ДВОЙНОЙ БЕТА-РАСПАД: современное состояние и перспективы

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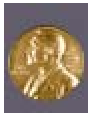
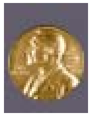
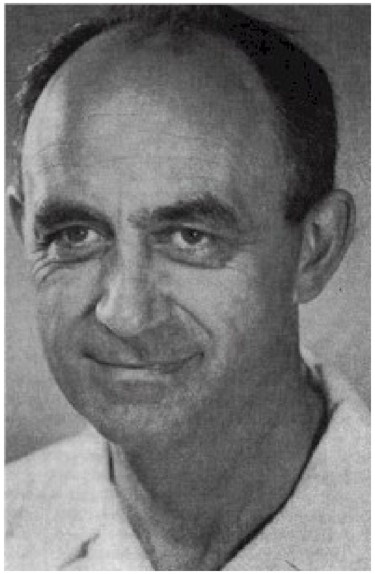
ПЛАН

- **Историческое введение**
- **Современное состояние (NEMO-3, CUORICINO)**
- **Эксперименты следующего поколения**
- **Заключение**

I. Historical introduction

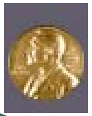





Neutrino was introduced by **W. Pauli** in 1930

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

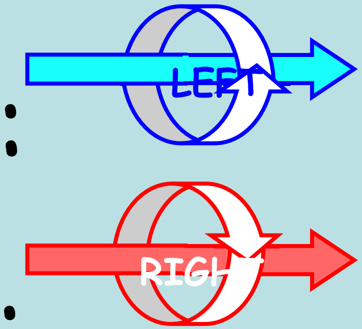
  M. Goeppert-Mayer in 1935:

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

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

ν:

$\bar{\nu}$:

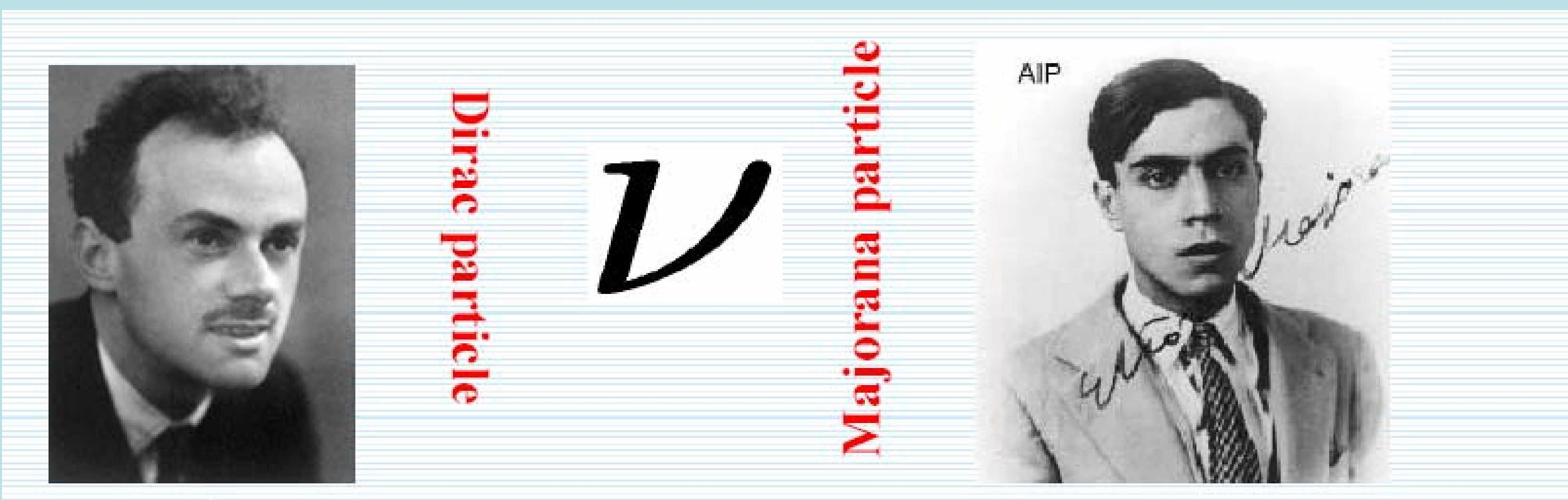


$\nu \neq \bar{\nu}$

$\nu = \bar{\nu}$

Dirac 

Majorana
=>1937



The birth of neutrinoless double beta decay

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

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

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

[Parity violation was not known at that time!]

First experiments

- **1948** – first counter experiment (Geiger counters, ^{124}**Sn**; $T_{1/2}(0\nu) > \mathbf{3 \cdot 10^{15}\ y}$)
- **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 **0**ν decay reached **$\sim 10^{21}$ y**!!!

1957 – situation is changed!

- **P** and **C** violation
- **V-A** structure of weak interaction
- **Helicity** of $\nu(\tilde{\nu})$ is **~ 100%**

$$\Downarrow$$

$2\beta(0\nu)$-decay is suppressed (if even possible?)

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

Best results in 1966-1975

- $T_{1/2}(0\nu;{}^{76}\mathbf{Ge})$ **> 5·10^{21} y**; Ge(Li) detector, **1973** (E. Fiorini et al.)

- $T_{1/2}(0\nu;{}^{48}\mathbf{Ca})$ **> 2·10^{21} y**; streamer chamber + magnetic field + plastic scint., **1970** (C. Wu et al.)
- $T_{1/2}(0\nu;{}^{82}\mathbf{Se})$ **> 3.1·10^{21} y**; streamer chamber
- + magnetic field + plastic scint., **1975** (C. Wu et al.)

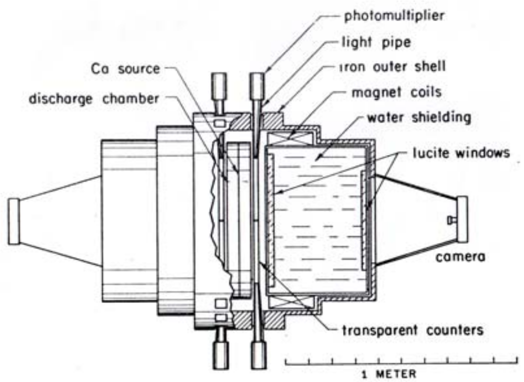
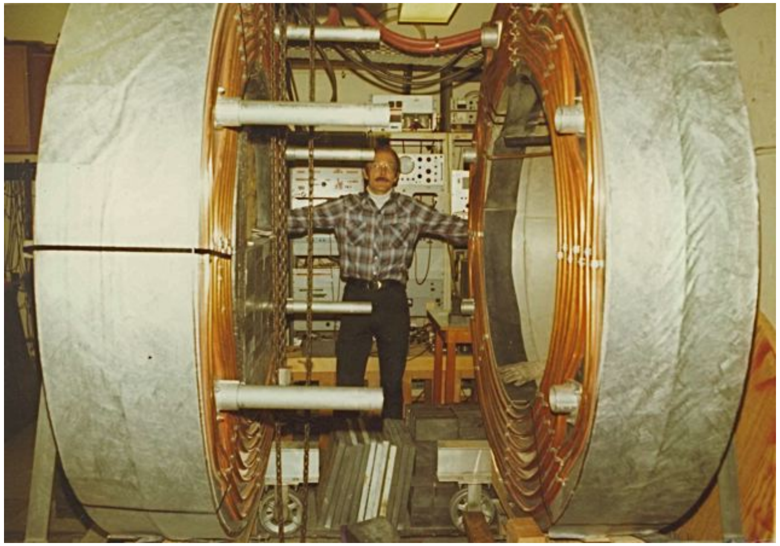


Fig. 3. Cutaway drawing of double beta decay apparatus.

- Geochemical experiments with ^{130}**Te**, ^{128}**Te**, ^{82}**Se** (**2**ν <u>measurements</u>: **~ 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

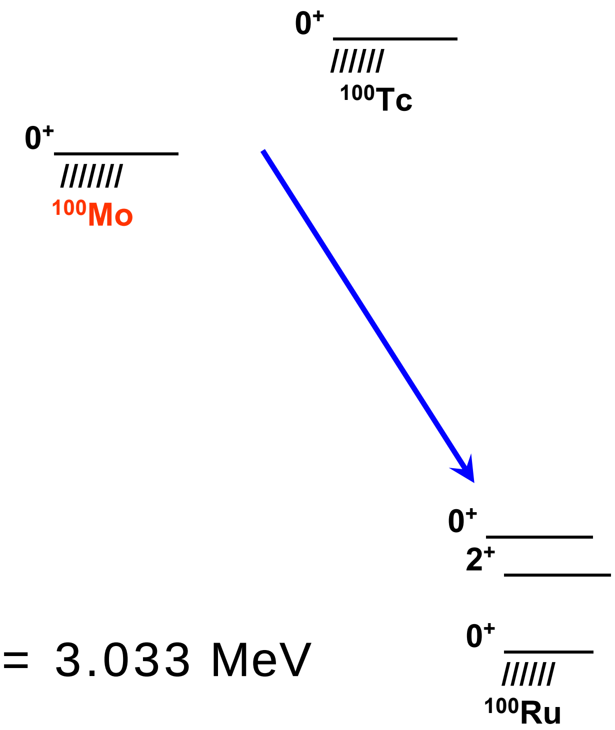
- $T_{1/2}(0\nu;^{76}\mathbf{Ge})$ **> (1.6-1.9)·10^25 y**;
  (HM and IGEX; enriched HPGe detectors)
- $T_{1/2}(0\nu)$ **> 10^{22}-10^{23}** y for ^{136}**Xe**, ^{82}**Se**, ^{116}**Cd**, ^{100}**Mo**
- **2ν**-decay was detected for many nuclei (TPC, ELEGANT-V, NEMO-2, HM, IGEX, Solotvino, Liq. Ar....) + transition to the 0^+ excited states (Soudan, Modane, TUNL-ITEP)

II. PRESENT STATUS

- 1. Inrtodution

- 2. Current experiments
  - NEMO-3 and CUORICINO
  - “small-scail” experiments

1. Introduction



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

$^{100}Mo \Rightarrow \; ^{100}Ru + 2e^-$

$^{100}Mo \Rightarrow \; ^{100}Ru + 2e^- + \chi^0 \; (+\chi^0)$

$^{100}Mo \Rightarrow \; ^{100}Ru + 2e^- + 2\nu$

There are 35 candidates for $2\beta^-$-decay

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

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

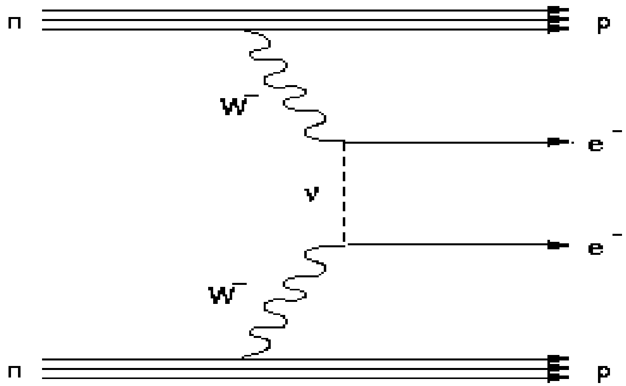
Nuclei	$Q_{2\beta}$, keV	Abundance, %
1. ^{48}Ca	4272	0.187
2. ^{150}Nd	3371.4	5.6
3. ^{96}Zr	3350	2.8
4. ^{100}Mo	3034.4	9.63
5. ^{82}Se	2996	8.73
6. ^{116}Cd	2805	7.49
7. ^{130}Te	2527.5	34.08
8. ^{136}Xe	2458.7	8.87
9. ^{124}Sn	2287	5.79
10. ^{76}Ge	2039.0	7.61
11. ^{110}Pd	2000	11.72

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

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).

- **This information can be obtained in 2β-decay experiments.**

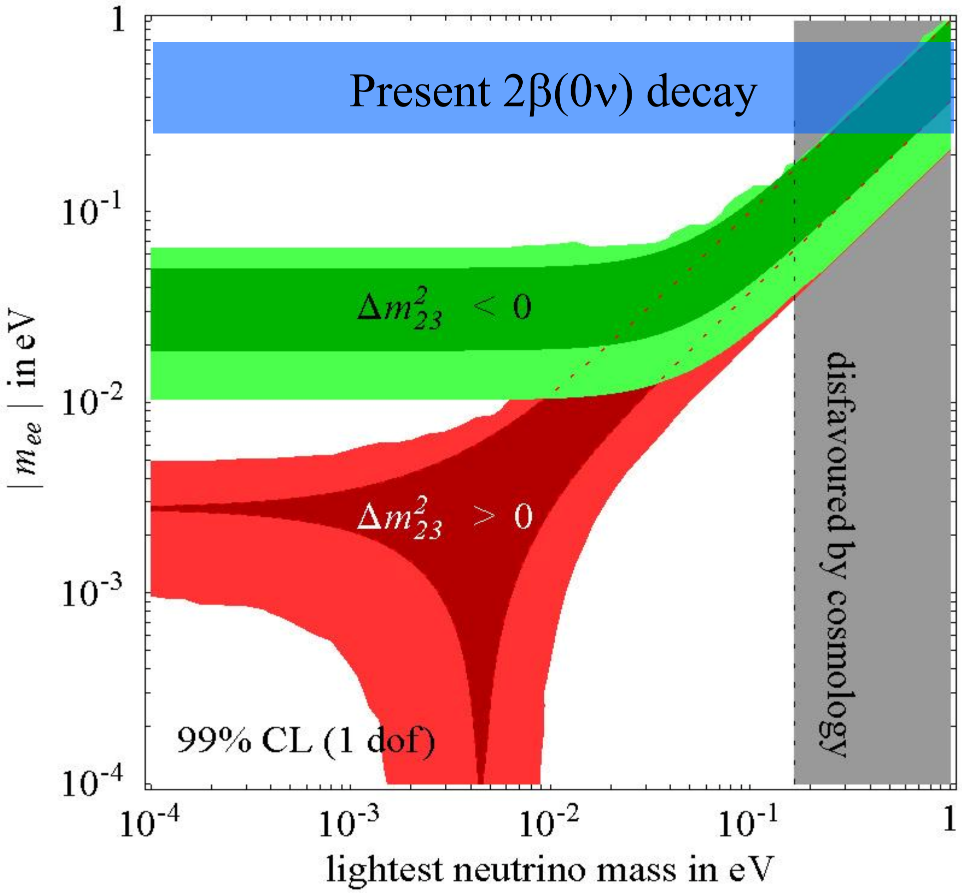
$$<m_\nu> = \left| \sum |U_{ej}|^2 e^{i\phi_j} m_j \right|$$

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.

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)

β: m_ν < 2 eV

2β: $\langle m_\nu \rangle$ < 0.75 eV

Cosmology : Σm_ν < 0.2-0.6 eV

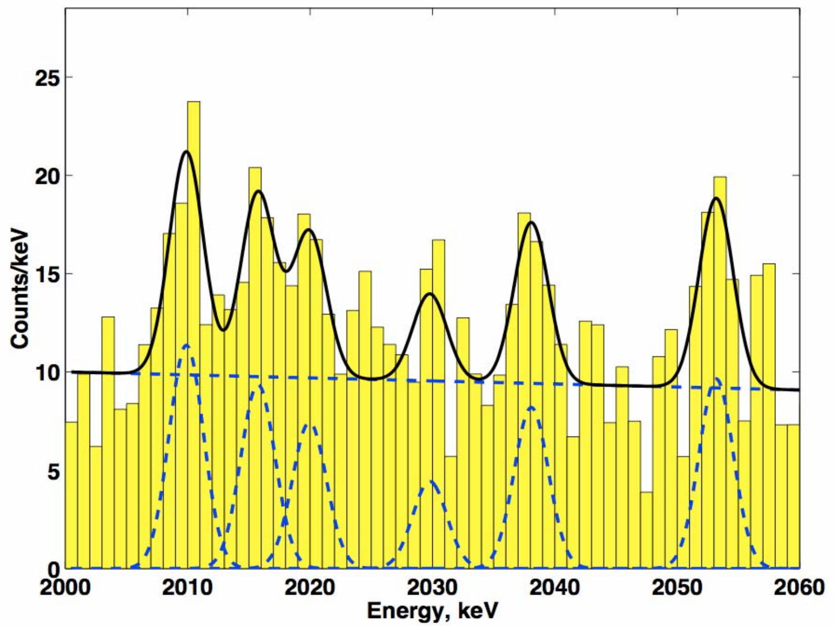
(~ 0.04 eV)

Best present limits on $<m_{\nu}>$

Nuclei	$T_{1/2}$, y	$<m_{\nu}>$, eV QRPA	$<m_{\nu}>$, eV [SM]	Experiment
^{76}Ge	$>1.9\cdot10^{25}$ $\approx1.2\cdot10^{25}$(?) $\approx2.2\cdot10^{25}$(?) $>1.6\cdot10^{25}$	< 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	$>2.8\cdot10^{24}$	< 0.35-0.59	< 0.77	CUORICINO
^{100}Mo	$>1.1\cdot10^{24}$	< 0.45-0.93	-	NEMO
^{136}Xe	$>4.5\cdot10^{23}$	< 1.41-2.67	< 2.2	DAMA
^{82}Se	$>3.6\cdot10^{23}$	< 0.89-1.61	< 2.3	NEMO
^{116}Cd	$>1.7\cdot10^{23}$	< 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

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

$0.24 < m_\nu < 0.58$ eV (± 3 sigma)

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

Mod.Phys.Lett. A21(2006)1547

Old data, new pulse shape anal.

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

$m_\nu = 0.32 \pm 0.03$ **eV**

n = 11±1.8 events ⇒

where is a statistical error?!

non-correct peak position?!

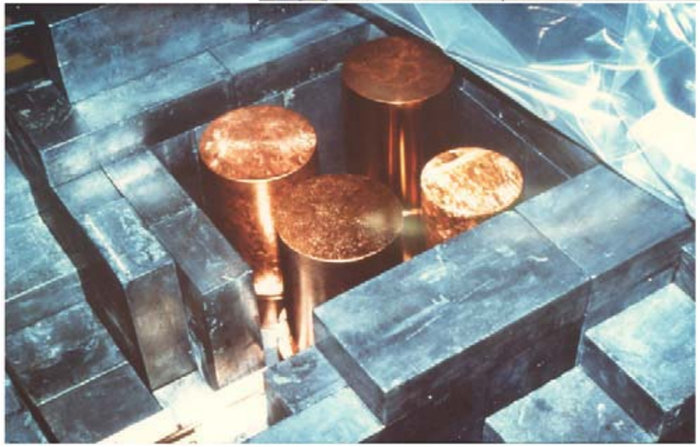
There are some problems with this result:

1) Only one measurement.
2) Only ~4σ level (independent analysis gives even ~ 2.7σ).
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.
7) Chkvorets'08 – 1.3σ

"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.

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

Recommended values for half-lives:

- ^{48}Ca - $(4.4^{+0.6}_{-0.5})\cdot10^{19}$ y
- ^{76}Ge – $(1.5 \pm 0.1)\cdot10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot10^{20}$ y
- ^{96}Zr – $(2.3 \pm 0.2)\cdot10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) – $(5.9^{+0.8}_{-0.6})\cdot10^{20}$ y
- ^{116}Cd – $(2.8 \pm 0.2)\cdot10^{19}$ y
- ^{128}Te(geo) – $(1.9 \pm 0.4)\cdot10^{24}$ y

  ^{130}Te – $(6.8^{+1.2}_{-1.1})\cdot10^{20}$ y
- ^{150}Nd - $(8.2 \pm 0.9)\cdot10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.33^{+0.45}_{-0.26})\cdot10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot10^{21}$ y

ECEC(2ν):

- ^{130}Ba(geo) - $(2.2 \pm 0.5)\cdot10^{21}$ y

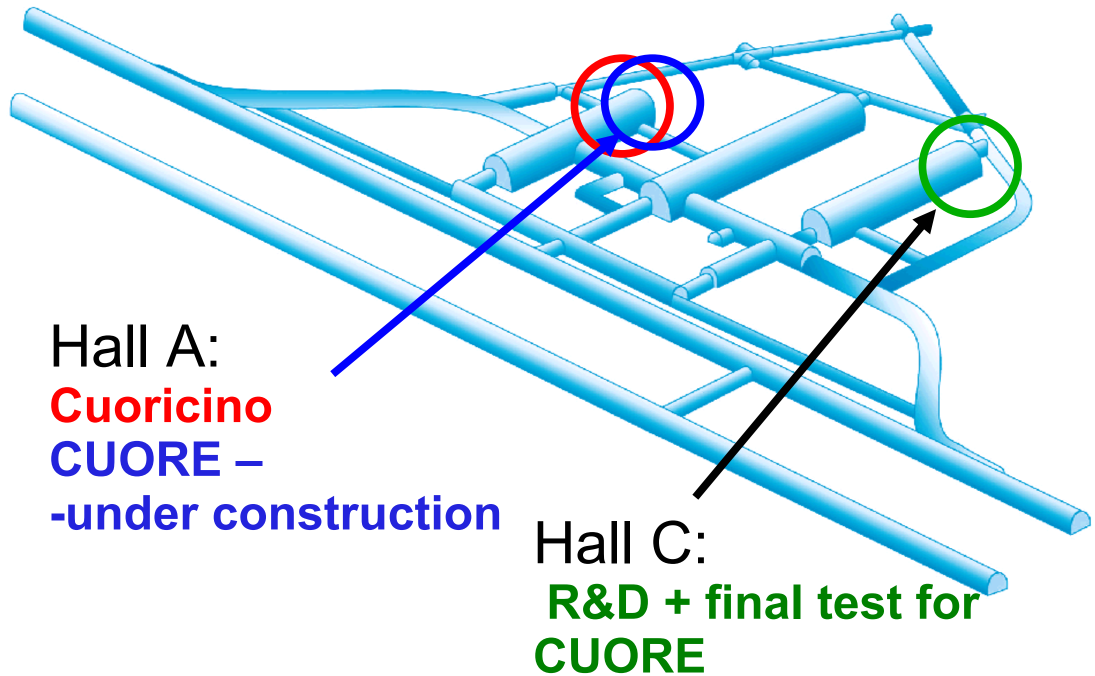
[A.S.B. Phys. Rev. C 81 (2010) 035501]

2. CURRENT EXPERIMENTS

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

CUORICINO

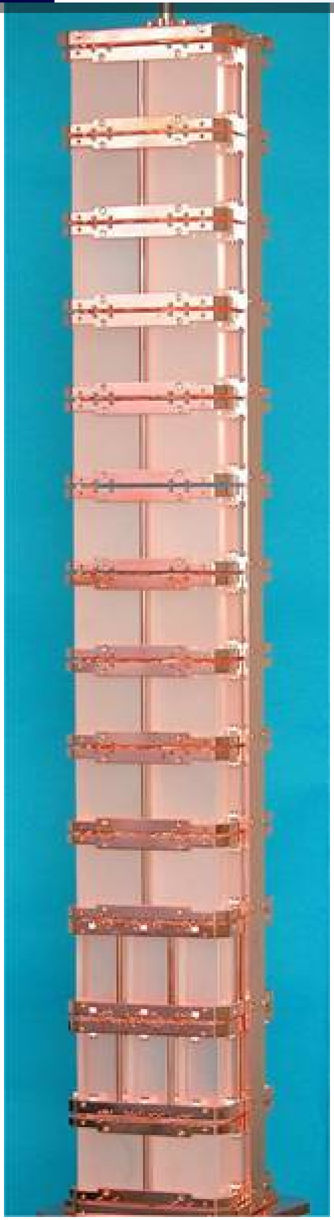
INFN - Laboratori Nazionali del Gran Sasso - L'Aquila – Italy



3200 m.w.e overburden - cosmic rays are no more a bkg problem

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

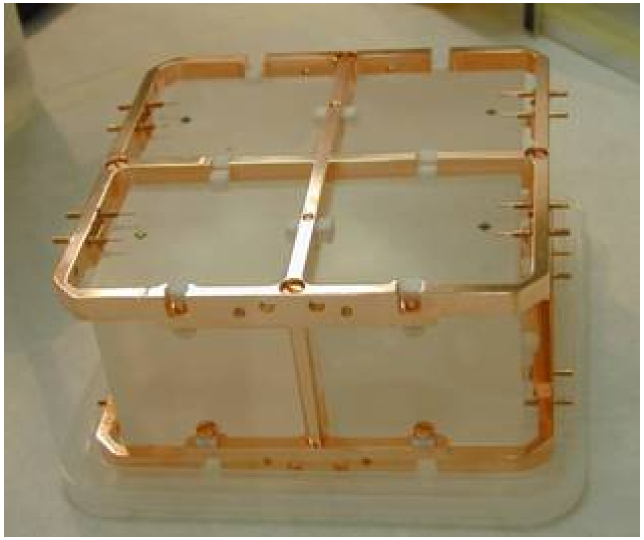
Cuoricino

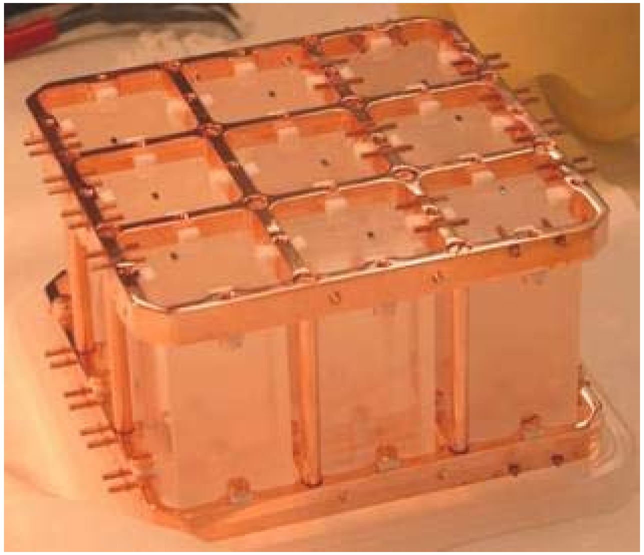


11 modules
4 detectors each
Dimension: 5x5x5 cm^3
Mass: 790 g

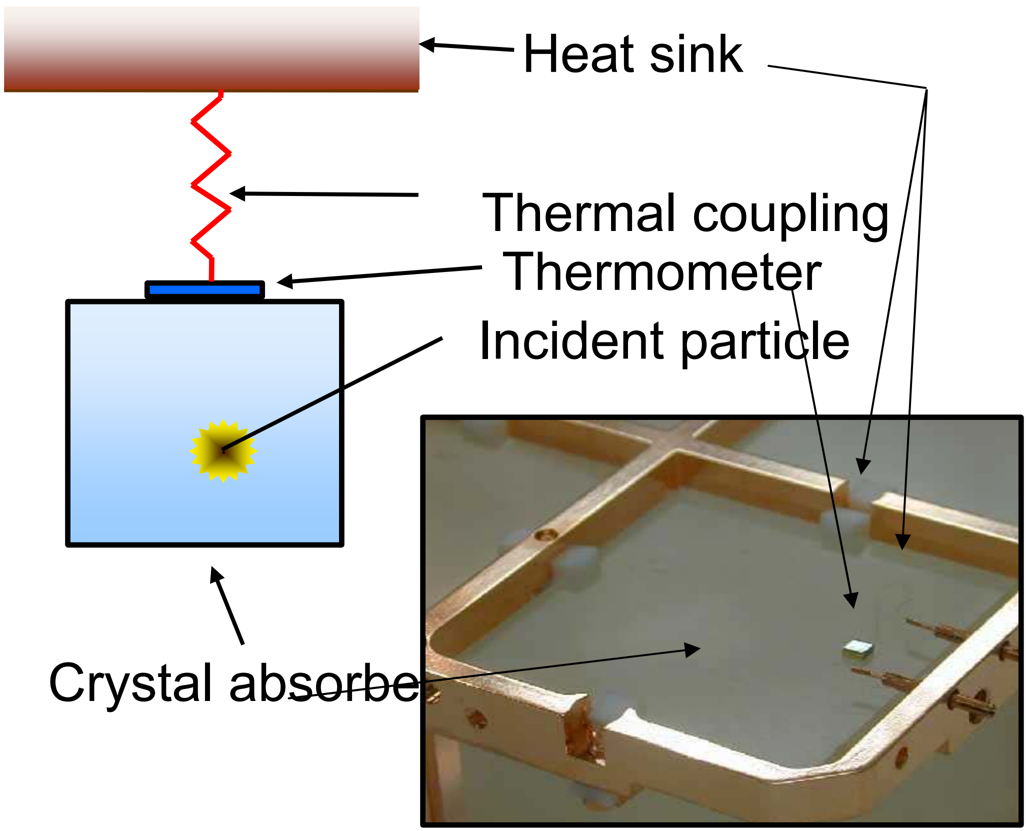
Total mass
40.7 kg
(~11 kg of ^{130}Te)

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. $T \ll 1K$)

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

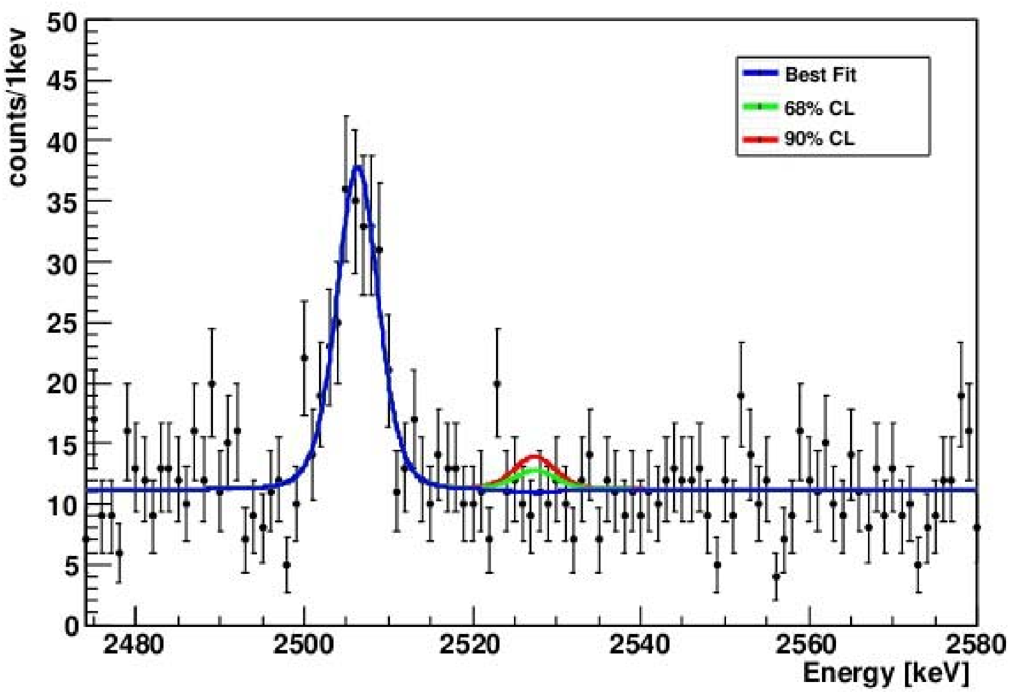
wide choice of absorber materials

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**-*0***n** *region*

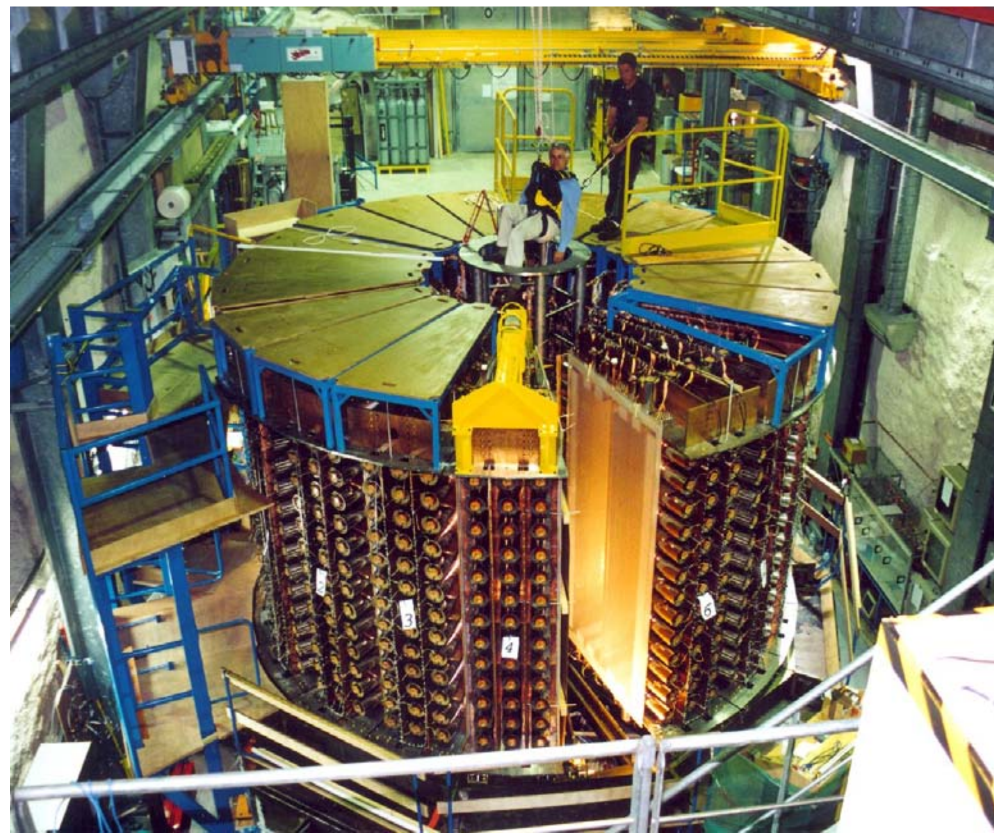
$$\tau^{0\nu}_{1/2} \geq 2.8 \cdot 10^{24}\, y\, (90\%\ CL) \quad \Rightarrow \quad \langle m_\nu \rangle \leq 0.3 - 0.7\ eV \quad (90\%\ CL)$$

[Experiment is stopped in July 2008]

NEMO-3 Collaboration

(Neutrino Ettore Majorana Observatory)

60 physicists, 17 labs



Laboratoire Souterrain de Modane

LABORATOIRE SOUTERRAIN DE MODANE

COMMISSARIAT À L'ÉNERGIE ATOMIQUE

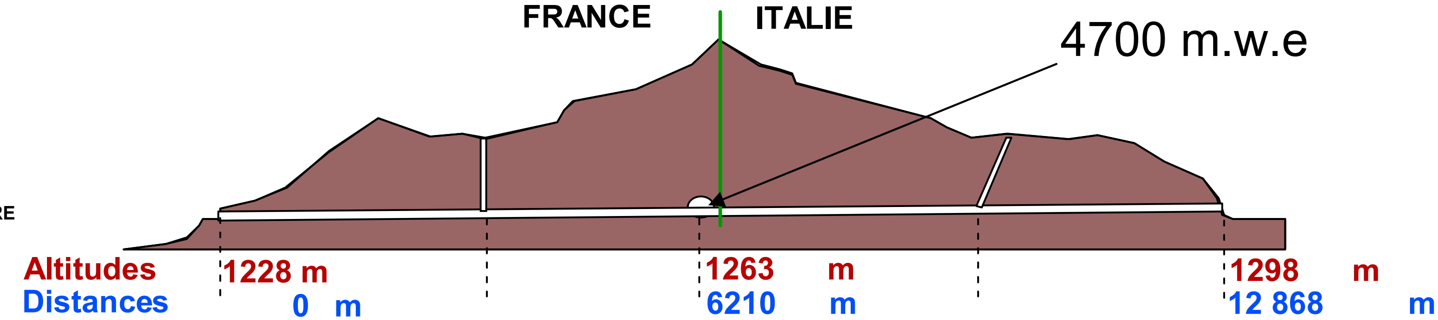
DSM

DIRECTION DES SCIENCES DE LA MATIÈRE

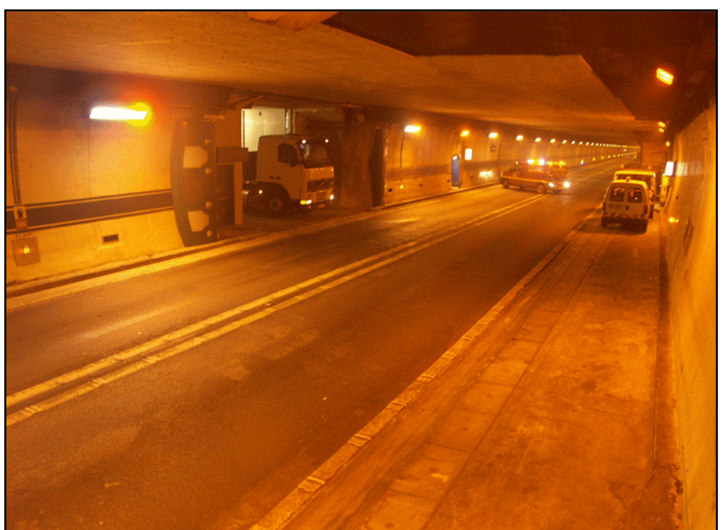
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

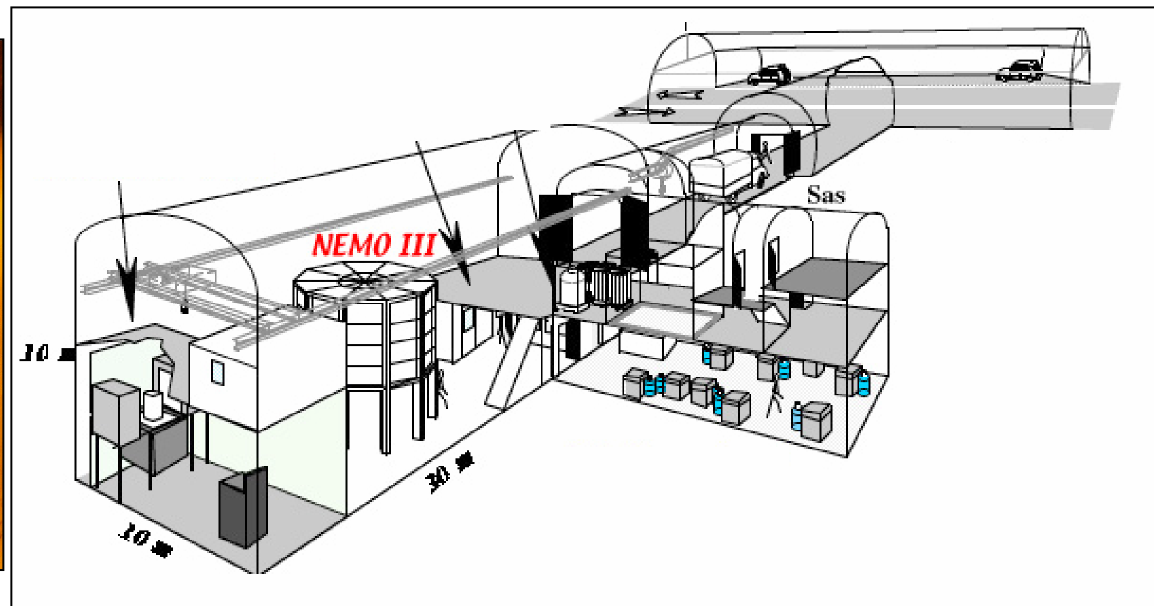
IN2P3

INSTITUT NATIONAL DE PHYSIQUE NUCLÉAIRE ET DE PHYSIQUE DES PARTICULES



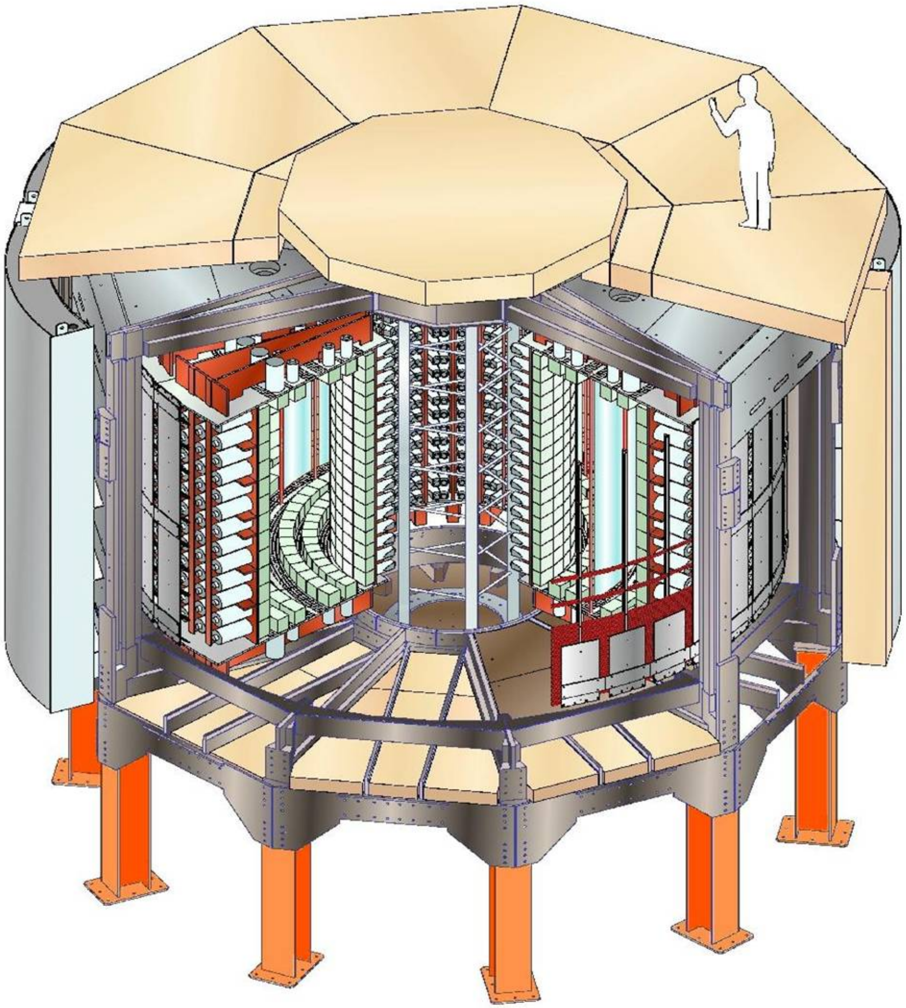
Built for Taup experiment (proton decay) in 1981-1982





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

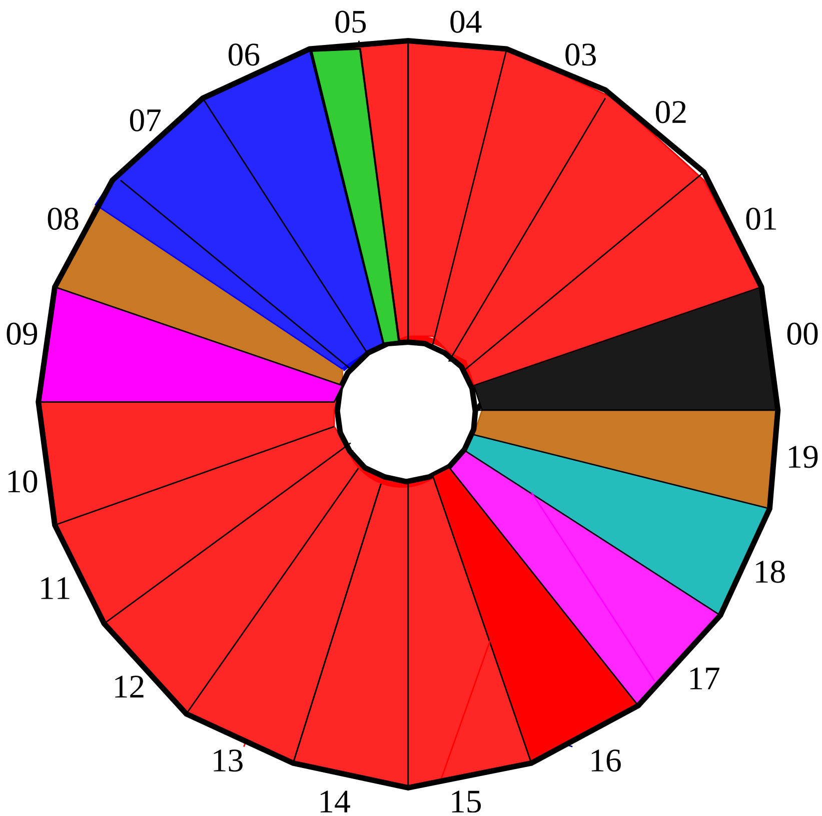
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

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

ββ decay isotopes in NEMO-3 detector



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

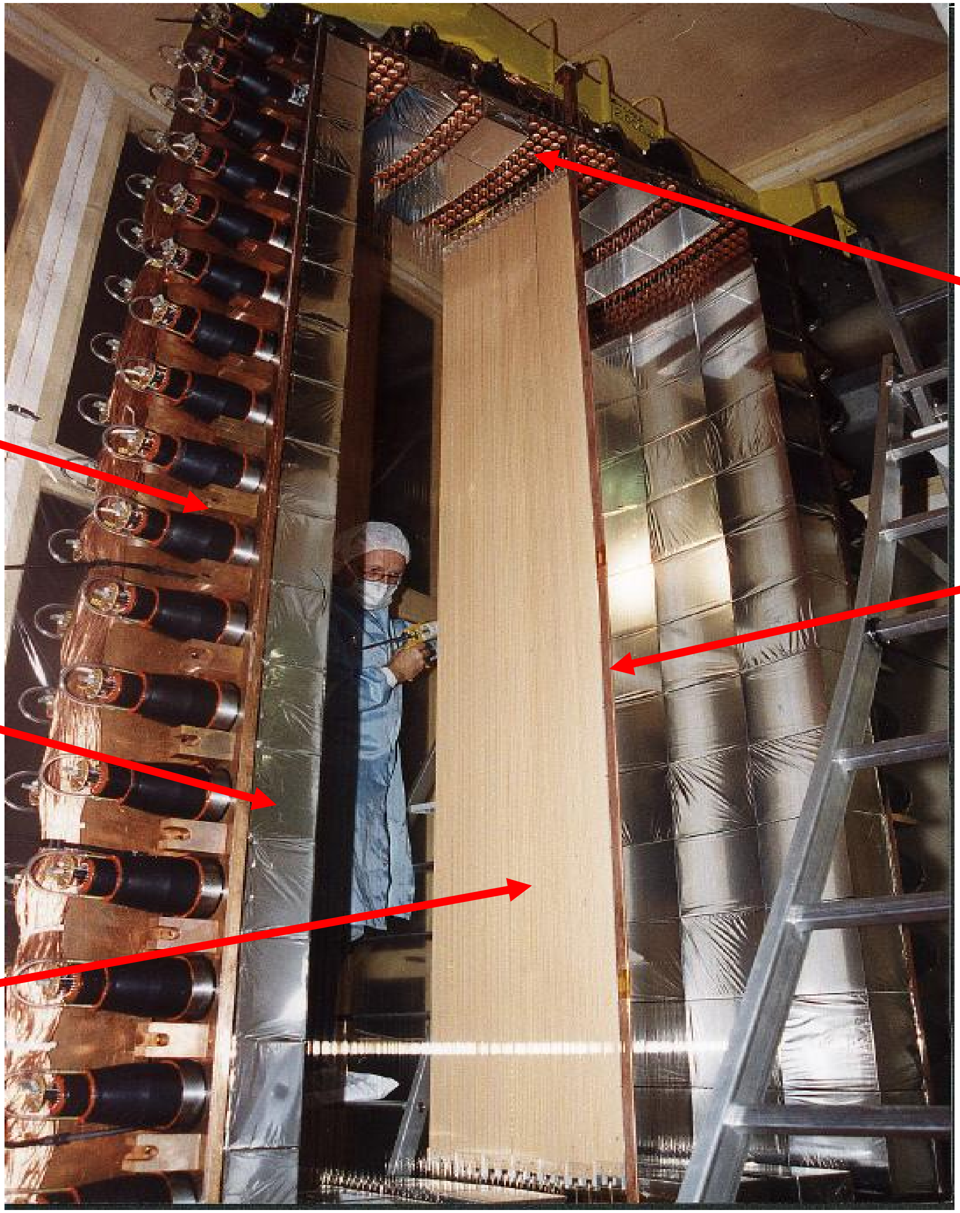
^{100}Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

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

ββ0ν search

(All enriched isotopes produced in Russia)

Sector interior view



PMT

scintillators

ββ isotope foils

cathode rings
wire chamber

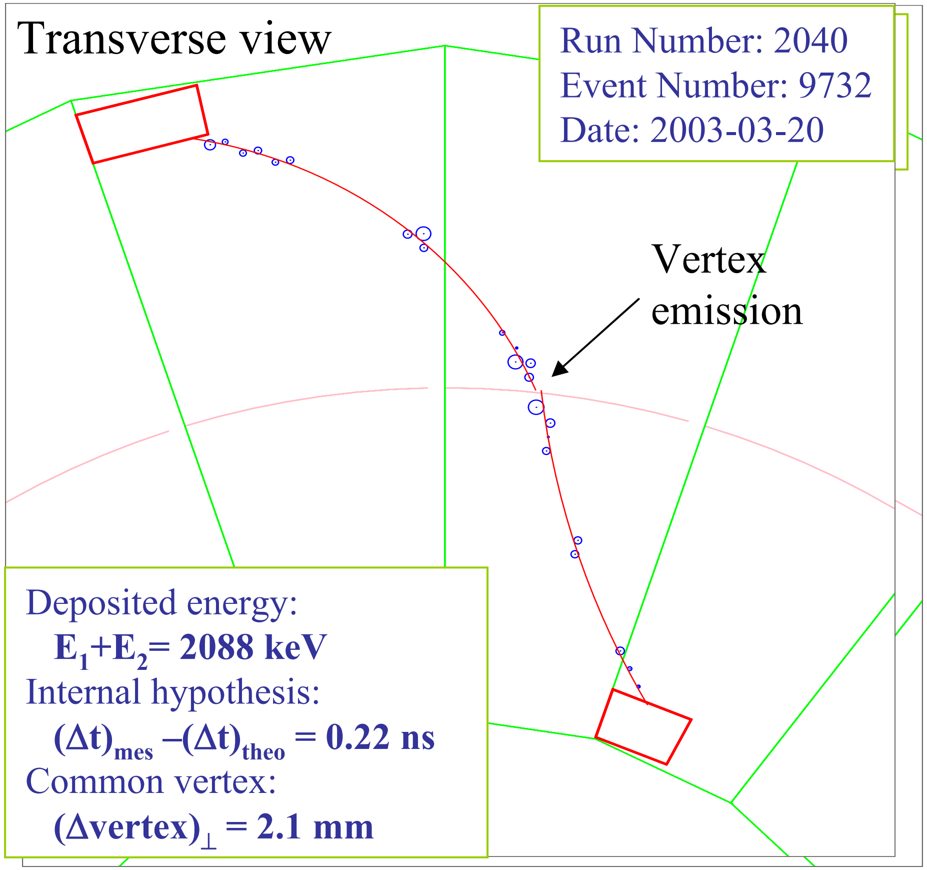
calibration tube

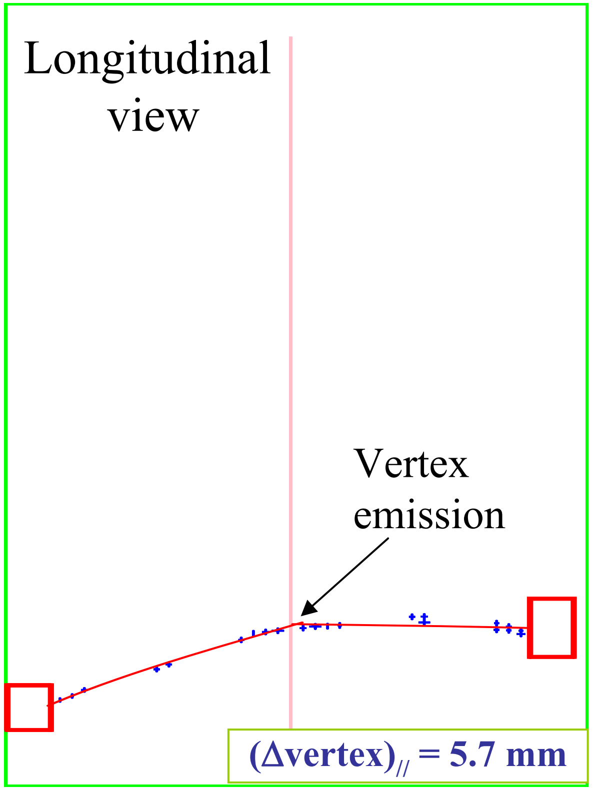
Calibration source

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

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





Trigger: at least 1 PMT > 150 keV

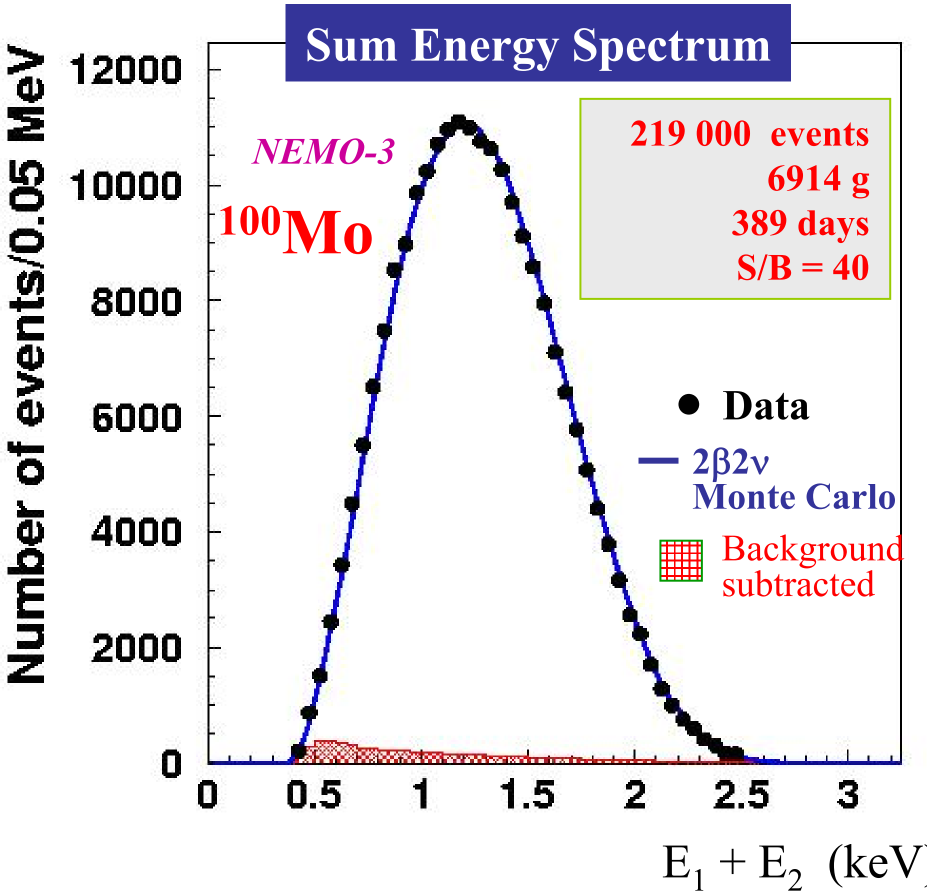
≥ 3 Geiger hits (2 neighbour layers + 1)

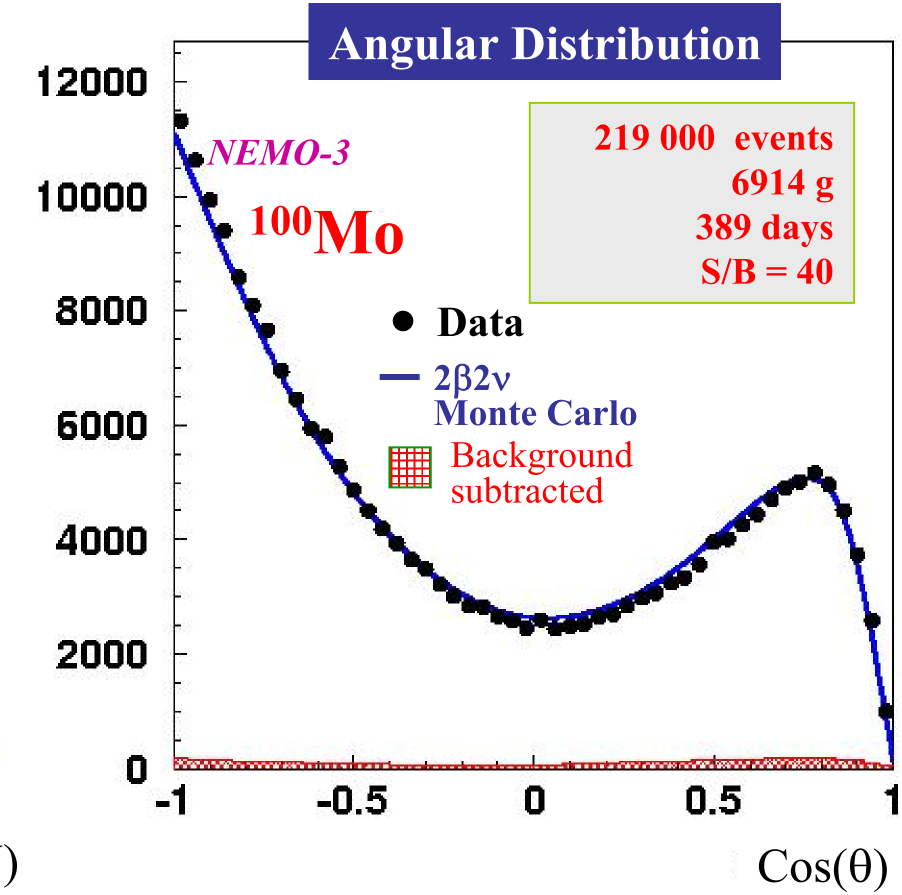
Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo 2β2ν preliminary results

(Data Feb. 2003 – Dec. 2004)



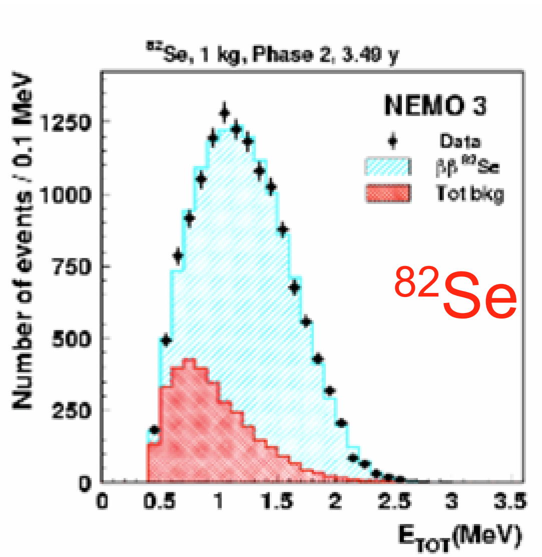


7.37 kg.y

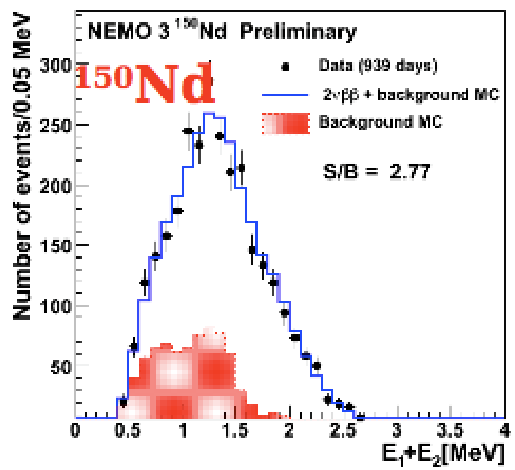
$T_{1/2} = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

Phys. Rev. Lett. 95 (2005) 182302

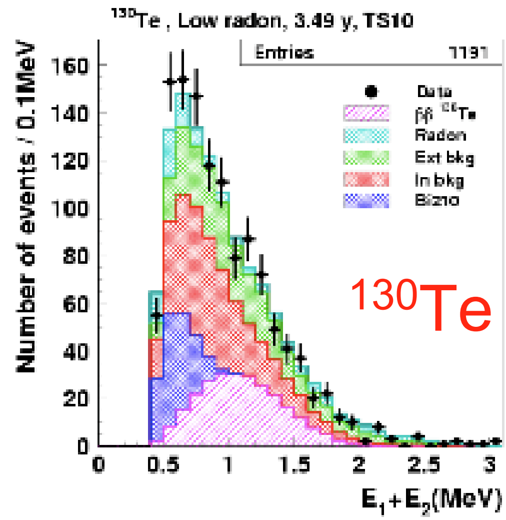
$2\nu\beta\beta$ results for other isotopes



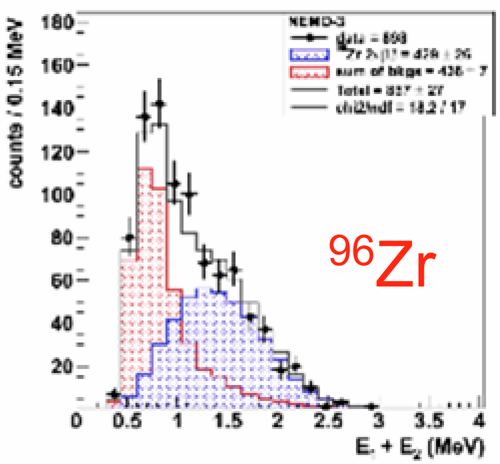
[9.6±0.1(stat)±1.0(sys)]×10^{19} yr
$M^{2\nu}$=0.049±0.004



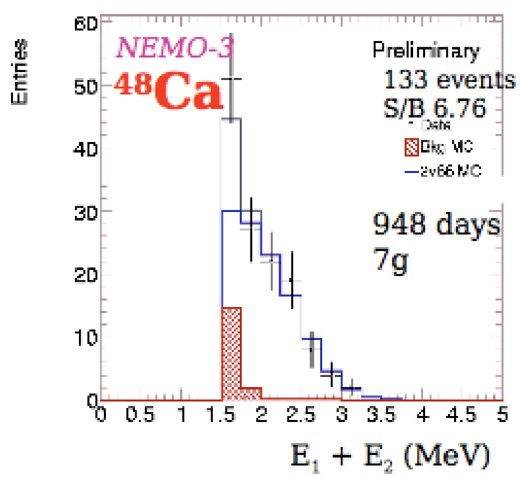
[9.11±0.25(stat)±0.63(sys)]×10^{18} yr
$M^{2\nu}$=0.030±0.002



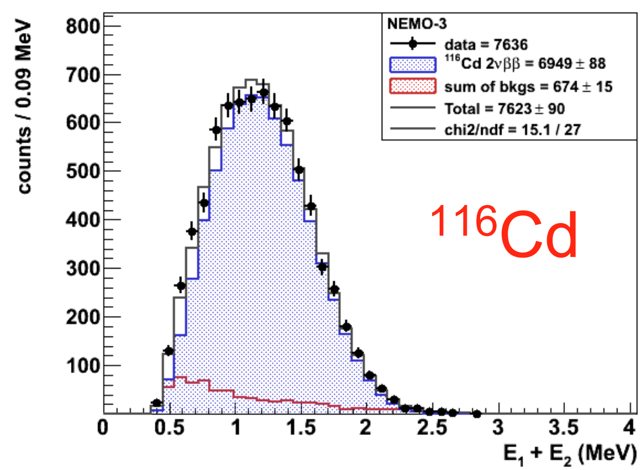
[$7.0^{+1.0}_{-0.8}$(stat) $^{+1.1}_{-0.9}$(sys)]×10^{20} yr
$M^{2\nu}$=0.0173±0.0025



[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



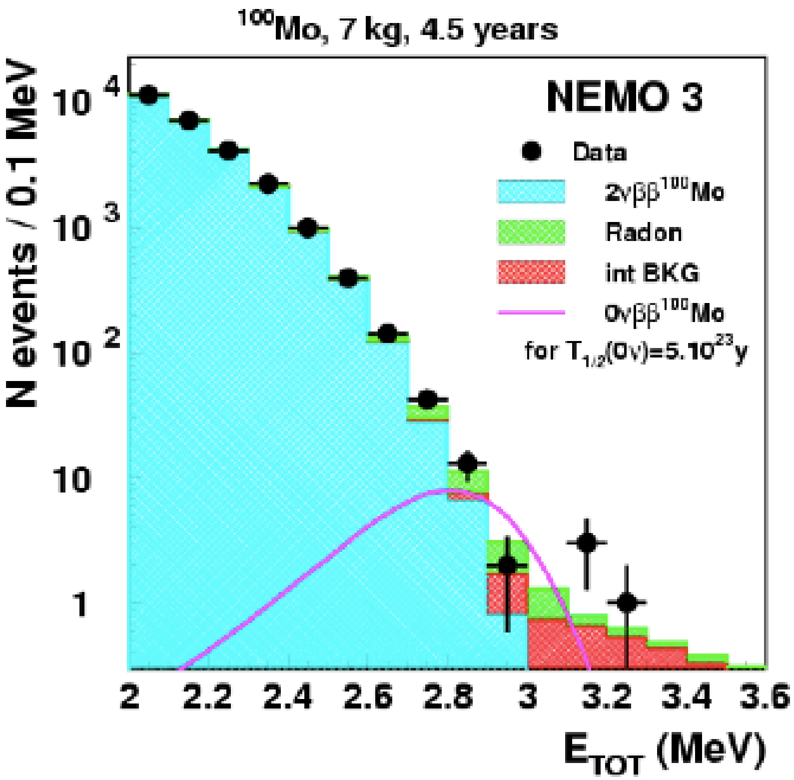
[2.88±0.04(stat)±0.16(sys)]×10^{19} yr
$M^{2\nu}$=0.0685±0.0025

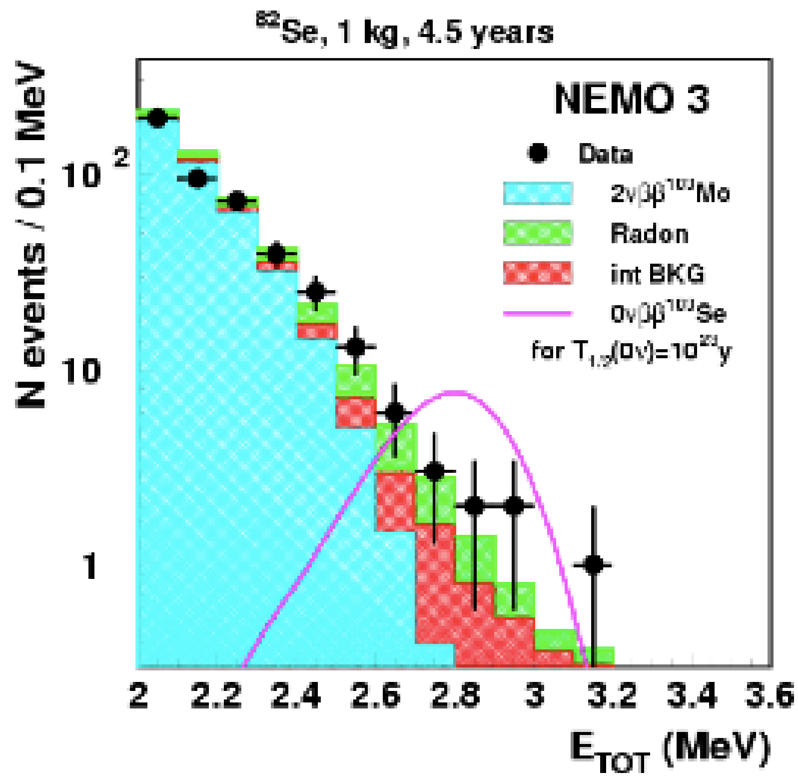
Summary of $2\nu\beta\beta$ results

Isotope	S/B	$(2\nu\beta\beta)$, y
^{100}Mo	40	$(7.11 \pm 0.02(stat)\pm0.54(syst))\cdot10^{18}$ (SSD favoured) *
$^{100}Mo(0^+_1)$	3	$(5.7^{+1.3}_{-0.9}(stat))\pm0.8(syst))\cdot10^{20}$ ** [NPA 781 (2006) 209]
^{82}Se	4	$(9.6\pm 0.3(stat)\pm1.0(syst))\cdot10^{19}$ *
^{116}Cd	7.5	$(2.88\pm 0.04(stat)\pm0.16(syst))\cdot10^{19}$ ***
^{130}Te	0.35	$(7.0^{+1.0}_{-0.8}(stat)\ ^{+1.1}_{-0.9}(syst))\cdot10^{20}$ ***
^{150}Nd	2.8	$(9.11^{+0.25}_{-0.22}(stat)\pm0.63(syst))\cdot10^{18}$ *** [PRC 80 (2009) 032501R]
^{96}Zr	1.0	$(2.35\pm 0.14(stat)\pm0.16(syst))\cdot10^{19}$ *** [NPA 847 (2010) 168]
^{48}Ca	6.8	$(4.4^{+0.5}_{-0.4}(stat)\pm0.4(syst))\cdot10^{19}$ ***

* 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.

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

- 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	$\langle m_\nu \rangle$, eV [NME ref.]
^{100}Mo	31	$> 1 \cdot 10^{24}$	< 0.47 – 0.96 [1-3]
^{82}Se	4.2	$> 3.2 \cdot 10^{23}$	< 0.9 – 1.6 [1-3]; < 2.5 [7]
^{150}Nd	0.095	$> 1.8 \cdot 10^{22}$	< 1.7 – 2.4 [4,5] ;< 4.8 – 7.6 [6]
^{130}Te	1.4	$> 9.8 \cdot 10^{22}$	< 1.6 – 3.1 [2,3]
^{96}Zr	0.031	$> 9.2 \cdot 10^{21}$	< 7.2 – 19.5 [2,3]
^{48}Ca	0.017	$> 1.3 \cdot 10^{22}$	< 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

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)

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	$\langle m_\nu \rangle$, 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	$2 \cdot 10^{26}$ $6 \cdot 10^{27}$	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

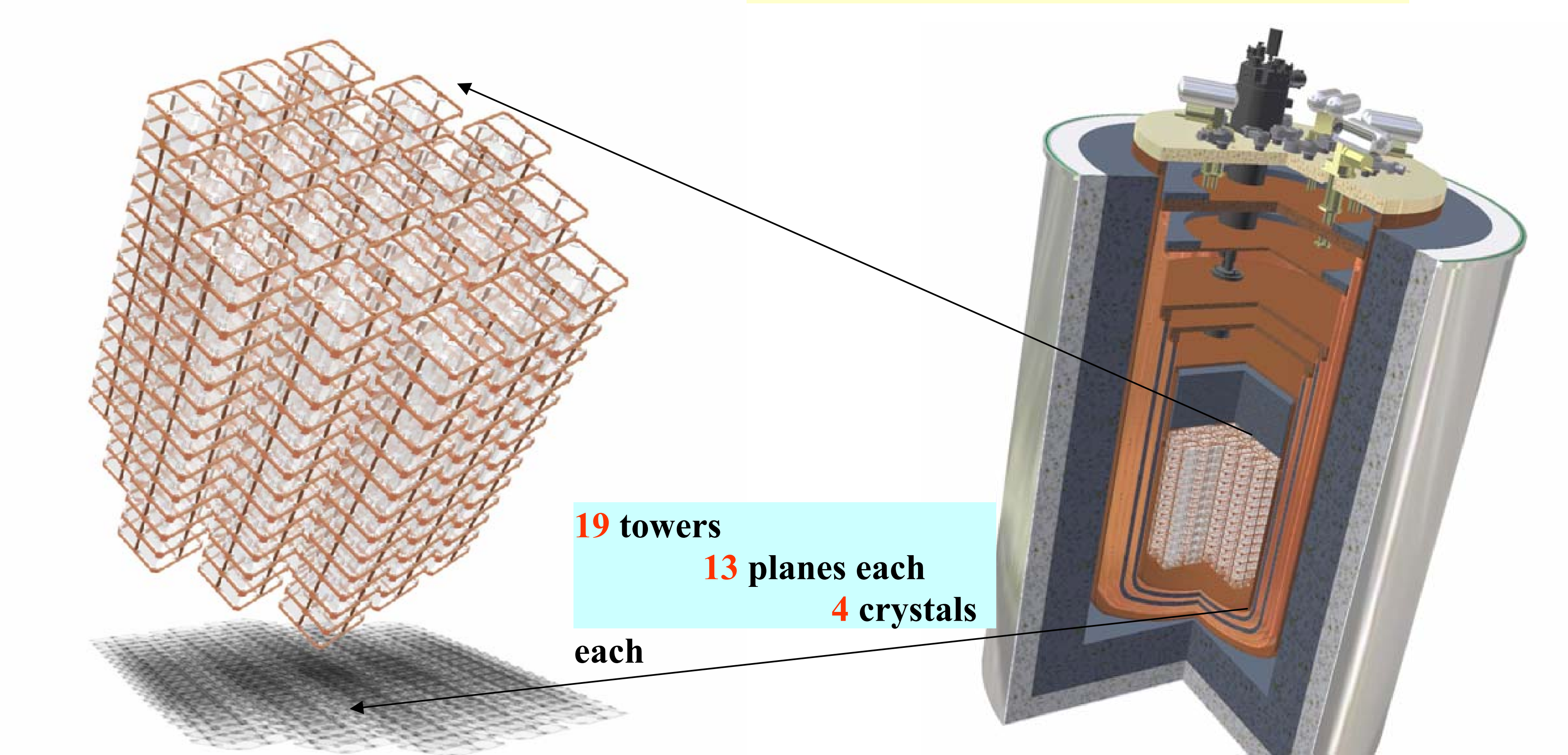
Cryogenic Underground Observatory for Rare Events

- 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



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

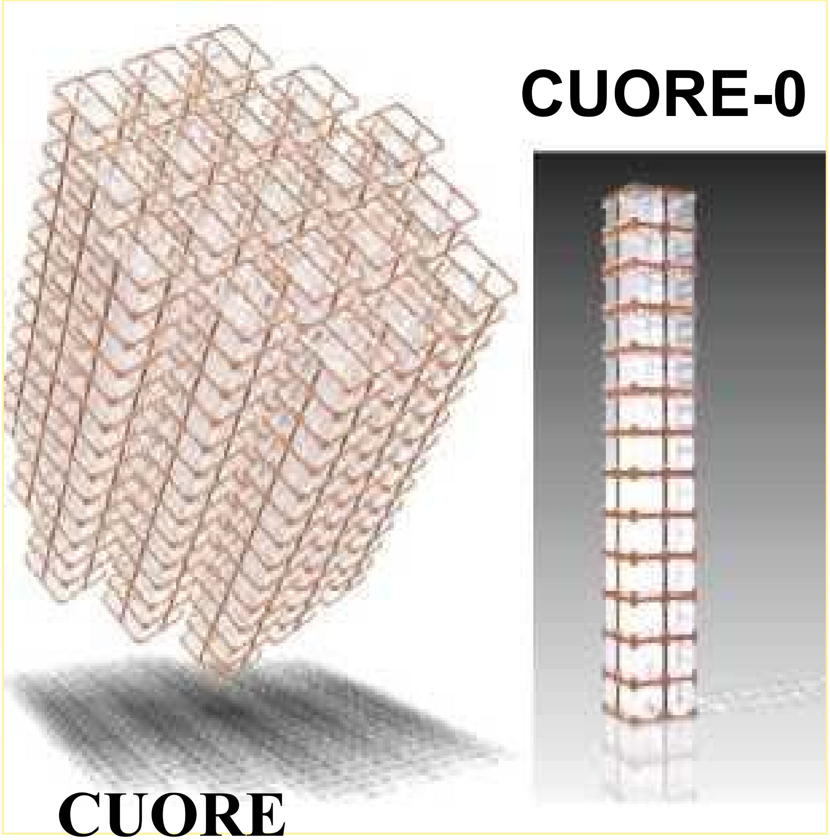
High statistics test of the many improvements/changes developped for the CUORE assembly procedure:

- 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**

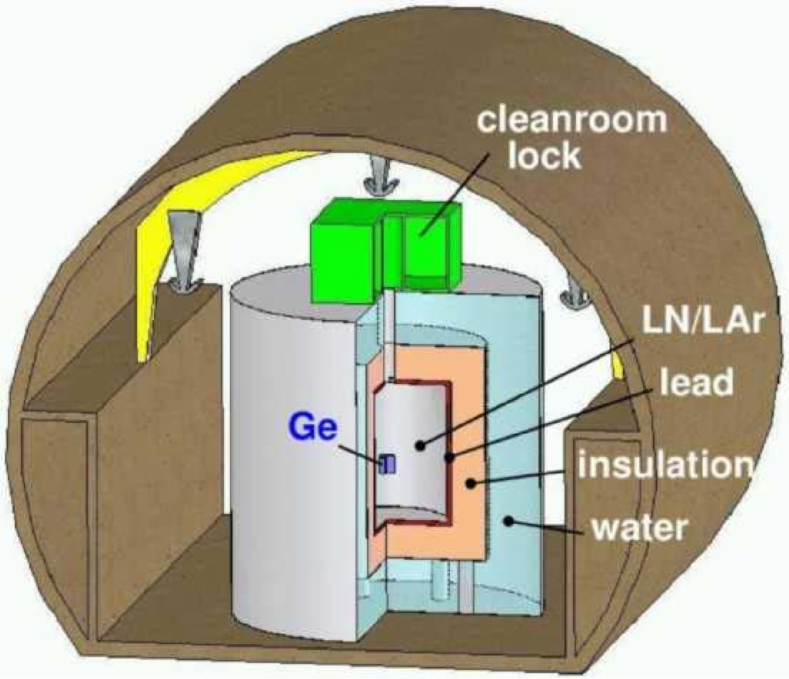
- "Optimistic":

  B = 0.001 /keV·kg·y; ΔE = 5 keV

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

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)

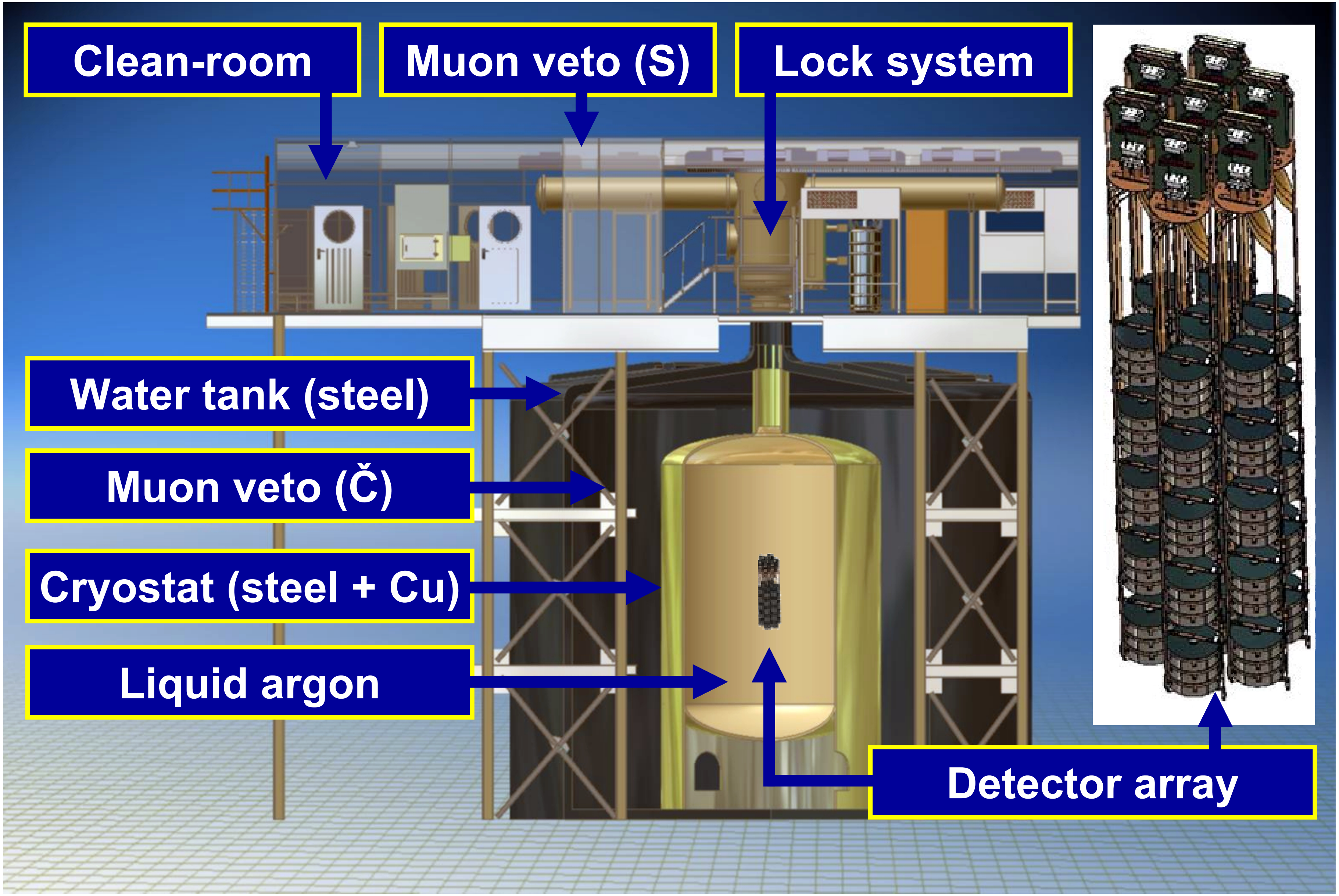
- Background: 0.001 counts / keV kg y
- Sensitivity after 100 kg y (~3 years): 2×10^{26} y ($\langle m_\nu$ < 70 - 200 meV)

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

~ 1 ton experiment in world wide collaboration with MAJORANA

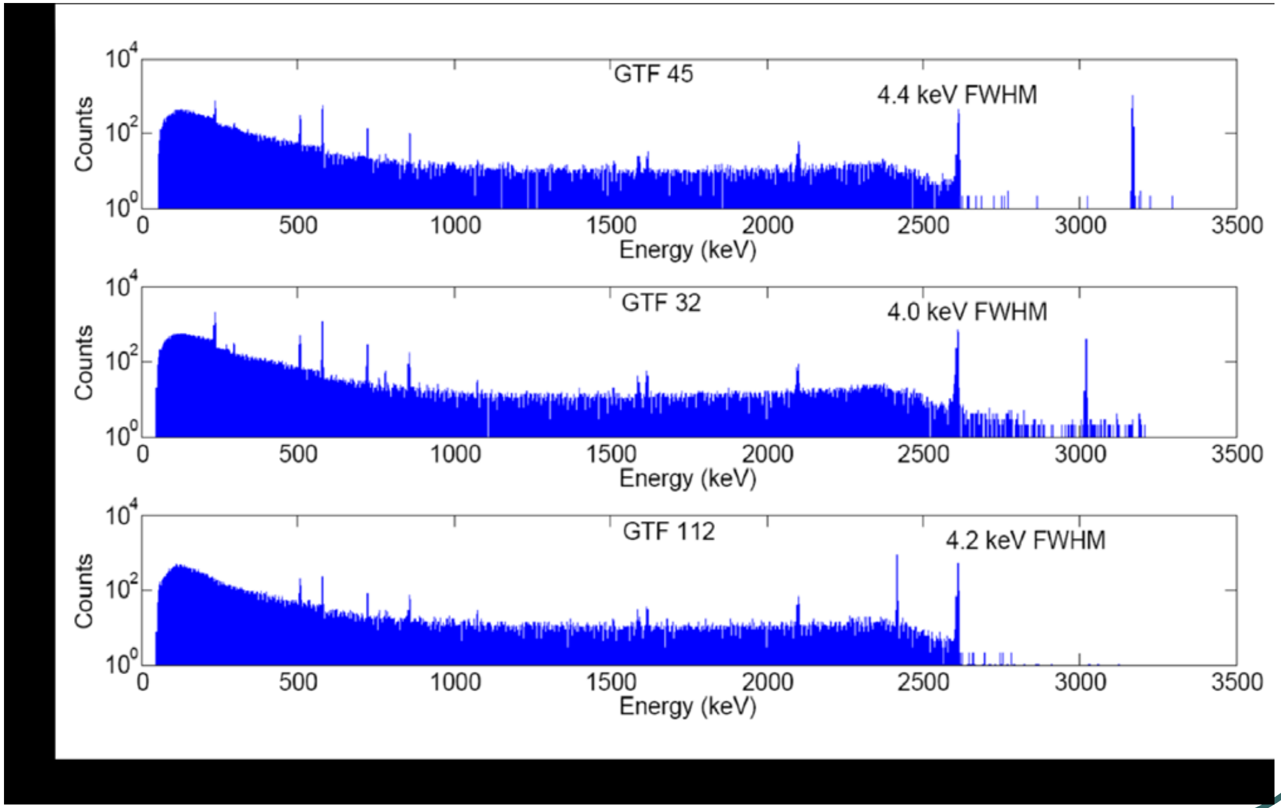
$\langle m_\nu \rangle < 10 - 40$ meV

GERDA: Technical realization

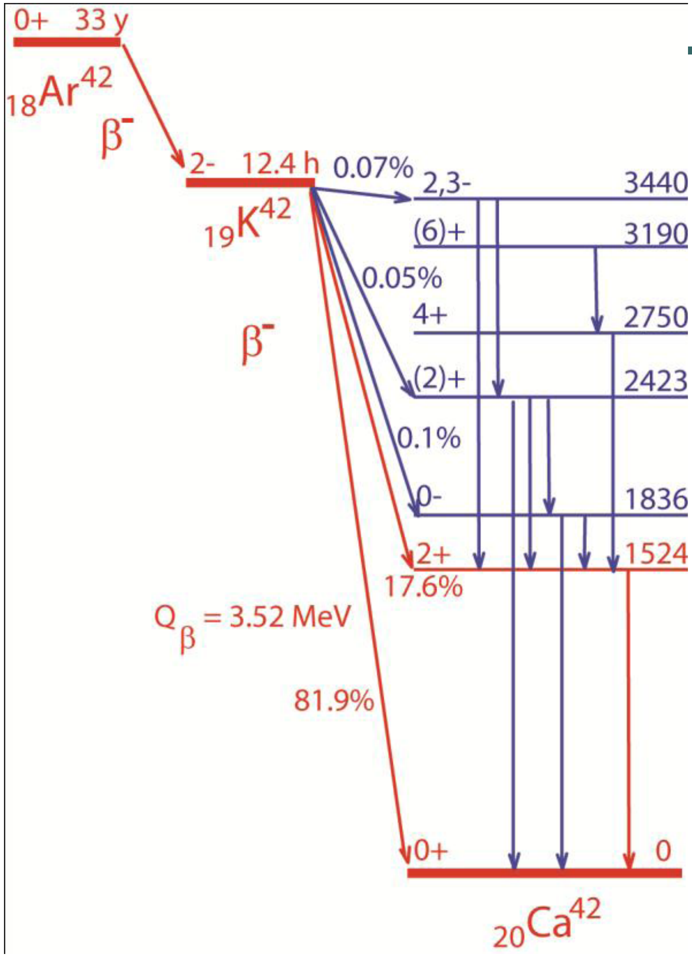


Operation of the 3 ^{nat}Ge detectors

Calibration by ^{232}Th source



^{42}Ar background problem



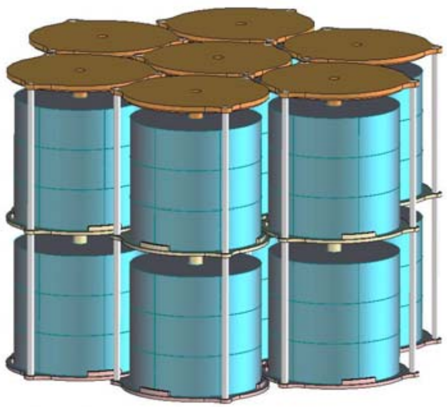
A.S. Barabash et al.,
NIM A 416 (1998) 179
$^{42}Ar / ^{40}Ar < 6 \cdot 10^{-21}$ (90 % CL)

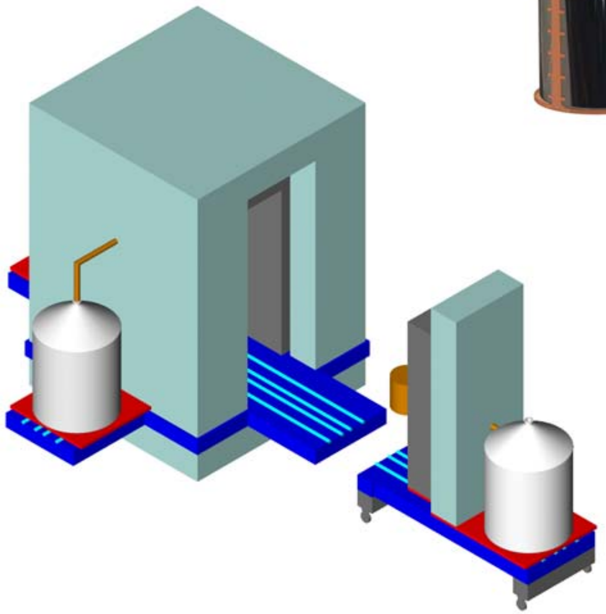
More then 10 times higher activity in GERDA???

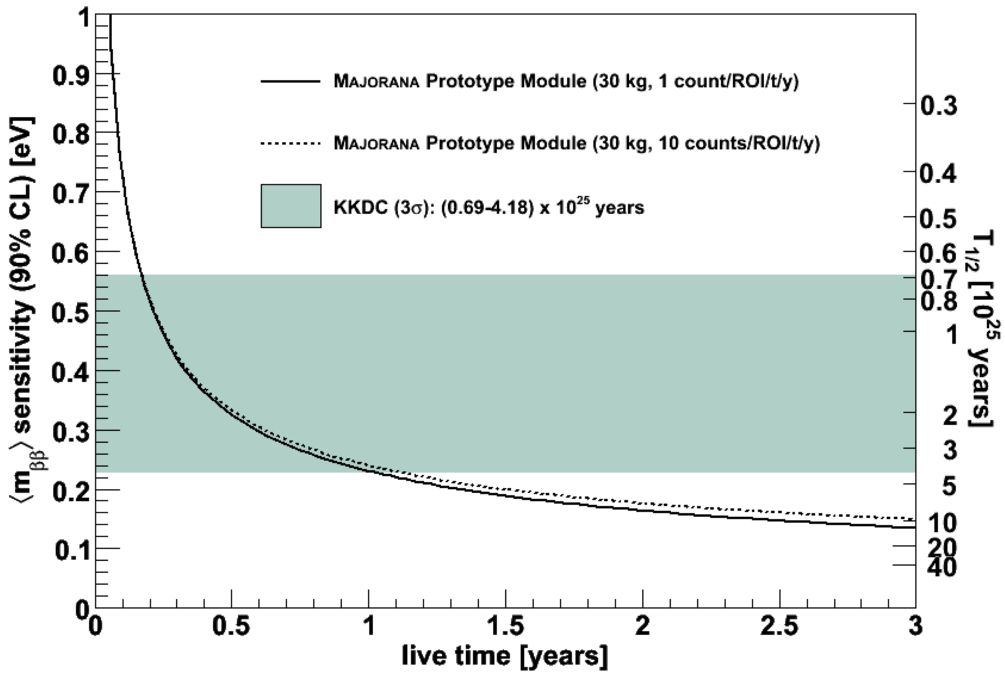
⇓

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.

MAJORANA Project

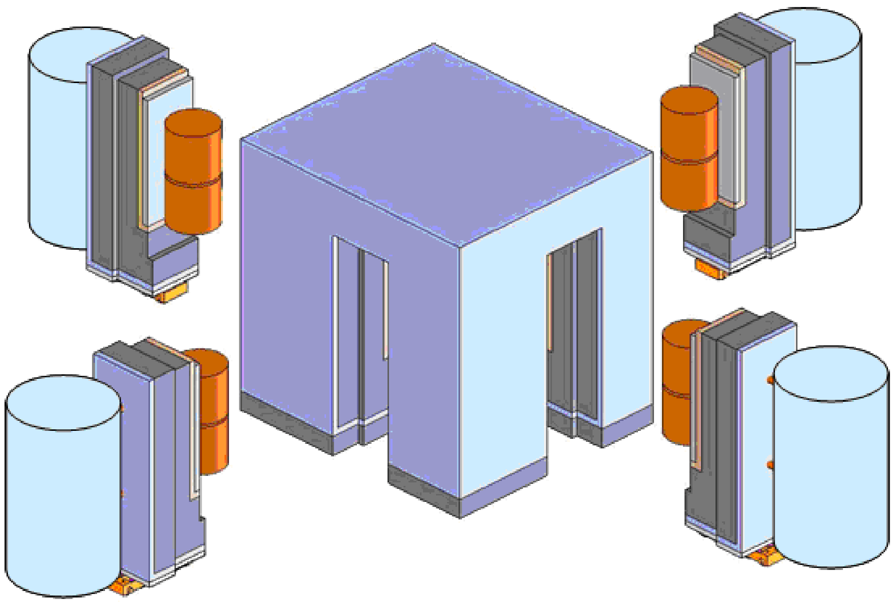




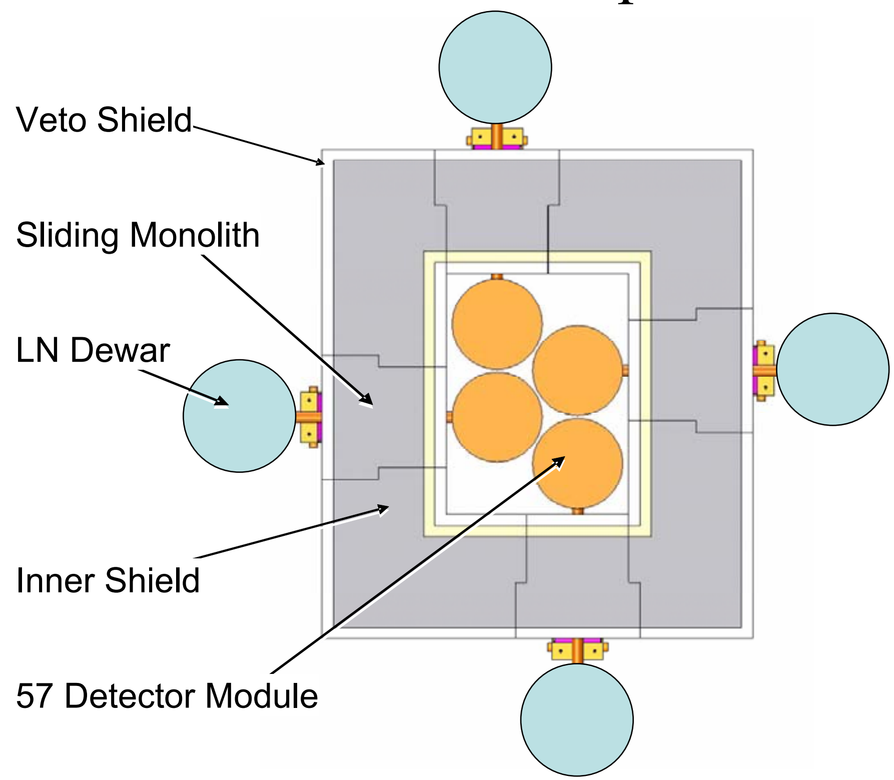


The Majorana Shield - Conceptual Design

- 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



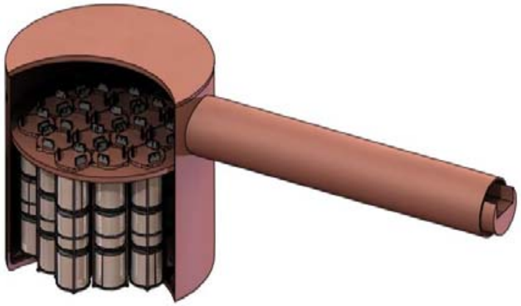
Top view



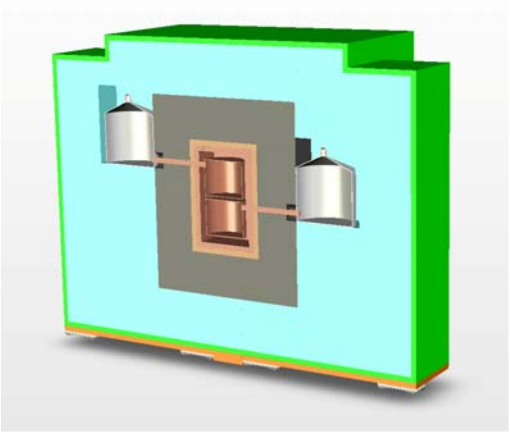
The MAJORANA DEMONSTRATOR Module

^{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.**

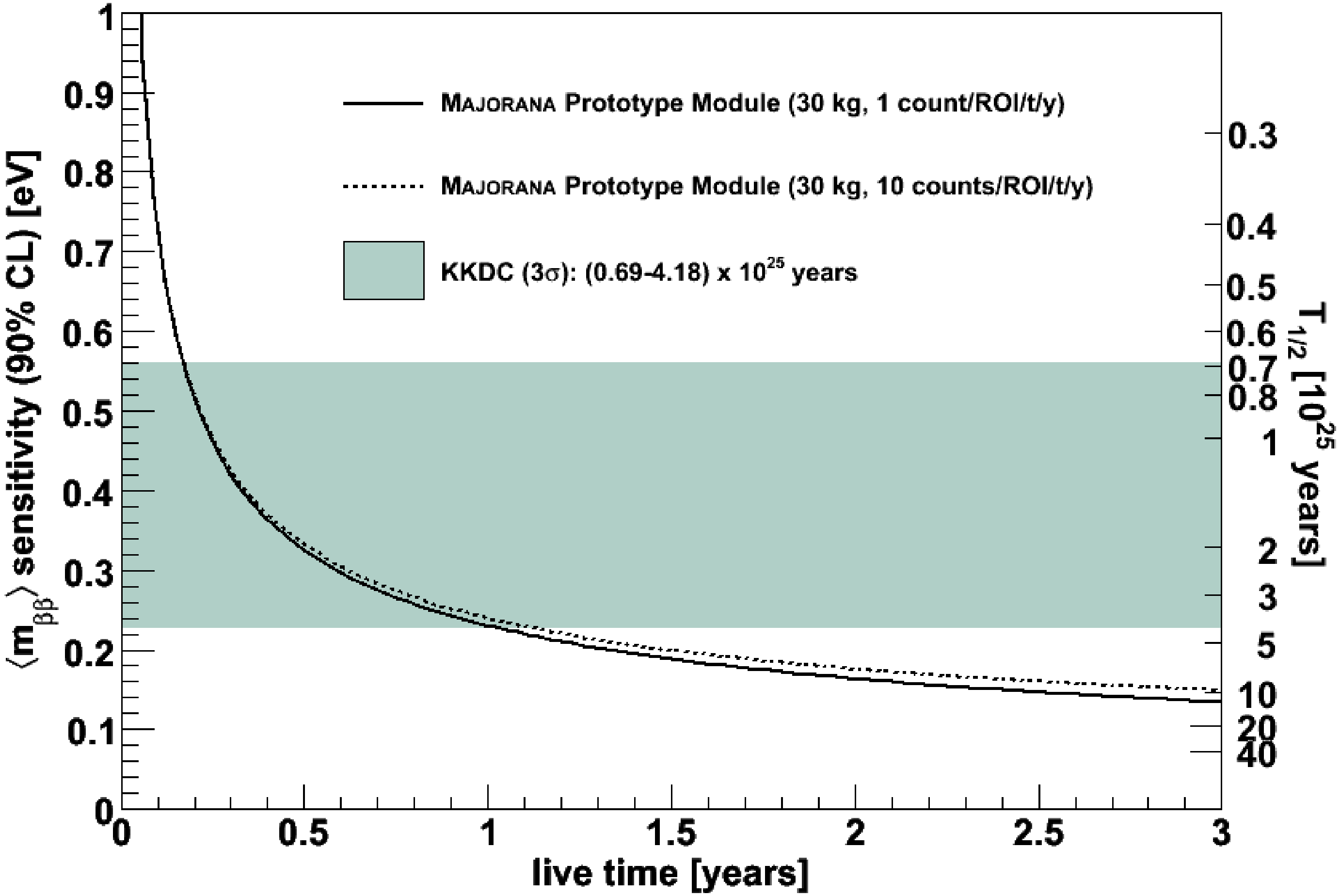


MAJORANA DEMONSTRATOR Module Sensitivity

- **Expected Sensitivity to $0\nu\beta\beta$**

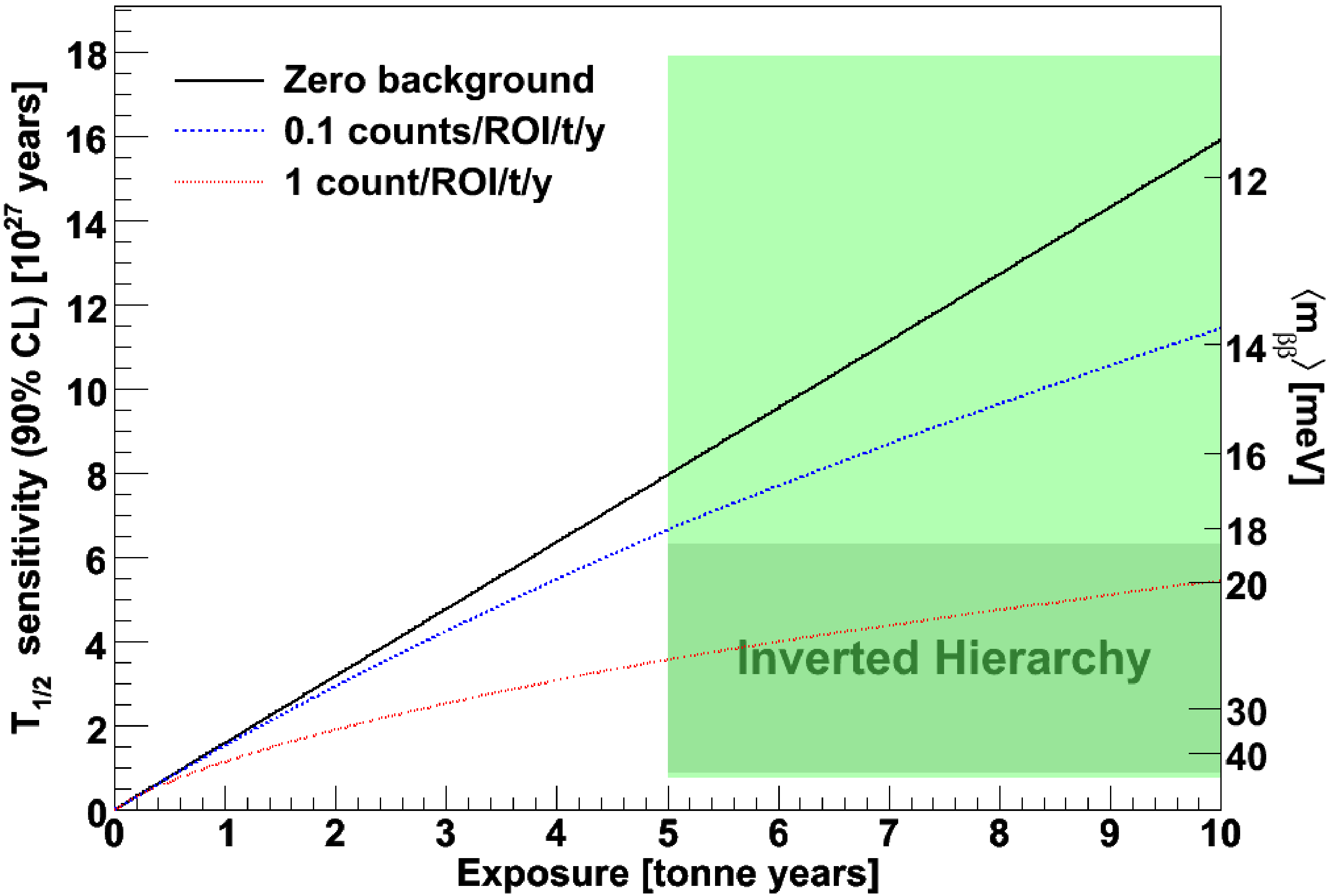
(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

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

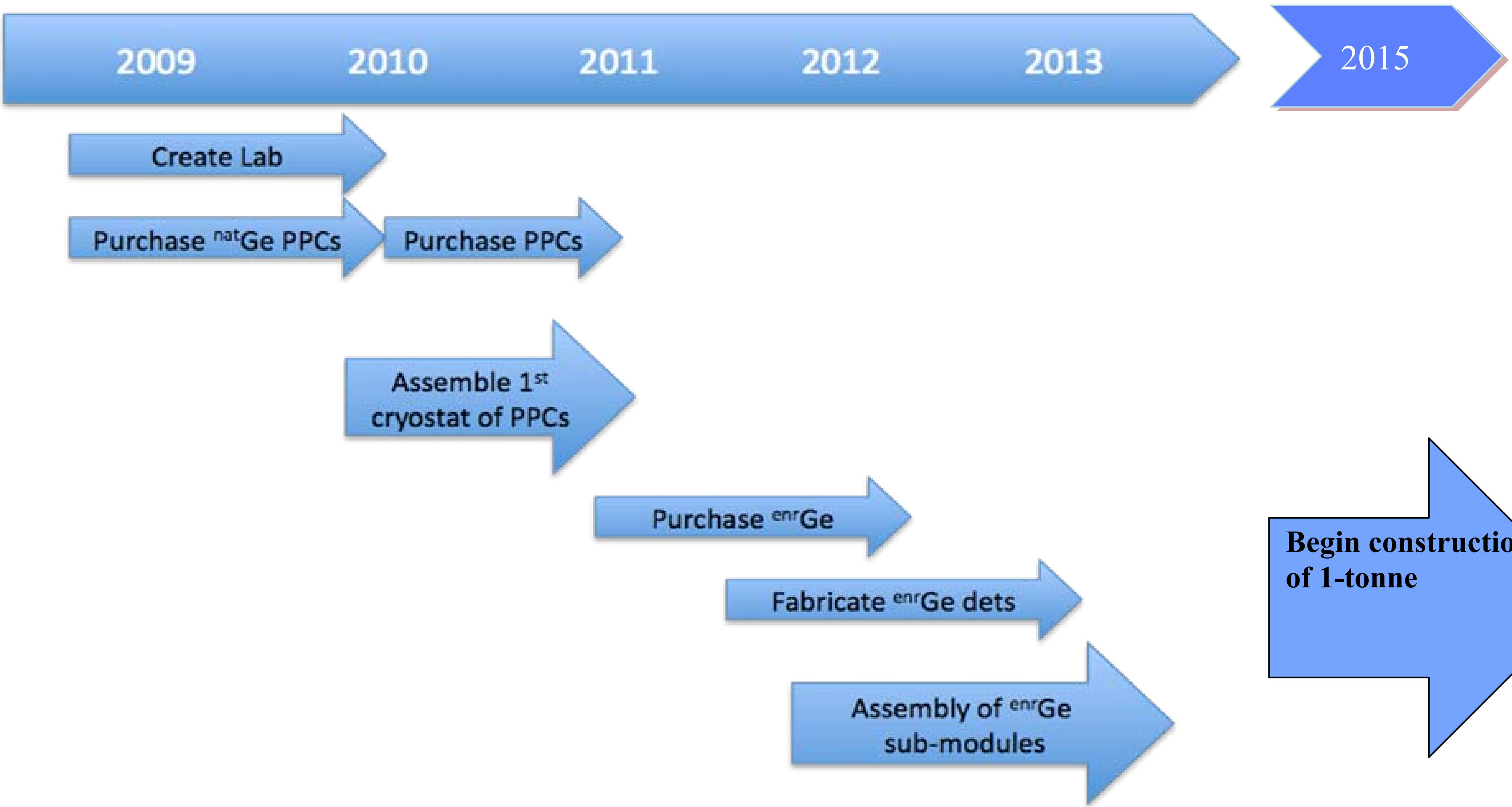


1-tonne Ge - Projected Sensitivity vs. Background

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

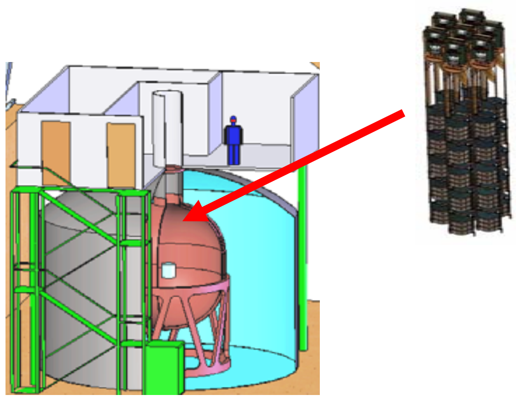


MAJORANA DEMONSTRATOR SCHEDULE



GERDA - Majorana

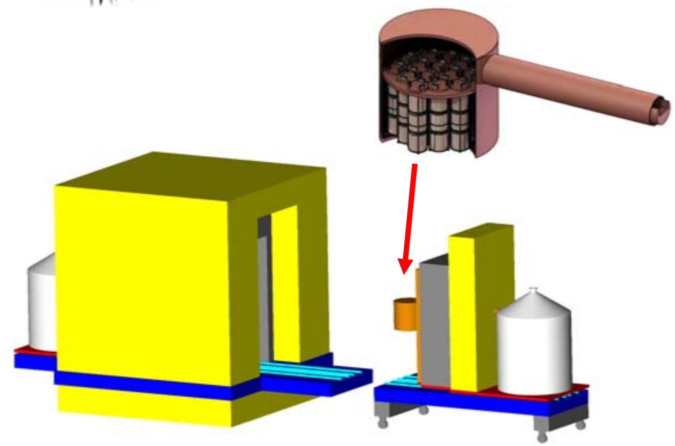
GERDA



- '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:

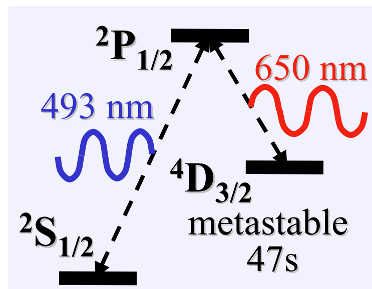
- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and Majorana

EXO (Enriched Xenon Observatory)
USA-RUSSIA-CANADA

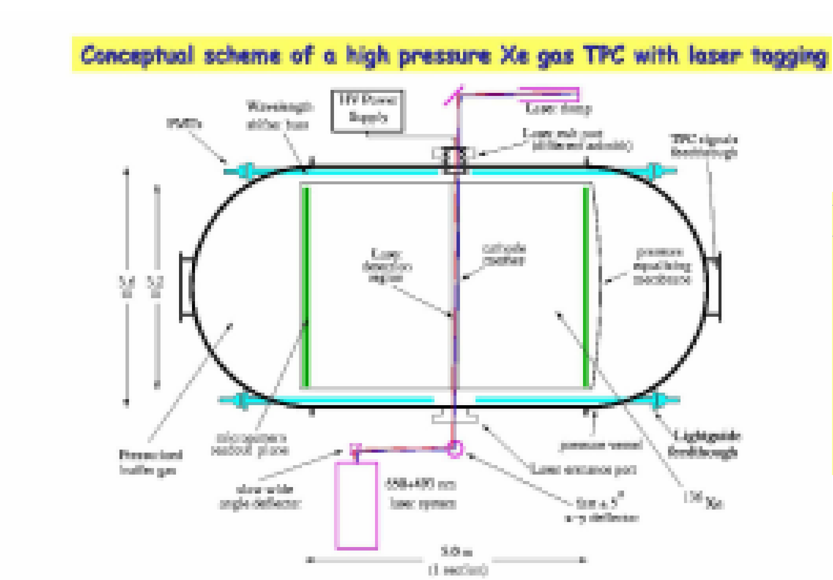
- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$ ($E_{2\beta} = 2.47$ MeV)
- **Main idea is**: to detect all products of the reaction with good enough energy and space resolution (M.Moe PRC 44(1991)931)

EXO

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



LXe TPC



Present R&D

- Ba^{+} spectroscopy in HP Xe / Ba^{+} extr.
- energy resolution in LXe (ion.+scint.)
- Prototype scale:
  - ▶ 200 kg enriched $L^{136}Xe$ without taggin
  - ▶ 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)

Full scale experiment at WIPP or SNOLAB

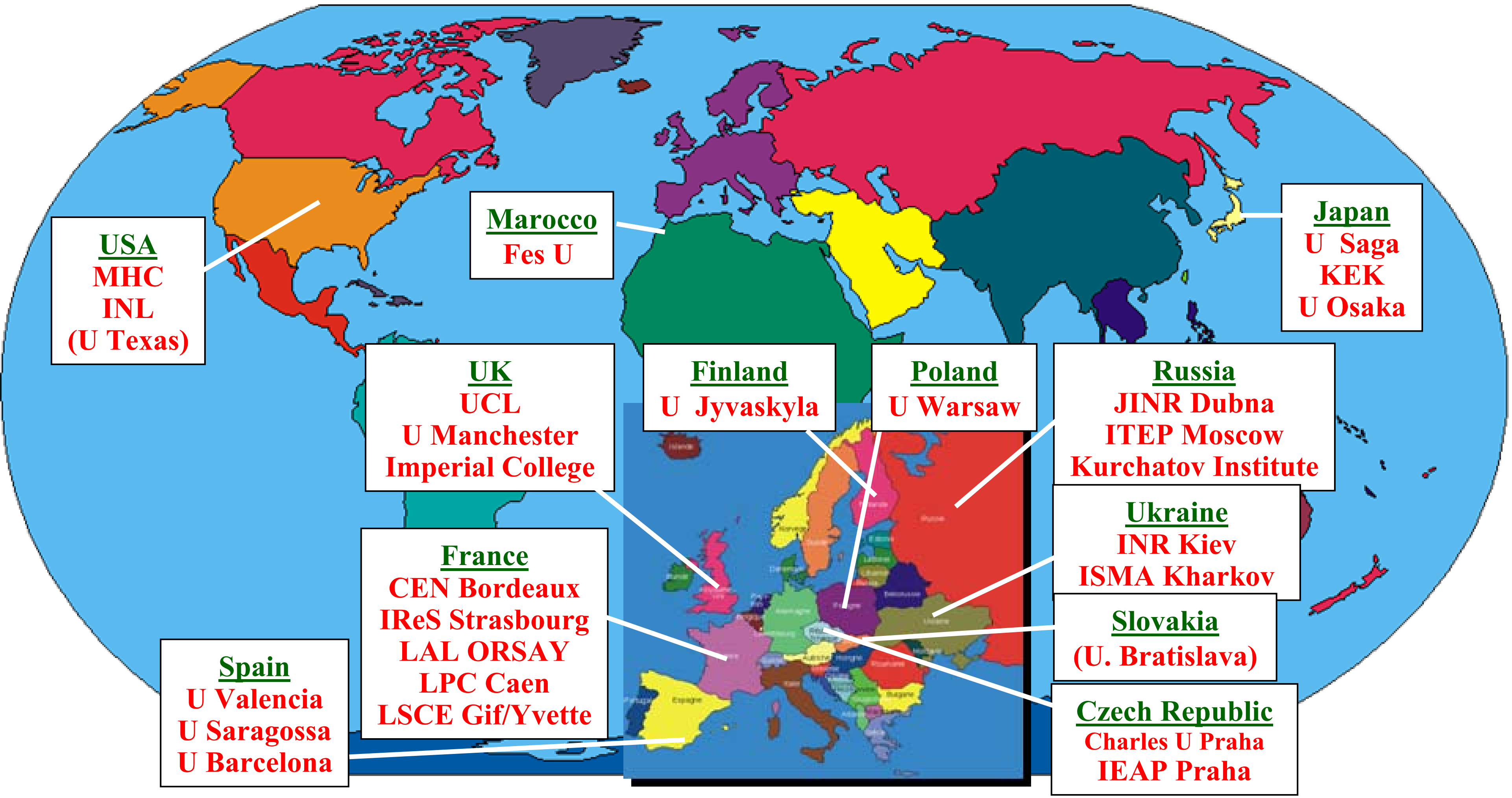
- **10 t** (for LXe ⇒ 3 m^3)
  - $b = 4\times10^{-3}$ c/keV/ton/y
  - $T_{1/2} > 1.3\times10^{28}$ y in 5 years
  - $<m_\nu> < 0.013 \div 0.037$ eV

EXO-200 (without Ba^{+} tagging)

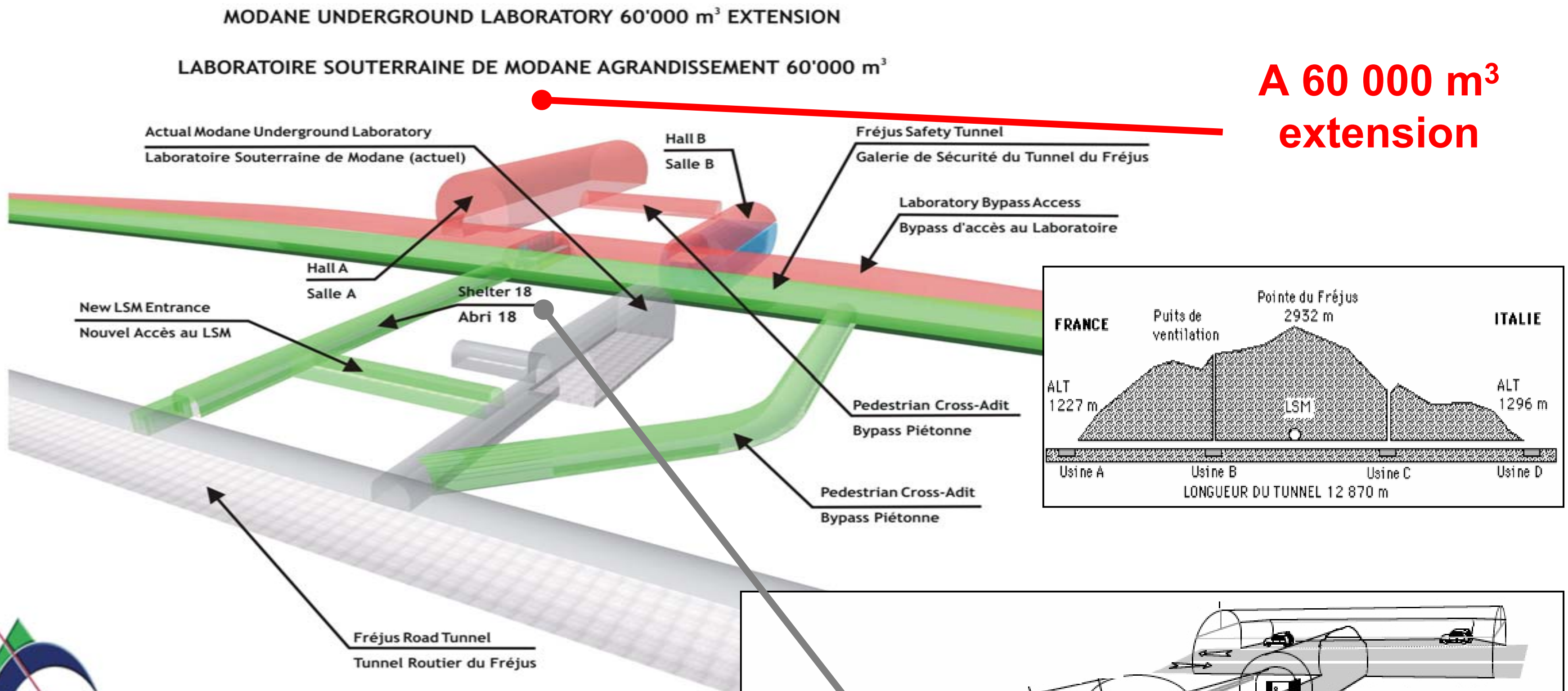
- **200 kg** of ^{136}Xe (80% enrichment) – **exist!**
- Location: WIPP (USA)
- $\Delta E/E$(FWHM) = **3.8%** at 2.5 MeV (ionization and scintillation readout)
- Background (5 y) = **40** events
- Sensitivity (5 y): **$6.4 \cdot 10^{25}$ y** (**$\langle m_\nu \rangle \sim 0.1\text{-}0.2$ eV**)
- Start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

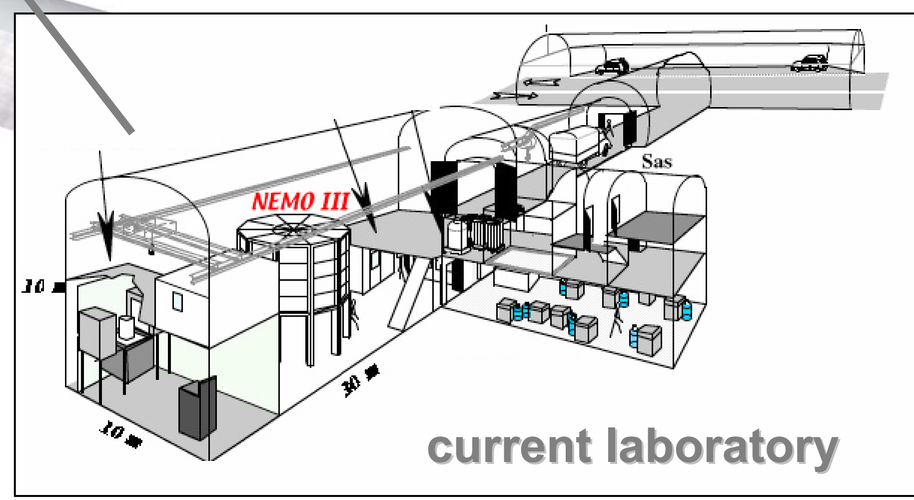
SuperNEMO Collaboration

~ 90 physicists, 12 countries, 27 laboratories



Possible location : LSM

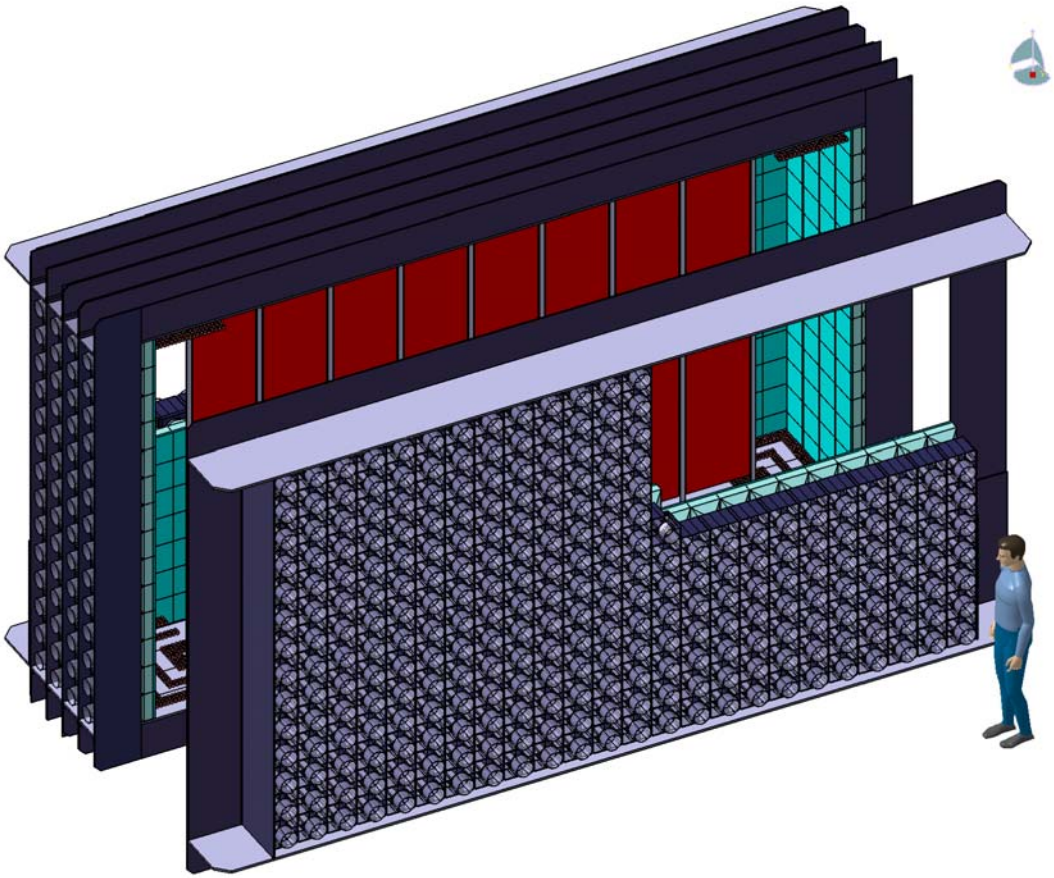




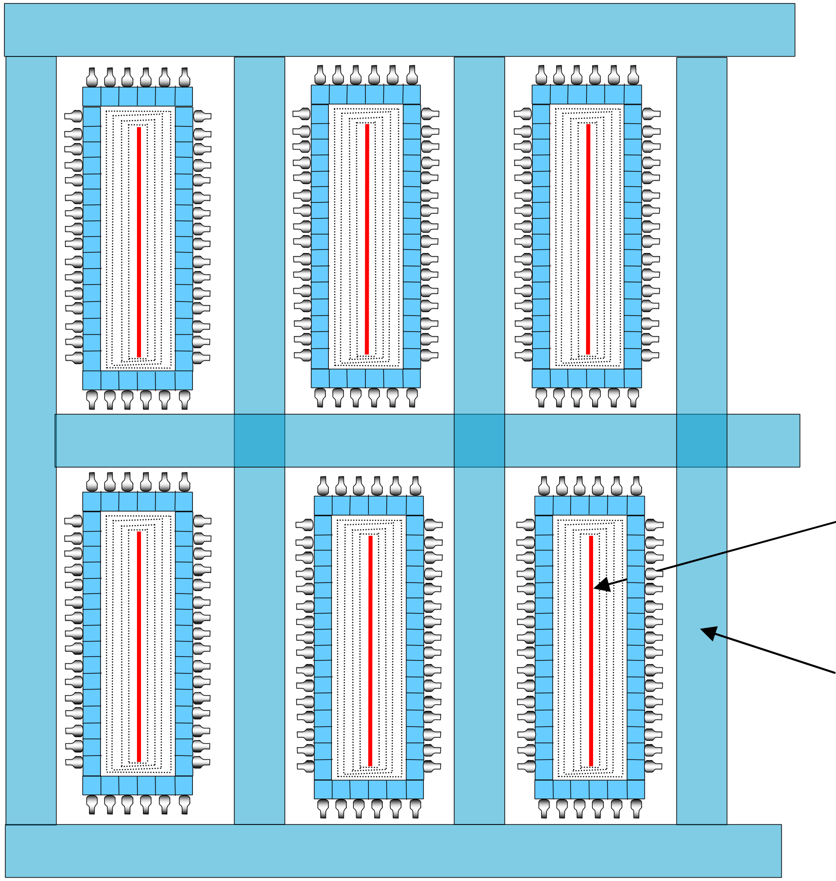
Demonstrator to be placed in NEMO3's current location

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
20 %	Efficiency $\varepsilon(\beta\beta0\nu)$	~ 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	$T_{1/2}(\beta\beta0\nu) >(1\text{-}2)\cdot10^{26}$ y $<m_\nu> \sim 40\text{-}110$ meV

Main R&D tasks:

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

SuperNEMO Demonstrator (1st module)

MAIN GOALS :

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

- To measure the radon background

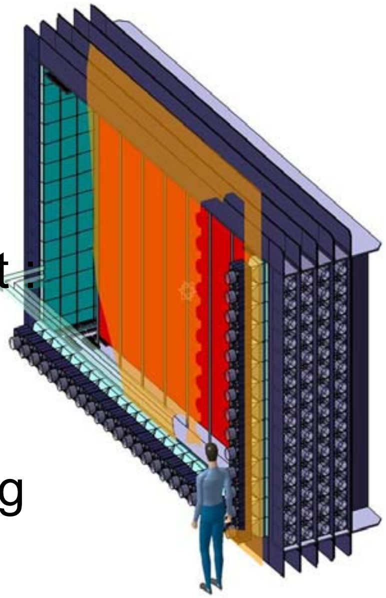
- To finalize detector design

- To produce competitive physics measurement :

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

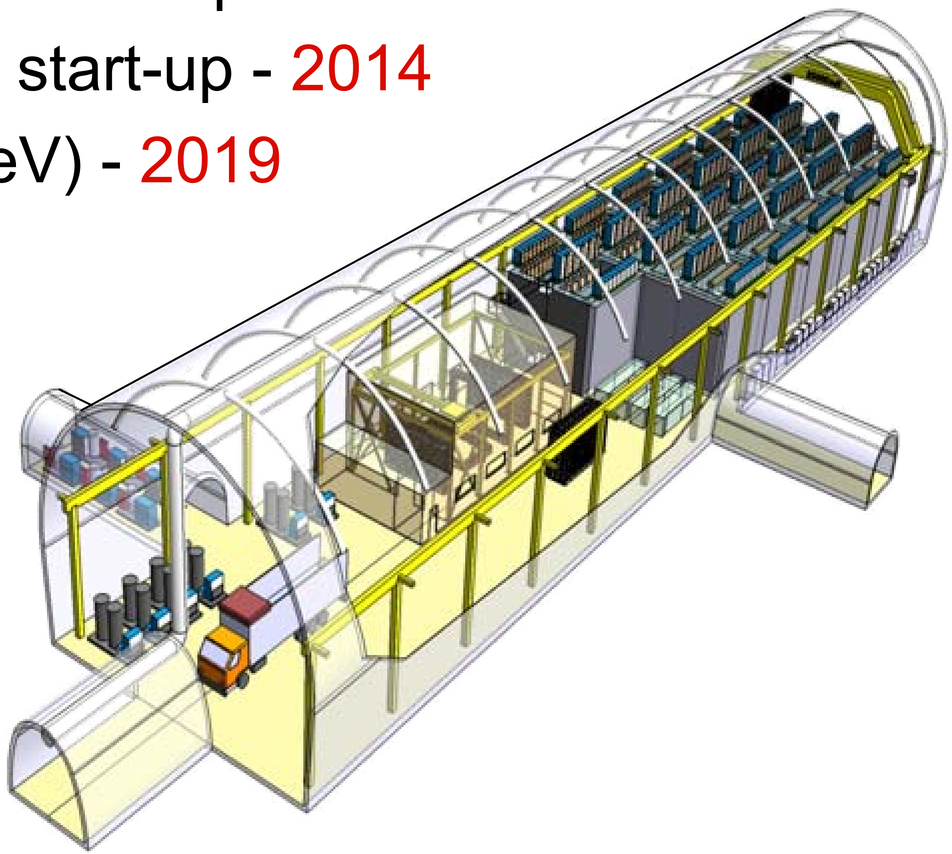
$< m_\nu >$ < 210 – 570 meV

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



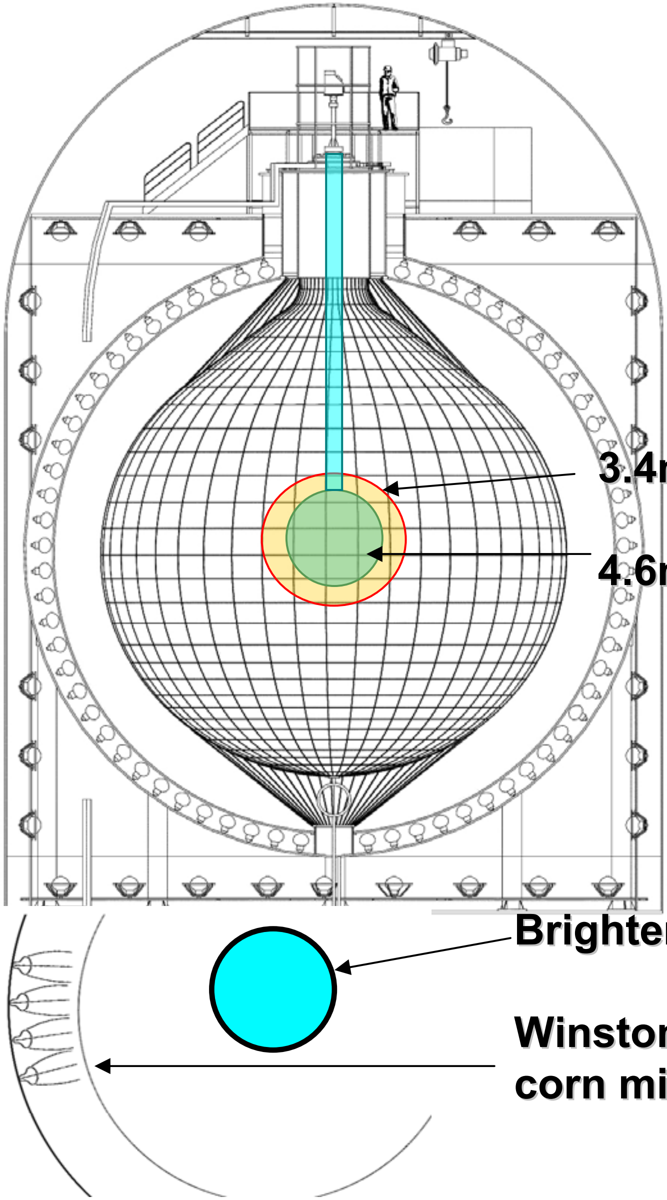
SuperNEMO schedule highlights

- 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

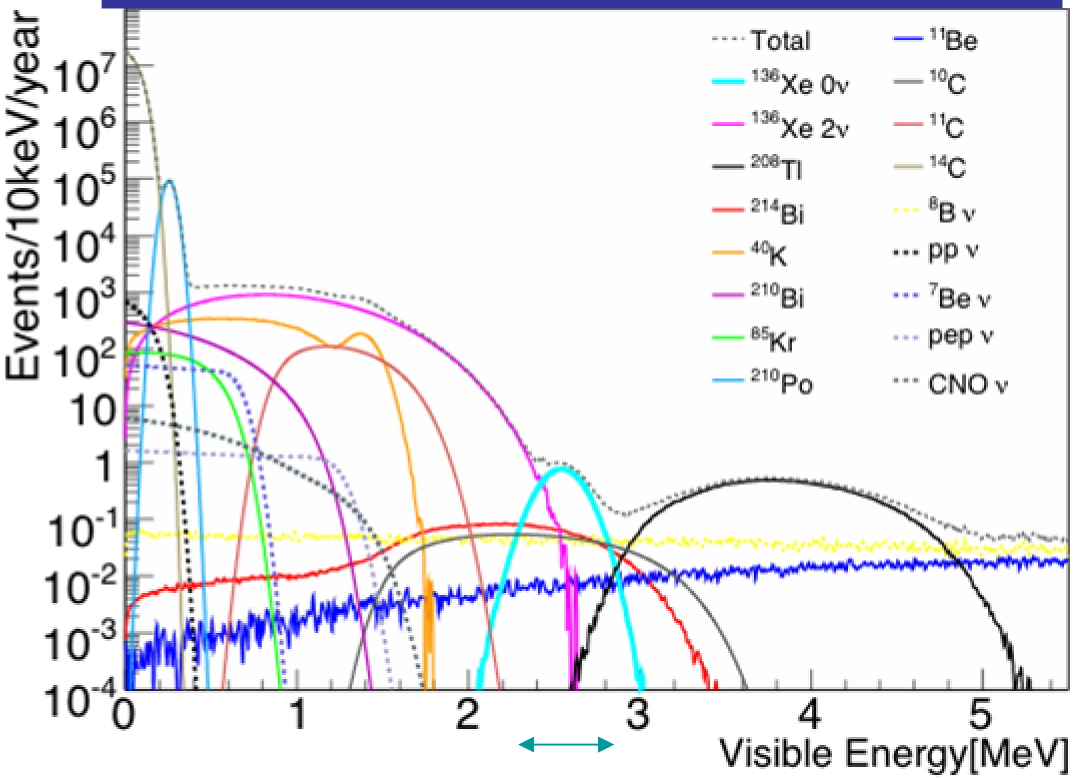
(1). ^{136}Xe 2$\nu\beta\beta$

(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,

Simulated Energy Spectrum at KamLAND



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

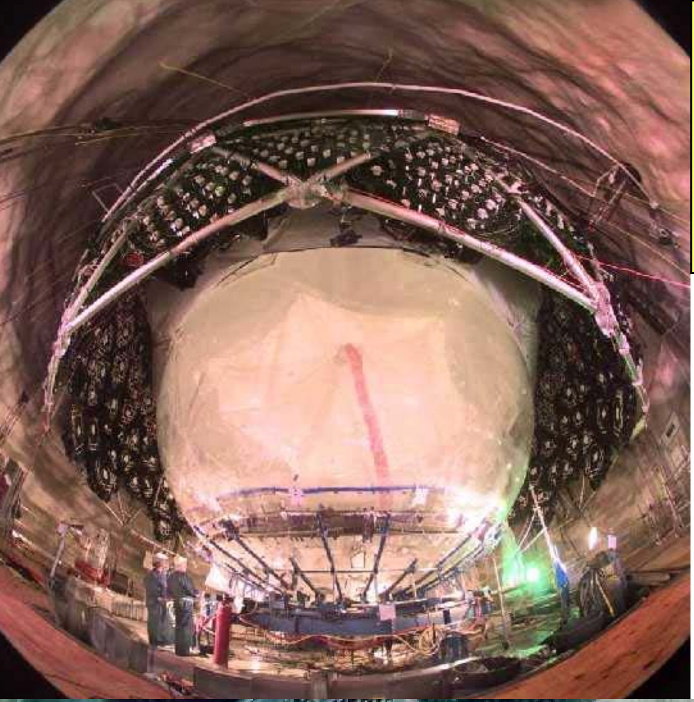
^{136}Xe 2ν	^{208}Tl	^{214}Bi	^{10}C	^{11}Be	^{8}B	Total	^{136}Xe 0ν
2.08 ±0.15	1.86×10^{-2} $\pm0.13\times10^{-2}$	2.40 ±0.01	3.09 ±0.01	0.26 ±0.01	1.52 ±0.03	9.35 ±0.23	18.08 ±0.02

[events/year]

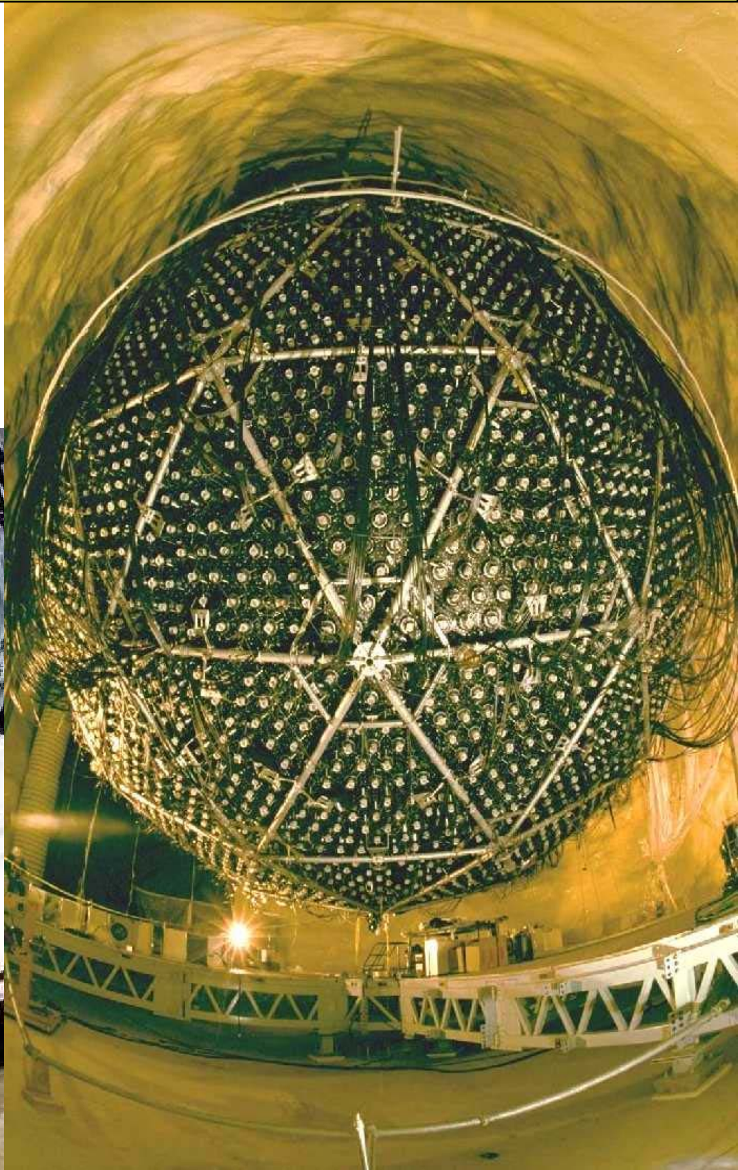
summary

- KamLAND is running for reactor, Geo, 7Be solar (to 2011)
- KamLAND have ability to do $0\nu\beta\beta$ experiment
- KamLAND-Zen project will start useing 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

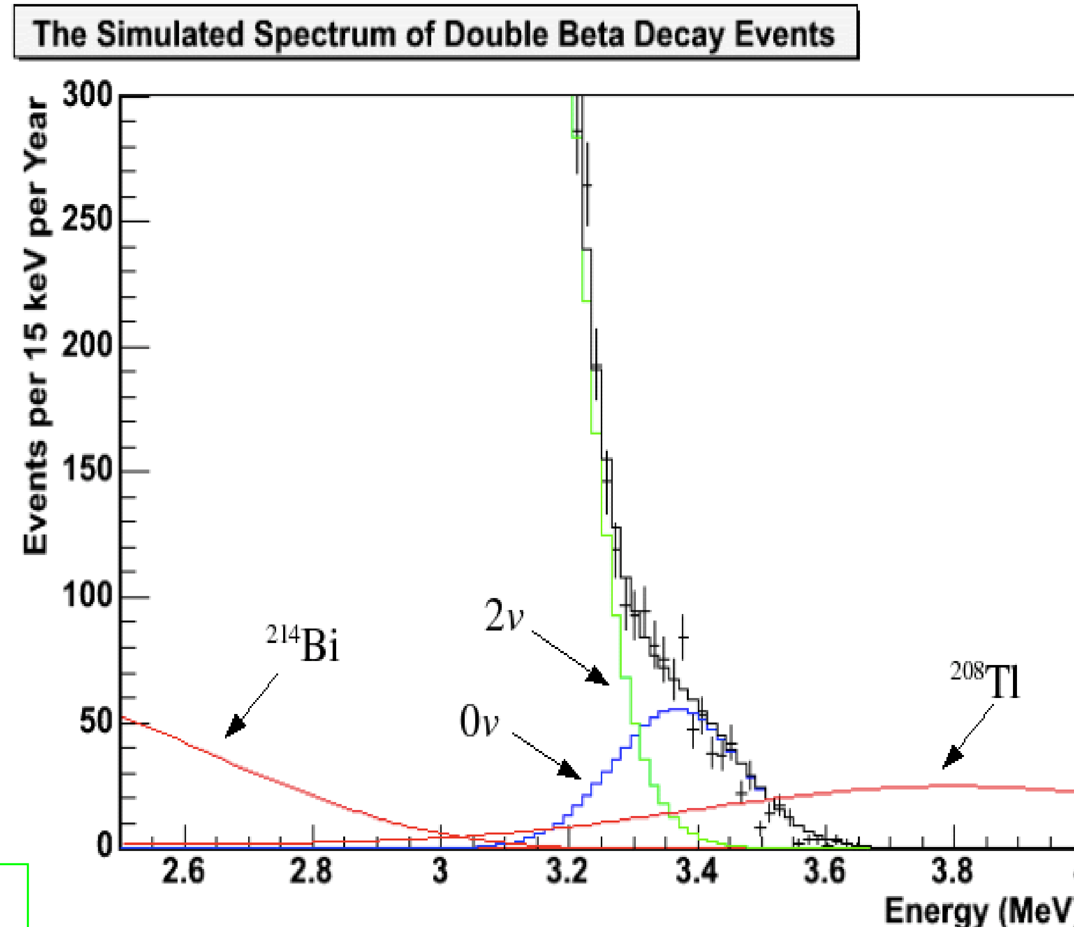
400 ± 21 pe/MeV (Monte Carlo)

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):** $m_\nu \sim 0.1$-**0.3 eV**
- **500 kg enriched ^{150}Nd** $m_\nu \sim 0.04$-**0.12 eV**

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

IV. Заключение

1. Большие успехи достигнуты в изучении **2ν**-распада.

2. Современное консервативное ограничение на **$\langle m_\nu \rangle$** из экспериментов по **2β(0ν)-**распаду составляет **0.75 eV**.

3. Существует указание на «наблюдение» **2β(0ν)-**распада в ^{76}Ge (**$\langle m_\nu \rangle \approx$ 0.3-0.5 eV**). Но это требует подтверждения («закрытия») в новых экспериментах с ^{76}Ge (это будет сделано в ближайшие несколько лет).

4. В **2011** году ожидается:
   - начало набора данных на установке **GERDA-I** (**18 кг ^{76}Ge**);
   - начало набора данных на установке **EXO** (**200 кг ^{136}Xe**);
   - начало набора данных на установке **KamLAND-Xe** (**400 кг ^{136}Xe**);
   - начало набора данных на установке **CUORE-0** (**11 кг ^{130}Te**).

5. В экспериментах нового поколения чувствительность к **$\langle m_\nu \rangle$** на уровне **~ (0.01-0.1) эВ** будет достигнута в ~ **2013-2020**.