supernemo collaboration

MANCHESTER 1824

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Searching for Double Beta Decay with NEMO-3 and SuperNEMO

supernemo collaboration

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University of Manchester

Prague, 22 May 2013

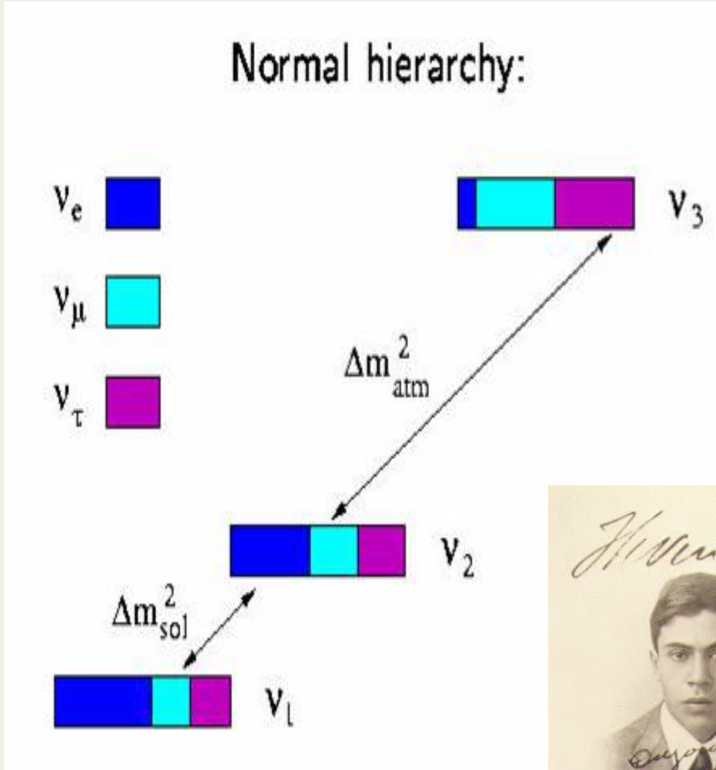
Neutrino Masses

We know relative mass scales from oscillations:

$$(\Delta m_{23})^2 \approx (50\ \text{meV})^2$$
$$(\Delta m_{12})^2 \approx (9\ \text{meV})^2$$

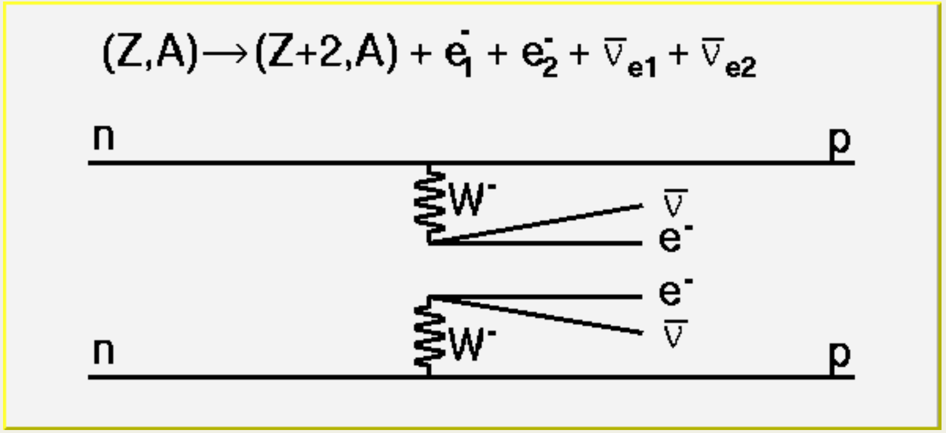
$m_{1,2,3}$ = mass eigenstates

Neutrinos can be (m > 0)
- Dirac (ν ≠ anti-ν)
- Majorana (ν = anti-ν)



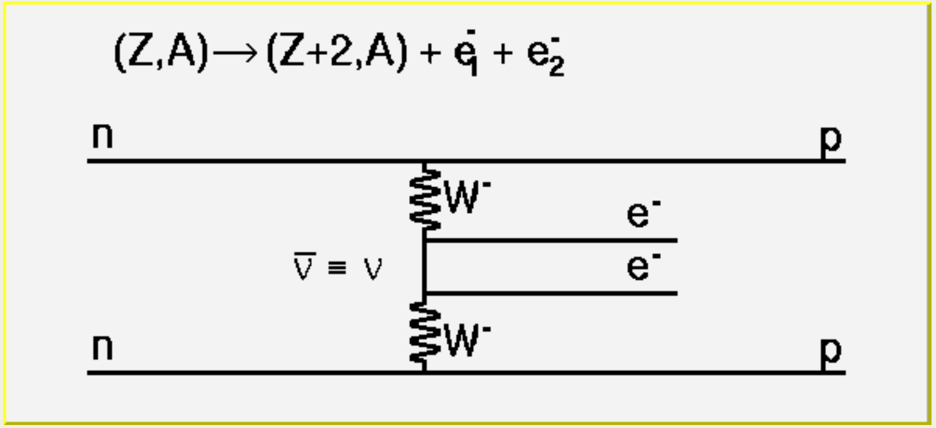
Majorana terms in Lagrangian:
- could explain small m_ν through seesaw mechanism (~ m_D/M_R)
- will violate lepton number

Double Beta Decay



$$\frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

predicted in 1935 by
Maria Goeppert-Mayer



$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

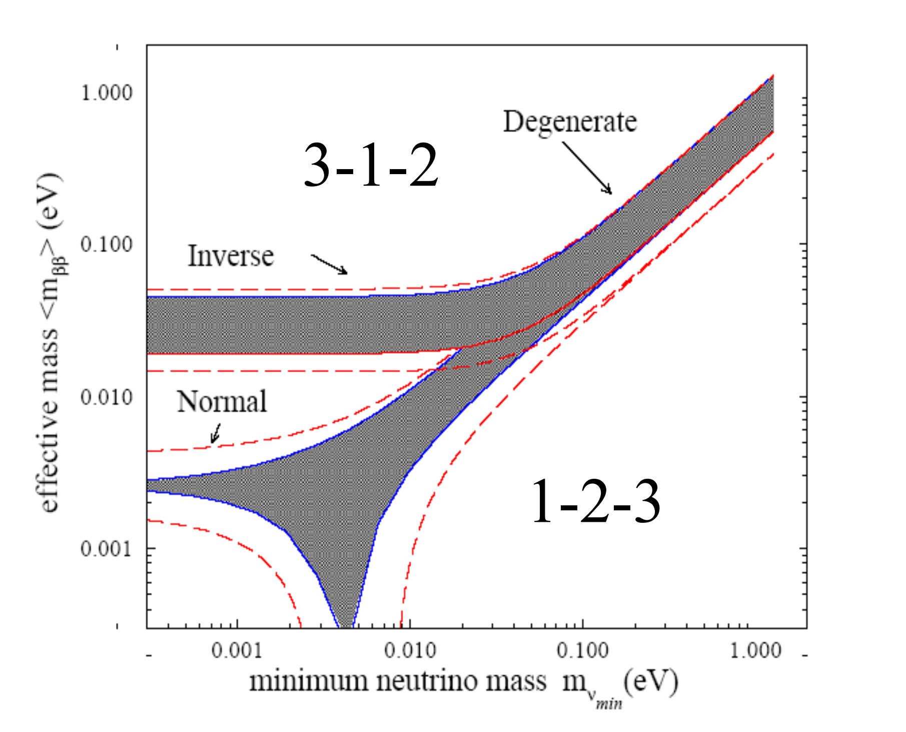
ΔL = 2 - only possible for
Majorana neutrinos with m > 0

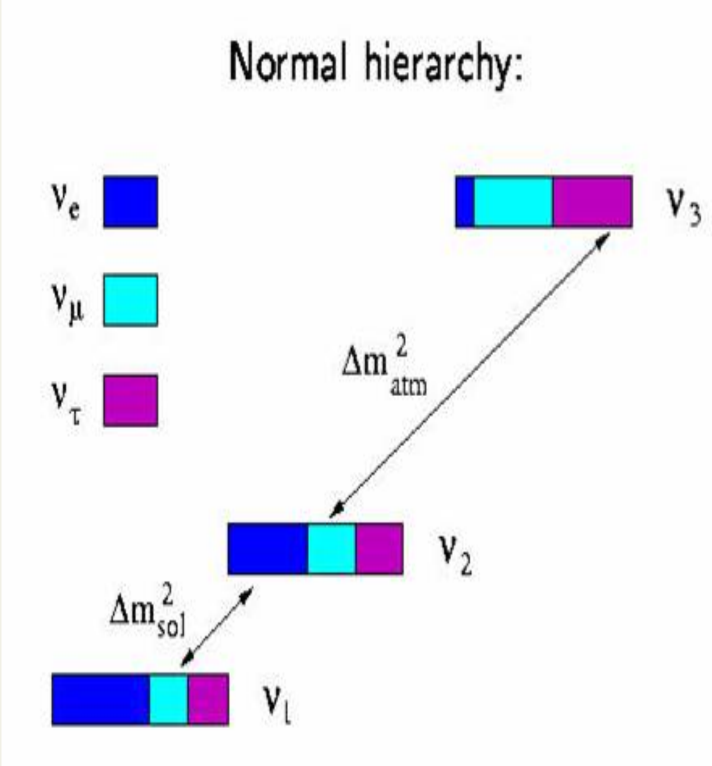
Beyond the SM:
Lepton Number Violation !

Normal Hierarchy

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$$

see S. Pascoli's talk

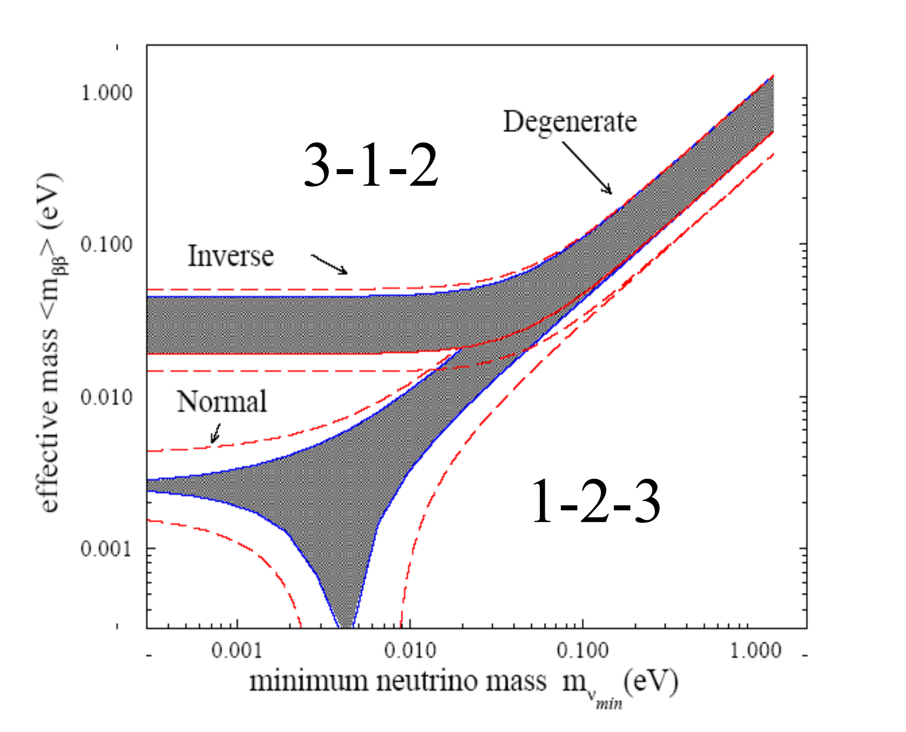


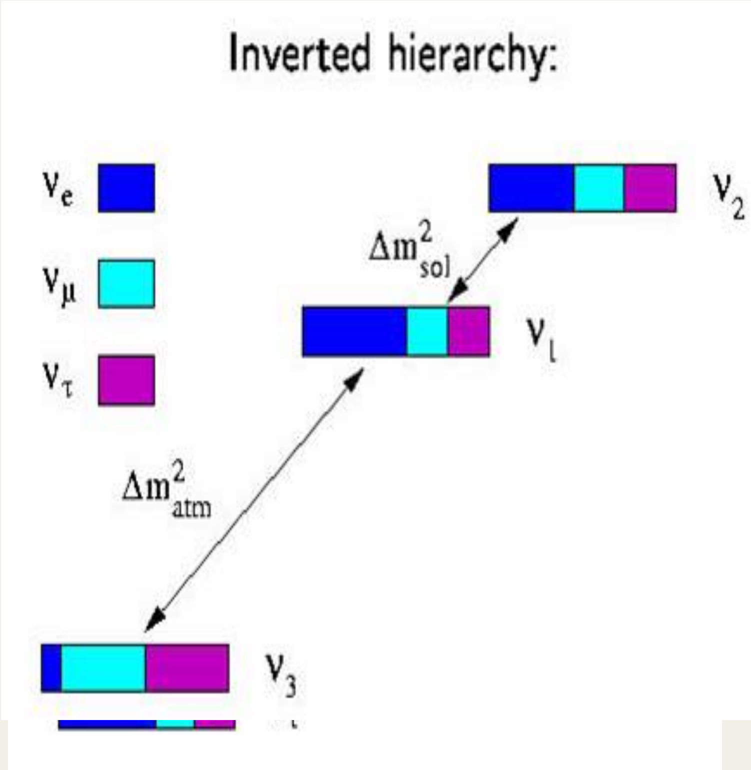


from oscillation fits

Inverted Hierarchy

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$$





from oscillation fits

PMNS Matrix

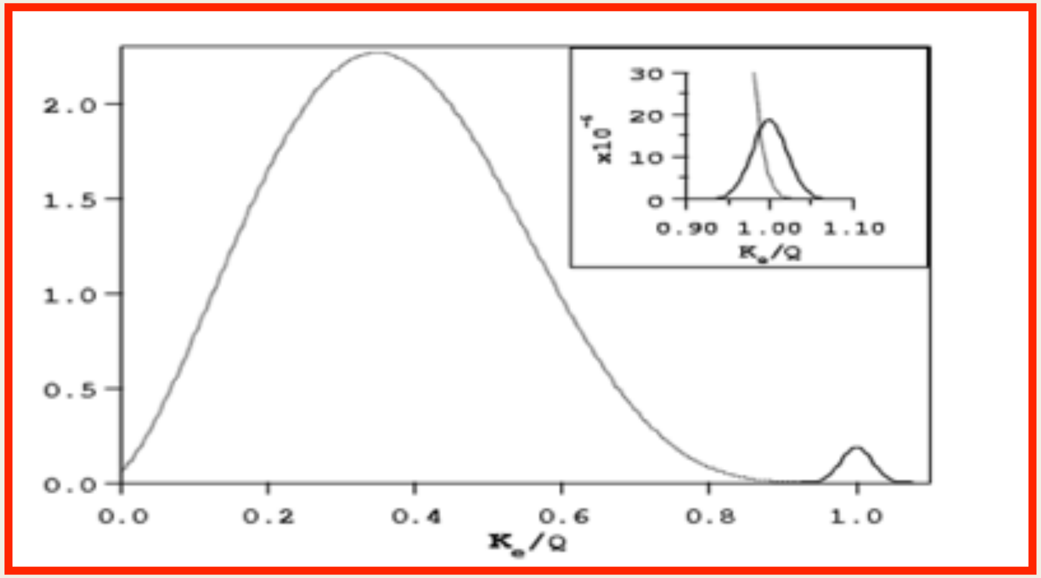
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana Phases

Double Beta Decay

Energy sum of two electron



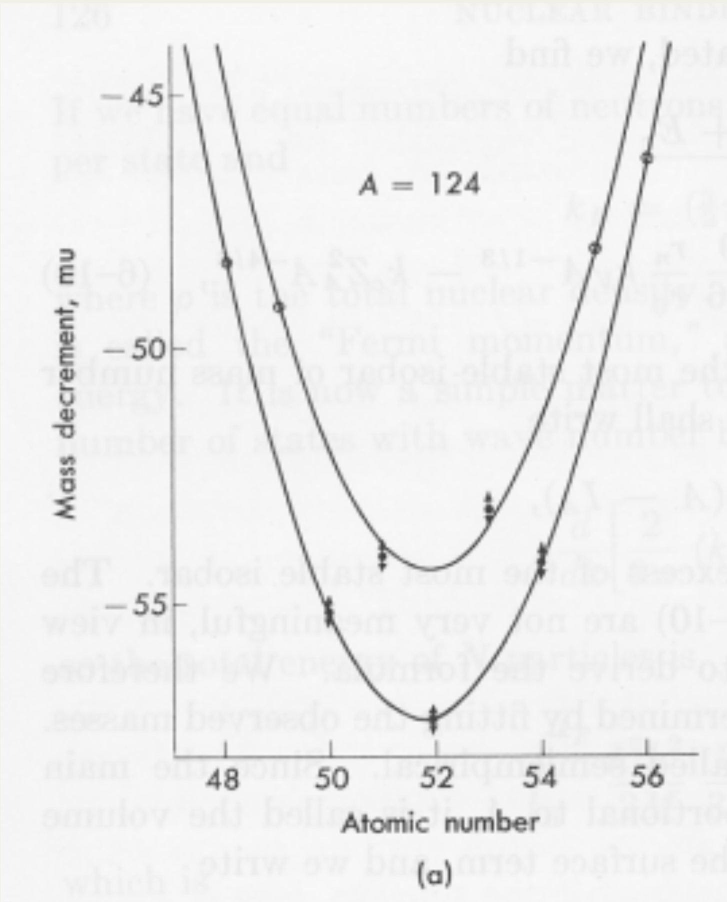
In many even-even nuclei, 'single' β decay is highly suppressed, leaving only ββ decay.

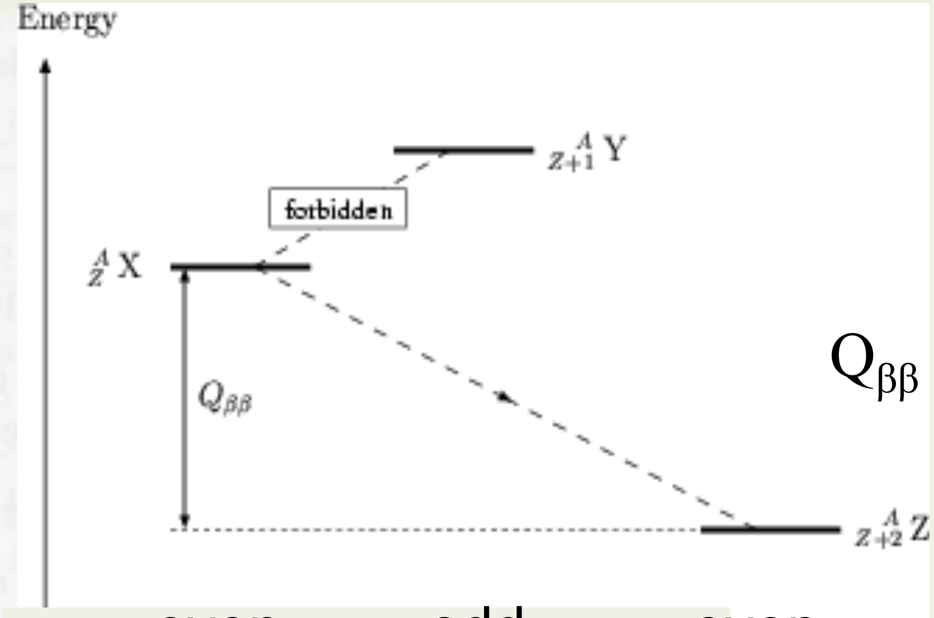
Only about ten isotopes can be used to search for double beta decay.

Many of them measured by NEMO.

Some nuclear physics

48-Ca, 76-Ge, 82-Se, 96-Zr, 100-Mo, 116-Cd, 128-Te, 130-Te, 150-Nd, and 238-U.

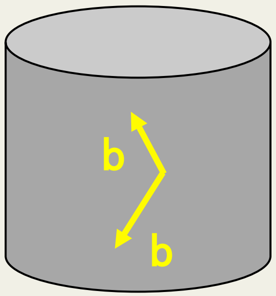




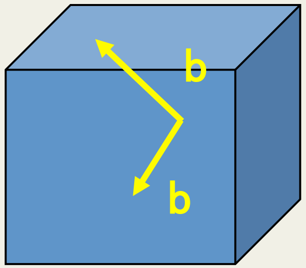
even even | odd-odd | even-even

Experimental Techniques

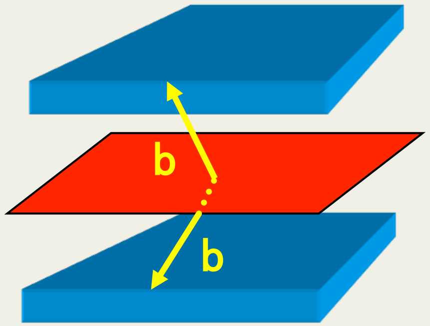
Calorimeter
Semi-conductors
Source = detector



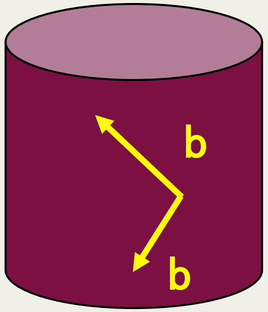
Calorimeter
Loaded Scintillator
Source = detector



Tracking + Calorimeter
Source ≠ detector



Xe TPC
Source = detector



NEMO Approach

NEMO Approach

Calorimetry plus tracking (source ≠ detector)

Detection of both electrons: reject unknown nuclear γ line

Three kinematic observables: study underlying physics mechanism

(i) individual electron energies
(ii) angular correlation
(iii) energy sum

Sources separated from the detector: measure $T_{1/2}$ for several isotopes

Background rejection through particle identification: e^-, e^+, γ, α particles

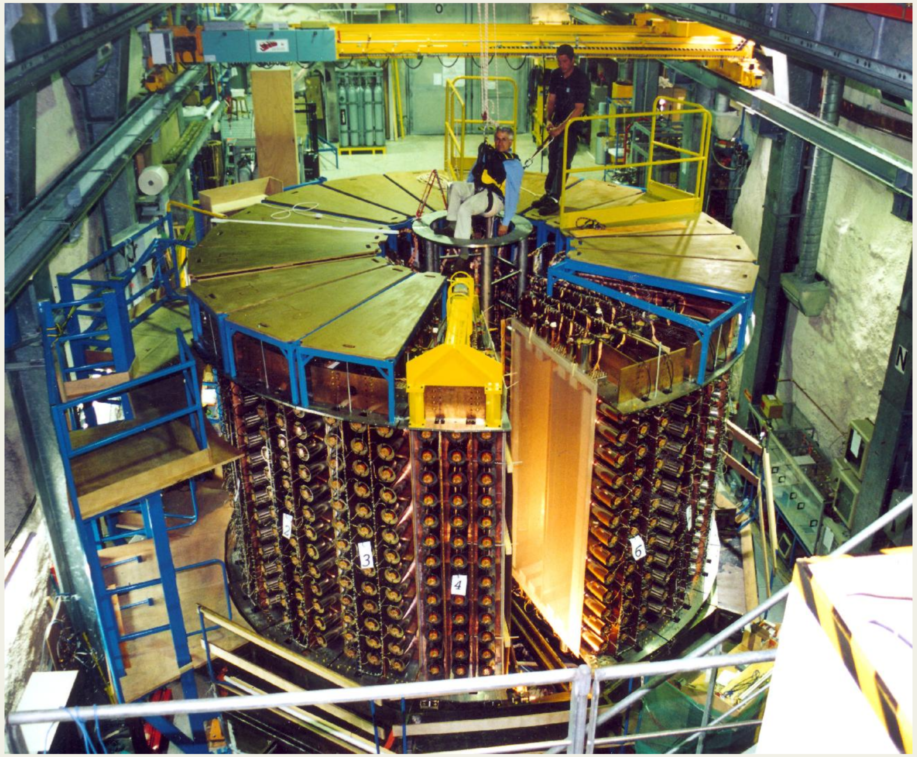
unique and complementary to source = detector experiments

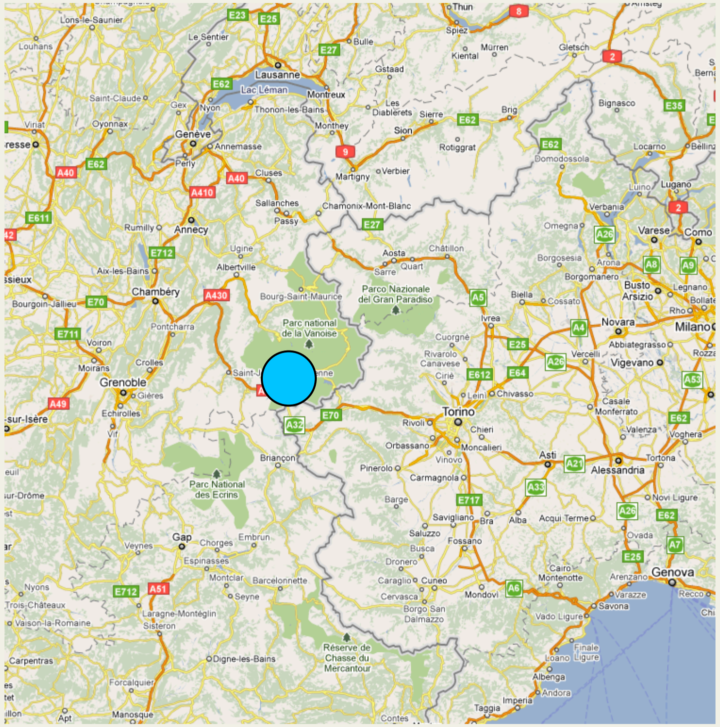
NEMO-3

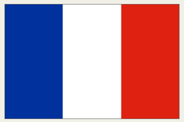
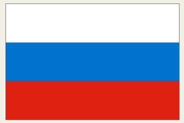
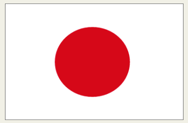
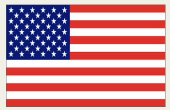
Neutrino Ettore Majorana Observatory

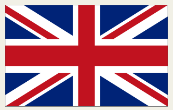
2003-2010

Modane – Frejus tunnel
at 1800 m (4800 m.w.e)

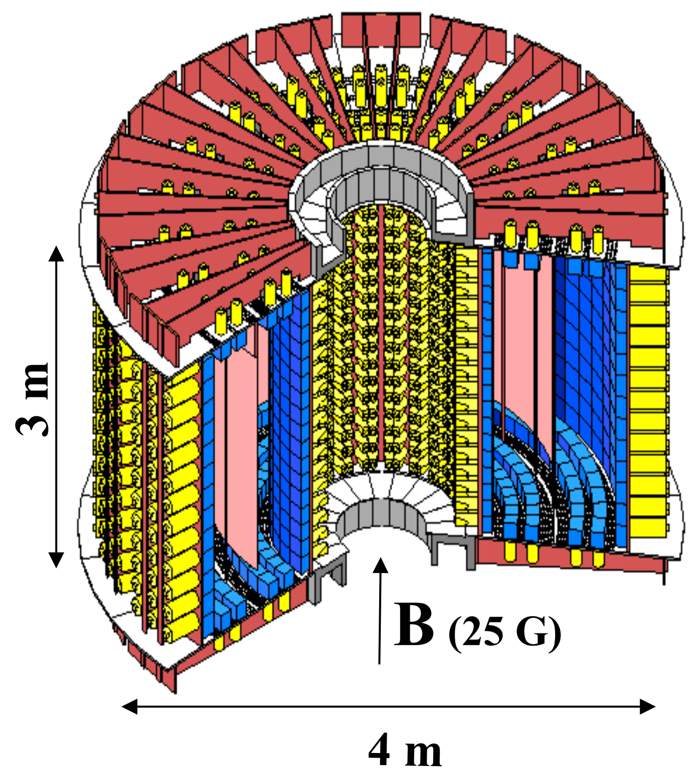






NEMO-3

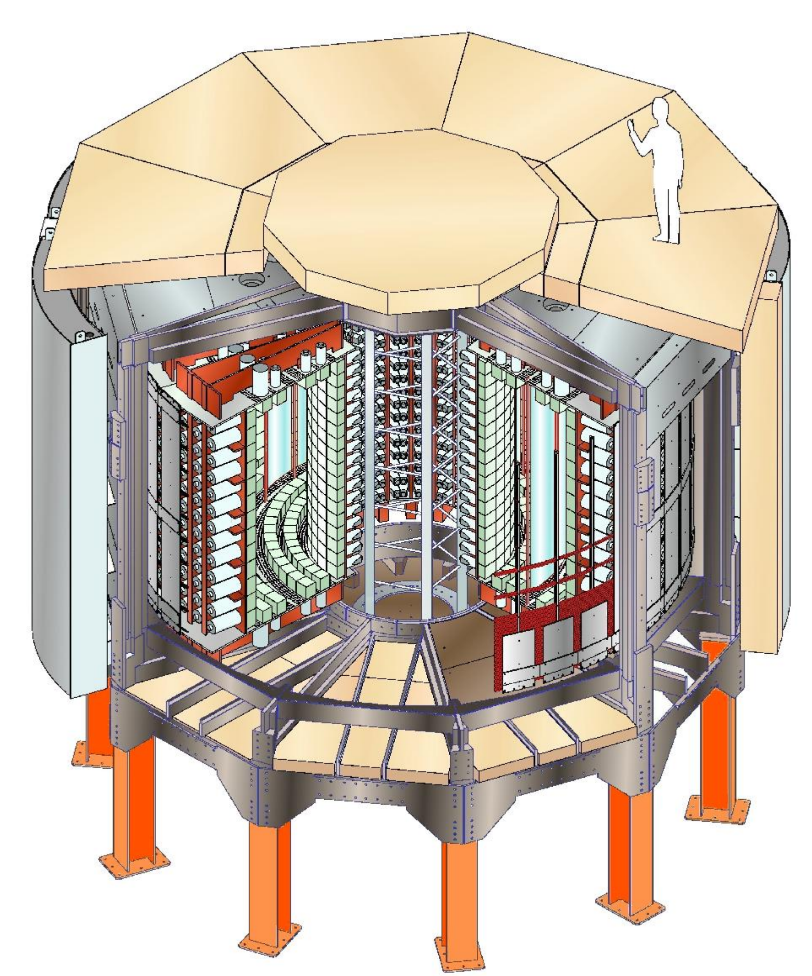


Source: ~10 kg of ββ isotopes
cylindrical, surface = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
$\sigma_\perp$ = 5 mm, σ_z = 1 cm (vertex)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs
time of flight σ = 250 ps

NEMO-3



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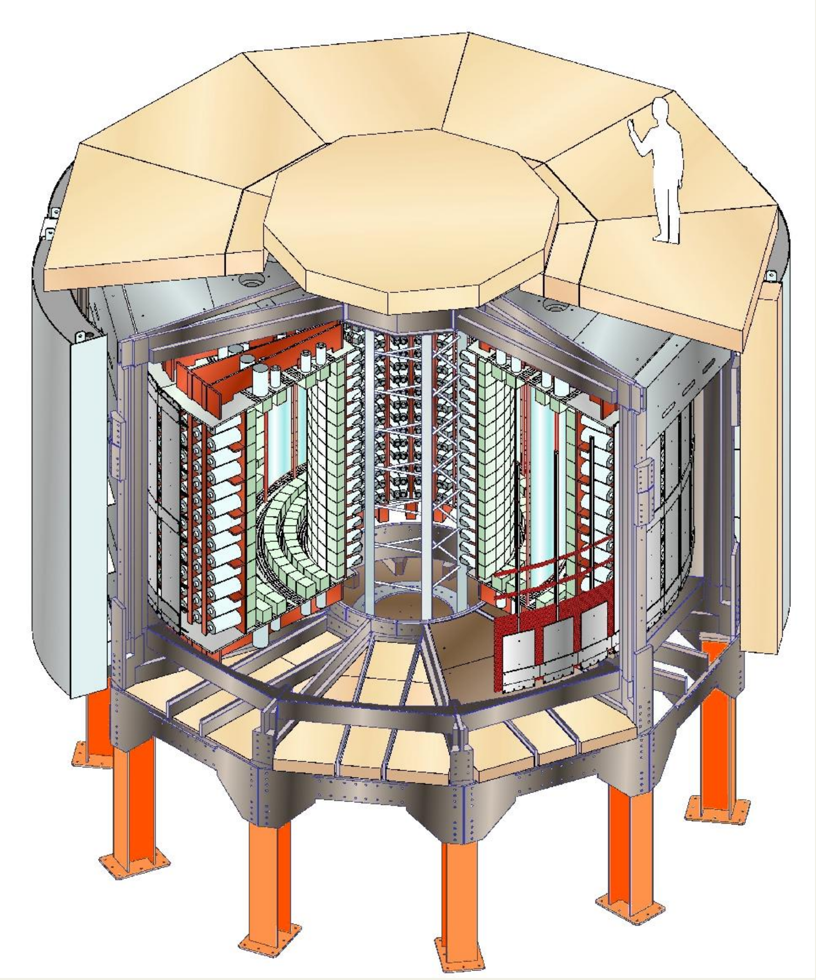
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs
time of flight $\sigma = 250$ ps

Magnetic field: 25 Gauss
Gamma shield: pure iron (18 cm)
Neutron shield: borated water, wood

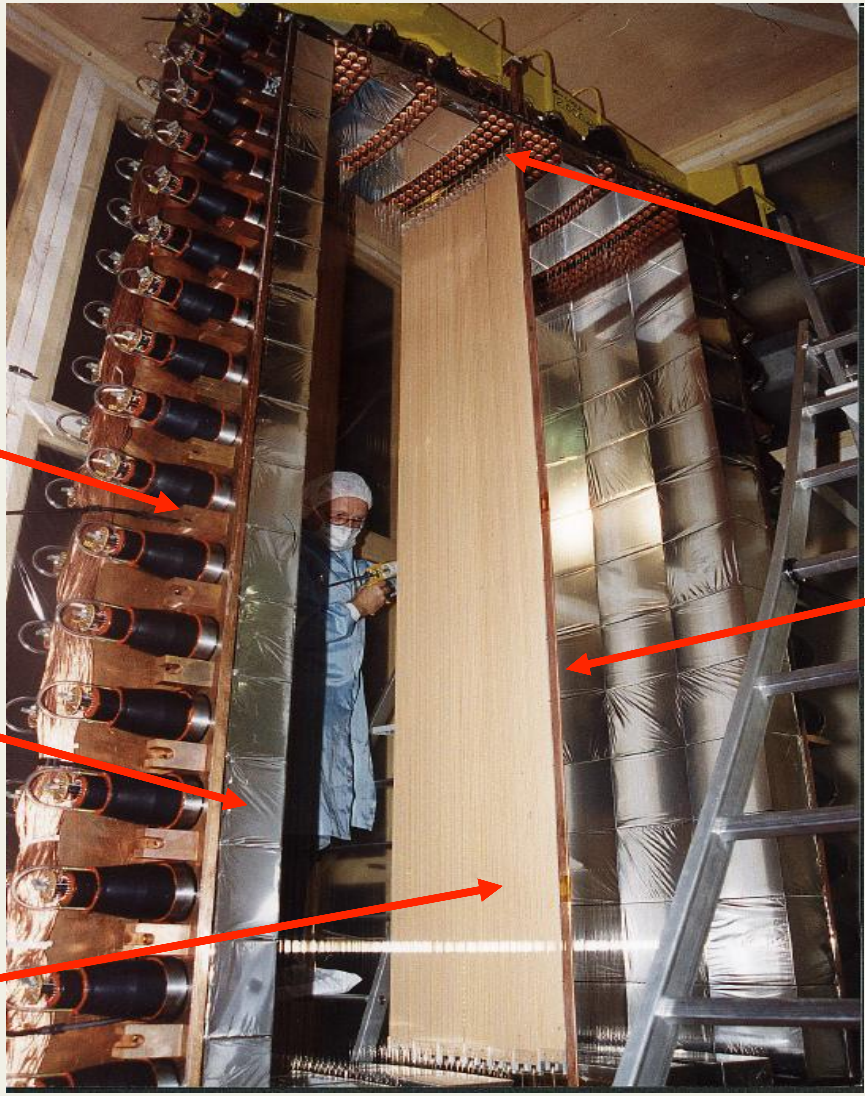
NEMO-3



Backgrounds:

- **natural radioactivity, mainly ^{214}Bi and ^{208}Tl**
- **radon**
- **neutrons (n,γ)**
- **muons**
- **ββ2ν**

One Sector: interior view



PMTs

scintillators

ββ isotope foils

cathode rings
wire chamber

Calibration tube

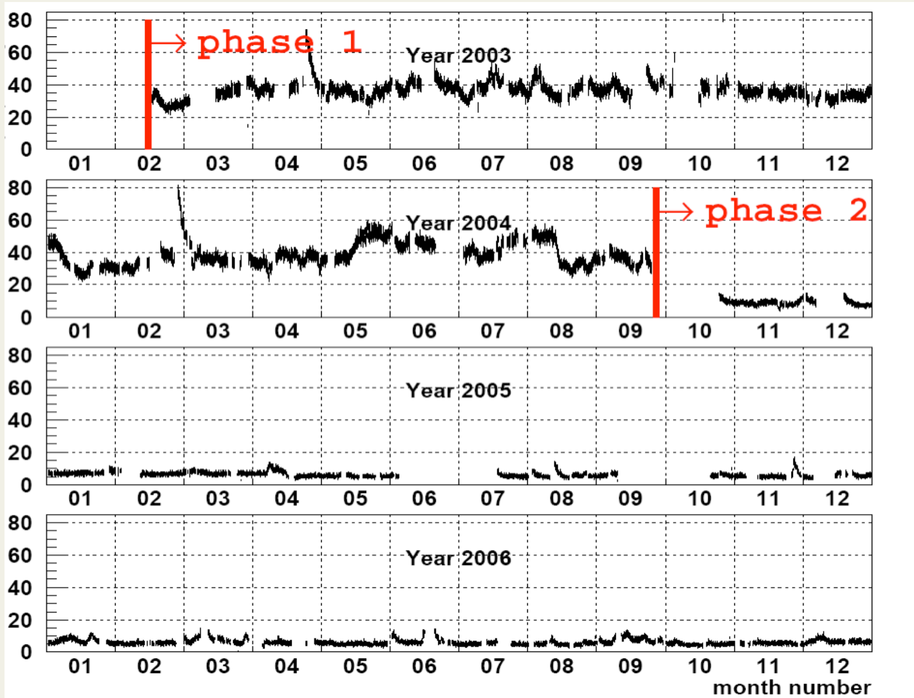
Finished Detector

The trapping time in activated charcoal is longer than ^{222}Rn half-life of 3.8 days.

Adsorption unit @-50°C

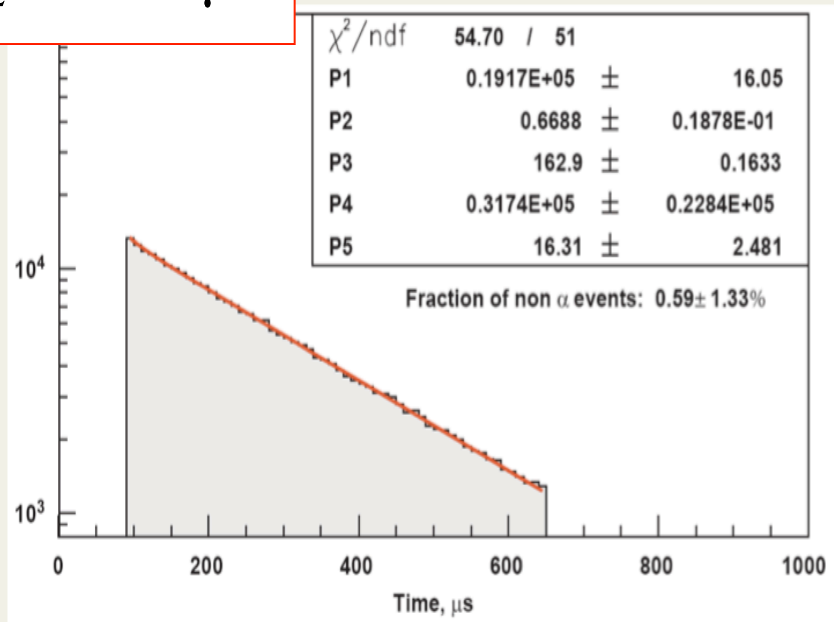
Radon-free air around the detector
- Phase I (Feb 2003 – Oct 2004): High Radon
- Phase II (Dec 2004 - 2010): Low Radon
  (Radon cont. reduced by factor 6)

Radon



Radon is deposited on foils and wires

$T_{1/2}$=162.9 μs

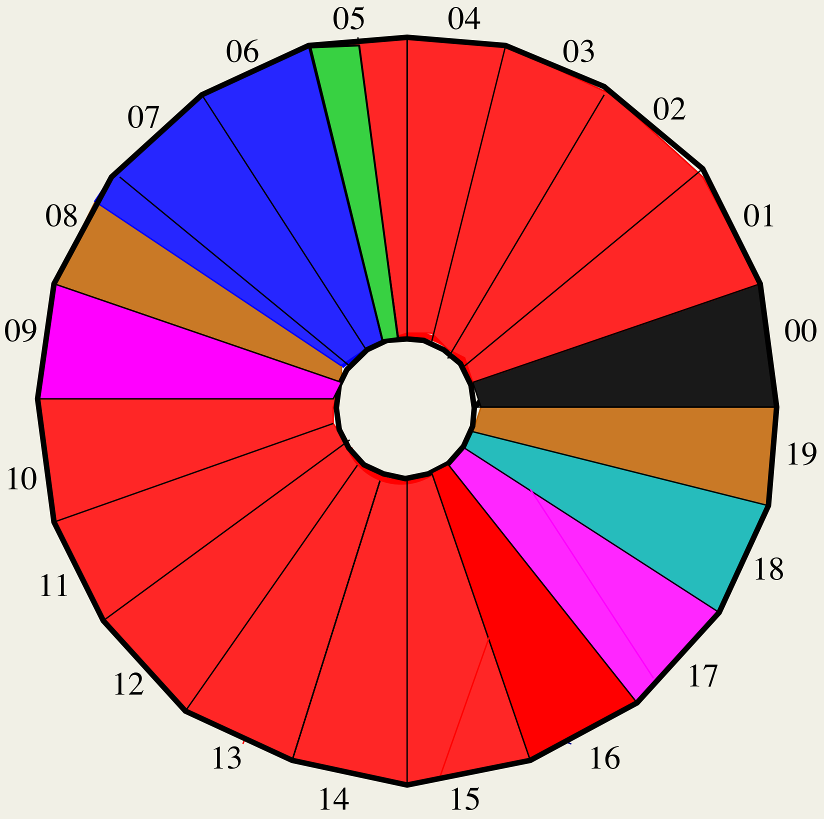


Delay time of α track (μs)

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

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

NEMO Isotopes



ββ2ν measurement

- ^{116}**Cd 405 g** — Q = 2805 keV
- ^{96}**Zr 9.4 g** — Q = 3350 keV
- ^{150}**Nd 37.0 g** — Q = 3367 keV
- ^{48}**Ca 7.0 g** — Q = 4272 keV
- ^{130}**Te 454 g** — Q = 2529 keV
- ^{nat}**Te 491 g**
- **Cu 621 g**

External bkg measurement

- ^{100}**Mo 6.914 kg** — Q = 3034 keV
- ^{82}**Se 0.932 kg** — Q = 2995 keV

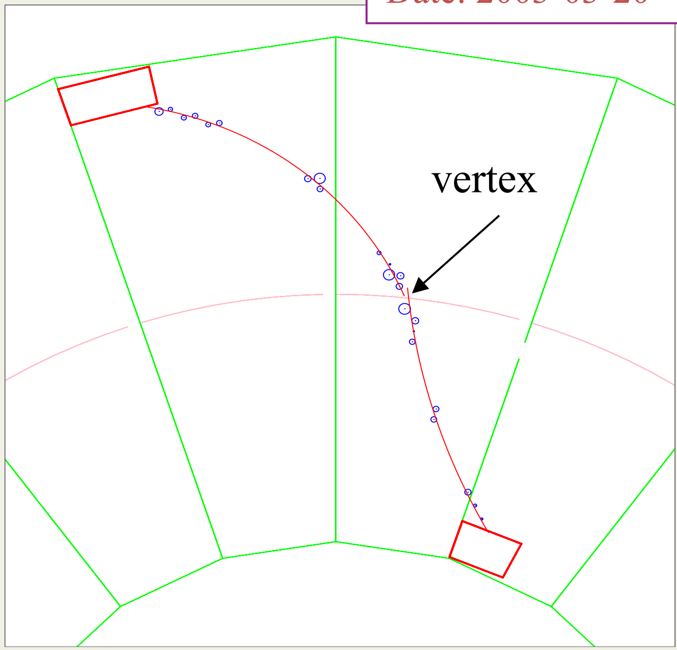
ββ0ν search

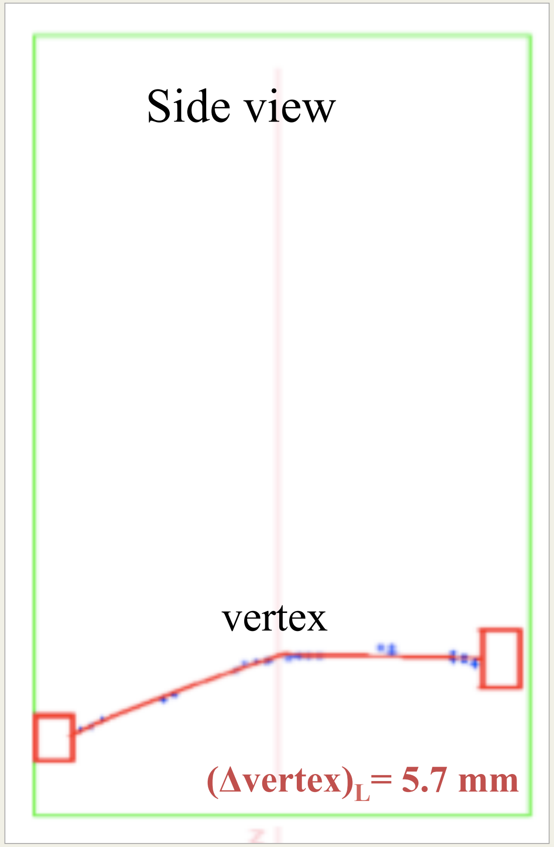
(All enriched isotopes produced in Russia)

ββ Event Display

Top view

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



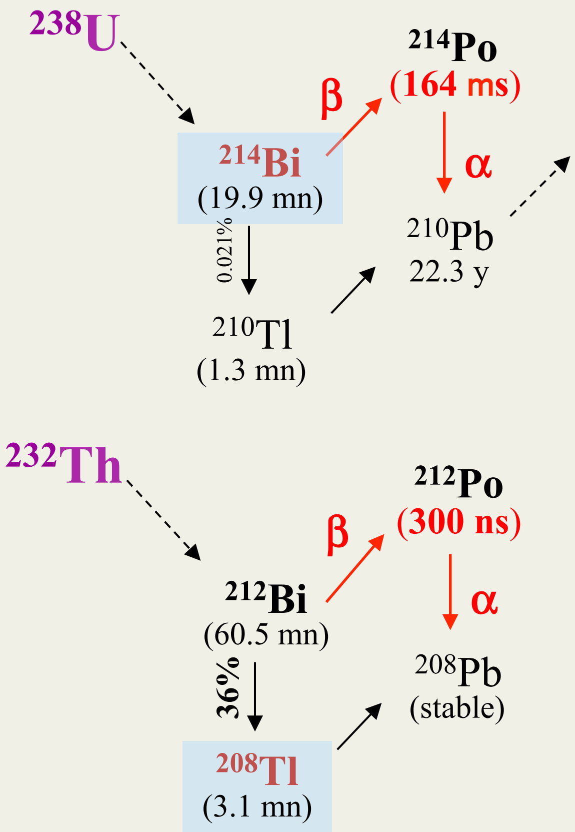


Deposited energy:
$E_1+E_2 = 2088$ keV
Internal hypothesis:
$(\Delta t)_{mes} - (\Delta t)_{theo} = 0.22$ ns
Common vertex:
$(\Delta vertex)_T = 2.1$ mm

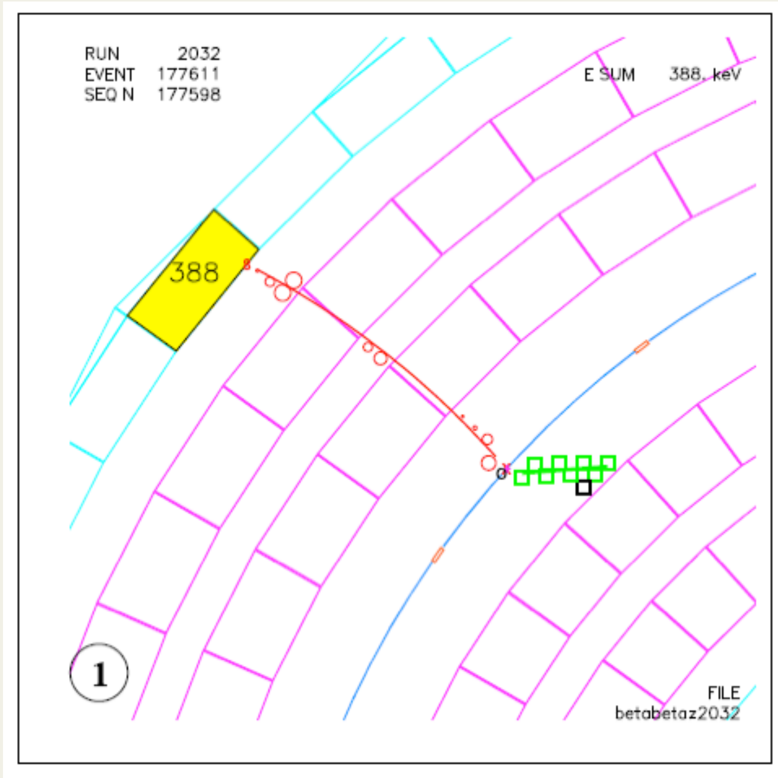
Trigger: **at least 1 PMT > 150 keV and 3 Geiger hits (2 neighbouring layers+1)**
Trigger rate = 7 Hz
≈ 30 ββ events per hour

Background

Bi-Po Process



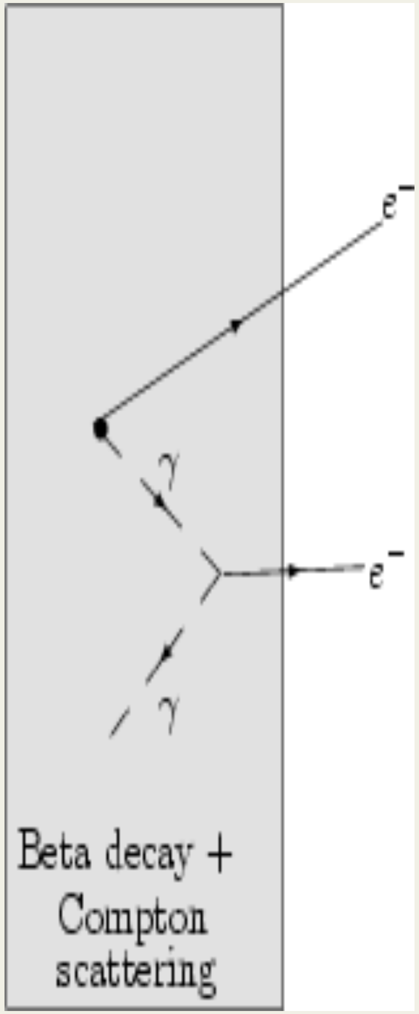
eα event



NEMO measures each component of its background (internal/external) using event topology and timing

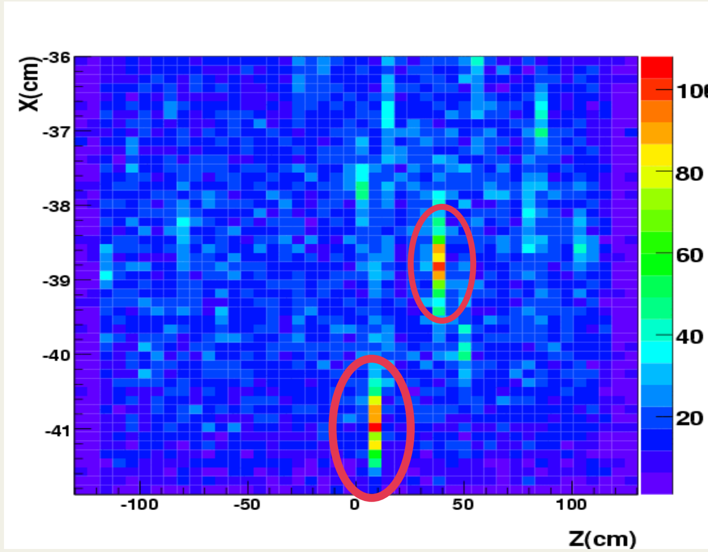
Control Channels

internal (foil) background

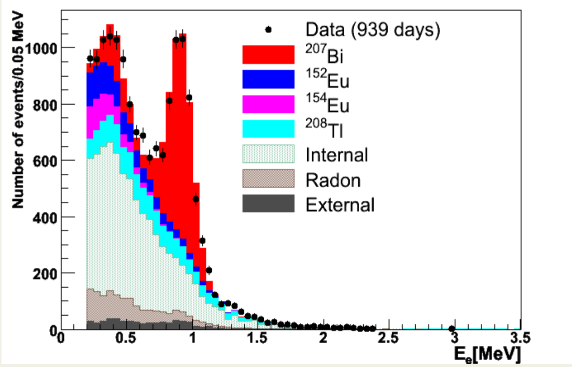


Example:
eγ control channel

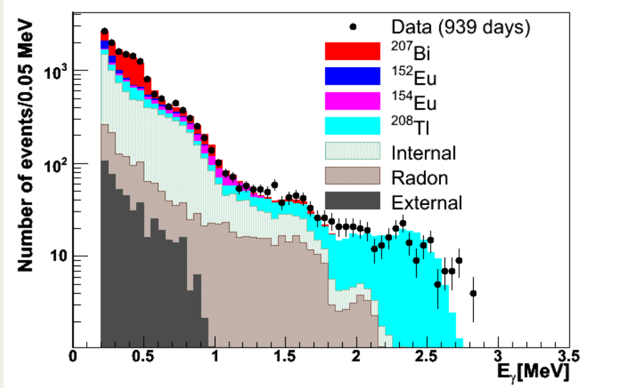
^{150}Nd foil



Energy of the electron



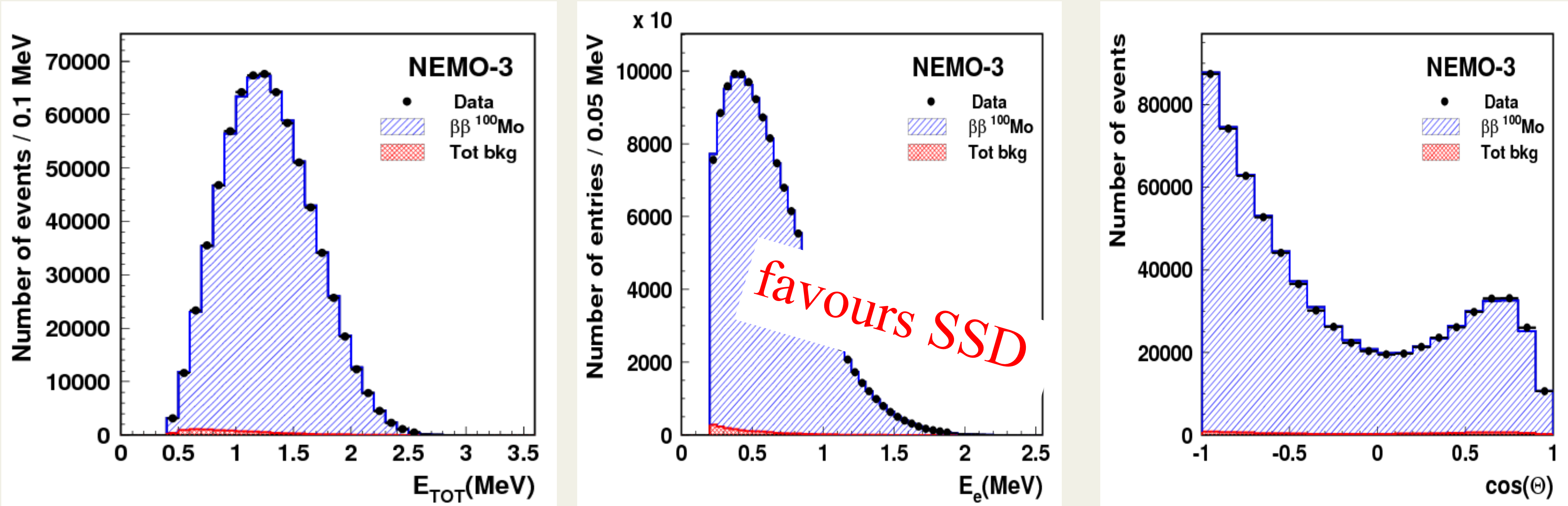
Energy of the photon



100-Mo ββ Results

"ββ machine"

Phase II data:

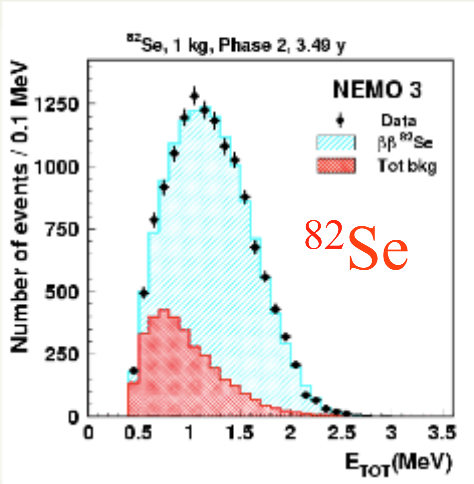


700,000 two-electron events with S/B=76

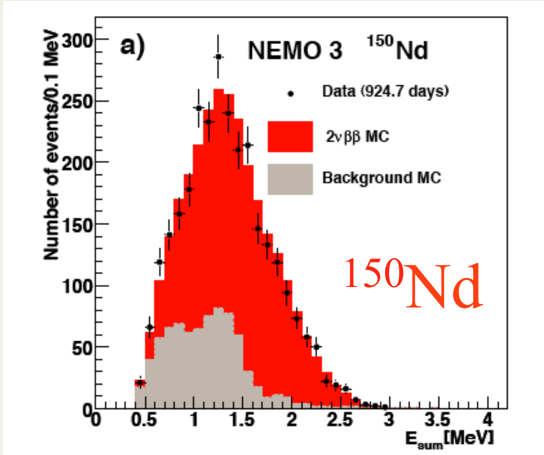
Half-life consistent with published value in PRL 95 (182302) 2005:

$T_{1/2}(\beta\beta 2\nu)$ = [7.11 ± 0.02(stat) ± 0.54(sys)] × 10^{18} yr, ≈ 1 yr, Phase I, S/B = 40

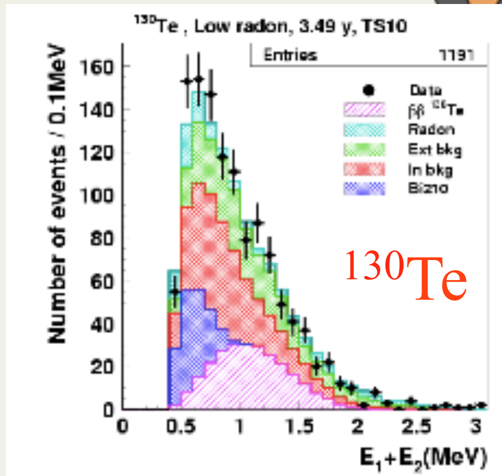
Other Isotopes



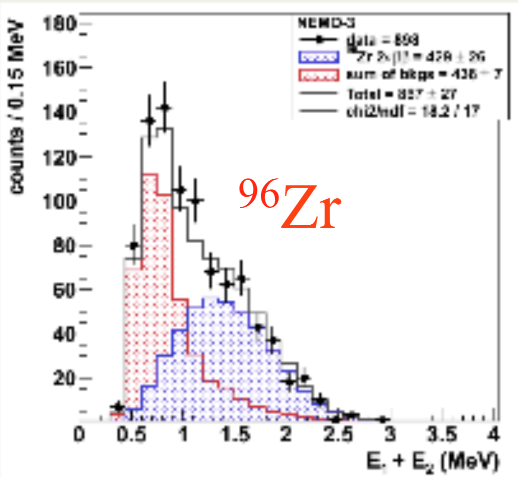
[9.6±0.1(stat)±1.0(sys)]×10^{19} yr



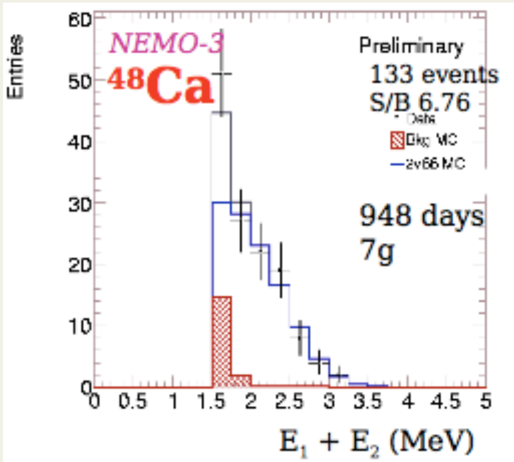
[9.11±0.24(stat)±0.63(sys)]×10^{18} yr



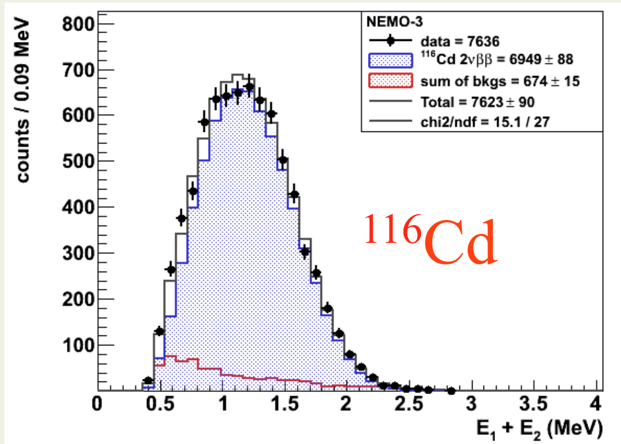
[7.0$^{+1.0}_{-0.8}$(stat) $^{+1.1}_{-0.9}$(sys)]×10^{20} yr



[2.35±0.14(stat)±0.16(sys)]×10^{19} yr



[4.4$^{+0.5}_{-0.4}$(stat)±0.4(sys)]×10^{19} yr



[2.88±0.04(stat)±0.16(sys)]×10^{19} yr

The University of Manchester

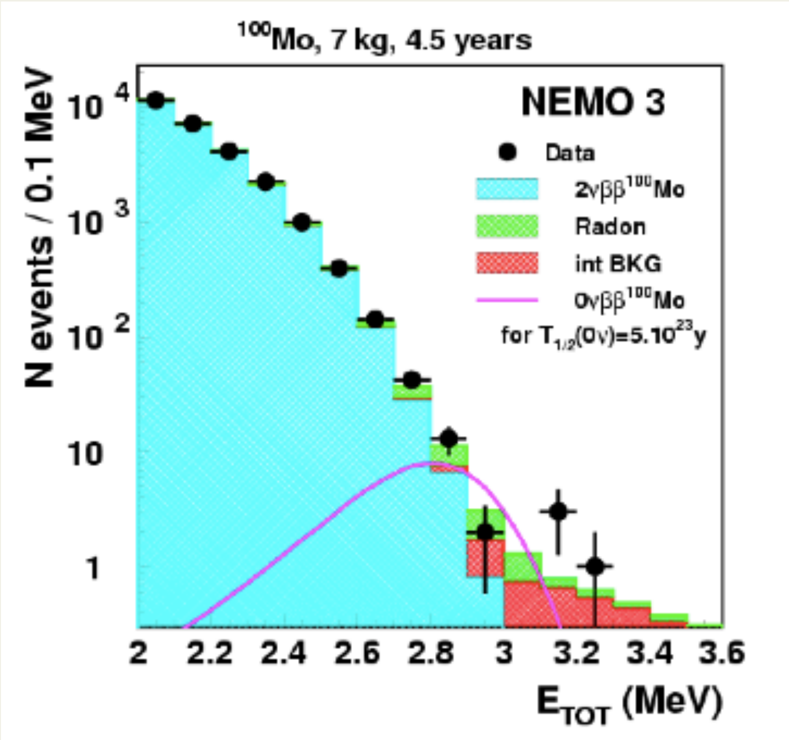
NEMO results on $\beta\beta 2\nu$

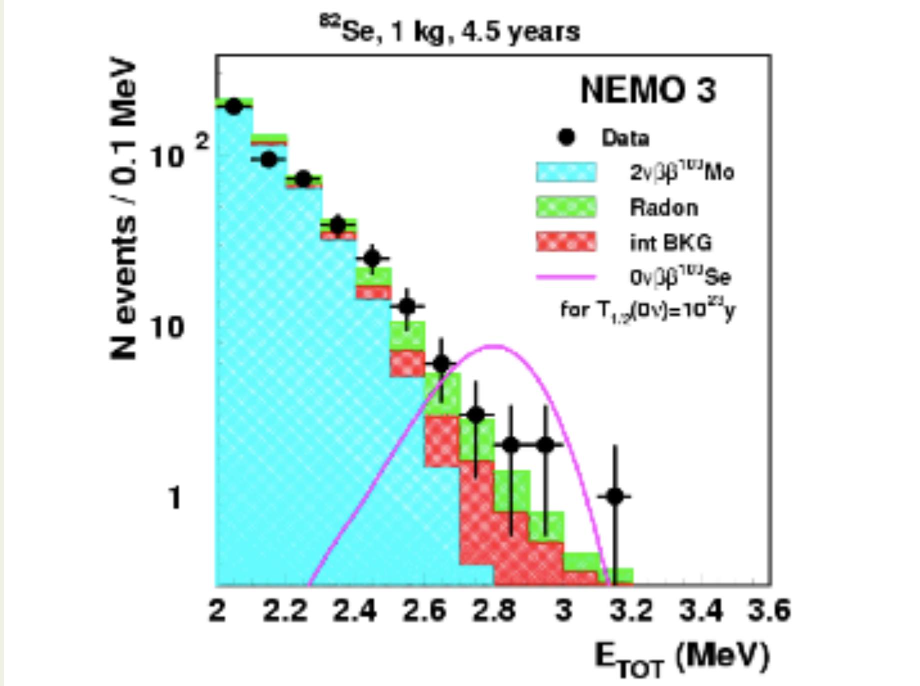
Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)		Reference
^{82}Se	932	2996	9.6 ± 1.0	World's best	PRL 95, 483 (2005)
^{116}Cd	405	2809	2.8 ± 0.3	World's best	
^{150}Nd	37	3367	0.91 ± 0.07	World's best	PRC 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	World's best	NPA 847, 168 (2010)
^{48}Ca	7	4271	4.4 ± 0.6	World's best	
^{100}Mo	6914	3034	0.71 ± 0.05	World's best	PRL 95, 483 (2005)
^{130}Te	454	2533	70 ± 14	First direct detection	PRL 107, 062504 (2011)

(^{130}Te interesting because there have been different lifetimes from geochemical experiments)

Limits on ββ0ν

Phase I + II



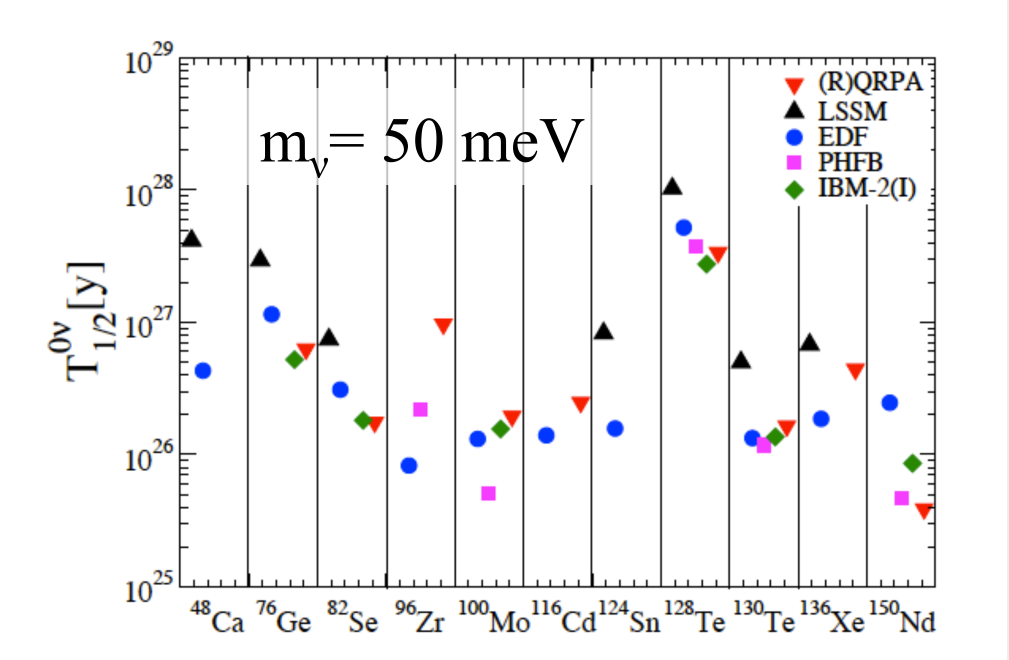


$T_{1/2}(0\nu) > 1.0\times10^{24}$ yrs at 90% CL
$m_{\beta\beta} < (0.31 - 0.96)$ eV [1-5]

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yrs at 90% CL
$m_{\beta\beta} < (0.94 – 1.71)$ eV [1-5]
$m_{\beta\beta} < 2.6$ eV [6]

[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)04430
[5] PHFB P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
[6] SM E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

Nuclear Matrix Elements



$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

Nuclear Matrix Elements main source of uncertainty in extracting neutrino mass.

J. Vergados et al., arXiv:1205.0649

Phase space factors

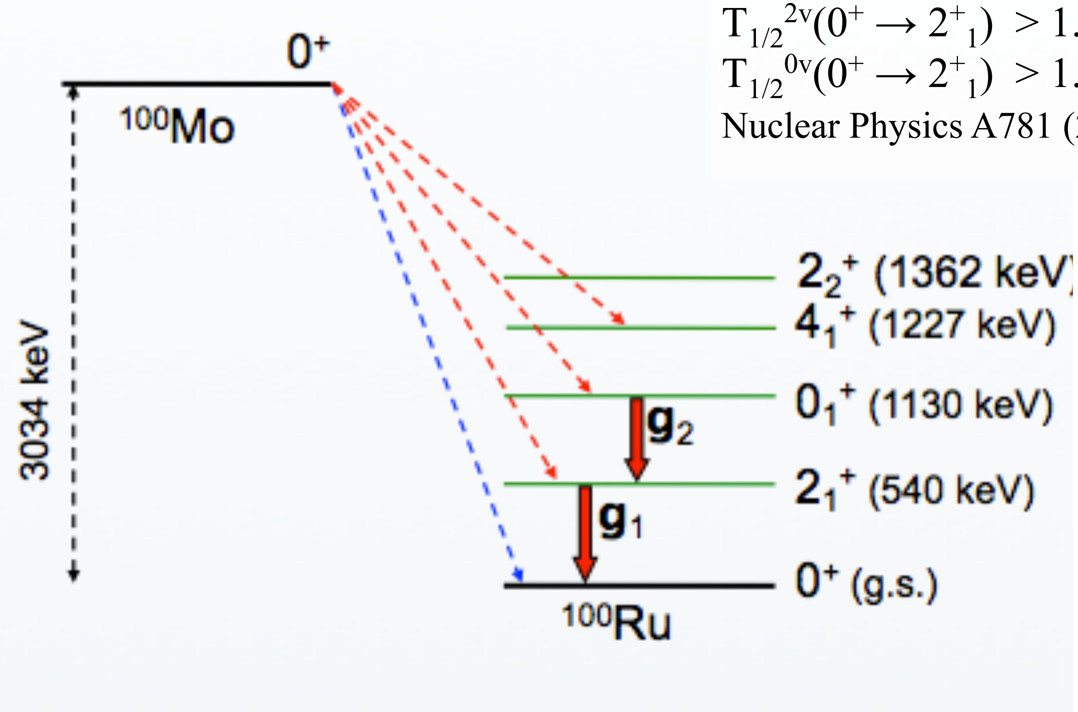
J. Phys. G: Nucl. Part. Phys. 34 667 (2007)

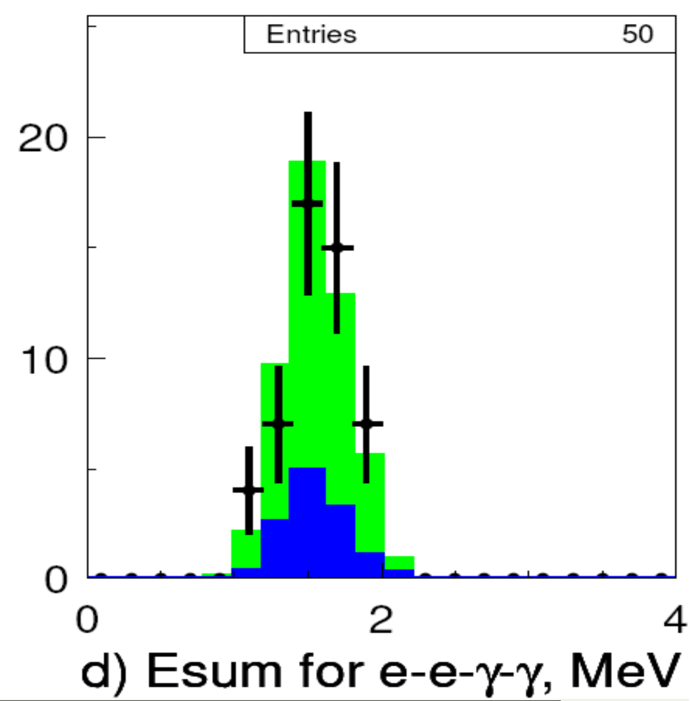
Isotope $Q_{\beta\beta}$ (MeV)	^{48}Ca 4.27	^{76}Ge 2.04	^{82}Se 3.0	^{96}Zr 3.35	^{100}Mo 3.03	^{116}Cd 2.8	^{130}Te 2.53	^{136}Xe 2.48	^{150}Nd 3.37
$G^{0\nu}$ (10^{-15} yr^{-1})	75.8	7.6	33.5	69.7	54.5	58.9	52.8	56.3	249

Excited States

Decays to excited states with several photons in final state

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}\,(\text{stat}) \pm 0.8\,(\text{syst}) \times 10^{20}$ y
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @90% C.L.
$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.
Nuclear Physics A781 (2006) 209-226.



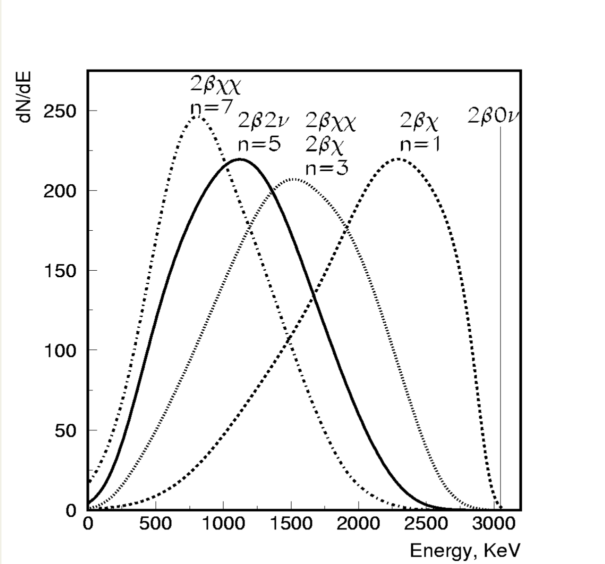


First direct observation

Other Searches

Majoron emission distorts
energy sum spectrum

Right handed currents changes
angular distributions



n: spectral index

	V+A*	n=1**	n=2**	n=3**	n=7**
Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $G_{ee}<(0.4-1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>2.4\cdot10^{23}$ $\lambda<2.0\cdot10^{-6}$	$>1.5\cdot10^{22}$ $G_{ee}<(0.7-1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5\cdot10^{20}$

** Phase I
* Phase I+II

From NEMO to SuperNEMO

$$T_{1/2}^{\beta\beta0\nu} > N_A \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{(N_{bg} \cdot \Delta E)}}$$

maximize M, ε, t

minimize product

NEMO-3		SuperNEMO
mainly ^{100}Mo, ^{82}Se	isotope	initially ^{82}Se
7 kg	isotope mass M	100-200 kg
8 %	efficiency ε	up to 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg Rn: 5mBq/m^3	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil Rn in the tracker	^{208}Tl ≤ 2 μBq/kg ^{214}Bi < 10 μBq/kg Rn ≤ 0.15 mBq/m^3
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

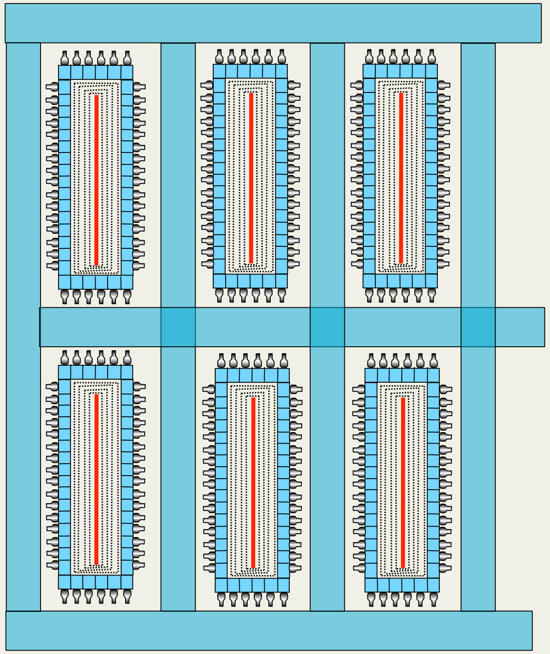
$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y
m_n < 300-800 meV

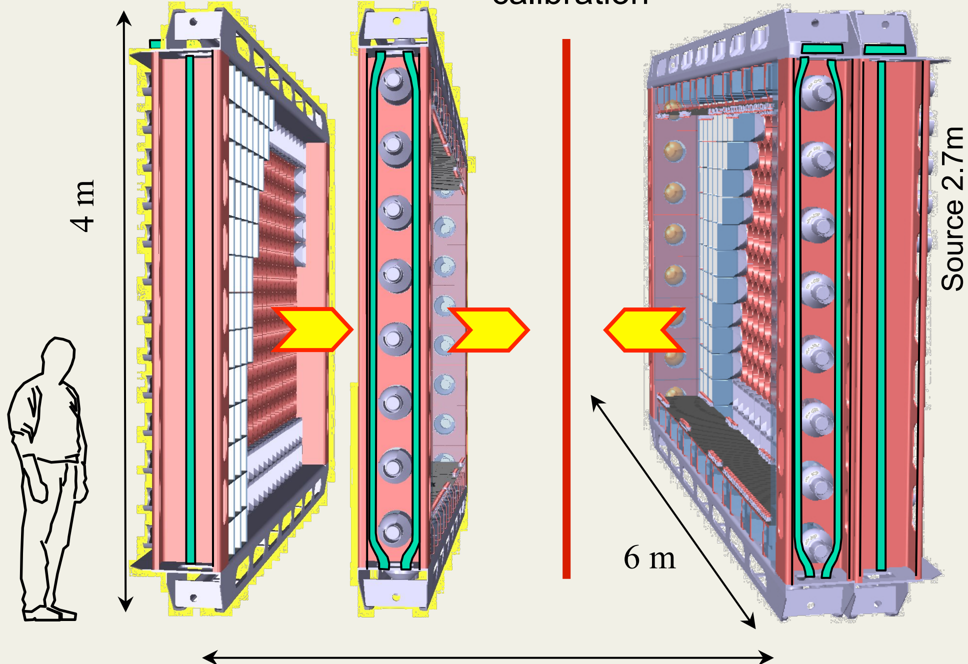
$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y
m_n < 40-100 meV

SuperNEMO

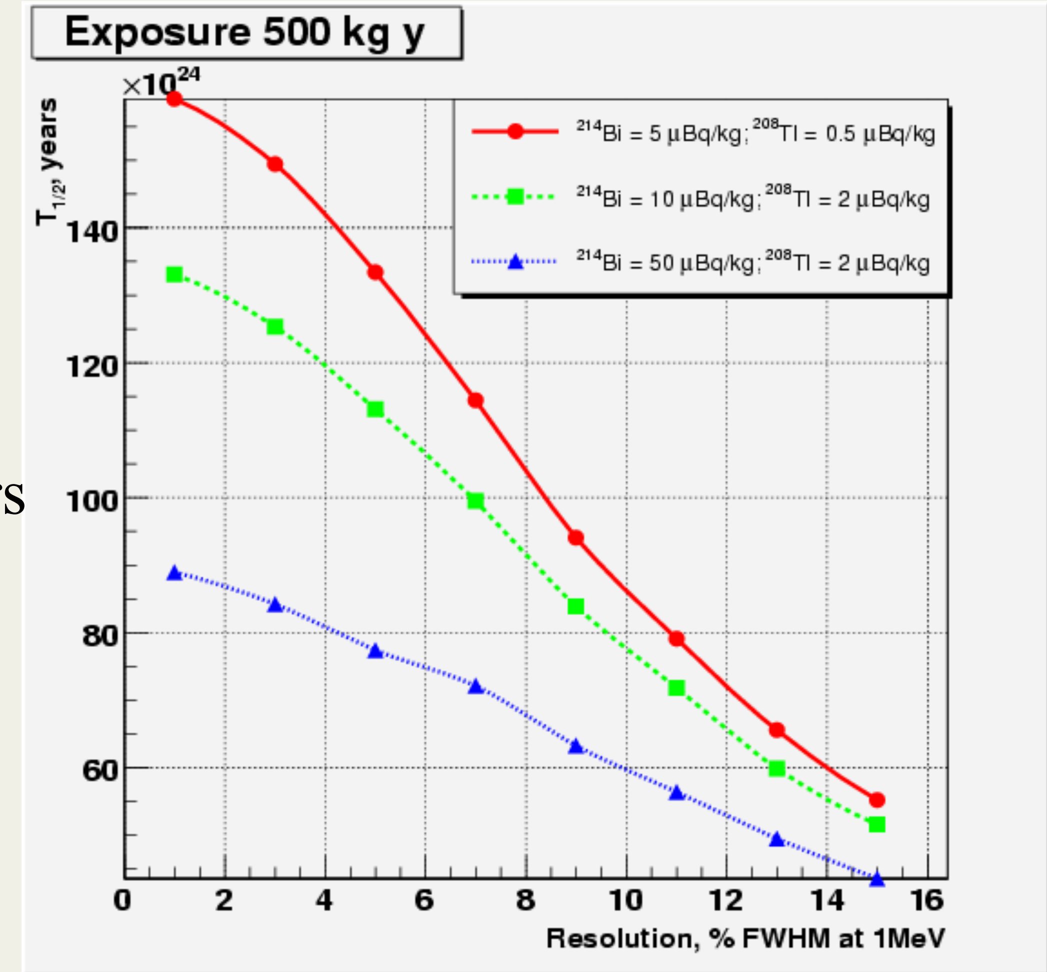
Planar and modular design:
~ 100 kg of enriched isotopes
(20 modules x 5 kg)

~100 collaborators





10^{26} years

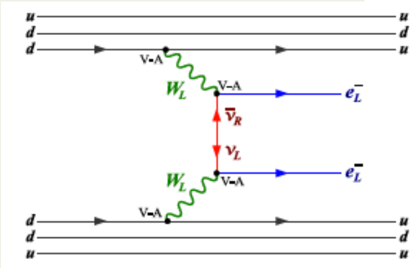


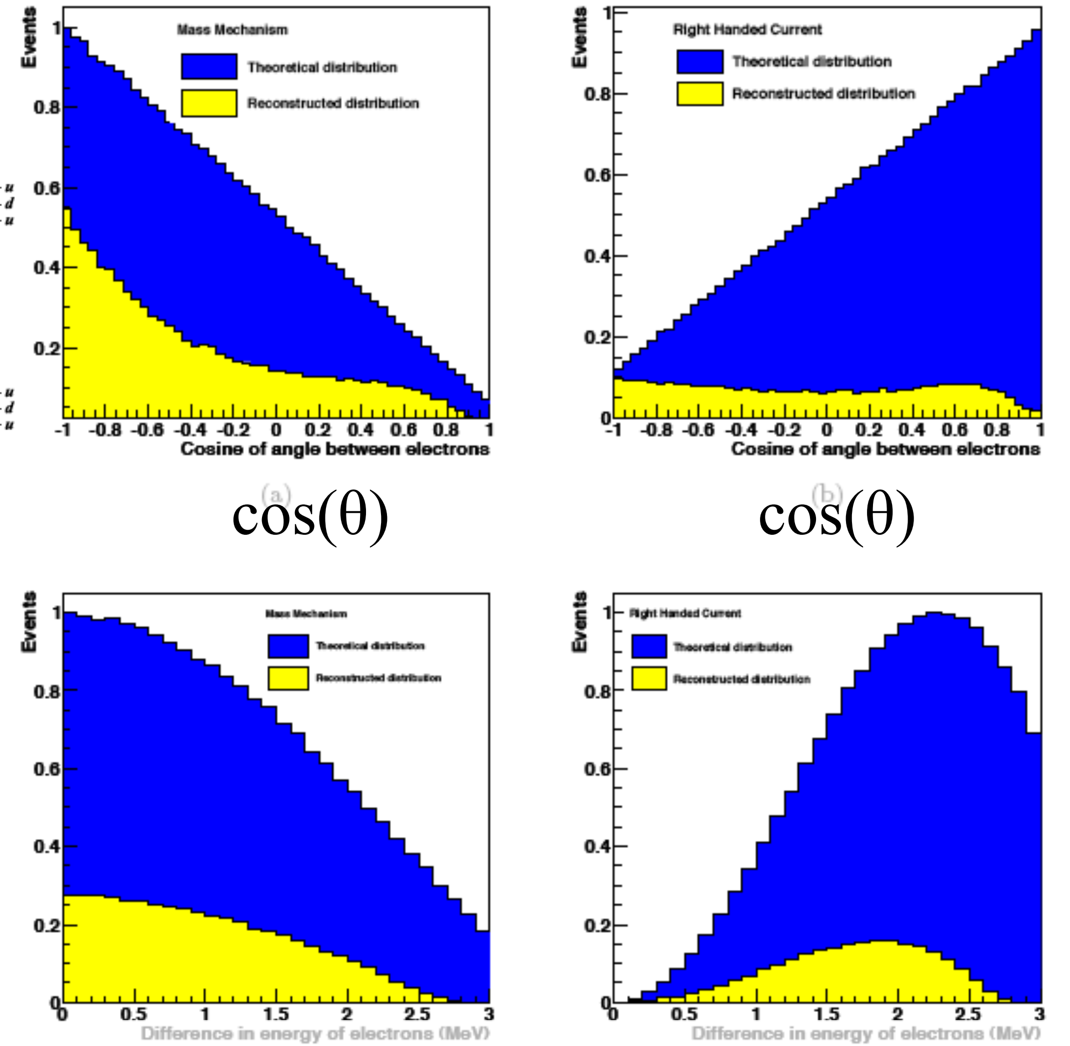
Exposure 500 kg y
×10^24
T1/2, years
140
120
100
80
60
0
2
4
6
8
10
12
14
16
Resolution, % FWHM at 1MeV
214Bi = 5 µBq/kg; 208Tl = 0.5 µBq/kg
214Bi = 10 µBq/kg; 208Tl = 2 µBq/kg
214Bi = 50 µBq/kg; 208Tl = 2 µBq/kg

Physics Studies: RHC

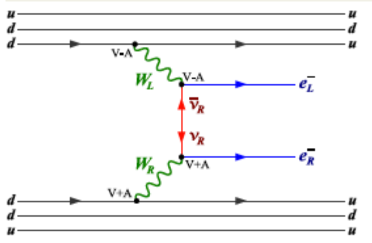
MM

RHC





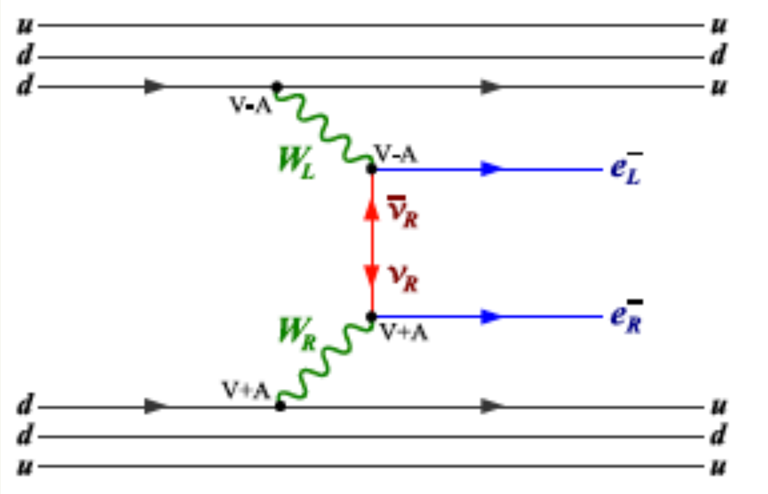
cos(θ) cos(θ)



Energy difference between electrons

Eur.Phys.J.C70, 927-943,2010

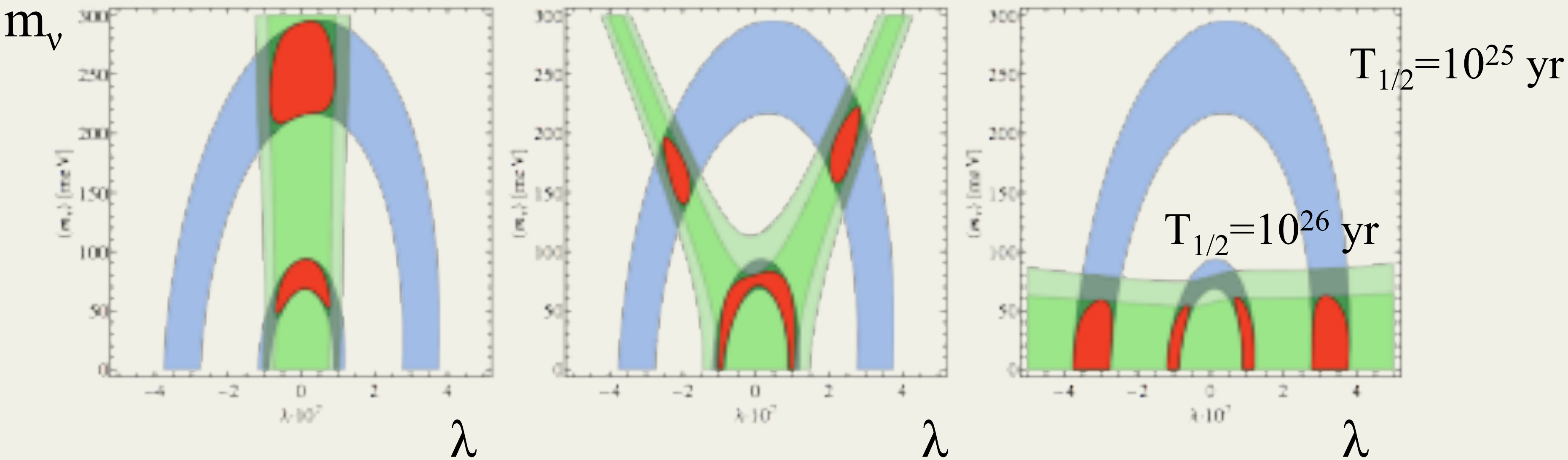
Physics Studies: RHC



Multi-parameter analysis exploiting reconstruction of kinematics in SuperNEMO

λ measures contribution from RHC

published in EPJC



Demonstrator

Demonstrate feasibility of large scale mass production

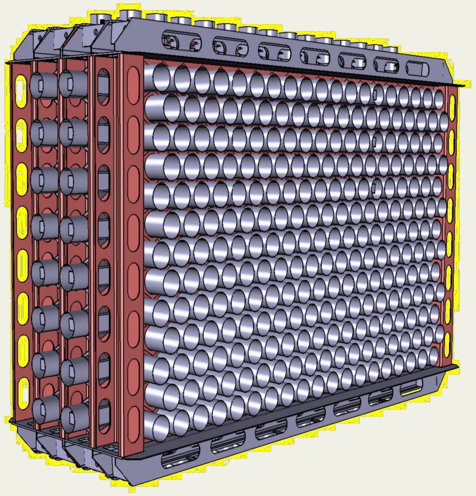
Zero background in search region.

Only possible with a realistic super-module

Finalise detector design

Produce a competitive physics measurement

Full production in process



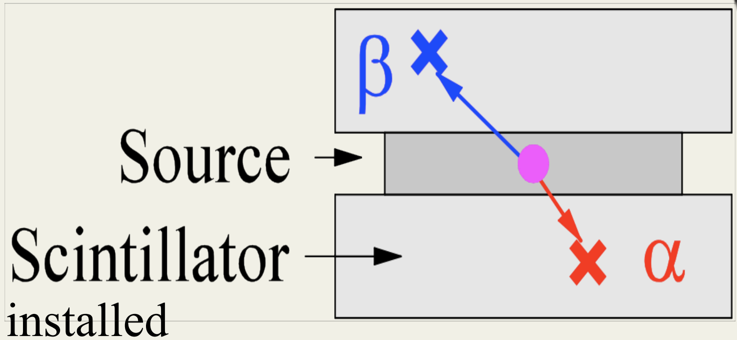
0.2 expected background events in energy window 2.8 - 3.2 MeV with 7 kg of ^{82}Se in 2-3 yrs

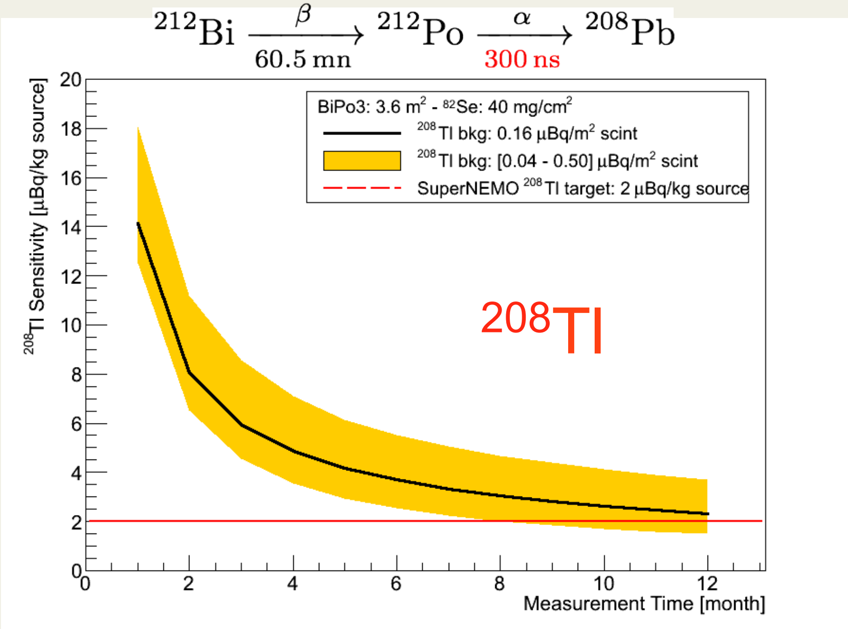
Sensitivity by 2017: $6.5 \cdot 10^{24}$ yr (90% CL)

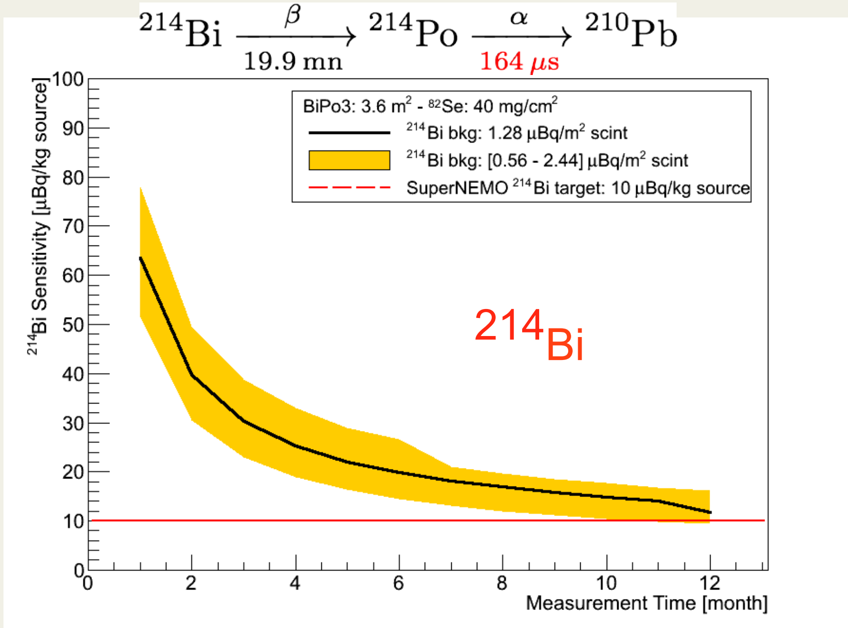
Equivalent to $3 \cdot 10^{25}$ yr for ^{76}Ge (using phase space ratio only)

^{82}Se source radiopurity

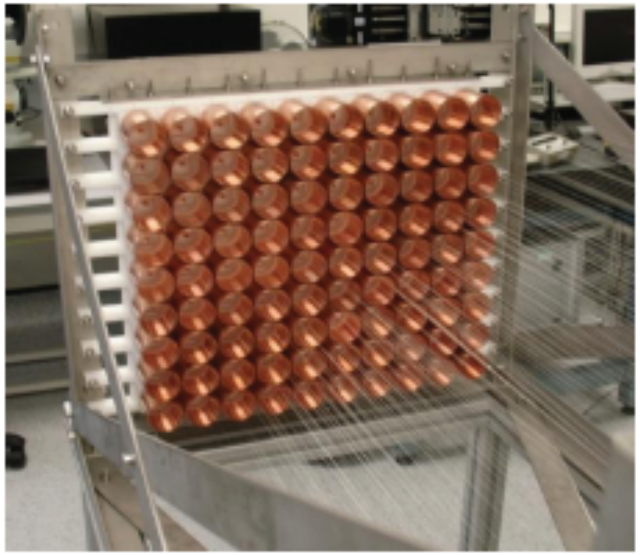
- Foils of 40-50 mg/cm^2
- Radiopurity
  - ^{208}Tl < 2 μBq/kg
  - ^{214}Bi < 10 μBq/kg
- Dedicated BiPo detector developed and installed in Canfranc (from July 2012)

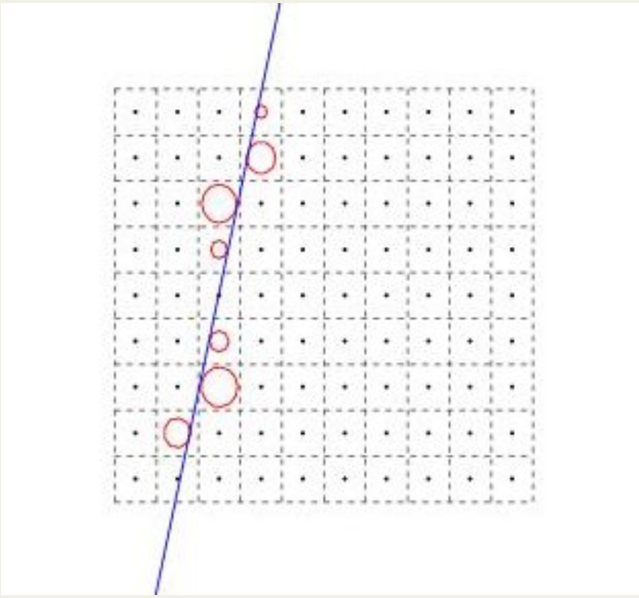






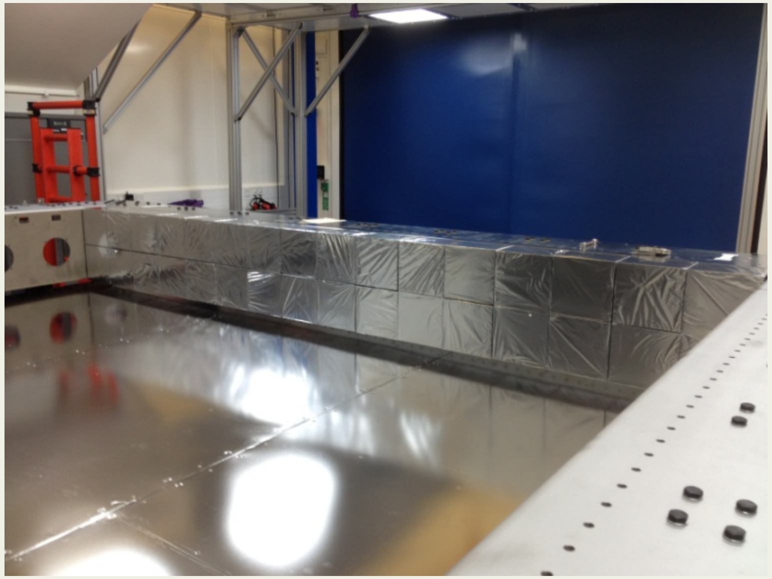
Tracker



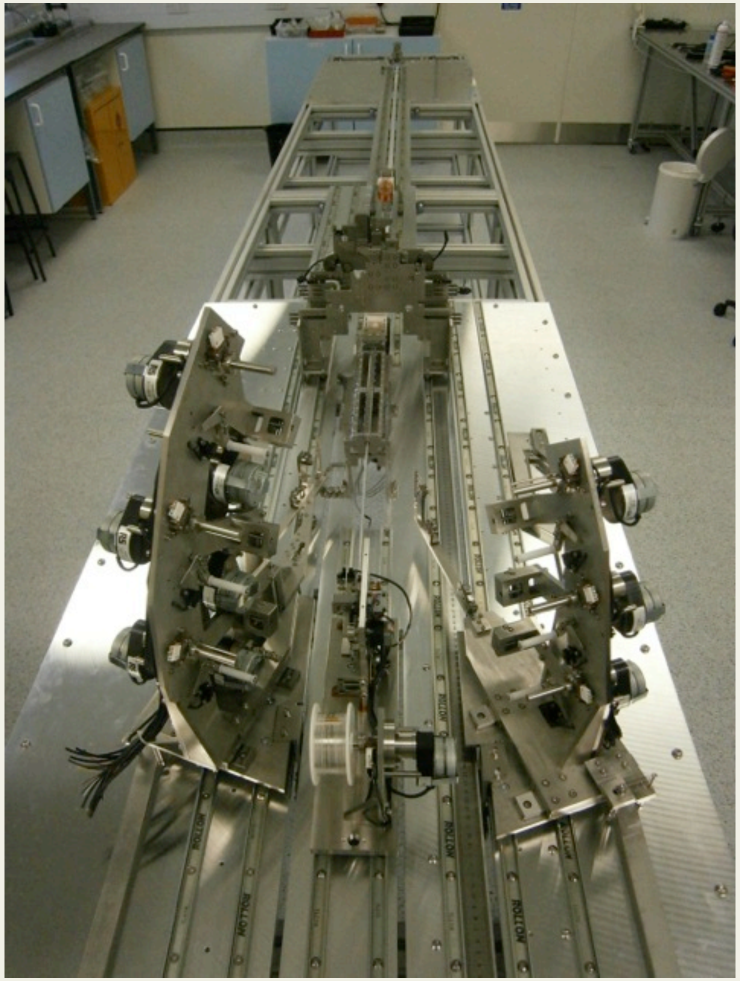


- Basic cell design developed and demonstrated with 90-cell prototype.
- Automated wiring robot (500k wires to be strung, crimped and terminated).
- Resolution 0.7 mm transverse, 1 cm longitudinal. Cell efficiency > 98%

Tracker



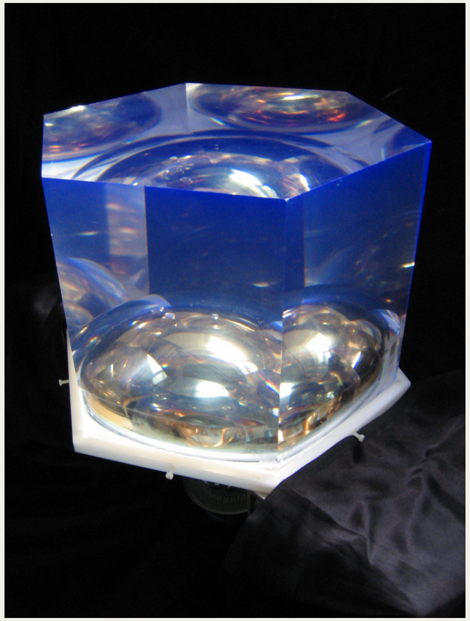
First section assembled in MSSL/UCL.

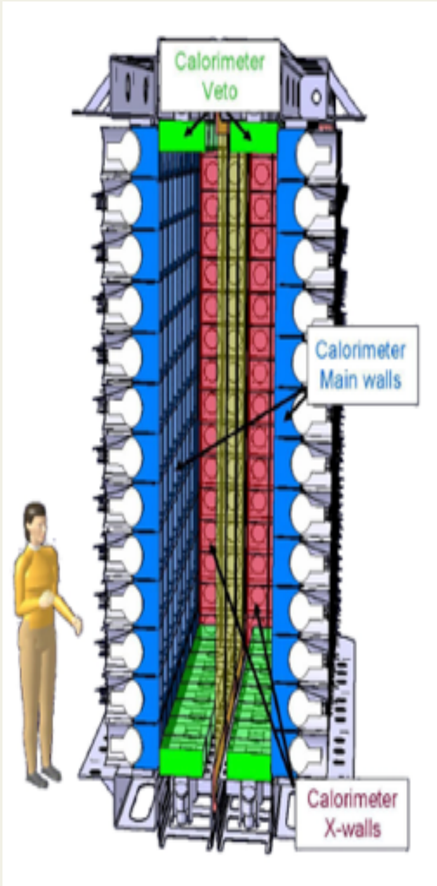


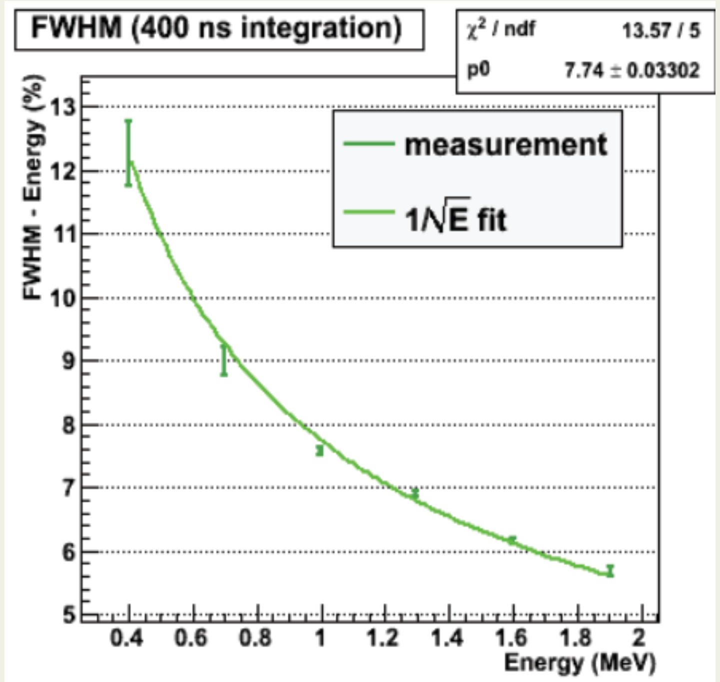
Wiring robot in Manchester

Calorimeter

Large R&D effort to improve energy and timing resolution for SuperNEMO







- Improved PMT QE (8")
- PVT instead of PS
- Optimized geometry and electronics

FWHM = 4% @ $Q_{\beta\beta}$ = 3 MeV

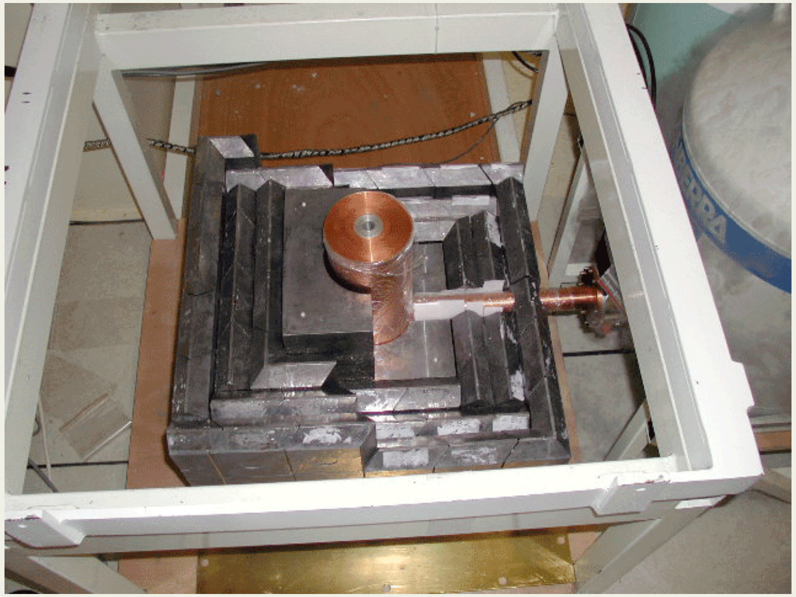
(8% in NEMO-III)

Nucl. Inst. Meth. A 625, 20 (2011)

HPGe and Radon Detectors

All material have to undergo radiopurity control. Challenging levels!

Three setups:
LSM (FR): 4 detectors (1 CENBG, 2 LSM, 1 JINR/Prague/LSM)
CEN Bordaux-Gradignan (FR): 3 detectors
Comenius University (SK) : 2.5 detectors

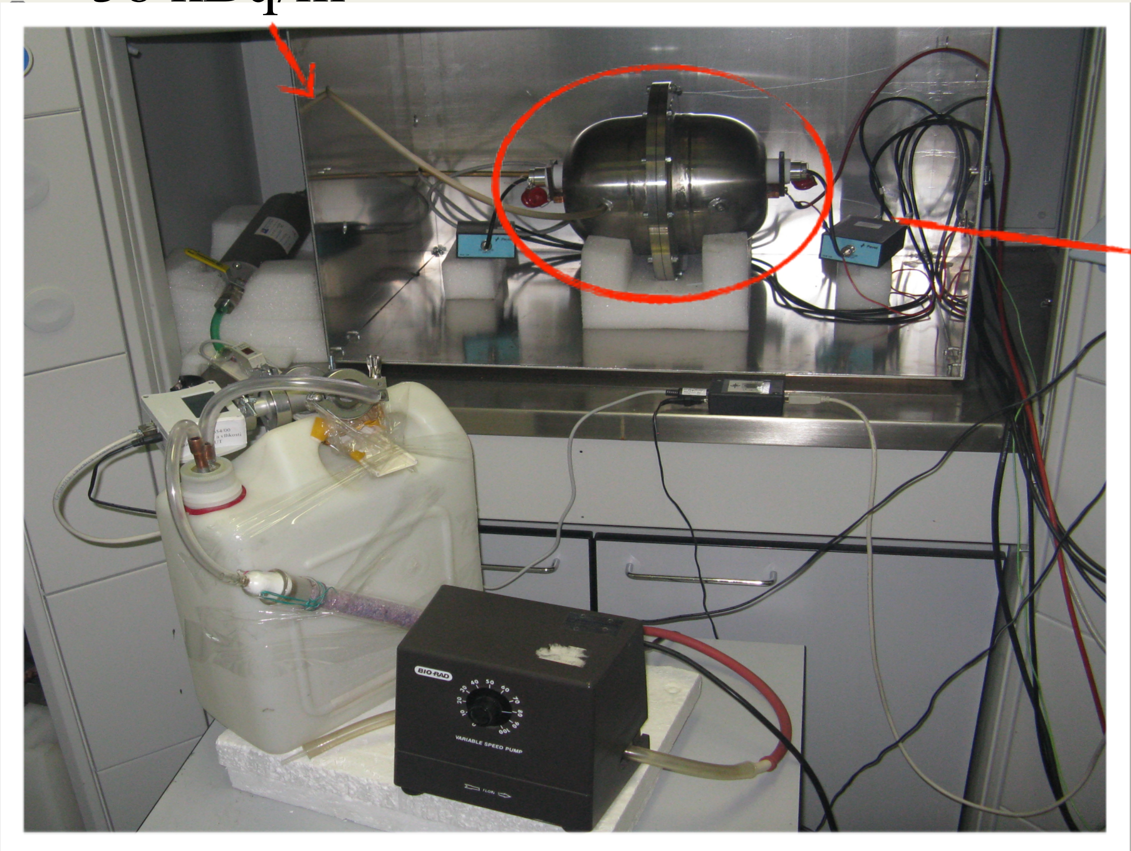


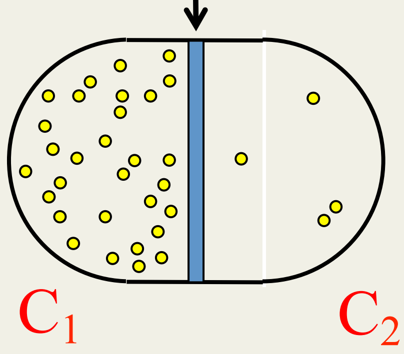
Radon Diffusion

Radon source

38 kBq/m^3

Diffusion chamber





$C_1/C_2 \rightarrow$ diffusion coefficient

Setup here in Prague

Enrichment/Purification

major cost factor

- 4.5 kg of ^{82}Se have been delivered from Russia, plus 1 kg from NEMO-III.
- Purification by chemistry at INL, Dubna/LSM or destillation (Russia).
- 100 kg feasible within the required timescale for full SuperNEMO.

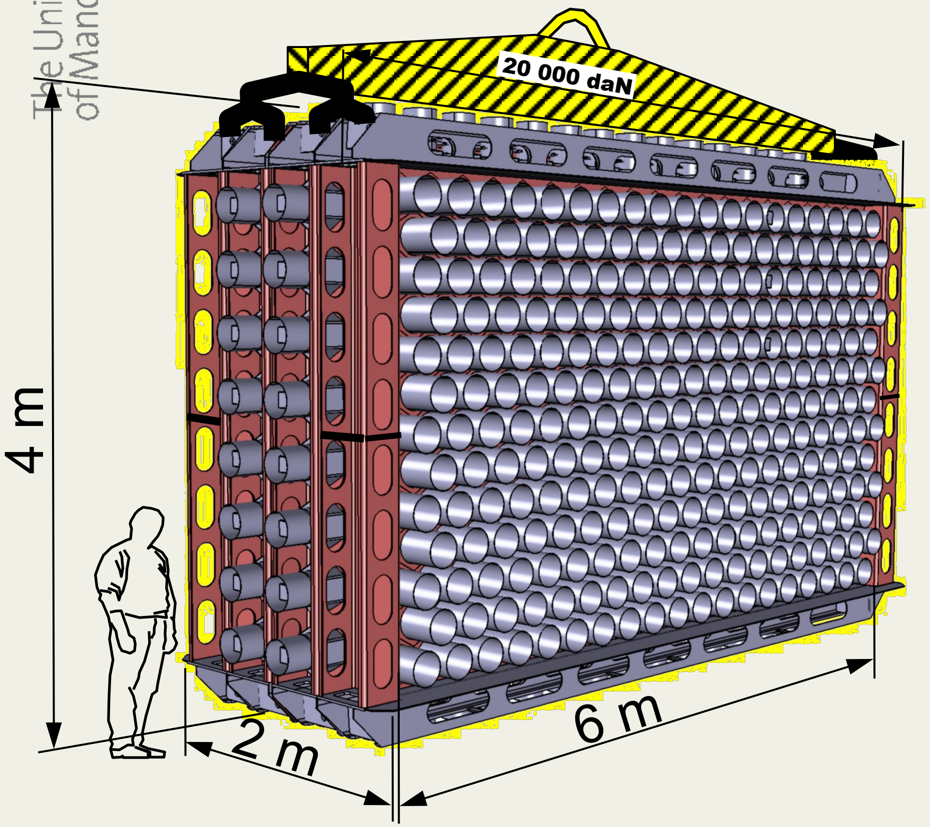
Choice of nucleus depends on:

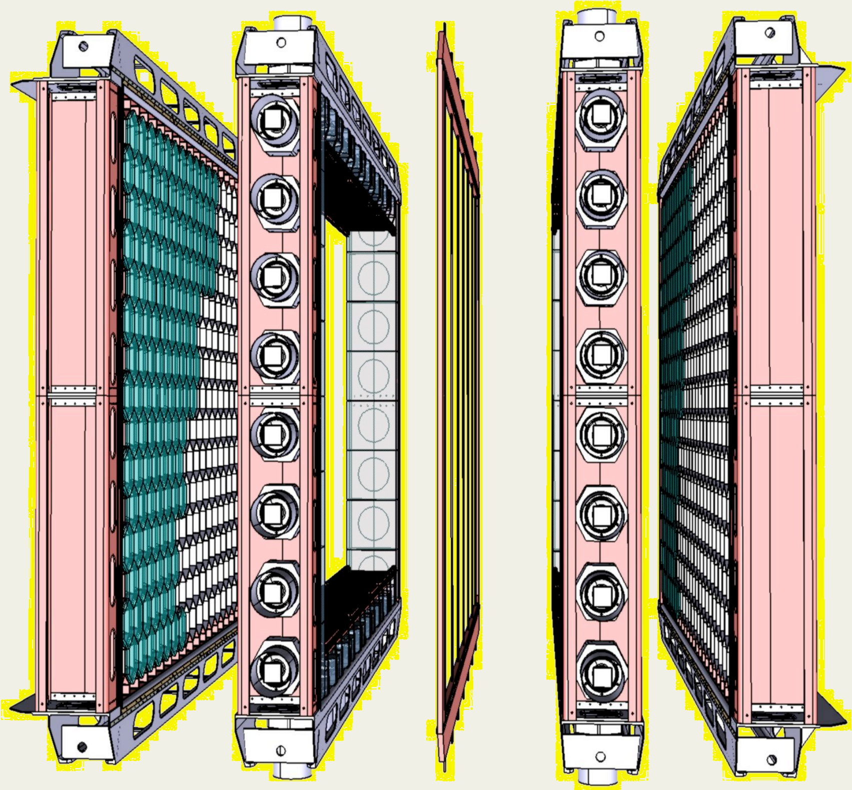
- enrichment possibilities
- high $Q_{\beta\beta}$ value
- Phase space
- non-$\beta\beta$ background

	^{150}Nd	^{82}Se	^{48}Ca	^{76}Ge
$Q_{\beta\beta}$(MeV)	3.37	3.00	4.27	2.04
$G^{0\nu}$x10^{-15}(y^{-1})	249	33.5	75.8	7.6

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

Demonstrator in LSM

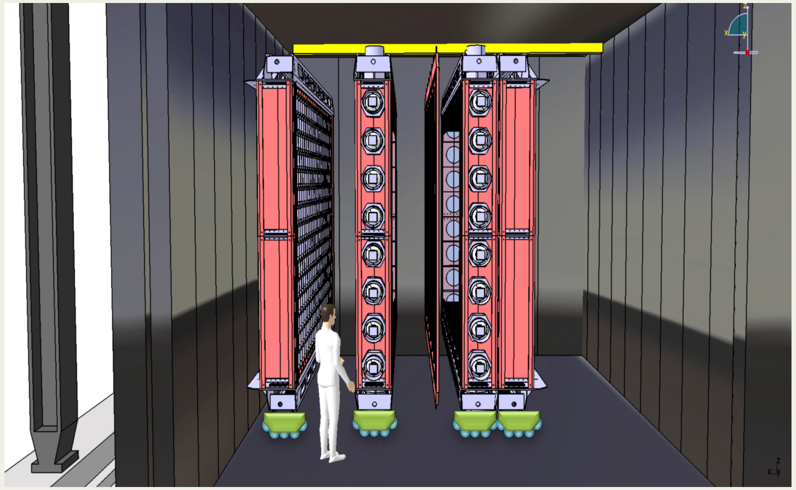


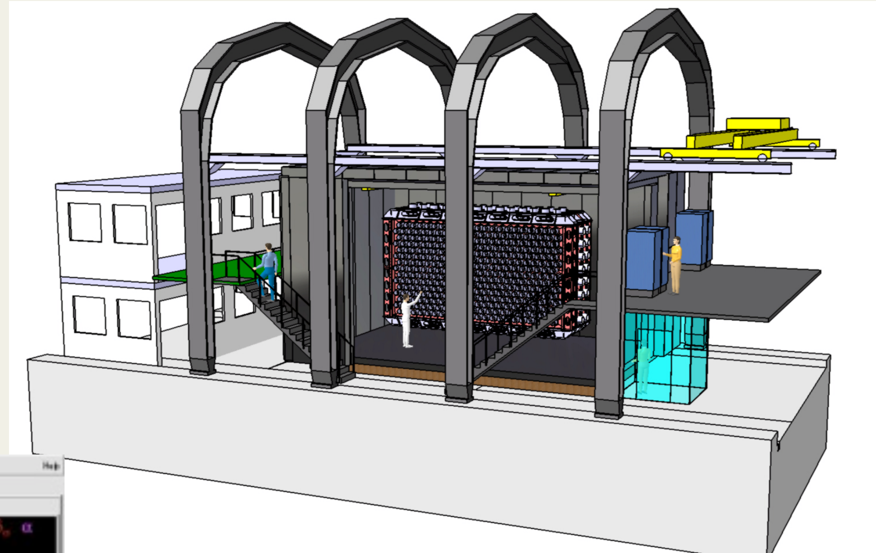


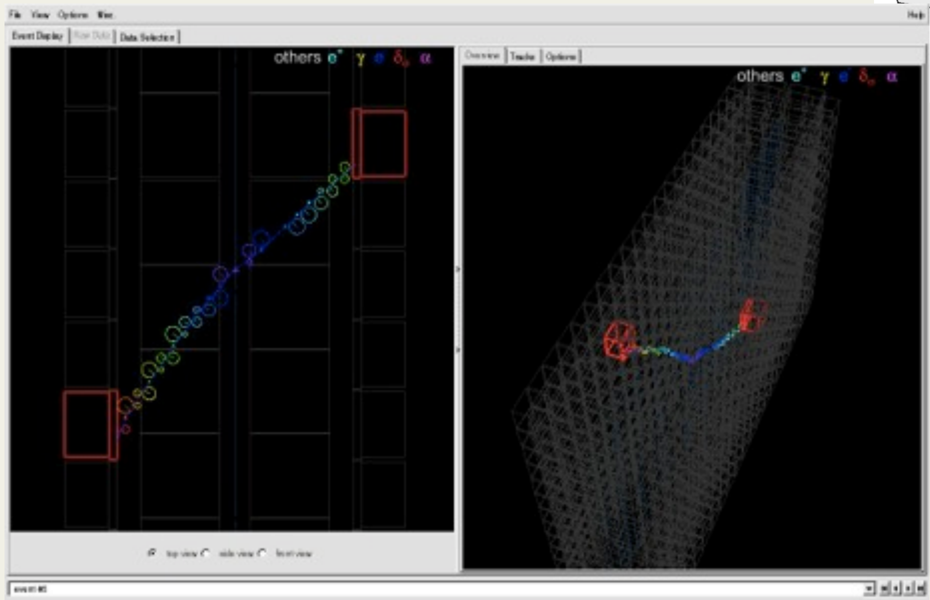
Demonstrator construction started:

Start running 2014-2015, in line with the schedule for LSM-extension.

Demonstrator in LSM



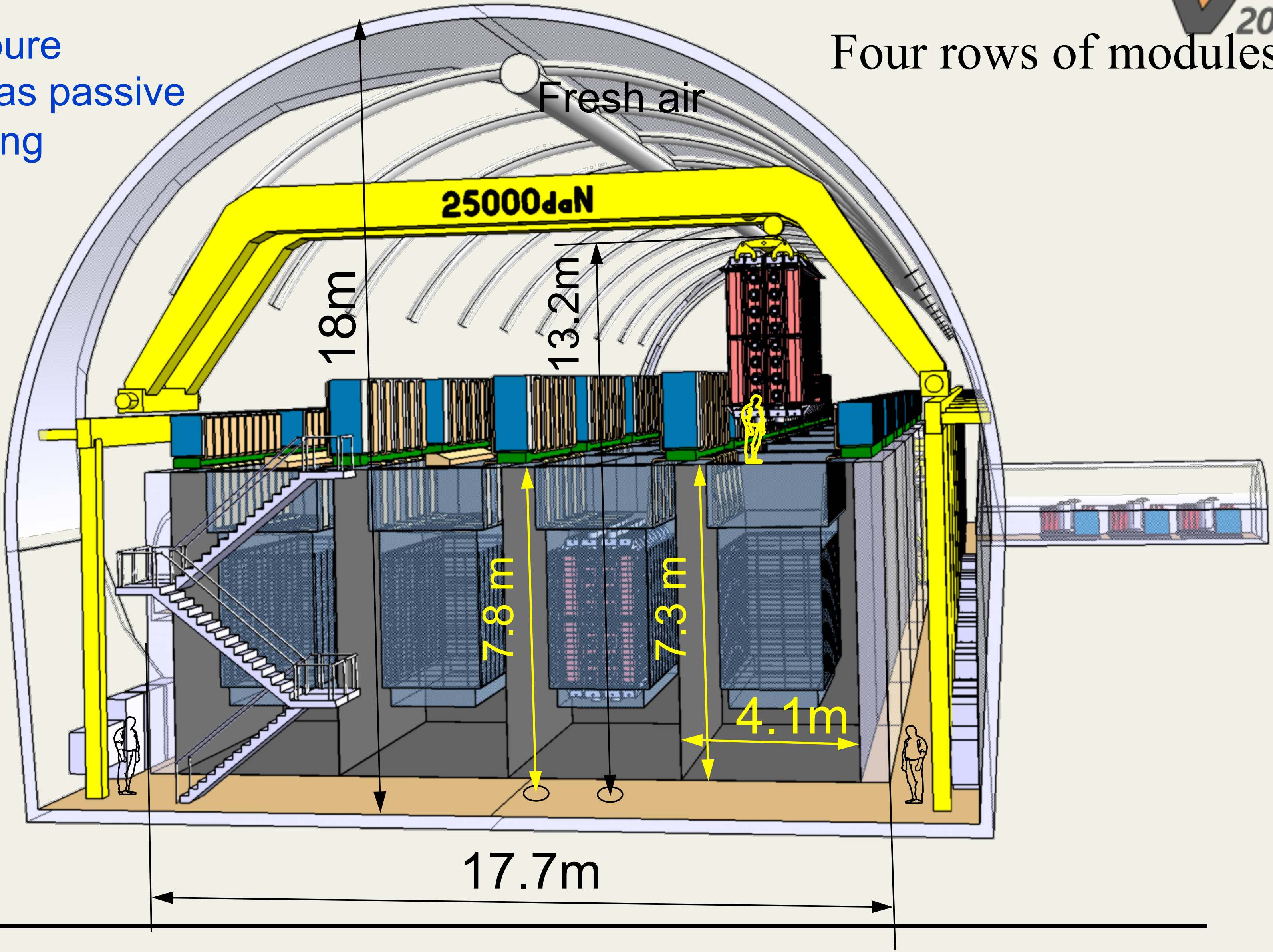




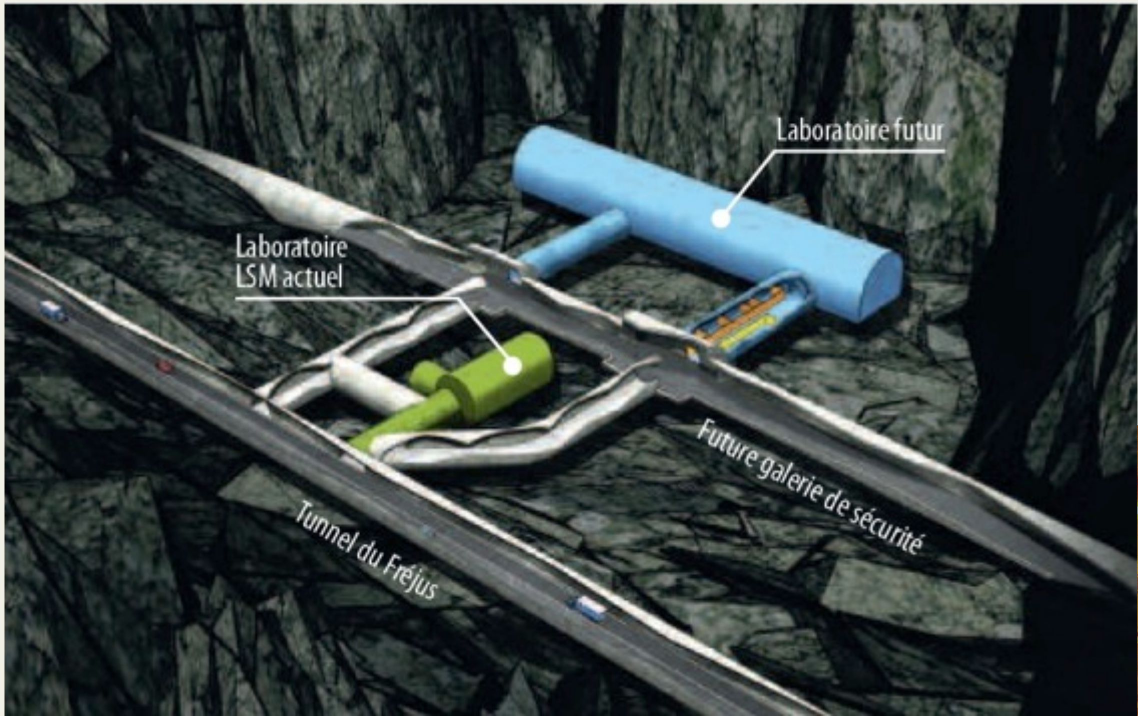
simulated event

Ultra pure water as passive shielding

Four rows of modules



LSM Extension



- 5 times the present LSM
- LSM extension funded

Schedule

Construction and deployment of successive SuperNEMO modules

Sensitivity with 100 kg:

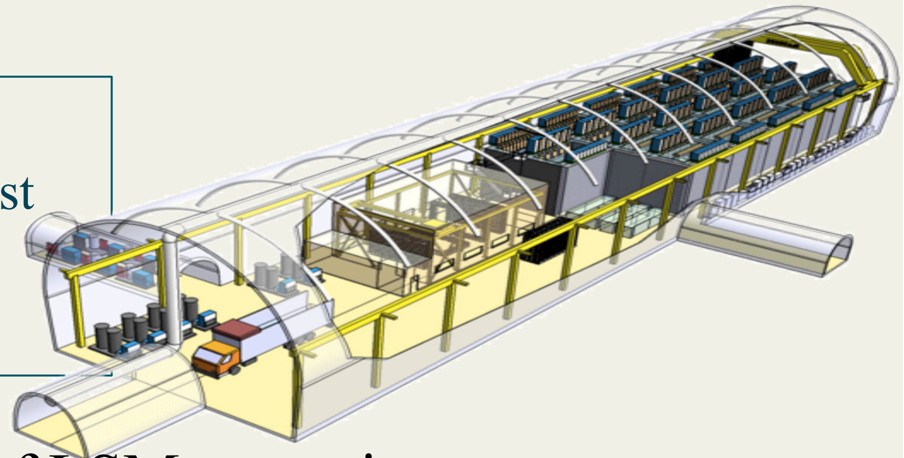
$T_{1/2}(0\nu\beta\beta) \sim 10^{26}$ yr → $m_\nu \sim 40$ —110 meV

Demonstrator module construction and commissioning

2013	2014	2015	2016	2017	2018	2019	2020	2021

Demonstrator module running

- Prove $B \sim 10^{-4}$ cts/keV/kg/yr: amongst best of any experiment
- Sensitivity of $T_{1/2} \sim 6.5 \times 10^{24}$ yr



Exact schedule depends on timing of LSM extension

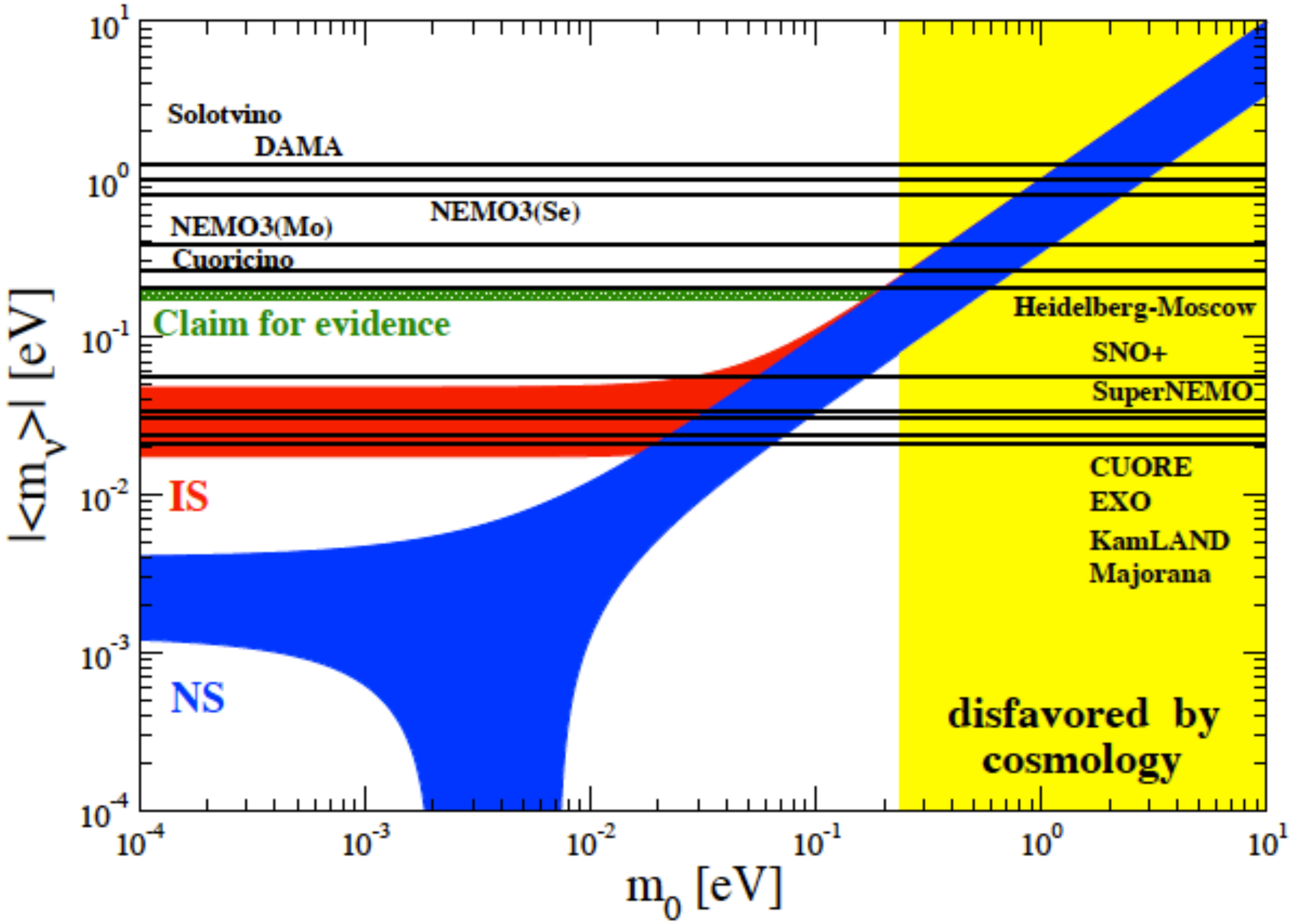
$$T_{1/2}^{\beta\beta 0\nu} > N_A \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{(N_{bg} \cdot \Delta E)}}$$

Experiment	ΔE (keV)	N_{bg} (cts/keV/kg/y	ΔE x N_{bg}	
H-M	4.5	0.06	0.3	CALO
Cuoricino	6	0.13	0.8	CALO
NEMO3	260	0.003	0.8	TRACKING
KamLAND-Zen	250	0.0028	0.7	CALO
EXO-200	120	0.0015	0.2	CALO
GERDA Phase I Phase 2	 4 4	 0.01 0.001	 0.04 0.004	 CALO CALO
CUORE	6	0.01	0.06	CALO
Majorana	4	0.003	0.01	CALO
SuperNEMO	120	0.0001	0.01	TRACKING

F. Piquemal

Latest Results

Experiment	isotope	Mass (kg)	Half-life limit in years	Neutrino mass limit in eV
H.M.	^{76}Ge	14	1.9 10^{25}	0.21 – 0.53
Cuoricino	^{130}Te	12	2.8 10^{24}	0.27 – 0.57
NEMO3	^{100}Mo	7	1.0 10^{24}	0.31 – 0.79
EXO-200	^{136}Xe	200	1.6 10^{25}	0.14 – 0.38
Kamland-Zen	^{136}Xe	400	6.2 10^{24}	0.26 – 0.54



J. Vergados et al., arXiv:1205.0649

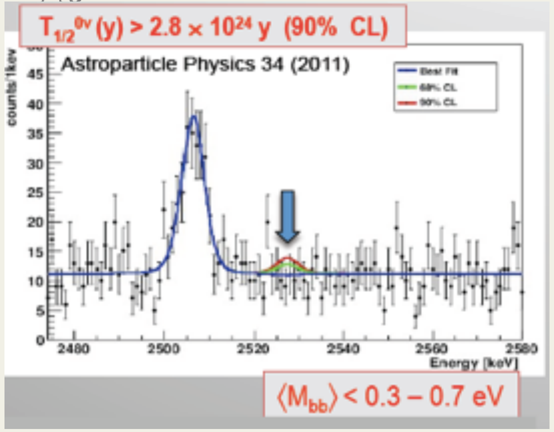
Summary

- NEMO-3 has produced a wealth of physics results; data analysis ongoing
  - ^{100}Mo: $T_{1/2} > 1.0 \times 10^{24}$ yrs, $\langle m_\nu \rangle < 0.31\text{-}0.96$ eV, 90%CL
  - Unprecedented 2νββ measurements: input for NME calculations
  - Ran until end of 2010. Invaluable test bench for SuperNEMO and other ββ experiments
- SuperNEMO will be capable of probing new physics at 40-100 meV neutrino mass scale
- First module (Demonstrator) will start taking data in 2014-5.
- SuperNEMO approach is unique
  - Event topology fully reconstructed
  - Isotope flexibility

The University of Manchester

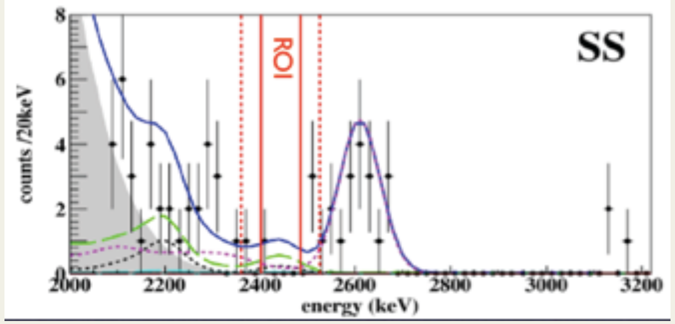
Backup

Cuoricino



Bolometer

EXO-200

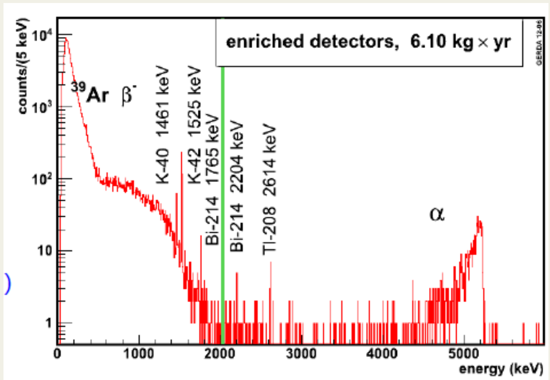


$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 140\text{–}380$ meV

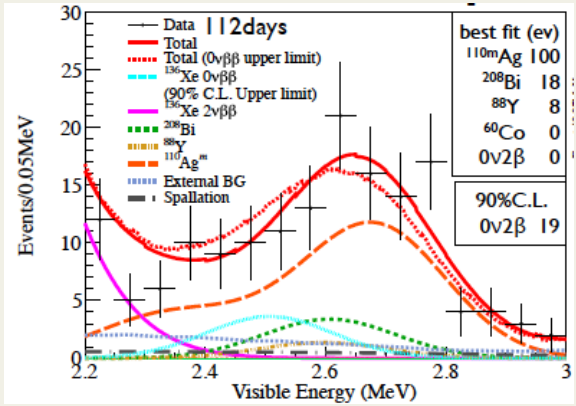
Liquid Xenon

KamLAND-ZEN

GERDA I



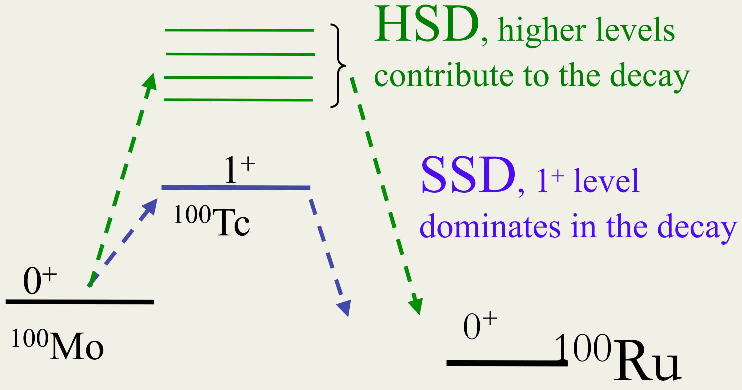
Ge diodes



$T^{0\nu}_{1/2} > 6.2 \times 10^{24}$ years (KL-Zen 112days)
$\langle m_{\beta\beta} \rangle$ <0.26~0.54 eV

Xe in liquid scintillator

Single State Dominance



E_{min} = smaller of two electron energies