Double beta decay experiments

F. Piquemal

Modane Underground Laboratory (CNRS/NI2P3 and CEA/Irfu)

Many thanks to : K. Zuber, S. Schoenert, K. Inoue, A. Giuliani, S. Elliot, M. Chen,
M. Nomachi, N. Ishihara. H.J. Kim, F. Danevich, L. Winslow

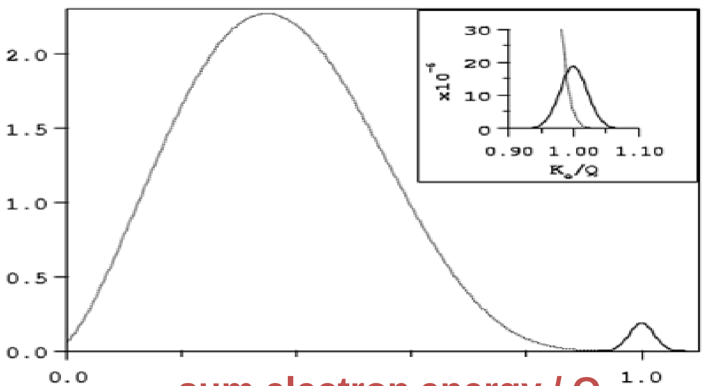
TPC 2014 Paris Decembre, 15-17 2014

Double beta decay : physics case

- **Nature of neutrino Dirac or Majorana**
- **Neutrino mass hierarchy**
- **Right-handed current interaction**
- **CP violation in leptonic sector**
- **Search of Supersymetry and new particles**

Double beta decay observables

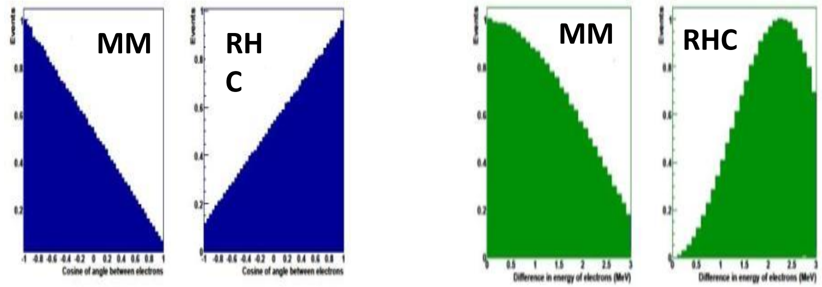
$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$



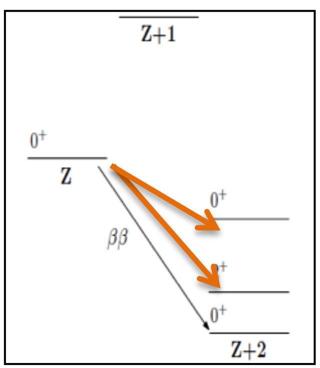
sum electron energy / Q

Angular distribution

$Ee_1 - Ee_2$ distribution



Mass vs Right-Handed Current mechanism



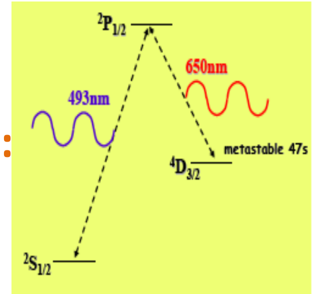
Decay to Excited States

$(A,Z) \rightarrow (A, Z+2) + 2\,e^- + 1,2\,\gamma$

1 or 2 additonnal γ-rays

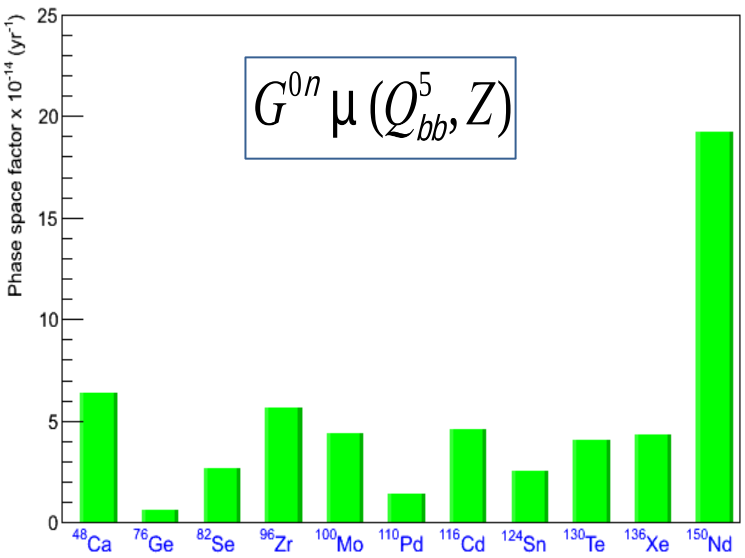
Identification
of daugther nucleus :

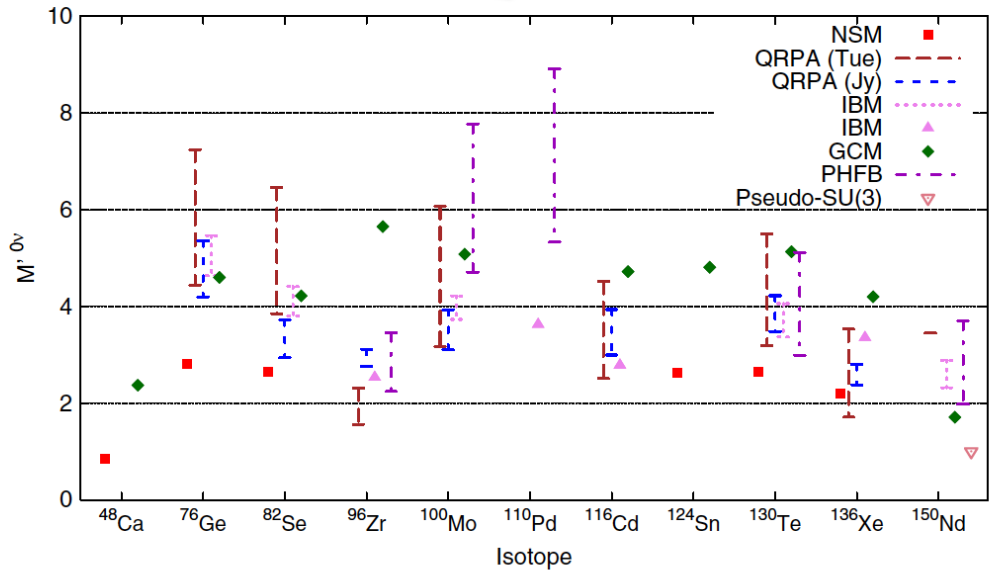
$Xe \rightarrow Ba^{++} + 2\,e^-$



Isotope choice

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$



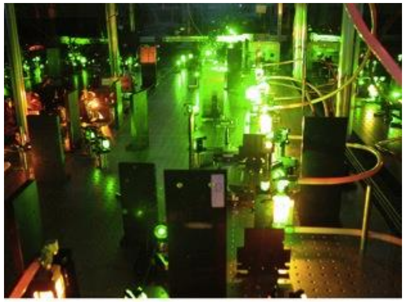


Dueck et al. Phys,. Rev. D **83** 113010(2011)

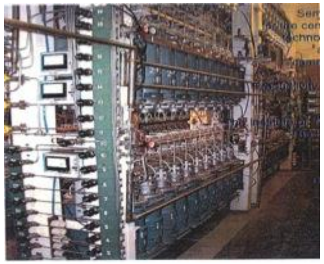
Isotope enrichment

Nucleus	Existing method	R&D
^{48}Ca		Laser separation, gazeous diffusion
^{76}Ge	Centrifugation	
^{82}Se	Centrifugation	
^{96}Zr		Laser separation
^{100}Mo	Centrifugation	
^{116}Cd	Centrifugation	
^{130}Te	Centrifugation	
^{136}Xe	Centrifugation	
^{150}Nd		Centrifugation, Laser

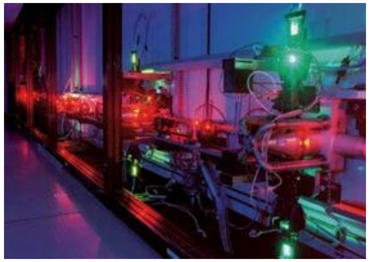
R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



R&D in Russia for ^{150}Nd enrichment by centrifugation



R&D in France for ^{150}Nd enrichment by laser



Backgrounds

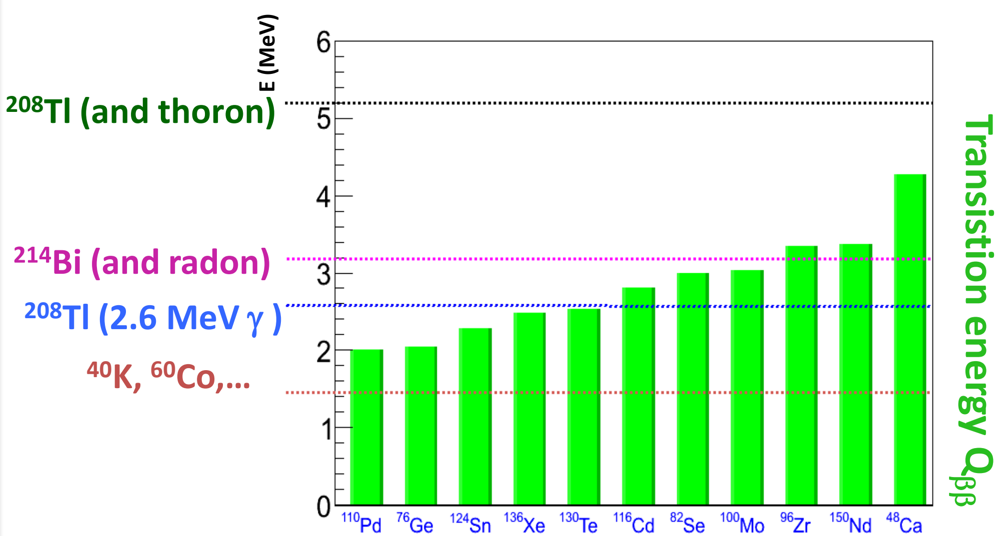
WITH Background

$$T_{1/2}^{0\nu}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M \,.\, t}{N_{Bckg} \,.\, \Delta E}} \qquad \langle m_\nu \rangle \propto \sqrt[4]{M}$$

ε :efficiency, M: Mass, t: time, N_{bckg}: Background events, ΔE: energie resolution, A: isotope mass

Background origins

Natural radioactivity



Other sources of background:

- Muons (underground labs)
- γ from ((n,γ) reactions , μ bremstrahlung
- Muon spallation products
- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution

Different strategies are possible to minimize the background

Next generation of experiments

Calorimeter

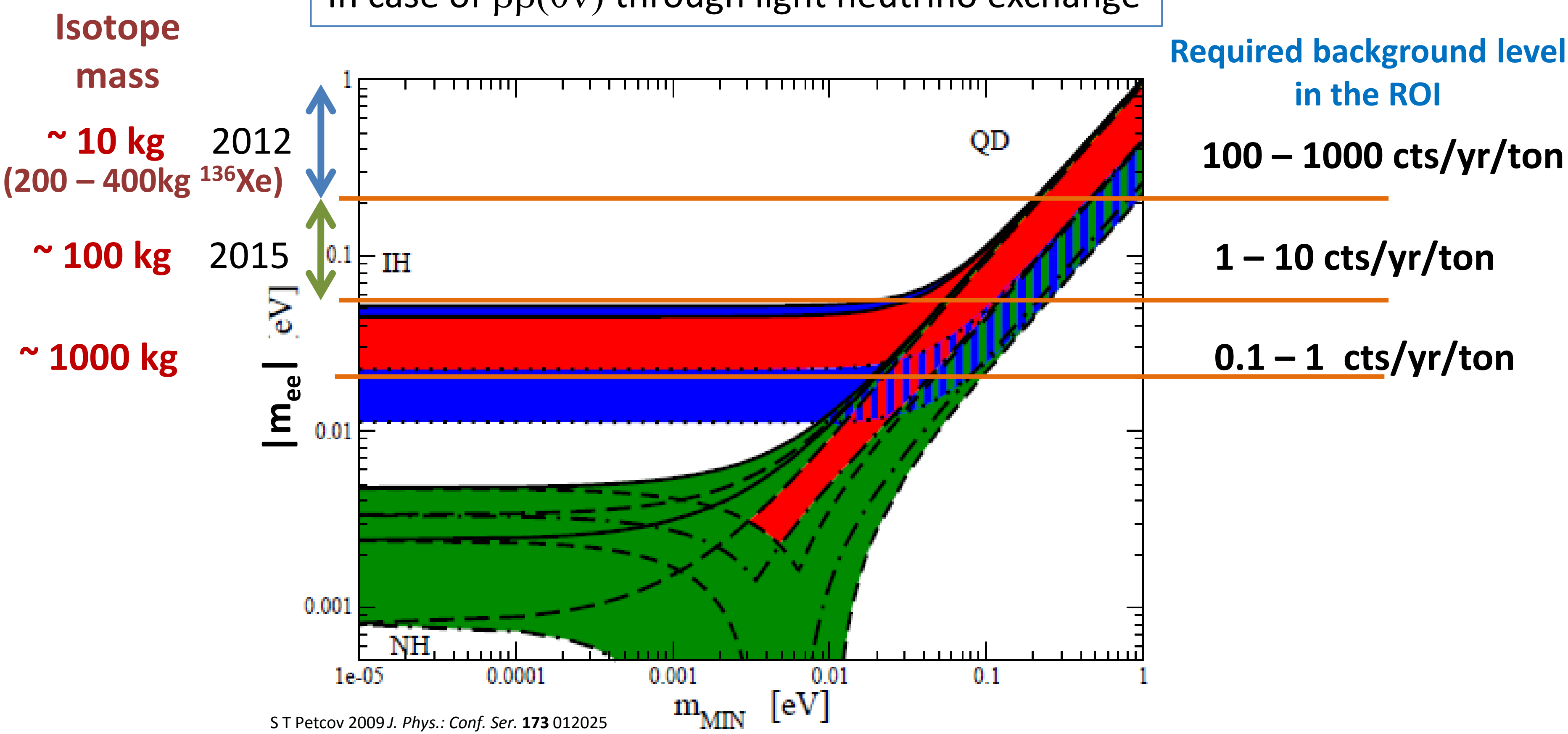
- **Ge diode** — ^{76}Ge — ε, ΔE → GERDA, MAJORANA
- **Bolometers** — ^{130}Te, ^{82}Se, ^{100}Mo — ε, ΔE → CUORE, LUCIFER, Lumineu, Amore
- **Liquid Xe** — ^{136}Xe — ε, M, (N_{bckd}) → EXO
- **Scintillator** — ^{136}Xe, , ^{48}Ca, ^{150}Nd, ^{100}Mo — ε, M → KamLAND-Zen, CANDLES, SNO+, Borexino, CdWO4, AMoRE

Tracker

- **Tracko-calo** — ^{82}Se (^{150}Nd, ^{48}Ca) — N_{Bckg} , isotopes → SuperNEMO
- **Pixellized CdZnTe** — ^{116}Cd — ε, N_{Bckd} → COBRA
- **TPC** — ^{136}Xe, ^{150}Nd — ε, N_{Bckd} → MTD, EXO-gas, NEXT

Goal of the next generation

In case of ββ(0ν) through light neutrino exchange



S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

10 kg: $T_{1/2} > 10^{24}$-10^{25} years   100 kg: $T_{1/2} > 10^{26}$-10^{27} years :

Next generation will use ≥ 100 kg (started with Xe experiments)

Improvements of background level needed

Tracking experiments

SuperNEMO	Construction
NEXT	R&D
EXO	R&D
MTD (DCBA)	R&D
COBRA	R&D

NEMO3

Tracking detector: drift chambers (6180 Geiger cells)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm (vertex)

Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification e^-, e^+, γ, α
Very high efficiency for background rejection

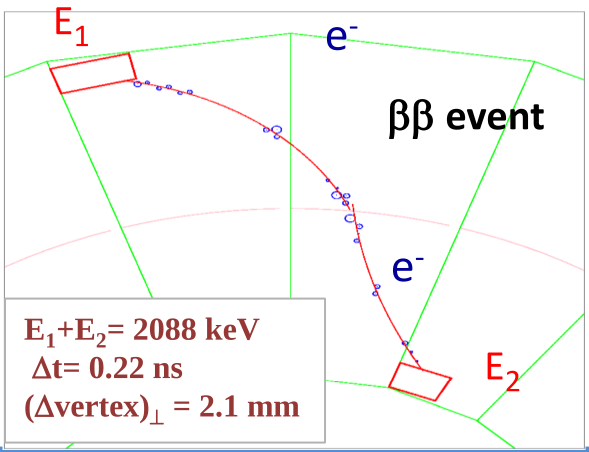
Background level @ $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : 1.2 10^{-3} cts/keV/kg/y

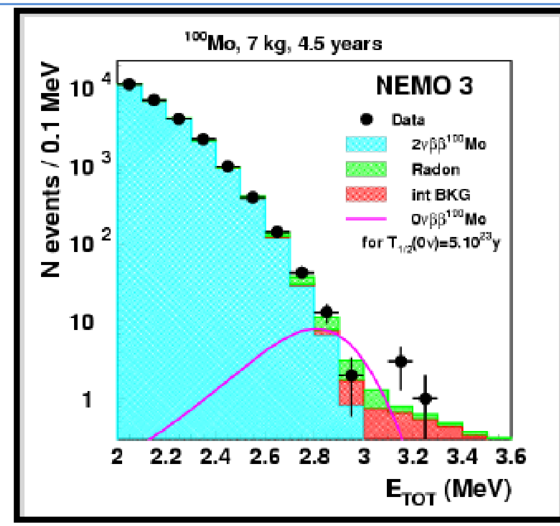
Multi-isotope (7 measured at the same time)

Running at Modane underground laboratory (2003 - 2011)

Unique feature

Measurement of all kinematic parameters: individual energies and angular distribution





[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

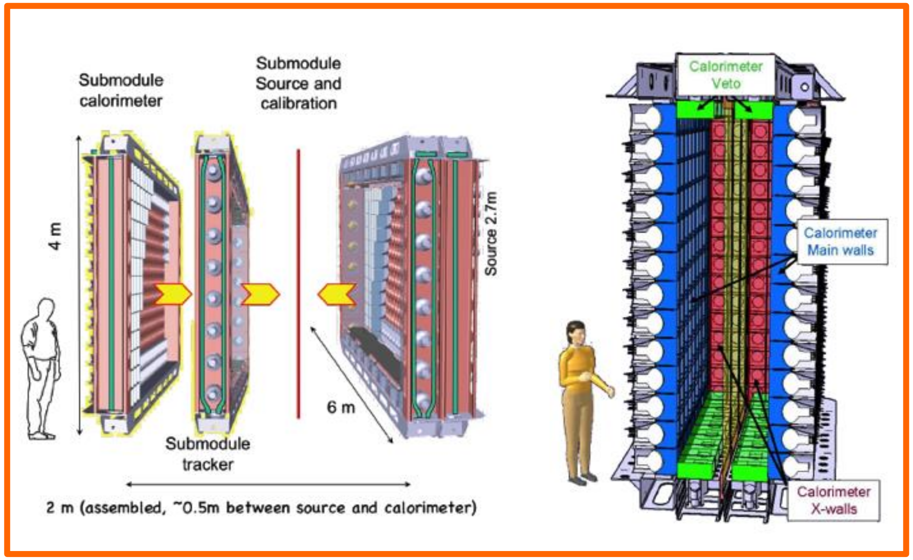
^{100}Mo $T_{1/2}$ ($\beta\beta0\nu$) > 1.0 10^{24} y (90% C.L.)

$\langle m_\nu \rangle$ < 0.31– 0.79 eV

Measurement of 7 isotopes $\beta\beta(2\nu)$ half-lifes
Excited states, Majoron limits for $\beta\beta(0\nu)$

SuperNEMO

A module



20 modules

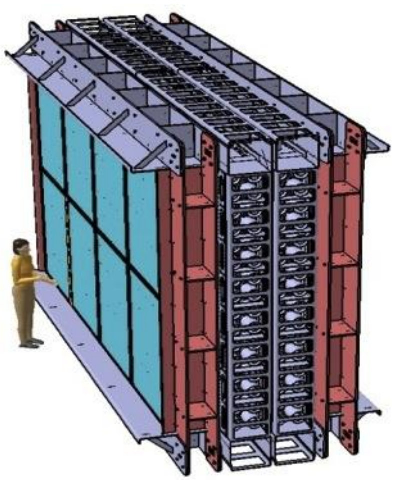
	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$\langle m_\nu \rangle$ sensitivity	200 – 400 meV	40 – 100 meV

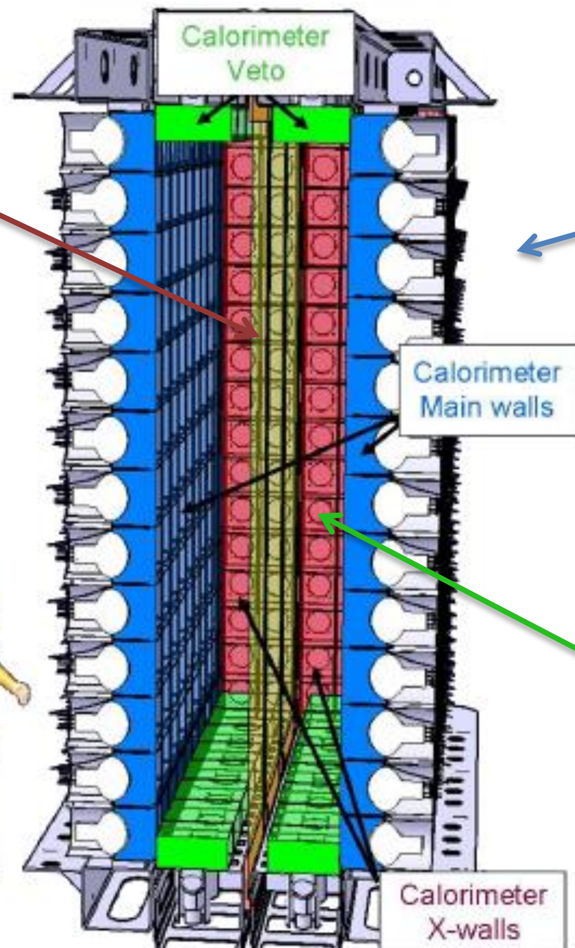
SuperNEMO

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

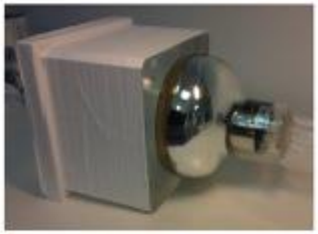
Global efficiency : 30 % (NEMO3 8%)

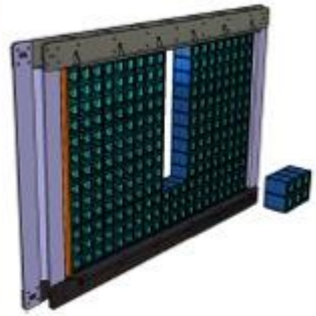
SuperNEMO Demonstrator status

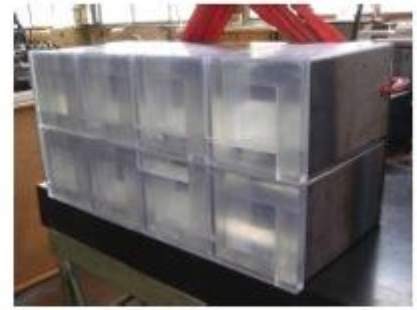
Calorimeter

- Scintillators production and 8'' Hamamatsu PMT's in production
- FE digitizer boards OK, control and trigger boards under development
- Blocks, wall design and technical tests OK → construction in progress 1st wall @ LSM in 2014

256 x 256 x 194 mm^3







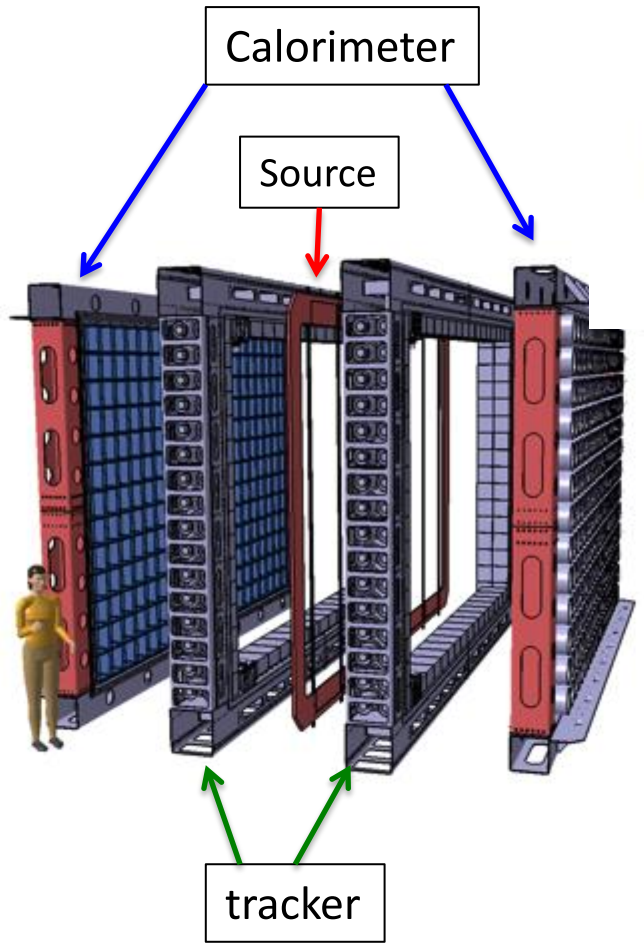
Tracker

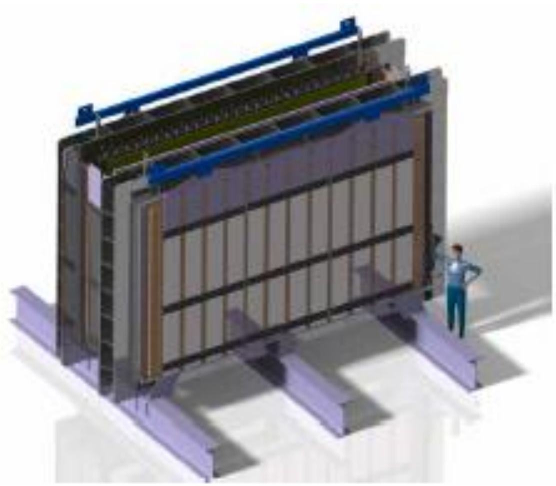
- Automated drift cells production ongoing with the wiring robot
- First 1 / 4 tracker C0 tested for radon emanation and cells propulation
- C0 commissioning at see-level and underground @LSM in 2014

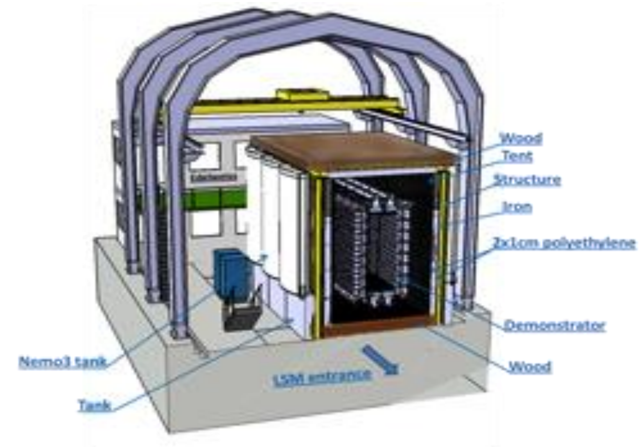
Source

- 5.5 kg of ^{82}Se , 4.5 kg already purified. Purchase of 1.5 kg in progress
- Source materials (glue, films,…) under HPGE and BiPO selection processes
- Calibration sources deployment system and LED survey system under test

SuperNEMO demonstrator module



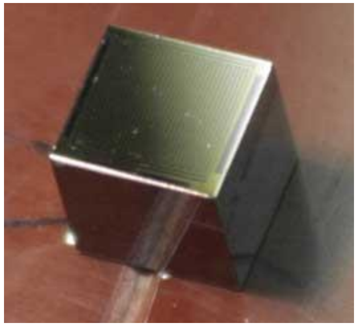


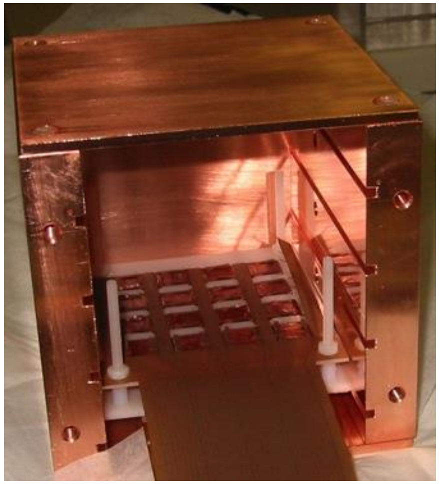


- Ultra low background detector
- Modular detector with 3 main components :
  - Central source foil frame : 7 kg of isotope
  - Tracking : 2 000 drift chambers
  - Calorimeter : 712 scintillators+ PMTs
- Shielded by iron (300 tons) and water
- Construction in progress
- Installation and commissioning at Modane Underground Laboratory 2015 – 2016
- Data taking 2016

No background expected for 2 years of data. 7 kg ^{82}Se $T_{1/2} > 6.6\ 10^{24}$ y $<m_\nu> < 0.16 – 0.44$ eV

Use large amount of CdZnTe Semiconductor Detectors

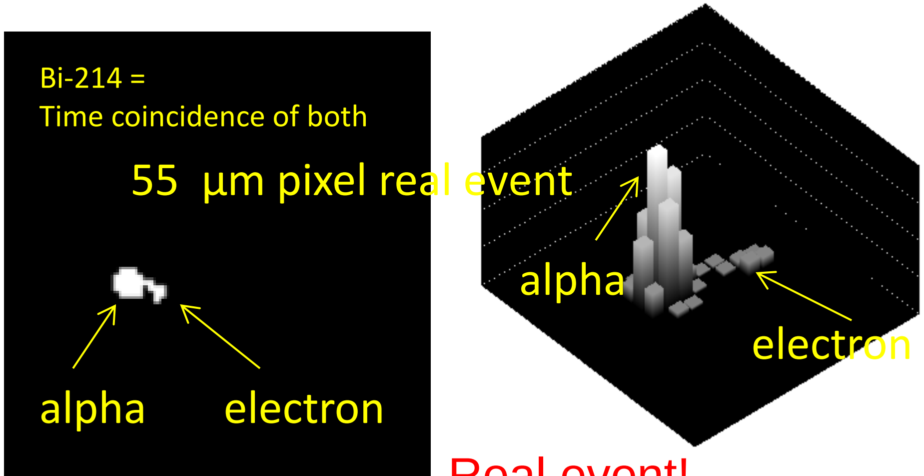




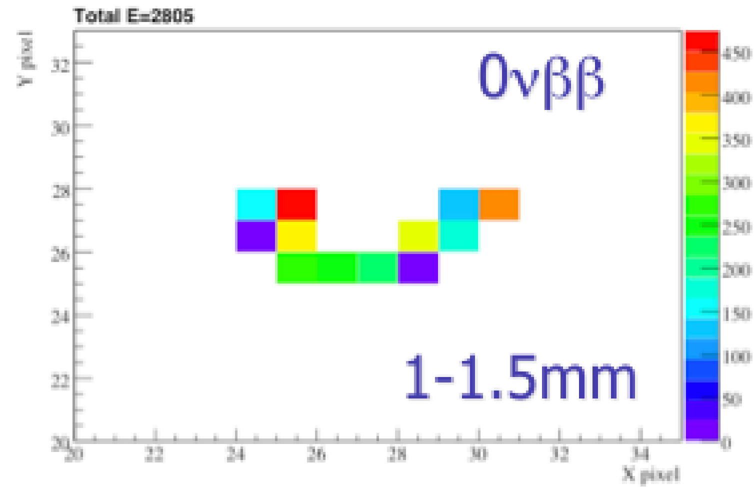
- Source = detector
- Focus on 116Cd
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Tracking/Pixelisation („Solid state TPC“)

K. Zuber, Phys. Lett. B 519,1 (2001)

Objective : Massive background reduction by particle identification

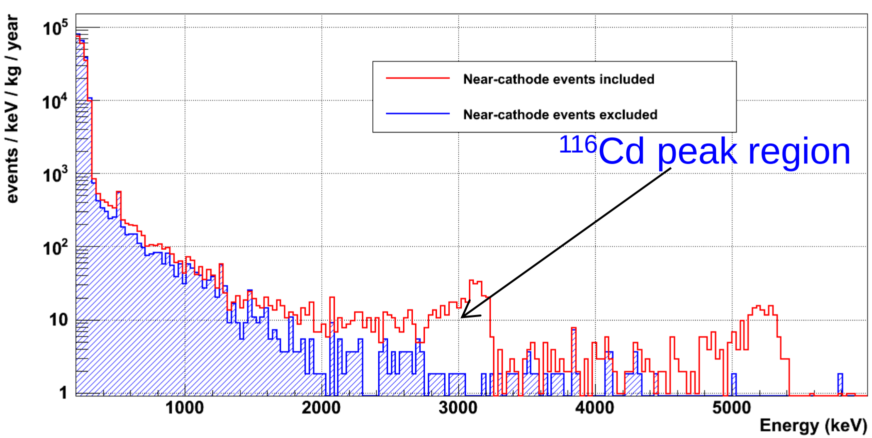


Real event!



Current spectrum (black), **12.73 kg*days**

Background at 2813 keV about 1 ct/keV/kg/yr



Currently ongoing upgrade:

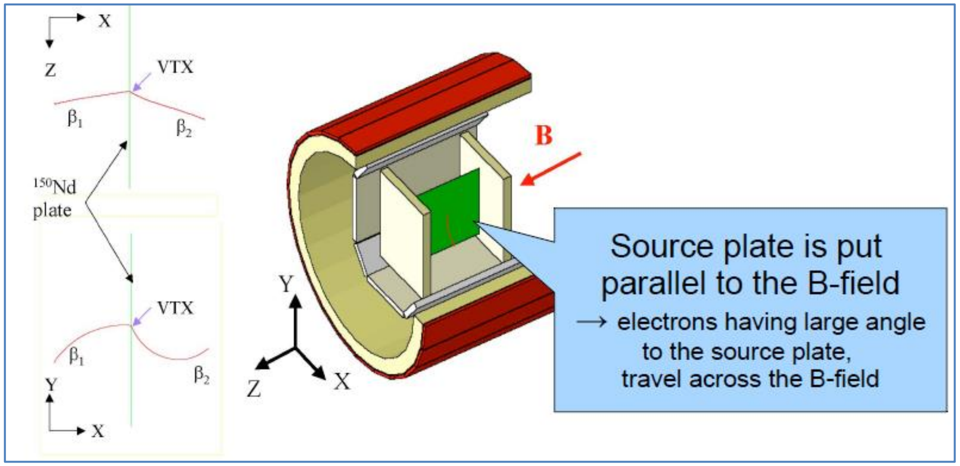
- 64 detectors (in hand) 32 running at LNGS
- Pulse shape information
- rejection of surface events

Magnetic Tracking Detector (DCBA)

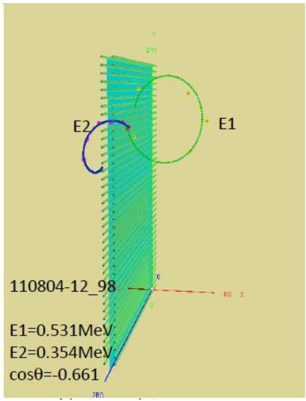
MTD (Magnetic Tracking Detector: temporary name) following of DCBA

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

Expected Energy Resolution 3.4% at $Q_{\beta\beta}$ for ^{150}Nd



Multi-isotope ^{150}Nd, ^{100}Mo, ^{82}Se
Several modules to reach $<m_\nu>$ 50 meV



DCBA-T2.5

2005 DCBA	• charge dividing • 6 mm pitch wires (xy + xz)
2007 DCBA-T2	• ^{100}Mo source (natural Mo 30g) • 0.6 - 0.8 kG magnetic field • Normal conducting magnet: 9h/day operation (Mon.-Fri)
2011 DCBA-T2.5	• 6 mm pitch wires (xy + xz) • ^{100}Mo source (natural Mo 30g) • 0.8 kG magnetic field • super-conducting magnet: 24h nonstop operation
now 2014 DCTA-T3	• 3 mm pitch wires (xy + xz)*8 • ^{150}Nd (5.6% in natural Nd_2O_3) • B=3 kG at the maximum
2017 MTD (tentative name)	• ^{82}Se ^{150}Nd(enriched) several 10 kg

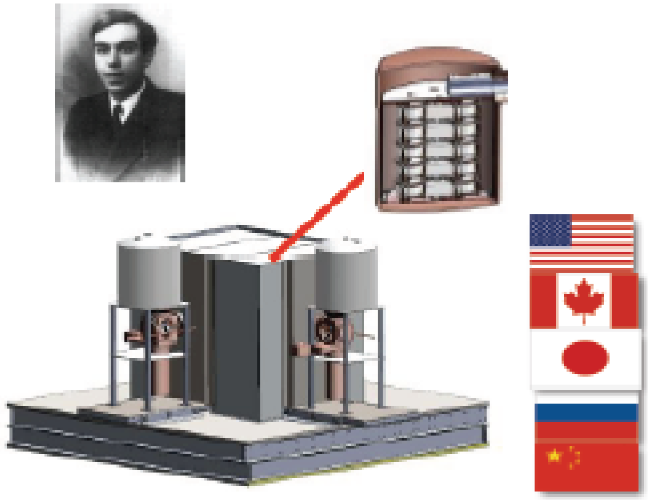
DCBA-T2 Chamber installed into the DCBA-T3 SC-Magnet

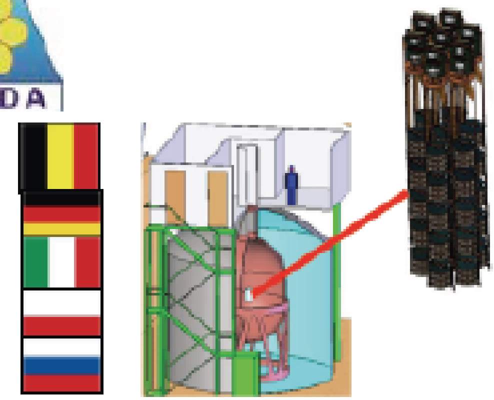
Calorimetric experiments

GERDA II	In progress
CUORE	In progress
KamLAND-Zen	In progress
CANDLES	Data taking
SNO+	In preparation
MAJORANA	Completion of R&D
LUCIFER	R&D
$ZnMoO_4$	R&D
Amore	R&D
$CdWO_4$	R&D

Ge diodes

MAJORANA DEMONSTRATOR and GERDA





- ^{76}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg ^{76}Ge and 10 kg ^{nat}Ge PPC detectors

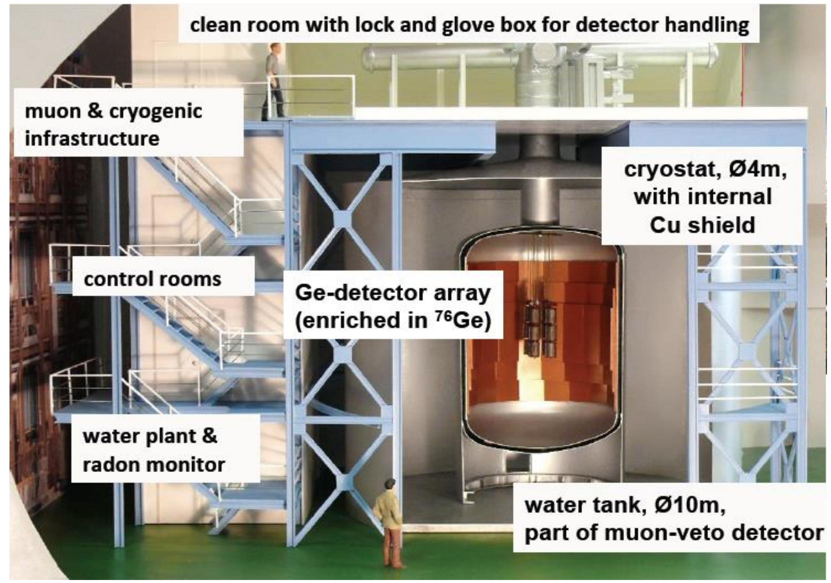
- ^{76}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: 18 kg (H-M/IGEX xtals)
- Phase II: +20 kg PPC detectors

Joint Cooperative Agreement:
Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale experiment
Select best techniques developed and tested in GERDA and MAJORANA

L. Winslow Neutrino 2014

GERDA II : Ge diodes

Ge detectors in liquid nitrogen installed @ LNGS



Phase I: 14.6 kg of enriched detectors

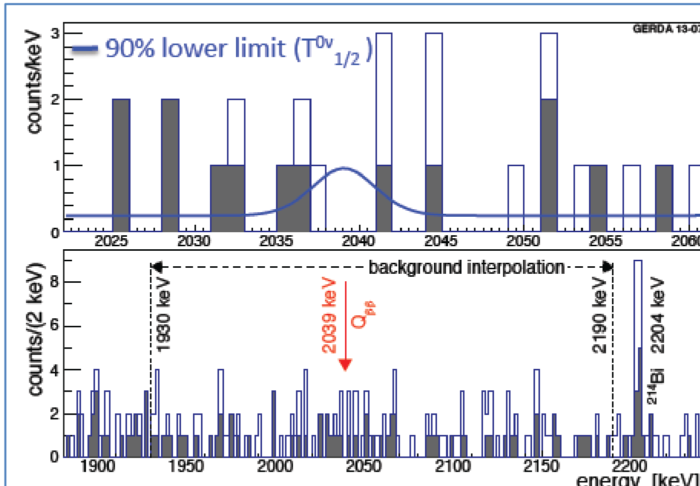
Background level after Pulse shape discrimination 0.01 cts/(keV.kg.yr).

Exposure 21.6 kg.yr

GERDA: $T_{1/2} > 2.1\ 10^{25}$ yr (90%CL)

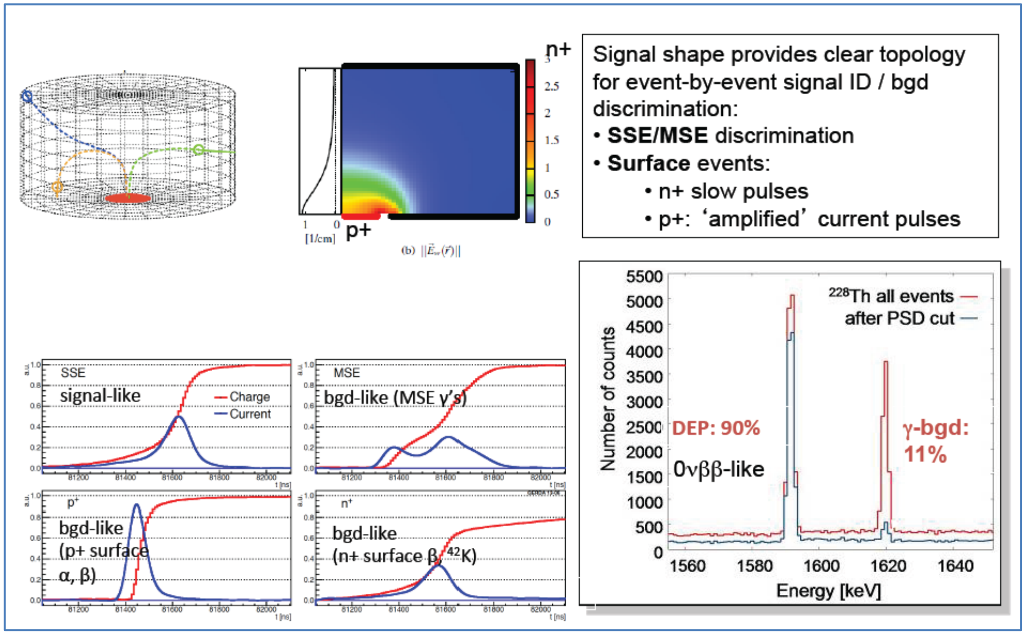
GERDA+ IGEX. HM $T_{1/2} > 3.0\ 10^{25}$ yr

$\langle m_\nu \rangle < 0.2 - 0.4$ eV



GERDA II : Ge diodes

Integration of the elements of GERDA phase II
40 kg of enriched Ge detectors



- First deployment of the liquid argon scintillation readout.
- First pilot string will be deployed together with the LAr scintillation read out.
- Deployment of the full array of enriched Ge detectors early next year.

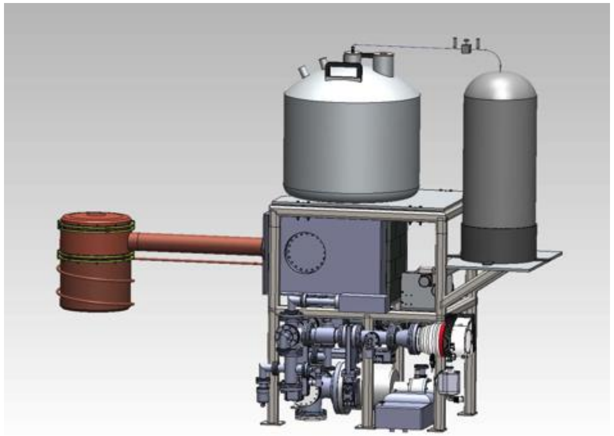
Phase II is designed to reach $T^{1/2} > 10^{26}$ years.

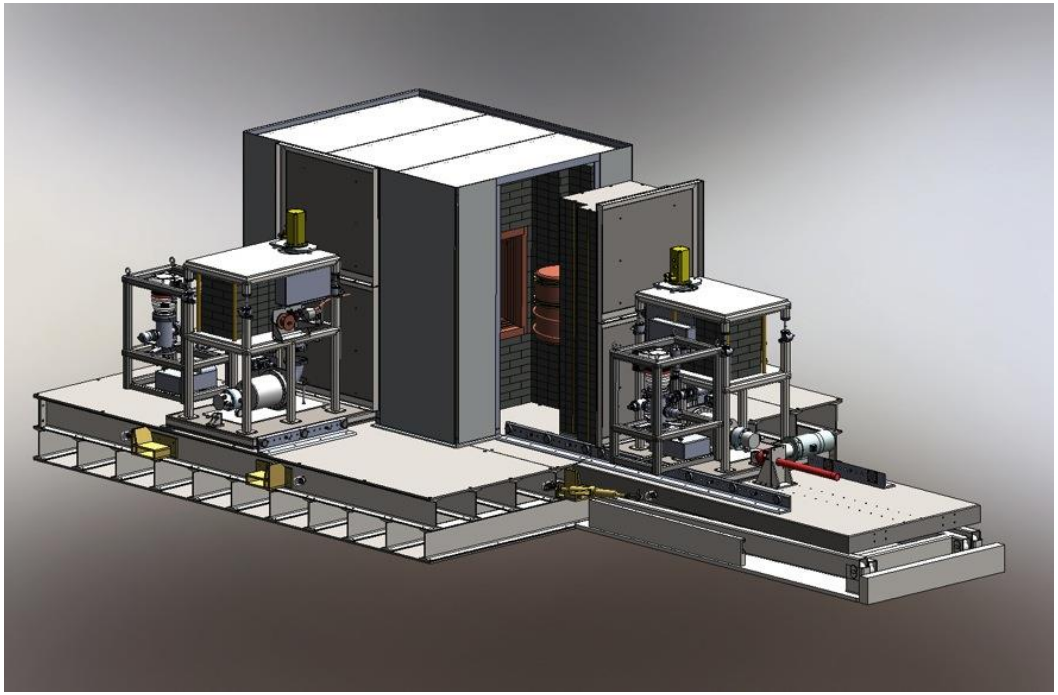
Majorana : Ge diodes

Improvement of the radiopurity of the materials, Pulse shape

- Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) **(Fall 2013)**
- Cryostat 2 (up to 7 strings ^{enr}Ge) **(Fall 2014)**

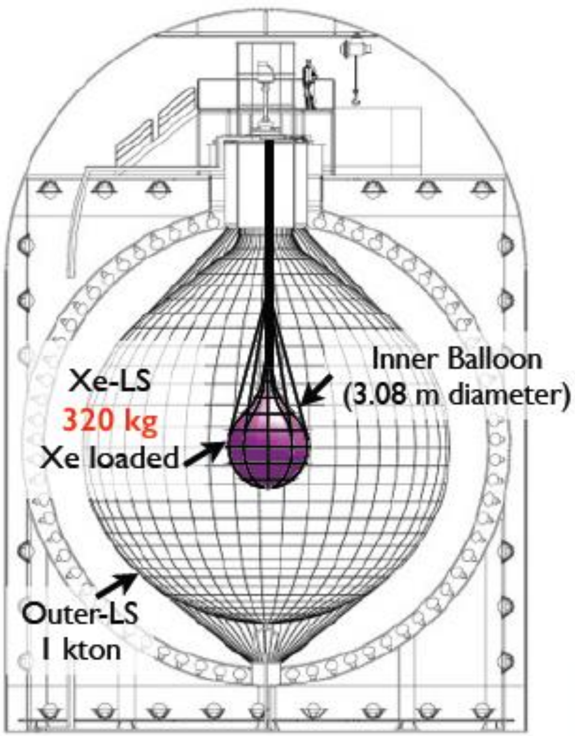
Final design of demonstrator 30 kg of ^{76}Ge and 10 kg of ^{nat}Ge





KamLAND-ZEN

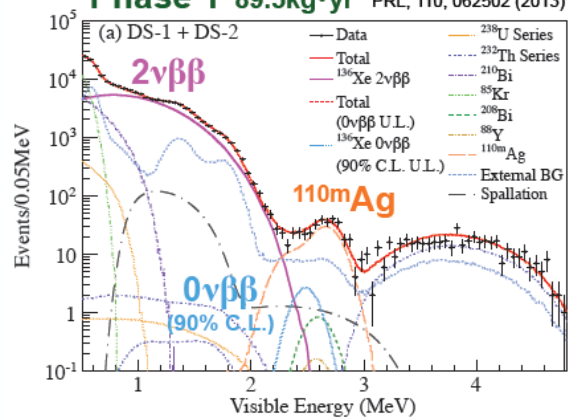
KamLAND-Zen (Kamioka)
Phase I



Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

$\sigma_E(2.5\text{MeV}) = 4\%$

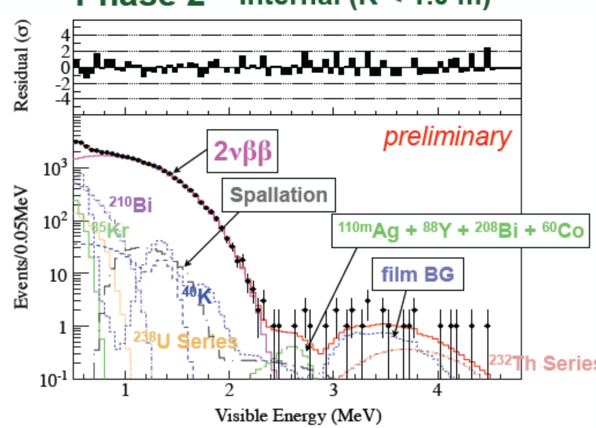
Phase 1 89.5kg•yr PRL, 110, 062502 (2013)



$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)

- Purification of liquid scintillator to remove ^{110m}Ag
- Improvement of spallation cut
- Improvement of fiducial volume selection

Phase 2 Internal (R < 1.0 m)



Half-life limit at 90% C.L.

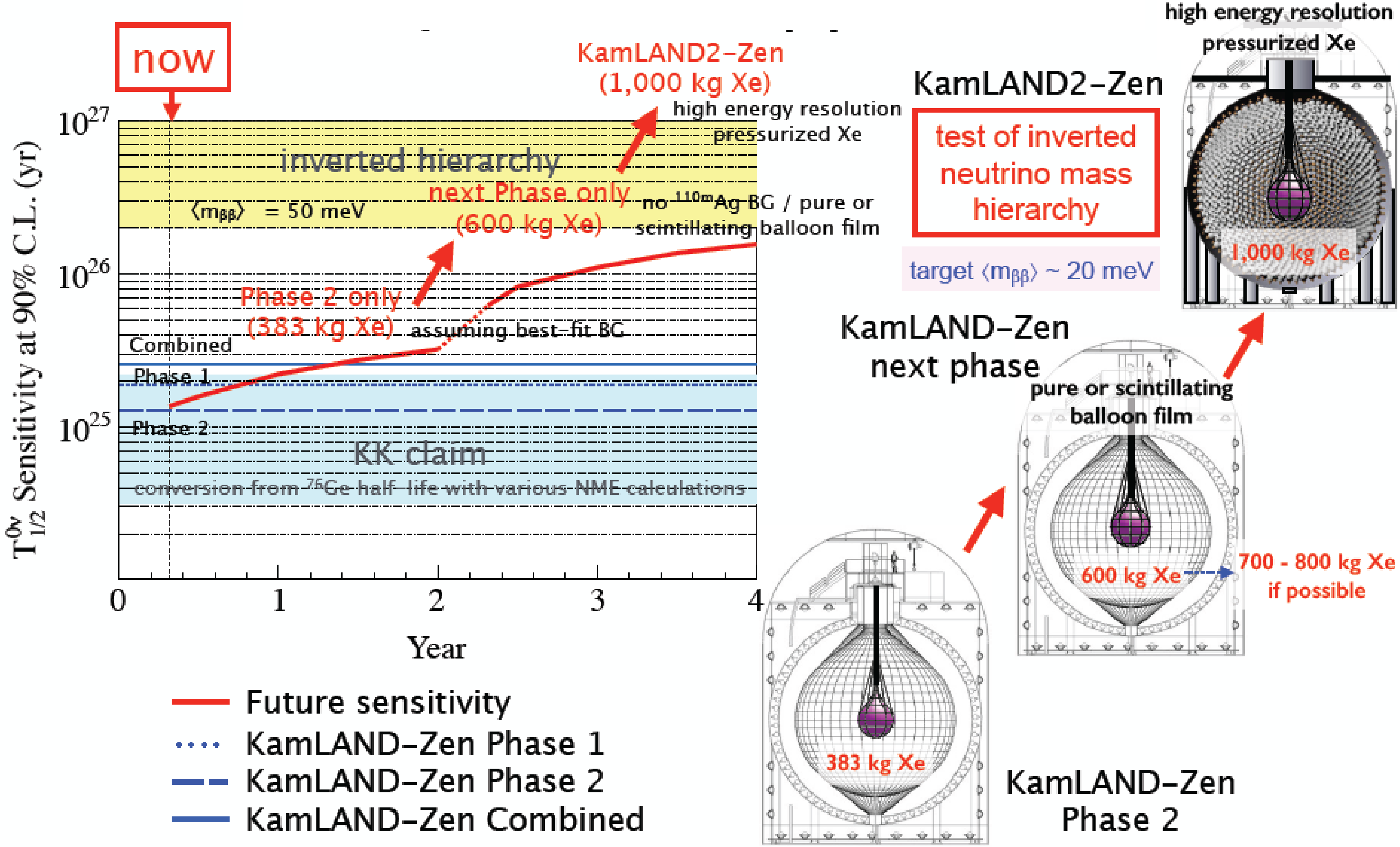
KamLAND-Zen

Phase 1	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14\text{-}0.28$ eV

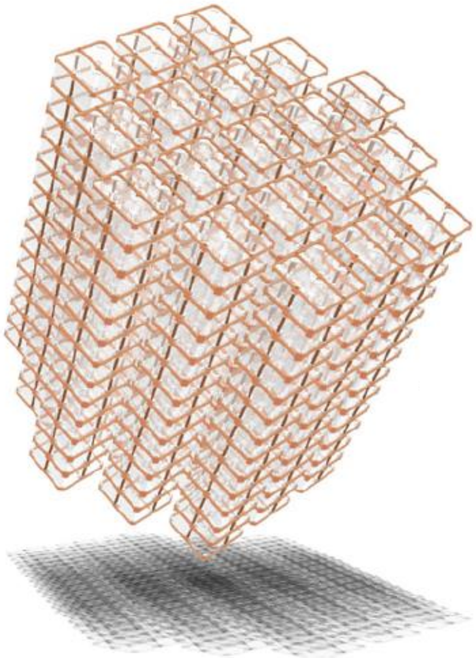
KamLAND-ZEN prospectives



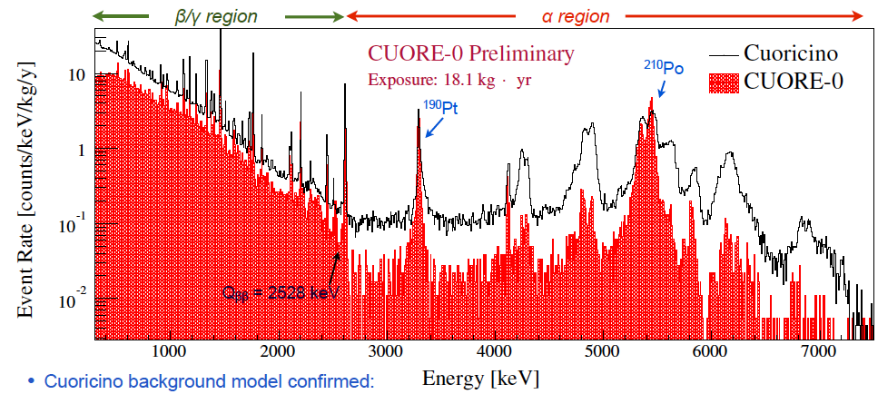
Detector improvements are planned in the near future

CUORE: bolometers

741 kg of TeO_2 bolometers (206 kg of ^{130}Te) @ LNGS



CUORE-0



- Cuoricino background model confirmed:

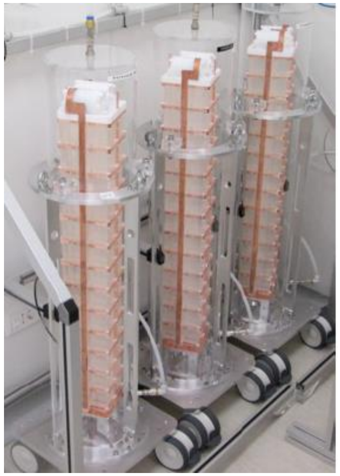
	0νββ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	0.063 ± 0.006	0.020 ± 0.001	78

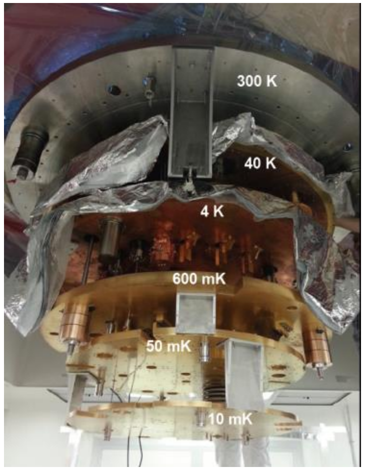
CUORE-0 has validated the energy resolution
And background results are encouraging

All the towers are assembled

Cryostat cooled down to 6 mK with 470 kg of Cu

Presently, cooling with 8 bolometers for test

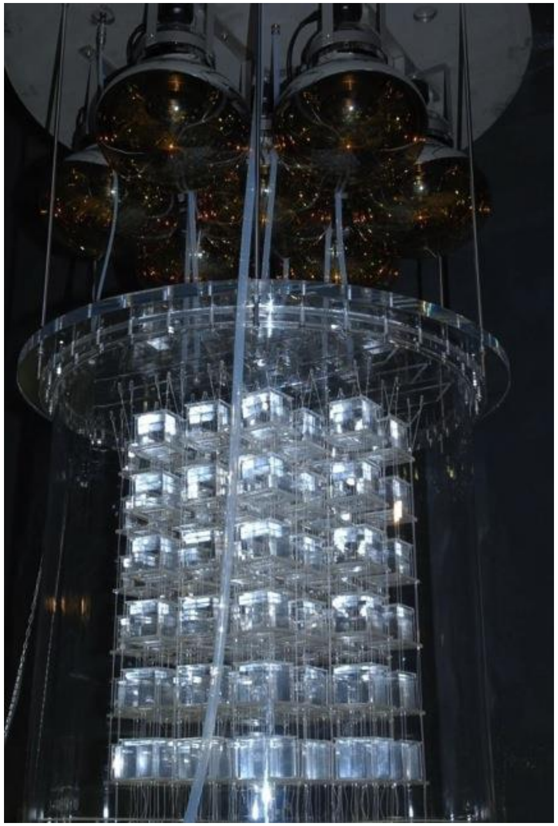


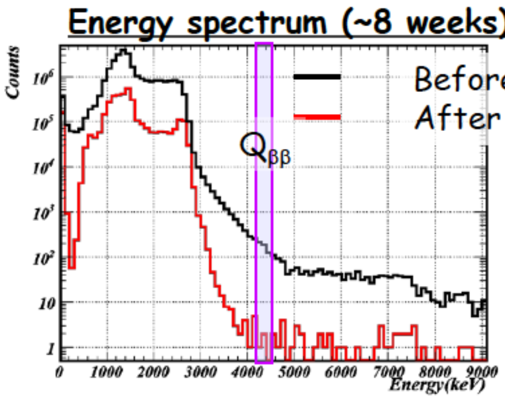


CANDLES III

96 CaF_2: 305kg (57 g of ^{48}Ca) + liquid scintillator
Measurement started in June 2011.

CANDLES III
@ Kamioka





	Pilot run data
Measurement time	4987 kg · days
Number of events	6
Expected BG	~1 (CaF_2 crystal) 3.4(γ-rays)
Sensitivity	0.8×10^{22} year

Cooling system(~0℃) (october 2014)

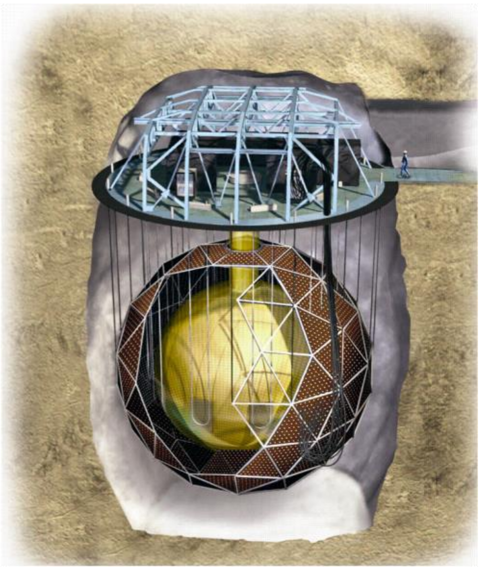
Coils to compensate magnetic filed

Improvement of energy resolution 4% (FWHM) @ $Q_{\beta\beta}$

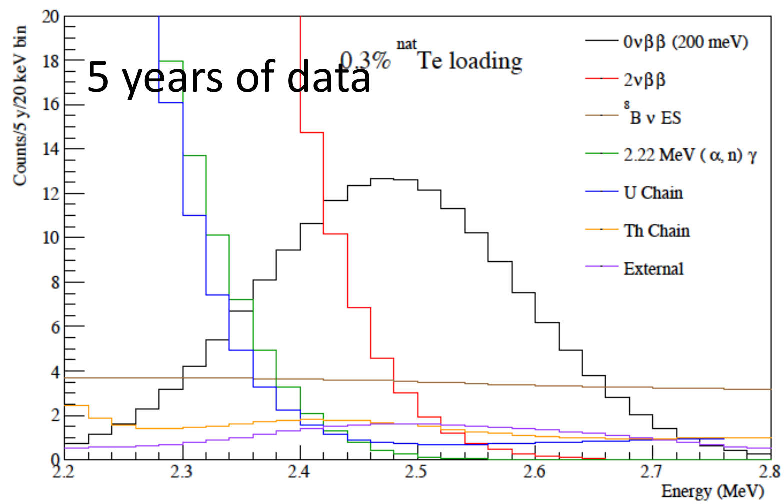
Enrichment of 48Ca (2%)

SNO+

^{Nat}Te dissolved in liquid scintillator (0.3% corresponding to 800 kg of ^{130}Te

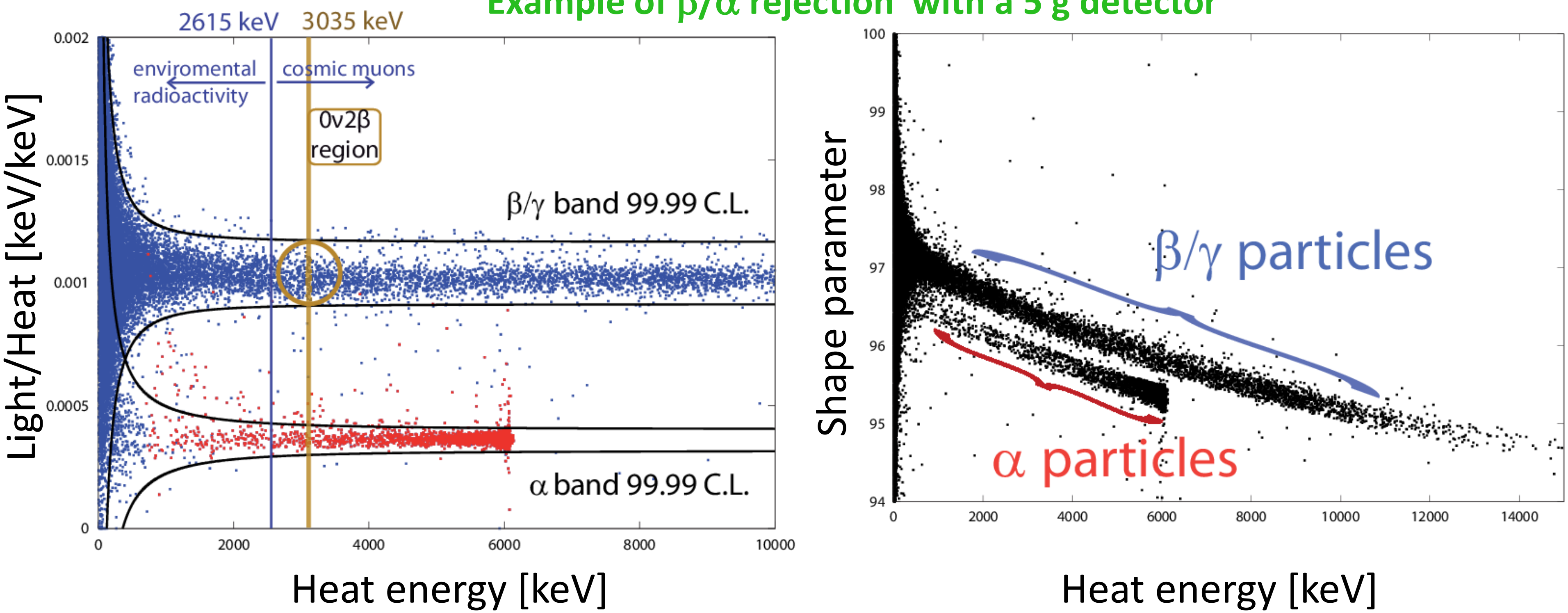


- electronics and DAQ upgrades completed
- now filling the SNO+ detector with water
- water-filled data taking starts in 2014
  - to study external backgrounds and detector optics
- now installing liquid scintillator purification plant
- liquid scintillator fill to start in 2015
- installation of tellurium purification skid and Te purification in late 2015
- addition of Te to SNO+ liquid scintillator and DBD run in 2016



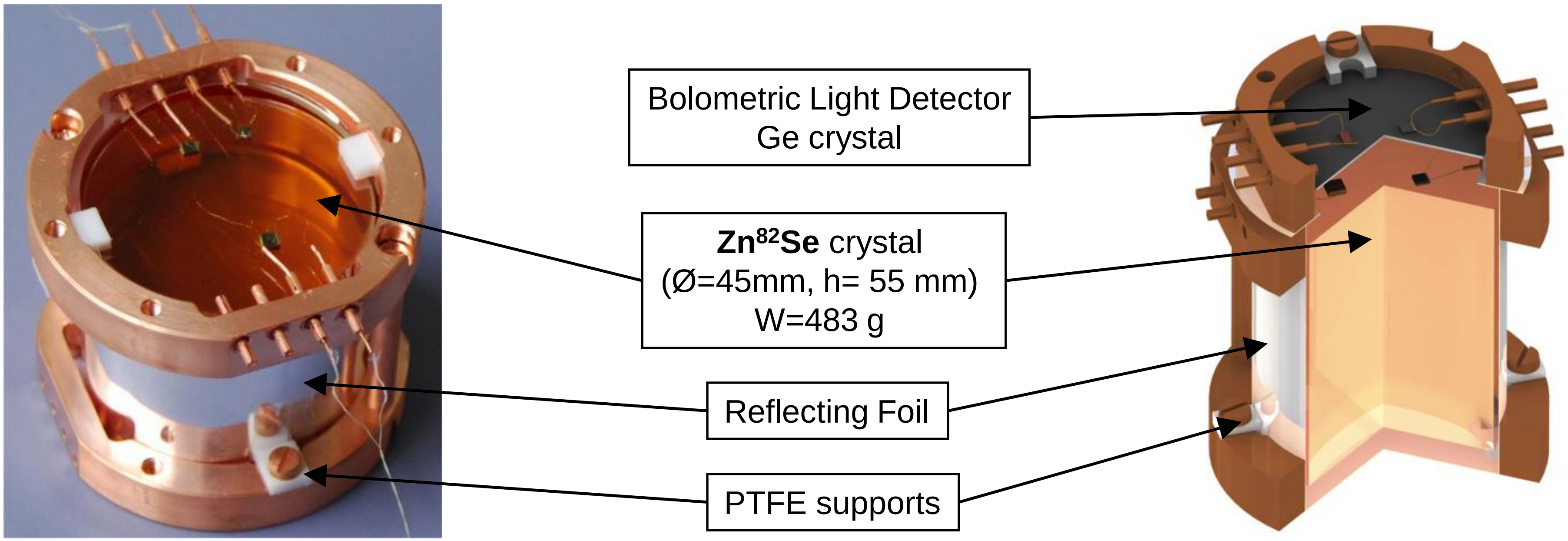
Scintillating bolometers

Example of β/α rejection with a 5 g detector



LUCIFER

Scintillating bolometers to recognize the α-induced background thanks to the readout of the scintillation light

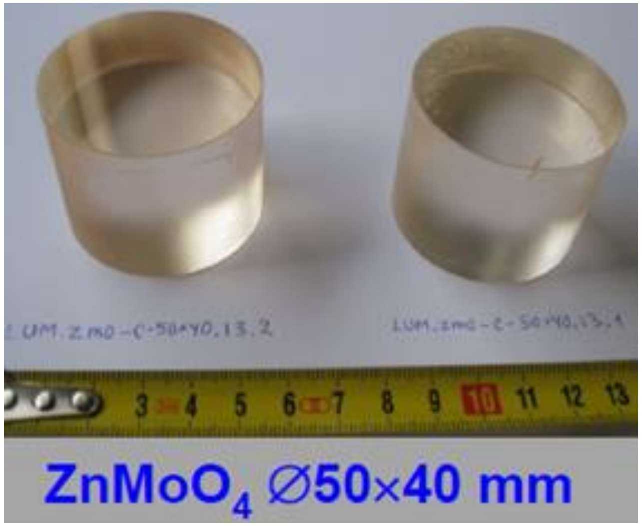


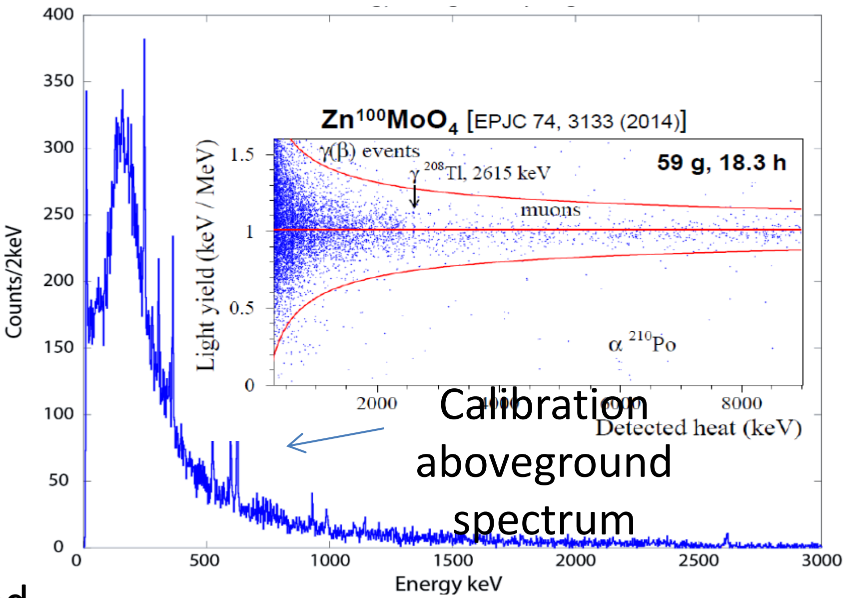
Array of 36$\div$44 enriched (95%) Zn^{82}Se crystals.

Expected background in the ROI (2995 keV) is ~ 3$\div$6 10^{-3} c/keV/kg/y

Energy resolution ~10 keV FWHM

LUMINEU





Two enriched crystals of 60 g each obtained

Excellent performance aboveground (CSNSM, Orsay)

No difference with respect to natural crystals

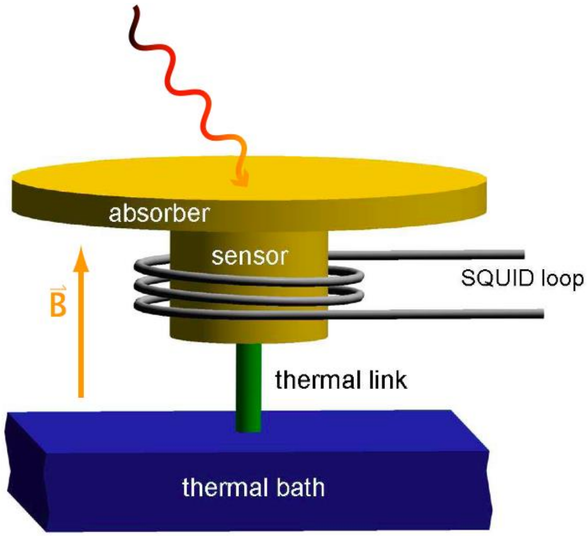
nderground tests of a few large mass enriched crystals (foreseen within June 2015)

- If radiopurity is confirmed:

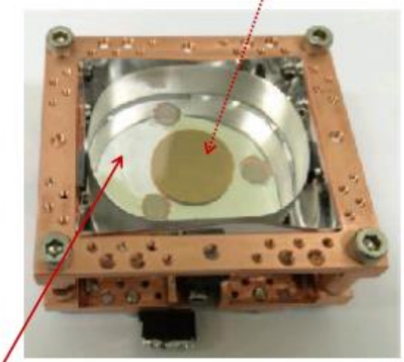
Start-up of **LUCINEU project** (LUCIFER+LUMINEU)

- Systematic production of ~ 40 crystals containing ~ 7 kg of ^{100}Mo (MoU INFN+IN2P3+ITEP)
- Cool down of this 40 crystal array during 2016 in LNGS and/or LSM (depending on cryostat availability)

(**A**dvanced **Mo**-based **R**are process **E**xperiment)



on bottom surface



196 g $^{40}Ca^{100}MoO_4$
(doubly enriched crystal)

$^{40}Ca^{100}MoO_4$ bolometers
15 keV FWHM, Eff = 0.8

AMoRE Pilot, 2015
5 bolometers de CaMoO → 1,5 kg

Stage	Start (run, yr)	Background (yr/keV/kg)	Sensitivity lim $T_{1/2}$ (yr)	$\langle m_\nu \rangle$ (eV)
AMoRE pilot	Jan. 2015 (1)	0.01	~1.5×10^{24}	<0.3 – 0.9
AMoRE 10	Sep. 2016 (3)	0.002	~2×10^{25}	0.08 - 0.22
AMoRE 200	Jan. 2019 (5)	0.0002	~4×10^{26}	0.016 - 0.047

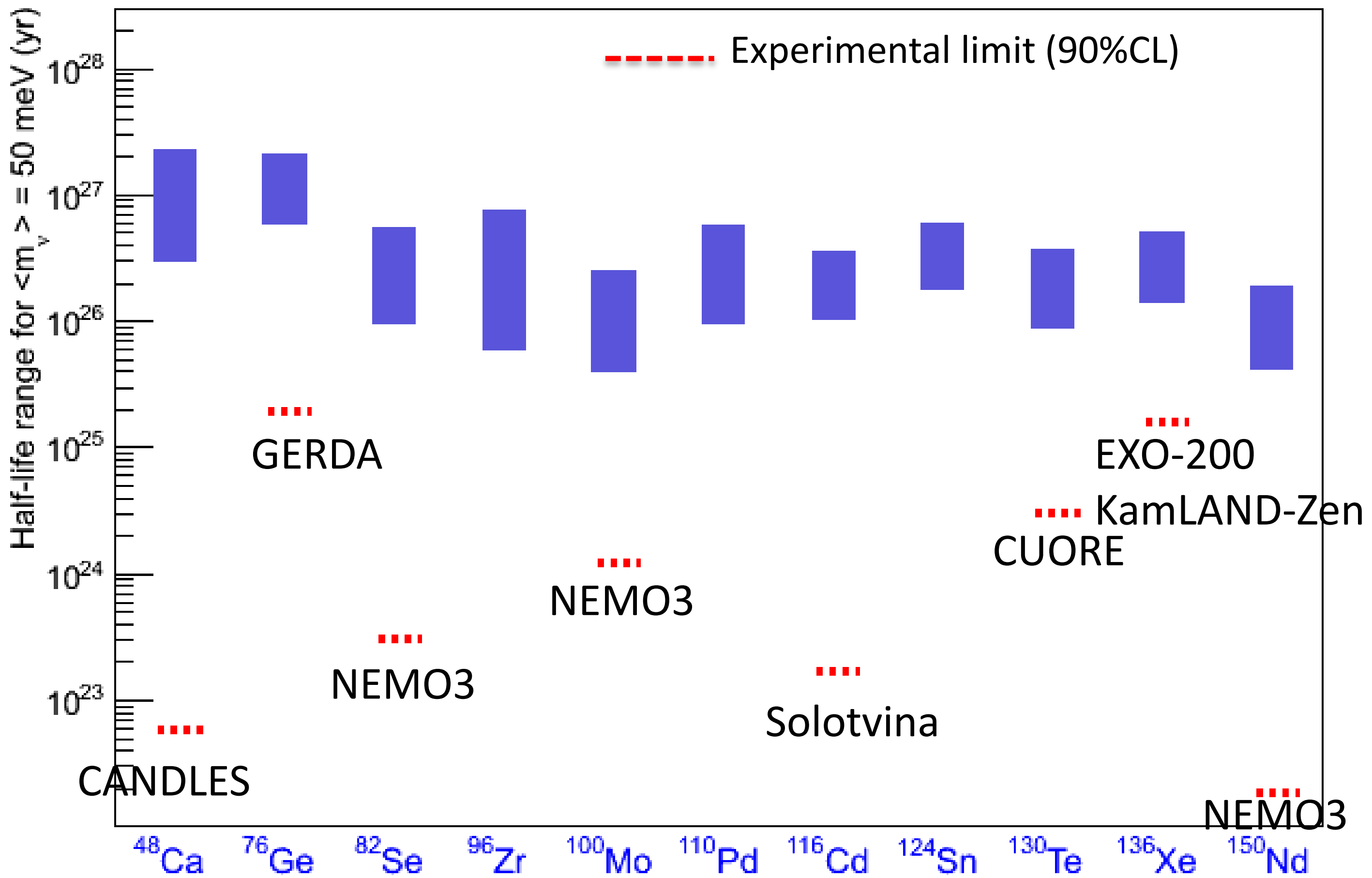
Studied isotopes

- ^{116}Cd → COBRA, $CdWO_4$
- ^{76}Ge → GERDA, MAJORANA
- ^{82}Se → SuperNEMO, LUCIFER
- ^{136}Xe → KamLAND-Zen, EXO - NEXO, NEXT
- ^{100}Mo → Lumineu, AMoRE
- ^{130}Te → CUORE
- $^{Nat(48)}Ca$ → CANDLES
- $^{Nat(150)}Nd$ → SNO+, Borexino

A dream ?

- ^{48}Ca → CANDLES, SuperNEMO, AMoRE
- ^{150}Nd → SNO+, SuperNEMO, MTD, Borexino

Half-life to reach for $\langle m_\nu \rangle$ = 50 meV



Summary

- **Present experiments at the level of $T_{1/2} > 10^{24} - 10^{25}$ years**
  $<m_\nu> < 0.15 - 0.5$ eV

- **Several experiments at 100 kg are needed to understand backgrounds and determine the best isotope and technique for higher mass**

- **Sensitivity : $T_{1/2} > 10^{26} - 10^{27}$ years**
  $<m_\nu> < 0.05 - 0.1$ eV
  Starting to test of the inverted hierarchy scenario

- **2015 - 2016 : starting of GERDA II, Majorana, SuperNEMO, SNO+, CUORE, scintilating bolometers**

- **Still a long way to reduce the background.**

- **In case of signal a tracking experiment will be needed to confirm it**