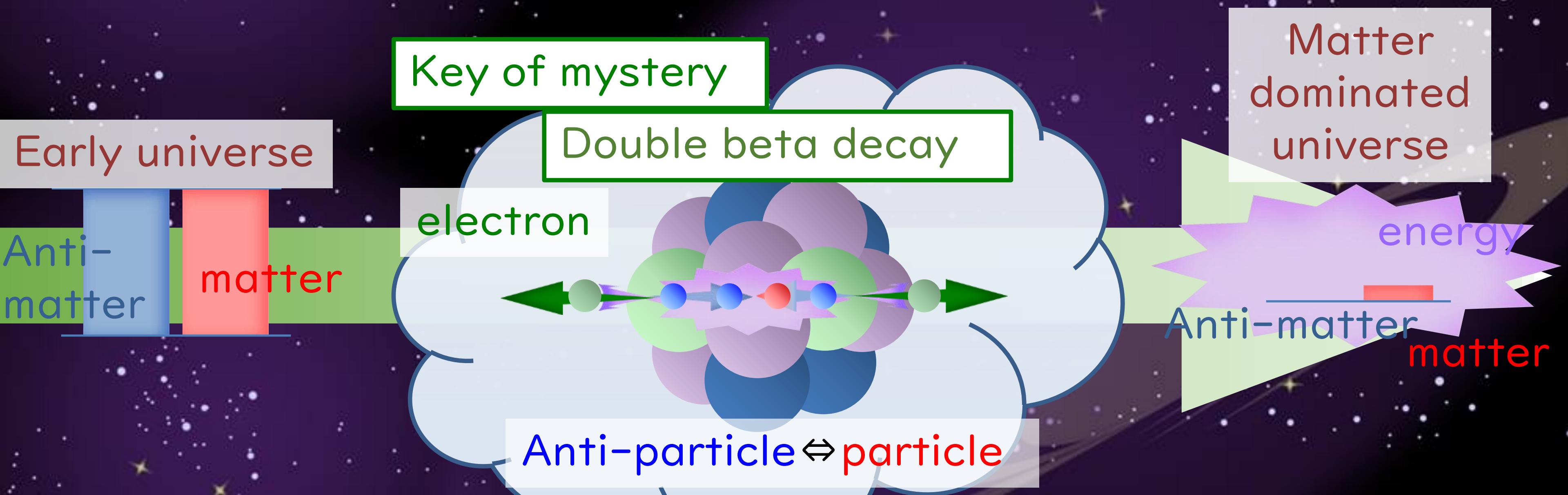
Neutrino-less Double Beta Decay
Experimental Review

大阪大学核物理研究センター
梅原さおり
Umehara, Saori
RCNP, Osaka University
umehara@rcnp.osaka-u.ac.jp

Contents

[double beta decay] and [matter dominated universe]

- Double beta decay : Key of mystery of [matter dominated universe]
  - Early universe : same amount of matter and anti-matter
  - But Current universe : asymmetry between matter and anti-matter
  - Leptogenesis：Explain by [Majorana nature] and [heavy neutrino]
  - We can test [Majorana nature] by「neutrino-less double beta decay」
    - Majorana nature of neutrino : particle = anti-particle



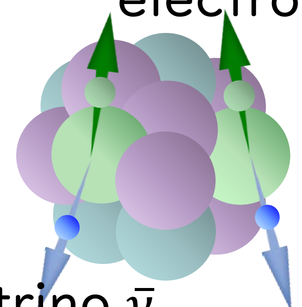
Test of Majorana nature

- Another way for test of Majorana nature : for example . . .
  - Neutrino beam experiment

Neutrino converts to anti neutrino
→Collision

But not realistic
to collide neutrinos by beam control

  - Double beta decay : realistic test

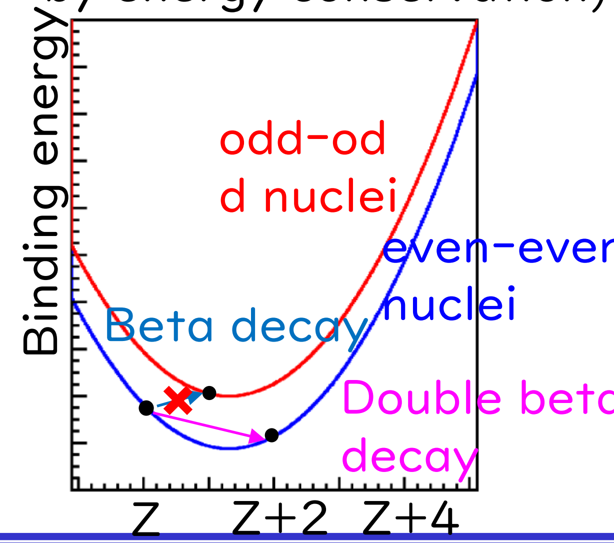


in nuclear size
in short time
two anti-neutrino

Beta decay is forbidden
$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}$

Double beta decays
$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$
$(A,Z) \rightarrow (A,Z+2) + 2e^-$

(beta decay is forbidden by energy conservation)



Neutrino-less double beta decay

- Two neutrino double beta decay and Neutrino-less double beta decay

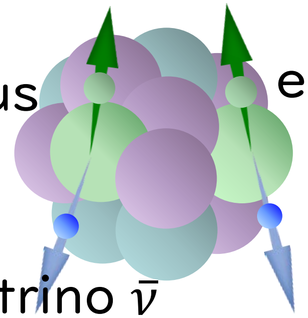
In standard model

Not observed

Lepton number non conservation

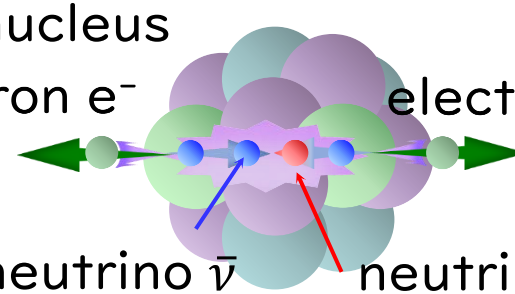
Two neutrino double beta decay (2νββ)

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



Neutrino-less double beta decay (0νββ)

$(A,Z) \rightarrow (A,Z+2) + 2e^-$



Dirac neutrino

$$\nu \neq \bar{\nu}$$

Paul Dirac

particle⇔anti-particle

Majorana neutrino

$$\nu = \bar{\nu}$$

Ettore Majorana

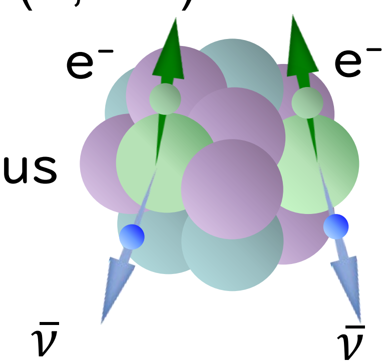
Double beta decay measurement

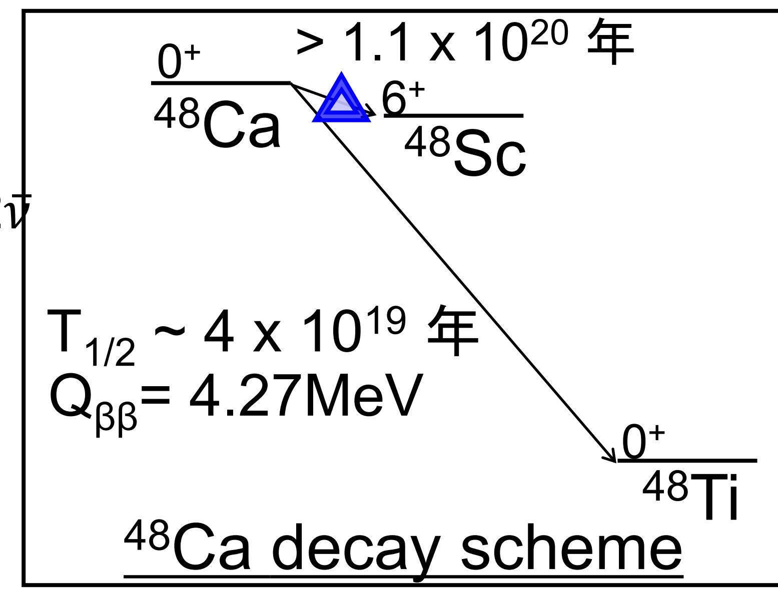
- Double beta decay
  - Decay rate : very rare event
    - 2νββ : half-life $T_{1/2}^{2\nu\beta\beta}$ $10^{18} \sim 10^{21}$ year
    - 0νββ : half-life $T_{1/2}^{0\nu\beta\beta}$ 10^{26} year～
      - $\frac{1}{T_{1/2}^{0\nu\beta\beta}} \propto G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$

Two neutrino double beta decay (2νββ)

(A,Z) → (A,Z+2) + 2e⁻ + 2$\bar{\nu}$

nucleus

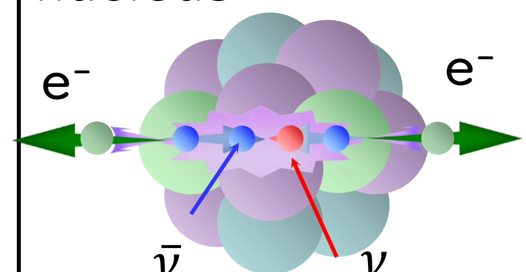




Neutrino-less double beta decay (0νββ)

(A,Z) → (A,Z+2) + 2e⁻

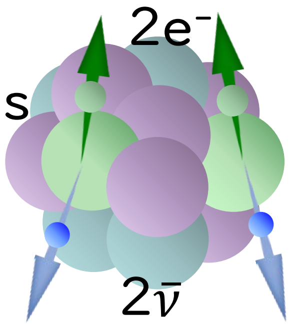
nucleus



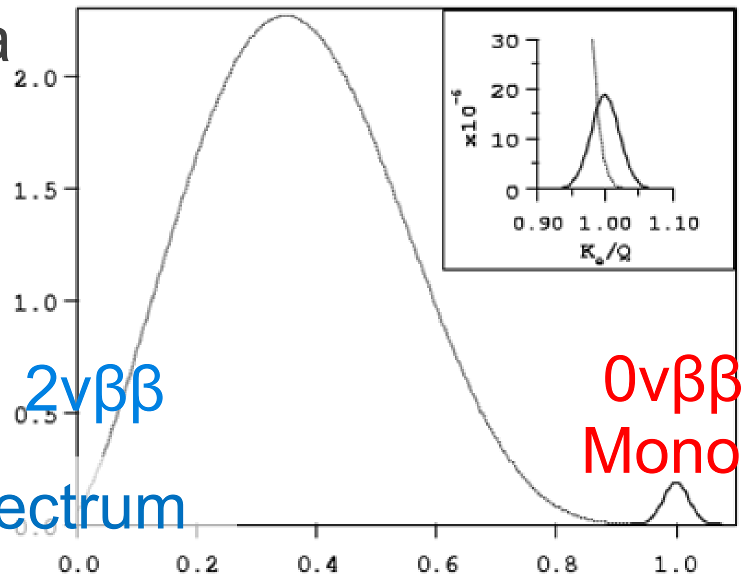
Double beta decay measurement

- Double beta decay measurement : by detection of two beta-rays
- Energy spectra of double beta decays

Sum energy spectra of two electrons

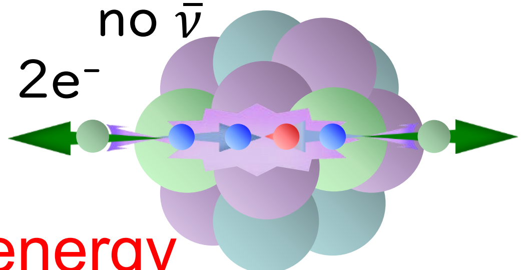


Continuous spectrum



sum energy of $2e^-/ Q_{\beta\beta}$

$0\nu\beta\beta/2\nu\beta\beta = 10^{-6}$
FWHM = 5% @ $Q_{\beta\beta}$



Ref : S.R.Elliot and P.Vogel, Ann. Rev.Nucl.Part.Sci.52(2002)115.

- Main backgrounds : 2νββ and radioactive contamination
  - Good energy resolution to reduce BG from 2νββ
  - High purity materials and Particle identification

Double beta decay

- Neutrino-less double beta decay
  - Key of mystery of the matter dominated universe
  - Majorana nature ($\nu \leftrightarrow \bar{\nu}$)
    - Lepton number non-conservation
  - $T_{1/2}^{0\nu\beta\beta} \propto \frac{1}{<m_\nu>^2}$

	Two neutrino double beta decay	Neutrino-less double beta decay
Sum energy of electron	continuous	Mono energy
Half-life	$10^{18} \sim 10^{21}$ years	10^{26} years～
experiments	Observed	Not observed

- Requirements for measurement

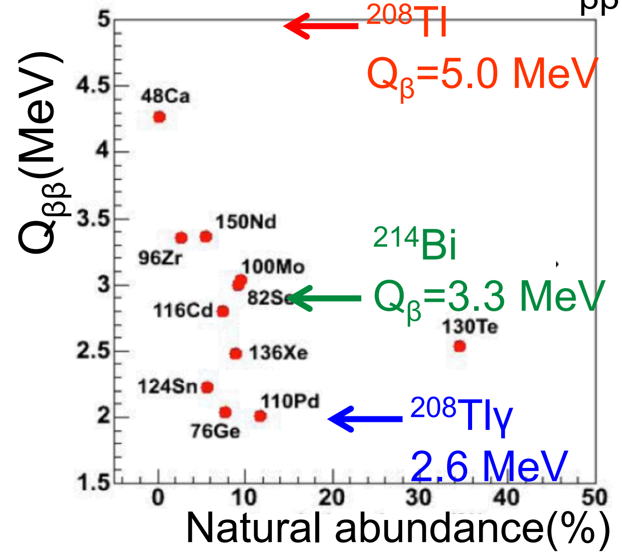
  Long half-life
  →very rare decay, need low background condition,
  To avoid background from 2νββ decay
  →good energy resolution

Double beta decay source

- Large detector scale
  - Need a few 100 kg ~ tonne scale source
    - For >10^{26} years half-life
- Large Isotopic abundance
  - large natural abundance

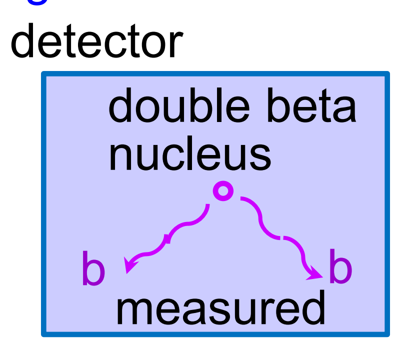
    or isotopic enrichment
- Large detection efficiency
  - Detector types

Natural abundance vs $Q_{\beta\beta}$



Source ⊆ Detector

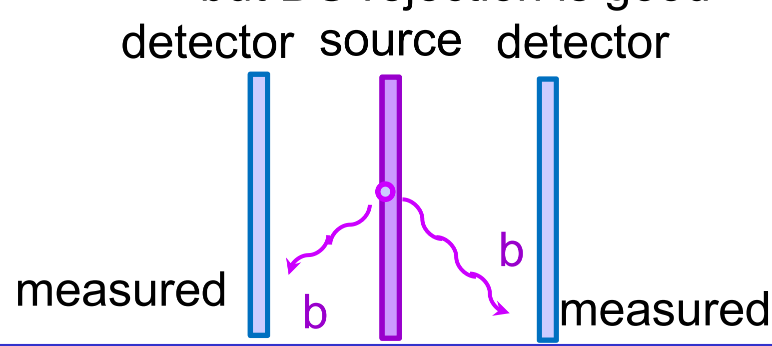
→ large detection efficiency



Source ≠ Detector

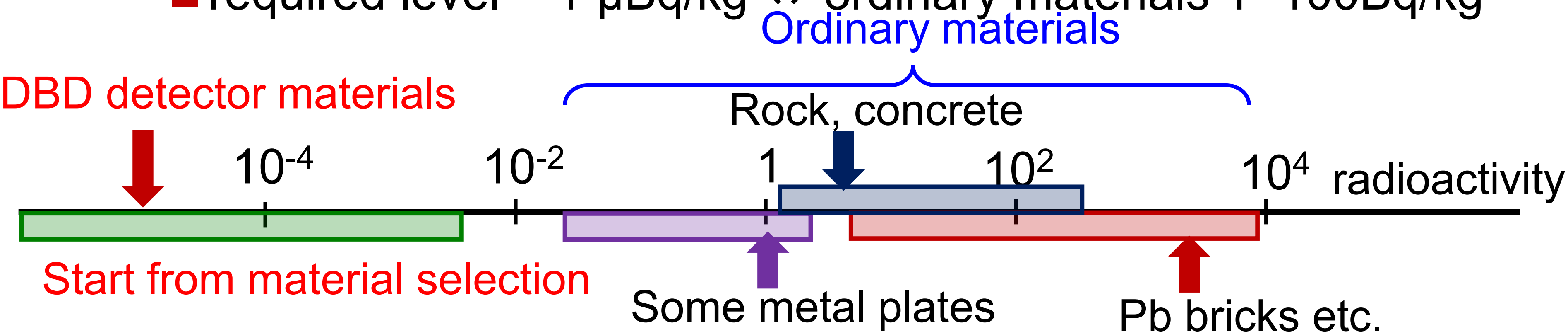
→ small efficiency,

but BG rejection is good

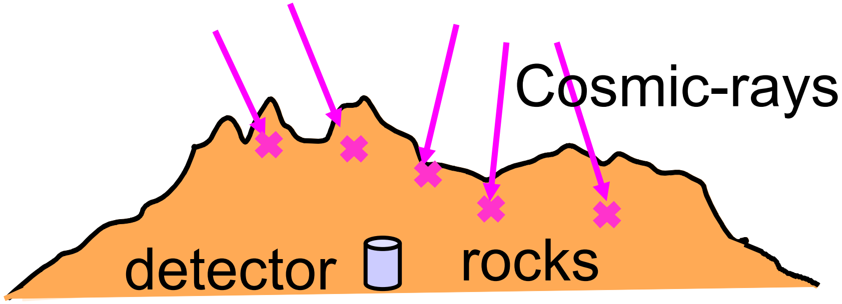


Backgrounds

- Background condition for double beta decay measurements
  - Low natural radioactivity : in U-chain, Th-chain
    - required level ~ 1 μBq/kg ⇔ ordinary materials 1~100Bq/kg



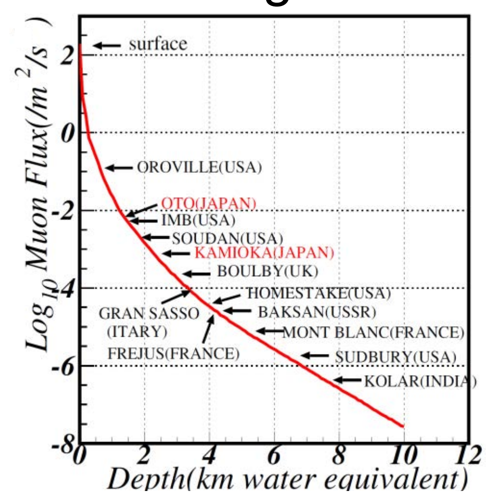
- Cosmic muon, neutrons
  - Underground laboratory



Muon flux : <1/100000 of sea level lab.

Neutron flux (thermal~fast) : < 100

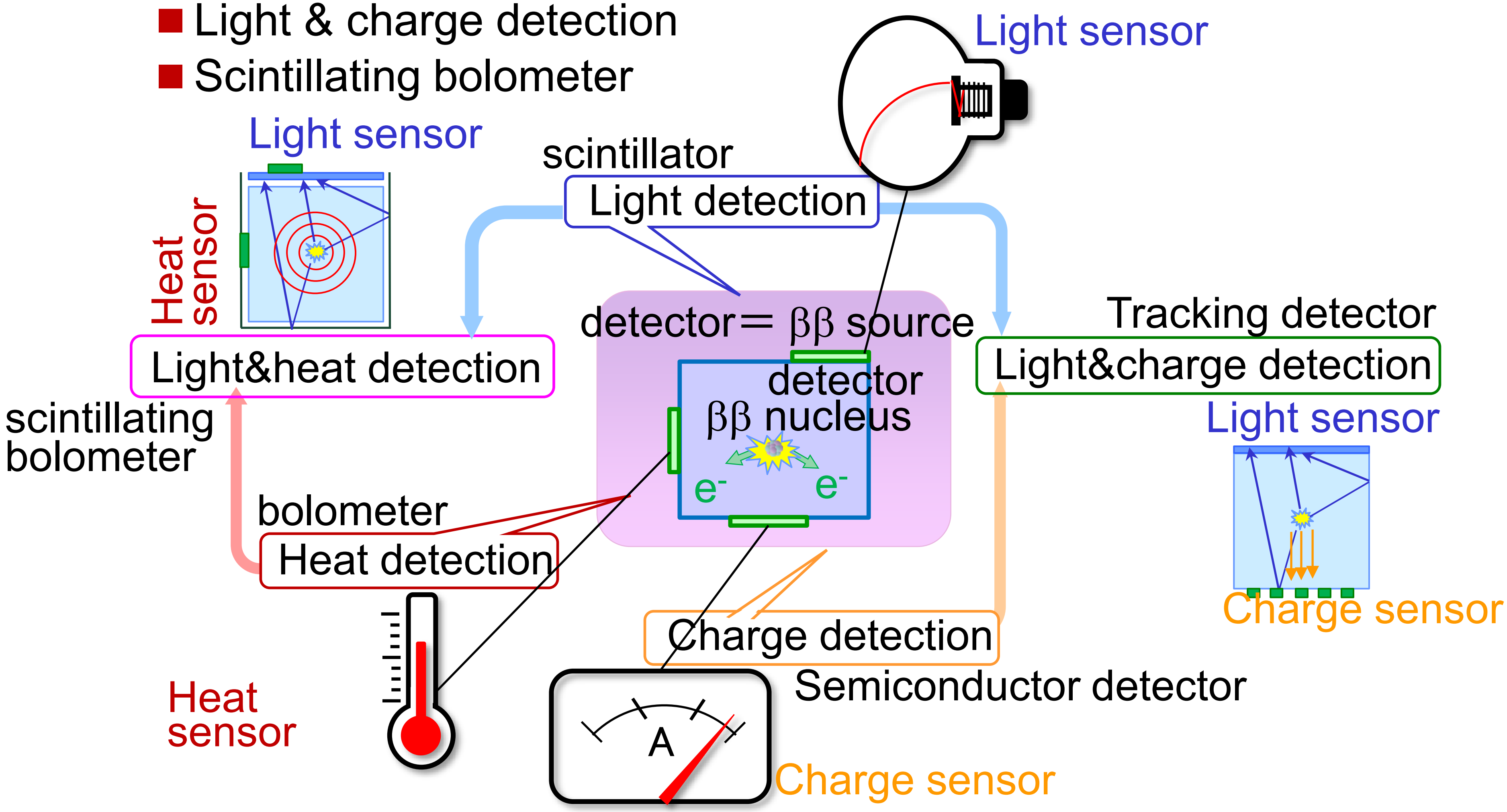
Muon flux in underground Labs



Ref : Data from Phys Rep 187(2000)203

Detector technology

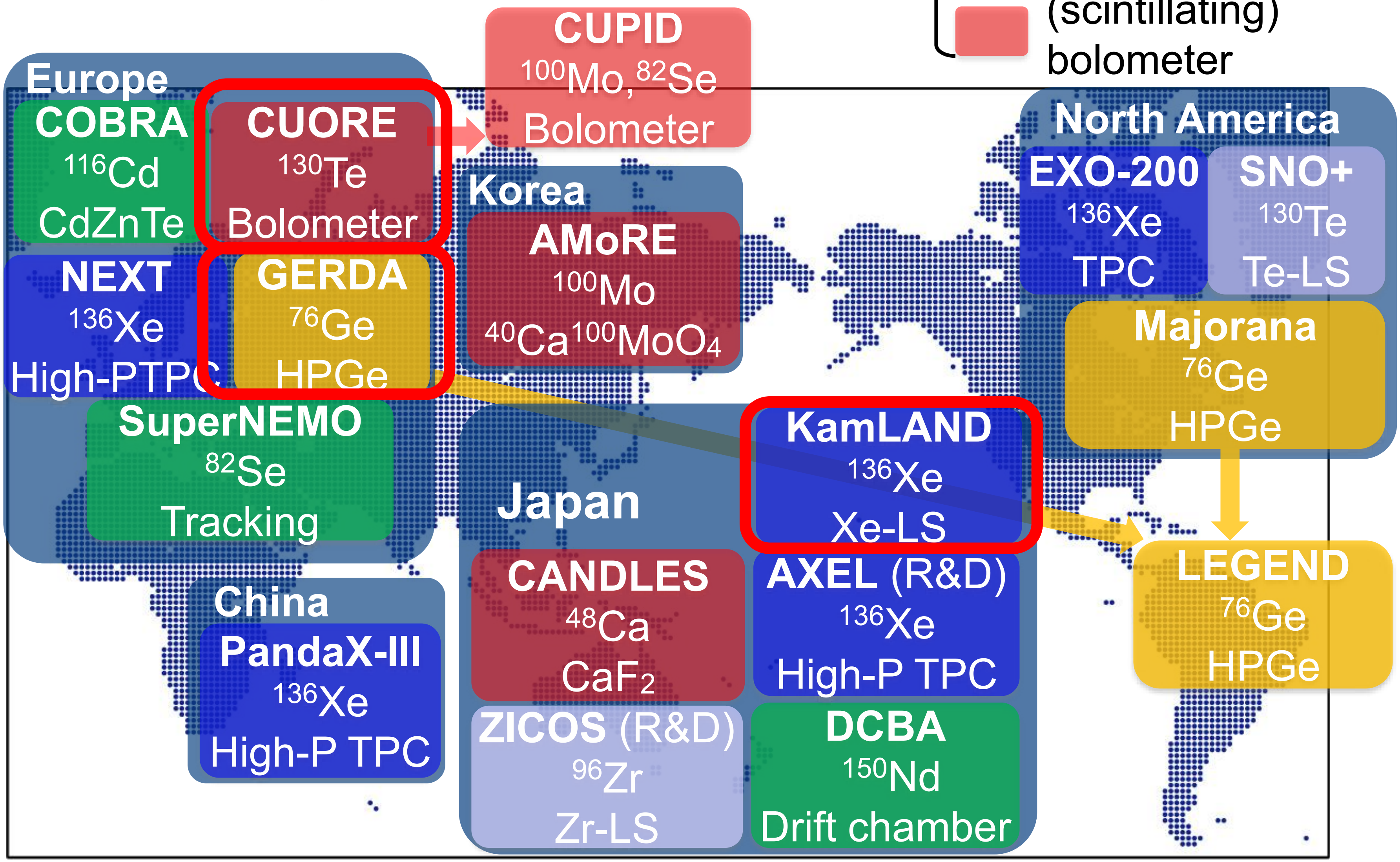
- Technology
  - legacy technique : scintillator, semi-conductor detector, bolometer
  - New technique
    - Light & charge detection
    - Scintillating bolometer



DBD Projects

Fluid type: ^{136}Xe, ^{130}Te, ^{96}Zr

Crystal type: ^{76}Ge, (scintillating) bolometer



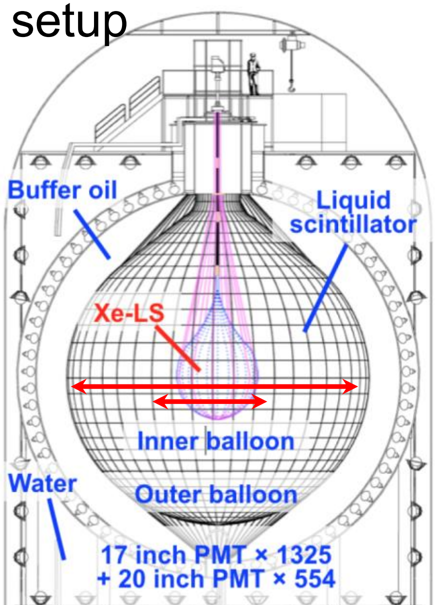
Many projects have been carried out so far and are proposed.

KamLAND, SNO+ etc.

Target nuclei in liquid scintillator

- KamLAND-ZEN
  - Large detector for liquid scintillator
    - 13m liquid scintillator area, 2-3.5m Xe area
  - Large target mass : 350kg(KamLAND-Zen400) → 720kg
  - Energy resolution : 4.5%(σ) @ $Q_{\beta\beta}$
  - Result : $T_{1/2} > 1.07 \times 10^{26}$ year, 60-160meV
  - Backgrounds:$2\nu\beta\beta$, radioactivity in balloon, liquid scintillator

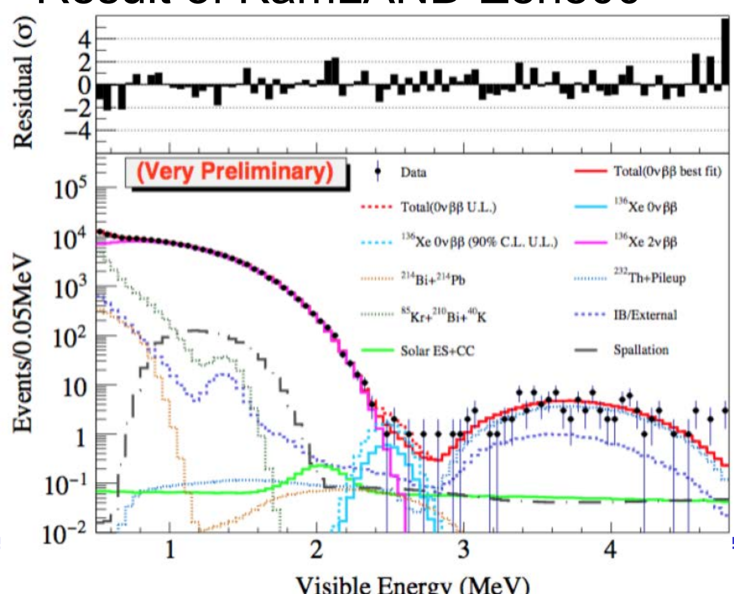
Detector setup



13m
2-3m

Y. Gando et al.,
J. Conf : 1468(2020)012142

Result of KamLAND-Zen800



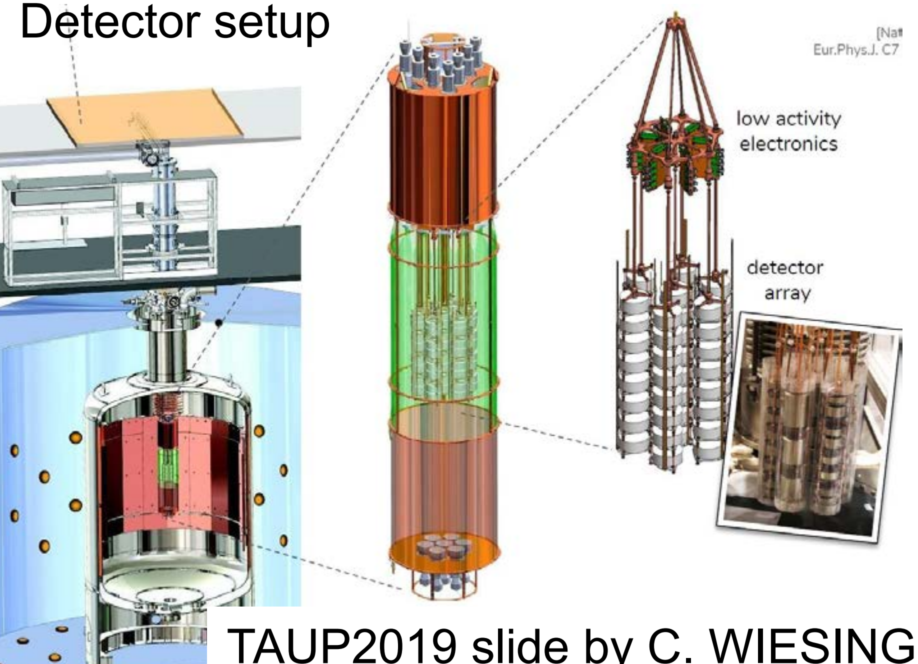
Ge semiconductor detector

GERDA, Majorana, LEGEND

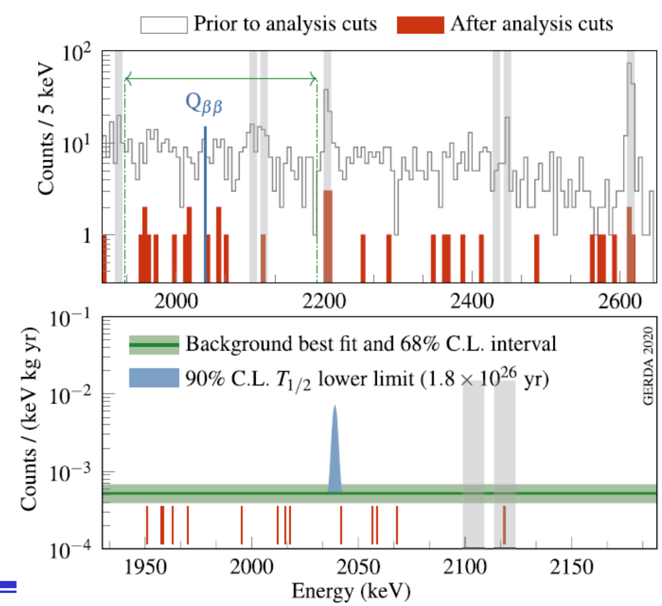
- GERDA
  - Ge detectors immersed in instrumented Liquid Ar
  - Good energy resolution : < 0.2%(FWHM) @ $Q_{\beta\beta}$
    - →low background condition
  - Detector mass: 44.2kg
  - Result : $T_{1/2}$ > 1.8 x 10^{26} year, 79-180 meV
  - Backround : 5.2 x 10^{-4} count/keV/kg/year (lowest)

M. Agostini et al., PRL 125(2020)252502

Detector setup



Result



TAUP2019 slide by C. WIESINGER

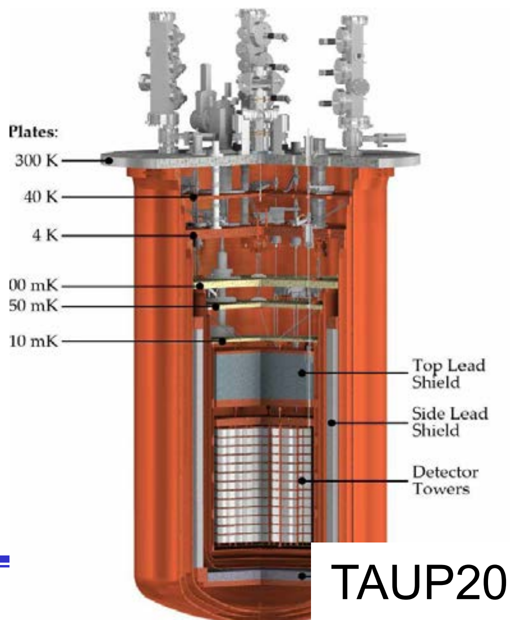
Scintillating bolometer

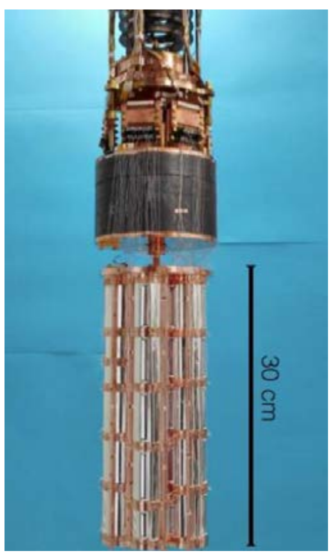
CUORE(bolometer), CUPID, AMoRE, CANDLES etc.

- CUORE(bolometer) → CUPID(scintillating bolometer)
  - energy resolution : 0.3 %(FWHM) @ $Q_{\beta\beta}$
    - low background condition
  - TeO_2 bolometer (not scintillating bolometer)
  - Detector mass: 206kg of ^{130}Te,
  - Result : $T_{1/2} > 3.2 \times 10^{25}$ year, 75-350meV
  - background : 1.49×10^{-2} counts/keV/kg/year

  α-rays and γ-rays from ^{208}Tl(2.6MeV)

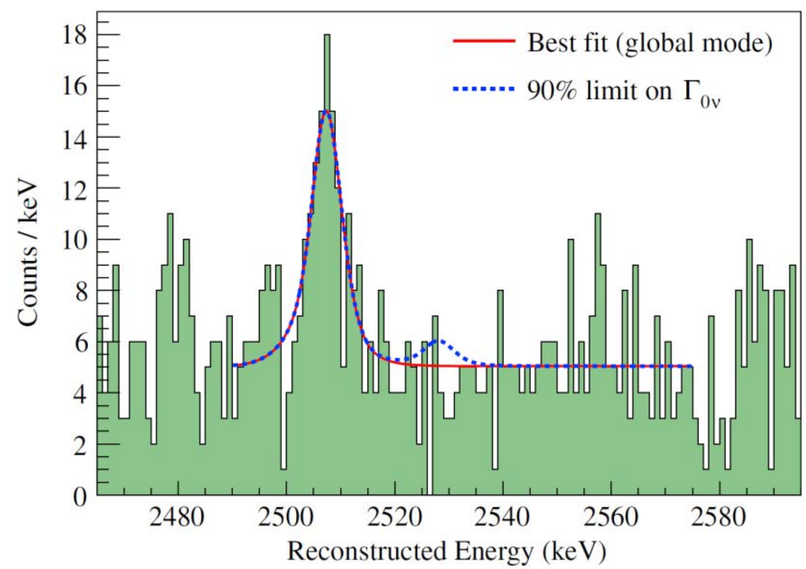
Detector setup





TAUP2019 slide by S. Pozzi

Result

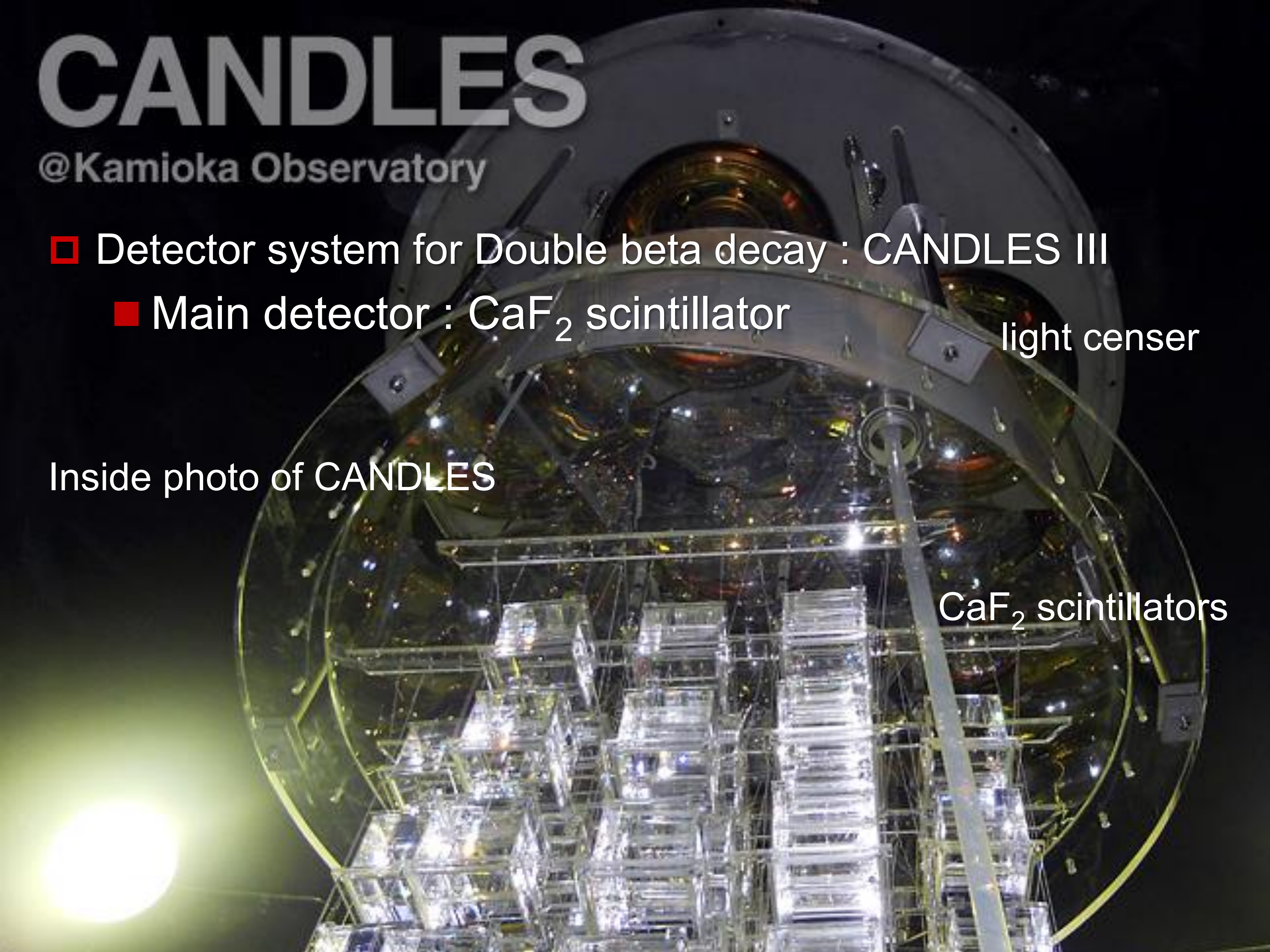


D. Q. Adams et al., PRL 124(2020)122501

CANDLES

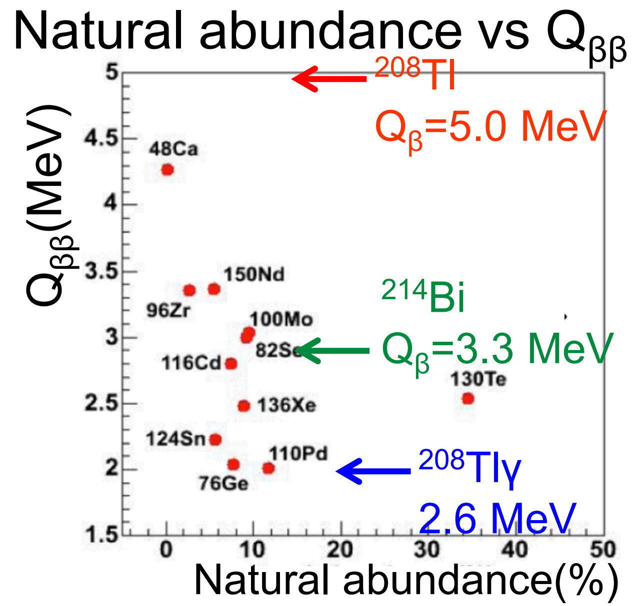
@Kamioka Observatory

- Detector system for Double beta decay : CANDLES III
  - Main detector : CaF_2 scintillator



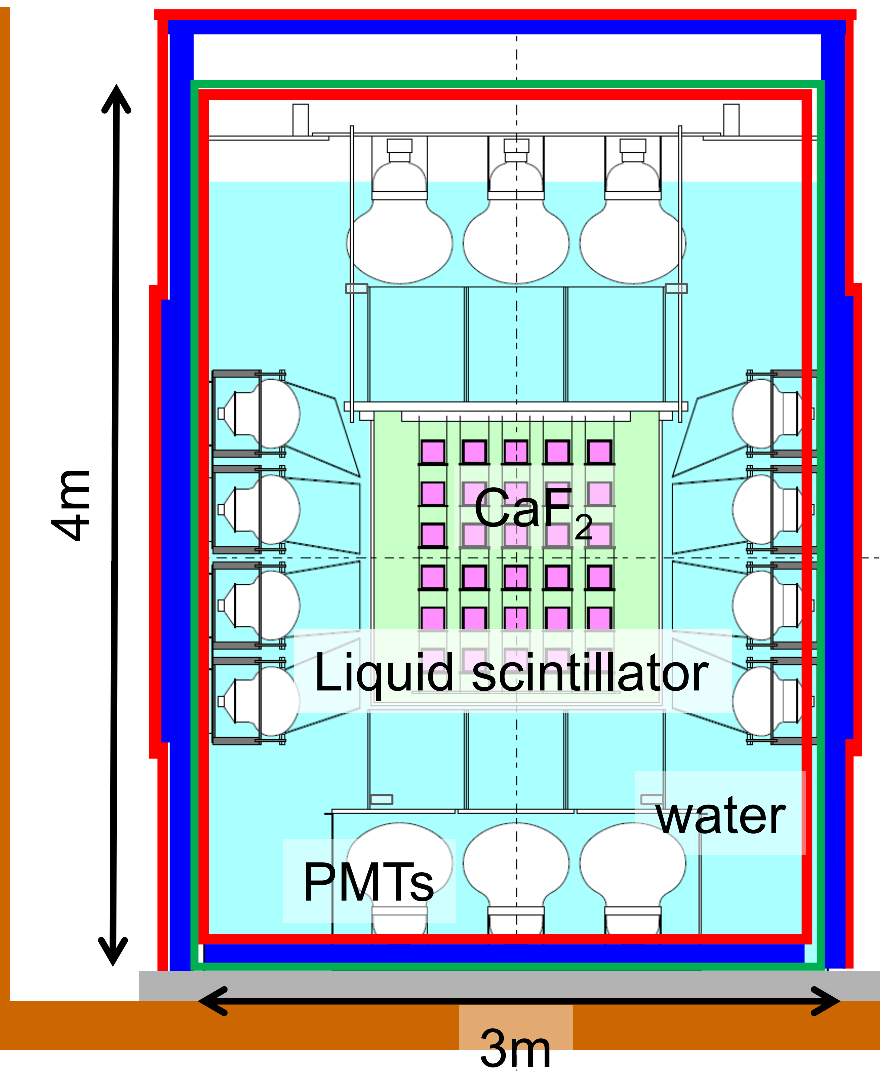
Double beta decay of ^{48}Ca

- Why ^{48}Ca ? : advantage of ^{48}Ca
  - higher $Q_{\beta\beta}$ value (4.27MeV) . . .
    →low background
    because Q $_{\beta\beta}$ value is higher than BG
    E_{max}=2.6MeV(^{208}Tl, γ-ray)
    3.3MeV(^{214}Bi,β-ray)
  - But small natural abundance 0.19%
- Double beta decay of ^{48}Ca by using CaF_2
  - CANDLES system
    - CANDLES III : current detector system
    - Enrichment + scintillating bolometer : for next system



CANDLES III

Ref : K. Nakajima et al, Astroparticle Phys, 100, (2018), 54-60
Ref : T. Iida et al, Nucl. Inst. Meth. A986, (2021), 164727

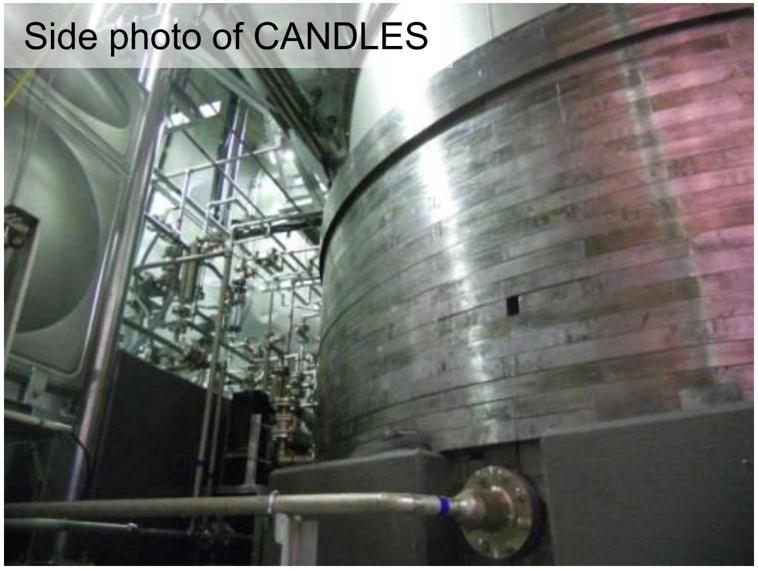


- CaF_2 scintillator (CaF_2 (pure))
  - 305kg (96modules × 3.2kg)
  - ^{48}Ca : 350g
- Liquid scintillator (LS)
  - 4π active shield($2m^3$)
- 62 Large photomultiplier tube
- Shielding system
  - Pb : 10-12cm
  - B_4C sheet : 5mm

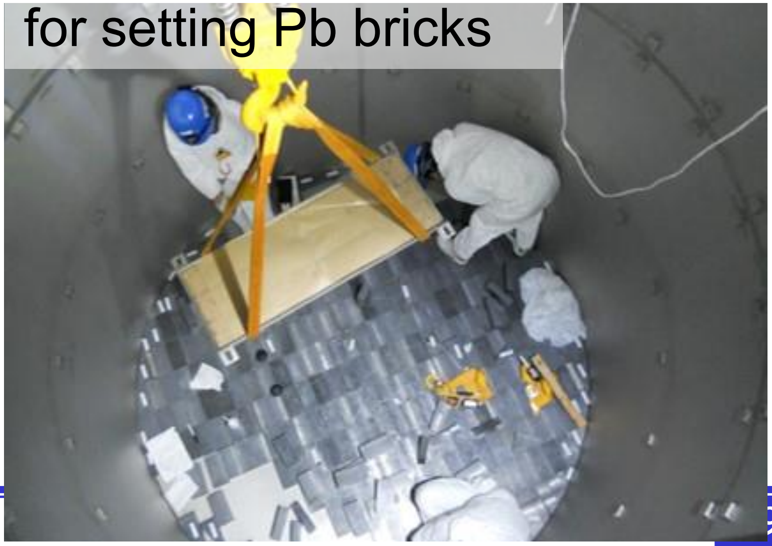
CANDLES tank(stainless steel)
Pb（γ-ray shield）
B sheet（neutron shield）

Detector construction:shielding system

- Shielding system
  - Pb shield, B_4C sheet

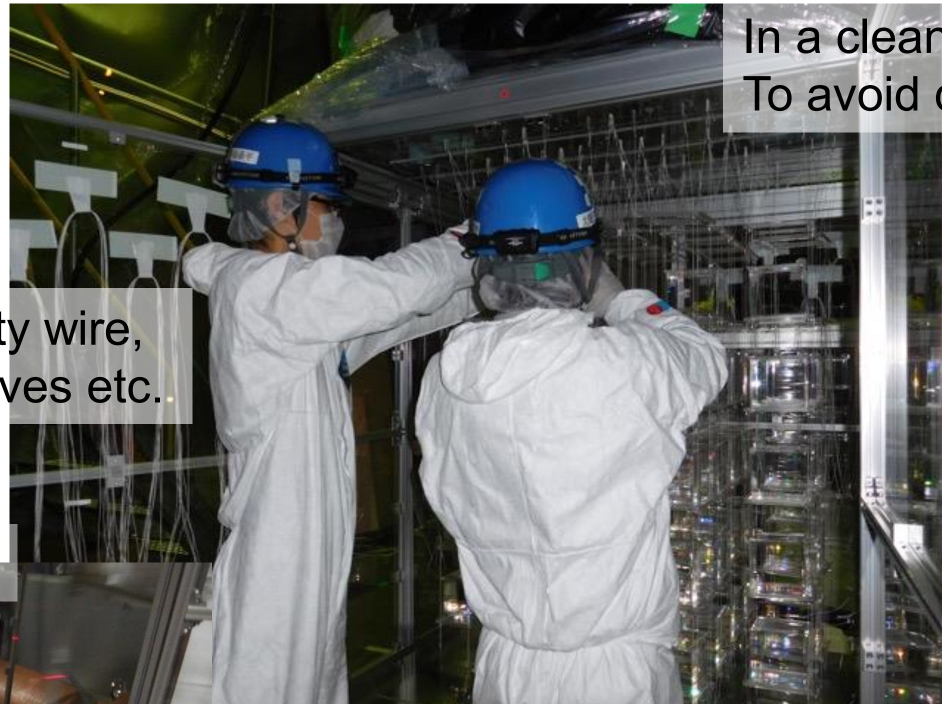


Work in the main tank for setting Pb bricks



Pb total mass : ~50ton

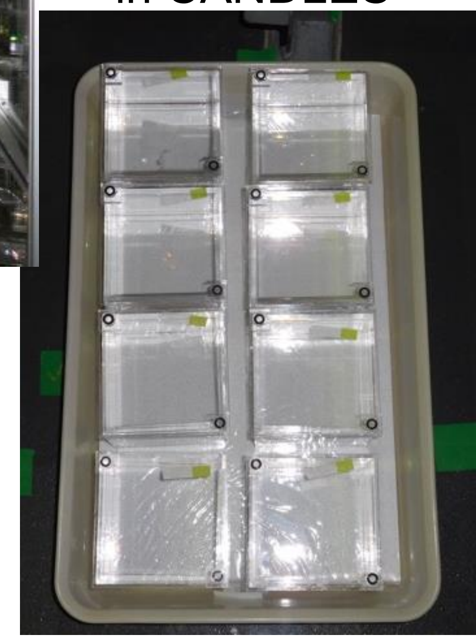
Detector construction : Crystals



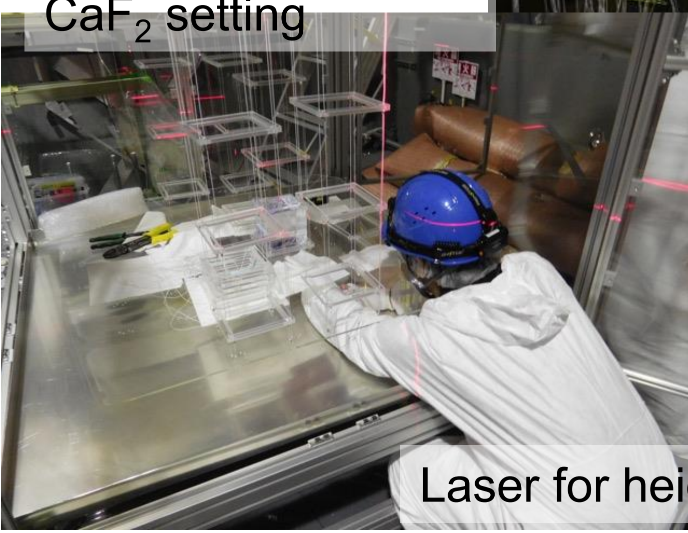
In a clean wear
To avoid dust

By using high purity wire,
acrylic frame, sleeves etc.

CaF_2 modules
Before installation
in CANDLES



CaF_2 setting



Laser for height adjustment for CaF_2

Result

◘ Result of measurement for 130days

Result with 21 high purity CaF_2

	結果
0νββ efficiency	0.36(21CaF_2)
Num. of eve.(exp)	0
Expected BG	1.02
Half life of ^{48}Ca	>5.6 × 10^{22}year
Sensitivity	2.8 × 10^{22}year

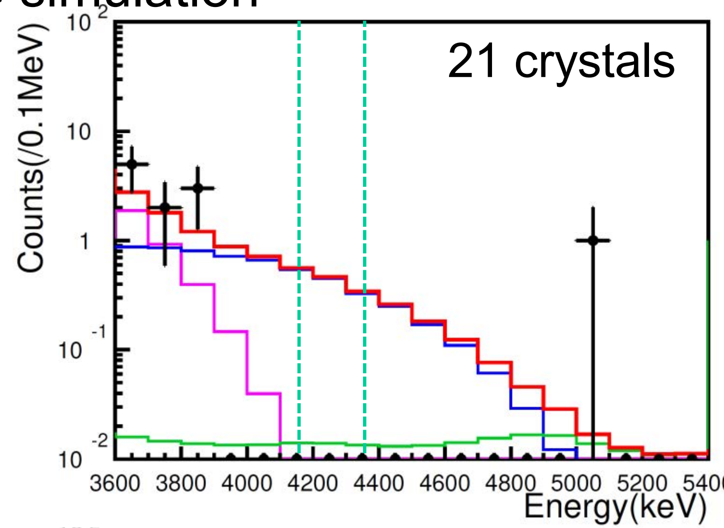
Ref : Phys. Rev. D103, (2021), 092008

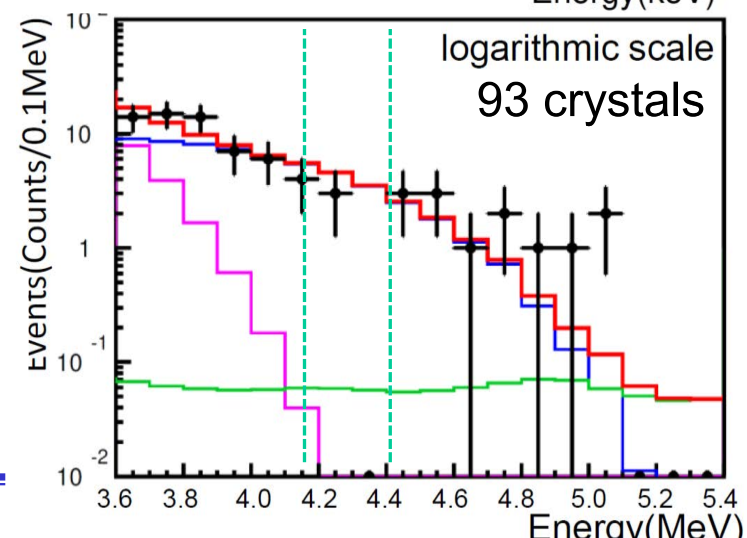
＊comparable to most stringent limit of ^{48}Ca
ELEGANT VI
measurement time : 4947kg・day(2 years <)
half life limit : 5.8×10^{22} year

*Achieved background rate
・< 10^{-3} events/keV/year/(kg of ^{nat}Ca)
・comparable to lowest background measurements

● experimental data
— simulation(total)
— γ-ray from N capture
— contamination in CaF2
— 2νββ

Energy spectrum and BG simulation



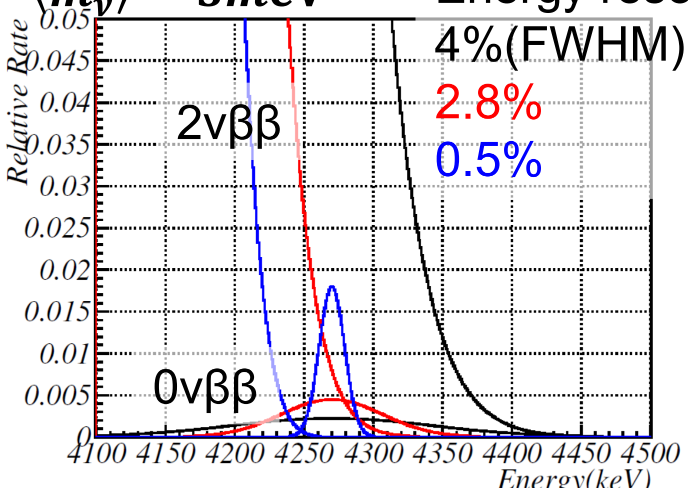


Future CANDLES

- Next step of double beta decay measurement

	CANDLES III	Next detector system
^{48}Ca Abundance	0.187%	50%
^{48}Ca Weight	0.35 kg	600 kg ~
Energy Resolution	6%	1.0% (required)
$\langle m_\nu \rangle$ sensitivity	500meV	~5 meV
Feature	Cooling CaF2 Low BG	Massive ^{48}Ca & high energy resolution IH ⇒ NH

$\langle m_\nu \rangle = 5meV$



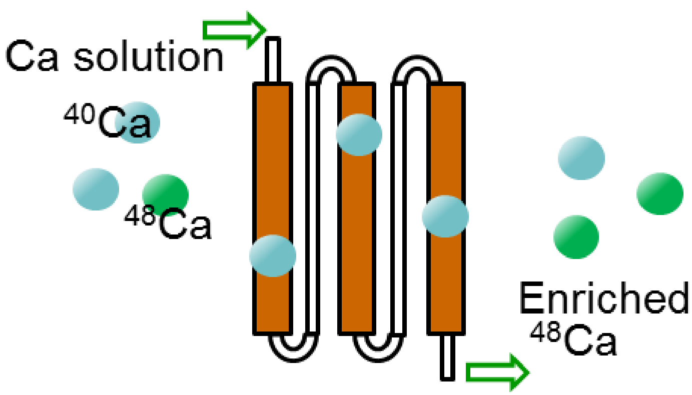
- Large amount of ^{48}Ca
  - Current CANDLES : limited by mass of ^{48}Ca
- Higher energy resolution
  - To reduce 2νββ events

Next detector system：enrichment

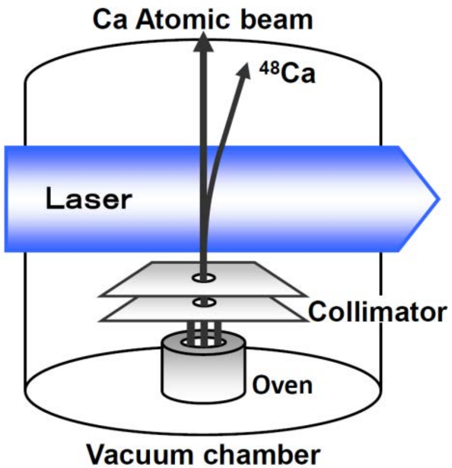
- ^{48}Ca
  - Natural abundance is low：0.19%

  →We can improve the detector sensitivity by enrichment
  - But enrichment of ^{48}Ca is difficult
- New enrichment techniques
  - Crown-ether, laser enrichment, Electrophoresis

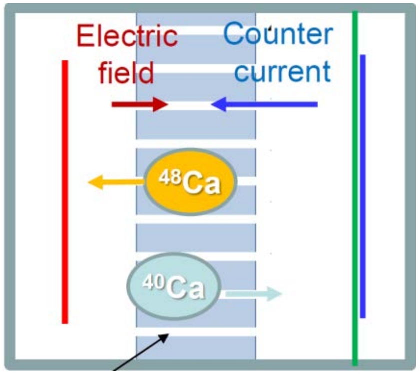
Chemical enrichment by crown-ether



Laser enrichment



Electrophoresis

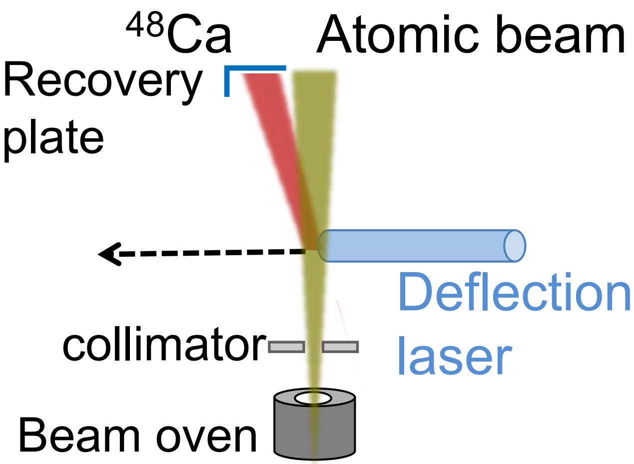


Fukui Univ.: H.Niki, I.Ogawa

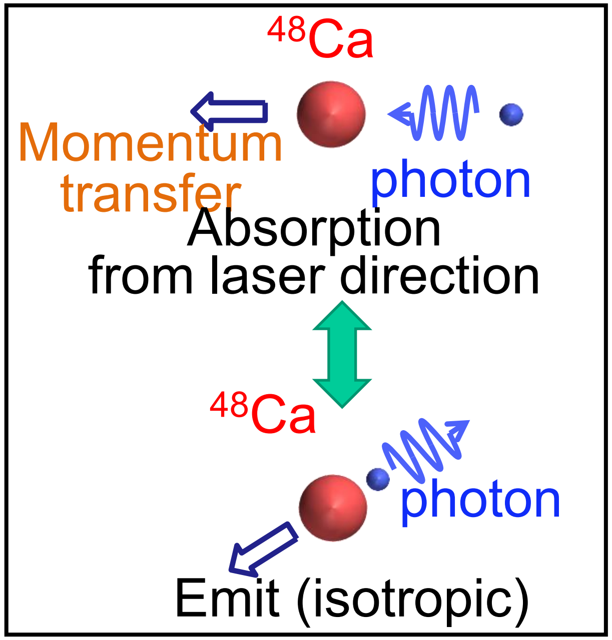
Next detector system：enrichment

- introduction of laser isotopic separation(LIS)

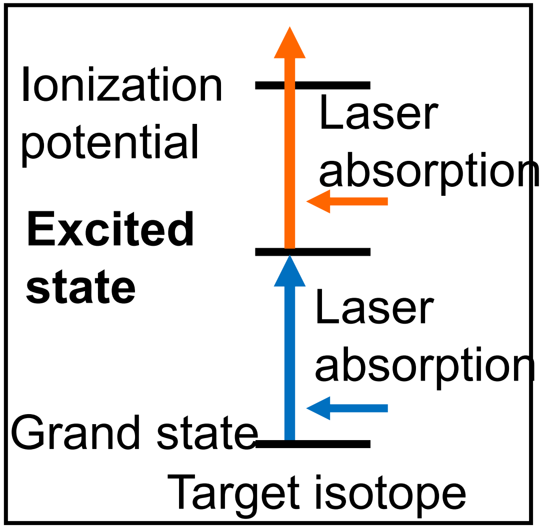
setup



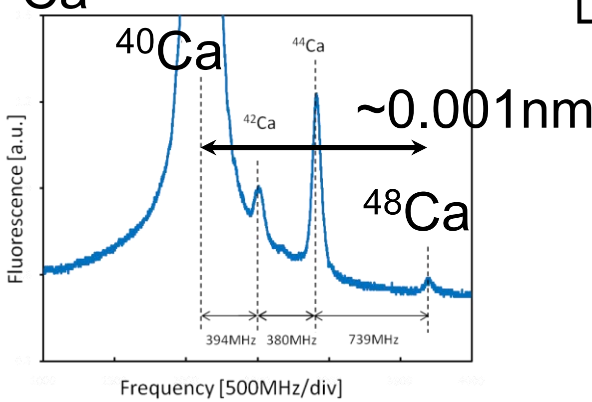
Deflection method



ref：ionization method



absorption wave spectrum for Ca



One laser for enrichment
- for deflection

Repeating excitation/de-excitation

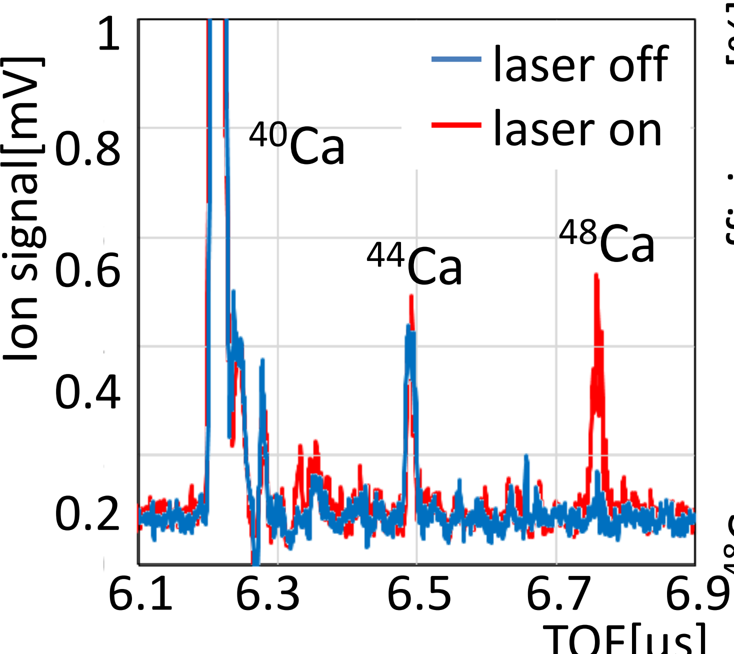
Two laser for enrichment
- for excitation
- for ionization

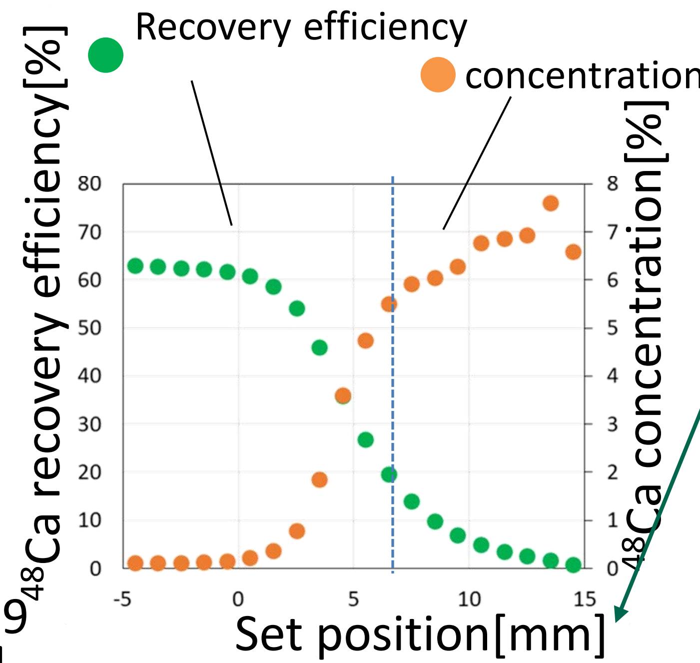
Korea group is also developing

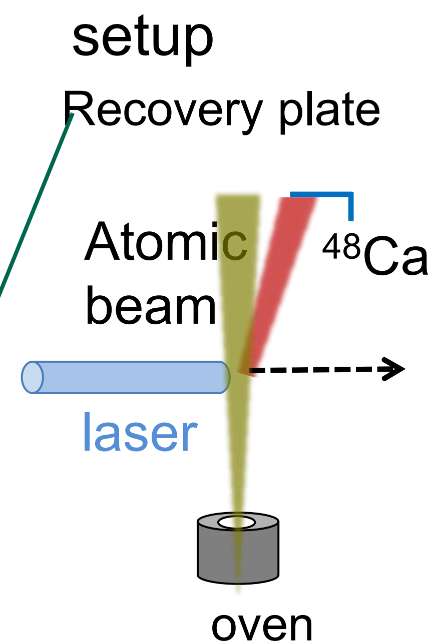
Laser isotope separation

Ref :K. Matsuoka et al, J. of Phys. : Conf. Ser. 1468, (2020), 012199
Ref : Presentation by I. Ogawa in SPLG2021

- Separation effect





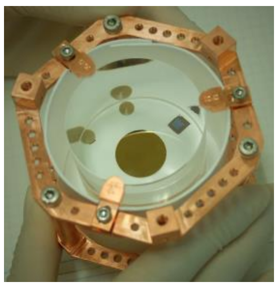


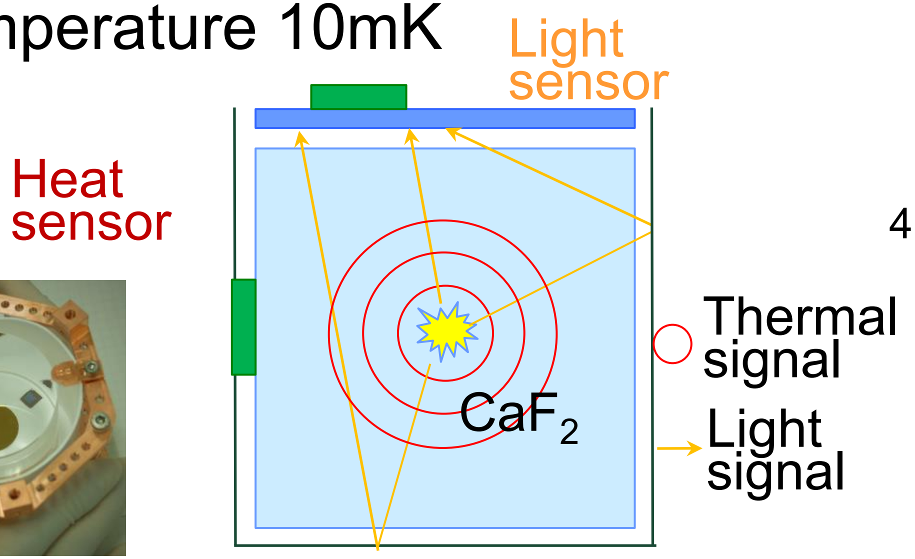
When Recovery plate is set at 6.5mm・・・
Recovery effi. 19.6% concentration 5.5%

- For high-concentration・high-recovery effi.
  - Large deflection
    - optimize irradiation system for deflection laser
    - High intensity blue laser

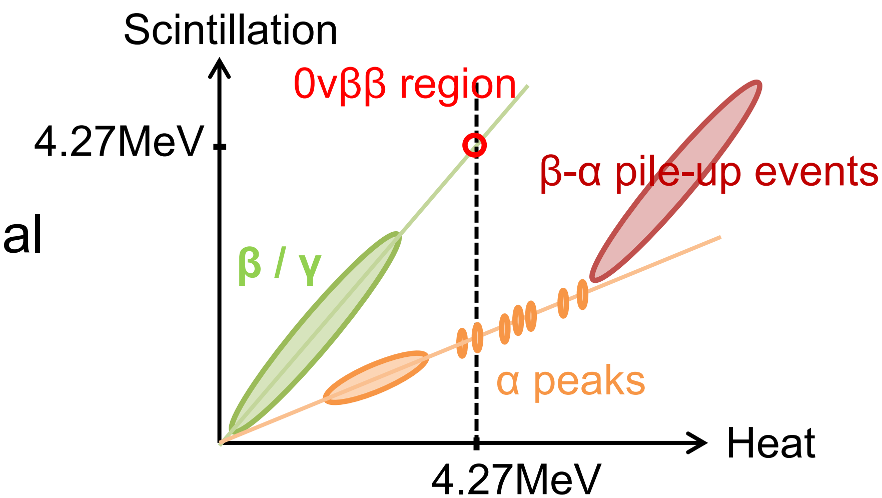
Next detector system：scintillating bolometer

Scintillating bolometer at low temperature 10mK





Particle identification by scintillating bolometer

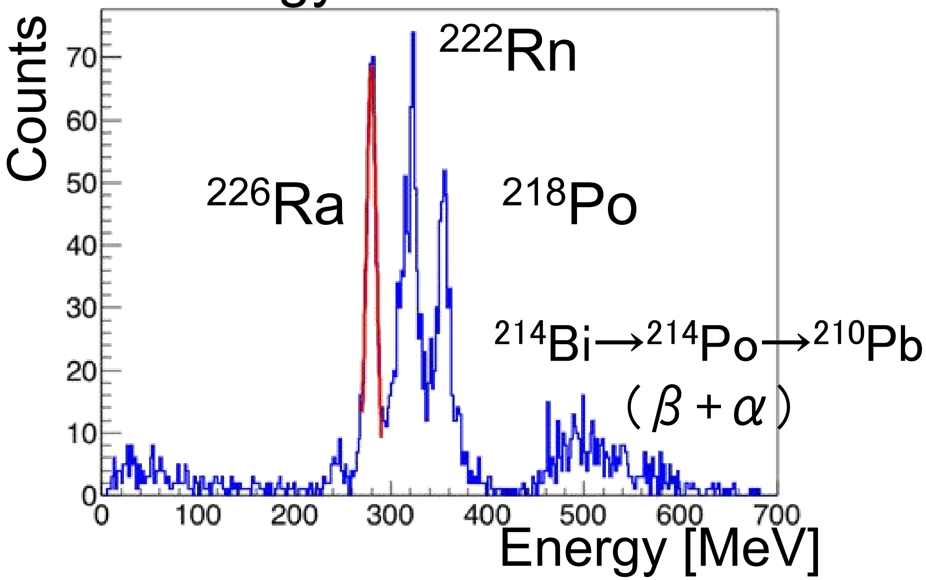


- Expected BG：2νββ events, α-rays
- bolometer：good energy resolution
  - For reduction of BG affects from 2νββ events
- Scintillating bolometer：good PI ability
  - For reduction of BG affects from α-ray

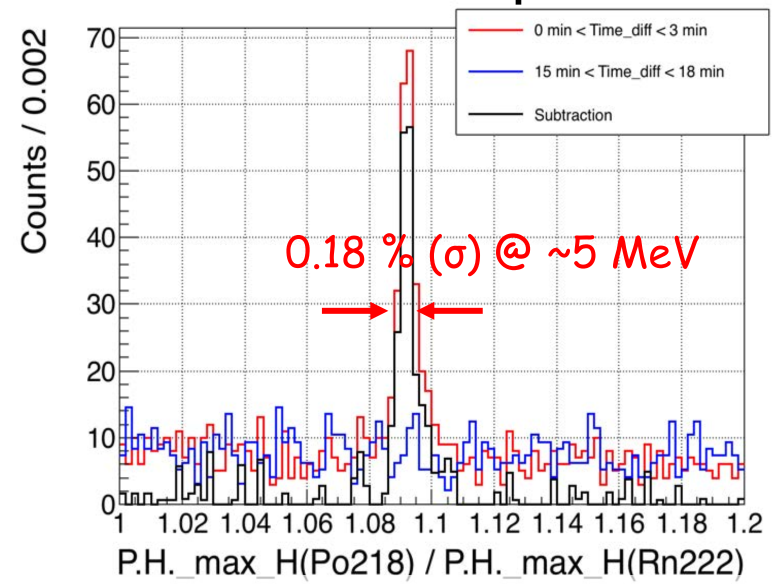
IBS Kim Yong-Hamb
AMoRE sub group
CANDLES sub group

Scintillating bolometer

Energy spectrum of α-events
Energy resolution 1.86%

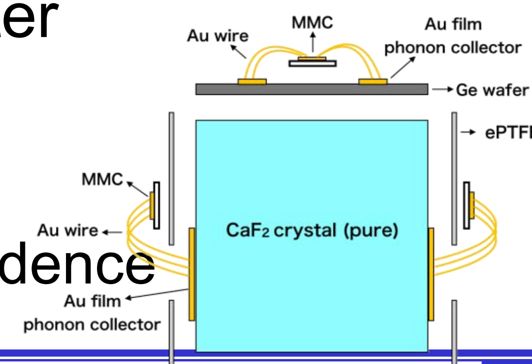


Energy ratio between two events at the same position



^{222}Rn→^{218}Po(3min)→^{214}Pb

- First result of CaF_2(pure) scintillating bolometer
  - Energy resolution(σ): 1.86±0.11%
    - But not best by position dependence
  - Additional sensor for removing position dependence



Ref :K. Tetsuno et al, J. of Phys. : Conf. Ser. 1468(2020)012132

Summary

- Neutrino-less Double beta decay
  - Crucial process for nuclear/particle physics
  - Testing of Majorana nature
  - Very rare decay : half-life > 10^{26} years
    - not observed yet
- Double beta decay measurements
  - Many projects have been carried out and proposed
  - Requirements : low background condition
  - Many techniques are applied
    - Scintillating bolometer, enrichment
  - To observe $0\nu\beta\beta$ with next-generation experiments