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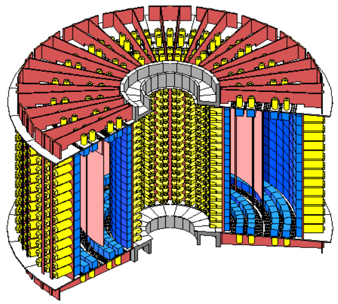
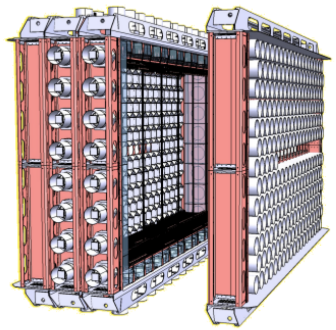
Double Beta Decay Searches with NEMO-3 and SuperNEMO

Anastasia Basharina-Freshville
University of Manchester
On behalf of the NEMO collaboration

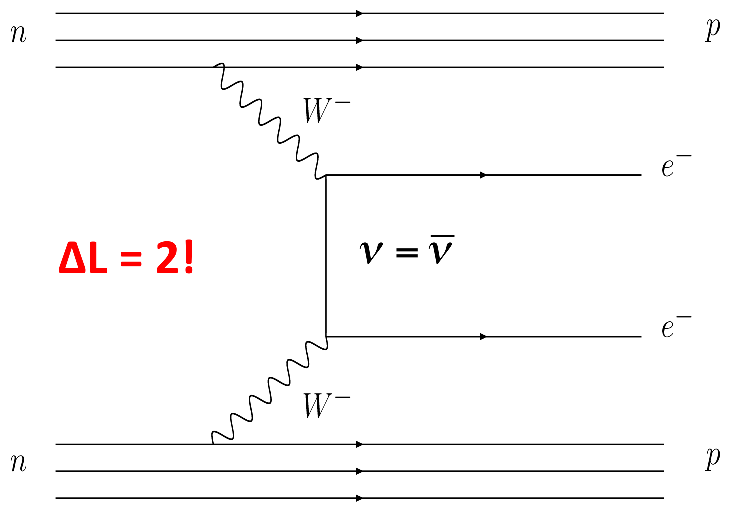
Rencontres du Vietnam – Beyond the Standard Model
17th July 2012

Outline:
- 0νββ decay
- The NEMO principle
- NEMO-3 detector and results
- SuperNEMO status


NEMO-3


SuperNEMO

Neutrinoless Double Beta Decay



ΔL = 2!

Neutrinoless double beta decay: 0νββ

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

- Beyond SM: Total lepton number violated by 2
- Most sensitive way to establish Majorana/Dirac nature of neutrino (requires the neutrino to be a Majorana particle)
- Most sensitive way to measure absolute neutrino mass in a lab environment (for Majorana neutrino)
- Possible access to neutrino mass hierarchy and Majorana CP-violation phases
- Link to matter-antimatter asymmetry (leptogenesis)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \eta^2$$

Half-life

Phase space (α $Q_{\beta\beta}^5$), well known

Nuclear matrix element, challenging

Lepton number violating parameter

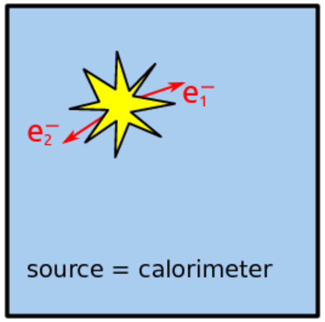
- η can be due to different mechanisms: Majorana mass of neutrino (η = $\langle m_{\nu e} \rangle$ effective mass), V+A, Majoron, H^{--}, leptoquarks, RPV SUSY, extra dimensions etc. or a combination of them.
- Therefore a detector which can probe different mechanisms and different isotopes is required!

Double Beta Decay Experimental Approach (1)

Source = detector (calorimeter only)

- Good energy resolution
- High detection efficiency
- No particle identification
- Background from radio-impurities

⟶ $E_1 + E_2 = Q_{\beta\beta}$ (for 0ν)

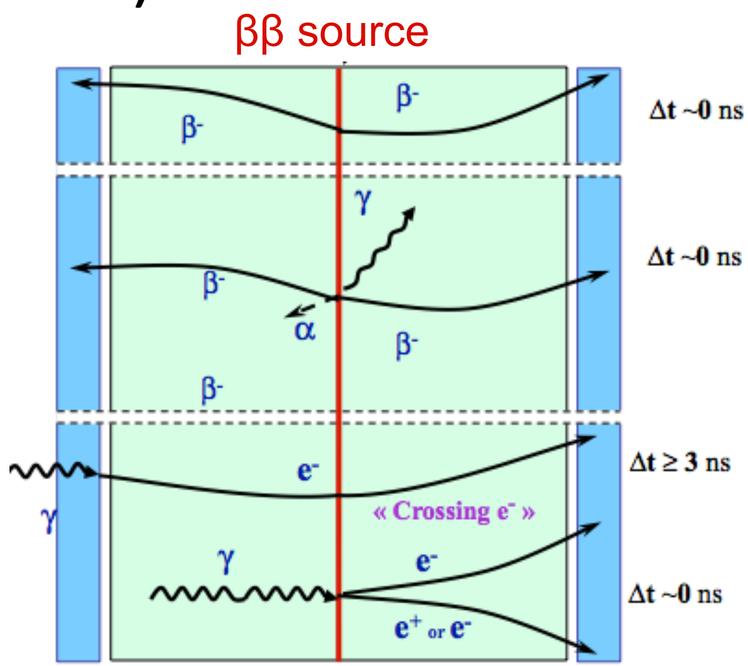


Source ≠ detector (tracker + calorimeter)

- Modest energy resolution
- Modest detection efficiency
- Several observables:
  - Two electrons
  - In coincidence
  - Originating from the same vertex
  - Angular distribution between two electrons

↓

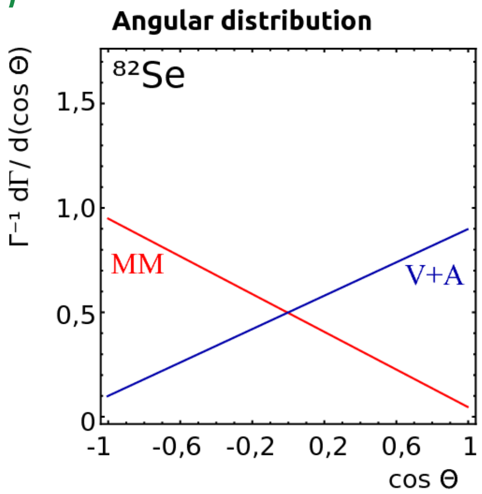
Kinematic measurement of ββ
Topological background suppression

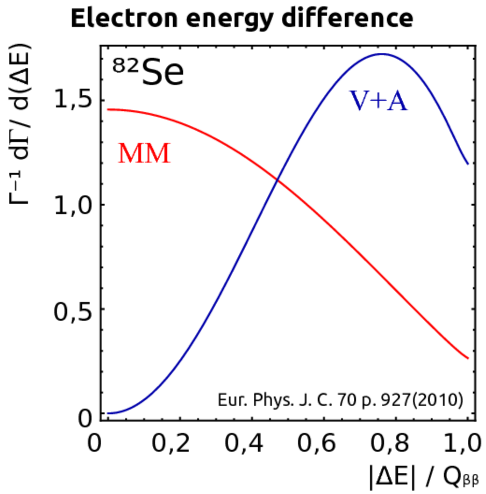


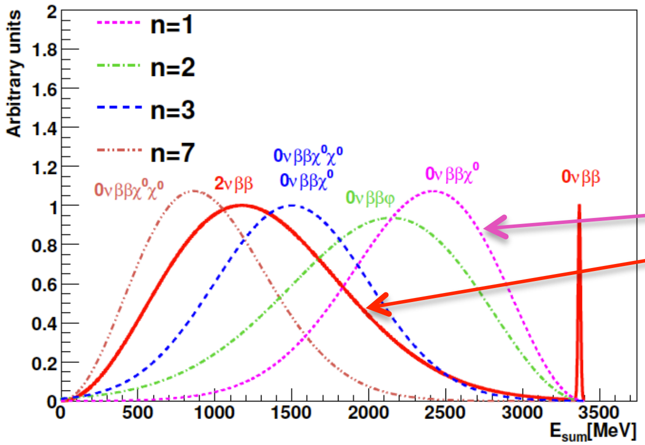
Double Beta Decay Experimental Approach (2)

- $E_1 + E_2$ → discrimination between $2\nu\beta\beta$ and $0\nu\beta\beta$

- E_1, E_2
- Angular distribution between electrons ($\cos\theta$) → discrimination between different $0\nu\beta\beta$ mechanisms

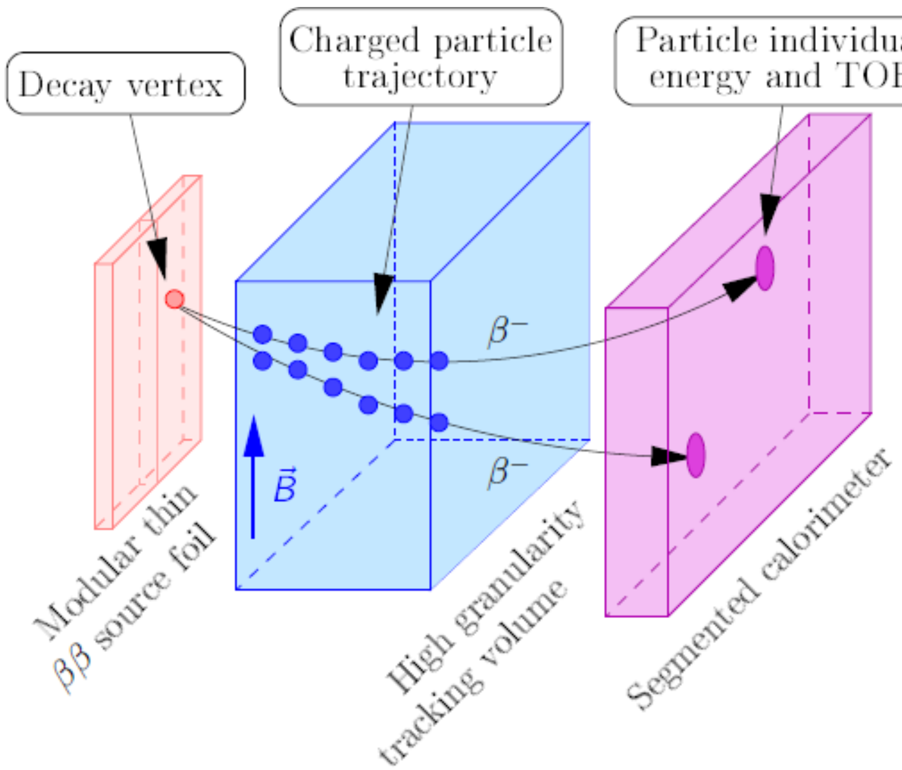






Decays that produce continuous spectra ($2\nu\beta\beta$, $0\nu\beta\beta B$ (Majoron particle emission)) are more sensitive to topological detection

The NEMO Principle



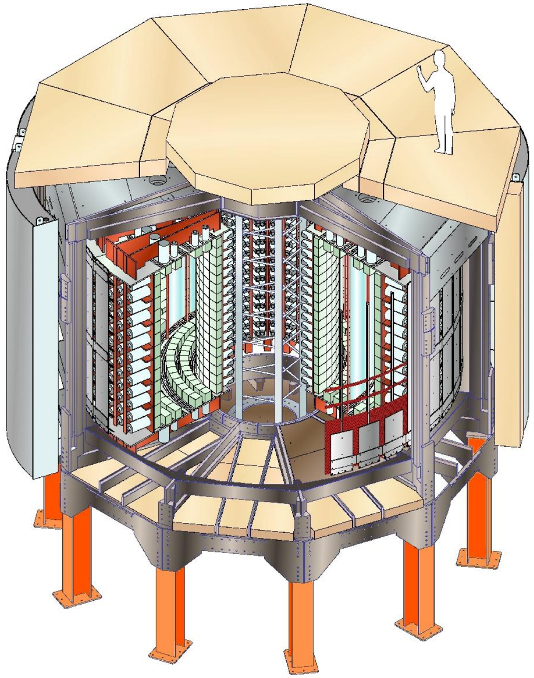
Observables measured in the final state:

- Kinematics of ββ decay: E_1, E_2, cosθ, Δt (time of flight)
- Particle ID: e^-, e^+, α, γ

→

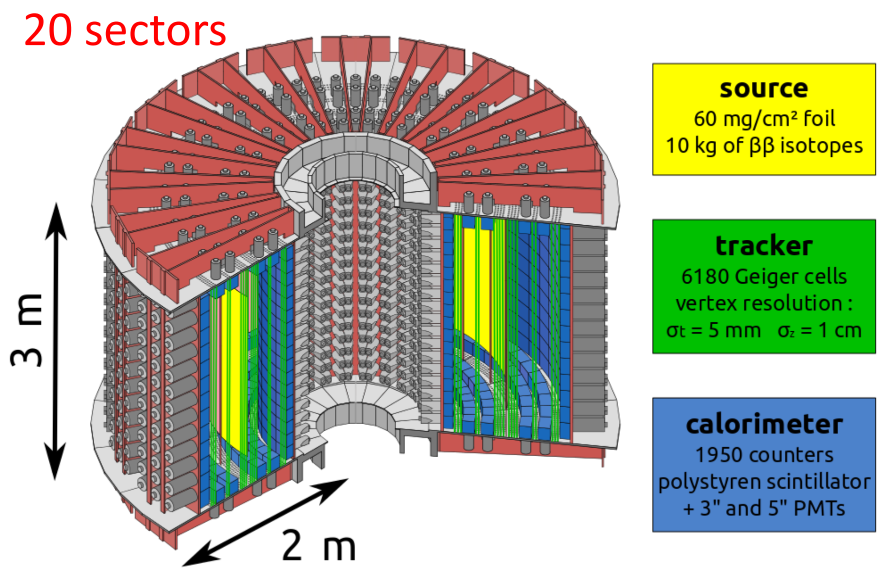
- Topological signature of events
- Powerful background identification and rejection
- Open to any lepton number violating process with possibility to disentangle mechanism

The Neutrino Ettore Majorana Observatory - 3 Detector (1)



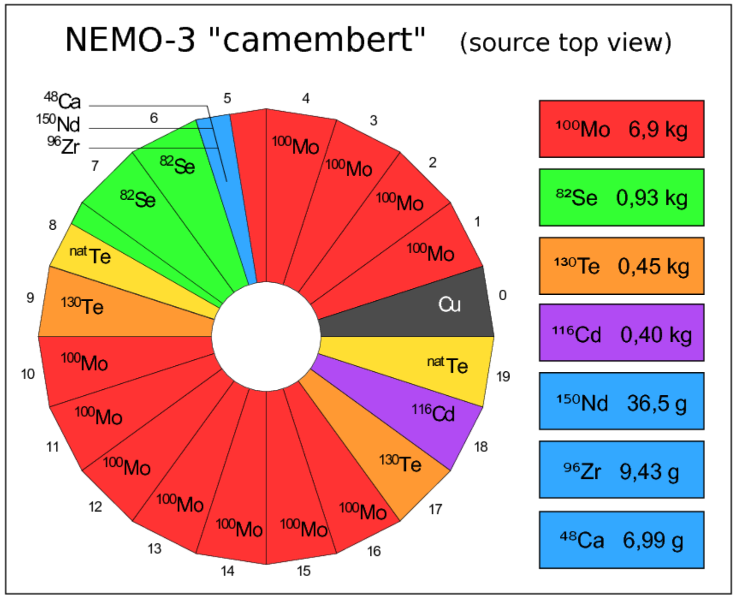
- Data taking from February 2003 – January 2011
- Located in the Laboratoire Souterrain de Modane (LSM) in the Frejus tunnel → 4800 mwe
- Magnetic field: 25 Gauss
- γ shield: 18cm of pure iron
- n shield:
  - 30cm of borated water (external wall)
  - 40cm of wood (top and bottom)
- Anti-radon "factory" installed in October 2004

The NEMO-3 Detector (2)



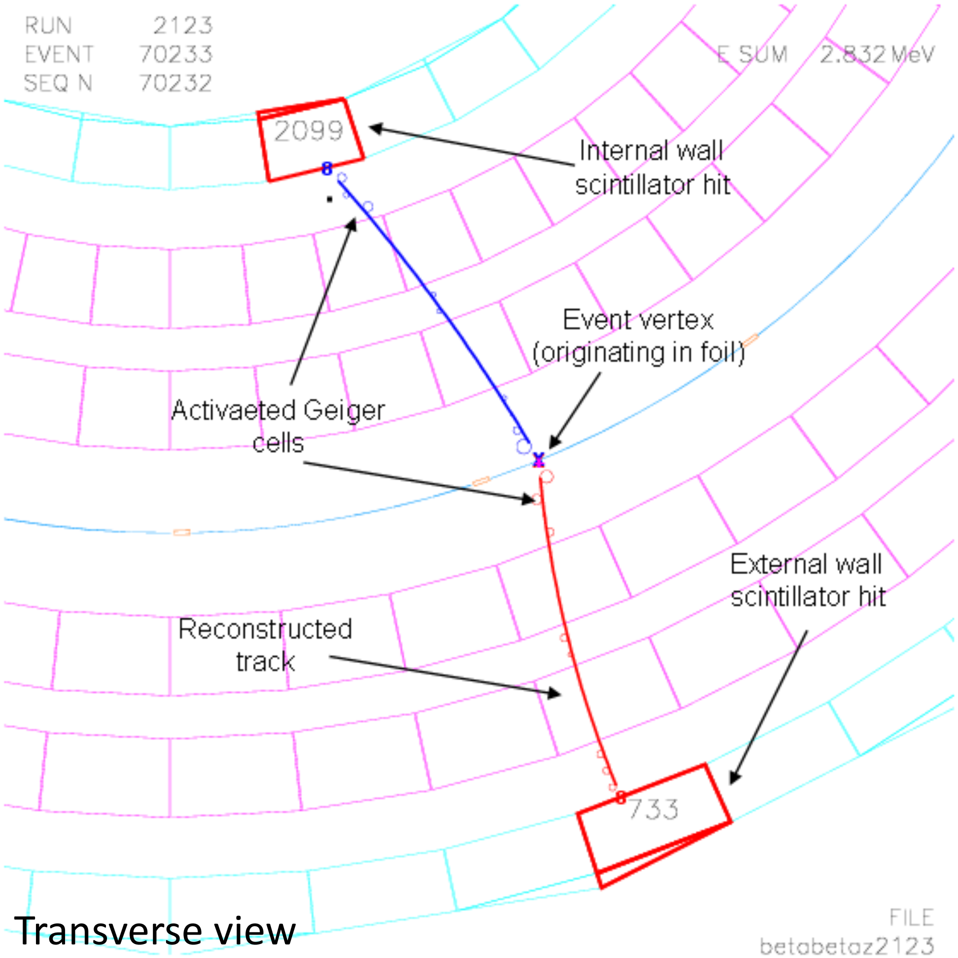
- 10 kg of 7 different ββ decay isotopes
- Calorimeter → energy and time measurements
  - 1940 scintillator blocks coupled to low radioactivity PMTs
- Tracker → topological event reconstruction
  - Drift wire chamber of 6180 cells operating in Geiger mode
  - Gas mixture:

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



Isotope	Mass (g)	Q_{bb} (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	

NEMO-3 Event Selection



Transverse view

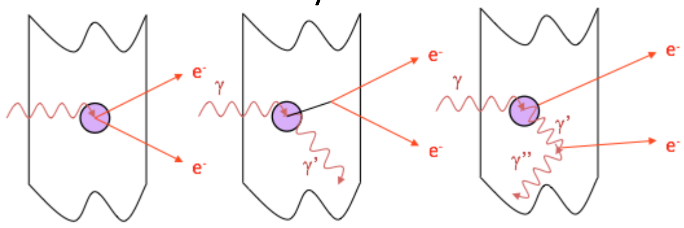
- 2 tracks of negative curvature
- Associated to 2 calorimeter hits (> 200 keV each)
- Common track vertex
- Internal hypothesis (external event rejection)
- No other isolated calorimeter hits (γ rejection)
- No delayed tracks (^{214}Bi rejection)

25 ββ events per hour (for ^{100}Mo)

NEMO-3 Backgrounds (1)

- External γ (if the γ is not detected in the calorimeter)

From: natural radioactivity of the detector or neutrons

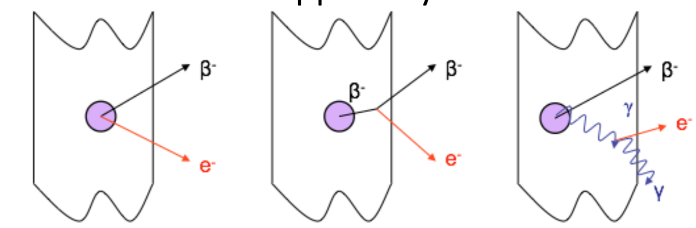


(a) Pair Creation (b) Compton Scattering + Møller Scattering (c) Double Compton Scattering

Large background for 2νββ, but small for 0νββ
(^{100}Mo and ^{82}Se $Q_{\beta\beta}$ ~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)

- Internal background

From: contamination in ββ decay source foils



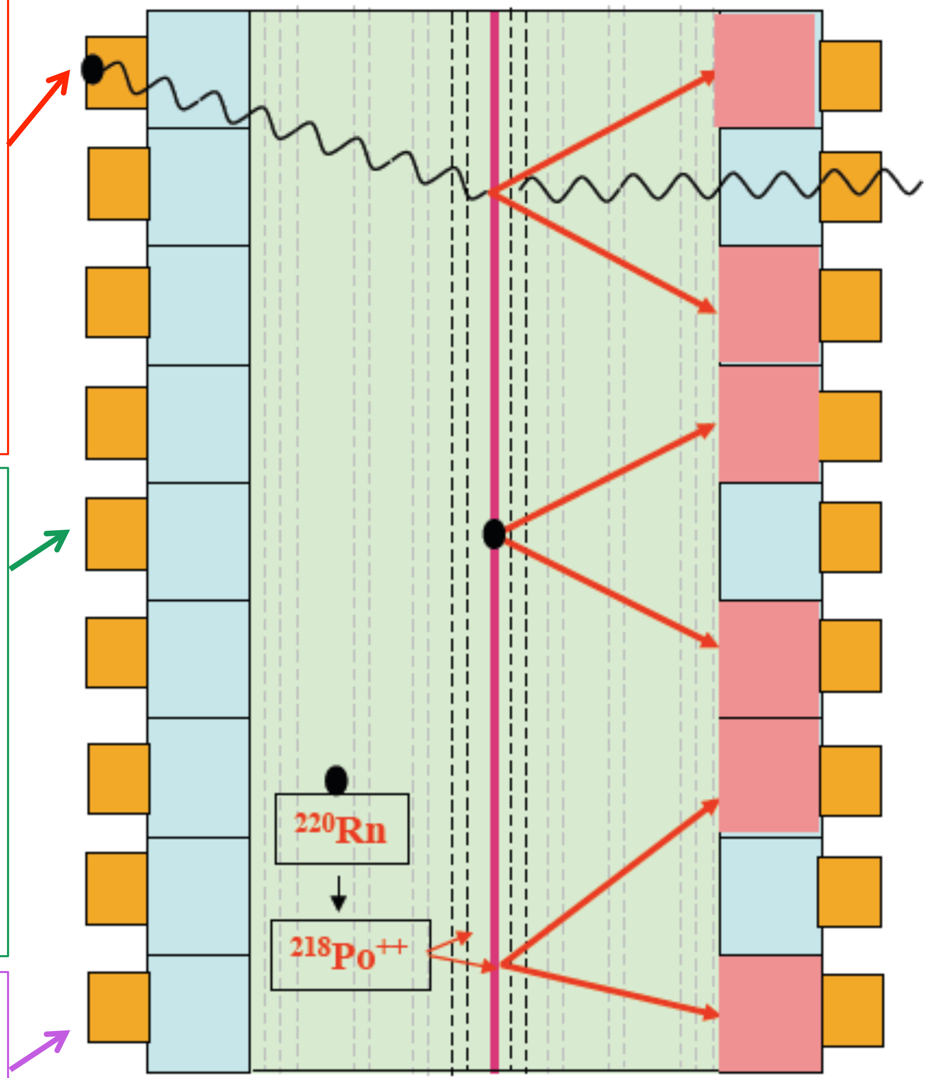
(a) β decay + Internal Conversion (b) β decay + Møller Scattering (b) β decay + Compton Scaterring

^{214}Bi from ^{238}U chain (Q_β = 3.3 MeV)
^{208}Tl from ^{232}Th chain (Q_β = 4.9 MeV)

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

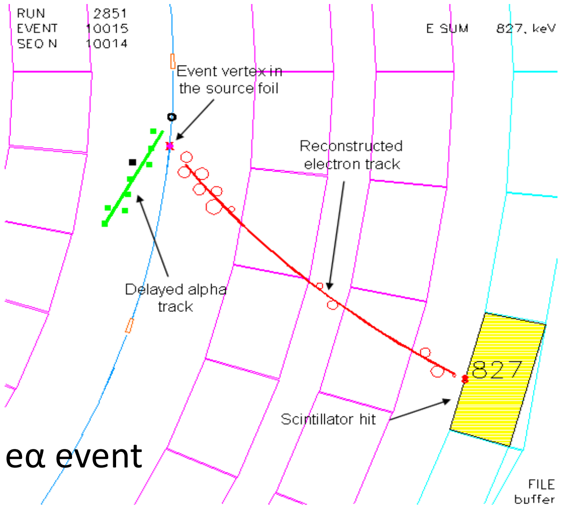
From: ^{222}Rn decays and deposits ^{214}Bi on the surface of the ββ foils and the wires near ββ foils

- 2νββ tail

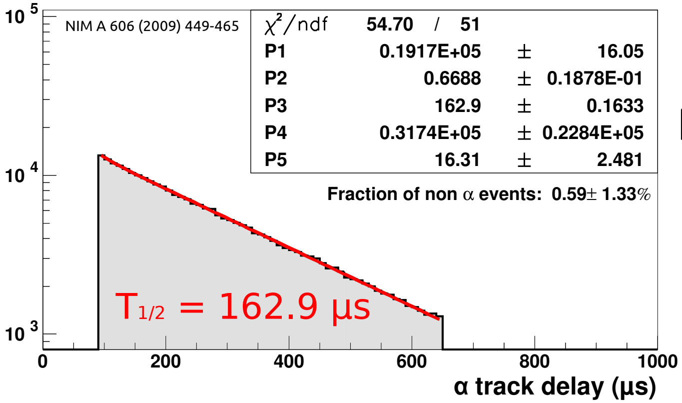


Each background is measured using NEMO-3 data

NEMO-3 Backgrounds (2) – Anti-Radon Factory



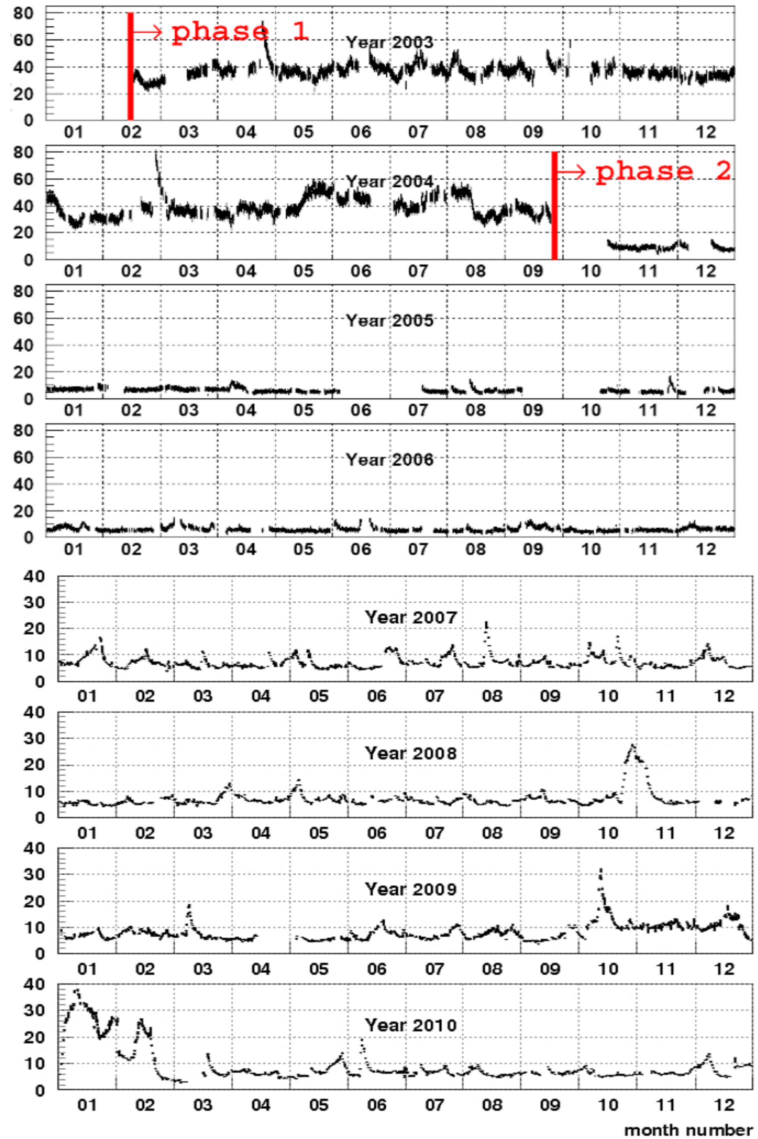
- Rn is trapped in cooled charcoal where it decays
- Factory: input = 15 Bq/m^3 ⟶ output = 15 mBq/m^3



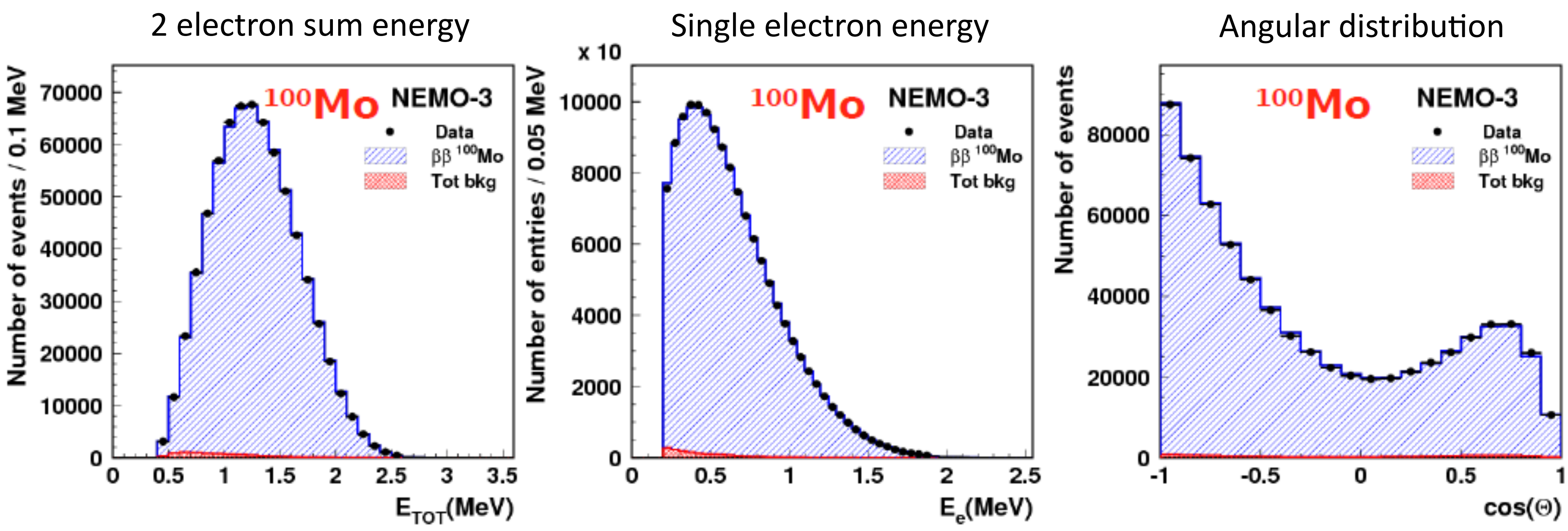
Inside the detector:

Phase 1: Feb 03 – Sep 04
A(Radon) ≈ 40 mBq/m^3

Phase 2: Dec 04 – Jan 11
A(Radon) ≈ 5 mBq/m^3



NEMO-3 2νββ Results (1)



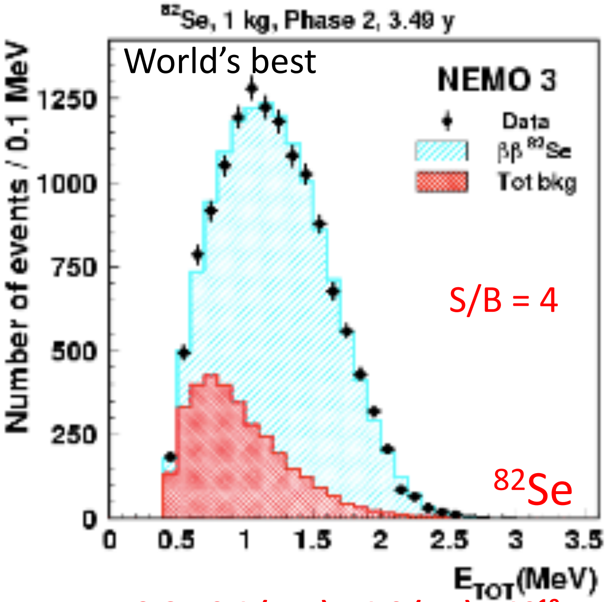
- > 700000 2-electron for 7kg of ^{100}Mo Phase 2 (4 years)
- Signal/Background ratio = 76

$$T_{1/2}^{2\nu\beta\beta} = 7.16 \pm 0.01\text{ (stat)} \pm 0.54\text{ (sys) x }10^{18}\text{ years [preliminary]}$$

Published phase 1: 7.11 ± 0.02 (stat) ± 0.54 (sys) x 10^{18} years [Phys. Rev. Lett. 95 182302 (2005)]

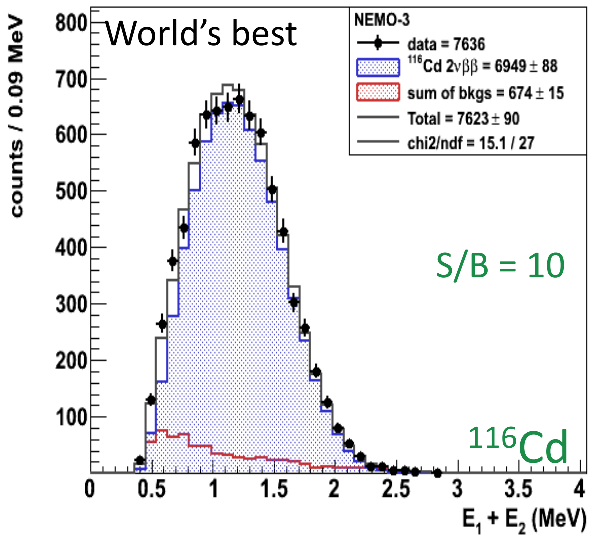
- Major background component for 0νββ search

NEMO-3 2νββ Results (2)



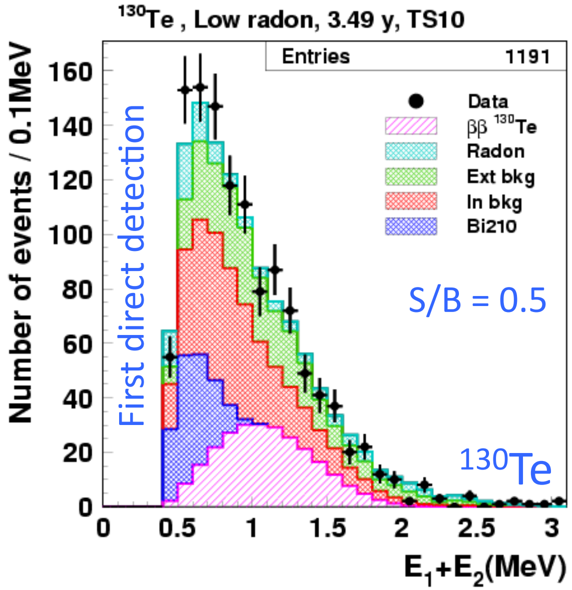
9.6 ± 0.1 (stat) ± 1.0 (sys) x 10^{19} yr

[preliminary]



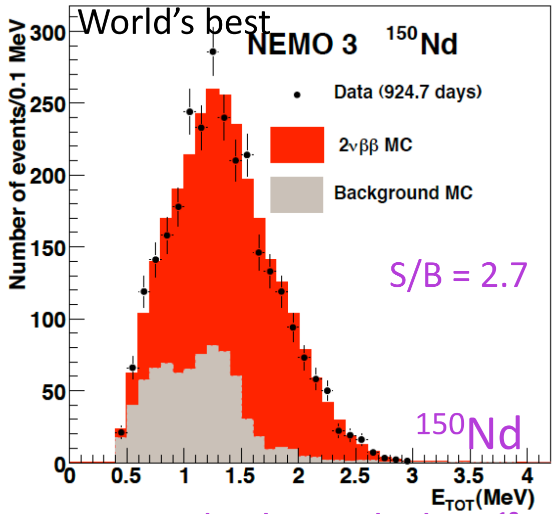
2.88 ± 0.04 (stat) ± 0.16 (sys) x 10^{19} yr

[preliminary]



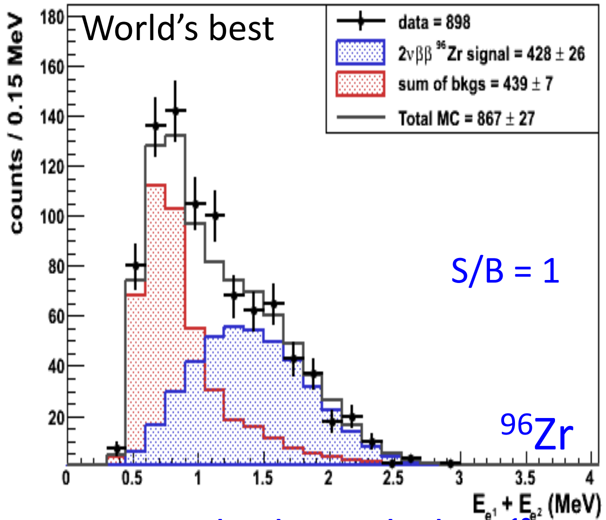
7.0 ± 0.9 (stat) ± 1.1 (sys) x 10^{20} yr

[Phys. Rev. Lett. 107, 062504 (2011)]



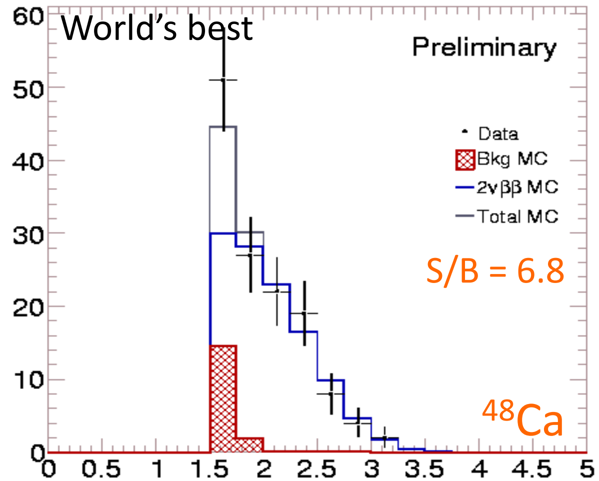
9.11 ± 0.25 (stat) ± 0.63 (sys) x 10^{18} yr

[Phys. Rev. C80, 032501 (2009)]



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

[Nucl. Phys. A 847 (2010)]

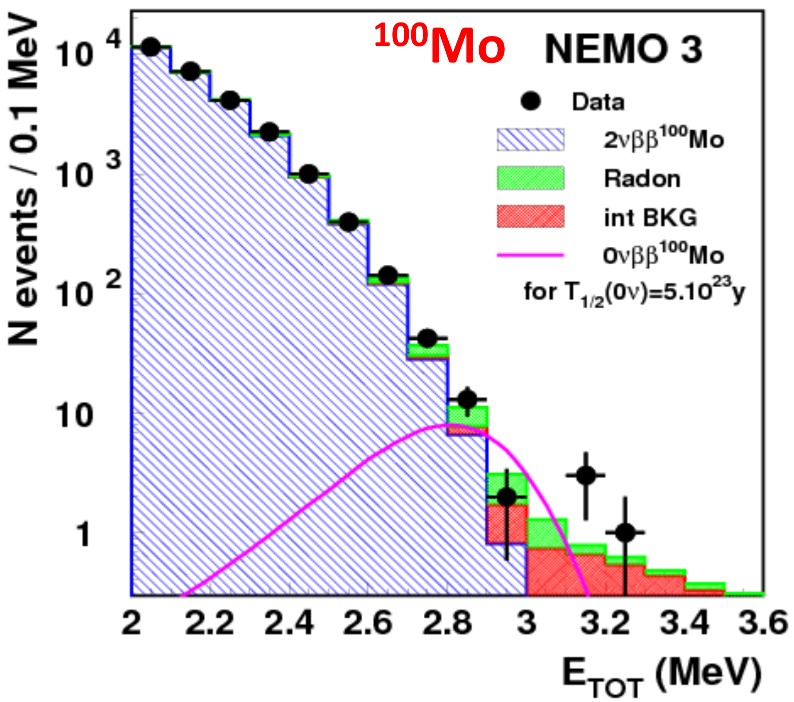


4.4 ± 0.5 (stat) ± 0.4 (sys) x 10^{19} yr

[preliminary]

NEMO-3 0νββ Results (1)

^{100}**Mo**: 7kg x 4.5 years

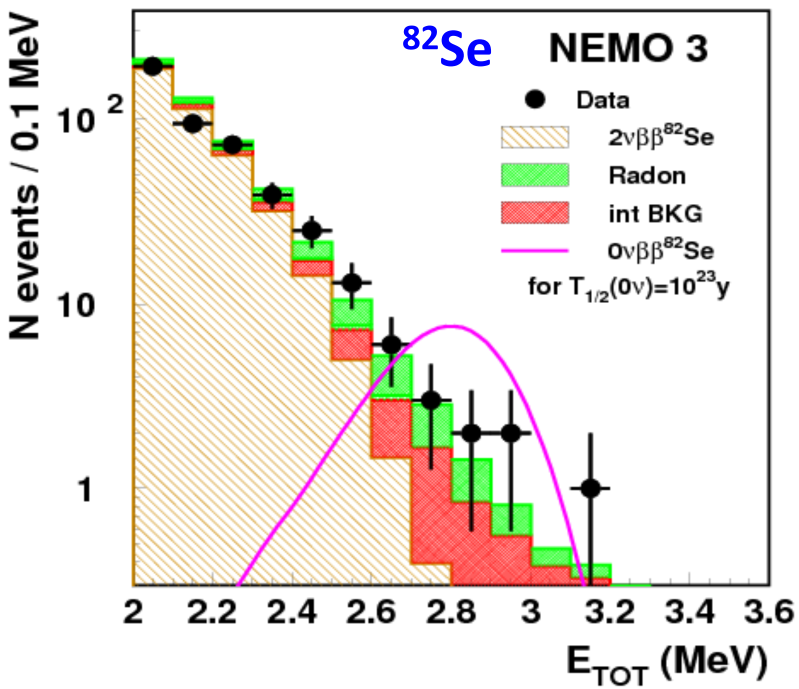


Events in [2.8-3.2]MeV:
Data = 18 Total MC = 16.4 ± 1.4

$T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{24}$ years (90% CL)

$\langle m_\nu \rangle < 0.31 – 0.96$ eV

^{82}**Se**: 1kg x 4.5 years



Events in [2.8-3.2]MeV:
Data = 14 Total MC = 11.3 ± 1.3

$T_{1/2}^{0\nu\beta\beta} > 3.2 \times 10^{23}$ years (90% CL)

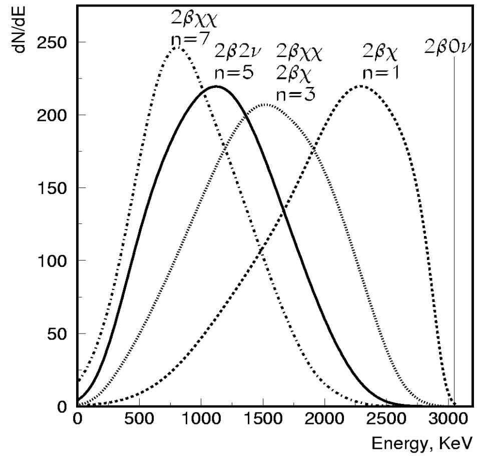
$\langle m_\nu \rangle < 0.94 – 2.6$ eV

c.f. EXO (May 2012) : $\langle m_\nu \rangle < 0.14 – 0.38$ eV for ^{136}Xe for 32.5 kg.yr

NME
QRPA Kortelainen and Suhonen, Phys. Rev. C75 051303 (2007)
QRPA Simkovic et al., Phys. Rev. C77 045503 (2008)
PHFB Rath et al., Phys. Rev. C82 064310 (2010)
QRPA Kortelainen and Suhonen, Phys. Rev. C76 024315 (2007)
IBM2 Barea and Iachello, Phys. Rev. C79 044301 (2009)
SM Caurrier et al., Phys. Rev. Lett. 100 052503 (2008)

NEMO-3 0νββ Results (2) – Other Modes + Excited States

Other modes:



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

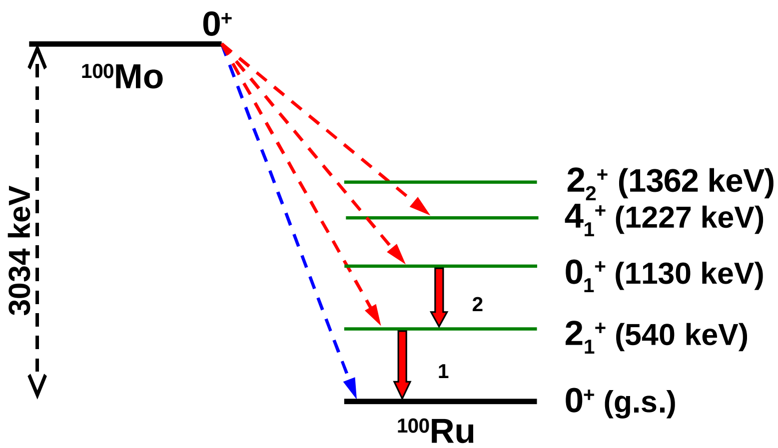
n: spectral index of Majoron mode emission, limits on half-life given in years
* Phase 1 + Phase 2 data (including 2008)
** Phase 1 data [R. Arnold et al. Nucl. Phys. A 765 (2006), 483]

Best uncertainty and limits:

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (sys) × 10^{20} yr
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ yr (90% C.L.)
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ yr (90% C.L.)
$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ yr (90% C.L.)

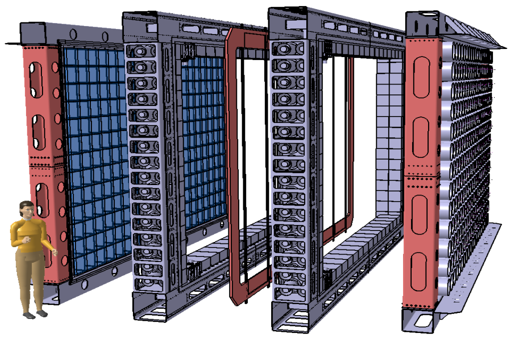
[Nucl. Phys. A 781 (2006), 209-226]

ββ Decays to excited states:



From NEMO-3 to SuperNEMO

NEMO-3	R&D since 2006 →	SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
7 kg x 5 years	Exposure	100 kg x 5 years
18%	0νββ efficiency	30%
8% at 3 MeV	Calorimeter energy resolution (FWHM)	4% at 3 MeV
^{208}Tl ~ 100 μBq/kg ^{214}Bi < 300 μBq/kg	Contaminants in ββ foil	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg
^{222}Rn ~ 5 mBq/m^3	Radon in the tracker	^{222}Rn ≤ 0.15 mBq/m^3
$T_{1/2}^{0\nu\beta\beta}$ >(1-2) x 10^{24} years $\langle m_\nu \rangle$ < 0.3 – 0.8 eV	Sensitivity	$T_{1/2}^{0\nu\beta\beta}$ > 1 x 10^{26} years $\langle m_\nu \rangle$ < 0.04 – 0.1 eV



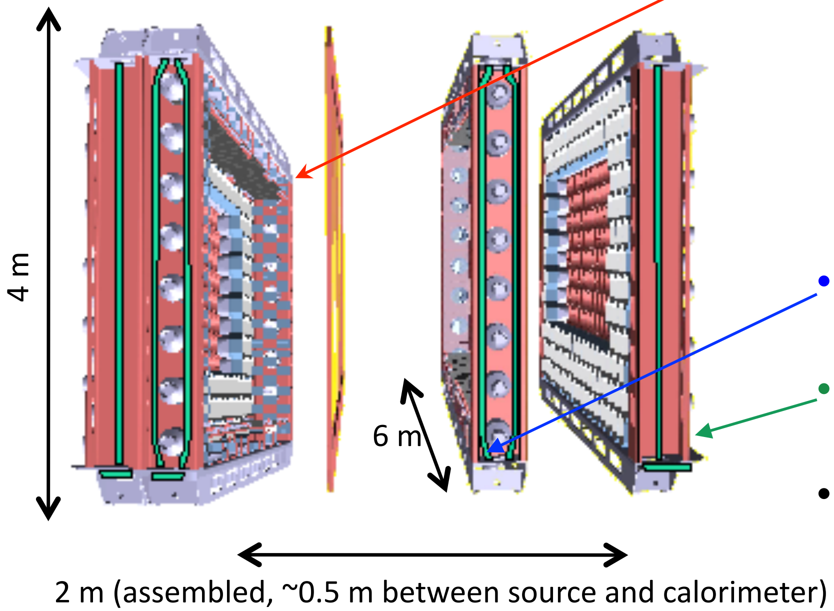
The SuperNEMO Detector

supernemo collaboration

- Modular detector with a planar geometry

1 module (of 20) consists of:

- Source foil:
  - 5 kg (total of 100 kg) of 40 mg/cm^2 (4 x 2.7 m^2)
  - ^{82}Se (high $Q_{\beta\beta}$, long $T_{1/2}^{2\nu\beta\beta}$, proven enrichment technology)
  - ^{150}Nd and ^{48}Ca being considered depending on enrichment possibilities
- Tracker: ~2000 drift cells in Geiger mode
- Calorimeter: ~550 scintillator blocks + PMTs
- Passive shielding (water) surrounding each module



SuperNEMO Sensitivity

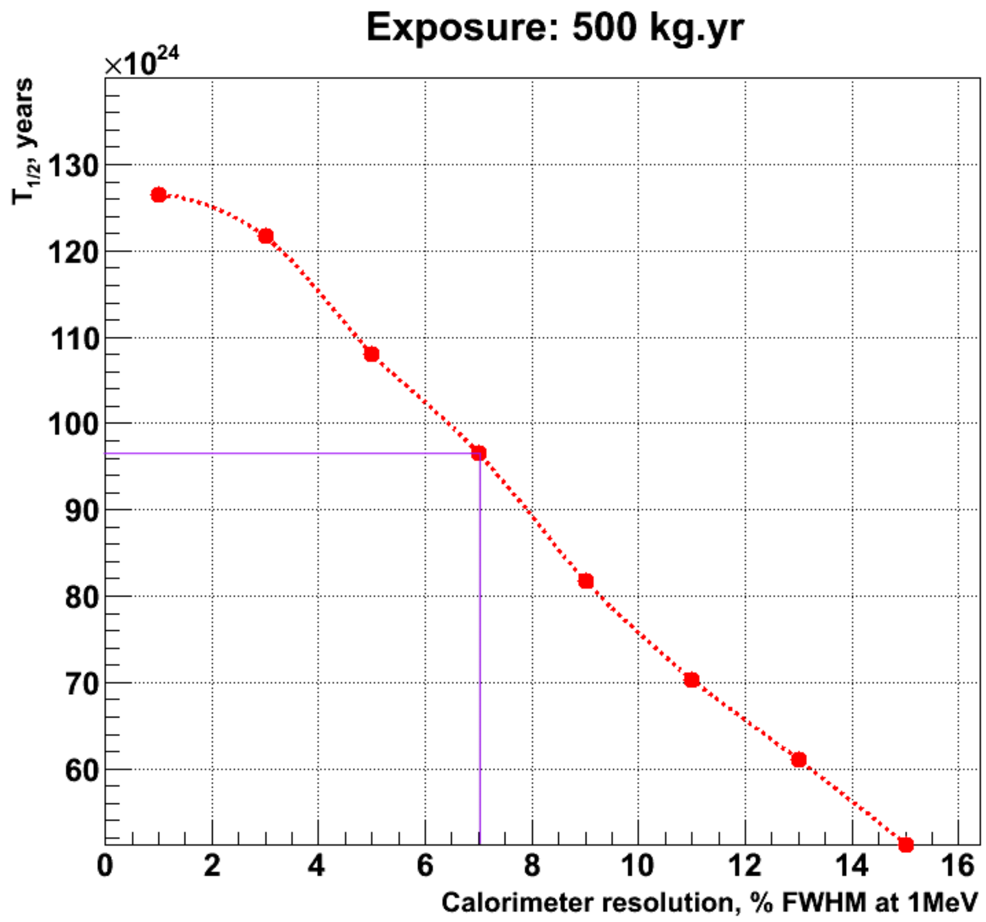
Sensitivity simulations:

- Based on GEANT-4
  - Detector effects
  - Full chain of backgrounds
  - Based on NEMO3 experience

- 500 kg years of ^{82}Se

$T_{1/2} > 10^{26}$ years $\longrightarrow$ $\langle m_\nu \rangle < 0.04 - 0.1$ eV
(90% C.L. with target detector parameters)

- Also look at:
  - Other 0ν mechanisms
  - Disentangling $\langle m_\nu \rangle$ and V+A modes
  - Decay to excited states
  - Other isotopes



SuperNEMO R&D: Source Radiopurity

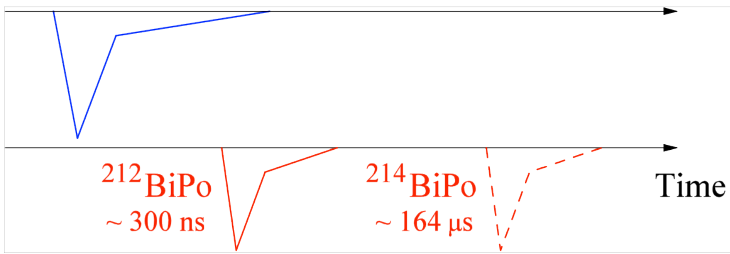
- 5kg of ^{82}Se ready
- Radiopurity requirements:
  - ^{208}Tl < 2 μBq/kg
  - ^{214}Bi < 10 μBq/kg

→ HPGe detectors do not have sensitivity for SuperNEMO requirements

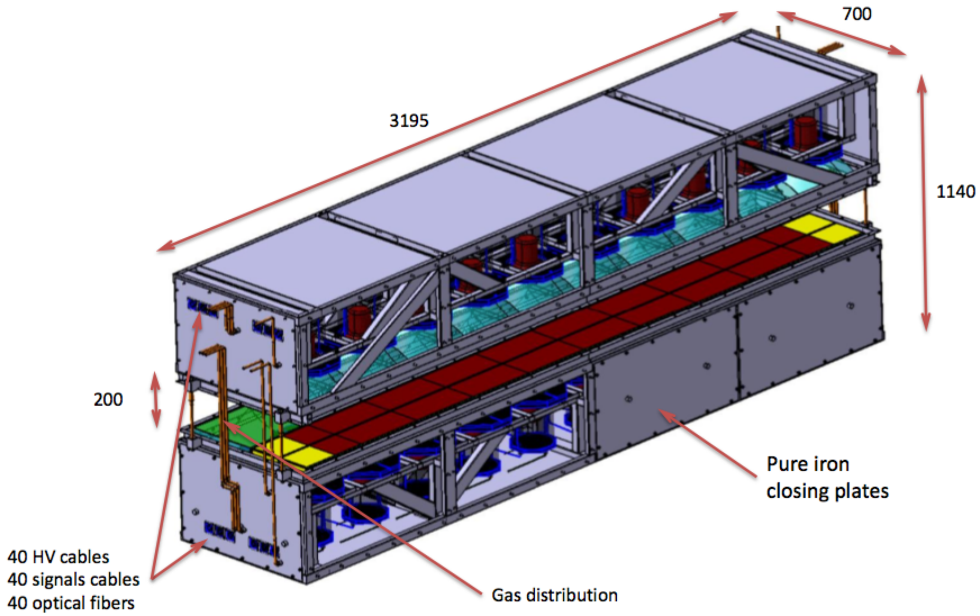
↓ Dedicated BiPo3 detector developed and installed at Canfranc

$$^{214}\mathrm{Bi} \xrightarrow[19.9\ \mathrm{mn}]{\beta} {}^{214}\mathrm{Po} \xrightarrow[164\ \mu s]{\alpha} {}^{210}\mathrm{Pb}$$

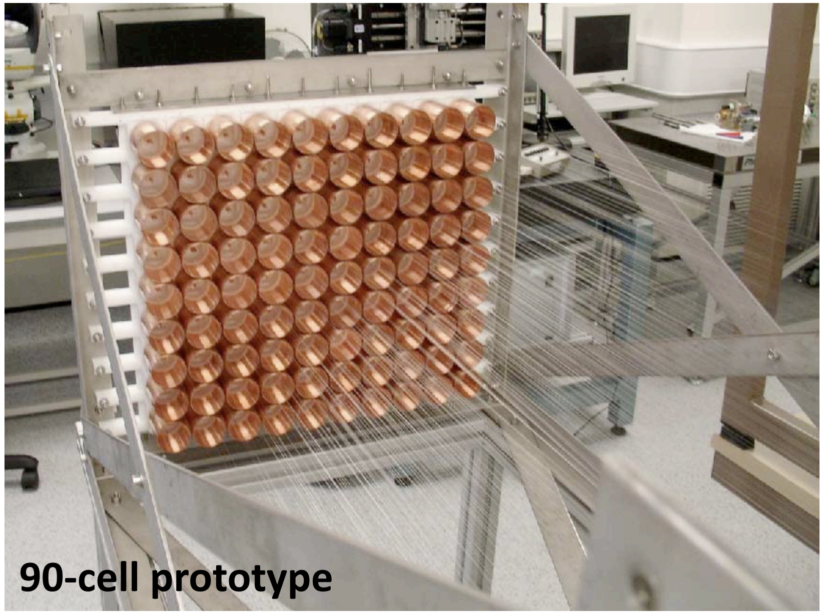
$$^{212}\mathrm{Bi} \xrightarrow[60.5\ \mathrm{mn}]{\beta} {}^{212}\mathrm{Po} \xrightarrow[300\ \mathrm{ns}]{\alpha} {}^{208}\mathrm{Pb}$$

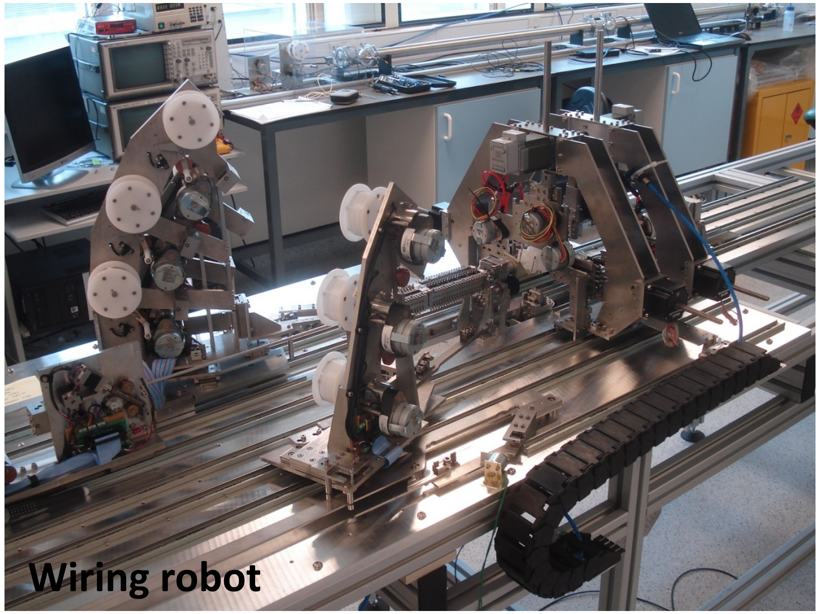


Sensitivity reached in 6 months:
^{208}Tl: ~5 μBq/kg
^{214}Bi: ~15 μBq/kg



SuperNEMO R&D: Tracker

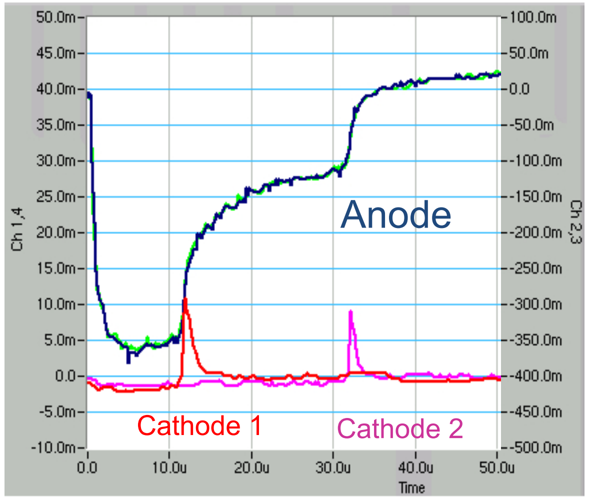




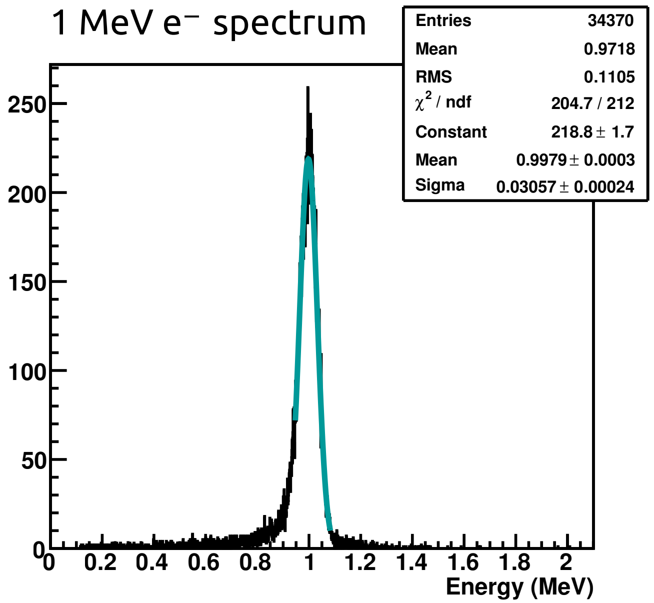
- Design verified with 90-cell prototype
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%

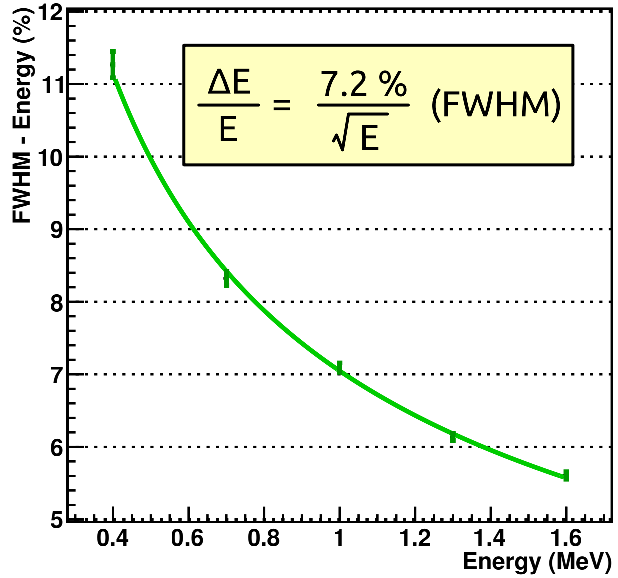
- Automated wiring robot being commissioned for mass production in ultra low background conditions
  - 500000 wires to string, crimp and terminate

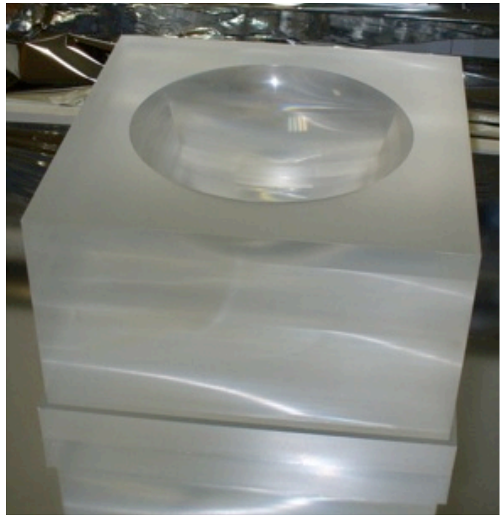
- Readout electronics under development

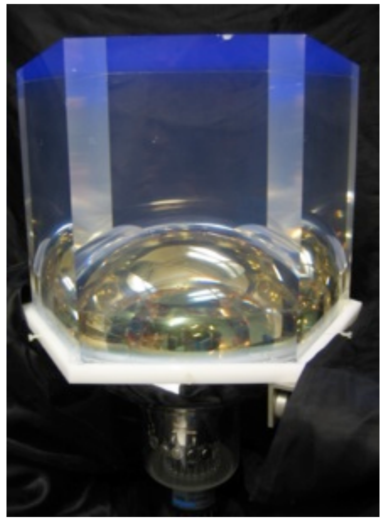


SuperNEMO R&D: Calorimeter









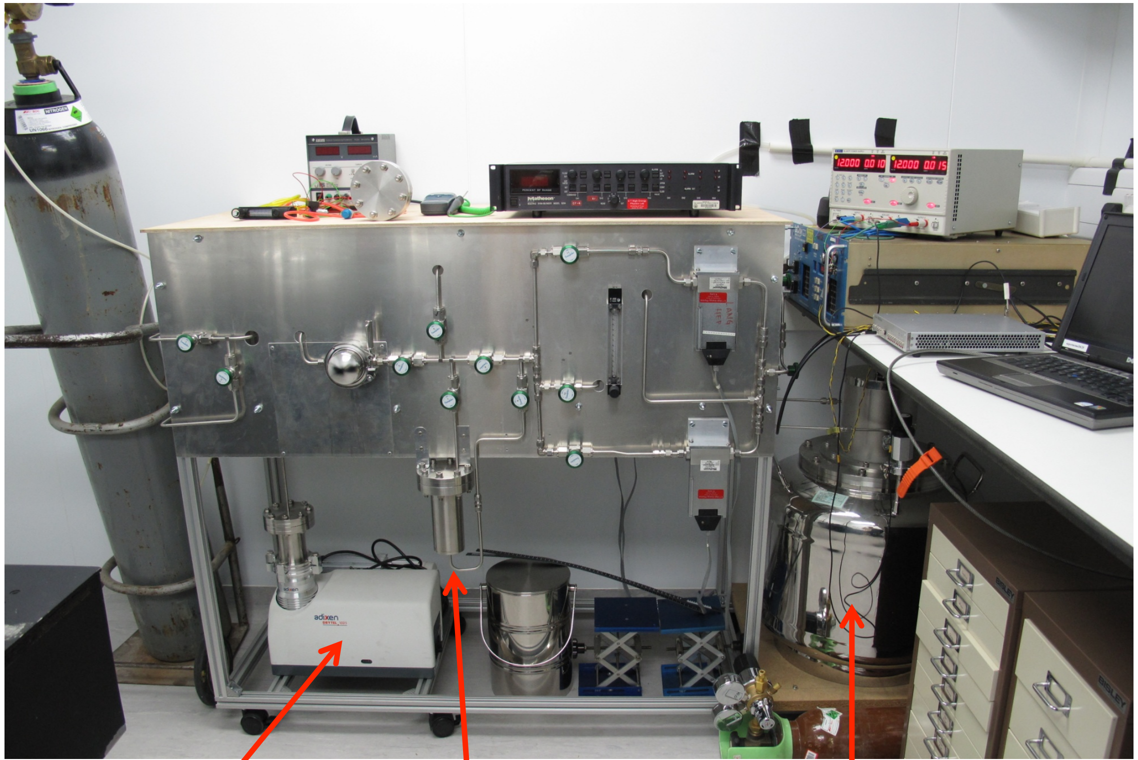
• Target ΔE/E reached with hexagonal and cubic blocks and high QE 8'' Hamamatsu R519MOD PMTs:

7.2% FWHM at 1 MeV

(equivalent to 4% at $Q_{\beta\beta}$ = 3.0 MeV)

(c.f. NEMO3: 14-17% at 1 MeV)

SuperNEMO R&D: Radon



Vacuum pump

Carbon trap

Radon detector
(electrostatic & pin diode)

- SuperNEMO requirement:

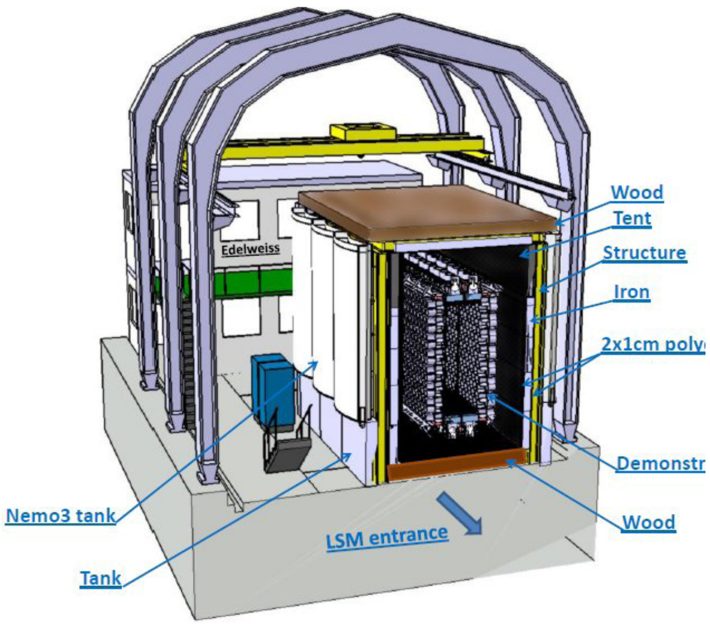
  Rn activity inside tracking volume
  < 150 μBq/m^3

- Radon concentration line developed for:

  - Measurements of Rn emanation from materials
  - Measurements of permeability through membranes and seals

- Radon concentration line sensitivity:
  < 50 μBq/m^3

SuperNEMO Demonstrator Construction



- Physics with 7kg of ^{82}Se in 2.5 years

$T_{1/2}^{0\nu\beta\beta}$ sensitivity > 6.5×10^{24} years

  - Sensitive to Klapdor claim

- A zero background experiment (< 0.06 events/year)

- Test of technology - proof that we can reach required background levels

- Construction is under way

- Location: LSM (in place of NEMO3), to be installed in 2014

SuperNEMO Schedule

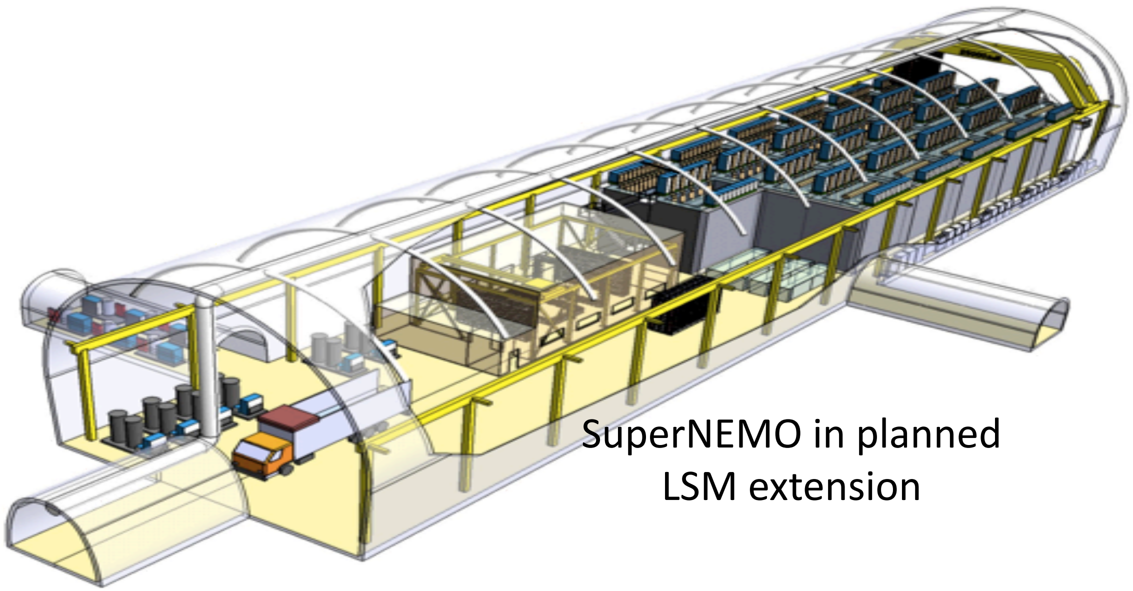
Demonstrator module construction and commissioning (2011–2013)

Demonstrator running (2014–2019)

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

Installation at LSM (2013–2014)

Construction, deployment and running of successive SuperNEMO modules (2015–2021)



Summary

- NEMO-3:
  - 8 years of successful data taking
  - Unique spectrum of results for $2\nu\beta\beta$ (unprecedented results, input for NME calculations) and $0\nu\beta\beta$ (different lepton violating mechanisms probed)

    $T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{24}$ years $\rightarrow$ $\langle m_\nu \rangle < 0.31 - 0.96$ eV (90% C.L.)
  - Analysis of full dataset in progress

- SuperNEMO:
  - Successful R&D to reach sensitivity of 50 – 100 meV by 2020
  - Demonstrator module under construction, to start taking data in 2014
  - Unique detector approach:

  event topology, isotope flexibility, modularity, probing of different $0\nu\beta\beta$ mechanisms

Backup Slides

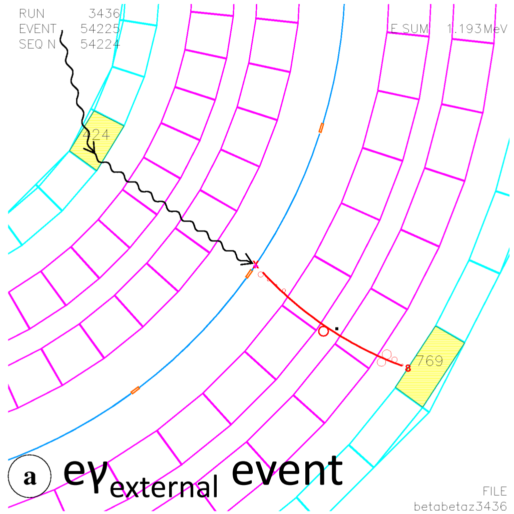
NEMO-3 Backgrounds (2)

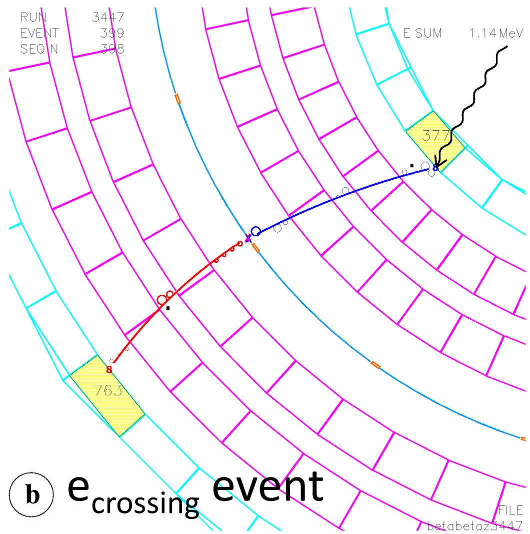
Each background is measured using NEMO-3 data:

Channel	Background measurement
$e\gamma_{external}$ $e_{crossing}$	External background: ^{40}K, ^{60}Co, ^{226}Ra etc.
e	Pure β emitters in foil: ^{40}K, ^{234m}Pa, ^{90}Y etc.
eγ eγγ eγγγ	β + Y emitters in foil: ^{207}Bi, ^{208}Tl, ^{214}Bi etc.
eα	^{222}Rn in gas and ^{214}Bi on foil and wires

• Analysis of external, internal and radon background through independent channels
• The background model is validated with a dedicated foil in the detector (pure Cu)

[NIM A606 (2009) 449-465]





SuperNEMO Sensitivity

$$T_{1/2}^{0\nu\beta\beta} > \frac{\ln 2\, N_A}{A} \frac{\eta}{\kappa_{CL}} \sqrt{\frac{Mt}{N_{bkg}\Delta E}}$$

↓

N_{bkg} (NEMO-3) $< 10^{-3}$
N_{bkg} (SuperNEMO) $\sim 6 \times 10^{-5}$

N_A = Avogadro's number,
A = atomic mass of isotope,
η = detector efficiency,
κ_{CL} = number of σs corresponding to the confidence level (1.64σ for a 90% C.L.),
M = isotope mass,
t = exposure time,
N_{bkg} = background index (in $kg^{-1}keV^{-1}yr^{-1}$),
ΔE = energy window of $0\nu\beta\beta$ decay at $Q_{\beta\beta}$ value, approximated by $\Delta E/E$ (energy resolution)