Double beta decay: history and current status

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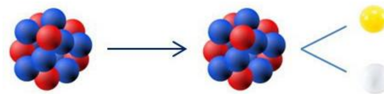
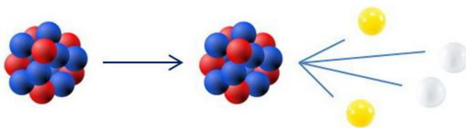
Oxford University, October 21, 2014, Oxford, UK

Contents

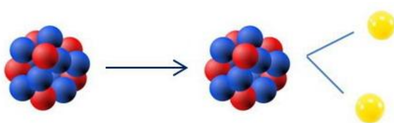
What is double beta (2β) decay

Single beta decay  $(A,Z) \rightarrow (A,Z+1) + e^{-} + \tilde{\nu}_e$

Two neutrino (2ν) double beta decay $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\tilde{\nu}_e$



Neutrinoless (0ν) double beta decay $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$



2β2ν - fully allowed in SM (however, very rare, $T_{1/2} \cong 10^{18} – 10^{24}$ y for already observed decays)

2β0ν - forbidden in SM (because of ΔL=2, not observed yet, $T_{1/2} > 10^{23} – 10^{25}$ y for the best experiments; predicted by many theories)

Also: $2\beta^{+}$ decay (emission of positrons instead of electrons), EC/β^{+} (electron capture + emission of β^{+}), 2EC process, 2β0νM (emission of one or two Majorons)

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

$$n_1 \rightarrow p_1 + e^- + \tilde{\nu}_e$$
$$\downarrow$$
$$\nu_e + n_2 \rightarrow p_2 + e^-$$

$2\beta0\nu$ requires:

1. $\tilde{\nu}_e = \nu_e$ (neutrino is Majorana particle; Dirac – $\tilde{\nu}_e \neq \nu_e$)
2. $m(\nu_e) \neq 0$ (or right-handed admixtures in weak or strong interactions, or …)

2β occurs in any system when $M_{at}(A,Z) > M_{at}(A,Z\pm2)$
However, for practical reasons, (A,Z) should be “stable” or long-living ($\beta^\pm$ should be forbidden energetically or suppressed by big change in spin/parity)

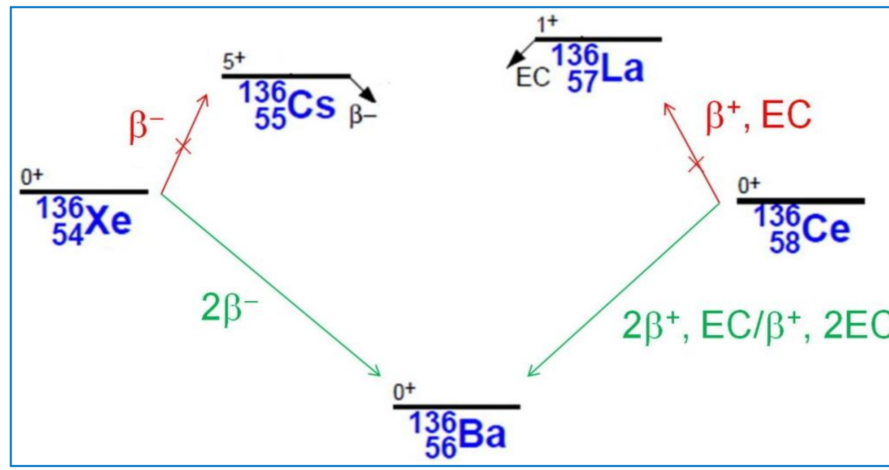


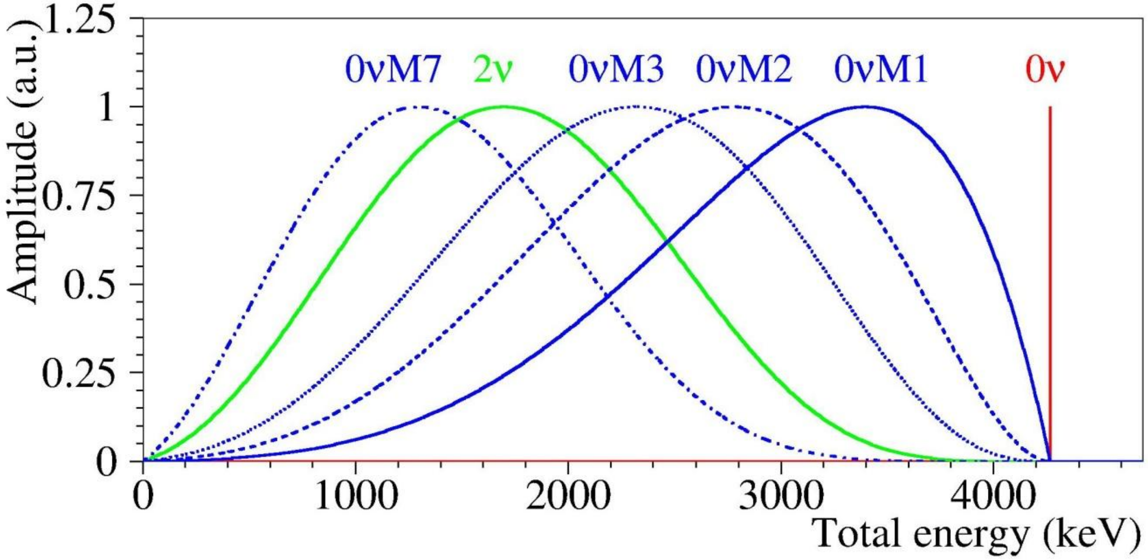
Table of Isotopes: around 3500 nuclides, but only 69 2β candidates (35 $2\beta^-$ and 34 $2\beta^+$)

Maximal energy release: $^{48}Ca \rightarrow {}^{48}Ti$, $Q_{2\beta} = \Delta M_{at} = 4.267$ MeV

Why $2\beta 0\nu$ is important?

- $\Delta L=2$ (new physics beyond SM; $\Delta L \rightarrow \Delta B$, matter-antimatter assymetry of the Universe)
- ν is Majorana or Dirac particle (Majorana gives see-saw mechanism to explain smallness of ν masses)
- absolute scale of neutrino masses (ν oscillations give only $m^2(\nu_i) - m^2(\nu_j)$) and masses hierarchy
- right-handed admixtures in weak and strong interactions
- sensitivity to some theoretical parameters SUSY, GUT, …
- existence of Majorons

Energy distributions in different modes of 2β decay (sum of e^- energies)

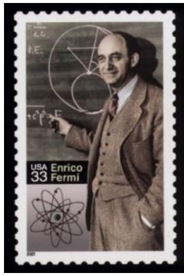


Experimental methods of 2β researches:

- Geochemical — Search for atoms of daughter (A,Z±2) in (A,Z) mother material accumulated during $10^6 - 10^9$ y (history and backgrounds are not controlled). First observation/indication of 2β decay (^{130}Te, 1950). Detected $2\beta^-$ – ^{82}Se, ^{96}Zr, ^{100}Mo, ^{128}Te, ^{130}Te; 2EC – ^{130}Ba.
- Radiochemical — History/bkg are controlled but time is limited (few tens of y). Detected $2\beta^-$ – ^{238}U.
- Direct detection — Preferred: bkg under control, many things can be measured (e^+ or e^- emitted, decay to g.s. or to excited level, 2ν or 0ν, total and individual e^- energies, angle between them, appearance of (A,Z±2) nuclei). Detected $2\beta^-2\nu$ – ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd; 2EC2ν – ^{78}Kr.

Brief history of 2β researches

1930 – Pauli, hypothesis on ν existence
1932 – Fermi, theory of β decay
1935 – Goeppert-Mayer, theor. idea of 2β2ν, $T_{1/2} \sim 10^{21}$ y
1937 – Majorana, Majorana neutrino
1939 – Furry, theor. idea of 2β0ν, $T_{1/2} \sim 10^{15}$ y
1948 – Fireman, first experiment, ^{124}Sn, $T_{1/2} > 3\times10^{15}$ y
1950 – Ingram & Reynolds, 1st geochem. evidence of 2β, ^{130}Te, $T_{1/2} = 1.4\times10^{21}$ y
1950 – Levine et al., 1st radiochem. exp., ^{238}U, $> 6\times10^{18}$ y
1966 – der Mateosian & Goldhaber, first use of "source = detector" approach, CaF_2 scint. enriched in ^{48}Ca (96.6% vs 0.187% of natural abundance), $> 2\times10^{20}$ y
1967 – Fiorini et al., 1st use of Ge(Li) to search for 2β0ν of ^{76}Ge, $> 3\times10^{20}$ y
1967 – Kirsten et al., 1st geochem. evidence of 2β of ^{82}Se, $T_{1/2} = 6\times10^{19}$ y
1975 – Hennecke et al., 1st geochem. ^{128}Te, 1.5×10^{24} y



1982 – Schechter-Valle theorem: if $2\beta0\nu$ is observed, $m(\nu) \neq 0$ and ν is Majorana

1984 – Fiorini & Niinikoski, proposal to use bolometers in search for $2\beta0\nu$

1987 – Elliott et al., 1st observation of $2\beta2\nu$ in direct exp. (36 events), ^{82}Se, $T_{1/2} = 1.1\times10^{20}$ y

1987 – Vasenko et al., 1st Ge detector enriched in ^{76}Ge to 86%

1990 – Vasenko et al., ^{76}Ge $2\beta2\nu$, 1st observation, $= 9.0\times10^{20}$ y

1990 – Vasenko et al., ^{100}Mo $2\beta2\nu$, 1st observation, $= 3.3\times10^{18}$ y

1991 – Turkevich et al., ^{238}U 2β, 1st observation, $= 2.0\times10^{21}$ y (radiochemical)

1993 – Artemiev et al., ^{150}Nd $2\beta2\nu$, 1st observation, $= 1.7\times10^{19}$ y

1995 – Ejiri et al., ^{116}Cd $2\beta2\nu$, 1st observation, $= 2.6\times10^{19}$ y

1996 – Balysh et al., ^{48}Ca $2\beta2\nu$, 1st observation, $= 4.3\times10^{19}$ y

1999 – Arnold et al., ^{96}Zr $2\beta2\nu$, 1st observation, $= 2.1\times10^{19}$ y

2001 – Klapdor-Kleingrothaus et al., ^{76}Ge $2\beta0\nu$, $> 1.9\times10^{25}$ y but also claim on observation with $T_{1/2} = 1.5\times10^{25}$ y

2001 – Meshik et al., ^{130}Ba 2EC, 1st observation, = 2.2×10^{21} y (geochemical)

2011 – Andreotti et al., ^{130}Te $2\beta0\nu$, > 2.8×10^{24} y

2011 – Ackerman et al., ^{136}Xe $2\beta2\nu$, 1st observation, = 2.1×10^{21}

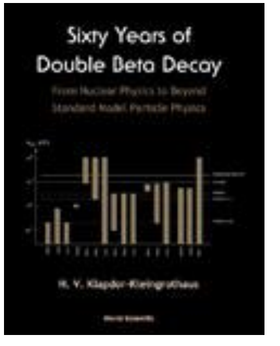
2013 – Gando et al., ^{136}Xe $2\beta0\nu$, > 1.9×10^{25} y

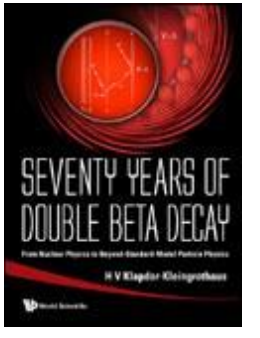
2013 – Gavrilyuk et al., ^{78}Kr 2EC2ν, 1st observation, = 9.2×10^{21}

2013 – Agostinelli et al., ^{76}Ge $2\beta0\nu$, > 2.1×10^{25} y

2014 – Arnold et al., ^{100}Mo $2\beta0\nu$, > 1.1×10^{24} y

Further historical details:
H.V. Klapdor-Kleingrothaus,
“Sixty years of double beta decay” (2001);
“Seventy years of double beta decay” (2010)
A.S. Barabash, Phys. At. Nucl. 74 (2011) 603.





Summary of current status of 2β2ν observations
(11 $2\beta^{-}2\nu$ and 2 2EC2ν, $T_{1/2} \cong 10^{18} - 10^{24}$ y)

They serves as **one of the best ways to test theoretical calculations for 2β0ν.**

List of nuclides for which 2β2ν processes was observed to-date or expected $T_{1/2}$ is < 10^{22} yr. $T_{1/2}^{2\nu,th}$ are calculated with semiempirical formula [Pri10]. Values of $T_{1/2}^{2\nu,exp}$, if not stated otherwise, are recommended values from [Bar13]. Energy release $Q_{2\beta}$ [Wan12] and natural abundance δ [Ber11] are also given.

No	Nuclide	$Q_{2\beta}$, keV	δ, %	$T_{1/2}^{2\nu,th}$, yr	$T_{1/2}^{2\nu,exp}$, yr
$2\beta^{-}2\nu$					
1	^{48}Ca	4267	0.187	$(2.6\pm1.3)\times10^{19}$	$=(4.4\pm0.6)\times10^{19}$
2	^{76}Ge	2039	7.73	$(8.5\pm4.3)\times10^{20}$	$=(1.6\pm0.1)\times10^{21}$
3	^{82}Se	2996	8.73	$(6.7\pm3.4)\times10^{19}$	$=(9.2\pm0.7)\times10^{19}$
4	^{96}Zr	3349	2.80	$(1.3\pm0.7)\times10^{20}$	$=(2.3\pm0.2)\times10^{19}$
5	^{100}Mo	3034	9.82	$(3.2\pm1.6)\times10^{19}$	$=(7.1\pm0.4)\times10^{18}$
6	^{116}Cd	2813	7.49	$(7.3\pm3.7)\times10^{19}$	$=(2.9\pm0.2)\times10^{19}$
7	^{128}Te	867	31.74	$(1.6\pm0.8)\times10^{24}$	$=(2.0\pm0.3)\times10^{24}$
8	^{130}Te	2528	34.08	$(4.0\pm2.0)\times10^{20}$	$=(6.9\pm1.3)\times10^{20}$
9	^{136}Xe	2458	8.86	$(4.5\pm2.3)\times10^{20}$	$=(2.2\pm0.1)\times10^{21}$
10	^{150}Nd	3371	5.64	$(5.8\pm2.9)\times10^{18}$	$=(8.2\pm0.9)\times10^{18}$
11	^{238}U	1144	99.27	$(1.9\pm0.9)\times10^{22}$	$=(2.0\pm0.6)\times10^{21}$
	^{110}Pd	2017	11.72	$(6.3\pm3.2)\times10^{20}$	$>6.0\times10^{16}$ [Bar87]
	^{124}Sn	2291	5.79	$(1.5\pm0.7)\times10^{21}$	$>1.0\times10^{17}$ [Bar87]
	^{148}Nd	1928	5.76	$(1.0\pm0.5)\times10^{21}$	–
	^{160}Gd	1731	21.86	$(7.2\pm3.6)\times10^{20}$	$>1.9\times10^{19}$ [Dan01]
2EC2ν					
12	^{78}Kr	2846	0.355		$=(9.2\pm5.7)\times10^{21}$ [Gav13]
13	^{130}Ba	2619	0.106		$=(2.2\pm0.5)\times10^{21}$

[Bar87] A.S. Barabash, preprint ITEP 56 (Moscow, 1987).
[Bar13] A.S. Barabash, AIP Conf. Proc. 1572 (2013) 11.
[Ber11] M. Berglund, M.E. Wieser, Pure Appl. Chem. 83 (2011) 397.
[Dan01] F.A. Danevich et al., Nucl. Phys. A 694 (2001) 375.
[Gav13] Yu.M. Gavrilyuk et al., Phys. Rev. C 89 (2013) 035501.
[Pri10] B. Pritychenko, preprint BNL-91299-2010, arXiv:1004.3280 [nucl-th].
[Wan12] M. Wang et al., Chinese Phys. C 36 (2012) 1603.

Rates of 2β2ν and 2β0ν decay:

$$\Gamma^{2\nu} = \frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q_{\beta\beta}, Z)|M^{2\nu}|^2, \qquad \Gamma^{0\nu} = \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \langle\eta\rangle^2.$$

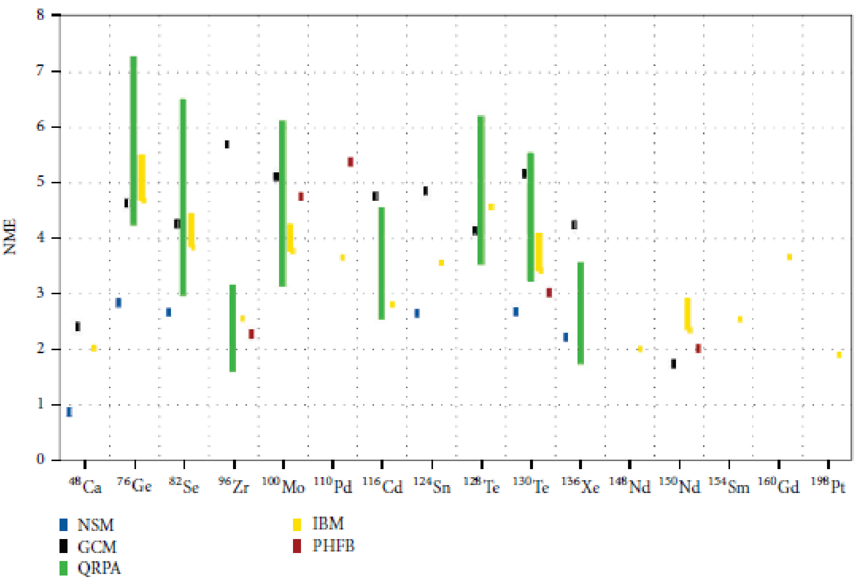
G – phase space factors ($\sim Z^3$, $\sim Q^5$ for 0ν and $\sim Q^{11}$ for 2ν)

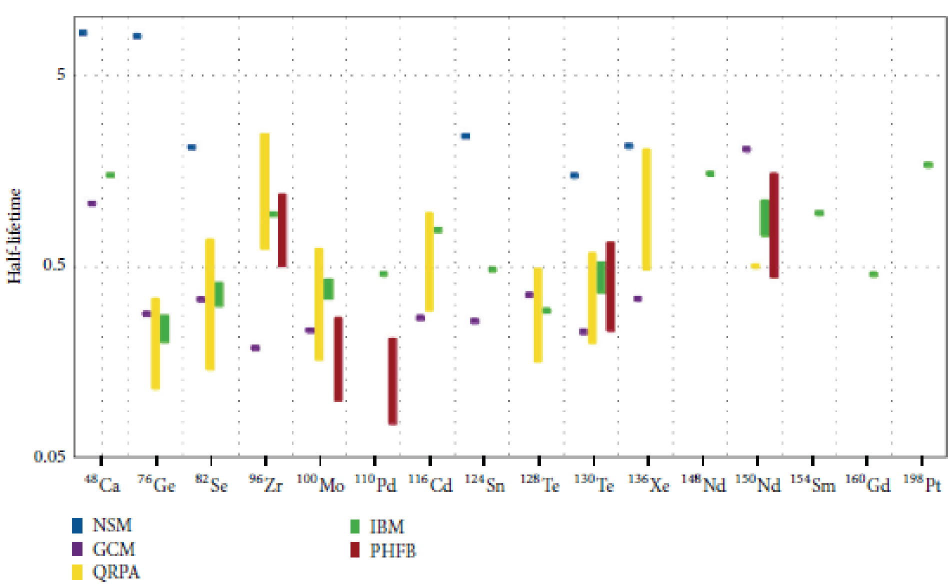
M – nuclear matrix elements (NME)

η – lepton number-violating parameter = $\langle m_\nu \rangle / m_e$ for mass mechanism (and we know from ν oscillations experiments that ν is massive: $\Delta m_{21}^2 \cong 7.5\times10^{-5}$ eV^2, $\Delta m_{32}^2 \cong 2.5\times10^{-3}$ eV^2)

NME and $T_{1/2}^{0\nu}$ in 10^{26} y for $\langle m_\nu \rangle$ = 50 meV

(from O. Cremonesi et al., AHEP (2014) 951432)





What means $T_{1/2}^{0\nu} = 10^{25}$ y:

$dN/dt = (-\ln 2/T_{1/2}) \times N$, 1 kg of ^{100}Mo (100%): $N = 6\times10^{24}$,
so during dt = 1 y we will have 0.4 decays

To see such a small number of decays we need:

– big mass (1 – 10 – 100 – 1000 kg)
– go underground to avoid background from cosmic μ and induced radioactivity
– ultra-pure detector itself and surrounding materials
– big time of measurements; perfect energy and time resolutions
– possibility to discriminate signals from e^-, γ, α, noise, pile-ups

Contamination in 1 μBq/kg by ^{238}U (= 8×10^{-14} g/g – good purity) will produce during 1 y 31 decays ($\times$ 14 = 442, if chain is in equilibrium)

Best $T_{1/2}$ limits for $2\beta0\nu$ decay:

^{76}Ge	> 2.1×10^{25} y (GERDA)	^{116}Cd	> 1.7×10^{23} (Solotvina)
^{82}Se	> 3.2×10^{23} y (NEMO-3)	^{130}Te	> 2.8×10^{24} (CUORICINO)
^{100}Mo	> 1.1×10^{24} y (NEMO-3)	^{136}Xe	> 1.9×10^{25} (KamL-Zen)

False discoveries in history of 2β decay searches

Because 2β investigations were always on the edge of human possibilities & technologies, there were several (~10) "discoveries" (2β2ν and 2β0ν) which were not confirmed in subsequent experiments. The reason was not the poor efforts (in experimenting or interpreting), but difficulty of the problem.

V.R. Lazarenko, Phys. Uspekhi 90 (1966) 601:
"… Double beta decay was "observed" more than once, however all these discoveries were disproved by subsequent experiments or raised doubts for some reasons …"

Full set of stories:
V.I.Tretyak, AIP Conf. Proc. 1417 (2011) 129 [arXiv: 1112.4183]
(see also slides at http://medex11.utef.cvut.cz/talks/TretyakVladimir.pdf).

Only one example below to demonstrate challenges of experiments.

2β2ν decay of ^{82}Se: 1980 – ^{82}Se

M.K. Moe, D.D. Lowenthal, Phys. Rev. C 22 (1980) 2186

13.75 g of Se (enriched in ^{82}Se to 97%) in form of foils of 5.6 mg/cm^2 (7.5 mg/cm^2 with Mylar), preliminary selection of all materials with NaI detector, cloud chamber with magnetic field (1 kG) + multiwire proportional counter, measurements at the Earth surface, shield of iron (>38 cm) and lead (15 cm).

Very detailed article (18 p) with thorough analysis of all possible sources of mimicking events. Measurements of E of each e$^-$ and angle between them.

Result: 20 events of 2e$^-$ (5 were caused by ^{214}Bi); good agreement between expected and measured spectra for energies of single electrons, their sum and opening angle

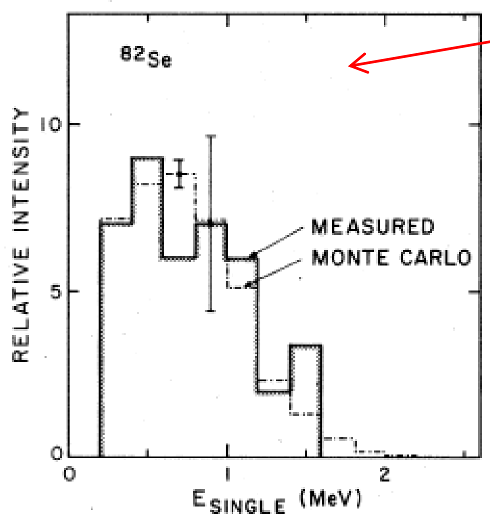


FIG. 12. The predicted and measured single electron energy spectra for negatron pairs from ^{82}Se.

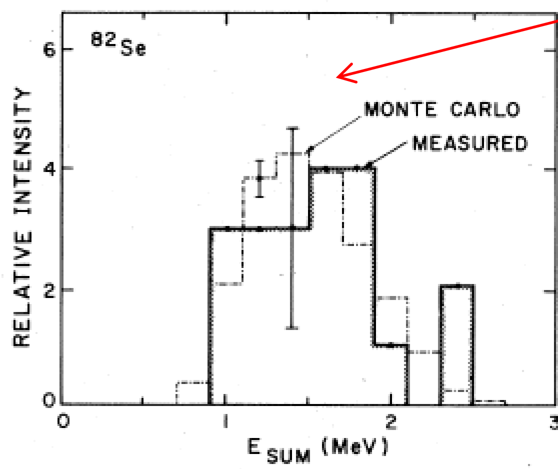
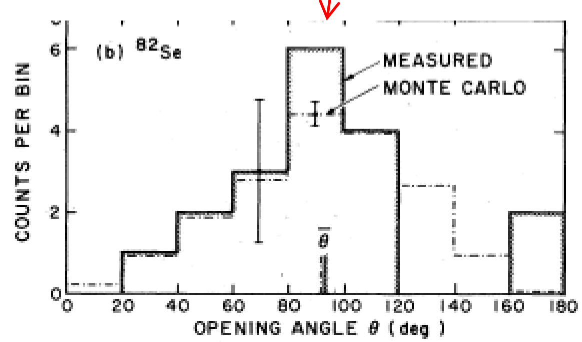


FIG. 13. The predicted and measured electron sum energy spectra for negatron pairs from ^{82}Se.



Abstract:

Pairs of negative beta particles have been observed originating from a ^{82}Se source during a cloud-chamber search for double beta decay. Backgrounds recognized in previous experiments were suppressed to well below the observed event rate, and no other significant backgrounds are apparent. Within the limited statistics of the small data sample, the observed single-electron energy spectrum, the two-electron sum energy spectrum, and the opening angle distribution are consistent with expectation for neutrino-accompanied double beta decay of ^{82}Se. The tentative assignment of the observed events to double beta decay, results in a ^{82}Se half-life of $(1.0 \pm 0.4) \times 10^{19}$ years, in good agreement with some very recent theoretical predictions. However, the result is in serious disagreement with the much longer half-lives measured in geochemical experiments. A planned follow-up experiment is described.

Electrons emitted simultaneously from one point. Agreement for single-electron spectrum, two-electron spectrum, opening angle and (some) theoretical predictions … The dream of experimentalist … Only one drawback: inconsistency with geochemical 2β $T_{1/2} \sim 10^{20}$ y.

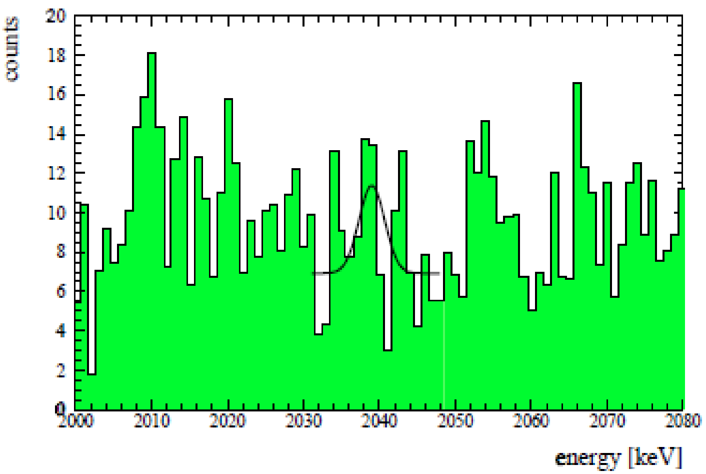
Next measurements of S.R. Elliott, A.A. Hahn, M.K. Moe with new apparatus – TPC with magnetic field – gave $T_{1/2} = (1.1^{+0.8}_{-0.3}) \times 10^{20}$ y [Phys. Rev. Lett. 59 (1987) 2020]. This work is considered as the first direct observation of 2β2ν decay (35 events during 7960 h). See reminiscences of Michael Moe in Annu. Rev. Nucl. Part. Sci. (2014).

Today value (NEMO-3, ~1 kg of ^{82}Se, 2750 events during 389 d, PRL 95 (2005) 182302): $T_{1/2} = (9.6 \pm 0.3) \times 10^{19}$ y

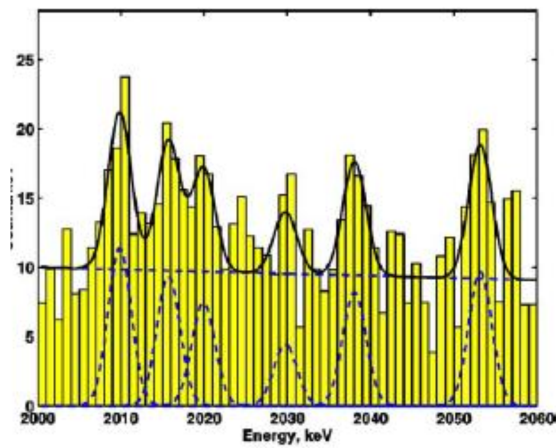
Recently finished 2β experiments: Heidelberg-Moscow (LNGS)

5 HP Ge detectors, ~86% enrichment in ^{76}Ge (11 kg of ^{76}Ge)
LNGS, 3600 m w.e., 1990-2003 – total statistics 71.7 kg×yr

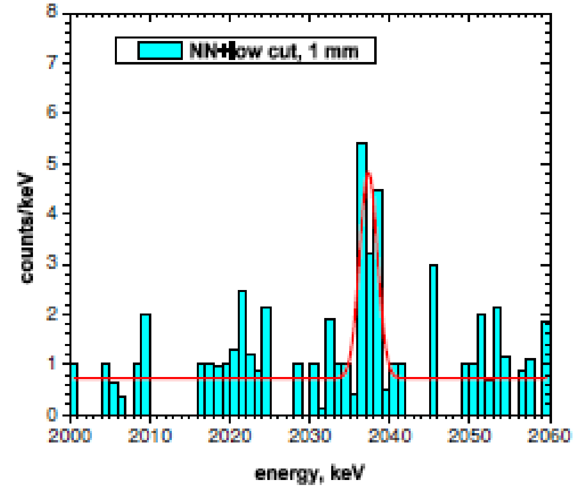
Claim of observation of $2\beta0\nu$ decay in ^{76}Ge (by part of HM collaboration):



MPLA 16 (2001) 2409:
55.0 kg×y, no PSA,
2.2-3.1σ effect
$T_{1/2} = 1.5_{-0.7}^{+16.8} \times 10^{25}$ y



PLB 586 (2004) 198:
71.7 kg×y, no PSA,
4.2σ effect
$T_{1/2} = 1.2_{-0.5}^{+3.0} \times 10^{25}$



MPLA 21(2006)1547:
PSA – 2 methods,
6.2σ effect
$T_{1/2} = 2.23_{-0.31}^{+0.44} \times 10^{25}$
(final value)

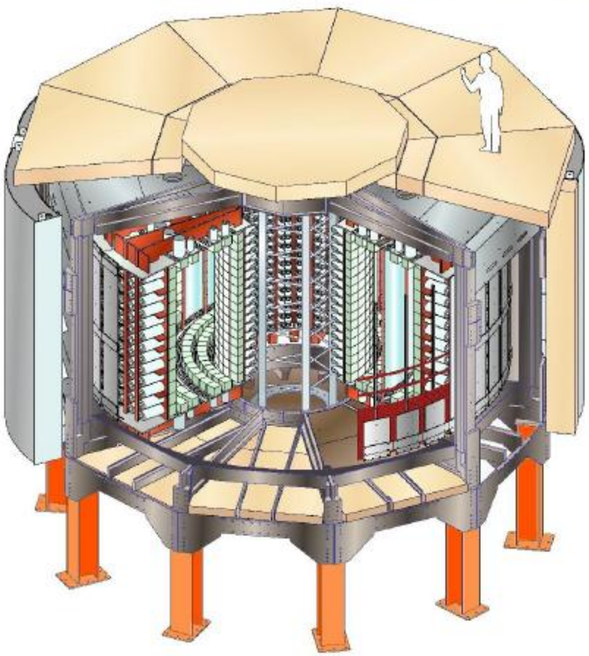
Evolution of the claim in time due to reanalysis of the data.

Should be checked with ^{76}Ge (GERDA, Majorana) but also with other isotopes.

Recently finished 2β experiments: NEMO-3 (Modane, France)

The NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², e ~ 60 mg/cm²

Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (e = 18 cm)
Neutron shield:
30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water + boron)

Particle ID: e^-, e^+, γ and α

NEMO-3 detector: NIM A536 (2005) 79

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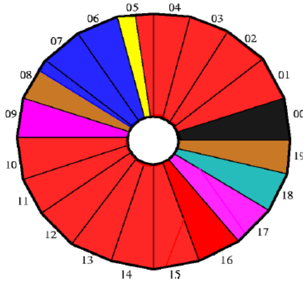
ββ decay isotopes in NEMO-3 detector



2νββ measurement
- ^{116}Cd 405 g, $Q_{\beta\beta}$ = 2805 keV
- ^{96}Zr 9.4 g, $Q_{\beta\beta}$ = 3350 keV
- ^{150}Nd 37.0 g, $Q_{\beta\beta}$ = 3367 keV
- ^{48}Ca 7.0 g, $Q_{\beta\beta}$ = 4272 keV

External bkg measurement
- ^{130}Te 454 g, $Q_{\beta\beta}$ = 2529 keV
- ^{nat}Te 491 g
- Cu 621 g

0νββ search
- ^{100}Mo 6.914 kg, $Q_{\beta\beta}$ = 3034 keV
- ^{82}Se 0.932 kg, $Q_{\beta\beta}$ = 2995 keV

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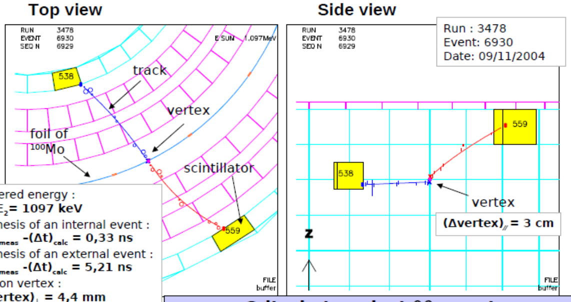
Selection of ββ events

The example of the typical ββ event - candidate for ββ2ν decay of ^{100}Mo



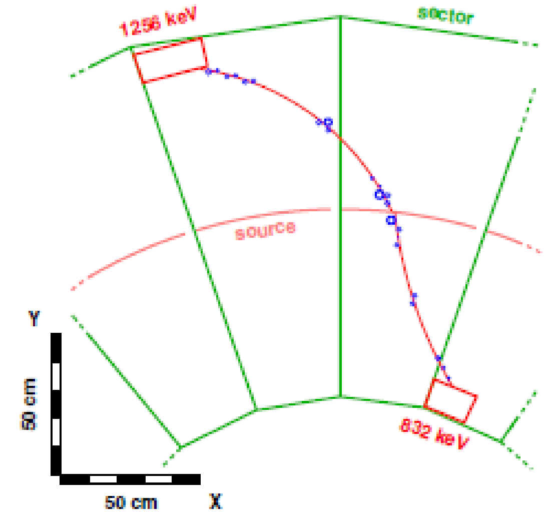
Registered energy :
E_1+E_2 = 1097 keV
Hypothesis of an internal event :
$(\Delta t)_{meas} - (\Delta t)_{calc}$ = 0,33 ns
Hypothesis of an external event :
$(\Delta t)_{meas} - (\Delta t)_{calc}$ = 5,21 ns
Common vertex :
$(\Delta vertex)_{\perp}$ = 4,4 mm

1 ββ event each 2,5 minutes

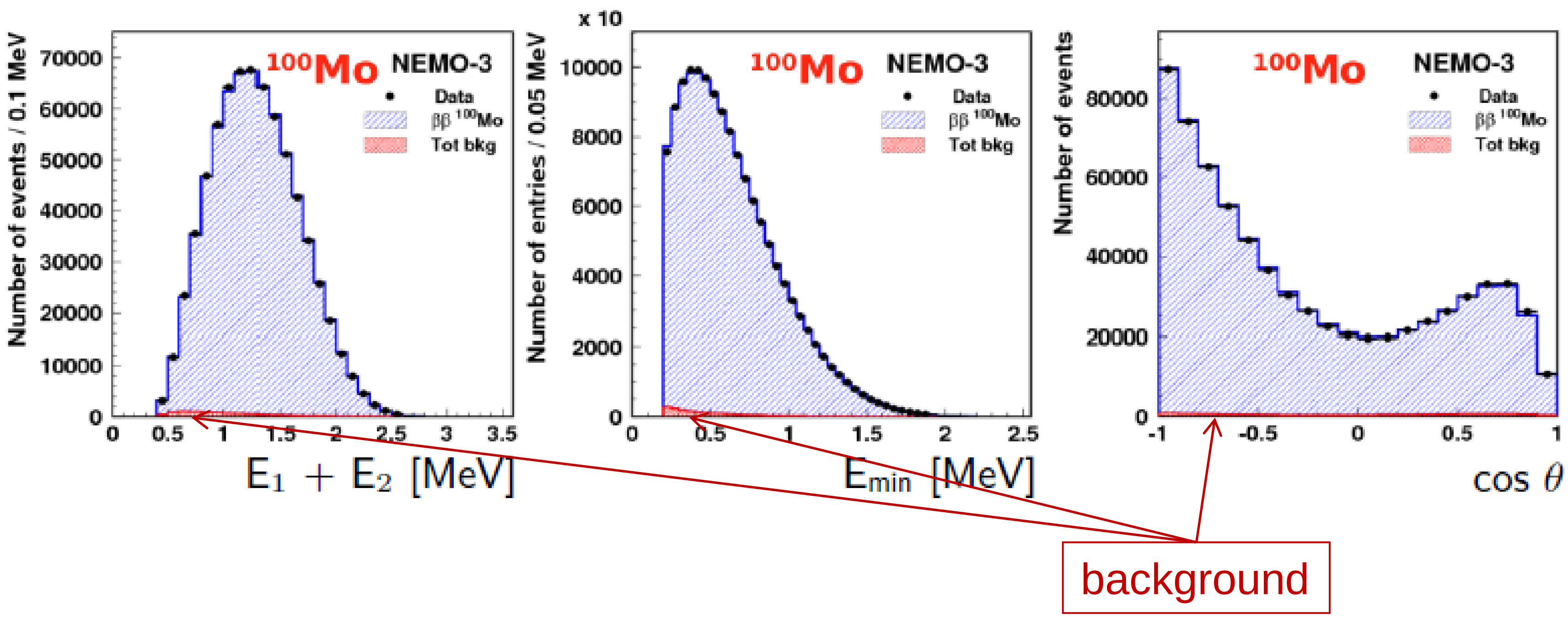
Criteria to select ββ events:
- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

15 June 2011, Prague — 10

NEMO-3 $2\nu2\beta$ of ^{100}Mo Measurement

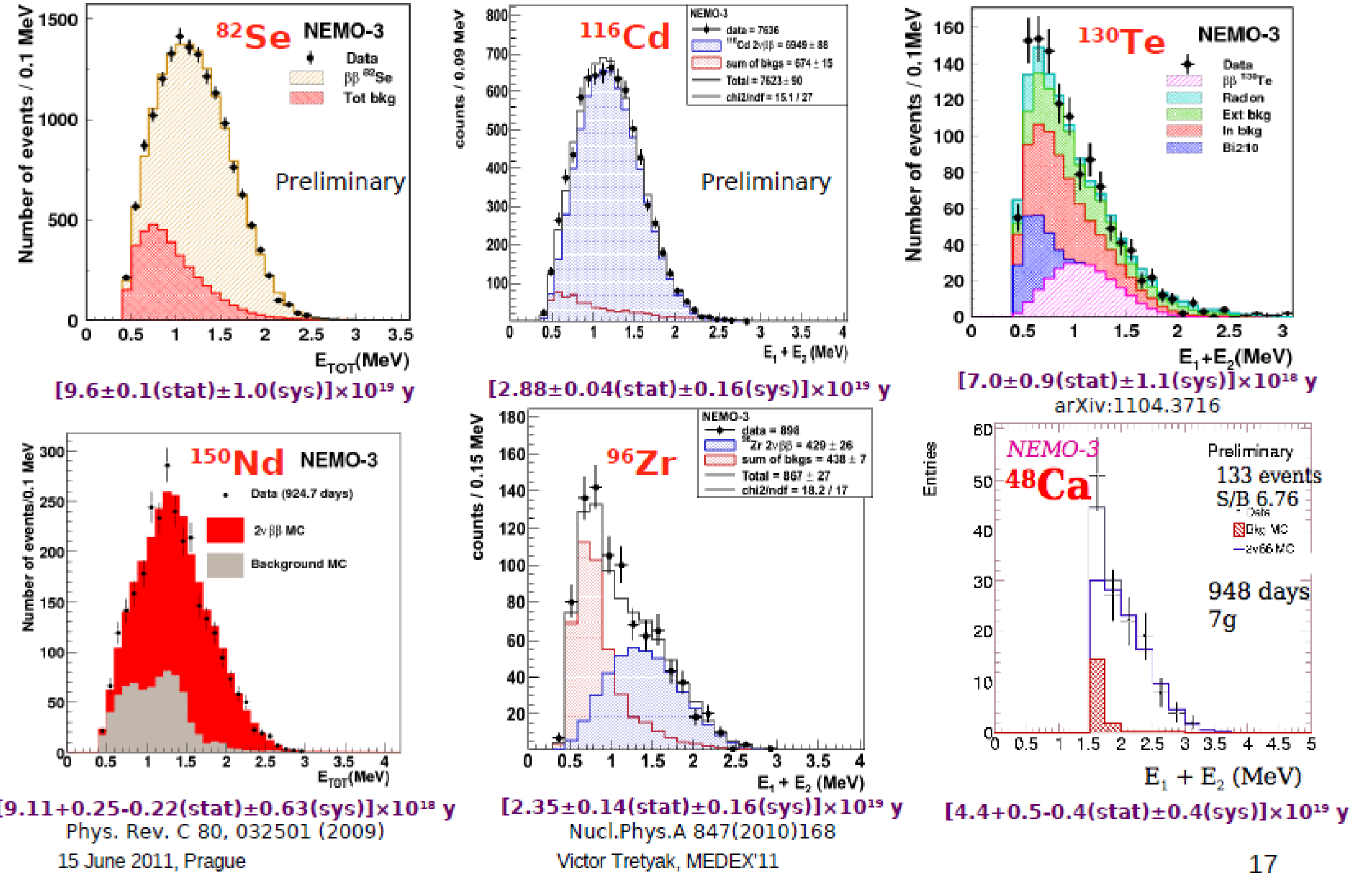


- 6.9 kg of ^{100}Mo
- $\sim$700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3$ %
- Signal to background ratio S/B = 76
- Preliminary half-life:
  $\mathcal{T}^{2\nu}_{1/2} = 7.16 \pm 0.01$ (stat) $\pm\, 0.54$ (syst) 10^{18} y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]



M. Bongrand, Neutrino'2014

2νββ Measurements



For 2β0ν:

^{100}Mo > 1.1×10^{24} y

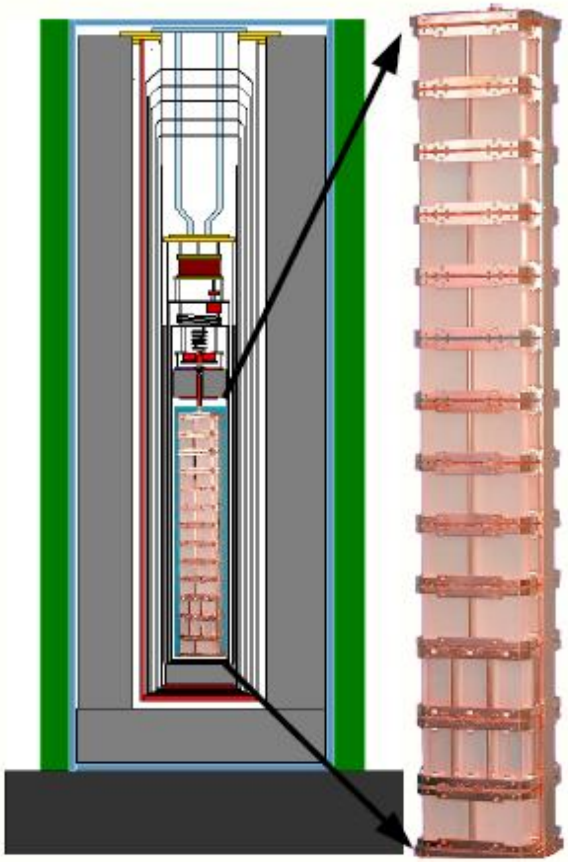
^{82}Se > 3.2×10^{23} y

Final data processing is near finish.

Recently finished 2β experiments: CUORICINO (LNGS, Italy)

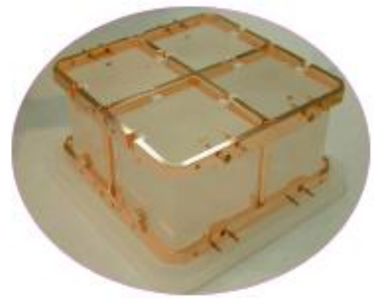
Detector

Detector maintained at ~10 mK by a $^3He/^4He$ dilution refrigerator



A tower of 62 TeO_2 crystals

11 floors made of 4 crystals
- not enriched
- Mass: 790g
- Dimensions: 5x5x5 cm^3



2 floors made of 9 crystals:
- Mass: 330g
- Dimensions: 3x3x6 cm^3
- 2 enriched in ^{128}Te (82%)
- 2 enriched in ^{130}Te (75%)

Total mass: 40.7 Kg (11.3 Kg in ^{130}Te)

Shieldings

Internal:

➔1cm low activity Pb (A < 4 mBq/Kg in ^{210}Pb)

External:

➔20cm Pb
➔20cm Borated Polyethylene
➔Anti-Rn box: Nitrogen overpressure

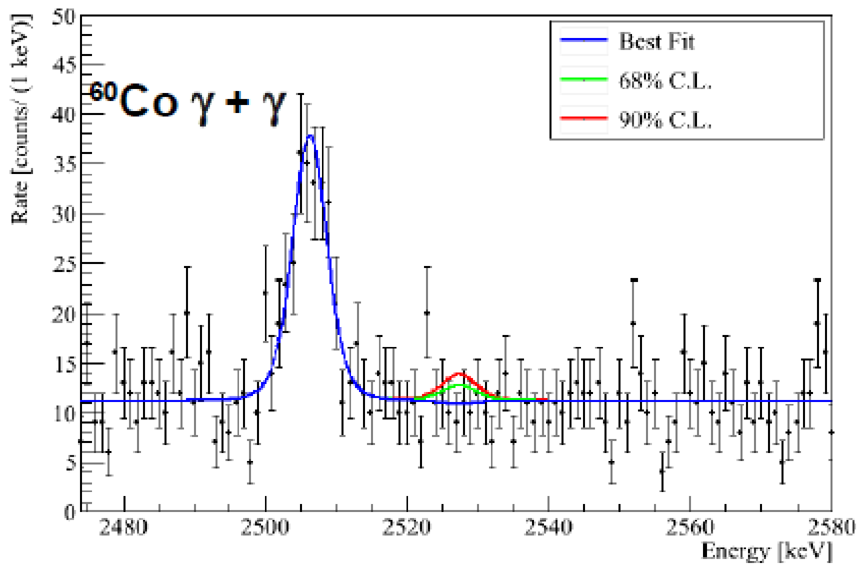
^{130}Te ββ0ν decay to the ground state

Bkg at Q-value: **0.17 counts/(keV kg y)**

Statistics: **19.75 kg(^{130}Te) y**

Maximum likelihood fit with 8 free parameters:
- 0νββ rate
- 3 flat bkg rates (big, small and enriched xtals)
- 3 ^{60}Co rates (big, small and enriched xtals)
- ^{60}Co sum energy (same for all detectors)

$$\Gamma^{0\nu} = (-0.2 \pm 1.4(stat) \pm 0.3(syst)) \times 10^{-25}\, y^{-1}$$



Half life limit: Bayesian approach with flat prior

$$T^{0\nu}_{1/2} > 2.8 \times 10^{24}\, y \quad @\, 90\,\%\, CL$$

Astropart. Phys. 34 (2011) 822–831

The CUORICINO limit on $m_{\beta\beta}$ is comparable with the one reported by the Heidelberg-Moscow experiment in ^{76}Ge, but can not exclude the claim of observation

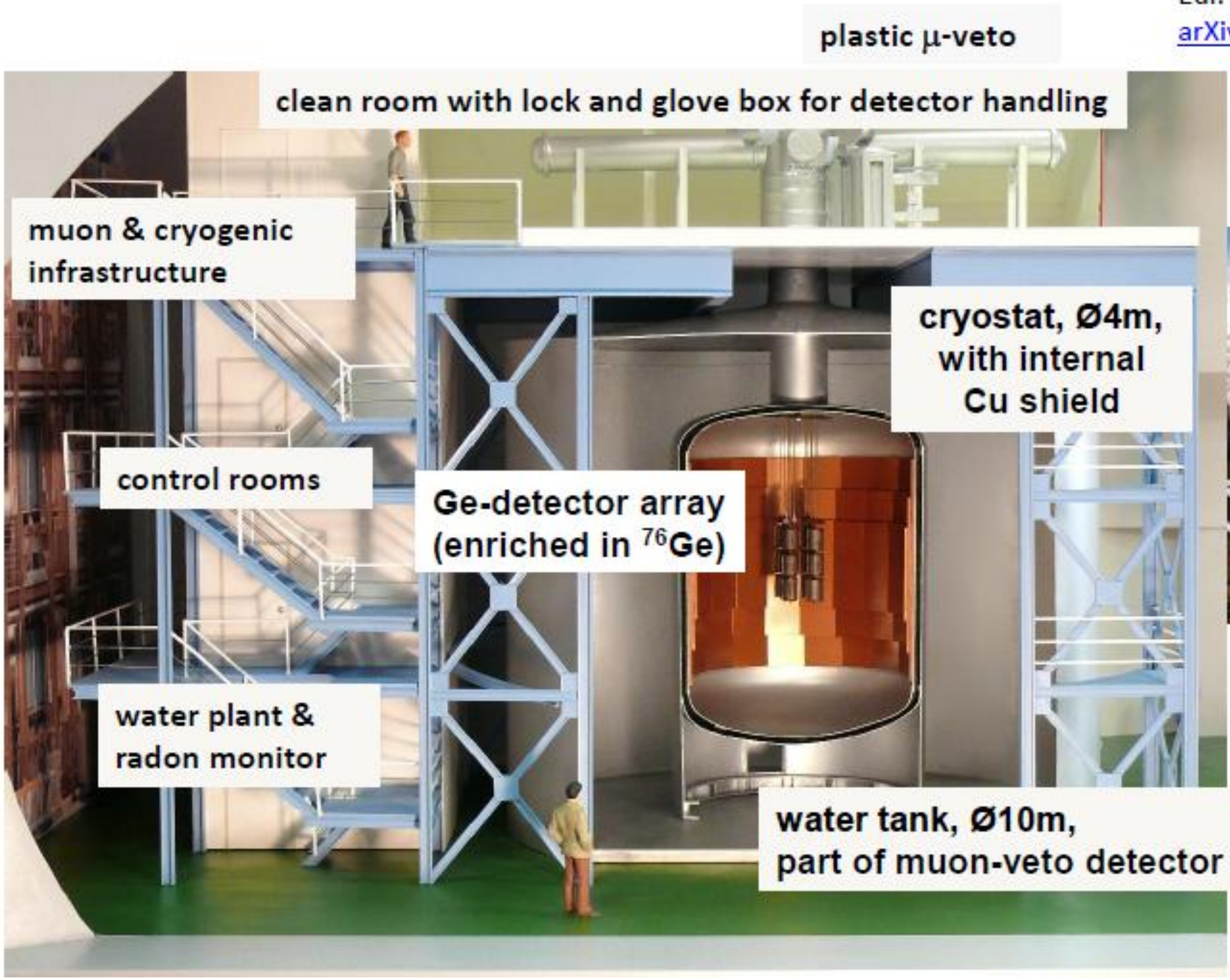
$m_{\beta\beta}$		
< (300 – 570) meV	(R)QRPA	Phys. Rev. C 77, 045503 (2008)
< (360 – 580) meV	pnQRPA	J. Phys. Conf. Ser. 173, 012012 (2009)
< (570 – 710) meV	ISM	Nucl. Phys. A 818, 139-151 (2009)
< 370 meV	IBM-2	Phys. Rev. C 79, 044301 (2009)

Main source of background: degraded α particles from TeO_2 and Cu surfaces

Data taking 2β experiments: GERDA (LNGS, Italy)

GERDA
16 institutions
~100 members

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

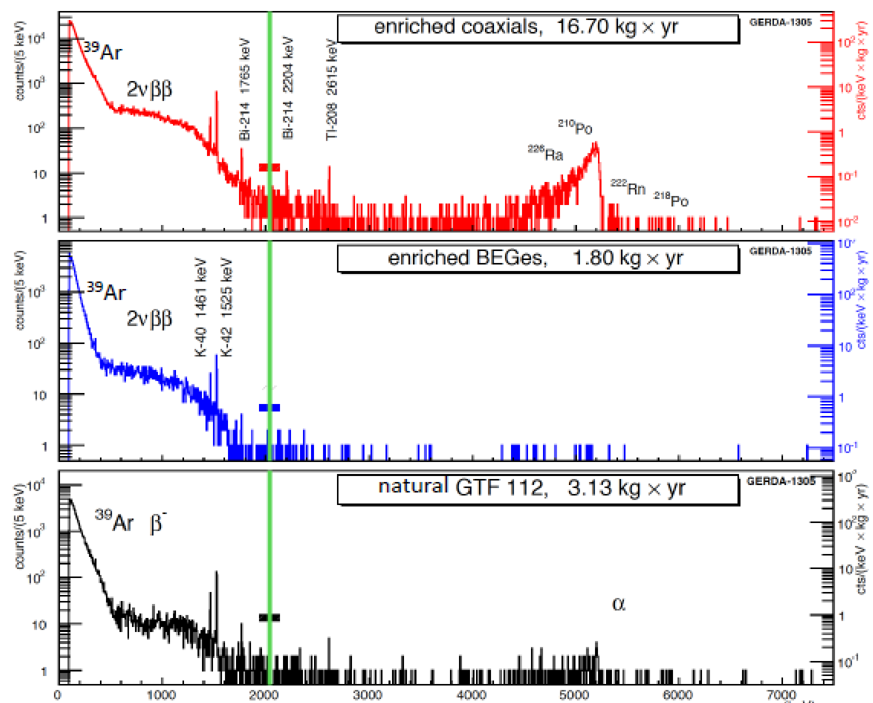


S. Schonert, Neutrino'2014

8 refurbished enriched diodes from HM & IGEX

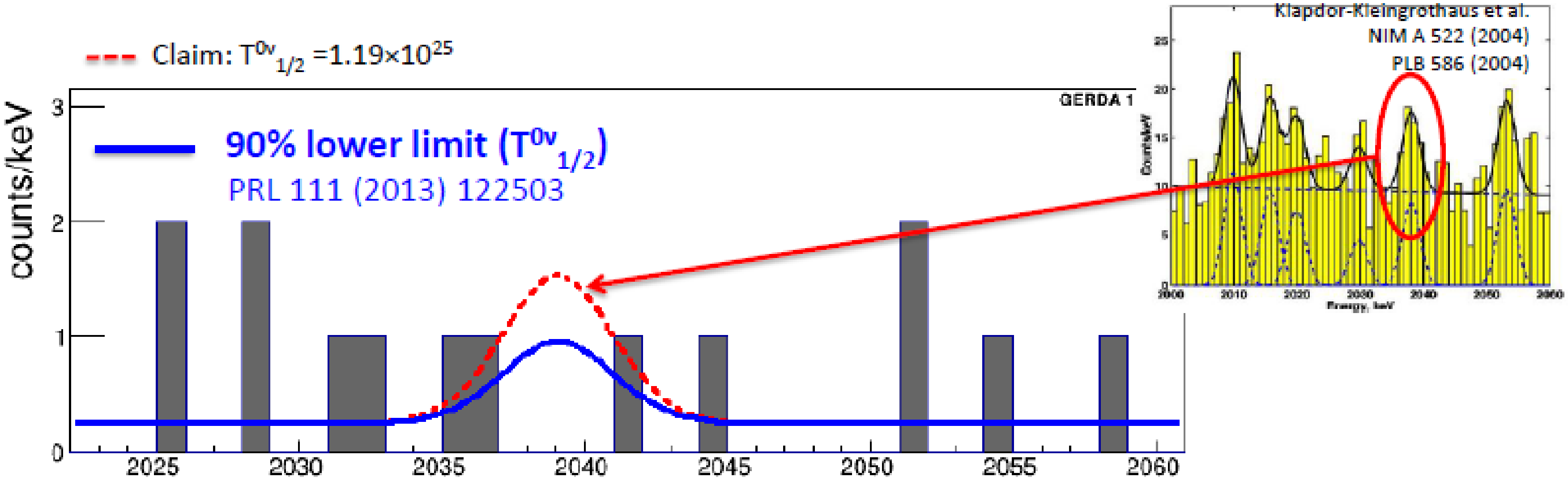
86% isotopically enriched in ^{76}Ge, 17.66 kg total mass, +1 natural Ge

Start in November 2011



$$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \times 10^{21}\ \text{y}$$

S. Schonert, Neutrino'2014



21.6 kg y, background rate after PSD: 0.01 cts / (keV kg y)

$T_{1/2}^{0\nu} > 2.1\times10^{25}$ y 90% C.L.

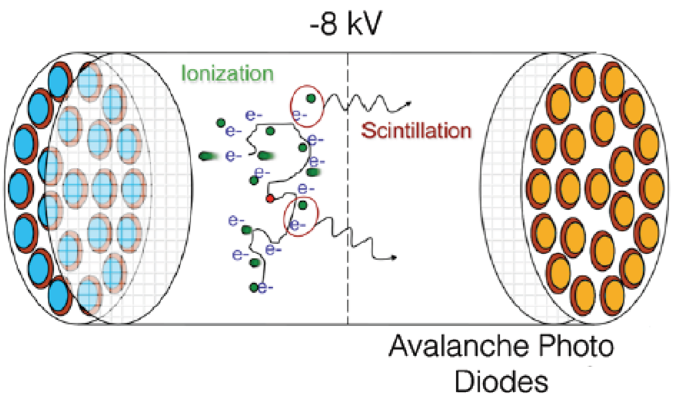
Transition to Phase II ongoing:

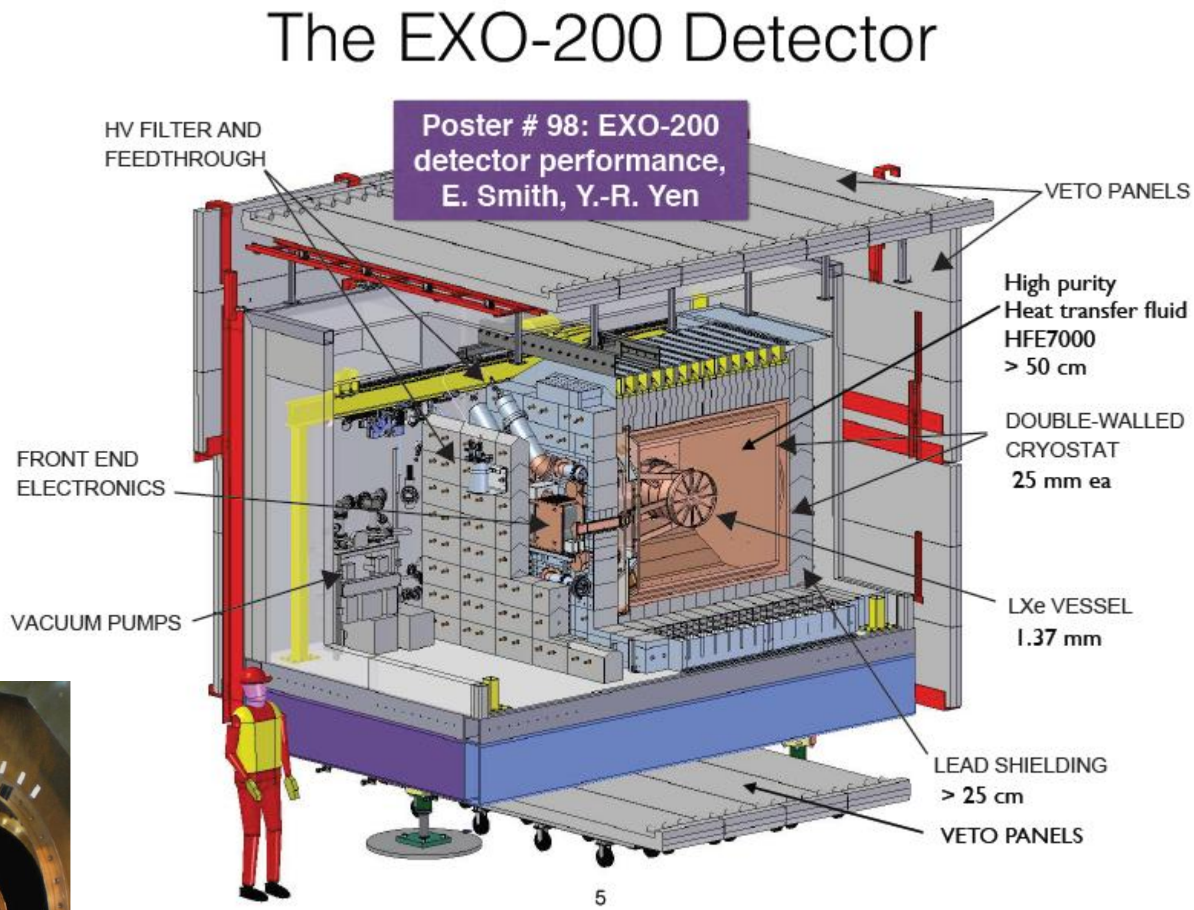
- Increase of target mass (+20 kg; total ≈40 kg of Ge detectors)
- New custom made BEGe detectors with enhanced PSD
- Liquid argon instrumentation
- Background ≤ 10^{-3} cts /(keV kg y)
- Explore $T_{1/2}^{0\nu}$ values in the 10^{26} y range

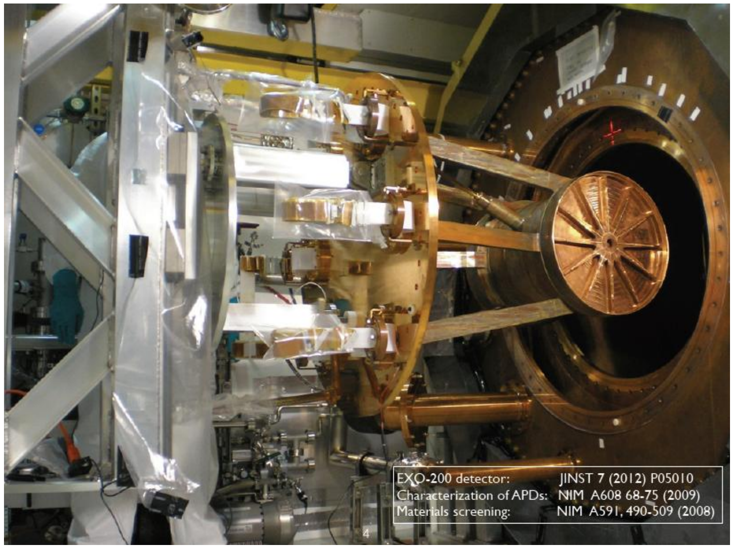
S. Schonert, Neutrino'2014

Data taking 2β experiments: EXO (WIPP, USA)

Liquid Xe Time Projection Chamber (TPC)
^{136}Xe - 80.6%

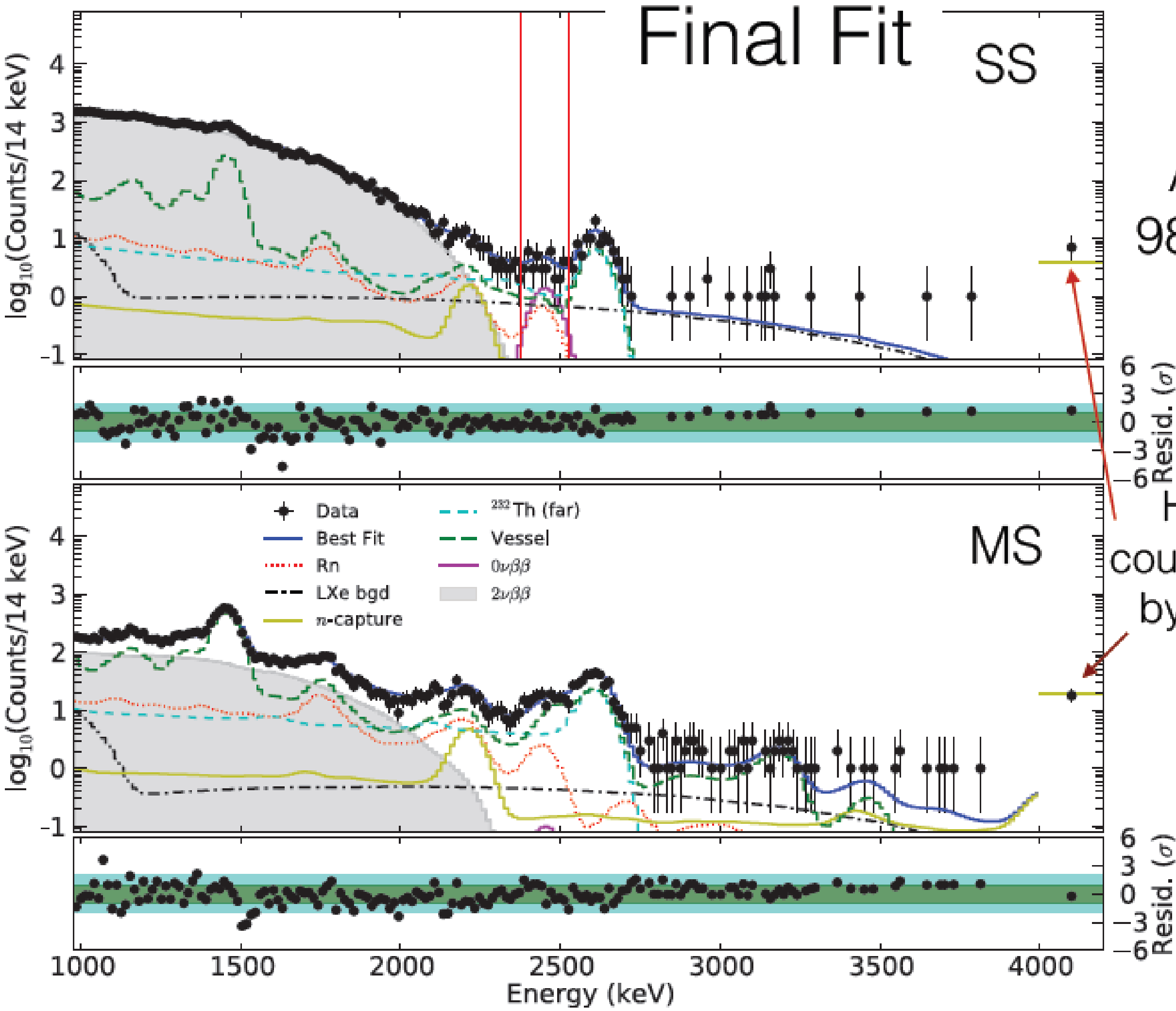






Reading ionization and scintillation signals.

M. Marino, Neutrino'2014



Analysis: 980 to 9800 keV

High-energy counts dominated by μ-produced neutrons

448 d, 100 kg y

$T_{1/2}^{2\nu}$ = (2.165±0.016(stat)±0.059(sys))×10^{21} y – the most precise value

S/B = 11:1

$T_{1/2}^{0\nu}$ > 1.1×10^{25} y 90% C.L.

Plans: EXO → nEXO (5 t ^{136}Xe)

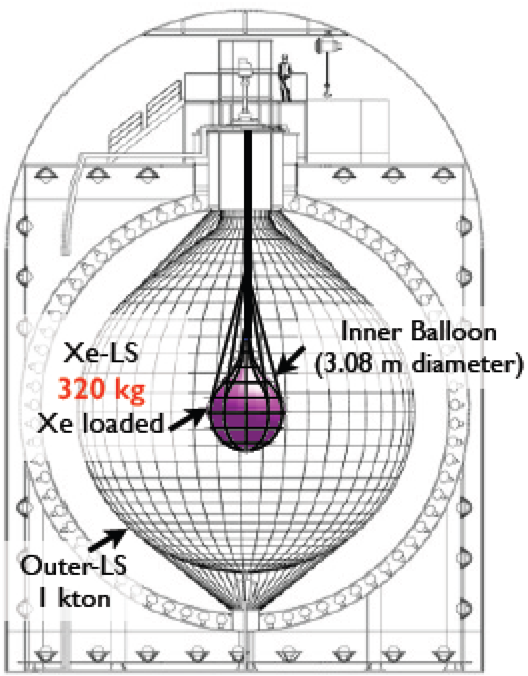
Detection of daughter Ba^{++} ions ?

Data taking 2β experiments: KamLAND-Zen (Kamioka, Japan)

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen Phase I



Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

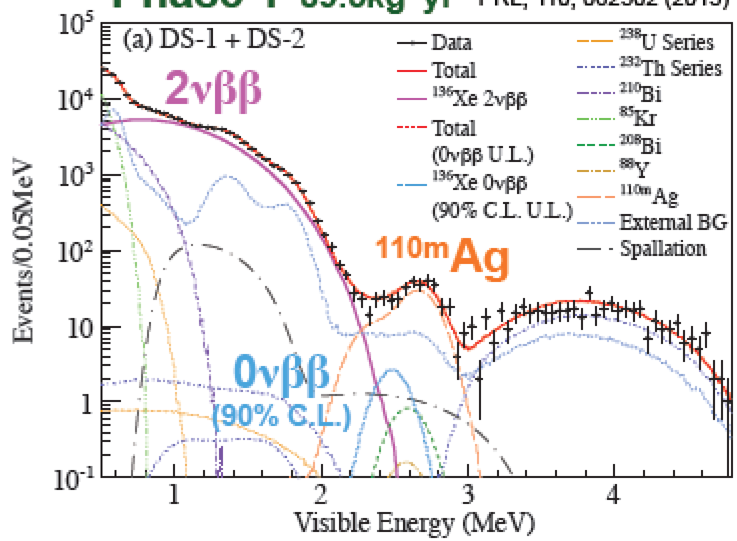
→ high scalability (a few ton of Xe)

realize double beta-decay search with low background

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.)

I. Shimizu, Neutrino'2014

Xe enriched in ^{136}Xe to ~90% dissolved (~2%) in 13 t of liquid scintillator

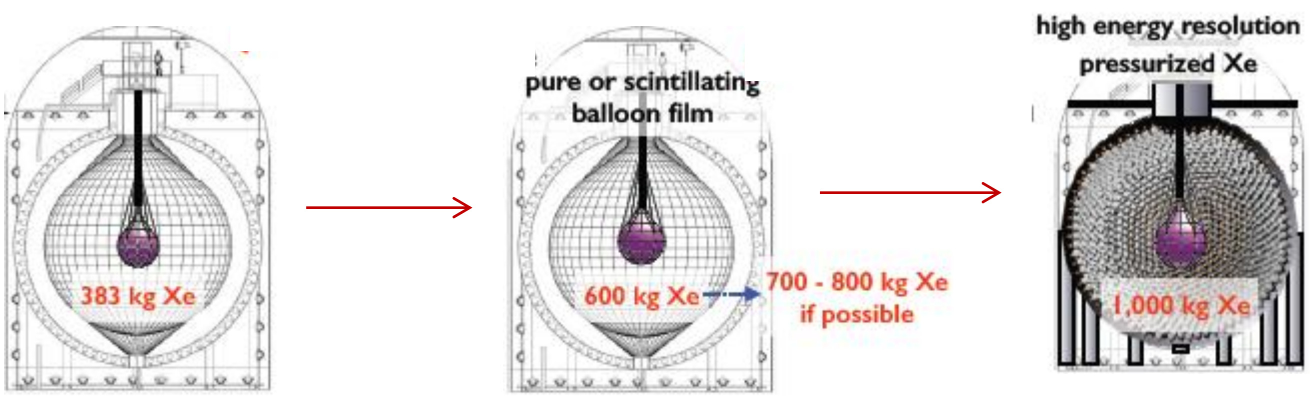
Unpleasant problem of (cosmogenic or Fukusima?) ^{110m}Ag, close to the expected $2\beta0\nu$ peak of ^{136}Xe. Possibility of purification.

Phase 1 (213 d):
$T_{1/2}^{2\nu} = (2.30\pm0.02(stat)\pm0.12(sys))\times10^{21}$ y
$T_{1/2}^{0\nu} > 1.9\times10^{25}$ y 90% C.L.

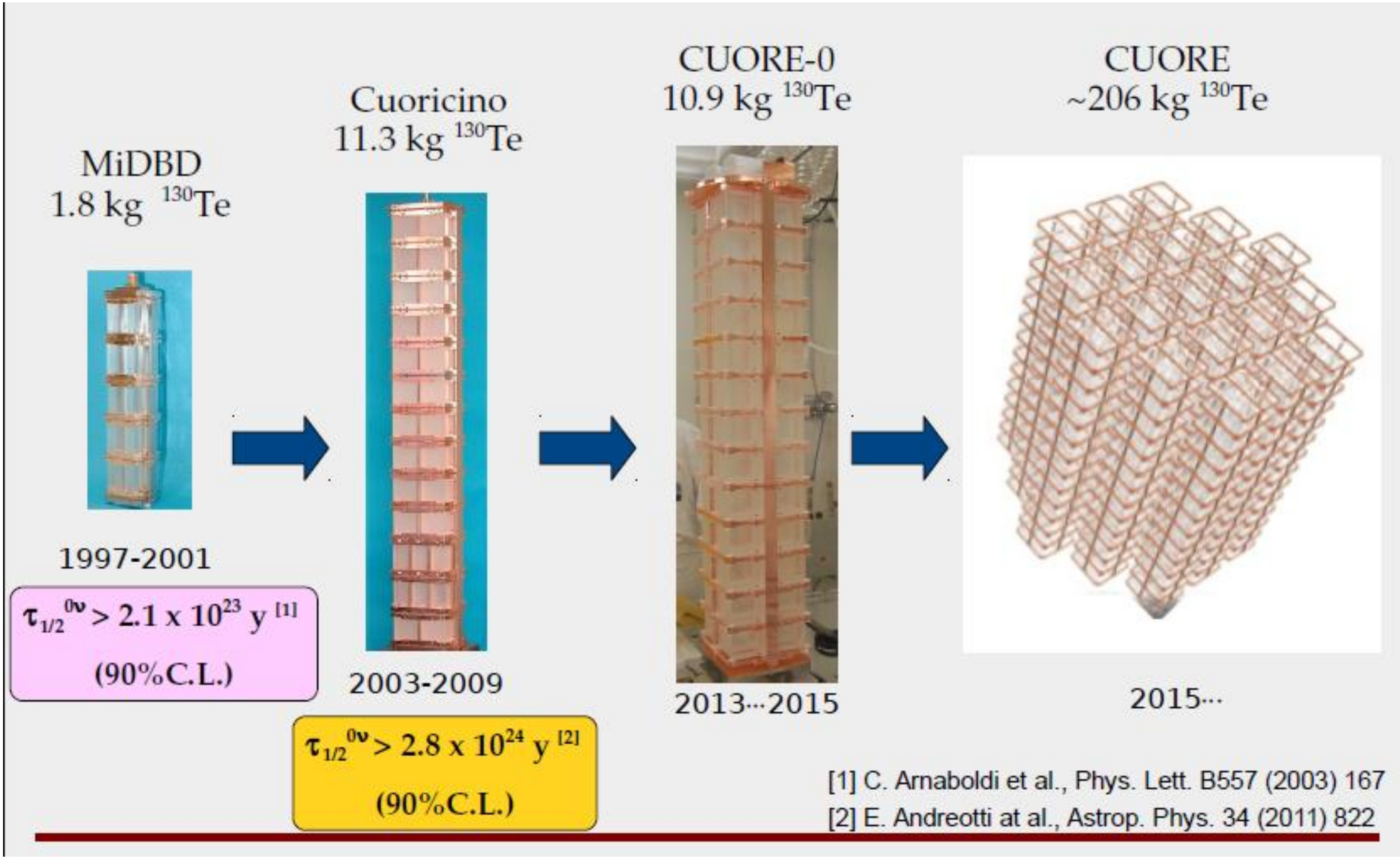
Phase 2 (115 d, 383 kg of Xe):
$T_{1/2}^{2\nu} = (2.32\pm0.05(stat)\pm0.08(sys))\times10^{21}$ y
$T_{1/2}^{0\nu} > 1.3\times10^{25}$ y 90% C.L.

Combined: $T_{1/2}^{0\nu} > 2.6\times10^{25}$ y 90% C.L. ($\langle m_\nu \rangle < 0.14$-$0.28$ eV)

Plans:



Future 2β experiments: CUORE (LNGS, Italy)



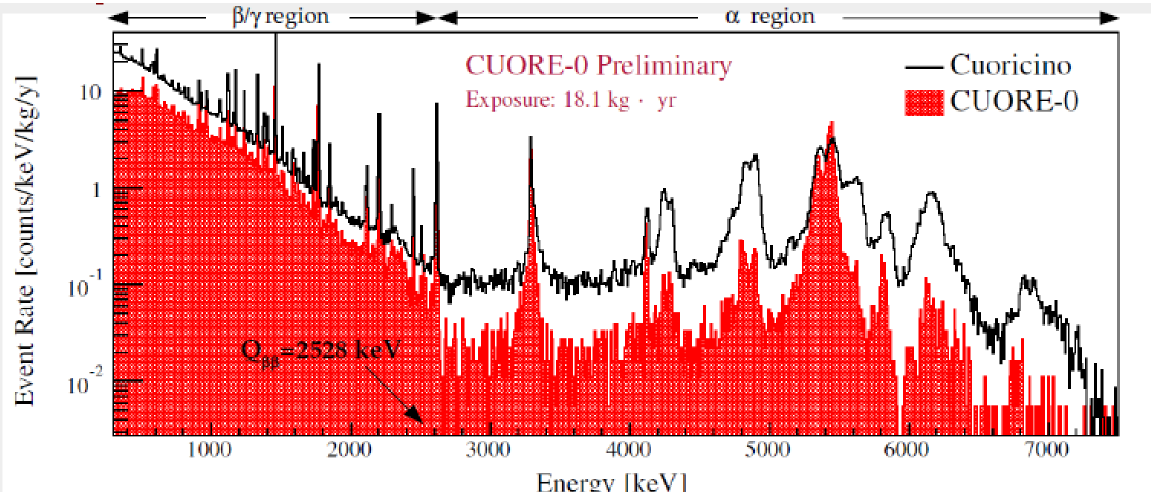
M. Sisti, ICHEP'2014

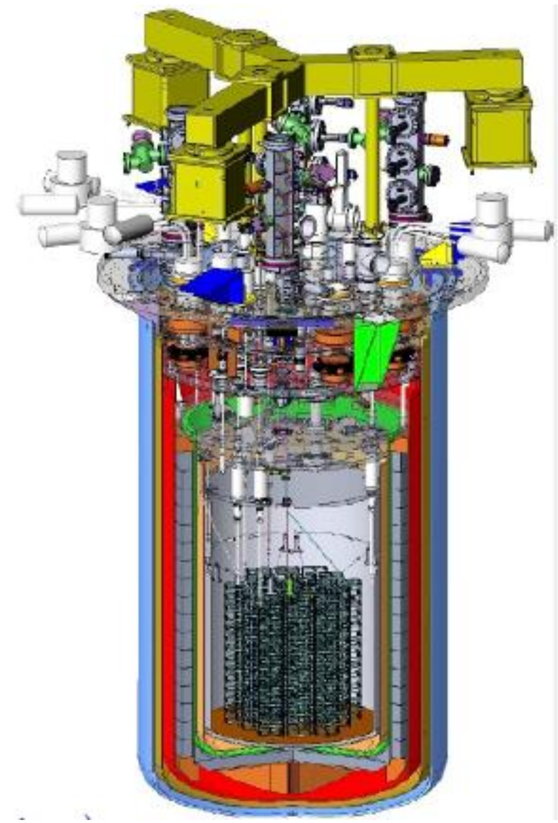
Array of 988 TeO_2 5×5×5 cm^3 detectors (750 g each)

M = 741 kg of TeO_2 = 206 kg of ^{130}Te

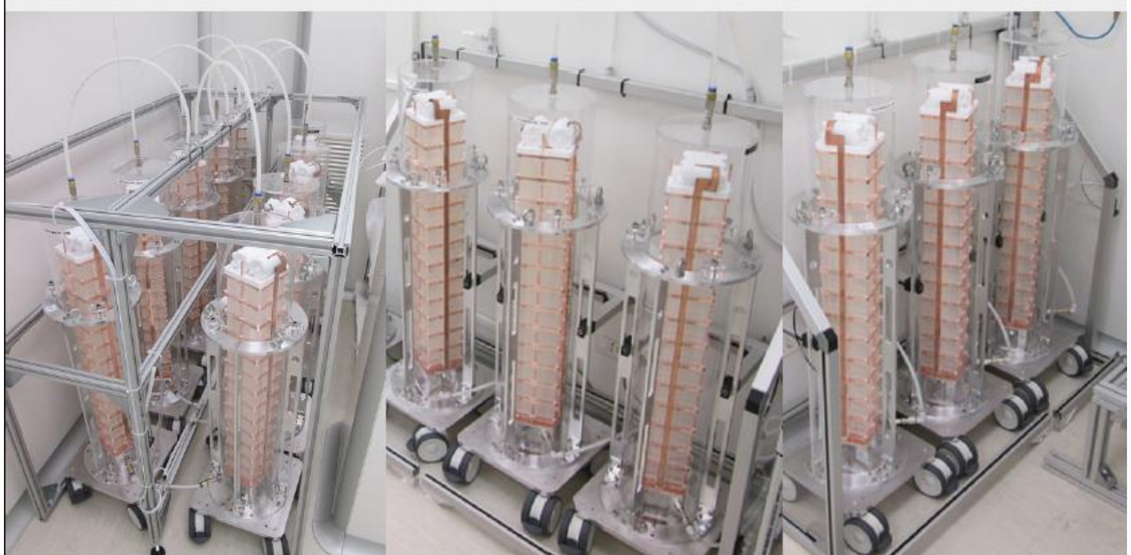
CUORE-0 is the first tower of the CUORE. With statistics of 18.1 kg y proves aim of COURE: FWHM = 5 keV.

6 times lower surface contamination with respect to CUORICINO





- All 19 towers have been assembled and instrumented
- Stored under nitrogen flushing while waiting to be installed



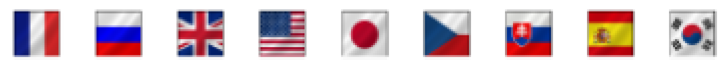
Start – 2015

Aim – 10^{26} y, m_ν – 100 meV

M. Sisti, ICHEP'2014

Future 2β experiments: SuperNEMO (Modane, France – Canfranc, Spain)

From NEMO-3 to SuperNEMO

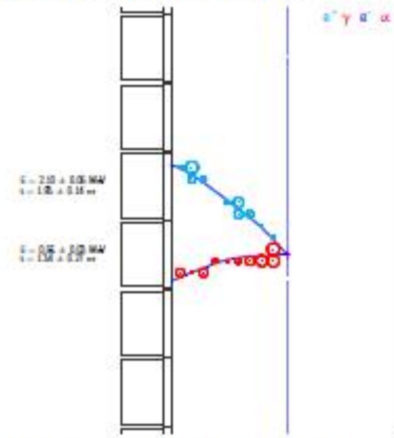


	NEMO-3	SuperNEMO
Mass	6.9 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
	7 isotopes	^{150}Nd, ^{48}Ca
Energy resolution (σ | FWHM)		
@ 3 MeV	3.4 | 8 %	1.7 | 4 %
Radon in tracker		
$\mathcal{A}(^{222}\mathrm{Rn})$	5.0 mBq/m^3	0.15 mBq/m^3
Sources contaminations		
$\mathcal{A}(^{208}\mathrm{Tl})$	$\sim$ 100 μBq/kg	$<$ 2 μBq/kg
$\mathcal{A}(^{214}\mathrm{Bi})$	60 - 300 μBq/kg	$<$ 10 μBq/kg
Total background		
cts·keV^{-1}·kg^{-1}·y^{-1}	1.3×10^{-3}	5×10^{-5}
Sensitivity (90 % CL)		
$\mathcal{T}^{0\nu}_{1/2}$	$> 1.1 \times 10^{24}$ y	$> 1 \times 10^{26}$ y
$\langle m_\nu \rangle$	$<$ 0.33 - 0.87 eV	$<$ 0.04 - 0.10 eV

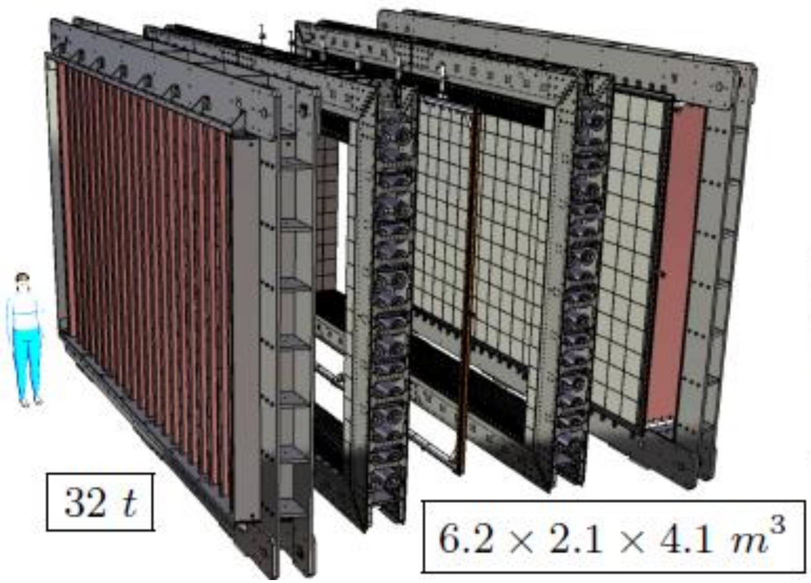
M. Bongrand, Neutrino’2014

SuperNEMO Demonstrator Goals

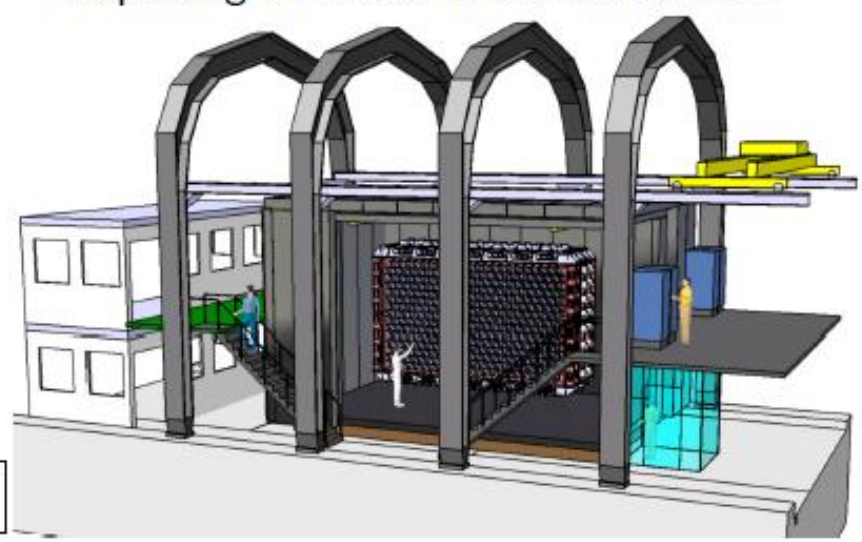
- SuperNEMO demonstrator module construction started in 2012
  - NEMO-3 sensitivity in only 5 months (90 % CL): $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.33 - 0.87$ eV
  - No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se
  - Sensitivity after 17.5 kg·y exposure (90 % CL): $\mathcal{T}^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.20 - 0.40$ eV



- Commissioning and physics data taking expected in Summer 2015

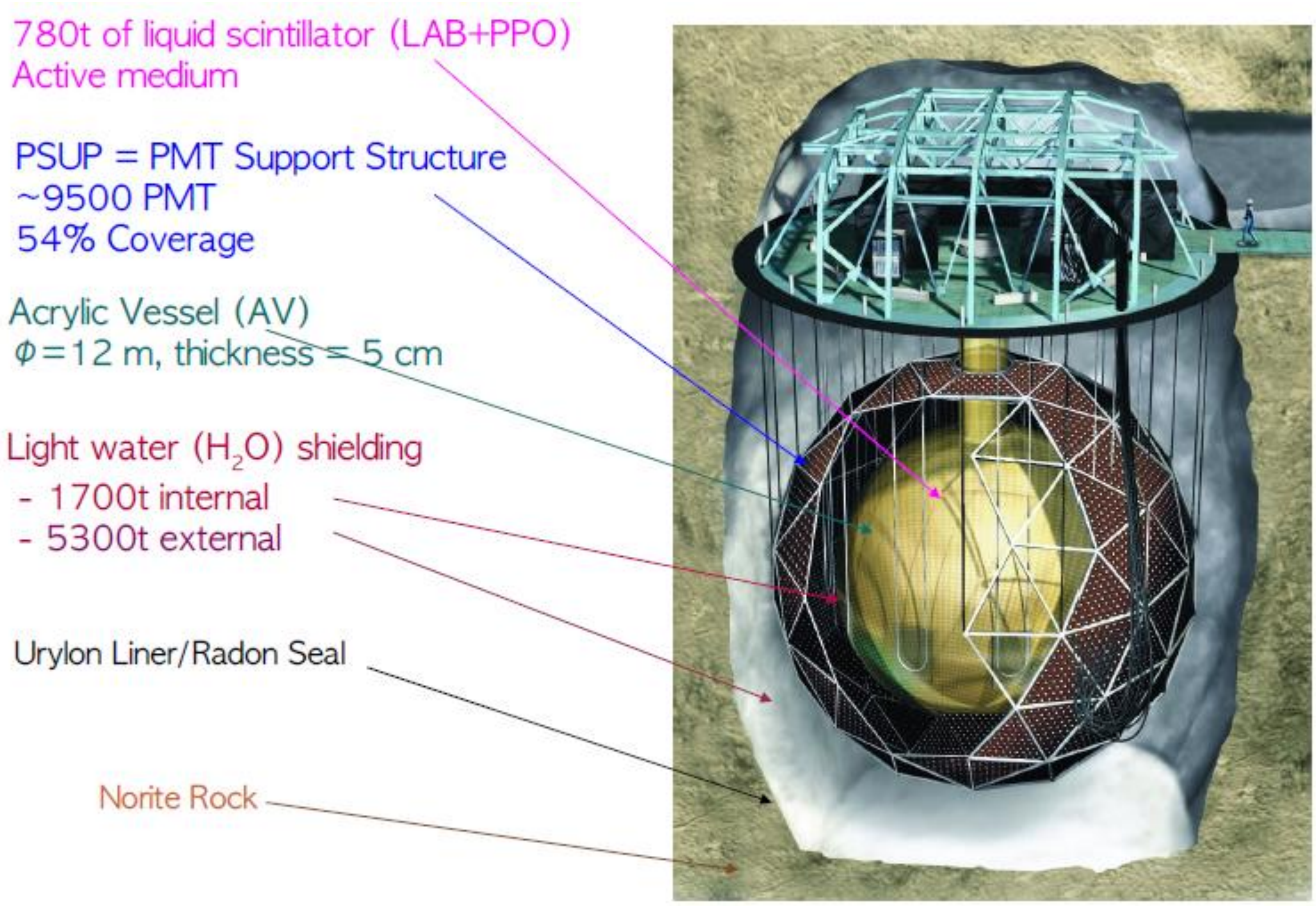


Replacing NEMO-3 in the actual LSM



M. Bongrand, Neutrino'2014

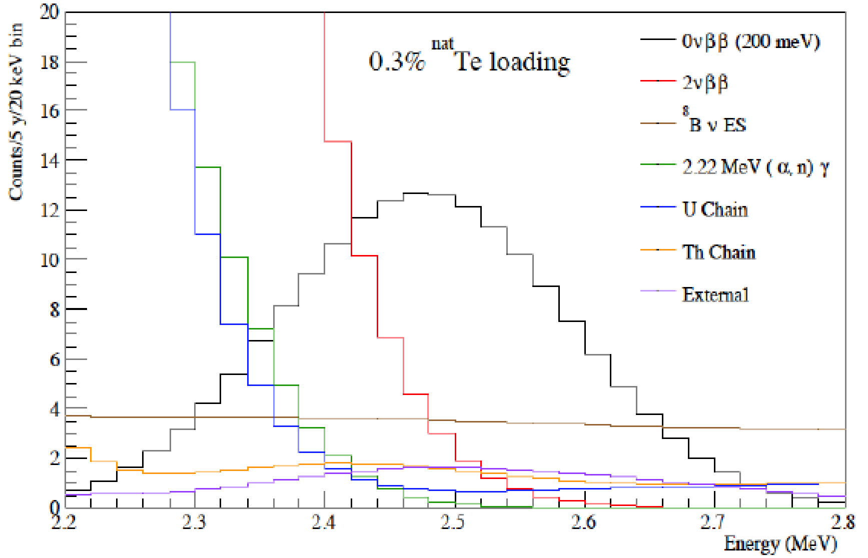
Future 2β experiments: SNO+ (Sudbury, Canada)



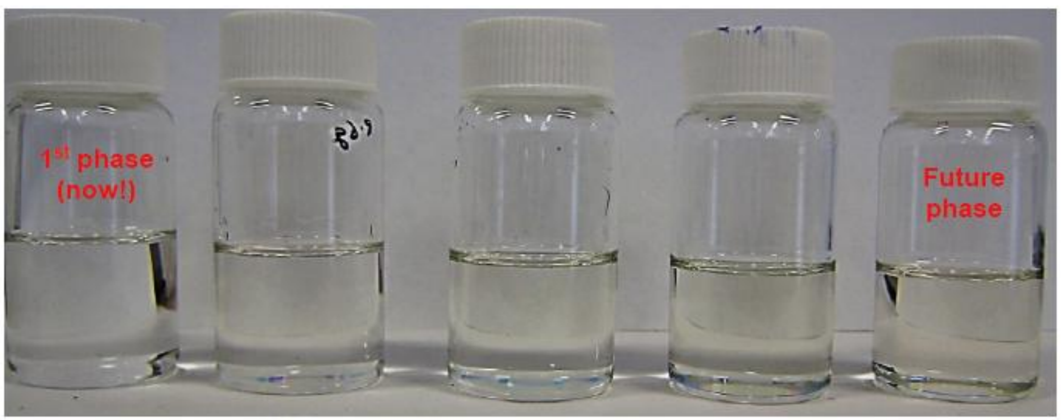
Location – 6000 m w.e. (only JinPing, China – 7500), 70 muons per day

V. Lozza, ICHEP'2014

0.3% ^{nat}Te loading – 800 kg of ^{130}Te (34% natural abundance)
LS + 0.3% Te is stable and clear (over 1 y)



Start of Te loading – 2016
Aim – 10^{26} y, m_ν – 200 meV



0.3% 0.5% 1% 3% 5%

In future, maybe higher Te loading to increase sensitivity

V. Lozza, ICHEP'2014

Future 2β experiments: LUCIFER (LNGS, Italy)

If background ≠ 0, experimental sensitivity:

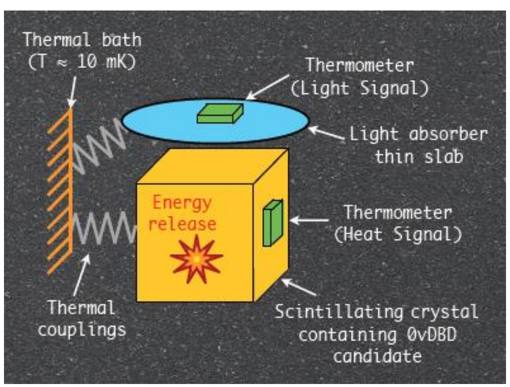
$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

Isotopic Abundance; Detection Efficiency; Detector Mass; Time; Atomic mass; Background level (count/keV kg year); Energy Resolution

Scintillating bolometers – very perspective techniques:

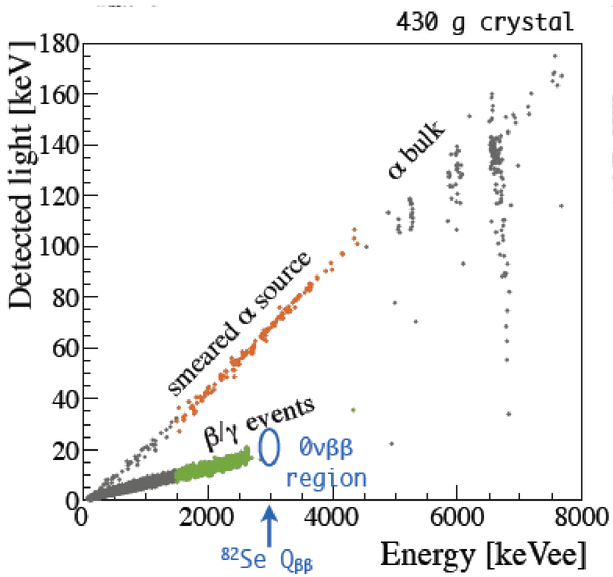
- good energy resolution (FWHM – few keV)
- big efficiency ("source = detector" approach)
- possibility to grow big and very pure crystals
- possibility to discriminate α, β/γ by registering heat and light
- possibility to discriminate noise, pile-up events by analyzing time shape of a signal

Drawback: bolometers are slow (~1 s) → pile-ups (two events as single)



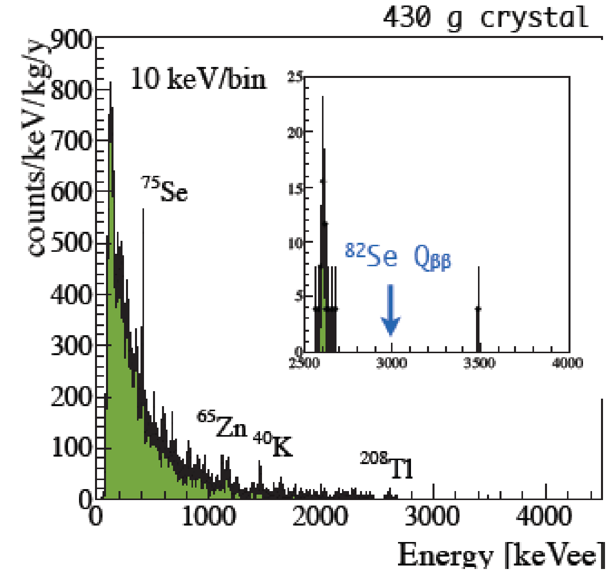
LUCIFER – ZnSe crystals enriched in ^{82}Se as scintillating bolometers
but also other crystals are tested
($ZnMoO_4$ – to use enriched ^{100}Mo,
$CdWO_4$ – to use enriched ^{116}Cd)

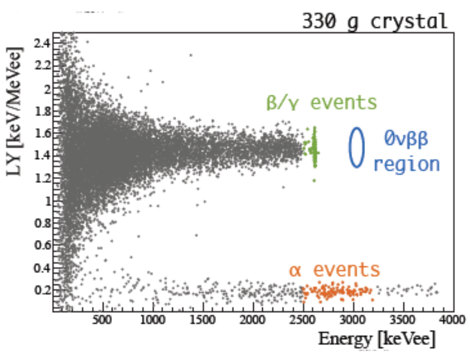
F. Orio, ICHEP'2014



ZnSe 430 g
FWHM = 16.5 keV at 3 MeV

Spectrum during 524 h

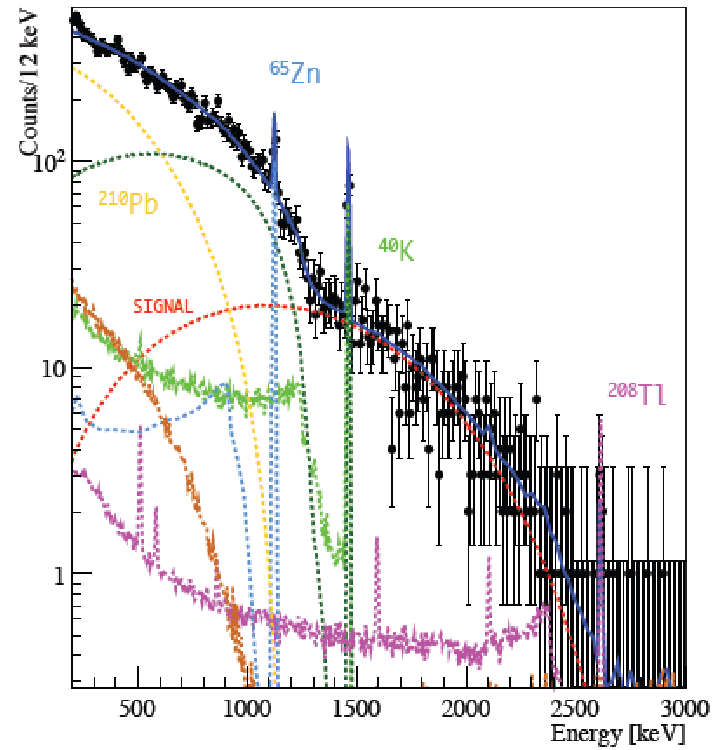




$ZnMoO_4$ 330 g

First bolometric measurement of $2\beta2\nu$ of ^{100}Mo

$T_{1/2}^{2\nu} = (7.15 \pm 0.37(stat) \pm 0.66(sys)) \times 10^{18}$ y

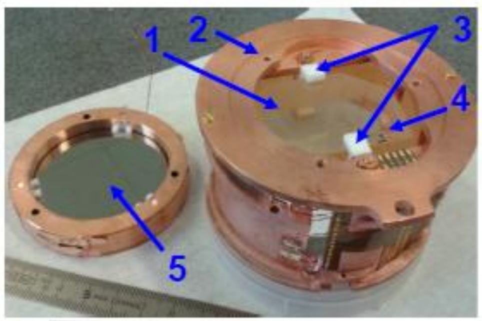


F . Orio, ICHEP’2014

Future 2β experiments: LUMINEU (Modane / LNGS)

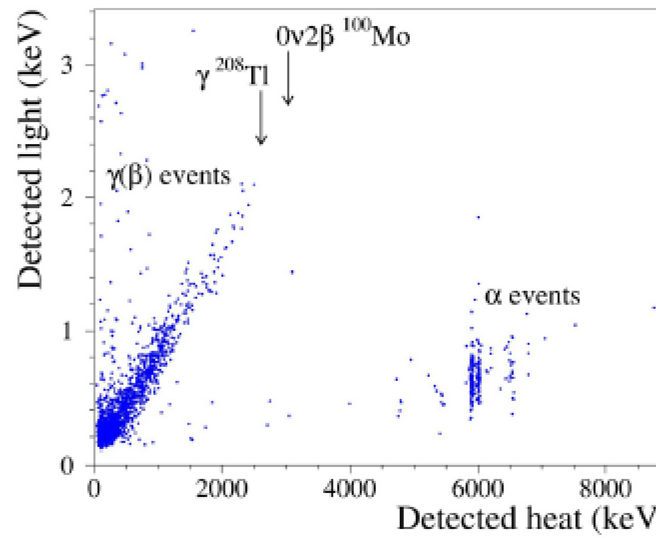
Aim of LUMINEU – to search for 2β0ν decay of ^{100}Mo using $Zn^{100}MoO_4$ crystals as scintillating bolometers

Pilot experiment – with 1 kg of ^{100}Mo with expansion to 10 kg

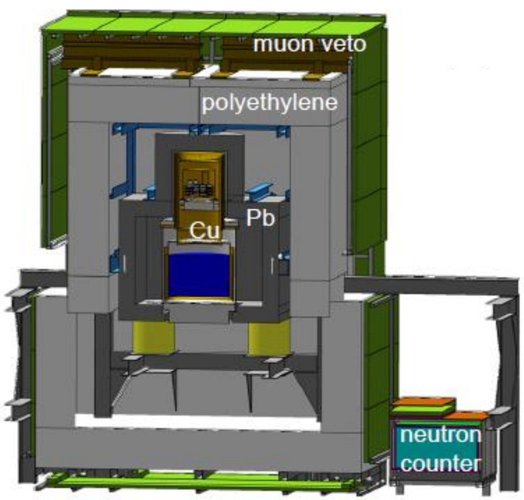


$ZnMoO_4$ scintillating bolometer

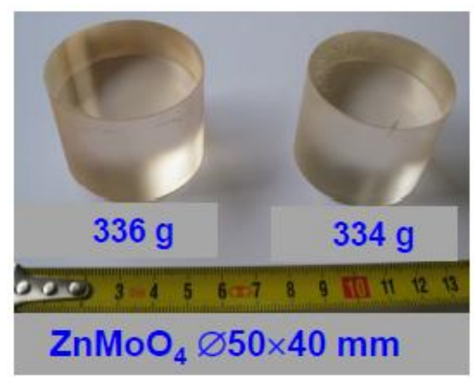
(1) 313 g $ZnMoO_4$ crystal grown in NIIC (Novosibirsk,Russia)
(2) Cu holder of the detector
(3) PTFE supporting elements
(4) Two NTD thermistors
(5) Two Ge light detectors



313 crystal in EDELWEISS set-up, 141 h

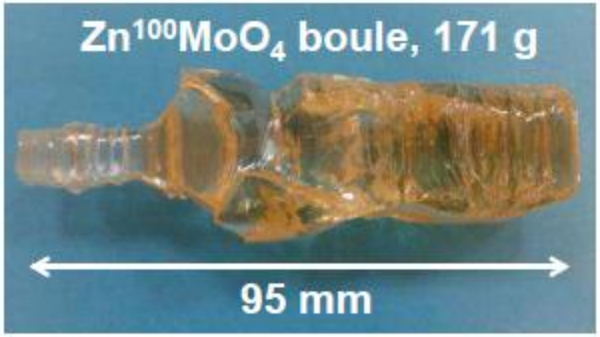


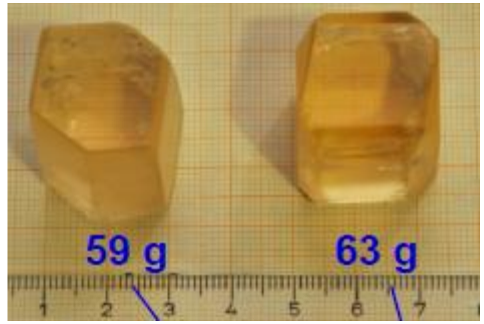
Large volume advanced (high-quality: purification, growth with LTG-Cz, recrystallization)



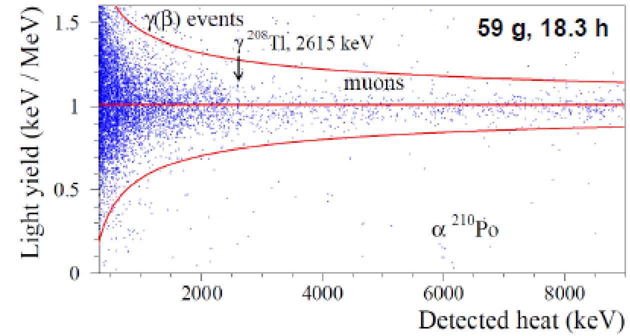
D.V. Poda, ICHEP’2014

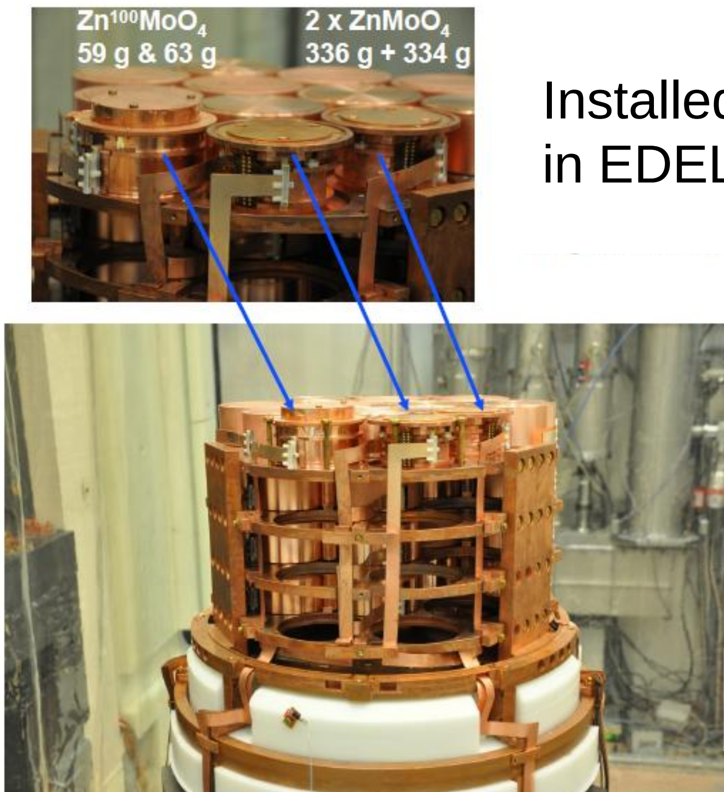
First enriched $Zn^{100}MoO_4$ crystals (LPD + NIIC)





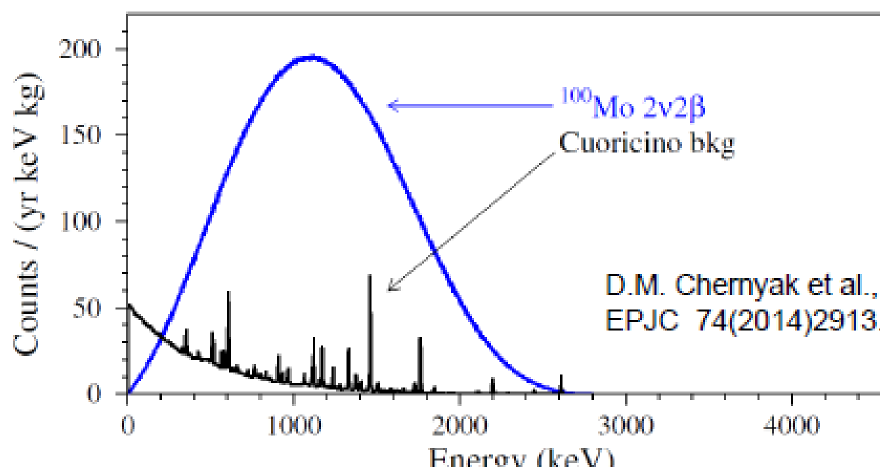
Above-ground test





Installed underground in EDELWEISS set-up

Hope for precise measurements of ^{100}Mo $2\beta2\nu$



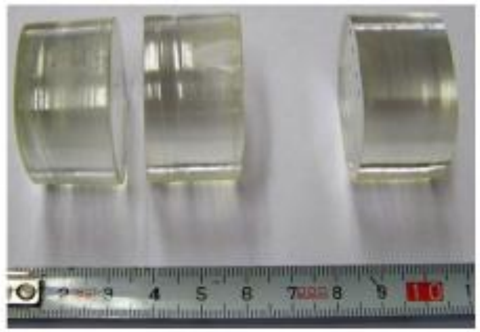
D.V. Poda, ICHEP'2014

Future 2β experiments: AMoRE (YangYang, Korea)

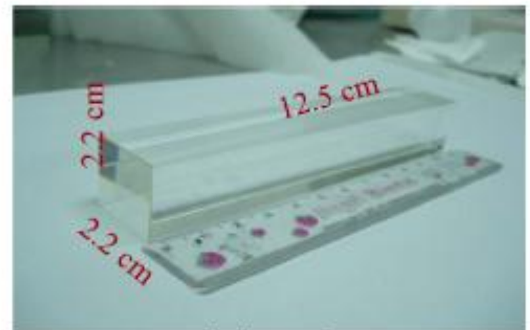
AMoRE – search for 2β0ν decay of ^{100}Mo using $Ca^{100}MoO_4$ crystals as scintillating bolometers. Aim – 10^{26} y, fully funded.

Early stages:

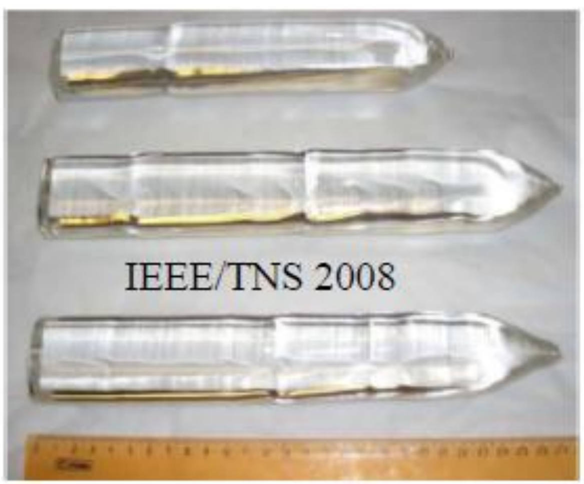
Korea(2003)

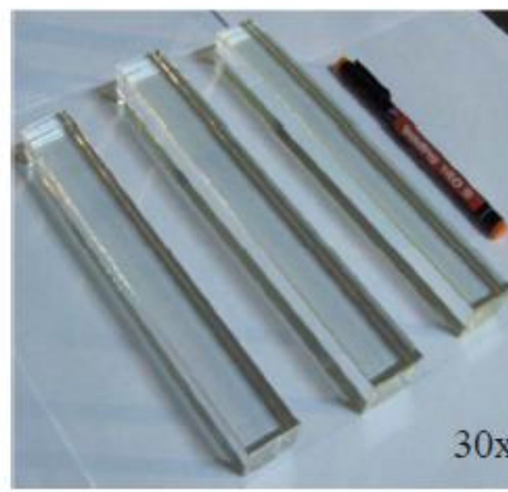


Ukraine-CARAT(2006)



Russia(2006)



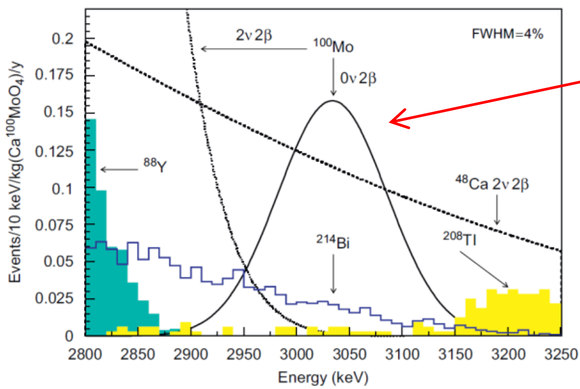


30x30x200mm

Y.H. Kim, TAUP'2013

Crystals should be depleted in ^{48}Ca (0.187% !) because of its $2\beta2\nu$ decay ($T_{1/2}^{2\nu} = 4.4\times10^{19}$ y !) with $Q_{2\beta}$(^{48}Ca, 4.3 MeV) higher than $Q_{2\beta}$(^{100}Mo, 3.0 MeV). Difficult to believe that rarest observed decay could be background in searches for even more rare events!

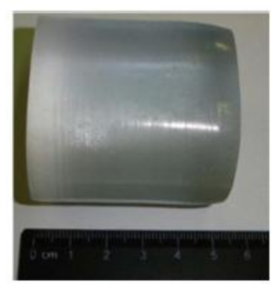
A.N. Annenkov et al. / Nuclear Instruments and Methods in Physics Research A 584 (2008) 334–345

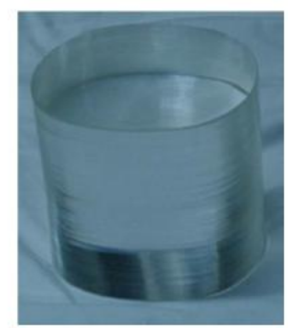


Plot for $T_{1/2}^{0\nu}(^{100}Mo) = 1.0\times10^{24}$ y

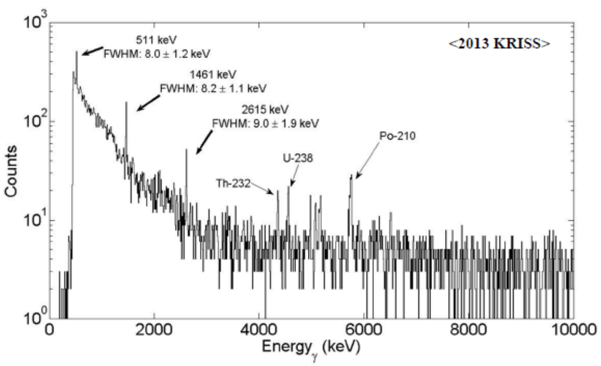
Depleted in ^{48}Ca and enriched in ^{100}Mo crystals (FOMOS, Moscow)

- SB28
  weight 196 g
- SB29
  weight 390 g
- S35
  weight ~300 g





216 g $CaMoO_4$(natural) with a phonon sensor only.



Energy (keV)	511	1461	2615
FWHM (keV)	8.0 ± 1.2	8.2 ± 1.1	9.0 ± 1.9

Y.H. Kim, TAUP'2013

Some other interesting experiments were not considered because of lack of time:
NEXT, MOON, CANDLES, XMASS, TGV, $^{106,116}CdWO_4$, DCBA, COBRA, …
- my apologies

Conclusions

Experimental searches for neutrinoless double beta decay is important and extremely interesting part of current nuclear and particle physics. Its discovery will mean existence of new physics beyond SM. While still not observed, its studies lead to detection of allowed $2\beta2\nu$ decay for 13 nuclei, with $T_{1/2} \sim 10^{18} - 10^{24}$ yr; and this is the rarest observed nuclear decay.

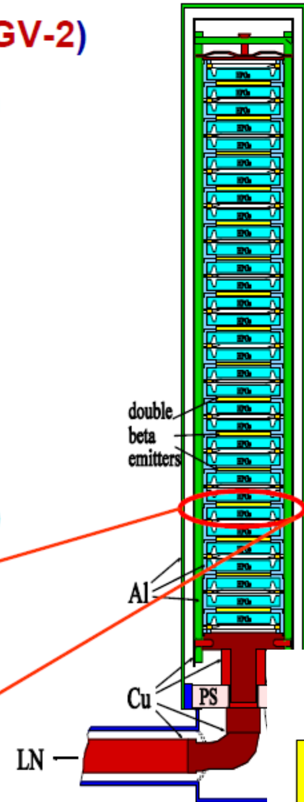
Many approaches are used in today (and future) $2\beta0\nu$ experiments: semiconductors (HPGe, Si, CdZnTe), scintillators (LXe, $CdWO_4$, …), bolometers (TeO_2), scintillating bolometers ($ZnMoO_4$, ZnSe, $CaMoO_4$), liquid and gas TPC, tracking + calorimeter technique, isotopes dissolved in liquid scintillator.

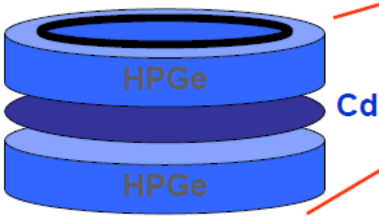
$2\beta0\nu$ is not observed on level of $T_{1/2} \sim 10^{23} - 10^{25}$ y, and aim of future experiments is $10^{26} - 10^{27}$ y. This is possible only with massive (~100 – 1000 kg) detectors. Such a sensitivity allows to investigate inverted hierarchy of neutrino masses.

Thank you for attention!

Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors ∅60 mm x 6 mm
with sensitive volume: 20.4 cm^2 x 6 mm
Total sensitive volume: ~400 cm^3
Total mass of detectors: ~3 kg
Total area of samples : 330 cm^2
Total mass of sample(s) : 10 ÷ 25 g
Total efficiency : 50 ÷ 70 %
E-resolution : 3 ÷ 4 keV @ ^{60}Co
LE-threshold : 5 ÷ 6 keV
Double beta emitters:
16 samples (~ 50 μm) of ^{106}Cd (enrich.75%)
13.6 g ~ 5.79 x 10^{22} atoms of ^{106}Cd



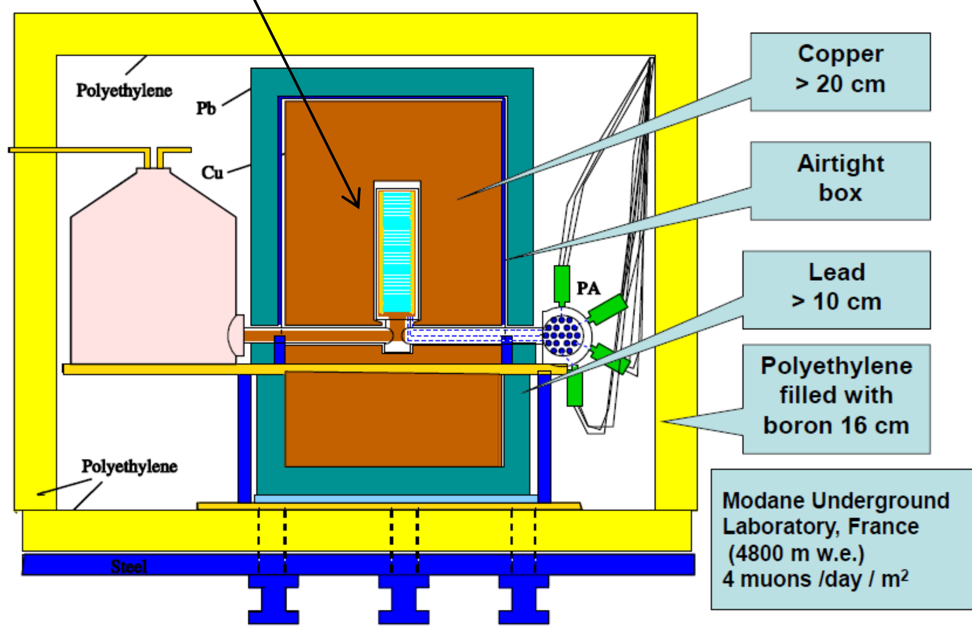


Russia, France, Czech Republic, Slovakia (in LSM, France)

Main interest - 2ε2ν capture
12900 h (phase 2)

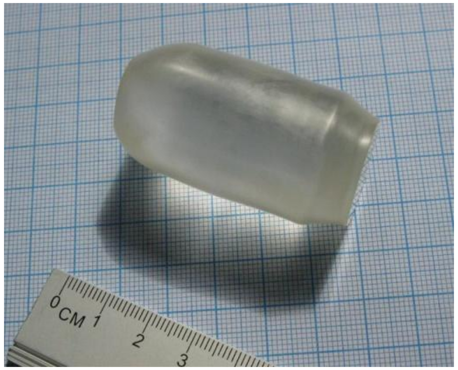
$T_{1/2}$ limits for different modes:
~ 10^{20} yr

PASSIVE SHIELDING



Plans:
13 g of ^{106}Cd → 23 g (98%)
Bigger sensitive surgaces
Pixel detectors?

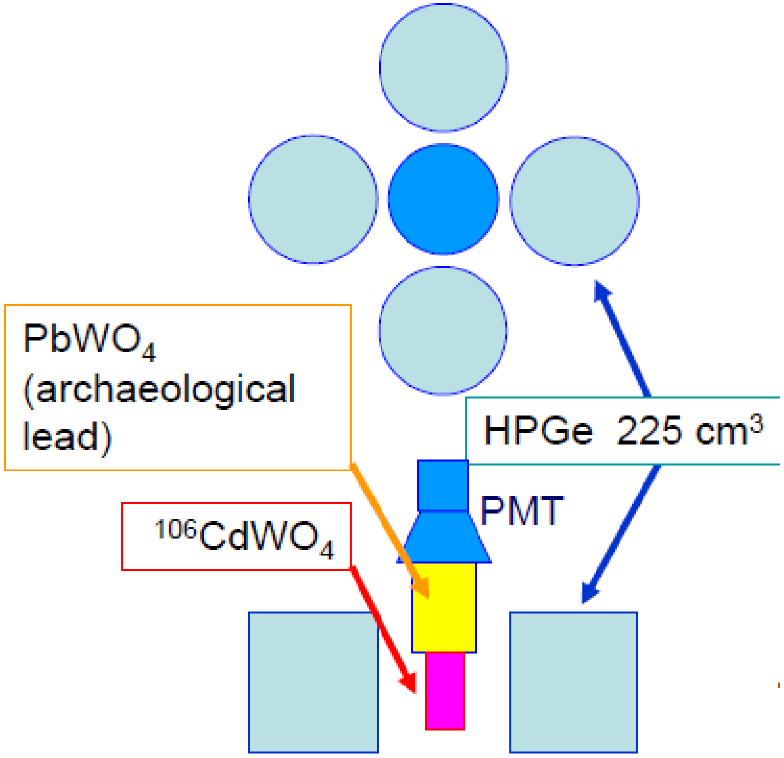
$^{106}CdWO_4$ experiment (Italy, Ukraine, Russia, Finland – in LNGS, Italy)

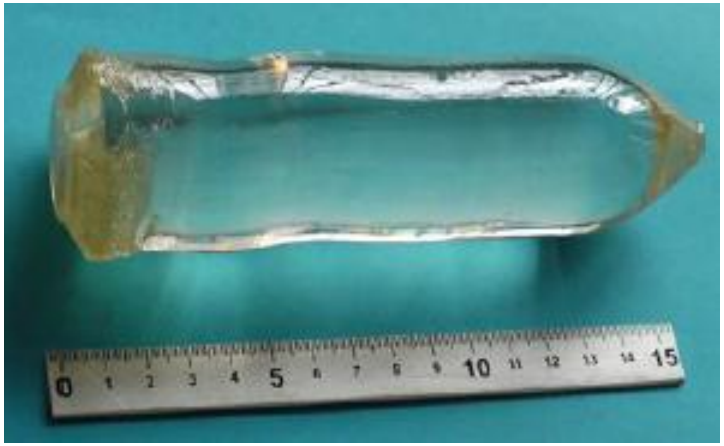
$^{106}CdWO_4$ boule (231 g) and $^{106}CdWO_4$ scintillator (215 g)
66% enrichment in ^{106}Cd, 6590 h

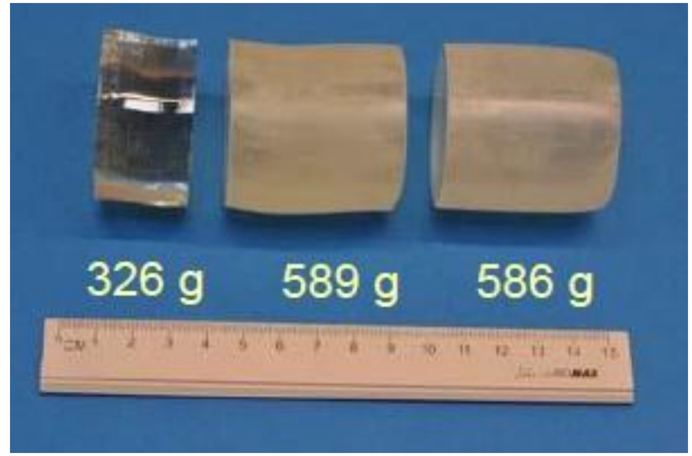
$T_{1/2}$ limits for different modes: 10^{20} – 10^{21} yr
(mostly better than in TGV-2)

Plans:
$^{106}CdWO_4$ ^{106}CdW with 4 HP Ge
(F.A. Danevich, MEDEX'2011)



$^{116}CdWO_4$ experiment (Italy, Ukraine, Russia – in LNGS, Italy)





$^{116}CdWO_4$ boule (1868 g) and $^{116}CdWO_4$ scintillators
82% enrichment in ^{116}Cd, data taking

Spectra for first 1322 h →
Background: 0.28 cnt/yr keV kg (0.04 in Solotvina)

Sensitivity for 2β0ν in 5 yr: (0.5 – 1.5)×10^{24} yr
[JINST 06(2011)P08011]

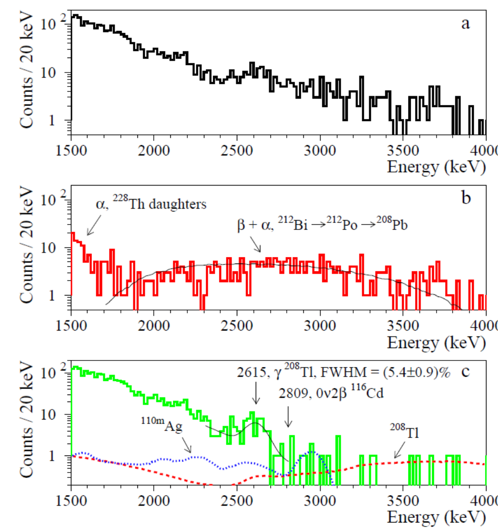
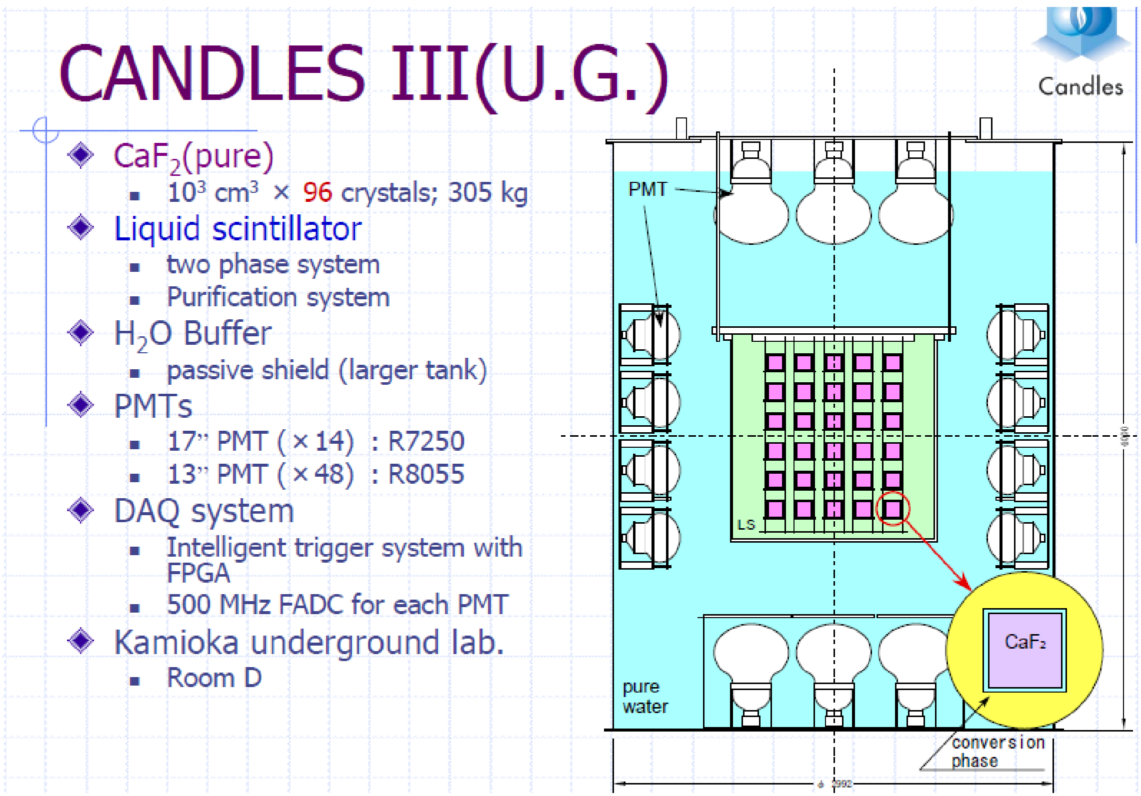


Figure 12. (Color online) (a) Initial sum spectrum of the two $^{116}CdWO_4$ detectors measured over 1322 h (total exposure 1554 kg×h) in anti-coincidence with the plastic scintillation counter and the active light-guides; (b) the spectra of α and $\beta + \alpha$ events selected by using the pulse-shape and the front edge analyses (see text) together with the simulated response function for the $^{212}Bi \to ^{212}Po \to ^{208}Pb$ decay chain; (c) β and γ events selected with the help of the pulse-shape and the front edge analyses (the efficiency of the selection procedure for γ quanta / β particles is 95%). The fit of the ^{208}Tl γ peak with the energy 2615 keV is shown by solid line. The Monte Carlo simulated energy spectra of internal ^{110m}Ag and ^{208}Tl in the $^{116}CdWO_4$ crystals are presented.

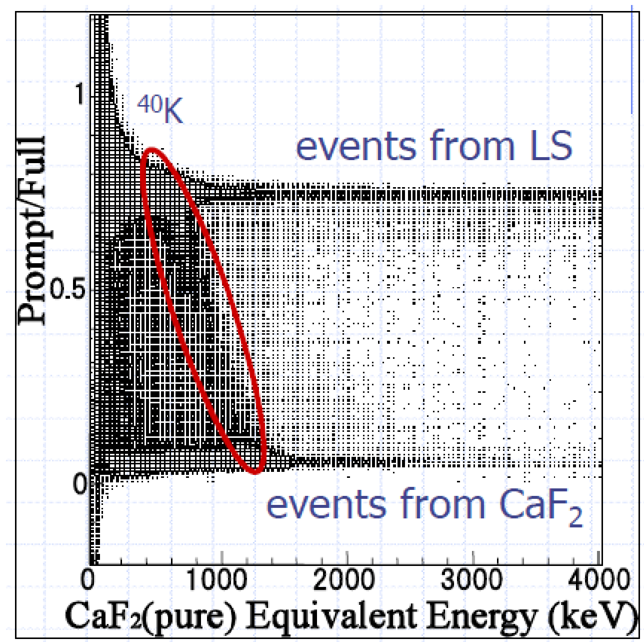
CANDLES experiment (Japan – in Kamioka, Japan)

^{48}Ca, 0.187%, 4.27 MeV – biggest 2β energy release
CaF_2(undoped) scintillators in 4π active shield (liquid scintillator)



CANDLES III – construction is finished

Efforts to enrich ^{48}Ca for future big experiment



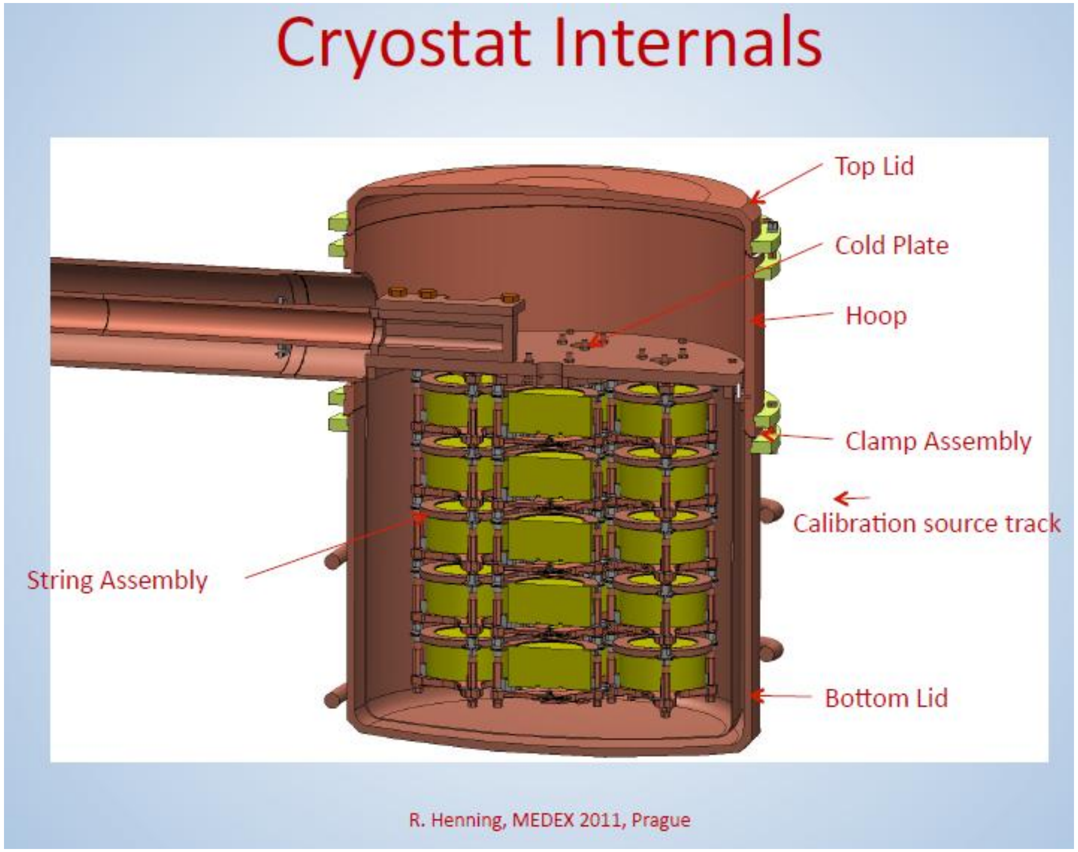
Pulse-shape discrimination – clear separation between signals in LS (10 ns) and CaF_2 (1 μs)

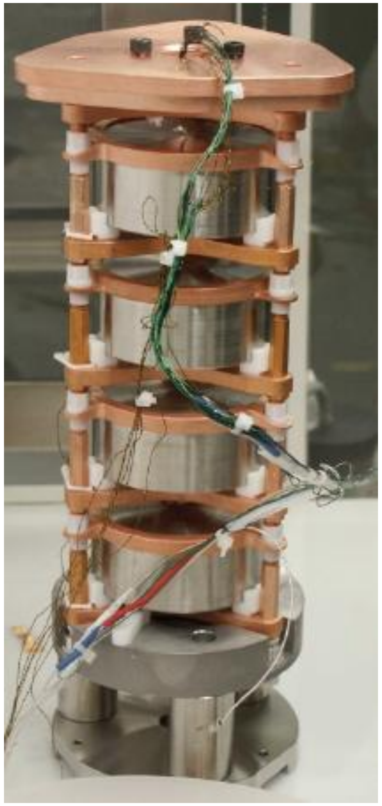
CANDLES III (U.G.)

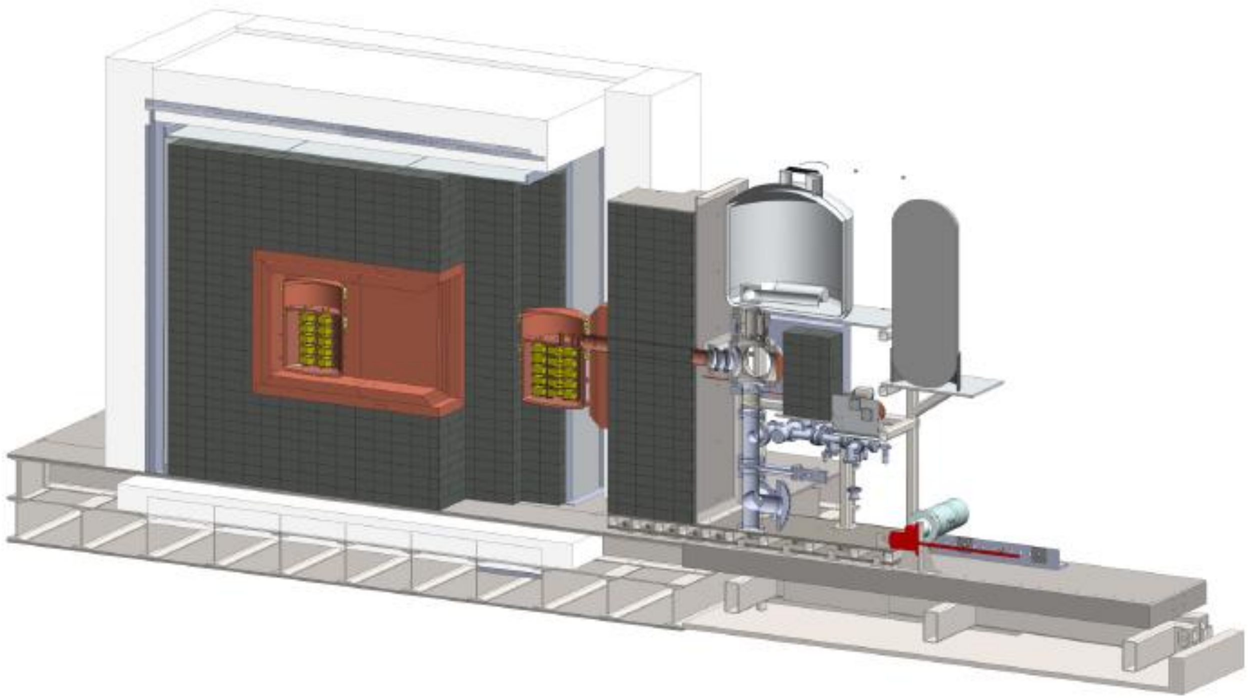
New experiments and projects

Majorana experiment (USA, Russia, Japan, Canada – in Sanford UL, USA or SNOLab, Canada)

Also ^{76}Ge (few stages up to 1 tonne), but not naked – in conventional cryostat





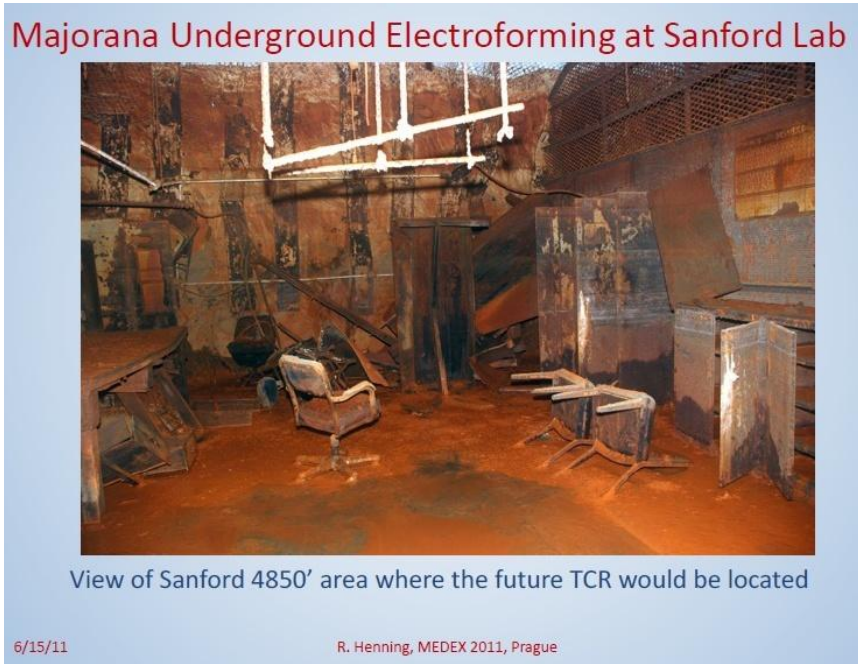


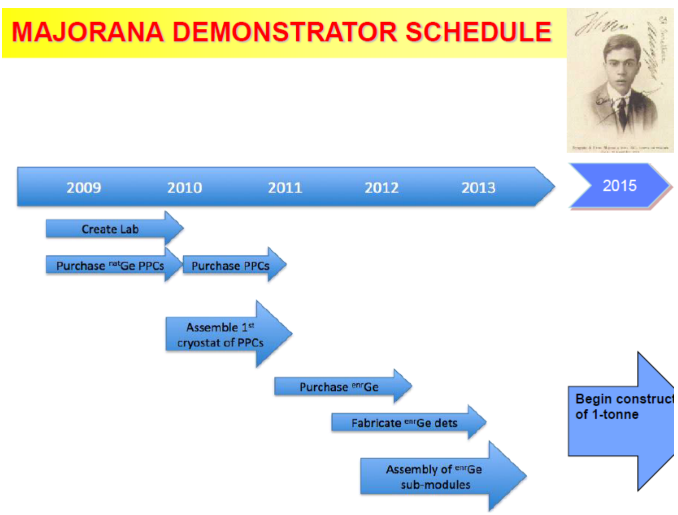
Majorana Demonstrator:

All ^{nat}Ge – summer 2012
First 12 kg ^{76}Ge – summer 2013
Additional 18 kg ^{76}Ge – spring 2014

(R. Henning, MEDEX'2011)

So, progress of GERDA is much faster





NEXT experiment (Spain, USA, Russia, France, Colombia, Portugal – in Canfranc, Spain)

^{136}Xe, TPC with Xe gas at high pressure

1 kg prototype in 2011 (first results are obtained)
Full set-up 100 kg in late 2013 (sensitivity around 100 meV in 5 yr)

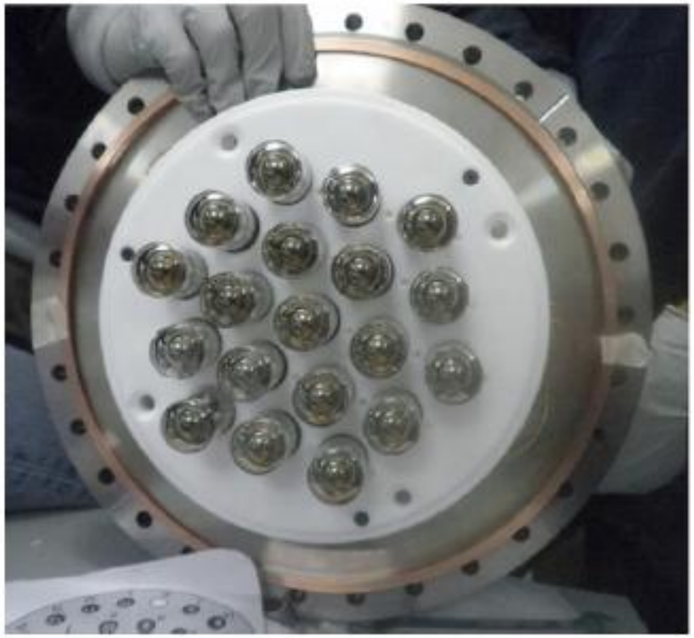


Figure 4.14: PMT Tracking plane installed at the TPC Anode in the commissioning of NEXT1 operation.

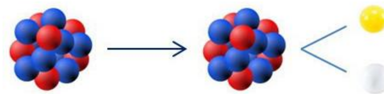
SUMMARY TABLE

Experiment	Isotope	Mass, kg	$T_{1/2}$, y	$<m_\nu>$, meV	Status
CUORE	^{130}Te	200	$2.1 \cdot 10^{26}$	40-90	Funded
GERDA	^{76}Ge	I. 17 II. 40 III.1000	$3 \cdot 10^{25}$ $2 \cdot 10^{26}$ $6 \cdot 10^{27}$	 70-200 10-40	Funded Funded R&D
MAJORANA	^{76}Ge	I. 30-60 II. 1000	$(1\text{-}2) \cdot 10^{26}$ $6 \cdot 10^{27}$	70-200 10-40	Funded R&D
EXO	^{136}Xe	200 1000	$6.4 \cdot 10^{25}$ $8 \cdot 10^{26}$	100-200 30-60	Funded R&D
SuperNEMO	^{82}Se	100-200	$(1\text{-}2) \cdot 10^{26}$	40-100	R&D
KamLAND-Xe	^{136}Xe	400 1000	$\sim 4 \cdot 10^{26}$ $\sim 10^{27}$	40-80 25-50	Funded R&D
SNO+	^{150}Nd	56 500	$\sim 4.5 \cdot 10^{24}$ $\sim 3 \cdot 10^{25}$	100-300 40-120	Funded R&D

A.S. Barabash 2010

Experiment	$M_{\beta\beta}$ ($\text{kg}_{\beta\beta}$)	ε	ΔE (keV)	c (10^{-3} counts/(keV $\cdot$ $\text{kg}_{\beta\beta}$ $\cdot$ year))	Bgr/ROI (cts/yr)
EXO-200	141	0.34	100	0.78–5	11–71
GERDA-1	15.2	0.95	4.2	12–70	0.77–4.5
GERDA-2	30.4	0.84	2	1.2–7	0.07–0.43
CUORE-0	10.9	0.83	5	180–390	9.8–21.3
CUORE	206	0.83	5	36–130	37.1–134
KamLAND-Zen	357	0.61	250	0.22–1.8	19.6–161
MAJORANA	17.2	0.85	2	1.2–12	0.04–0.41
SNO+	44	0.50	220	9–70	87–680
NEXT	89.2	0.33	18	0.2–1	0.32–1.6
SuperNEMO	7	0.28	130	0.6–6	0.55–5.5

Experiment	$T^{0\nu}_{1/2}$ (years)	$m_{\beta\beta}$ (meV)
CUORE-0	8.67×10^{24}	203
CUORE	8.86×10^{25}	63
GERDA-1	4.49×10^{25}	252
GERDA-2	1.37×10^{26}	121
EXO200	8.20×10^{25}	82
NEXT	9.13×10^{25}	78
KamLAND-Zen	1.32×10^{26}	65
SNO+	5.38×10^{24}	182
SuperNEMO	9.15×10^{25}	258
Majorana	7.19×10^{25}	258



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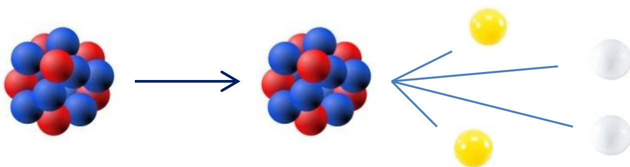
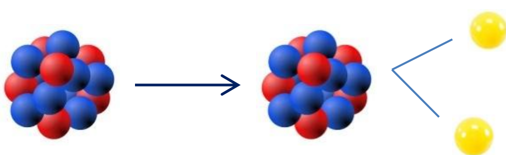
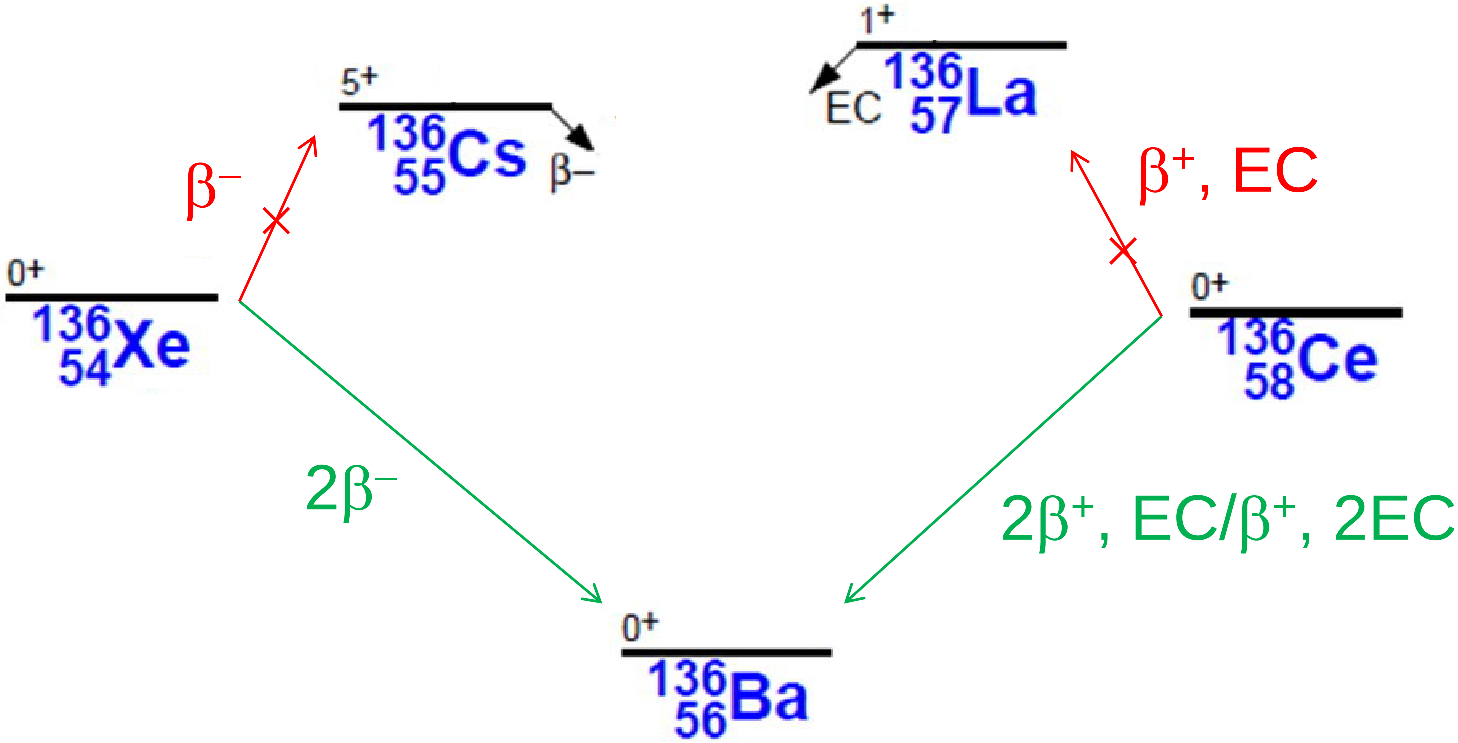
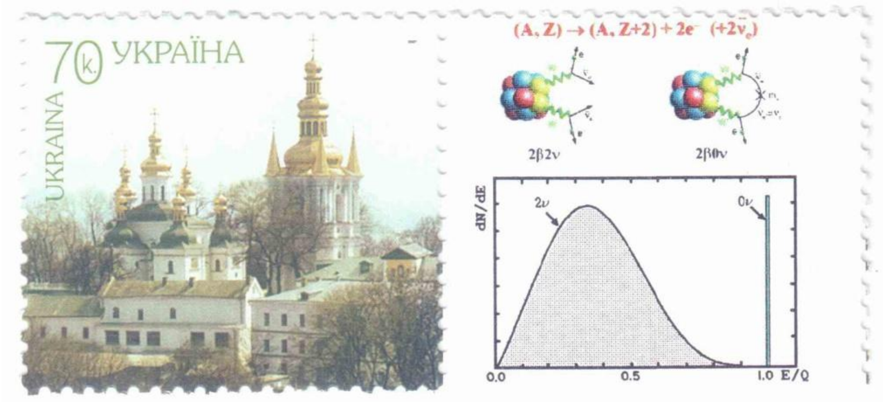






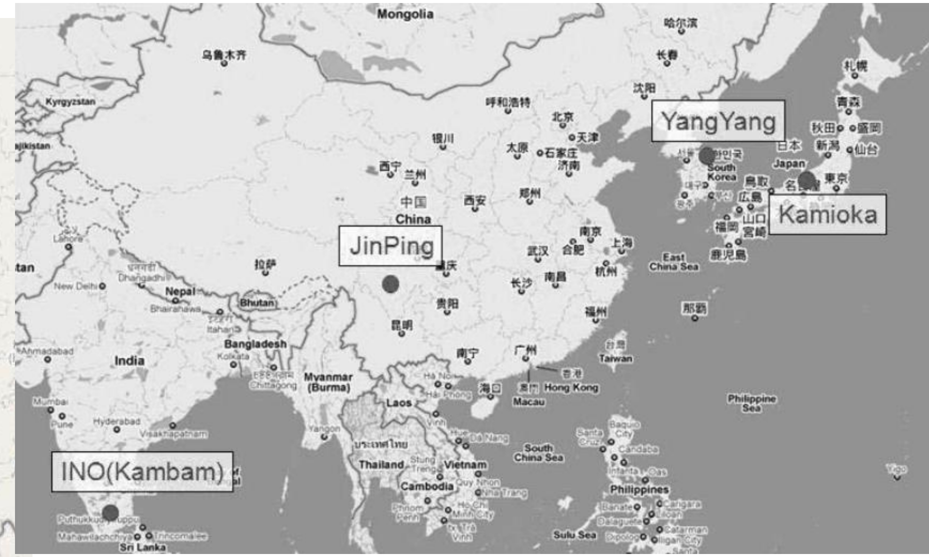
1+
136 57 La
EC
5+
136 55 Cs
β–
β–
β+, EC
0+
136 54 Xe
0+
136 58 Ce
2β–
2β+, EC/β+, 2EC
0+
136 56 Ba



70 k.
УКРАЇНА
UKRAINA
(A, Z) → (A, Z+2) + 2e⁻ (+2ν̄e)
2β2ν
2β0ν
dN/dE
2ν
0ν
0.0
0.5
1.0 E/Q

70 k.
УКРАЇНА
UKRAINA
NEMO-3

Underground laboratories



L. Pandola, AIP Conf. Proc. 1338 (2011) 12

M. Nakahata, AIP Conf. Proc. 1338 (2011) 20