text{charge in partial gate}}{\text{charge in full gate}}$$

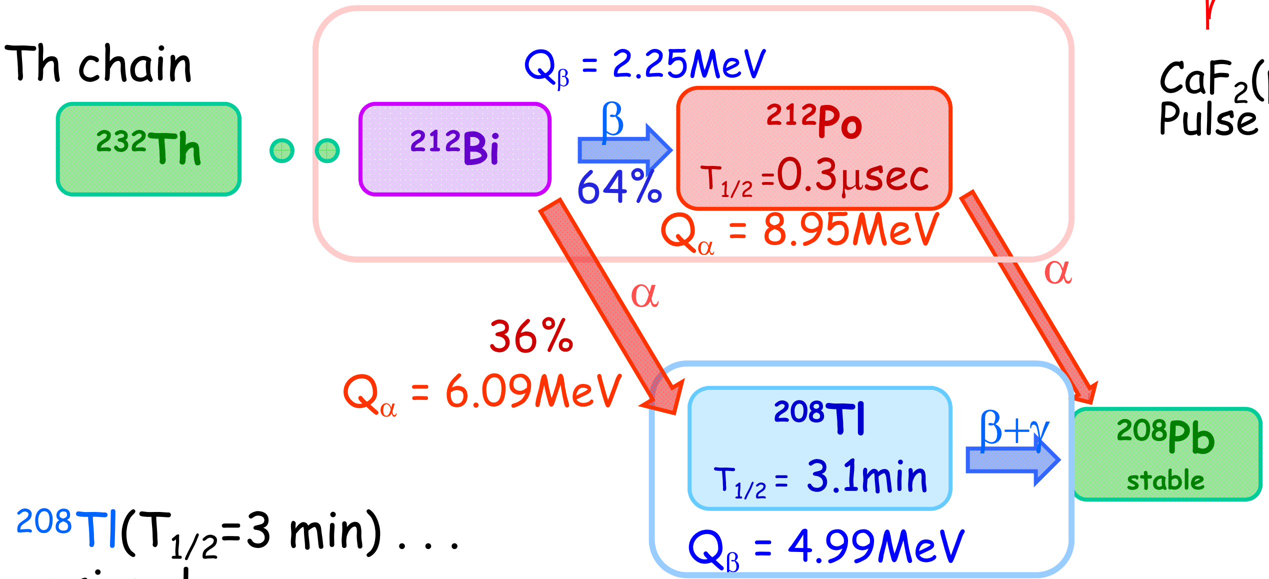
Background @ Q value region

Candles

- No natural BG @ ~4 MeV
  - Maximum energy
    - γ~ 2.6 MeV, β~3.3 MeV, α(max)~2.5 MeV(quench)
  - However,

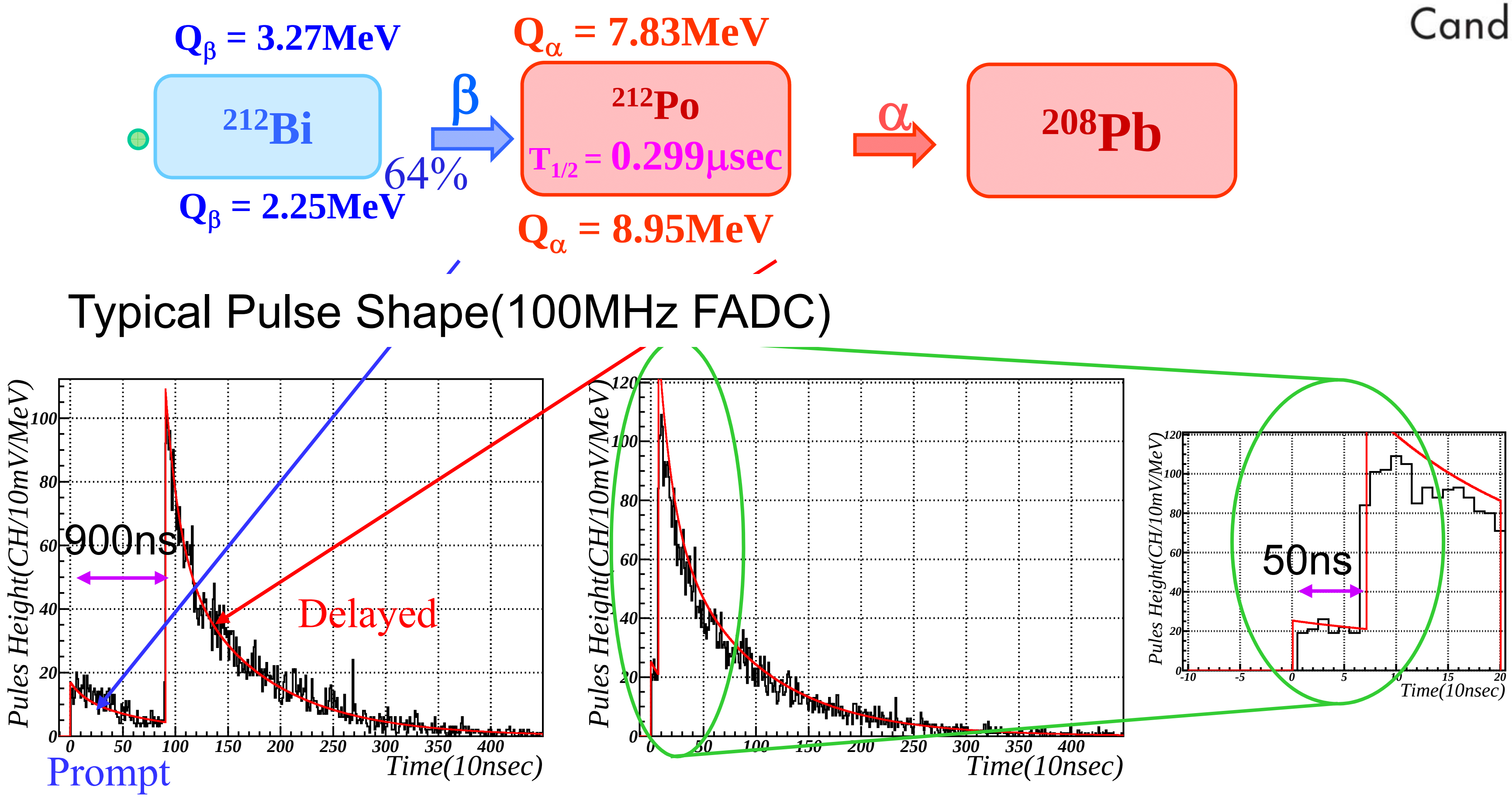


CaF_2(pure) decay time: ~1μs
Pulse shape measurement



^{212}Bi ^{208}Tl($T_{1/2}$=3 min) . . .
pre-α signal
Position and low BG.

Rejection of Double Pulse



Reduction

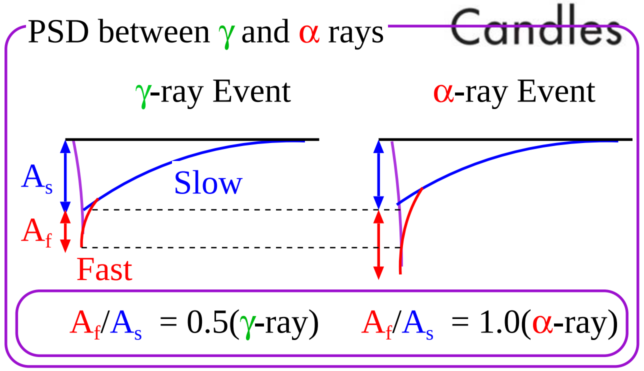
100MHz FADC ΔT > 30ns(3ch) ; ~3%

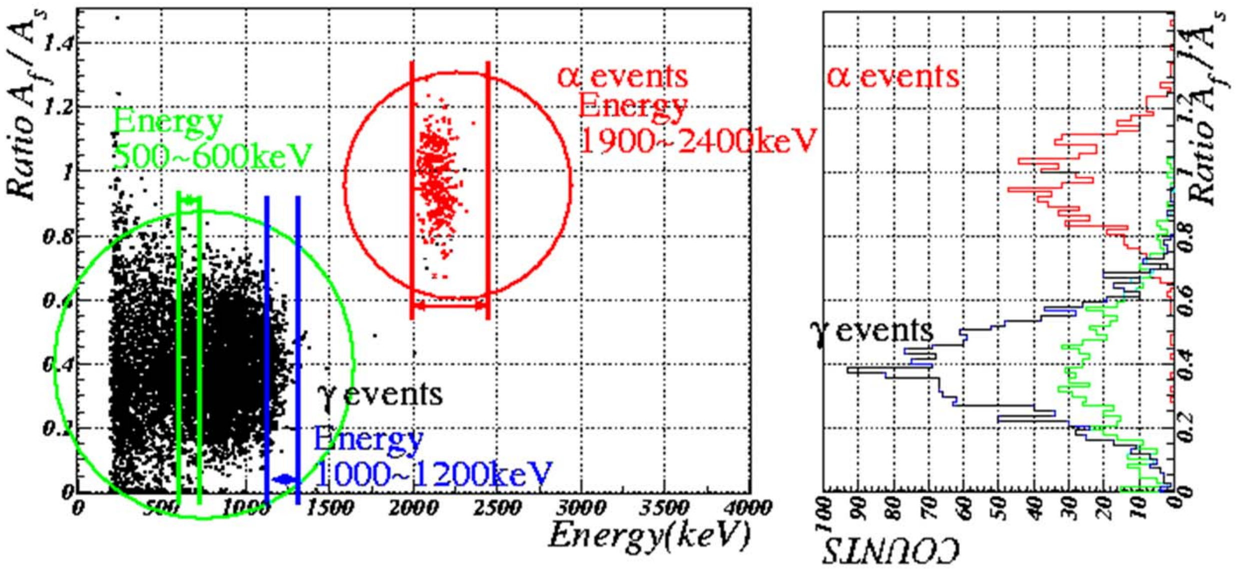
500MHz FADC (under preparation) . . . ΔT > 5ns ; ~1%

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%

^{208}Tl（pre- ^{212}Bi signal）

$^{212}Bi \rightarrow ^{208}Tl \rightarrow ^{208}Pb$

Th chain

^{232}Th ・・ ^{212}Bi —α 36%→ ^{208}Tl $T_{1/2}$ = 3.0min —β +γ→ ^{208}Pb stable

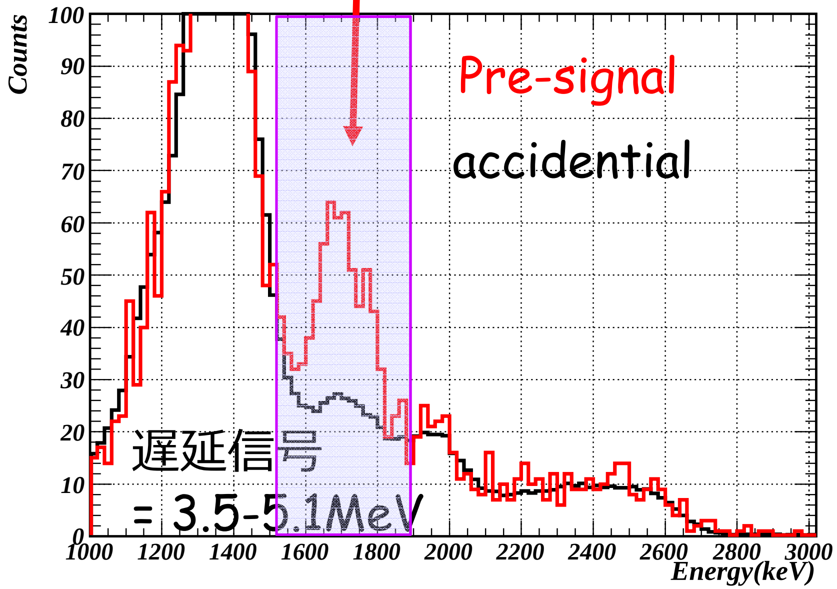
Q_α = 6.2MeV (Ee=1.7MeV)

Q_β = 5.0MeV

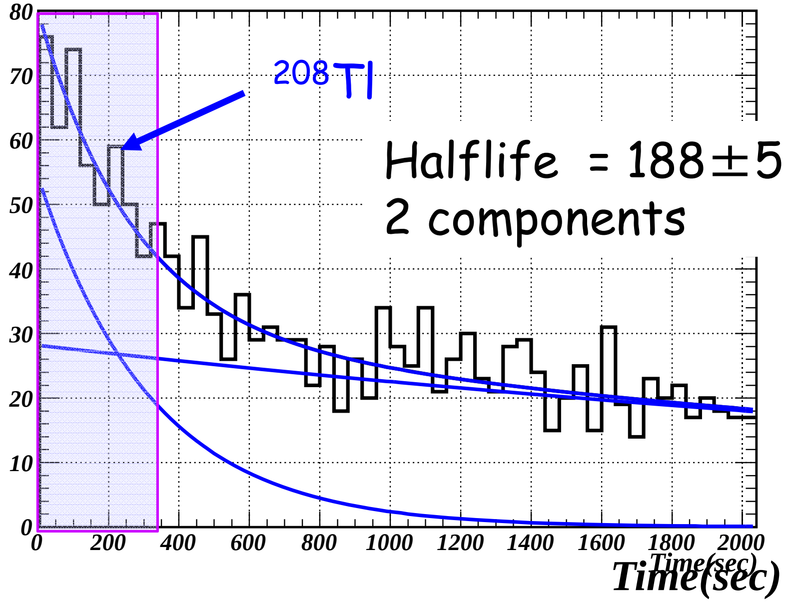
E_{max}=5.0MeV

^{212}Bi ^{208}Tl($T_{1/2}$=3 min.) . . . same crystal

A in ^{212}Bi



Δt分布



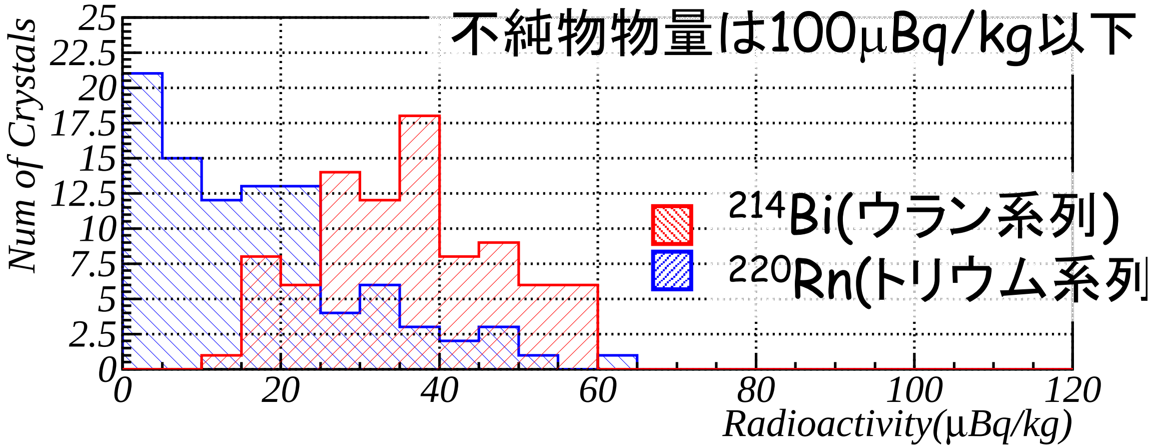
- ^{212}Bi
- rejection 50(56)%、acceptance85(74)%。
- dead-time free DAQ system

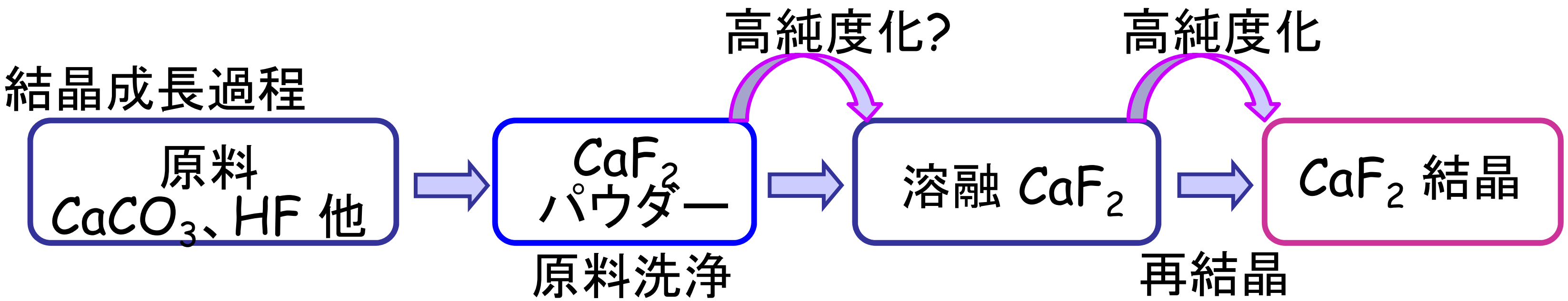
CANDLES結晶高純度化

- 高純度化
  - CANDLES III用

    :平均17μBq/kg
  - 今後更に一桁低減
    - 歩留り
    - 原料選定:CAN III
    - 原料洗浄、再結晶

CANDLES III用結晶の不純物量分布



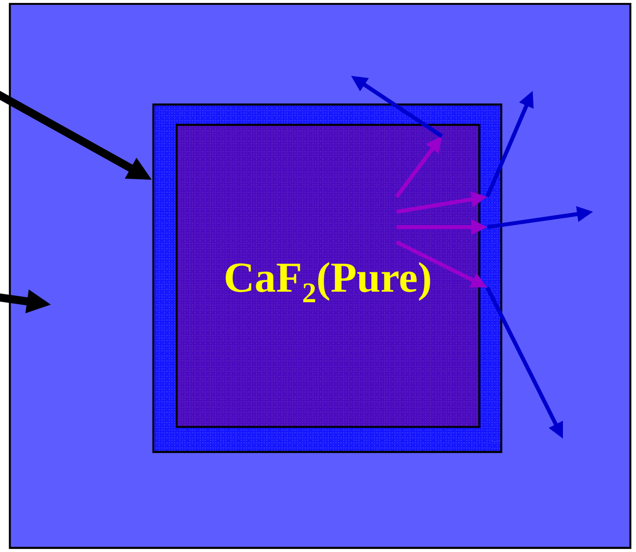


不純物物量の低減

・高純度化過程を追加し、歩留りの改善。

Two Phase System
-- Energy resolution --

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



CaF_2 Emission (~285nm) — UV light

⇩

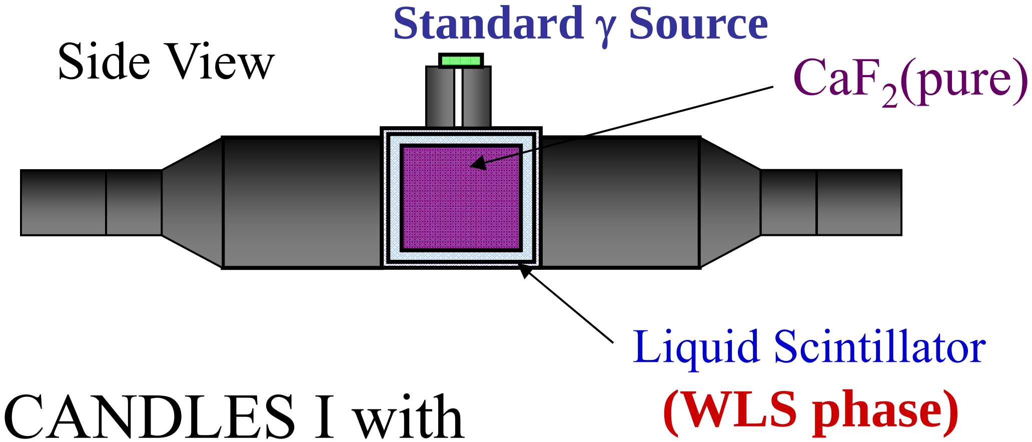
Conversion by WLS(350~400nm) — Visible light

⇩ propagate

PMT

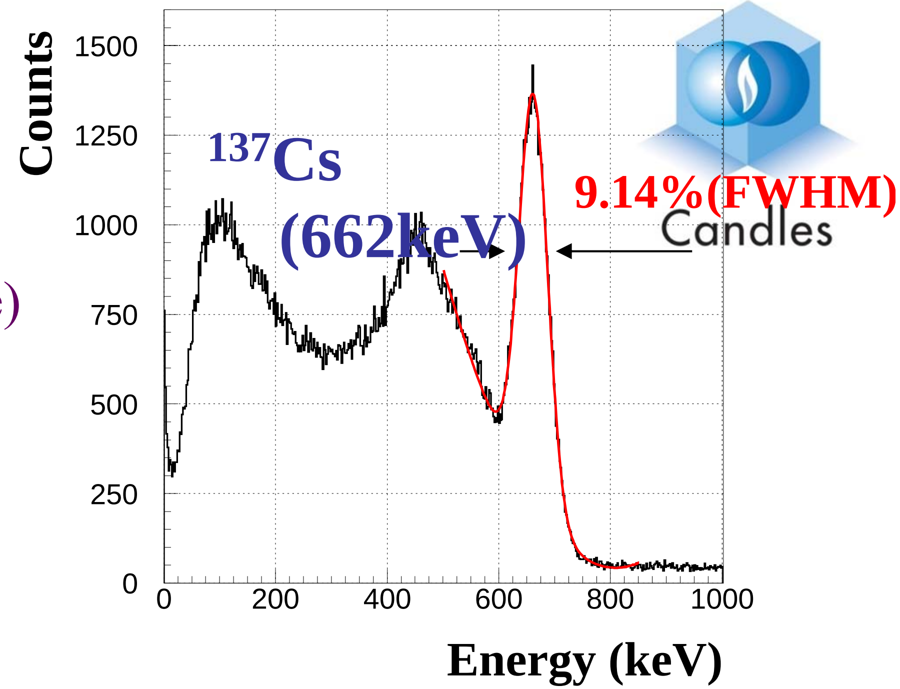
High resolution and
High veto efficiency

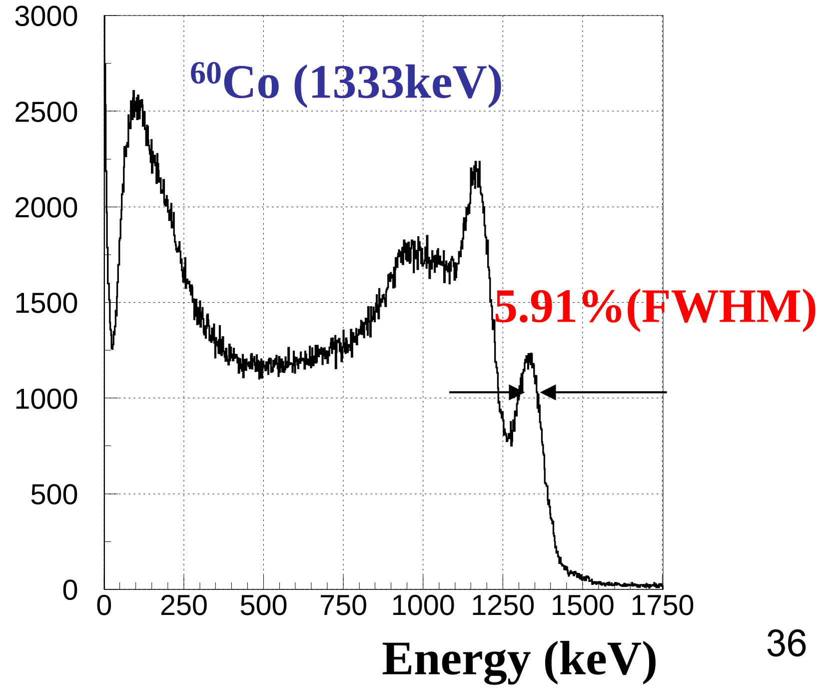
Energy resolution



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%

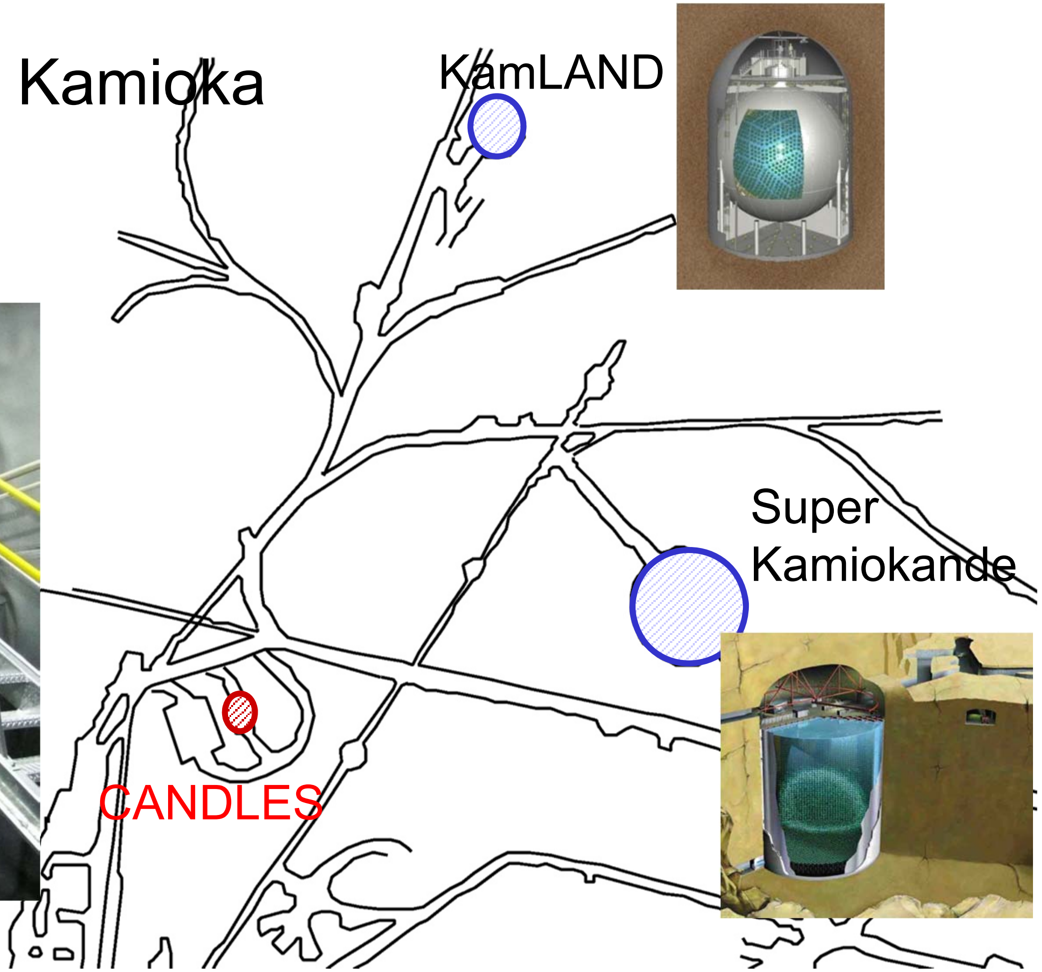




CANDLES III(UG)

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

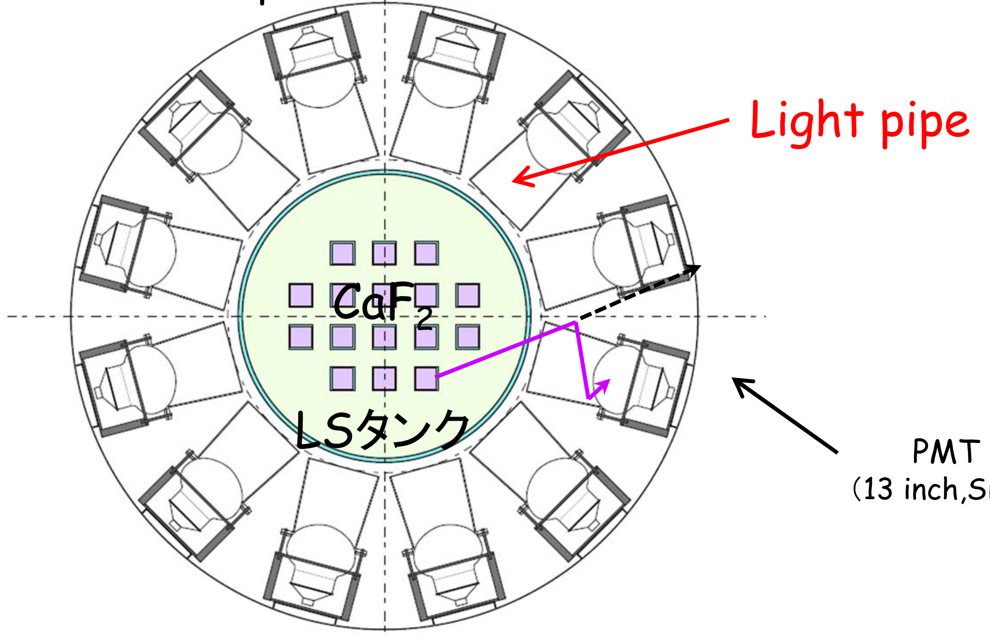
CANDLES III(UG)

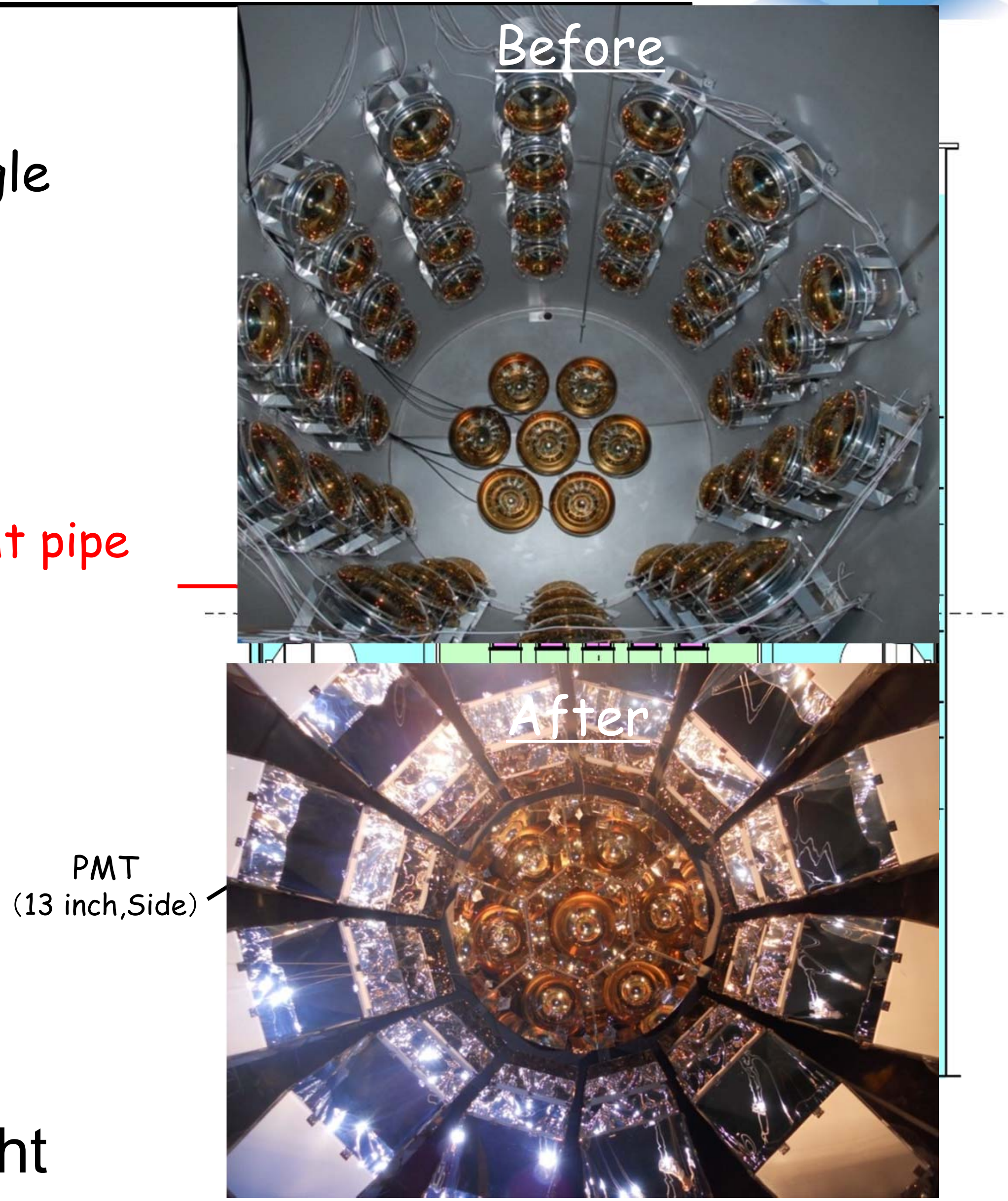


Light pipe

- Light collection
  - Increase PMTs solid angle
  - Reflection film:
    ~93% @ 420nm

CANDLES top view





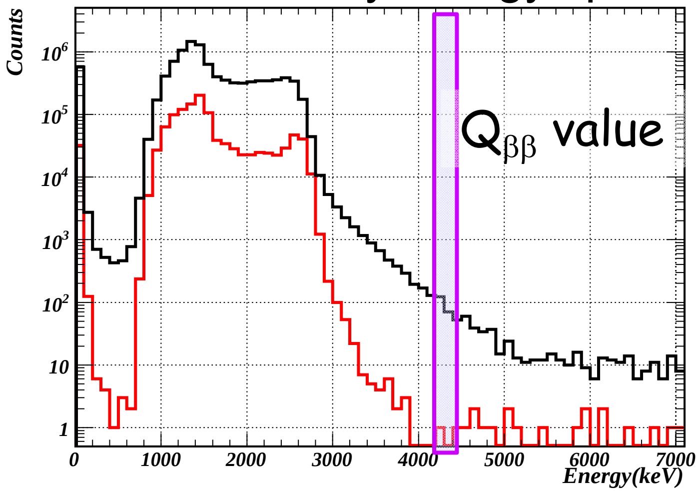
60% increase of light

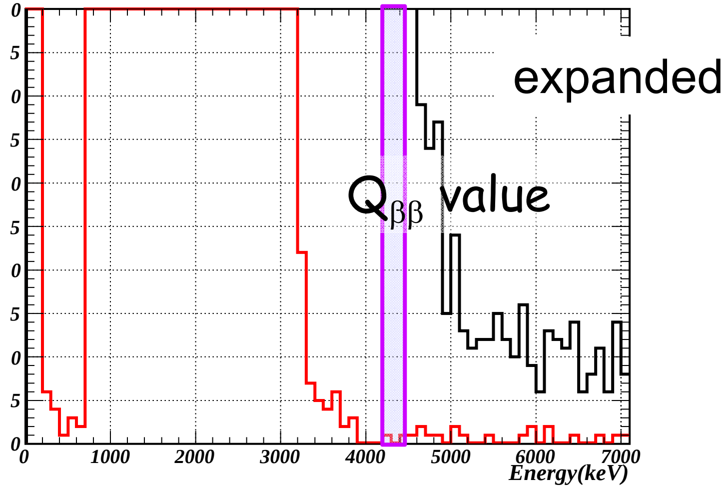
Current energy spectrum

Commissioning run

- : 27days、26 crystals

Preliminary energy spectra





Further study is underway.

Cut condition

- χ_β<1.5(90%)
- -3σ<SI<1σ(84%)
- ^{208}Tl red. (<720sec)
- Bi-Po (<10nsec)
- Pure crystals 26

Remained events

crystals	26 (<10μBq/kg)	91
4.19-4.42MeV（Q v.）	1 /0.23MeV	13
4-5MeV（^{212}Bi、^{208}Tl）	7 /MeV	32
5.5-6.5MeV	6 /MeV	23

バックグランドの起源
-- 結晶内BG --

Candles

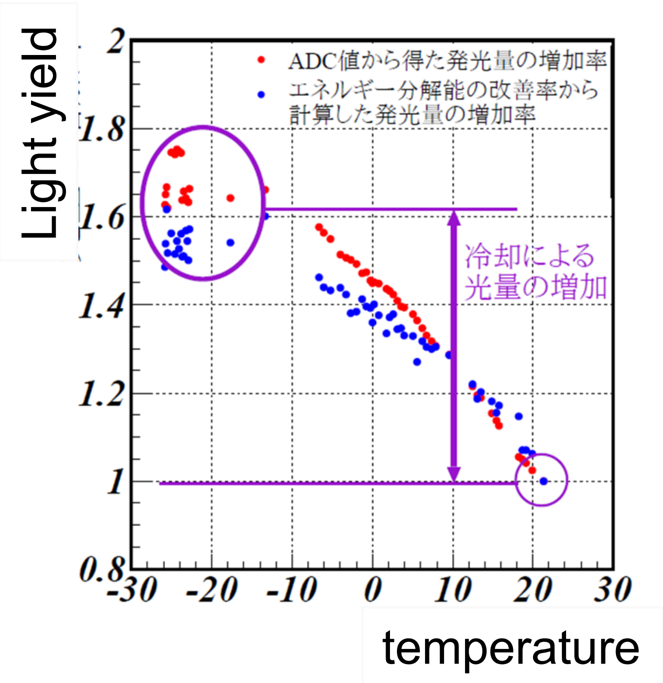
- 事象数
  - シミュレーションとの比較

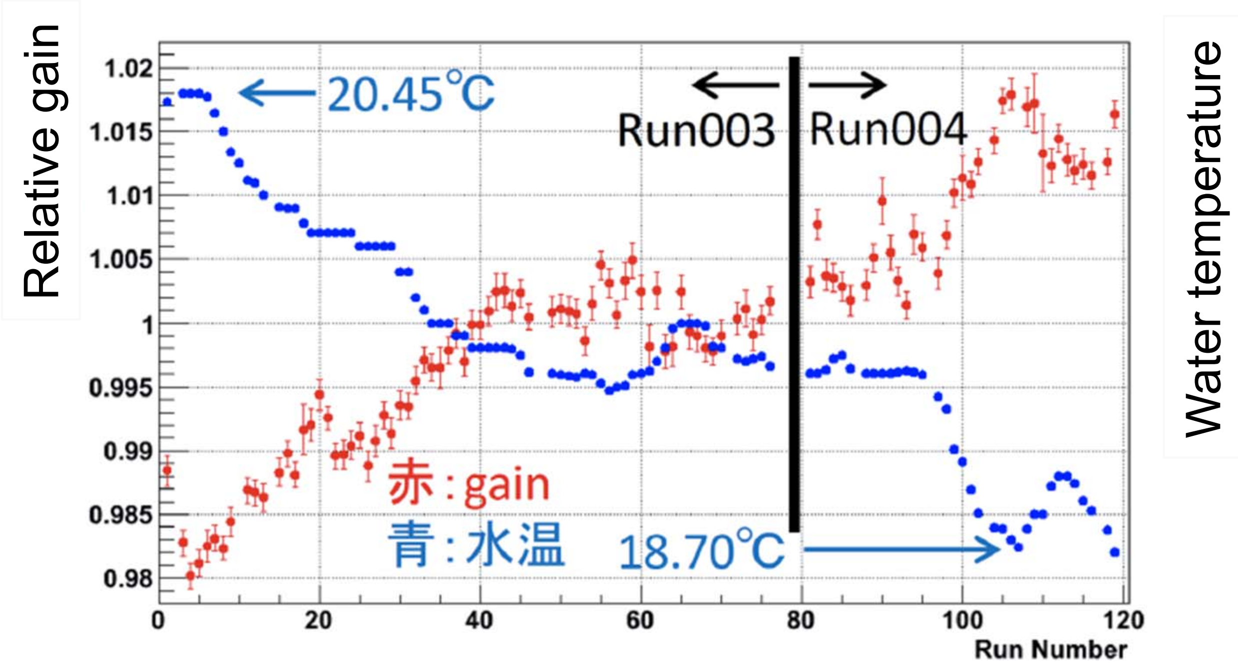
	測定データ	^{212}Bi(Sim)	^{208}Tl(Sim)
26個：4.19-4.42MeV（Q値）	1 /0.23MeV	0.04	0.2-0.3
26個：4-5MeV（^{212}Bi、^{208}Tl）	7 /MeV	0.15	0.7-0.9
26個：5.5-6.5MeV	6 /MeV	0	0
91個：4.19-4.42MeV（Q値）	13 /0.23MeV	0.59	3.3-4.2
91個：4-5MeV（^{212}Bi、^{208}Tl）	32 /MeV	1.99	8.9-12.5
91個：5.5-6.5MeV	23 /MeV	0	0

結晶内部の不純物起源のバックグラウンド
・現システムにおいてほぼ予定通りの除去率
バックグランド除去効率改善
・DAQ高速化
・マルチサイト事象の除去

Improve energy resolution

- CaF_2
  - Light yield increase at low temperature
- Test experiment





Observed: 2%/deg. increae

Cool CANDLES III from 20 to 0 degrees.

40% increase: This year

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
  - Now running with minor improvement

Current status

- CANDLES IV
  - 600 x10cm^3 CaF_2 (~3 μBq/kg) ~0.1 eV
- CANDLES V
  - Enrichment and ~100kg of ^{48}Ca (~10meV)

-- Enrichment of ^{48}Ca --

Candles

First experimental results

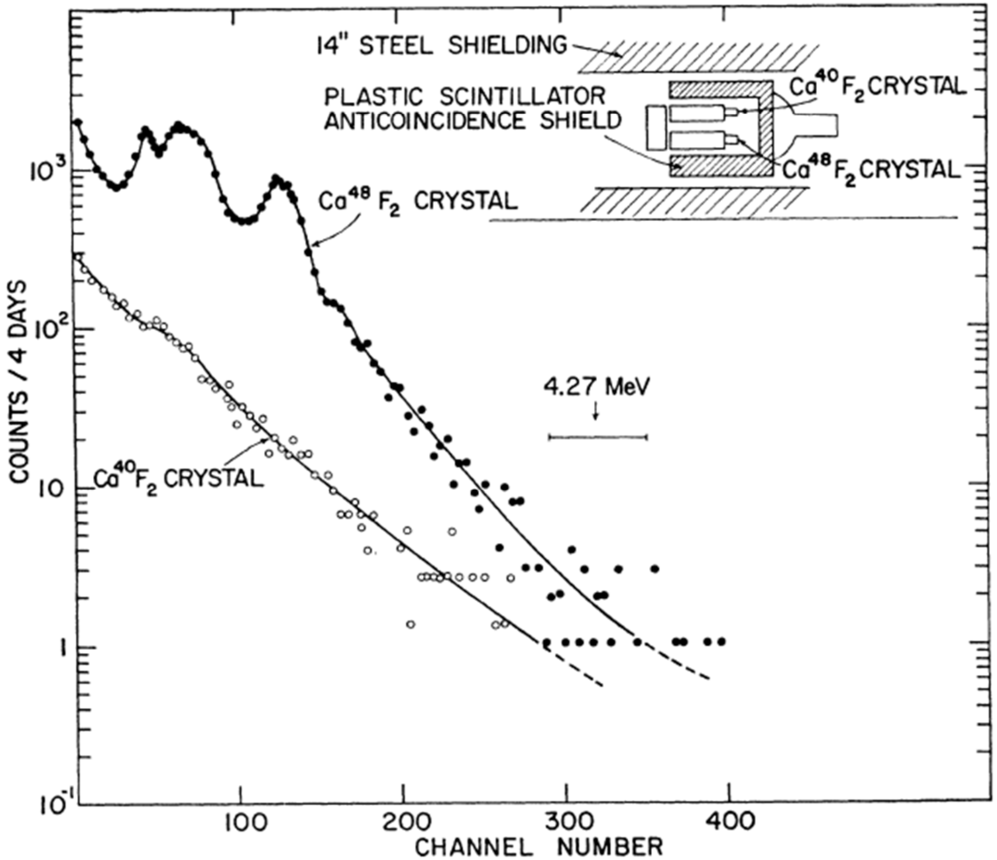
Limits for Lepton-Conserving and Lepton-Nonconserving Double Beta Decay in Ca^{48}†

E. DER MATEOSIAN AND M. GOLDHABER

PHYSICAL REVIEW 146 (1966) 810

$^{48}CaF_2(Eu)$, 11.4 g
$\rightarrow T_{1/2}^{0\nu} > 2\times10^{20}$ yr

96.59 % enriched ^{48}Ca
Isotope Separation Department
Oak Ridge National Laboratory



Isotope enrichment Price Level

B.A. Barabash, J. Phys. G: Nucl. Part. Phys. 39(2012)085103

Isotope	Criteria for the Best 0νββ Isotope						0νββ Project
	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (y^{-1})	$T^{2\nu\beta\beta}_{1/2}$ (10^{20} y)	Isotope Enrichment			
				Abundance (%)	Method	Price Level	
^{130}Te	2.533	1.70	6.8	33.8 → 95	GC	0.3	CUORE
^{136}Xe	2.462	1.81		8.9 → 90	GC	0.2	EXO
^{76}Ge	2.039	0.24	15	7.8 → 90	GC	1 ($80/g)	GERDA MAJORANA
^{82}Se	2.995	1.08	0.92	9.2 → 90	GC	1.5	SuperNEMO
^{100}Mo	3.034	1.75	0.07	9.6 → 90	GC	1	AMORE
^{116}Cd	2.802	1.89	0.28	7.5 → 90	GC	2.5	
^{48}Ca	4.274	2.44	0.44	0.187 → 25	EMIS ALSIS	160 < 5	CANDLES
^{150}Nd	3.667	8.00	0.08	5.6 → 90	EMIS	170	
^{96}Zr	3.350	2.24	0.23	2.8 → 60	EMIS	400	-

^{48}Ca needs orders-of-magnitude cost-effective method

濃縮法

- 物理的方法
  - 遠心分離法:ガス(核燃料)
  - レーザー法:核燃料では実用化されず
    - R&D
  - 質量分析法:^{48}Ca等、ガス化出来ない元素
- 化学的方法
  - 反応率の差:重水素、ホウ素
  - クラウンエーテル(樹脂)法
    - 樹脂法:梅原
    - マイクロリアクター:硲
- 電気泳動法

福井

Massive
cost-effective

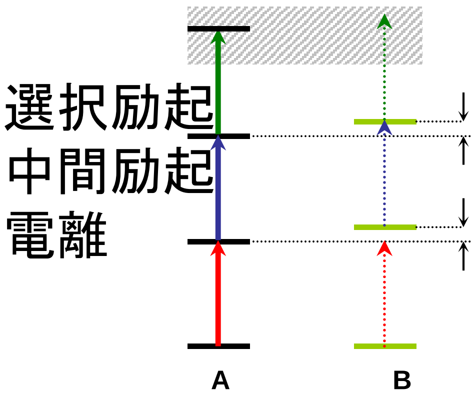
大阪

LISOP of Ca-48

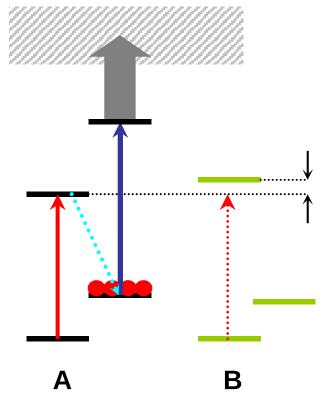
Hard to separate by AVLIS due to small IS

Candles

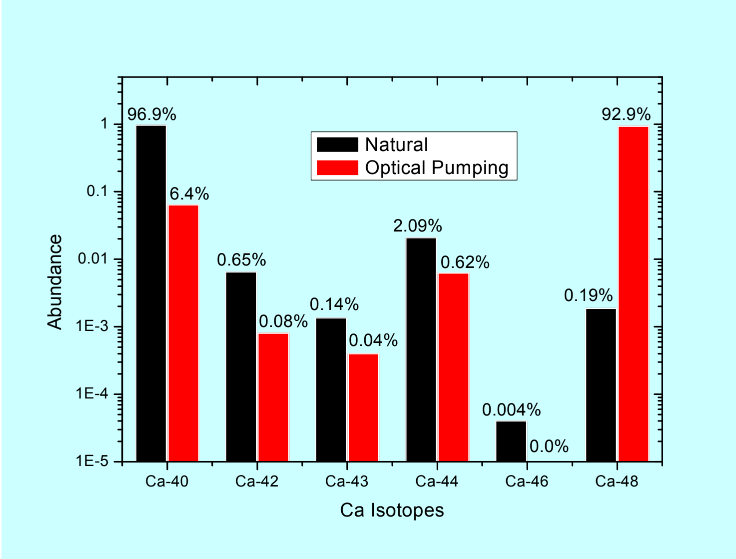
- AVLIS
  - Multistep photoionization process : isotope selectivity and ionization (trade-off)
- LISOP (laser isotope separation based-on optical pumping)
  - ISOP (isotope selective optical pumping) provides excellent isotope selectivity.
  - Non-selective ionization process provides good efficiency.



<3-step photoionization>



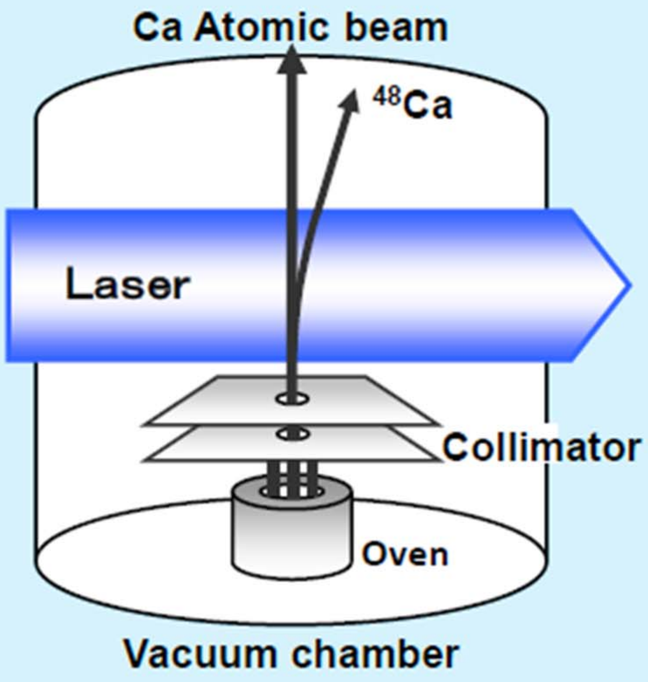
<ISOP followed by photoionization>

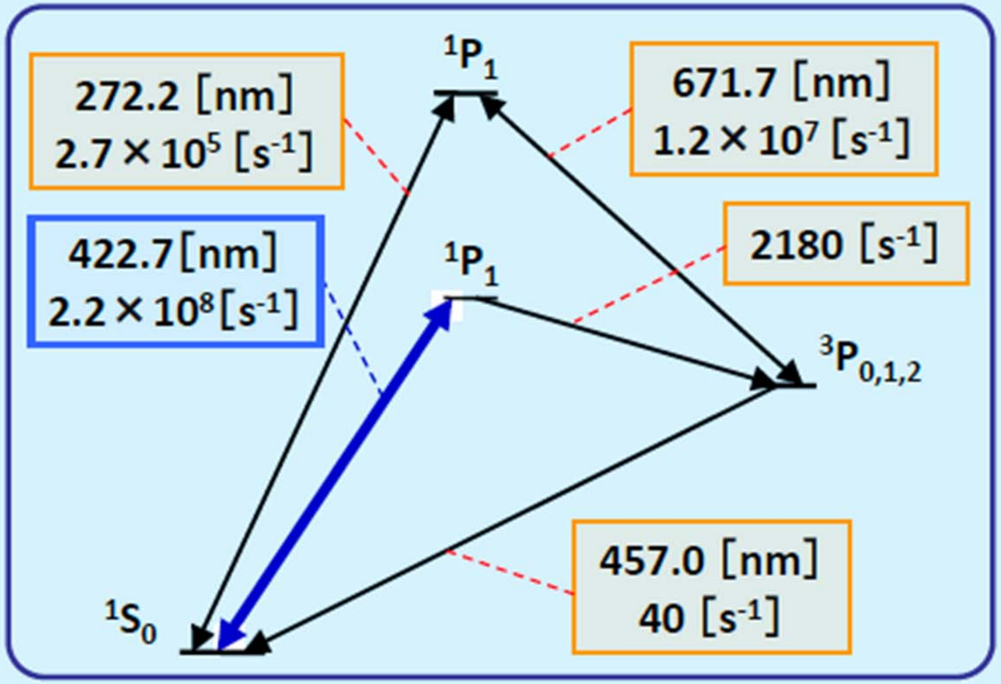


Simulation of Optical Pumping Process

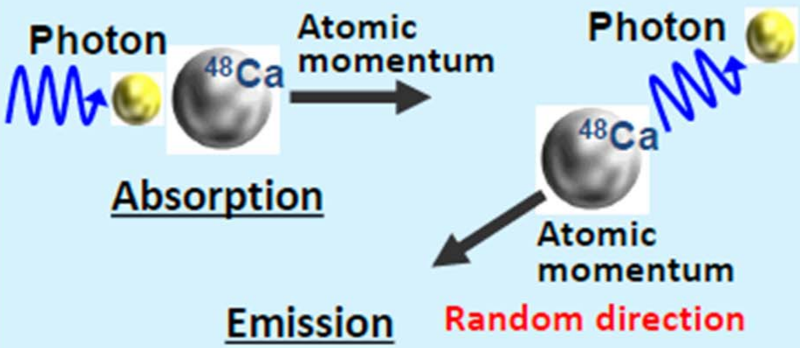
Do-Young Jeong, KAERI

Deflection of ^{48}Ca by Radiation Pressure





Energy levels and Transition Probabilities



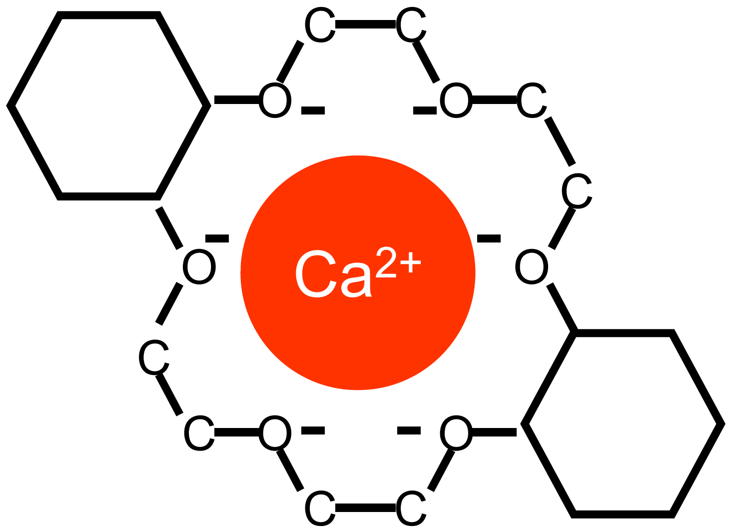
$^1P_1 - {}^1S_0$ transition

- Large transition probability
- Quasi Two-Level System

仁木＠福井大

^{48}Ca enrichment in CANDLES

- Enrichment of ^{48}Ca
  - Natural abundance: 0.2 %
  - room to improve 500 times
    - ββ decay nuclei
    - S/N
- Crown ether
  - Light Ca ion: absorbs more
  - Separation coefficient
    - $\varepsilon \sim (3.5 \pm 0.5) \times 10^{-3}$
  - Crown ether resin



Dicyclohexano 18-crown-6

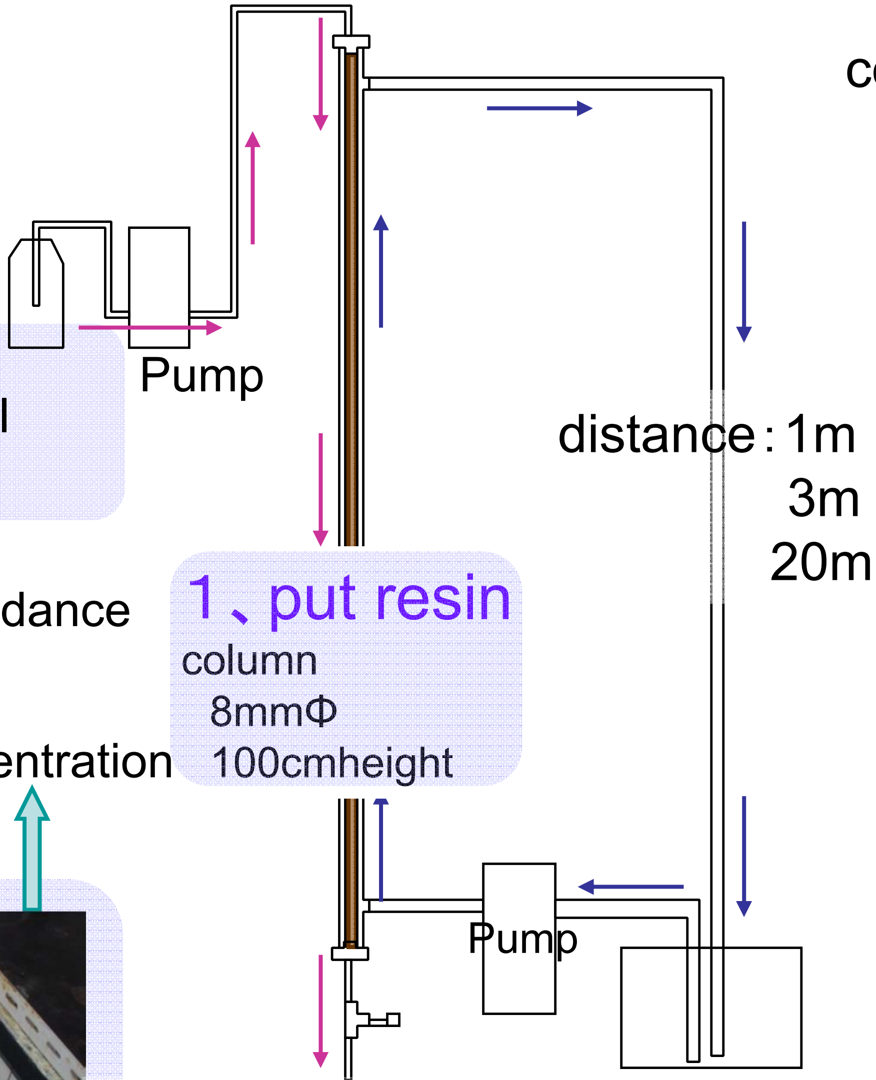
DC18C6

Experiment

- **Breakthrough method （migration）**

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

1、put resin
column
8mmΦ
100cmheight



5、measure abundance

4、measure concentration

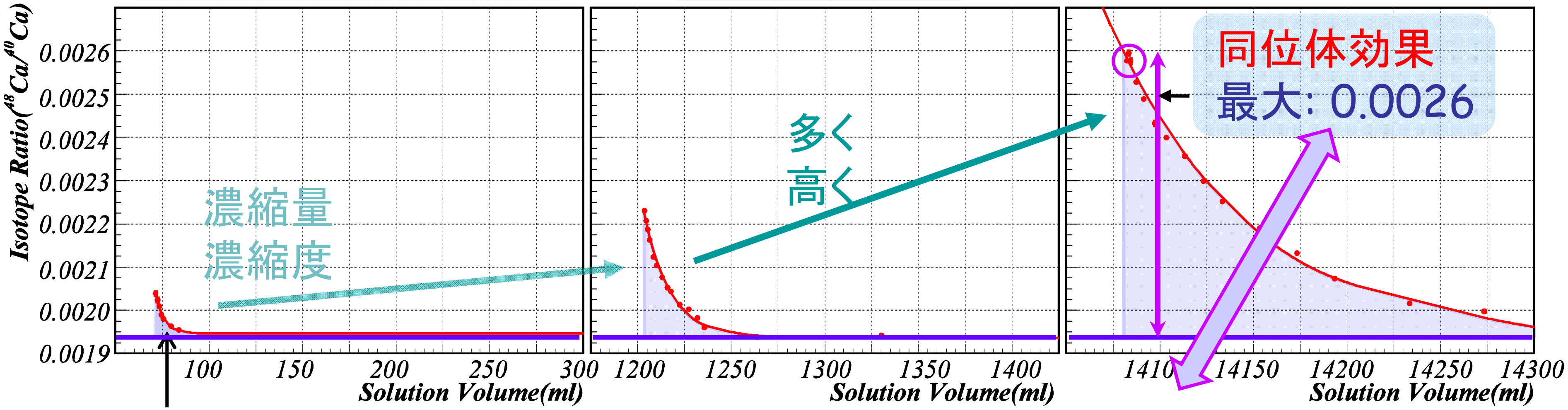
3. Fraction collector

column

CANDLES IV : ^{48}Ca濃縮

- 同位体効果

~7時間 : 1m 泳動距離 → ~70時間 : 20m → ~250時間 : 200m



クラウンエーテルによる濃縮量

自然同位体比
= 0.0019

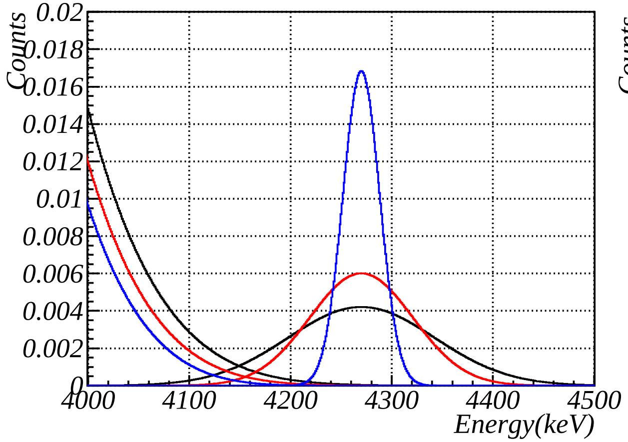
濃縮効果

- 長い泳動距離 = 多い濃縮量と高い濃縮度
- ^{48}Ca 大量化 → 現在、体積10～100倍システム
  大量化の際に想定される問題の確認

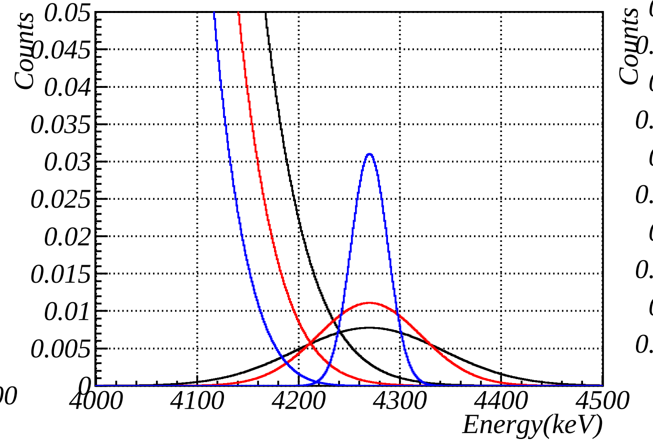
2νββエネルギースペクトル
-- エネルギー分解能 --

エネルギー分解能4%
エネルギー分解能2.8%
エネルギー分解能1%

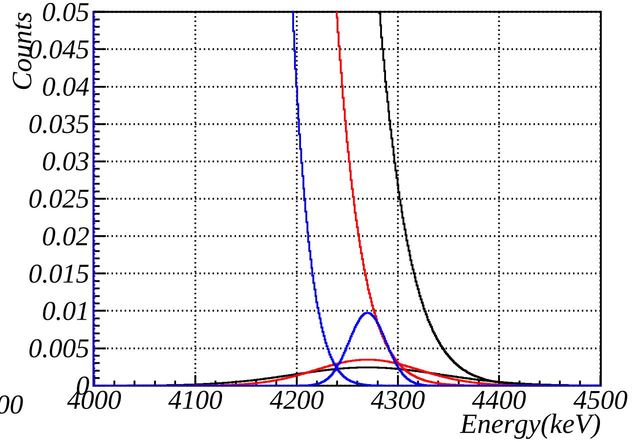
CANDLES IIIサイズ
<mν>=0.5eVの時のレート比



CANDLES IVサイズ
<mν>=0.08eV



CANDLES Vサイズ
<mν>=0.009eV



測定は、
エネルギー分解能4%
を予定。

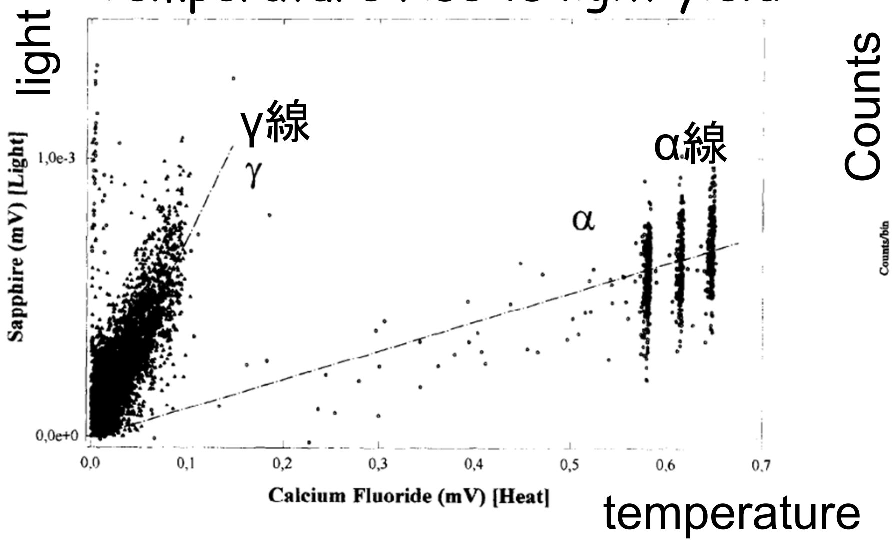
測定は、
エネルギー分解能2.8%
を予定。

測定は、
エネルギー分解能1%
を予定。

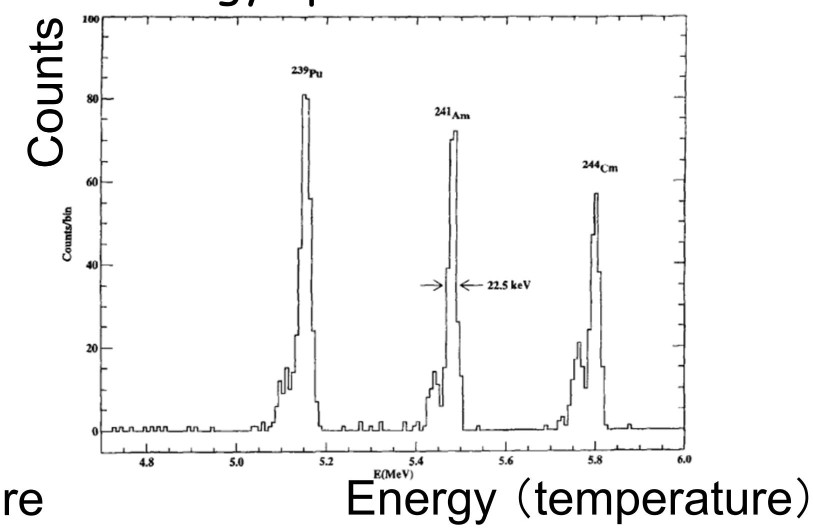
CANDLES V : bolometer

- Once enrichment is realized;
  - Energy resolution better than 1% → bolometer
- Previous study
  - CaF_2(Eu) as a bolometer

Temperature rise vs light yield



Energy spectrum



CaF_2
energy resolution ~ 0.5% @ 5.5 MeV