DOUBLE BETA DECAY EXPERIMENTS

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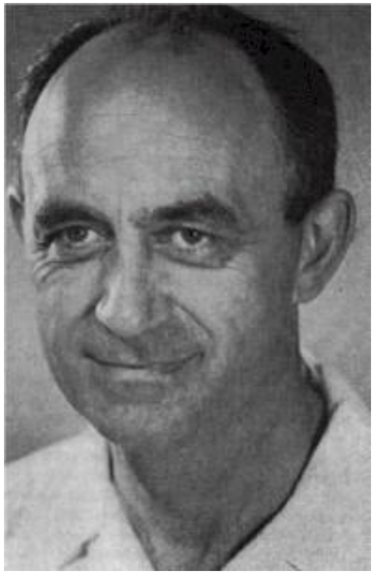
Plan

- Historical introduction
- Present status
- Future experiments

I. Historical introduction

Neutrino was introduced by **W. Pauli** in 1930



β-decay theory (weak interaction) was formulated by **E. Fermi** in 1933:

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

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

The birth of double beta decay

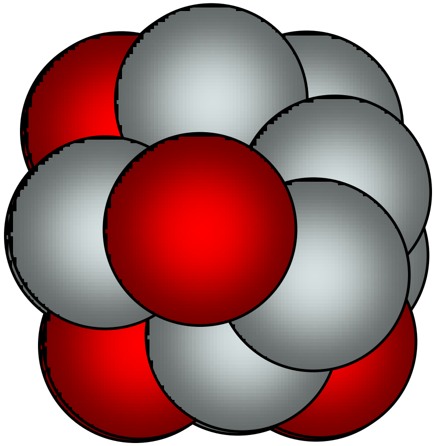
- $2\beta(2\nu)$ decay was introduced by

  M. Goeppert-Mayer in 1935:

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

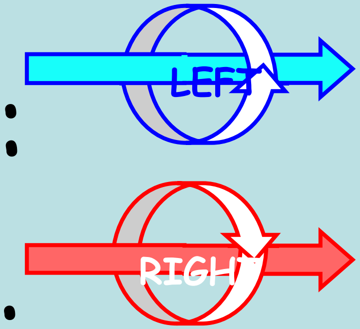
$(T_{1/2} \sim 10^{21}\text{-}10^{22}\ y)$

2ν-ββ Decay
$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\tilde{\nu})$



From S. Schoenert

ν:



$\bar{\nu}$:

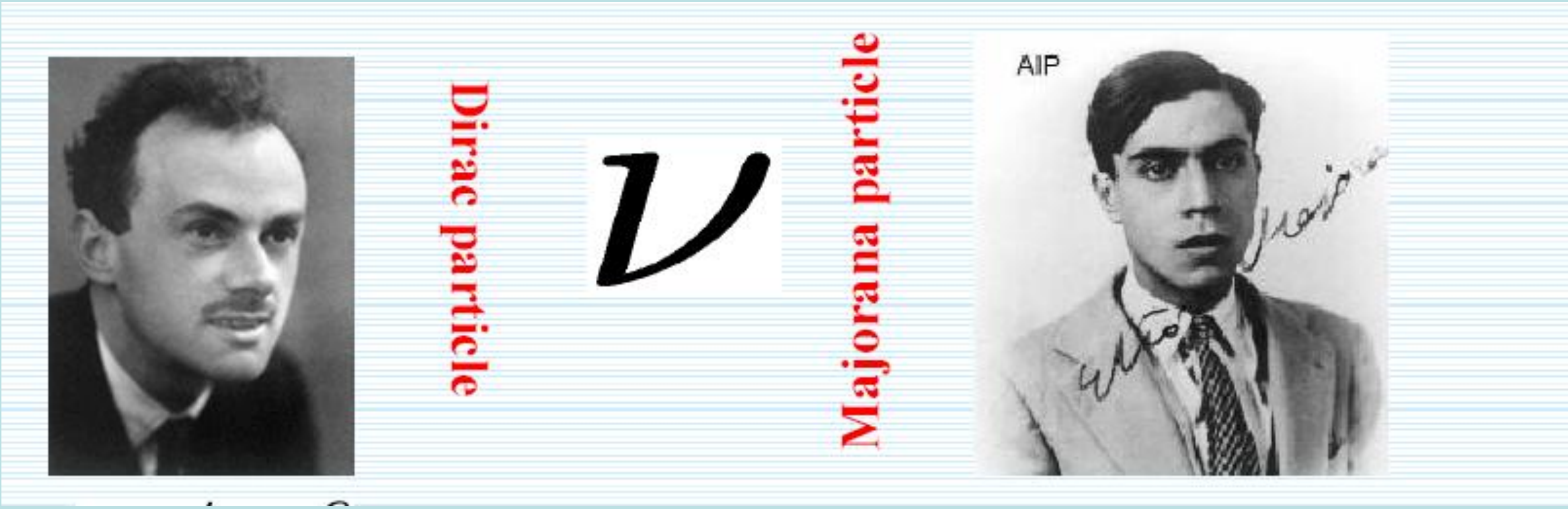
$\nu \neq \bar{\nu}$

Dirac

$\nu = \bar{\nu}$

Majorana

=>1937



Racah's chains (G. Racah, 1937)

- $(A,Z) \rightarrow (A,Z+1) + e^{-} + \tilde{\nu}$ ($\nu = \nu^{\sim}$) $\rightarrow$
  $\nu + (A,Z) \rightarrow (A,Z+1) + e^{-}$
- So, it will be possible to see difference between Dirac and Majorana neutrinos!
- **W.H. Farry (1938)** $\rightarrow$ no any practical possibilities to use this (there were no reactors at that time!)

The birth of neutrinoless double beta decay

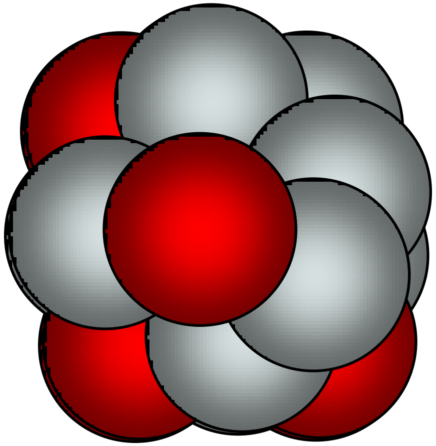
- $2\beta(0\nu)$ decay was introduced by W.H. Farry in 1939:

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} \qquad (4)$$

($T_{1/2} \sim 10^{15}$-10^{16} y)

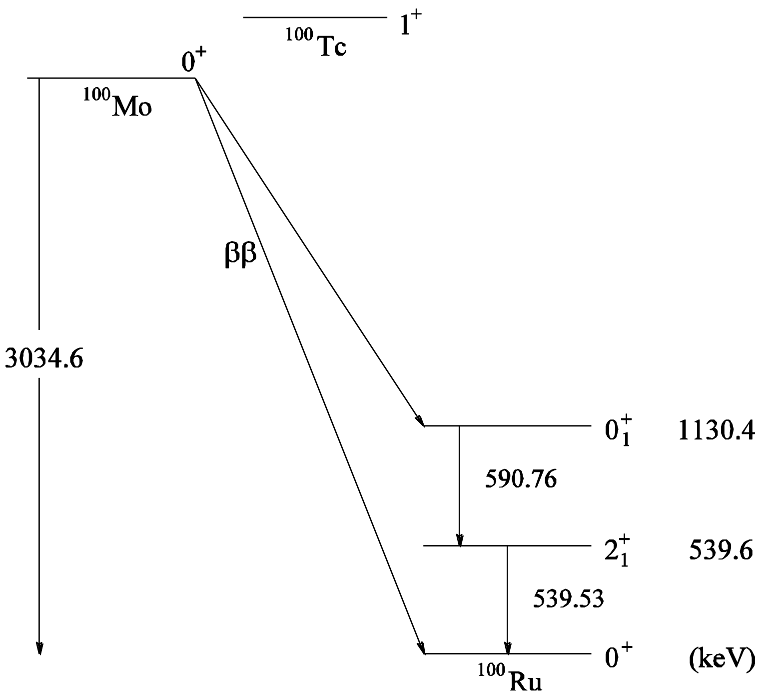
[Parity violation was not known at that time!]

0ν-ββ Decay
(A,Z) → (A,Z+2) + 2e⁻



From S. Schoenert

Double beta decay scheme



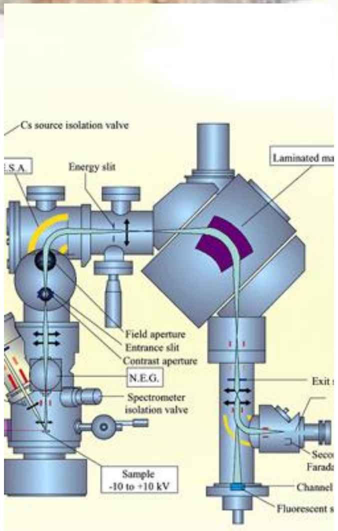
First experiments

- **1948** – first counter experiment (Geiger counters, ^{124}**Sn**; $T_{1/2}(0\nu) > $ **$3 \cdot 10^{15}$ y**)
- **1950** – **first evidence** for **$2\beta2\nu$** decay of ^{130}**Te** in first geochemical experiment:

  $T_{1/2} \approx 1.4 \cdot 10^{21}$ y!!!
- **1950-1965** – a few tens experiments

  with sensitivity **$\sim 10^{16}$-10^{19} y**
- **1966-1975** – in 3 experiments sensitivity to **0ν** decay reached **$\sim 10^{21}$ y**!!!

Geochemical experiments



1. **Selection** of mineral, contains **2β** nuclei (**^{130}Te, ^{82}Se,** for example).
2. **Age and geological history** of the mineral (age is ~ (0.1-4)x10^9 yr) have to be known.
3. **Extraction** of daughter atoms (**Xe, Kr,** for example).
4. Determination of isotopic composition (using **mass-spectrometer**).
5. Excess of **^{130}Xe** or **^{82}Kr**, for example, gives information about **2β-decay rate.**

Measurement time is a few billion years!

1957 – situation is changed!

- **P** and **C** violation
- **V-A** structure of weak interaction
- **Helicity** of ν(ν˜) is **~ 100%**

⇓

2β(0ν)-decay is suppressed (if even possible?)

and $T_{1/2}(0\nu) > T_{1/2}(2\nu)$

Best results in 1966-1975

- $T_{1/2}(0\nu;^{76}\mathrm{Ge}) > 5\cdot10^{21}$ y; Ge(Li) detector, **1973** (E. Fiorini et al.)

- $T_{1/2}(0\nu;^{48}\mathrm{Ca}) > 2\cdot10^{21}$ y; streamer chamber + magnetic field + plastic scint., **1970** (C. Wu et al.)
- $T_{1/2}(0\nu;^{82}\mathrm{Se}) > 3.1\cdot10^{21}$ y; streamer chamber + magnetic field + plastic scint., **1975** (C. Wu et al.)

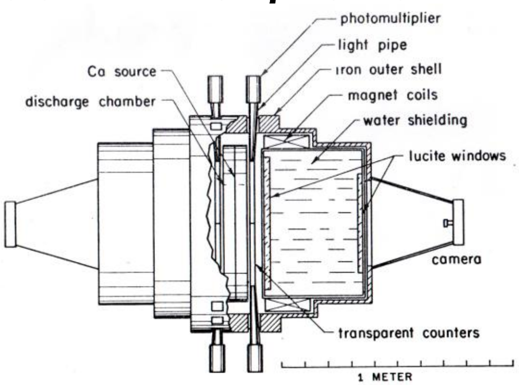
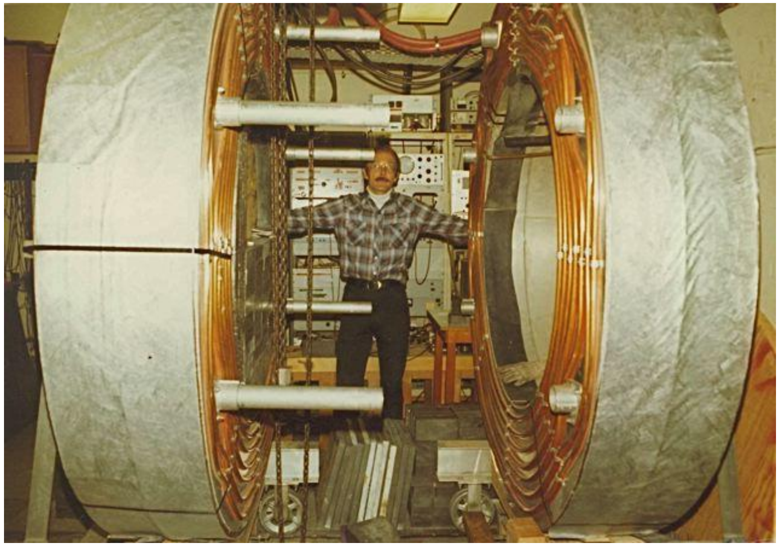


Fig. 3. Cutaway drawing of double beta decay apparatus.

- Geochemical experiments with **^{130}Te, ^{128}Te, ^{82}Se** (**2ν** measurements: **~ 10^{21}, ~10^{24}** and **~10^{20}** y)

Main achievements in 1976-1987

- **2β2ν** decay was first time detected in direct (counting) experiment ⇒
  $T(^{82}Se)_{1/2} = 1.1^{+0.8}_{-0.3} \cdot 10^{20}$ y
  (35 events; TPC, **1987**, S. Elliott, A. Hahn, **M. Moe**)



- First time **enriched Ge** detector was used in experiment (ITEP-ErFI; **1987**)

Main achievements in 1988-2001

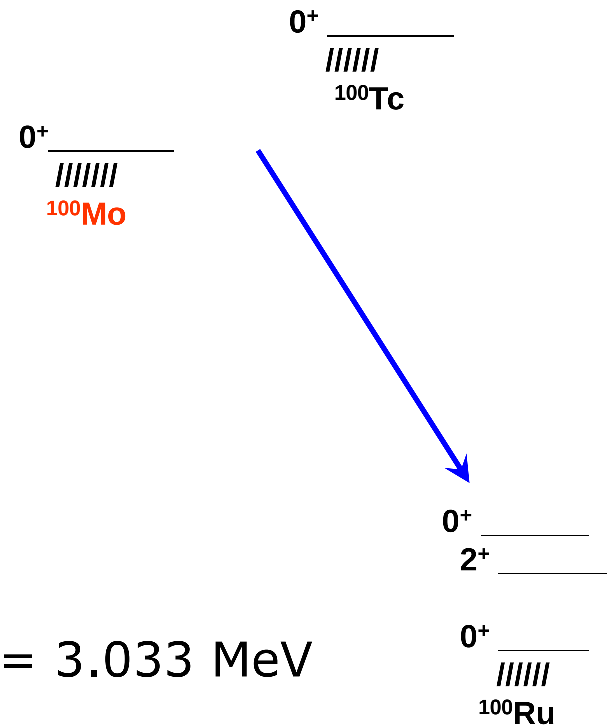
- $T_{1/2}(0\nu;{}^{76}\mathrm{Ge})$ **> (1.6-1.9)·10²⁵ y**;
  (HM and IGEX; enriched HPGe detectors)
- $T_{1/2}(0\nu)$ **> 10^{22}-10^{23}** y for **^{136}Xe, ^{82}Se, ^{116}Cd, ^{100}Mo**
- **2ν**-decay was detected for many nuclei (TPC, ELEGANT-V, NEMO-2, HM, IGEX, Solotvino, Liq. Ar....) + transition to the 0^+ excited states (Soudan, Modane, TUNL-ITEP)

II. PRESENT STATUS

- 1. Introduction
- 2. Current experiments

  - NEMO-3 and CUORICINO
  - "small-scale" experiments
  - ECEC(0ν) resonance transitions

1. Introduction



$Q_{\beta\beta}$ = 3.033 MeV

^{100}Mo ⇒ ^{100}Ru + 2e$^-$

^{100}Mo ⇒ ^{100}Ru + 2e$^-$ + χ^0 (+χ^0)

^{100}Mo ⇒ ^{100}Ru + 2e$^-$ + 2v

There are 35 candidates for 2β^--decay

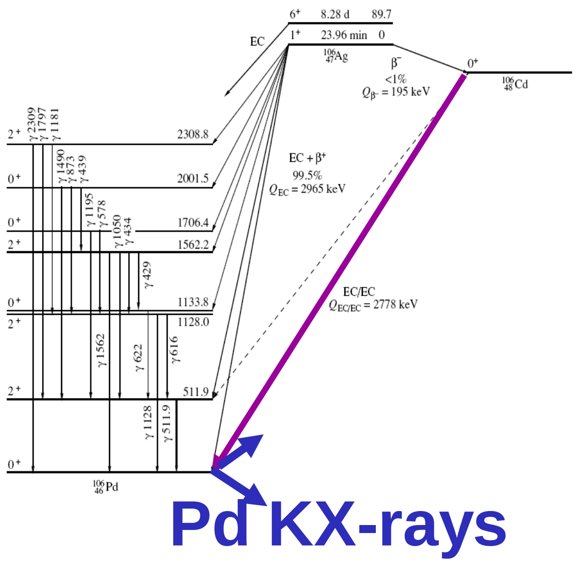
W ~ Q^5 (0ν); W ~ Q^7 (0$\nu\chi^0$)
W ~ Q^{11} (2ν)

Candidates with $Q_{2\beta}$ > 2 MeV

Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

Natural γ-rays background - E < 2.615 MeV.
So, there are **6 gold** and **5 silver** isotopes

2β⁺, ECβ⁺ and ECEC processes



$2\beta^+$:

(A,Z) $\rightarrow$ (A,Z-2) + $2\beta^+$ + 2X (+ 2ν)

(6 nuclei candidates)

$EC\beta^+$:

e^-_b + (A,Z) $\rightarrow$ (A,Z-2) + β^+ + X (+ 2ν)

(16 nuclei candidates)

ECEC:

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

(34 nuclei candidates)

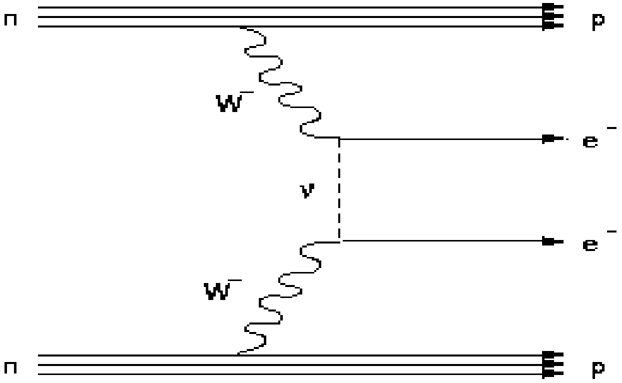
Candidates for 2β^+ transition

Nuclei	ΔM, keV	Abundance, %
1. ^{124}Xe	2865	0.09
2. ^{78}Kr	2806	0.35
3. ^{106}Cd	2771	**1.25**
4. ^{96}Ru	2719	**5.54**
5. ^{130}Ba	2611	0.101
6. ^{136}Ce	2400	0.185

NEUTRINOLESS DOUBLE BETA DECAY

Experimental signature:

2 electrons
$E_{\beta 1} + E_{\beta 2} = Q_{\beta\beta}$



Oscillation experiments $\Rightarrow$ **Neutrino is massive!!!**

- However, the oscillatory experiments cannot solve the problem of the origin of neutrino mass (**Dirac or Majorana?**) and cannot provide information about the absolute value of mass (because the Δm^2 is measured).

- **<u>This information can be obtained in 2β-decay experiments.</u>**

$$<m_\nu> = \left| \sum |U_{ej}|^2 e^{i\phi_j} m_j \right|$$

Thus searches for double beta decay are sensitive not only to masses but also to mixing elements and phases ϕ_j.

What one can extract from 2β-decay experiments? ⇒

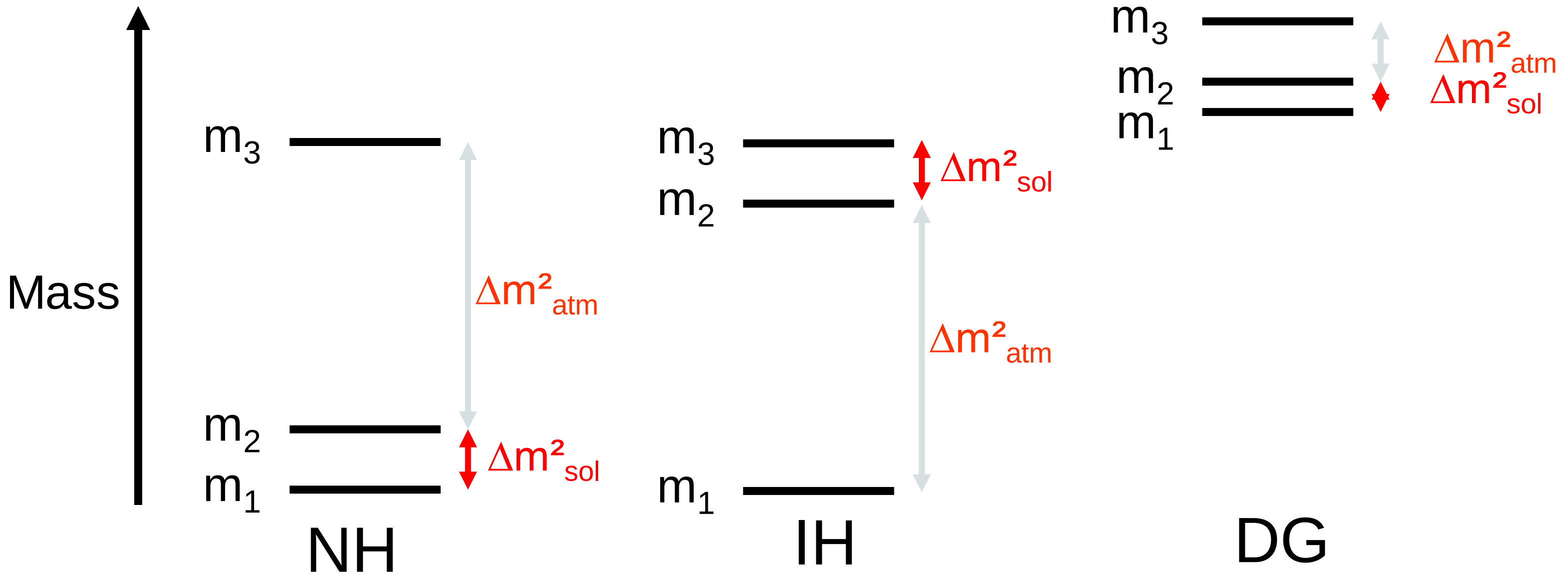
- Nature of neutrino mass (**Dirac or Majorana?**).
- Absolute mass scale (value or limit on m_1).
- Type of hierarchy (normal, inverted, quasi-degenerated).
- **CP** violation in the lepton sector.

Neutrinoless double beta decay is being actively searched, because it is closely related to many fundamental concepts of nuclear and particle physics:

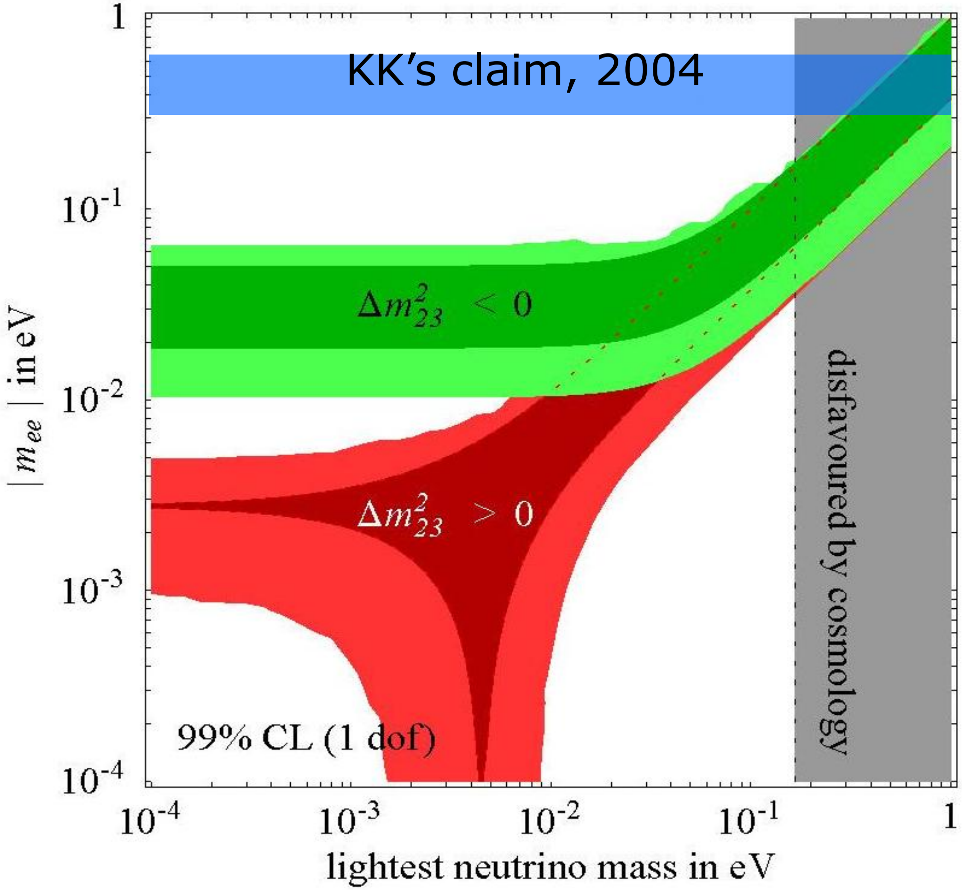
- - the lepton number nonconservation;
- **- the existence of neutrino mass and its origin**
- **(Dirac or Majorana?);**
- - the presence of right-handed currents in electroweak
- interactions;
- - the existence of Majoron;
- - the structure of Higg's sector;
- - the supersymmetry;
- - the heavy sterile neutrino;
- - the existence of leptoquarks.

Input for $\langle m_{ee} \rangle$ from ν-oscillations

Solar/Reactor -ν: θ_{12}, Δm^2_{sol} **Atmosph.-ν: Δm^2_{atm}** **Reaktor-ν: θ_{13}**



DBD and neutrino mass hierarchy



Degenerate: can be tested

Inverted: can be tested by next generation of 2β experiments.

Normal: inaccessible (new approach is needed)

Best present limits on <m_ν>

Nuclei	$T_{1/2}$, y	<m_ν>, eV QRPA	<m_ν>, eV [SM]	Experiment
^{76}Ge	>$1.9 \cdot 10^{25}$ ≈$1.2 \cdot 10^{25}$(?) ≈$2.2 \cdot 10^{25}$(?) >$1.6 \cdot 10^{25}$	< 0.22-0.41 ≈ 0.28-0.52(?) ≈ 0.21-0.38(?) <0.24-0.44	< 0.69 ≈ 0.87(?) ≈ 0.64(?) <0.75	HM Part of HM'04 Part of HM'06 IGEX
^{130}Te	>$2.8 \cdot 10^{24}$	< 0.35-0.59	< 0.77	CUORICINO
^{100}Mo	>$1.1 \cdot 10^{24}$	< 0.45-0.93	-	NEMO
^{136}Xe	>$4.5 \cdot 10^{23}$	< 1.41-2.67	< 2.2	DAMA
^{82}Se	>$3.6 \cdot 10^{23}$	< 0.89-1.61	< 2.3	NEMO
^{116}Cd	>$1.7 \cdot 10^{23}$	< 1.45-2.76	< 1.8	SOLOTVINO

A Recent Claim

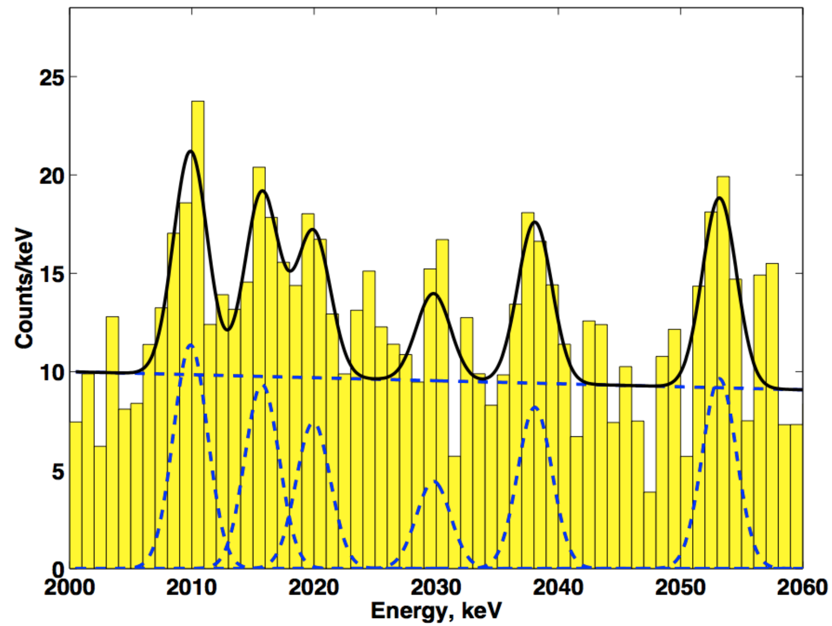
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

Used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data

$\tau_{1/2}$ = 1.2 x 10^{25} y (4.2 σ)

0.24 < m_ν < 0.58 eV (± 3 sigma)

(NME from Eur. Lett. 13(1990)31)



Mod.Phys.Lett. A21(2006)1547

Old data, new pulse shape anal.

$\tau_{1/2} = 2.23^{+0.44}_{-0.31}$ x 10^{25} y (6 σ)

m_ν = 0.32 ± 0.03 eV

n = 11±1.8 events ⇒

where is a statistical error?!

non-correct peak position?!

There are some problems with this result:

1) Only one measurement.
2) Only ~4σ level (independent analysis gives even ~ 2-2.7σ).
3) In contradiction with HM'01 and IGEX.
4) Moscow part of Collaboration: **NO EVIDENCE**.
5) ^{214}Bi peaks are overestimated.
6) "Total" and "analyzed" spectra are not the same.

"2β community": very conservative reaction

In any case new experiments are needed, which will confirm (or reject) this result

Heidelberg-Moscow experiment

Gran Sasso
5 HPGe detectors
(~ 11 kg of ^{76}Ge)

1990-2003
(full statistics:
71.7 kg·y)

Two neutrino double beta decay

- Second order of weak interaction
- Direct measurement of NME values!
  $\Rightarrow$

  - The only possibility to check the quality of NME calculations!!!

  - g_{pp} (QRPA parameter $\Rightarrow$ NME(0ν)!)

  $\Downarrow$

- This is why it is very important to measure this type of decay for many nuclei, for different processes (**$2\beta^-$, $2\beta^+$, $K\beta^+$, 2K, excited states**) and with high accuracy.

$2\beta(2\nu)$ decay was first time discussed by M. Goeppert-Mayer in 1935

Two neutrino double beta decay

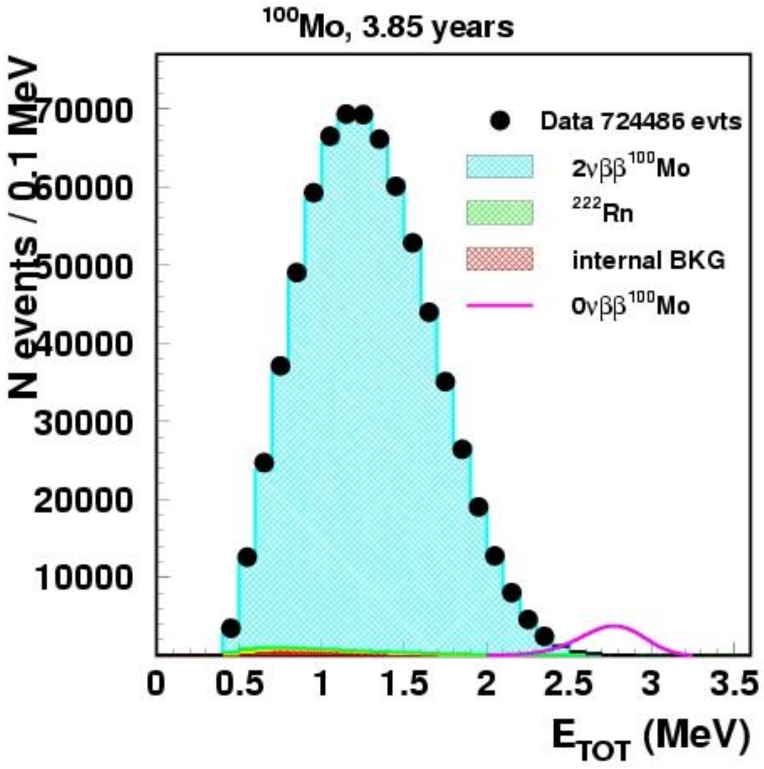
- By present time **$2\beta(2\nu)$** decay was detected in **10** nuclei:
  ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U

For **^{100}Mo** and **^{150}Nd** **$2\beta(2\nu)$** transition to **0^+** **excited states** was detected too

ECEC(2ν) in **^{130}Ba** was detected in geochemical experiment

Main goal is: precise investigation of this decay

$2\beta(2\nu)$ spectrum for ^{100}Mo (NEMO-3)



~ 700000 2ν events

Background is ~ 2%!!

All parameters of decay are measured!!!

Recommended values for half-lives:

- ^{48}Ca - $(4.4^{+0.6}_{-0.5})\cdot 10^{19}$ y
- ^{76}Ge – $(1.5 \pm 0.1)\cdot 10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot 10^{20}$ y
- ^{96}Zr – $(2.3 \pm 0.2)\cdot 10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot 10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) – $(5.9^{+0.8}_{-0.6})\cdot 10^{20}$ y
- ^{116}Cd – $(2.8 \pm 0.2)\cdot 10^{19}$ y
- ^{128}Te(geo) – $(1.9 \pm 0.4)\cdot 10^{24}$ y

^{130}Te – $(6.8^{+1.2}_{-1.1})\cdot 10^{20}$ y

- ^{150}Nd - $(8.2 \pm 0.9)\cdot 10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.33^{+0.45}_{-0.26})\cdot 10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot 10^{21}$ y

ECEC(2ν):

- ^{130}Ba(geo) - $(2.2 \pm 0.5)\cdot 10^{21}$ y

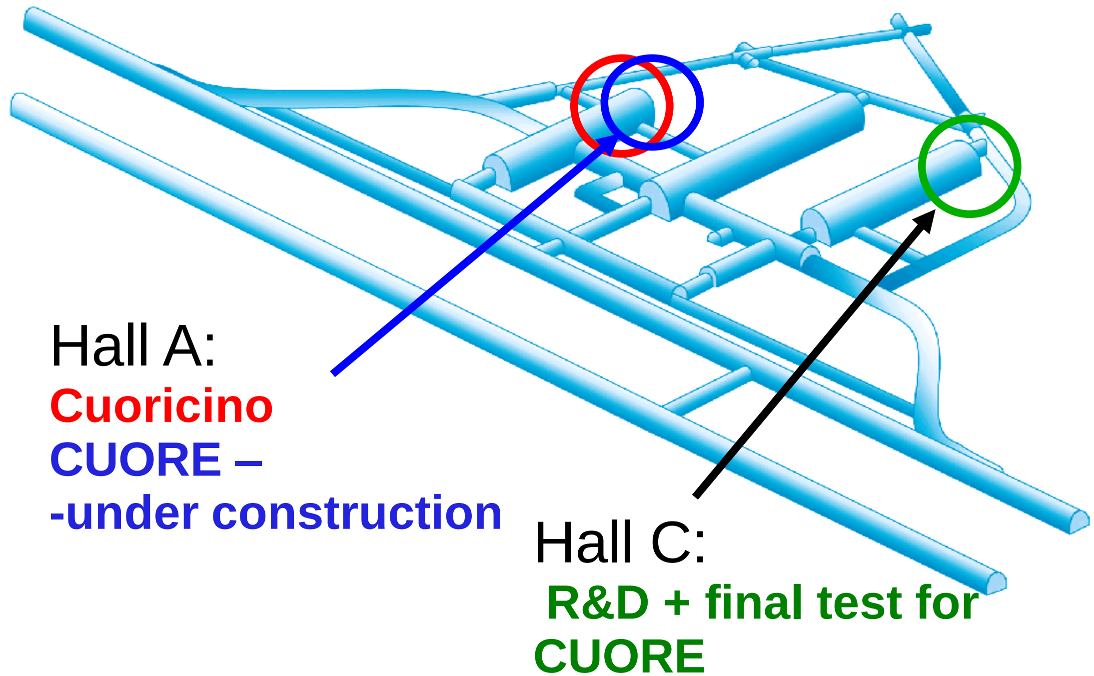
[A.S.B. Phys. Rev. C 81 (2010) 035501]

2. CURRENT EXPERIMENTS

- **NEMO-3** and **CUORICINO**
- Others (TGV, Baksan, DAMA, COBRA, ITEP-TPC, TUNL-ITEP, excited states,…)

CUORICINO

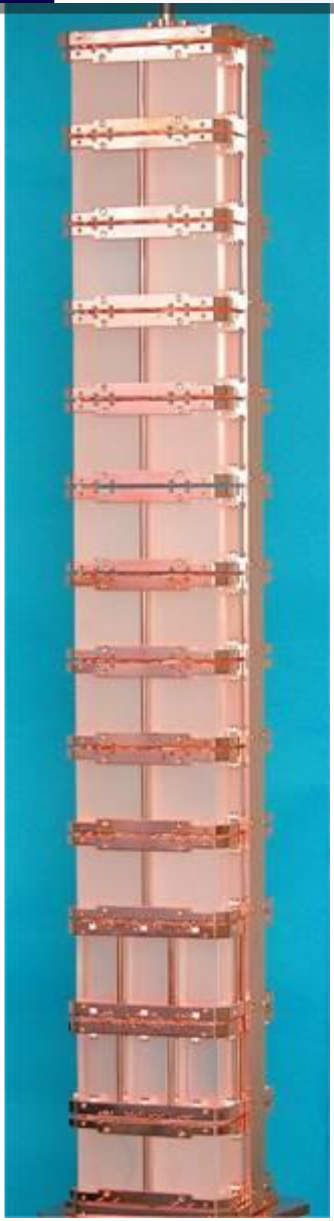
INFN - Laboratori Nazionali del Gran Sasso - L'Aquila – Italy



<u>3200 m.w.e overburden - cosmic rays are no more a bkg problem</u>

- **n flux is reduced to ~10^{-6} n/cm^2/s**
- **μ flux is ~ 2/m^2/h**

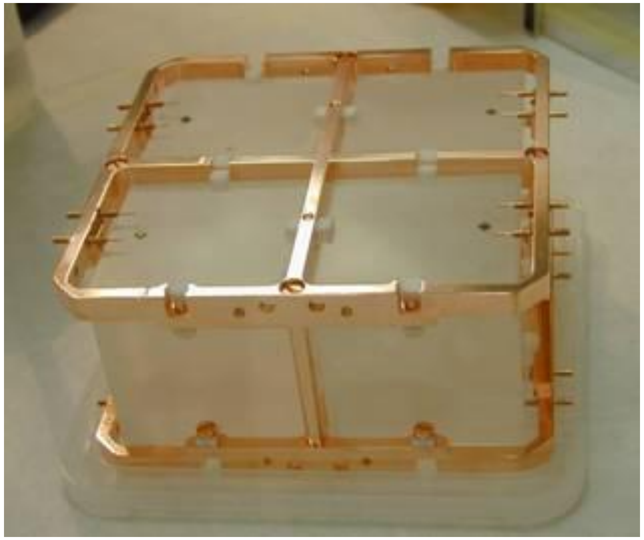
Cuoricino

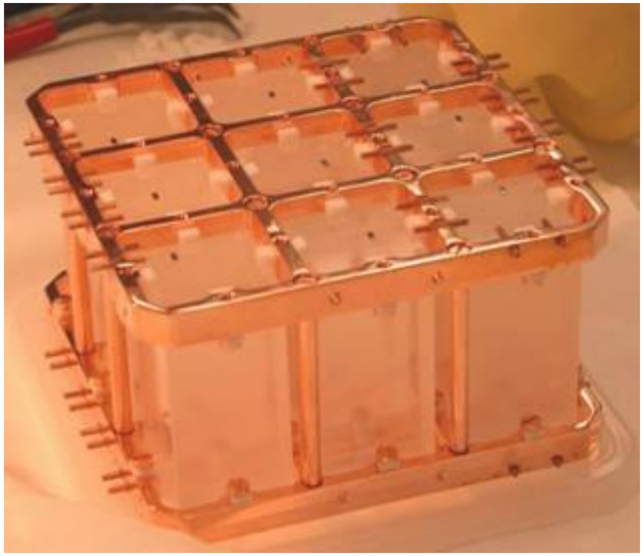


11 modules
4 detectors each
Dimension: 5x5x5 cm^3
Mass: 790 g

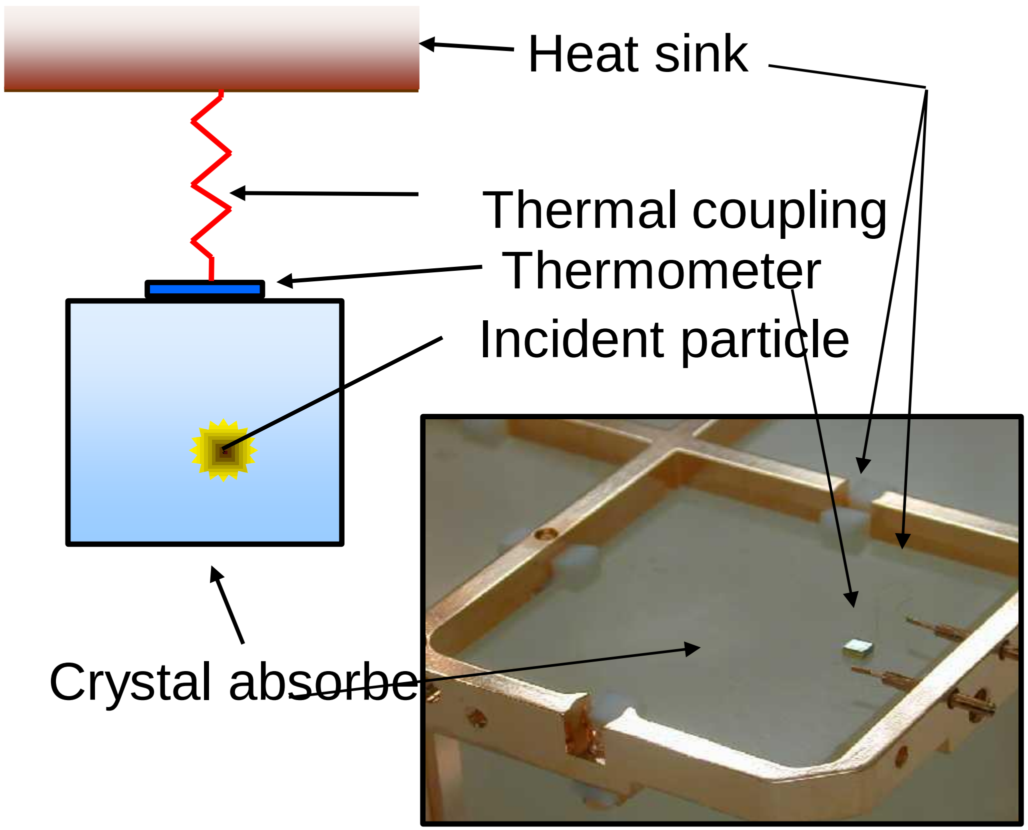
Total mass
40.7 kg
(~11 kg of ^{130}Te)

2 modules
9 detectors each,
Dimension: 3x3x6 cm^3
Mass: 330 g





Low Temperature Detectors (LTD)



Detection Principle

$\Delta T = E/C$

C: thermal capacity

low *C*

low *T* (i.e. $T \ll 1$K)

dielectrics, superconductors

ultimate limit to E resolution: statistical fluctuation of internal energy *U*

$\langle \Delta U^2 \rangle = k_B T^2 C$

Thermal Detectors Properties

good energy resolution

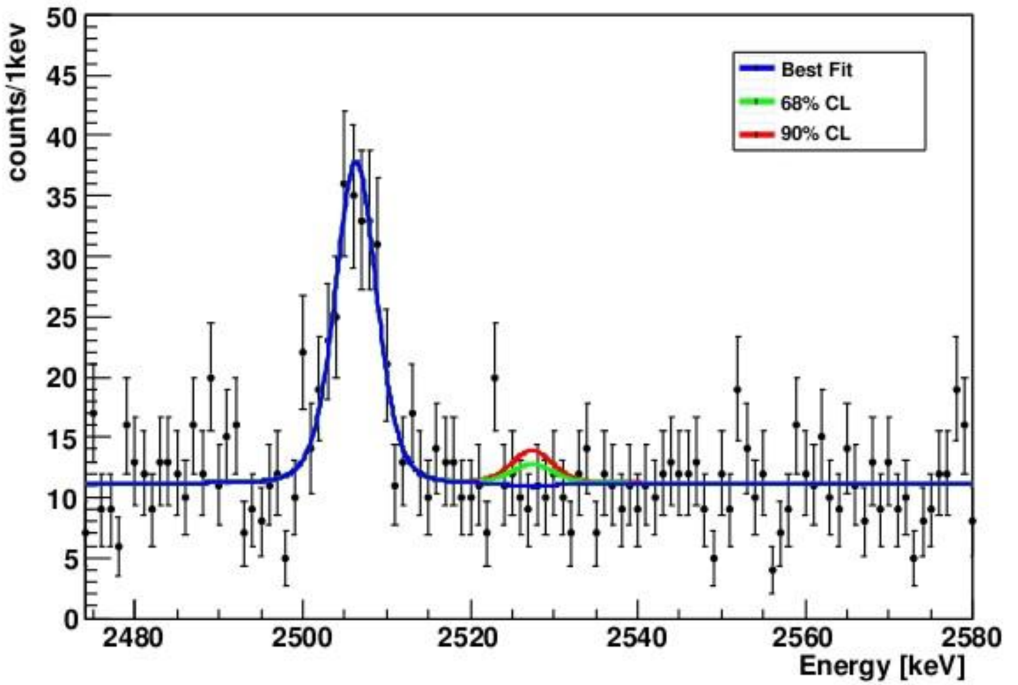
wide choice of absorber materials

true calorimeters

slow $\tau = C/G \sim 1 \div 10^3$ ms

T = 8 mK

Cuoricino result on ^{130}Te $\beta\beta0\nu$ decay



Total statistic
~ 19.75 kg (^{130}Te) × y

b = 0.18 ± 0.01 c/keV/kg/y

Maximum Likelihood
flat background + fit of 2505 peak

Anticoincidence background spectrum the bb-0n region

$$\tau^{0\nu}_{1/2} \geq 2.8 \cdot 10^{24}\, y \left(90\%\, CL\right)$$

➡

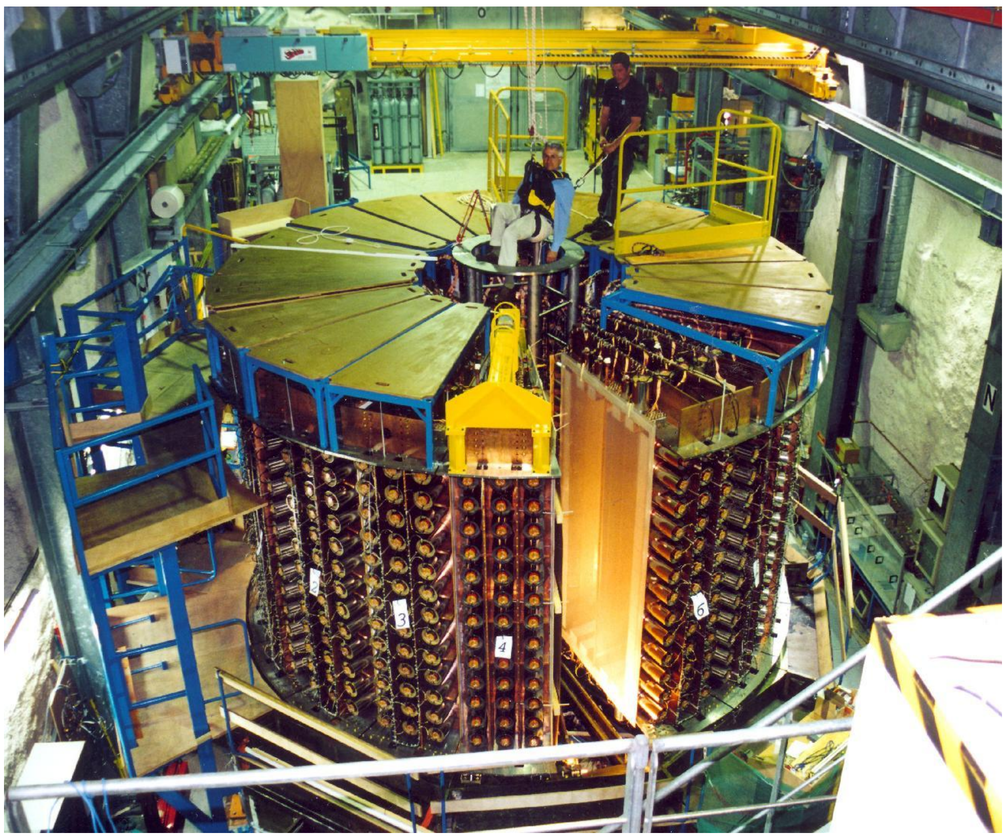
$$\left\langle m_\nu \right\rangle \leq 0.3 - 0.7\, eV \quad \left(90\%\;\; CL\right)$$

[Experiment is stopped in July 2008]

NEMO-3 Collaboration

(Neutrino Ettore Majorana Observatory)

60 physicists, 17 labs



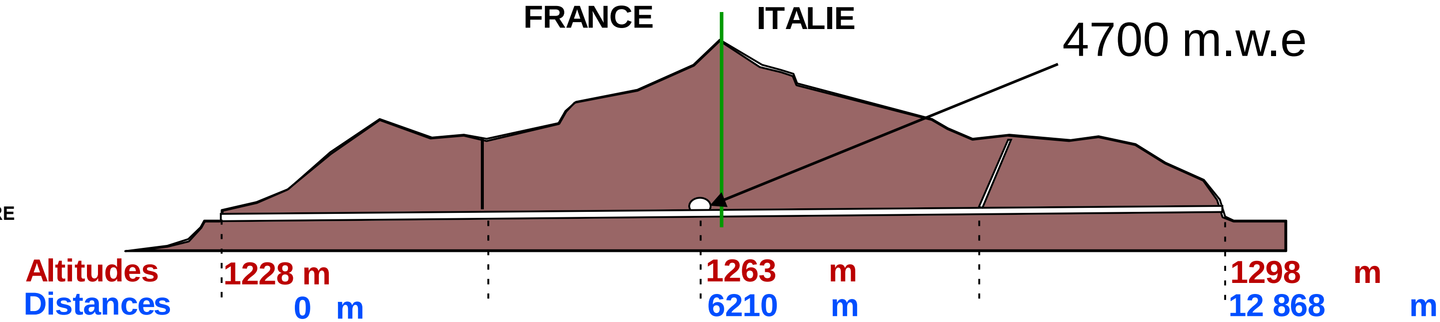
Laboratoire Souterrain de Modane

COMMISSARIAT À L'ÉNERGIE ATOMIQUE

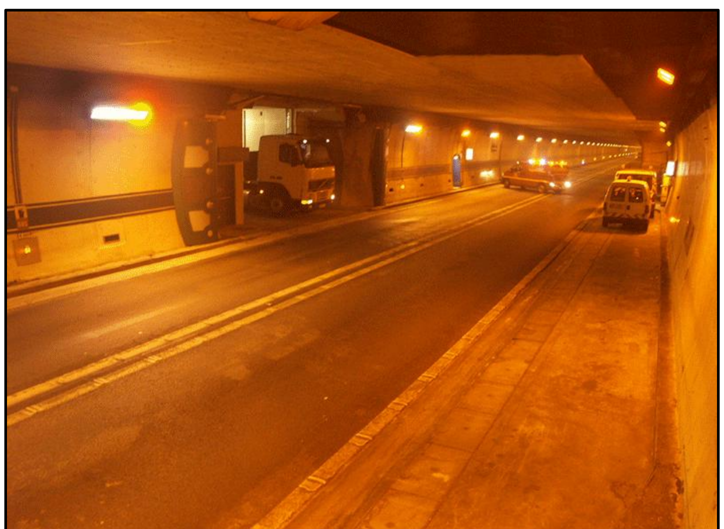
DIRECTION DES SCIENCES DE LA MATIÈRE

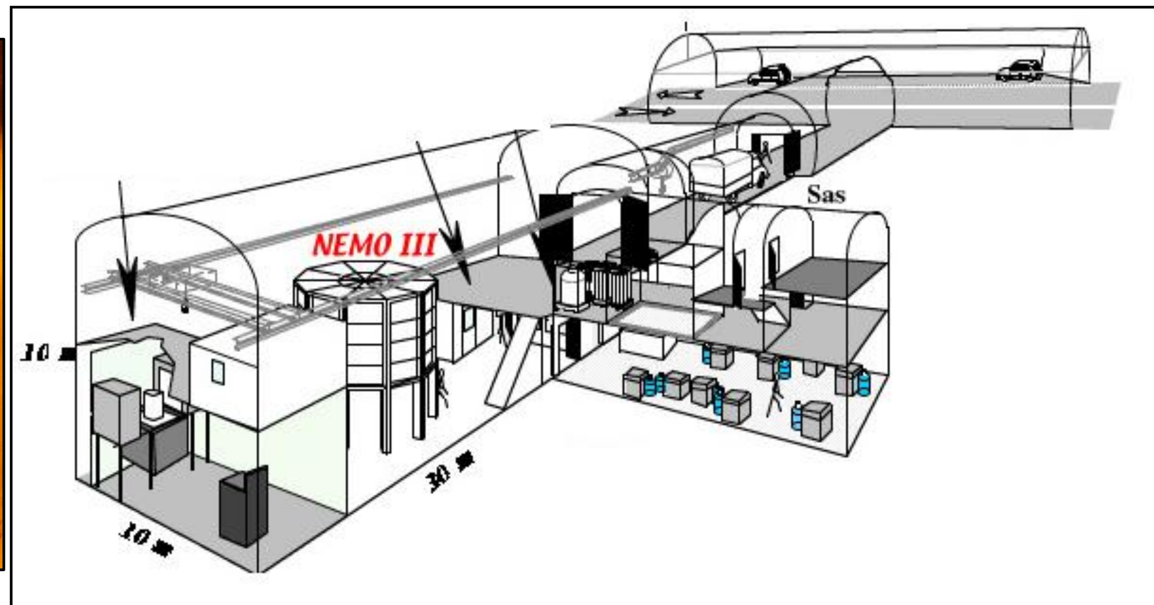
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT NATIONAL DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES



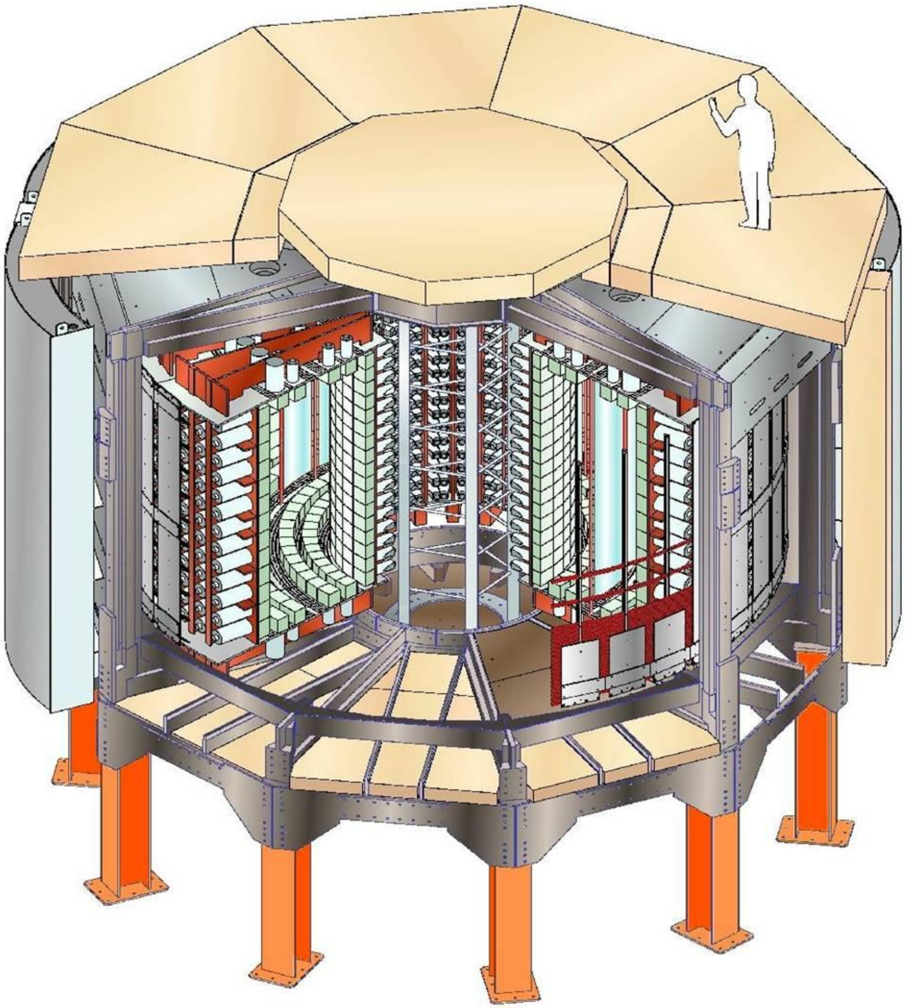
Built for Taup experiment (proton decay) in 1981-1982





The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 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

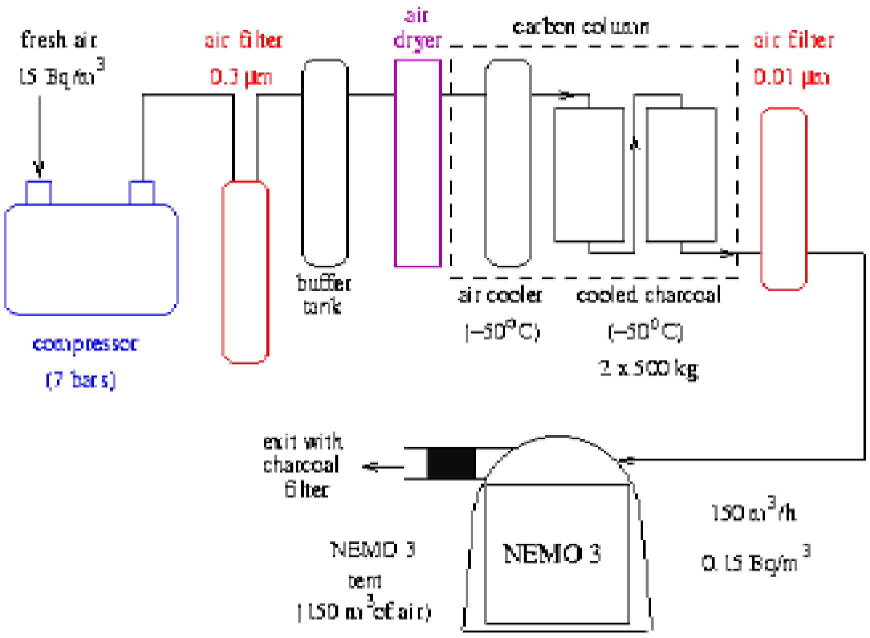
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

Able to identify e^-, e^+, γ and α

Finished detector

Radon purification facility



Running since Oct. 4th, 2004 in FréjusUnderground Lab.

1 ton charcoal @ -50°C, 7 bars

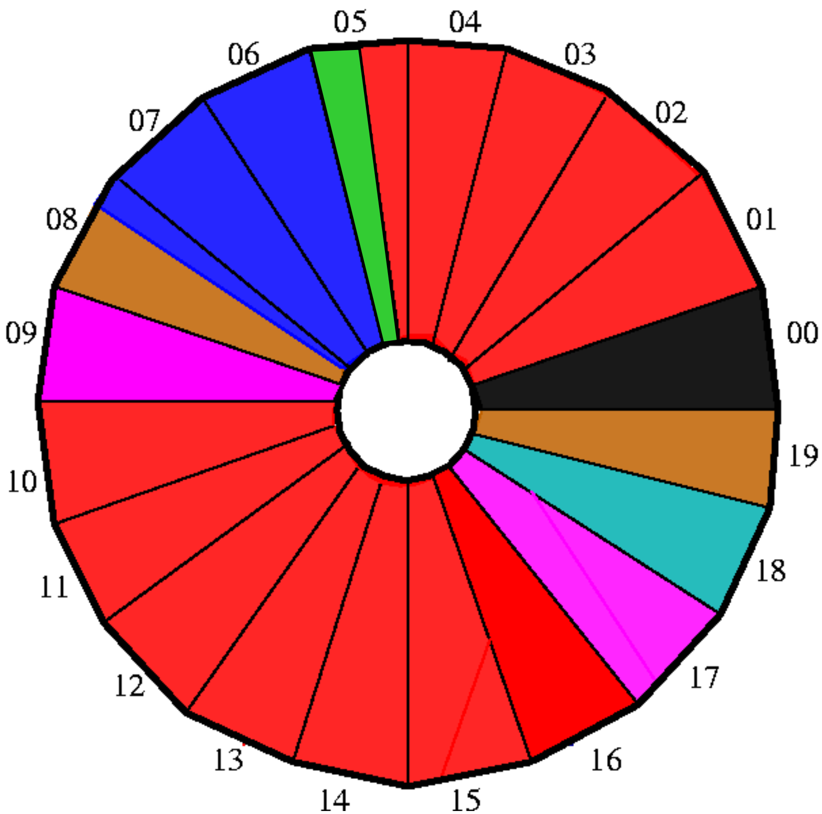
Flux: 150 m^3/h

Activity of ^{222}Rn :

Before Facility = 15 Bq/m^3

After Facility < 15 mBq/m^3

ββ decay isotopes in NEMO-3 detector



^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

^{82}Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν 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

^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

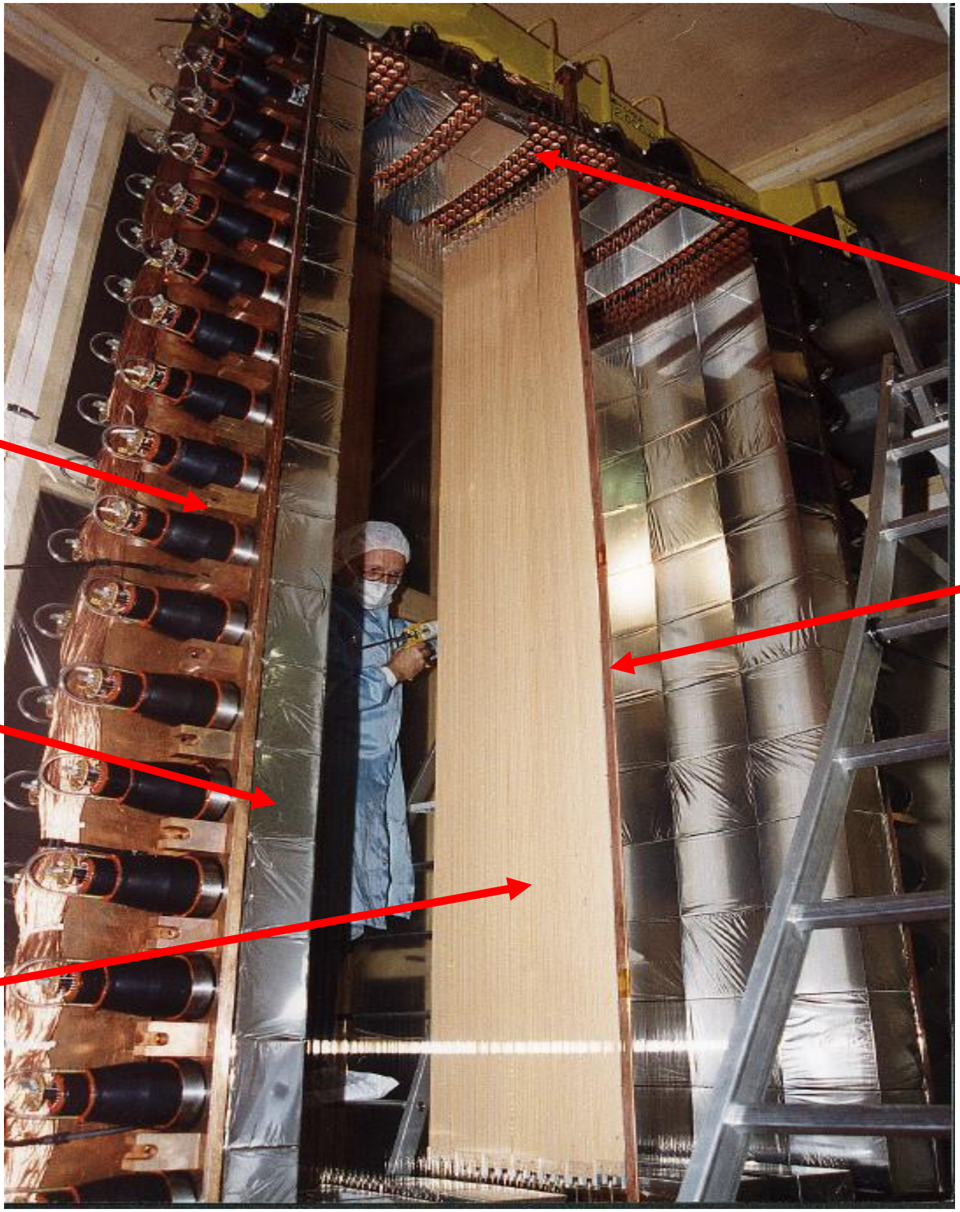
^{nat}Te 491 g

Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

Sector interior view



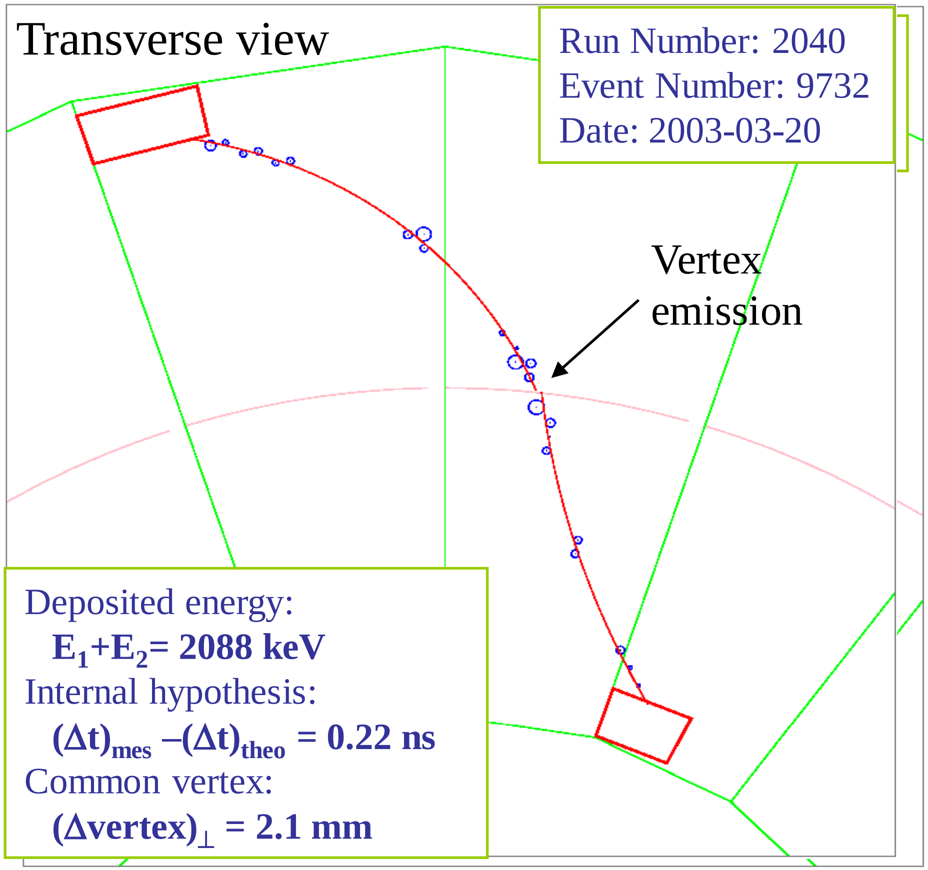
Calibration source

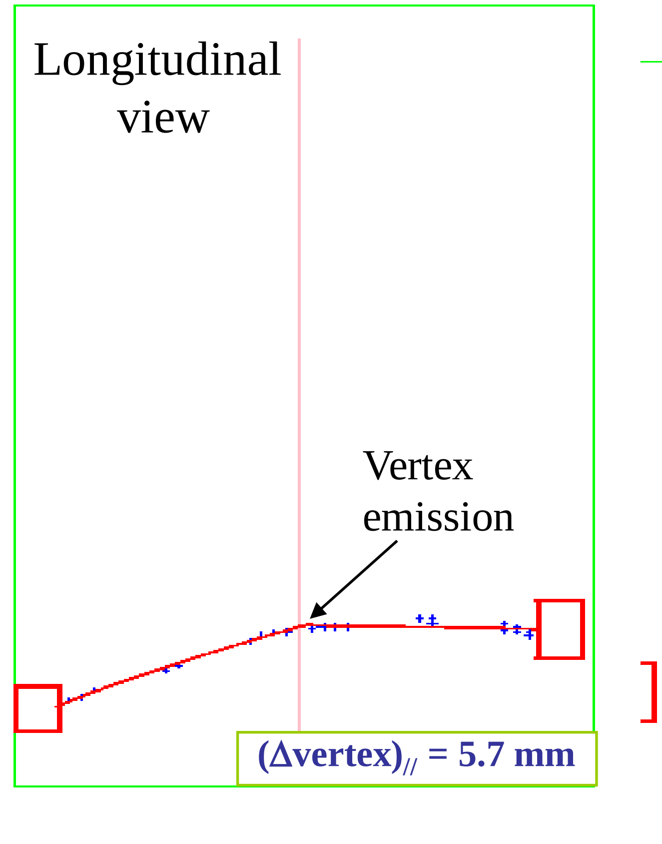
^{207}Bi
2e− (IC) lines
~0.5 ,~1 MeV
^{90}Sr
^{60}Co

Sources preparation

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





Trigger: at least 1 PMT > 150 keV

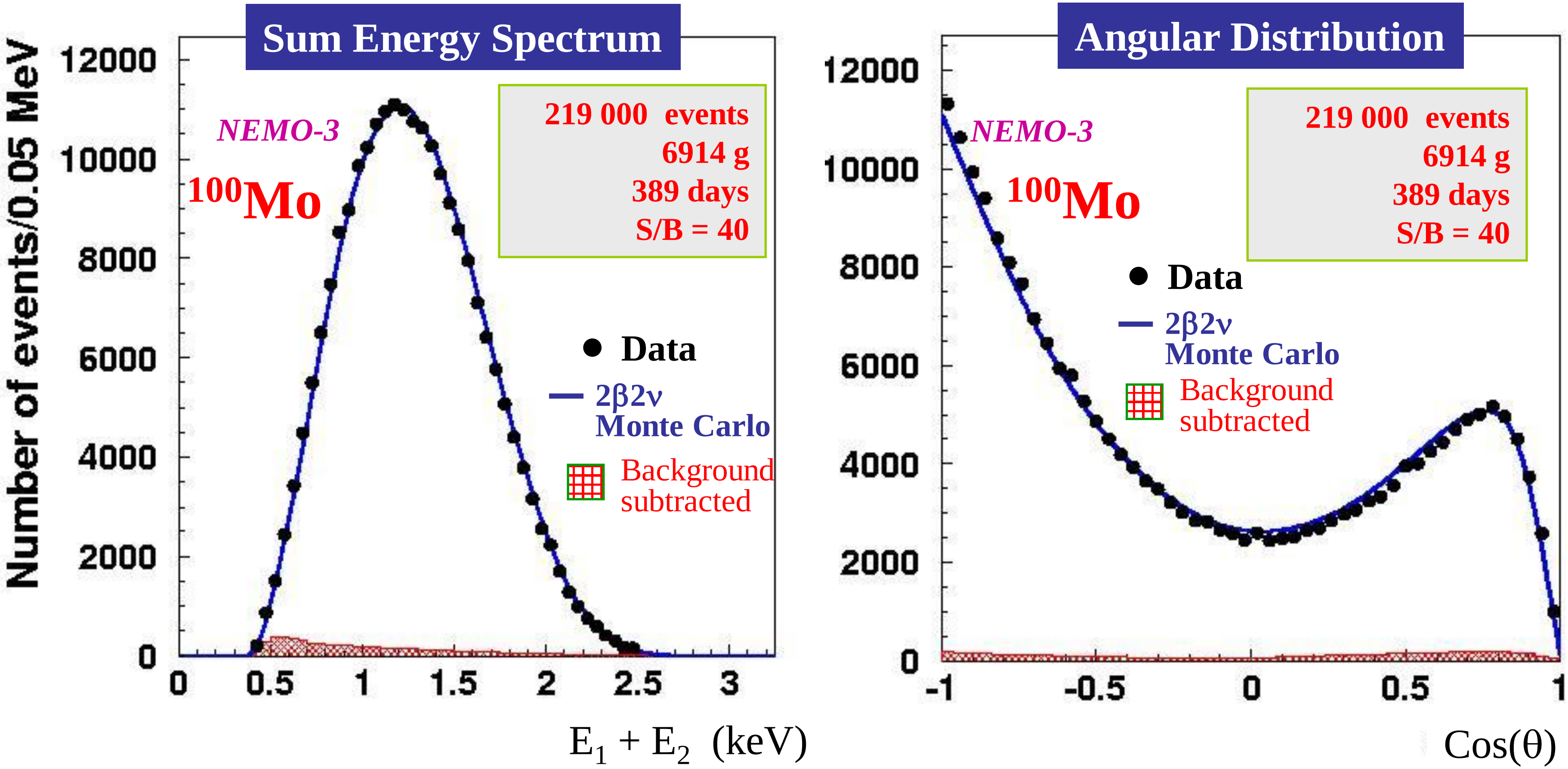
≥ 3 Geiger hits (2 neighbour layers + 1)

Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo 2β2ν result

(Data Feb. 2003 – Dec. 2004)

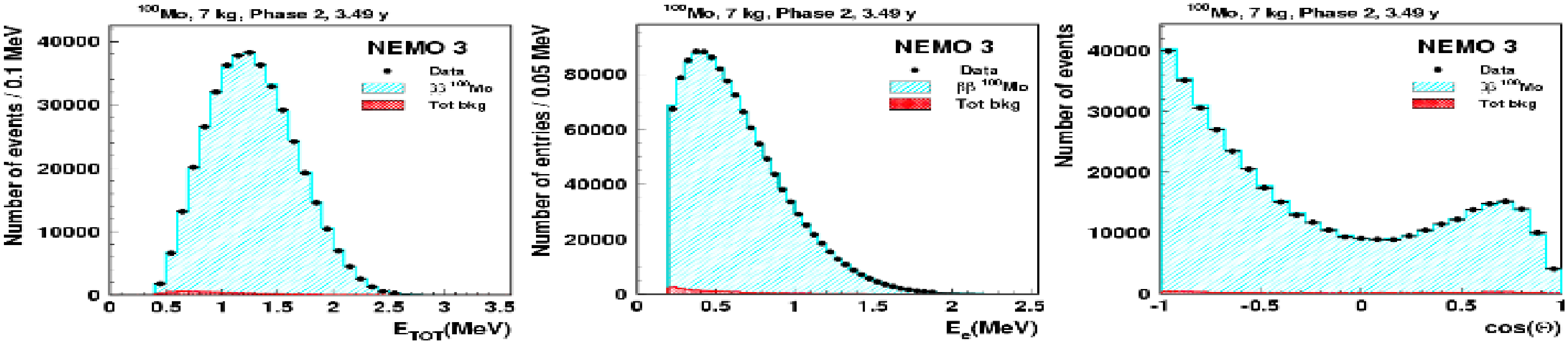


7.37 kg.y

$T_{1/2} = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ y

Phys. Rev. Lett. 95 (2005) 182302

^{100}Mo (7kg), 2νββ



$T_{1/2}(2\nu) = [7.17 \pm 0.01(stat) \pm 0.54(sys)] \times 10^{18}$ yr ⇒ ~3.5 yr,
Phase II (low Rn), S/B = 76

$M^{2\nu}(^{100}Mo) = 0.126 \pm 0.006$

to be compared with earlier published in PRL 95 (182302) 2005:

$T_{1/2}(2\nu) = [7.11 \pm 0.02(stat) \pm 0.54(sys)] \times 10^{18}$ yr ⇒ ~1 yr, Phase I, S/B = 40

NEMO-3 to run until Nov’10. Special runs to improve systematics.

Decay to the excited 0^+ (^{100}Mo $2\nu\beta\beta$)

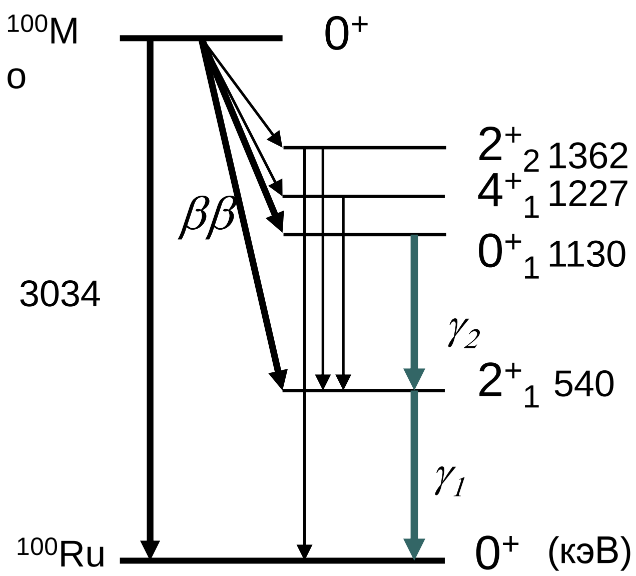
Decay to the excited 0^+ state (1130keV) of ^{100}Ru

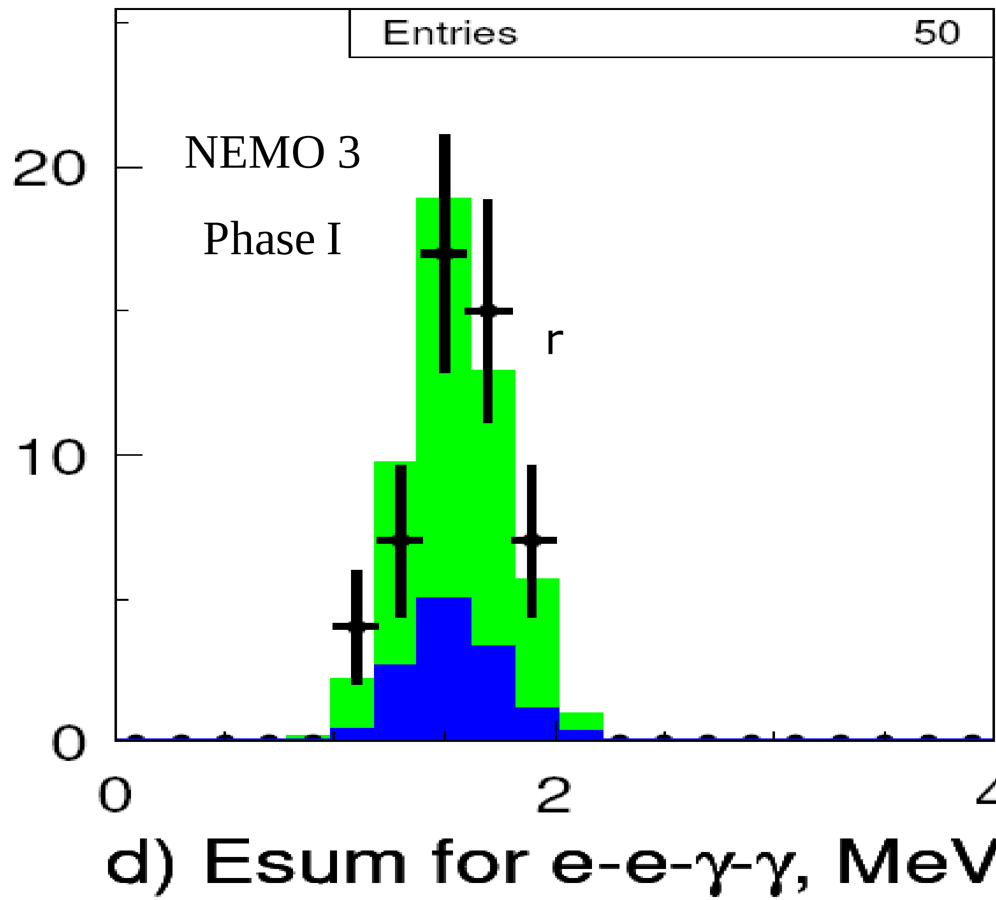
$T_{1/2} = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y

Nuclear Physics A781 (2006) 209-226.

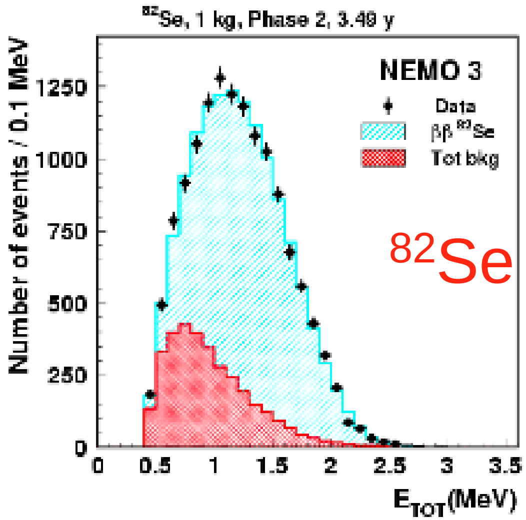
Direct Observation

With all the particles detected on the final state

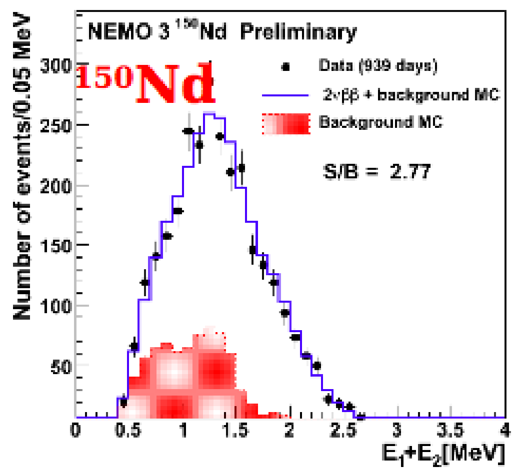




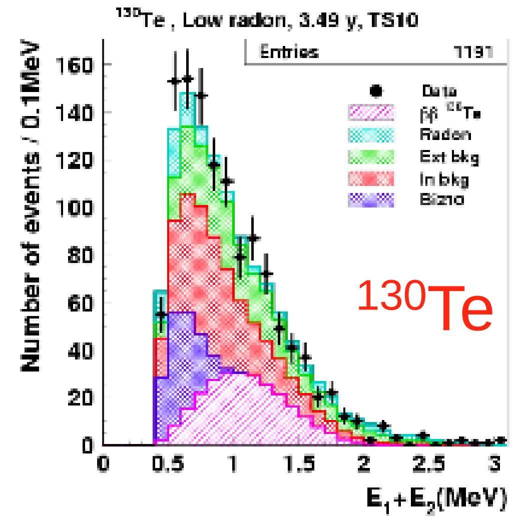
2νββ results for other isotopes



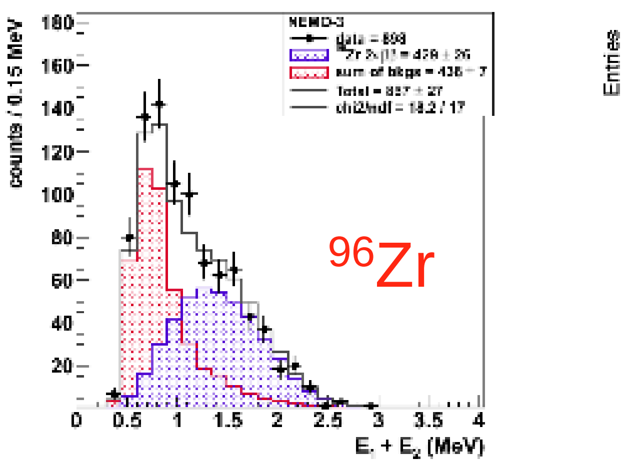
[9.6±0.1(stat)±1.0(sys)]×10^{19} yr
$M^{2\nu}$=0.049±0.004



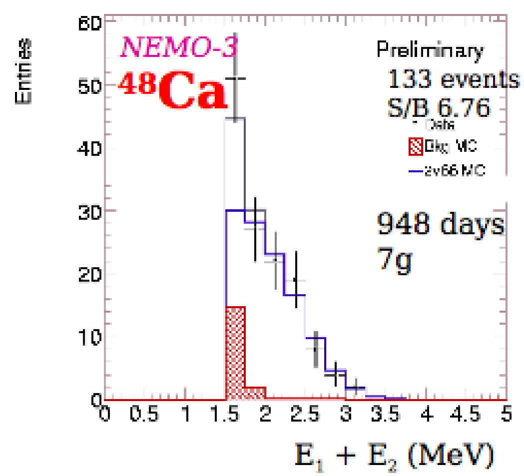
[9.11±0.25(stat)±0.63(sys)]×10^{18} yr
$M^{2\nu}$=0.030±0.002



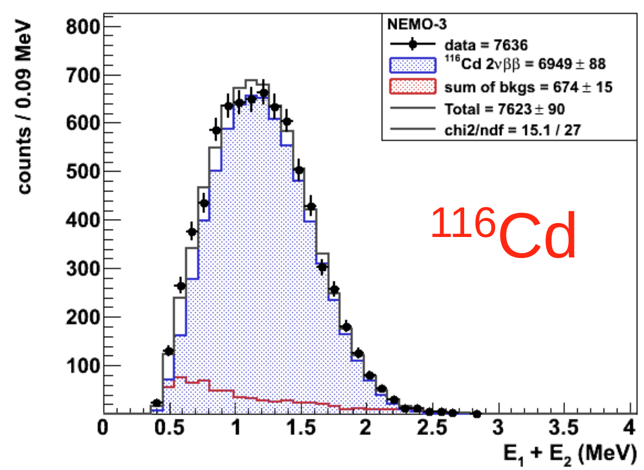
[7.0$^{+1.0}_{-0.8}$(stat) $^{+1.1}_{-0.9}$(sys)]×10^{20} yr
$M^{2\nu}$=0.0173±0.0025



[2.35±0.14(stat)±0.16(sys)]×10^{19} yr
$M^{2\nu}$=0.049±0.002



[4.4$^{+0.5}_{-0.4}$(stat)±0.4(sys)]×10^{19} yr
$M^{2\nu}$=0.0238±0.0015



[2.88±0.04(stat)±0.16(sys)]×10^{19} yr
$M^{2\nu}$=0.0685±0.0025

Summary of 2νββ results with NEMO-3

Isotope	S/B	(2νββ), y
^{100}Mo	40	$(7.11 \pm 0.02(stat) \pm 0.54(syst)) \cdot 10^{18}$ (SSD favoured) *
$^{100}Mo(0^+_1)$	3	$(5.7^{+1.3}_{-0.9}(stat)) \pm 0.8(syst)) \cdot 10^{20}$ ** [NPA 781 (2006) 209]
^{82}Se	4	$(9.6 \pm 0.3(stat) \pm 1.0(syst)) \cdot 10^{19}$ *
^{116}Cd	7.5	$(2.88 \pm 0.04(stat) \pm 0.16(syst)) \cdot 10^{19}$ ***
^{130}Te	0.35	$(7.0^{+1.0}_{-0.8}(stat)\ ^{+1.1}_{-0.9}(syst)) \cdot 10^{20}$ ***
^{150}Nd	2.8	$(9.11^{+0.25}_{-0.22}(stat) \pm 0.63(syst)) \cdot 10^{18}$ *** [PRC 80 (2009) 032501R]
^{96}Zr	1.0	$(2.35 \pm 0.14(stat) \pm 0.16(syst)) \cdot 10^{19}$ *** [0906.2694]
^{48}Ca	6.8	$(4.4^{+0.5}_{-0.4}(stat) \pm 0.4(syst)) \cdot 10^{19}$ ***

* Phase 1 data, Phys. Rev. Lett. 95 (2005) 182302. Additional statistics are being analysed, to be published soon.
** Phase 1 data.
*** Phases 1 and 2, preliminary.

The ββ2ν half-life of ^{130}Te has been a long- standing mystery:

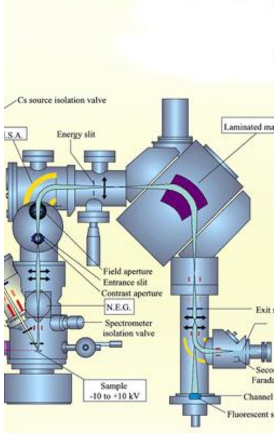
- Geochemical experiments:
  (26 ± 2.8) x 10^{20} years (Kirsten 83)
  (27 ± 1) x 10^{20} years (Bernatowicz 93)

  (7.9 ± 1) x 10^{20} years (Takaoka 96)
  ~8 x 10^{20} years (Manuel 91)

- Is the difference between 'old' and 'young' ores due to time dependence of constants..? [A.S.B. JETP Lett. 68 (1998) 1]

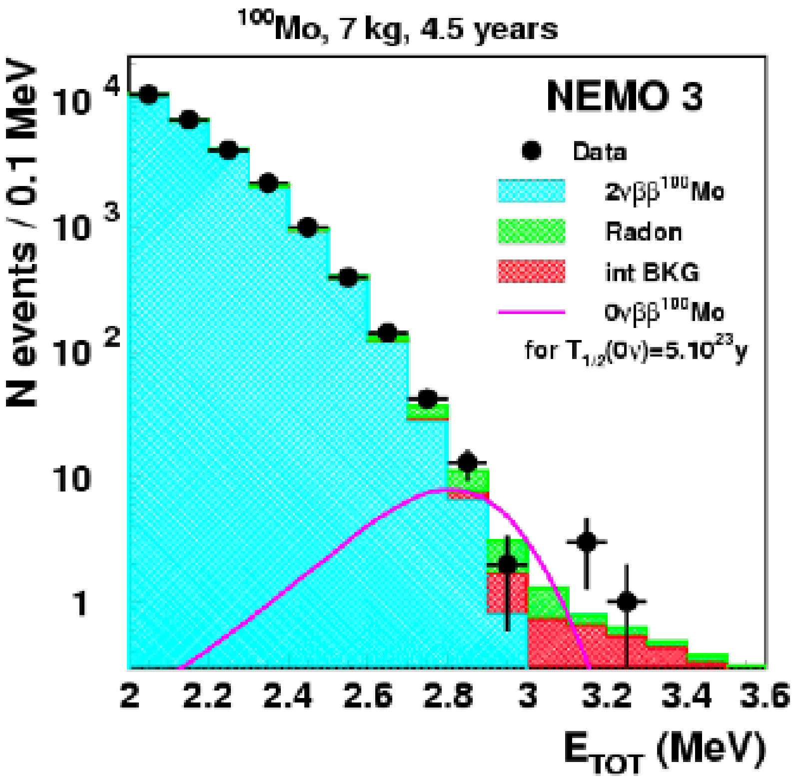
- Using geochemical ratio of ^{82}Se/^{130}Te and present half-life value for ^{82}Se from direct experiments:
  (9 ± 1) x 10^{20} years (recommended value, A.S.B. 2001)

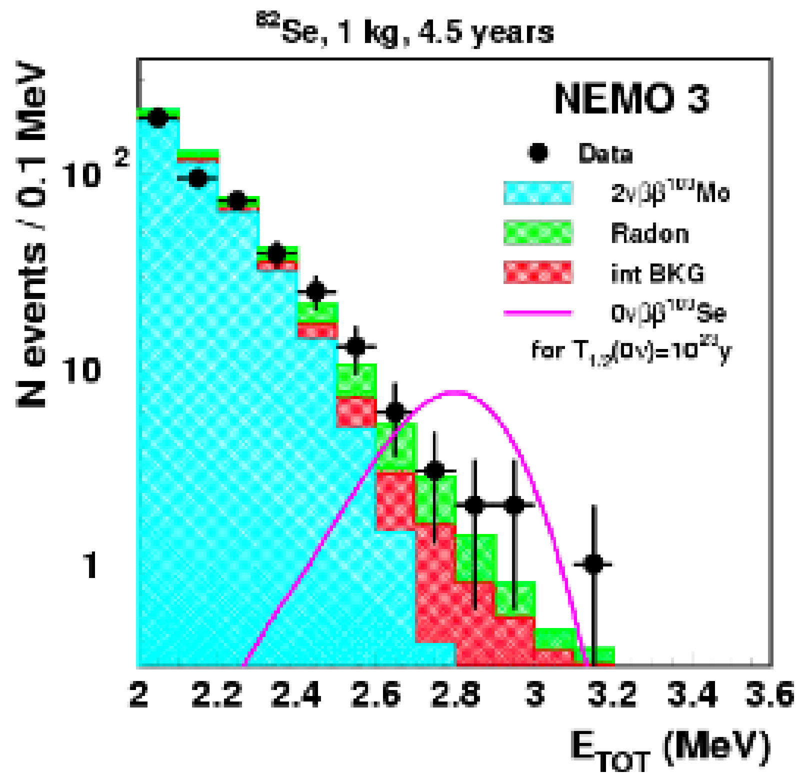
- Direct measurement:
  [6.1 ± 1.4 (stat)$^{+2.9}_{-3.4}$ (syst)] x 10^{20} years (Arnaboldi 2003)



$T_{1/2}$ = [7.0± 0.9(stat)±1.0(syst)]·10^{20} (NEMO-3)

0νββ for ^{100}Mo(~7kg) and ^{82}Se (~1kg)





[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

$\langle m_\nu \rangle < (0.47 - 0.96)$ eV

[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

$\langle m_\nu \rangle < (0.94 - 2.5)$ eV

Summary of 0νββ results with NEMO-3

- No evidence for non conservation of the leptonic number
- Current limits on 0νββ (at 90% C.L.):

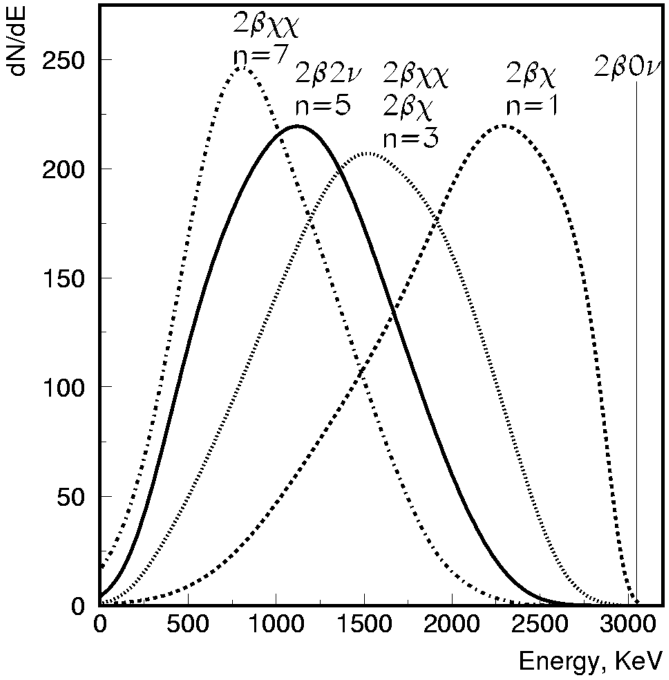
Isotope	Exposure (kg·y)	$T_{1/2}(0\nu\beta\beta)$, y	⟨m_ν⟩, eV [NME ref.]
^{100}Mo	26.6	> 1 · 10^{24}	< 0.47 – 0.96 [1-3]
^{82}Se	3.6	> 3.6 · 10^{23}	< 0.9 – 1.6 [1-3]; < 2.3 [7]
^{150}Nd	0.095	> 1.8 · 10^{22}	< 1.7 – 2.4 [4,5] ;< 4.8 – 7.6 [6]
^{130}Te	1.4	> 9.8 · 10^{22}	< 1.6 – 3.1 [2,3]
^{96}Zr	0.031	> 9.2 · 10^{21}	< 7.2 – 19.5 [2,3]
^{48}Ca	0.017	> 1.3 · 10^{22}	< 29.6 [7]

- NME references:

  - [1] M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
  - [2] M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
  - [3] F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
  - [4] V.A. Rodin et al. Nucl.Phys. A 793 (2007) 213
  - [5] V.A. Rodin et al. Nucl.Phys. A 766(2006) 107
  - [6] J.H.Hirsh et al. Nucl.Phys. A 582(1995) 124
  - [7] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

Majorons and V+A currents

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi^0(\chi^0)$$



best limits

	V+A *	n=1 **	n=2 **	n=3 **	n=7 **
Mo	**$>3.2\cdot10^{23}$** $\lambda<1.8\cdot10^{-6}$	**$>2.7\cdot10^{22}$** $g_{ee}<(0.4\text{-}0.9)\cdot10^{-4}$	**$>1.7\cdot10^{22}$**	**$>1.0\cdot10^{22}$**	**$>7\cdot10^{19}$**
Se	**$>1.2\cdot10^{23}$** $\lambda<2.8\cdot10^{-6}$	**$>1.5\cdot10^{22}$** $g_{ee}<(0.6\text{-}1.9)\cdot10^{-4}$	**$>6\cdot10^{21}$**	**$>3.1\cdot10^{21}$**	**$>5\cdot10^{20}$**

n: spectral index, limits on half-life in years

* PI+PII data

** PI data, ***R.Arnold et al. Nucl. Phys. A765 (2006) 483***

New results for ^{96}Zr and ^{150}Nd

	n = 1	n = 2	n = 3	n = 7
^{96}Zr [1]	$1.9\cdot10^{21}$ $\langle g_{ee} \rangle < (1.5\text{-}5.7)\cdot10^{-4}$	$9.9\cdot10^{20}$	$5.8\cdot10^{20}$	$1.1\cdot10^{20}$
^{150}Nd [2]	$1.5\cdot10^{21}$ $\langle g_{ee} \rangle < (1.7\text{-}3)\cdot10^{-4}$	$5.4\cdot10^{20}$	$2.2\cdot10^{20}$	$4.7\cdot10^{19}$

[1] Nucl-ex/0906.2694.
[2] Phys. Rev. C 80 (2009) 032501R.

Other interesting results with NEMO-3 (using information obtained with 2ν-decay of ^{100}Mo)

- **SSD** mechanism is confirmed for 2ν decay of ^{100}Mo [Phys.At.Nucl. 69(2006) 2090]
- **"Bosonic"** properties of neutrino is checked[1)] :

  - pure "bosonic" neutrinos are excluded;
  - conservative upper limit $\sin^2\chi < 0.6$ is obtained

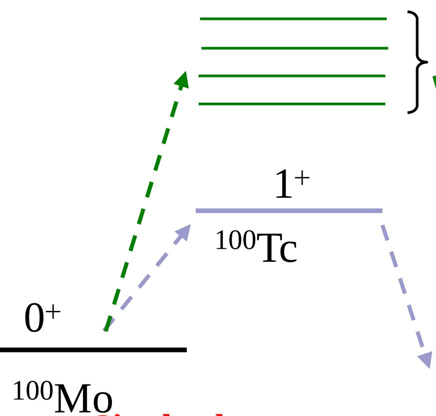
  [Nucl. Phys. B 782 (2007) 90]

1) **A. Dolgov and A. Smirnov, PL B621 (2005) 1**

Single electron spectrum $2\nu\beta\beta$ (^{100}Mo)

$T_{1/2} = 7.11 \pm 0.02\,(stat) \pm 0.54\,(syst) \times 10^{18}$ y
Phys. Rev. Lett. 95 (2005) 182302

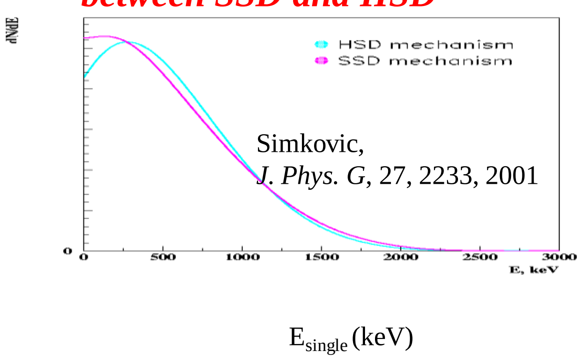
SSD model confirmed

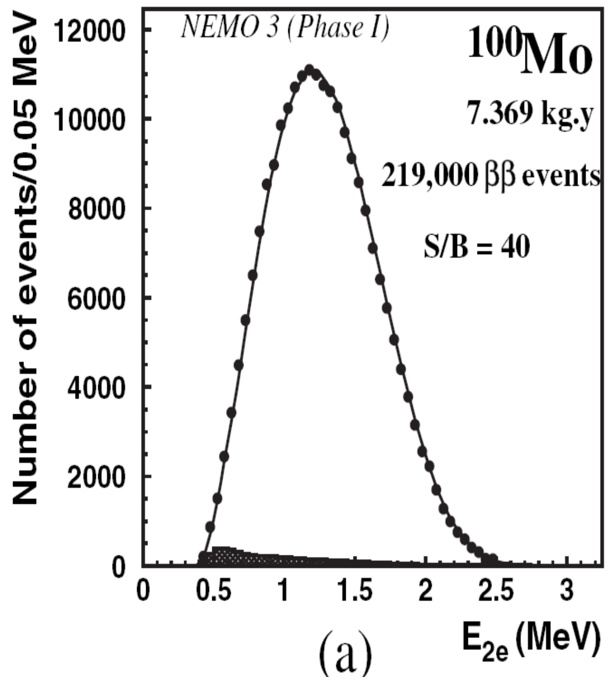


HSD, higher levels contribute to the decay

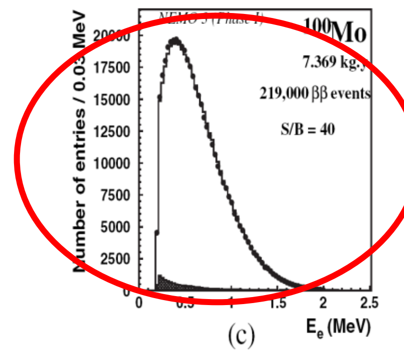
SSD, 1^+ level dominates in the decay
(Abad et al., 1984, *Ann. Fis.* A 80, 9)

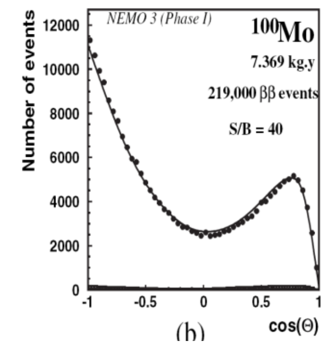
Single electron spectrum different between SSD and HSD

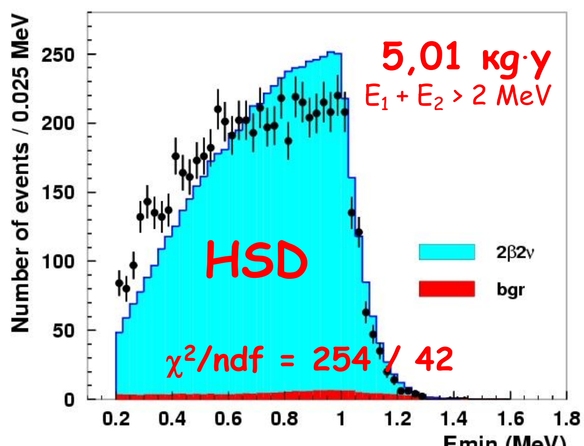


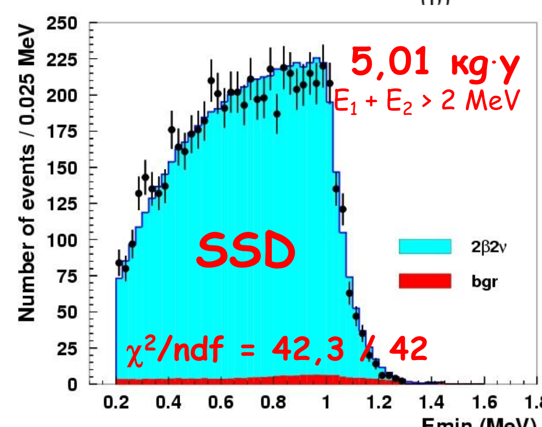


SSD simulation









Search for "bosonic" neutrino using 2β decay data

- In 2005 **Dolgov and Smirnov** assumed that the **PEP** is violated for neutrinos and, consequently, neutrinos obey the Bose-Einstein statistics [PL B 621 (2005) 1]
- **Consequencis of this assumption:**

a) neutrino may form cosmological Bose condensate (dark matter!)

b) "wrong" statistic of neutrino could modify Big Bang nucleosynthesis

c) spectra of the supernova neutrino may be changed

d) **PEP** violation for neutrino can be tested in the two neutrino **double beta decay** experiments

Why it can be possible for neutrino?

- **PEP never was checked for neutrino**
- Neutrino is a neutral particle
- Neutrino can be a Majorana particle ($\nu \equiv \nu'$)
- Neutrino has a very small mass

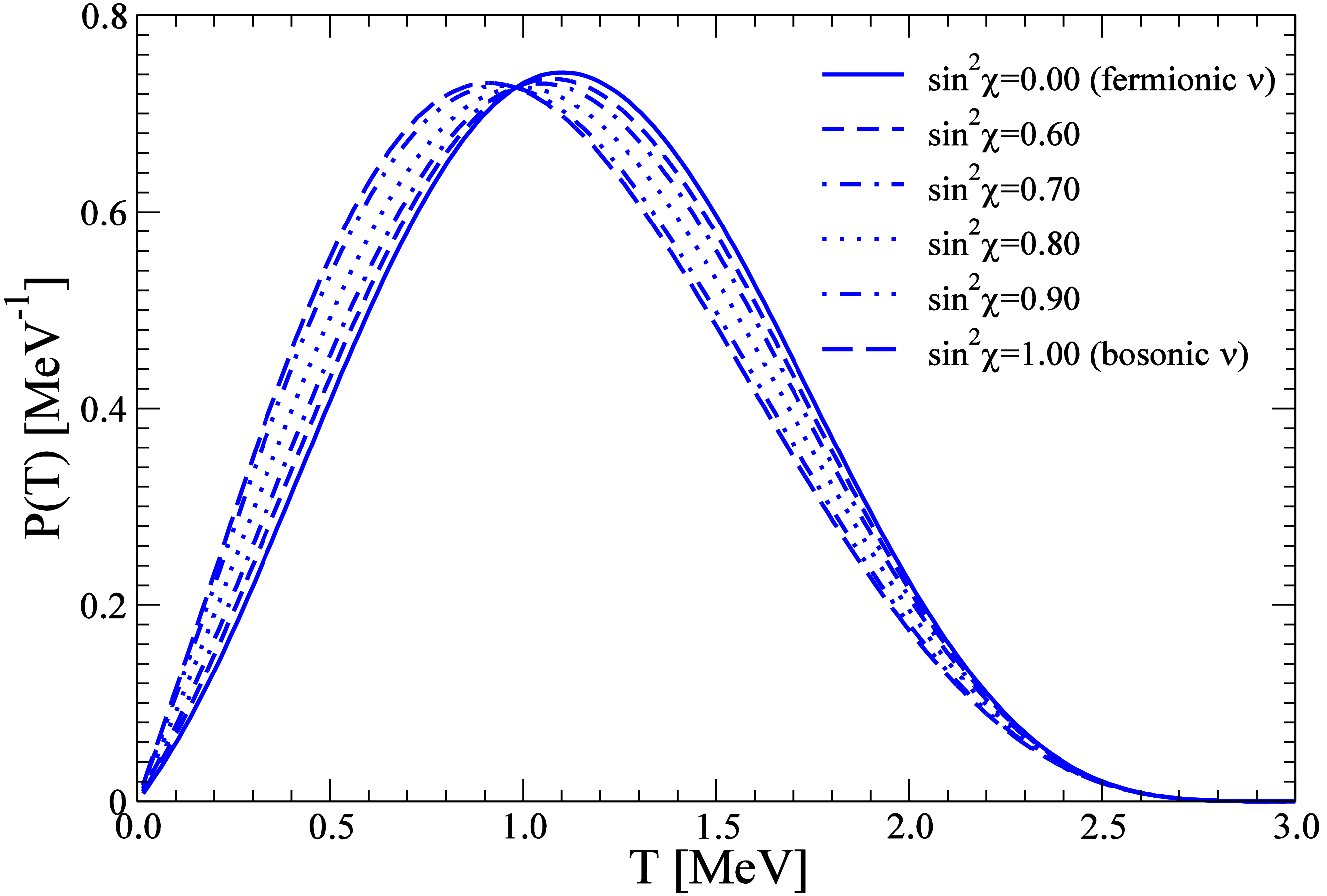
If neutrino is bosonic (or partially bosonic) particle one can see the effect in 2β(2ν) decay:

- Probability of decay will be changed
- Sum and single electron energy spectra will be changed
- Angular distribution will be changed

So, 2β(2ν) decay is nice process to check possible PEP violation in neutrino sector

The normalized distribution of the total energy of two electrons

$^{100}Mo(0^+_{g.s.}) \rightarrow {}^{100}Ru(0^+_{g.s.})$ [A.S. Barabash, A.D. Dolgov, R. Dvornicky, F. Simkovic and A.Yu. Smirnov, Nucl.Phys. B 782 (2007) 90.]



Large admixture of bosonic ν is excluded: $\sin^2\chi < 0.6$

Prospects for the future with NEMO-3

- Data taking with **NEMO-3** up to November **2010**
- **0ν:**

  ~ **(1.5-2)·10^{24}** y for ^{100}Mo **(<m_ν> ~ 0.3-0.7 эВ);**

  ~ **6-7·10^{23}** y for ^{82}Se **(<m_ν> ~ 0.6-1.2 эВ)**

  ~ **10^{22}-10^{23}** y for ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{130}Te and ^{150}Nd

- **2ν:**

  Precise measurements with 7 nuclei ($T_{1/2}$, 2e^-, e^-, angular spectra);

  Excited state transitions

- **Majoron:**

  ~ **5·10^{22}** y for ^{100}Mo **(<g_{ee}> ~ (3-6)·10^{-5})**

  ~ **10^{21}-10^{22} y** for ^{48}Ca, ^{82}Se, ^{96}Zr, ^{116}Cd, ^{130}Te and ^{150}Nd

- **SSD**
- **"Bosonic" neutrino**

Most active "small" experiments

- **TGV-II** (multi HPGe; ^{106}Cd; Modan))
- **TUNL-ITEP** (2xHPGe; exsited states in **^{100}Mo**, **^{150}Nd**; USA)
- **Baksan** (proportional counter; ^{136}Xe, ^{78}Kr)
- **DAMA-KIEV** (scintillators; ^{136}Ce, ^{64}Zn, ^{180}W…; Gran Sasso)
- **ITEP-Bordeaux** (HPGe; excited states: **^{100}Mo**, ^{82}Se, **^{150}Nd**, ^{74}Se, ^{112}Cd,…; Modan)
- **COBRA** (CdZnTe semiconductor; Gran Sasso)

$2\beta^+$, β^+EC and ECEC processes:

- **0ν-transitions:**

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

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

$2e_b + (A,Z) \rightarrow (A,Z-2) + \gamma(2\gamma, e^+e^-, e^-, \ldots) + 2X$

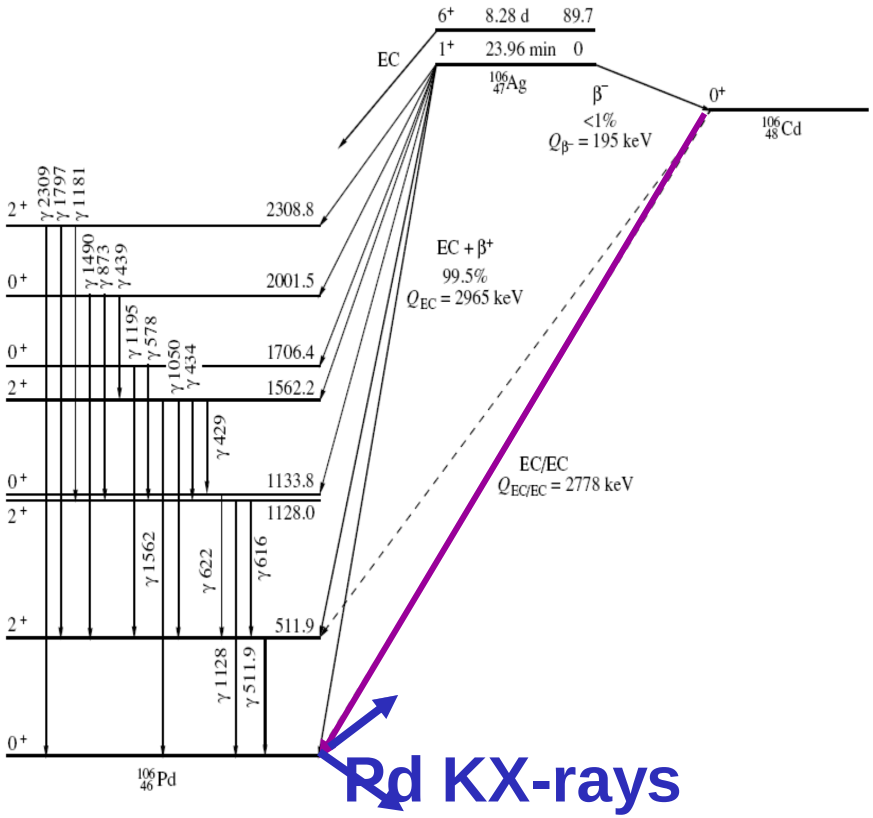
- **2ν-transitions:**

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

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

$2e_b + (A,Z) \rightarrow (A,Z-2) + 2\nu + 2X$

Decay scheme of ^{106}Cd



Q value

- **2β⁺:** $Q' = \Delta M - 4m_e - 2\varepsilon_b$ $(Q'_{max} \approx 0.8\ \text{MeV})$

(6 nuclei)

- **β⁺EC:** $Q' = \Delta M - 2m_e - \varepsilon_b$ $(Q'_{max} \approx 1.8\ \text{MeV})$

(22 nuclei)

- **ECEC:** $Q' = \Delta M - 2\varepsilon_b$ $(Q'_{max} \approx 2.8\ \text{MeV})$

(34 nuclei)

[$Q(2\beta^-) \approx 3$ MeV]

Theoretical half-life estimations

Transition to the ground state. For the best candidates (**$\langle m_\nu \rangle$ = 1 eV**):

$\beta^+\beta^+$ (0ν) ~ 10^{27}-10^{28} y
β^+EC(0ν) ~ 10^{26}-10^{27} y
ECEC(0ν) ~ 10^{28}-10^{31} y

(One can compare these values with
~ 10^{24}-10^{25} y for 2β^--decay)

Transition to the ground state. For the best candidates (**2ν**):

$\beta^+\beta^+$ (2ν) ~ 10^{27}-10^{28} y
β^+EC(2ν) ~ 10^{22}-10^{23} y
ECEC(2ν) ~ 10^{20}-10^{22} y

Present experimental sensitivity is ~ 10^{21} y

A.P. Meshik et al., Phys. Rev. C 64 (2001) 035205

$^{130}Ba \rightarrow {}^{130}Xe$ (ECEC)

- Mineral barite ($BaSo_4$) with age ~ $1.7 \cdot 10^8$ yr was investigated
- Gas-retention age of the barite was found as **$(1.34 \pm 0.12) \cdot 10^8$ yr** (using K-Ar and U-Xe methods)
- Xe was extracted from the sample and excess of **^{130}Xe** was found
- **$T_{1/2} = (2.2 \pm 0.5) \cdot 10^{21}$ yr (2ν)**

Telescope Germanium Vertical (TGV-2)
(Russia-France-Czech Republic)

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 %

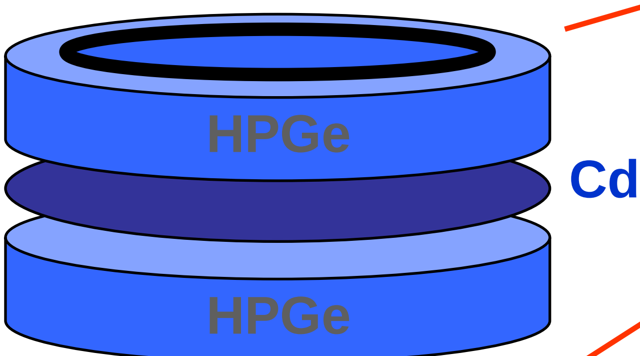
E-resolution : 3 ÷ 4 keV @ ^{60}Co

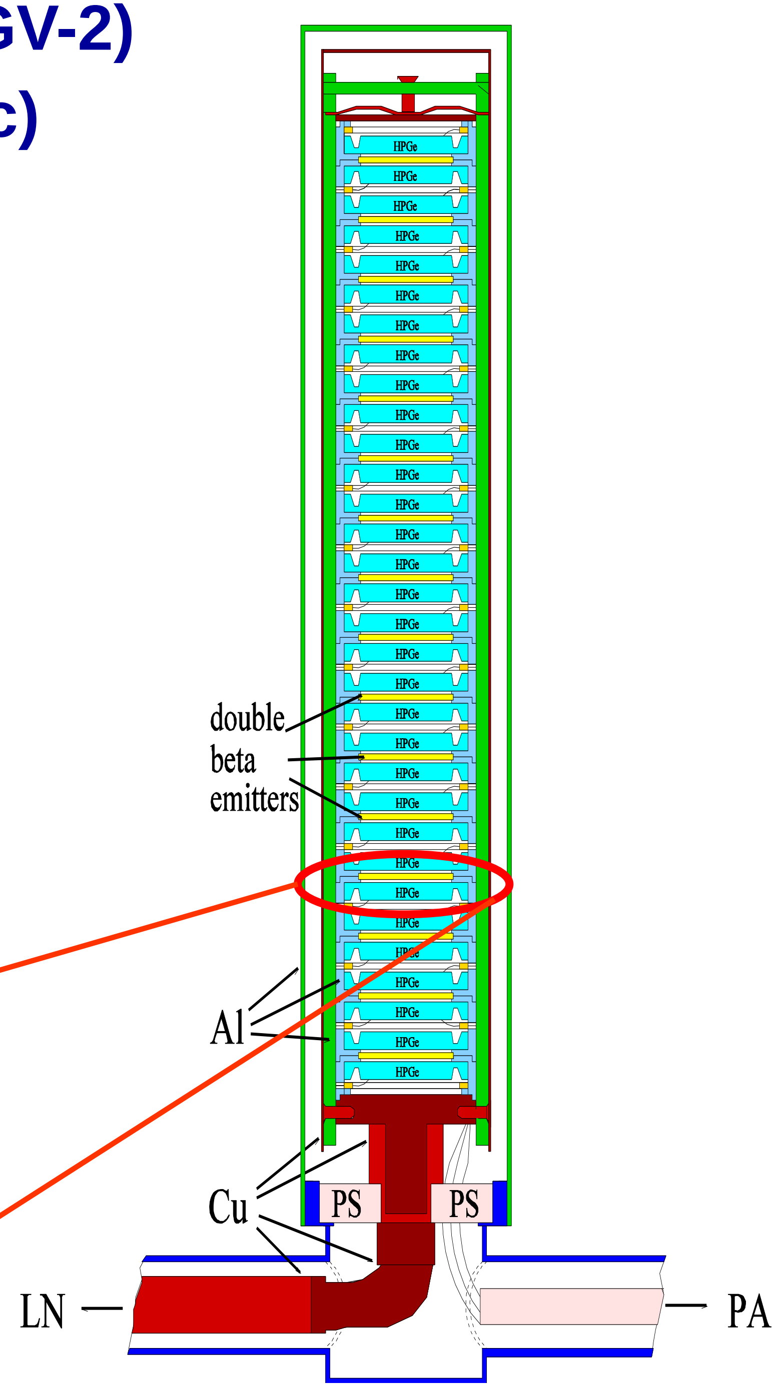
LE-threshold : 40÷50 keV (5 ÷ 6 keV)

Double beta emitters:

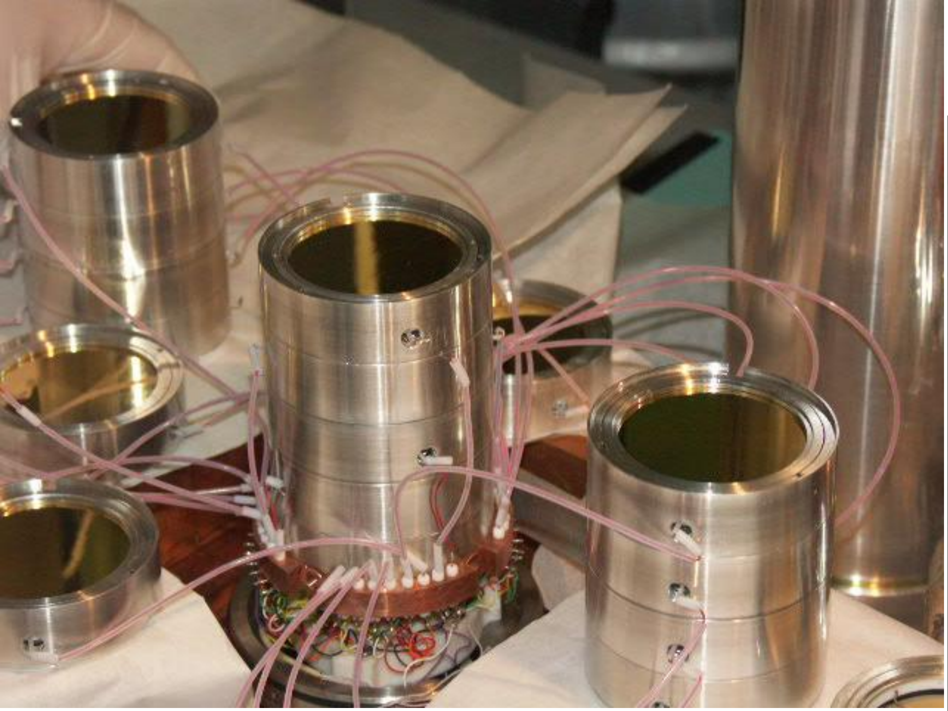
16 samples (~ 50 μm) of ^{106}Cd (enrich.75%)

13.6 g ~ 5.79 x 10^{22} atoms of ^{106}Cd





TGV-2



Detectors: 32 HPGe Ø 60 mm x 6 mm

Sensitive volume 20.4 cm^2 x 6 mm

Total sensitive volume ~ 400 cm^3

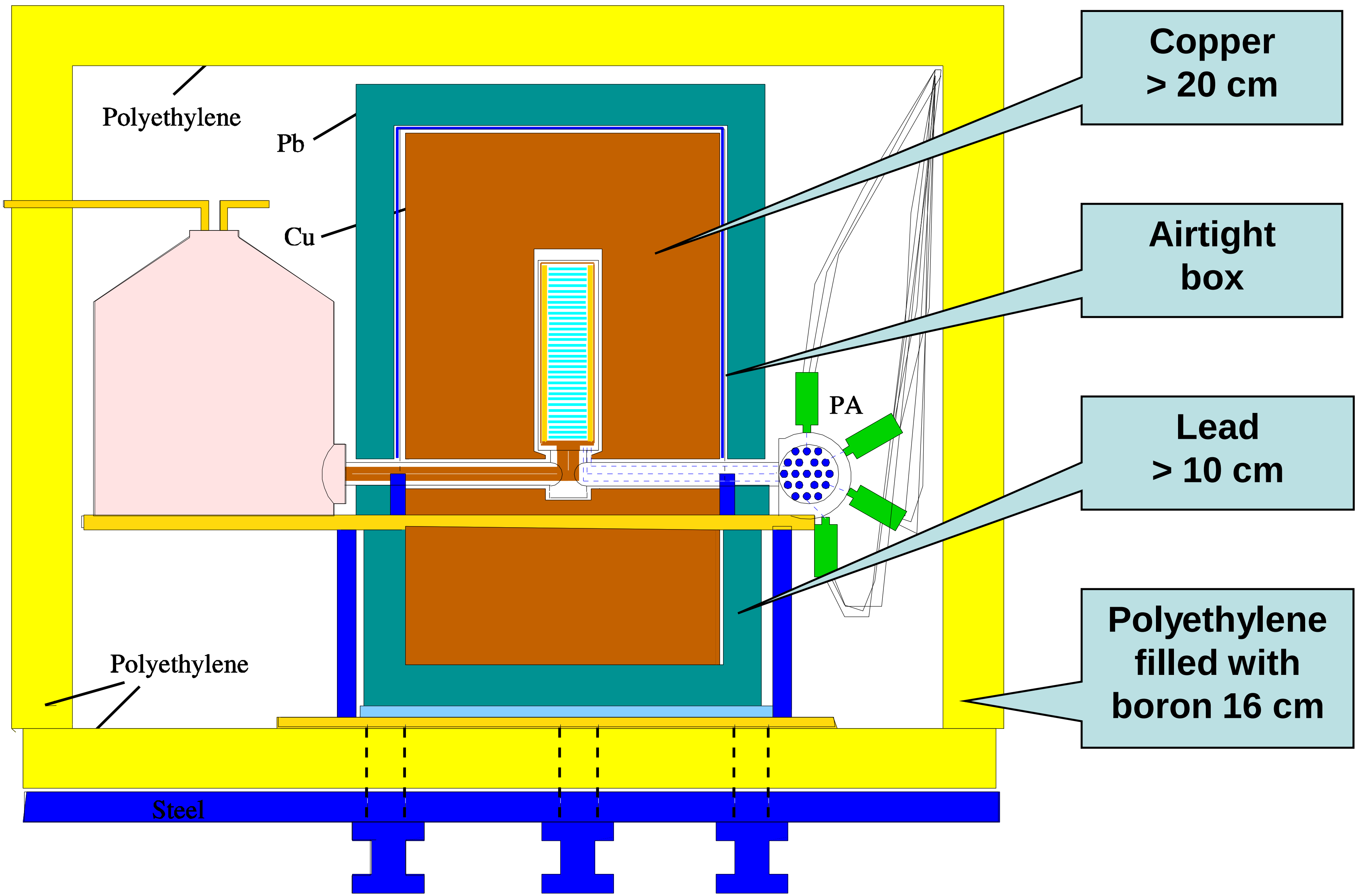
Total mass ~3 kg

Details of cryostat ~2500 g (Al, Cu, …)

Al ~ 1200 g (including holders ~ 360 g)

Cu ~ 1300 g

PASSIVE SHIELDING



Phase II results (13.6 g of ^{106}Cd and t = 12900 h)

- ECEC (2ν) - $T_{1/2} > 4.2 \cdot 10^{20}$ y (90% CL)
- ECβ⁺ (2ν) - $T_{1/2} > 1.1 \cdot 10^{20}$ y
- 2β⁺ (2ν) - $T_{1/2} > 1.4 \cdot 10^{20}$ y

Plan for the future: ~ 10^{21} y

ECEC(0ν); resonance conditions

- In **1955** **(R.Winter, Phys. Rev. 100 (1955) 142)** it was mentioned that if there is **excited** level with "right" energy then decay rate can be very high.

  (Q'-E* has to be close to zero. Q'-energy of decay to g.s., E*-energy of excited state)
- In **1982** the same idea for transition to excited and **ground** states was discussed (**M. Voloshin, G. Mizelmacher, R. Eramzhan, JETP Lett. 35 (1982)).**
- In **1983** (**J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15**) this idea was discussed for **^{112}Sn** (transition to 0^+ excited state). It was shown that enhancement factor can be on the level **$\sim 10^6$!**

J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15

$^{112}Sn \rightarrow {}^{112}Cd\ [0^+(1871)]$

ΔM = 1919.5±4.8 keV (old value)

$Q'(KK;0^+) = \Delta M - E^*(0^+) - 2E_K =$

$= (-4.9 \pm 4.8)$ keV

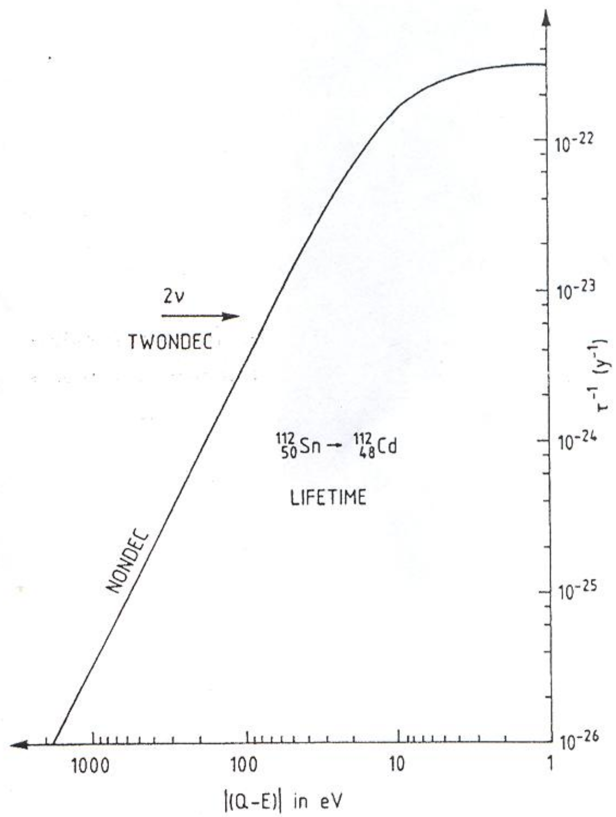
$T_{1/2}(0\nu) \approx 3 \cdot 10^{24}$ y (for $<m_\nu> = 1$ eV)

(if Q' ~ 10 eV)

[ECEC(2ν) transition is strongly suppressed!!!]

Nice signature: in addition to **two X-rays** we have here **two gamma-rays** with strictly fixed energy (617.4 and 1253.6 keV)

J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15



$^{112}Sn \rightarrow ^{112}Cd(0^+;1870$ keV)

The ECEC(0ν) mode is shown as a function of the degeneracy parameter Q-E

Resonance conditions

- In **2004** the same conclusion was done by **Z. Sujkowski and S. Wycech (Phys. Rev. C 70 (2004) 052501).**

$\Downarrow$

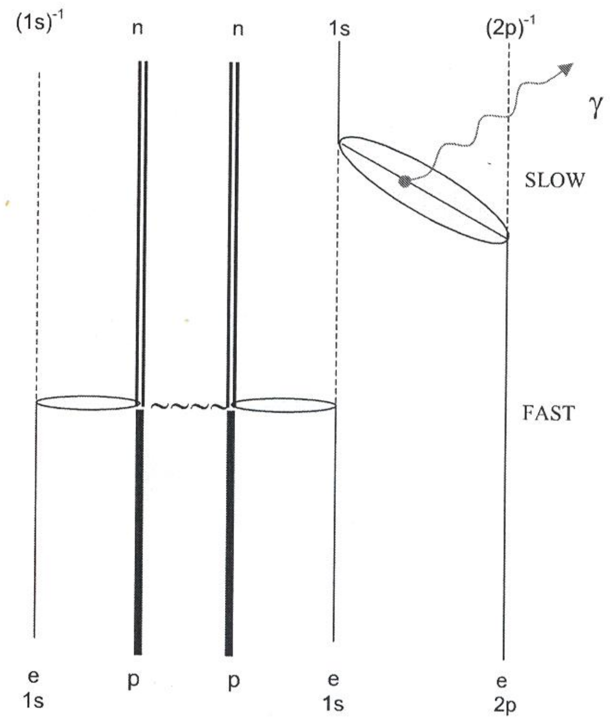
Resonance condition (using single EC(ν,γ) argument):

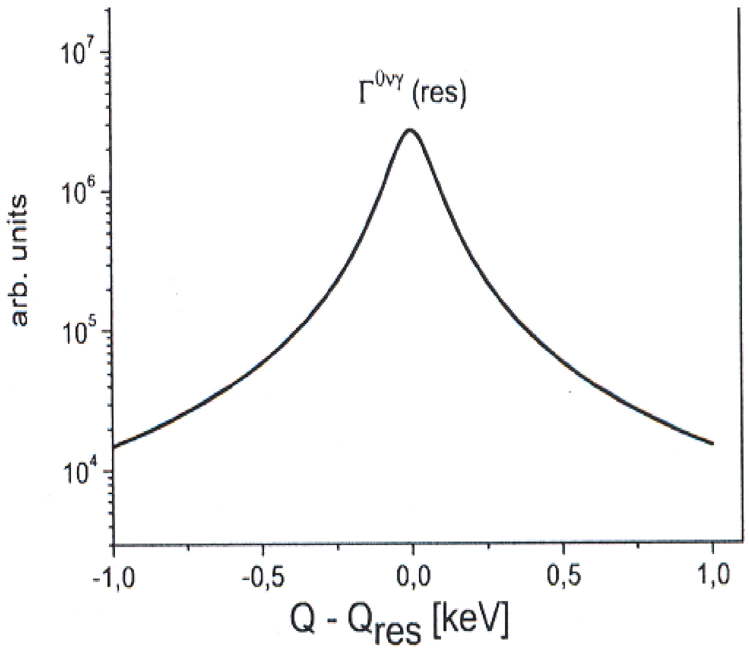
$$E_{brems} = Q'_{res} = |E(1S,Z\text{-}2) - E(2P,Z\text{-}2)|$$

(i.e. when the photon energy becomes comparable to the **2P-1S** level difference in the final atom)

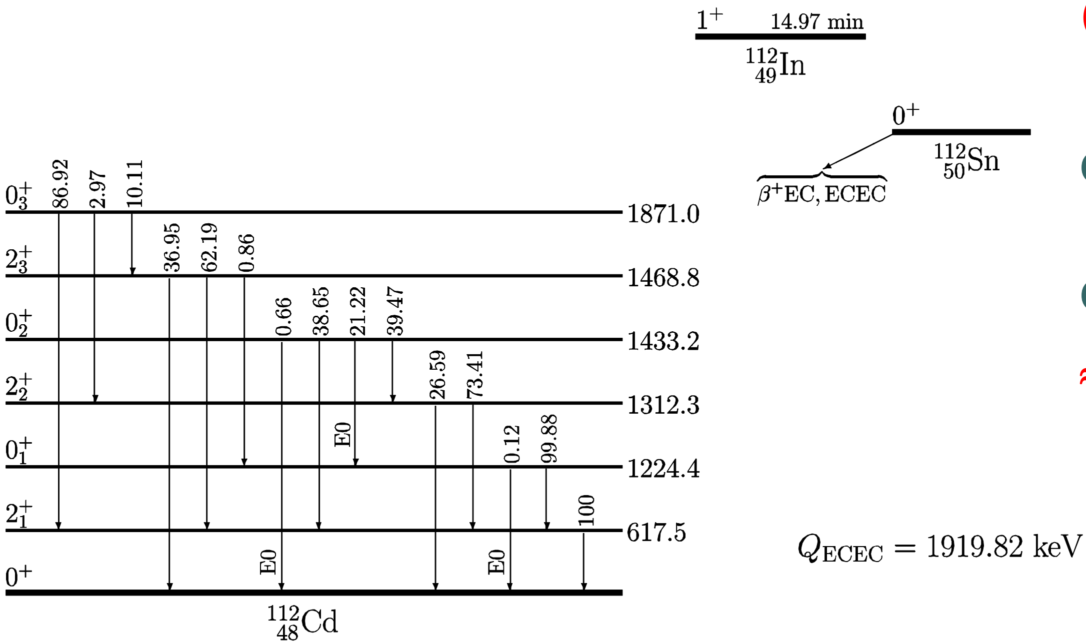
$|Q' - Q'_{res}| < 1$ **keV**

Z. Sujkowski and S. Wycech





Decay-scheme of ^{112}Sn



Here ΔM = 1919.82±0.16 keV

(PRL 103 (2009) 042501)

$Q' = \Delta M - 2E_b = 1866.42$ keV

$Q'(E^*) = Q' - 1871.137(72)$

$\approx -4.71 \pm 0.23$ keV

Isotope-candidates (transition to the excited state)

Nuclei	A, %	ΔM, keV	E*, keV	Δ, keV	E_K *)	E_{L2} *)
^{74}Se	0.89	1209.7±2.3 **1209.240±0.007 (new!)**	1204.2 (2^+)	2.5±0.1 (LL)	11.1	1.23
^{78}Kr	0.35	2846.4±2.0	2838.9 **(2^+?)**	4.5±2.1 (LL)	12.6	1.47
^{96}Ru	5.52	2718.5±8.2	2700.2 (2^+) 2712.68 **(?)**	**-4.5±8.2 (KL)** **0±8.2 (LL)**	20	2.86
^{106}Cd	1.25	2770±7.2	2741.0 (4^+) 2748.2 ($2,3^-$)	**1.1±7.2 (KL)** **-5.6±7.2 (KL)**	24.3	3.33
^{112}Sn	**0.97**	1919.5±4.8 **1919.82±0.16 (new!)**	**1871.137 (0^+)** 1870.74(4^+)	**-4.7±0.23 (KK)** -4.3±0.21 (KK)	**26.7**	**3.73**
^{130}Ba	0.11	2617.1±2.0	2608.42 **(?)** 2544.43 **(?)**	**-1.2±2.0 (LL)** **3.7±2 (KK)**	34.5	5.10
^{136}Ce	0.20	2418.9±13	2399.87 **($1^+,2^+$?)** 2392.1 **($1^+,2^+$?)** - ??? 2390.79(3^-)	**7.5±13 (LL)** **-16±13 (KL)** **-14.6±13 (KL)**	37.4	5.62
^{162}Er	0.14	1843.8±5.6	1745.7(1^+) 1782.68(2^+)	-9.5±5.6 (KK) **-1±5.6 (KL)**	53.8	8.58

*) E_K and E_{L2} are given for daughter nuclei

2^+: suppression factor is **~ 10^4**

g.s.-g.s. transitions

^{152}Gd (0.2%), ^{164}Er (1.56%),
^{180}W(0.13%)

(There are only X-rays in this case)

$0^+_{g.s.}$-$0^+_{g.s.}$

- **^{152}Gd-^{152}Sm**
  $\Delta M = 54.6 \pm 3.5$ keV
  K – 46.8 keV
  $L_1 = 7.73$; $L_2 = 7.31$; $L_3 = 6.71$ keV

  $\Delta = 0 \pm 3.5$ keV
  (KL case)

- **^{164}Er-^{164}Dy**
  $\Delta M = 23.3 \pm 5.5$ keV
  K – 53.78 keV
  $L_1 = 9.05$; $L_2 = 8.58$; $L_3 = 7.79$ keV

  $\Delta = 5.7 \pm 3.9$ keV
  (LL case)

- **^{180}W-^{180}Hf**
  $\Delta M = 144.4 \pm 6.1$ keV
  K – 65.34 keV
  $L_1 = 11.27$; $L_2 = 10.74$; $L_3 = 9.56$ keV

  $\Delta = 13.7 \pm 4.5$ keV
  KK -?

^{180}W-$^{180}Hf(2^+; 93.32$ keV)
$\Delta M = 51.08 \pm 6.1$ keV

Table. Best present limits on ECEC(0ν) to the excited state (for isotope-candidates with possible resonance conditions)

Nuclear (natural abundance)	$E^*(J^{\pi}_{f})$	$T_{1/2}$, y	Experiment, year
^{74}Se (0.89%)	1204.20 (2^+)	$> 5.5 \cdot 10^{18}$	Modane (ITEP-Bordeaux), 2007
^{78}Kr (0.35%)	2838.49 (2^+)	**$> 1.2 \cdot 10^{21}$ *)**	Baksan (INR), 2010
^{96}Ru (5.54%)	2700.21 (2^+) 2712.68 (?)	$> 4.9 \cdot 10^{18}$ $> 1.3 \cdot 10^{19}$	Gran Sasso (DAMA-Kiev), 2009
^{106}Cd (1.25%)	2741.0 (4^+) 2748.2 ($2,3^-$)	$> 1.7 \cdot 10^{20}$	TGV-II, 2010
^{112}Sn (0.97%)	**1871.13 (0^+)** 1870.74 (4^+)	**$> 1.3 \cdot 10^{21}$** **$> 1.1 \cdot 10^{21}$**	Modane (ITEP-Bordeaux), 2010
^{130}Ba (0.106%)	2608.4 (?) 2544.43 (?)	**$> 1.5 \cdot 10^{21}$ *)**	Geochemical, 2001
^{136}Ce (0.185%)	2399.87 ($1,2^+$) 2392.1 ($1,2^+$)	$> 4.1 \cdot 10^{15}$ $> 2.4 \cdot 10^{15}$	Gran Sasso (DAMA-Kiev), 2009
^{162}Er (0.14%)	1745.7 (1^+)	-	-

*) Estimation from existing experimental data

Problems

- There is no good theoretical description of the ECEC processes and “resonance” conditions
- Accuracy of **ΔM** (and **Q** as a result) is not very good **(~ 2-10 keV)** and has to be improved
- Quantum numbers are not known in some cases

[It is possible to improve the accuracy of **ΔM** to **~ 10-100 eV**:

^{112}Sn: ΔM = 1919.82±0.16 keV, PRL 103 (2009) 042501;

^{74}Se: ΔM = 1209.240±0.007 keV, PRC 81 (2010) 032501R

ΔM = 1209.169±0.049 keV, PLB 684 (2010) 17]

III. FUTURE EXPERIMENTS

- Main goal is:

To reach a sensitivity ~ **0.01-0.1 eV** to **$<m_\nu>$** (inverted hierarchy region)

- Strategy is:

- to investigate different isotopes (**>2-3**);

- to use **different** experimental technique

Here I have selected a few propositions which I believe will be realized in the nearest future (~3-10 years)

- **CUORE** (^{130}**Te**, cryogenic thermal detector)
- **GERDA** (^{76}**Ge**, HPGe detector)
- **MAJORANA** (^{76}**Ge**, HPGe detector)
- **EXO** (^{136}**Xe**, TPC + Ba^+)
- **SuperNEMO** (^{82}**Se or** ^{150}**Nd**, tracking detector)
- **KamLAND-Xe** (^{136}**Xe**, liquid scintillator)
- **SNO+** (^{150}**Nd**, liquid scintillator)

Other proposals: CANDLES, COBRA, XMASS, MOON, DCBA, NEXT, LUCIFER, ...

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

CUORE

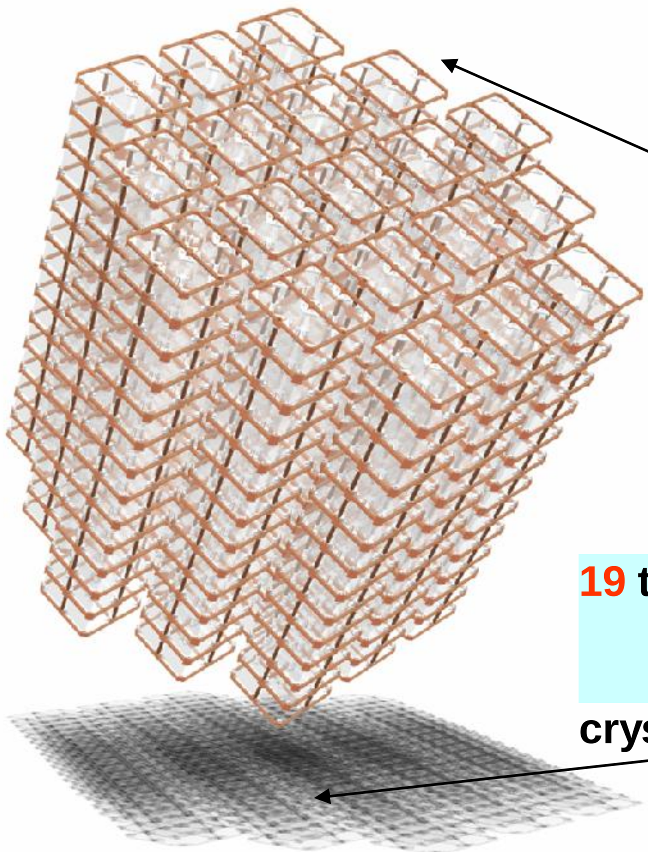
Cryogenic Underground Observatory for Rare Events

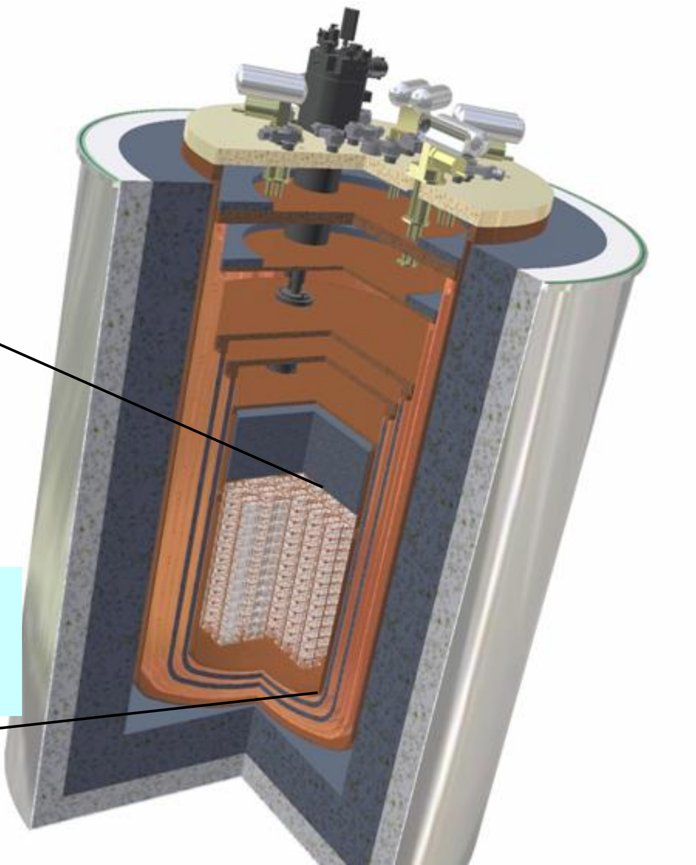
- Closely packed array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g)

741 kg TeO_2 granular calorimeter

600 kg Te = 203 kg ^{130}Te

- Single high granularity detector





19 towers

13 planes each

4 crystals each

CUORE schedule

2008-2009:
Hut construction
Crystals production
Utilities

2010=2011:
Clean room
External Shielding
Cryogenics
CUORE-0

2012:
Internal Shielding
Detector assembly
Faraday Cage
Front-end & DAQ

2013:
Data taking

CUORE-0

CUORE-0 = first CUORE tower to be installed in the CUORICINO dilution refrigerator (hall A @ LNGS)

Motivations

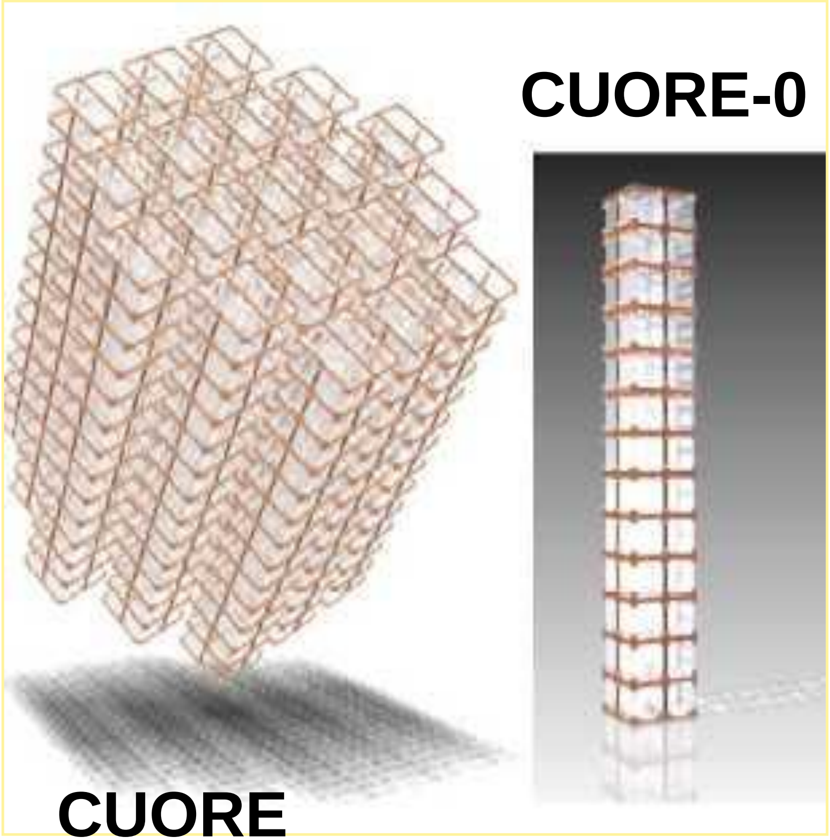
High statistics test of the many improvements/changes developped for the CUORE assembly procedure:

- gluing
- holder
- zero-contact approach
- Wires
- …

CUORE demonstrator: expected background in the DBD and alpha energy regions reduced by a factor 3 with respect ro CUORICINO

0.07 counts/keV/kg/y

Powerful experiment: it will overtake soon CUORICINO sensitivity



CUORE 5 y sensitivity

- “Realistic”:

  B = 0.01 /keV·kg·y; ΔE = 5 keV

  $T_{1/2} > 2.1 \cdot 10^{26}$ y, **<m> < 0.04-0.09 eV**

- “Optimistic”:

  B = 0.001 /keV·kg·y; ΔE = 5 keV

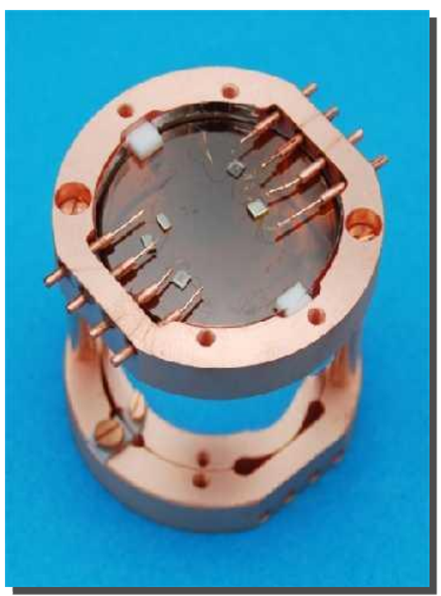
  $T_{1/2} > 6.5 \cdot 10^{26}$ y, **<m> < 0.02-0.05 eV**

Scintillating bolometers

$CdWO_4$: 508g

- Already tested different scintillating crystals ($CdWO_4$, CaF_2, $CaMoO_4$, $SrMoO_4$, $PbMoO_4$, ZnSe, …).
- With some of them we have obtained excellent results (for example $CdWO_4$, $CaMoO_4$ and ZnSe).

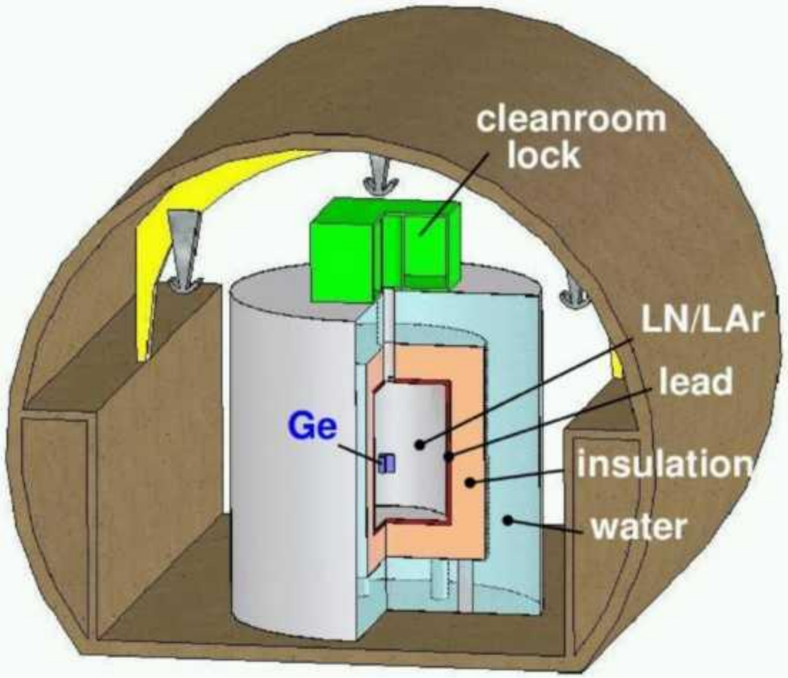
ZnSe:337 g



$CaMoO_4$: 157g

GERDA

Germany, Italy, Belgium, Russia



Goal: analise HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)

Concept: naked Ge crystals in LAr

- 1.5 m (LAr) + 10 cm Pb + 2 m water
- 2-3 orders of magnitude better bkg than present Status-of-the-Art
- active shielding with LAr scintillation

3 phases experiment

Phase I: operate refurbished HM & IGEX enriched detectors (~18 kg)

- Undergriound commissioning
- Background: 0.01 counts/ keV kg y
- Scrutinize ^{76}Ge claim with the same nuclide (5s exclusion/confirmation)
- Half life sensitivity: 3×10^{25} y
- Start data taking: 2011

Phase II: additional ~20 kg ^{76}Ge diodes (segmented detectors)

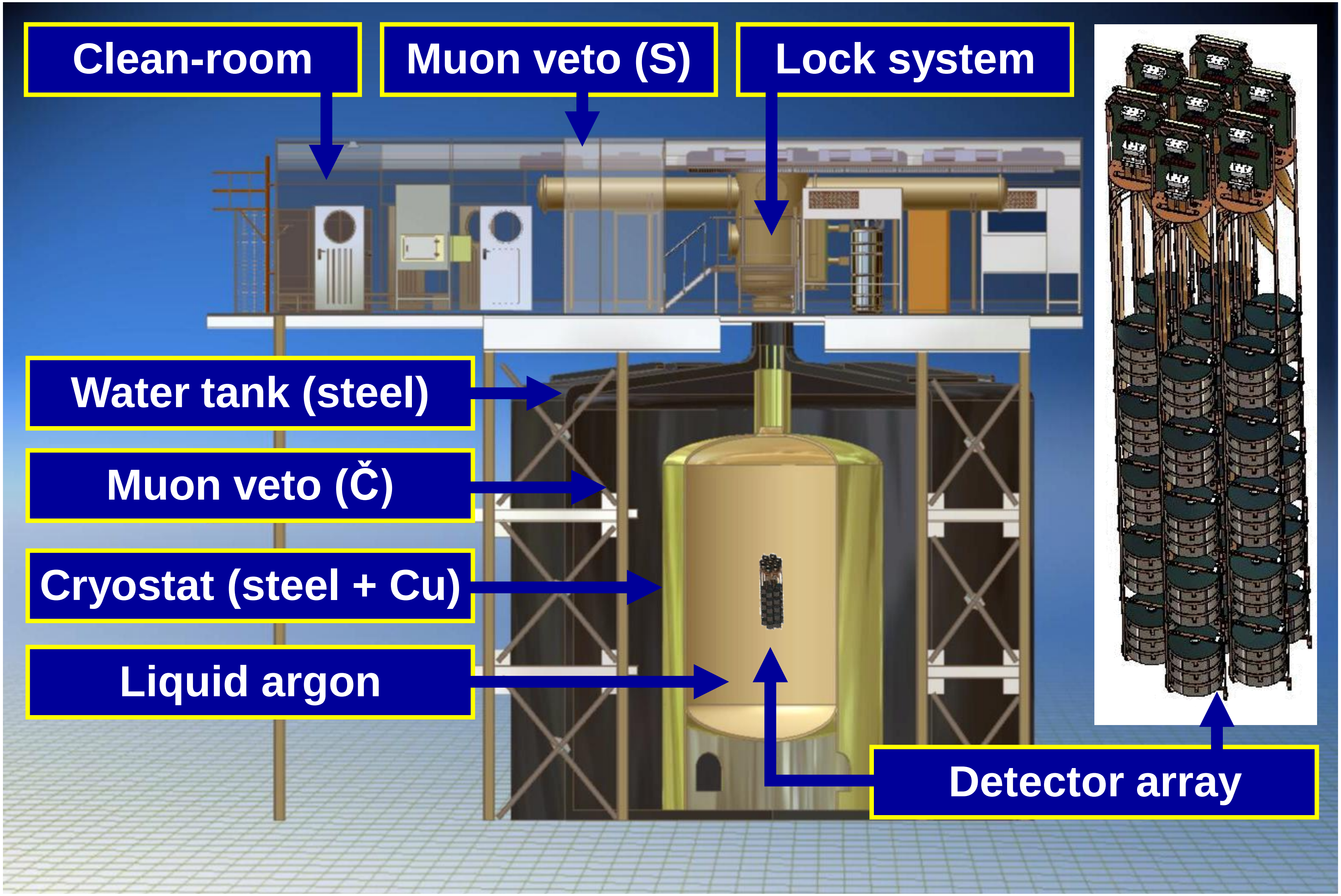
- Background: 0.001 counts / keV kg y
- Sensitivity after 100 kg y (~3 years): 2×10^{26} y ($\langle m_\nu$ < 70 - 200 meV)

Phase III: depending on physics results of Phase I/I

~ 1 ton experiment in world wide collaboration with MAJORANA

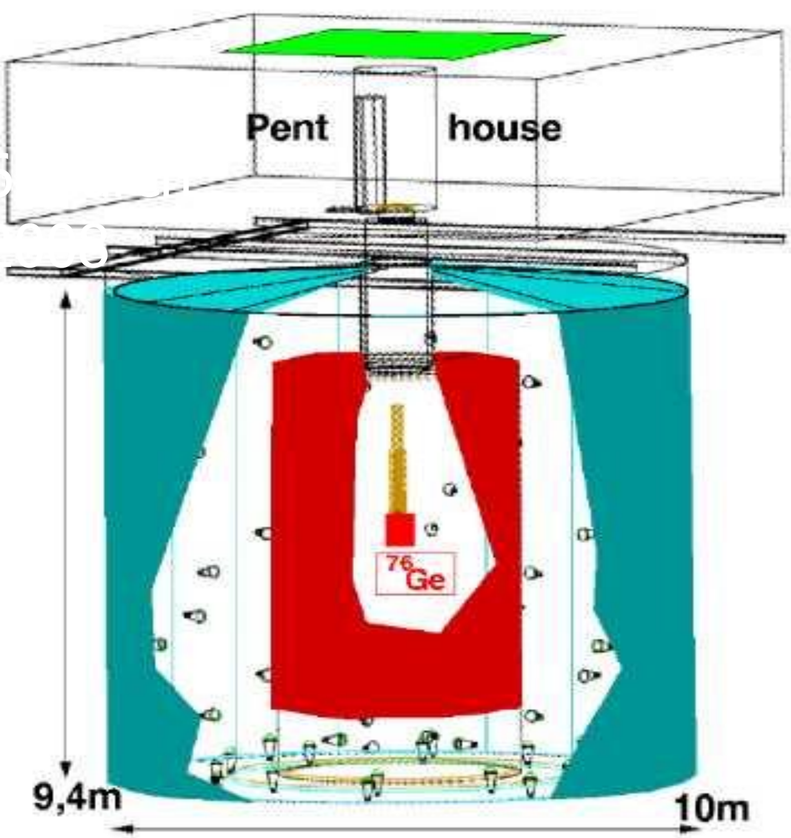
$\langle m_\nu \rangle < 10 - 40$ meV

GERDA: Technical realization



GERDA Water Tank and Muon Veto

- Active shield
- Filled with ultra-pure water from Borexino plant
- 66 PMTs: Cherenkov detector
- Plastic scintillator on top of cleanroom



Phase I:

18 kg germanium

20 kg·y exposure

10^{-2} counts/(kg·keV·y)

Phase II:

35 kg germanium

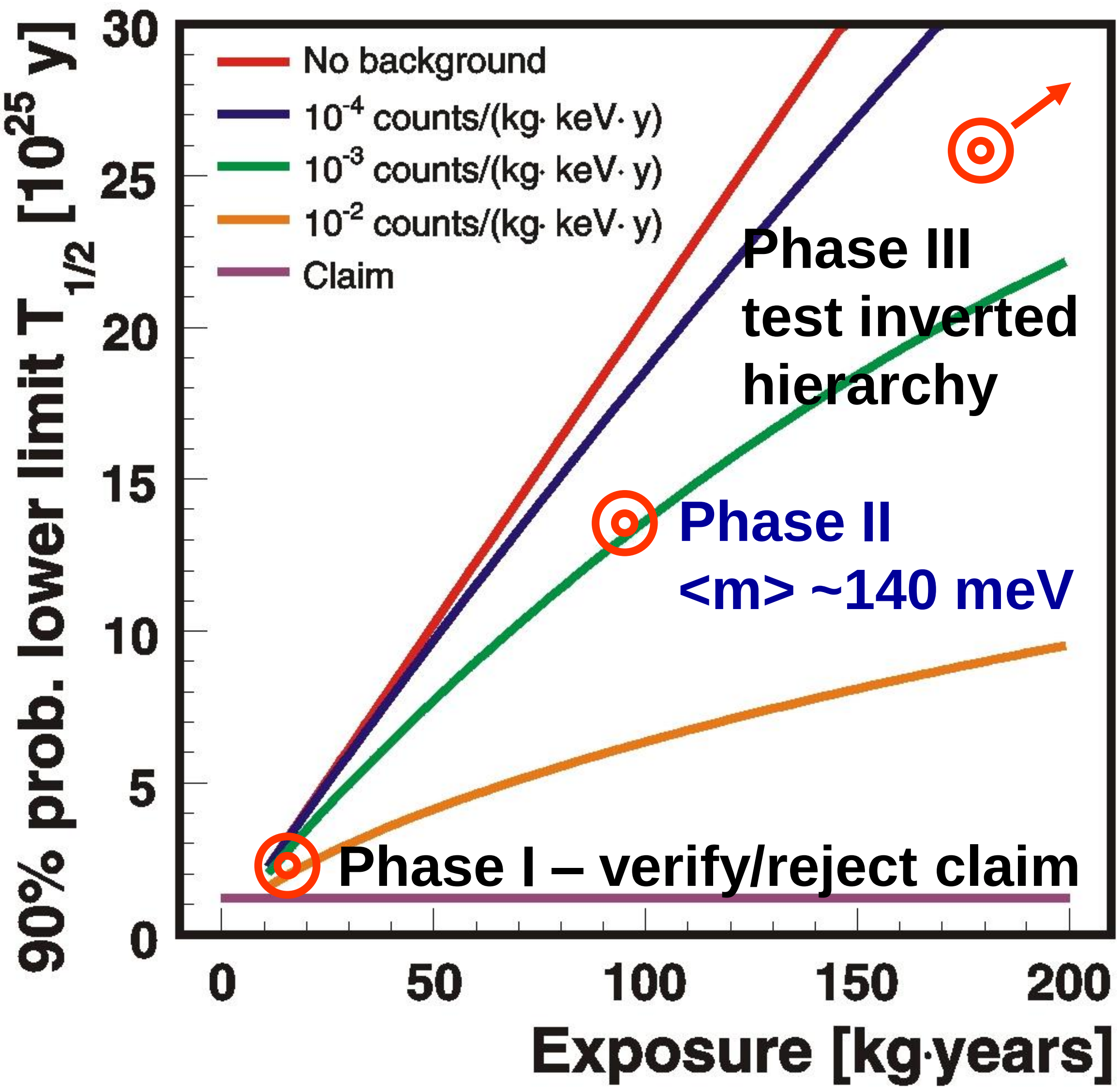
100 kg·y exposure

10^{-3} counts/(kg·keV·y)

Phase III:

1000 kg germanium

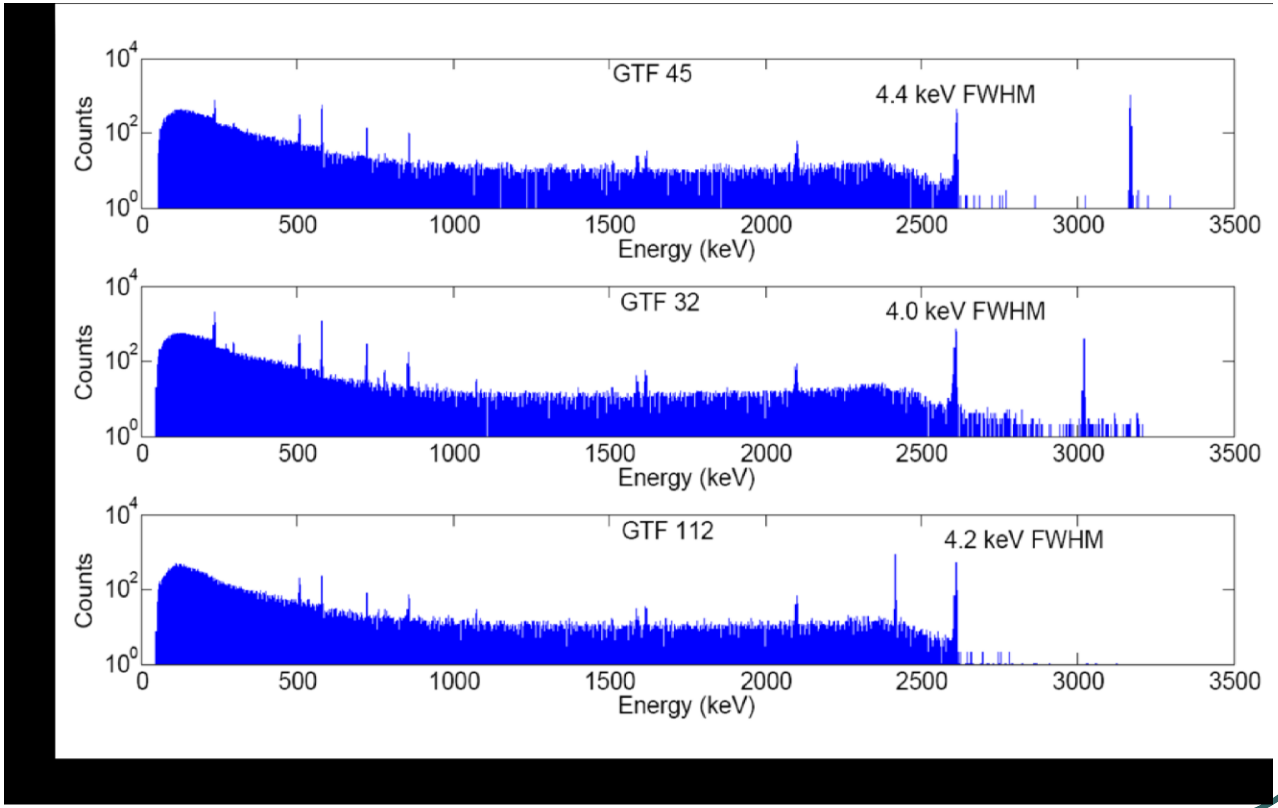
$\lesssim 10^{-4}$ counts/(kg·keV·y)



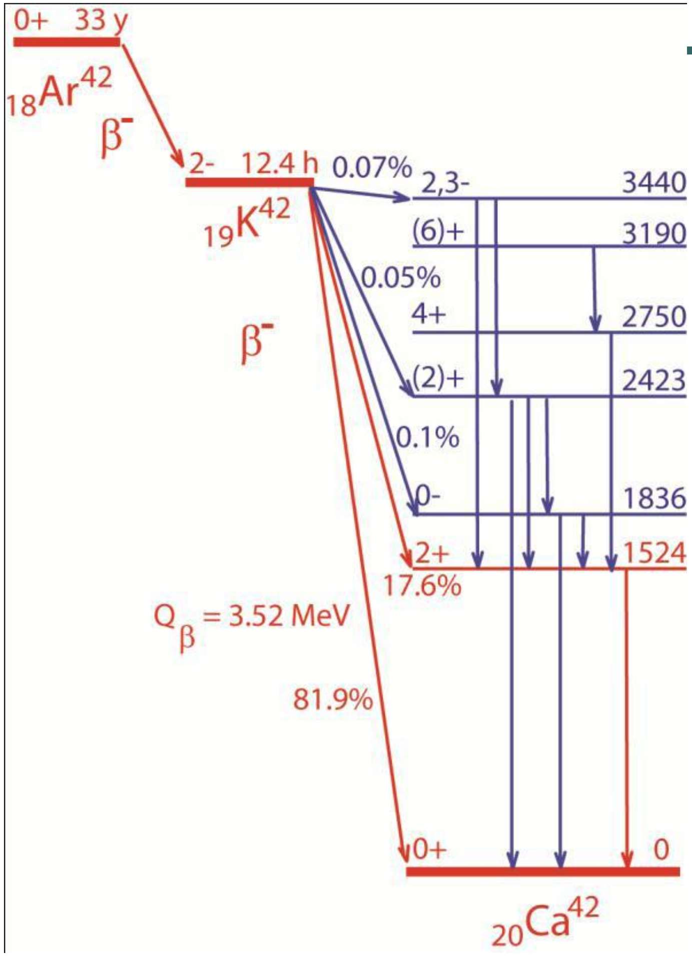
A. Caldwell, KK, Phys. Rev. D **74** (2006) 092003

Operation of the 3 ^{nat}Ge detectors

Calibration by ^{232}Th source



^{42}Ar background problem



A.S. Barabash et al.,
NIM A 416 (1998) 179
$^{42}Ar/^{40}Ar < 6 \cdot 10^{-21}$ (90% CL)

More then 10 times higher activity in GERDA???

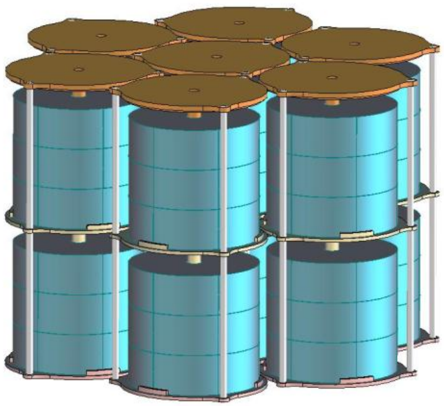
⇓

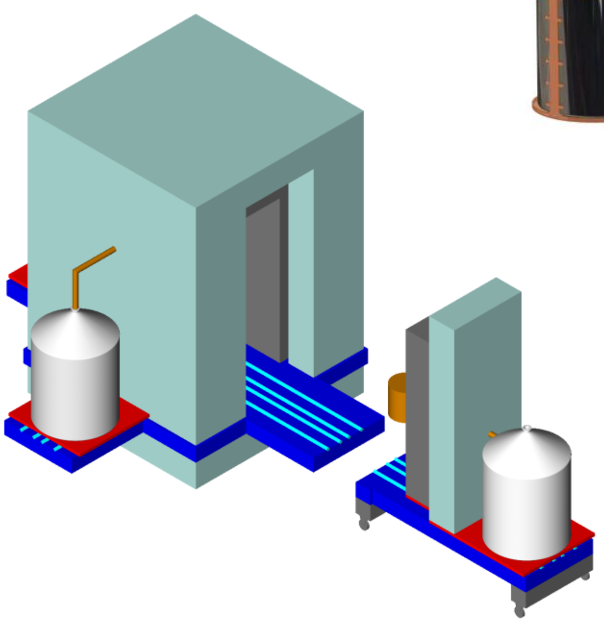
No contradiction. GERDA measure not ^{42}Ar, but local activity of ^{42}K. ^{42}K is created as ions and concentrated around Ge detectors, wires and so on because of electric field.

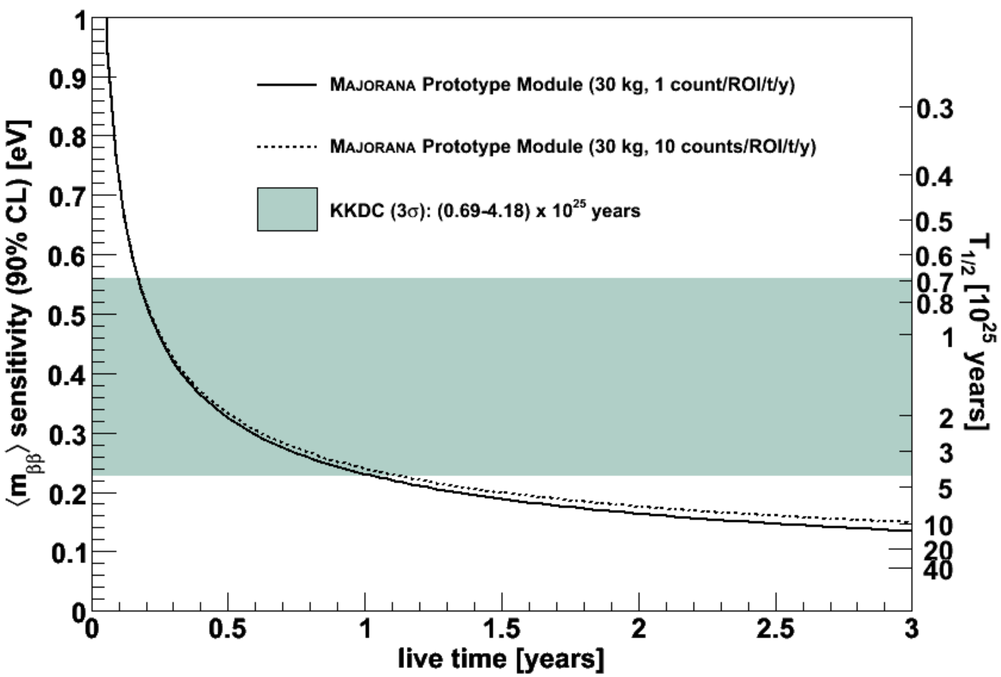
Possible GERDA time-schedule

1. Test with natural Ge crystals – 2010.
2. **Phase I** (**18 kg** of enriched HPGe) – 2011.
3. **Phase II (40 kg)** – 2012-2014.
4. **Phase III (1000 kg)** – 2015-2025 (common experiment with MAJORANA?)

MAJORANA Project

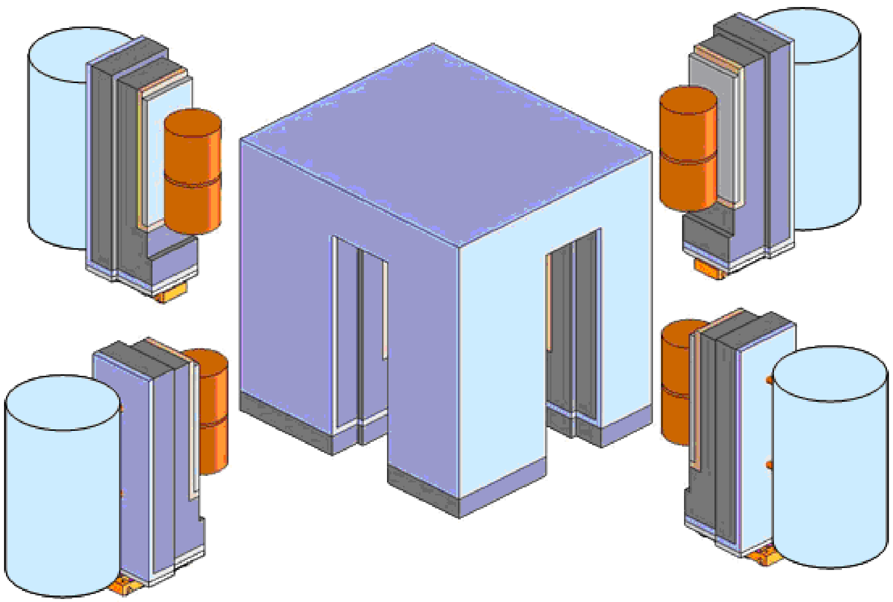


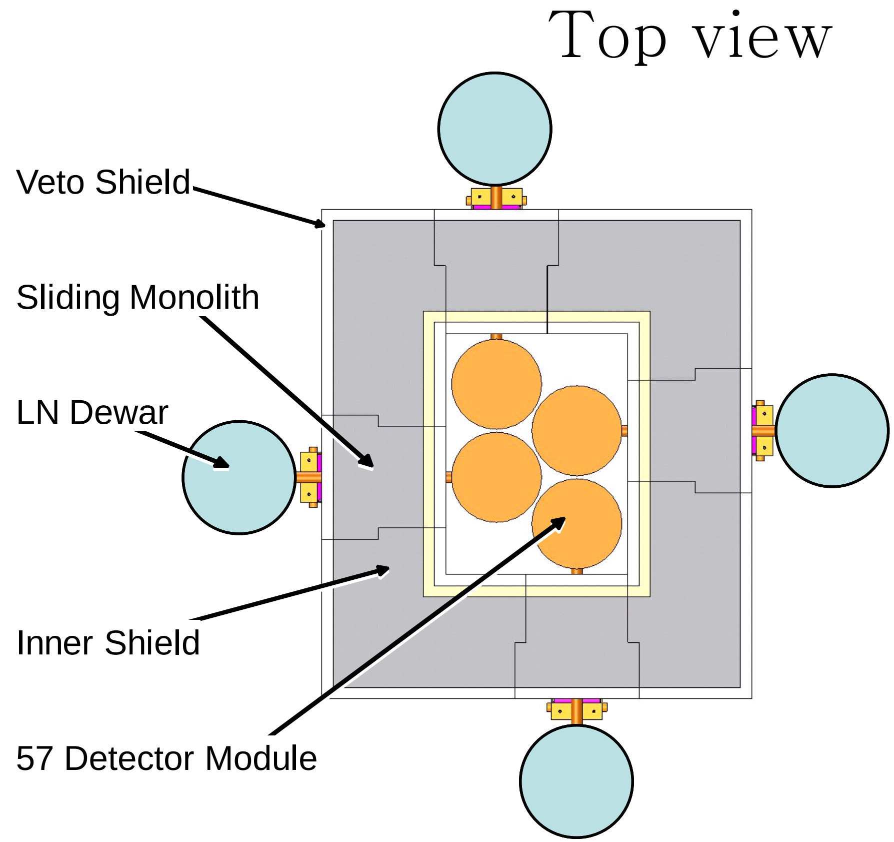




The Majorana Shield - Conceptual Design

- Deep underground: >5000’
- Allows modular deployment, early operation
- Contains up to eight 57-crystal modules
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active 4π veto detector

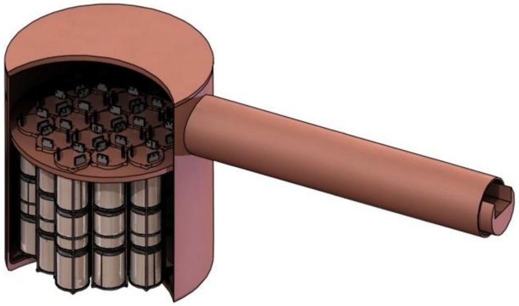




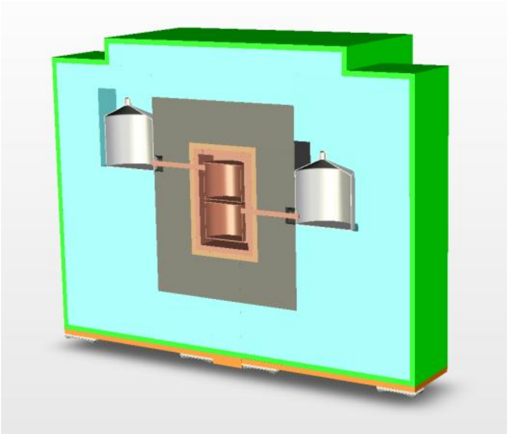
The MAJORANA DEMONSTRATOR Module

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- **60-kg of Ge detectors**
  - 30-kg of 86% enriched ^{76}Ge crystals required for science goal.
  - 60-kg required for sensitivity to background goal.
  - Examine detector technology options p- and n-type, segmentation, point-contact.



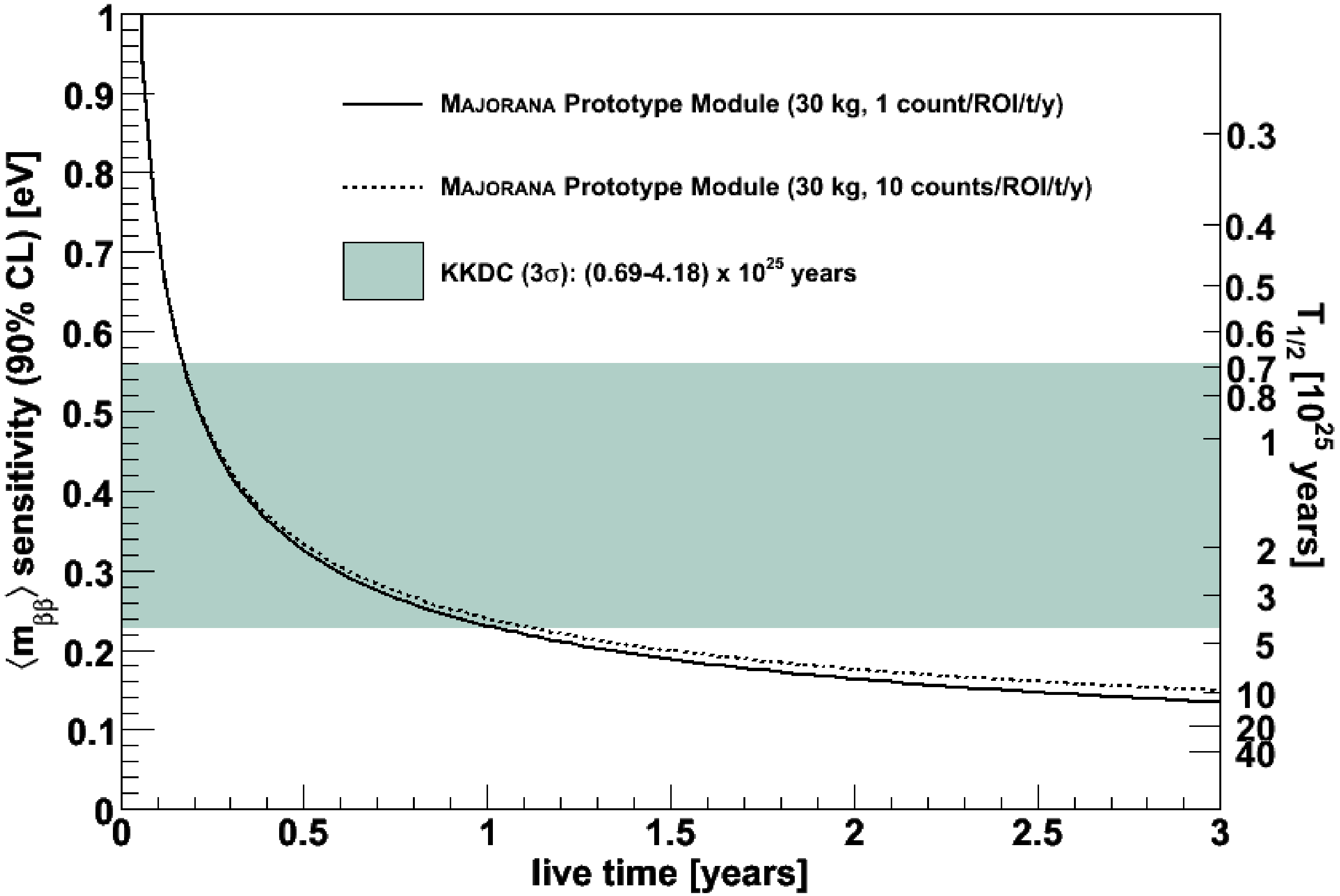
- **Low-background Cryostats & Shield**
  - ultra-clean, electroformed Cu
  - Initial module will have 3 cryostats
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto
- **Located underground 4850' level at SUSEL/DUSEL.**

MAJORANA DEMONSTRATOR Module Sensitivity

- **Expected Sensitivity to 0νββ**

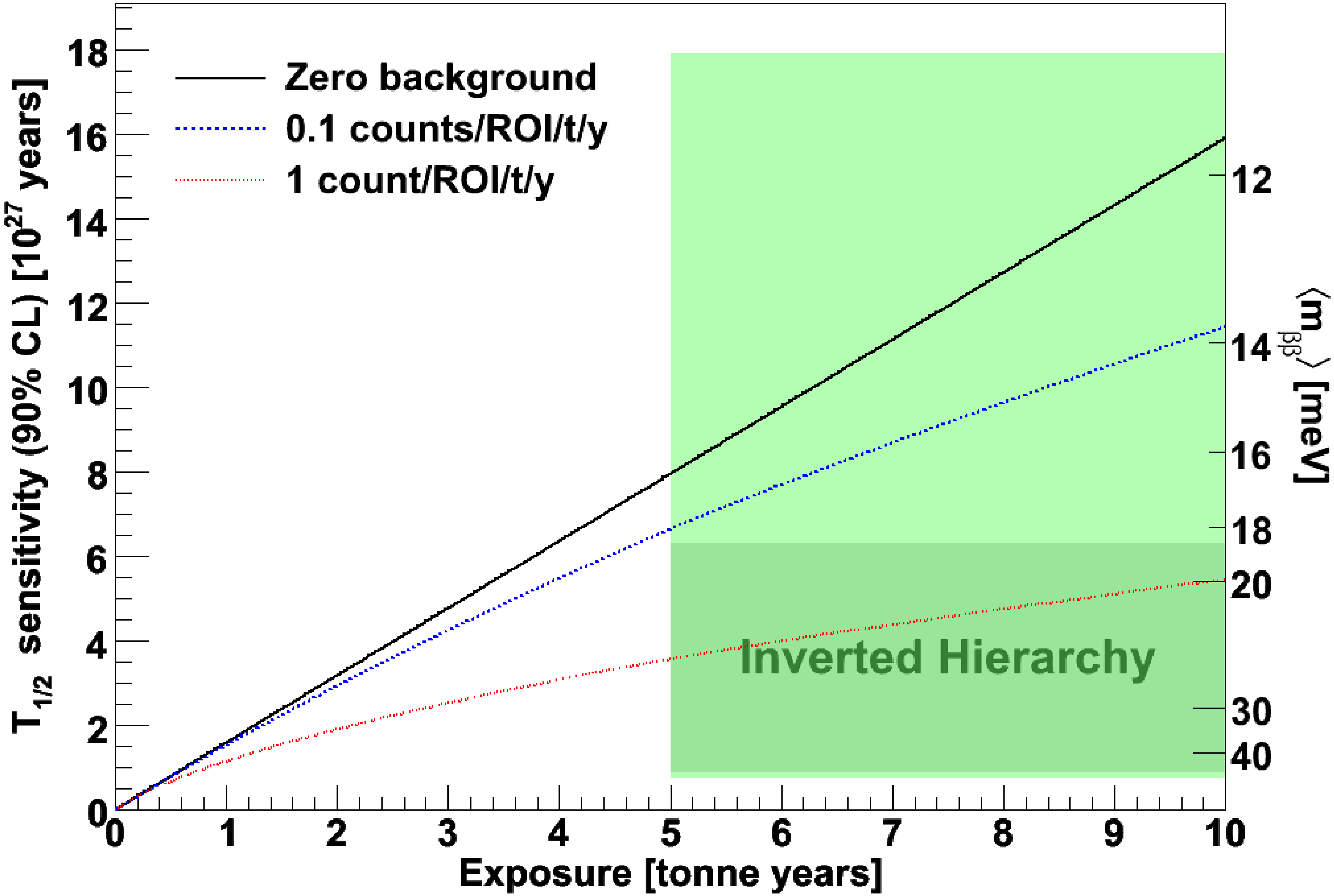
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

$T_{1/2} \geq 10^{26}$ y (90% CL).Sensitivity to <m_ν> < 140 meV (90% CL) [Rod05,err.]

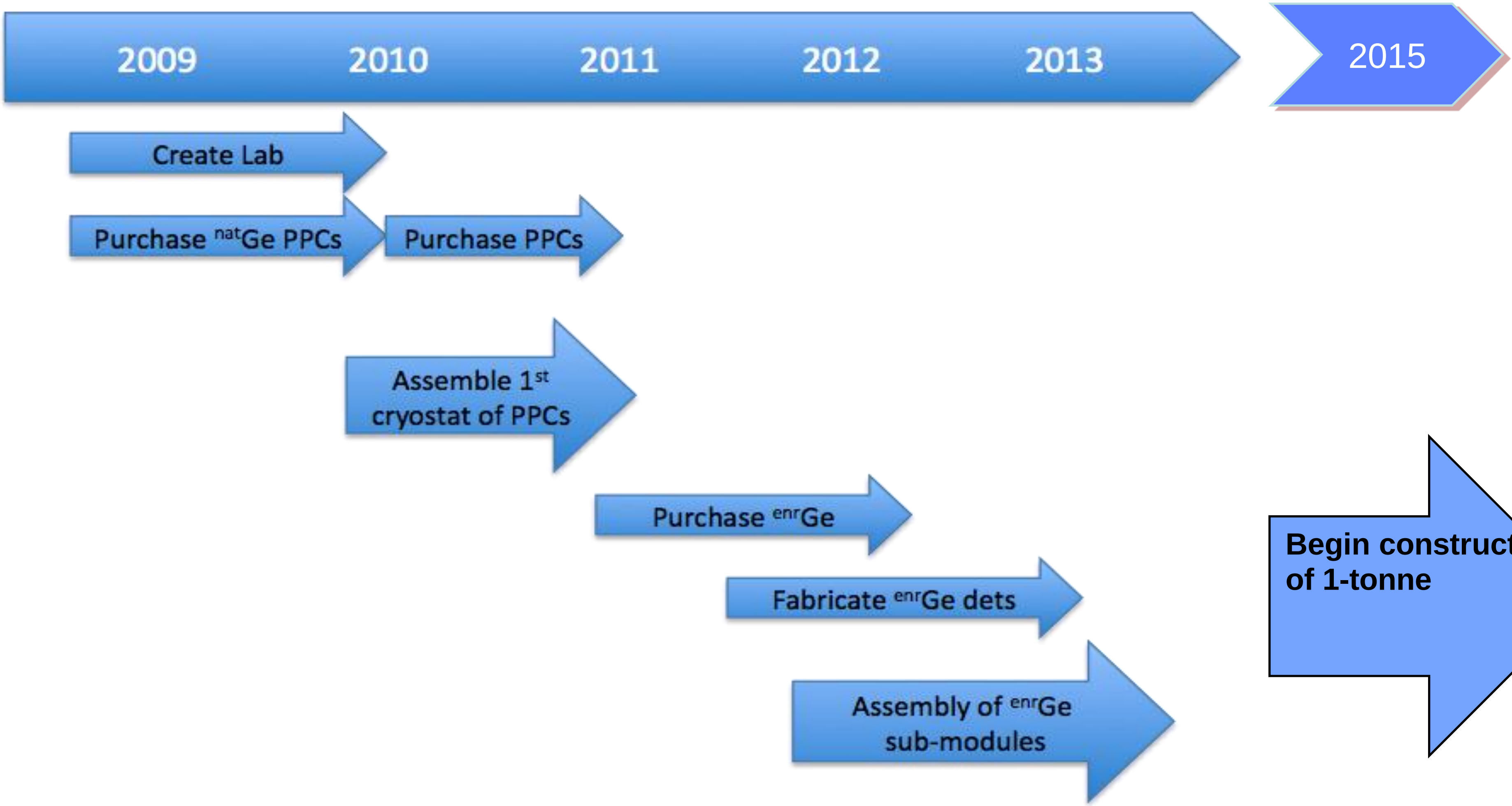


1-tonne Ge - Projected Sensitivity vs. Background

$$T_{1/2}^{0\nu} = \ln(2)N\varepsilon t/\mathrm{UL}(B)$$

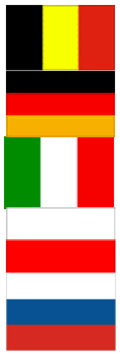


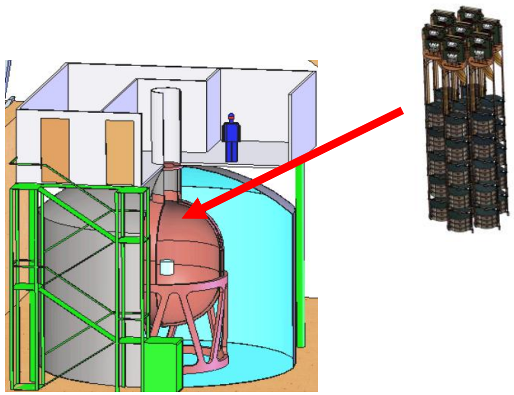
MAJORANA DEMONSTRATOR SCHEDULE



GERDA - Majorana

GERDA

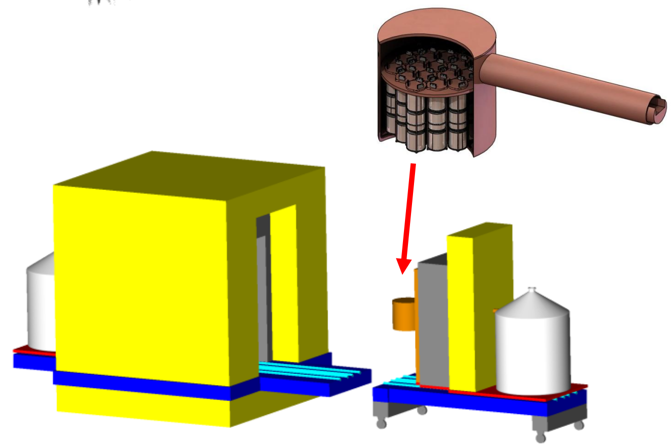




- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (~2011): ~18 kg (HdM/IGEX diodes)
- Phase II (~2012): add ~20 kg new detectors

Total ~40 kg

Majorana



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module

Total 60 kg

Joint Cooperative Agreement:

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and Majorana

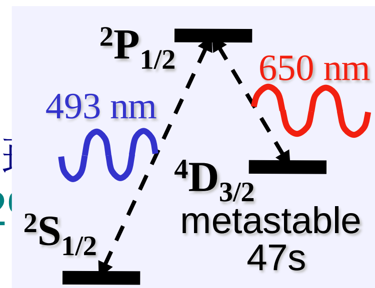
EXO (Enriched Xenon Observatory) USA-RUSSIA-CANADA

- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$ ($E_{2\beta} = 2.47$ MeV)
- **Main idea is**: to detect all products of the reaction with good enough energy and space resolution (M.Moe PRC 44(1991)931)

Tracking

EXO

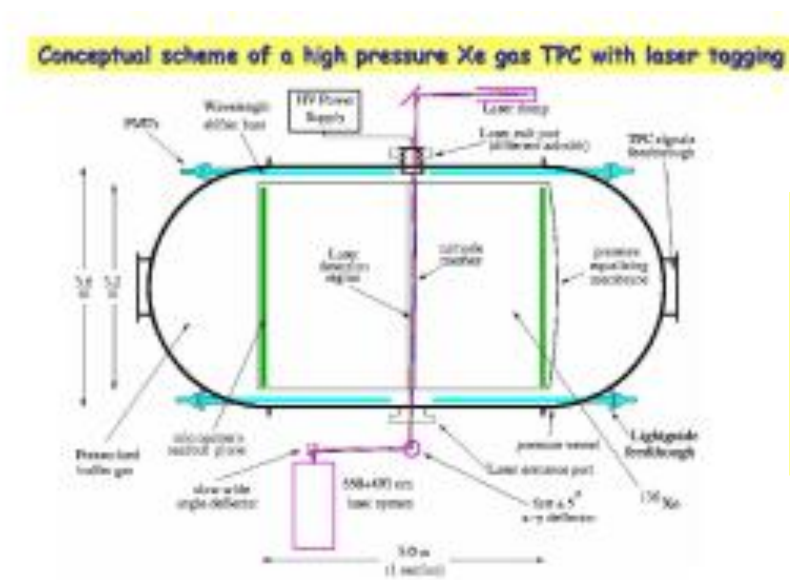
- concept: scale Gotthard experiment adding Ba tagging to suppress background (^{136}Xe咯 ^{136}Ba乂乂+2e)
- single Ba乂 detected by optical spectroscopy
- two options with 63% enriched Xe
  - ☆High pressure Xe TPC
  - ☆LXe TPC + scintillation
- calorimetry + tracking
- expected bkg only by 国国-2
  - ☆energy resolution 爐$_E$ = 2



Present R&D

- Ba$^+$ spectroscopy in HP Xe / Ba$^+$ ext
- energy resolution in LXe (ion.+scint.
- Prototype scale:
  - ▶ 200 kg enriched L^{136}Xe without tag
  - ▶ all EXO functionality except Ba id
  - ▶ operate in WIPP for ~two years
- Protorype goals:
  - ▶ Test all technical aspects of EXO (except Ba id)
  - ▶ Measure 2ν mode
  - ▶ Set decent limit for 0ν mode (probe Heidelberg- Moscow)

LXe TPC



Full scale experiment at WIPP or SNOLAB

10 t (for LXe ℬ 3 m^3)

b = 4×10^{-3} c/keV/ton/y

❄$_{1/2}$ ⌛ **1.3×10^{28} y** in 5 years

<m_ν> ⌛ 0.013 ÷ 0.037 eV

1 ton EXO

- **Liquid (gas) Xe TPC + Ba^+ tagging**
- 1 ton of **^{136}Xe** (**80%** enrichment)
- **ΔE/E(FWHM)** = **3.8%** at 2.5 MeV (ionization and scintillation readout)
- Background (5 y) = **1** event
- Sensitivity (5 y): **$8 \cdot 10^{26}$ y** (**$\langle m_\nu \rangle \sim$ 0.03-0.06 eV**)

EXO-200 (without Ba^+ tagging)

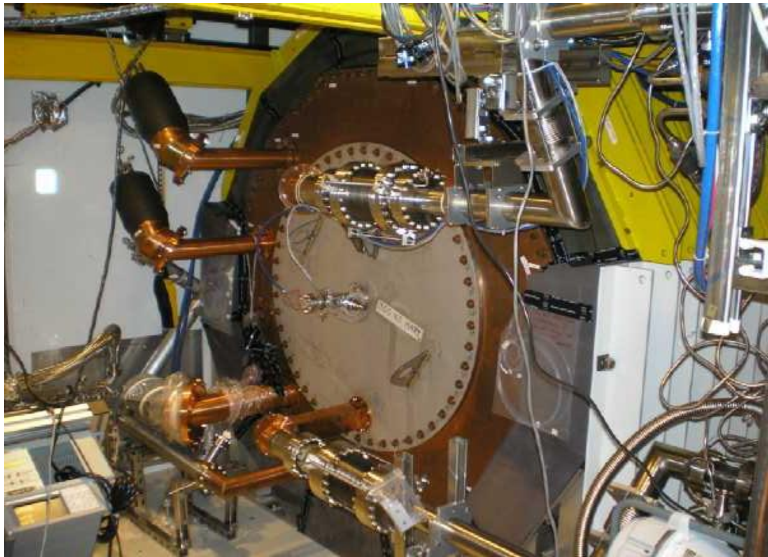
- **200 kg** of ^{136}Xe (80% enrichment) – **exist!**
- Location: WIPP (USA)
- **ΔE/E(FWHM)** = **3.8%** at 2.5 MeV (ionization and scintillation readout)
- Background (5 y) = **40** events
- Sensitivity (5 y): **$6.4 \cdot 10^{25}$ y** (**$<m_\nu>$ ~ 0.1-0.2 eV**)
- Start of measurements: in **~ 2010-2011**

EXO-200

Intermediate Prototype without Barium Tagging

- TPC Vessel fully machined at Stanford under 7 m.w.e shielding; E-beam welding used for all but final weld to minimize introduction of radioactive background
- 200 kg enr. Xe (80% in 136Xe)
- Vessel complete, welded to door

- Half detectors almost complete
  - (APDs, cables under assembly)
  - Detector at WIPP: lead shielding, Xe plumbing almost complete, cryogenics tests in progress

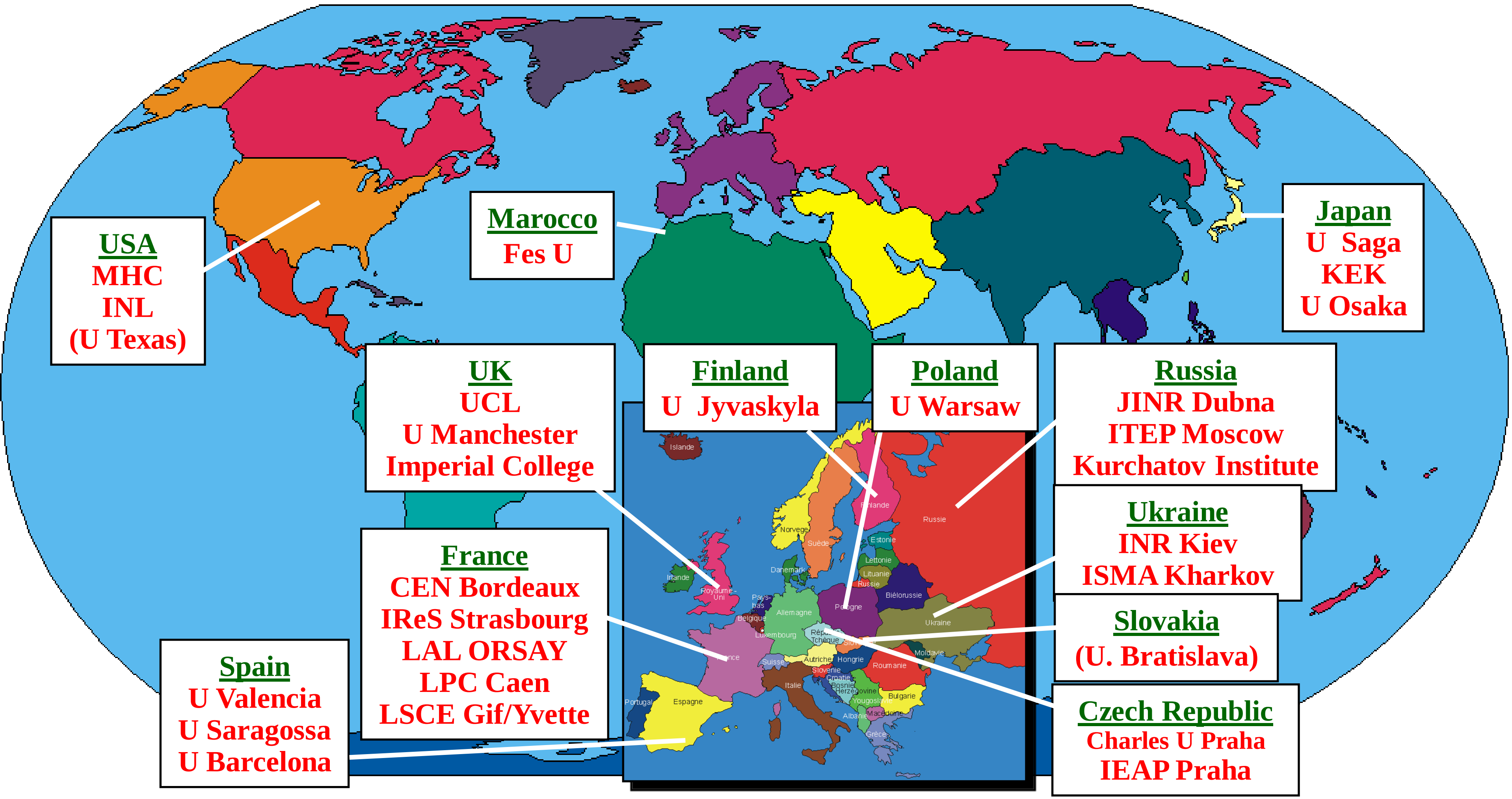


Schedule:

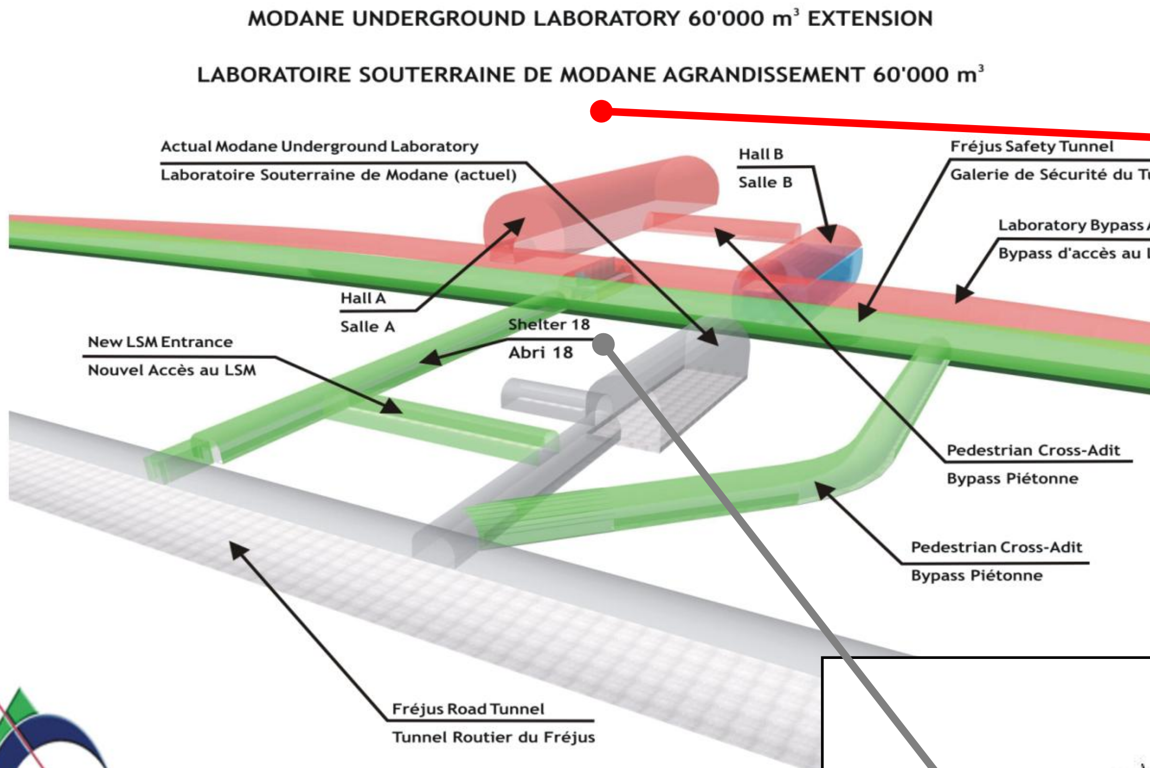
- engineering run Summer 09
- physics run Fall 09
- First 2nu measurement 2010
- 0nu 3–5 years

SuperNEMO Collaboration

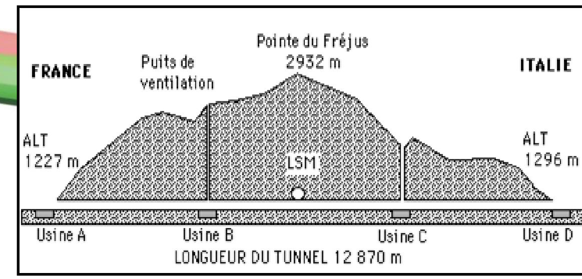
~ 90 physicists, 12 countries, 27 laboratories

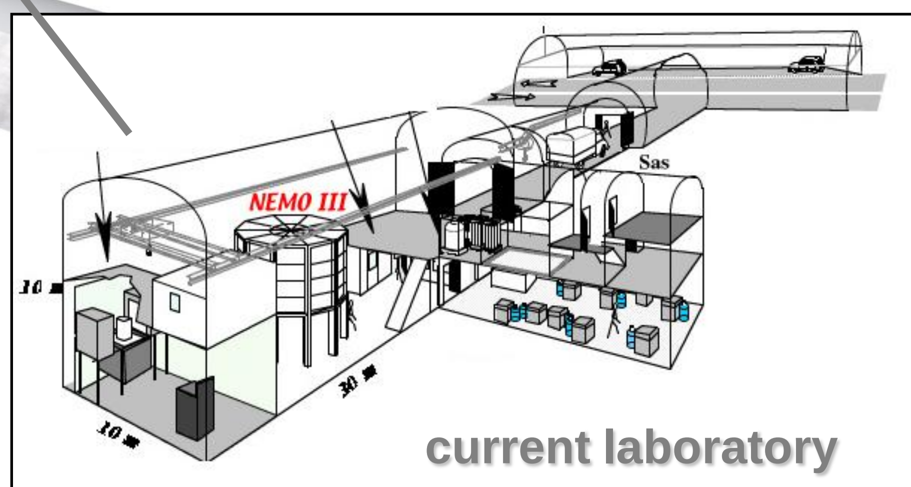


Possible location : LSM



A 60 000 m³ extension

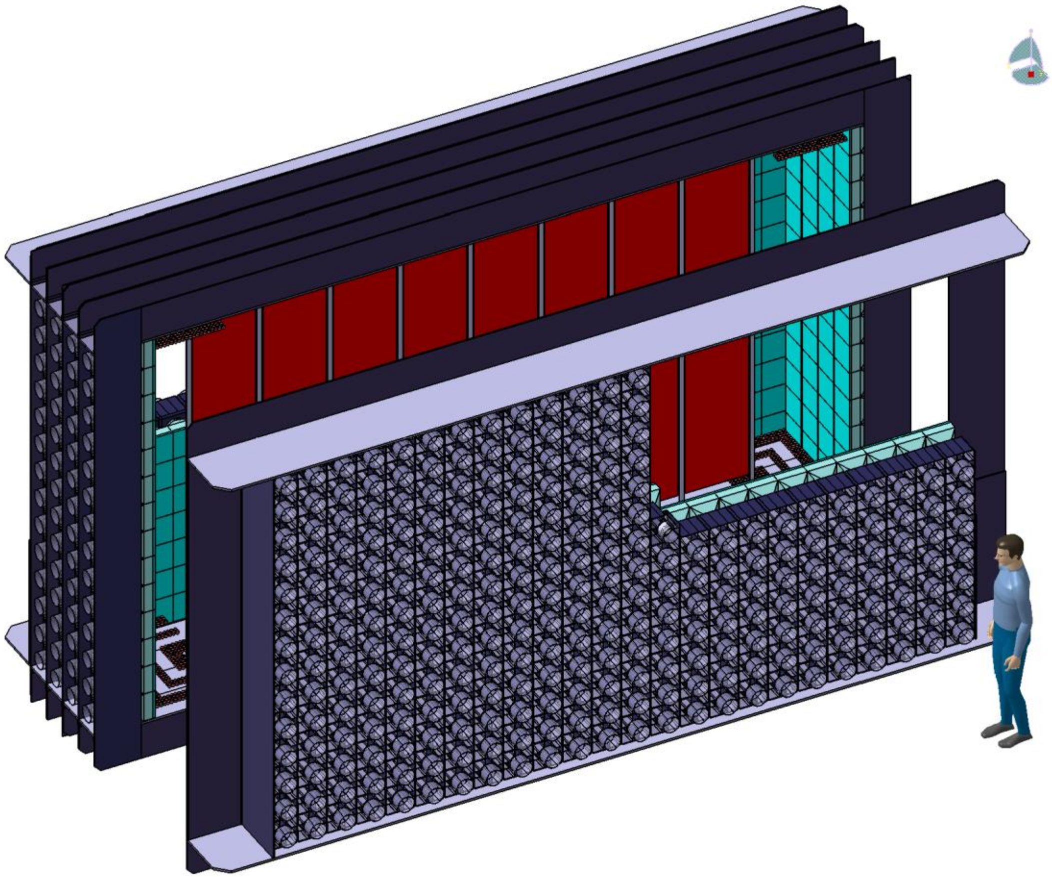


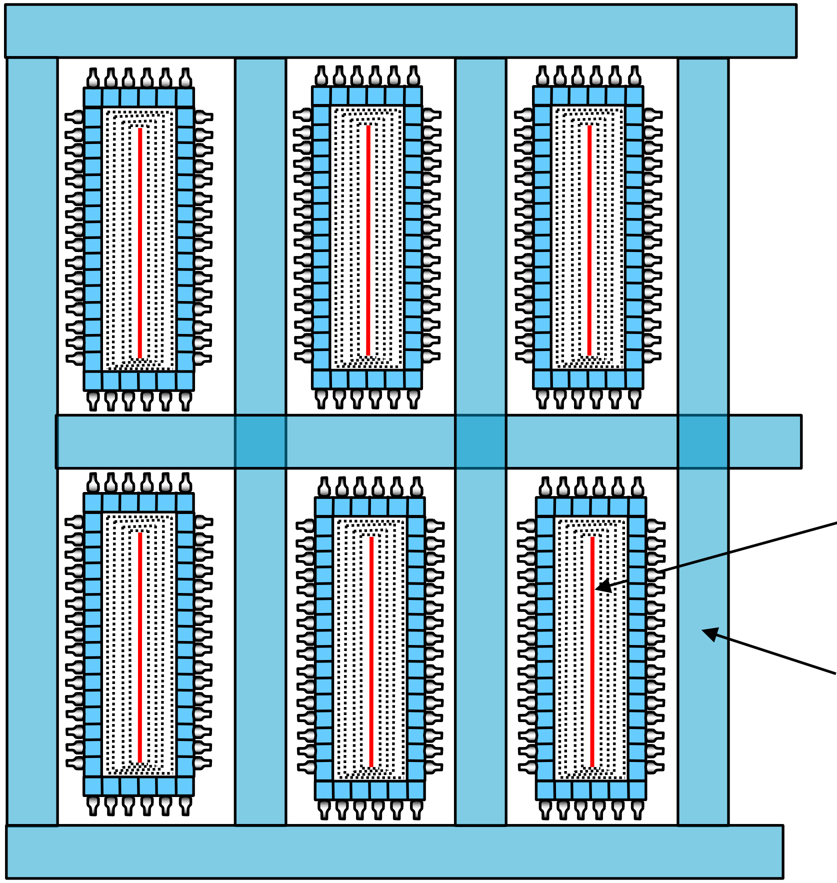


Demonstrator to be placed in NEMO3's current location

Full SuperNEMO detector in a new cavity (extension finished on 2012)

Very preliminary design





Single sub-module
with ~7 kg of isotope

~20 sub-modules for 100+ kg of isotope
surrounded by shielding

From NEMO-3 to SuperNEMO

NEMO-3		SuperNEMO
^{100}Mo	Choice of isotope	^{82}Se or ^{150}Nd
7 kg	Isotope mass M	100-200 kg
8% @3MeV	Energy resolution FWHM (calorimeter)	4% @ 3MeV
18 %	Efficiency ε(ββ0ν)	~ 30 %
^{208}Tl < 20 μBq/kg ^{214}Bi < 300 μBq/kg	***Internal radiopurity*** ***^{208}Tl and ^{214}Bi*** ***in the ββ foils***	^{208}Tl < 2 μBq/kg (*If ^{82}Se*: ^{214}Bi < 10 μBq/kg)
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $<m_\nu> < 0.3 – 1.3$ eV	**SENSITIVITY**	$T_{1/2}(\beta\beta0\nu) > (1\text{-}2)\cdot 10^{26}$ y $<m_\nu> \sim 40\text{-}140$ meV

Main R&D tasks:

1) ββ source production
2) Energy resolution
3) Radiopurity
4) Tracking

SuperNEMO Demonstrator (1^{st} module)

MAIN GOALS :

- To demonstrate the feasibility of large scale detector with requiered performance (efficiency, energy resolution, radiopurity, …)

- To measure the radon background

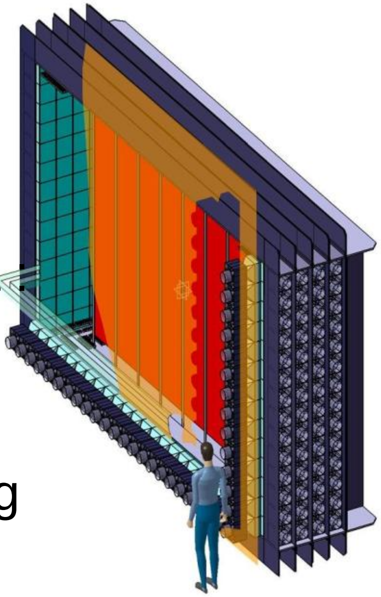
- To finalize detector design

- To produce competitive physics measurement :

$T_{1/2}(\beta\beta0\nu) > 6.5 \times 10^{24}$ years

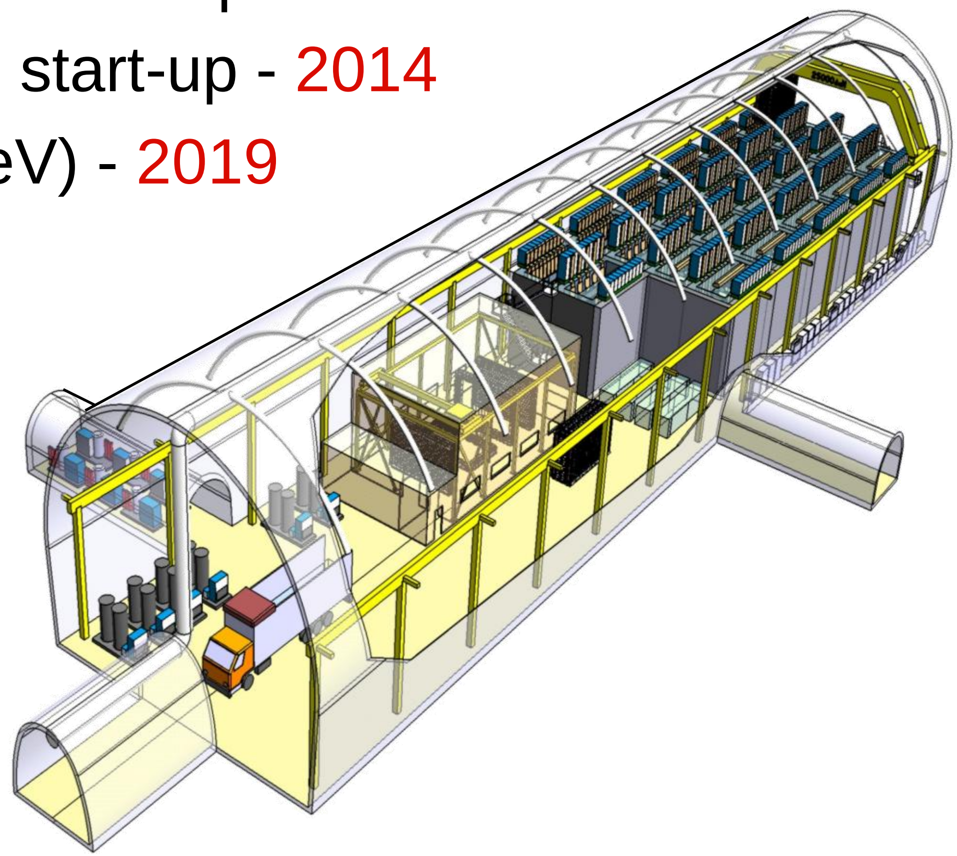
$< m_\nu > \; < \; 210 – 570$ meV

with 7 kg of ^{82}Se after ~ 2 years of demonstrator data taking



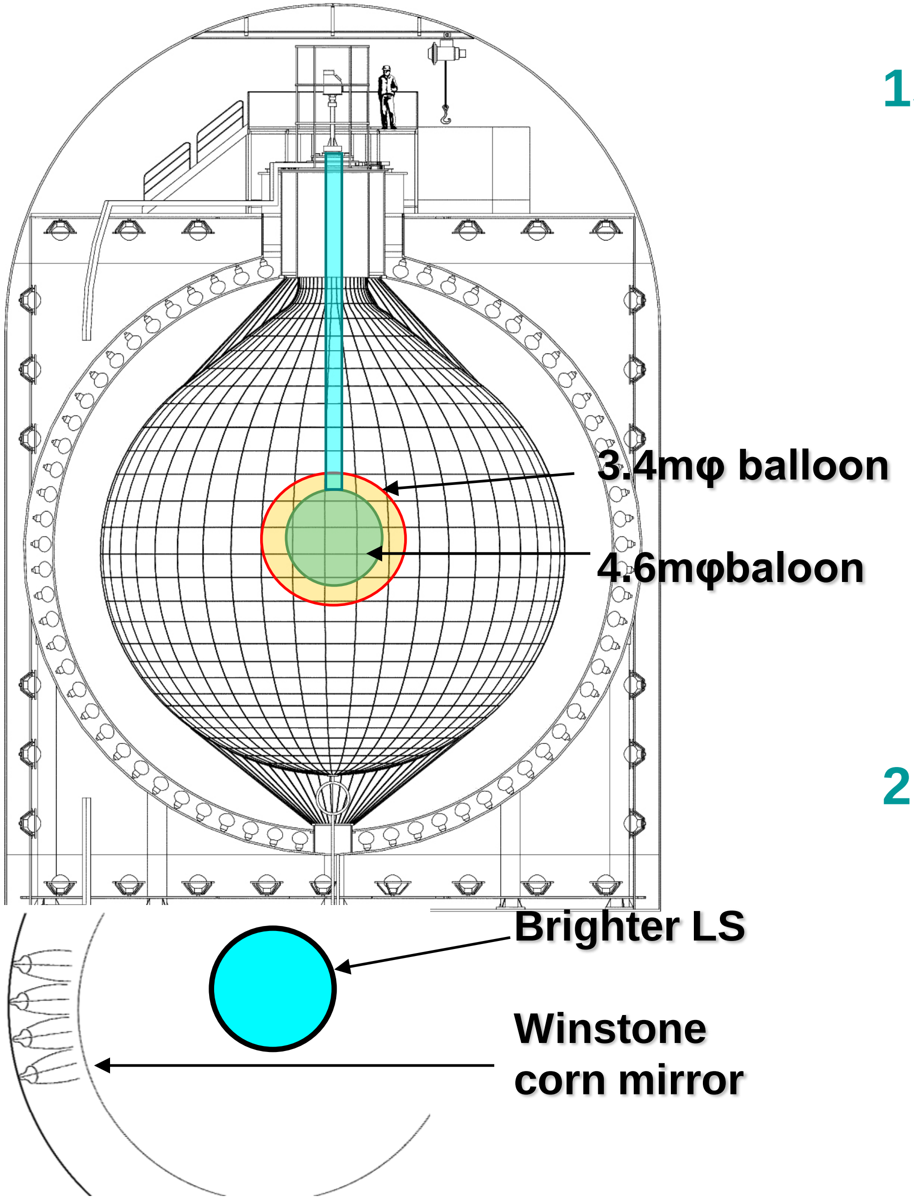
SuperNEMO schedule highlights

- NEMO-3 decommissioning - early 2011
- Demonstrator construction - 2010-2012
- Demonstrator physics run start-up - 2013
- Full detector construction start-up - 2014
- Target sensitivity (~0.05 eV) - 2019



KK claim to be verified with Demonstrator by 2015

KamLAND-Zen project



1st phase enriched Xe 400kg

R=1.7m balloon

$V=20.5m^3$,$S=36.3m^2$

LS : C10H22(81.8%)+PC(18%)

+PPO+Xe(~2.5wt%)

ρLS : 0.78kg／ℓ

high sensitivity with low cost

tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg

R=2.3m balloon

$V=51.3m^3$,$S=66.7m^2$

improvement of energy resolution

(brighter LS, higher light concentrator)

Background study using KamLAND MC (GEANT4)

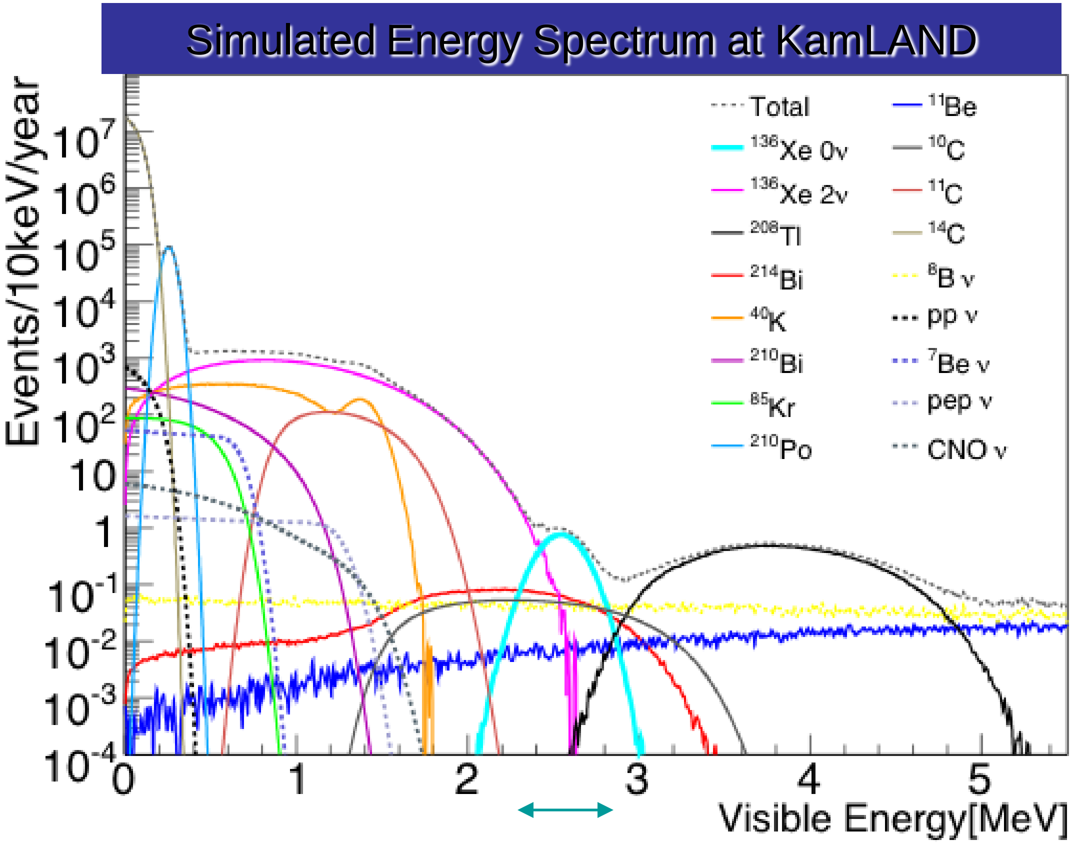
Major BG

(1). ^{136}**Xe 2νββ**

(2). spallation isotopes : ^{10}C, ^{11}Be => 1/10 using new electronics help

(3). ^{8}B solar neutrinos <4.9 events/d/kton on KamLAND

(4). from Mini Balloon (MIB) material : ^{208}Tl, ^{214}Bi => vertex cut,



Assumed

- 400kg 90% enriched Xe loaded LS
- MIB contamination (238U, 232Th, 40K) = (10-12, 10-12, 10-11)[g/g]
- neutrino effective mass <mν> = 150meV (the lower limit of the current claimed detection)
- $T_{1/2}(2\nu\beta\beta) > 10^{22}$y
- $T_{1/2}(0\nu\beta\beta) > 1.14\times10^{24}$y
- ^{10}C 90% tag, ^{214}Bi 66% tag

Summary of BG and signal in signal region

^{136}Xe 2ν	^{208}Tl	^{214}Bi	^{10}C	^{11}Be	^{8}B	Total	^{136}Xe 0ν
2.08 ±0.15	1.86×10^{-2} $\pm0.13\times10^{-2}$	2.40 ±0.01	3.09 ±0.01	0.26 ±0.01	1.52 ±0.03	9.35 ±0.23	18.08 ±0.02

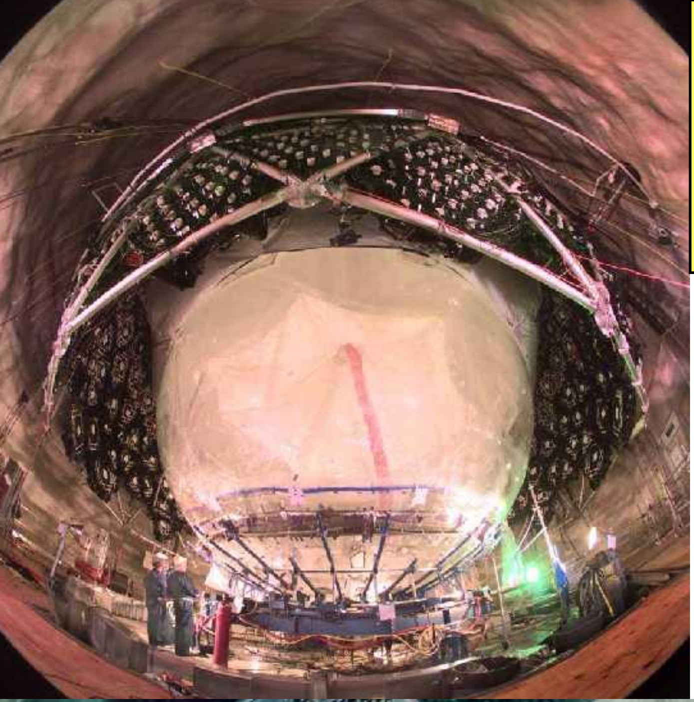
[events/year]

Masayuki Koga ICHEP2010

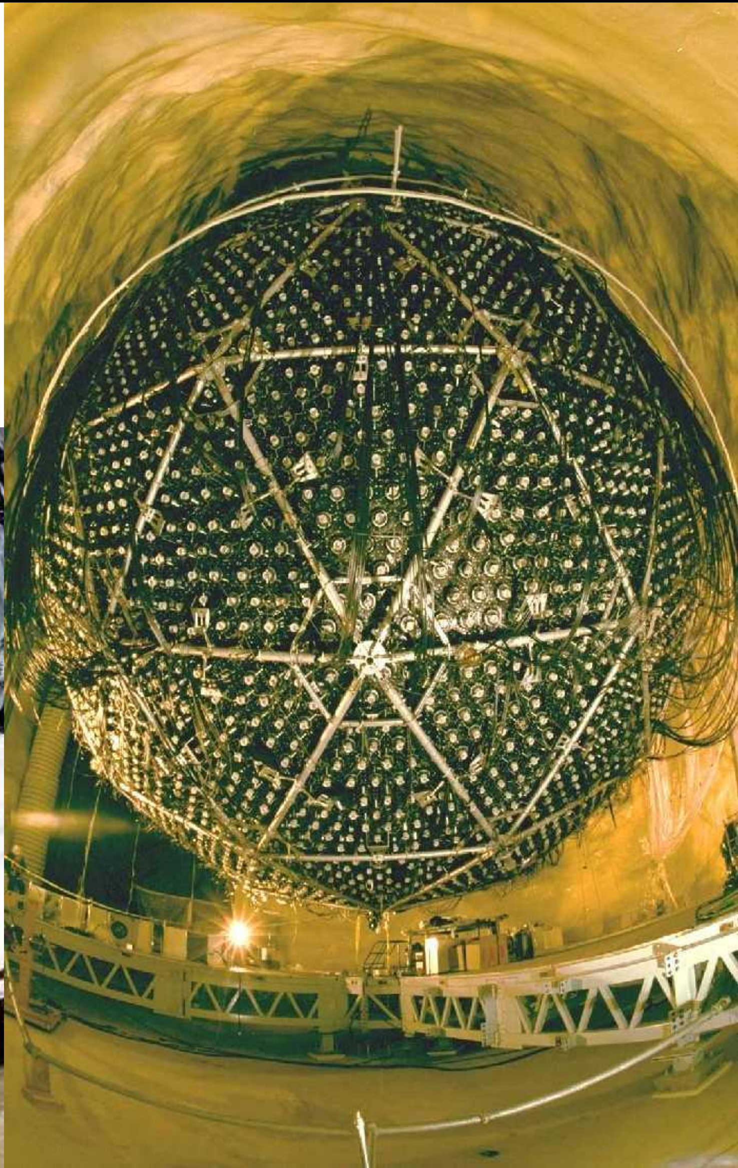
summary

- **KamLAND** is running for reactor, Geo, 7Be solar (to 2011)
- **KamLAND** have ability to do **0νββ** experiment
- **KamLAND-Zen** project will start using 400kg 90% enriched Xe from May 2011
- Target sensitivity on **400kg** Phase ~60meV @2years
- Planning **Xe1000** phase (from 2013 or 2015: depend on funding)

SNO: One million pieces transported down in the 9 ft x 12 ft x 9 ft mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.



Over 70,000 Showers to date and counting



SNO+

SNO+: SNO filled with liquid scintillator

A liquid scintillator detector has poor energy resolution

Huge quantities of isotope (high statistics) and low backgrounds however help compensate

- source in–source out capability
- large, homogeneous liquid detector leads to well-defined background model
- possibly source in–source out capability
- using the technique that was developed originally for LENS and now also used for Gd-loaded scintillator
- SNO+ collaboration managed to load Nd into pseudocumene and in linear alkylbenzene (>1% concentration)
- with 1% Nd loading (natural Nd) a very good neutrinoless double beta decay sensitivity is predicted, but…

Nd loaded sintillator:

1% loading (Natural Nd) large light absorption by Nd

47 ± 6 pe/MeV (Monte Carlo)

0.1% loading (Isotopically enriched to 56% Nd) acceptable

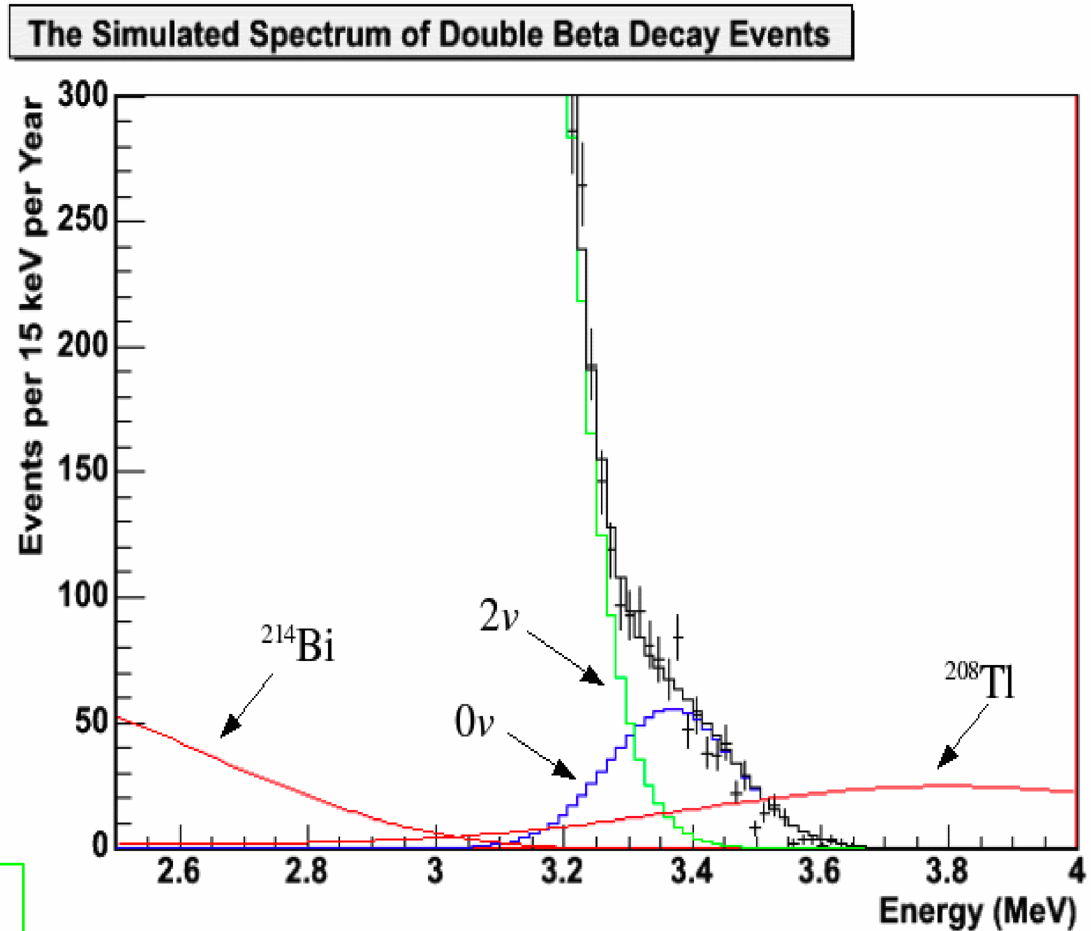
400 ± 21 pe/MeV (Monte Carlo)

SNO+ (2)

- Using existing SNO infrastructure
- Well understood detector

1057 events per year with 500 kg ^{150}Nd-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.



Sensitivity Limits (3 yrs):

- **Natural Nd (56 kg isotope):**
  m_ν ~ 0.1-0.3 eV
- **500 kg enriched ^{150}Nd**
  m_ν ~ 0.04-0.12 eV

Funded by NSERC for final design/engineering and initial construction 2008-2010
End of 2010 → ready for scintillator filling

IV. Conclusion

1. **Significant advance has been made in the investigation of 2ν-decay.**

2. **Present conservative limit on $<m_\nu>$ from 2β(0ν)-decay experiments is ~ 0.75 eV.**

3. **There is indication on "evidence" of 2β(0ν)-decay in ^{76}Ge ($<m_\nu> \approx$ 0.3-0.5 eV). But it has to be confirmed (or rejected) in new experiments with ^{76}Ge (it will be done in a few years).**

4. **NEMO-3 will be stopped in November 2010 and will reach a sensitivity to $<m_\nu>$ on the level ~ (0.3-0.7) eV.**

5. **In 2011:**
   - **start data taking with GERDA-I (^{76}Ge);**
   - **start data taking with EXO-200 (^{136}Xe);**
   - **start data taking with KamLAND-Xe (^{136}Xe);**
   - **start data tacking with CUORE-0 (^{130}Te).**

6. **New generation of experiments will reach sensitivity to $<m_\nu>$ on the level ~ (0.01-0.1) eV in ~ 2013-2020.**