地下非加速器実験

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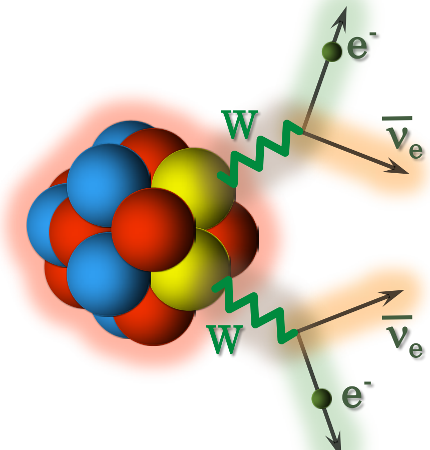
Double beta decay
世界の現状・将来計画

CANDLES実験

Double Beta Decay

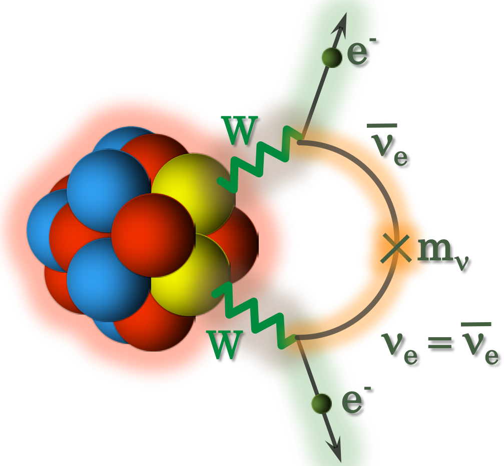
- Two decay modes are usually discussed for ββ decay:

① 2νββ decay : $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$



- allowed by the Standard Model.
- already observed in more than 10 isotopes.
- Lifetimes ; $\tau > 10^{18}$ yr

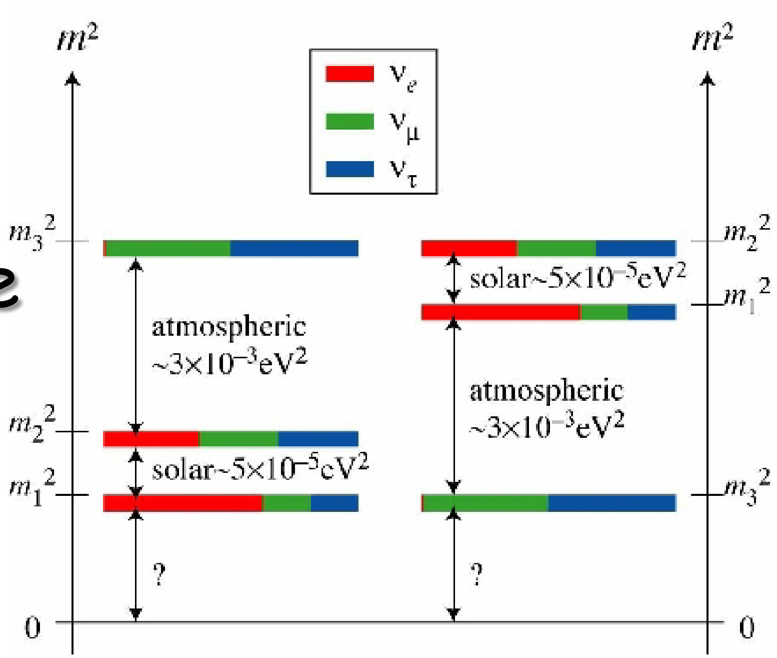
② 0νββ decay : $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- process beyond the Standard Model.
  - Lepton number violation
  - non-zero neutrino mass
  - **Majorana particle**
- not observed yet, except for the KKDC claim.
- predicted lifetimes ; $\tau > 10^{26}$ yr

Physics Implications of 0νββ

- Dirac or Majorana particle
  - 0νββ discovery ➔ Majorana
    - only practical technique to investigate the Majorana nature of ν
  - ΔL ≠ 0 (Lepton number non-conservation) → Leptogenesis ?
    - B-asymmetry in the Universe
  - See-Saw mechanism ?
    - $m_\nu = m_D{}^2/M_R \ll m_D$
- Mass hierarchy/Mass scale
  - Normal or Inverted ?
  - Effective Majorana mass

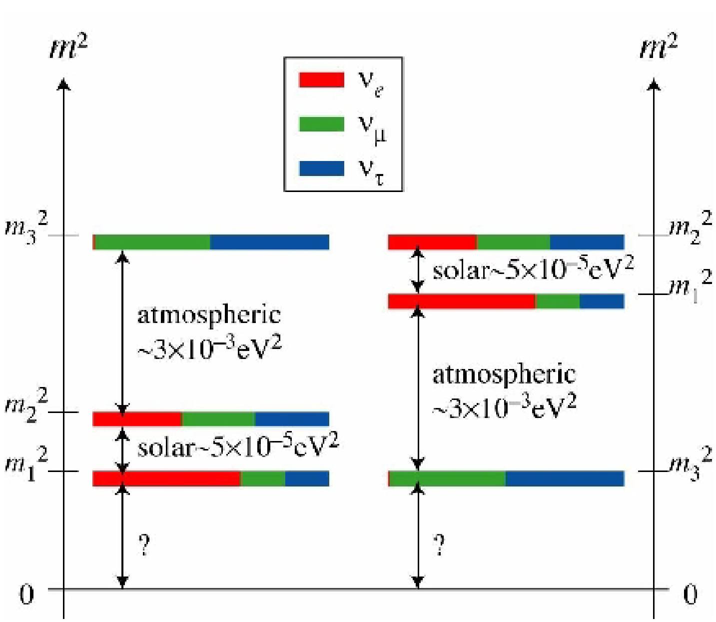


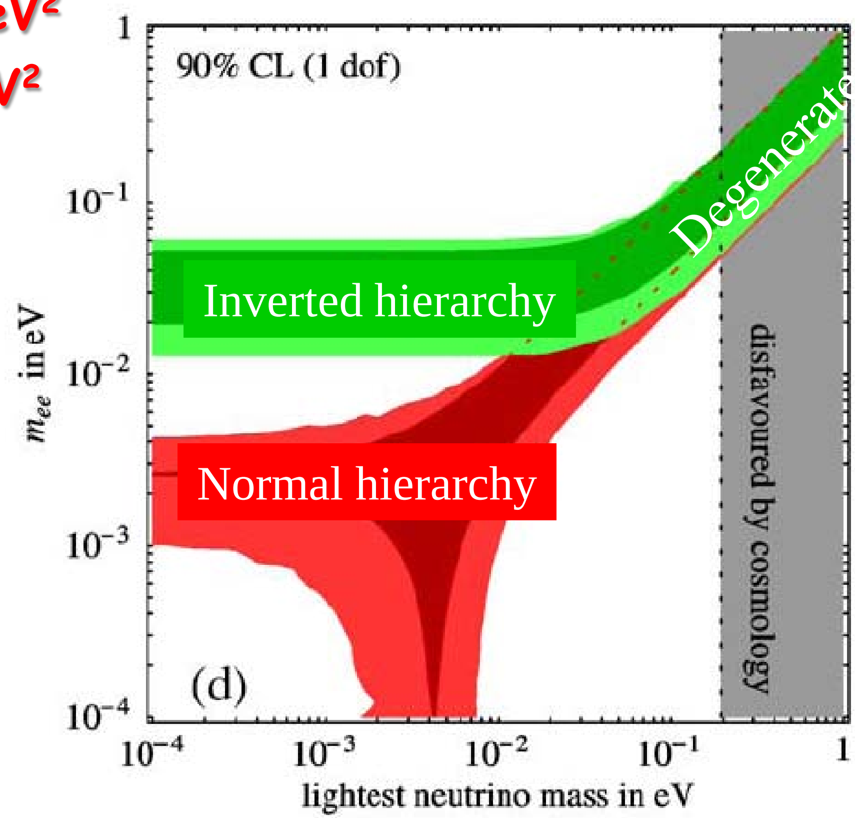
Prediction from Neutrino Osillations

$$|\langle m_\nu \rangle| = |\sum U_{e_i}^2 m_i| = |\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}|$$

$\Delta m^2_{atm} = \Delta m^2_{31} = (2.3 \pm 0.2)\ 10^{-3}\ eV^2$

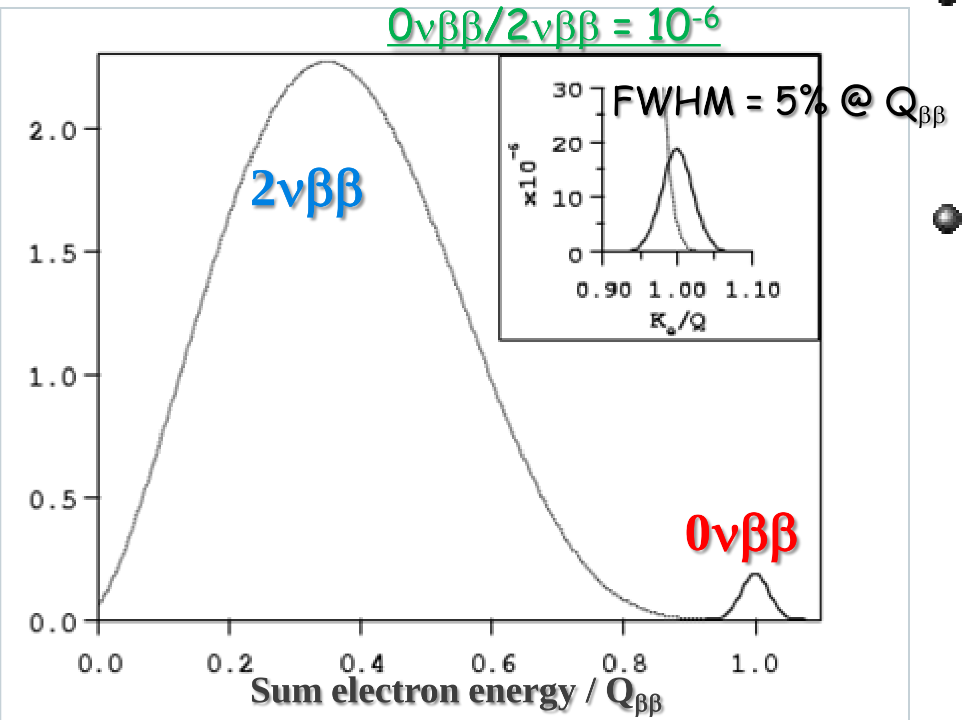
$\Delta m^2_{sol} = \Delta m^2_{12} = (7.9 \pm 0.3)\ 10^{-5}\ eV^2$





- (Next generation) $0\nu\beta\beta$ decay experiment;
  ➔ sensitivity target ~ a few tens meV.

Signature of 0νββ



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

- 0νββ decay ;
  - **peak at $Q_{\beta\beta}$**
- 2νββ ;
  - **continuum to $Q_{\beta\beta}$ end point**
  - two electrons from vertex
  - production of daughter isotope

The shape of the two electron sum energy spectrum enables to distinguish the two different decay modes. ← Good energy resolution.

Sensitivity of $0\nu\beta\beta$

- Neutrino mass sensitivity ;

$$\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (N_{BG} \cdot \Delta E / M \cdot T_{live})^{1/4}$$

assuming background is increased by $M \cdot T_{live}$ scaling

- $M \cdot T_{live}$: exposure (kg.yr)
  - massive isotope
- N_{BG} : background rate @ $Q_{\beta\beta}$ (events/keV/kg/yr)
  - reduce radioactivity
  - go to underground ← cosmogenic BG
- ΔE : energy resolution (keV)
  - Good energy resolution

Requirements for 0νββ Experiment

- Nuclear sensitivity ➔ large 0νββ decay rate

$$\langle m_\nu \rangle \propto T_{0\nu}^{-1/2} \propto (N_{BG} \cdot \Delta E / M \cdot T_{live})^{1/4}$$

- Large mass
  - Natural abundance/Isotopic enrichment
- Low background
  - Radiopurity for source, detector materials
  - Large $Q_{\beta\beta}$ against natural RI
  - Shieldings
  - Underground operation against cosmo-genic
  - Slow 2νββ rate (high energy tail)
- Good energy resolution
  - can separate 0ν/2ν spectra
  - minimize $Q_{\beta\beta}$ analysis-window
- And others for T_{live}...
  - easy to operate (demonstrated technology)

} For Detector

$0\nu\beta\beta$ and Neutrino Mass

- Decay rate (observable quantity) ;

$$T_{0\nu}^{-1} \sim G_{0\nu}(Q_{\beta\beta},Z)\ \ |M_{0\nu}|^2\ \ \langle m_\nu \rangle^2$$

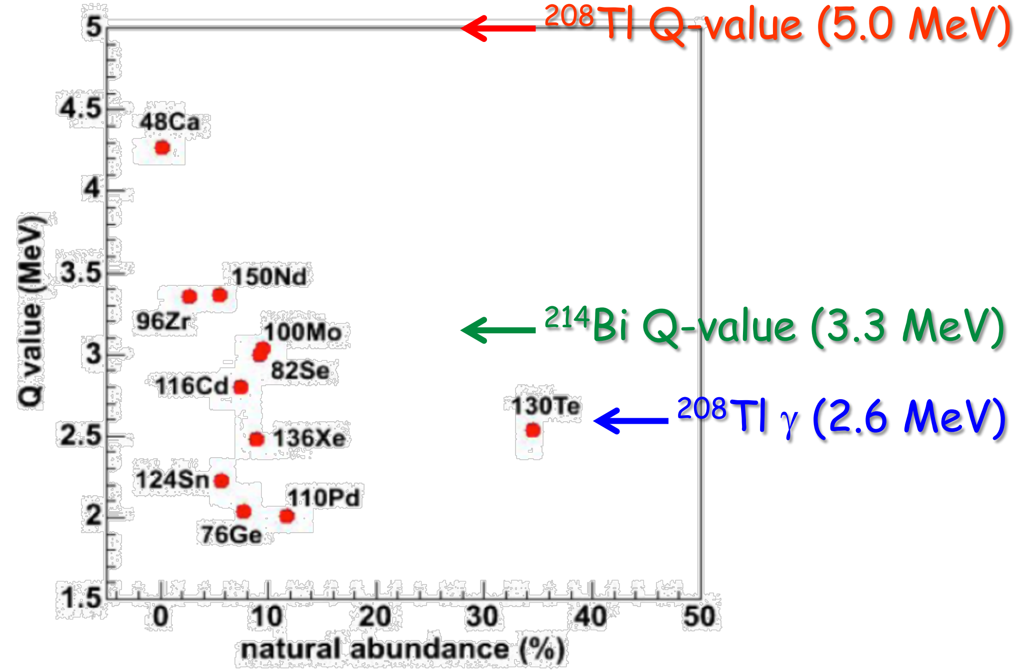
assuming light neutrino exchange **(Mass term)**

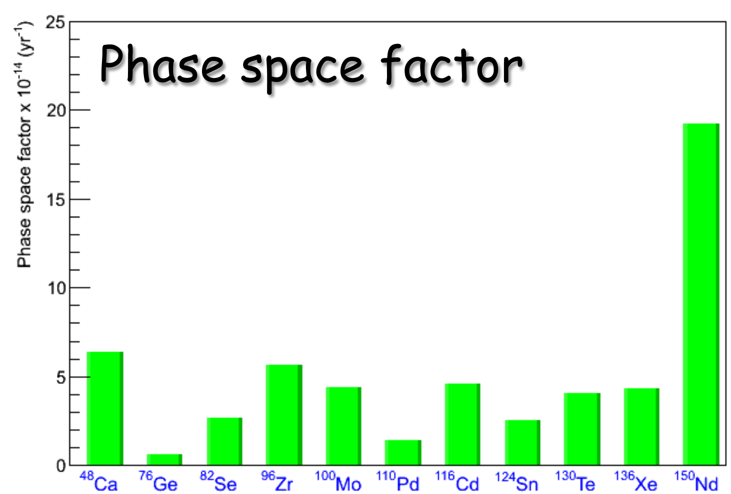
- $G_{0\nu}$: phase-space factor
- $|M_{0\nu}|^2$: Nuclear matrix element
  - only theoretical calcurate with nuclear models
  - Uncertainty ; factor of ~2
- $\langle m_\nu \rangle$: (effective) Majorana mass
  - $\langle m_\nu \rangle = |\sum U_{ei}^2\, m_i|$
  - U_{ei} ; (complex) neutrino mixing matrix

Choice of ββ Isotopes

- Favorable isotopes

Isotopes	Q (MeV)	Abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	2.8
$^{96}Zr \rightarrow ^{96}Mo$	3.350	9.6
$^{100}Mo \rightarrow ^{100}Ru$	3.034	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6





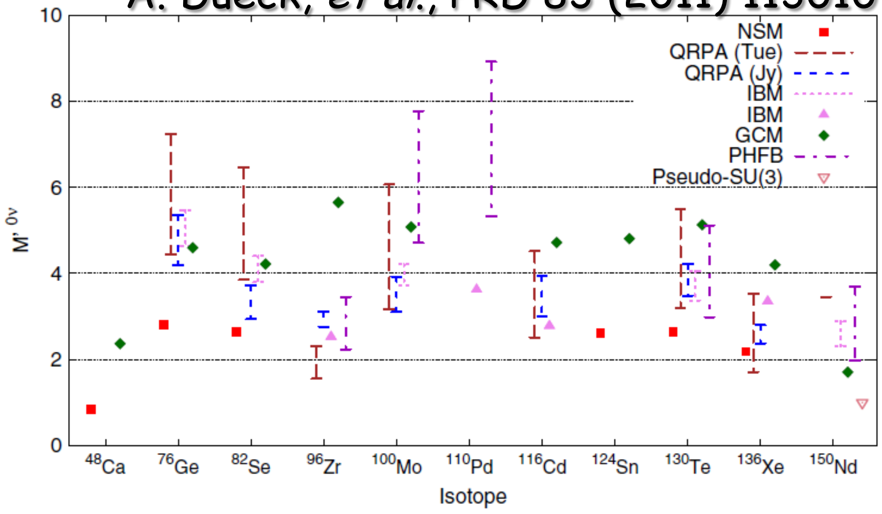
Theoretical Ucertainty

- Nuclear matrix elements
  - only theoretical calcurate with nuclear models
  - Uncertainty ; factor of ~2
  - Model dependent

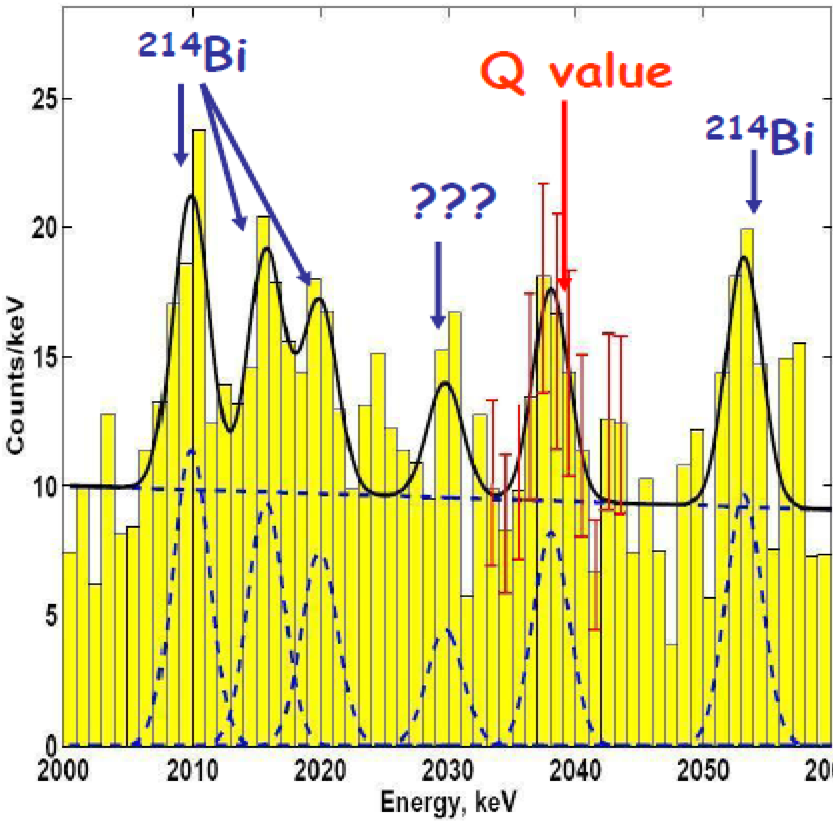
Important to observe $0\nu\beta\beta$ by several Isotopes !

  - Measuring $2\nu\beta\beta$ decay rate → check reliability of calcuration

A. Dueck, *et al.*, PRD 83 (2011) 113010



KKDC Claim



Published by part of collaboration members
H.V.Klapdor-Kleingrothaus, et al.,
Mod. Phys. Lett. A21(2006) 1547

- Heidelberg-Moscow experiment
  - ~ 11 kg of enriched ^{76}Ge
- Fitted by
  - 6 gaussians + linear BG
- Excess events at Q-value
  - 28.75 ± 6.86
- Claimed significance ; 4.2 σ
- Results
  - $T_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{24}$ year
  - $\langle m\nu \rangle = 0.32 \pm 0.03$ eV
- BG candidate
  - For ex. $^{206,207}Pb(n,\gamma)$

This result was a controversial matter

Experimental Projects

- Source = Detector (Calorimetric)

Ionization	GERDA (^{76}Ge) MAJORANA (^{76}Ge) COBRA (^{116}Cd)
Bolometers	CUORE (^{130}Te) LUCIFER (^{82}Se) $ZnMoO_4$ (^{100}Mo) AMoRE (^{100}Mo)
Scintillator	KamLAND-ZEN (^{136}Xe) SNO+ (^{150}Nd) CANDLES (^{48}Ca)
Liquid Xe	EXO (^{136}Xe) XMASS (^{136}Xe)

- Source ≠ Detector (Tracking)

Super-NEMO (^{82}Se) MOON (^{100}Mo)	Tracking + Calorimeter
DCBA(MTD) (^{150}Nd) NEXT (^{136}Xe)	TPC

- Requirements for Detectors
  - Large mass
  - Low background
  - Good energy resolution
  - And others for T_{live}..
  - Various isotopes

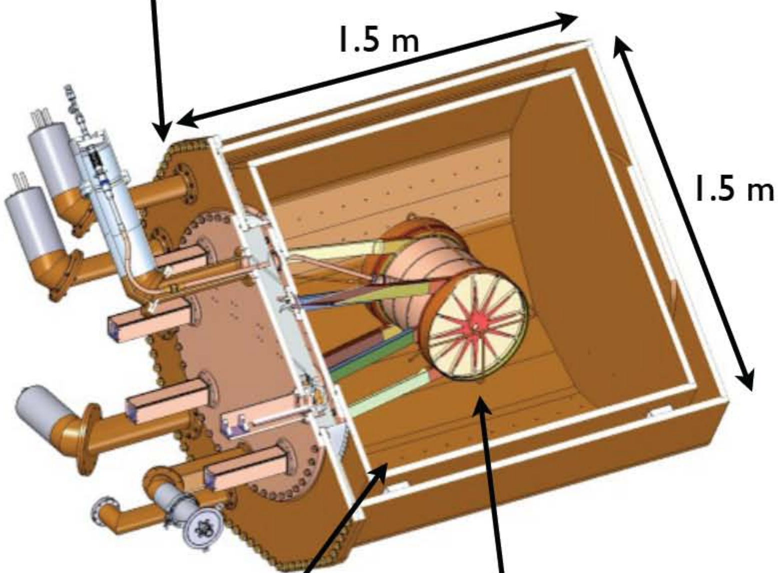
検出器技術が多様化 ➔ とりあえず大雑把に分類

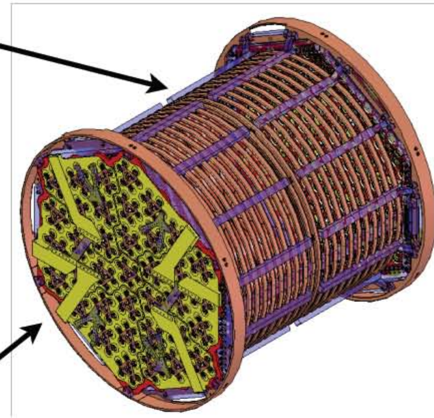
EXO-200

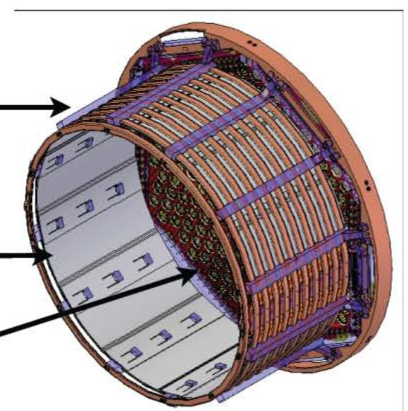
- EXO-200 (first phase)
  - 200 kg enriched ^{136}Xe (80%) ; Liquid TPC
  - Operating (as of early 2011) underground
  - Probe Majorana m_ν ~ 100 meV scale
  - Confirm or refute KKDC result
  - Demonstrate feasibility of ton-scale xenon experiment

- "Full-EXO" (second phase)
  - 1-10 ton-scale enriched 136Xe 0νββ experiment
  - Probe Majorana mv ~ 5-20 meV scale
  - R&D effort for "Ba-tagging" of 0νββ daughter nucleus as a means of radioactive background rejection

EXO-200 cryostat and TPC



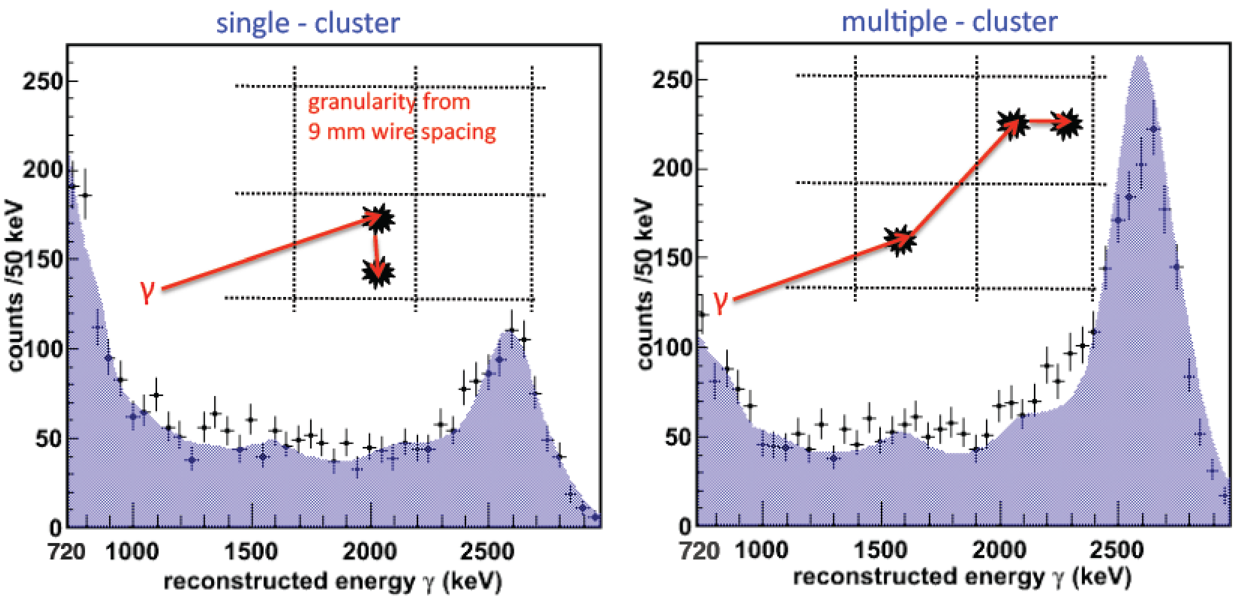




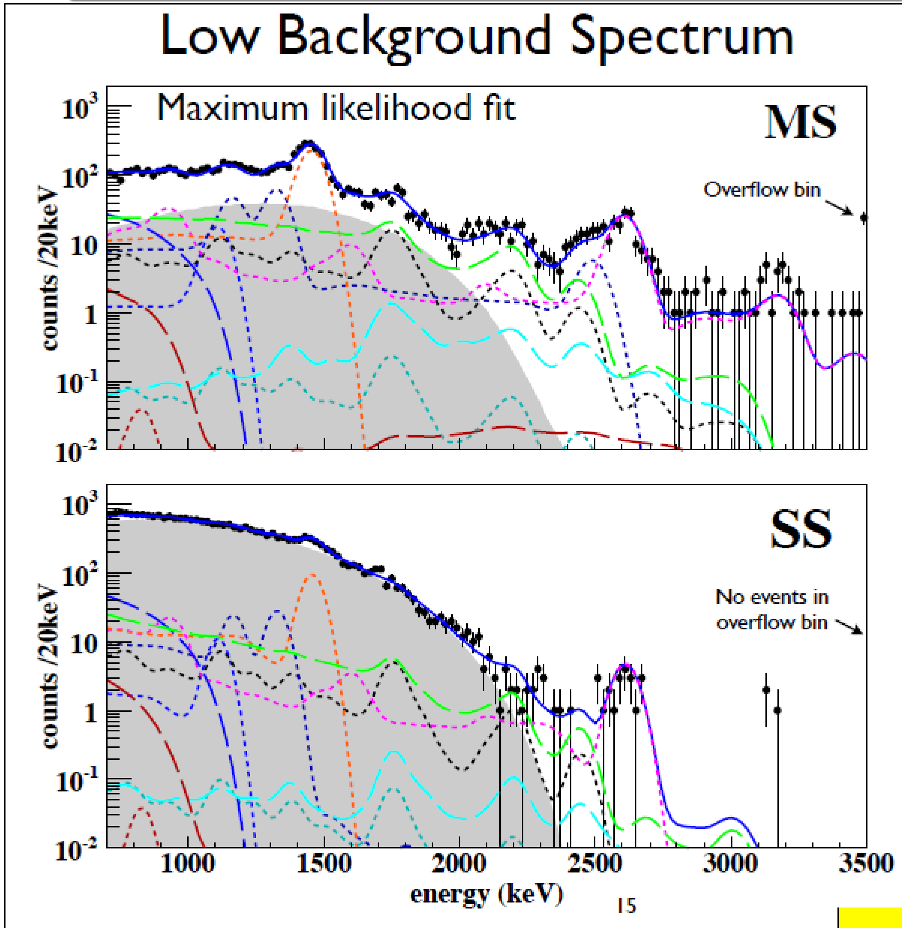
BG Rejection in EXO

- Constructed by radio-pure materials
- Multi-site events reduction

Example: 228Th energy calibration



Recent EXO-200 result



Slide : J.Farine in Neutrino2012

Trigger fully efficient above 700 keV

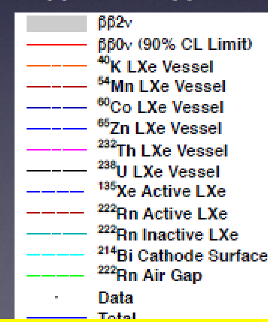
Low background run livetime: **120.7 days**

Active mass: **98.5 kg LXe (79.4 kg ^{136}LXe)**

Exposure **32.5 kg.yr**

Total dead time from vetos: **8.6%**

Various background PDFs fitted along with 2νββ and 0νββ PDFs



$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) = (2.23 ± 0.017 stat ± 0.22 sys)·10^{21} yr

In agreement with previously reported value by

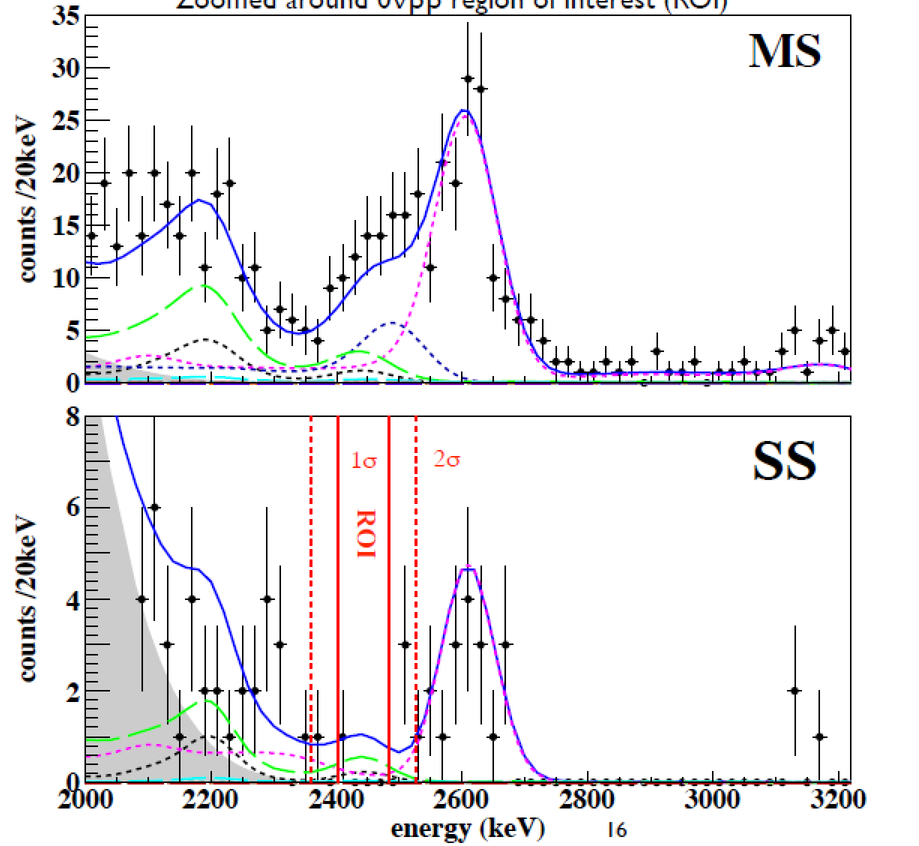
EXO-200 Phys.Rev.Lett. 107 (2011) 212501

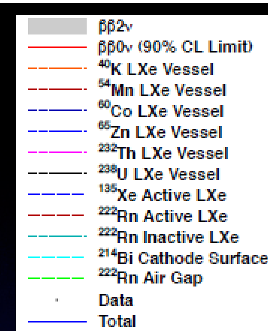
and

KamLAND-ZEN Phys.Rev.C85:045504,2012)

Low Background Spectrum

Zoomed around 0νββ region of interest (ROI)





Constraints:

- SS to MS ratio within ±8.5% of values predicted by MC (set by largest variations in source data)
- other systematic uncertainties

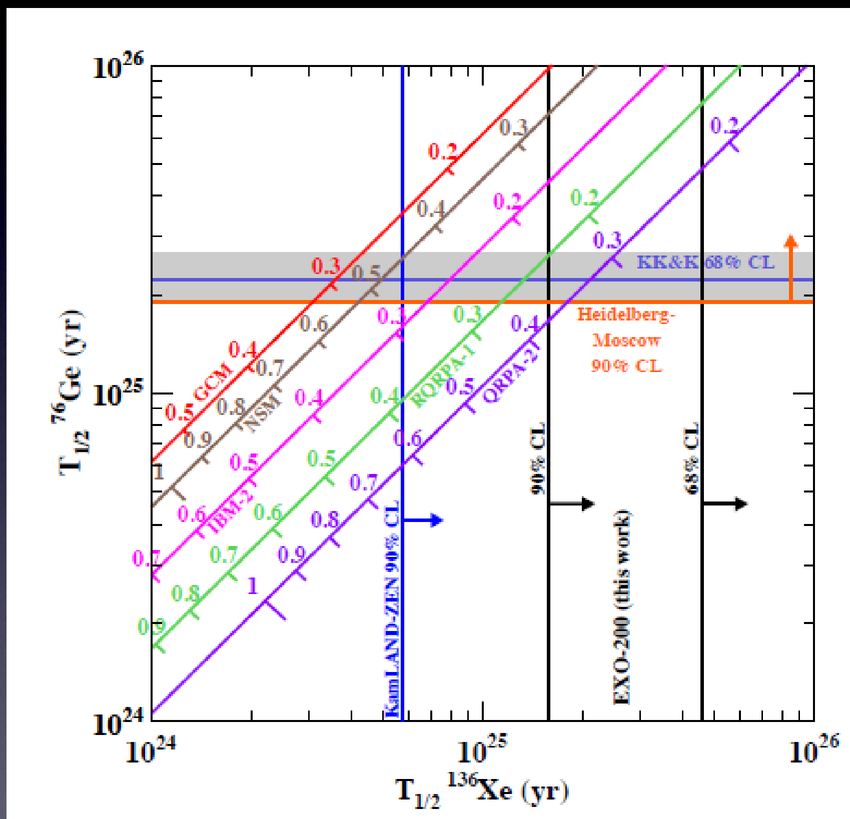
Profile likelihood fit to entire SS and MS spectra to extract limits for $T_{1/2}^{0\nu\beta\beta}$

No 0ν signal observed

EXO-200 result

Slide : J.Farine in Neutrino2012

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$



Interpret as lepton number violating process with effective Marojana mass $\langle m_{\beta\beta} \rangle$:

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M_{nucl}\right|^2 \langle m_{\beta\beta} \rangle^2$$

From profile likelihood:

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr

$\langle m_{\beta\beta} \rangle < 140\text{–}380$ meV

(90% C.L.)

arXiv:1205.5608 – Subm. to PRL

A. Gando et al. Phys. Rev. C 85 (2012) 045504

H.V. Klapdor-Kleingrothaus et.al. Eur. Phys. J. A12 (2001) 147

H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547.

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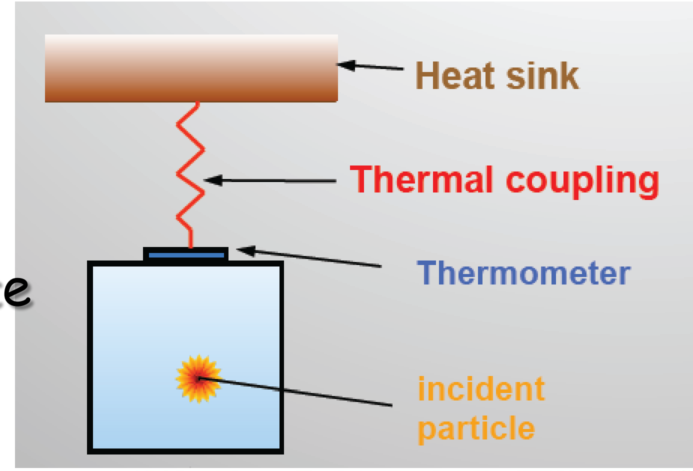
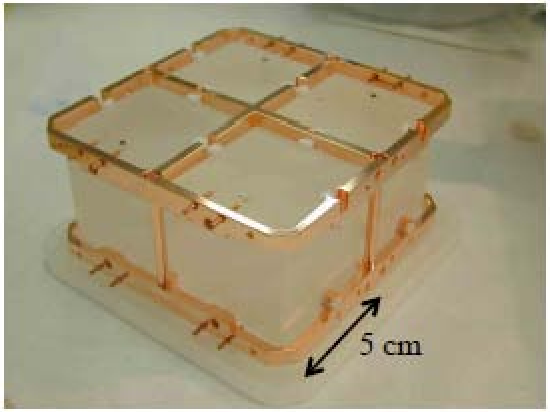
CUORE

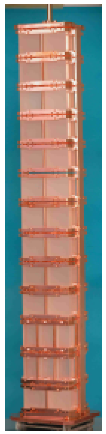
- Crystals of TeO_2 are cooled to ~ 10 mK inside a dilution-refrigerator cryostat.
- Cold crystals have such small heat capacities that single interactions produce measurable rises in temperature
- Temperature pulses are measured by thermistors glued to the crystals
- A pulse's amplitude is proportional to the energy deposited in the crystal
- High natural abundance (~ 34%), so enrichment isn't necessary.
- Good Q-value @ 2528 keV:
  - above natural γ energies
  - large phase space



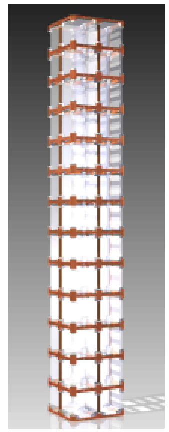


CUORE

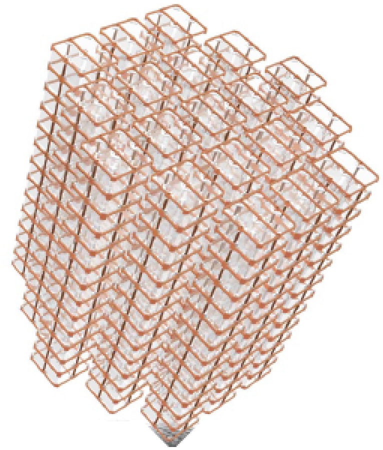
Cuoricino/CUORE program



Cuoricino
2003–2008
11 kg ^{130}Te



CUORE-0
2012–2014
11 kg ^{130}Te



CUORE
2013–2018
206 kg ^{130}Te

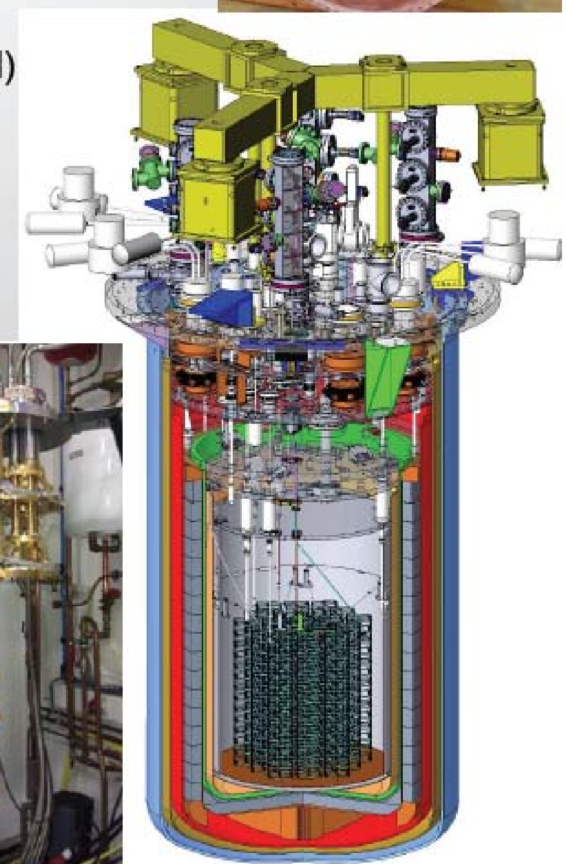
- CUORE: Cryogenic Undergound Observatory for Rare Events
- All cryogenic bolometer experiments searching for $0\nu\beta\beta$ decay in ^{130}Te

	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.05	0.01
E resolution (keV) FWHM @ 2615 keV	7	5–6	5
$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.	300–710	200–500	40–90

CUORE Schedule

CUORE status

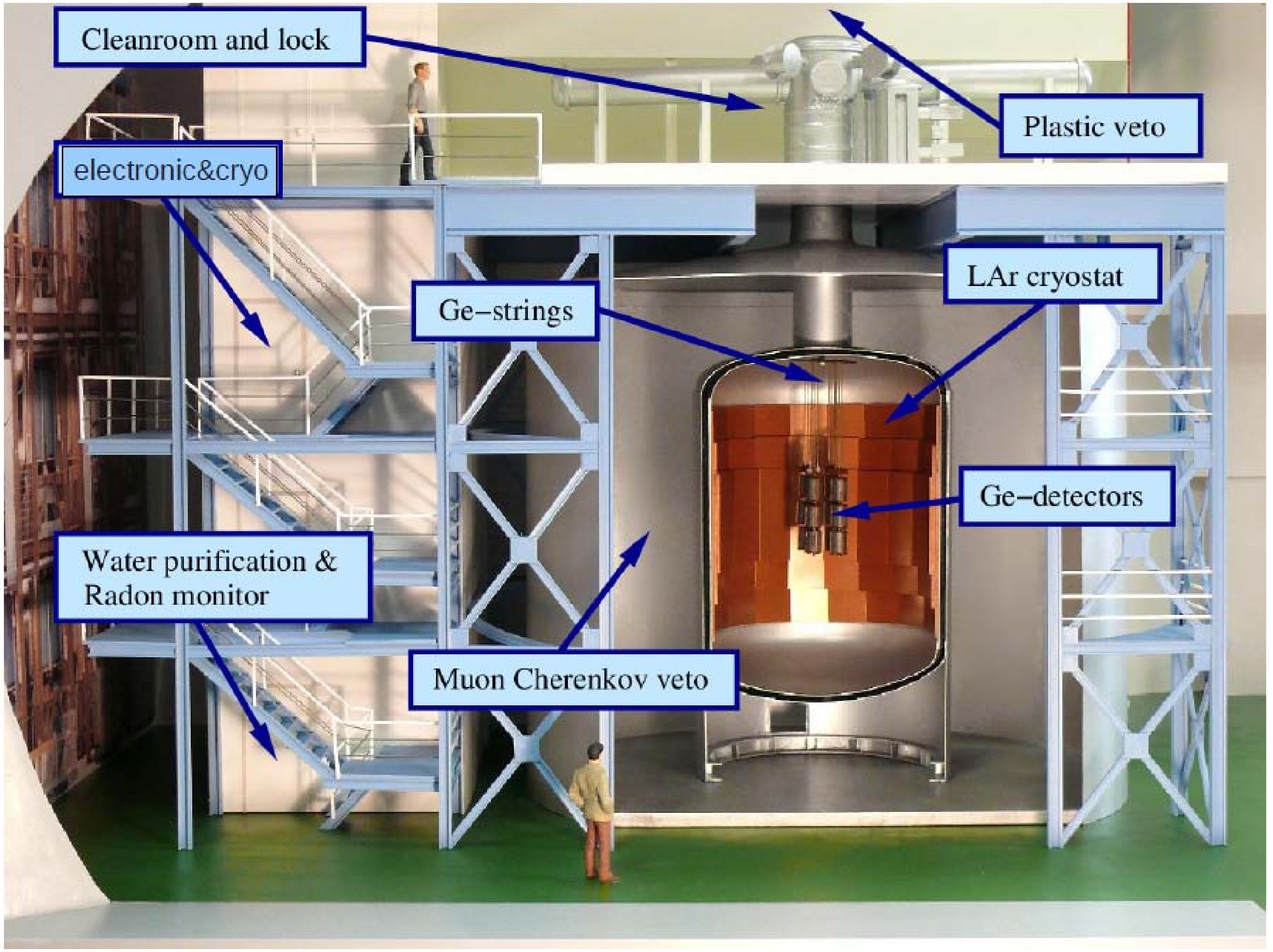
- Crystals, almost all arrived (all at LNGS by the end of 2012)
- Copper parts are being machined and cleaned
- Dilution unit delivered to LNGS (though some repairs needed)
- CUORE Hut, and most of all the infrastructures, ready
- Detector assembly line, ready (small modifications)
- Radon abatement system installed
- 3 (of 6) cryostat vessels delivered soon at LNGS
- Commissioning of the cryostat second half of 2012



Crystals	12/12
Thermistors	13/03
Cleaned Cu parts	13/12
Cryogenic	13/12
Tower Assembly	14/04
Detector insertion	14/07
Cool Down	14/11

GERDA

- Ge detectors in the Liquid Ar Scintillator.
- LAr works as active shielding.



Ge detectors in GERDA-I

summary

GERDA : searching for the $0\nu\beta\beta$ decay in ^{76}Ge

concept works : diodes enriched in ^{76}Ge on strings in liquid argon (Lar) @ LNGS

- GERDA is running and taking data
- statistics: 1.11.2011 – 21.5.2012 (^{enr}Ge exposure 6.10 kg yr)
- systematics: blinding 2019 – 2059 keV
- background index (BI) : 0.020 +0.006 -0.004 cts/(keV kg yr) [68% coverage]

- LAr: ^{42}Ar (^{42}K) activity determined: (93.0 ± 6.4) μBq/kg
- ^{76}Ge $T_{1/2}^{2\nu}$ = (1.88 ± 0.10) 10^{21} yr

all results are preliminary !!!

- preparations for Phase II progressing well:

  increase in mass by add. ~20kg (26+ BEGe) & BI = 10^{-3} cts/(keV kg yr)

  9 crystals pulled – milestone completed successfully !!

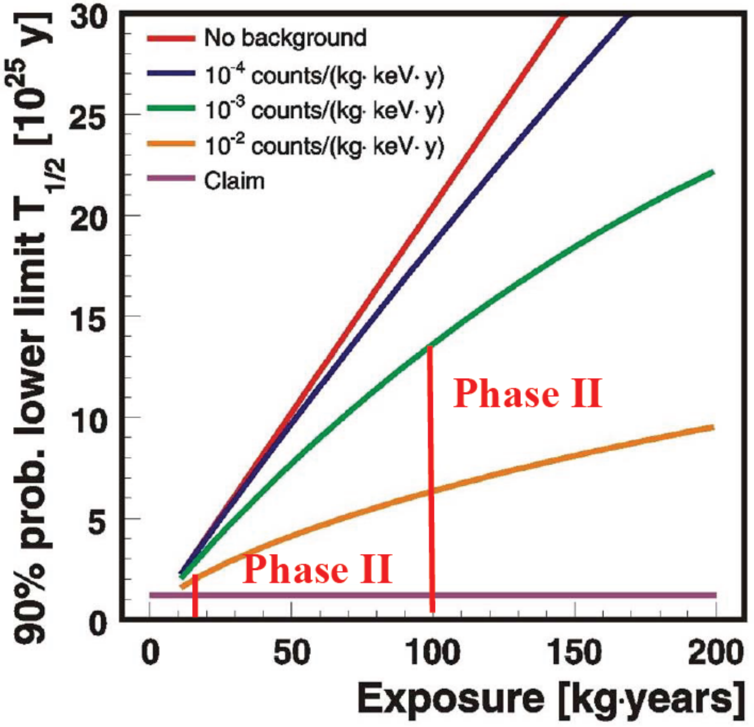
complete Phase I and start Phase II in early 2013

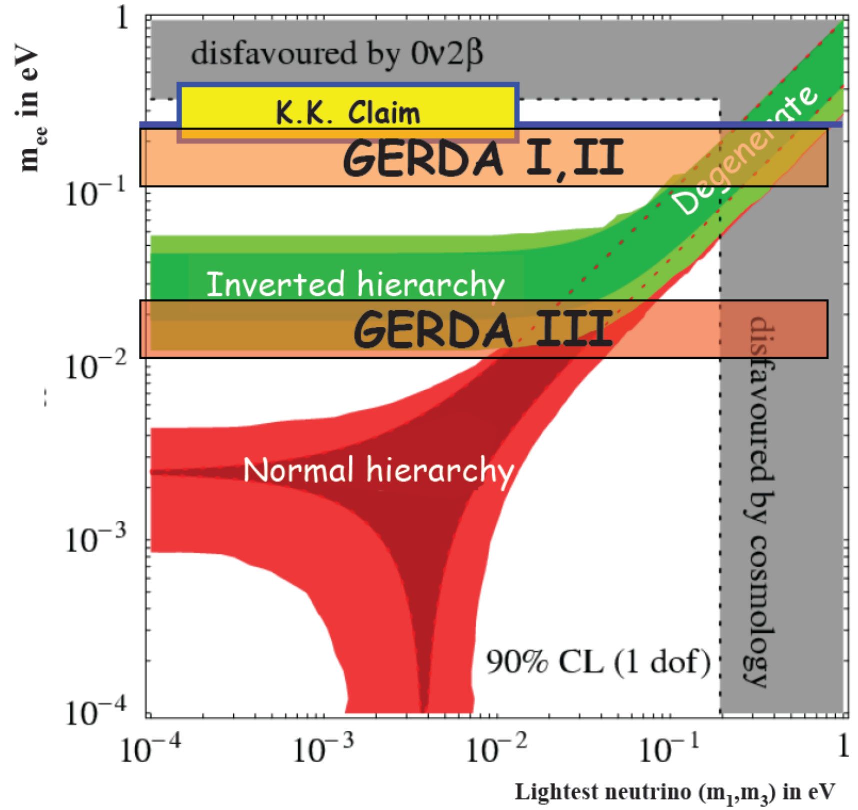
GERDA Current status

- Concept works : diodes enriched in ^{76}Ge in liquid argon (Lar) @ LNGS
- GERDA is running and taking data
- Phase-I
  - statistics: 1.11.2011 – 21.5.2012 (enrGe exposure 6.10 kg yr)
  - systematics: blinding 2019 – 2059 keV
  - background index (BI) : 0.020 +0.006 -0.004 cts/(keV kg yr) [68% coverage]
  - LAr: 42Ar (42K) activity determined: (93.0 $\pm$ 6.4) μBq/kg
  - ^{76}Ge T1/2($2\nu\beta\beta$) = (1.88 $\pm$ 0.10) 10^{21} yr
  - all results are preliminary !!!
- Preparations for Phase II progressing well:
  - increase in mass by add. ~20kg (26+ BEGe) & BI = 10^{-3} cts/(keV kg yr)
  - 9 crystals pulled – milestone completed successfully !!
- **complete Phase I and start Phase II in early 2013**

GERDA Sensitivity

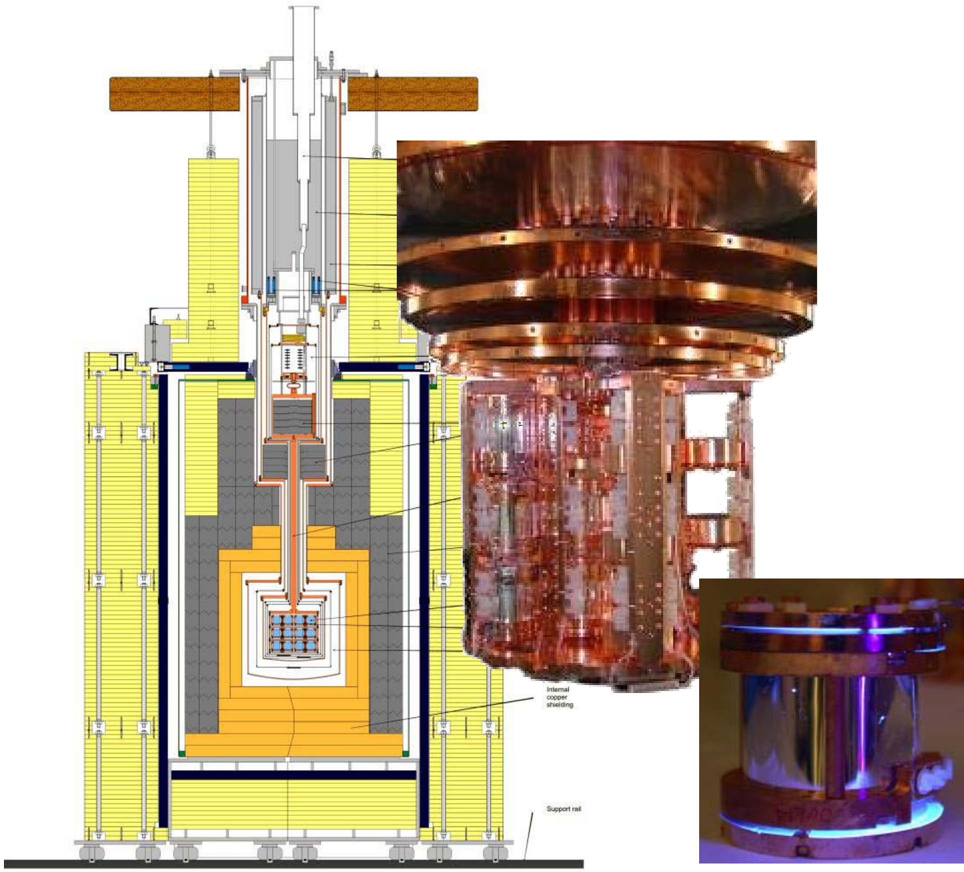
Exposure [kg·years]	Background [counts/(kg·keV·y)]	Limit $T_{1/2}$ [y]	Limit $<m_{\beta\beta}>$ [meV]
15 (Phase I)	10^{-2}	$>2 \cdot 10^{25}$	<270
100 (Phase II)	10^{-3}	$>1.4 \cdot 10^{26}$	<110

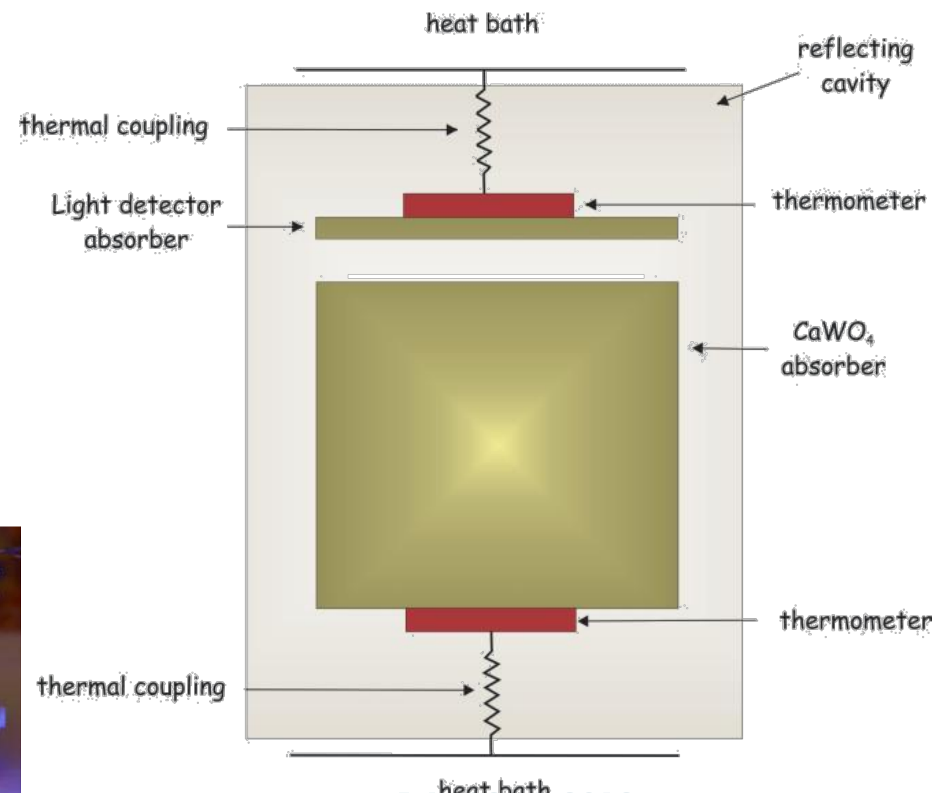




Scintillating Bolometer

- CRESST-II at LNGS for DM search ($CaWO_4$)
  - e/γ backgrounds will produce scinti. Light
  - WIMP induced recoils, little or no light.

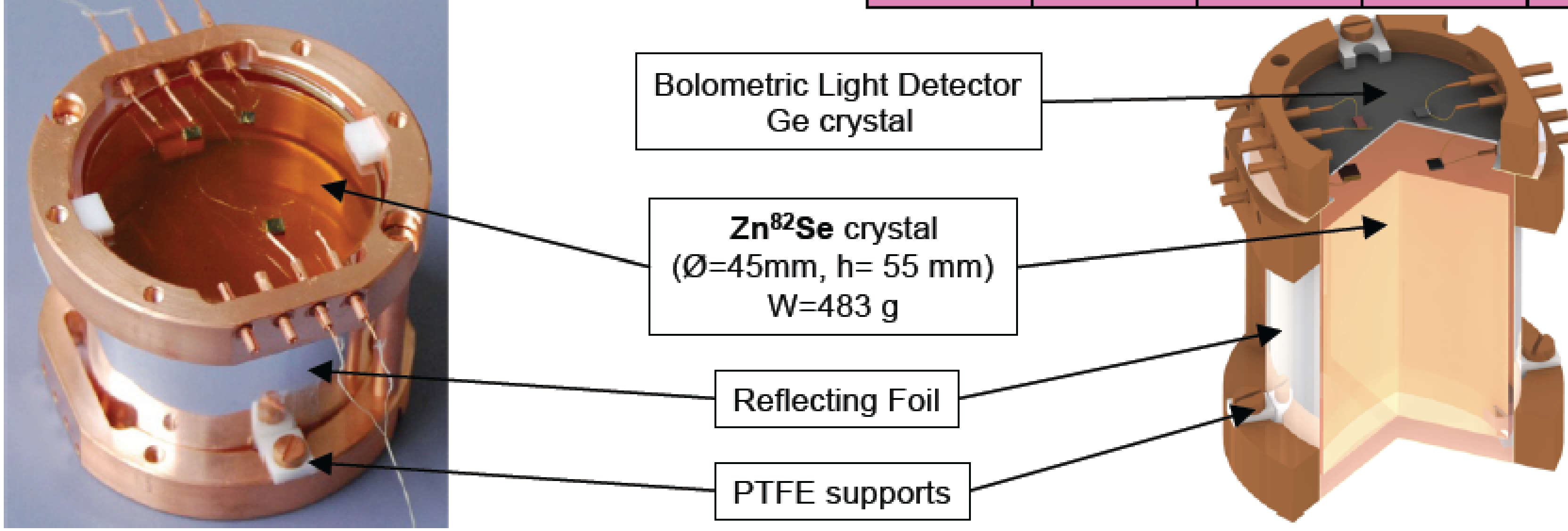




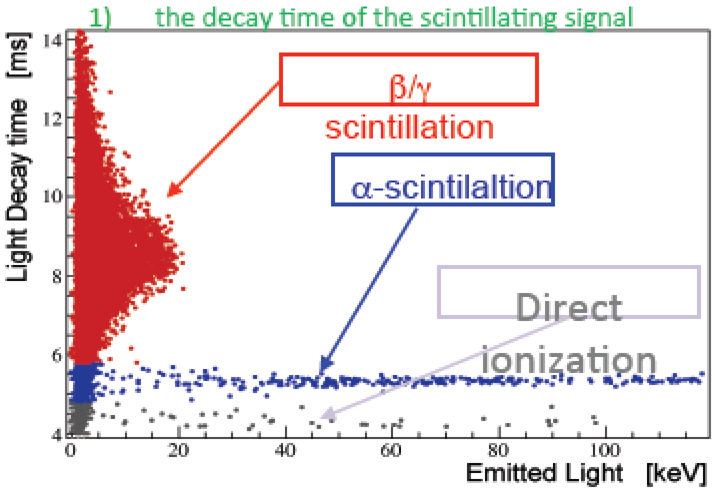
LUCIFER

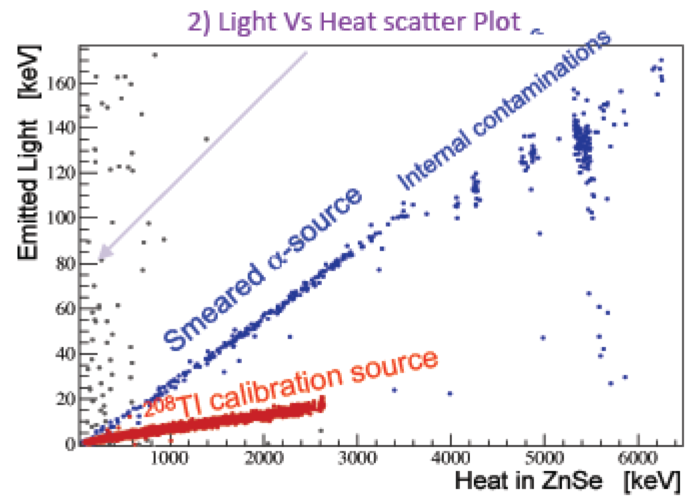
- Scintillating bolometers to recognize the α-induced background thanks to the readout of the scintillation light
- Array of 36 ~ 44 enriched (95%) $Zn^{82}Se$ crystals.
- Expected background in the ROI (2995 keV) is
  ~ 3~6 x 10^{-3} c/keV/kg/y
- Energy resolution ~10 keV FWHM

	$Q_{\beta\beta}$ (keV)	Useful material (% weight)	LY (keV/MeV)	QF
$CdWO_4$	2809	32	~17	~0.16
$ZnMO_4$	3034	44	~1	~0.2
ZnSe	2995	56	~7	~4



LUCIFER

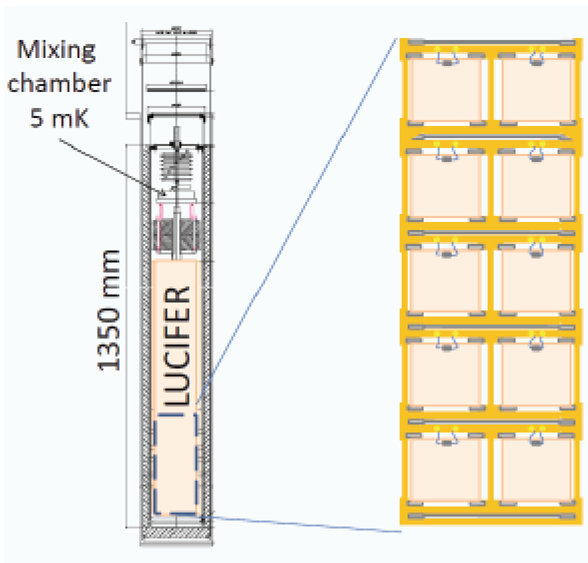


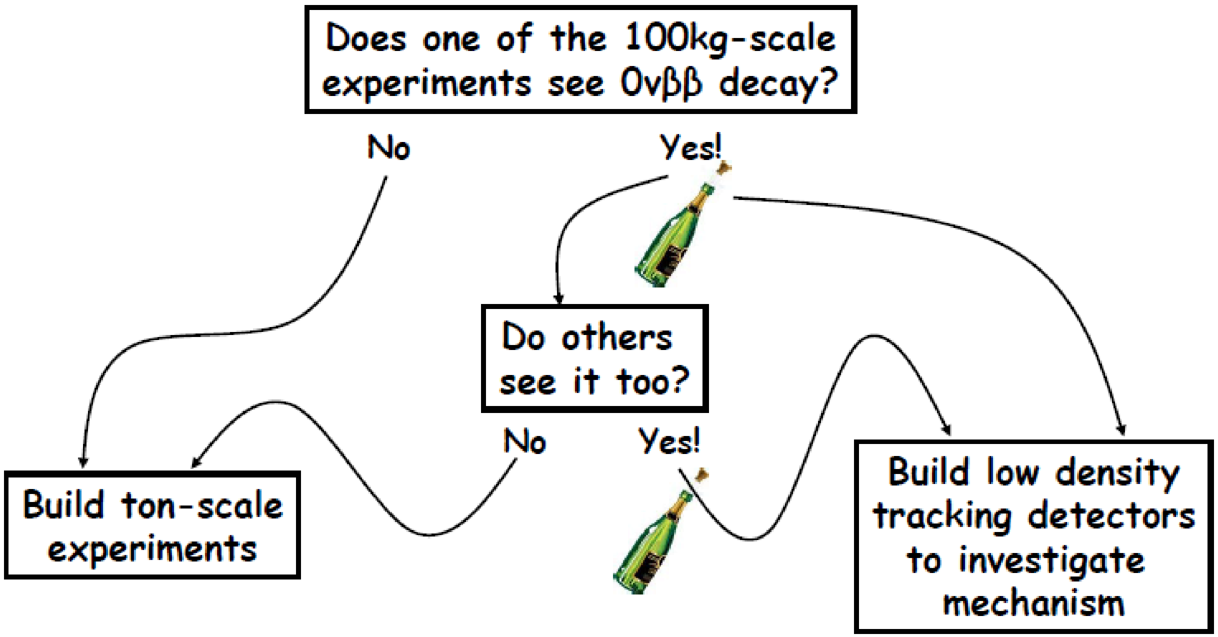


- The α-induced background is recognized:
  - 1) the decay time of the scintillating signal
  - 2) the different scintillation yield between α and γ/β particles (the "usual" light Vs Heat scatter

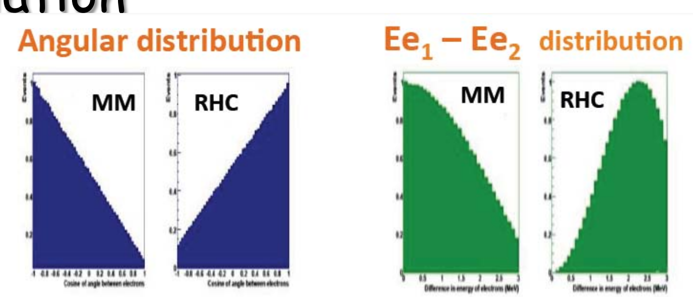
- LUCIFER will be located in CUORICINO (now CUORE-0) cryostat, once CUORE-0 will finish their data taking (2015)

Tower: 12 single modules





- Energy & angular correlation
  → Mechanism of 0νββ



Mass vs Right-Handed Current mechanism

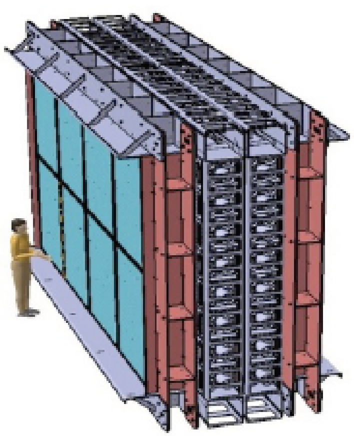
SuperNEMO Demonstrator

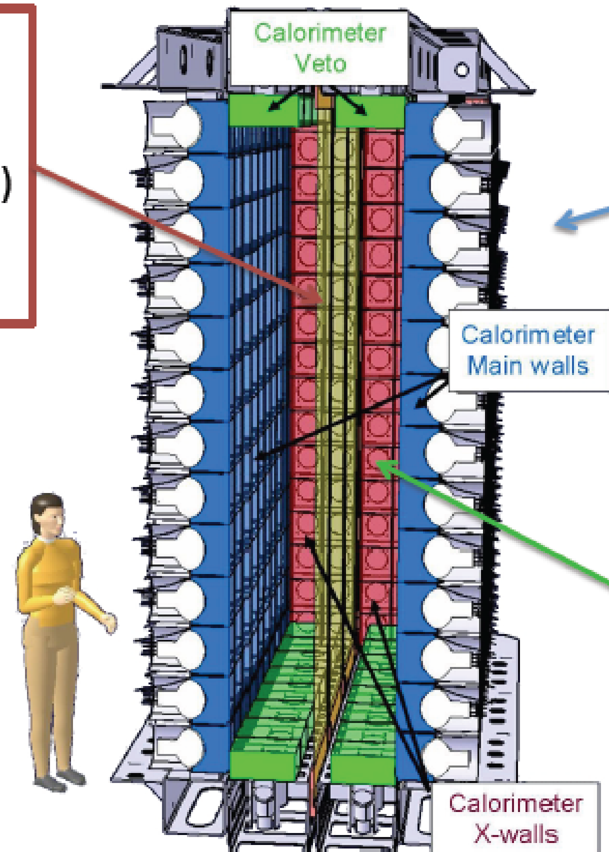
Slides : F. Piquemal in Neutrino2012

Objective: to reach the background level for 100 kg
to perform a no background experiment with 7 kg isotope of ^{82}Se in 2 yr

Source

^{214}Bi < 10 μBq/kg
(NEMO3 100 μBq/kg)
208Tl < 2 μBq/kg
(NEMO3 100 μBq/k)





Calorimeter

ΔE/E < 4% @ 3 MeV
(NEMO3 8.6% at 3MeV)

Tracker

3.7 m long (NEMO3 2.7 m)
σ_t = 5 mm, σ_z = 1 cm
Radon < 0.15 mBq/m^3
(NEMO3 5 mBq/m^3)
Wiring robot

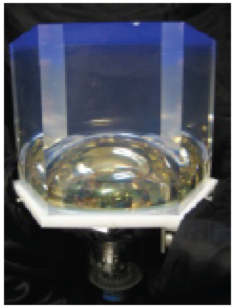
Global efficiency : 30 % (NEMO3 8%)

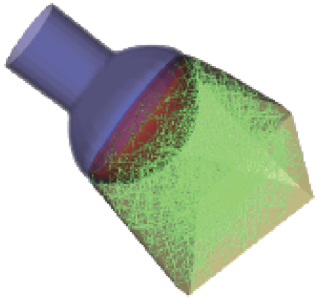
SuperNEMO demonstrator

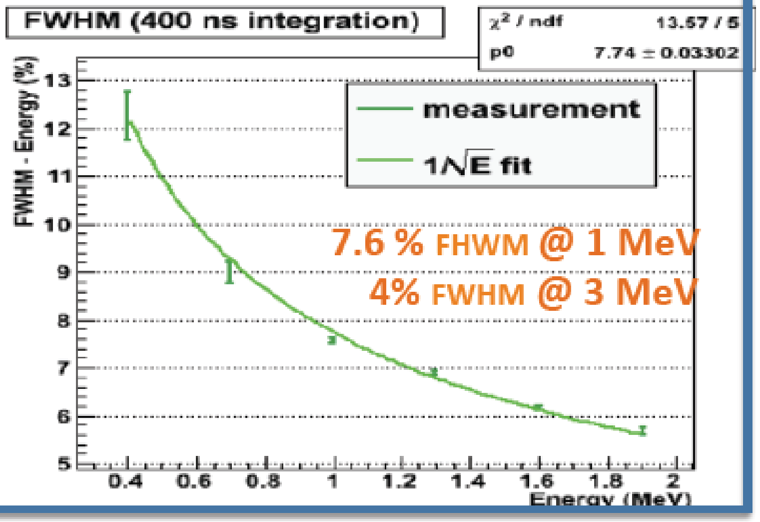
Calorimeter

Scintillator PVT size: 25.6x25.6x12 cm^3

8'' Hamamatsu PMT







Tracker

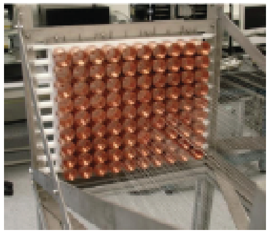
Size cell: l=3.7 m, ϕ = 44 mm

σ_t: 0.7 mm, σ_L: 1cm

Efficiency > 98%

Radon in gas < 0.15 mBq/m^3

Wiring robot

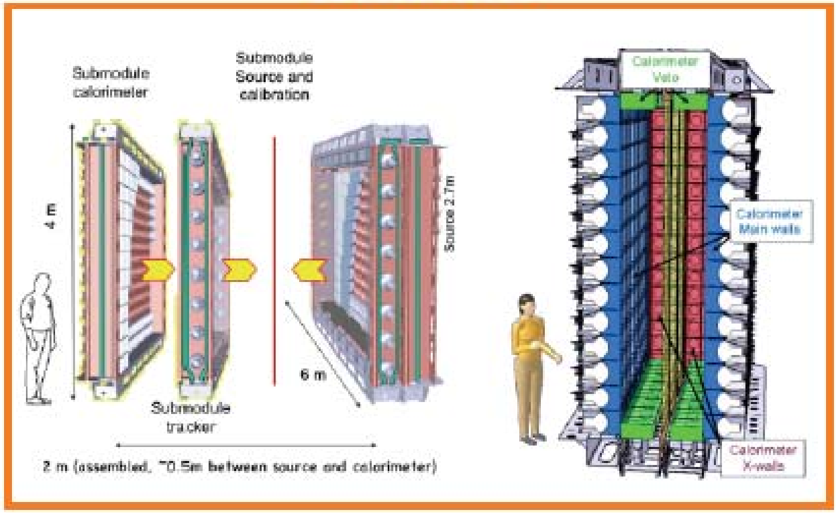


Radon concentration line for tracker gas

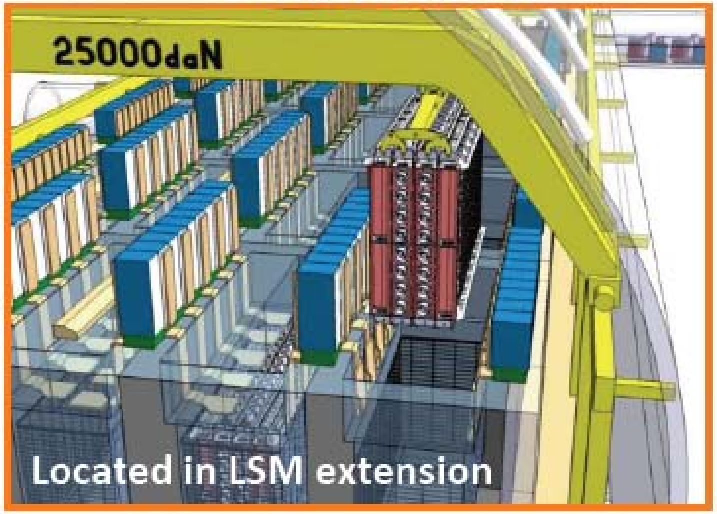
Sensitive to 0.05 mBq/m^3

SuperNEMO

A module



20 modules



	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	$6.6\ 10^{24}$ y (No background)	$1.\ 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	200 – 400 meV	40 – 100 meV

DCBA

DCBA experiment

Slides : H. Iwase in DBD11

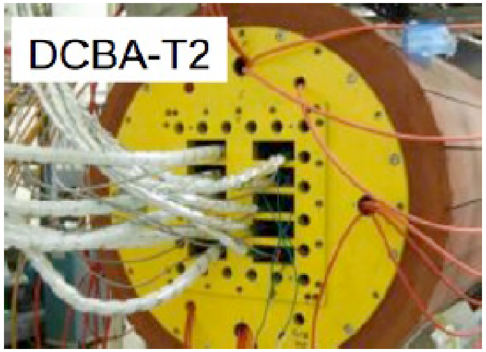
2005 DCBA
- charge dividing

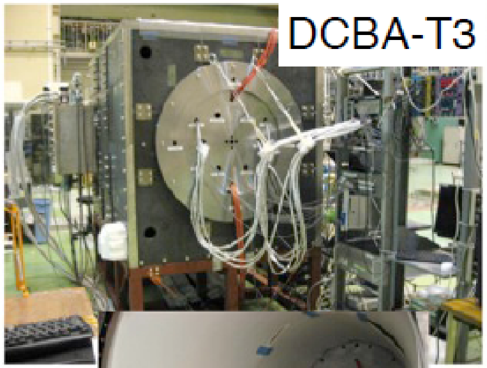
2007 DCBA-T2
- 6 mm pitch wires (xy + xz)
- ^{100}Mo source (natural Mo 30g)
- 0.6 - 0.8 kG magnetic field
- conducting magnet: 9h/day (Mo. - Fr.)

2011 present DCBA-T2.5 [24h operation]
- 6 mm pitch wires (xy + xz)
- ^{100}Mo source (natural Mo 30g)
- 0.8 kG magnetic field
- **super-conducting magnet**: 24h nonstop operation

2013 DCBA-T3 [higher resolution]
- 3 mm pitch wires (xy + xz)x6
- ^{150}Nd (natural Nd_2O_3)
- maximum 3 kG

2017 MTD (tentative name) [higher event rates]
- ^{150}Nd (condensed, several 10 kg)



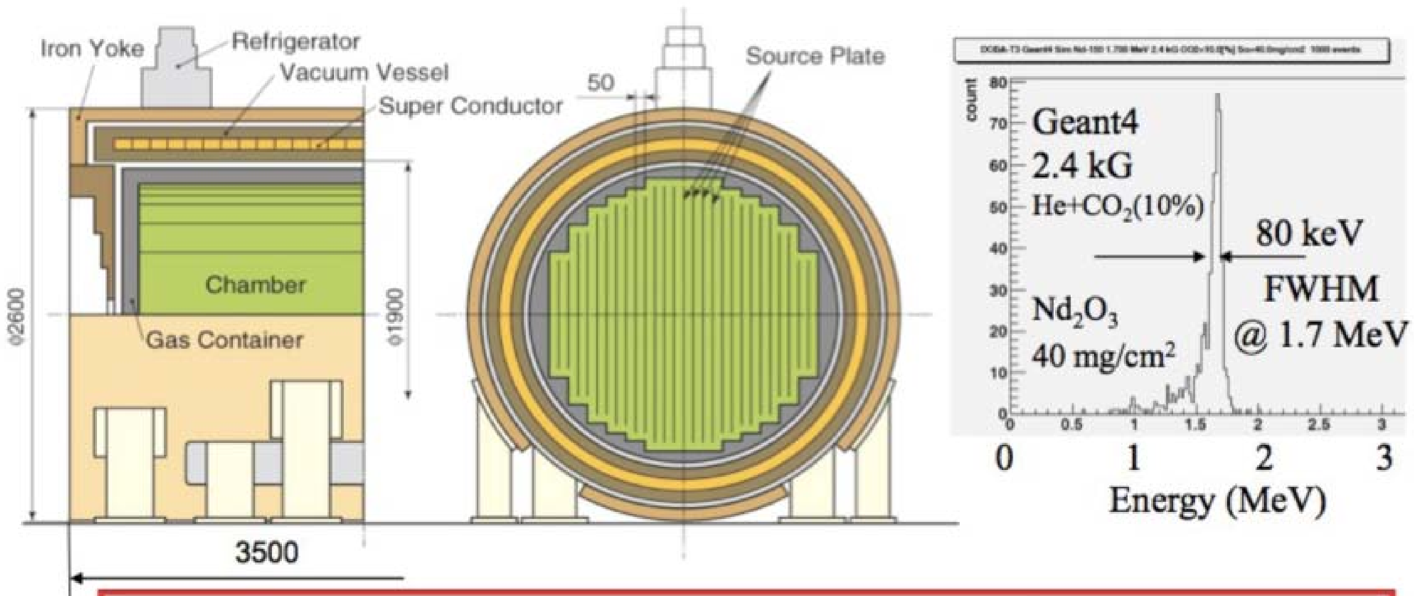


DCBA-T2-detector in T3 (=T2.5)

Magnetic Tracking Detector (MTD)

MTD - the next DCBA

Chamber cell : the same as DCBA-T3, Source plate: 80 m^2/module
Thickness: 40 mg/cm^2, Source weight: 32 kg/module 27 source plates



Expected Energy Resolution $\dfrac{\mathrm{FWHM}(E_{sum}) = \sqrt{2} \times 80\mathrm{keV}}{Q_{\mathrm{Nd\text{-}150}}(3370\mathrm{keV})} \approx 3.4\%$

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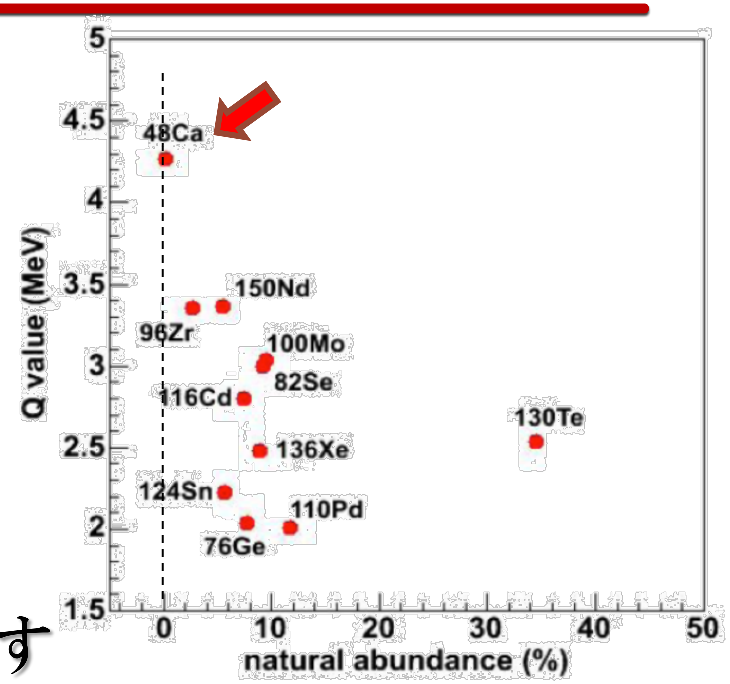
- ここからは、時間の許す範囲で

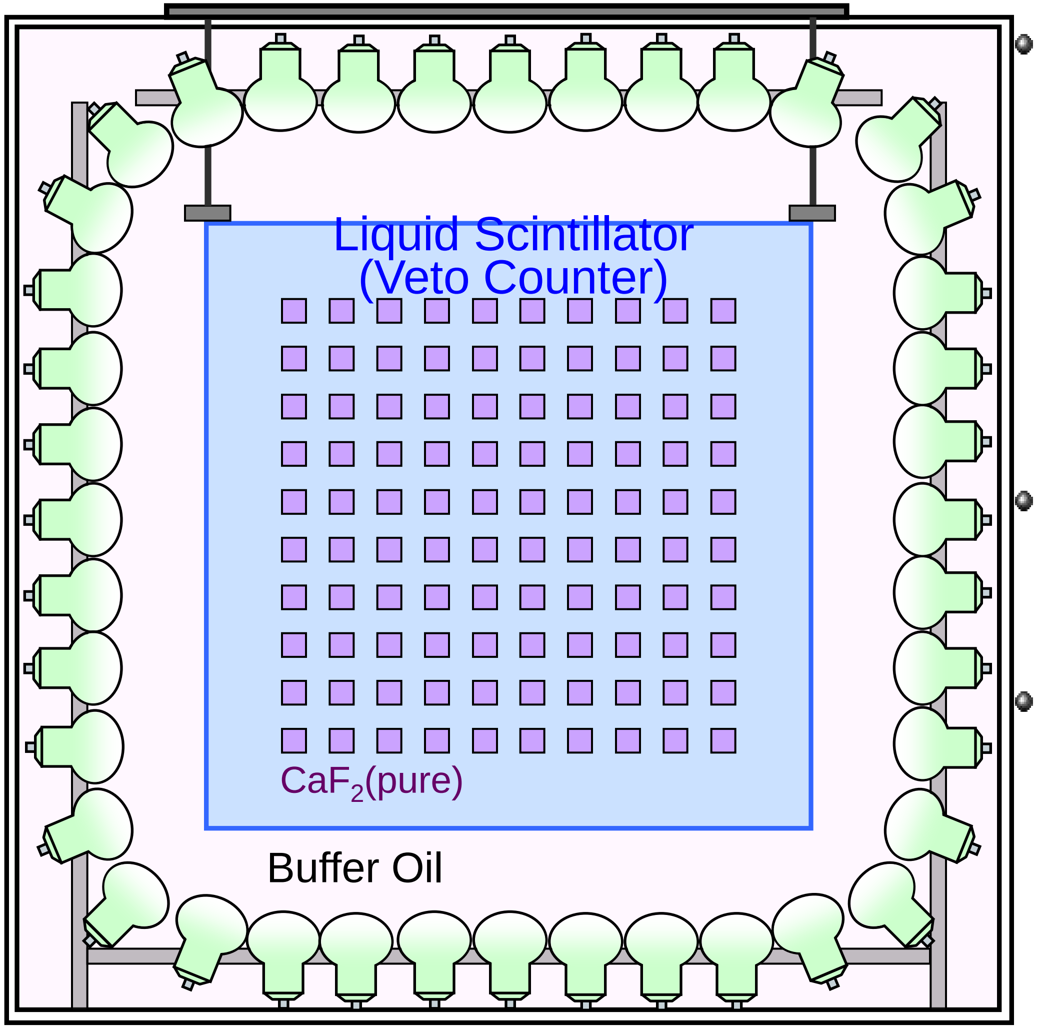
CANDLES

- $0\nu\beta\beta$ by ^{48}Ca isotope
  - Highest Q-value (4.27MeV)
  - ➔ Low background
    - γ-ray ; 2.6 MeV (^{208}Tl)
    - β-ray ; 3.3 MeV (^{214}Bi)
  - Background Free検出器を目指す



Conceptual Design of CANDLES

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



Large PMT

- CaF_2(pure) scintillator
  - Transparent Crystal
  - Long attenuation length (>10m@350nm)
  - ββ decay source = detector
  - Wave length Shifting mechanism

    CaF2(pure) ; 280nm emmision

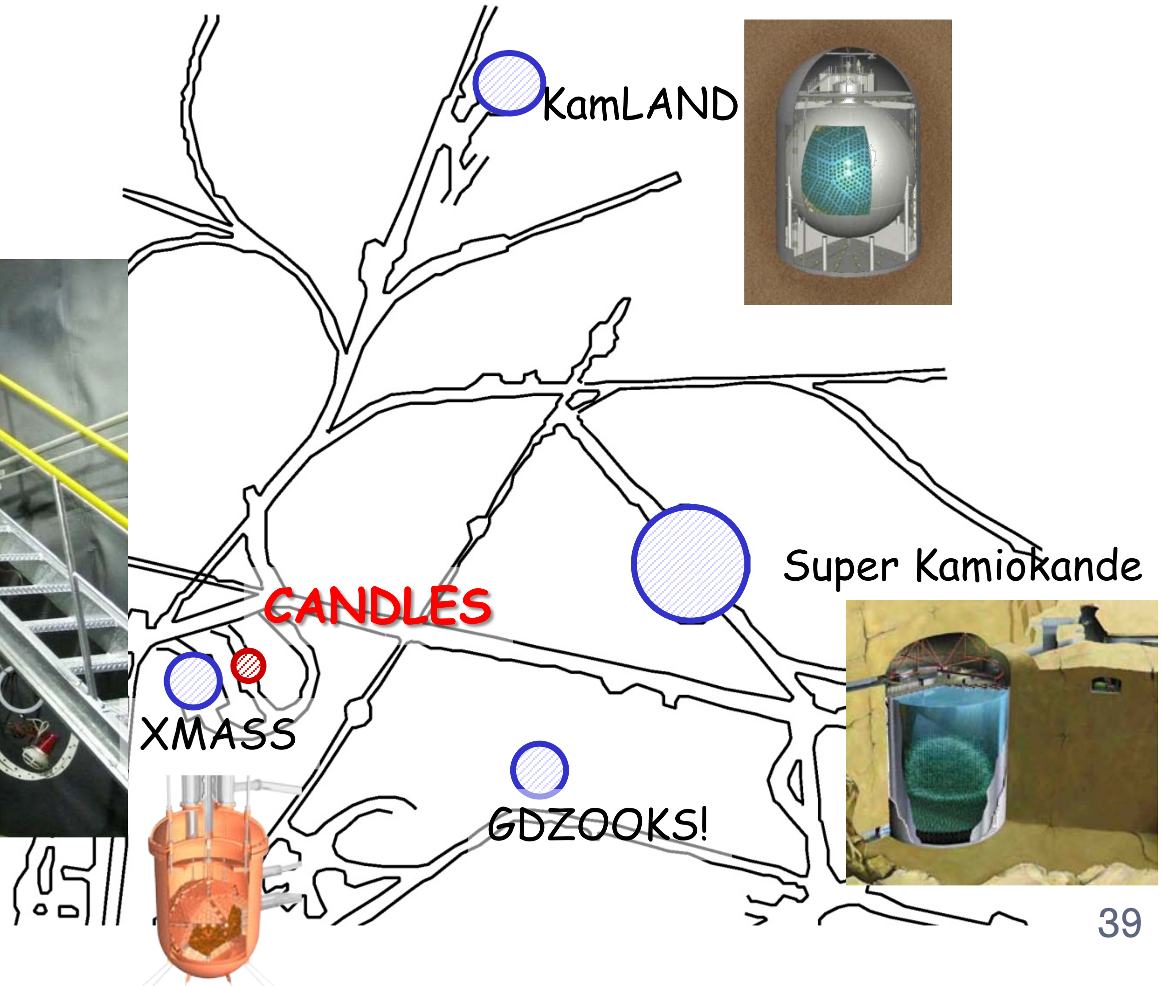
    WLS (bis-MSB) ; → 420nm emission
- Liquid scintillator
  - 4π active shield
- Large photomultiplier tube
  - Signals from both scintillators are detected simultaneously

CANDLES III at Kamioka

- CANDLES III
  - 3m diameter × 4m height (water tank)

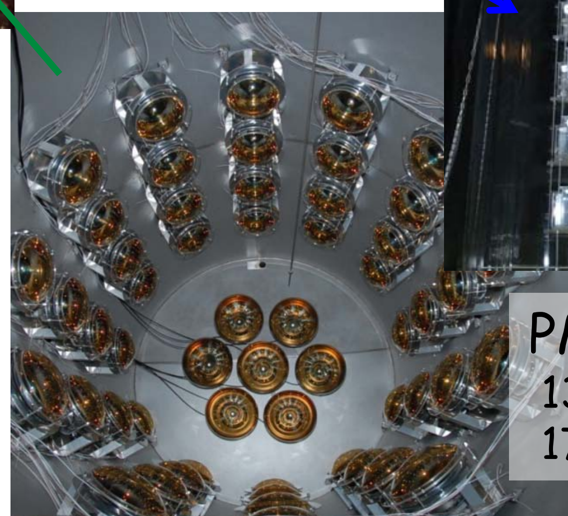
CANDLES III

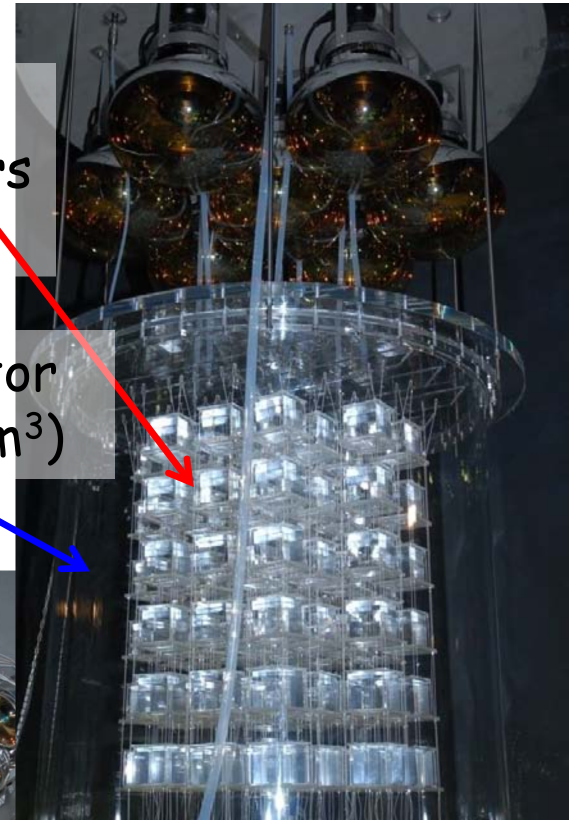
Kamioka Lab. Map



CANDLES III Detector

- Data taking from June, 2012





Main detector

CaF_2 scintillators (305kg)

Liquid scintillator acrylic tank ($2m^3$)

Light-pipe system

Gain ×1.8

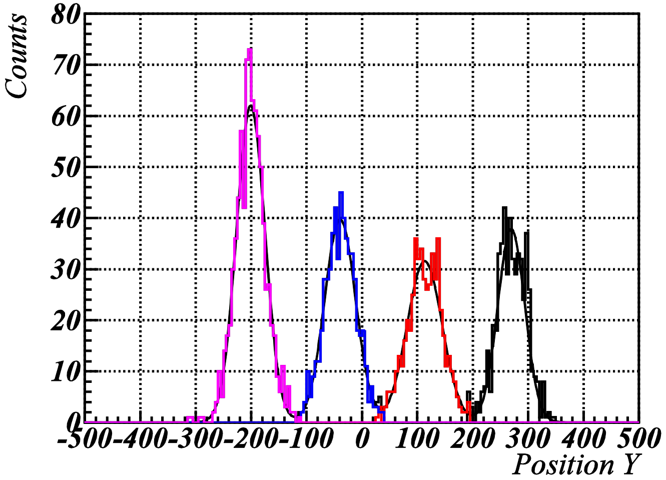
PMTs

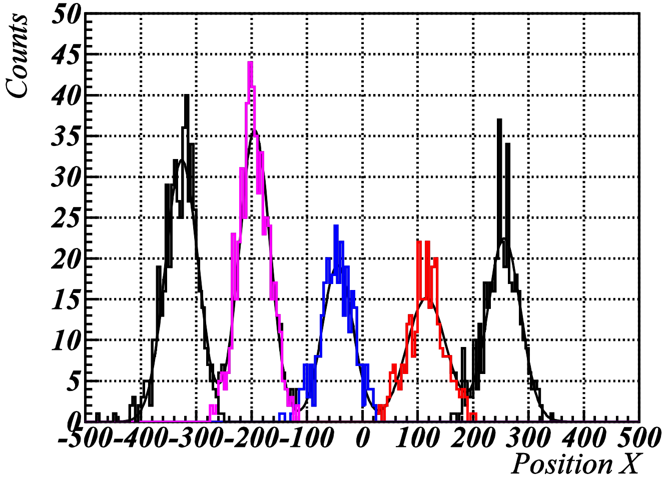
13 inch (side) ; x 48本

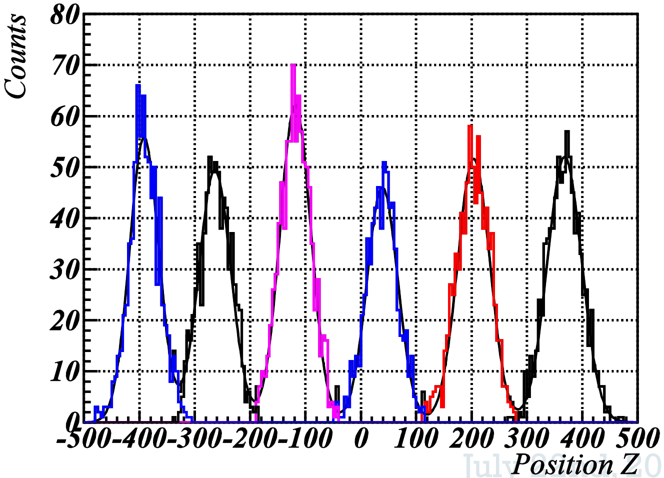
17 inch (top & bottom) ; x 14本

Event Reconstruction

- Event reconstruction
  - Under developing the reconstruction tools

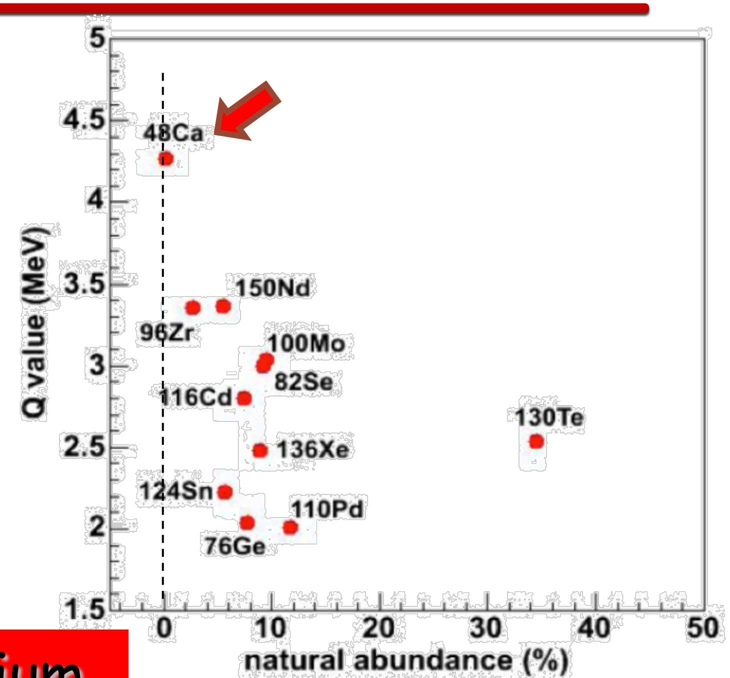






Isotope Enrichment

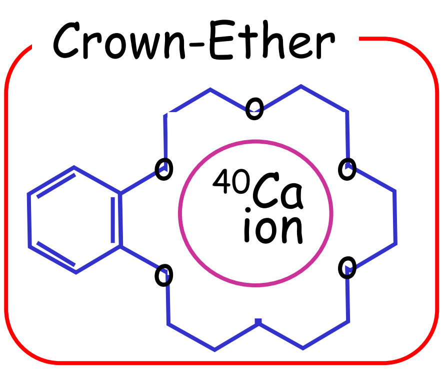
- Enrichment of ββ isotopes
  - ^{136}Xe, ^{100}Mo, ^{76}Ge, ^{82}Se, ^{116}Cd … : Available
  - ^{48}Ca, ^{150}Nd ; Difficult (limited small amount)



- Technologies for ^{48}Ca Enrichment
  - Gas diffusion ×
  - Gas centrifuge ×
  - Chemical process ○

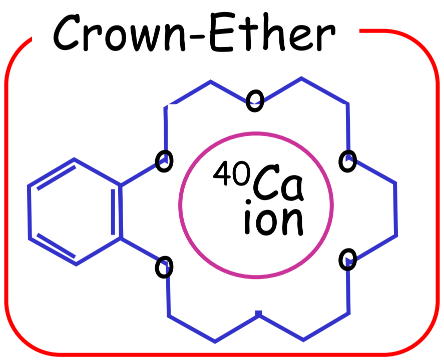
No gaseous compound for Calcium

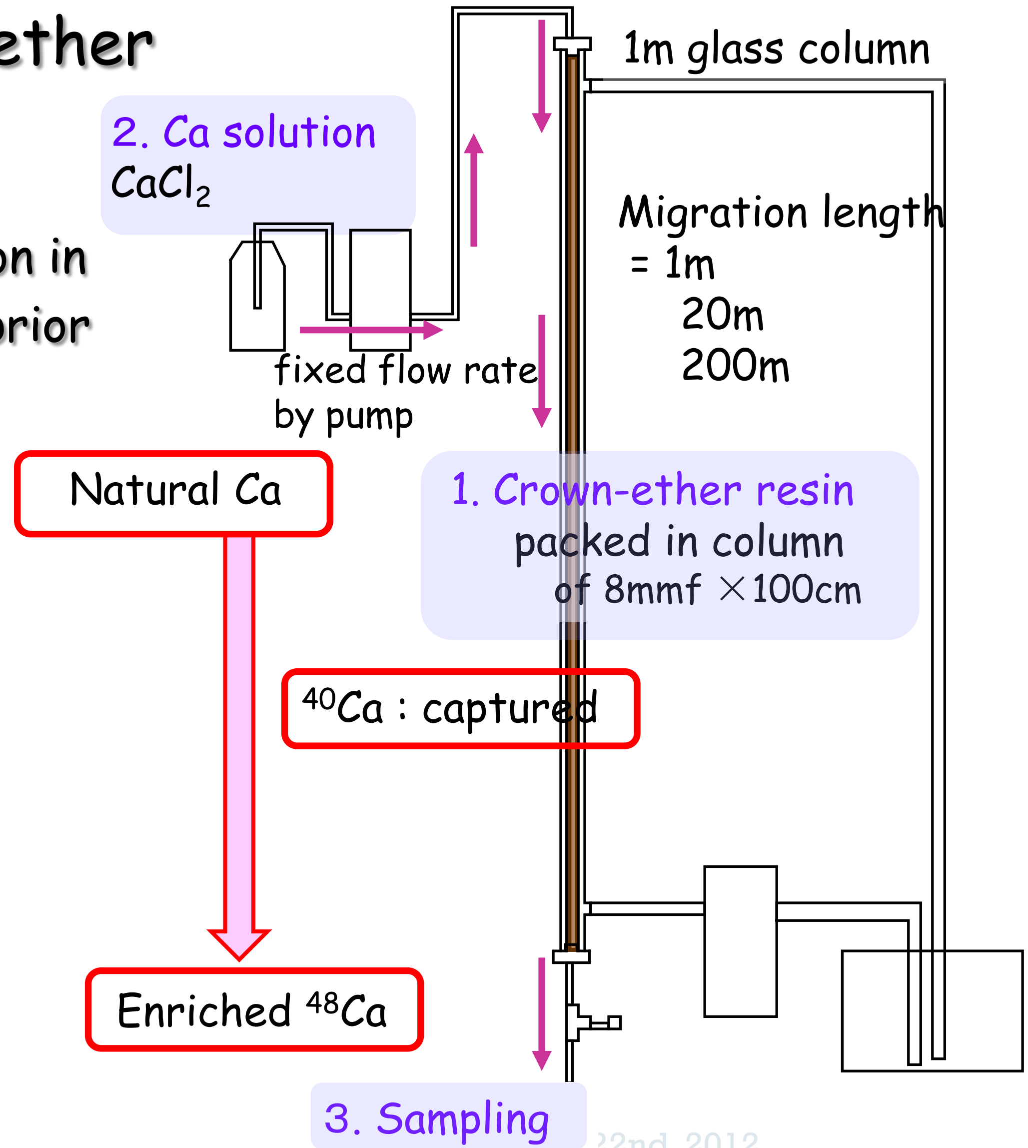
- Isotope enrichment by Crown-Ether
  - Crown-ether rings adsorb Calcium ions
  - For calcium, ^{40}Ca adsorption in crown-ether is slightly prior



R&D : Enrichment of ^{48}Ca

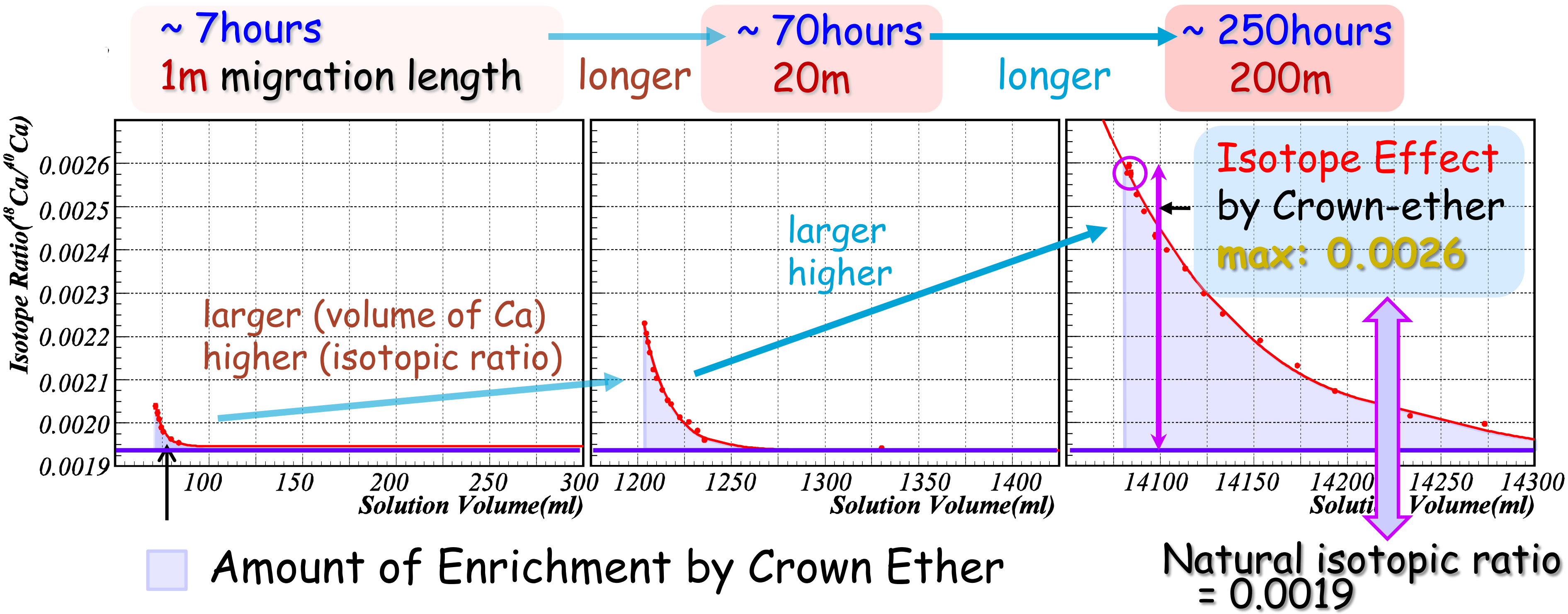
- Enrichment by crown-ether
  - Crown-ether rings adsorb Calcium ions
  - For calcium, ^{40}Ca adsorption in crown-ether is slightly prior





Possible Enrichment

- Isotope Enrichment with Longer Migration Time (Length)



Isotope Effect (Enrichment Effect)

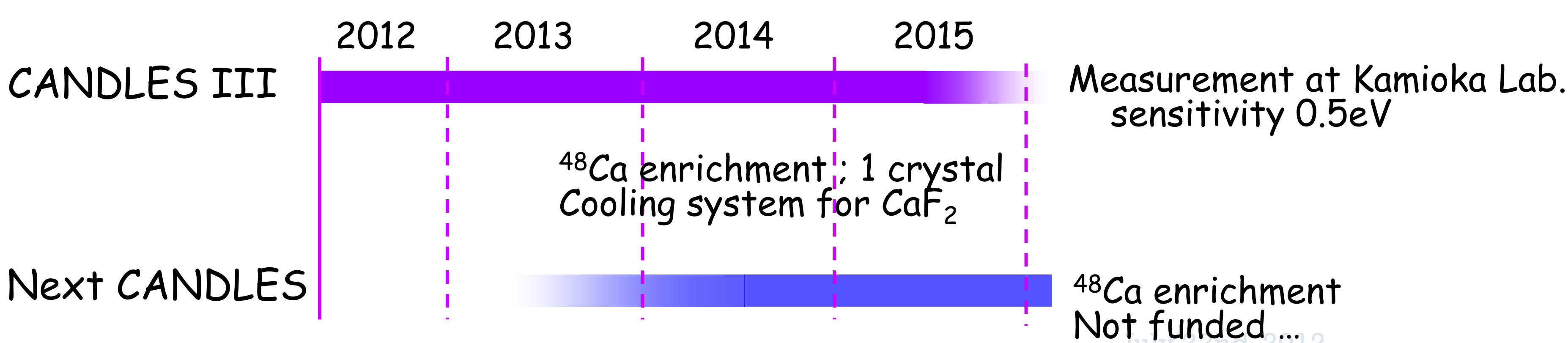
- The longer migration time(length) =
  the larger volume and the higher isotopic ratio
- ^{48}Ca enrichment → next CANDLE system

Future Prospects

- CANDLES Series

	CANDLES III	Next CANDLES
Crystal	3.2kg×96 crystals	
Total Mass	305kg	2 ton
Energy Resolution	4.0%(Req.)	2.8%(Req.)
$2\nu\beta\beta$	0.01	$<$0.2
^{212}Bi,^{208}Tl	0.26	~0.1
Expected BG	0.27/year	$<$ 0.3 /year
$\langle m_n \rangle$	0.5 eV	0.05

2% ^{48}Ca
and cooling system for CaF_2



Summary

- Several experiments at ~ 100 kg are running and prepared.
- Sensitivity : KKDC claimed region → 50 – 100 meV
  - To explore inverted hierarchy region
- Required ;
  - Several isotopes
  - Several method ,for ex.
    - Scintillating bolometer (BG reduction)
    - Tracking (Understand $0\nu\beta\beta$ mechanism)

- CANDLES III at Kamioka Lab.
  - 300kg of CaF_2(pure) scintillators
  - Pre-measurement for performance test
  - Expected sensitivity : 0.5 eV for $\langle m_\nu \rangle$
- R&D (for next CANDLES)
  - Enriched $^{48}CaF_2$(pure) scintillators
    + Cooling system for CaF_2(pure)
  - Sensitivity : ~0.2 eV~0.05eV