Latest Results from NEMO-3 and Status of SuperNEMO

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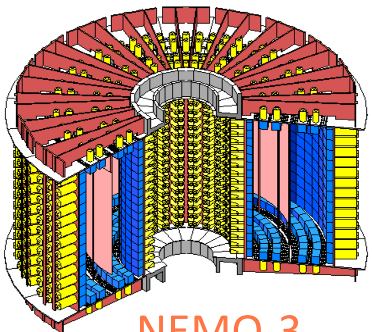
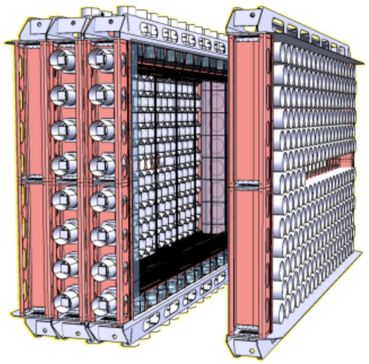
On behalf of the NEMO Collaboration



NEMO-3



SuperNEMO

Outline:

1. $0\nu\beta\beta$ fundamentals
2. NEMO technique
3. NEMO-3 results
4. Status of SuperNEMO

ICHEP2012 Melbourne
36th International Conference on High Energy Physics
4 – 11 July 2012
Melbourne Convention and Exhibition Centre

Fundamentals of 0νββ and 2νββ

$$\frac{1}{T^{2\nu}_{1/2}} = G_{2\nu}(Q^{11}_{\beta\beta}, Z) \bullet \left| M_{2\nu} \right|^2$$

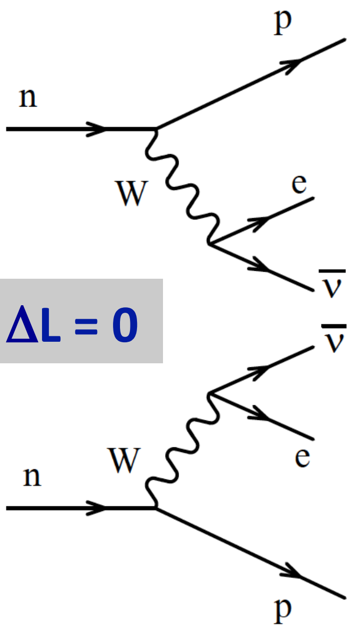
G = phase space (well known)

M = nuclear matrix element (challenging)

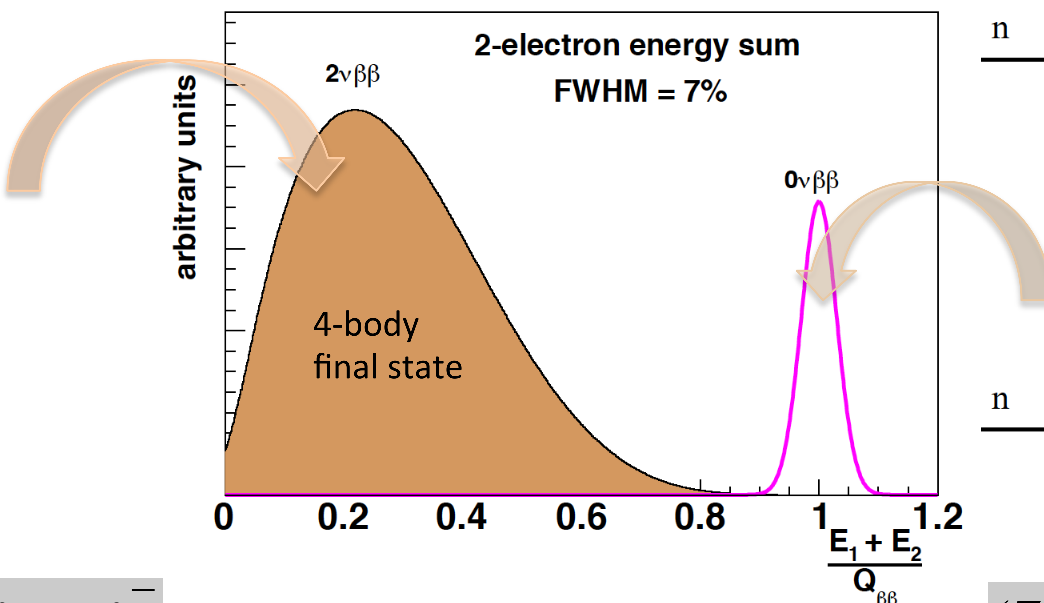
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q^{5}_{\beta\beta}, Z) \bullet \left| M_{0\nu} \right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

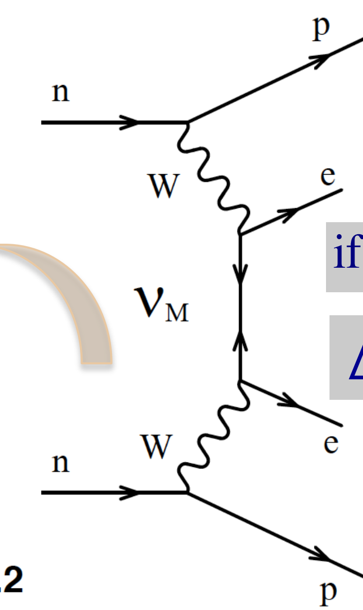
$$\left| \langle m_{\beta\beta} \rangle \right| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha^*} + m_3 |U_{e3}|^2 e^{i\beta^* - 2i\delta} \right|$$

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



ΔL = 0





if $m_\nu \neq 0$

ΔL = 2

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

$(2\nu\beta\beta)$

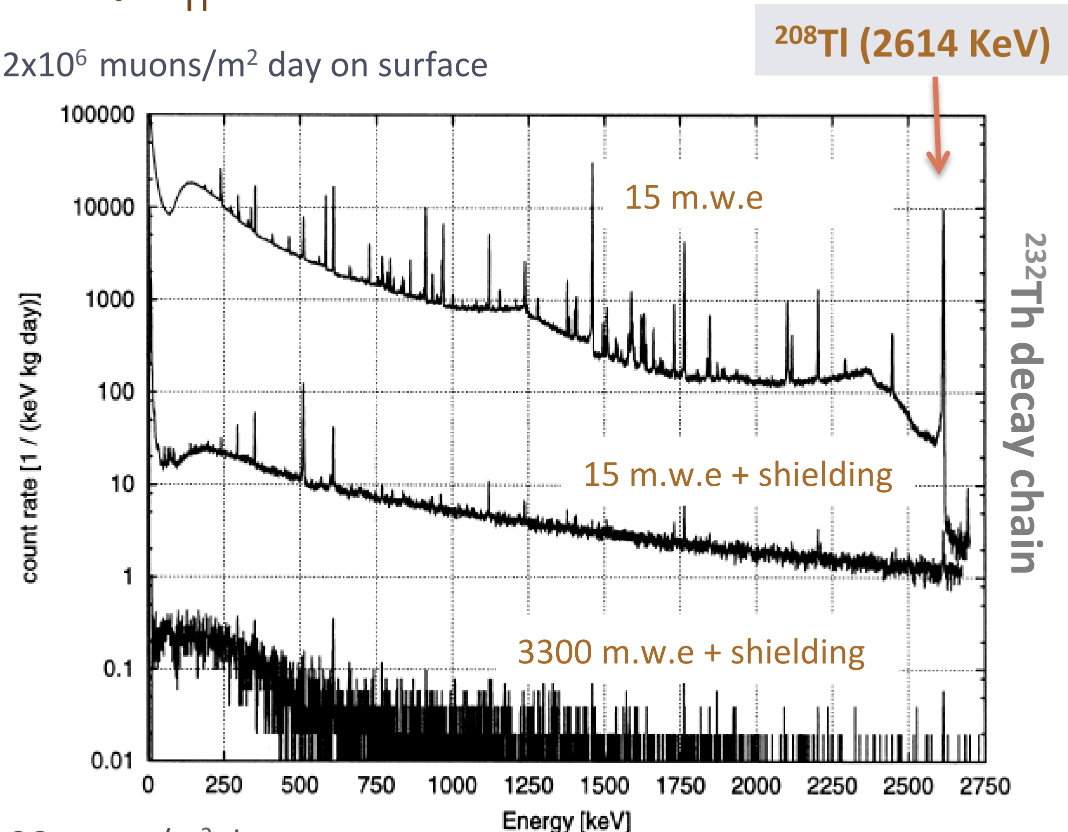
$(Z, A) \rightarrow (Z+2, A) + 2e^-$

$(0\nu\beta\beta)$

Practical fundamentals

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

2x10^{6} muons/m^{2} day on surface



26 muons/m^{2} day

(Applied Rad and Isotopes 53 (2000) 191)

NEMO-3

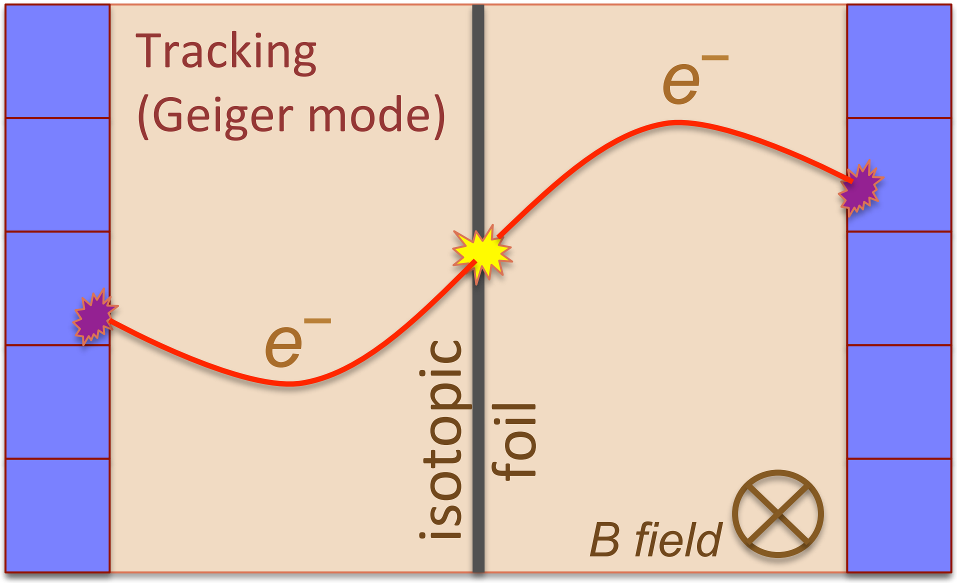
	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.272	0.187
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.035	9.6
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{116}Cd \rightarrow ^{116}Sn$	2.805	7.5
$^{130}Te \rightarrow ^{130}Xe$	2.529	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8

Top 11 $\beta\beta$ emitters with $Q_{\beta\beta} > 2$ MeV

Challenge:
- ✓ suppress backgrounds
- ✓ identify the final state

The multi-observable principle:

topology, kinematics, timing



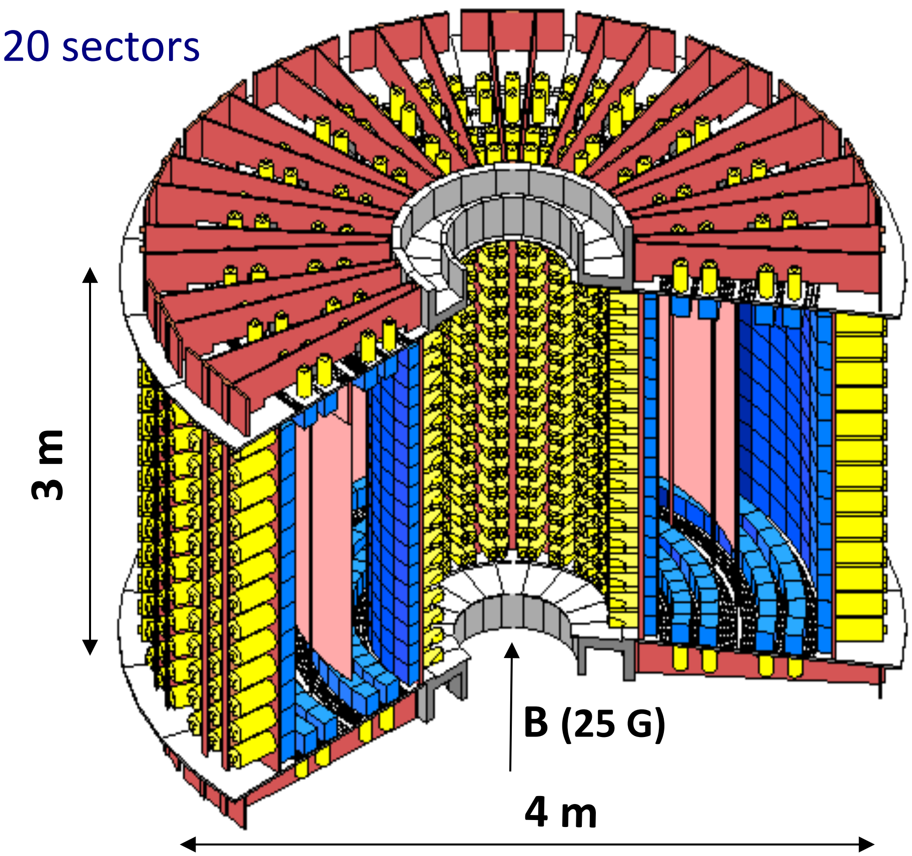
Plastic scintillator calorimeter

Radio-pure materials
and a multi-layer shielding

NEMO-3 detector

Fréjus Tunnel : 4,800 m.w.e.

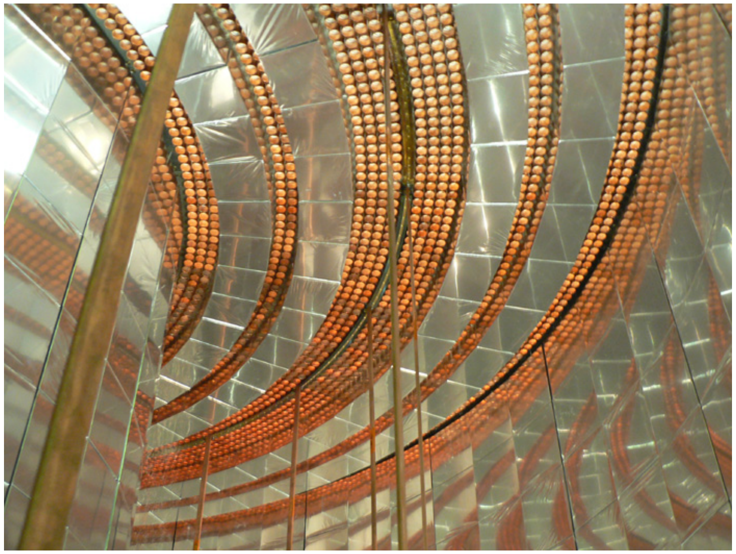
Phase 1: Feb, 2003 → Sep, 2004
Phase 2: Oct, 2004 → Jan, 2011

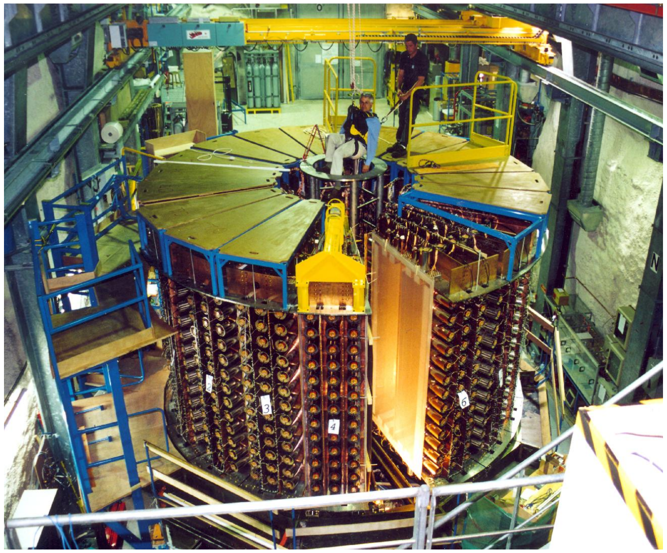


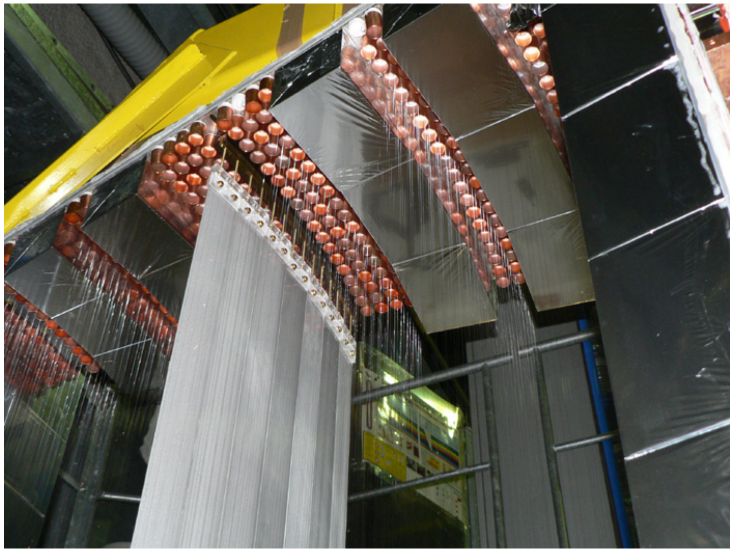
Particle ID: e^-, e^+, γ and α

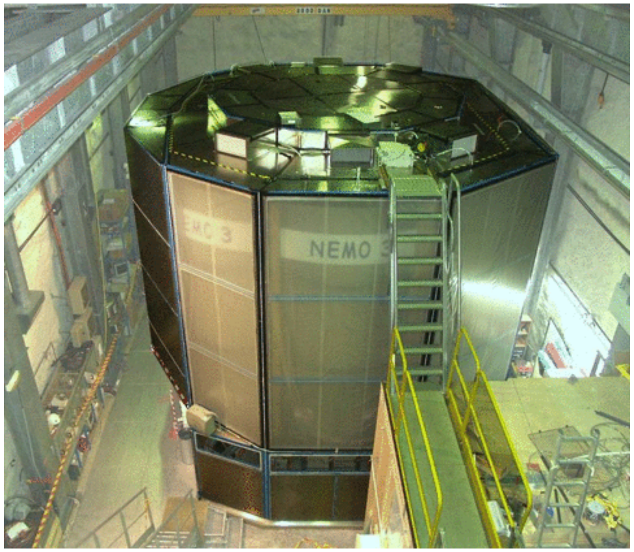
- ✓ Source: 10 kg of $\beta\beta$ isotopic foils
  area = 20 m^2, thickness ~60 mg/cm^2
- ✓ Tracking detector:
  drift wire chamber (9 layers)
  in Geiger mode (6180 cells)
  Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- ✓ Calorimeter:
  1940 plastic scintillators
  low radioactivity 3'' & 5'' PMTs
- ✓ B field : 25 Gauss
- ✓ Shielding:
  gamma shield: pure iron (d = 18cm)
  neutron shield:
  30 cm water (ext. wall)
  40 cm wood (top / bottom)
  (since March 2004: water + boron)

NEMO-3 data taking: 2003 - 2010



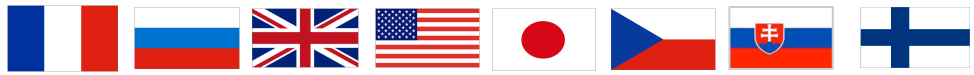






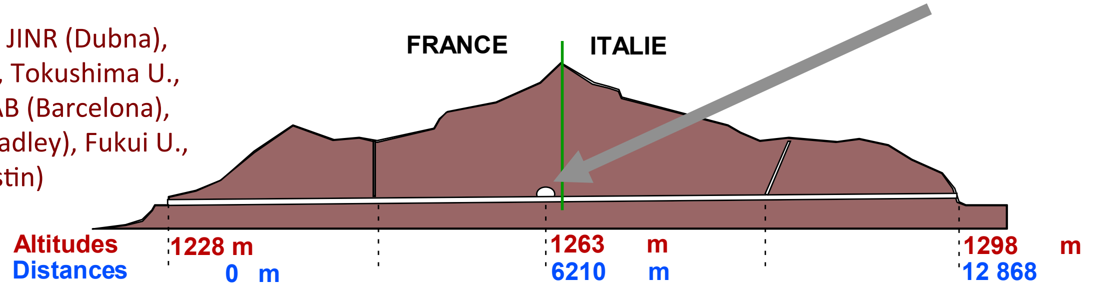
Laboratoire Souterrain de Modane (LSM)
(Frejus Tunnel)

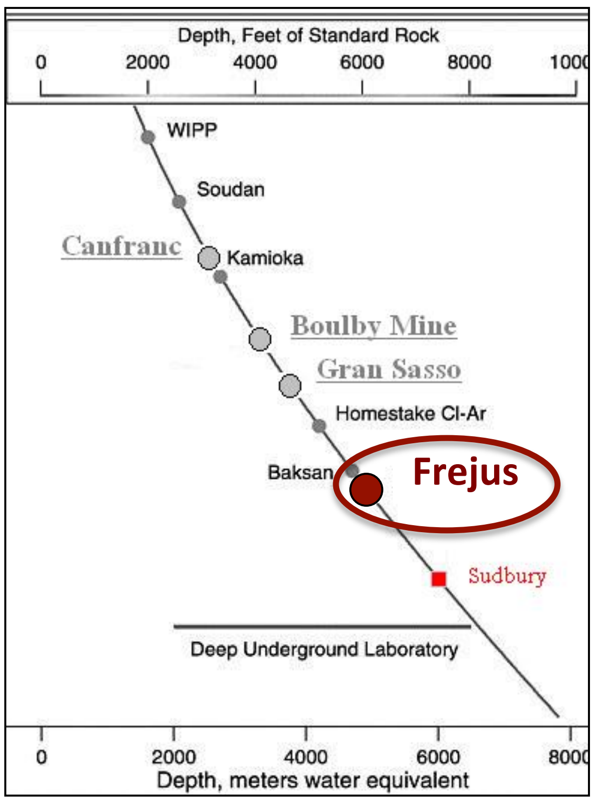
NEMO Collaboration

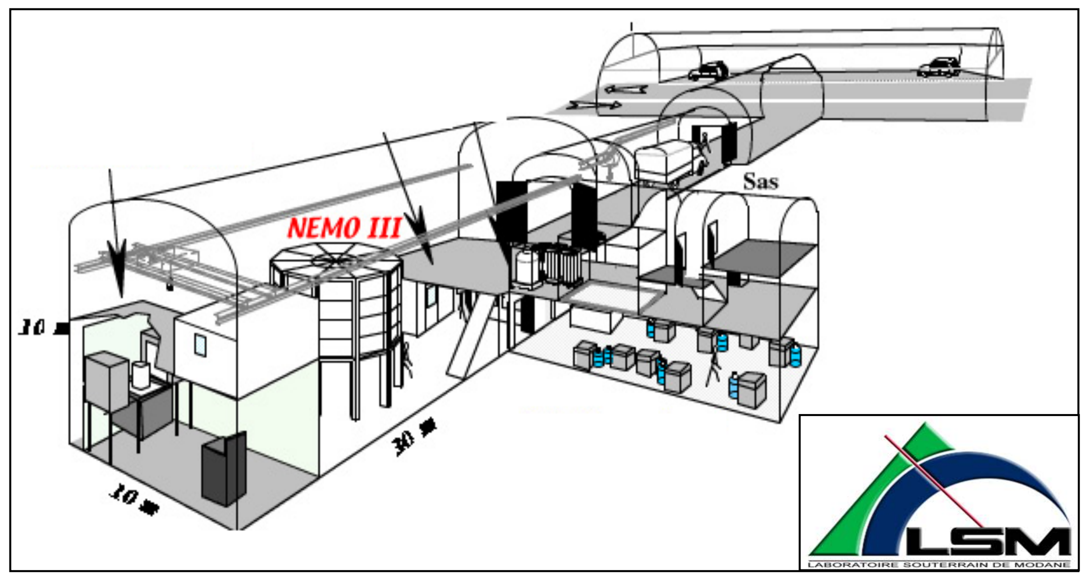


LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., Cornelius U. (Bratislava), Osaka, IEAP & Charles U. (Prague), UAB (Barcelona), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui U., INR (Kiev), CPPM (Marseilles), U. Warwick, Texas (Austin)

4,800 m.w.e



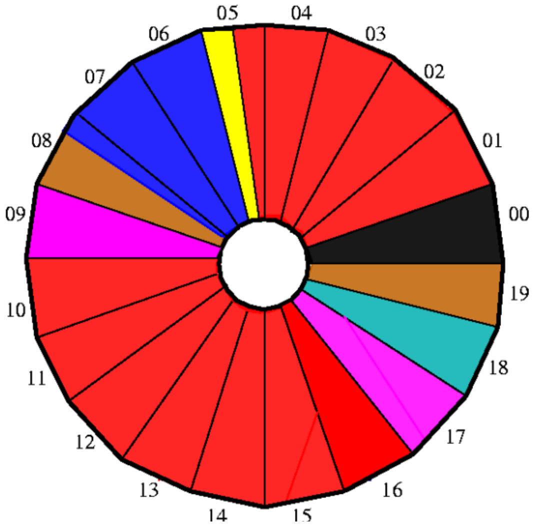




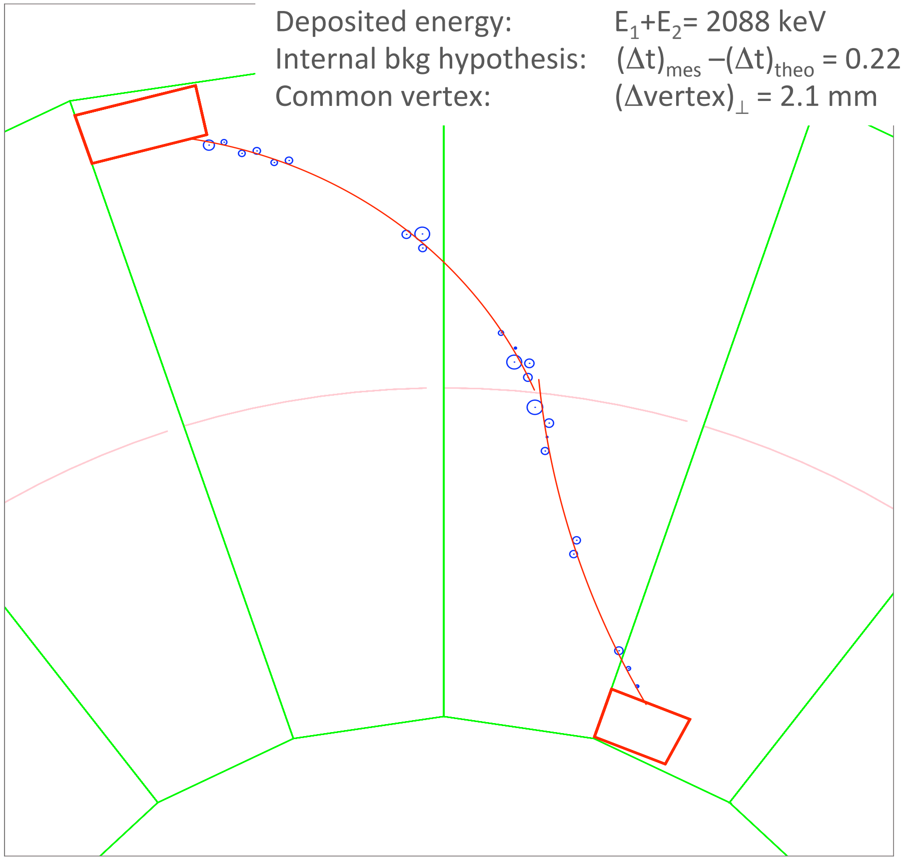
Built for Taup experiment (proton decay) in 1981-1982

NEMO-3: 7 isotopes + events images

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)
^{100}Mo	6 914	3035
^{82}Se	932	2995
^{116}Cd	405	2805
^{96}Zr	9.4	3350
^{150}Nd	37	3367
^{48}Ca	7	4272
^{130}Te	454	2529
^{nat}Te	491	
^{nat}Cu	621	



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

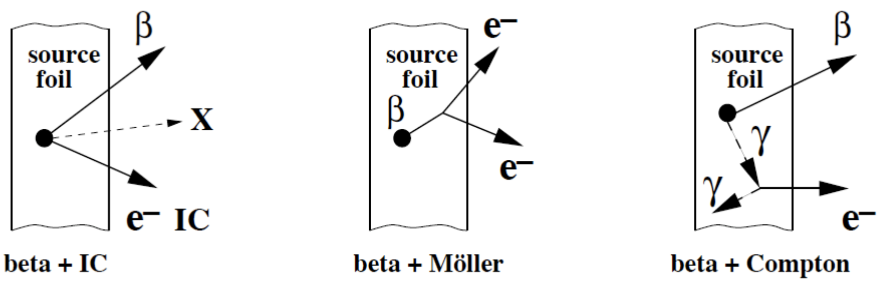


- ✓ Trigger: at least 1 PMT > 150 keV
  ≥ 3 Geiger hits (2 neighbouring layers+1)
- ✓ Trigger rate = 7 Hz
- ✓ 25 ββ events per hour

NEMO-3 backgrounds

1. Internal background (in addition to a potential $2\nu\beta\beta$ tail)

(due to ^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) radio-impurities of the isotopic source foil)

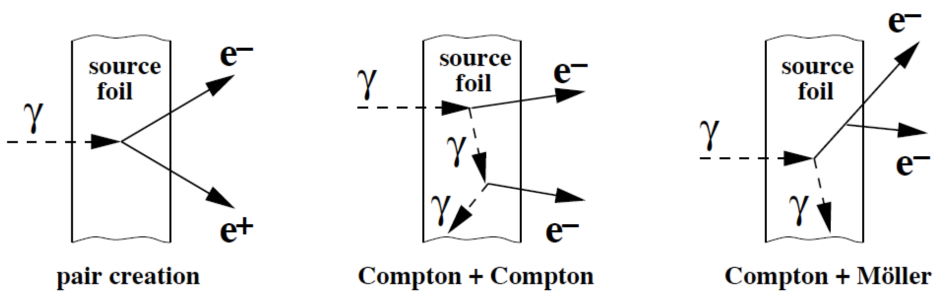


(dominant)

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

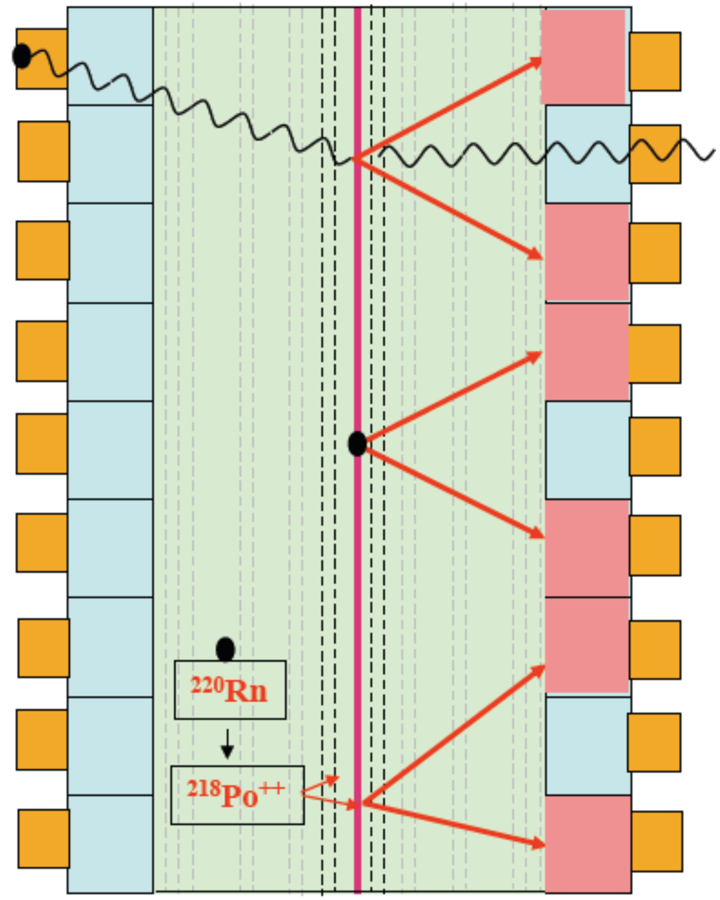
2. External background (if the γ is not detected)

(due to radio-impurities of the detector)



3. Radon (^{214}Bi) inside the tracking detector

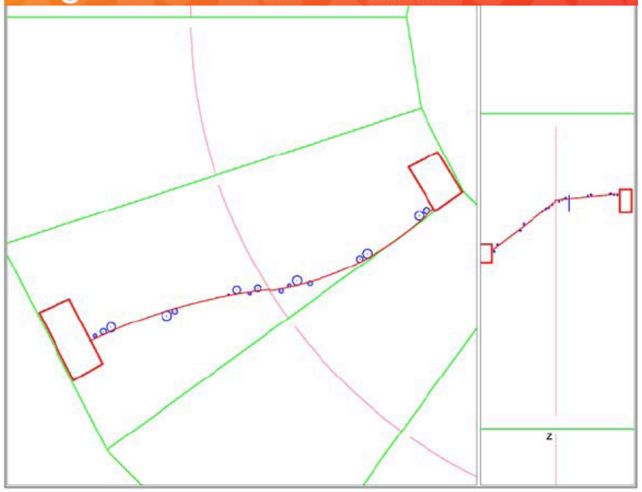
- deposits on the wire near the $\beta\beta$ foil
- deposits on the surface of the $\beta\beta$ foil



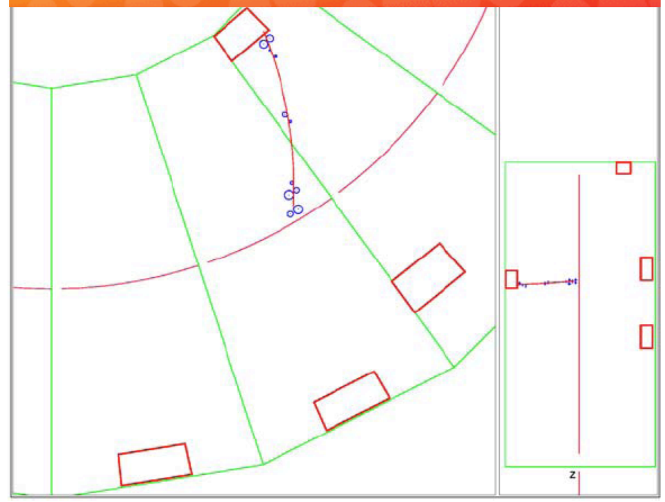
Each bkg is measured using the NEMO-3 data

Signal and background signatures

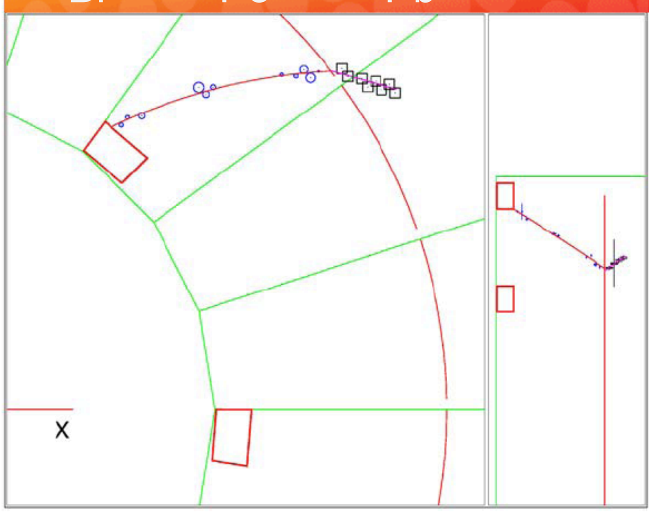
$2e^-$ event
signal



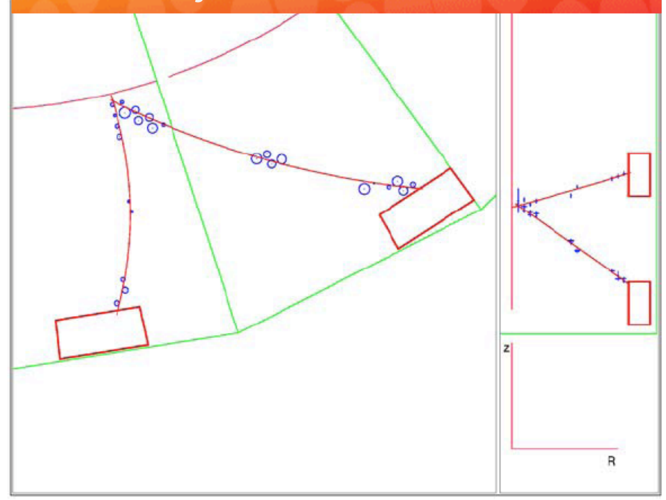
$e^- \gamma\gamma\gamma$ event
measure ^{208}Tl



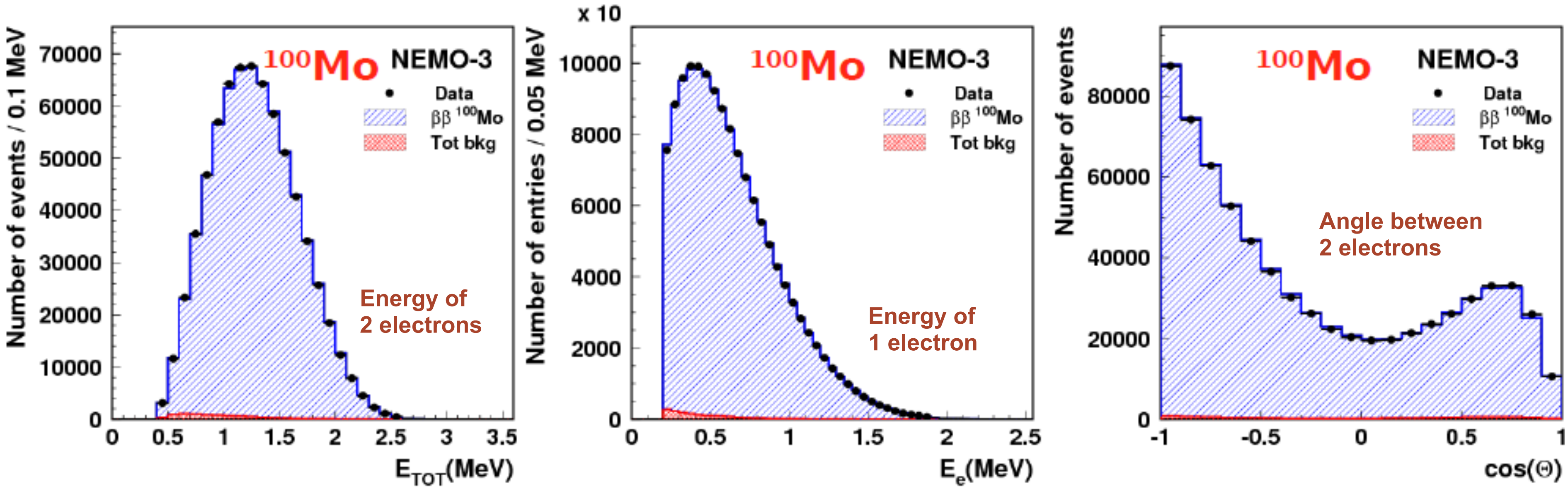
β - α (delay track) event
^{214}Bi $\rightarrow$ ^{214}Po $\rightarrow$ ^{210}Pb



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



NEMO-3 flagship measurements
$2\nu\beta\beta$ results (not final)



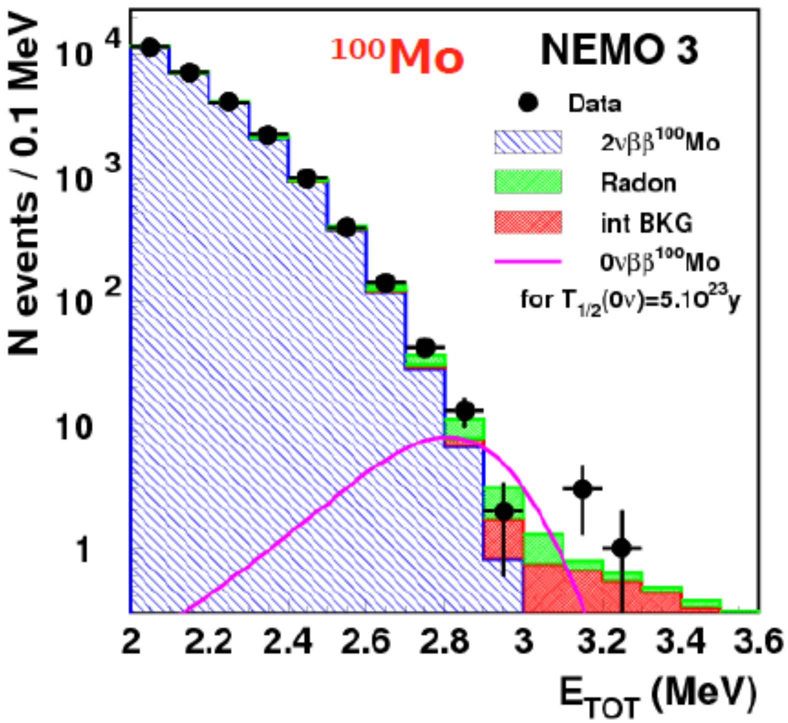
> 700 000 of 2-electron

Signal/Background : 76

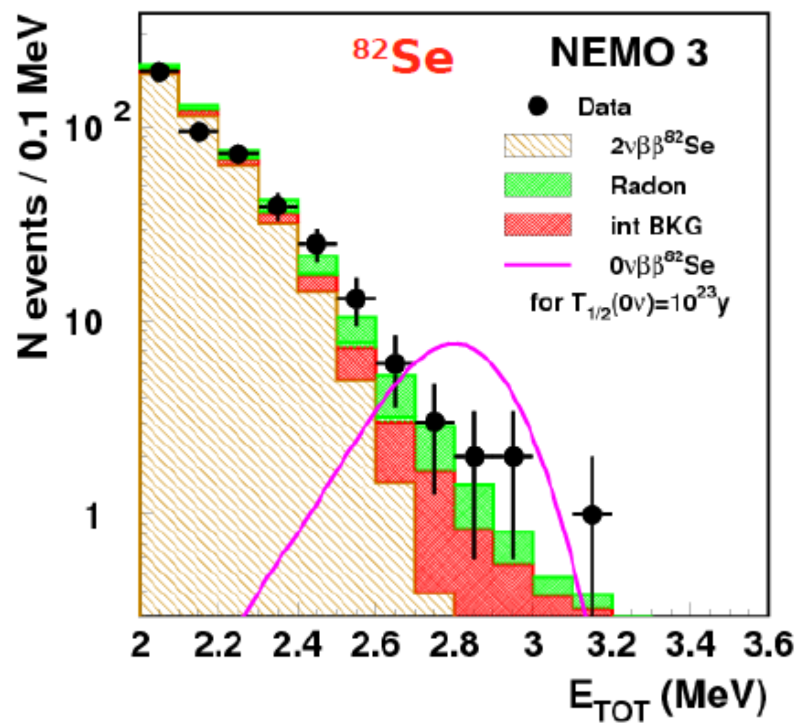
$T_{1/2}$ ($2\nu\beta\beta$) = (7.16 ± 0.01) x 10^{18} y (preliminary)

published Phase 1 $T_{1/2}$ = [7.11 ± 0.02 (stat) ± 0.54 (sys)] x 10^{18} y

NEMO-3 flagship measurements: ^{100}Mo and ^{82}Se $0\nu\beta\beta$ results (not final)



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected



[2.6 – 3.2] MeV 14 observed events, 11.3 ± 1.3 expected

^{100}Mo (for exposure of 31.2 kg * y)

$T_{1/2}$ $(0\nu\beta\beta) > 1.0 \times 10^{24}$ y (90% C.L.)

$m_{\beta\beta} < 0.31 – 0.96$ eV

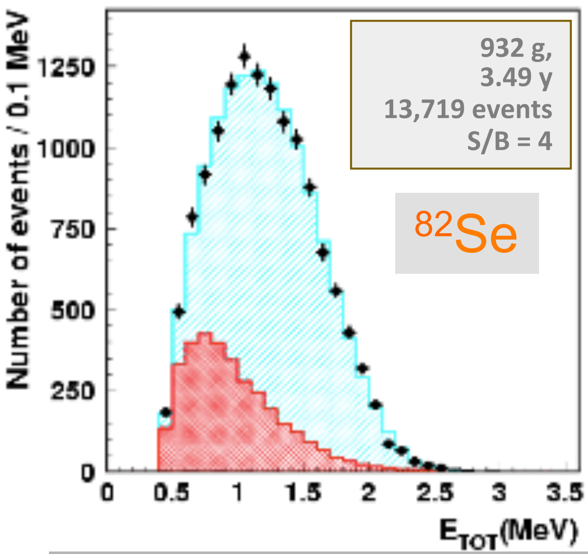
^{82}Se (for exposure of 4.2 kg * y)

$T_{1/2}$ $(0\nu\beta\beta) > 3.2 \times 10^{23}$ y (90% C.L.)

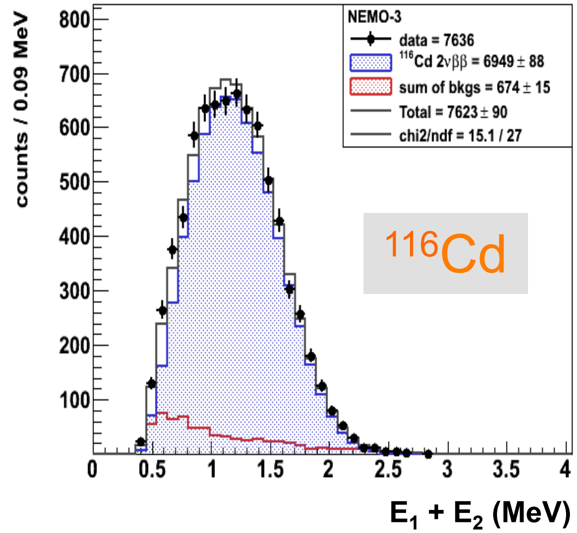
$m_{\beta\beta} < 0.94 – 2.6$ eV

[1] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] QRPA F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
[4] IBM2 J.Barrea and F.Iachello Phys.Rev.C 79(2009)044301
PHFB [5] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
SM [6] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

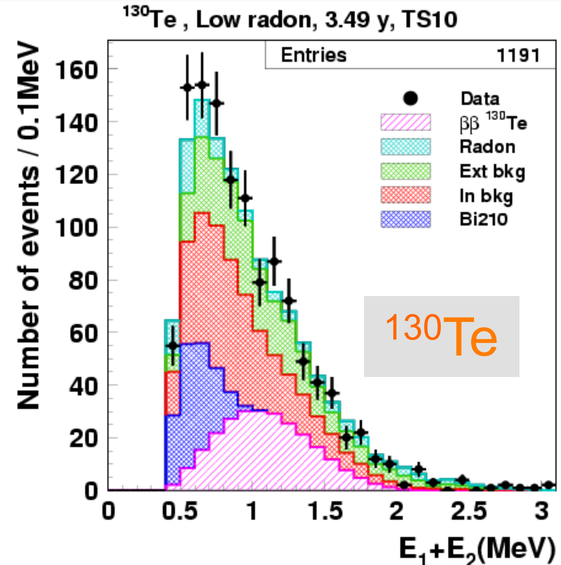
NEMO-3 2νββ results (not final)



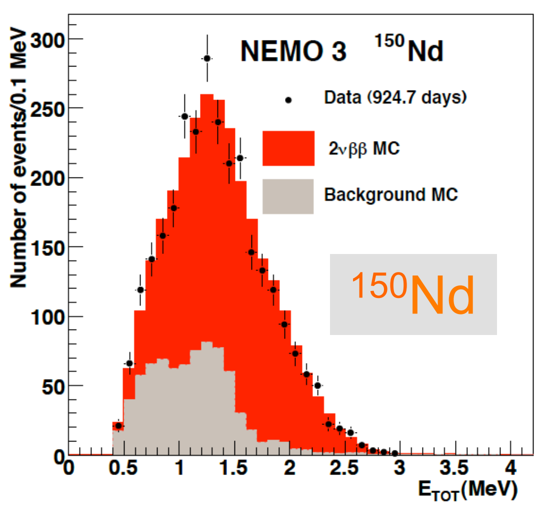
$[\, 9.6 \pm 0.1\ _{(stat)} \pm 1.0\ _{(syst)}\,] \times 10^{19}$ y



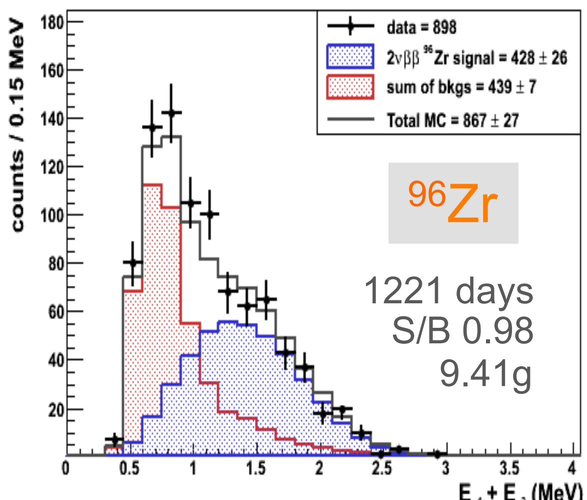
$[\, 2.88 \pm 0.04_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y



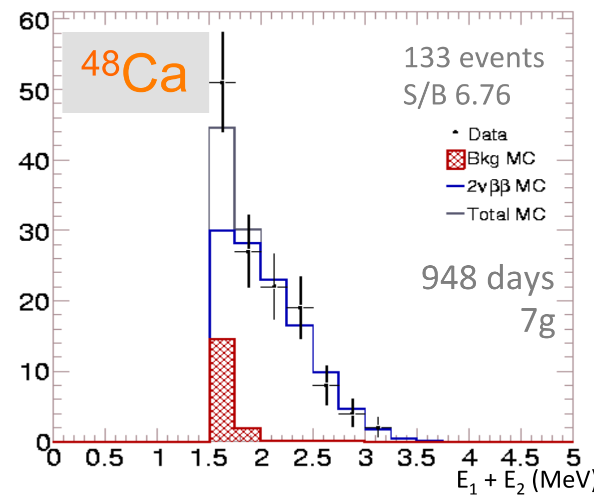
$[\, 7.0 \pm 0.9_{(stat)} \pm 1.1_{(syst)}\,] \times 10^{20}$ y



$[\, 9.11\ ^{+0.25}_{-0.22}\ _{(stat)} \pm 0.63_{(syst)}\,] \times 10^{18}$ y



$[\, 2.35 \pm 0.14_{(stat)} \pm 0.16_{(syst)}\,] \times 10^{19}$ y

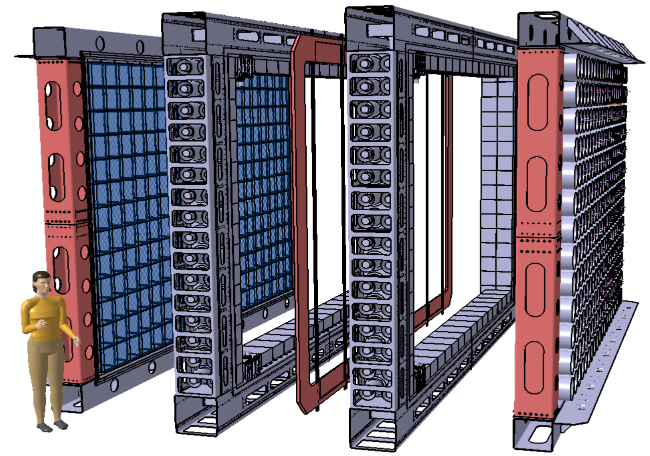


$[\, 4.4\ ^{+0.5}_{-0.4}\ _{(stat)} \pm 0.4\ _{(syst)}\,] \times 10^{19}$ y

NEMO-3 → SuperNEMO

20 wedges: 10 kg of 7 isotopes

20 planar modules, each w/ 5-7 kg
Can do different isotopes & locations



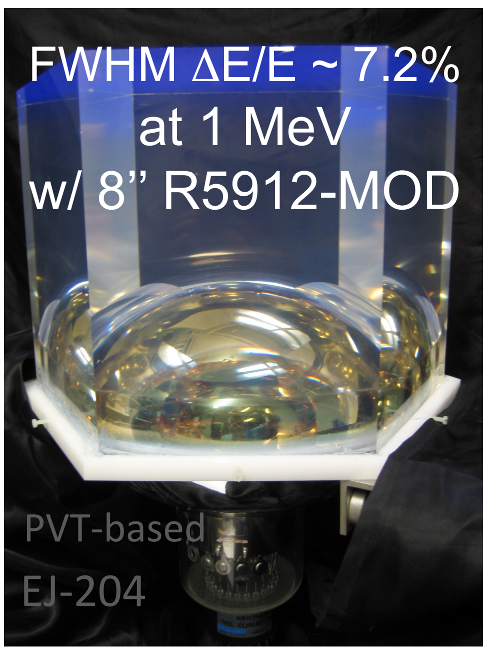
NEMO-3	→	SuperNEMO
^{100}Mo, ^{82}Se, ^{150}Nd, ^{130}Te, ^{116}Cd, ^{96}Zr, ^{48}Ca		^{82}Se, … ^{150}Nd, ^{48}Ca
7 kg		100 - 200 kg (7 kg Demonstrator)
$T_{1/2}(0\nu\beta\beta) >$ 2 x 10^{24} y $m_{\beta\beta}$ < 0.3 – 0.8 eV		$T_{1/2}(0\nu\beta\beta) >$ 1 x 10^{26} y $m_{\beta\beta}$ < 40 – 100 meV

SuperNEMO R&D and Demonstrator construction

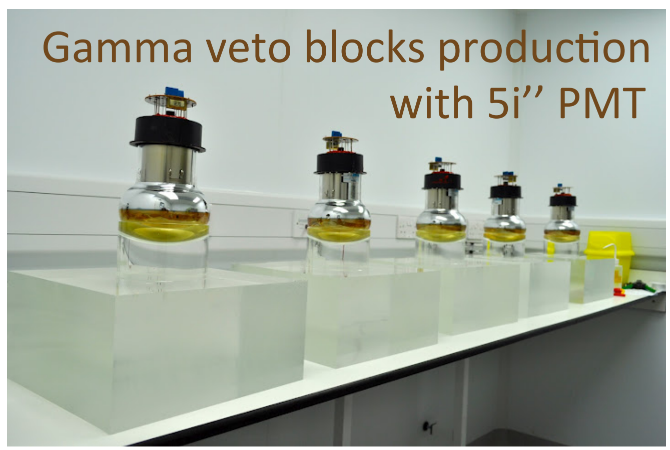
- First SuperNEMO module (Demonstrator) under construction (through 2014)
- (Most of) R&D completed; optimizing costs, some systems under full production
- Major improvements in:

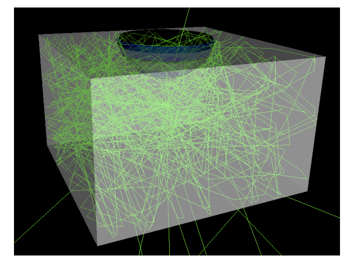
  energy resolution, source foil radio-purity measurements, radon emanation and hermeticity, source installation, ^{207}Bi calibration, tracking, software, …
- Some highlights below:

Main walls blocks

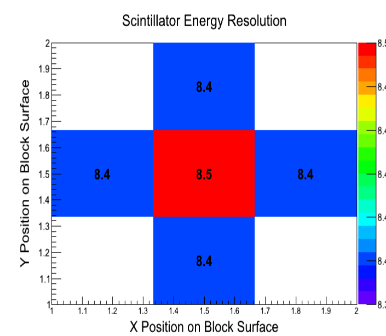


Calorimeter:
main walls
and gamma veto walls



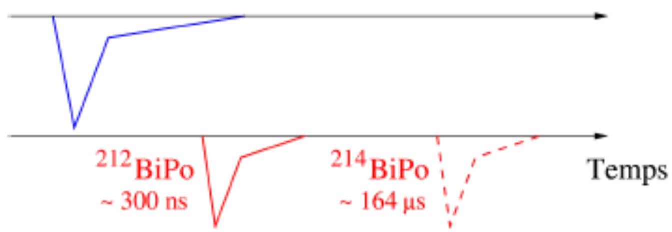


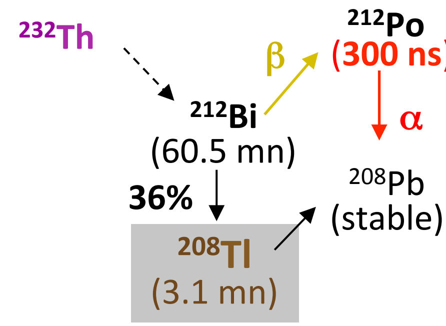
G4 simulations → agreement with measurements

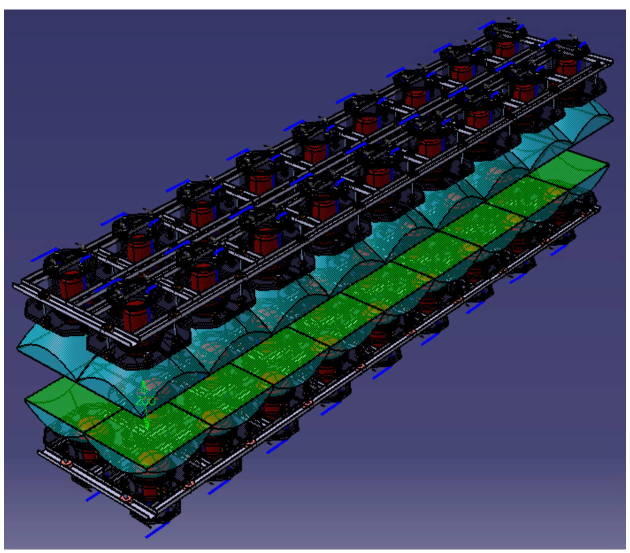


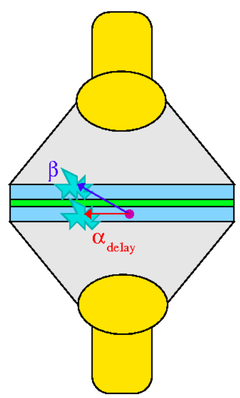
- BiPo detector - to test the source foil radio-purity
- Sensitivity in 6 months
  - ^{208}Tl: ~ 5 μBq / kg
  - ^{214}Bi: ~ 15 μBq / kg
- Will operate at the Canfranc Lab

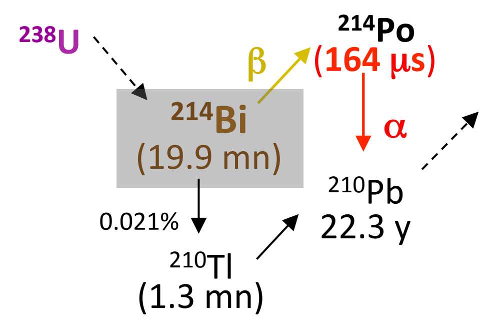
Bi → Po → Pb







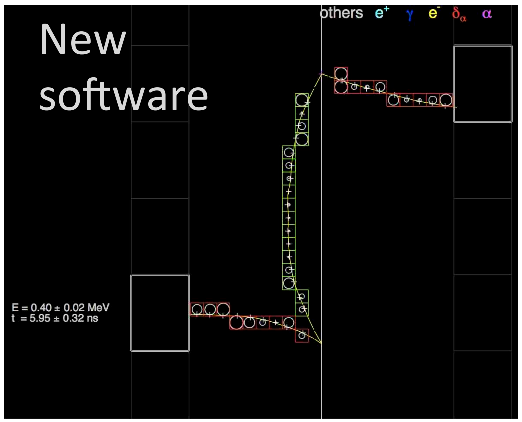


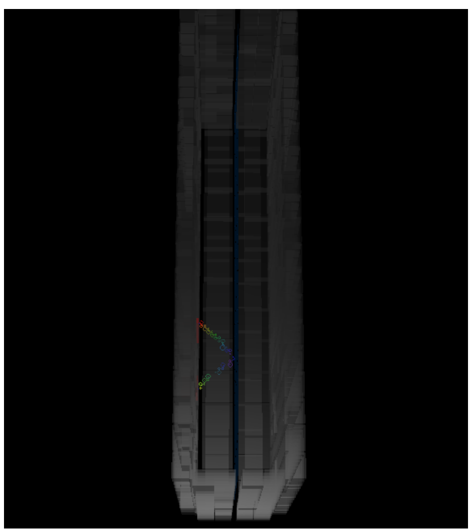


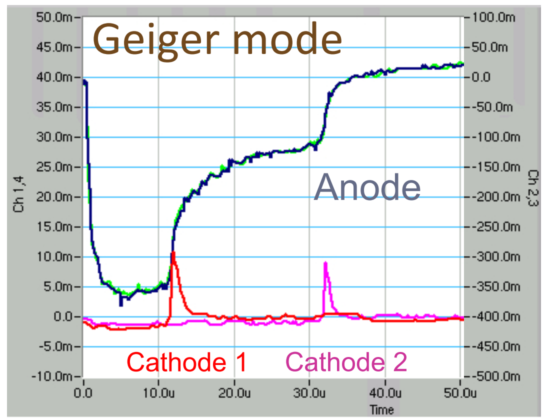
Tracker construction

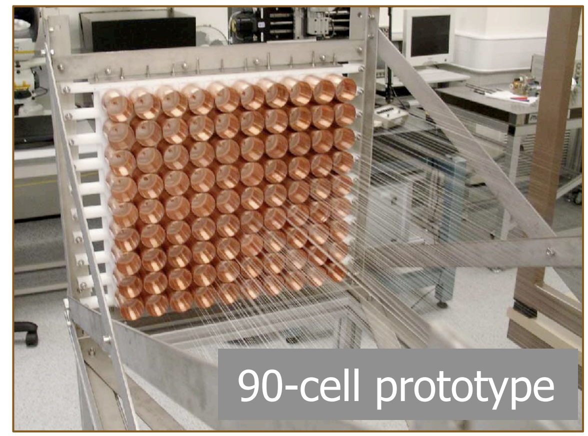
(automatic wiring)

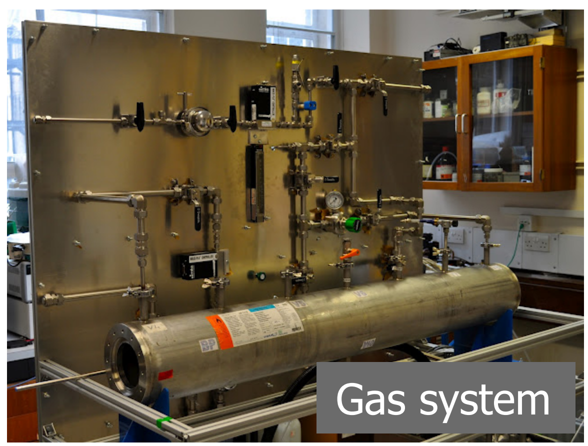
He-Ar (w/ isoprop.)
or
He-Ne (w/ isoprop.)

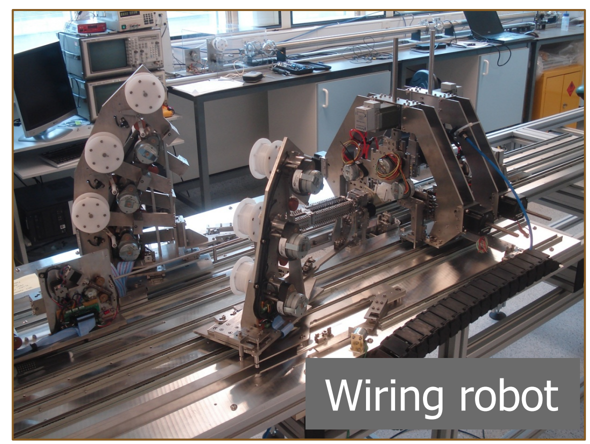


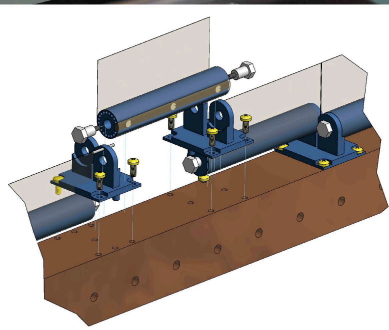




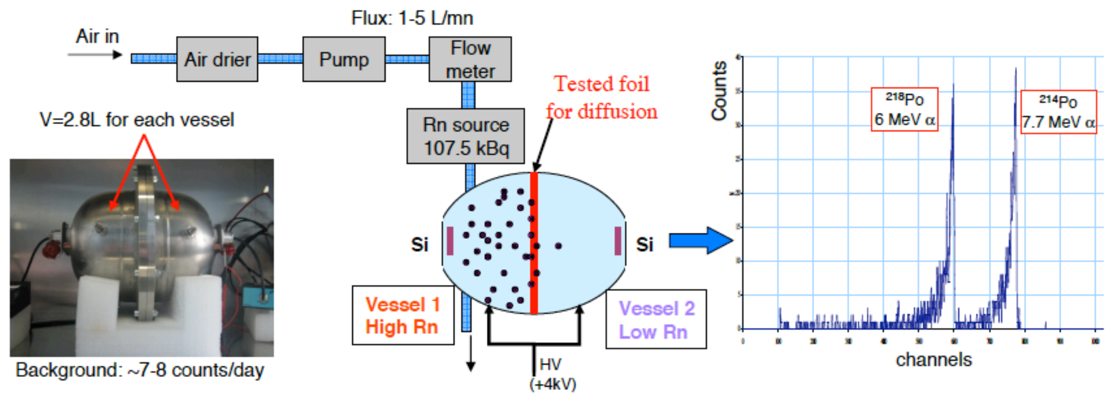








Material radon emanation screening



Radon concentration line (sensitivity < 0.15 mBq/m^3)

Summary

- **NEMO-3** produces a unique spectrum of results on $0\nu\beta\beta$ and $2\nu\beta\beta$

^{100}Mo: $T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{24}$ y (90% CL) $m_{\beta\beta} < (0.31 - 0.96)$ eV
^{82}Se: $T_{1/2}^{0\nu\beta\beta} > 3.6 \times 10^{23}$ y (90% CL) $m_{\beta\beta} < (0.94 - 2.6)$ eV

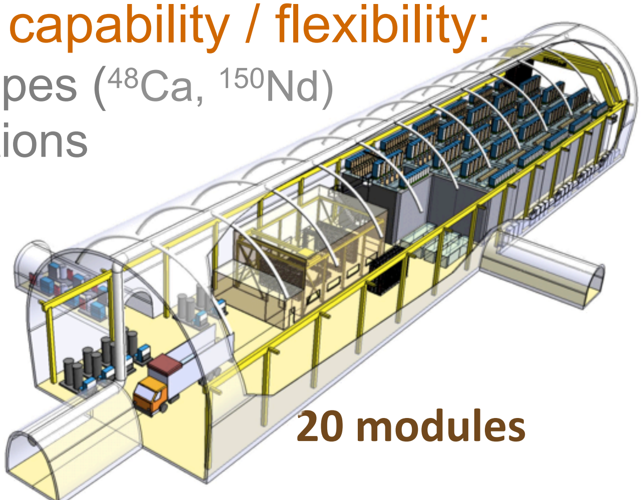
  - ✓ Results for 5 other isotopes: ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd
  - ✓ Testing transitions models: excited states, V+A, Majorons, SSD, HSD, …
  - ✓ Stay tuned for results with final samples

- **SuperNEMO** (Demonstrator in 2014)
  - ✓ ^{82}Se; sensitivity:

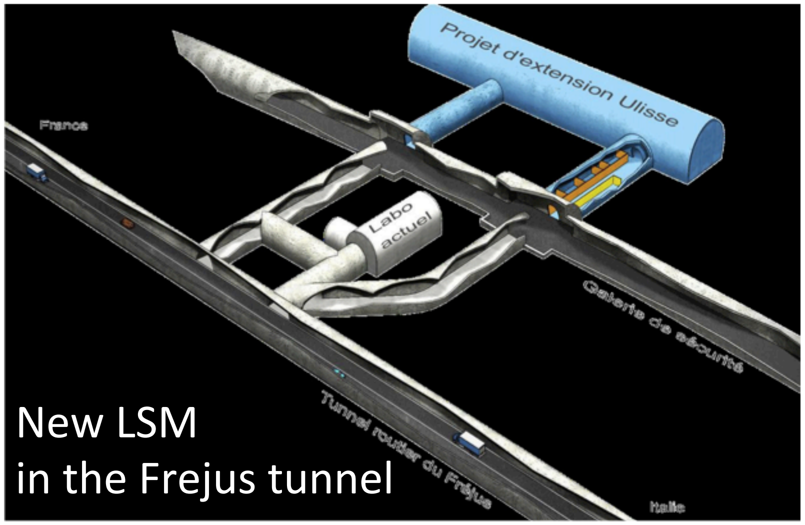
$T_{1/2}(0\nu\beta\beta)$ = $(1 - 2) \times 10^{26}$ y (500 kg*y exposure) → $m_{\beta\beta} \leq 40 - 140$ meV

- **SuperNEMO** capability / flexibility:
  - ✓ Other isotopes (^{48}Ca, ^{150}Nd)
  - ✓ Other locations

supernemo collaboration



20 modules



New LSM
in the Frejus tunnel

NEMO Collaboration, Chateau d'Yquem, June'2012

BACKUP SLIDES FOR NEMO-3 & SUPERNEMO

Summary of $2\nu\beta\beta$ NEMO-3 results

Isotope	Exposure [days]	$T_{1/2}(2\nu\beta\beta)$ [years]
^{100}Mo	389 [Phase 1 (1)] 1,468 [Phase 2]	[7.11 ± 0.02 (stat) ± 0.54 (syst)] × 10^{18} [7.16 ± 0.02 (stat) ± 0.54 (syst)] × 10^{18} (2011)
^{82}Se	389 [Phase 1 (1)] 1,468 [Phase 2]	[9.6 ± 0.3 (stat) ± 1.0 (syst)] × 10^{18} [9.6 ± 0.1 (stat) ± 1.0 (syst)] × 10^{18} (2011)
^{150}Nd	925 [Phase 1 + 2 (2)]	[$9.11\,^{+0.25}_{-0.22}$ (stat) ± 0.63 (syst)] × 10^{18}
^{130}Te	1,275 [Phase 2 (3)]	[7.0 ± 0.9 (stat) ± 1.1 (syst)] × 10^{20}
^{116}Cd	1,471 [Phase 1 + 2]	[2.88 ± 0.04 (stat) ± 0.16 (syst)] × 10^{19}
^{96}Zr	1,221 [Phase 1 + 2 (4)]	[2.35 ± 0.14 (stat) ± 0.16 (syst)] × 10^{19}
^{48}Ca	943 [Phase 1 + 2]	[$4.4\,^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst)] × 10^{19}

(1) R. Arnold et al., Phys. Rev. Lett. 95 182302 (2005)
(2) J. Argyriades et al., Phys. Rev. C 80, 032501R (2009)
(3) R. Arnold et al., PRL 107, 062504 (2011)
(4) J. Argyriades et al., Nucl. Phys. A 847, 168 (2010)

Phase 1: Feb, 2003 → Sep, 2004
Phase 2: Oct, 2004 → Jan, 2011

Summary of 0νββ NEMO-3 results

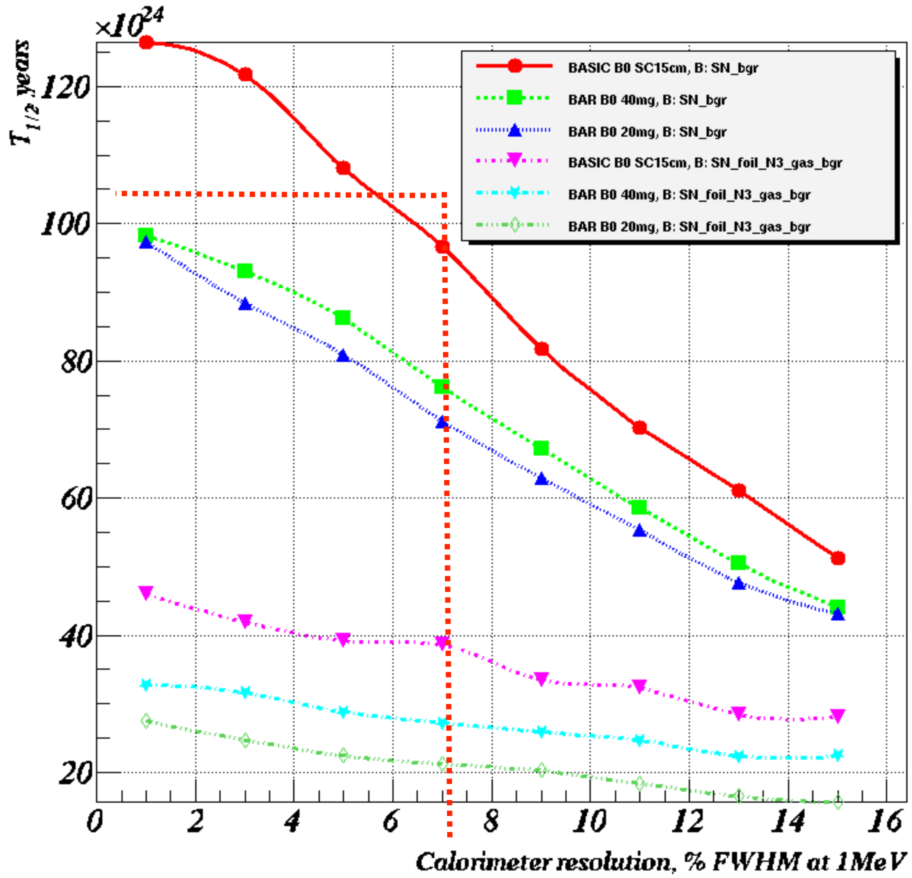
Isotope	Exposure [kg·y]	$T_{1/2}(0\nu\beta\beta)$ [years]	$\langle m_\nu \rangle$ [eV]	NME reference
^{100}Mo	31.2	$> 1.0 \cdot 10^{24}$	**< 0.31 – 0.96**	2-5,8
^{82}Se	4.2	$> 3.2 \cdot 10^{23}$	**< 0.94 – 1.6** **< 2.6**	1,3-5,8 7
^{150}Nd	0.095	$> 1.8 \cdot 10^{22}$	**< 1.5 – 6.8**	4-6,8
^{130}Te	1.6	$> 1.3 \cdot 10^{23}$	**< 1.3 – 2.7** **< 3.6**	2-5,8 7
^{116}Cd	1.65	$> 1.3 \cdot 10^{23}$	**< 1.3 – 3.2**	2-5,8
^{96}Zr	0.031	$> 9.2 \cdot 10^{21}$	**< 7.2 – 19.5**	2-5,8
^{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
[8] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310

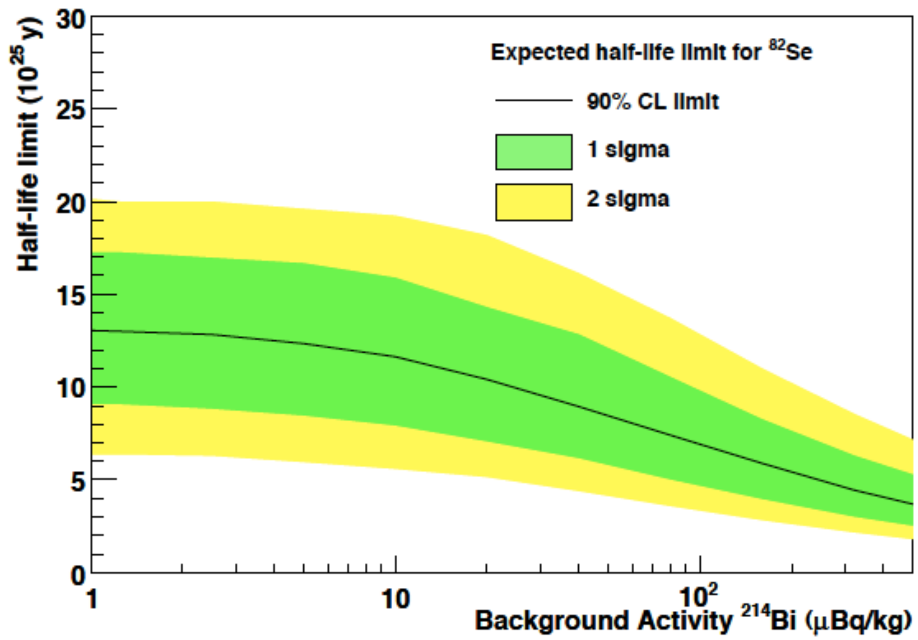
^{82}Se Sensitivity ($0\nu\beta\beta$)

Exposure 500 kg y



Calorimeter resolution (% FWHM at 1 MeV)

GEANT-4 based model of the detector combined with NEMO-3 experience.



^{82}Se sensitivity

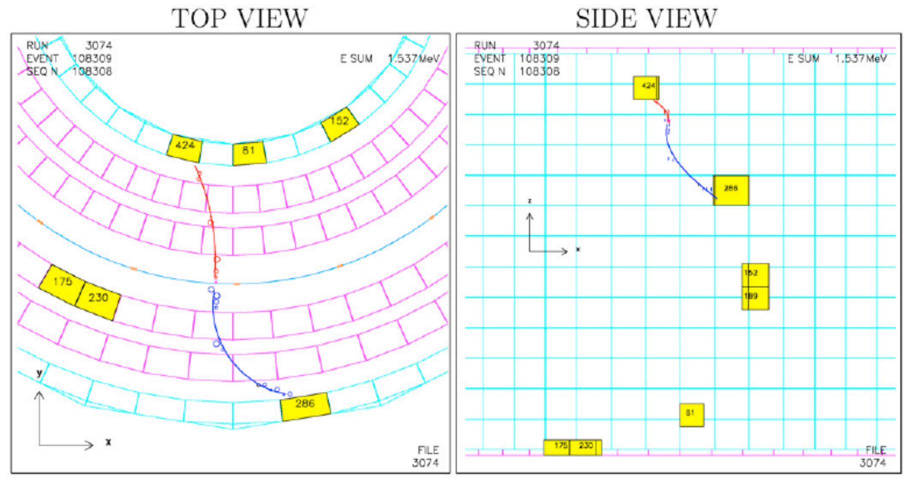
Exposure 500 kg * y

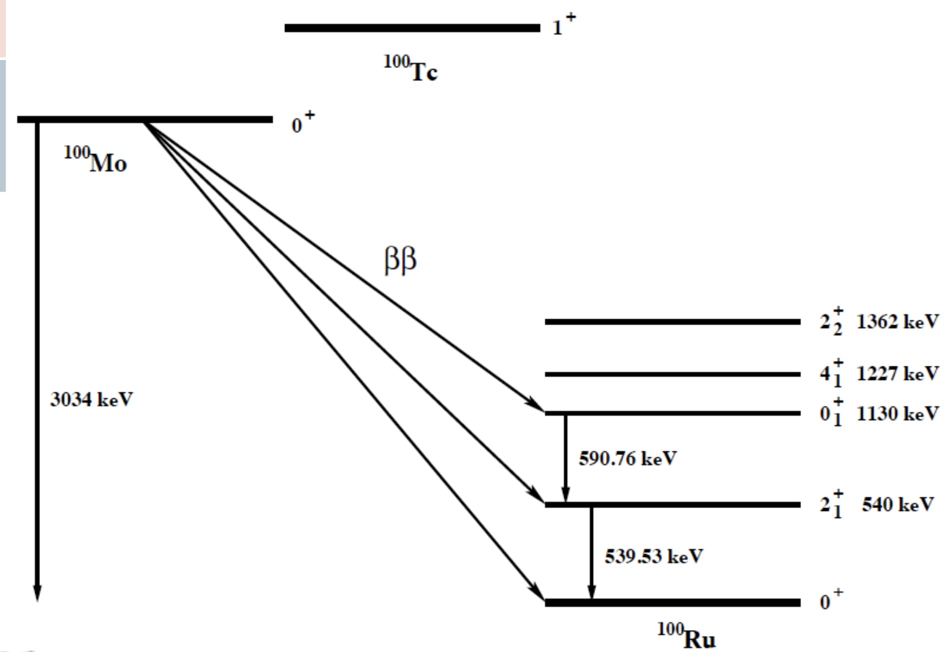
- ✓ $T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y
- ✓ $\langle m_\nu \rangle < 0.04 - 0.11$ eV

NEMO-3: $\beta\beta$ of ^{100}Mo to excited states

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

Best limits or uncertainties





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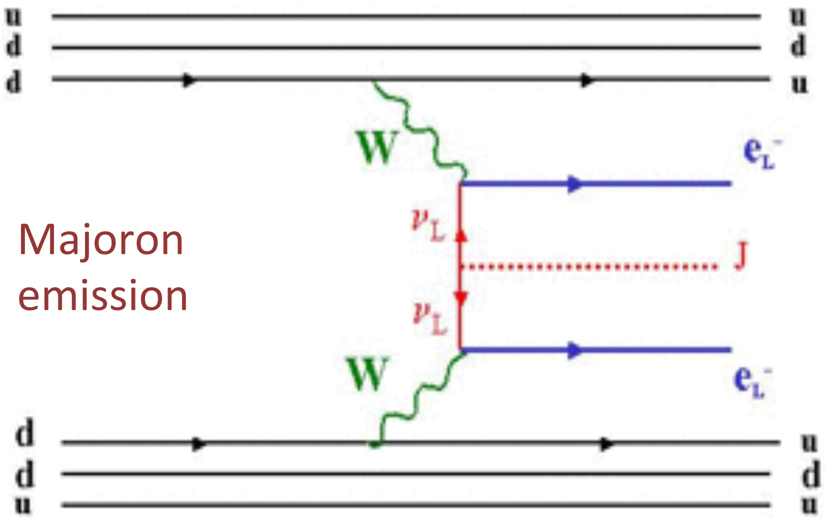
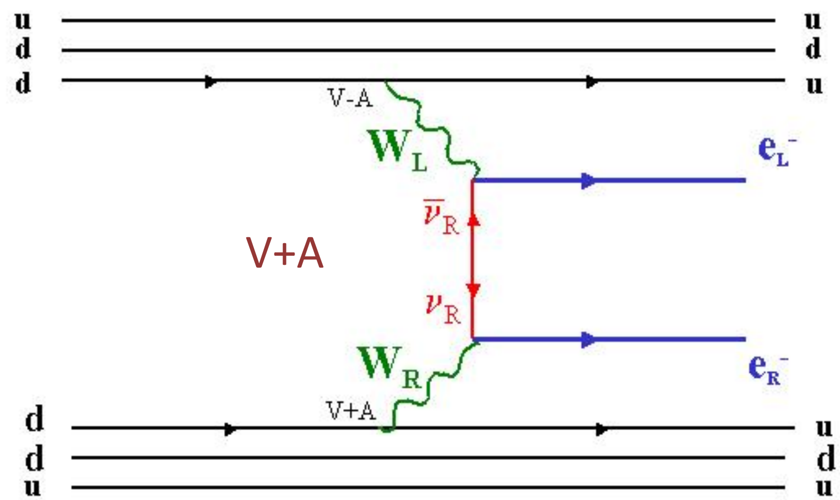
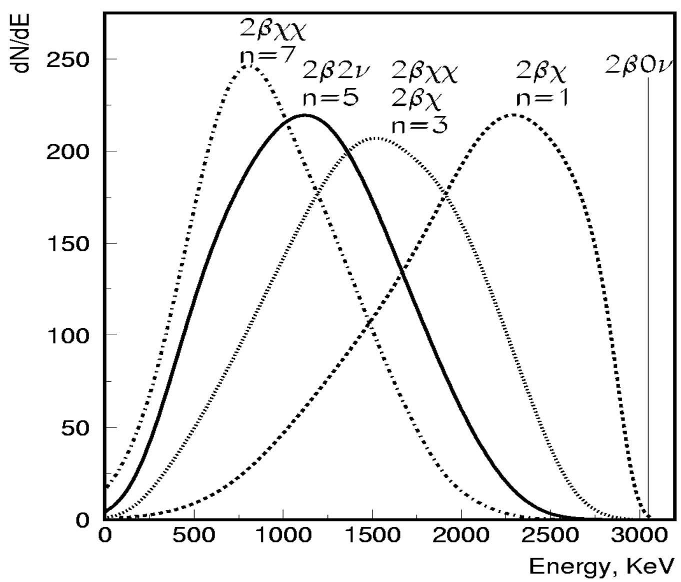
NEMO-3 - other physics

Majoron emission



V+A





	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	$>2.4\cdot10^{23}$ $\lambda<2.\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{22}$	$>5\cdot10^{20}$

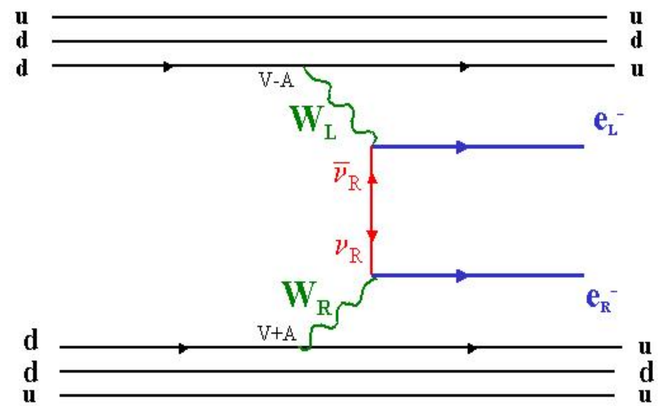
* Phase 1+Phase 2 data

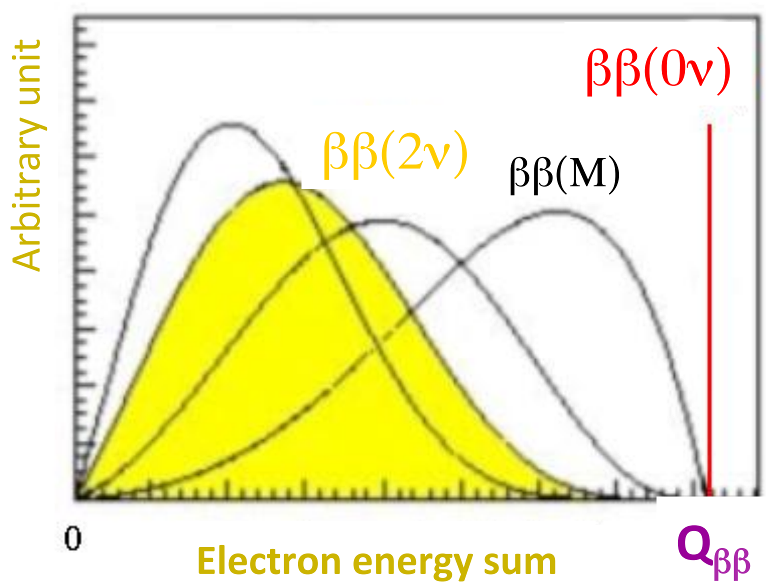
** Phase 1 data, *R. Arnold et al. Nucl. Phys. A765 (2006) 483*

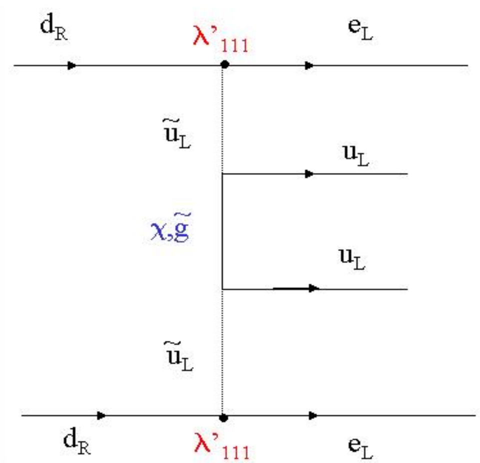
Neutrinoless double beta decay

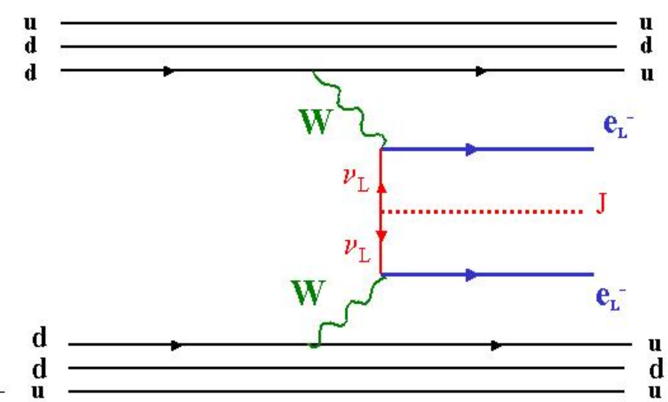
$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

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}, …







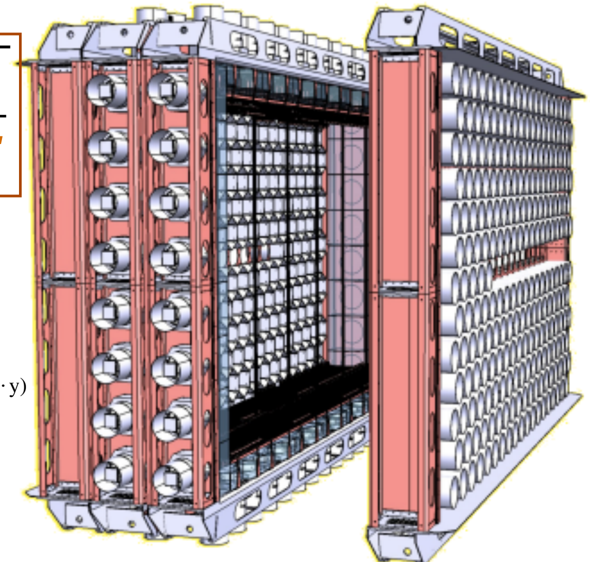


+ difference in angular distributions

NEMO-3 → SuperNEMO

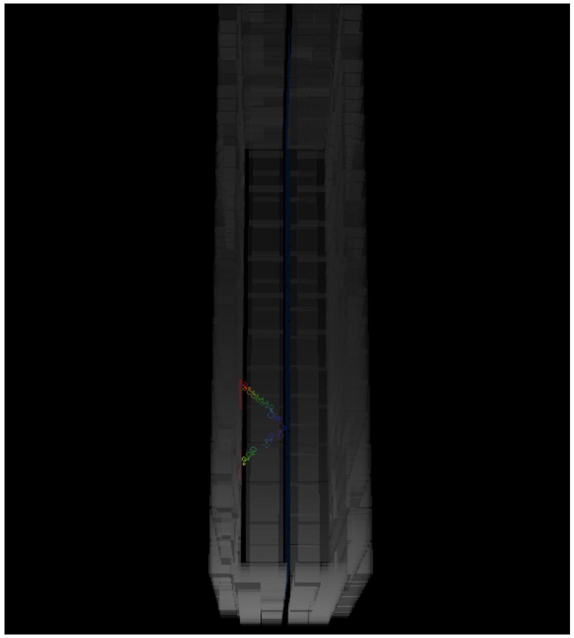
$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times 10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta E}}$$

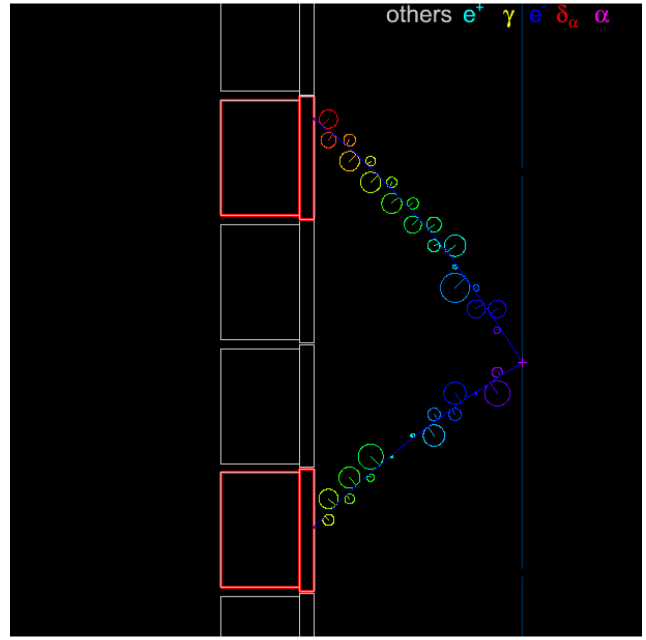
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source
M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts $(\text{keV}\cdot\text{kg}\cdot\text{y})$
ΔE – energy resolution (keV)

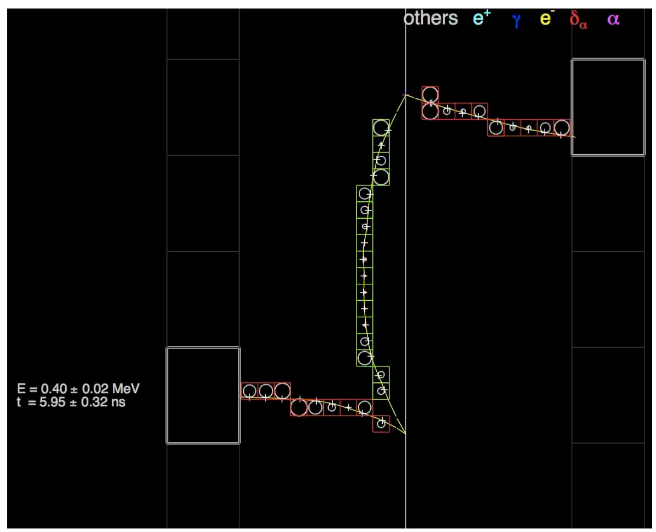


NEMO-3	R&D since 2005	SuperNEMO
^{100}Mo	isotope	^{82}Se (maybe also ^{150}Nd or ^{48}Ca)
7 kg	mass	100 kg
A(^{208}Tl) < 20 μBq/kg A(^{214}Bi) < 300 μBq/kg Rn ~ 5-6 mBq/m^3	Radio-purity of the foil Radon in the tracker	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg Rn < 0.1 mBq/m^3
8%	efficiency	30%
8% FWHM @ 3 MeV	Energy resolution	4% FWHM @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ y $<m_n> < 0.3 – 0.8$ eV	sensitivity	$T_{1/2}(0\nu\beta\beta) > 1 \times 10^{26}$ y $<m_n> < 40 – 100$ meV
1 module	modularity	>20 modules (new lab)

Improved simulations and tracking







Phenomenology of 0νββ and 2νββ (1)

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

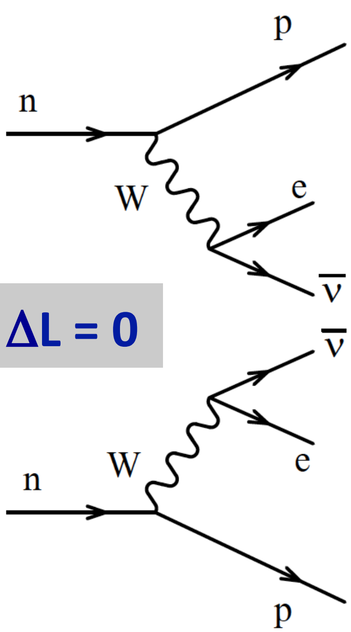
G = phase space (well known)

M = nuclear matrix element (challenging)

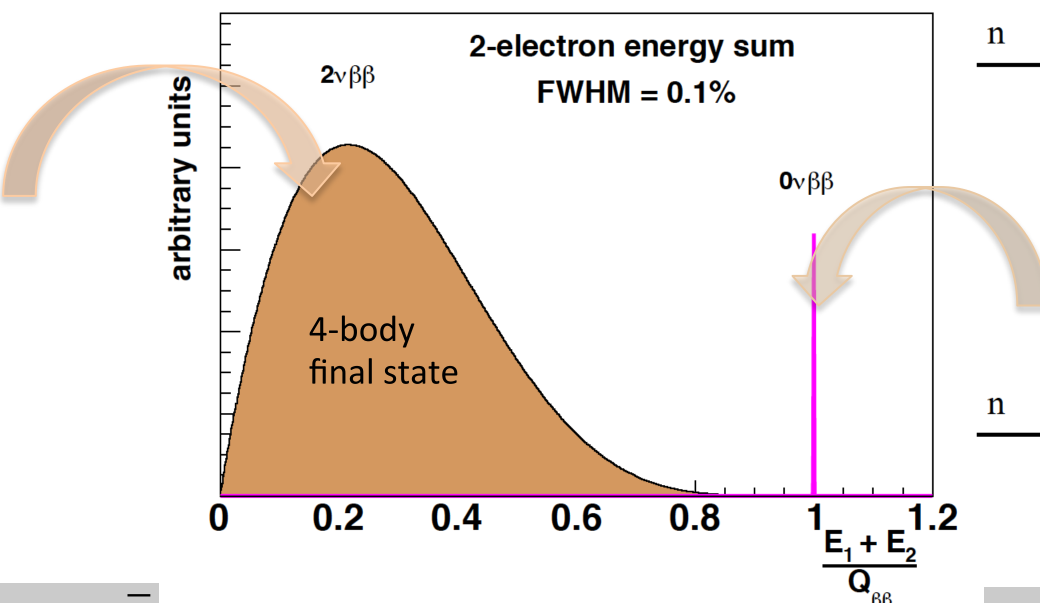
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left|M_{0\nu}\right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$

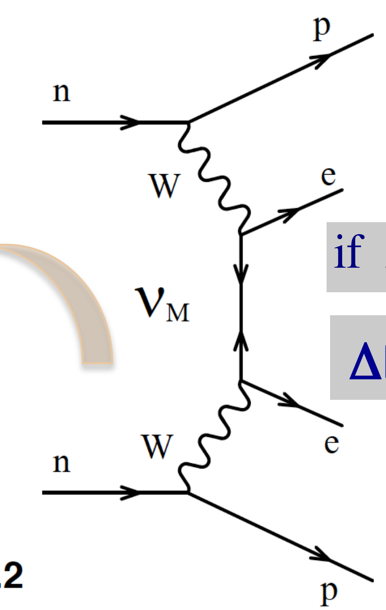
$$\left|\left\langle m_{\beta\beta} \right\rangle\right| \equiv \left| \; m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i\alpha^*} + m_3 \left|U_{e3}\right|^2 e^{i\beta^* - 2i\delta} \; \right|$$

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



ΔL = 0





if $m_\nu \neq 0$

ΔL = 2

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

$(2\nu\beta\beta)$

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

$(0\nu\beta\beta)$

Phenomenology of 0νββ and 2νββ (1)

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

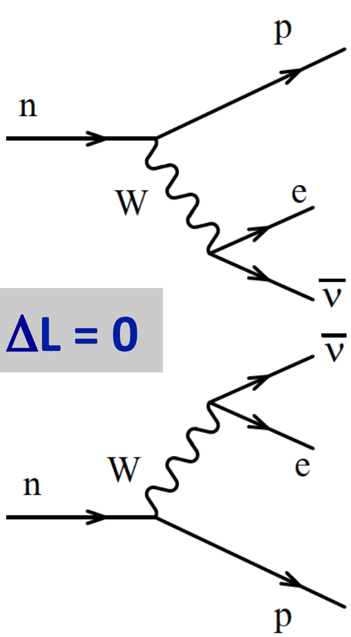
G = phase space (well known)

M = nuclear matrix element (challenging)

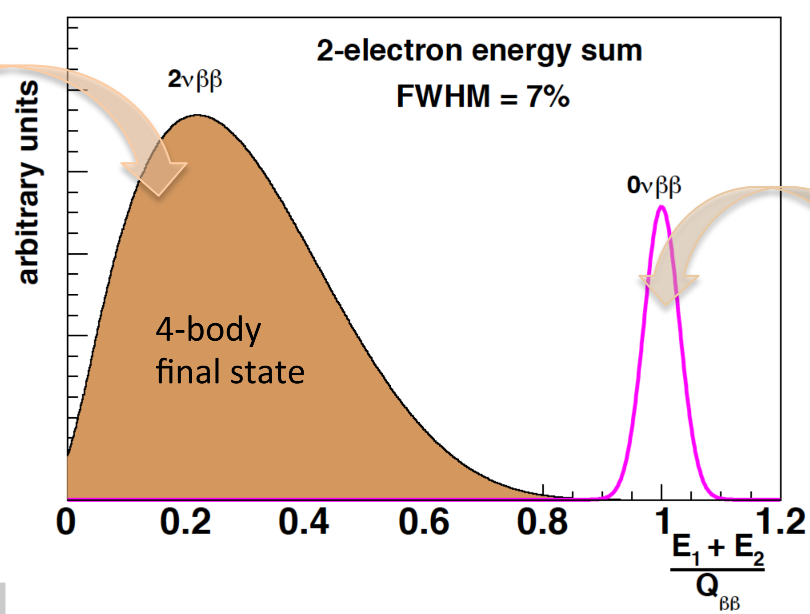
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left|M_{0\nu}\right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

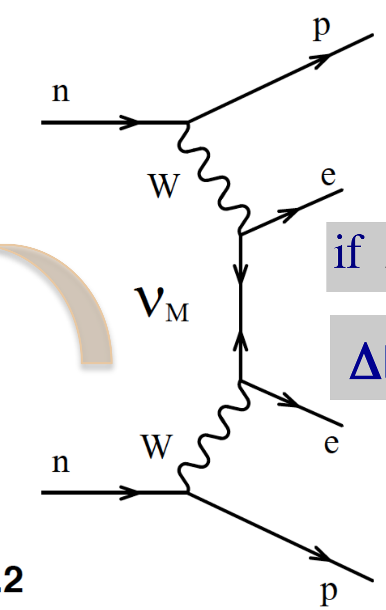
$$\left|\langle m_{\beta\beta} \rangle\right| \equiv \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha^*} + m_3 |U_{e3}|^2 e^{i\beta^* - 2i\delta} \right|$$

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



ΔL = 0





if $m_\nu \neq 0$

ΔL = 2

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

$(2\nu\beta\beta)$

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

$(0\nu\beta\beta)$

Phenomenology of 0νββ and 2νββ (2)

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

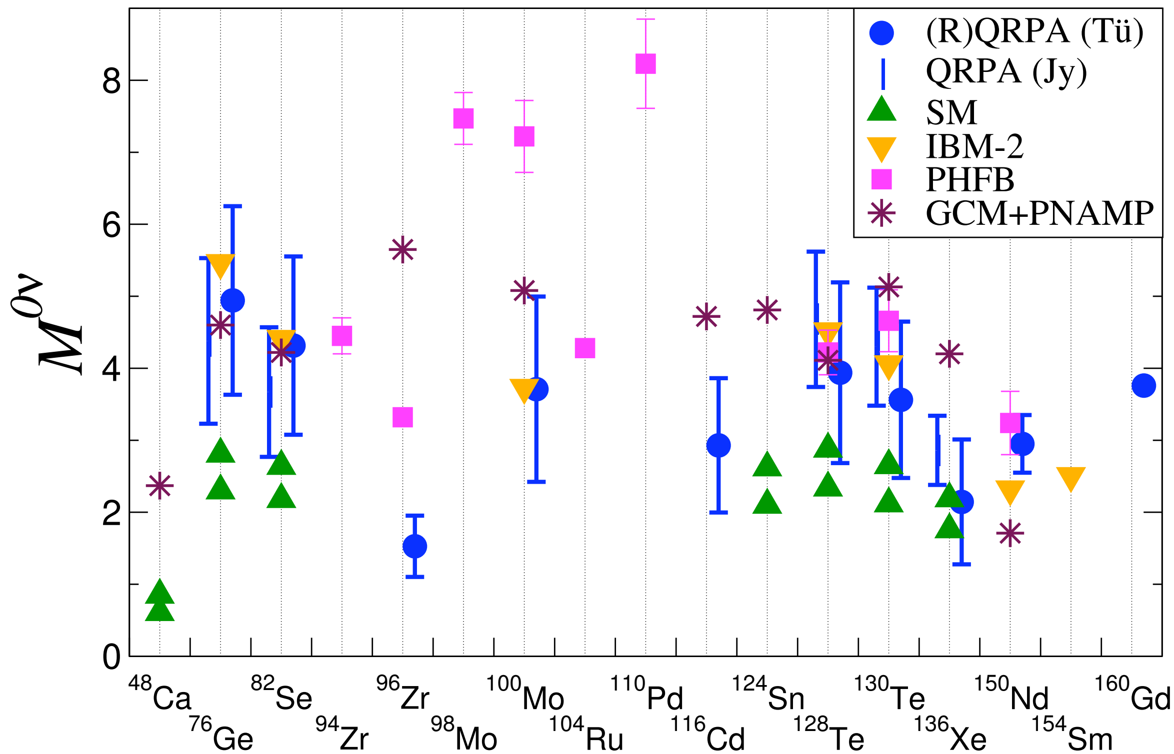
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left|M_{0\nu}\right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

G = phase space (well known)

M = nuclear matrix element (challenging)

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

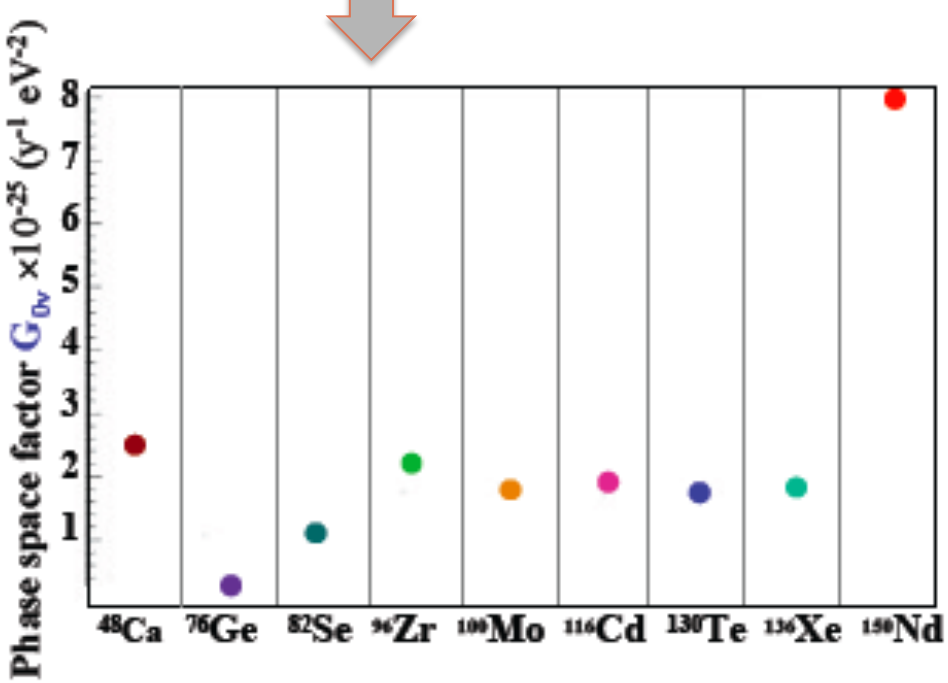
α^*, β^* = linear combinations of α and β



From V. Rodin, TAUP 2011 in Munich

Practical matters

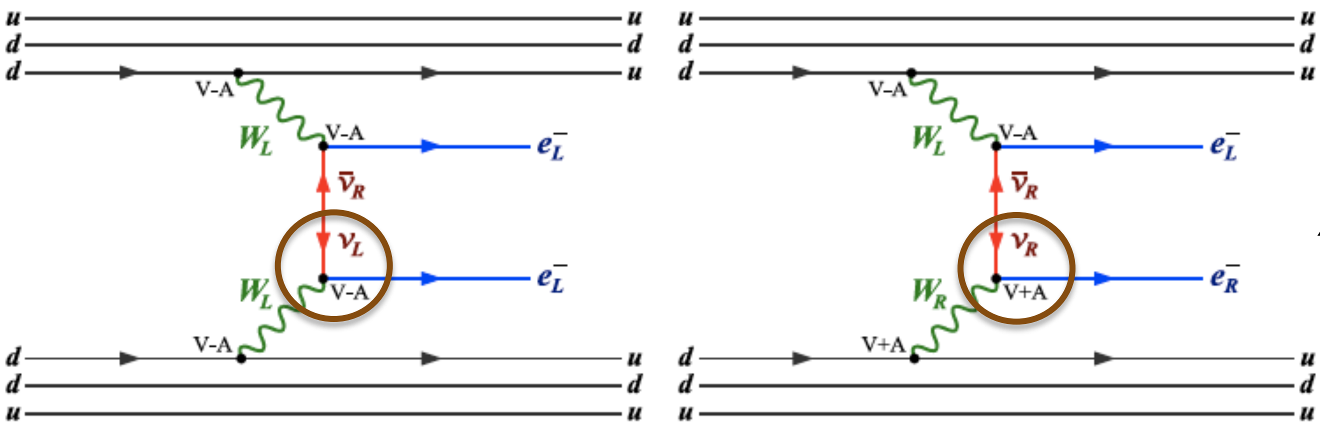
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} \bullet \left| M_{0\nu}^{GT} \right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$



NEMO-3

	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.272	0.187
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.035	9.6
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{116}Cd \rightarrow ^{116}Sn$	2.805	7.5
$^{130}Te \rightarrow ^{130}Xe$	2.529	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8

Top 11 ββ emitters with $Q_{\beta\beta}$ > 2 MeV



$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}$$

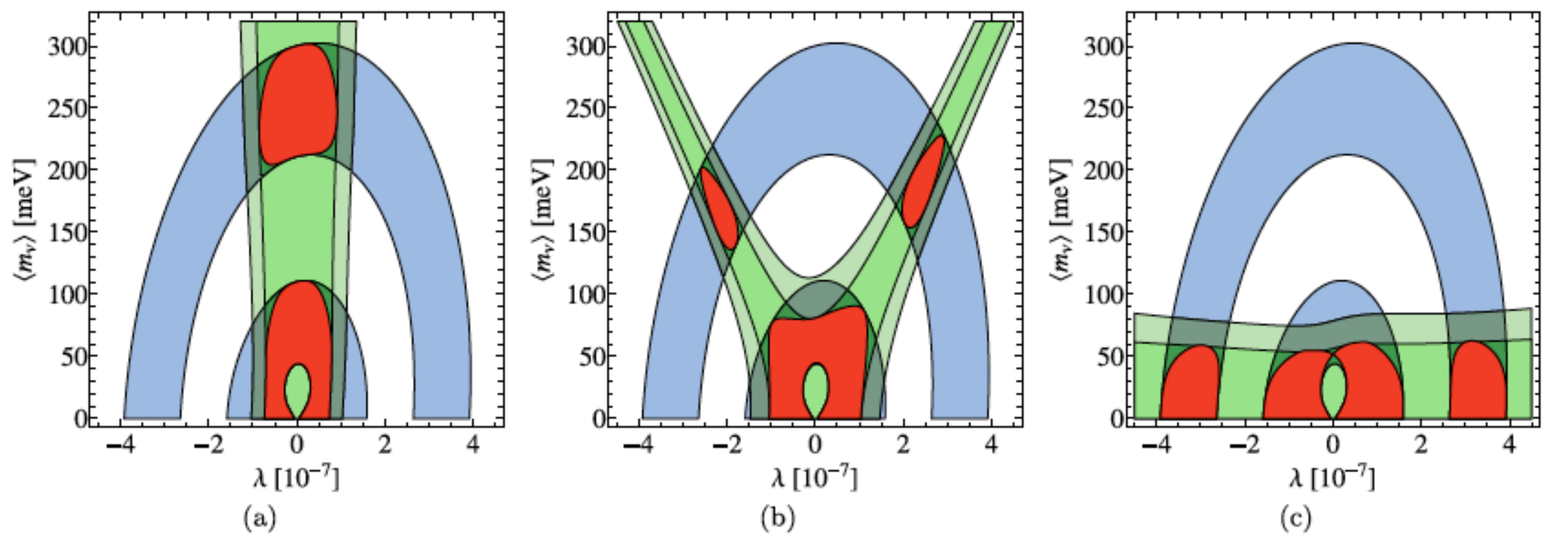
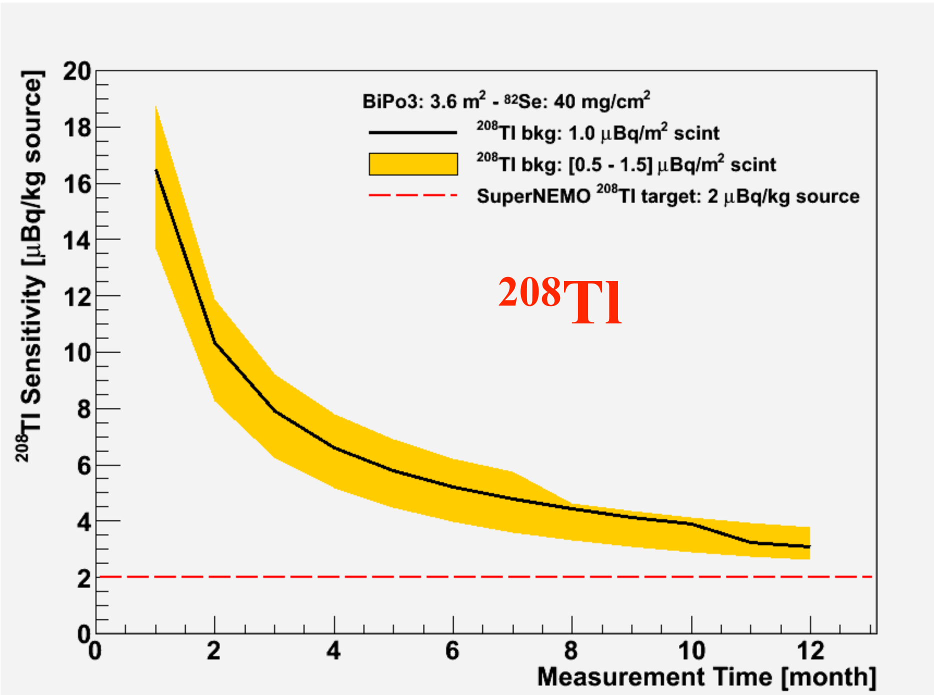
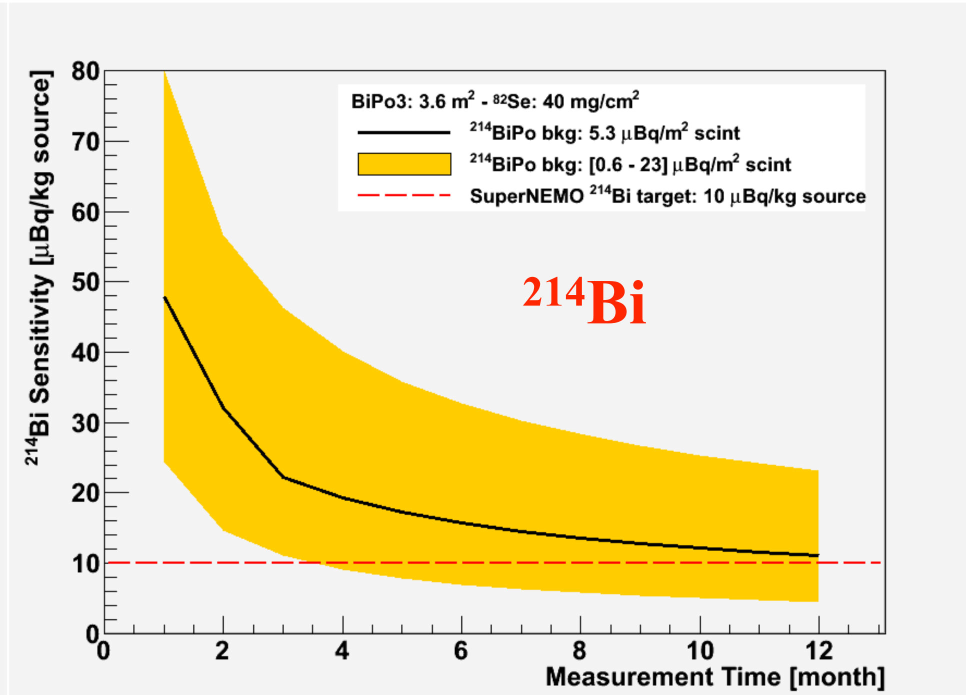


Fig. 11 (Color online) Constraints at one standard deviation on the model parameters m_ν and λ for ^{82}Se from: (1) an observation of $0\nu\beta\beta$ decay half-life at $T_{1/2} = 10^{25}$ y (*outer blue elliptical contour*) and 10^{26} y (*inner blue elliptical contour*); (2) reconstruction of the angular (outer, lighter green) and energy difference (inner, darker green) distribution shape; (3) combined analysis of (1) and (2) using decay rate and energy distribution shape reconstruction (*red contours*). The admixture of the MM and RHC$_\lambda$ contributions is assumed to be: **a** pure MM contribution; **b** 30% RHC$_\lambda$ admixture; and **c** pure RHC$_\lambda$ contribution. NME uncertainties are assumed to be 30% and experimental statistical uncertainties are determined from the simulation

Assuming: ^{82}Se foil 40 mg/cm^2
Total surface BiPo-3 = 3.6 m^2
Energy threshold = 100 keV for prompt and delay signals (ε ~5%)

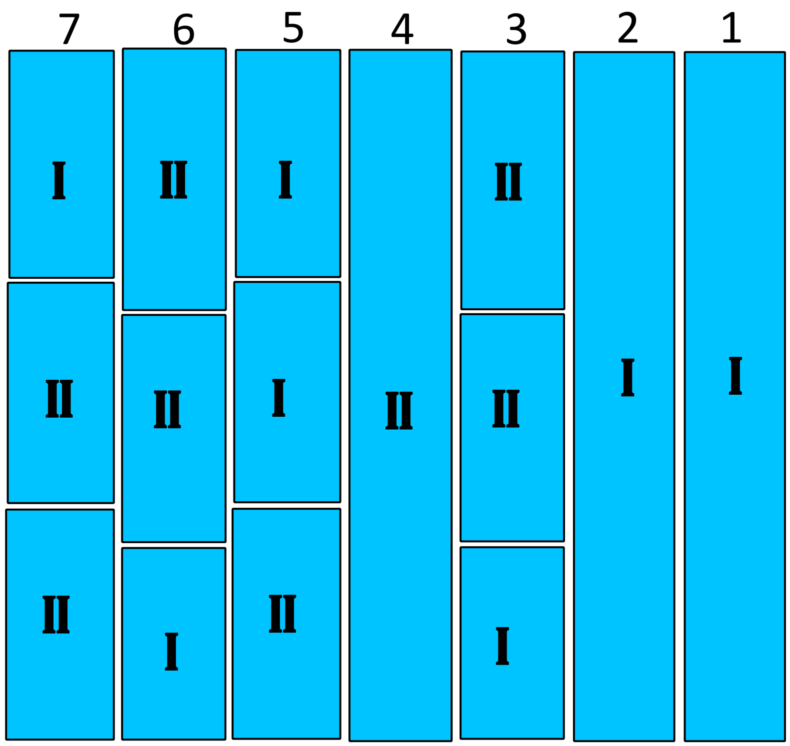




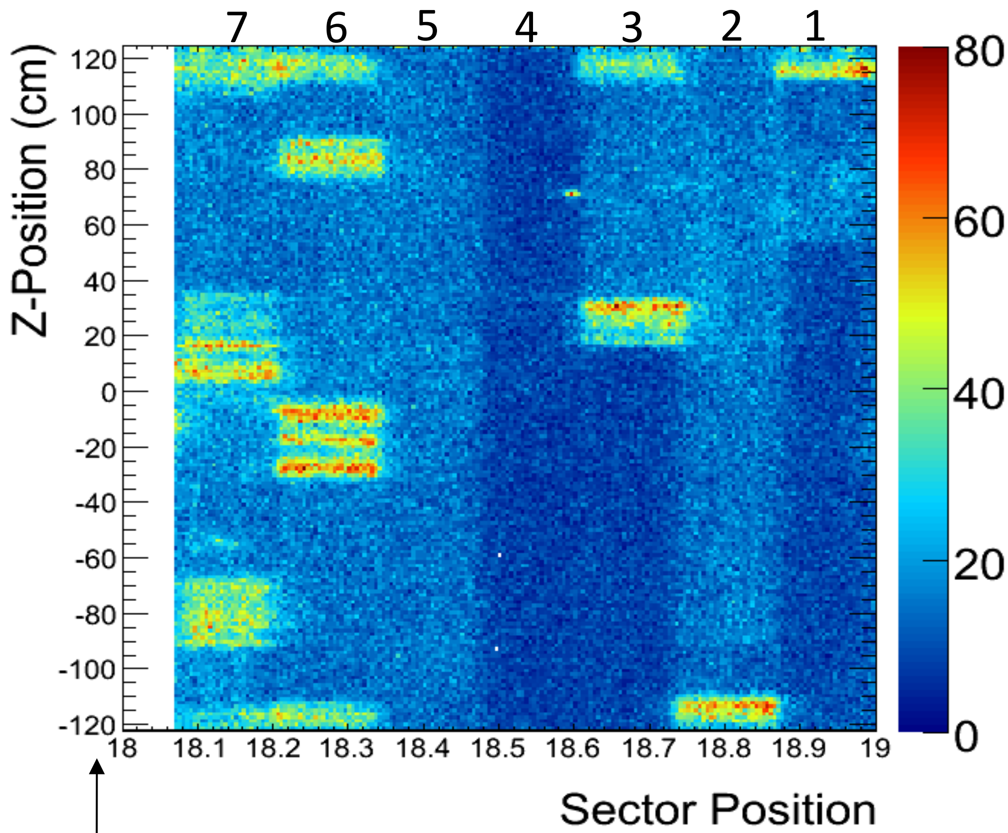
SuperNEMO demonstrator:

- Foils 270×13.55 cm^2, 8 foils installed in BiPo-3 ⇒ Total surface = 2.93 m^2
  efficiency reduced by 2.9/3.6 = 20%
- If thickness = 53 mg/cm^2
  efficiency reduced by 40/53 = 25%

Cadmium Foil
Activity and Hot Spots



Production foil parts

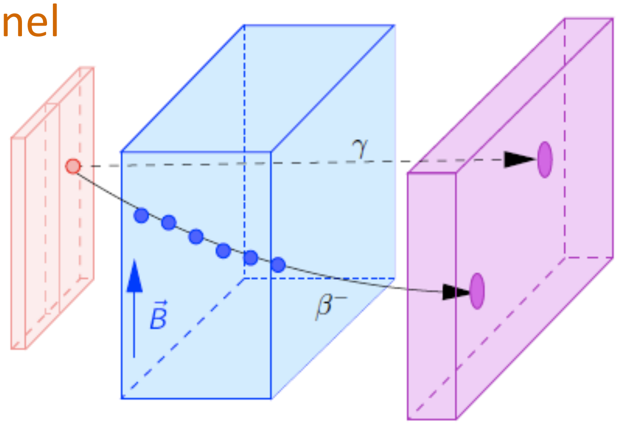


calibration tube

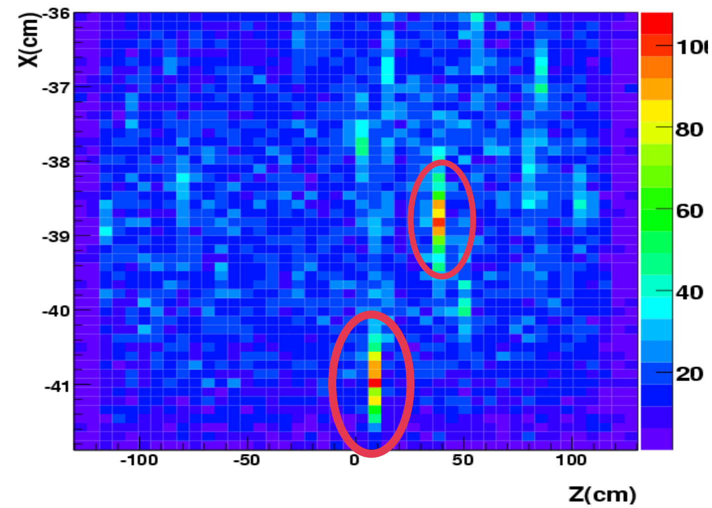
Vertex at the foil for
1 electron data

Background: control channels

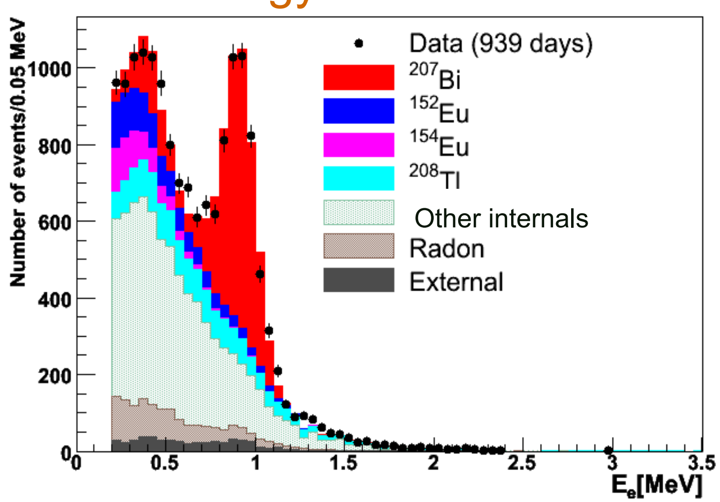
Example:
eγ control channel



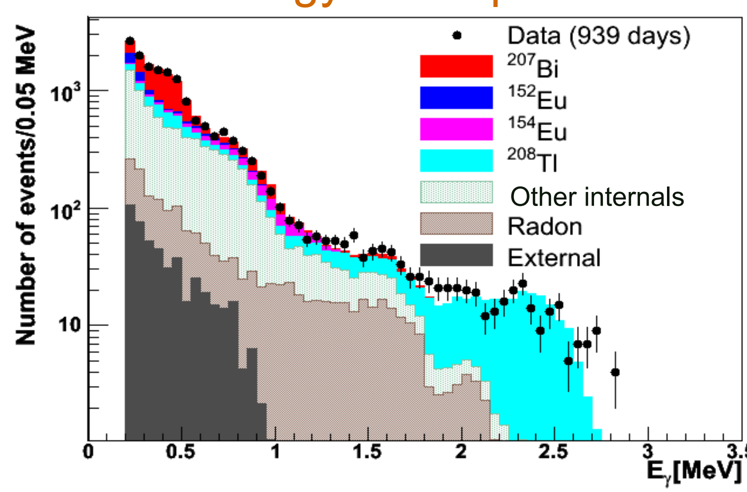
150-Nd foil



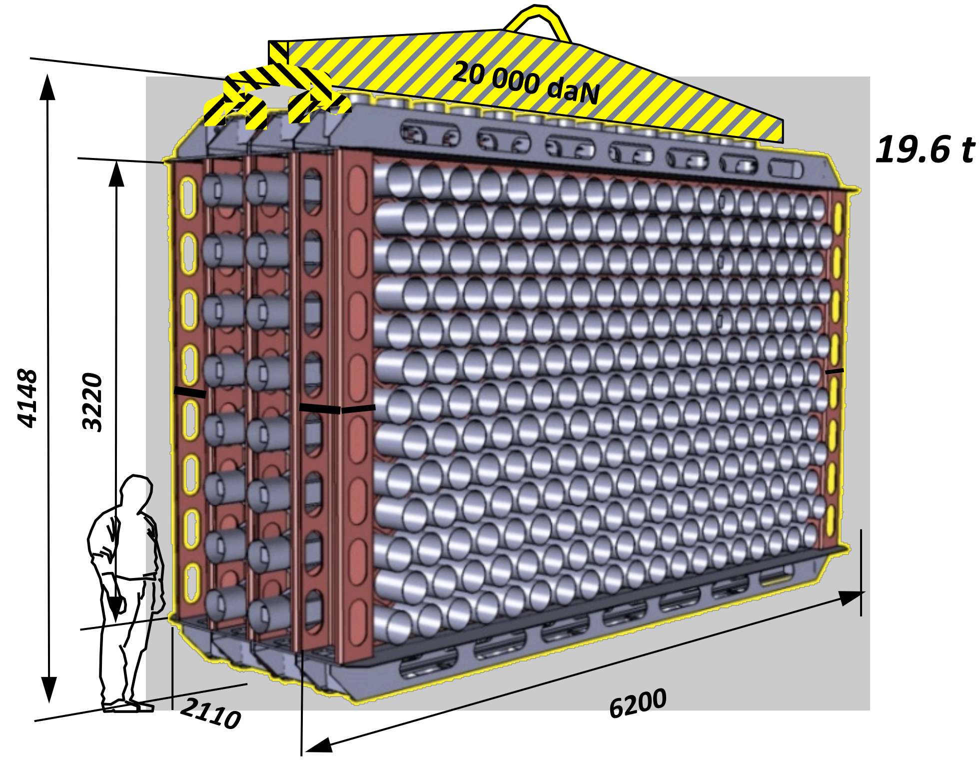
Energy of the electron



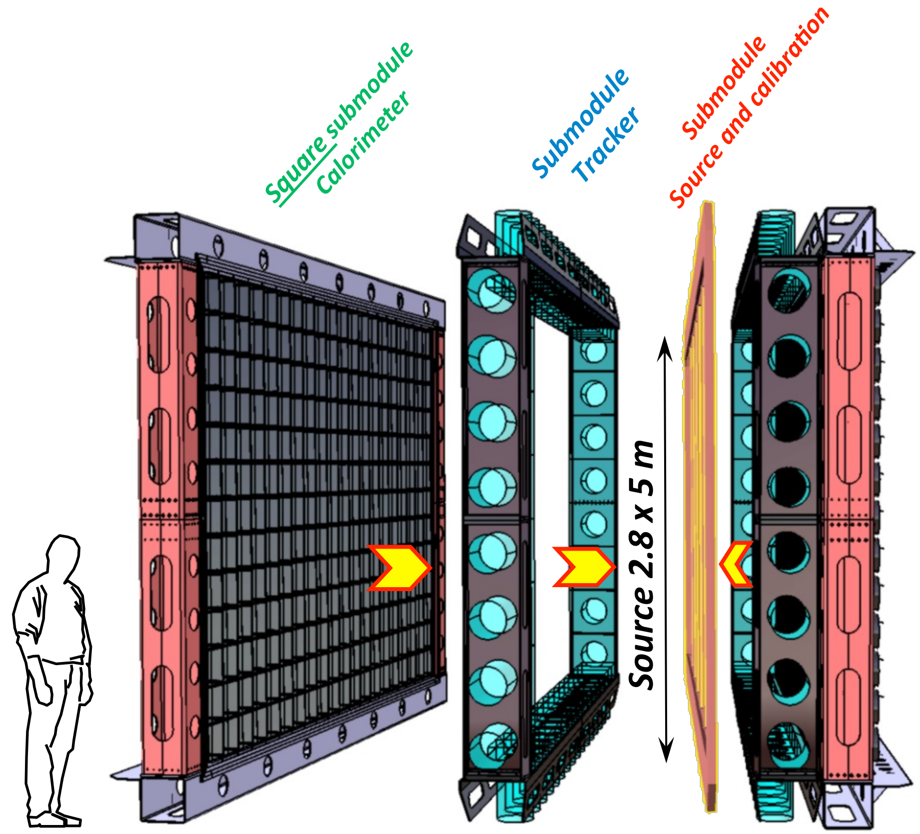
Energy of the photon

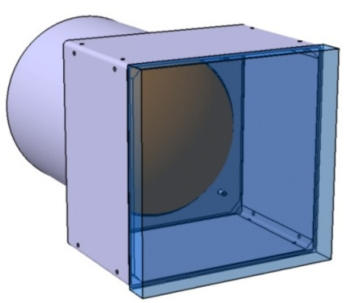


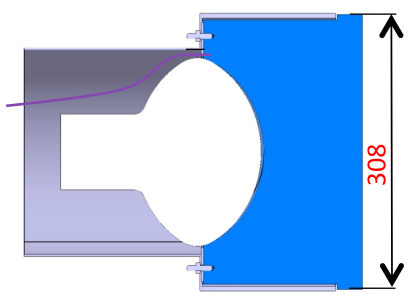
SuperNEMO Demonstrator module



Source Se: 6,3kg

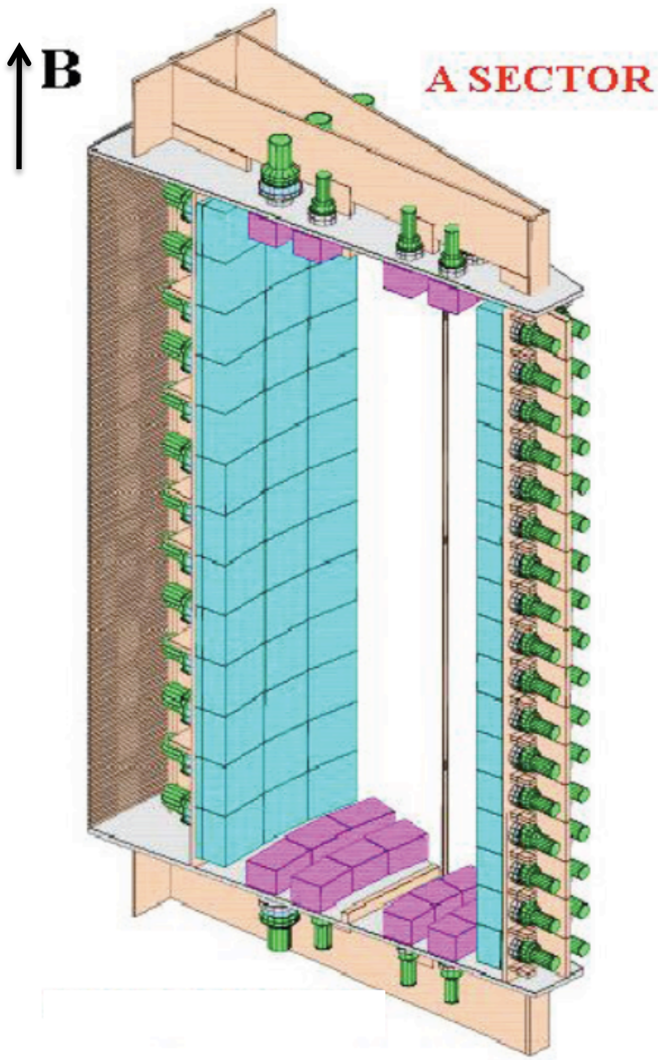






« Calorimeter square design »

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

wood

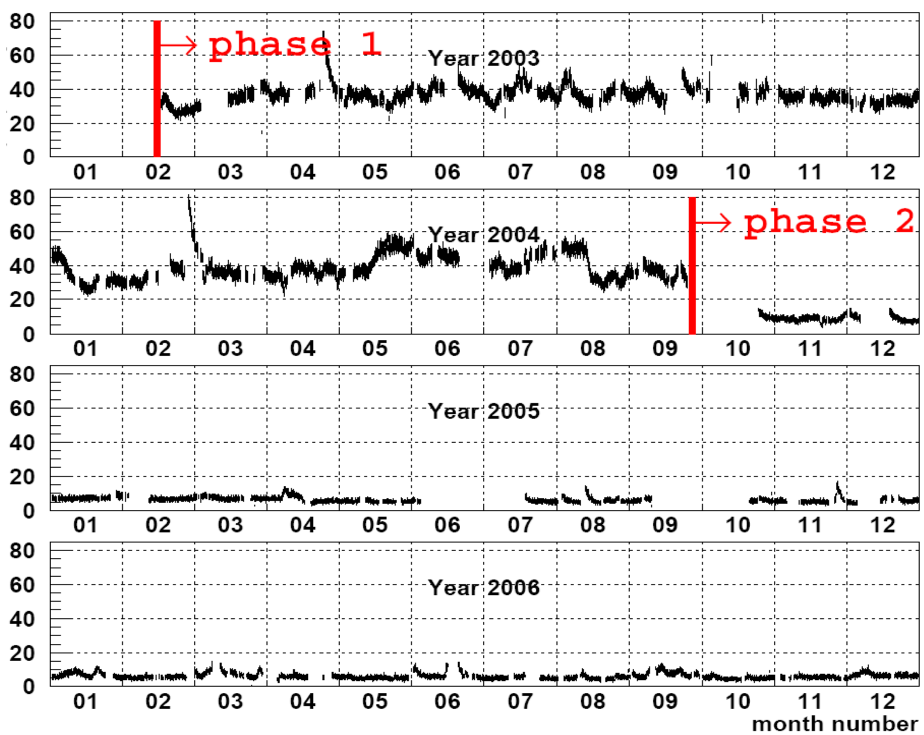
coil

Iron shield

Water tank

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

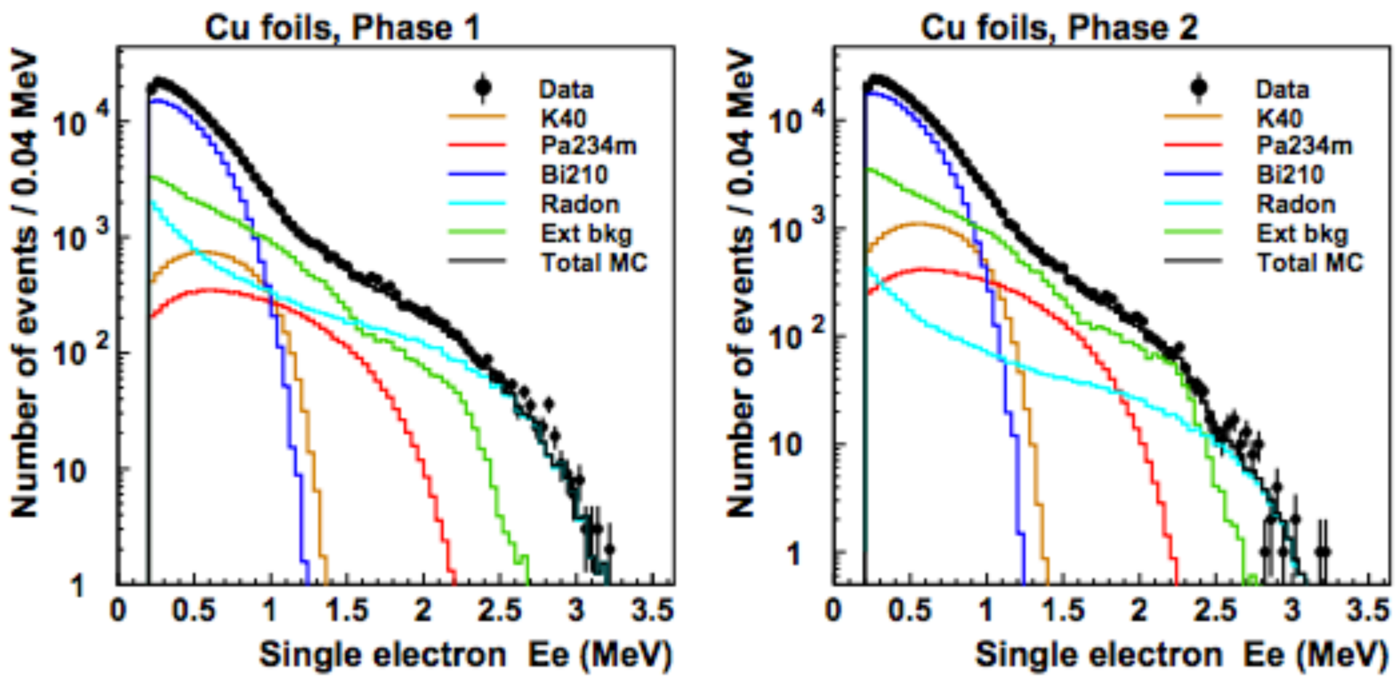


Adsorption unit @-50°C

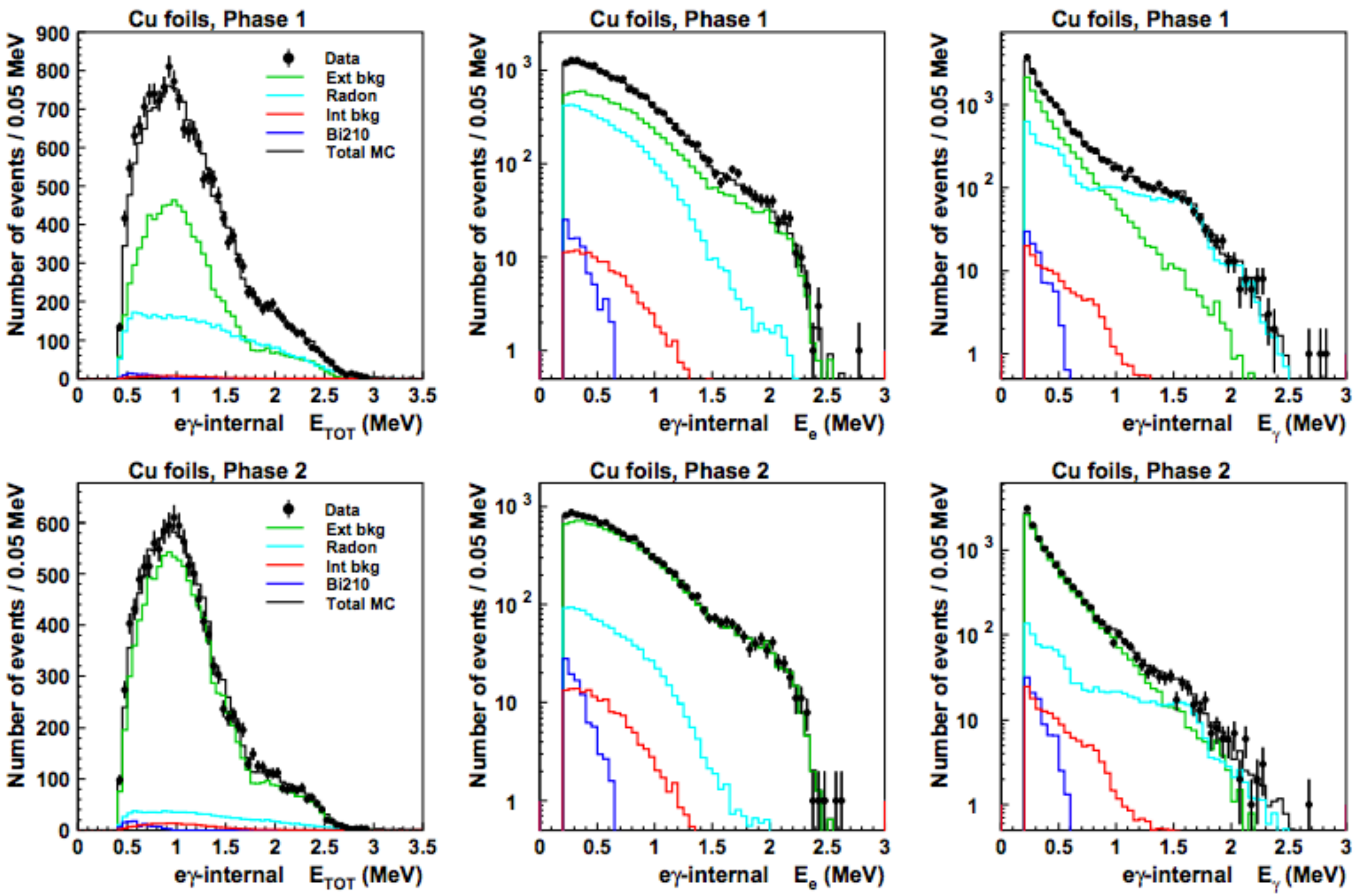
Input: A(^{222}Rn) 15 Bq/m^3

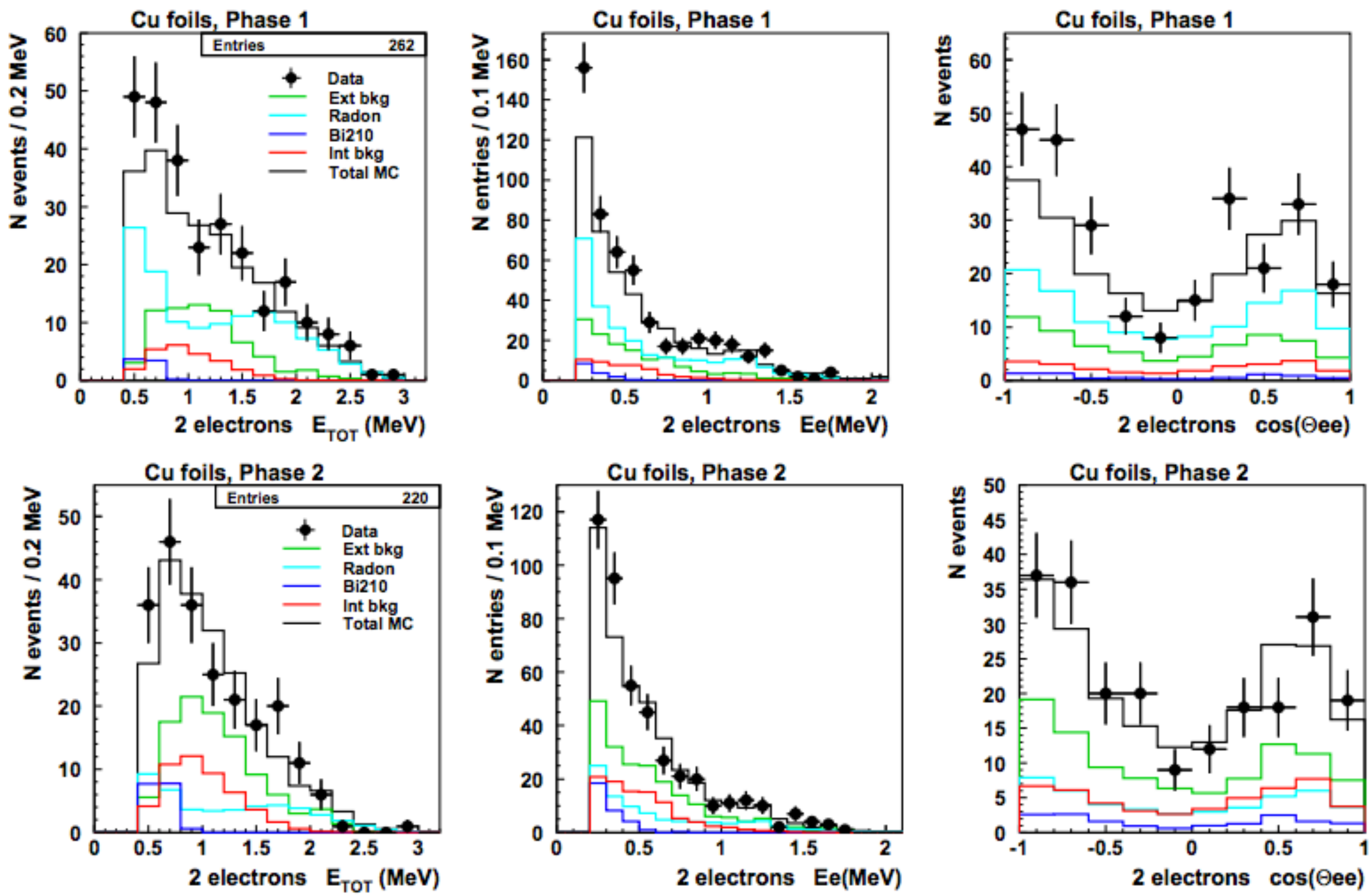
Output: A(^{222}Rn) < 15 mBq/m^3 !!
reduction factor of 1000

Phase 1 versus Phase 2 backgrounds



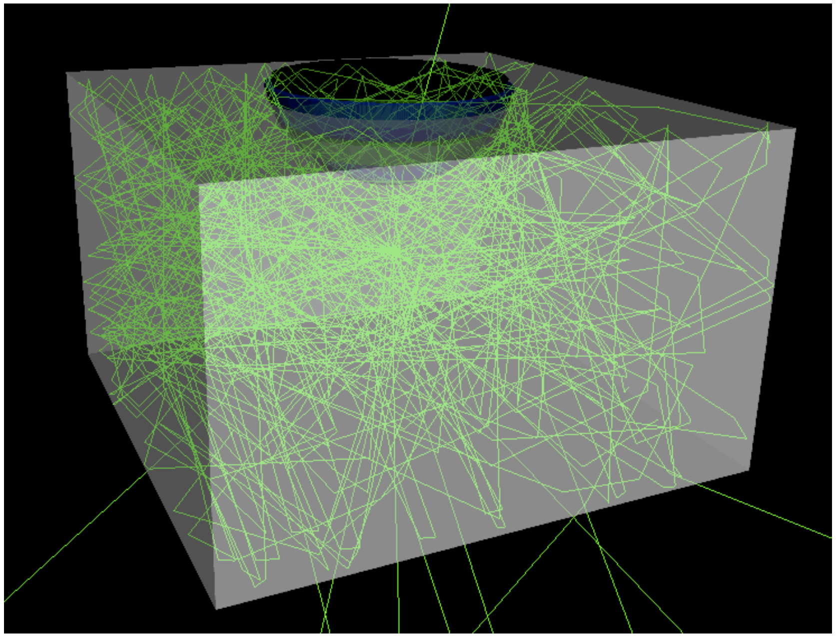
Phase 1 backgrounds

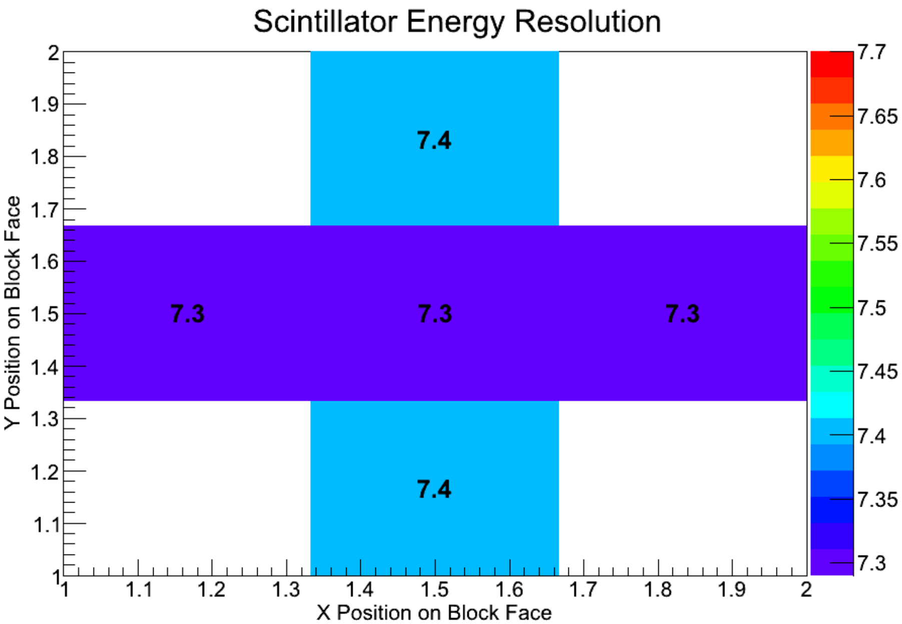




Cu foils, Phase 1
Entries 262
Data
Ext bkg
Radon
Bi210
Int bkg
Total MC
N events / 0.2 MeV
2 electrons E_TOT (MeV)
N entries / 0.1 MeV
2 electrons Ee(MeV)
N events
2 electrons cos(Θee)
Cu foils, Phase 2
Entries 220

Main wall calorimeter simulations



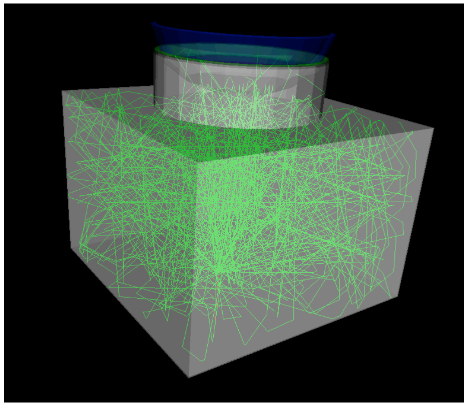


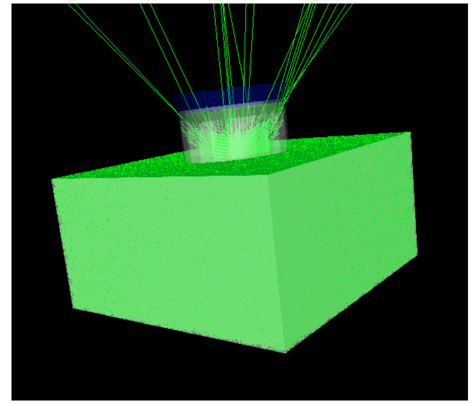
- Visualization of a GEANT-4 simulation of of a main wall calorimeter block (left), and diagram showing simulated resolution by electron entrance position on the block surface (right).

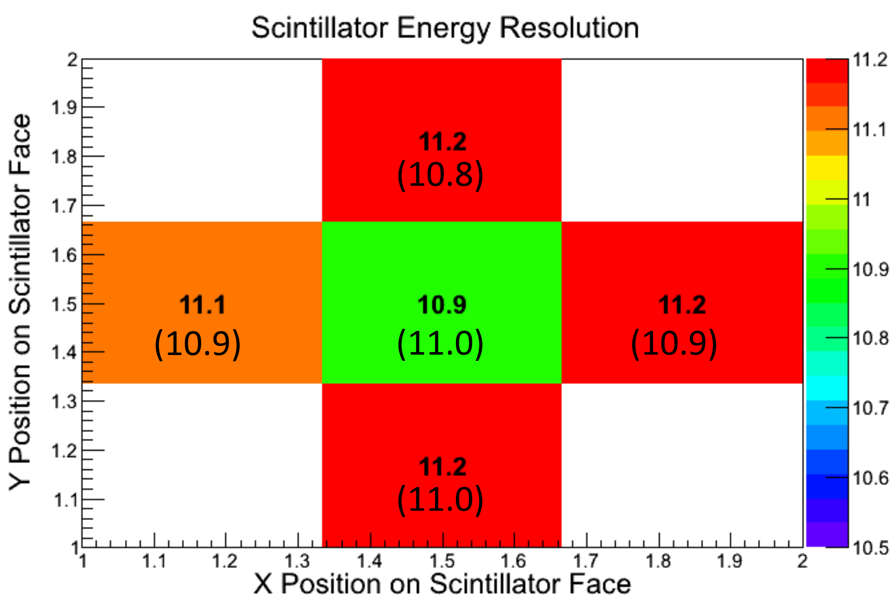
- All simulated values are in agreement with measurements.

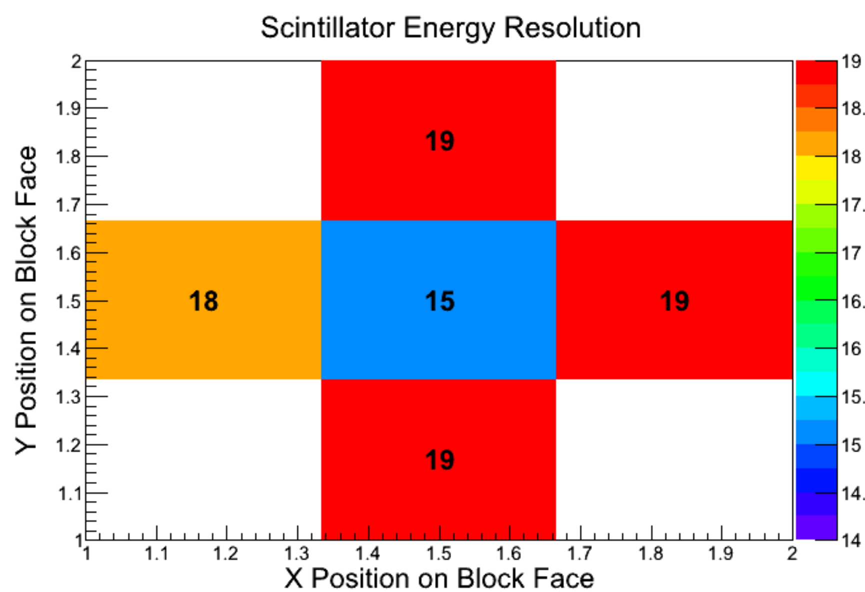
X-Wall

V-Wall



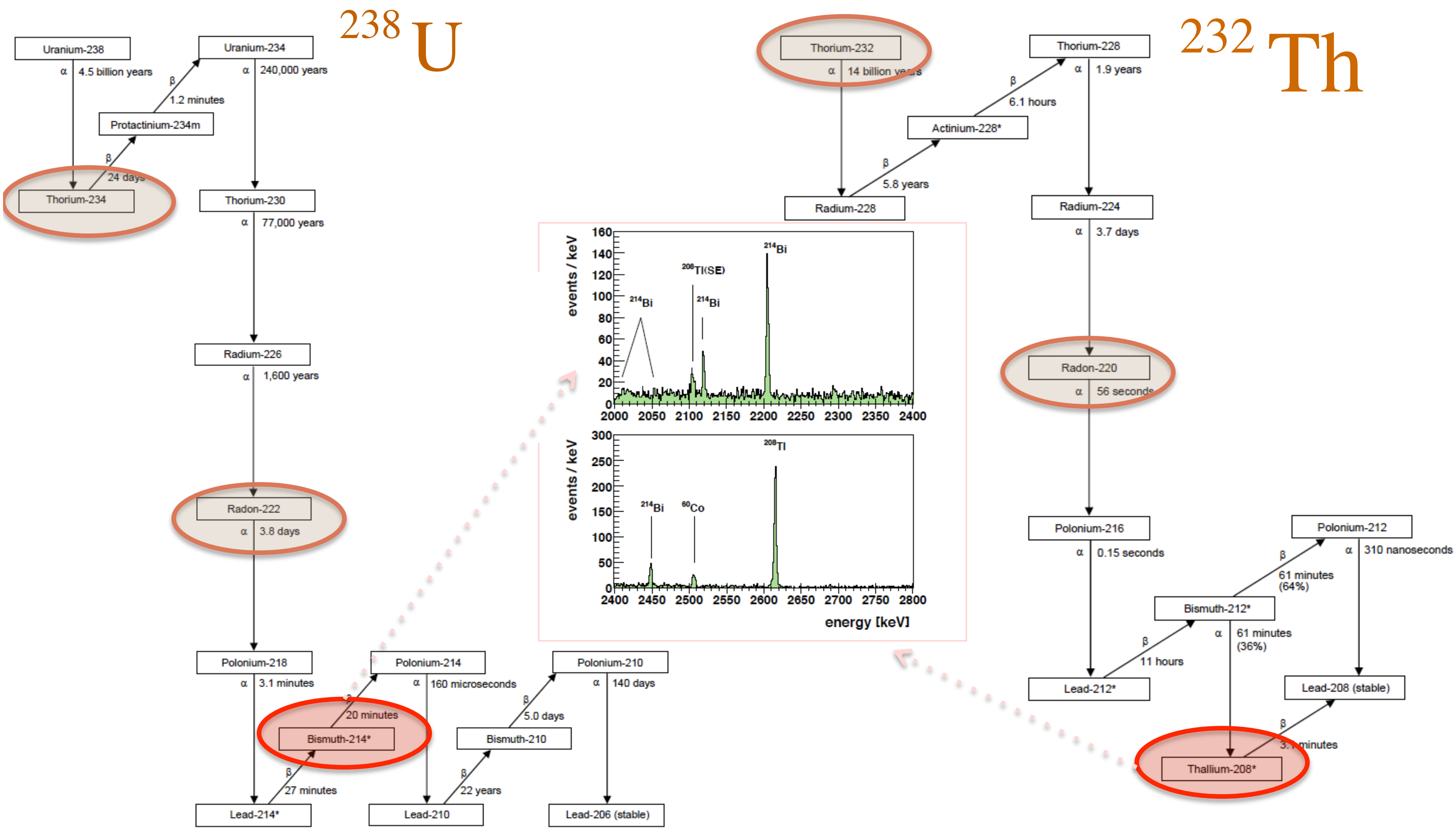






- Visualization and resolutions by electron entry position for X-wall (left) and V-wall (right) calorimeter blocks.
- Measured positional values are in parenthesis; no such values are available for the V-wall blocks.

Perennial problem – natural radioactivity



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