22nd International Workshop on
Weak Interactions and Neutrinos WIN'09
Electroweak Symmetry Breaking
Weak Decays, CP Violation and CKM
Neutrino Physics
Dark Matter

A search for neutrinoless double beta decay:

Latest results from the NEMO-3 experiment
and
Plans for SuperNEMO

Karol Lang
The University of Texas at Austin

On behalf of
the NEMO Collaboration

Outline:

- $0\nu\beta\beta$ and $2\nu\beta\beta$ – some practical factors
- The NEMO-3 experiment
- Latest results from NEMO-3
- SuperNEMO
- Summary and outlook

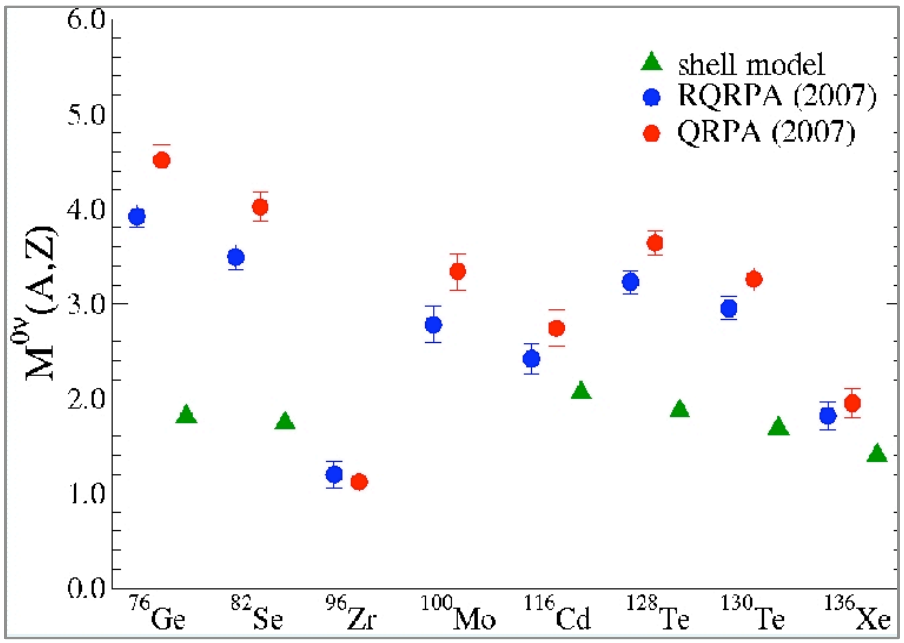
2νββ and 0νββ

$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta}^{11}, Z) \bullet \left| M_{2\nu}^{GT} \right|^2$$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left| M_{0\nu}^{GT} \right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

Phase space
(very well known)

Nuclear matrix element (NME)
(challenging to calculate)



$$\left| \langle m_{\beta\beta} \rangle \right| \equiv \left| \; m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha^*} + m_3 |U_{e3}|^2 e^{i\beta^* - 2i\delta} \; \right|$$

α^*, β^* = linear combinations of α and β

Practical factors

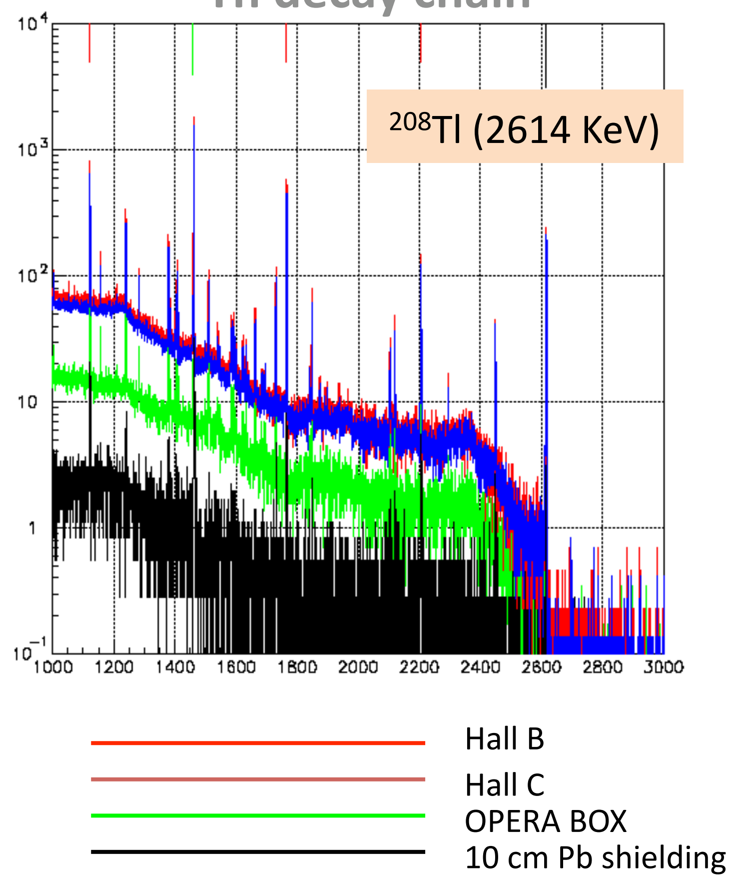
NEMO-3

	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

(11) $\beta\beta$ emiters with $Q_{\beta\beta} > 2$ MeV

- Natural radioactivity and cosmic rays dominate the source of backgrounds → need to go underground + lots of local shielding
- ^{238}U and ^{232}Th decay chains produce the most troubling gammas (highest energies):
  - ^{214}Bi
  - ^{208}Tl

^{232}Th decay chain



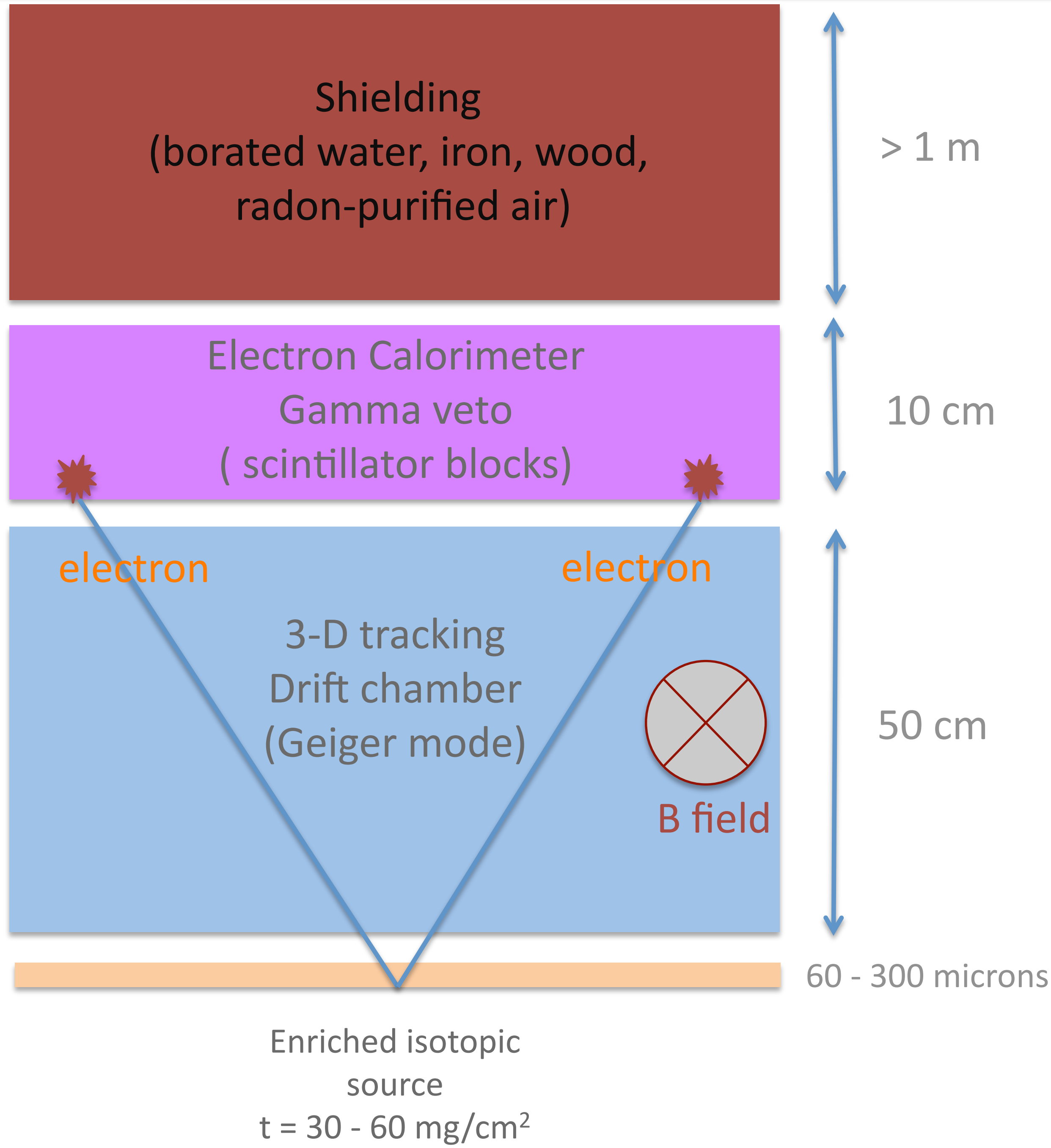
Borrowed from:
F. T. Avignone, S. R. Elliott and J. Engel,
``Double Beta Decay, Majorana Neutrinos, and Neutrino Mass,''
Rev.\ Mod.\ Phys.\ {\bf 80}, 481 (2008) [arXiv:0708.1033 [nucl-ex]].

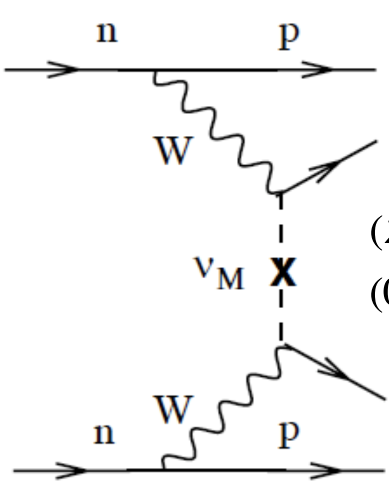
NEMO-3 technique schematics

Measurables

Energy
Time

3-D Position
Angle, Vertex
Time





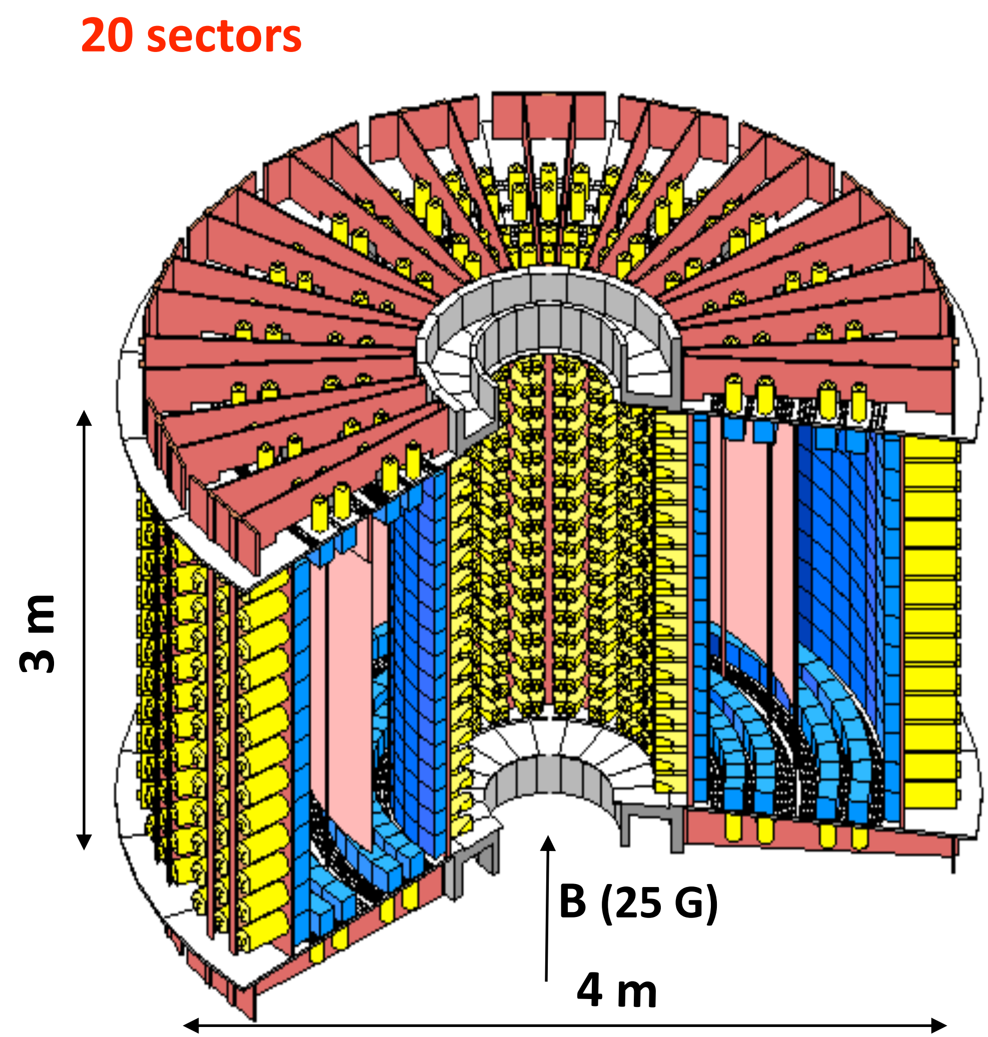
ΔL=2

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

and if $m_\nu \neq 0$

NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopic foils
area = 20 m², thickness ~ 60 mg/cm²

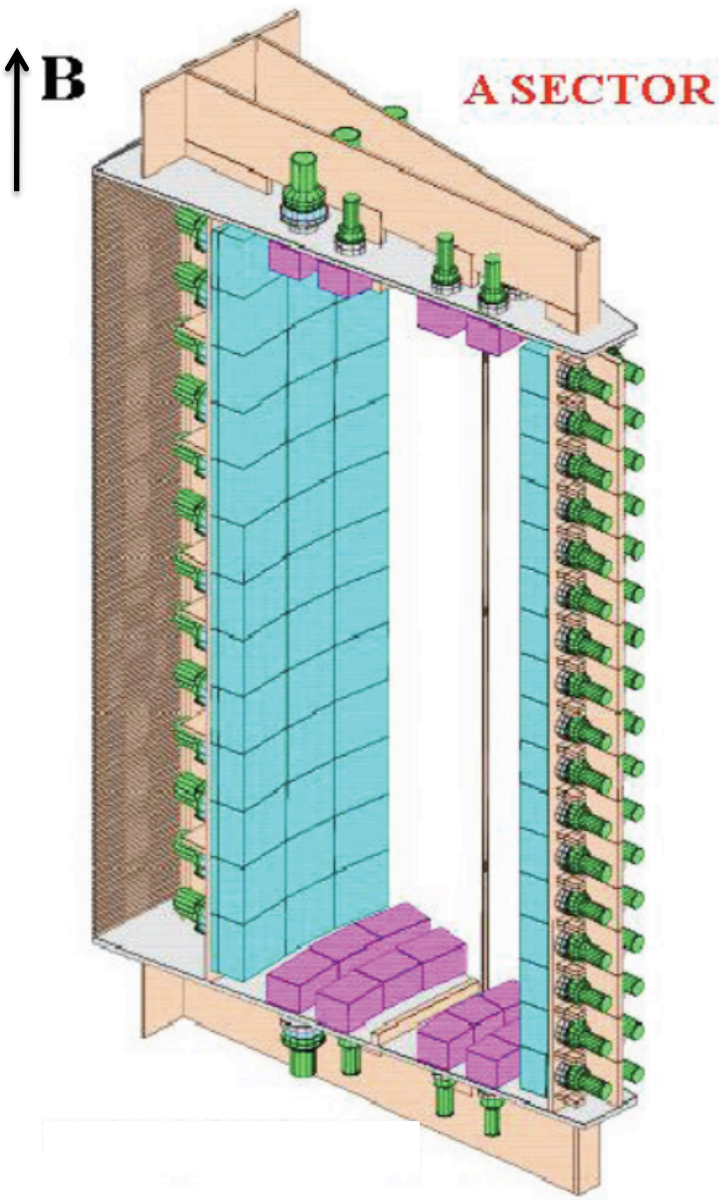
Tracking detector:
drift wire chamber operating (9 layers)
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators (PS + PTP + POPOP)
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: pure iron (d = 18cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since March 2004: water + boron)

Particle ID: e^-, e^+, γ and α

NEMO-3 detector



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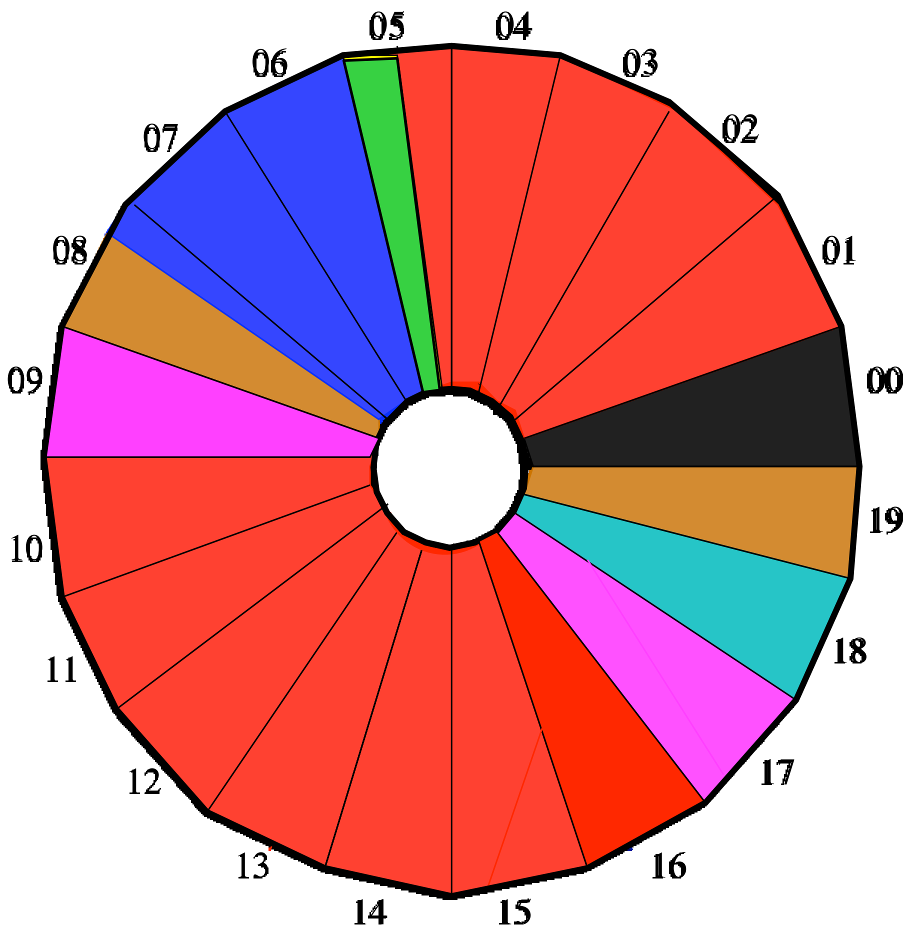
ββ decay isotopes NEMO-3



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

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

0νββ search

2νββ measurement

^{116}Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

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

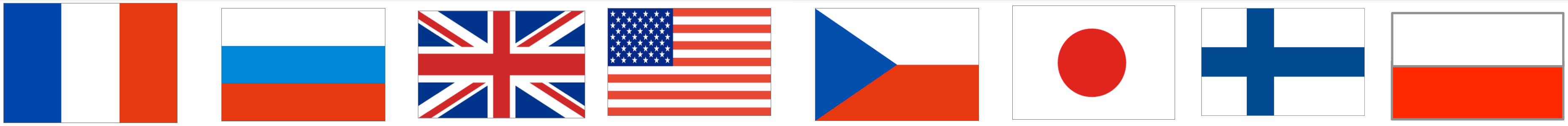
^{nat}Te 491 g

Cu 621 g

External bkg measurement

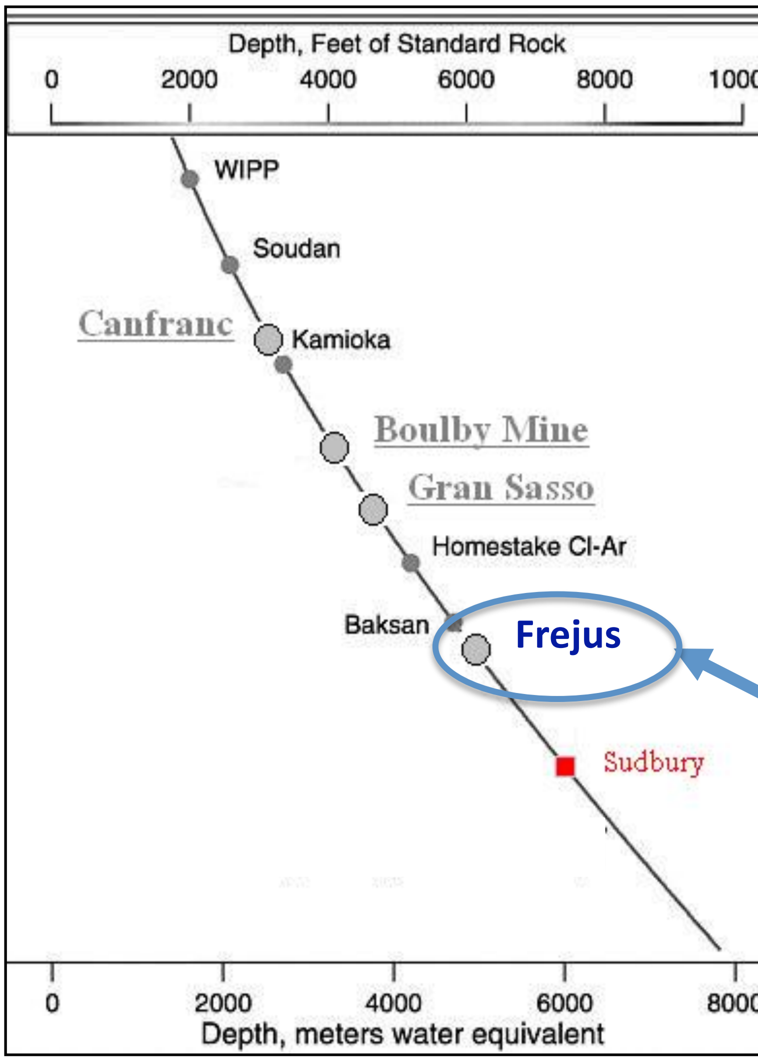
(All enriched isotopes produced in Russia)

Laboratoire Souterrain de Modane
(Frejus tunnel)



NEMO collaboration:
80 physicists / 30 institutions

LSM, France
(Tunnel Frejus, depth of ~4,700 mwe)



Laboratoire Souterrain de Modane

LABORATOIRE SOUTERRAIN DE MODANE

COMMISSARIAT À L'ÉNERGIE ATOMIQUE

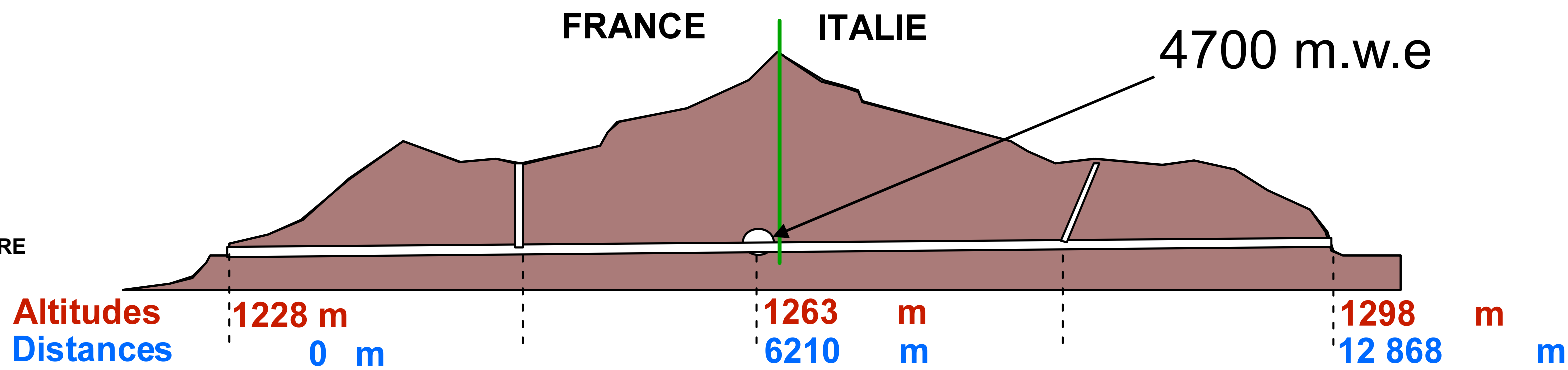
DSM

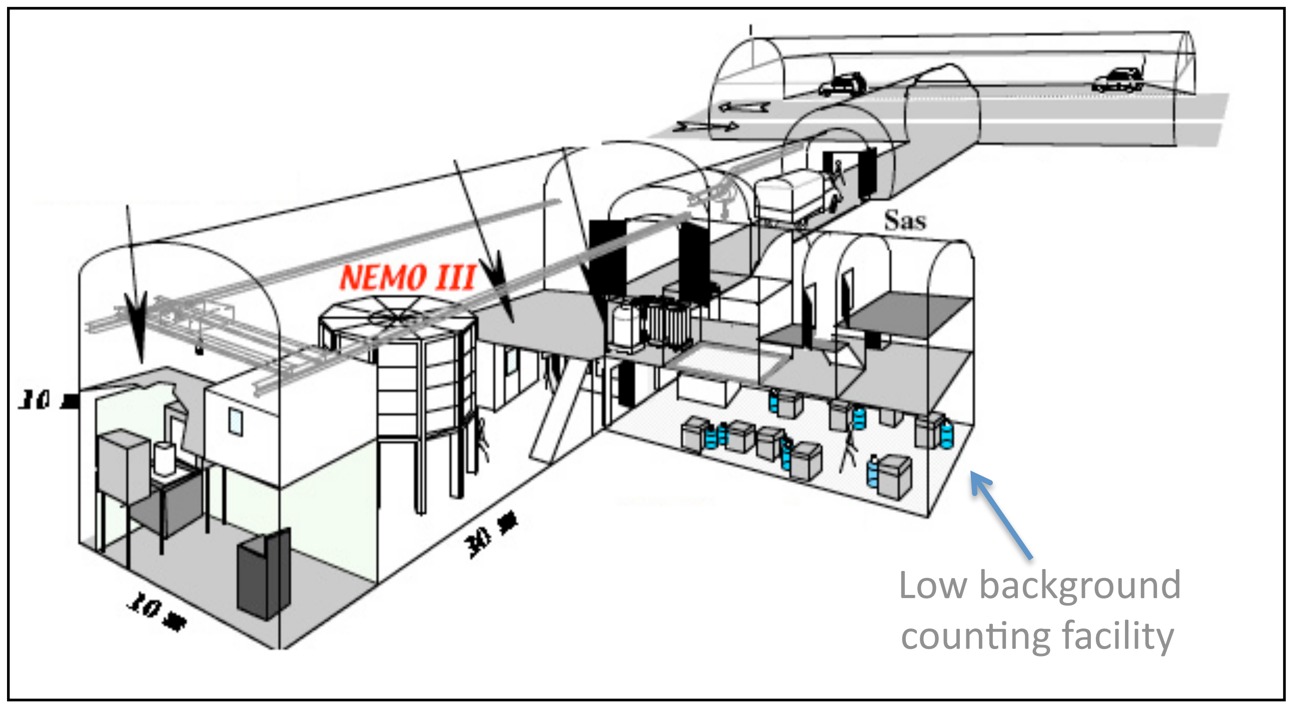
DIRECTION DES SCIENCES DE LA MATIÈRE

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

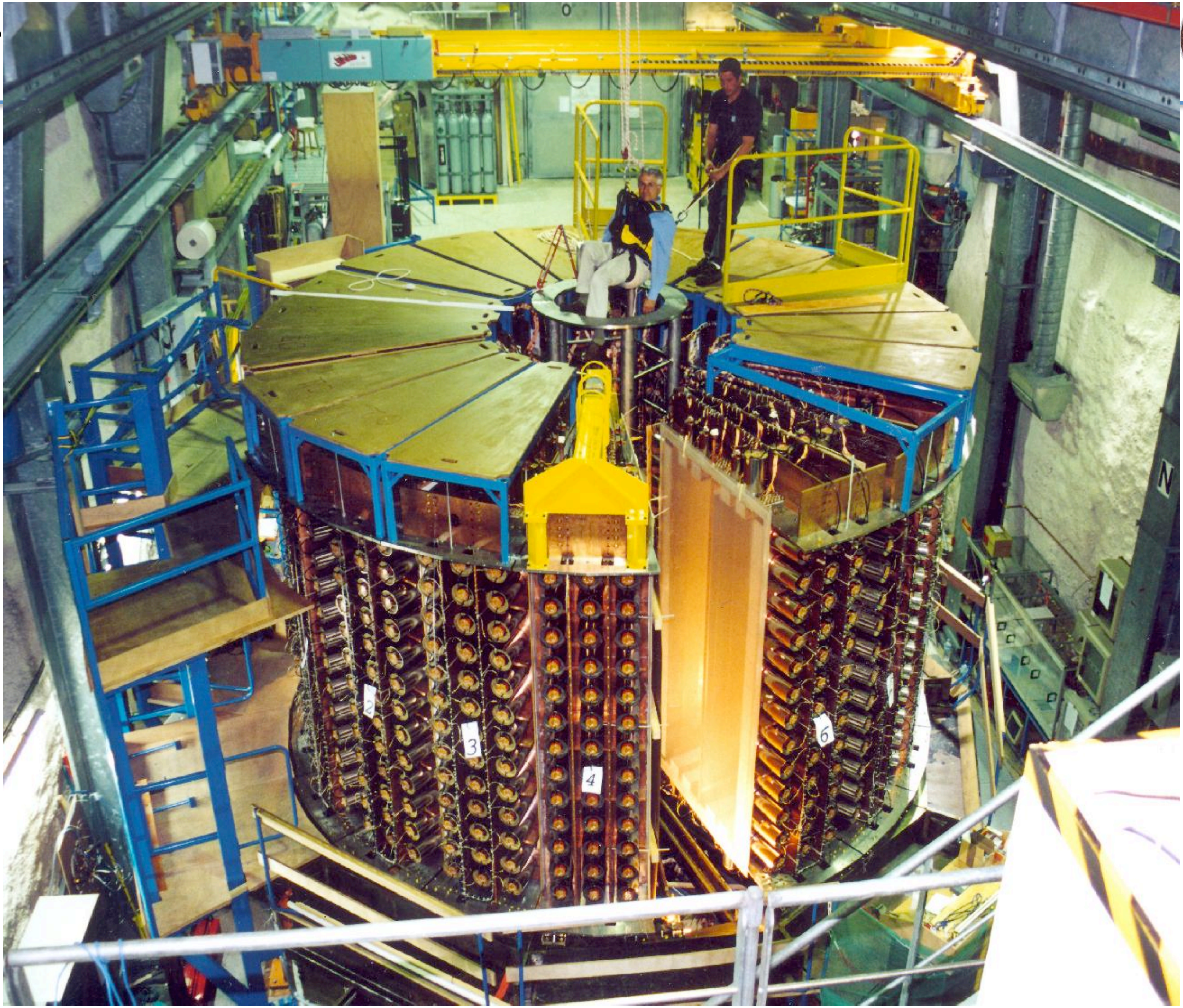
PMTs

scintillators

ββ isotope foils

Cathod rings
Wire chamber

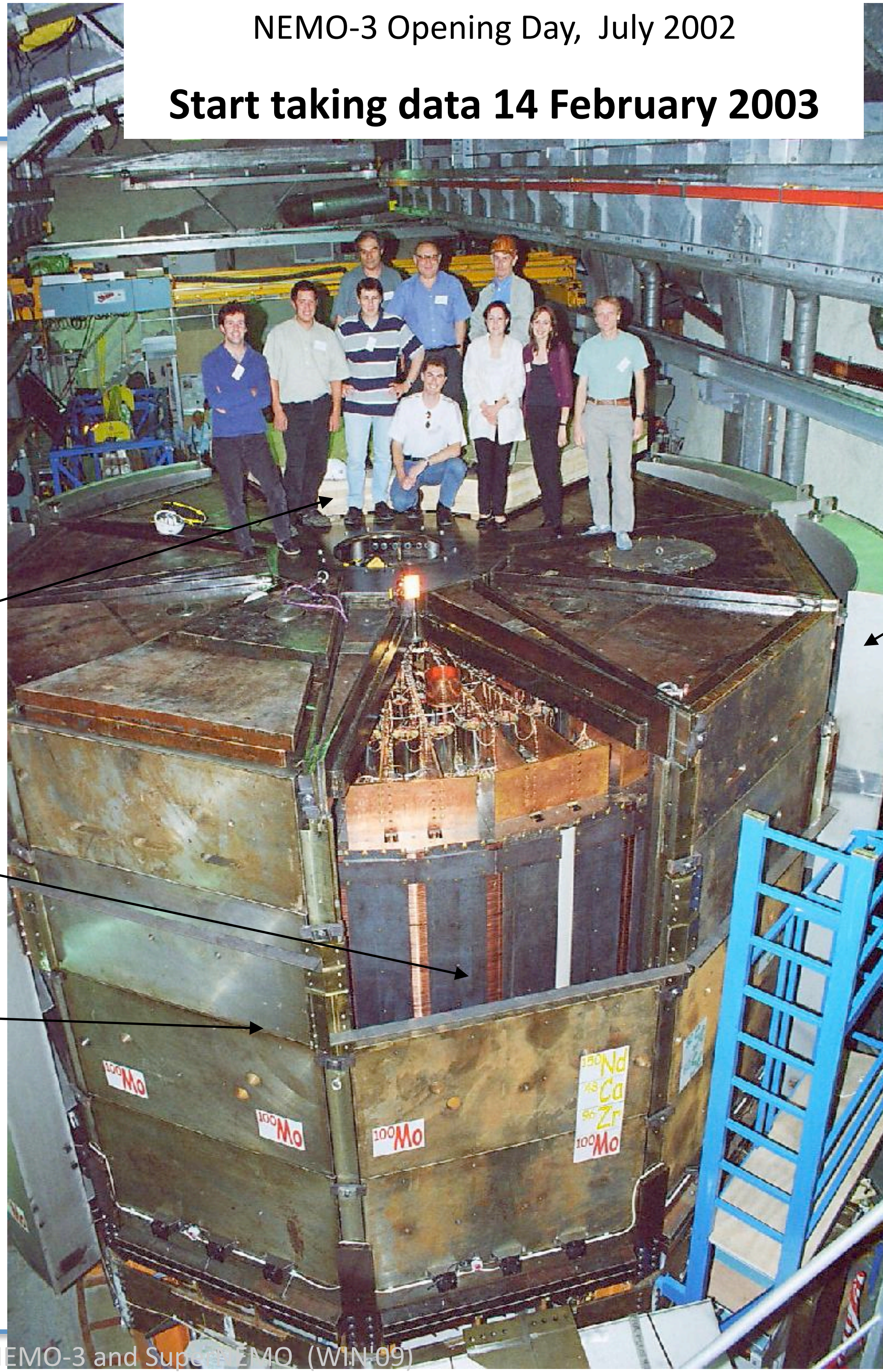
Calibration tube



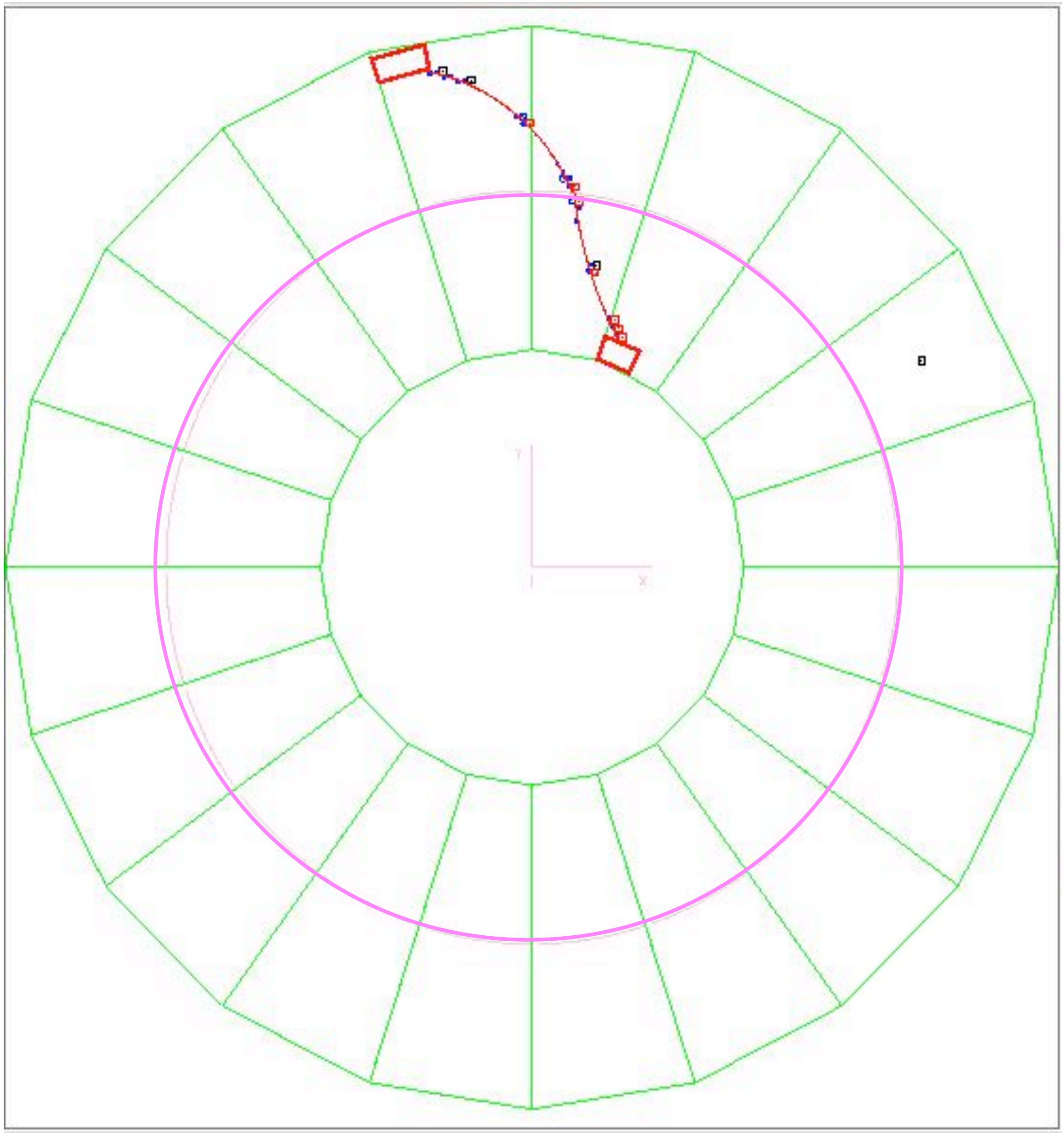
During installation AUGUST 2001

NEMO-3 Opening Day, July 2002

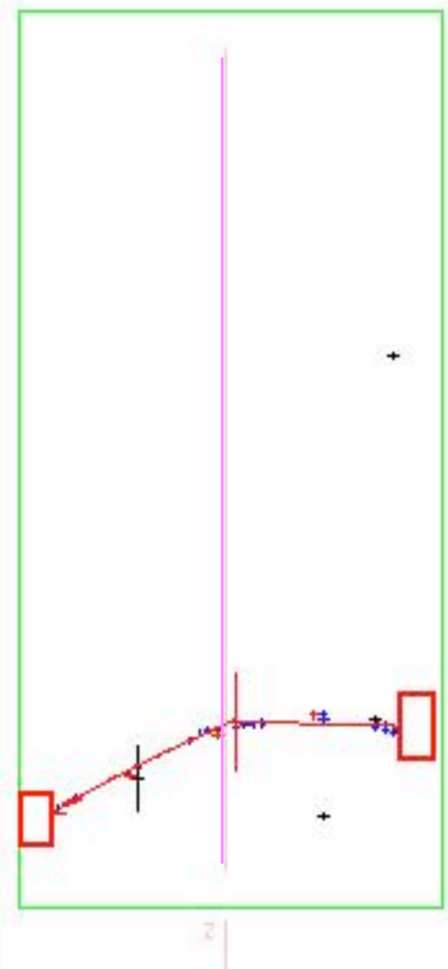
Start taking data 14 February 2003



Finished detector



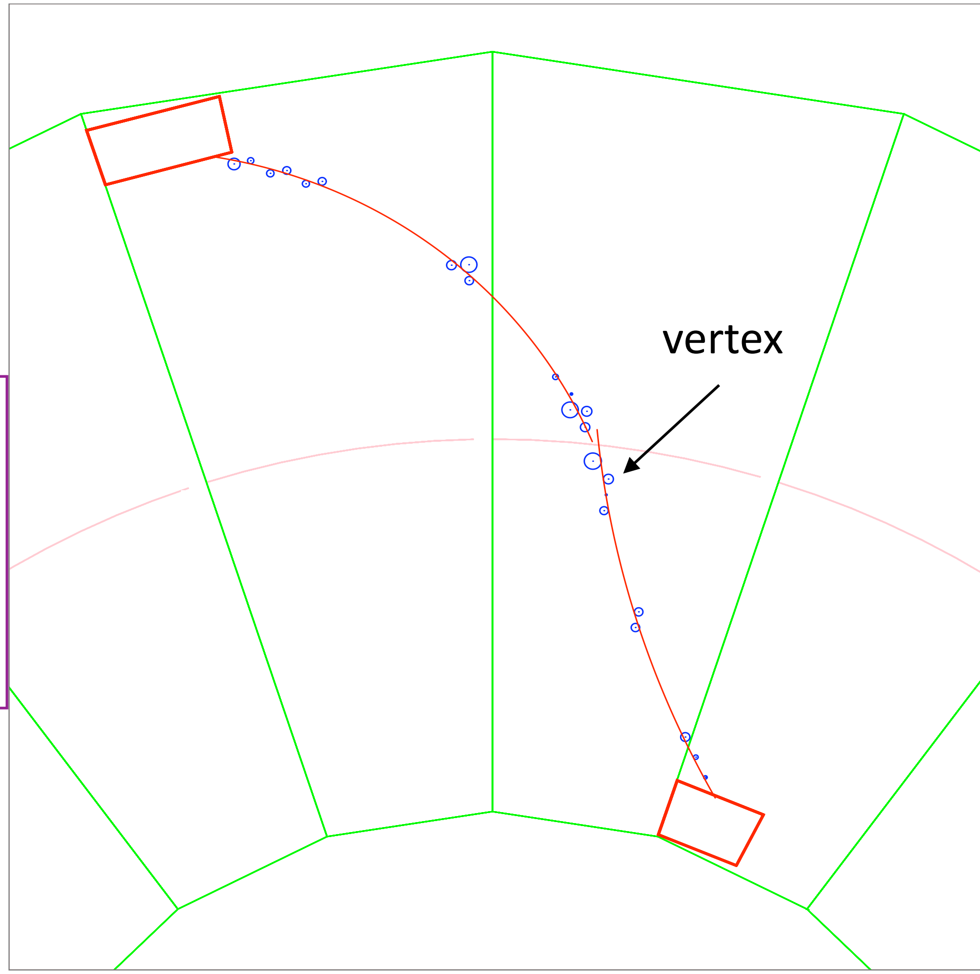
Top view



Side view

Typical ββ2ν event observed from ^{100}Mo

Typical $2\nu\beta\beta$ event observed in ^{100}Mo



Run Number: 2040
Event Number: 9732
Date: 2003-03-20

Deposited energy:
E_1+E_2= 2088 keV
Internal hypothesis:
$(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex:
$(\Delta vertex)_{\perp}$ = 2.1 mm

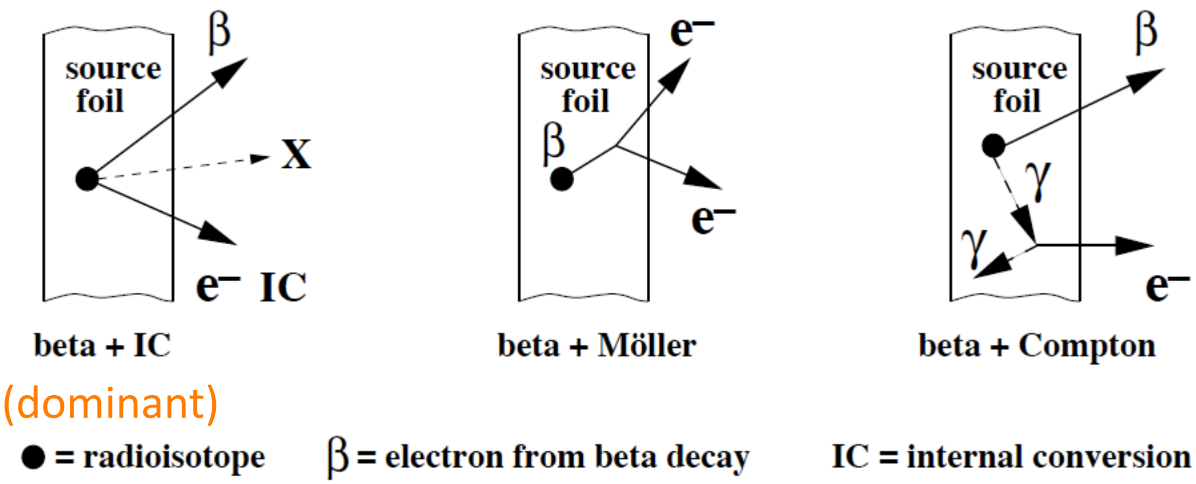
Trigger: **at least 1 PMT > 150 keV**
≥3 Geiger hits (2 neighbouring layers+1)

Trigger rate = 7 Hz

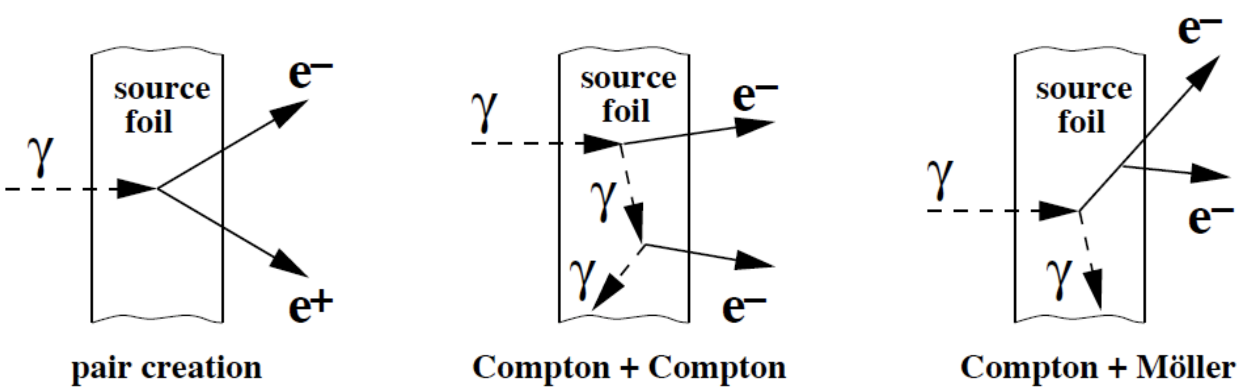
25 ββ events per hour

NEMO-3 backgrounds

- Internal background (in addition to a potential $2\nu\beta\beta$ tail)
  (due to radio-impurities of the isotopic source foil)

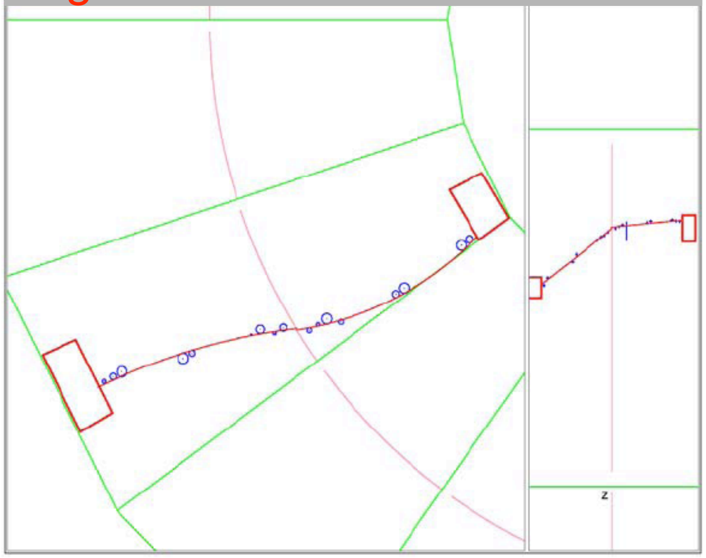


- External background
  (due to radio-impurities of the detector)

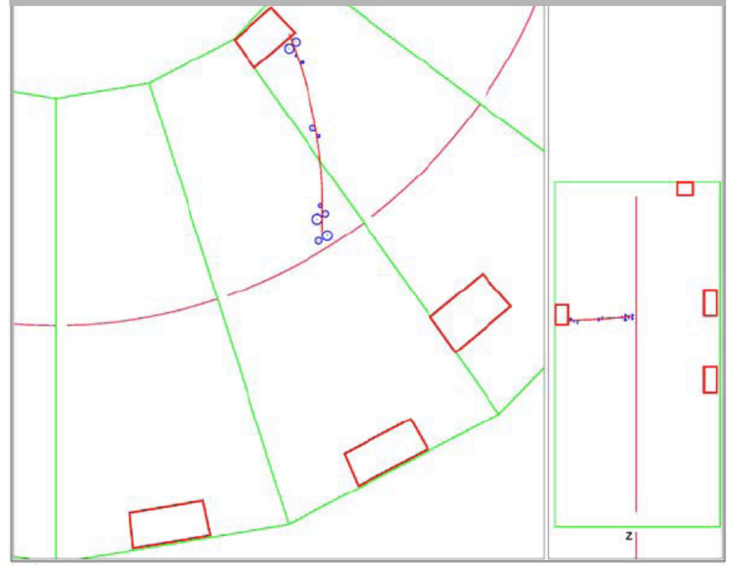


Signal and background signatures

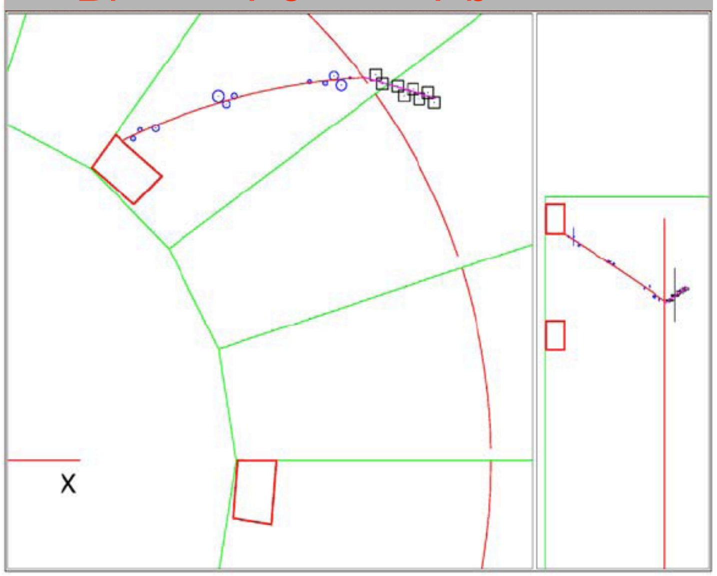
$2e^-$ event
signal



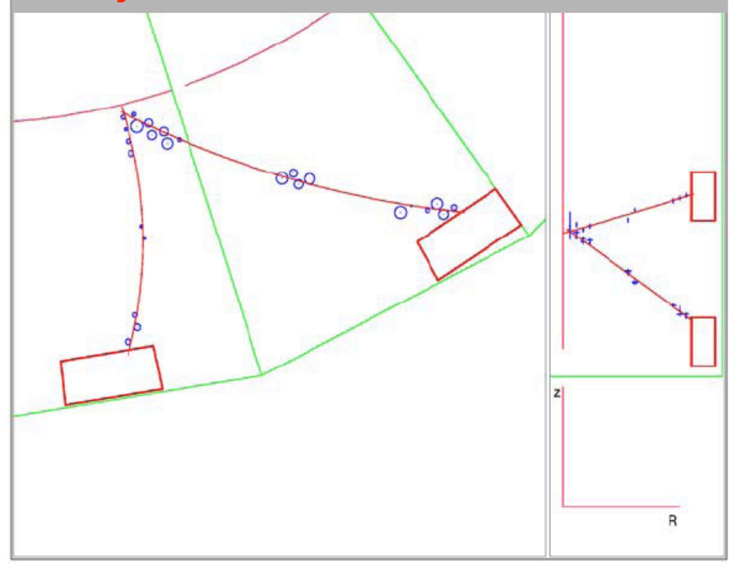
$e^-\ \gamma\gamma\gamma$ event
measure ^{208}Tl



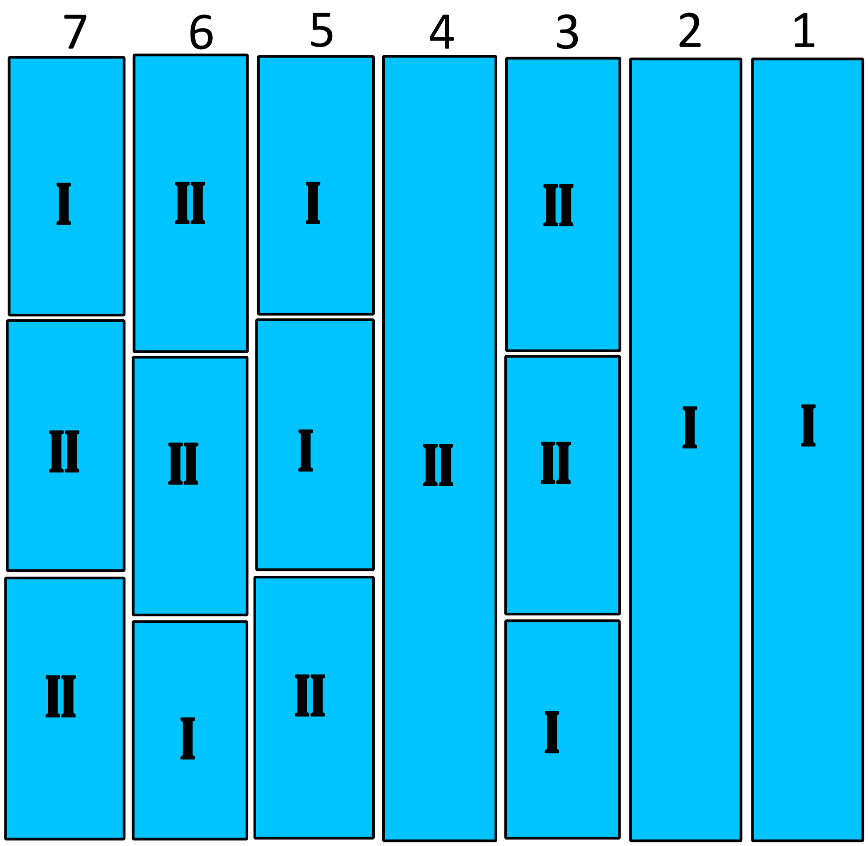
β - α (delay track) event
$^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$



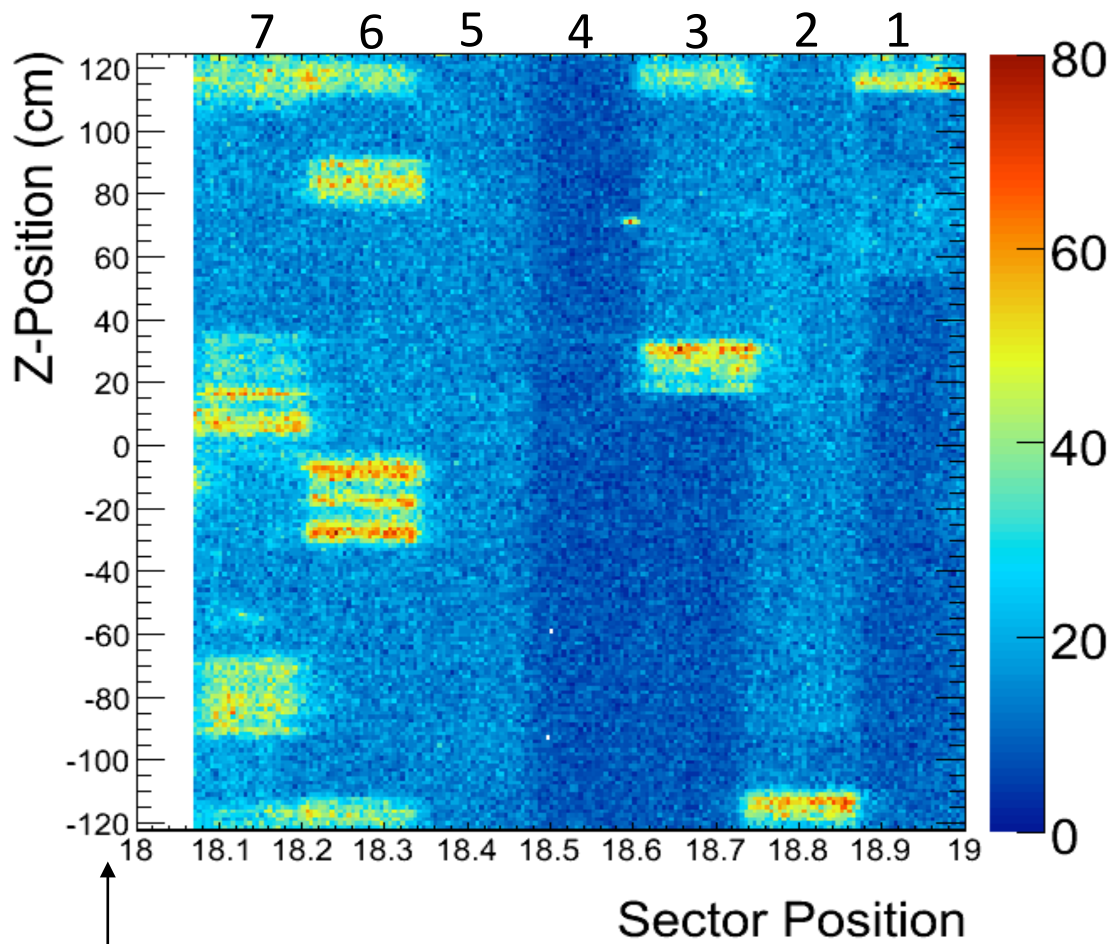
$e^+ - e^-$ pair event
B rejection



Cadmium Foil(s)
Activity and Hot Spots



Production foil parts

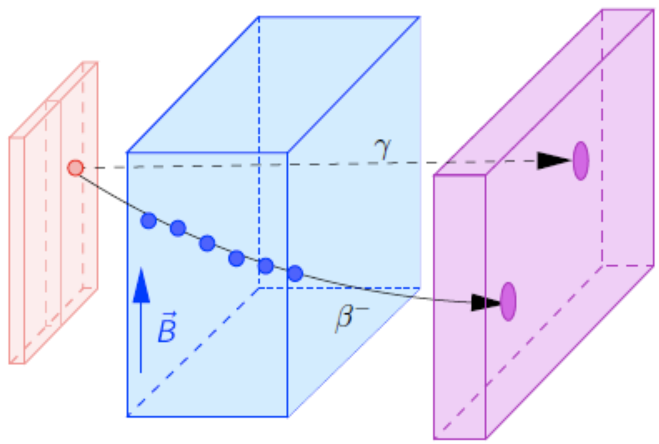


calibration tube

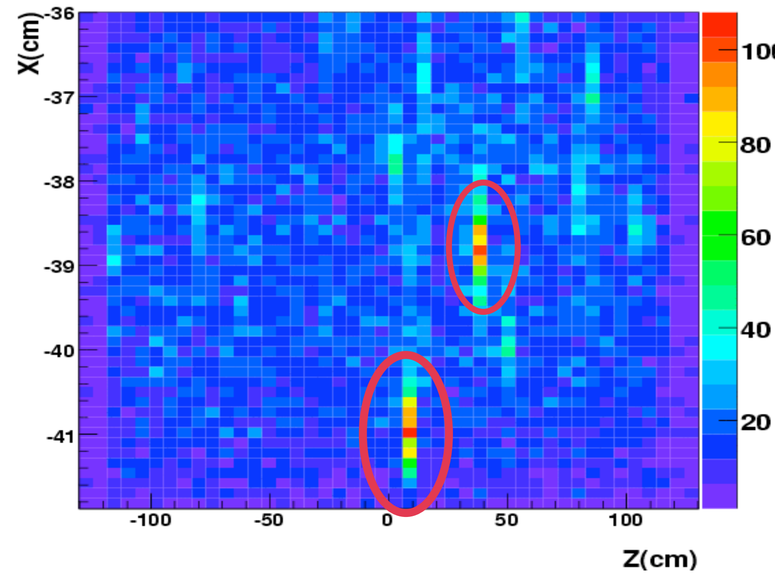
Vertex at the foil for
1 electron data

Background: control channels

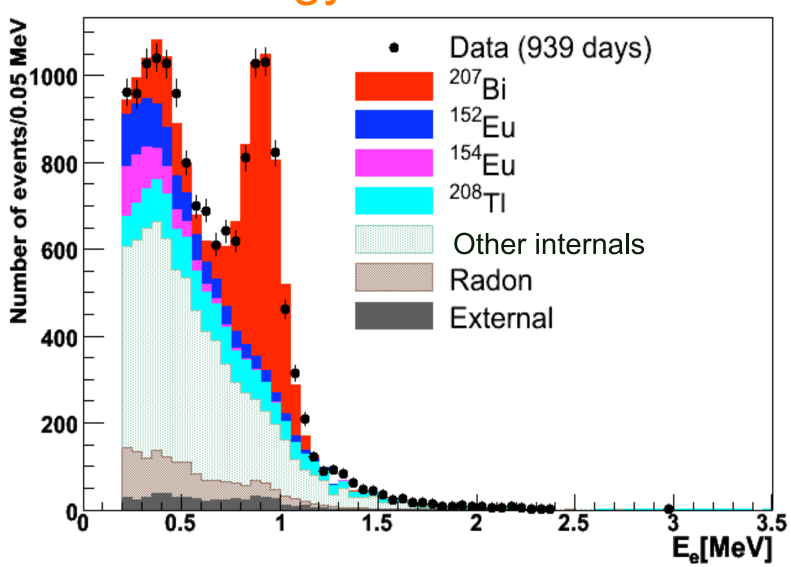
Example:
eγ control channel



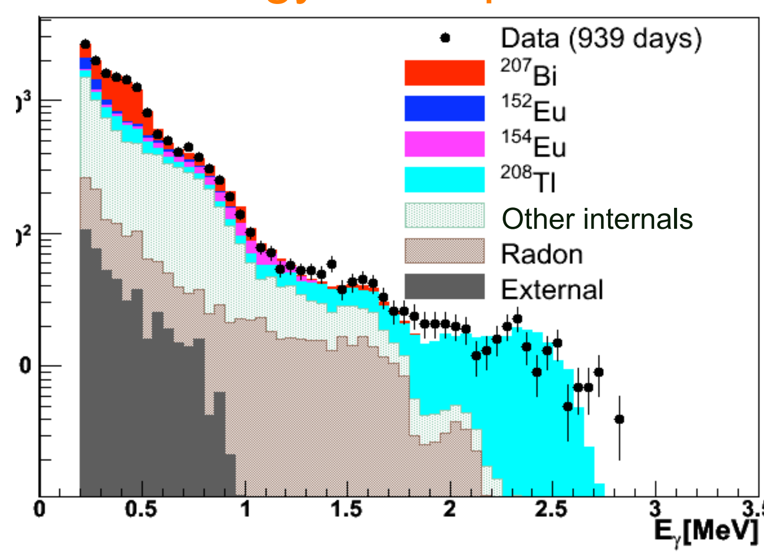
150-Nd foil



Energy of the electron



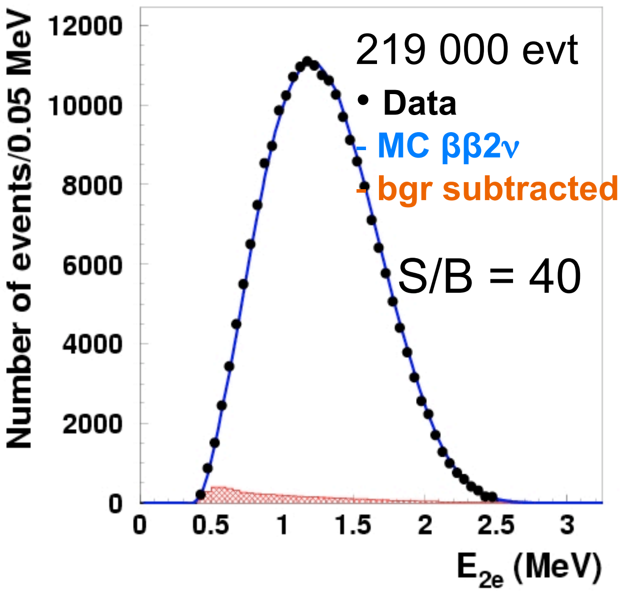
Energy of the photon



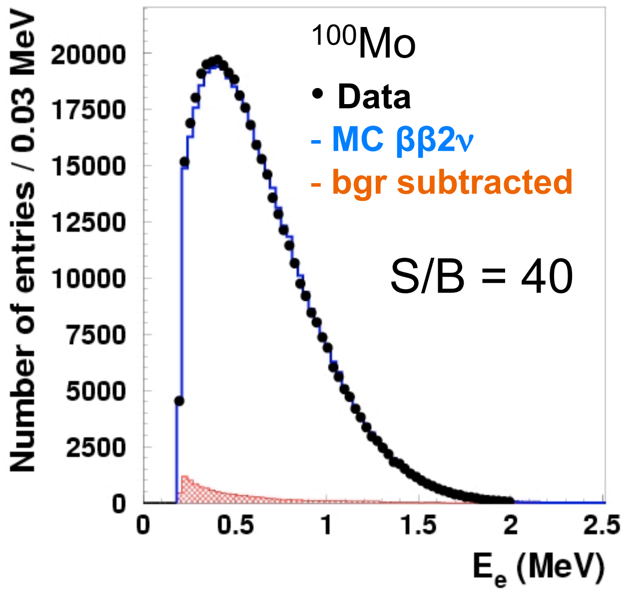
Previous results for ^{100}Mo: ββ2ν

Phase I (high Radon): Feb 2003 – Dec 2004 (389 days)

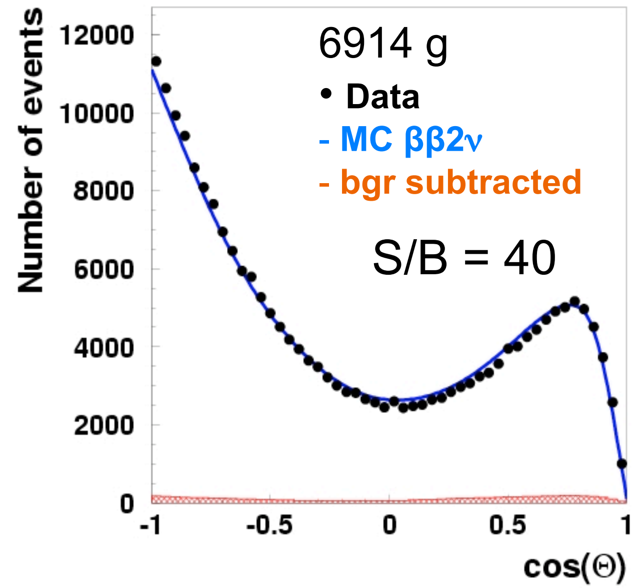
Sum energy spectrum



Single electron energy spectrum



Angular distribution



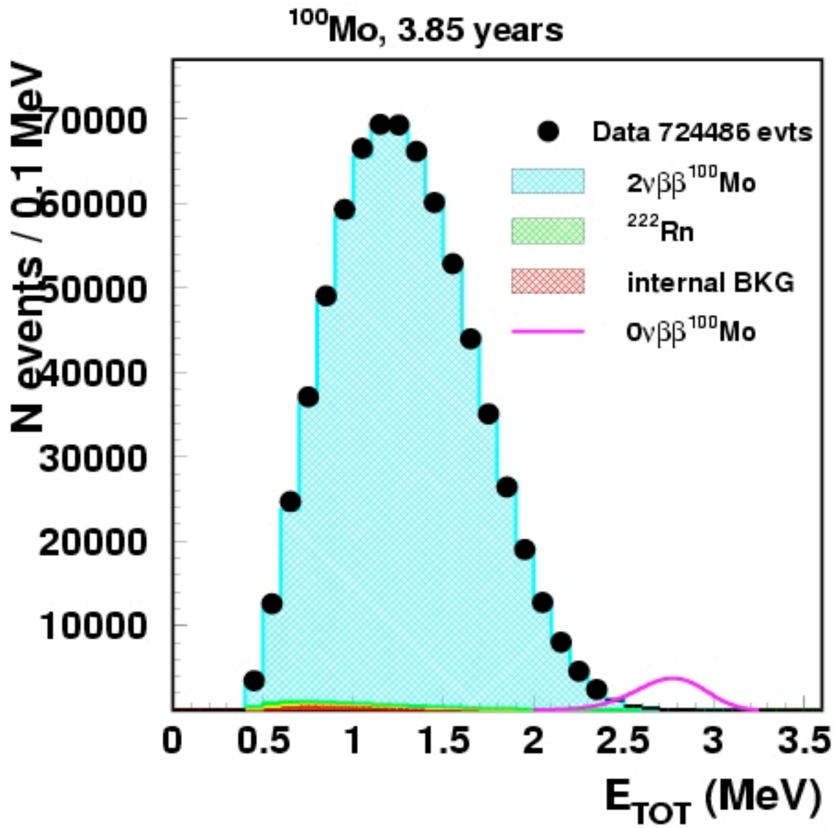
^{100}Mo: $T_{1/2}$(ββ2ν) =(7.11 ± 0.02(stat) ± 0.54(syst))·10^{18} y

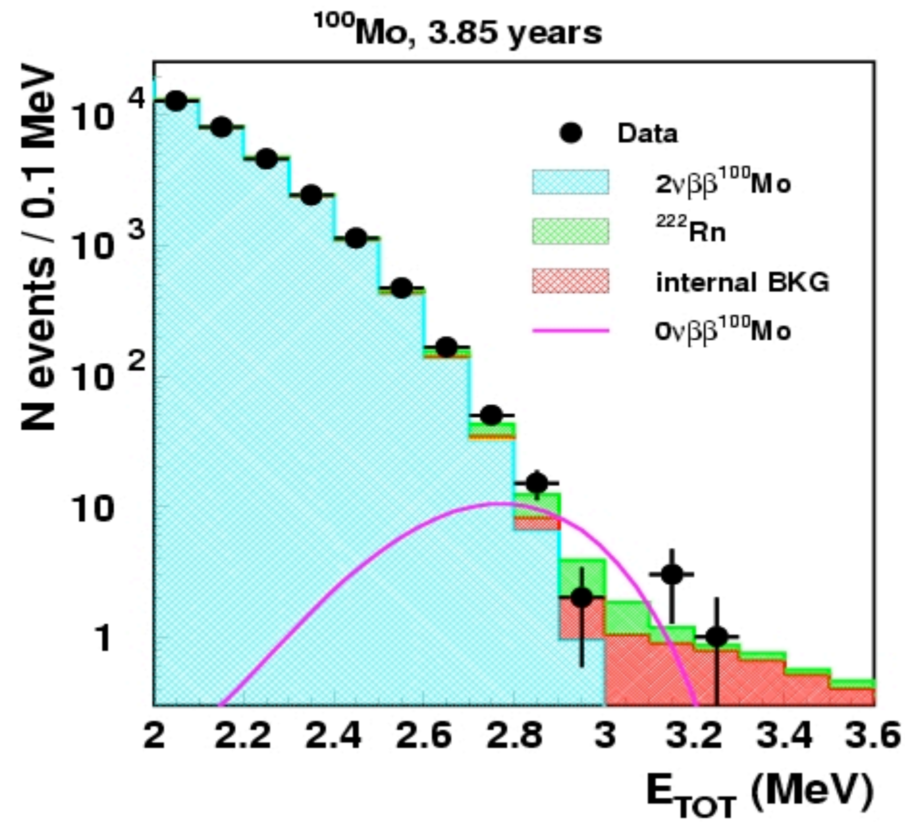
Phys.Rev.Lett. 95, 182302 (2005)

«ββ factory» – tool for precision tests

$0\nu\beta\beta$ of ^{100}Mo

Data until the end of 2008





[2.8 , 3.2] MeV:
Data: 20 events, Expected: 18.6 events
Excluded at 90% C.L. 9.6 events
Efficiency ε= 0.0726

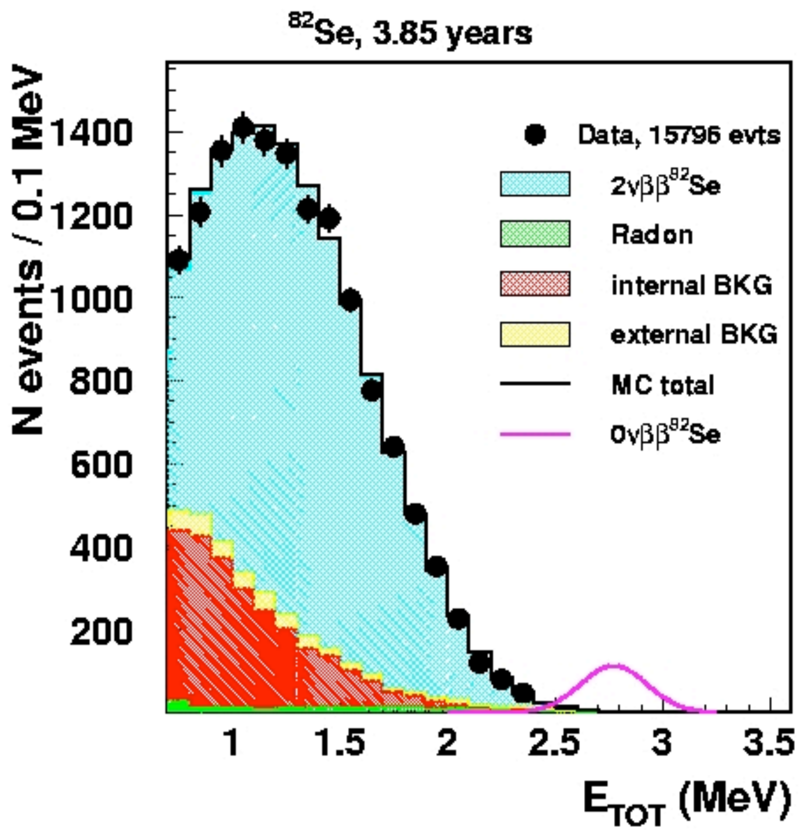
MCLIMIT : [2.0, 3.2] eV
18 events excluded
Total mean 0v efficiency ε = 0.174

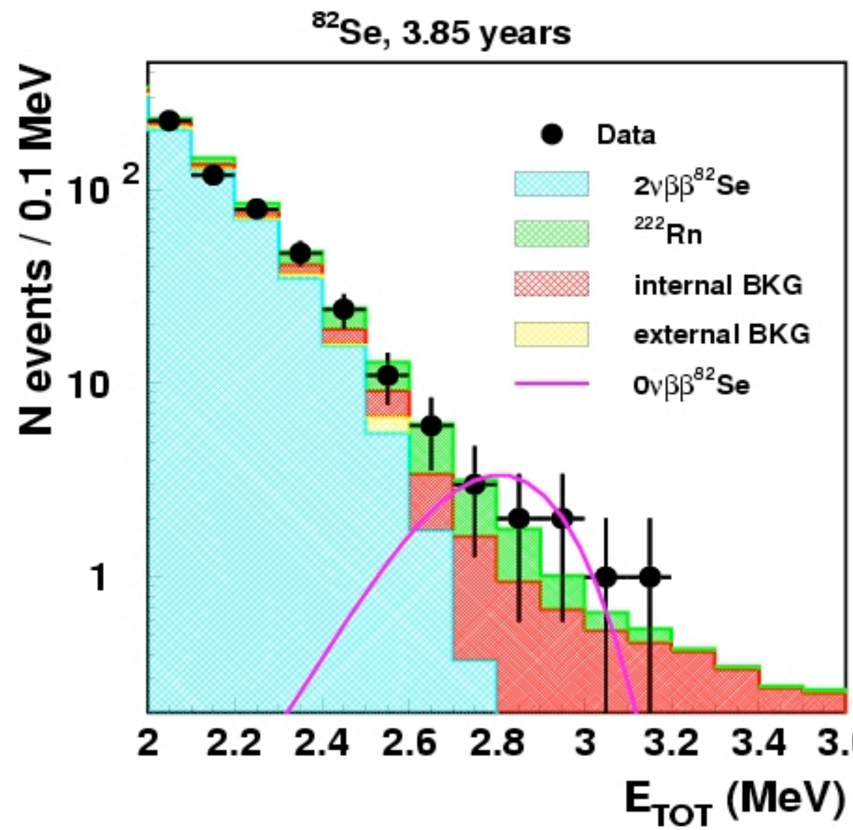
Both simple counting and likelihood methods are consistent

$T_{1/2}$ ($0\nu\beta\beta$) > 1.1 x 10^{24} y @ 90% C.L.
$\langle m_\nu \rangle$ < 0.45 – 0.93 eV

$0\nu\beta\beta$ of ^{82}Se

Data until the end of 2008



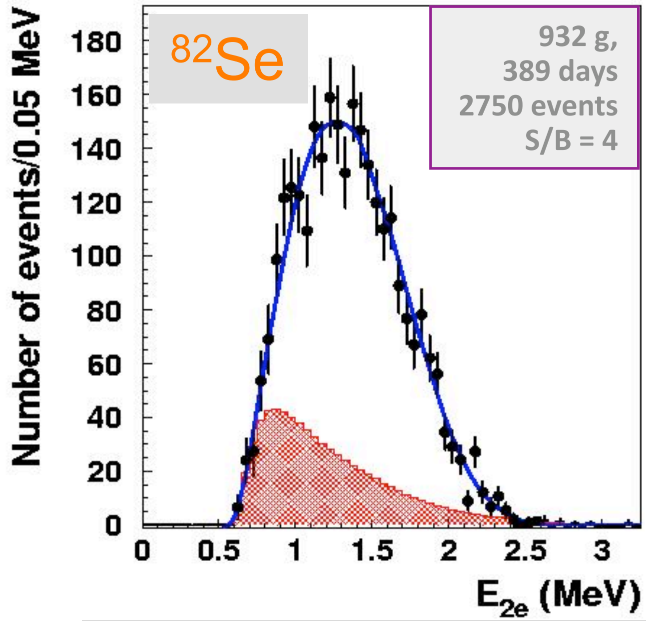


[2.6 , 3.2] MeV:
Data: 15 events, Expected: 13.2 events
Excluded at 90% C.L. 8.9 events
Efficiency ε= 0.151

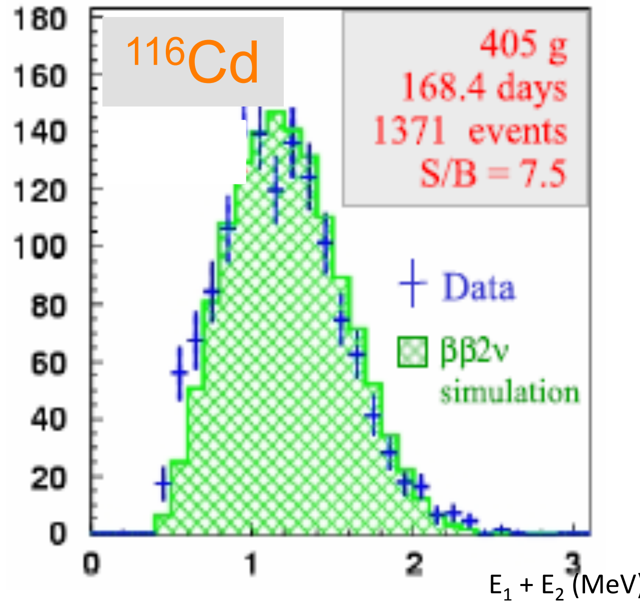
MCLIMIT : [2.0, 3.2] MeV
9.8 events excluded
Total mean 0v efficiency ε = 0.182

$T_{1/2}$ ($0\nu\beta\beta$) > 3.6 x 10^{23} y @ 90% C.L.
$<m_\nu>$ < 0.89 – 1.61 eV

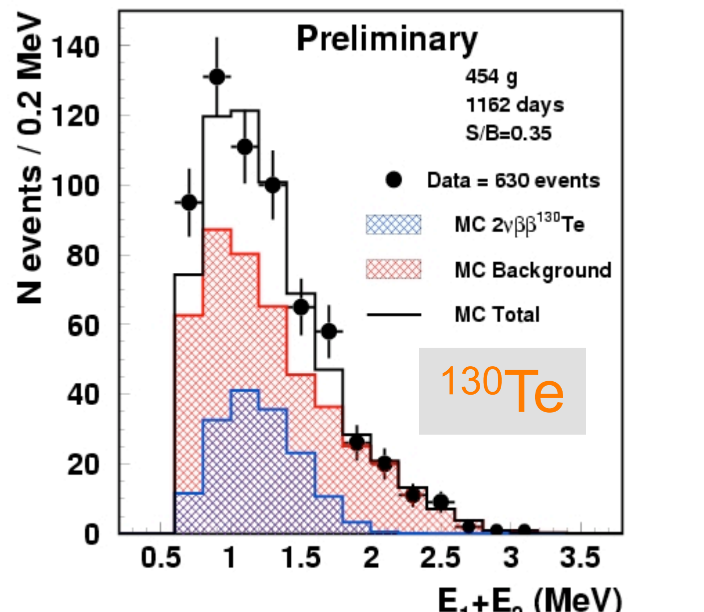
Results of $2\nu\beta\beta$ measurements
Summer 2009



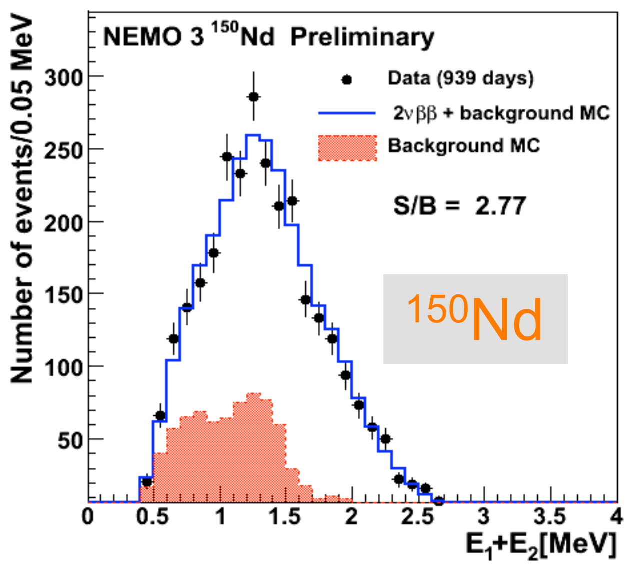
9.6 ± 0.3 (stat) ± 1.0 (sys) 10^{19} y



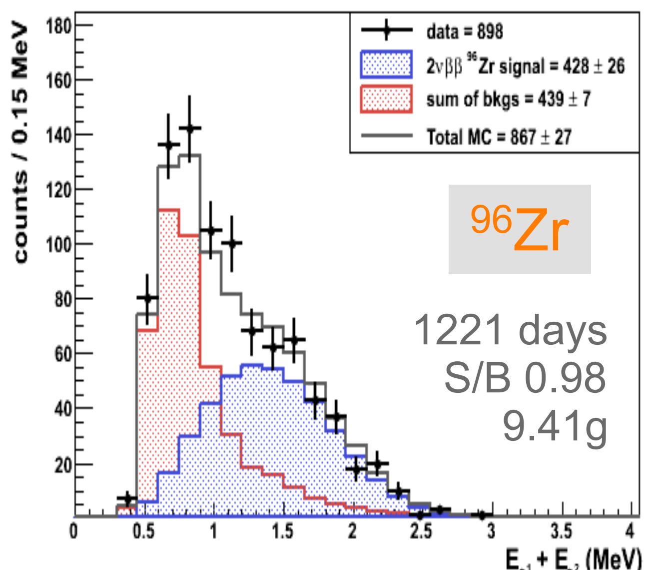
2.8 ± 0.1 (stat) ± 0.3 (sys) 10^{19} y



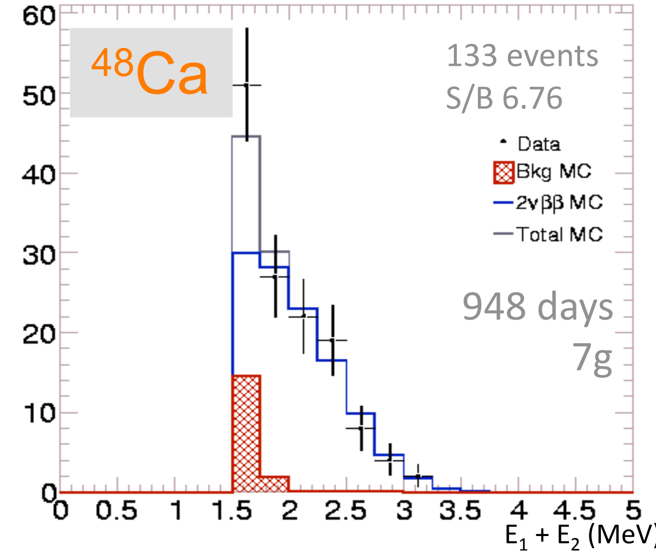
6.9 ± 0.9 (stat) ± 1.0 (sys) 10^{20} y



$9.11^{+0.25}_{-0.22}$(stat) ± 0.63 (sys) 10^{18} y



2.35 ± 0.14 (stat) ± 0.16 (sys) 10^{19} y



$4.4^{+0.5}_{-0.4}$ (stat)± 0.4 (sys) 10^{19} y

Results of 0νββ results
Summer 2009

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

Isotope	Exposure (kg·y)	$T_{1/2}(0\nu\beta\beta)$ [years]	$\langle m_\nu \rangle$ [eV]	NME reference
^{100}Mo	26.6	$> 1.1 \cdot 10^{24}$	**< 0.45 – 0.93**	1-3
^{82}Se	3.6	$> 3.6 \cdot 10^{23}$	**< 0.9 – 1.6**	1-3
			< 2.3	7
^{150}Nd	0.095	$> 1.8 \cdot 10^{22}$	**< 1.5 – 2.5**	4,5
			< 4.0 – 6.8	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

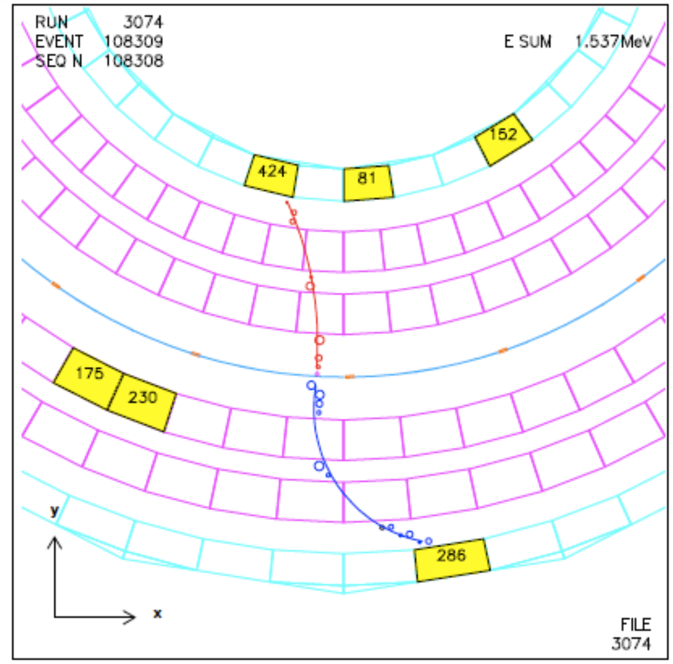
- Nuclear Matrix Elements references:

[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

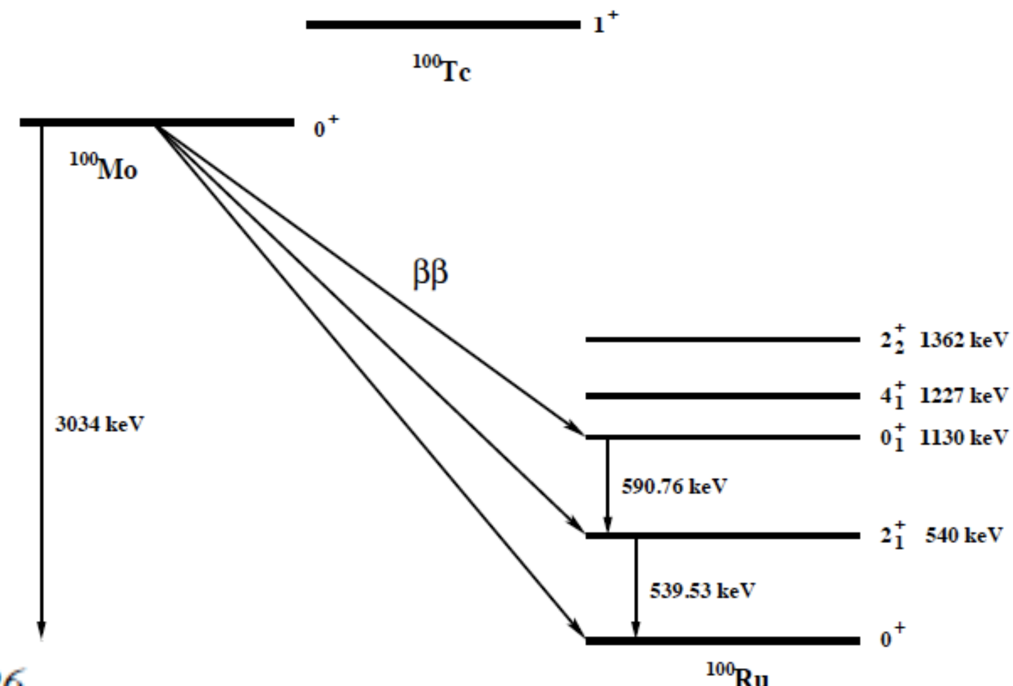
2νββ and 0νββ of ^{100}Mo to excited states

Transition	$T_{1/2}$ (y) (this work)	Theory
0νββ $0^+ \to 2^+_1$	$> 1.6 * 10^{23}$ (*)	$6.8 * 10^{30}$ $<m_\nu>$ $2.1 * 10^{27} < \lambda >$
2νββ $0^+ \to 2^+_1$	$> 1.1 * 10^{21}$	$2.1 * 10^{21}$ - $5.5 * 10^{25}$
0νββ $0^+ \to 0^+_1$	$> 8.9 * 10^{22}$(*)	$7.6 * 10^{24}$ $<m_\nu>$ - $2.6 * 10^{26}$ $<m_\nu>$
2νββ $0^+ \to 0^+_1$	$[5.7^{+1.3}_{-0.9}$(stat) +/- $0.8 * 10^{20}$ (*)	$1.5 * 10^{20}$ - $2.1 * 10^{21}$

(*) Best limits or uncertainties



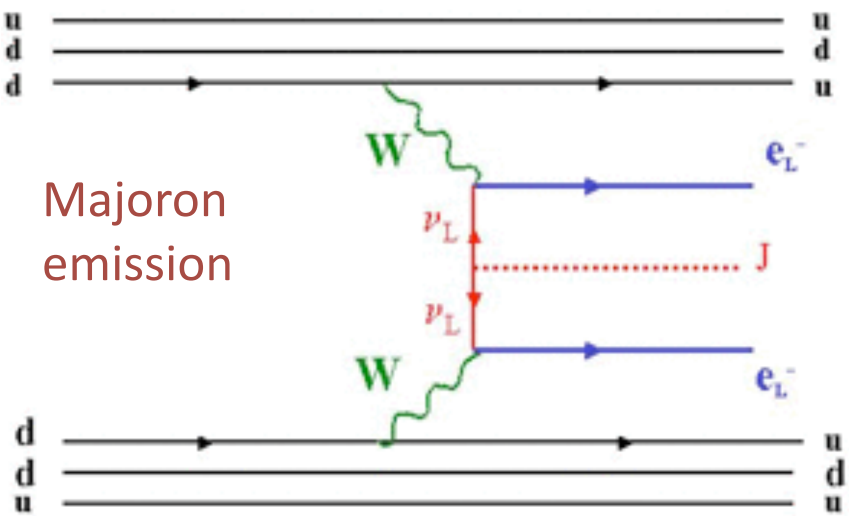
In-time coincidence



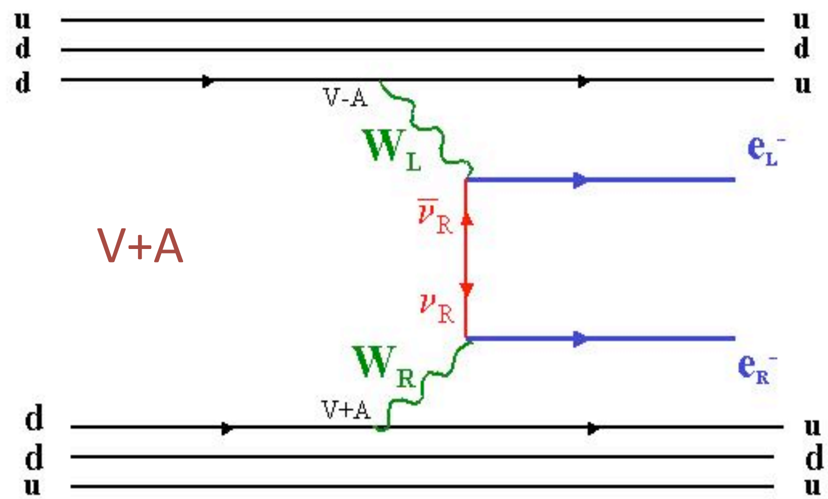
NEMO Collaboration / Nuclear Physics A 781 (2007) 209–226

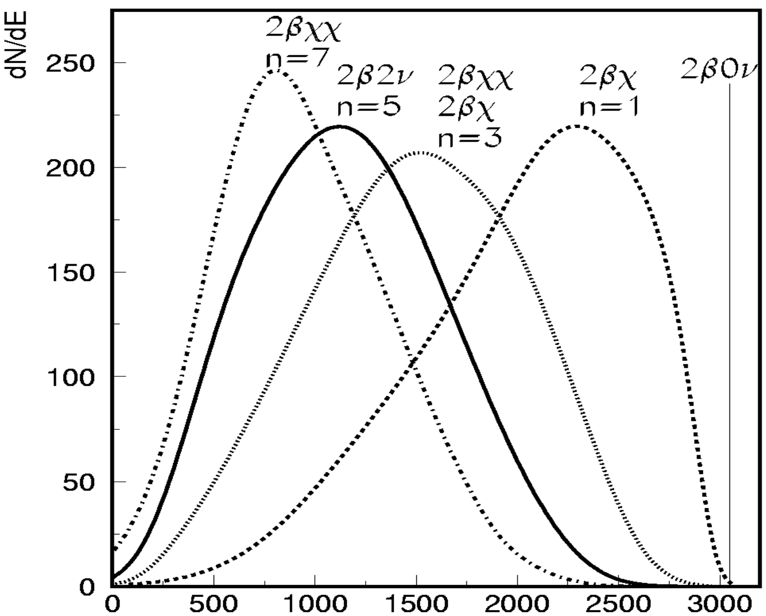
V+A currents & Majoron

Majoron emission



V+A





Energy (keV)

	V+A *	Majoron(s) emission (n=spectral index)**			
	$T_{1/2}(0\nu\beta\beta)$ [years]	n=1	n=2	n=3	n=7
^{100}Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $g_{ee}<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>2.4\cdot10^{23}$ $\lambda<2.\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{22}$	$>5\cdot10^{20}$

* Phase I+Phase II data

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

NEMO-3 → SuperNEMO challenges

F. T. Avignone, S. R. Elliott and J. Engel,
``Double Beta Decay, Majorana Neutrinos, and Neutrino Mass,''
Rev. Mod. Phys. 80, 481 (2008) [arXiv:0708.1033 [nucl-ex]].

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times 10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta E}}$$

n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source
M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts (keV · kg · y)
ΔE – energy resolution (keV)

NEMO-3		SuperNEMO
^{100}Mo	isotope	^{82}Se
7 kg	isotope mass M	100-200 kg
8 %	efficiency ε	~ 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil	^{208}Tl < 2 μBq/kg ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

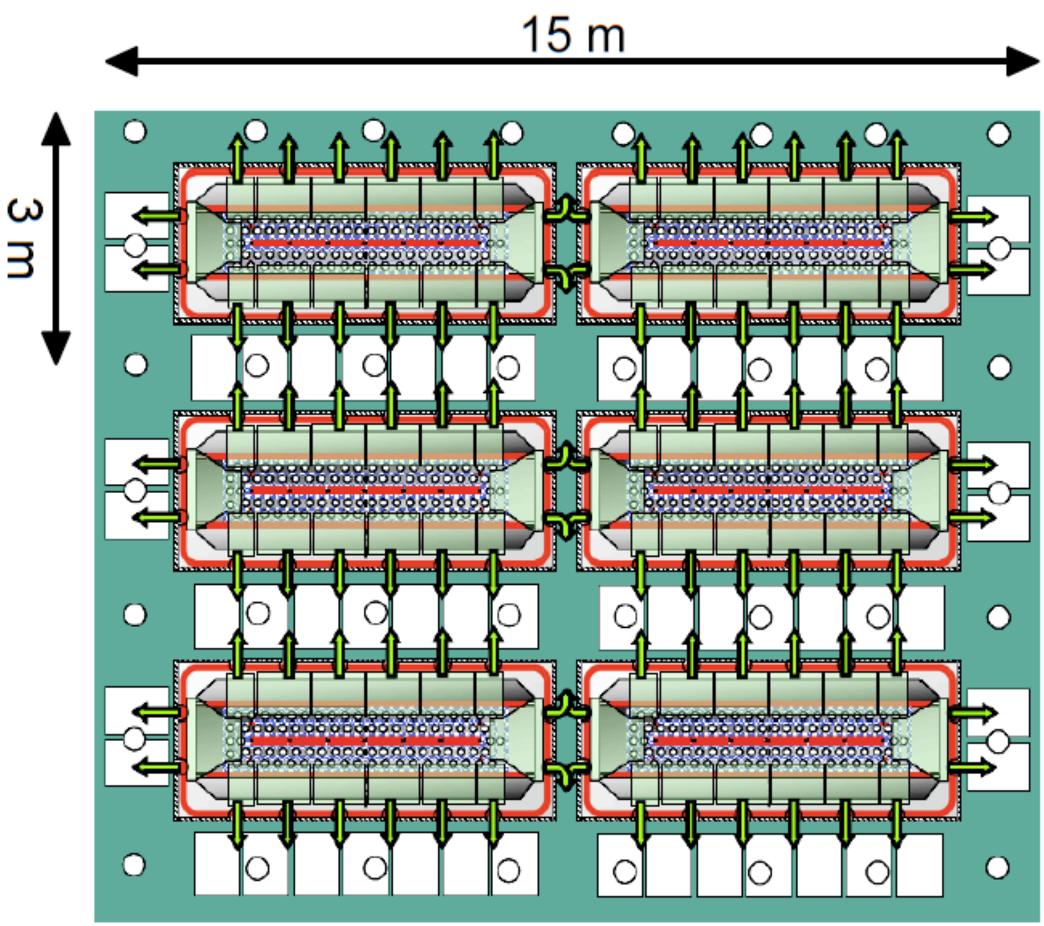
$T_{1/2}(0\nu\beta\beta) > 1.4 \times 10^{24}$ y
$\langle m_\nu \rangle < 390 – 810$ meV

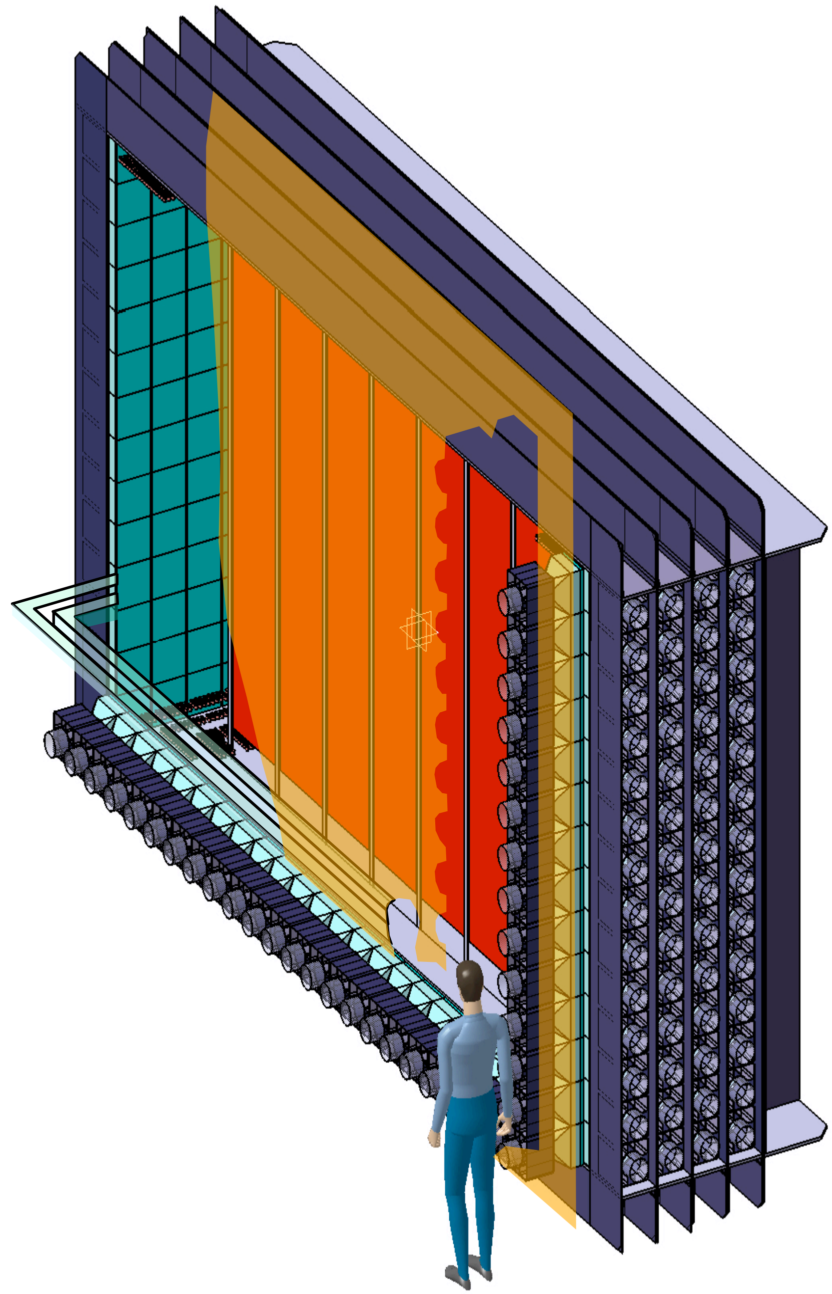
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y
$\langle m_\nu \rangle < 40 - 100$ meV

SuperNEMO - conceptually

20 modules for 100 kg

Source: ~ 5kg (4 0 mg/cm^2, 12m^2)
Tracking: ~2,100 drift cells).
Calorimeter: ~600 blocks

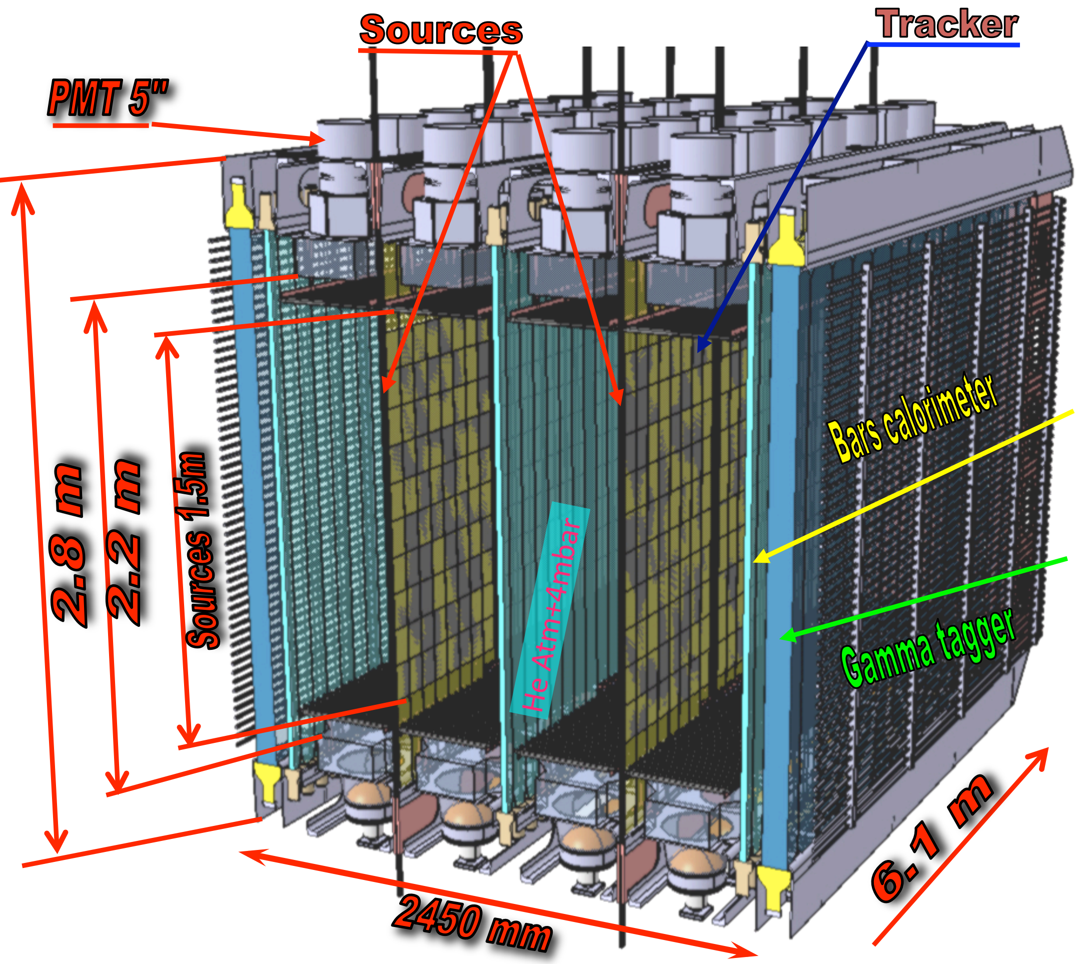


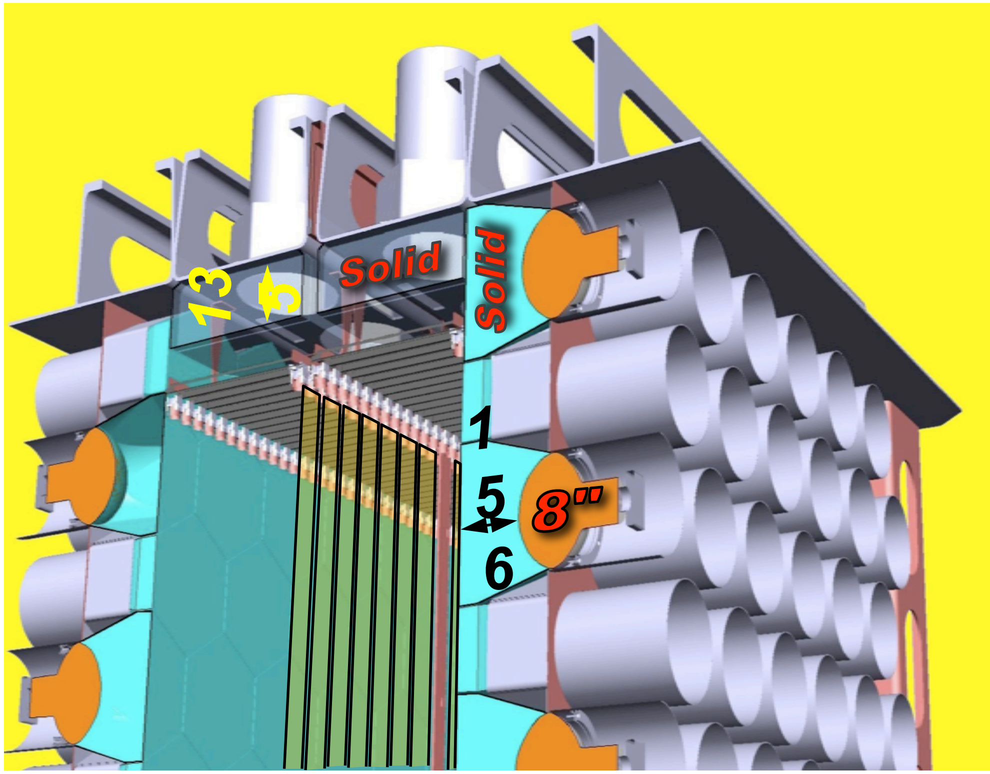


LABORATOIRE DE L'ACCÉLÉRATEURLINÉAIRE

IN2P3-CNRS et Université PARIS-SUD Centre Scientifique d'Orsay - Bât 200 - B.P. 34 91898 ORSAY Cedex (France)

J.FORGET & C.BOURGEOIS – SuperNEMO module

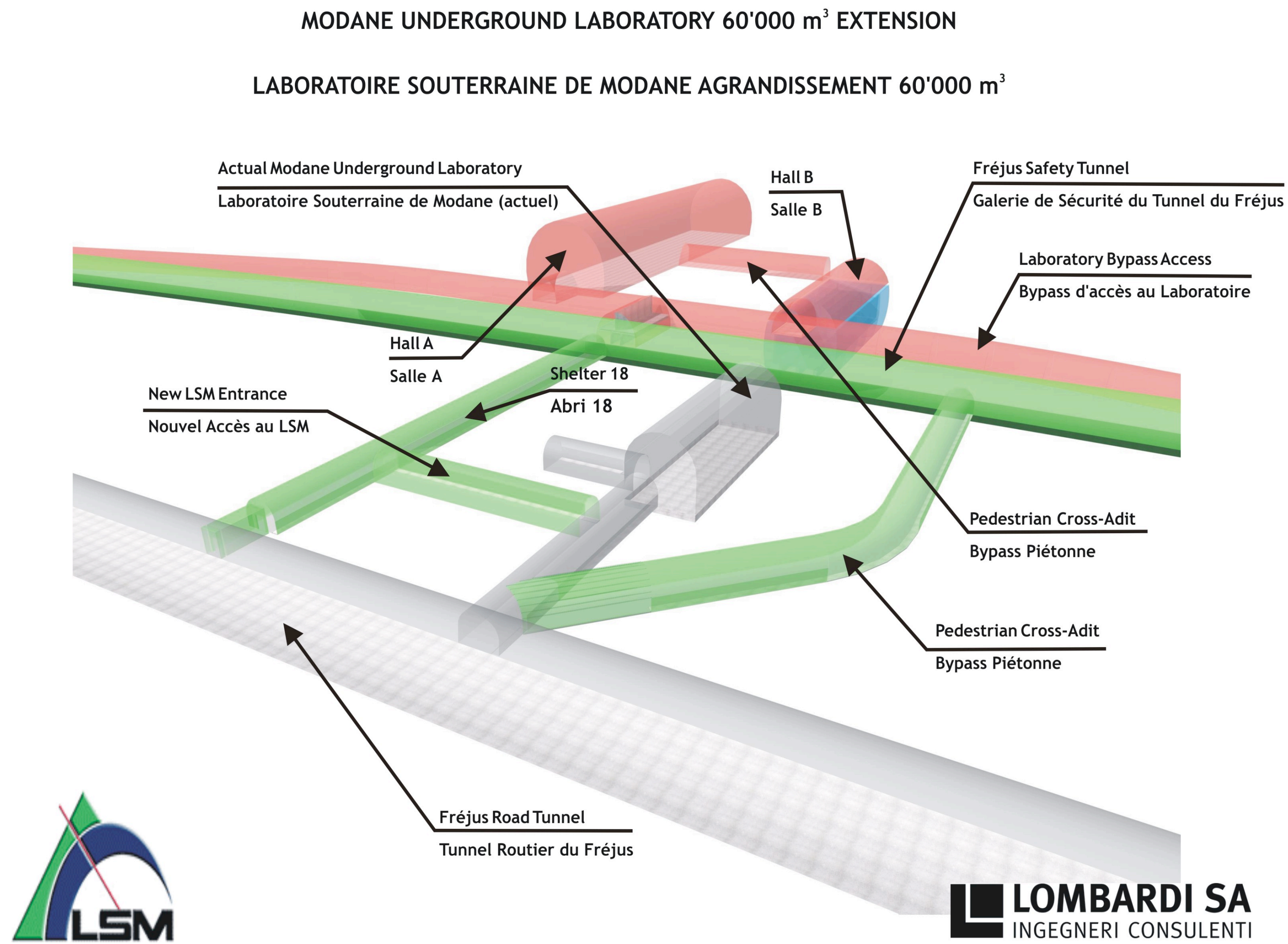




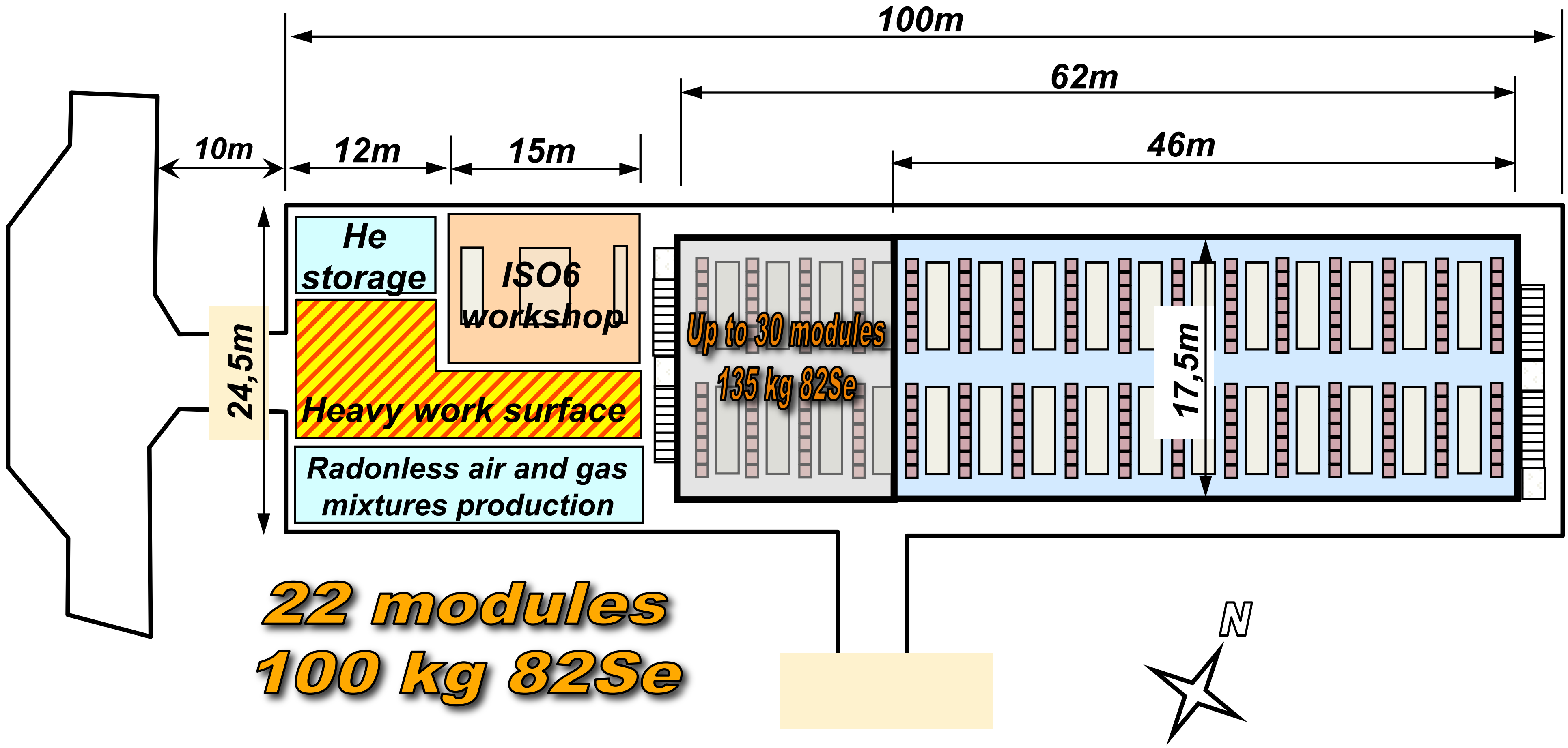
Bars design

Blocks design

ULISSE project

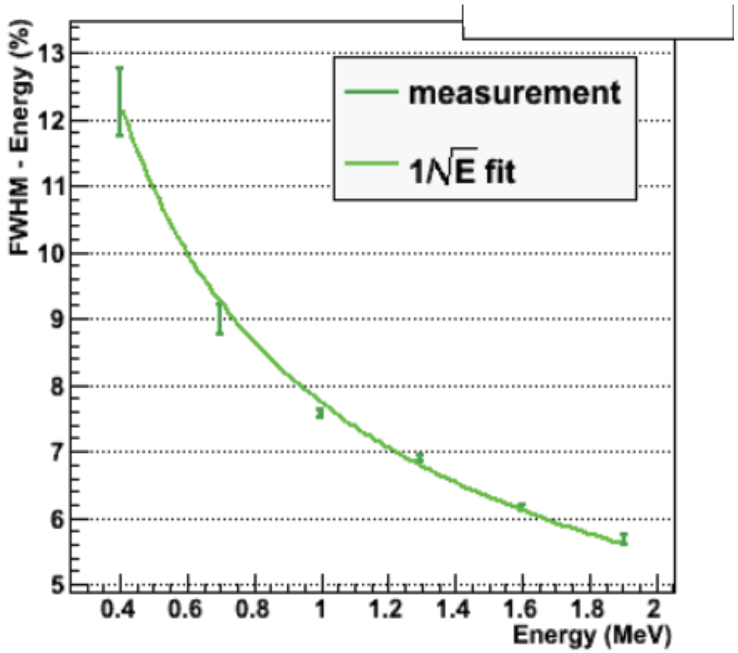


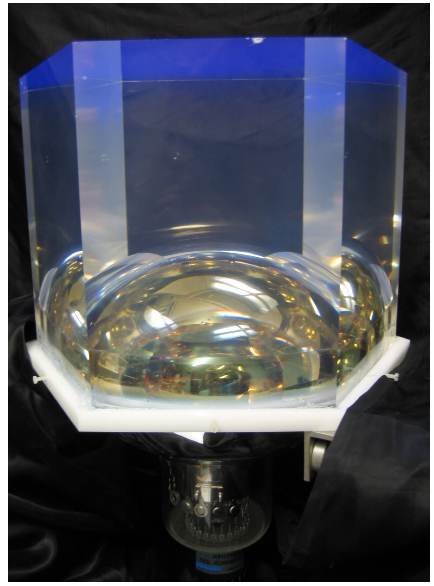
Future LSM Hall A



SuperNEMO: Calorimeter R&D

ΔE/E ~ 7.2 % at 1 MeV (corrected)

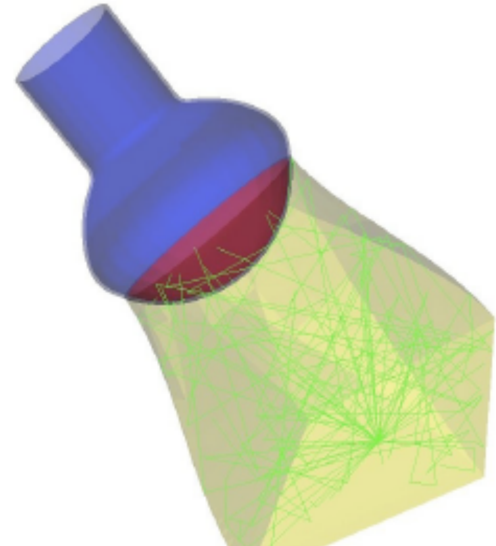




8” Hamamatsu
R5912-MOD
Super-Bialkali
8 Dynodes

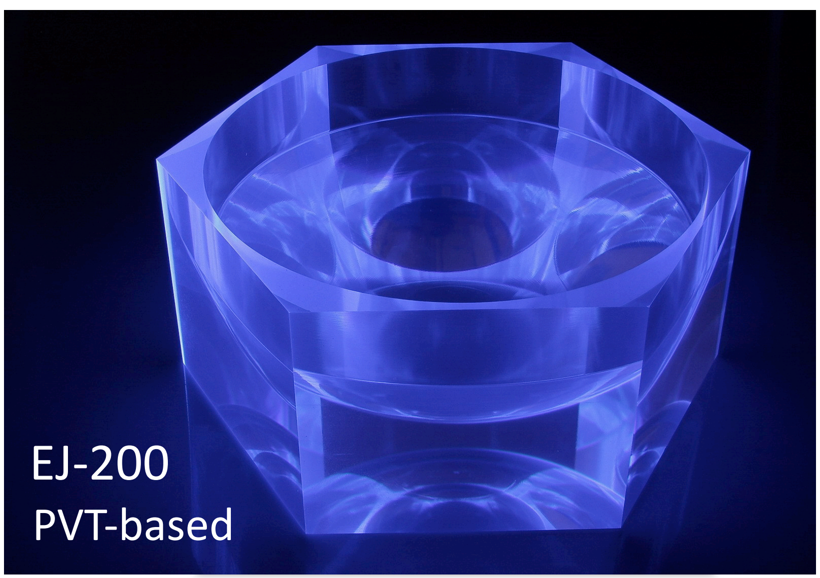
Or

~~**8” Photonis**~~
~~**“35% QE”**~~



GEANT4 optical simulation

2m-long scintillator bars
(a cheaper option)

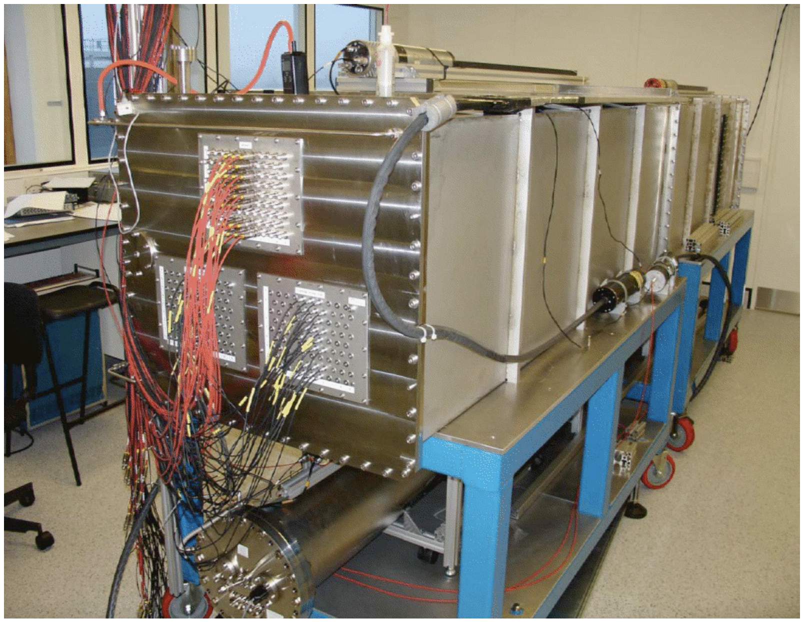


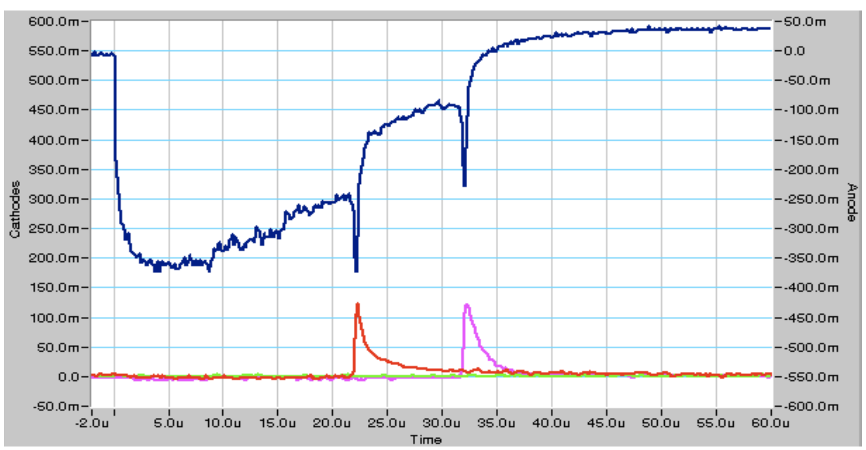
Similar
to BC408

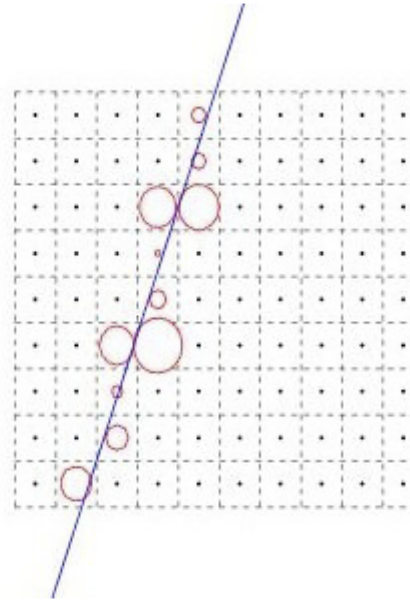
SuperNEMO tracker R&D

- Optimize length, wire material and diameter, read-out, gas mixture etc
- Several 1-cell and two 9-cell prototypes built and tested
- 90-cell prototype:

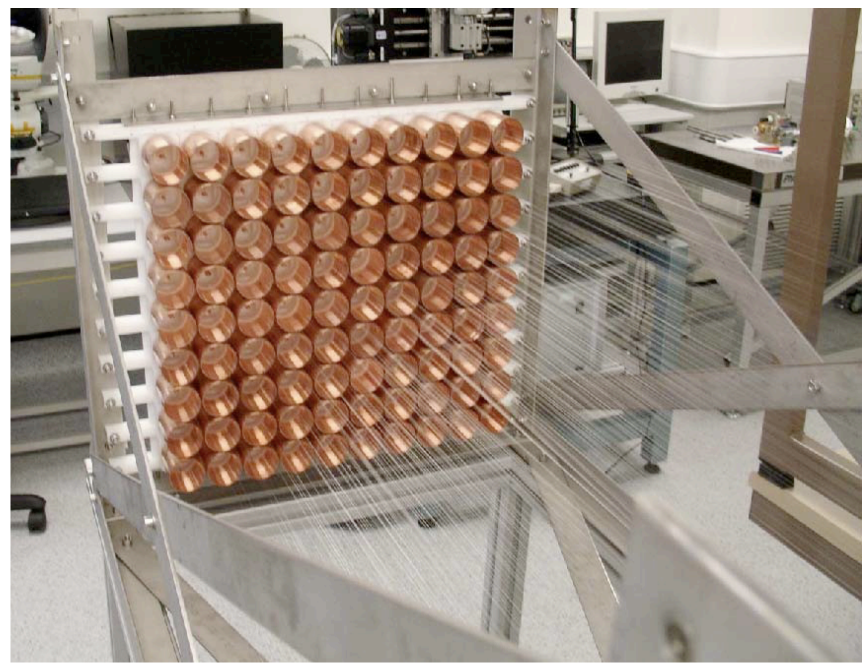
r – resolution	**0.7 mm**
z – resolution	**1.3 cm**





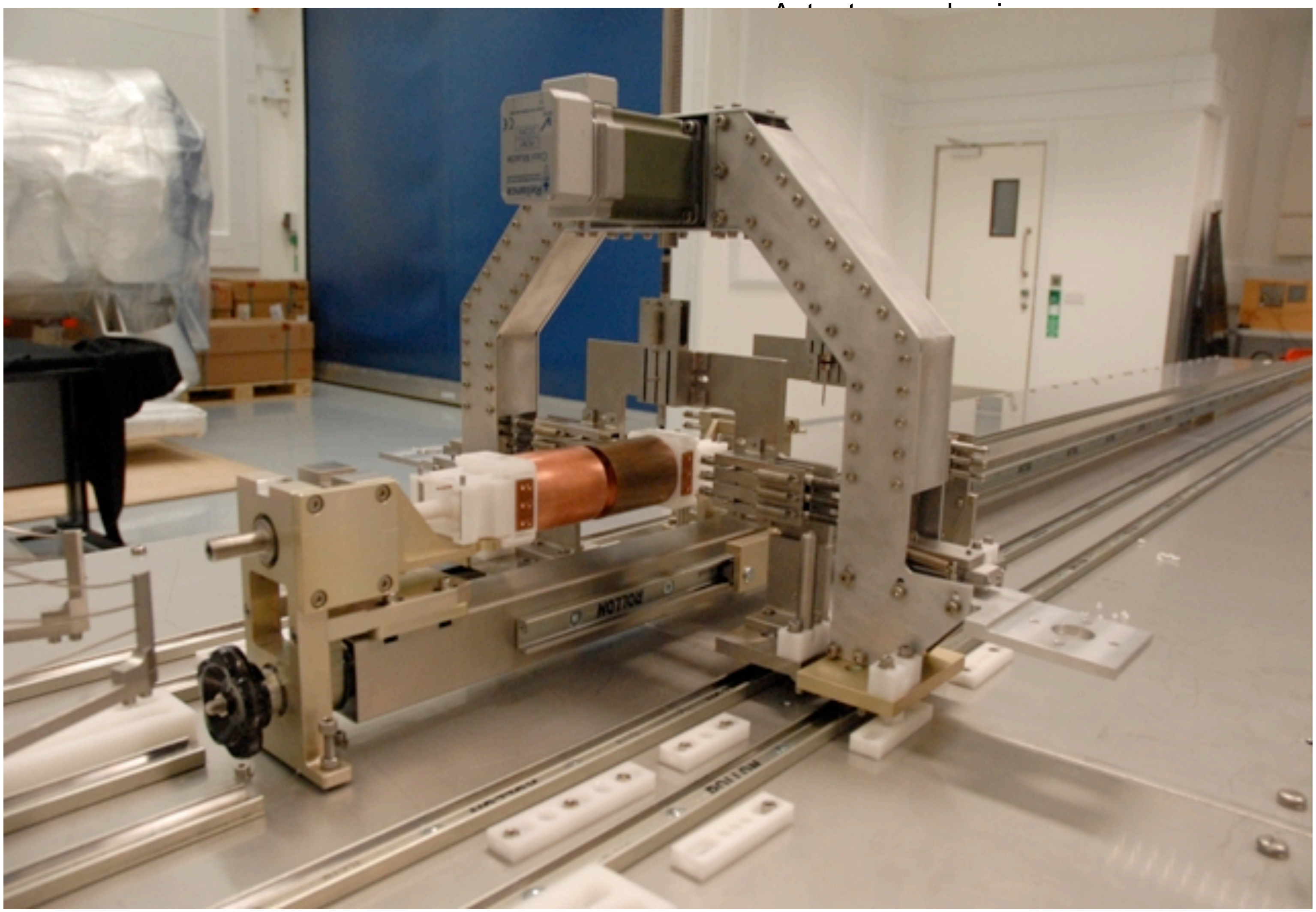


90-cell prototype
Manchester



Tracker: fully automated wiring

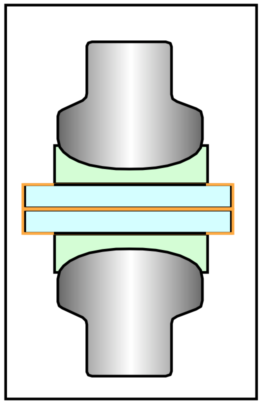
- ~500,000 wires to be strung, crimped, terminated
- Wiring robot being developed in collaboration with Mullard Space Science Lab (UCL)

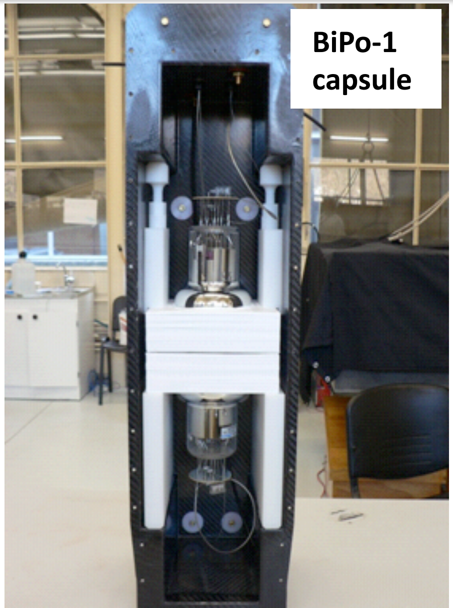


BiPo R&D

(for measuring foil radio-purity)

BiPo-1 capsule

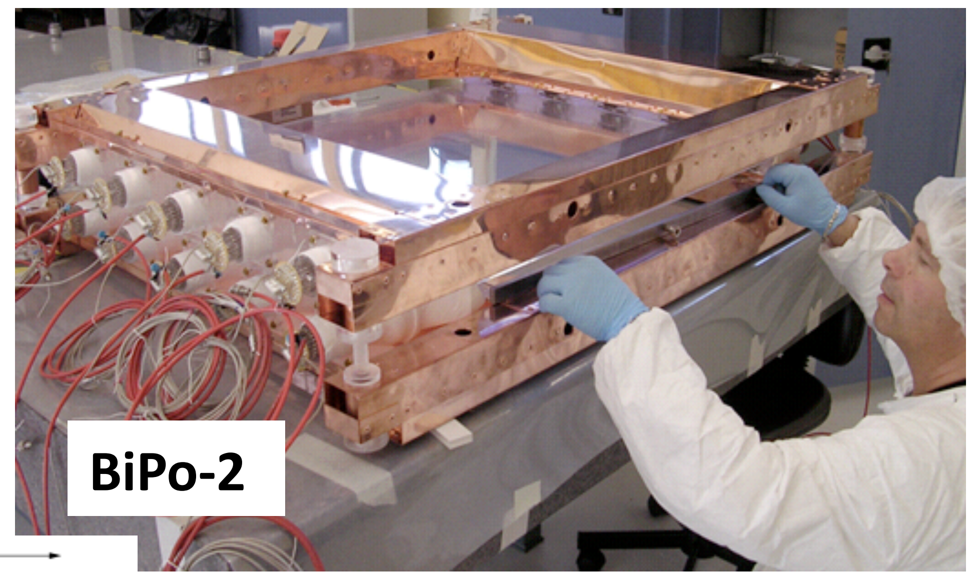


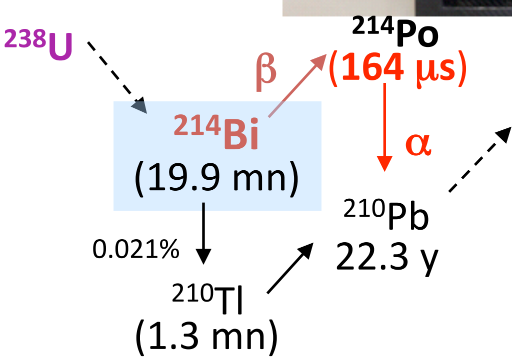


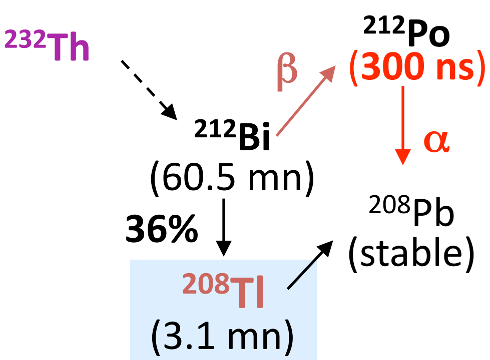
Objectives :

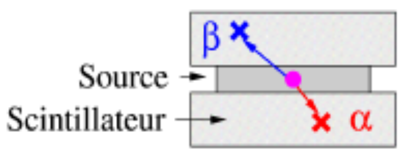
to mesure ^{208}Tl < 2 μBq/kg & ^{214}Bi < 10 μBq/kg in ββ source foil (5kg/month)

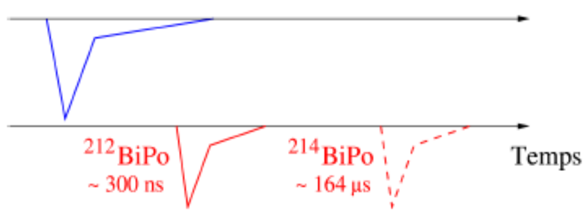
- ✓BiPo-1: 10 capsules in operation since 12/2007,
- ✓current sensitivity < 7.5 μBq/10m² x 40 mg foil
- ✓BiPo-2 and Phoswhich under development











Summary and outlook

- NEMO-3 running (through 2010) and produces unique results
  - ✓ many best results in $0\nu\beta\beta$ and $2\nu\beta\beta$

    ^{100}Mo (2009): $T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{24}$ y (90% CL) $\langle m_\nu \rangle <$ (450 – 930) meV

    ^{82}Se (2009): $T_{1/2}^{0\nu\beta\beta} > 3.6 \times 10^{23}$ y (90% CL) $\langle m_\nu \rangle <$ (900 – 2300) meV

  - ✓ results for 5 other isotopes: ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd
  - ✓ results on transitions to excited states, V+A, Majorons, SSD vs HSD, …

- Next: SuperNEMO
  - ^{82}Se
  - sensitivity $T_{1/2}(0\nu) = (1\text{-}2) \times 10^{26}$ y (500 kg*y exposure)

    $\langle m_\nu \rangle \leq$ 40 – 140 meV (NME uncertainty QRPA + SM)