A search for neutrinoless double beta decay with NEMO-3 and SuperNEMO experiments

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Warszawa, 15 maja 2009

Outline:

- Physics motivation for $0\nu\beta\beta$
- Practical factors
- The NEMO-3 experiment
- SuperNEMO
- Outlook

Credits:

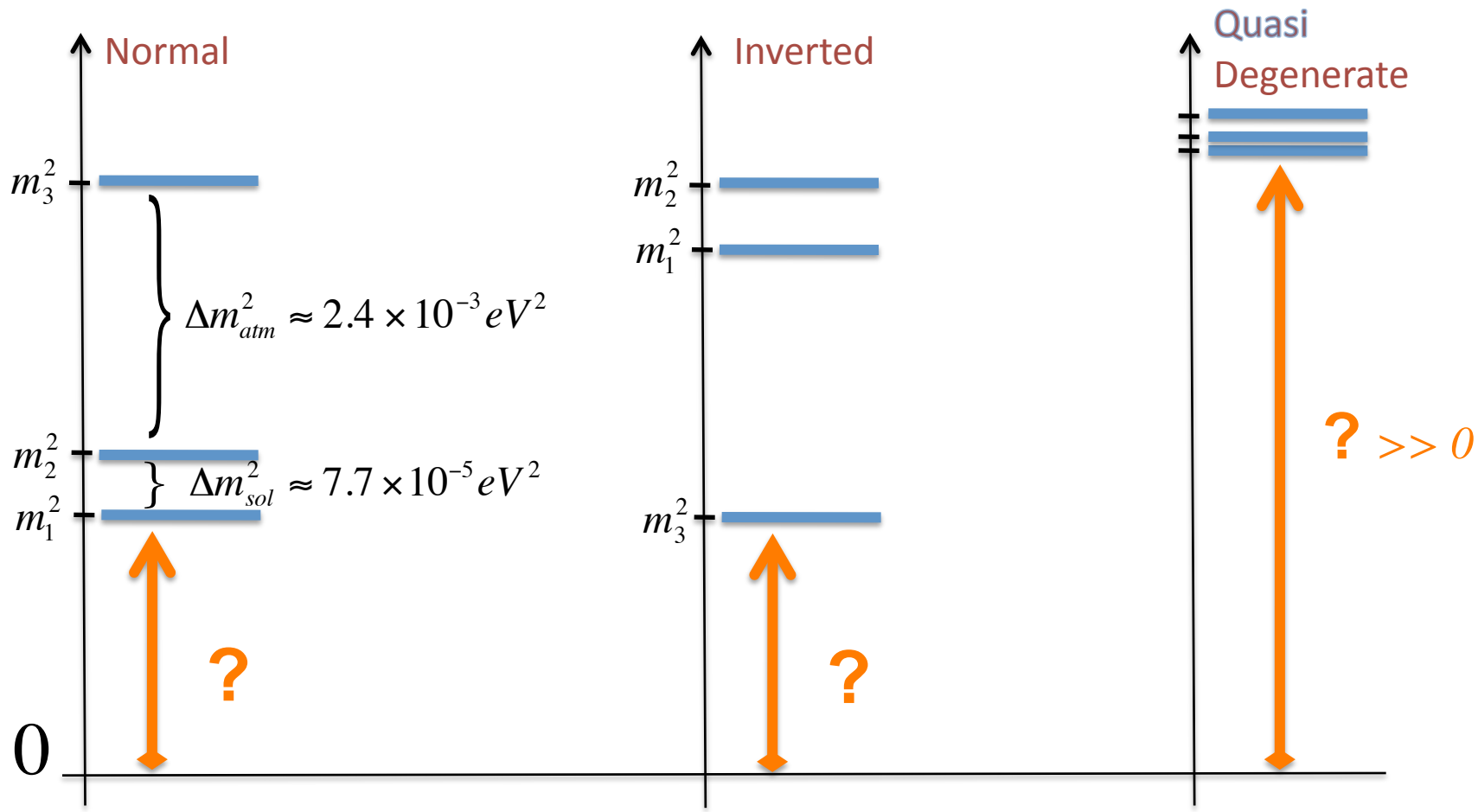
✓Most images from NEMO colleagues

UT group:

✓so far has worked primarily on SuperNEMO

✓joined NEMO-3 work-force recently

Neutrino mass and mass ordering



$m(\text{“}\nu_e\text{”}) < 2.2$ eV

Mainz-Troitsk ^{3}H decay

$\Sigma m_\nu < 0.14 - 1.3$ eV

Cosmological models

$m(\text{“}\nu_\mu\text{”}) < 190$ keV

$m(\text{“}\nu_\tau\text{”}) < 18.2$ MeV

Main open questions

- What is the absolute mass scale?
- What is the mass ordering ("mass hierarchy")?
- How strong is the subdominant mixing (angle θ_{13} in the PMNS matrix) ?
- Do neutrinos violate CP symmetry (angle δ in the PMNS matrix)?
- Are neutrinos Majorana ($\nu \equiv \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$) particles?
- Are there sterile neutrinos?
- …

Main open questions and $0\nu\beta\beta$

- ✓ What is the absolute mass scale?
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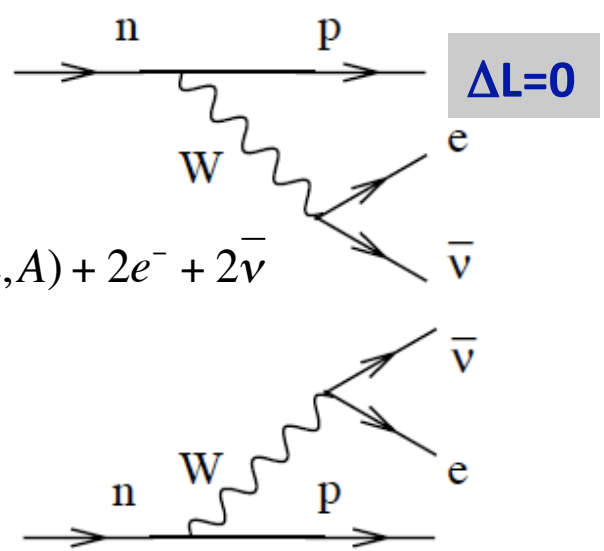
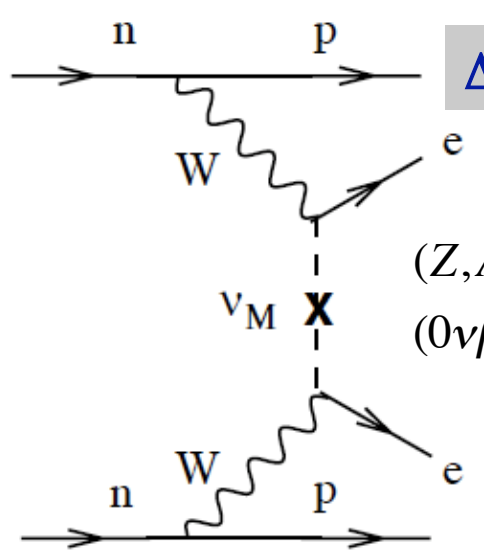
- ❑ Are there sterile neutrinos?



ΔL=0

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

$(2\nu\beta\beta)$



ΔL=2

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

$(0\nu\beta\beta)$

and if $m_\nu \neq 0$

Majorana mass and the see-saw mechanism

With massive neutrinos, we need to add a right-handed neutrino field

$$e_R \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \nu_R$$

$$L_{m_\nu} = m_D \phi \bar{\nu}_R \nu_L + M_R \phi \bar{\nu}_R^c \nu_R^c + m_D \phi \bar{\nu}_L^c \nu_R^c \qquad [\bar{\nu}_L^c, \bar{\nu}_R] \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R^c \end{bmatrix} + \text{h.c.}$$

$$D_\nu = \begin{bmatrix} \frac{m_D^2}{M_R} & 0 \\ 0 & M_R \end{bmatrix}$$

$$m_1 \simeq \frac{m_D^2}{M_R} \qquad \text{and} \qquad m_2 \simeq M_R$$

$$L_{m_\nu} = m_1 \bar{\nu}_1 \nu_1 + M_R \bar{\nu}_2 \nu_2$$

$$\nu_1 = -i(1 - \frac{1}{2}\rho^2)(\nu_L - \nu_L^c) + i\rho(\nu_R^c - \nu_R)$$

$$\nu_2 = \rho(\nu_L + -\nu_L^c) + (1 - \frac{1}{2}\rho^2)(\nu_R + \nu_R^c)$$

Neutrino mixing and oscillations

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

3 mixing angles + 1 phase

$(c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta} \\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Solar

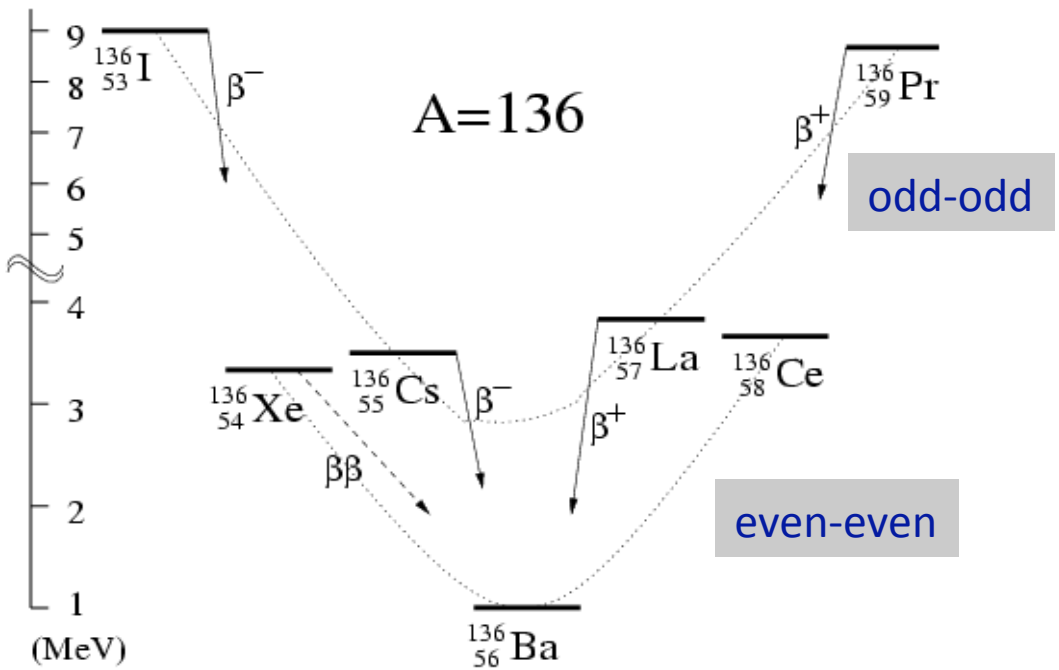
Atmospheric Reactor
$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

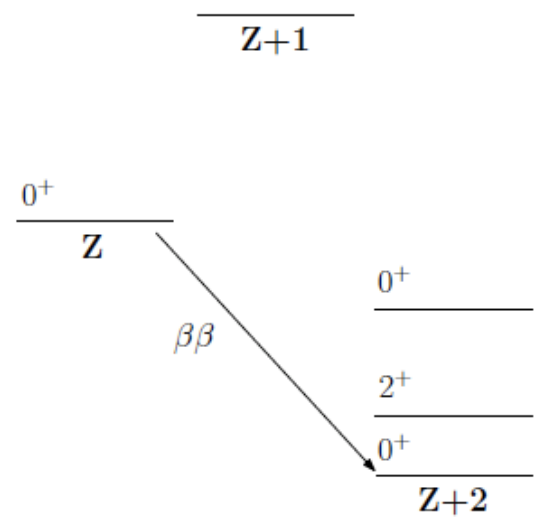
Atmospheric
$\nu_\mu \leftrightarrow \nu_\tau$

Majorana Phases
$0\nu\beta\beta$

Phenomenology of 0νββ and 2νββ

- pairing interaction between nucleons (even-even nuclei more bound than the odd-odd nuclei)
- e.g. ^{136}Xe and ^{136}Ce are stable against β decay, but unstable against ββ decay ($\beta^-\beta^-$ for ^{136}Xe and $\beta^+\beta^+$ for ^{136}Ce)





m(A,Z) > m(A,Z+2)

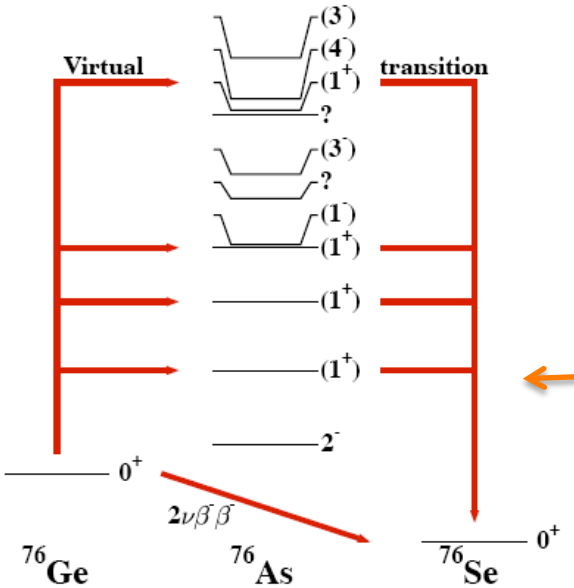
There are 35 $\beta^-\beta^-$ emitters
6 $\beta^+\beta^+$

Phenomenology of 0νββ and 2νββ (2)

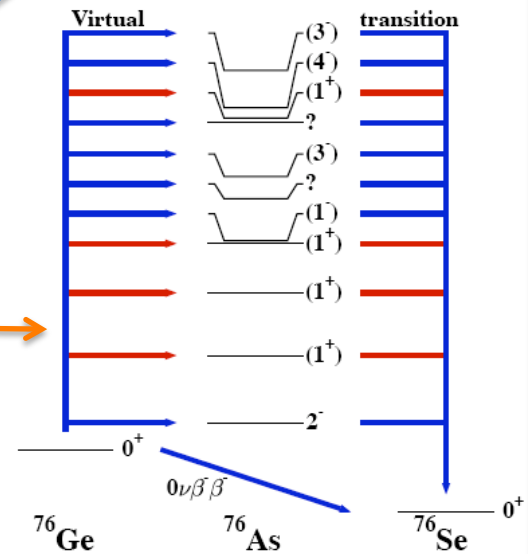
$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta}^{11}, Z) \bullet \left| M_{2\nu}^{GT} \right|^2$$

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

Phase space
(very well known)



Nuclear matrix element (NME)
(challenging to calculate)

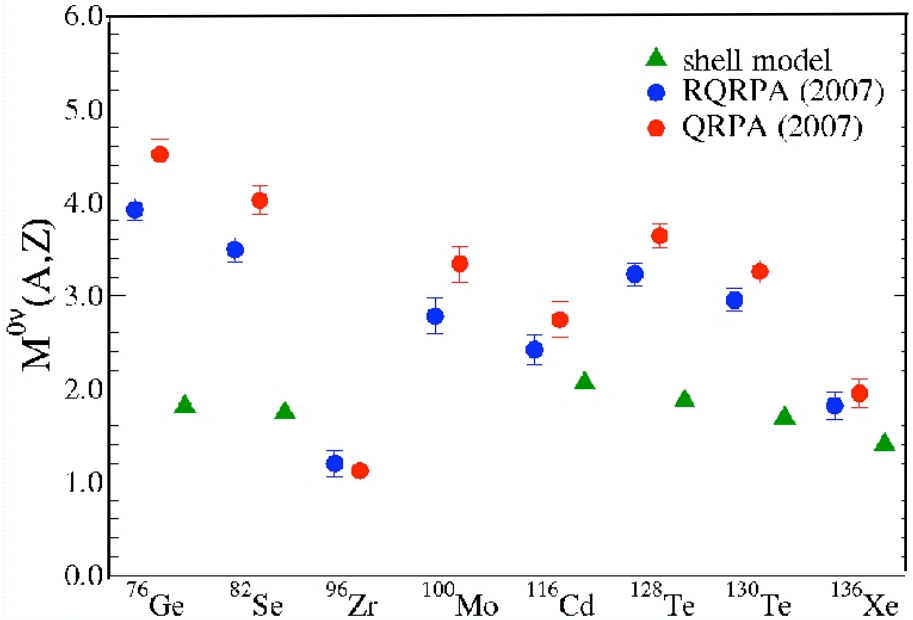


$$\left| \left\langle m_{\beta\beta} \right\rangle \right| \equiv \left| \; m_1 \left| U_{e1} \right|^2 + m_2 \left| U_{e2} \right|^2 e^{i\alpha^*} + m_3 \left| U_{e3} \right|^2 e^{i\beta^* - 2i\delta} \; \right|$$

$\alpha^*, \beta^* =$ linear combinations of α and β

Nuclear matrix elements

Shell Model (*Poves et al.*) vs QRPA



Different QRPA calculations

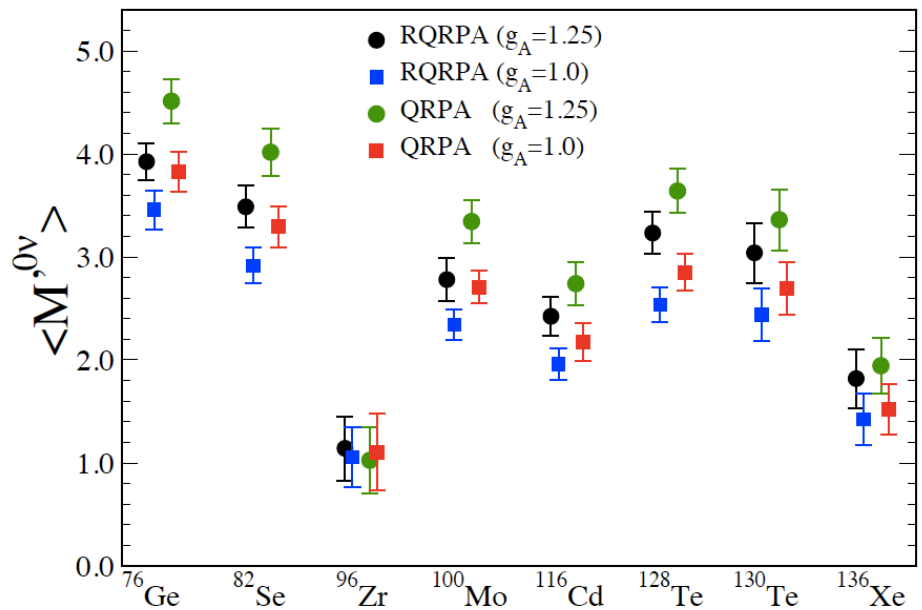


FIG. 1: Average nuclear matrix elements $\langle M'^{0\nu}\rangle$ and their variance (including the uncertainty coming from the experimental error in $M^{2\nu}$) for both methods and for all considered nuclei. For ^{136}Xe the error bars encompass the whole interval related to the unknown rate of the $2\nu\beta\beta$ decay.

Large uncertainties for the extraction of $<m_\nu>$

QRPA = quasi random phase approximation

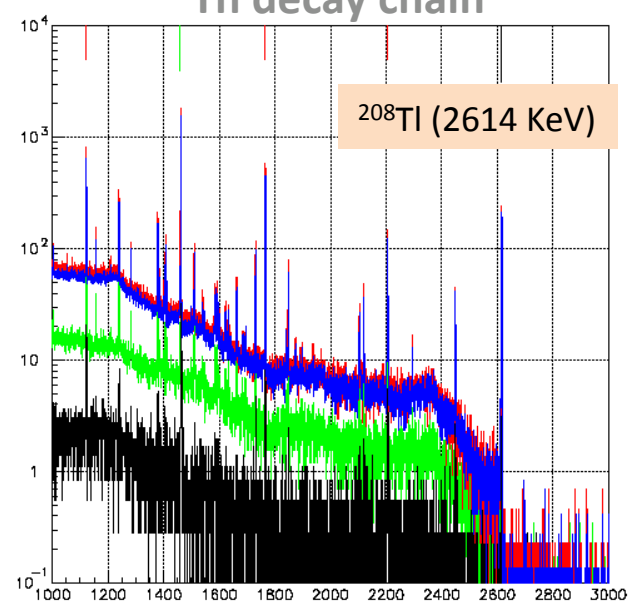
Practical matters

	$Q_{\beta\beta}$ (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

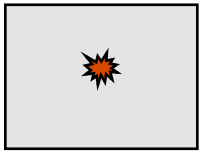


Hall B
Hall C
OPERA BOX
10 cm Pb shielding

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]].

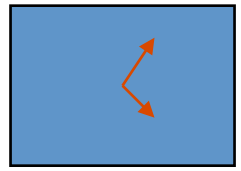
Experimental techniques

Calorimeter
Source=detector



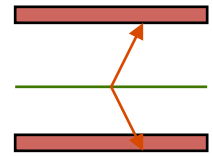
Resolution, efficiency

TPC (Xe)



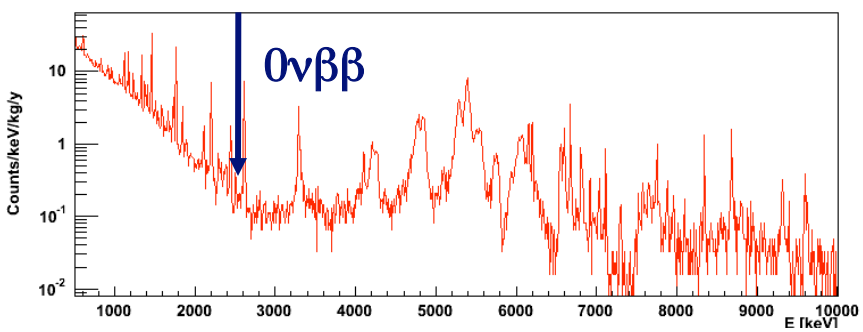
Efficiency, Mass

Tracking and calorimeter
Source ≠ detector



Background, isotope choice

Main features:
- High energy resolution
- Modest background rejection



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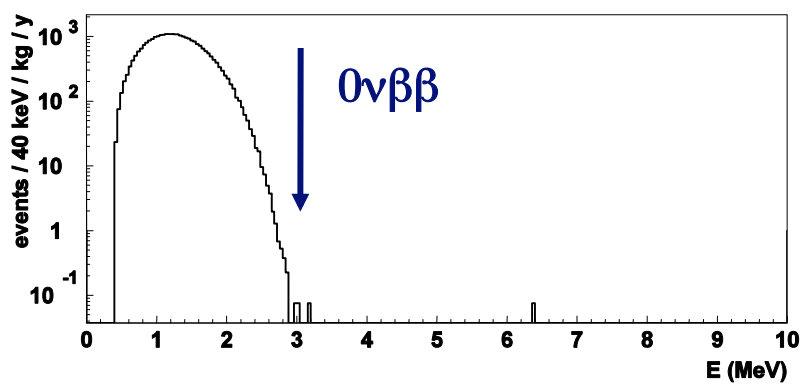
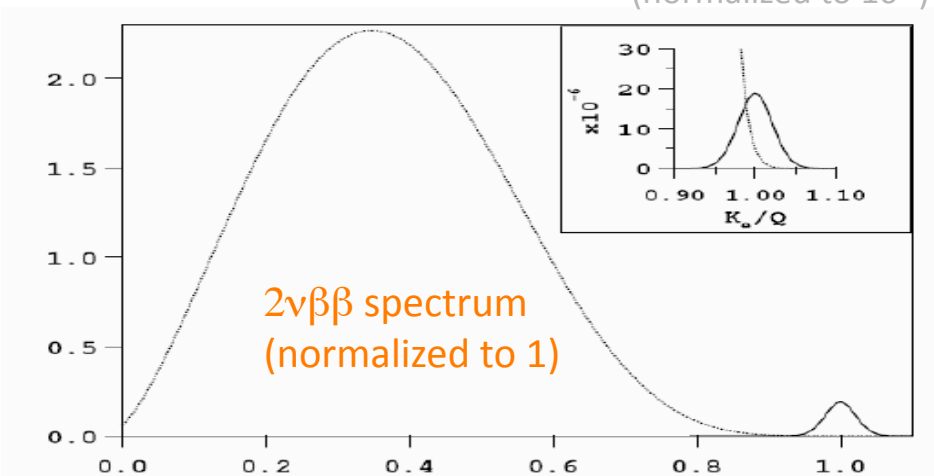


Choice of an isotope

0νββ spectrum
(5% FWHM)
(normalized to 10^{-6})



$E_1 + E_2$ (normalized to $Q_{\beta\beta}$)

0νββ spectrum
(5% FWHM)
(normalized to 10^{-2})

from S. Elliott and P. Vogel

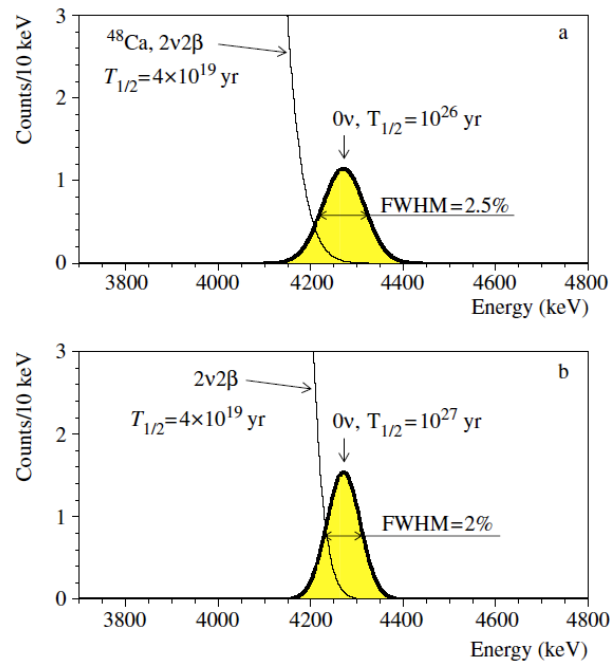


Figure 21. A demonstration of the impact of energy resolution of $|Q_{\beta\beta}|$ on the interference from $2\nu\beta\beta$-decay events.

F. T. Avignone, G. S. King and Yu. G. Zdesenko, ``Next generation double-beta decay experiments: Metrics for their evaluation,'' New J. Phys. 7, 6 (2005).

History of 0νββ and 2νββ

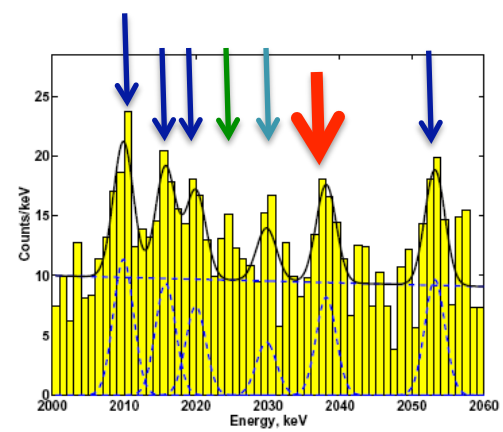
1935	Rate of 2νββ first calculated by Maria Goeppert-Mayer (suggested by E. Wigner)
1937	Majorana proposes his theory of two-component neutrino ($\nu \equiv \bar{\nu}$)
1937-9,1952	G. Racah, W.H. Furry, Primakoff discuss 0νββ
1949, 1955	Half-life limits (Fireman, Fremlin, R.Davis)
1967	Geochemical evidence for 2νββ
1987	Laboratory evidence for 2νββ for (S. Elliot, A. Hahn, M. Moe, ^{82}Se)
	Phys. Rev. Lett. 59, 2020 - 2023 (1987)
	Direct evidence for two-neutrino double-beta decay in 82Se
2001-2006	Controversial claim of observation of 0νββ (Klapdor-Kleingrothaus *et al.*)

- **0νββ peak**
  2039 keV peak has 4.2σ significance $\langle m_\nu \rangle$ =~ 0.3-0.6 eV
- Weak ^{214}Bi lines
  2010.7, 2016.7, 2021.8, 2052.9 keV
- ? Electron conversion of 2118keV γ line 2030keV
- ?

First evidence for neutrinoless double beta decay, with enriched ^{76}Ge in Gran Sasso 1990-2003.

H.V. Klapdor-Kleingrothaus[a] *

[a]Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany



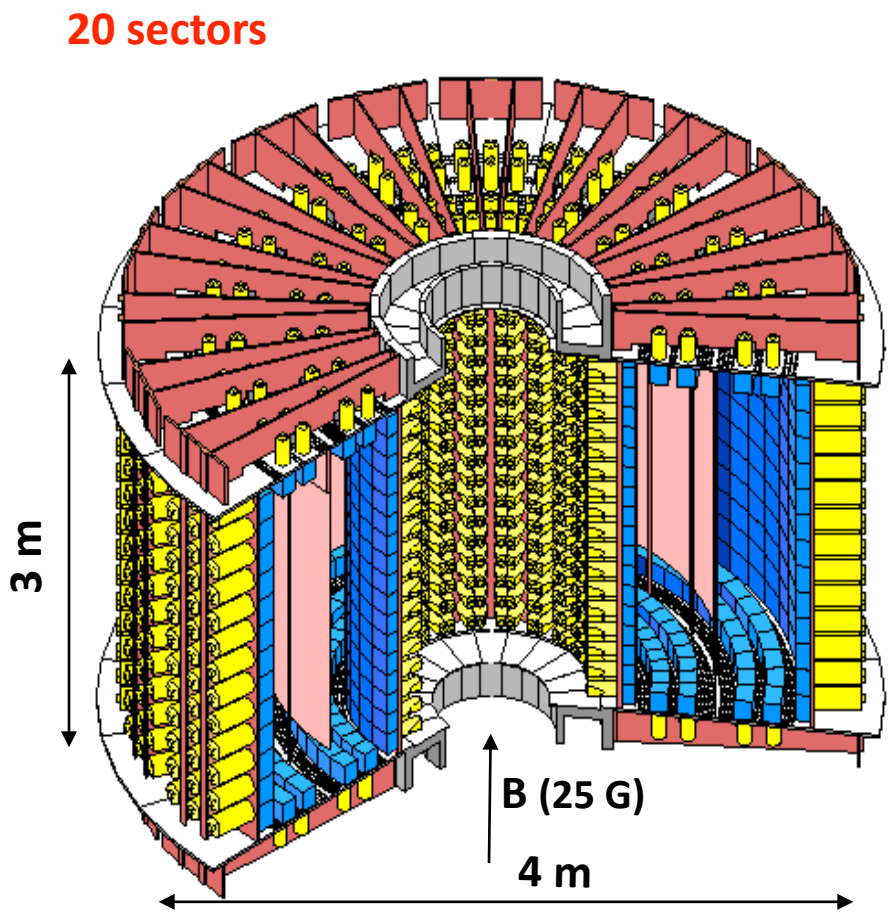
^{76}Ge

Exposure (total): 71.7 kg.y

Figure 1. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), in the range 2000 - 2060 keV and its fit, for the period: August 1990 to May 2003 (71.7 kg y) (see [3]).

NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopic foils

area = 20 m^2, thickness ~ 60 mg/cm^2

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 coupled to low radioactivity PMTs

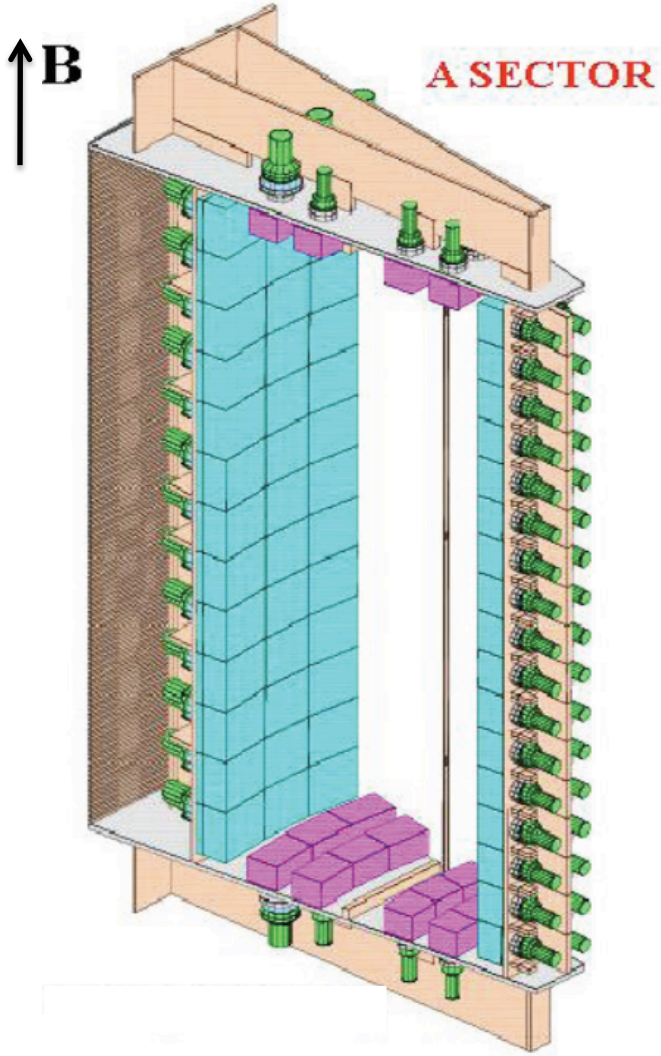
Magnetic field: 25 Gauss

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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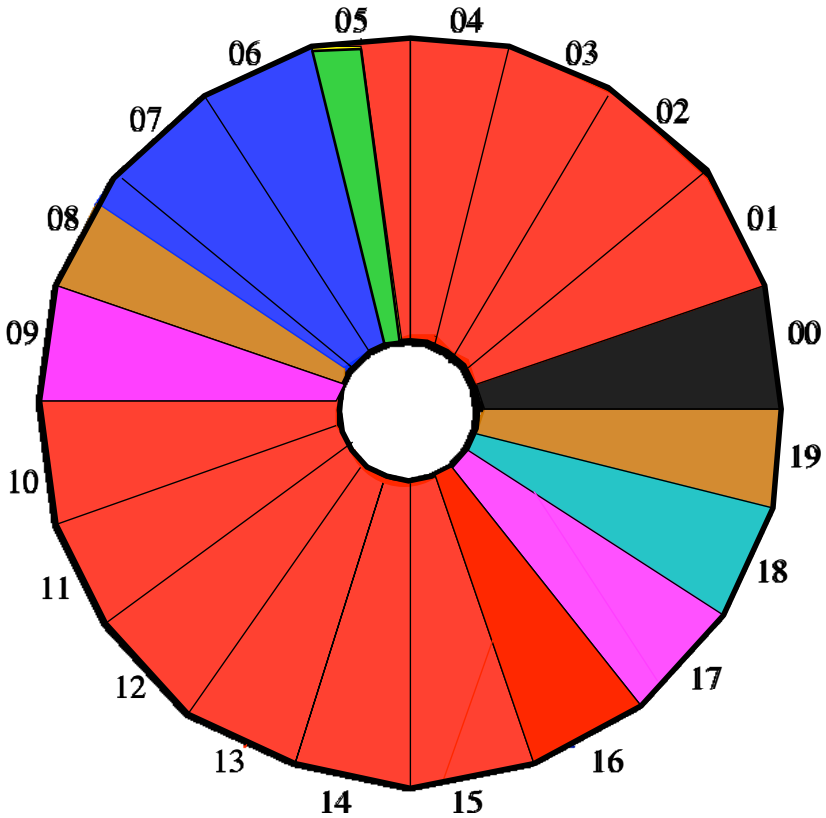
ββ decay isotopes NEMO-3



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

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

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

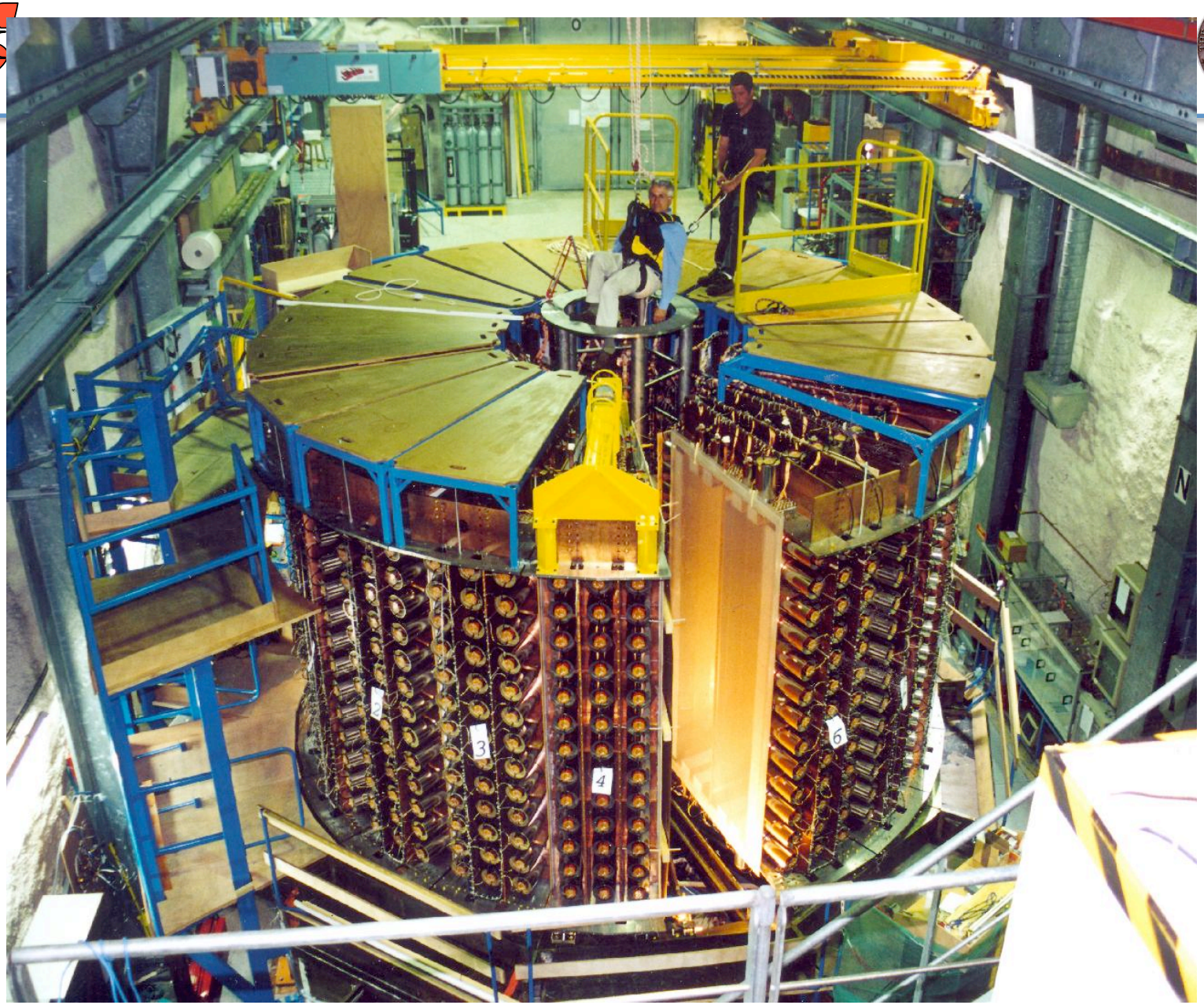
^{nat}Te 491 g

Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

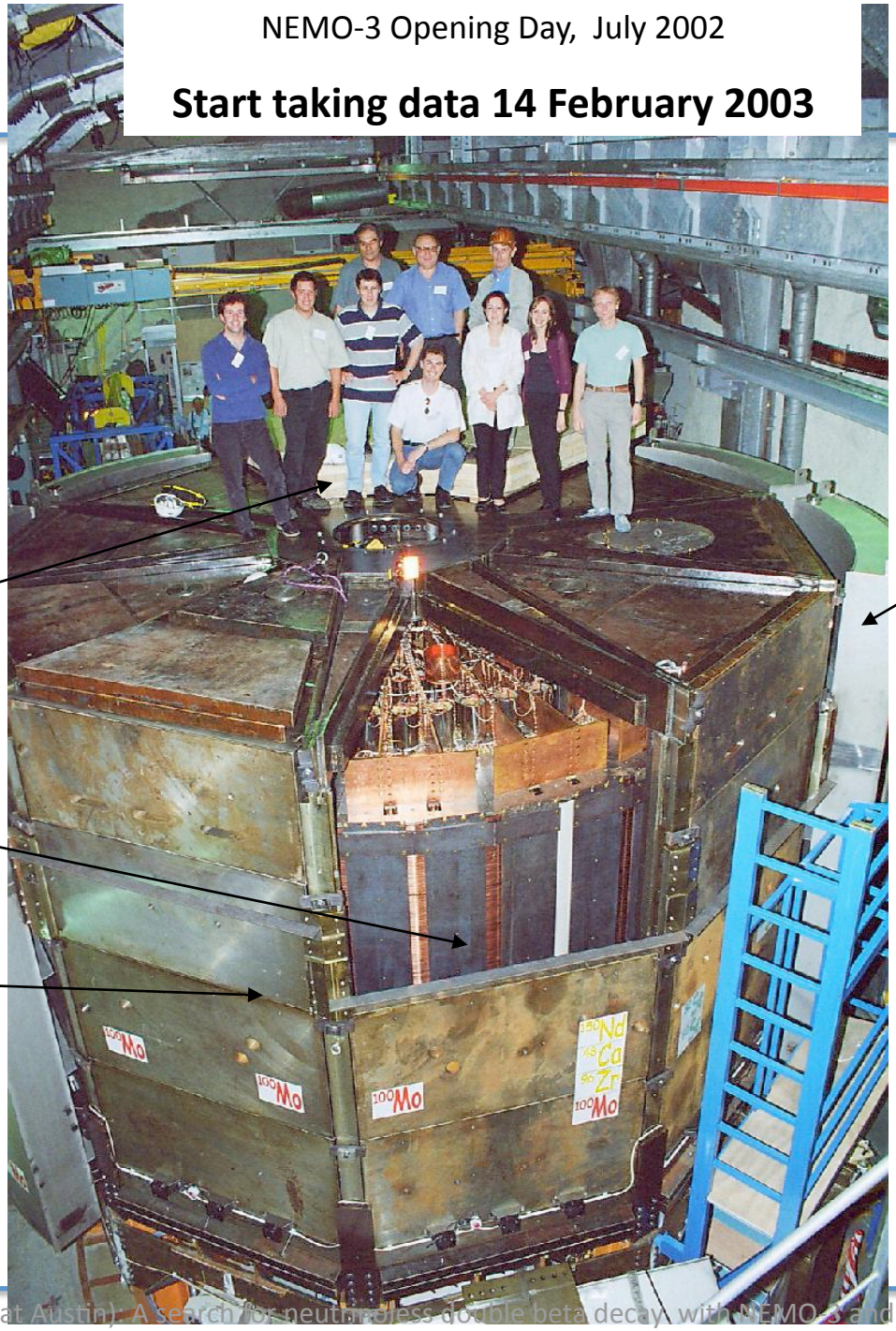

Cathod rings
Wire chamber
PMTs
Calibration tube
scintillators
ββ isotope foils



During installation AUGUST 2001

NEMO-3 Opening Day, July 2002

Start taking data 14 February 2003



Water tank

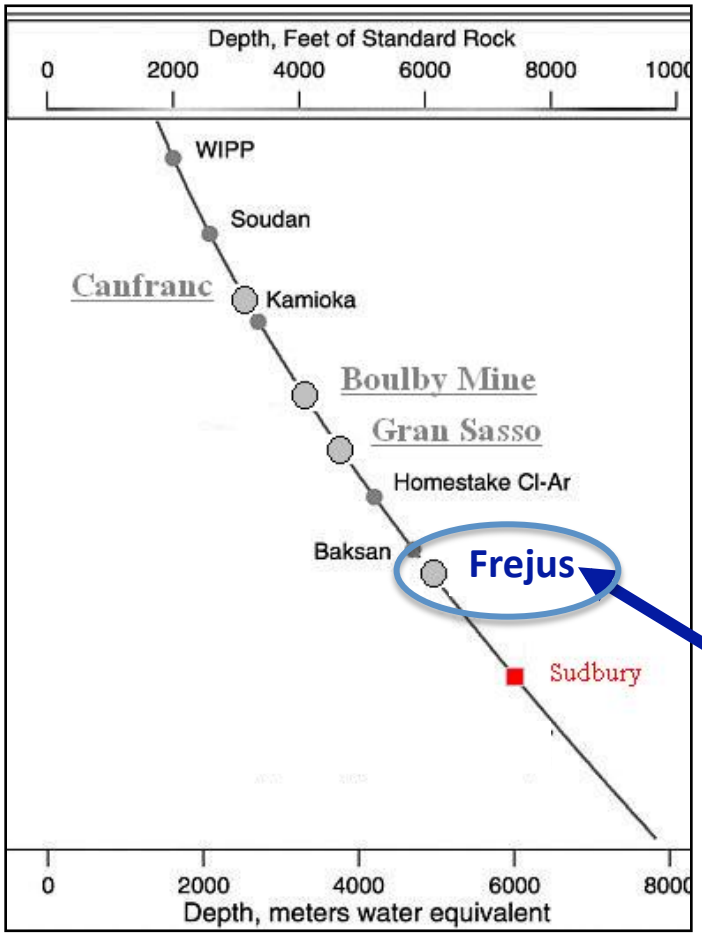
wood

coil

Iron shield

Finished detector

Laboratoire Souterrain de Modane
(Frejus tunnel)



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

Laboratoire Souterrain de Modane

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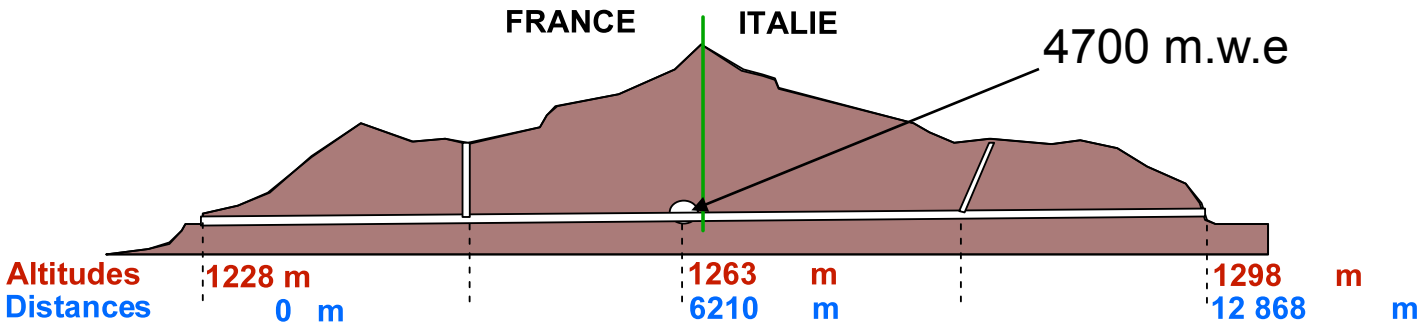
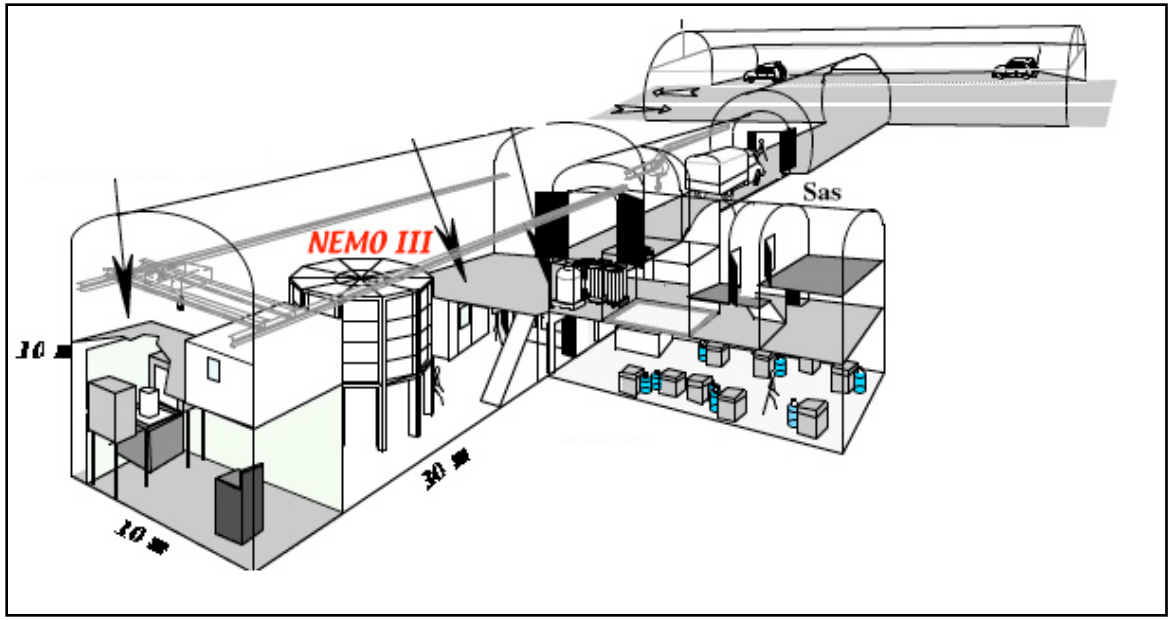
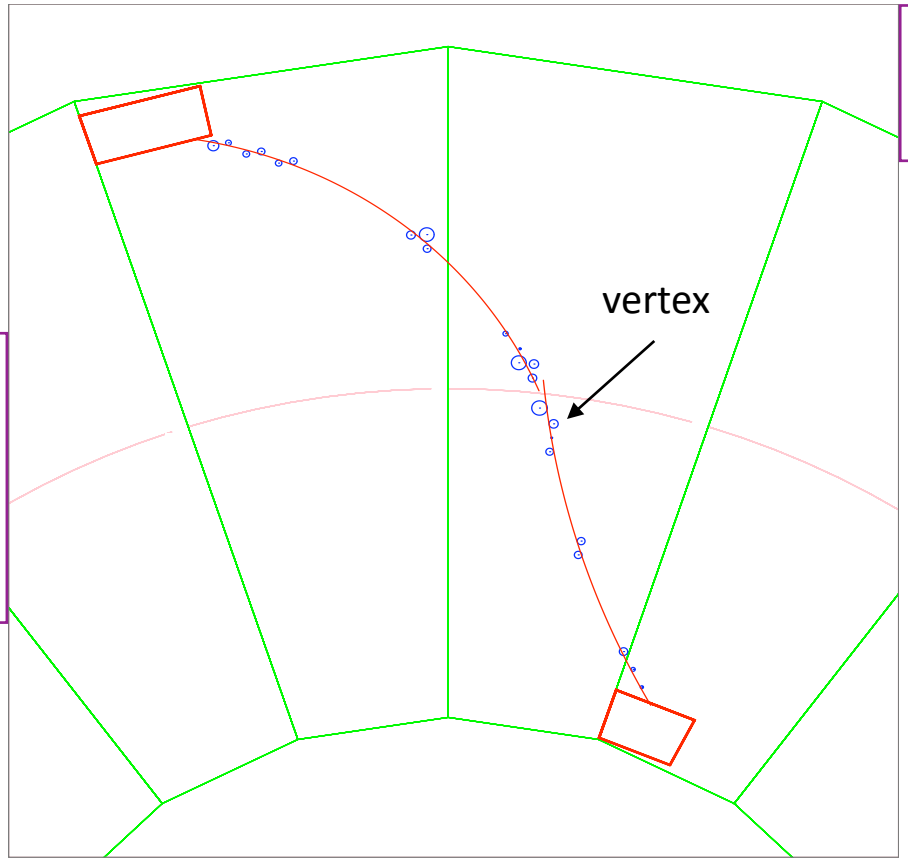


Built for τaup experiment (proton decay) in 1981-1982



Typical ββ2ν event observed in ^{100}Mo

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

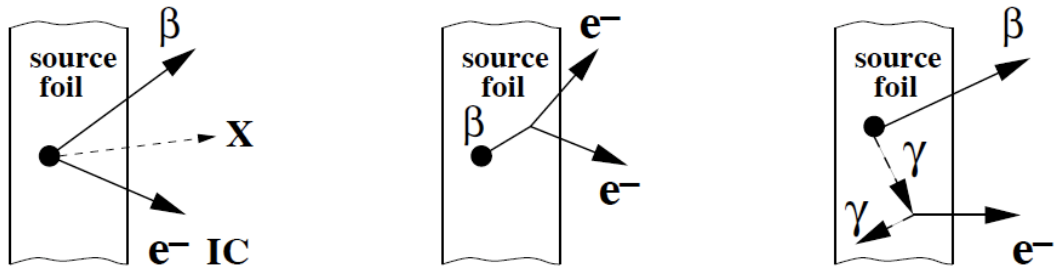


Deposited energy:
E_1+E_2= 2088 keV
Internal hypothesis:
$(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex:
$(\Delta vertex)_{\perp}$ = 2.1 mm

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

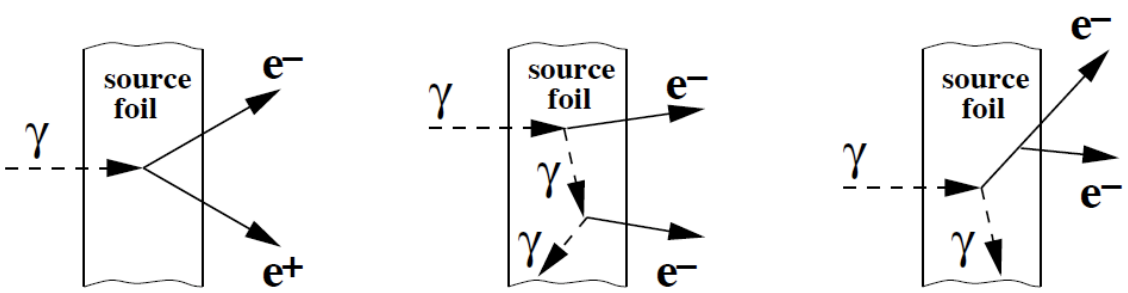
- Internal background (in addition to a potential $2\nu\beta\beta$ tail)
  (due to radio-impurities of the isotopic source foil)



beta + IC (dominant) | beta + Möller | beta + Compton

● = radioisotope β = electron from beta decay IC = internal conversion

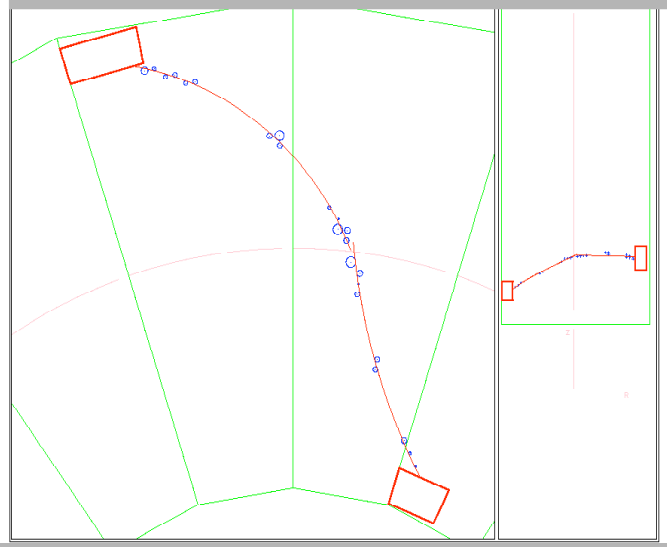
- External background
  (due to radio-impurities of the detector)



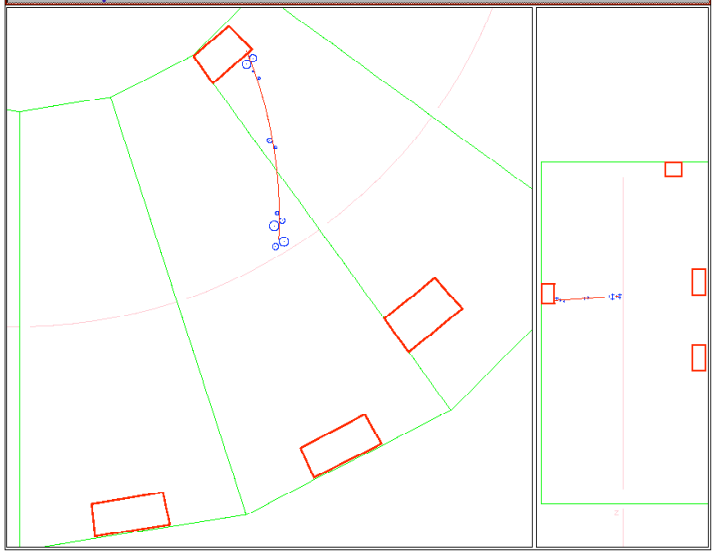
pair creation | Compton + Compton | Compton + Möller

Signal and background signatures

2e$^-$ event

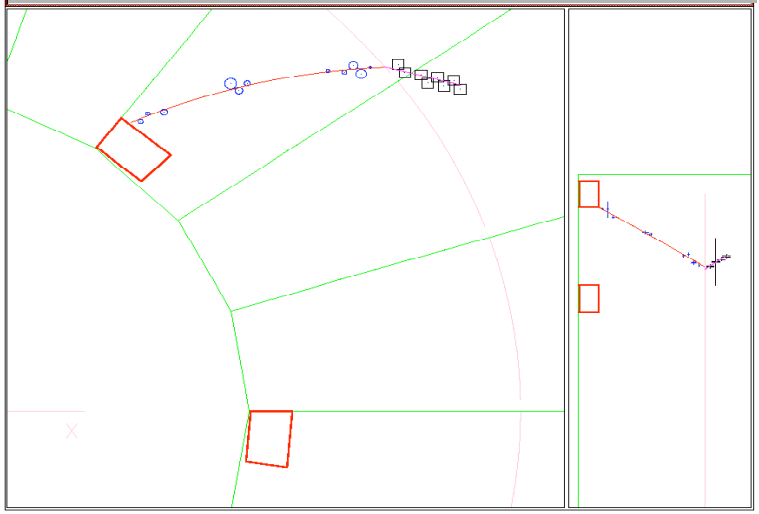


e$^-$Nγ event to measure ^{208}Tl

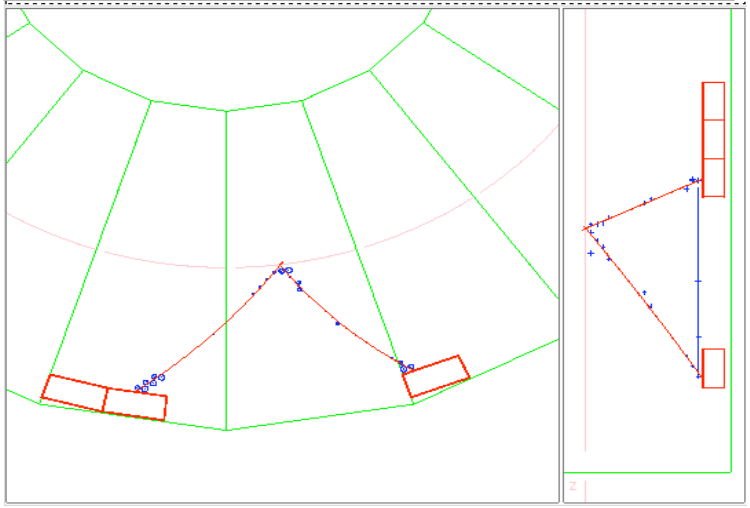


β - α (delay track) event

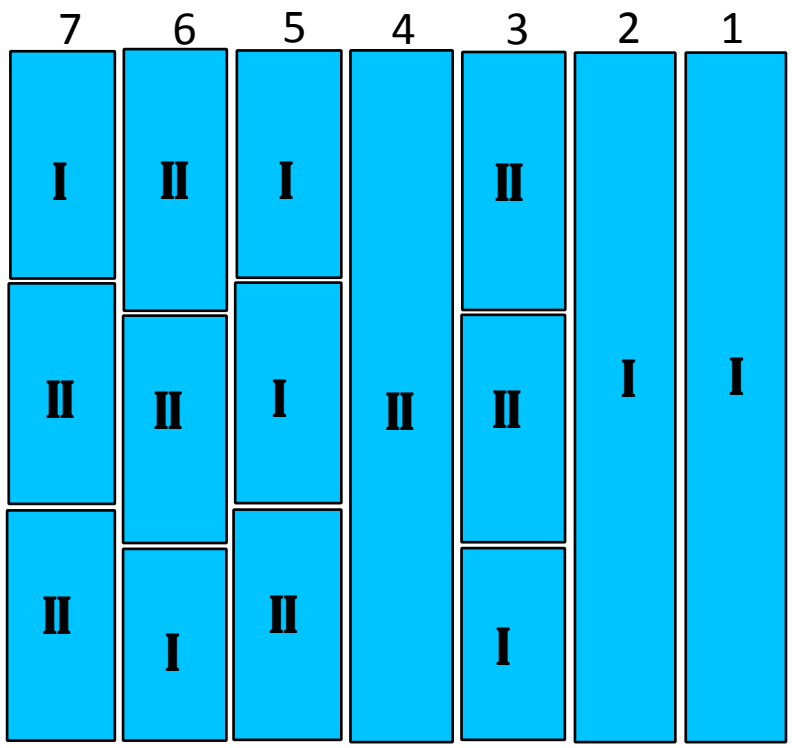
^{214}Bi → ^{214}Po → ^{210}Pb



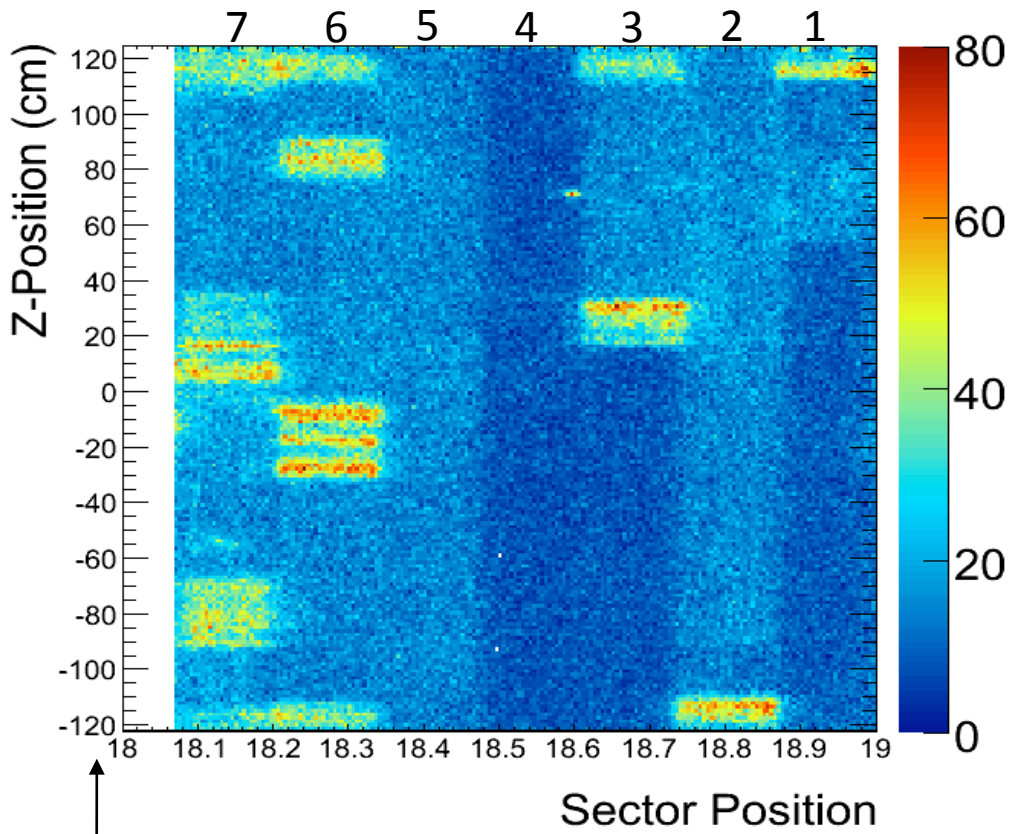
e$^+$ – e$^-$ pair event B rejection



Cadmium Foil
Activity and Hot Spots



Production foil parts

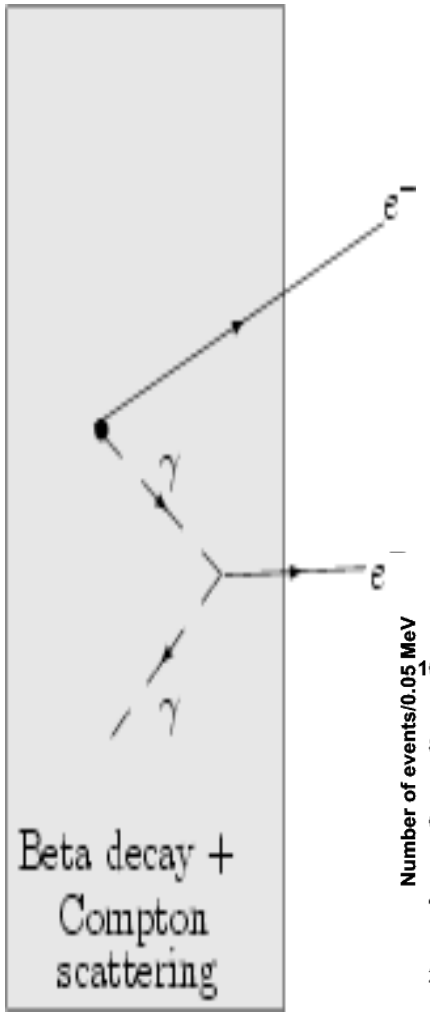


Vertex at the foil for
1 electron data

calibration tube

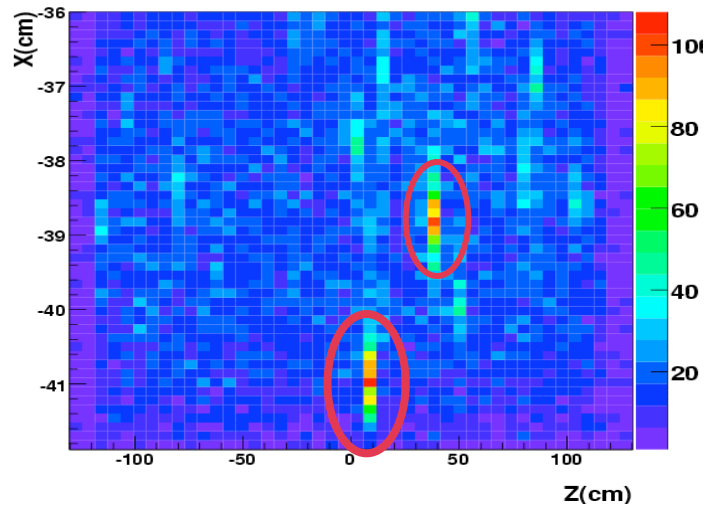
Background: control channels

internal bkg

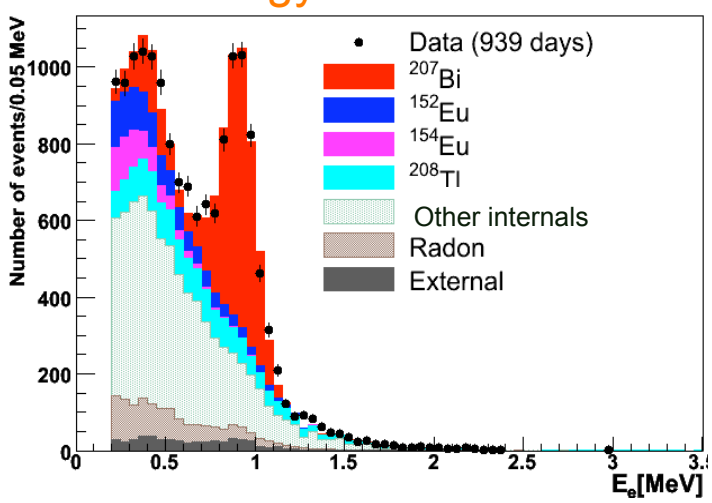


Example:
eγ control channel

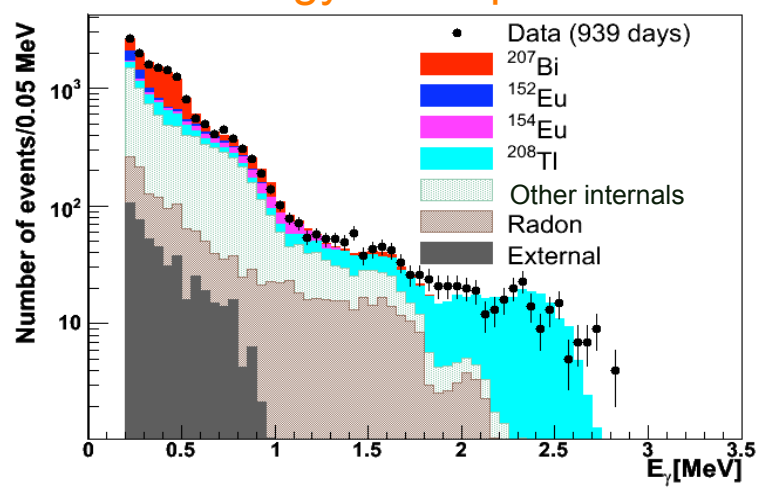
150-Nd foil



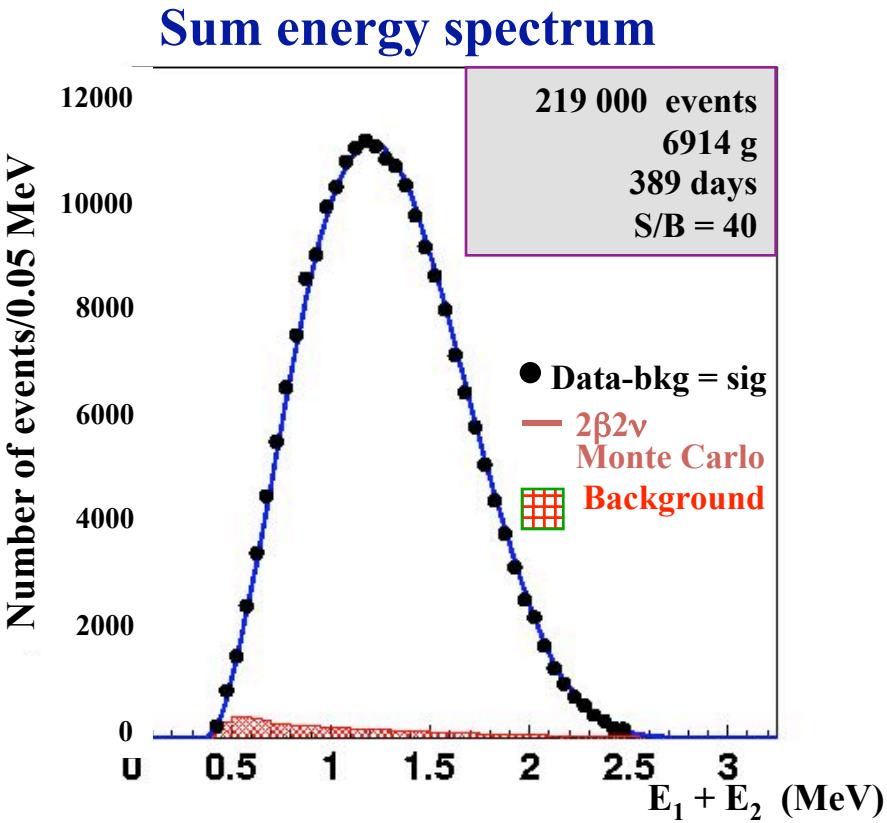
Energy of the electron

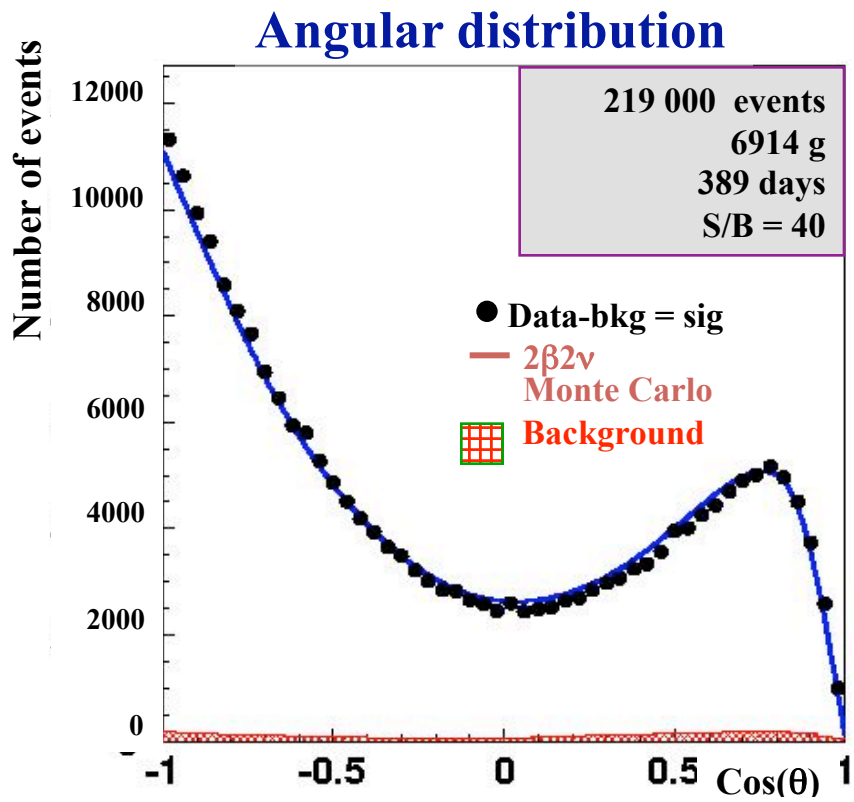


Energy of the photon



^{100}Mo 2νββ results





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

Phase 1: Feb. 2003 – Dec. 2004
"High Radon"

Phys. Rev. Lett. 95 182302 (2005)

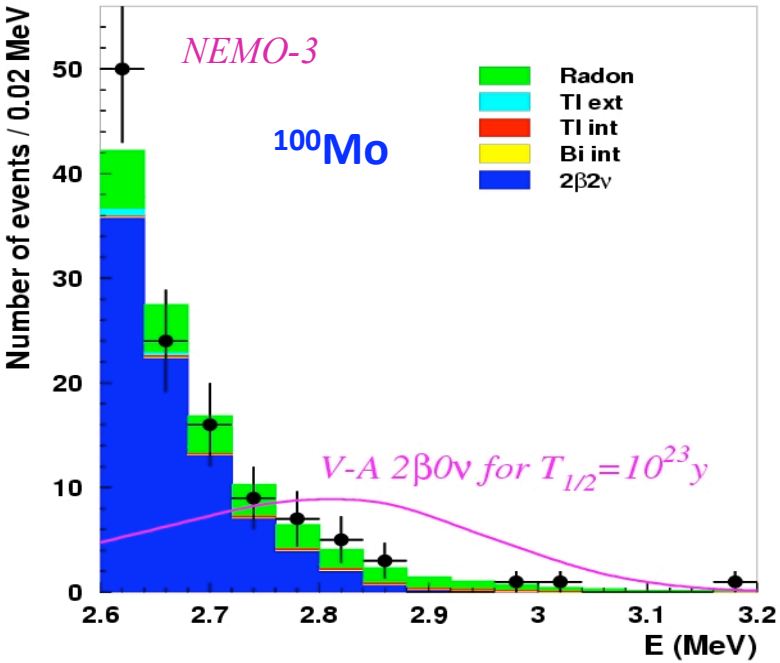
Now have in excess of 0.5M events and will update later this year.

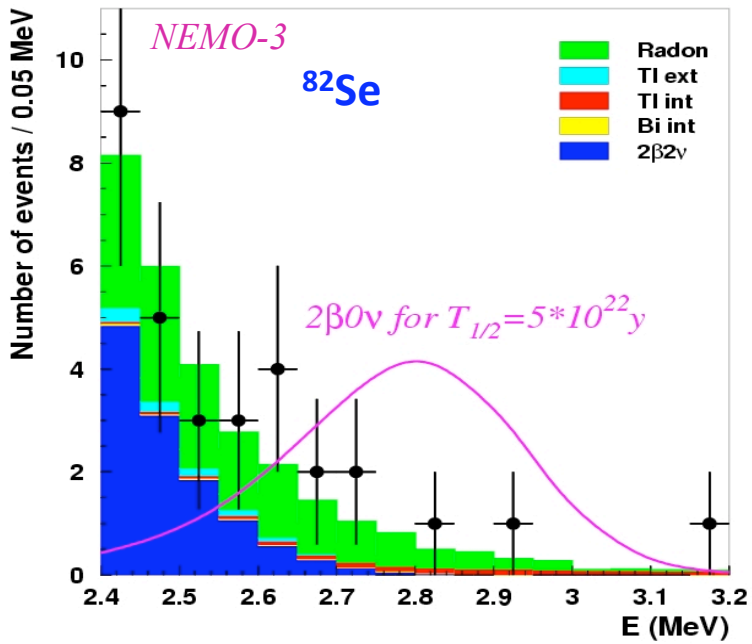
$0\nu\beta\beta$ search for ^{100}Mo and ^{82}Se

693 days of data
Phase I + Phase II

Data until spring 2006

693 days of data
Phase I + Phase II





$T_{1/2} > 5.8 \times 10^{23}$ y @ 90% C.L.

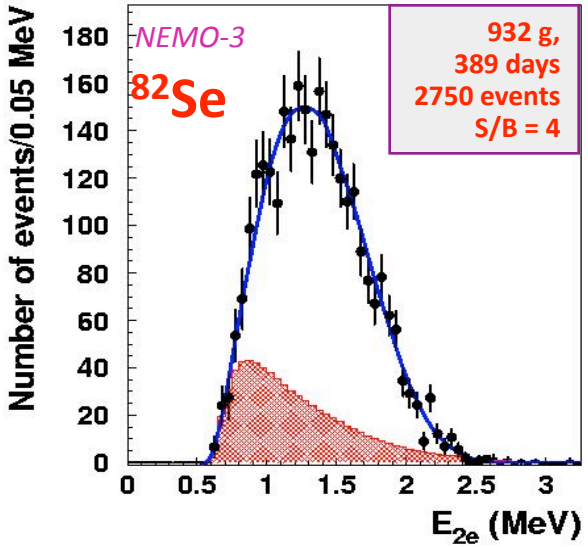
$\langle m_\nu \rangle < (0.6 - 1.3)$ eV [1-3]

$T_{1/2} > 2.1 \times 10^{23}$ y @ 90% C.L.

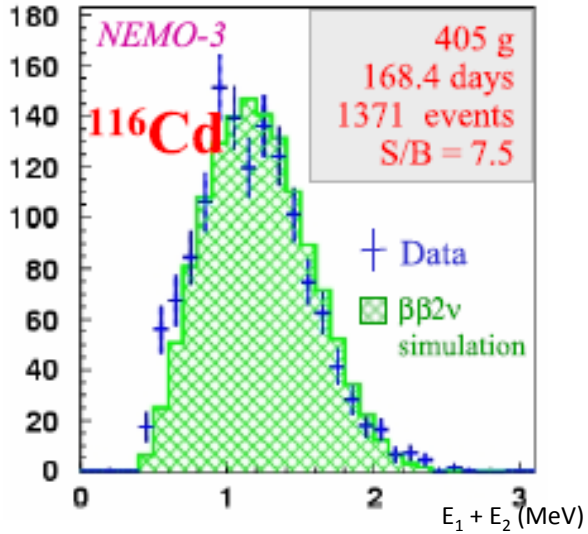
$\langle m_\nu \rangle < (1.2 - 2.2)$ eV [1-3]

NME:
[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] V.A.Rodin et al., Nucl.Phys. A 793 (2007) 213.

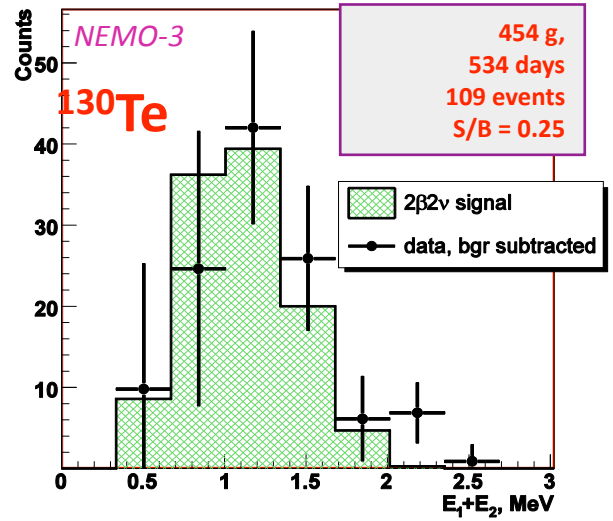
Other results from NEMO-3: 2νββ



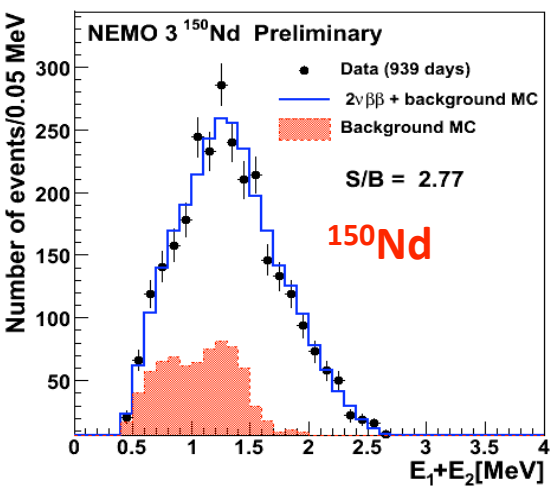
9.6 ± 0.3 (stat) ± 1.0 (sys) 10^{19} y



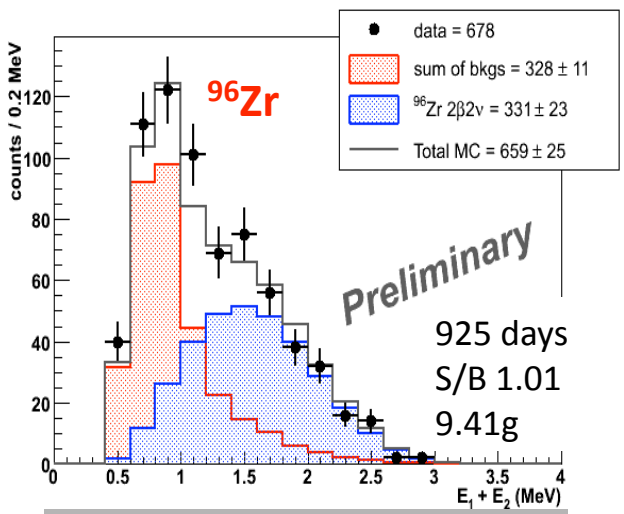
2.8 ± 0.1 (stat) ± 0.3 (sys) 10^{19} y



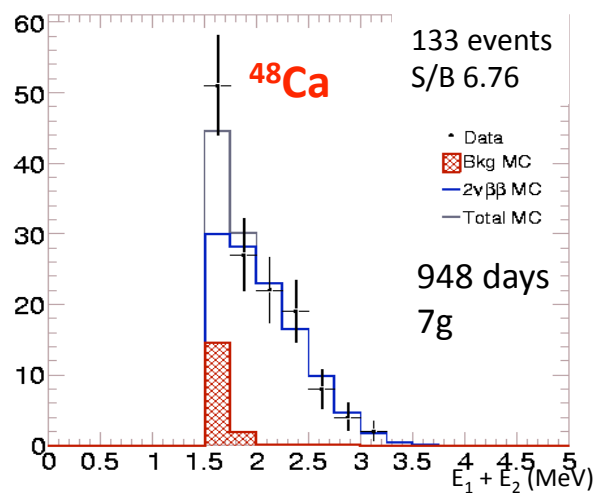
7.6 ± 1.5 (stat) ± 0.8 (sys) 10^{20} y



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



2.3 ± 0.2 (stat) ± 0.3 (sys) 10^{19} y



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

From NEMO-3 to SuperNEMO: challenges

$$T_{1/2}(0\nu\beta\beta) > \ln 2 \times \frac{N_A}{A} \times \frac{M \times \varepsilon \times T_{obs}}{N_{90}(\Delta E/E)}$$

No background

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 *if* ^{82}*Se*: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 - 1.3$ eV		$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y $\langle m_\nu \rangle < 50$ meV

From NEMO-3 to 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]].

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta E}}$$

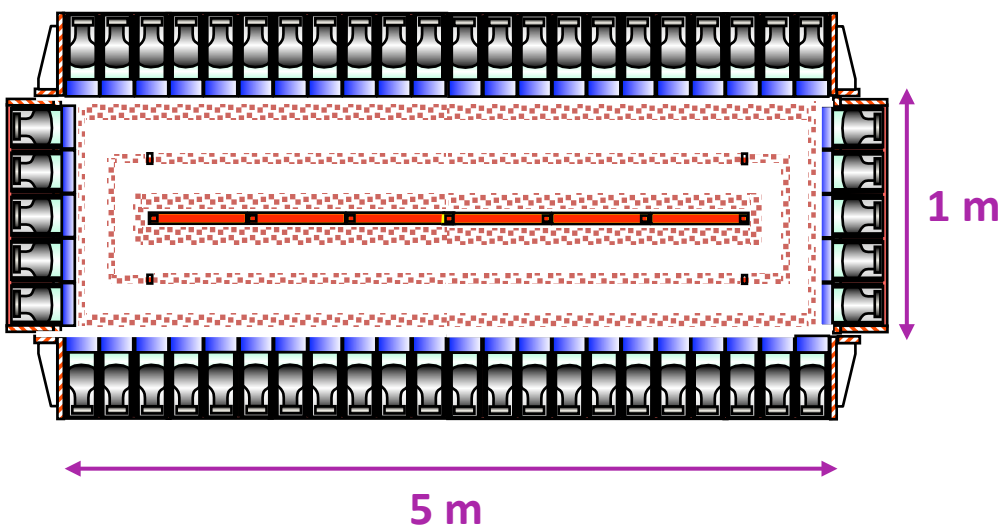
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source
M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts ($\mathrm{keV}\cdot\mathrm{kg}\cdot\mathrm{y}$)
ΔE – energy resolution (keV)

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 *if ^{82}Se*: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 - 1.3$ eV		$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y $\langle m_\nu \rangle < 50$ meV

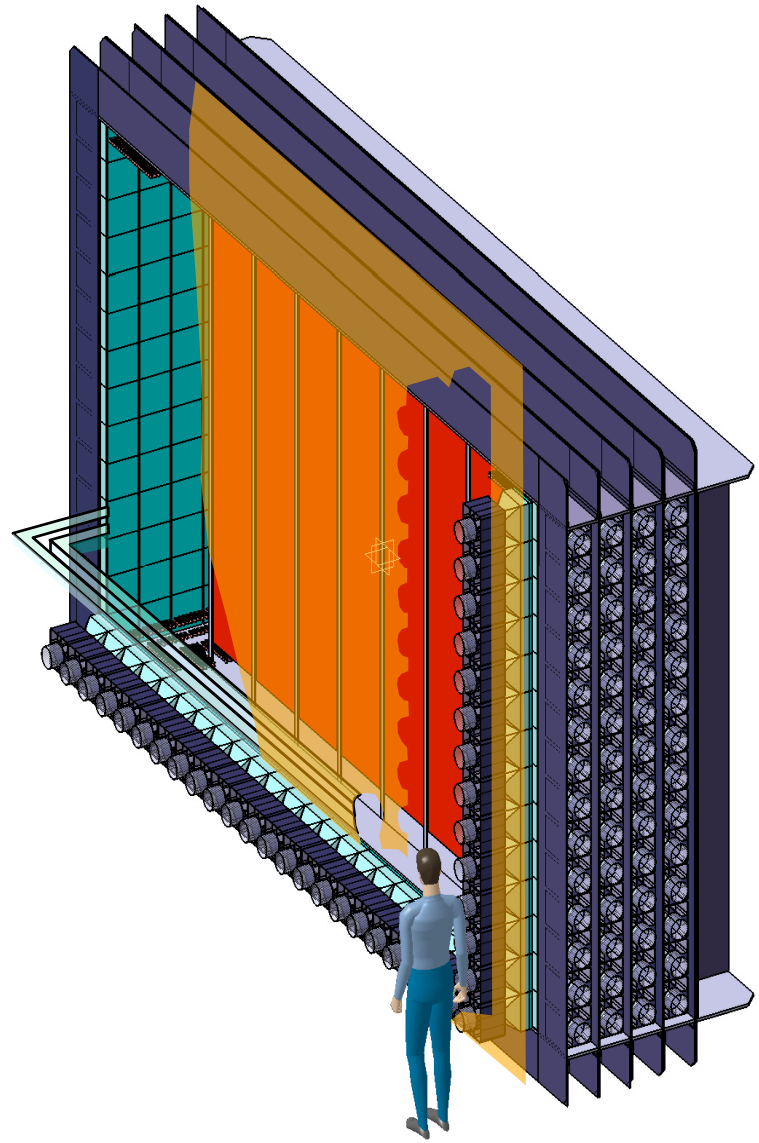
SuperNEMO - conceptually

20 modules for 100 kg

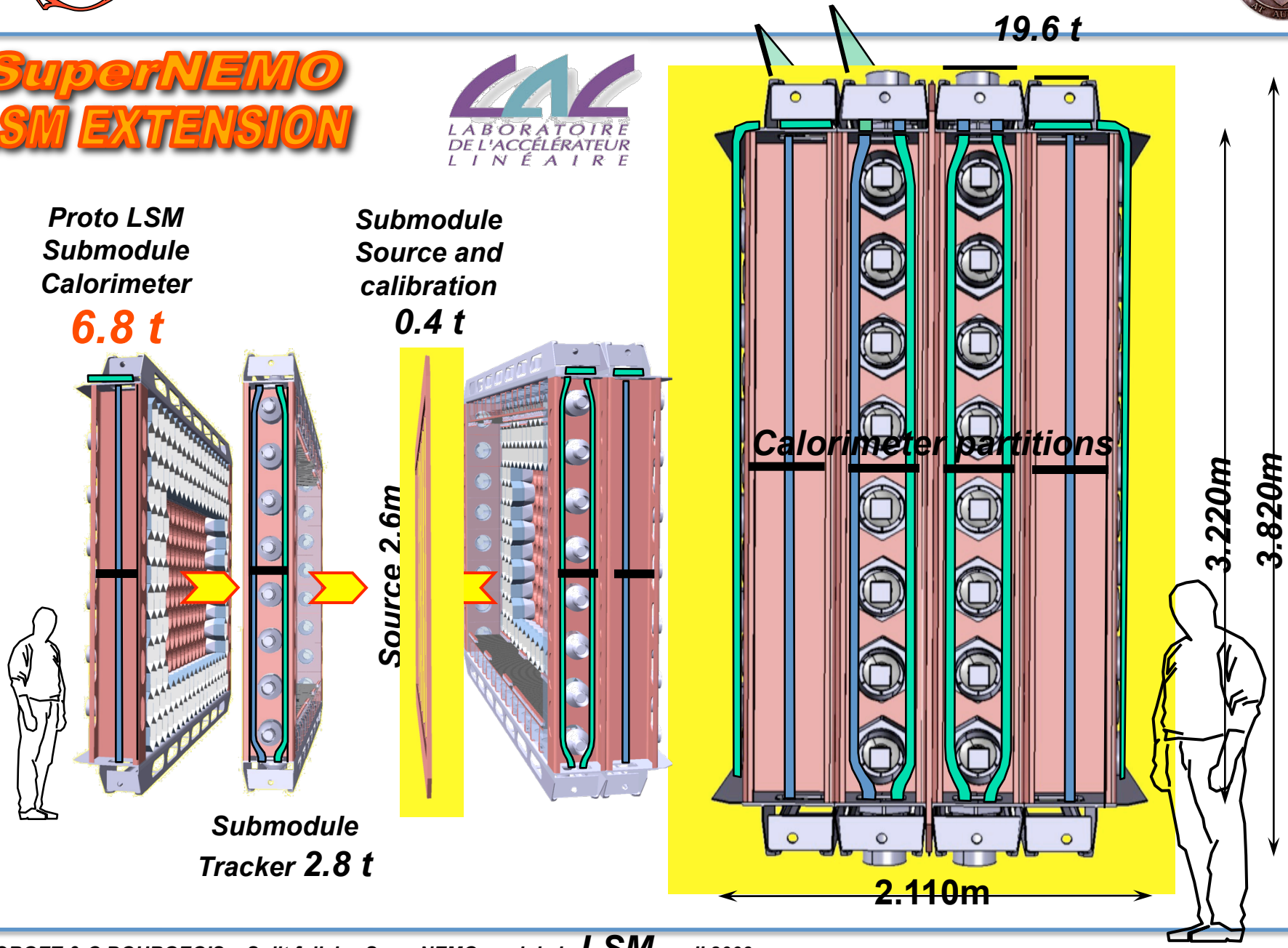
Source: ~ 5kg (4 0 mg/cm², 12m²)
Tracking: ~2,100 drift cells).
Calorimeter: ~600 blocks

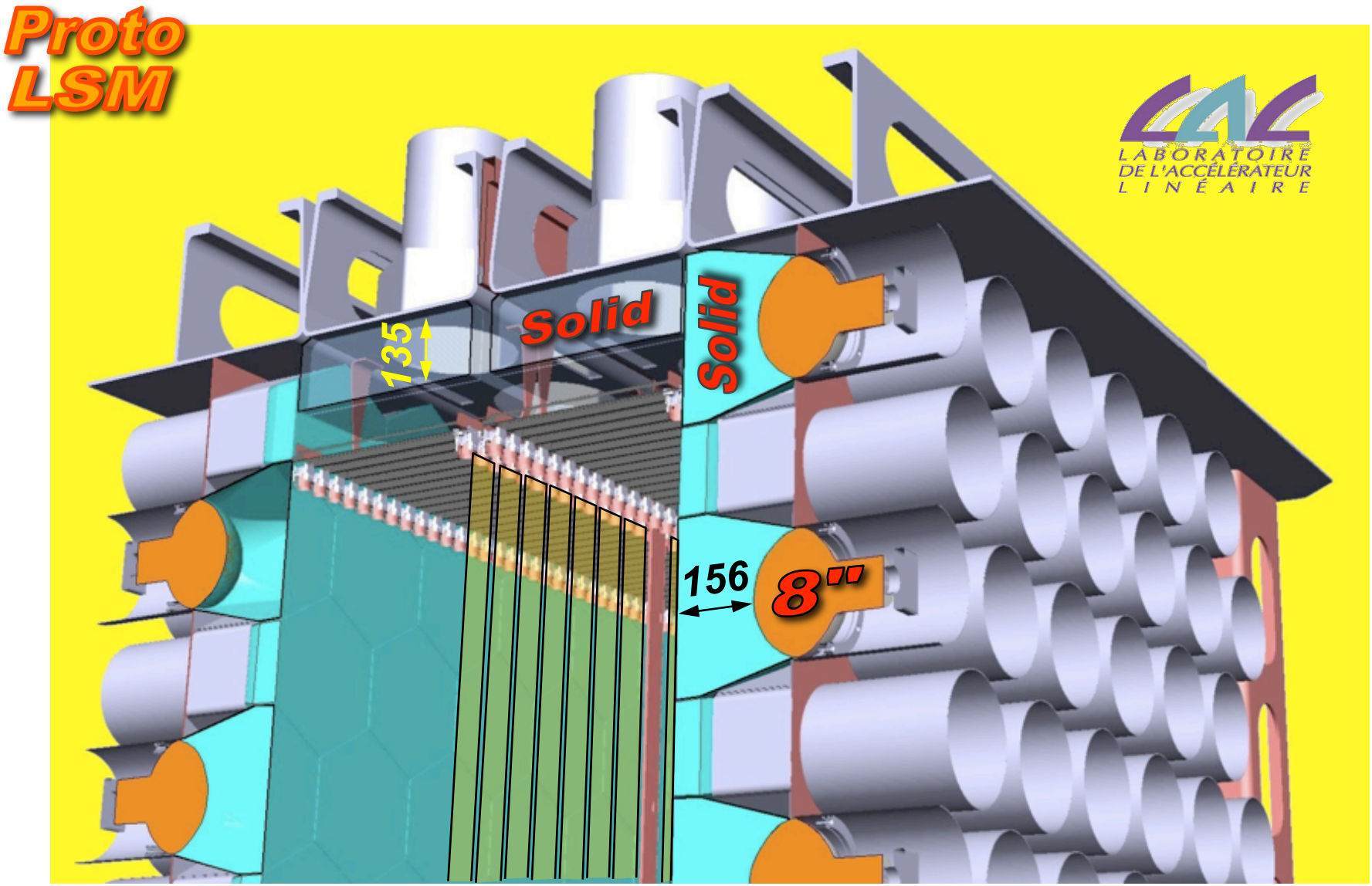


Top view



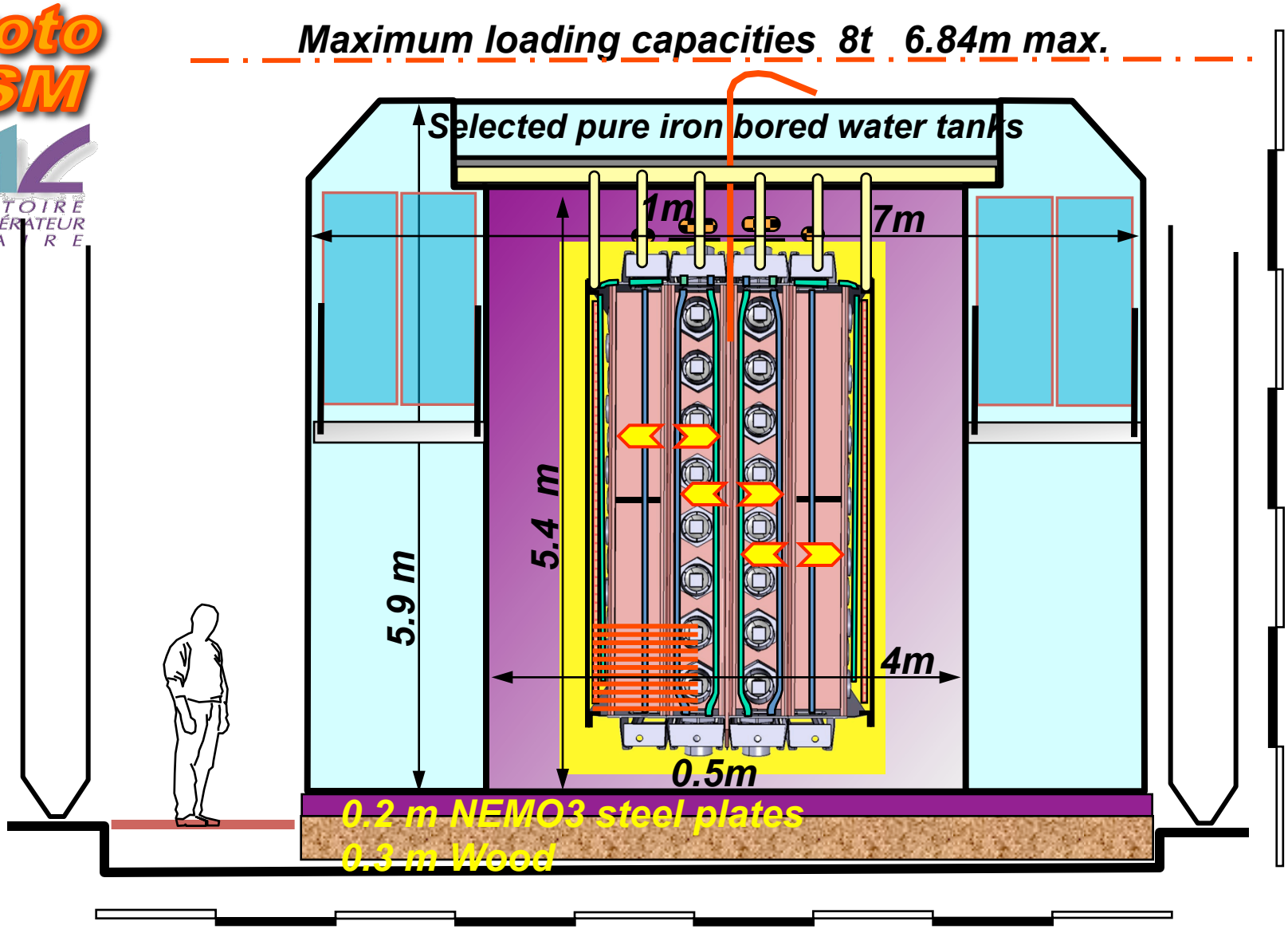
SuperNEMO LSM EXTENSION




Proto
LSM
LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE
Solid
Solid
135
156
8"

Proto LSM

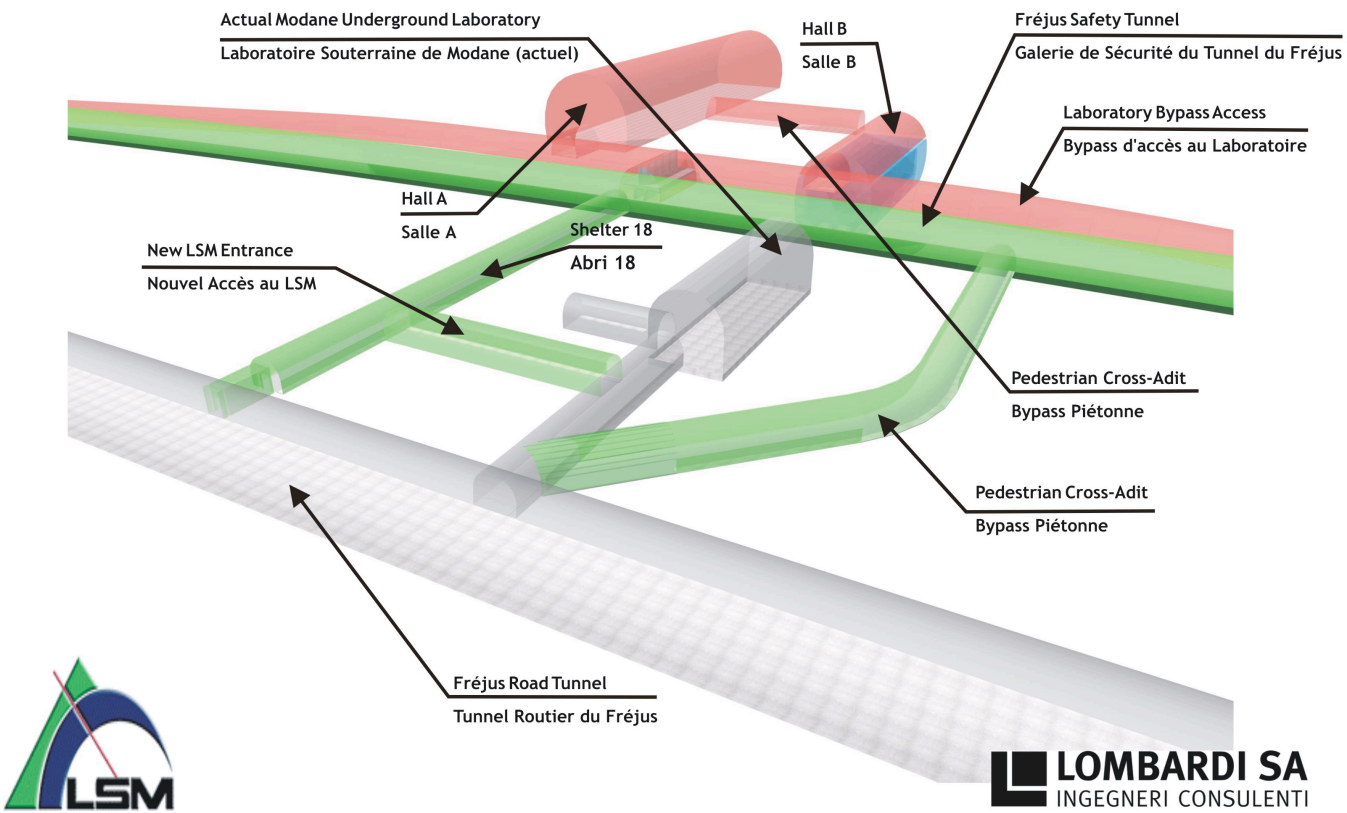
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE



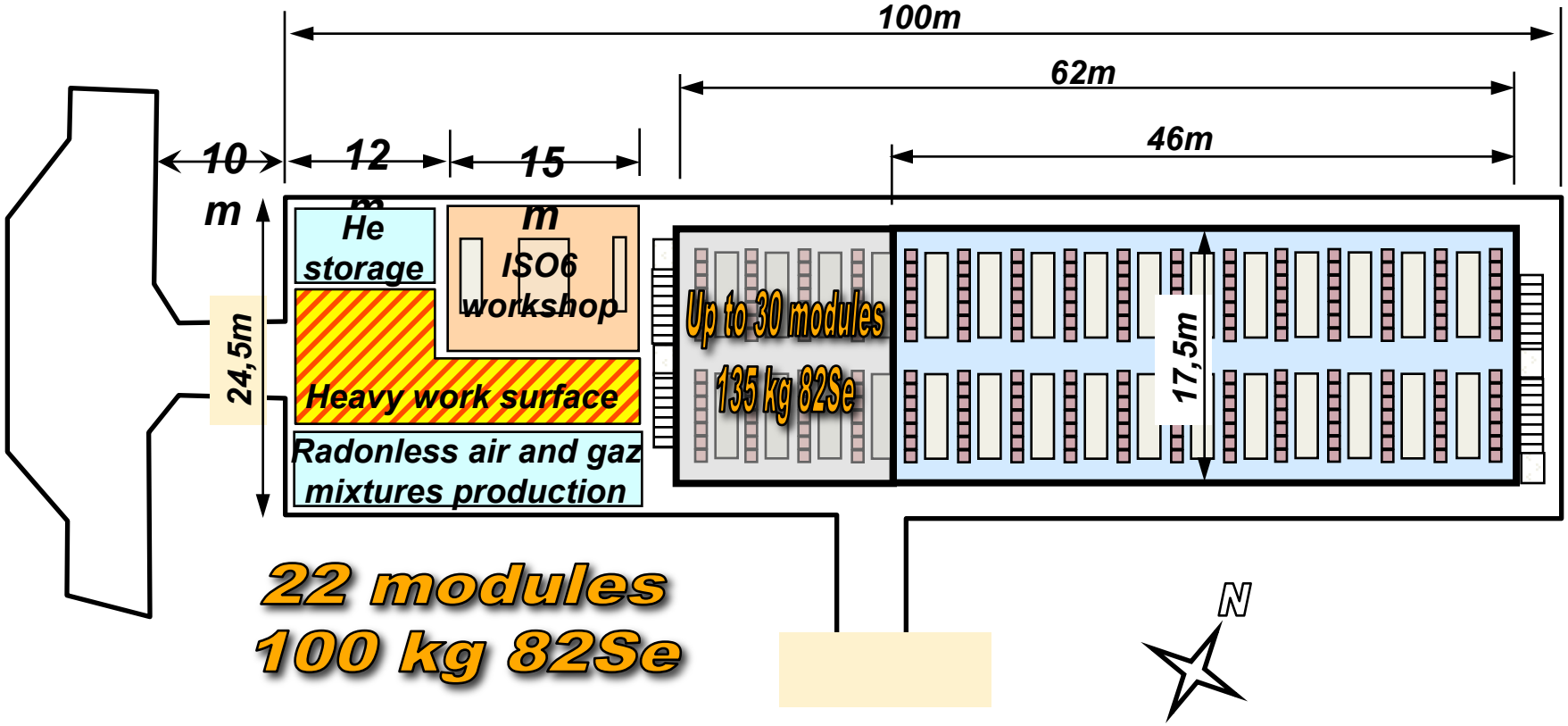
ULISSE project

MODANE UNDERGROUND LABORATORY 60'000 m^3 EXTENSION

LABORATOIRE SOUTERRAINE DE MODANE AGRANDISSEMENT 60'000 m^3

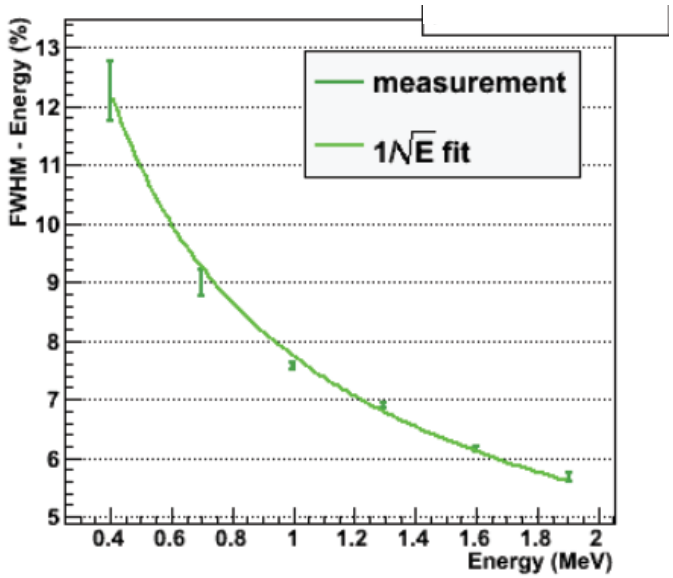


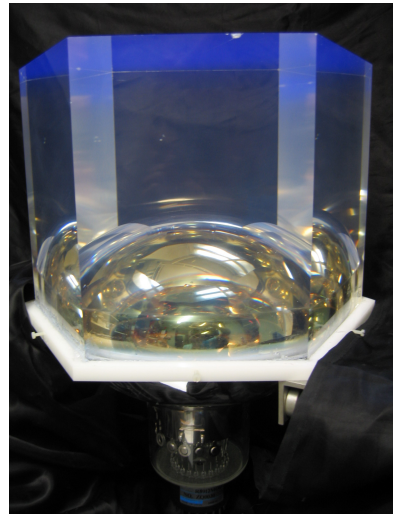
Future LSM Hall A



SuperNEMO : Calorimeter R&D

ΔE/E ~ 7.2 % at 1 MeV (corrected)





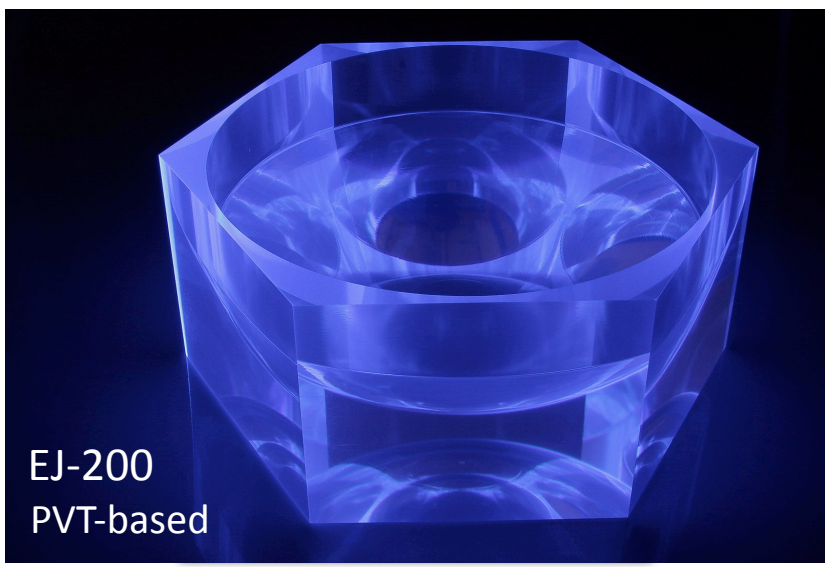
8" Hamamatsu R5912-MOD Super-Bialkali 8 Dynodes

Or

8" Photonis "35% QE"

(now unlikely)

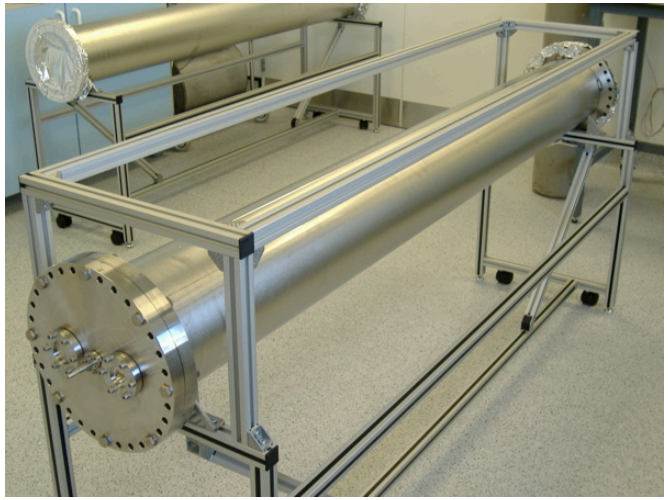
2m-long scintillator bars
(a cheaper option)

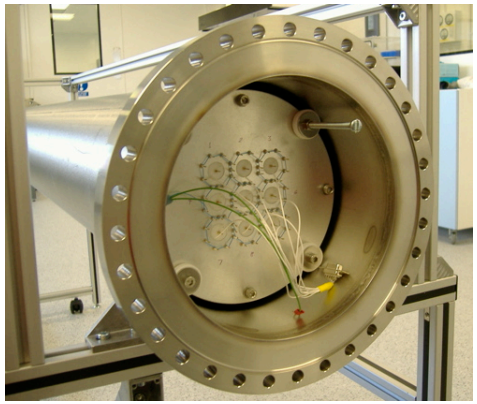


Similar
to BC408

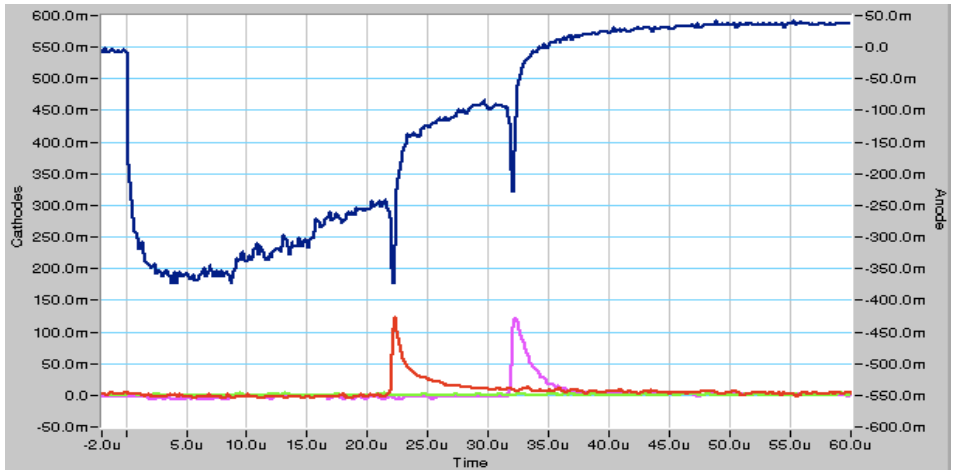
Tracker R&D

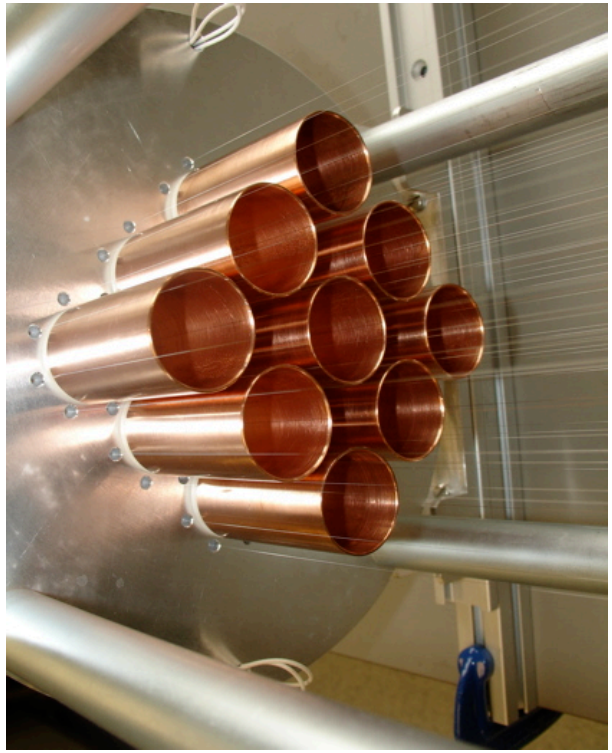
- Optimize length, wire material and diameter, read-out, gas mixture etc
- Several 1-cell and two 9-cell prototypes built and tested
- 90-cell prototype being built





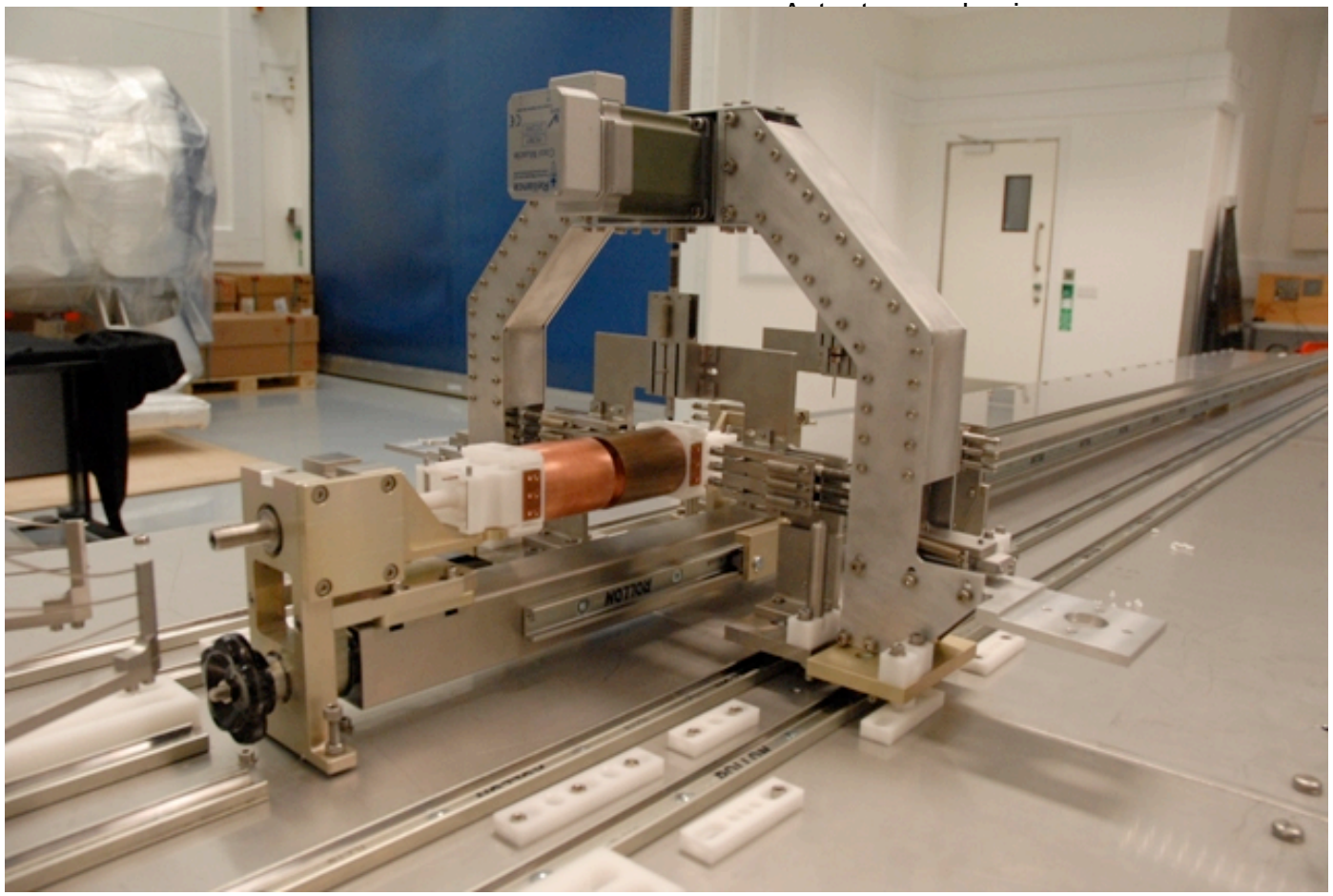
9-cell prototype in Manchester





Tracker: fully automated wiring

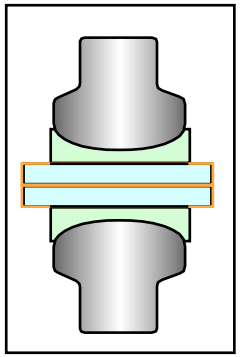
- ~500,000 wires to be strung, crimped, terminated
- Wiring robot being developed in collaboration with Mullard Space Science Lab (UCL)

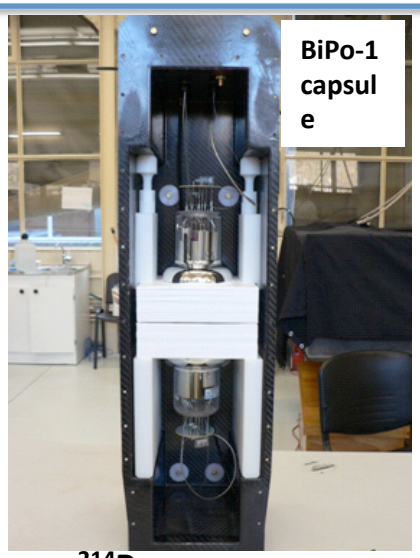


BiPo R&D

(for measuring foil radio-purity)

BiPo-1 capsule

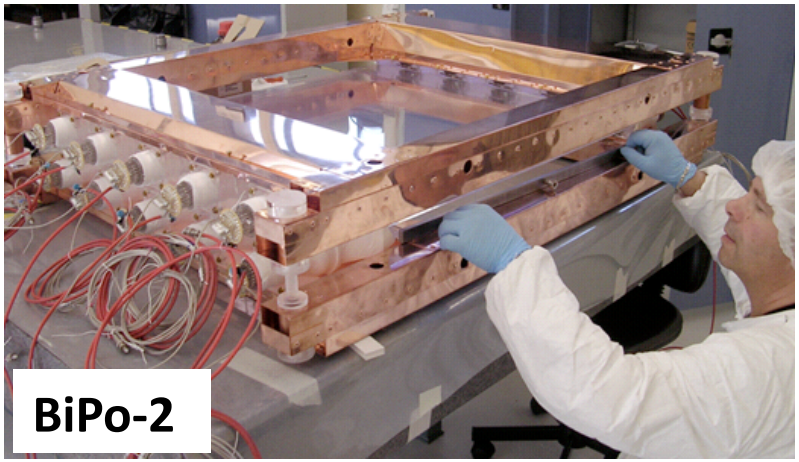


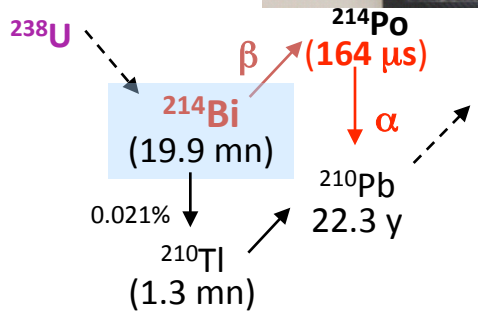


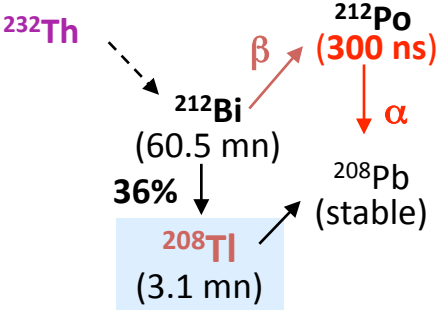
Objectives :

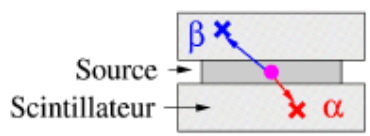
to mesure ^{208}Tl < 2 μBq/kg & ^{214}Bi < 10 μBq/kg in ββ source foil (5kg/month)

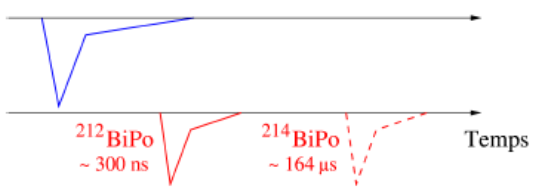
- ✓BiPo-1: 10 capsules in operation since 12/2007,
- ✓current sensitivity < 7.5 μBq/10m^2 x 40 mg foil
- ✓BiPo-2 and Phoswhich: started in 04/2008: results expected in the end of 2008







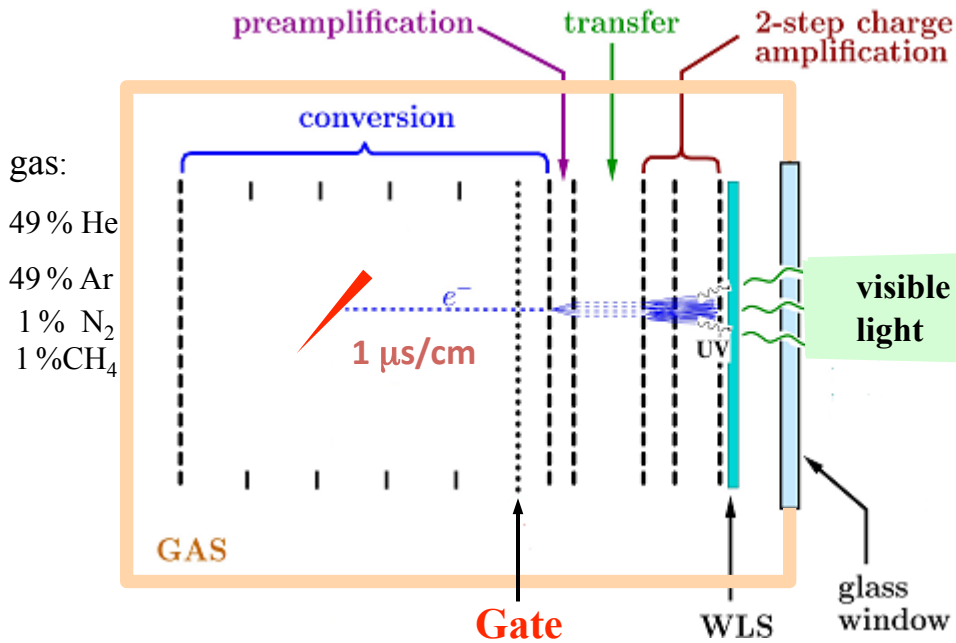


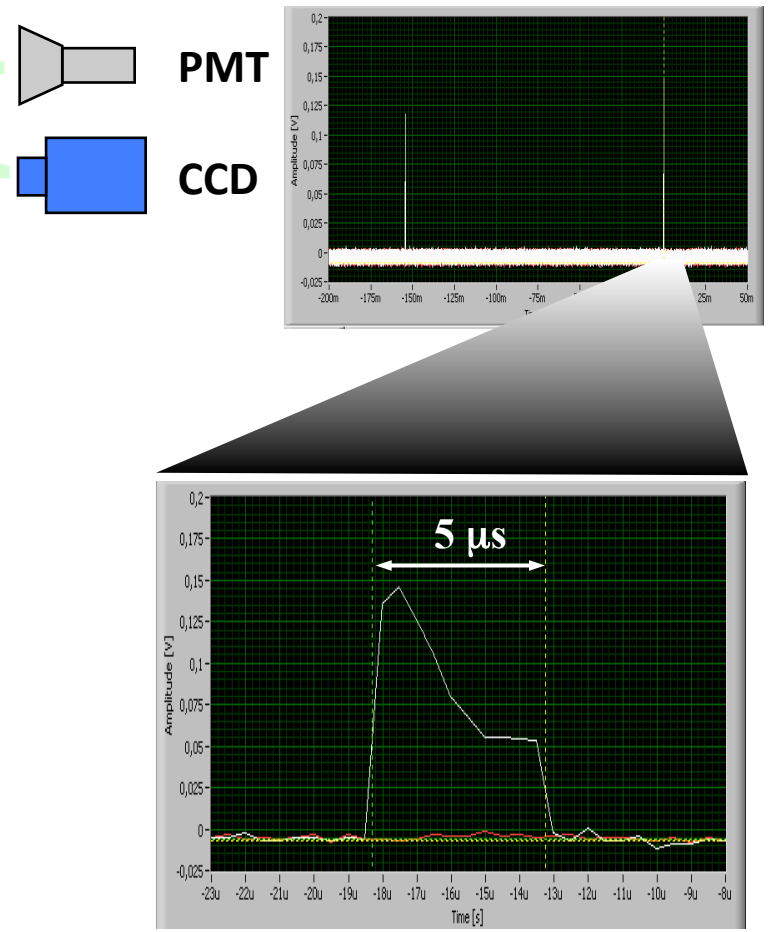


Optical Time Projection Chamber

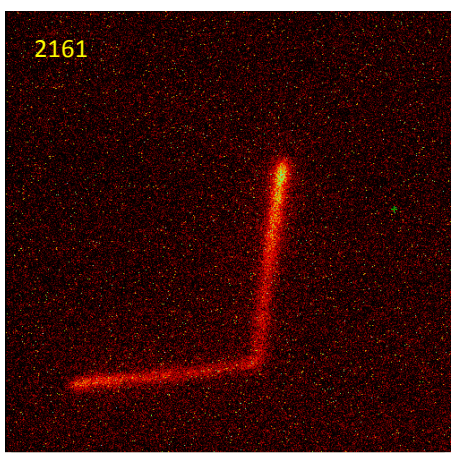
(for measuring radon contamination in the fill gas)

Search for $^{220}Rn - \alpha - ^{216}Po - \alpha$ decay





two triggers within 300 ms gate



W. Dominik, Z. Janas *et al.*, University of Warsaw

Goals and plans

Sensitivity

^{82}Se: $T_{1/2}(0\nu)$ = (1-2) 10^{26} yr — depending on final mass, background and efficiency

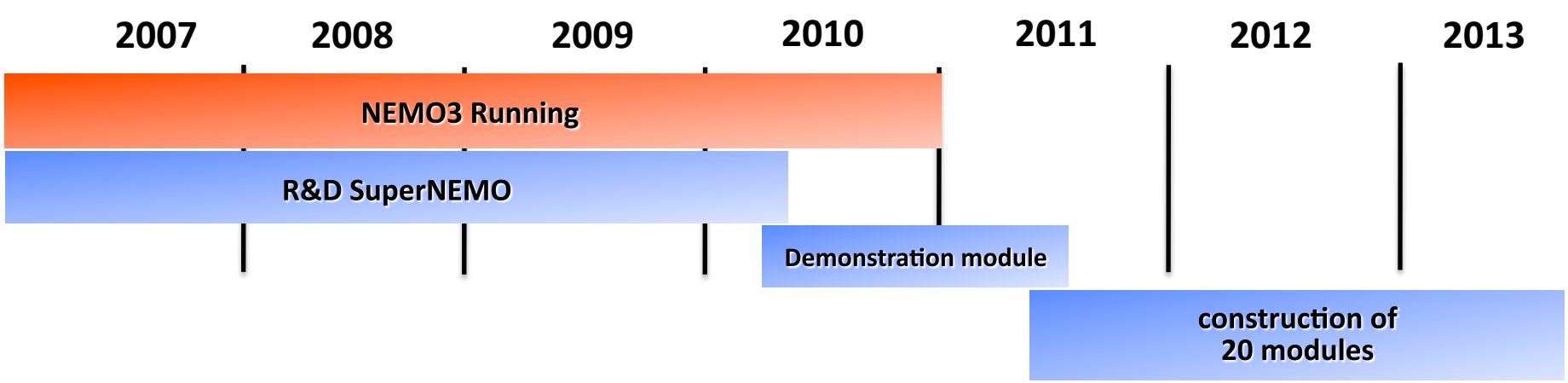
$\langle m_\nu \rangle \leq$ 0.060 – 0.100 eV — includes uncertainty in $T_{1/2}$ + MEDEX'07 NME

^{150}Nd: $T_{1/2}(0\nu)$ = 5 10^{25} yr

$\langle m_\nu \rangle \leq$ 0.045 eV — (but deformation not taken into account)

^{150}Nd enrichment

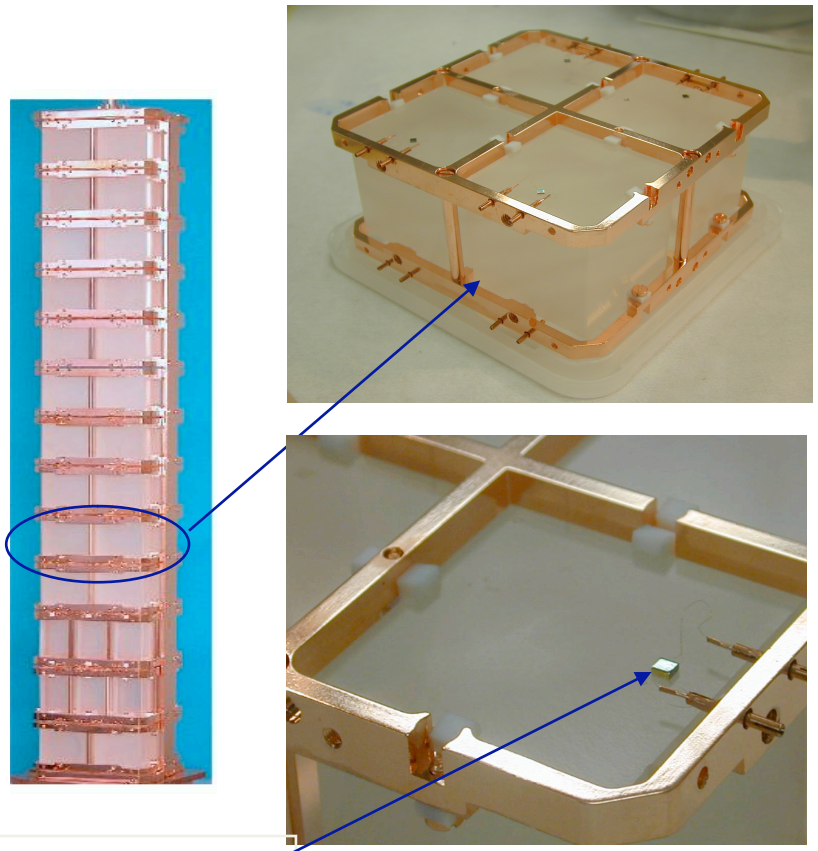
- ✓ (practically) large amounts can only be produced through the atomic vapor laser ionization separation (AVLIS)
- ✓ developed for U enrichment by CEA-MENPHIS (France) facility recently mothballed
- ✓ SuperNEMO / SNO++ consortium is working towards a trial run with ^{150}Nd



CUORICINO

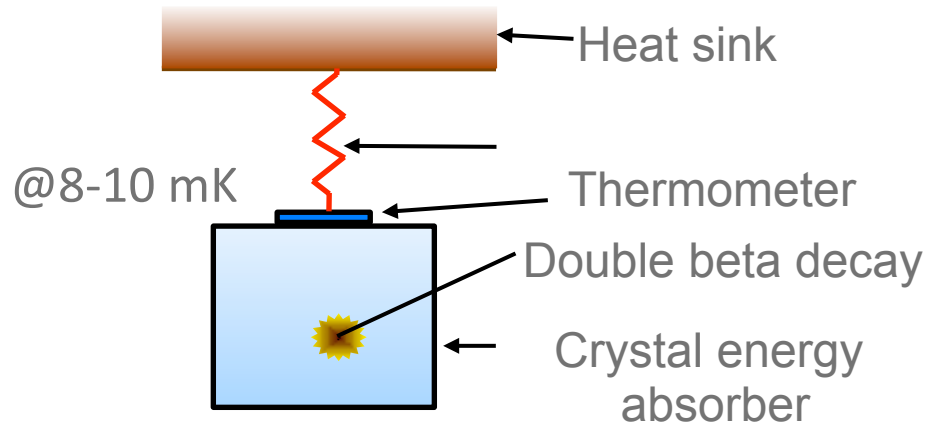
62 bolometers
40.7 kg active mass
Exposure: 11.83 kg y of ^{130}Te

Bolometers of TeO_2 ($Q_{\beta\beta}$= 2.528 MeV)



Thermometer
(Neutron transition doped Ge chip)

Signal: ΔT

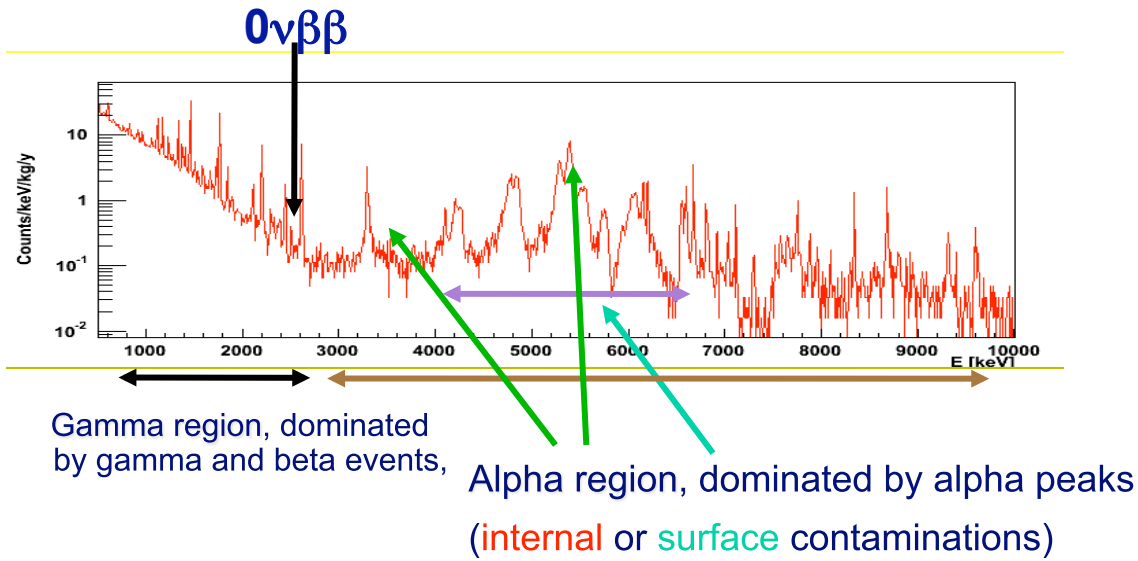


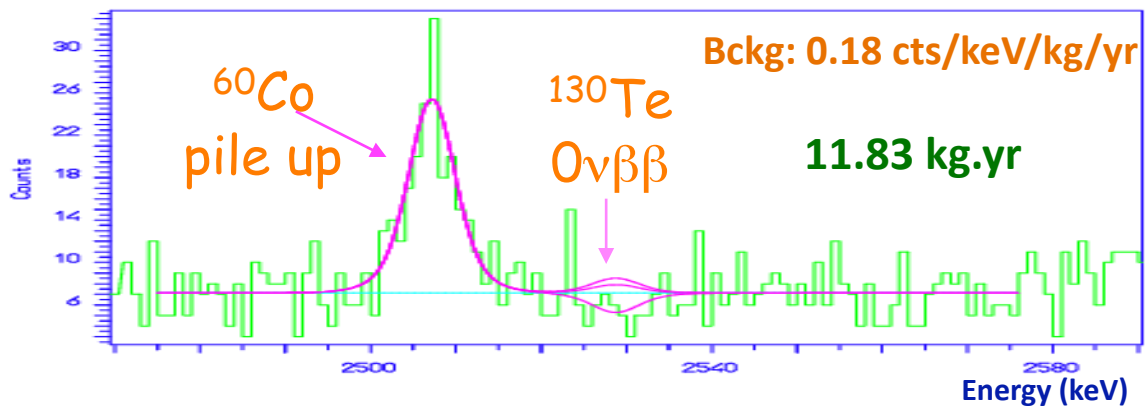
- **Energy resolution 5-7 keV (FWHM)**
- **Natural abundance for ^{130}Te: 34%**
- **High efficiency: 86%**

- **But no electron vs γ discrimination**
- **Background from internal and surface contamination in α emitters**

Operated at Gran Sasso 2003 - 2008.

CUORICINO results

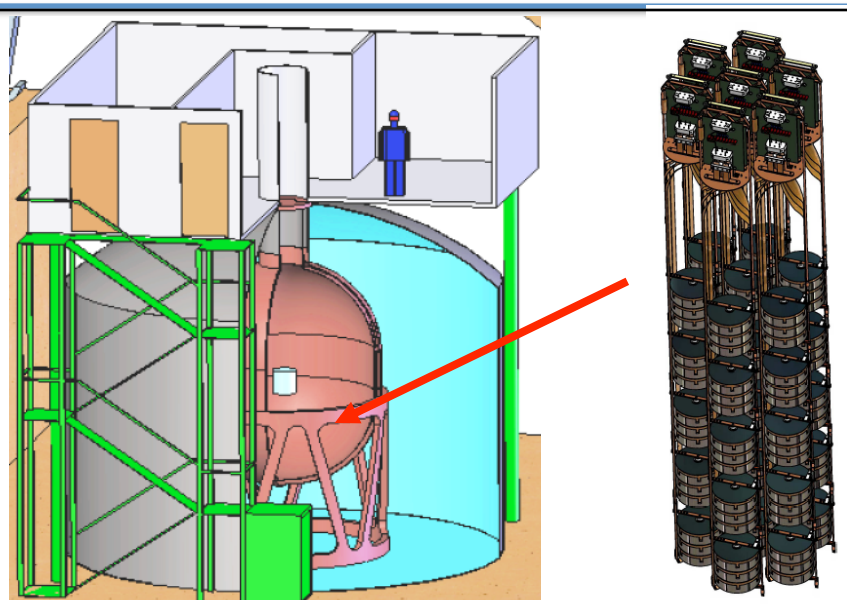




$T_{1/2} > 3.0 * 10^{24}$ yr (90% CL) $\langle m_\nu \rangle < 0.19 – 0.68$ eV (90% CL)

Expected final sensitivity ~2009: $T_{1/2} > 6.\ 10^{24}$ yr $\langle m_\nu \rangle < 0.1 – 0.7$ eV

GERDA



(Germany, Italy, Belgium, Russia, Poland)

Use of liquid nitrogen or argon for active shielding

Segmentation

Improvement of Pulse Shape Analysis

PHASE I: 17.9 kg of enriched ^{76}Ge (from HM and IGEX)

In 1 year of data (if B=10^{-2} cts/keV/kg/an) check of Klapdor's claim

Start 2009 at Gran Sasso, results 2010 $T_{1/2} > 3\ 10^{25}$ yr $\langle m_\nu \rangle < 250$ meV

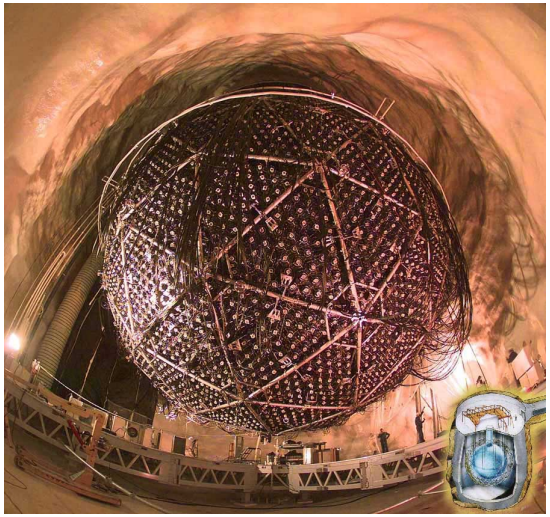
PHASE II: 40 kg of enriched ^{76}Ge (20 kg segmented)

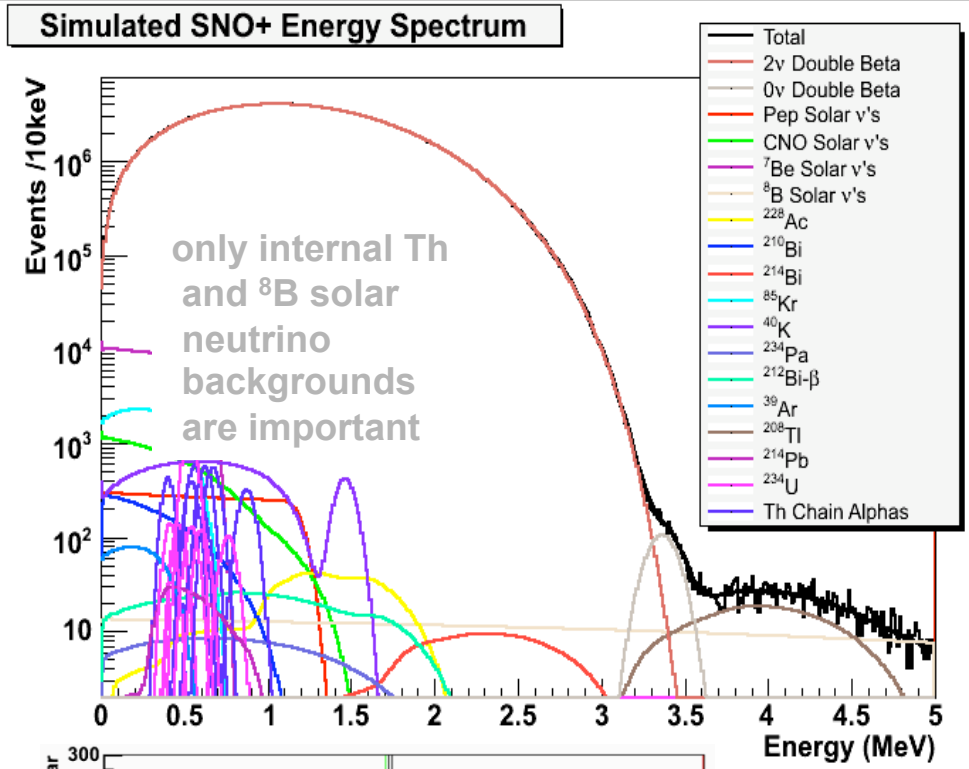
if B=10^{-3} cts/keV/kg/an $T_{1/2} > 2\ 10^{26}$ yr in 3 years of data $\langle m_\nu \rangle < 110$ meV

PHASE III: if PHASE I and II succeed 1 ton if B=10^{-3} cts/keV/kg/an

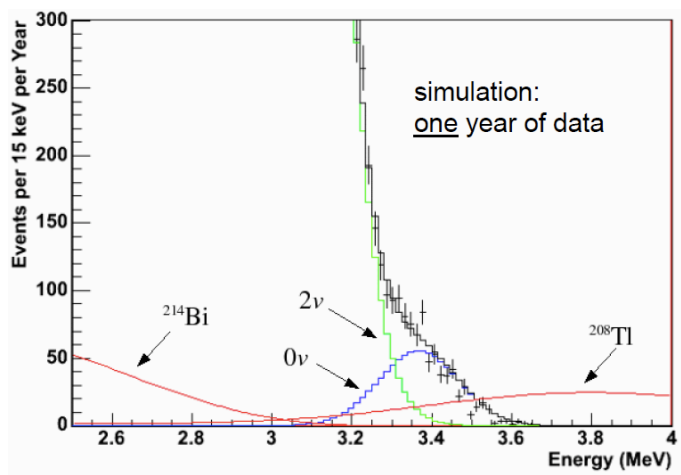
$T_{1/2} > 5\ 10^{27}$ yr in 3 years of data $\langle m_\nu \rangle < 20$ meV

SNO++





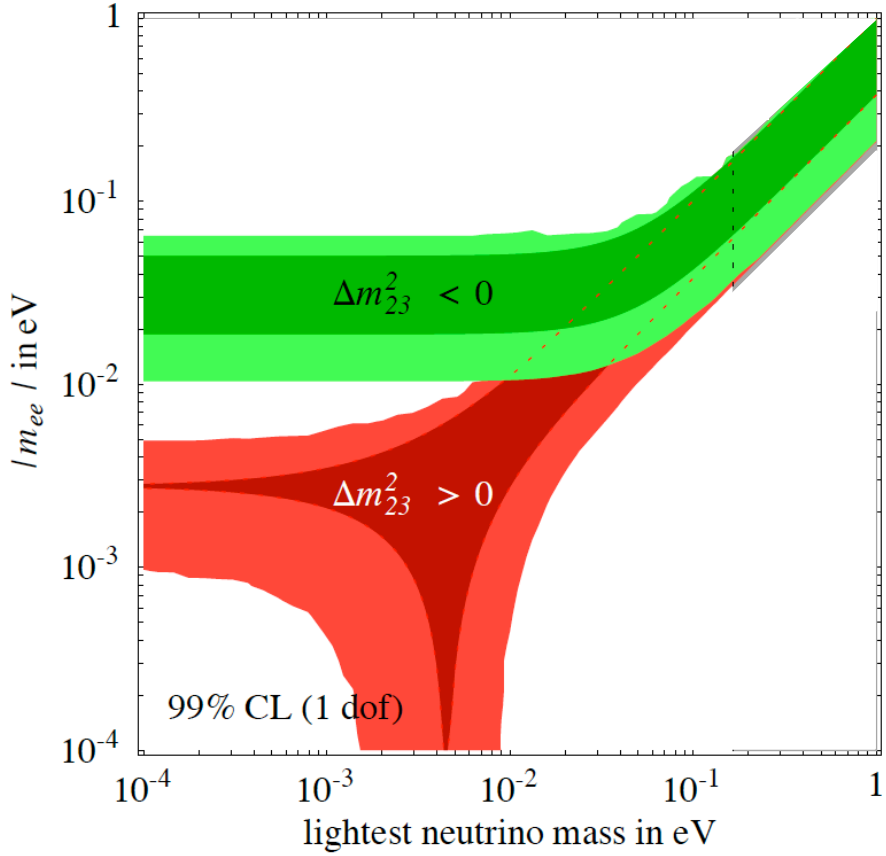
- ✓SNO+ (1000 tons of LAB)
- ✓0.1% ^{nat}Nd - 56kg of ^{150}Nd (doped with $NdCl_3$)
- ✓Sensitivity <m>~150 meV
- ✓With enriched Nd: <m>~40 meV
- ✓Energy resolution 6.4% at $Q_{\beta\beta}$
- ✓In situ purification!
- ✓Start filling in 2010



500 kg of ^{150}Nd
1 year
$<m_\nu>$ = 150 meV

✓(Interest in KamLAND)

"The gauge"



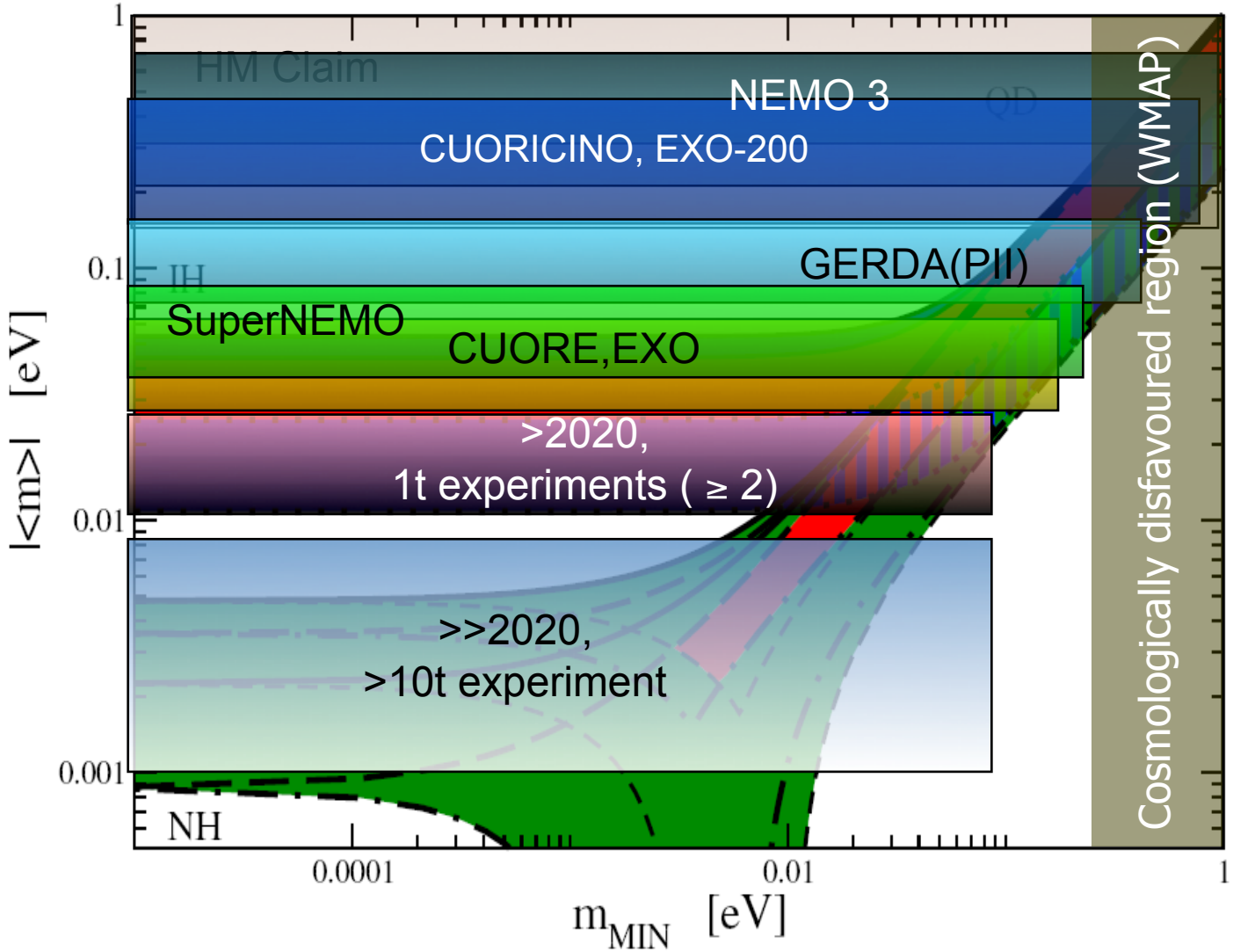
A. Strumia and F. Vissani, ``Neutrino masses and mixings.'' arXiv:hep-ph/0606054.
F. Feruglio, C. Hagedorn, Y. Lin and L. Merlo, ``Theory of the Neutrino Mass,'' arXiv:0808.0812 [hep-ph].

$$\Delta m^2_{sol} = (7.66 \pm 0.35) \times 10^{-5}\ \mathrm{eV}^2$$
$$\Delta m^2_{atm} = (2.38 \pm 0.27) \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{13} < 0.032 \quad (\theta_{13} < 10.3^0) \quad (2\sigma)$$
$$\sin^2\theta_{23} = 0.45^{+0.16}_{-0.09} \quad (\theta_{23} = (42.1^{+9.2}_{-5.3})^0) \quad (2\sigma)$$
$$\sin^2\theta_{12} = 0.326^{+0.05}_{-0.04} \quad (\theta_{12} = (34.8^{+3.0}_{-2.5})^0) \quad (2\sigma)$$

$$|m_{ee}| = |\cos^2\theta_{13}(\cos^2\theta_{12}m_1 + \sin^2\theta_{12}e^{2i\alpha}m_2) + \sin^2\theta_{13}e^{2i\beta}m_3|$$

$$\left|\langle m_{\beta\beta}\rangle\right| \equiv \left| (0.70^{+0.02}_{-0.04})m_1 + (0.30^{+0.04}_{-0.02})m_2 e^{i\alpha^*} + (\leq 0.05)m_3 e^{i\beta^* - 2i\delta} \right|$$

Projections



S. Pascoli, S.T.P., 2006

Summary and outlook

- Neutrinoless double beta decay provides a unique tool to some of the main questions in particle physics:
  - ✓ Are neutrinos Majorana particles?
  - ✓ What are neutrino masses?
  - ✓ What is the neutrino mass ordering?
- Active experimental and theoretical field
  - ✓ many techniques
  - ✓ backgrounds always challenging
    (projections rely on background expectations!)
  - ✓ will need a confirmation
  - ✓ need further improvement in theory (NME)
- NEMO-3 is a particle physics-like approach
  (attractive to "traditional" particle physicists)
  - ✓ has produced many best results in $0\nu\beta\beta$ and $2\nu\beta\beta$
  - ✓ ^{100}Mo (now): $T_{1/2}^{0\nu\beta\beta} > 5.8 \times 10^{23}$ y (90 % CL) $\langle m_\nu \rangle < (600 - 1300)$ meV
  - ✓ expected in 2009: $T_{1/2}^{0\nu\beta\beta} > 2 \times 10^{24}$ y (90 % CL) $\langle m_\nu \rangle < (300 - 700)$ meV
- SuperNEMO is a next step to reach
  $T_{1/2}^{0\nu\beta\beta} > 2 \times 10^{26}$ y $\langle m_\nu \rangle < \sim 50$ meV

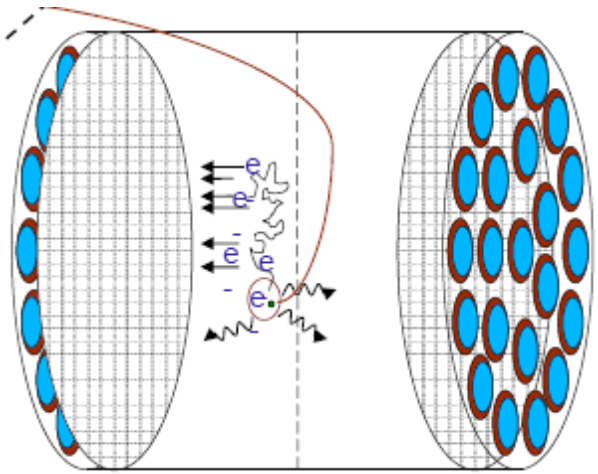
“Nobody goes there anymore; it's too crowded.”

Yogi Berra, a famous baseball player

Backup slides

EXO

(USA, Canada, Switzerland, Russia)



Liquid Xe TPC

Energy measurement by ionization + scintillation

Tagging of Baryum ion ($^{136}Xe \rightarrow {}^{136}Ba^{++} + 2\ e^{-}$)

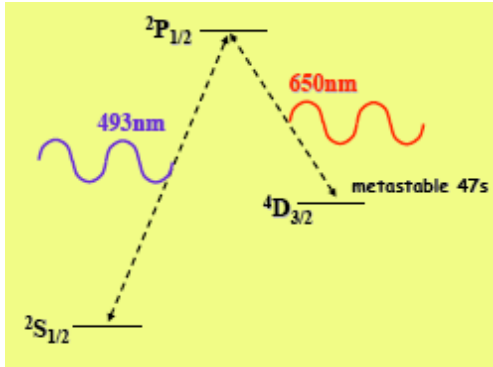
Large mass of Xe

Identification of final state → background rejection

But no e^{-} identification

Poor background rejection without Ba ion tagging

R&D for Ba ion tagging in progress



Prototype EXO-200

200 kg of ^{136}Xe, no Ba ion tagging

Installation in progress in WIPP underground lab 2007

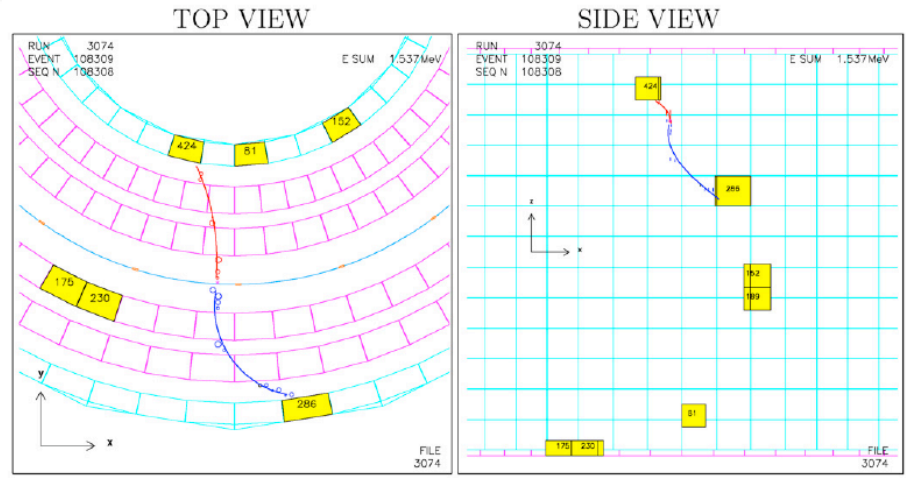
Could measure $\beta\beta(2\nu)$ of ^{136}Xe

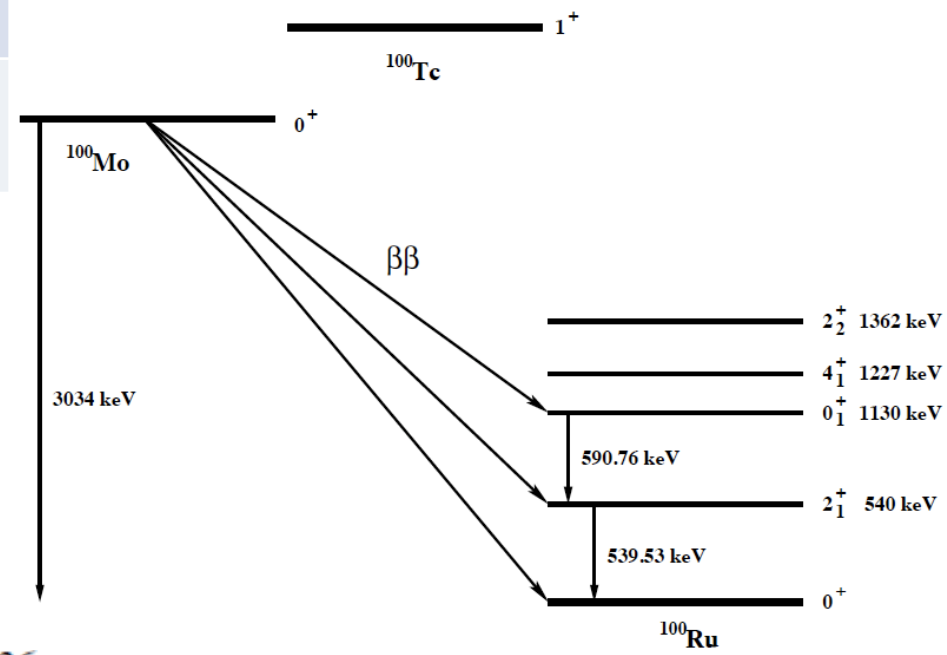
EXO 200 (2 years) $T_{½} > 6.4\ 10^{25}$ yr (90% CL) **$<m_\nu> < 0.27- 0.38$ eV**

NEMO-3: ββ of ^{100}Mo to excited states

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

Best limits or uncertainties

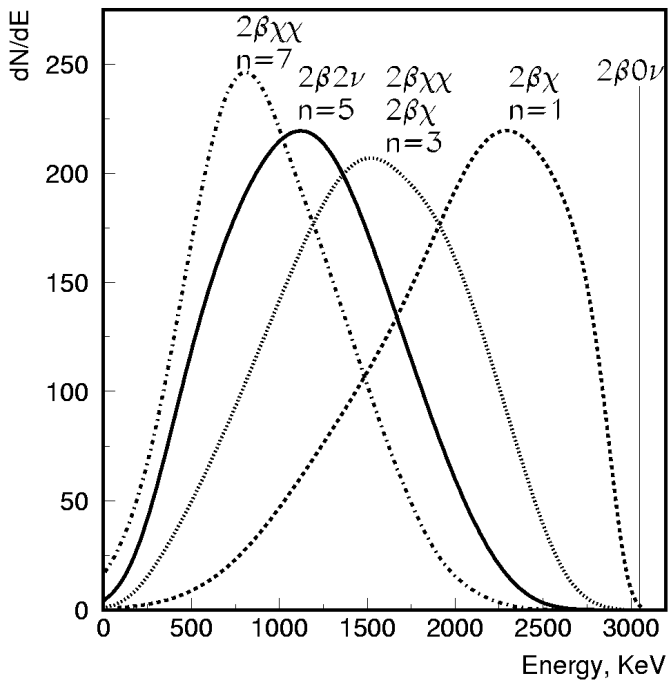




NEMO Collaboration / Nuclear Physics A 781 (2007) 209–226

NEMO-3: Majorons and V+A currents

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

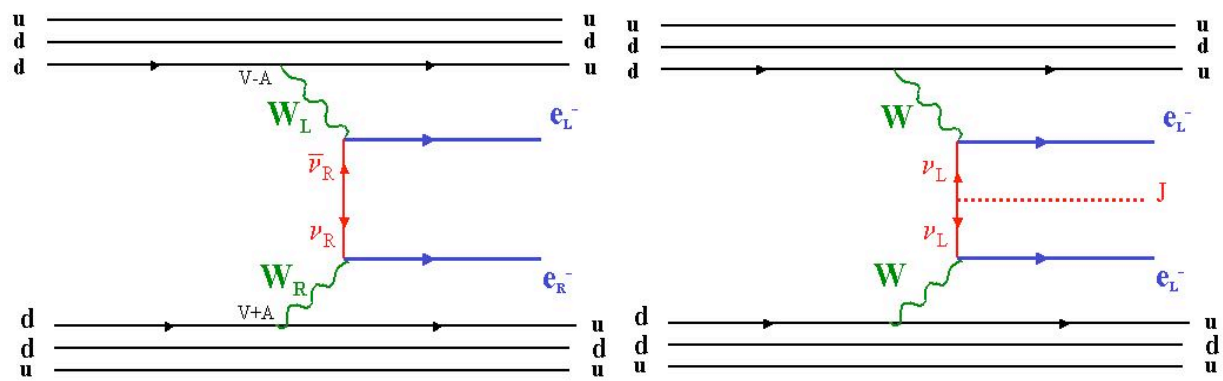


	V+A *	n=1 **	n=2 **	n=3 **	n=7 **
Mo	$>3.2\cdot10^{23}$ $\lambda<1.8\cdot10^{-6}$	$>2.7\cdot10^{22}$ $g_{ee}<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>1.2\cdot10^{23}$ $\lambda<2.8\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6.0\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5.0\cdot10^{20}$

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

world's best limits

$$\frac{dN}{dE} \approx E(Q-E)^n\left(1+2E+\frac{4E^2}{3}+\frac{E^3}{3}+\frac{E^4}{30}\right)$$



* Phase I+Phase II data

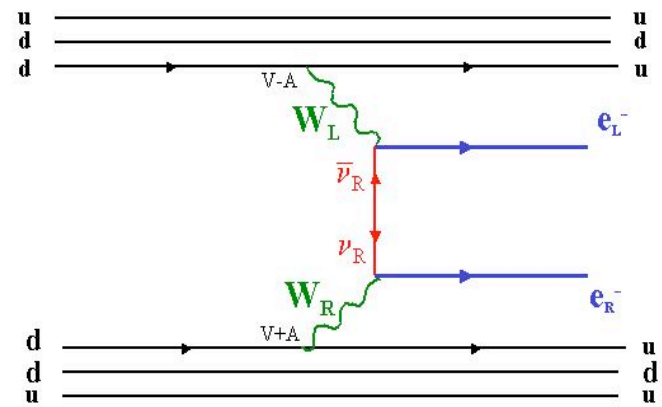
** Phase I data,

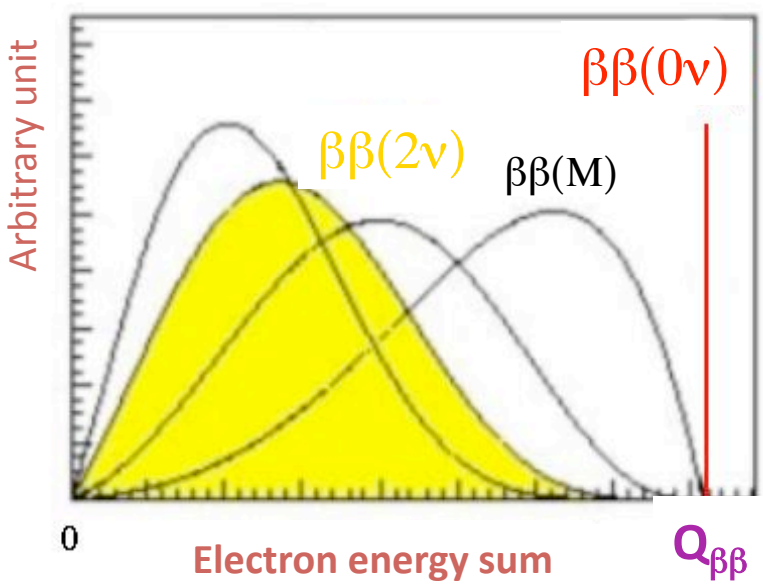
R.Arnold et al. Nucl. Phys. A765 (2006) 483

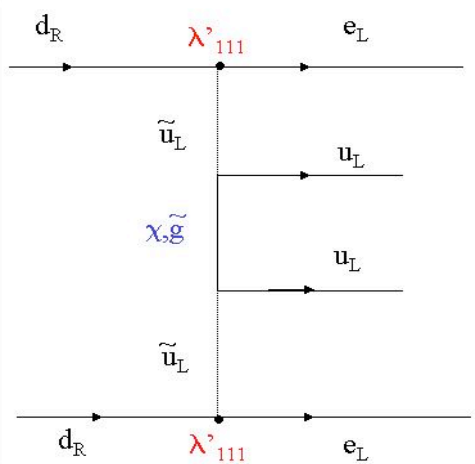
Neutrinoless double beta decay

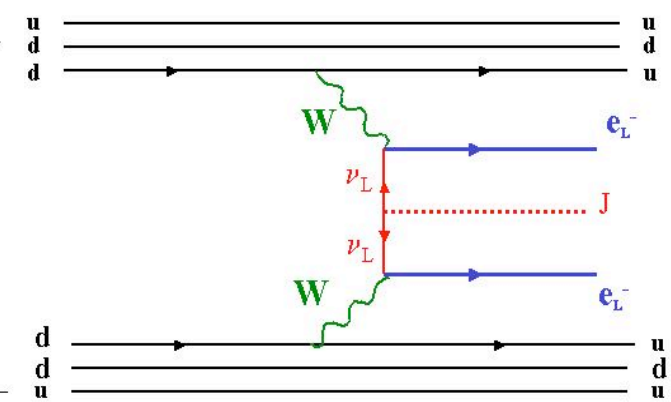
$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

Process:	Parameters
1) Light neutrino exchange	$\langle m_\nu \rangle$
2) (V+A) current	$\langle m_\nu \rangle, \langle \lambda \rangle, \langle \eta \rangle$
3) Majoron emission	$\langle g_M \rangle$
4) SUSY	λ'_{111}, λ'_{113}, λ'_{131}, …





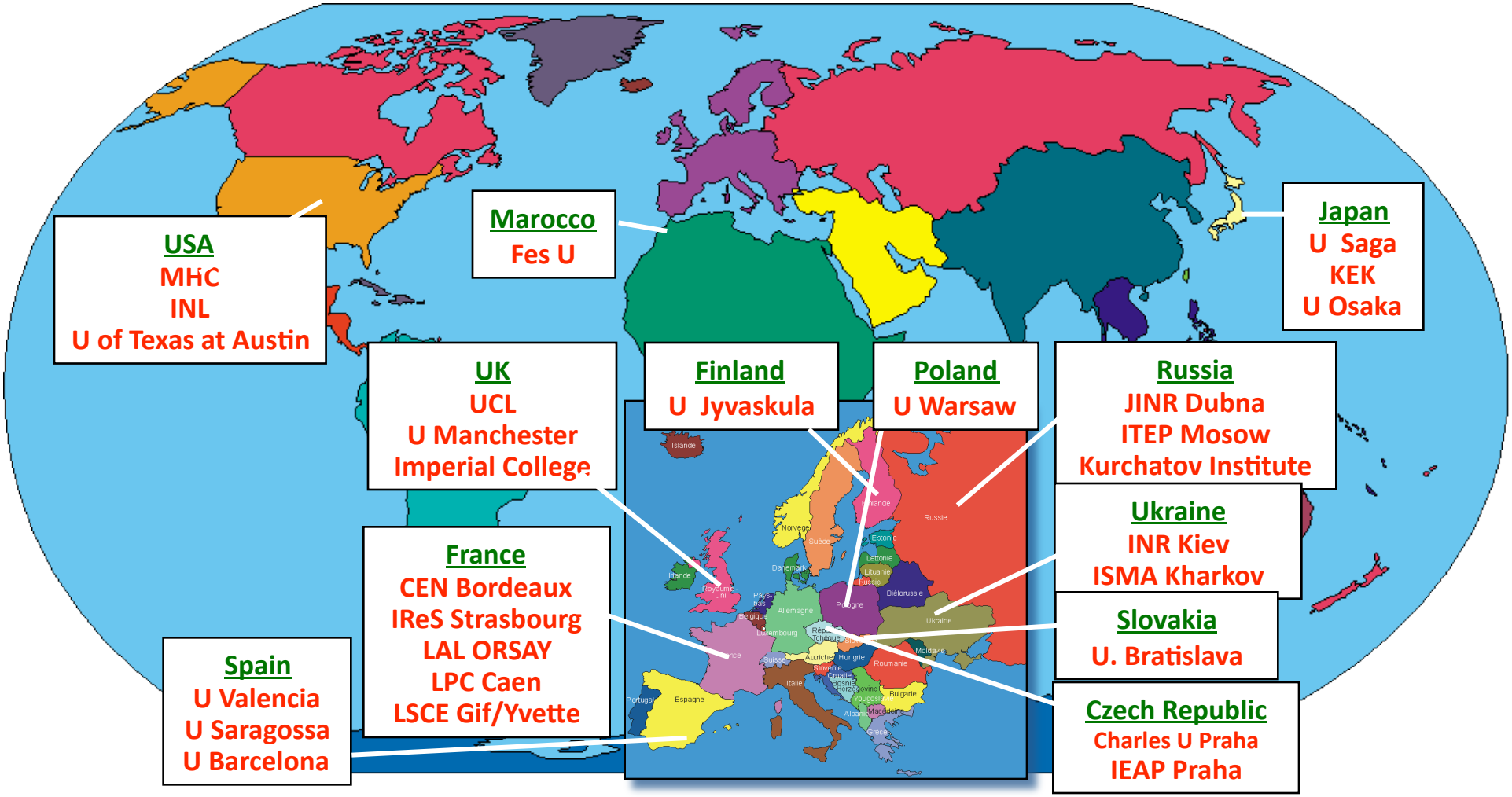




+ difference in angular distributions

SuperNEMO Collaboration

~ 60 physicists, 12 countries, 27 laboratories



0νββ search is a very dynamic field

Experiment	Isotope(s)	Technique	Main characteristics
NEMO3	^{100}Mo,^{82}Se	Tracking + calorimeter	Bckg rejection, isotope choice
SuperNEMO	^{82}Se, ^{150}Nd	Tracking + calorimeter	Bckg rejection, isotope choice
Cuoricino	^{130}Te	Bolometers	Energy resolution, efficiency
CUORE	^{130}Te	Bolometers	Energy resolution, efficiency
GERDA	^{76}Ge	Ge diodes	Energy resolution, eficiency
Majorana	^{76}Ge	Ge diodes	Energy resolution, efficiency
COBRA	^{130}Te, ^{116}Cd	ZnCdTe semi-conductors	Energy resolution, efficiency
EXO	^{136}Xe	TPC ionisation + scintillation	Mass, efficiency, final state signature
MOON	^{100}Mo	Tracking + calorimeter	Compactness, Bckg rejection
CANDLES	^{48}Ca	CaF_2 scintillating crystals	Efficiency, Background
SNO++	^{150}Nd	Nd loaded liquid scintillator	Mass, efficiency
XMASS	^{136}Xe	Liquid Xe	Mass, efficiency
CARVEL	^{48}Ca	CaWO4 scintillating crystals	Mass, efficiency
Yangyang	^{124}Sn	Sn loaded liquid scintillator	Mass, efficiency
DCBA	^{150}Nd	Gazeous TPC	Bckg rejection, efficiency

Summary of NEMO-3 results

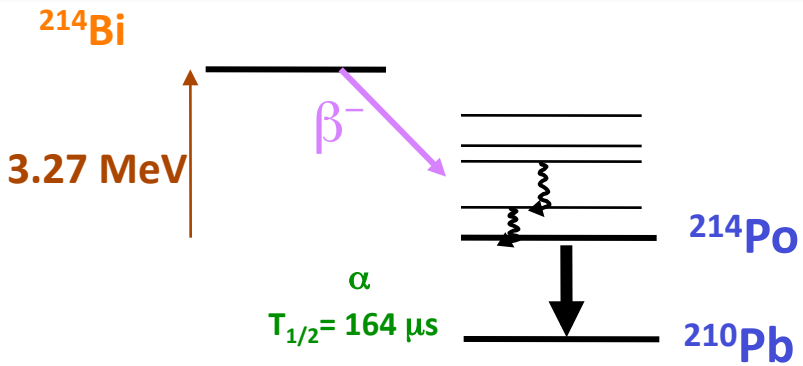
Isotope	Data	$T_{½}$ (ββ2ν) - years
^{100}Mo *	389 days - Phase 1	**7.11 ± 0.02 (stat) ± 0.54 (syst) $\times 10^{18}$**
^{82}Se *	389 days - Phase 1	**9.6 ± 0.3 (stat) ± 1.0 (syst) $\times 10^{18}$**
^{116}Cd	168 days - Phase 1	**2.8 ± 0.1 (stat) ± 0.3 (syst) $\times 10^{19}$**
^{96}Zr	925 days - Phase 1	**2.3 ± 0.2 (stat) ± 0.3 (syst) $\times 10^{19}$**
^{48}Ca	948 days - Phase 1	**$4.4\ ^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst) $\times 10^{19}$**
^{130}Te	534 days – Phases 1 + 2	**7.6 ± 1.5 (stat) ± 0.8 (syst) $\times 10^{20}$**
^{150}Nd	925 days – Phases 1 + 2	**$9.11\ ^{+0.25}_{-0.22}$ (stat) ± 0.63 (syst) $\times 10^{18}$**

* *R. Arnold et al., Phys. Rev. Lett. 95 182302 (2005)*

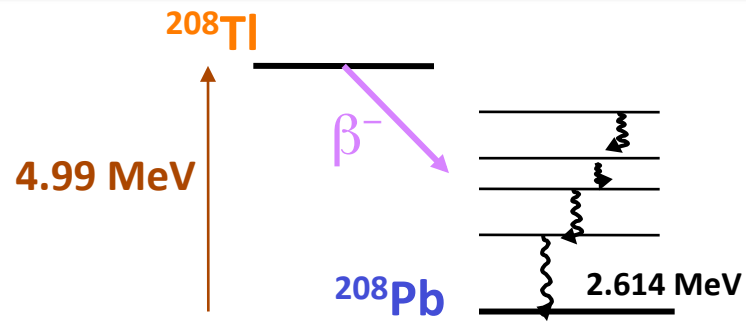
Isotope	Data	$T_{½}$ (ββ0ν) - years	$<m_\nu>$
^{100}Mo	693 days - Phases 1 + 2	**$> 5.8 \times 10^{23}$**	**< 0.6 – 1.3 eV**
^{82}Se	693 days - Phases 1 + 2	**$> 2.1 \times 10^{23}$**	**< 1.2 – 2.2 eV**

- More backup slides

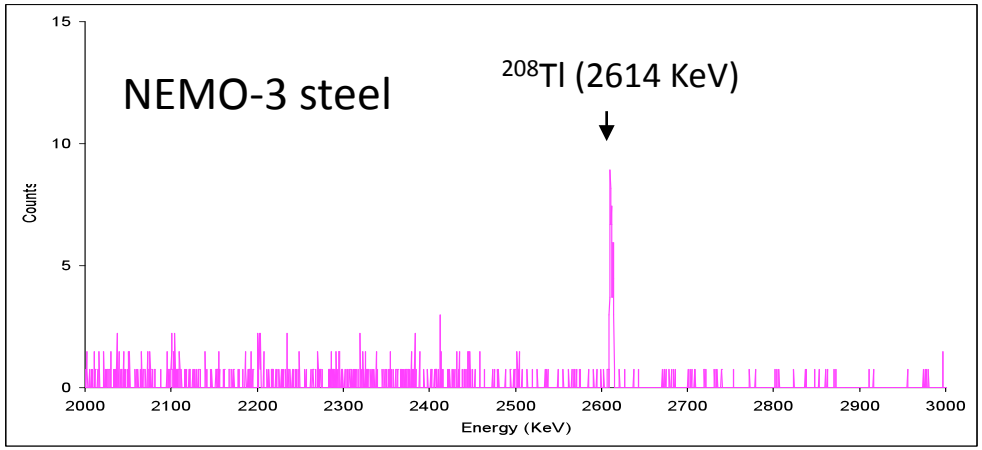
Background origins



^{238}U decay chain



^{232}Th decay chain



Sources:

- Radon and thorium
- Neutrons ((n,γ) reactions) γ up to 10 MeV
- Muons (cosmogenic)
- Muon bremstrahlung
- High energy γ (n,γ) in materials

Minimize by:
Detector Shieldings
Underground laboraratory

Laboratoire Souterrain de Modane

Muon Flux
0.17 μ m^{-2} h^{-1}

Neutron Flux	
1.6 10^{-6} n cm^{-2} s^{-1}	(0-0.63 eV)
4 10^{-6} n cm^{-2} s^{-1}	(2-6 MeV)

Radon
15 Bq/m^3
(150 m^3/h air at 20 mBq/m^3)

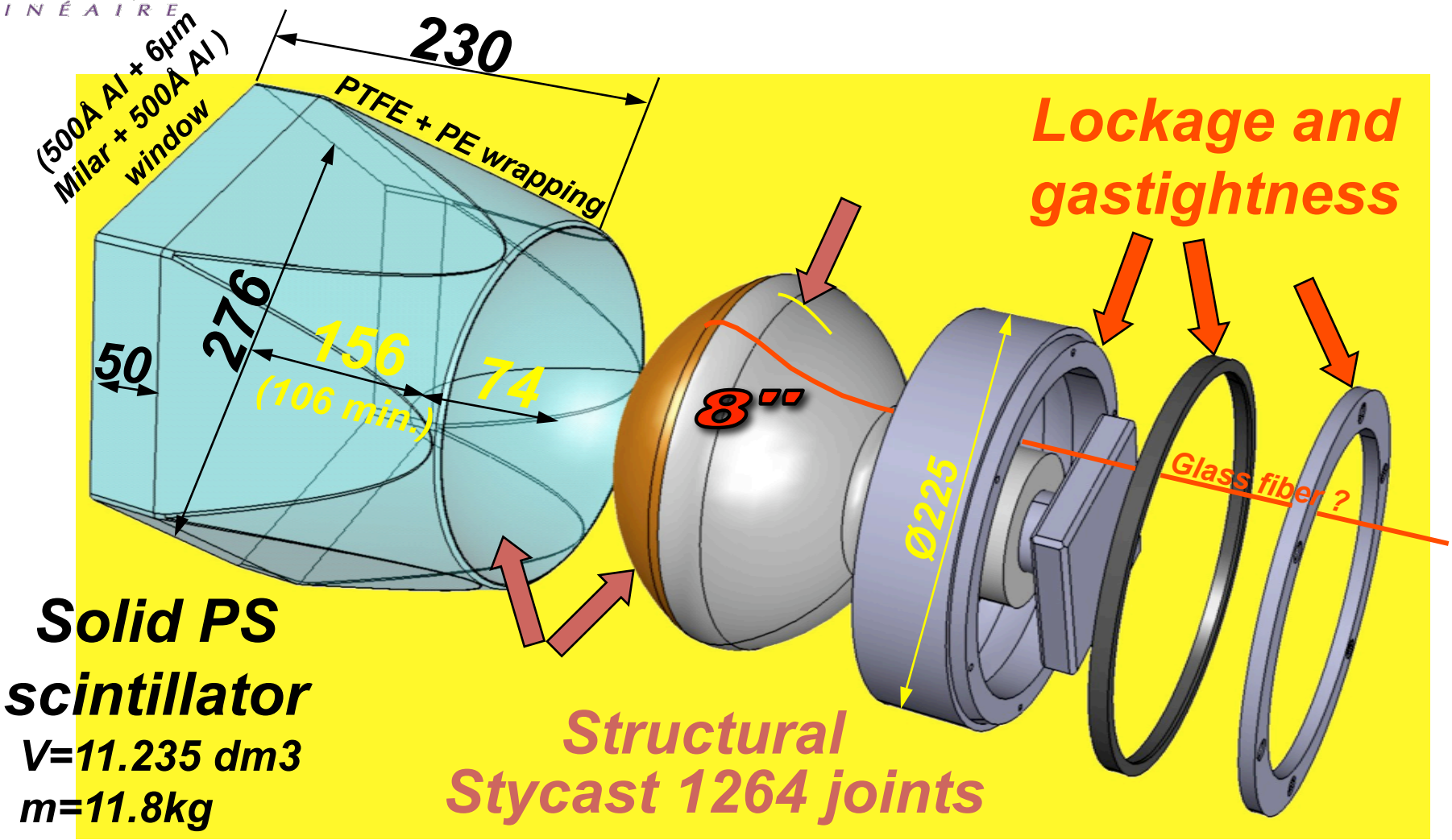
Primordial Radionuclides		
^{238}U	0.84 ppm	Rock
	1.9 ppm	Concrete
^{232}Th	2.45 ppm	Rock
	1.4 ppm	Concrete
K	213 Bq/kg	Rock
	77 Bq/kg	Concrete

Low counting facility at LSM

13 HPGe from 6 different laboratories of CNRS and CEA are available at LSM

- ❑- Material selection for astroparticle physics,
- ❑- Environnemental measurements
- ❑- Applications (wine dating, salt origin,…)
- ❑- Developements of Ge detector

Basic solid exa 276 block with its components

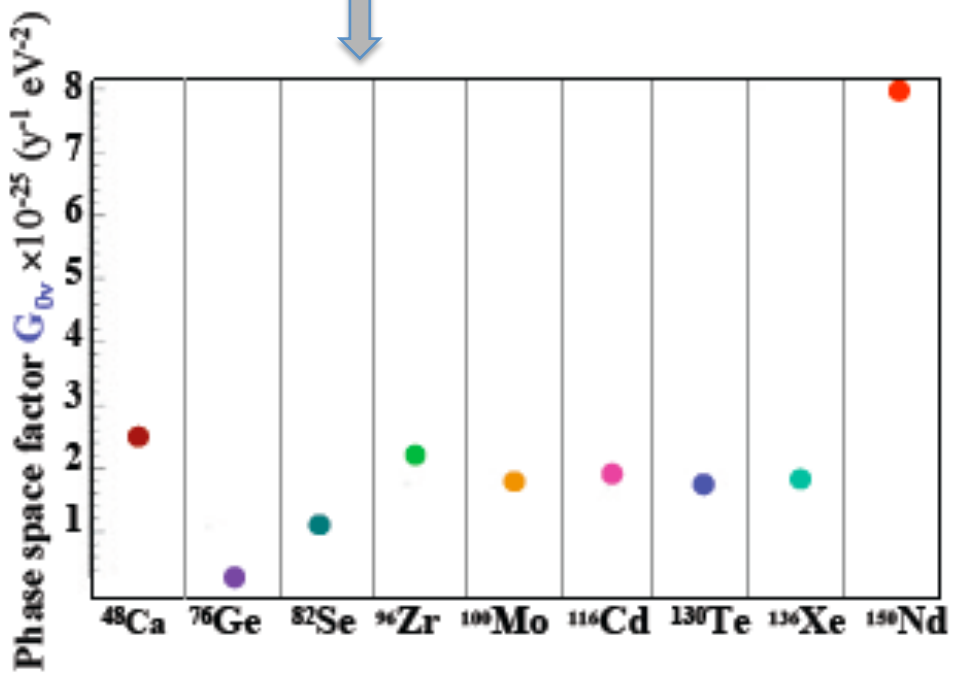


Practical matters

	$Q_{\beta\beta}$ (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

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



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]].

Poszukiwania bezneutrinowego podwójnego rozpadu beta w detektorach NEMO-3 i SuperNEMO

Karol Lang
The University of Texas at Austin

Streszczenie

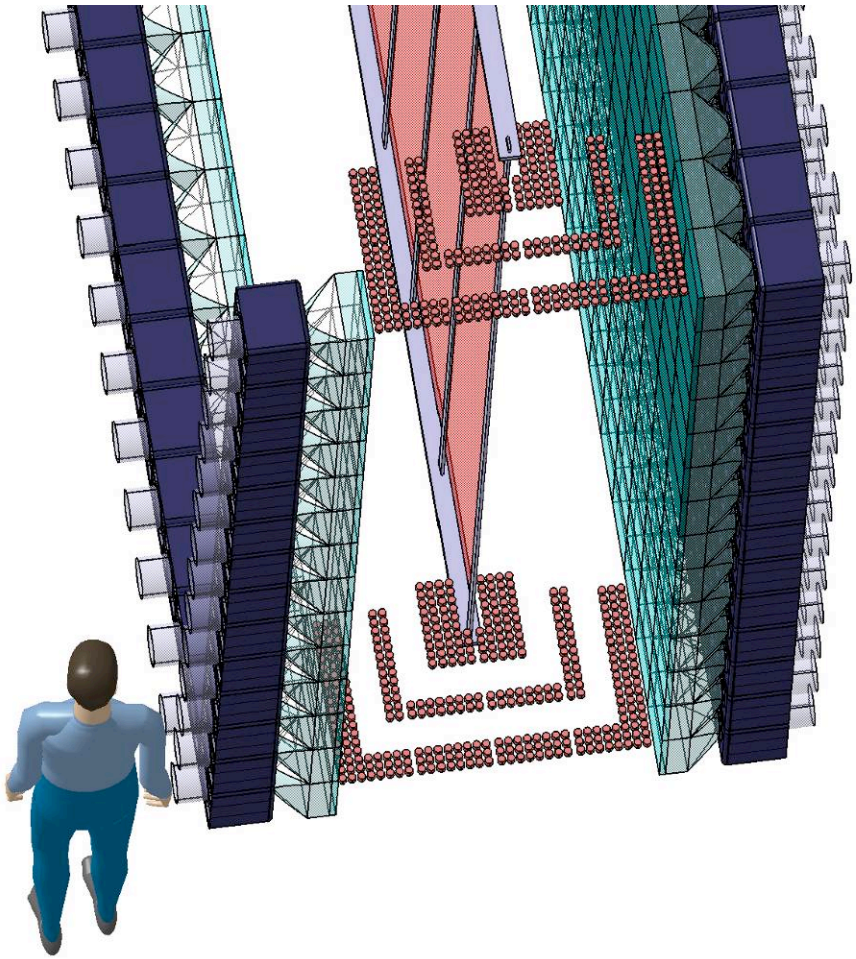
Z obserwacji oscylacji neutrin wynika, że cząstki te posiadają masę. Odkrycie to odnowiło i pogłębiło zainteresowanie procesem bezneutrinowego podwójnego rozpadu beta, który oferuje jedyną praktyczną drogę do określenia czy neutrina są cząstkami typu Majorany czy typu Diraca. Eksperyment NEMO-3, usytuowany w podziemnym laboratorium w Modane (Francja) w tunelu Fréjus, wykorzystuje technikę dryfowej komory śladowej, plastikowego kalorymetru scyntylacyjnego i czasu przelotu do pomiaru energii, topologii oraz identyfikacji dwóch elektronów w stanie końcowym podwójnego rozpadu. W referacie przedstawimy ostatnie wyniki z NEMO-3 i przedyskutujemy stan planowanego eksperymentu SuperNEMO, który będzie bardziej czułym detektorem "nowej generacji".

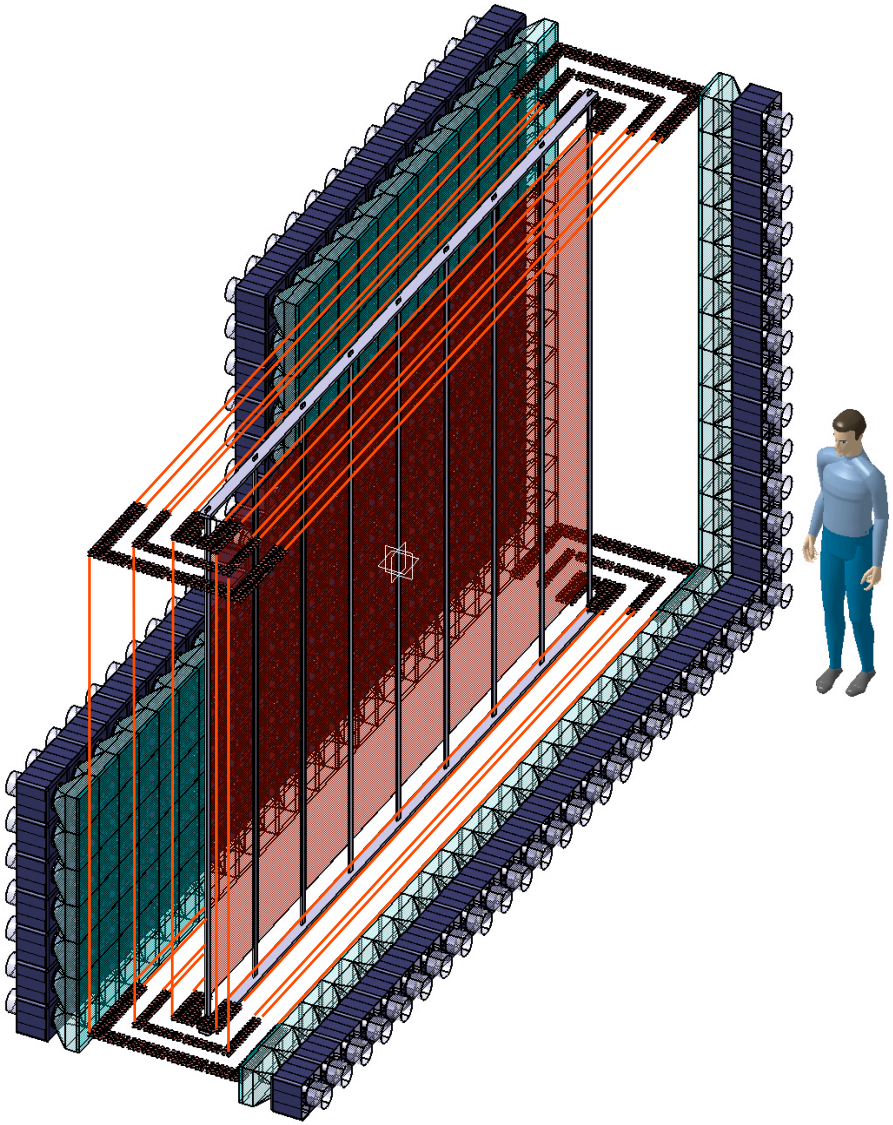
A search for neutrinoless double beta decay with NEMO-3 and SuperNEMO detectors

Abstract

The observation of neutrino oscillations has proved that neutrinos have mass. This discovery has renewed and strengthened the interest in neutrinoless double beta decay experiments which provide the only practical way to determine whether neutrinos are Majorana or Dirac particles. NEMO-3, located in the Modane Underground Laboratory in the Frejus Tunnel under the French-Italian Alps, is an ongoing experiment looking for neutrinoless double beta decays using a powerful technique for detecting a two-electron final state by employing an apparatus combining tracking, calorimetry, and the time-of-flight measurements. We will present results from NEMO-3 and will discuss the status of SuperNEMO, the next generation experiment that will exploit the same experimental technique to extend the sensitivity of the current search.

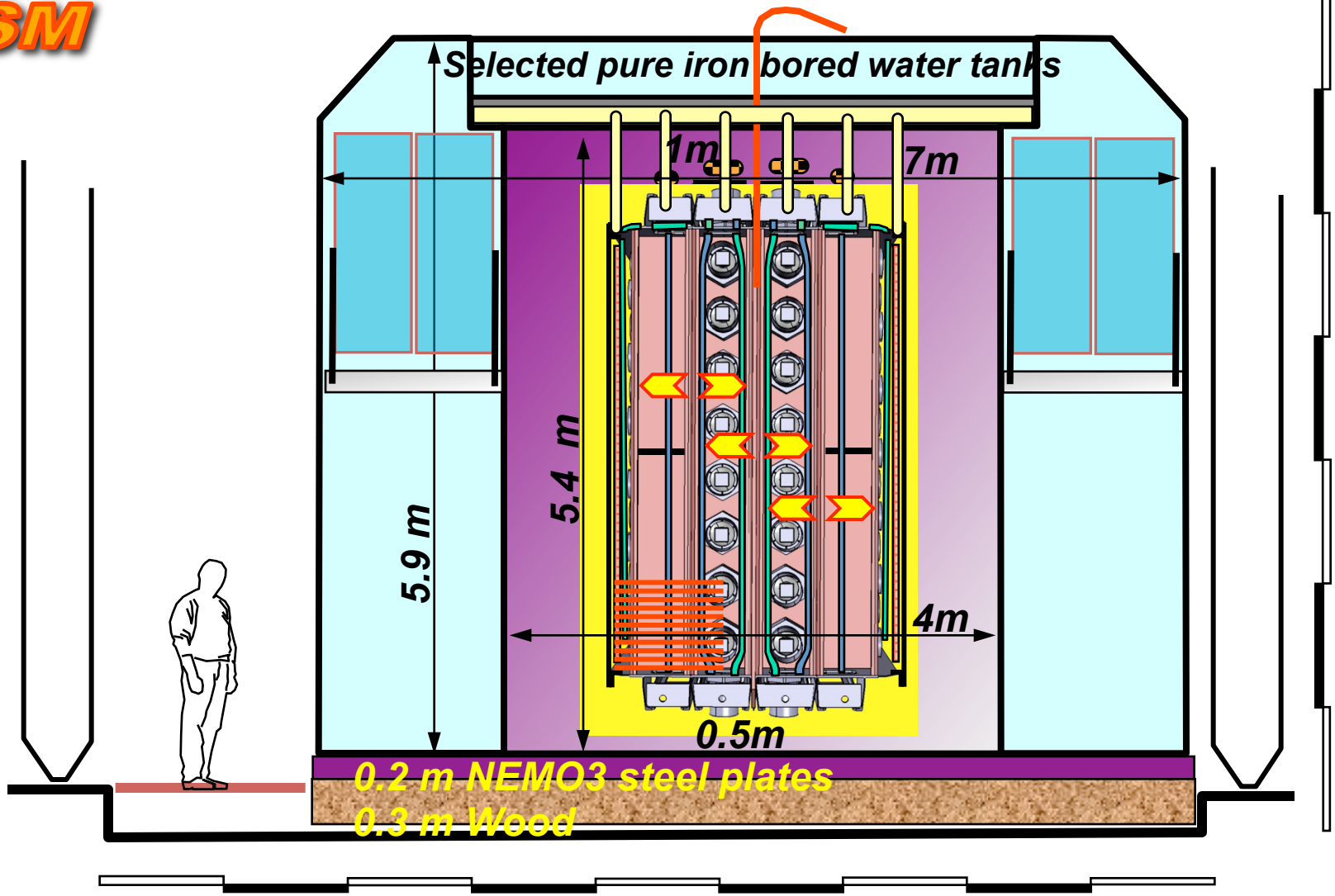
SuperNEMO design study



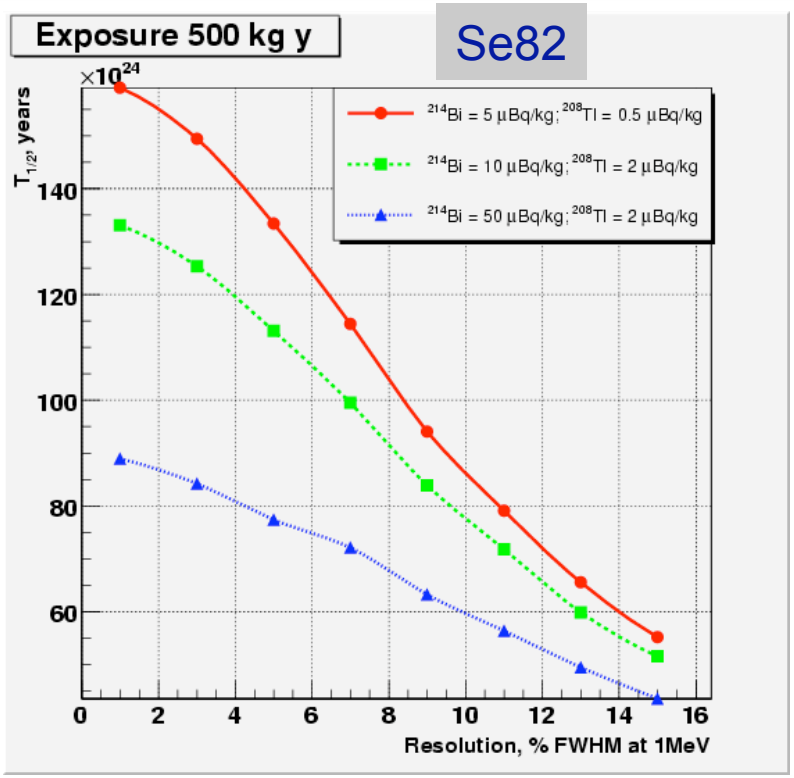


Proto LSM

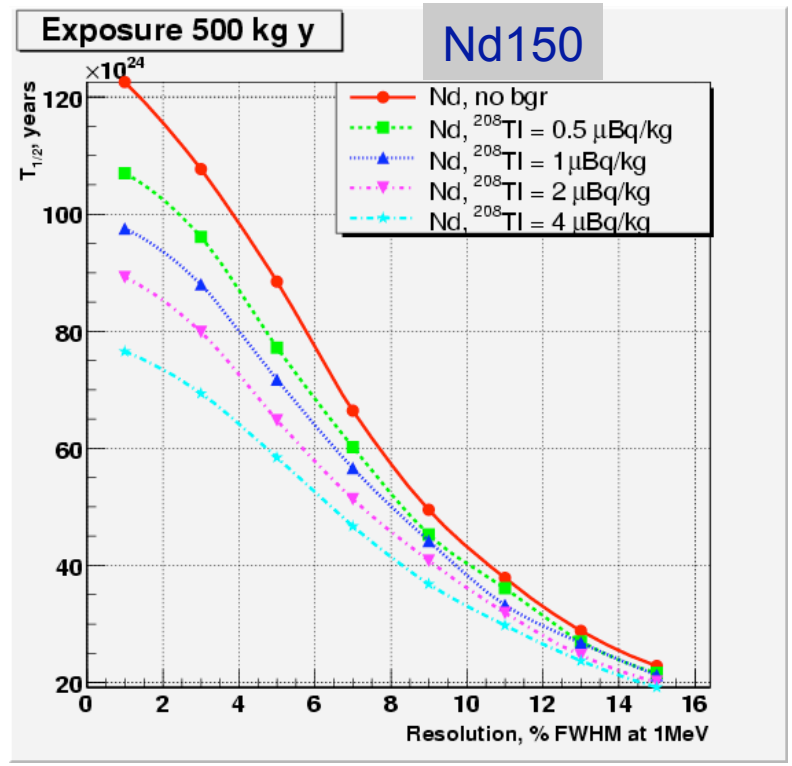
Maximum loading capacities 8t 6.84m max.



SuperNEMO simulations and physics reach



"Conservative" scenario



Sensitivity

^{82}Se: $T_{1/2}(0\nu)$ = (1-2) 10^{26} yr — depending on final mass, background and efficiency

$\langle m_\nu \rangle \leq$ 0.060 – 0.100 eV — includes uncertainty in $T_{1/2}$ + MEDEX'07 NME

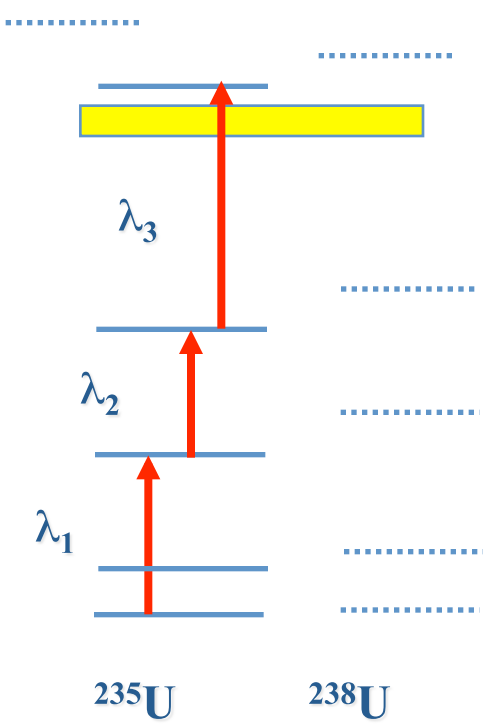
^{150}Nd: $T_{1/2}(0\nu)$ = 5 10^{25} yr

$\langle m_\nu \rangle \leq$ 0.045 eV — (but deformation **not** taken into account)

CEA-MENPHIS

Laser-vapor interaction
SILVA / AVLIS
(Atomic Vapor Laser Ionization Separation)

2 Isotopes ^{235}U and ^{238}U
5 energy levels
and 4 transitions



Photoionization

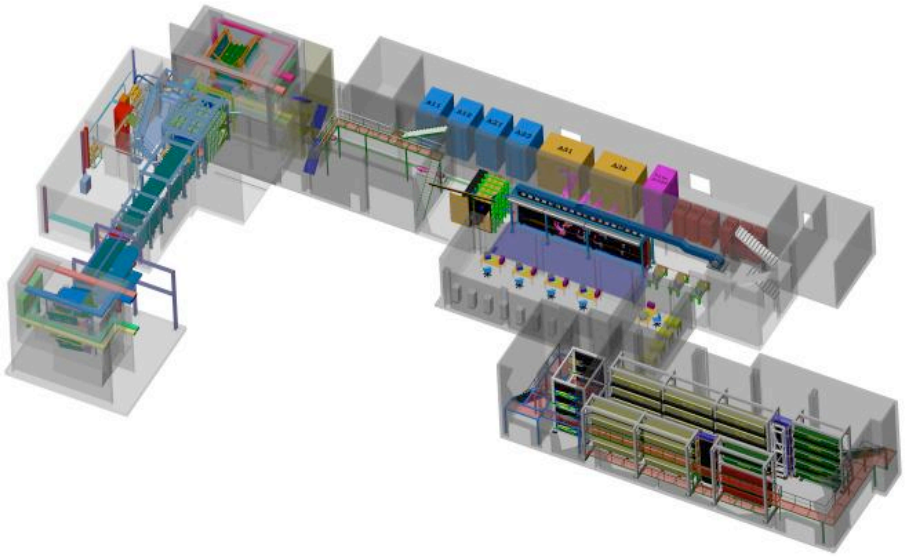
1973 : Atomic isotope separation by laser : initial patent
1980 : Basic research at CEA (spectroscopy, evaporation)
1985 : SILVA/AVLIS selected as advanced process :
USA, France, Japan
1994 : Tens of grams produced at the industrial assay
1994-1998 : Technological demonstrations (by parts)
Mid 1999 : AVLIS shut down in US ; early 2003 in Japan
2000 : Decision for a conclusive 4 years program
2000 - 2003 : MENPHIS construction and preliminary R&D.
2003 : Demonstrations on MENPHIS

Design : 2001
Building : 2002
1st test : early 2003
1st full scale exp. : June 2003

204 kg @ 2.5% ^{235}U

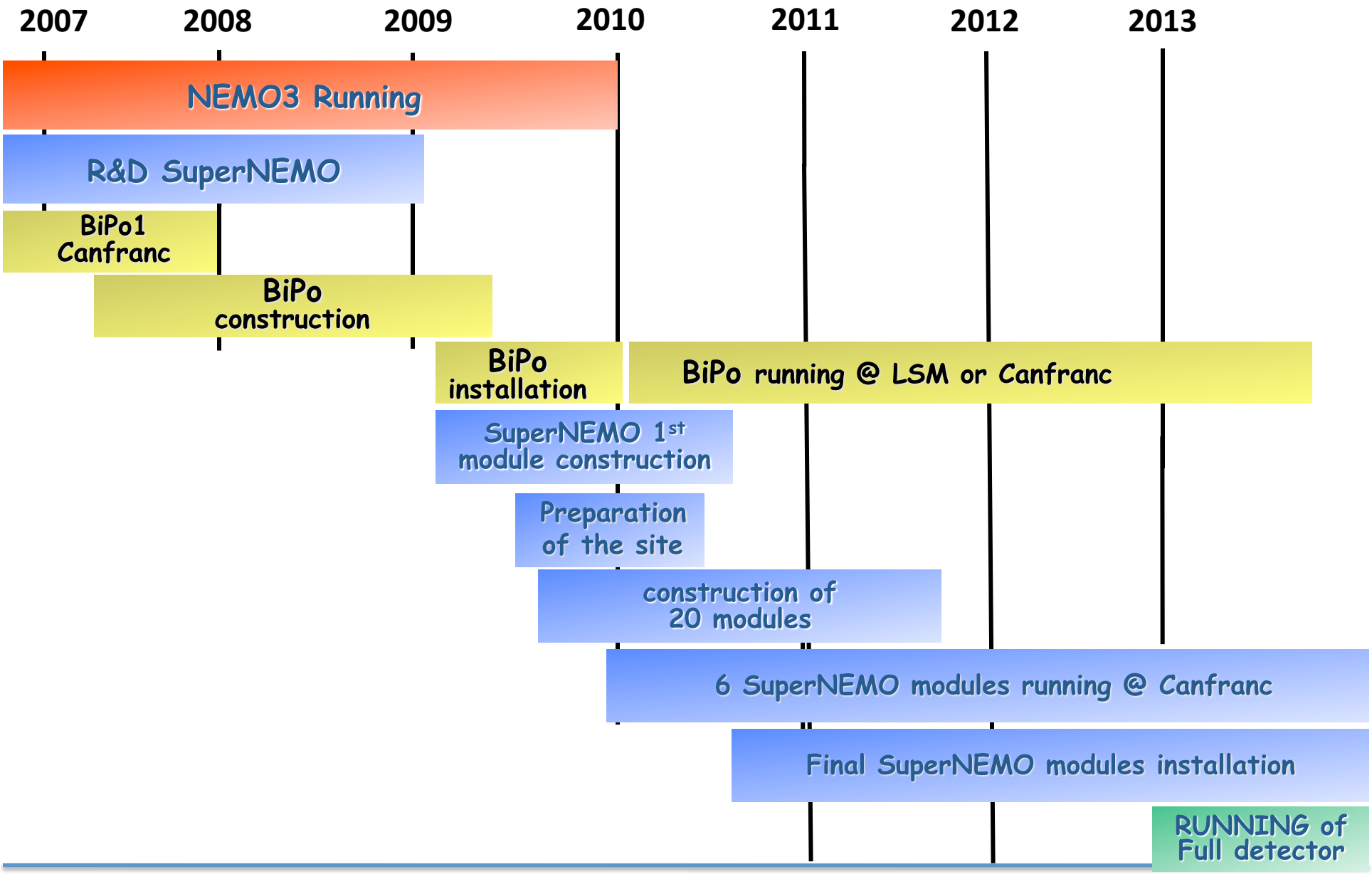
Grams/hr

150 Nd possible

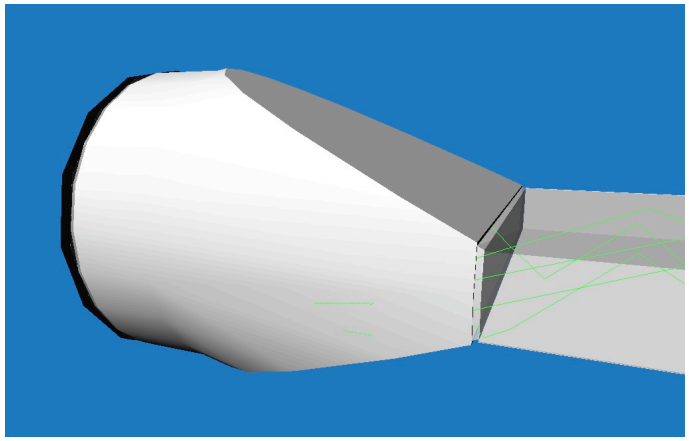


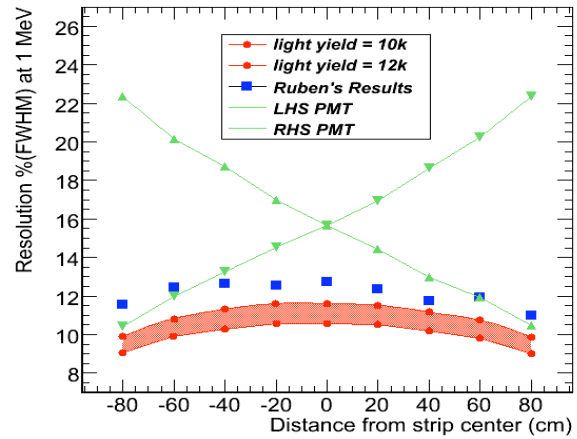
(from Alain Petit)

SuperNEMO schedule summary

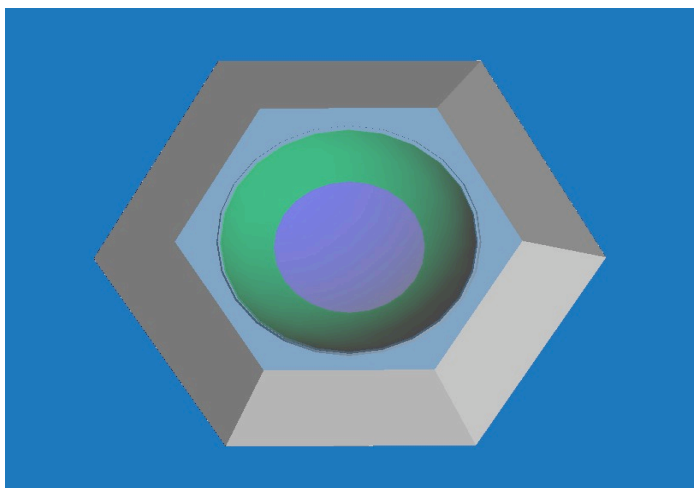


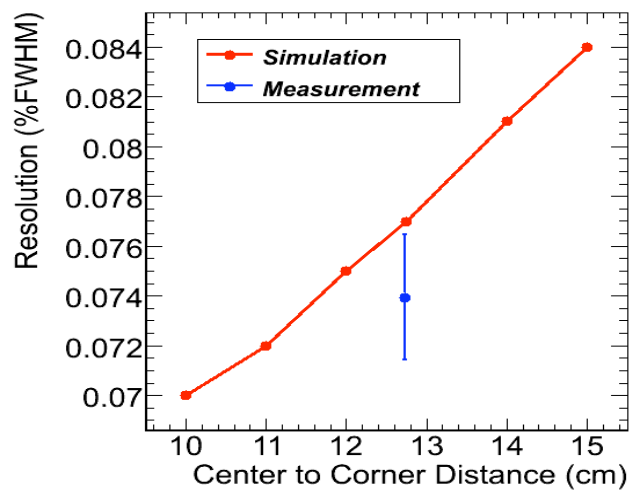
Bar and Block Scintillator Simulation





2 m x 2 cm x 10 cm bar with light guides. 1 MeV electrons simulated at various distances along the length of the bar. Current measurements (~10% FWHM) agree well with simulation.

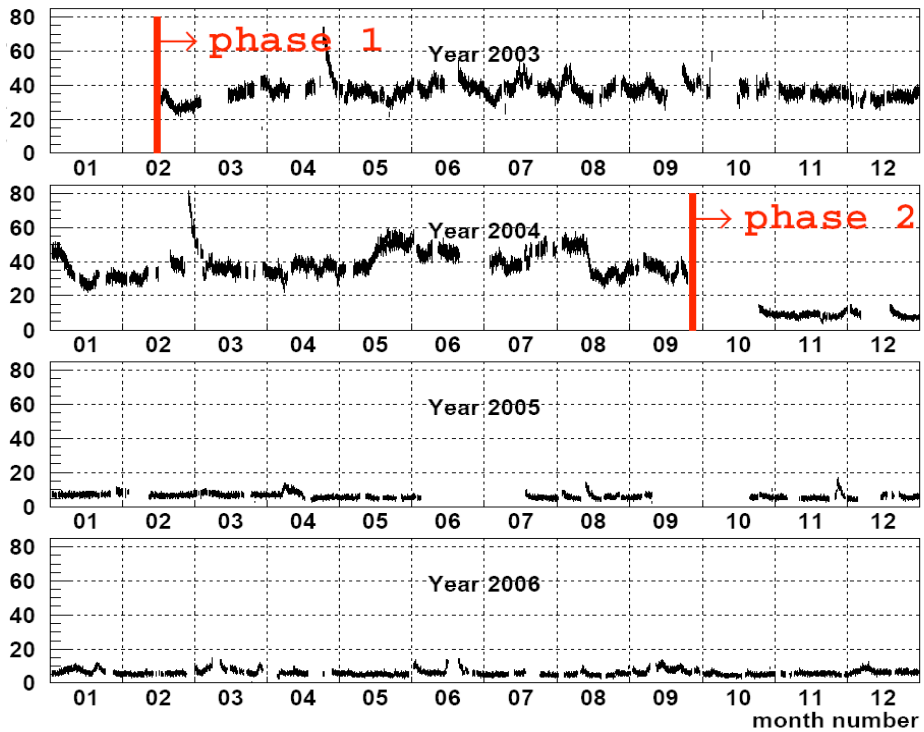




Simulation of large (18 cm tall) hexagonal scintillator for SuperNEMO. Simulations show that resolution is linearly dependent on block size; an important SuperNEMO design parameter.

Radon Trapping Facility

- Radon trapping facility installed in September 2004.
- The trapping time in activated charcoal longer than ^{222}Rn half-life of 3.8 days.
- Radon level reduced by almost factor of 10 in the detector by installing radon trapping facility



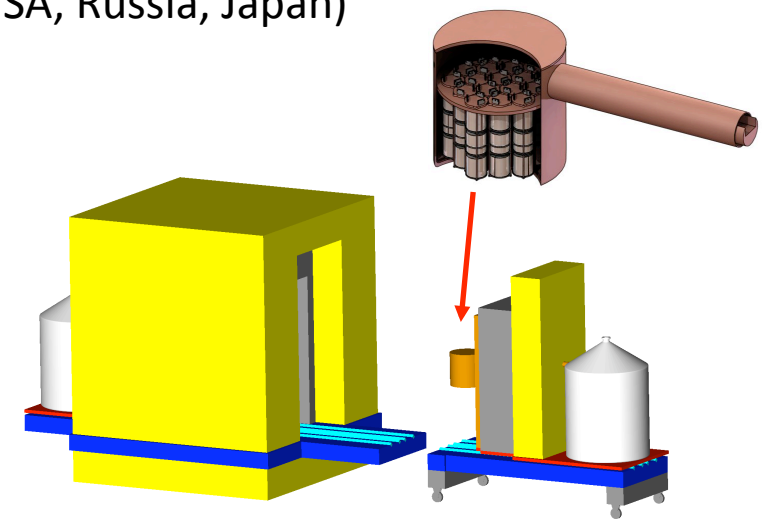
Adsorption unit @-50°C

Input: A(^{222}Rn) 15 Bq/m^3

Output: A(^{222}Rn) < 15 mBq/m^3 !!
reduction factor of 1000

Majorana

(USA, Russia, Japan)



Very pure material
(Electroformed cooper)

Segmentation
PSD improvement
Deep underground

Goal 500 kg of ^{76}Ge (module of 60 kg)

R&D phase 30-60 kg of 86% enriched ^{76}Ge crystals

Some of the crystal segmented

Bckg goal ~ ≤1 count/ROI/t-y (after analysis cuts)

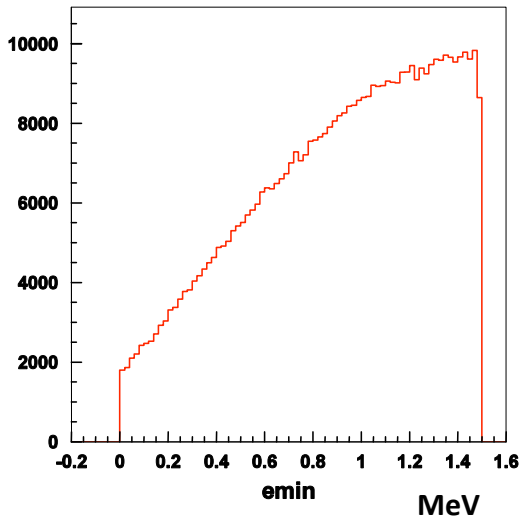
30 kg of enriched Ge, running 3 yr . Data taking schedule for 2011

$T_{1/2} > 1.\ 10^{26}$ yr $\langle m_\nu \rangle < 140$ meV (could confirme or refute Klapdor)

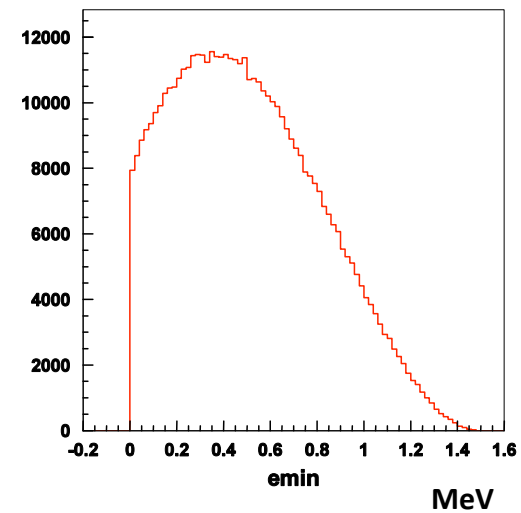
Collaboration with Gerda for 1 ton detector

0νββ observables

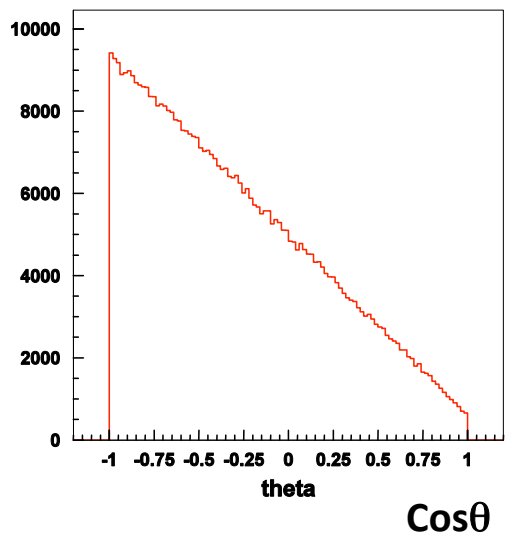
Light neutrino exchange



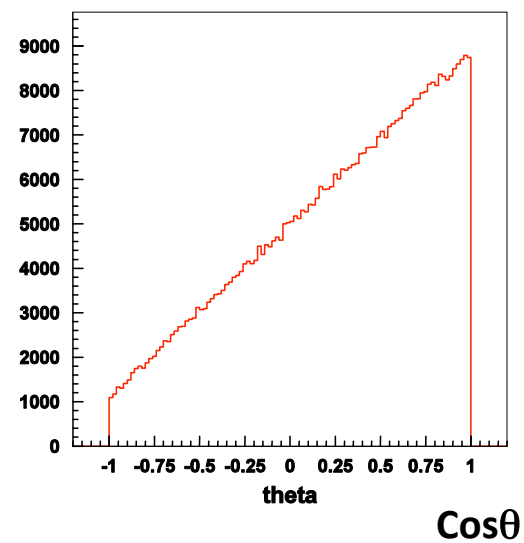
V+A current



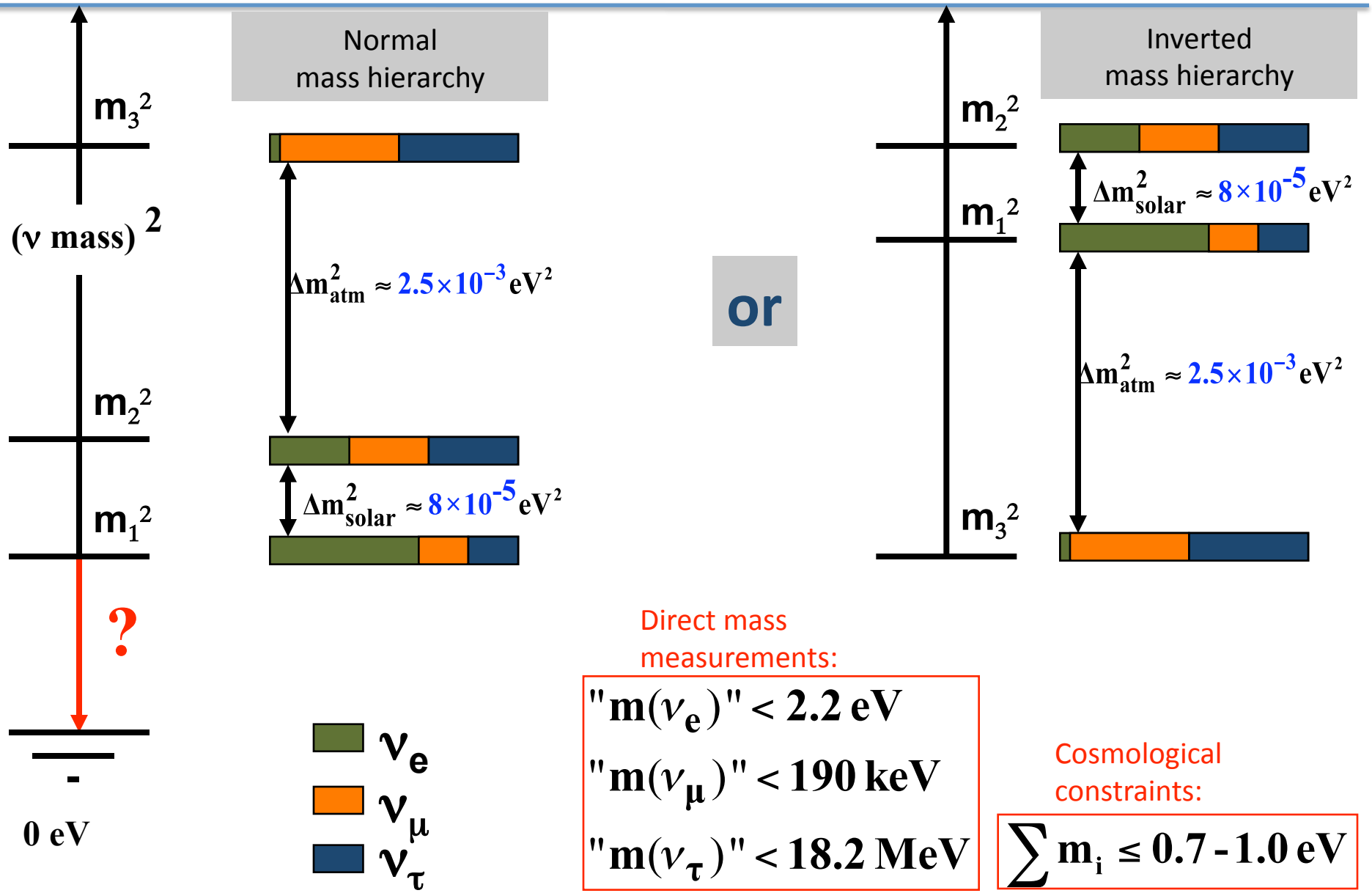
Minimum energy



Angular distribution



What we've learned in last 10 years



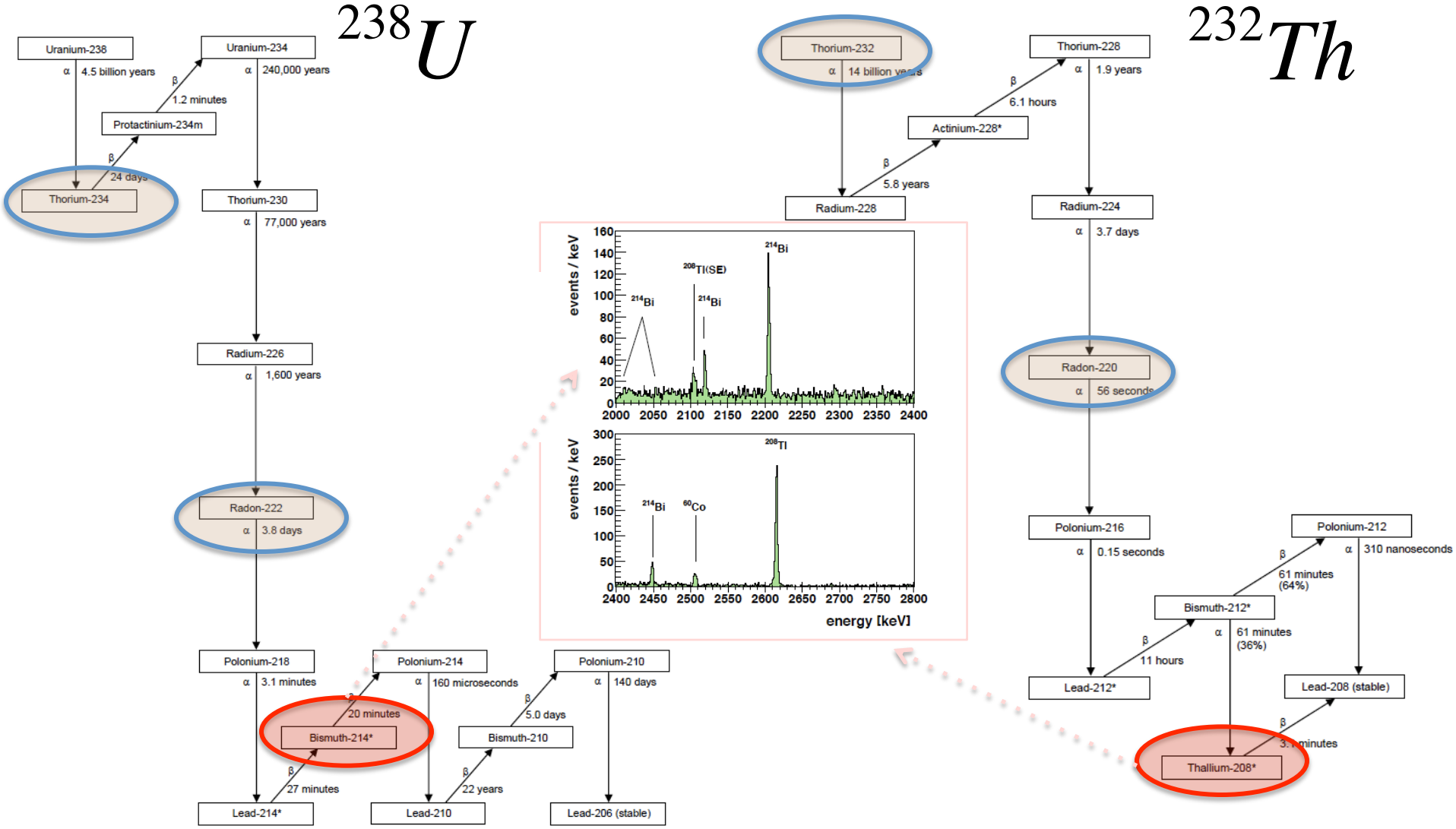
Direct mass measurements:

$$"m(\nu_e)" < 2.2\ \text{eV}$$
$$"m(\nu_\mu)" < 190\ \text{keV}$$
$$"m(\nu_\tau)" < 18.2\ \text{MeV}$$

Cosmological constraints:

$$\sum m_i \leq 0.7 - 1.0\ \text{eV}$$

Perennial problem – natural radioactivity



Thorium and radon are diffusive radioactive out-gased into the air from the rock.

$2\nu\beta\beta$ half-life of ^{130}Te

The $\beta\beta2\nu$ half-life of ^{130}Te has been a long-standing mystery:

Geochemical (^{130}Te $\rightarrow$ ^{130}Xe):

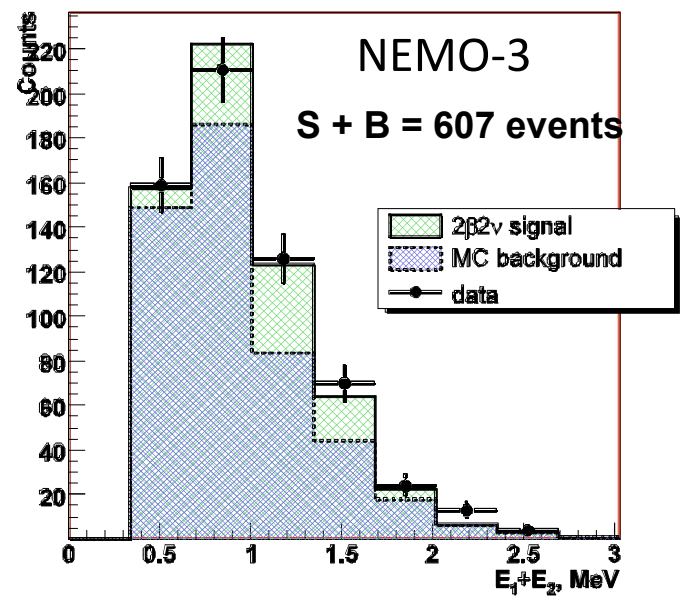
- $(25 \pm 2) \times 10^{20}$ years (Kirsten 83) ~1 billion years
- $(27 \pm 2) \times 10^{20}$ years (Bernatowicz 93)
- $(7.9 \pm 1) \times 10^{20}$ years (Takaoka 96) ~100 million years
- ~8×10^{20} years (Manuel 91)

Difference between 'old' and 'young' ores due to time dependence of G_F..?

Direct measurements:

$(6.1 \pm 3.5) \times 10^{20}$ years (Arnaboldi 2003)

$(7.6 \pm 1.7) \times 10^{20}$ years (NEMO-3)



History of 0νββ and 2νββ

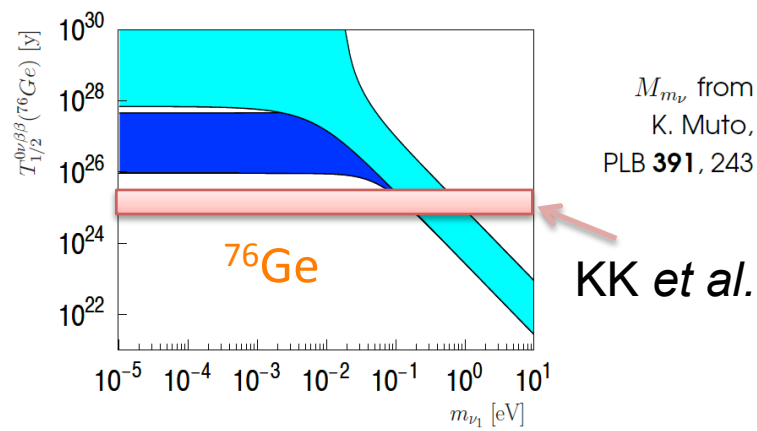
1935	rate of 2νββ first calculated by Maria Goeppert-Mayer
1937	Majorana proposes a two-component neutrino
1937-1939	G. Racah, W.H. Furry discuss 0νββ
1949	Half-life limits (Fireman, Fremlin)
1967	Geochemical evidence for 2νββ
1987	Laboratory evidence for 2νββ for (S. Elliot, A. Hahn, M. Moe, ^{82}Se)
	Phys. Rev. Lett. 59, 2020 - 2023 (1987)
	Direct evidence for two-neutrino double-beta decay in 82Se
2001-2006	Controversial claim of observation of 0νββ (Klapdor-Kleingrothaus)

- Weak ^{214}Bi lines
  2010.7, 2016.7, 2021.8, 2052.9 keV
- ? Electron conversion of 2118keV γ line 2030keV
- ?
- **0νββ peak**
  2039 keV peak has 4.2σ significance $\langle m_\nu \rangle$ = 0.2-0.6 eV

First evidence for neutrinoless double beta decay, with enriched ^{76}Ge in Gran Sasso 1990-2003.

H.V. Klapdor-Kleingrothaus[a] *

[a]Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany



$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2\theta_{\odot} = [0.23, 0.38]$, $\sin^2\theta_R = [0, 0.051]$

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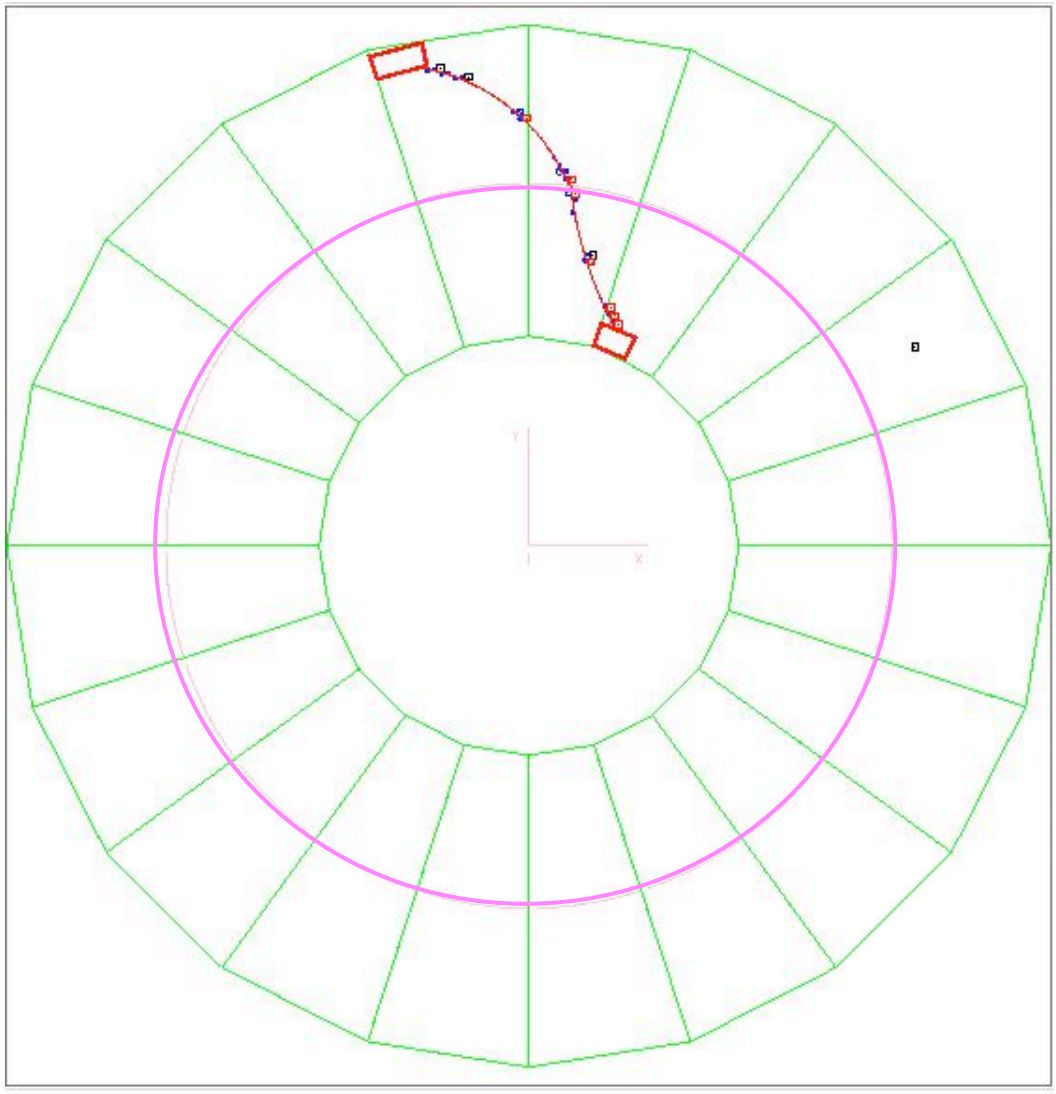
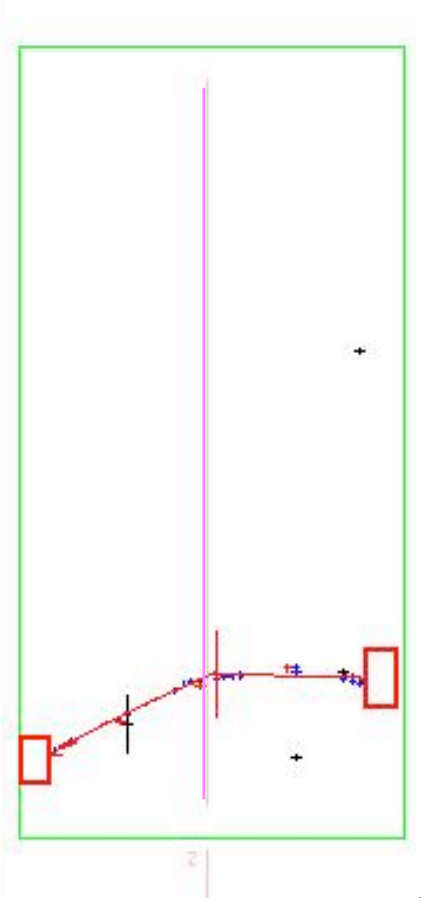
ββ events selection in NEMO-3



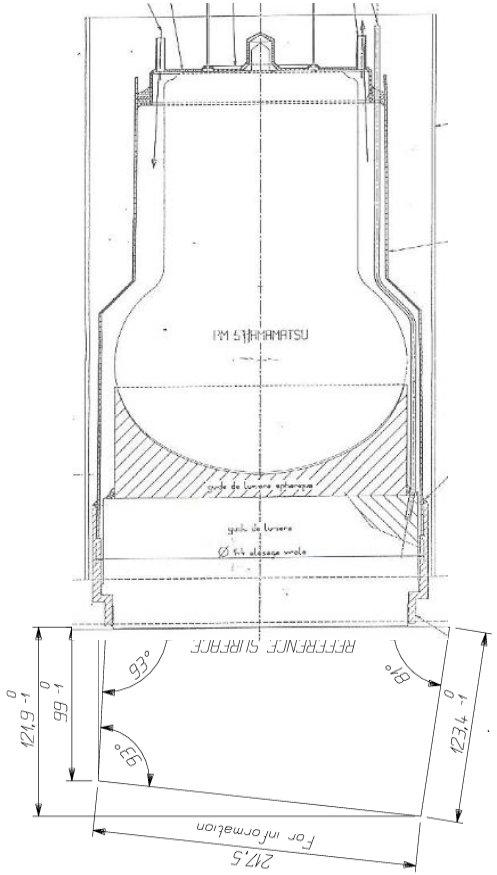
Top view



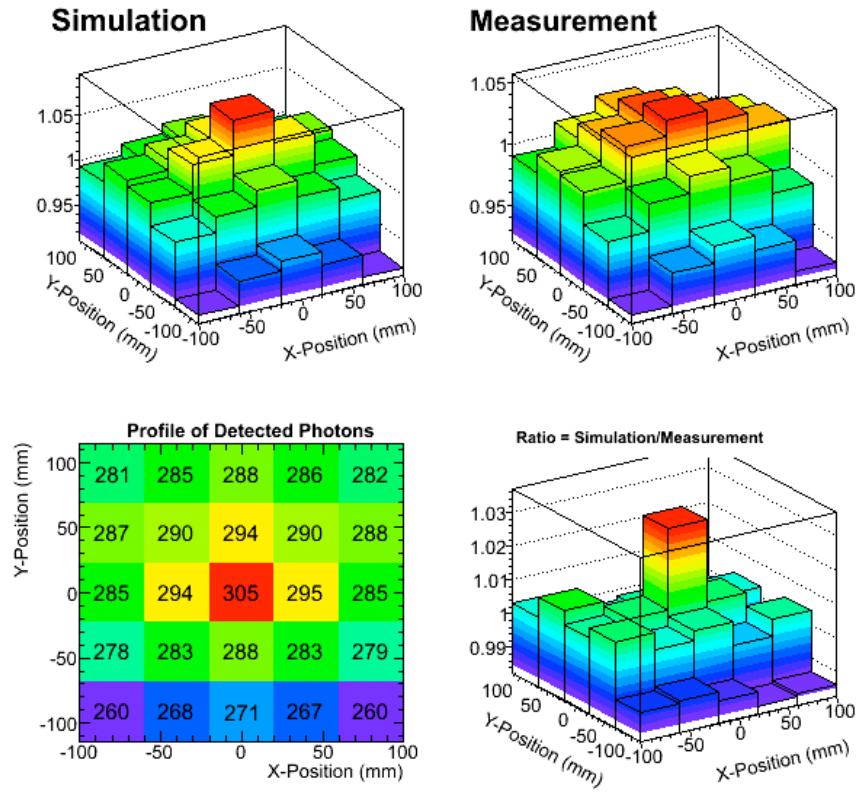
Side view

Typical ββ2ν event observed from ^{100}Mo

Impact Corrections for NEMO-3



NEMO-3 “external” type scintillator / PMT

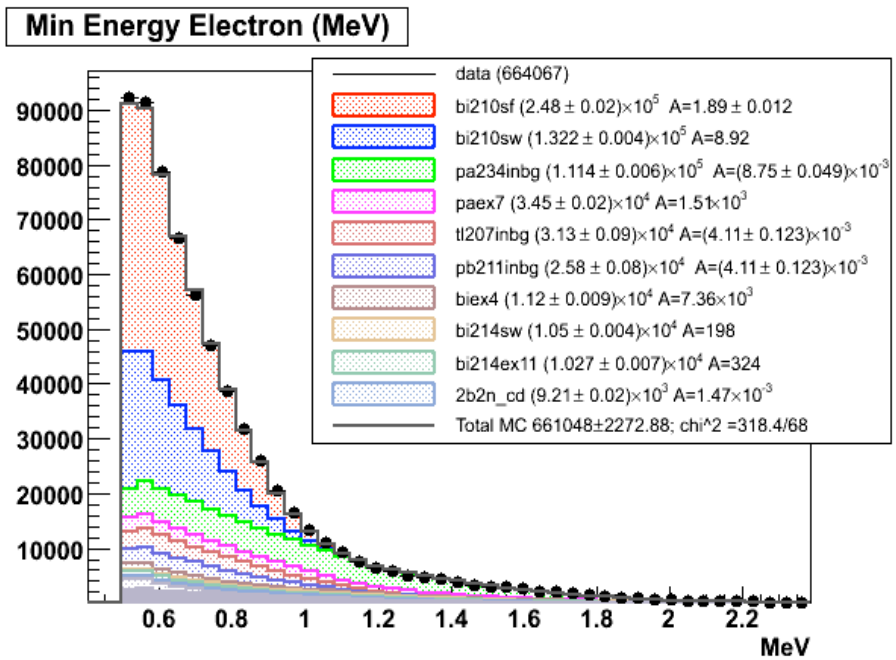


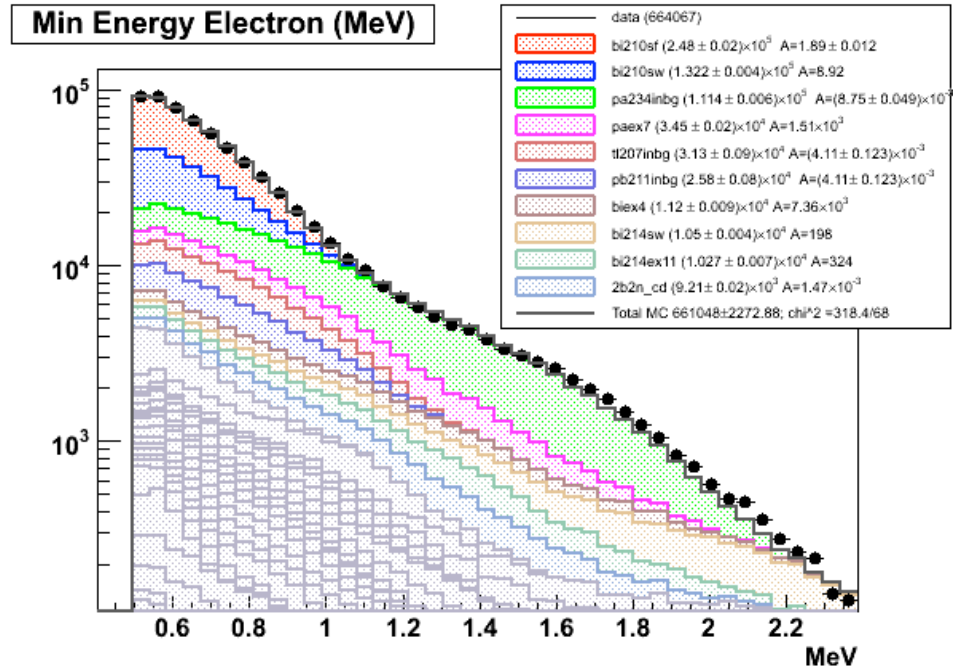
Comparison of optical simulations with measured NEMO-3 data shows agreement to within 2% over the block surface. Geometry and input files are key to reproducing measurements.

Resolution (FWHM): 14.0 +/- 0.5 (simulation)

13.5 +/- 1.0 (measurement)

Cadmium backgrounds
Total 1e: Model 3



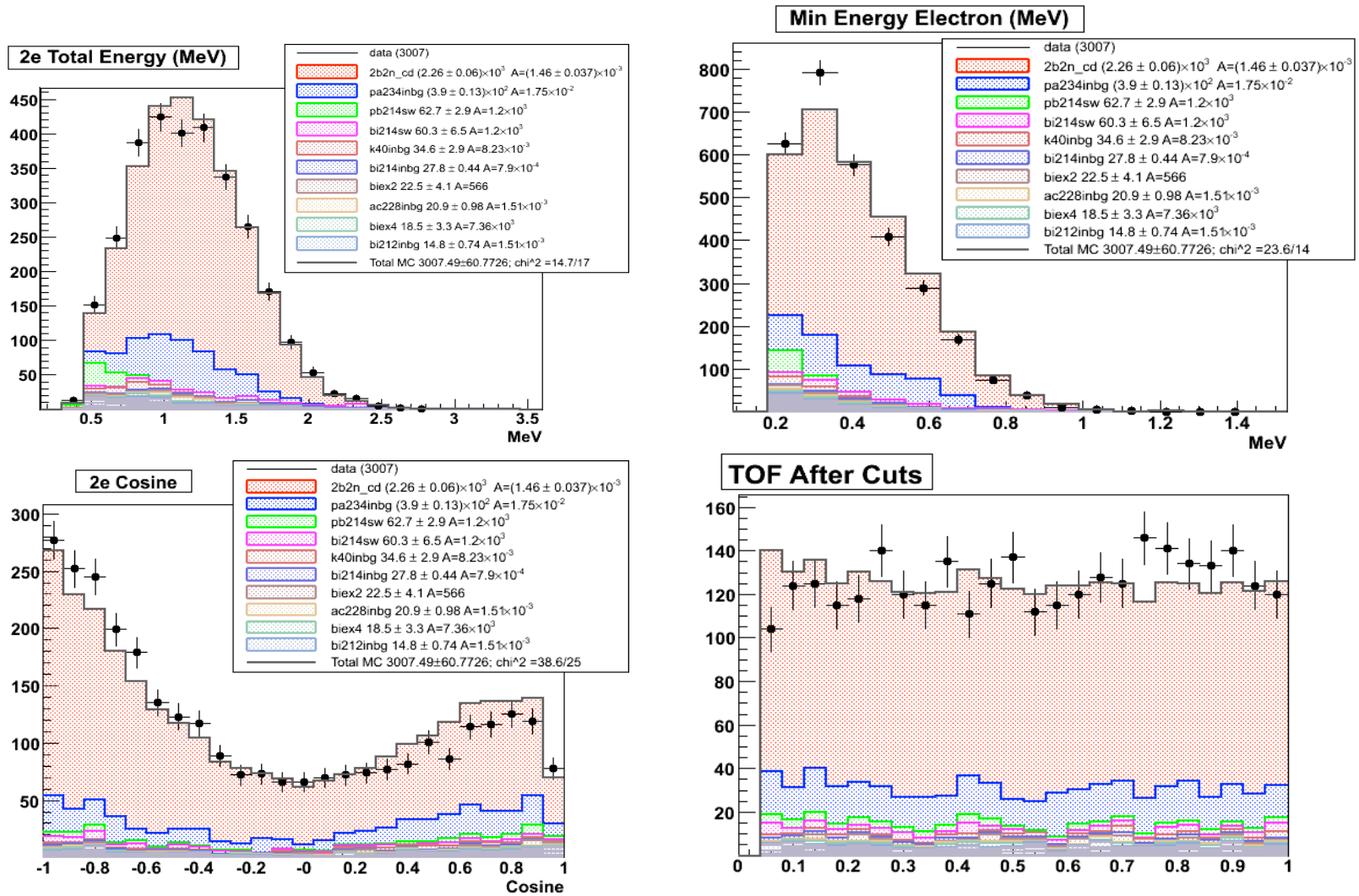


- External: Victor's Model F
- Bismuth on surface of wires: Vera's Model
- Radon on surface of wires: Vera's Model

Internal Backgrounds from HPGe measurements:

K-40 A = 8.23 mBq
Tl-207 A = 0.38 mBq
Pb-211 A = 0.38 mBq
Bi-214 A = 0.79 mBq
Pb-214 A = 0.79 mBq
Ac-228 A = 1.51 mBq
Bi-212 A = 1.51 mBq
Tl-208 A = 0.33 mBq
Cs-137 A = 1.47 mBq
Pa-234m A = 17.51 mBq

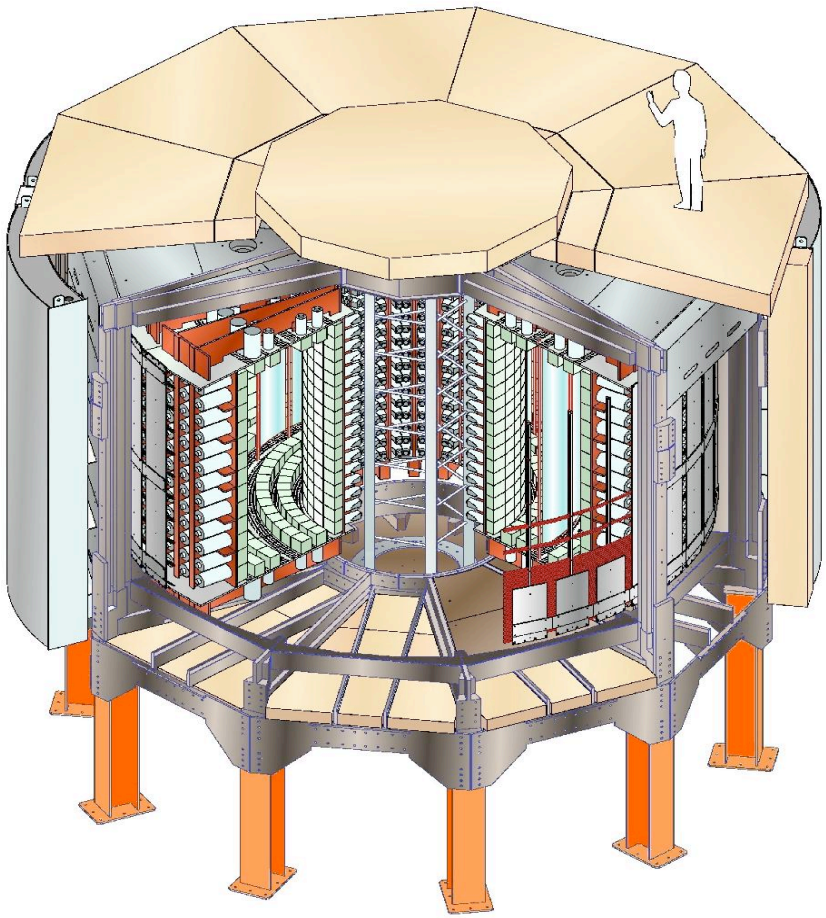
Preliminary Cd-116 Results



Cd-116 double beta events for Phase I NEMO-3 data (SSD hypothesis). Plots show the energy sum of both electrons, smallest energy of the two electrons, cosine of the angle, and TOF probability.

NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopic foils

area = 20 m^2, thickness ~ 60 mg/cm^2

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 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

$\Delta L = 2$ processes

$K^+ \rightarrow \pi^- \mu^+ \mu^+$

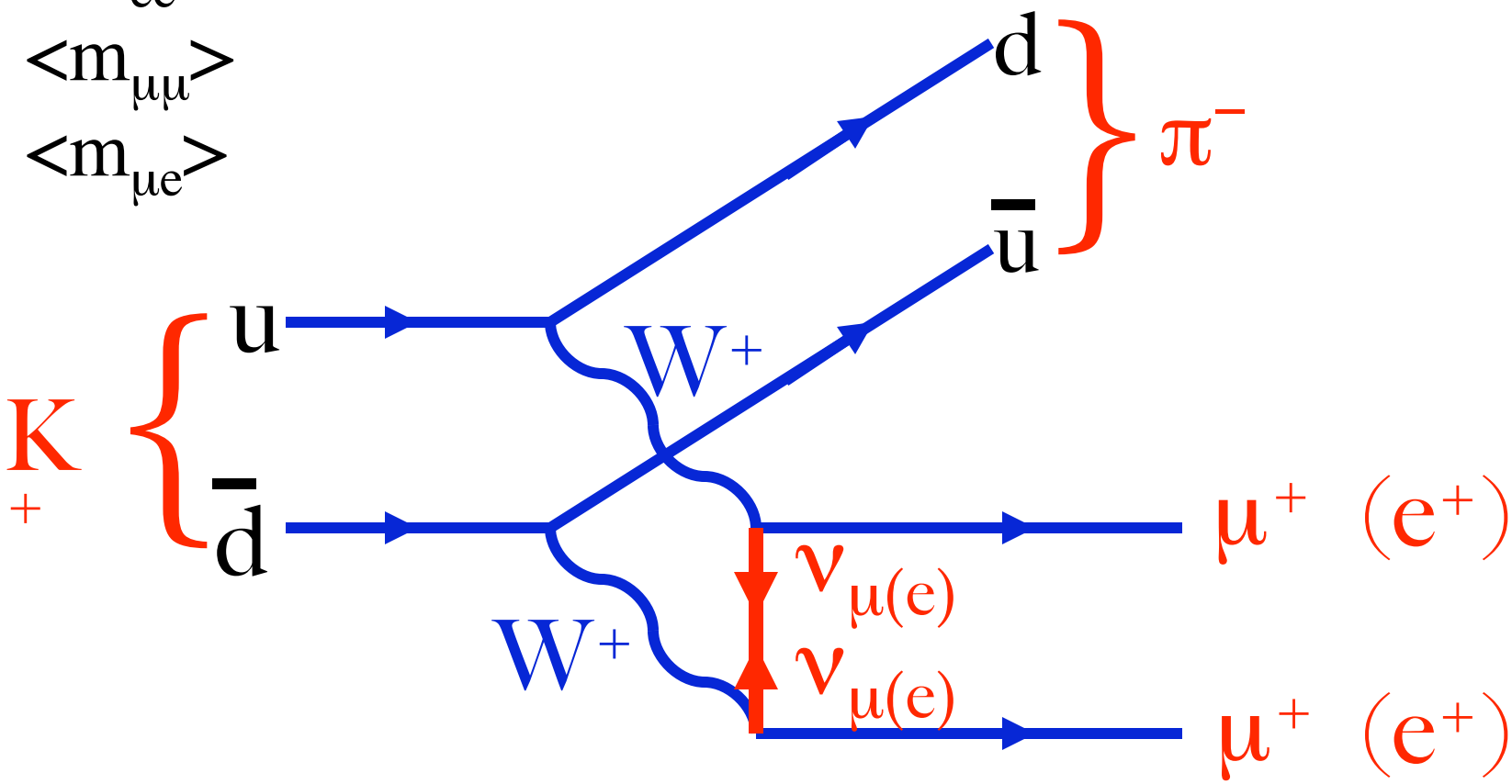
$K^+ \rightarrow \pi^- e^+ e^+$

$K^+ \rightarrow \pi^- \mu^+ e^+$

$\langle m_{ee} \rangle$

$\langle m_{\mu\mu} \rangle$

$\langle m_{\mu e} \rangle$



μ^- to e+ conversion

$$\mu^- + (A,Z) \rightarrow (A, Z\text{-}2) + e^+$$

$$\Delta L = 2$$