Latest results from NEMO-3 and status of SuperNEMO

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On behalf of the NEMO-3/SuperNEMO collaboration

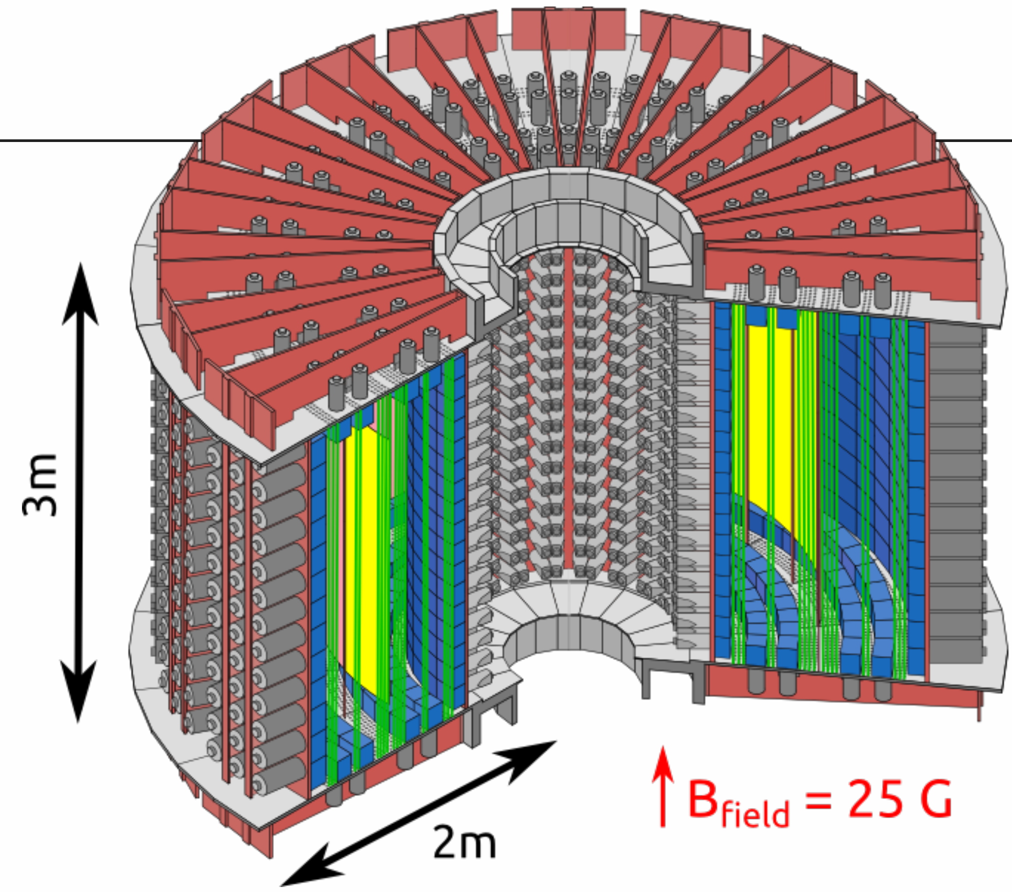
NEMO-3

ββ decay experiment combining tracker and calorimetric measurement

Located at the Modane underground laboratory (~4800 m.w.e.)

10 kg of different ββ isotopes

Taking data from February 2003 to January 2011



sources
60 mg/cm² foils
10 kg of ββ isotopes

tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

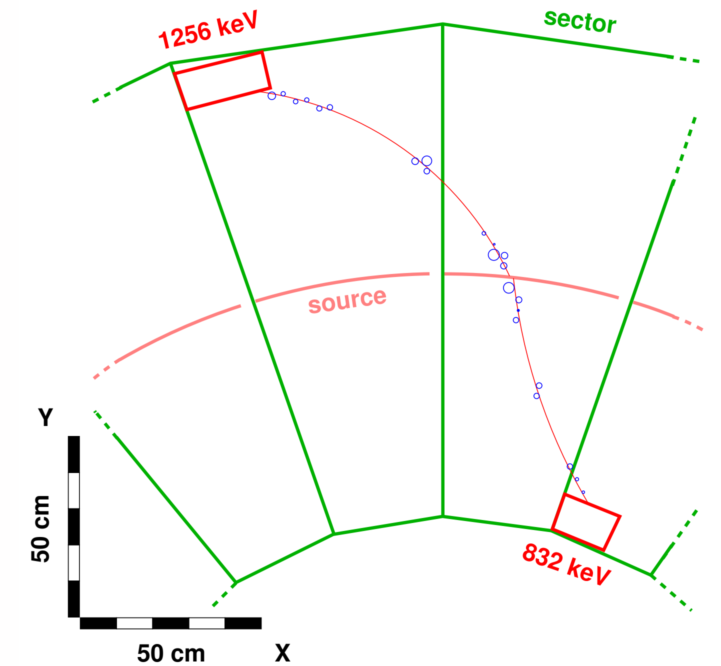
calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

Full reconstruction of 2e⁻ kinematics: unique!

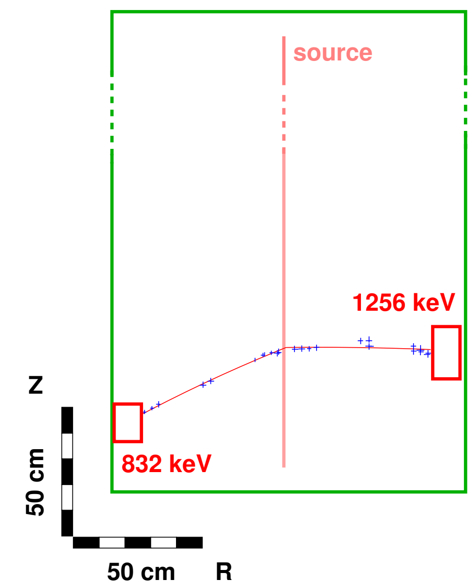
Excellent background rejection

Equivalent to best calorimetric experiment

Top view



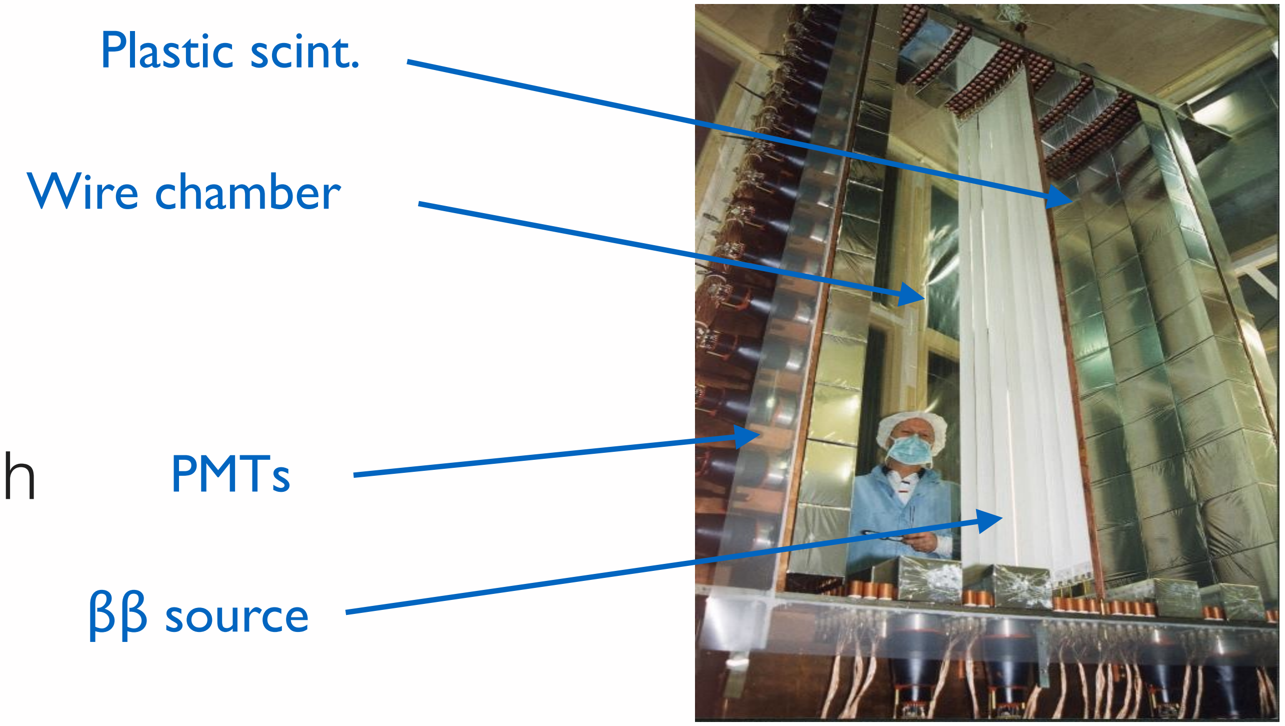
Longitudinal view



NEMO-3: the detector

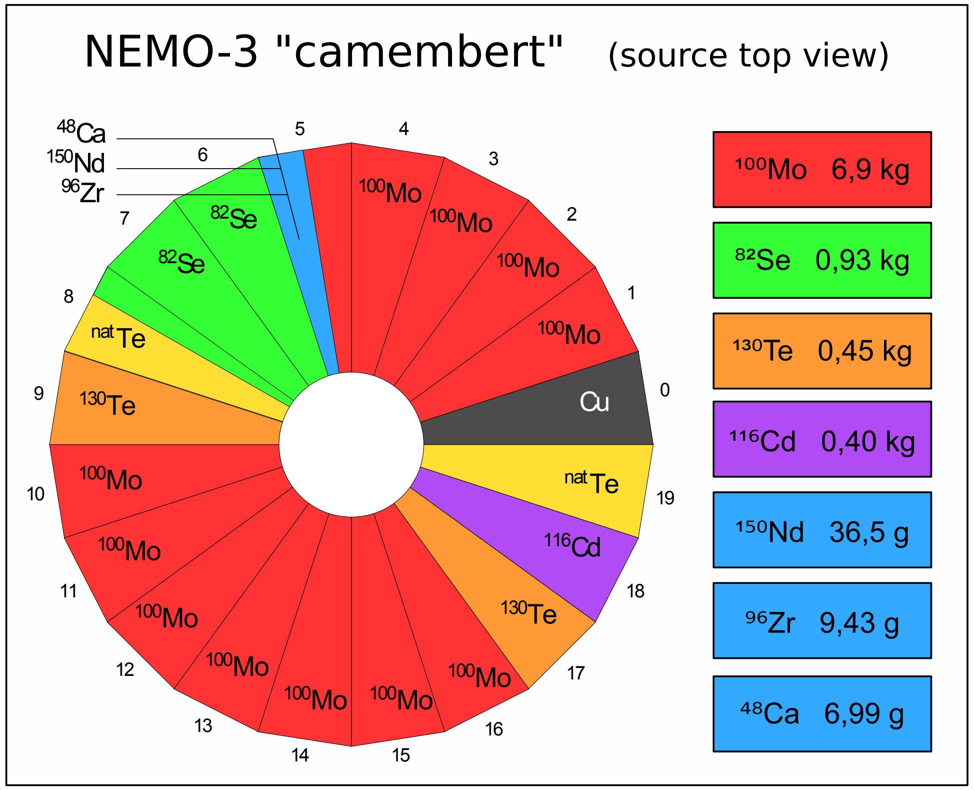
The detector:

- Central ββ source plane
- Wire drift chamber in Geiger mode
- Plastic scintillator calorimeter coupled with low radioactivity PMTs
- Gamma & Neutron shield



The ββ source:

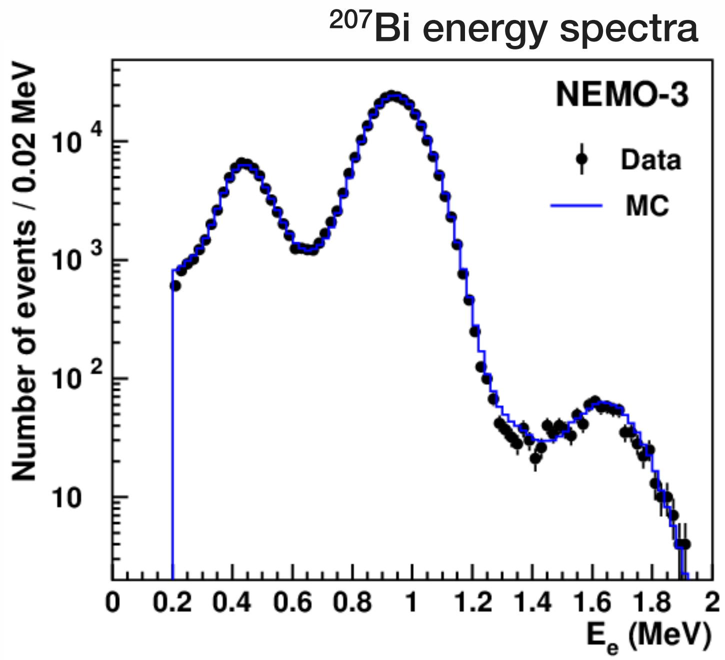
- 7 different isotopes: Mainly ^{100}Mo (7 kg) & ^{82}Se (1 kg)
- Cu & ^{Nat}Te blank foils: Cross-check background measurements



NEMO-3: energy calibration

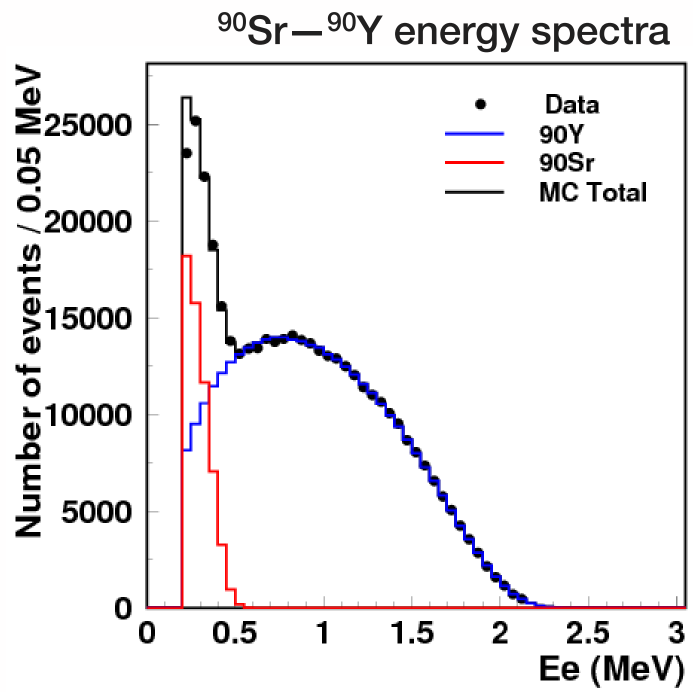
Radioactive sources:

- ^{207}Bi: 482 keV and 976 keV conversion electron
- $^{90}Sr - ^{90}Y$: β-decay end point Q_β = 2280 keV
- ^{207}Bi: 1682 keV conversion electron to test energy scale: 99% PMTs Data/MC < 0.2%



Laser inter-calibration system:

- Gain and time survey twice a day PMTs linearity < 1% for E < 4 MeV
- 82% of PMTs stable < 5% over the whole data taking



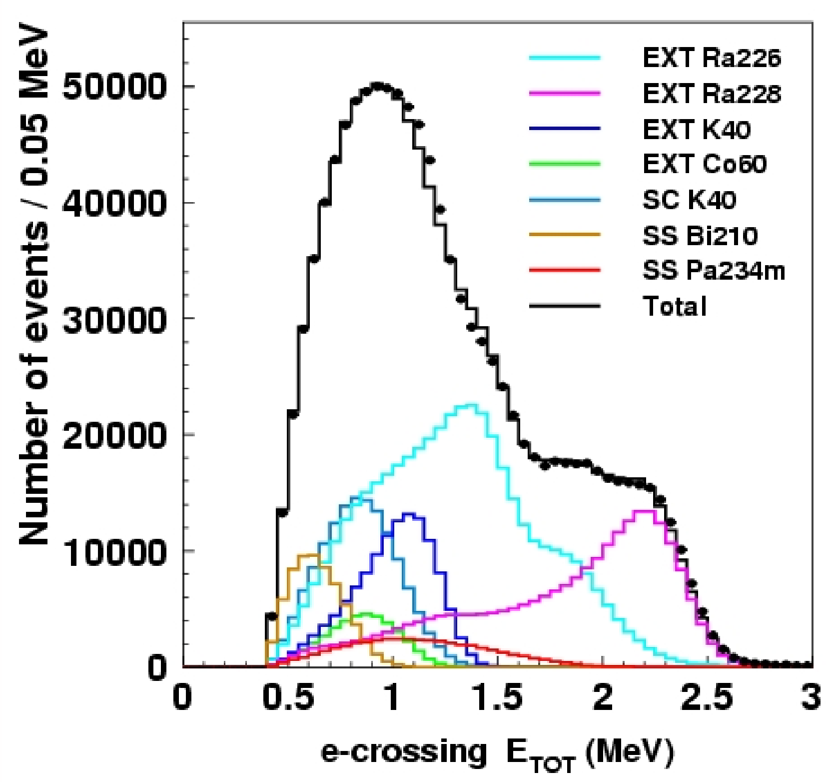
NEMO-3: backgrounds

[NIM A 606: 449-465, 2009]

External background:

- Radio-impurities in surrounding material, γ from (n,γ)
- μ bremsstrahlung

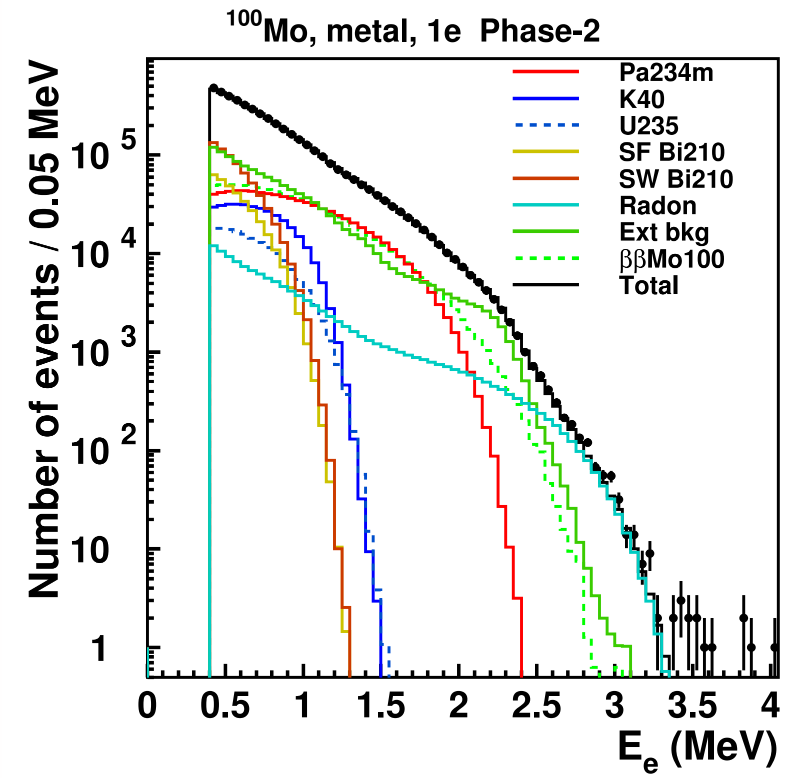
Measured through e^- + γ and e^- crossing channels



Internal background:

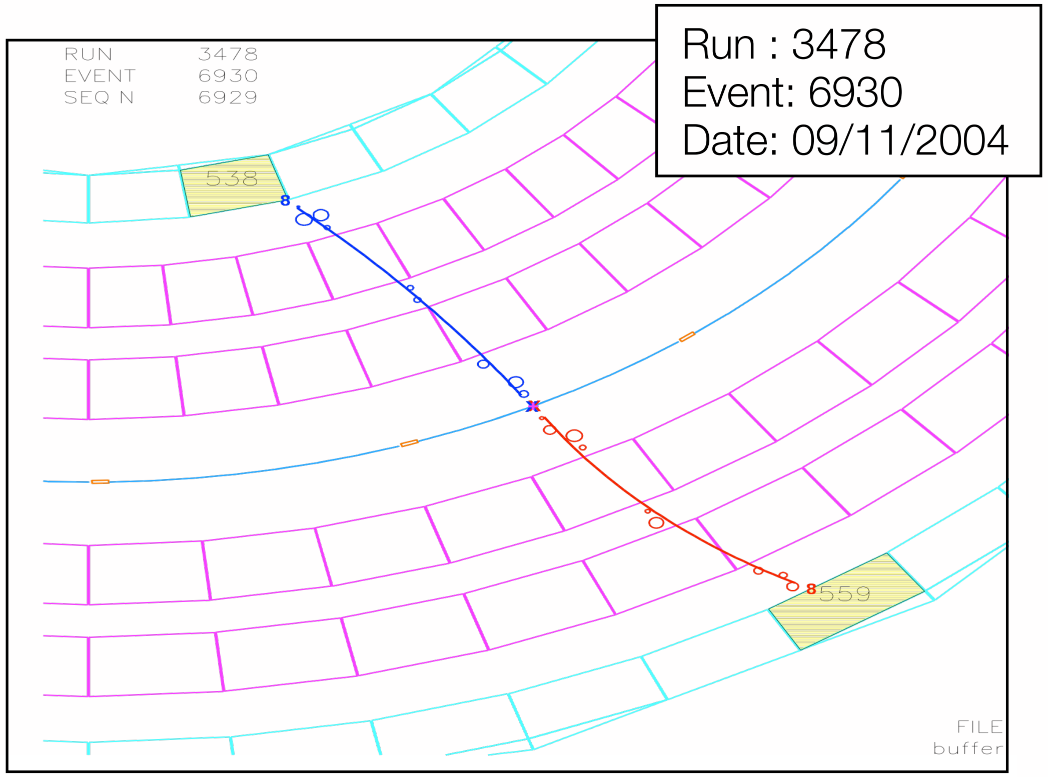
- ^{208}Tl and ^{214}Bi contamination in foil source
- ^{214}Bi from Rn decay in tracker volume

Measured through e^- + Nγ, e^- + α and single e^- channels



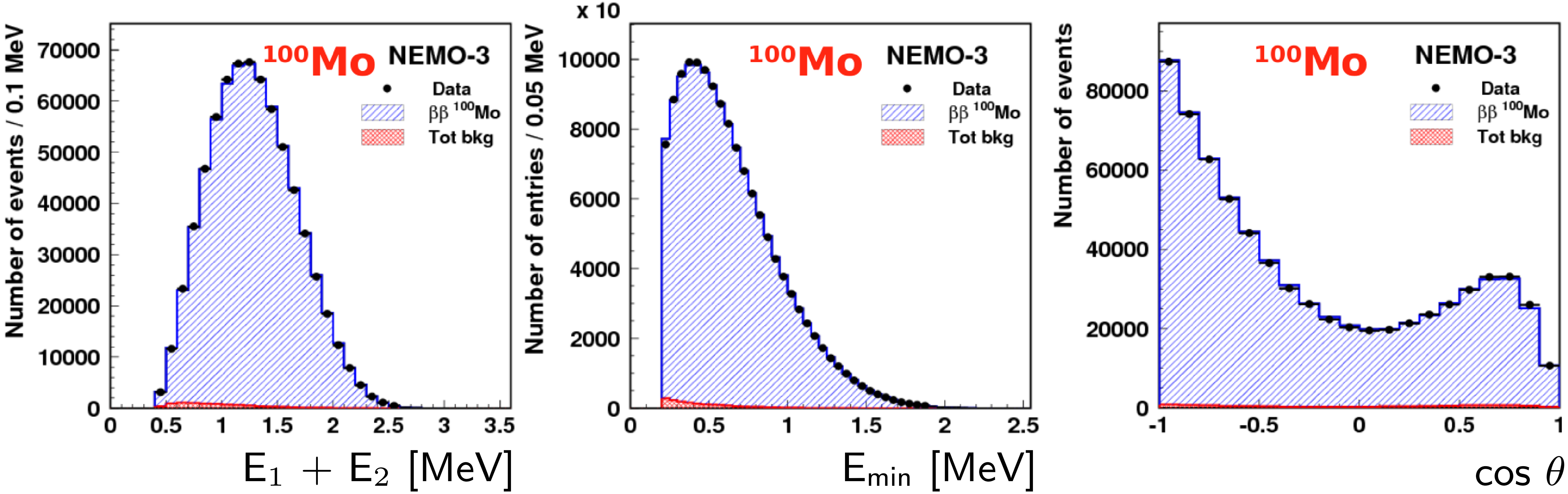
NEMO-3: ^{100}Mo 2νββ results

- About 700 000 2νββ events
- Detection efficiency = 4.3 ± 0.7 %
- Signal over Background ratio = 76



$T^{2\nu}_{1/2} = [\ 7.16 \pm 0.01\ (stat) \pm 0.54\ (syst)\ ] \times 10^{18}\ y$

Consistent with previously published [PRL 95 (2005) 182302]

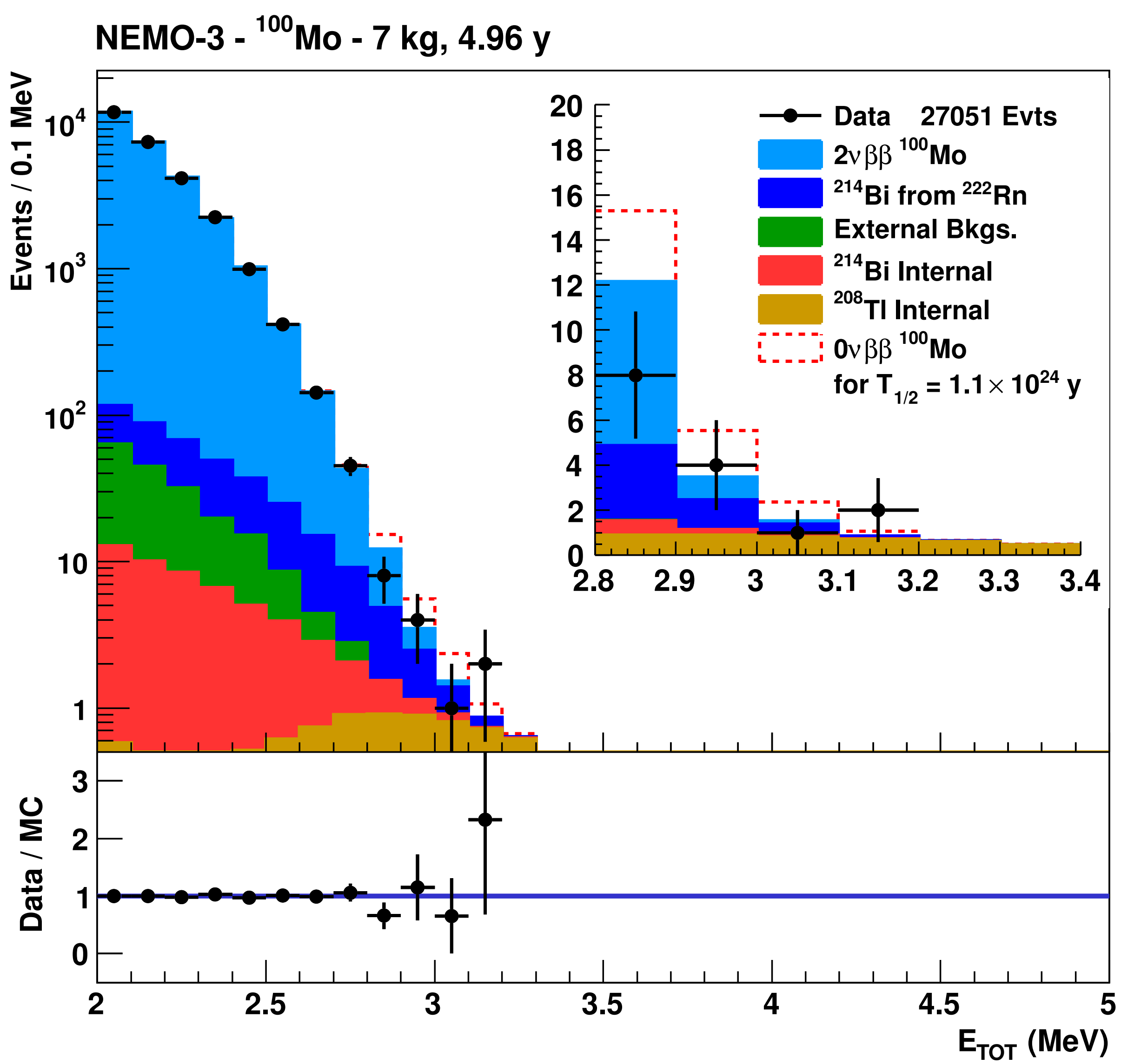


[Phys. Rev. D. 89.111101 (2014)]

Detailed paper to be published in the following weeks

NEMO-3: ^{100}Mo 0νββ result

- No event excess after 34.3 kg×y exposure
- $T^{0\nu}_{1/2} > 1.1\times10^{24}$ y (90 % C.L.) → $\langle m_\nu \rangle < 0.3 - 0.9$ eV



Expected background in [2.8 - 3.2] MeV

2νββ	8.45 ± 0.05
^{214}Bi from radon	5.2 ± 0.5
External	< 0.2
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
Total	18.0 ± 0.3
Data	15

Total background: 1.3×10^{-3} cts / (keV×kg×y)

[Phys. Rev. D. 89.111101 (2014)]

Detailed paper to be published in the following weeks

NEMO-3: ^{100}Mo 0νββ result

- $T^{0\nu}_{1/2}$ limit set with a modified frequentist analysis [N.I.M. A 434 (1999) 435]
- Using full information in E_{Tot} = [2.0; 3.2] MeV
- Detection efficiency: 11.3 ± 0.8 %
- Account for statistical and systematic uncertainties and their correlation

Systematics

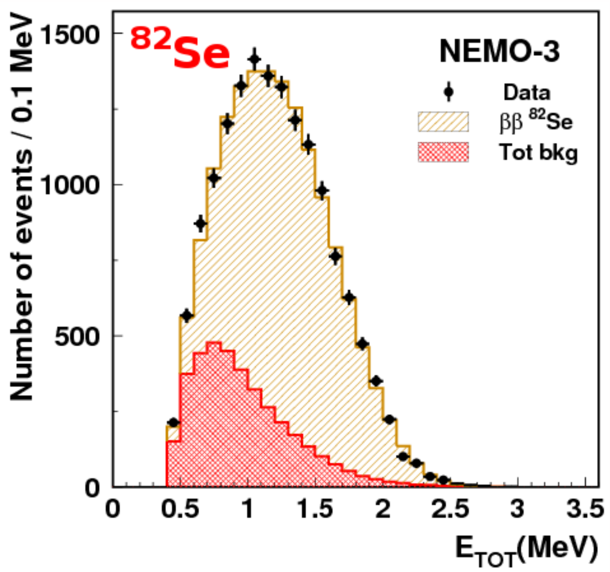
0νββ detection efficiency	7.0%
2νββ events in window	0.7%
^{214}Bi contamination	10.0%
^{208}Tl contamination	10.0%

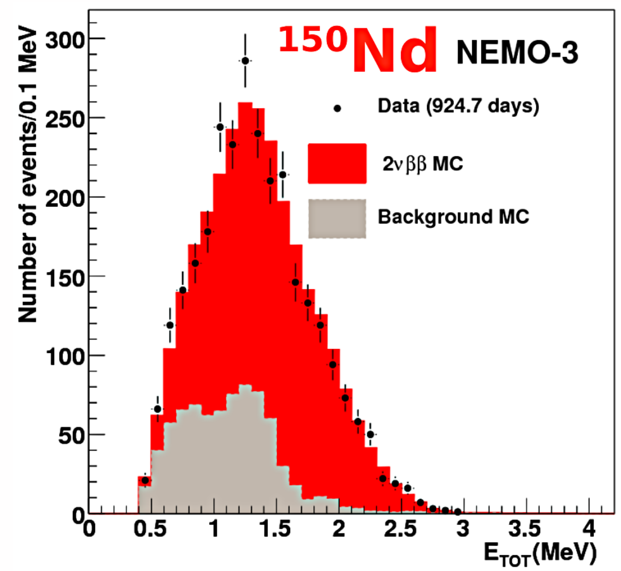
Limits at 90% C.L. in units of 10^{24} y

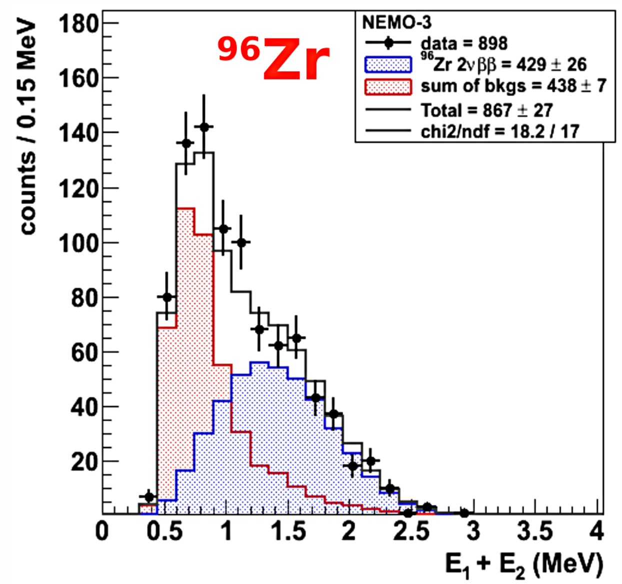
Process	Stat. Only	Stat. + Syst.	Expected
Mass mechanism	1.1	1.1	1.0 [0.7; 1.4]
RH Current ⟨λ⟩ ($q_{r.h.}$ — $l_{r.h.}$)	0.7	0.6	0.5 [0.4; 0.8]
RH Current ⟨η⟩ ($q_{l.h.}$ — $l_{r.h.}$)	1.0	1.0	0.9 [0.6; 1.3]
Majoron (n=1)	0.050	0.044	0.039 [0.027; 0.059]

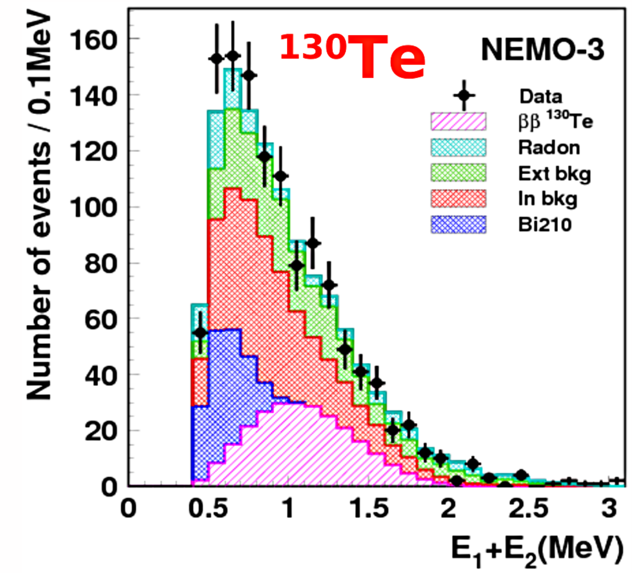
NEMO-3: other results

Other isotopes: only partial exposure has been published









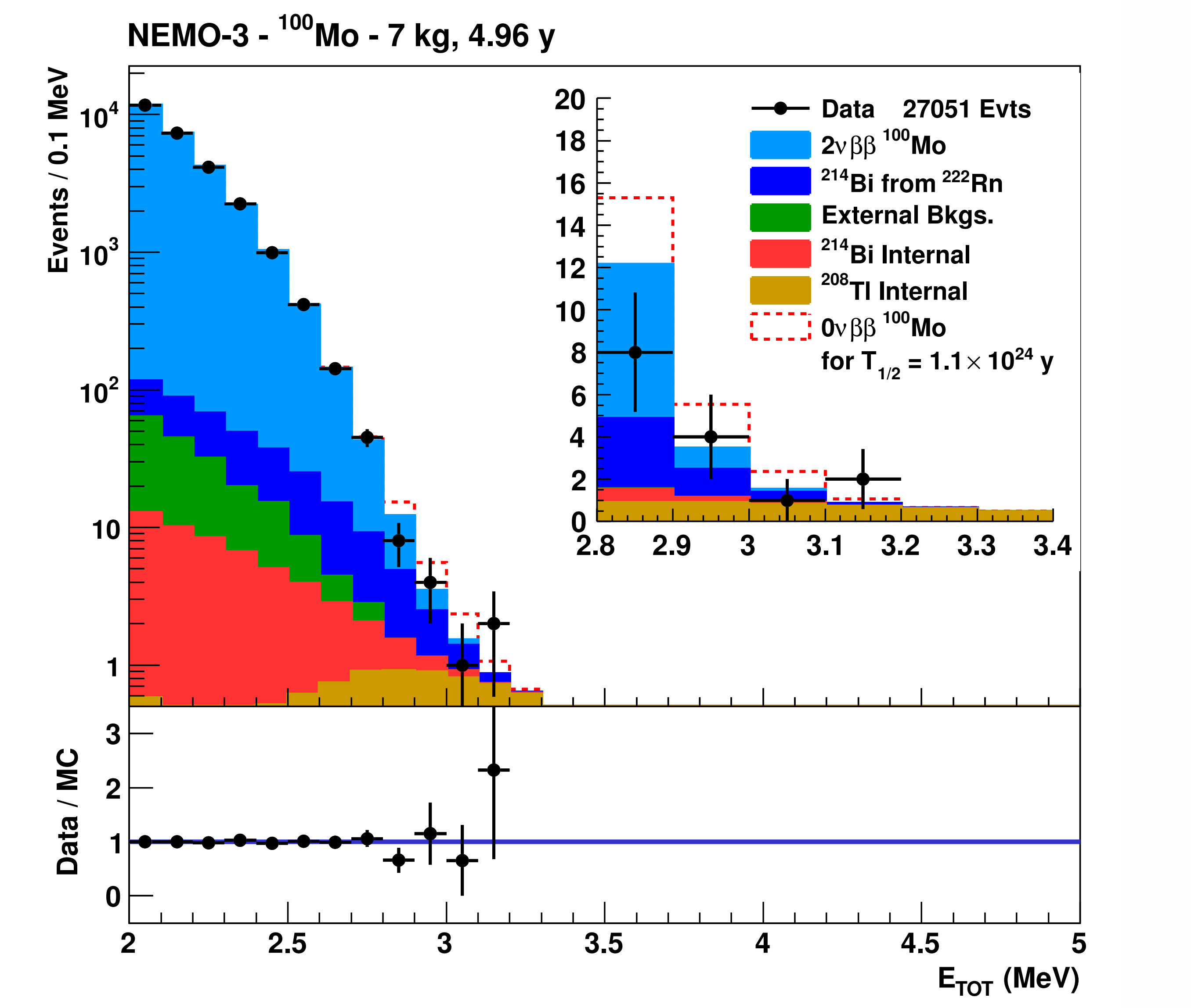
Isotope	Mass [g]	Exposure [days]	$T_{1/2}$ (2ν) [x 10^{19} y]	$T_{1/2}$ (0ν) [y] @ 90% C.L.	⟨$m_ν$⟩ [eV] @ 90% C.L.	Reference
^{82}Se	932	389	9.6 ± 1.0	> 1.0 x 10^{23}	< 1.7 - 4.9	Phys.Rev.Lett. 95 (2005) 182302
^{150}Nd	37	925	0.90 ± 0.07	> 1.8 x 10^{22}	< 4.0 - 6.3	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	1221	2.35 ± 0.21			Nucl.Phys.A 847(2010) 168
^{130}Te	454	1275	70 ± 14			Phys. Rev. Lett. 107, 062504 (2011)

Analysis of whole statistics ongoing (^{82}Se, ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{150}Nd)…stay tuned!

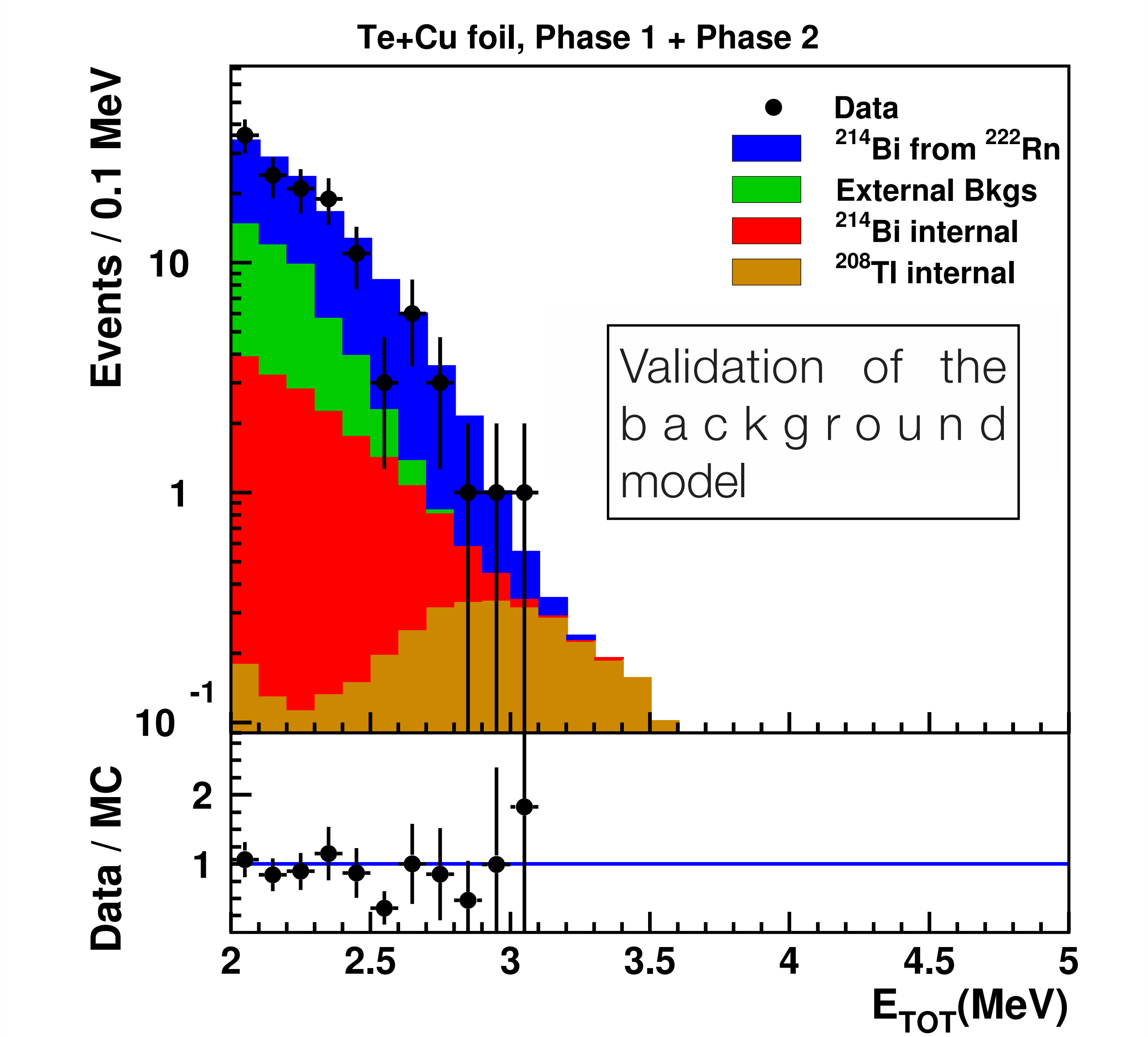
^{100}Mo 0νββ decay to the ^{100}Ru excited states [Nuclear Physics A781 (2007) 209-226]

NEMO-3: high energy background

No events in ^{100}Mo foils
after 34.3 kg×y > 3.2 MeV



No events in Cu & Te foils
after 13.5 kg×y > 3.1 MeV



Promising background free technique for high $Q_{\beta\beta}$ isotopes

^{48}Ca (4.272 MeV), ^{150}Nd (3.368 MeV) or ^{96}Zr (3.350 MeV)

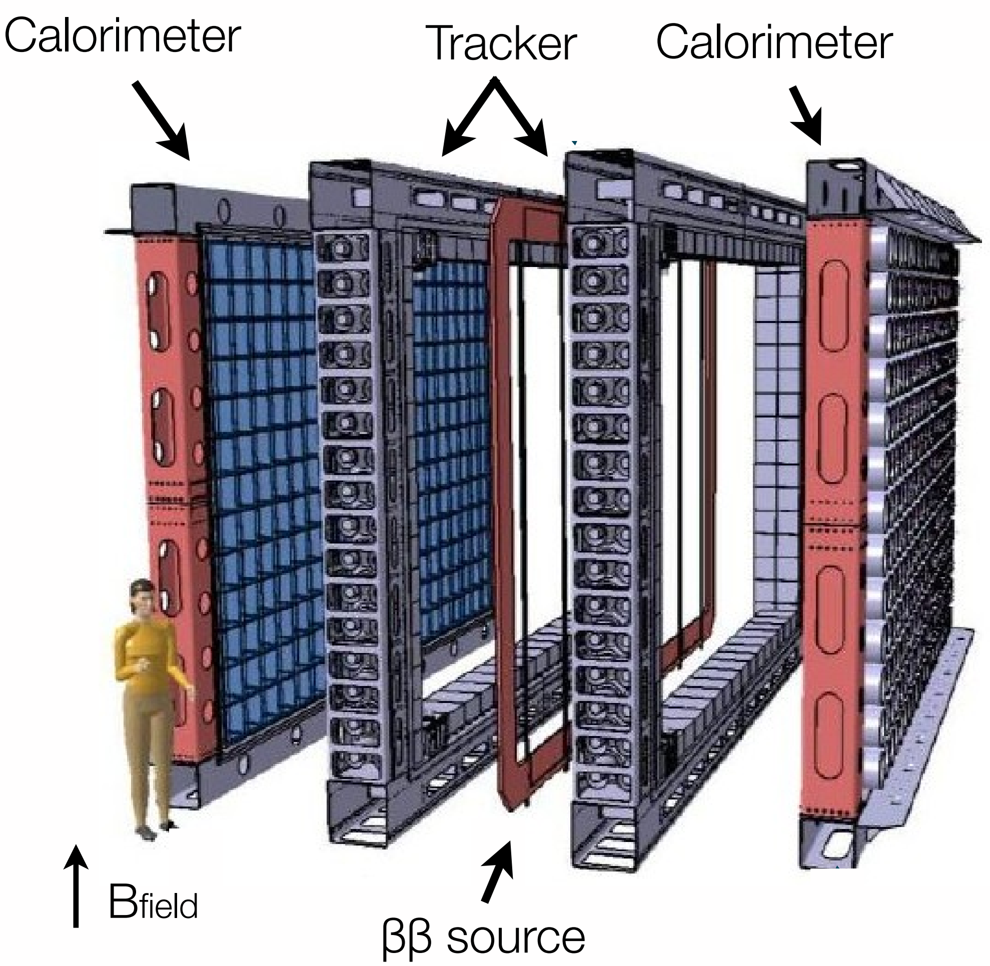
[Eur. Phys. J. C70: 927-943,2010]

SuperNEMO: toward the new generation

Extrapolate a well known technique:

- 100 kg of ββ emitter in 20 detection module
- Approach Inverted Hierarchy region

	NEMO-3	SuperNEMO
Efficiency	18%	~30%
Isotope	7 kg ^{100}Mo	~100 kg ^{82}Se (^{150}Nd, ^{48}Ca)
Exposure	35 kg y	~500 kg y
Energy res.	8% @ 3 MeV	4% @ 3 MeV
^{208}Tl (source)	~100 μBq/kg	< 2 μBq/kg
^{214}Bi (source)	~ 300 μBq/kg	< 10 μBq/kg
Rn (in tracker)	5 mBq/m^3	0.15 mBq/m^3
$T_{1/2}$	10^{24} y	10^{26} y
$\langle m_\nu \rangle$	0.3 - 0.9 eV	0.04 - 0.1 eV



A challenge in many aspects:

- R&D program in the past years almost completed!
- Next step: Demonstrator module

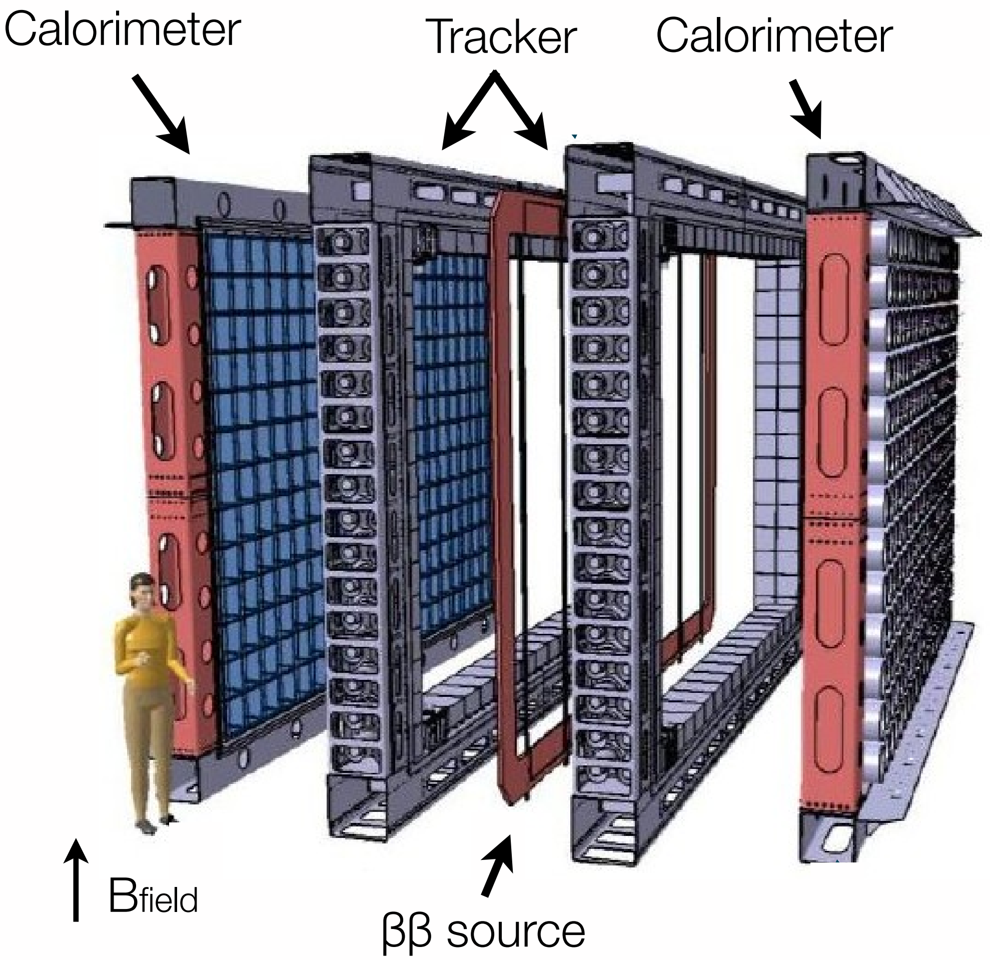
SuperNEMO: the demonstrator module

One SuperNEMO module → 7 kg ^{82}Se running ~2.5 y

- To be installed @ LSM (replacing NEMO-3)
- Match SuperNEMO requirements

Reach NEMO-3 (^{100}Mo) sensitivity in 4.5 months

- Sensitivity: $\langle m_\nu \rangle$ ~ 0.20 - 0.40 eV

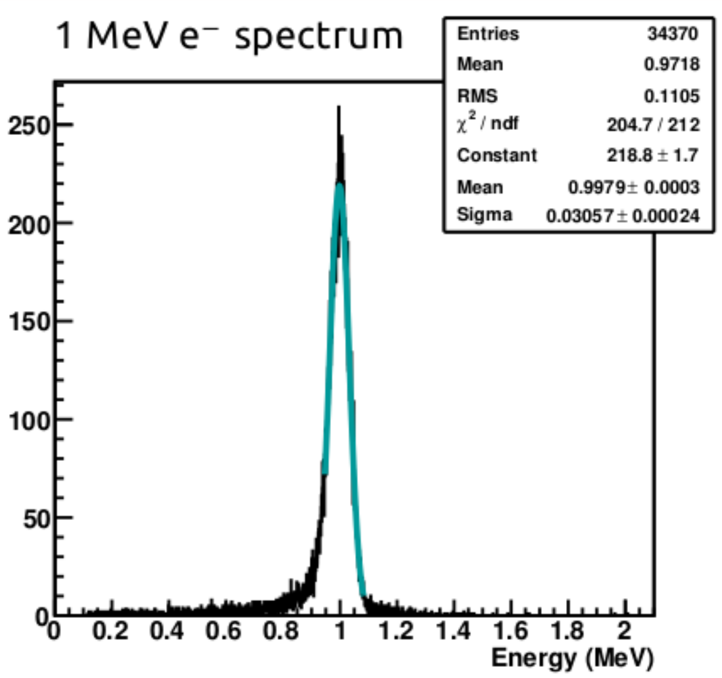


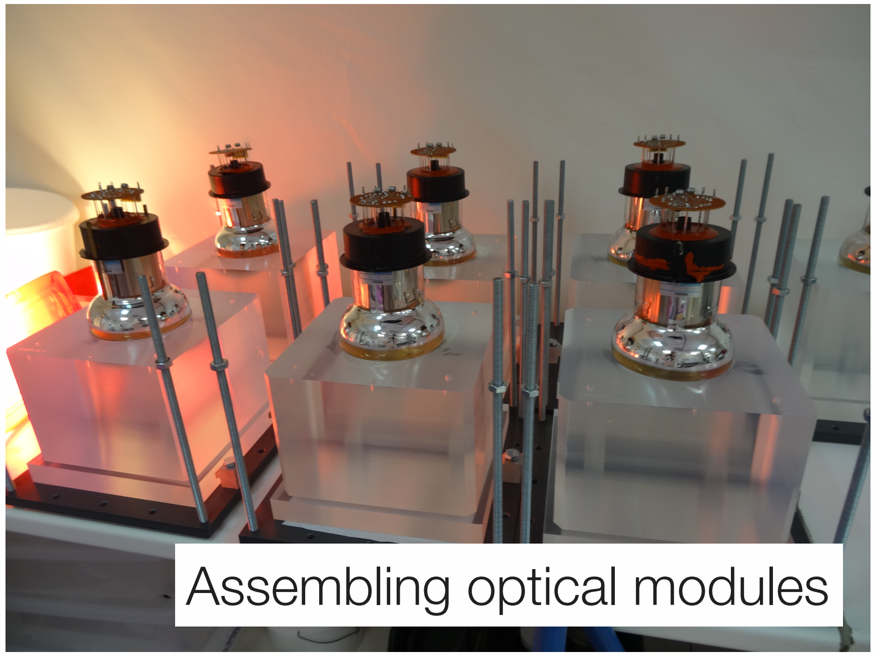
Schedule:

- Calorimeter & tracker under production
- Installation starting in 2015
- Commissioning & First data by 2016

SuperNEMO: the calorimeter

- 5” and 8” high quantum efficiency PMT directly coupled to a scintillator block with optimised geometry
- Energy resolution tests: 7.8 % FWHM @ 1 MeV
- Electronics, optical modules, shield & mechanical structure under production

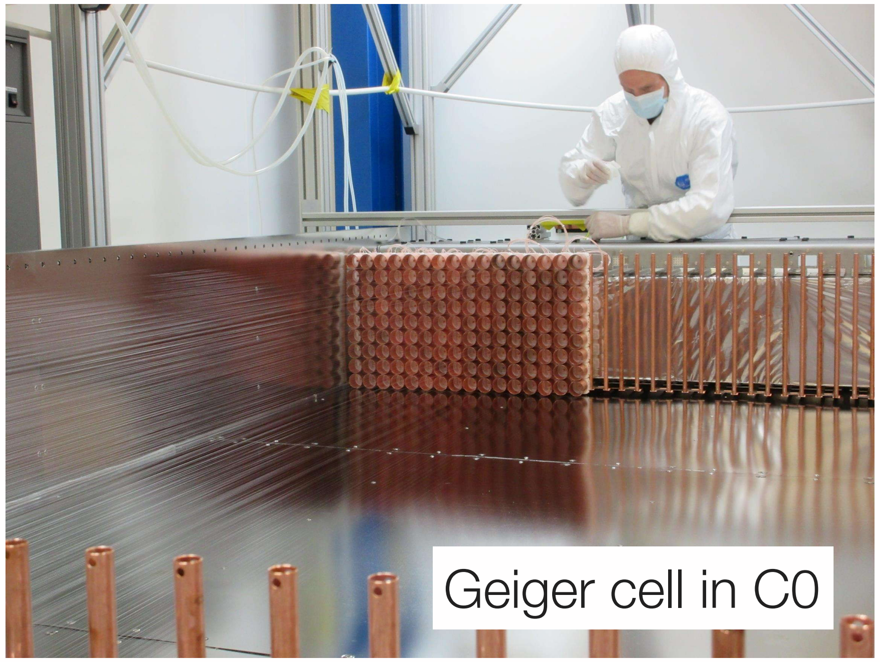


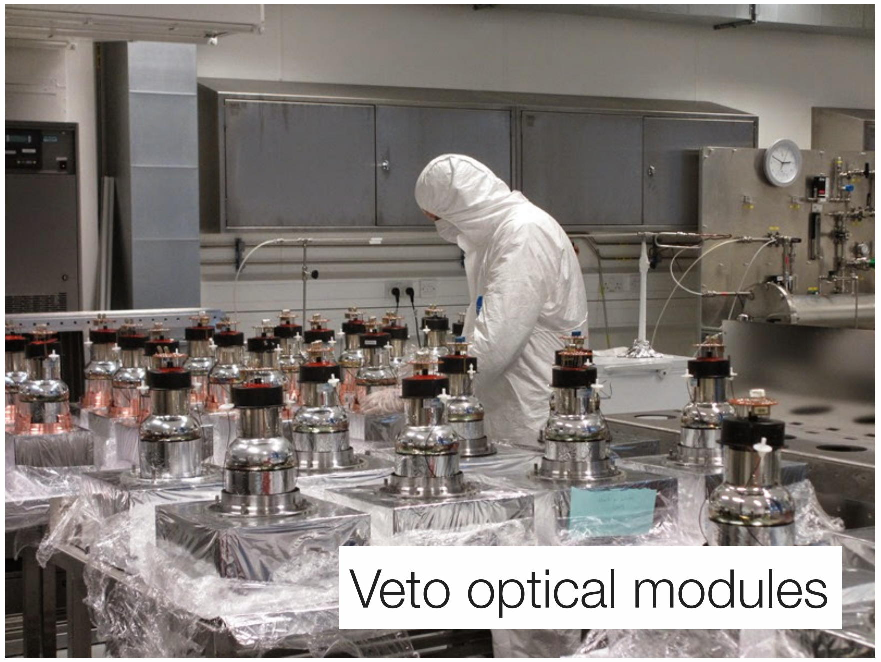

Assembling optical modules

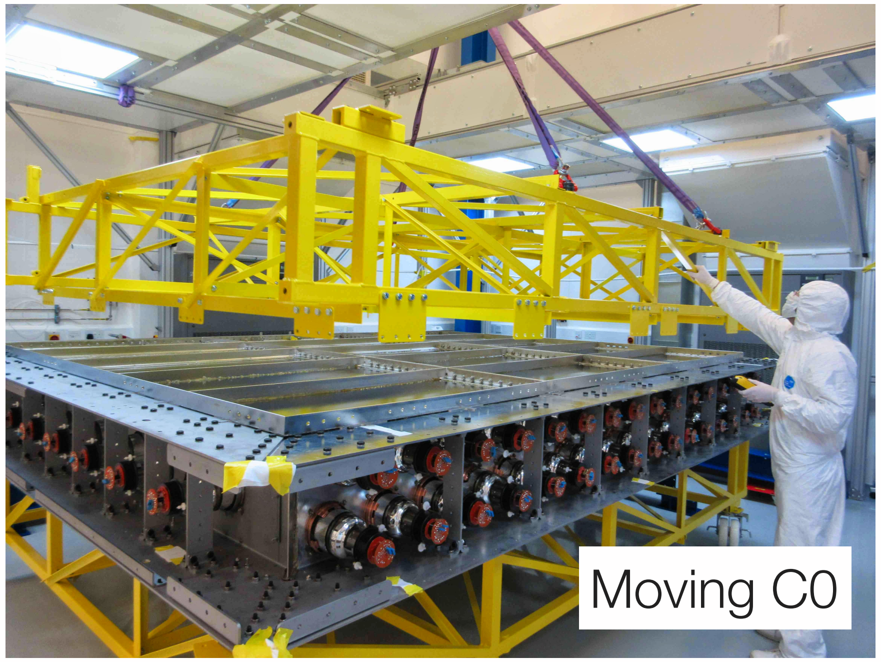

Calorimeter main wall

SuperNEMO: the tracker

- 2034 Geiger cells in a Rn-tight tracker chamber surrounded by Optical Modules
- Drift cells under production. Tracker assembly in 4 pieces (C0 to C3)
- Commissioning of C0 ongoing at sea level, C1 under construction.
- Preliminary radon emanation : 0.236 ± 0.035 mBq/m^3 — close to the requirement!

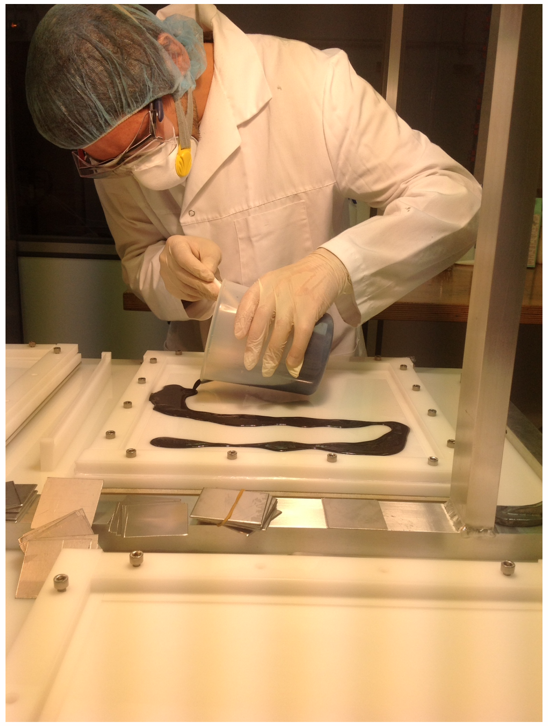

Geiger cell in C0


Veto optical modules

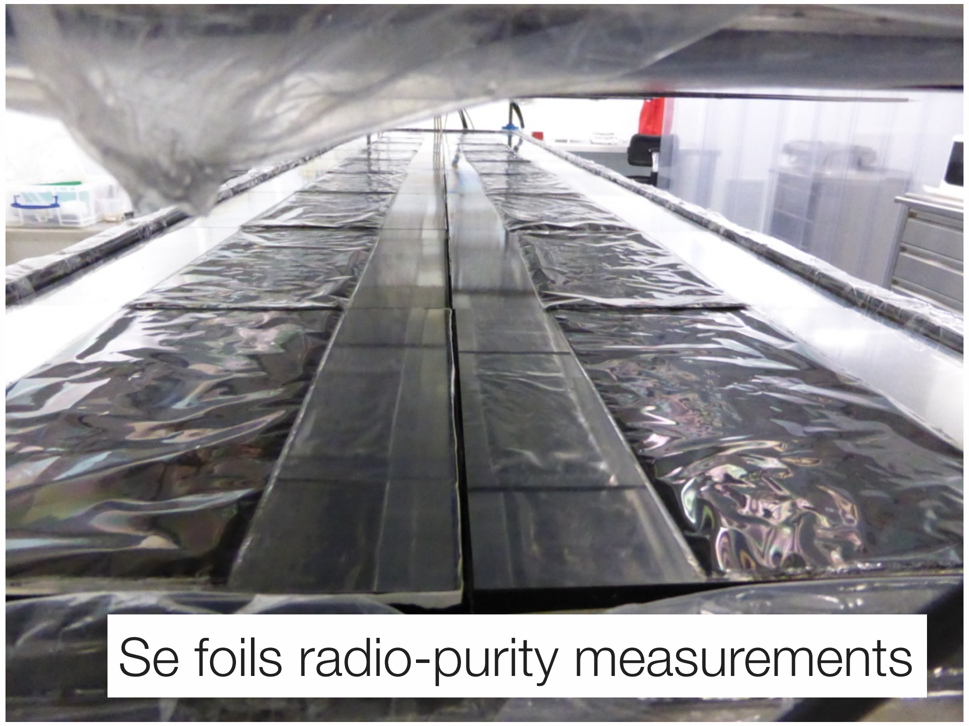

Moving C0

SuperNEMO: the source foil

- About 37 foils installed on the source frame in the detector center
- ^{82}Se powder mixed with PVA glue + mylar or nylon mechanical support
- Limits on foil contamination in ^{208}Tl (2 μBq/kg) and ^{214}Bi (10 μBq/kg) are challenging
- Purification technique under investigation: chemical chromatography, distillation, etc.

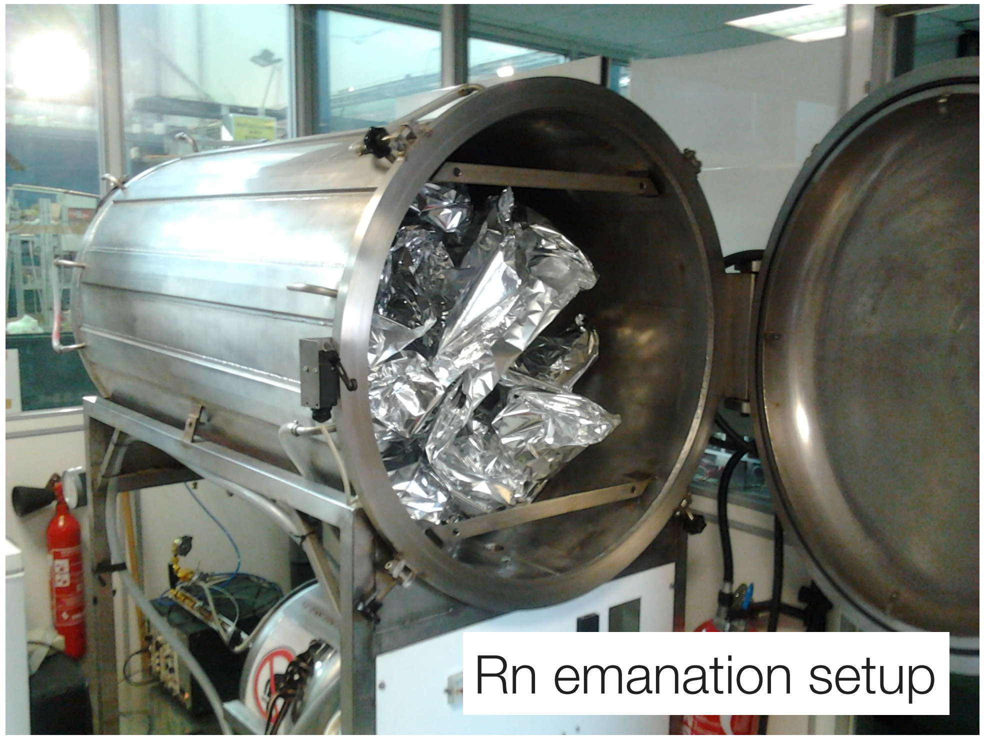


Training foil production technique



Se foils radio-purity measurements

SuperNEMO: radio-purity measurements

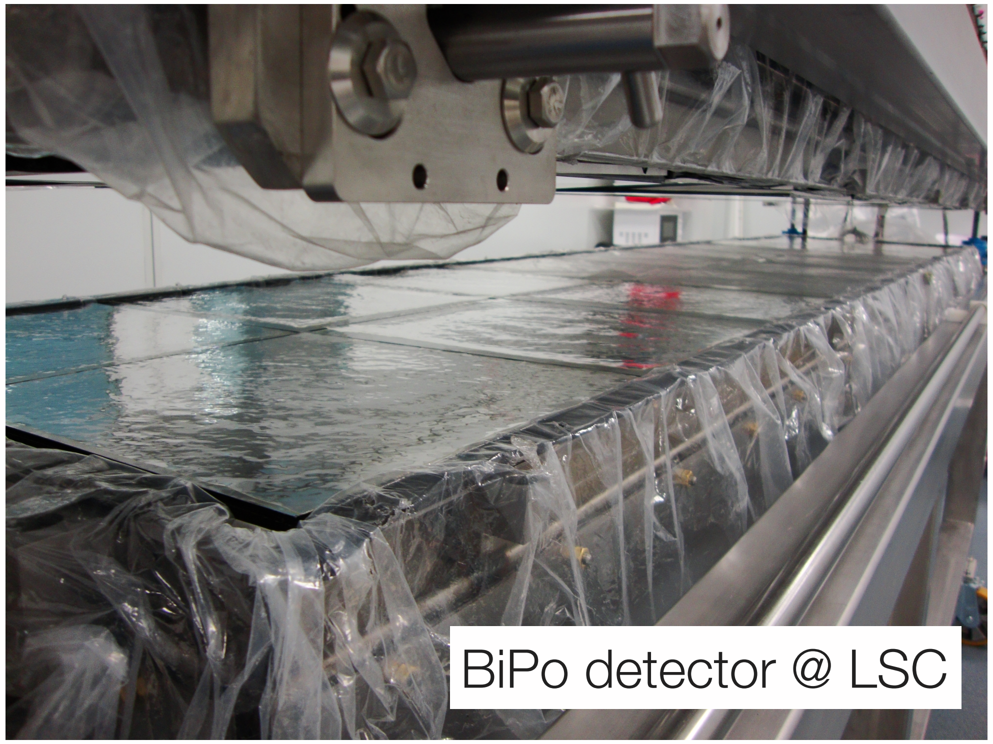


Radon:

- Control the Radon emanation of the materials
- Radon purification/absorption with dedicated setup

Detector radio-purity budget:

- Material validation with HPGe detectors



Source foils:

- Dedicated setup operating at LSC (Canfranc): detect delayed β-α from Bi-Po chain
- First two ^{82}Se foils currently under measurement

Summary & conclusions

Tracking + Calo. technique

- Unique: allowing direct reconstruction of the $2e^-$
- Full signature of $0\nu\beta\beta$ events and powerful background rejection
- Background-free technique for high energy $Q_{\beta\beta}$ isotopes

Latest NEMO-3 results

- Total ^{100}Mo exposure of 34.3 kg×y shows no event excess
- $T^{0\nu}_{1/2} > 1.1\times10^{24}$ y → $\langle m_\nu \rangle < 0.3 - 0.9$ eV @ (90 % C.L.)
- Other isotopes: re-analysis of full statistics ongoing

SuperNEMO demonstrator

- Under construction: commissioning by 2016
- Foresee to run for 2.5 years with 7 kg of ^{82}Se
- $T^{0\nu}_{1/2} > 6.5\times10^{24}$ y → $\langle m_\nu \rangle < 0.20 - 0.40$ eV @ (90 % C.L.)

Future: Full SuperNEMO

- 20 demonstrator-like modules
- 100 kg of ^{82}Se running for 5 years
- $T^{0\nu}_{1/2} > 1 \times10^{26}$ y → $\langle m_\nu \rangle < 0.04 - 0.10$ eV @ (90 % C.L.)

Backup slides

What is the status?

1993 - 2000:

HdM (35.5 kg x y) & **IGEX**, ^{76}Ge

- $T^{0\nu}_{1/2} > 1.9\ 10^{25}$ y @ 90% C.L.

HdM claim: $\langle m_{\beta\beta} \rangle = 0.32 \pm 0.03$ eV

2000 - 2010:

Cuoricino (19.75 kg x y): TeO_2 bolometer

- ~11 kg ^{130}Te: $T^{0\nu}_{1/2} > 2.8\ 10^{24}$ y @ 90% C.L.

NEMO3 (34.7 kg x y Mo): tracking + calorimetry

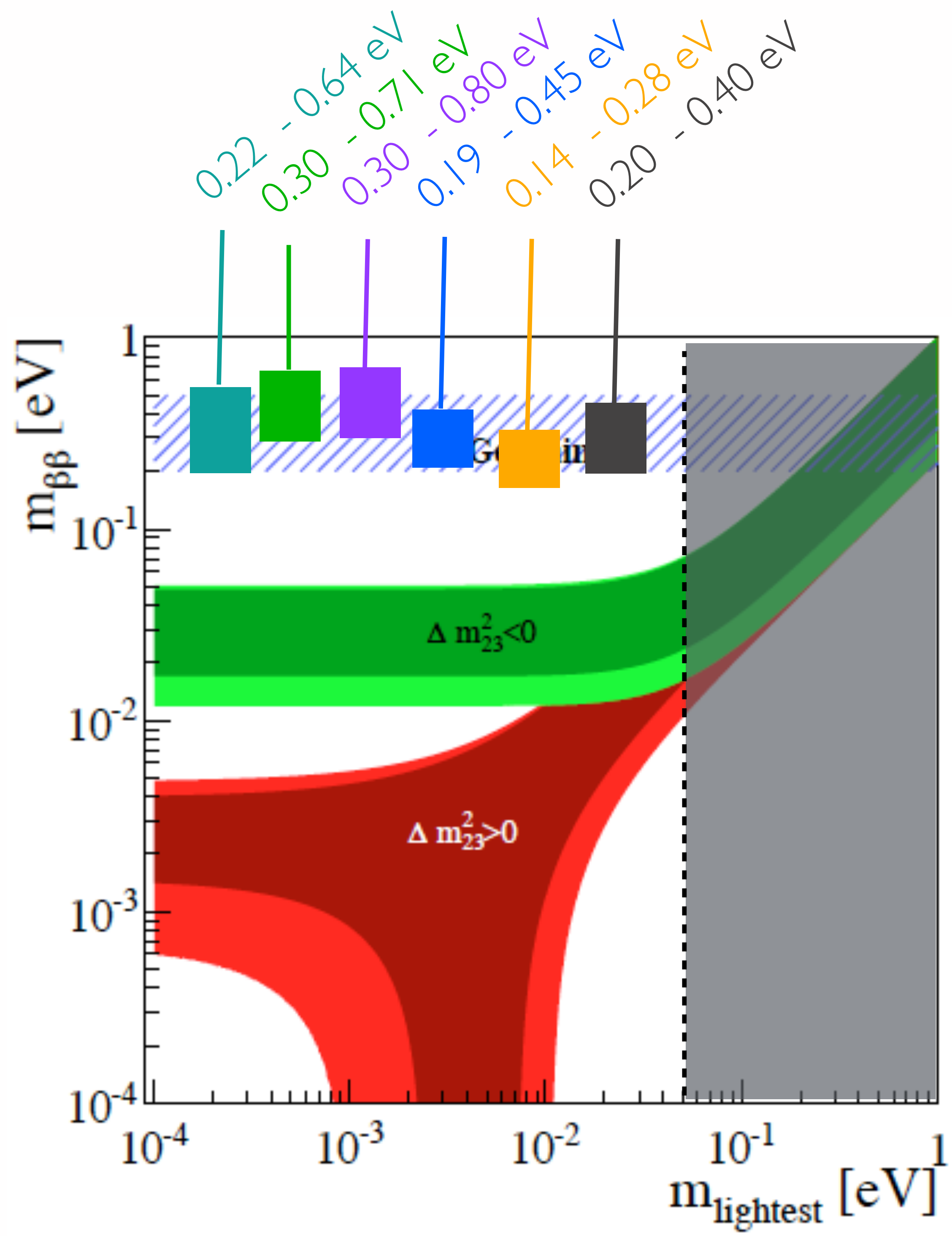
- ~7 kg ^{100}Mo: $T^{0\nu}_{1/2} > 1.1\ 10^{24}$ y @ 90% C.L.

Since 2011: new generation, R&D for future scaling

EXO200 (> 95 kg x y): Liquid Xe TPC

Kamland-ZEN (190 kg x y): Liquid Scintillator

GERDA Phase 1 (>20 kg x y): Ge diodes



Future projects

CUORE, Gerda, Majorana, Lucifer, AMORE, NEXT, COBRA, EXO, SNO+, KamLAND-Zen, CANDLES, SuperNEMO, DCBA, ...

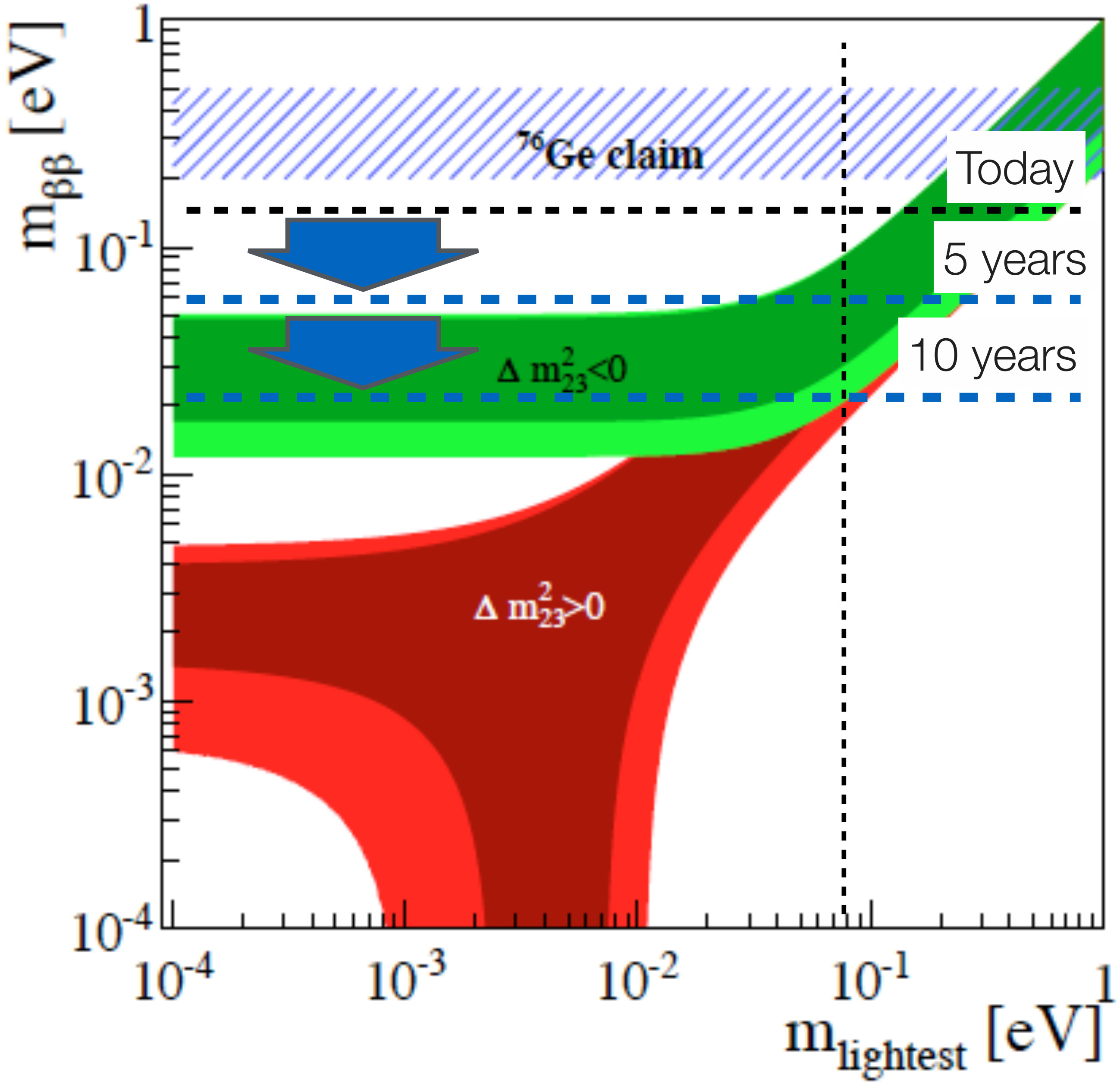
5 years time scale:

- M ~ 10 - 50 kg of ββ isotope
- Background level 10^{-3} cts. /(keV kg y)
- Explore quasi-degenerate region

10 years time scale:

- M ~ 100 kg - 1t of ββ isotope
- Background level 10^{-4} cts. /(keV kg y)
- Approach Inverse Hierarchy region

$$T_{1/2}^{0\nu} > \frac{N_A \ln 2}{n_\sigma} \times \frac{\epsilon}{A} \times \sqrt{\frac{M \times t}{B \times \Delta E}}$$



- Extended R&D: Energy resolution, particle ID, radio-purity
- Multi-phase approach: demonstrate scalability and background levels

Which isotope?

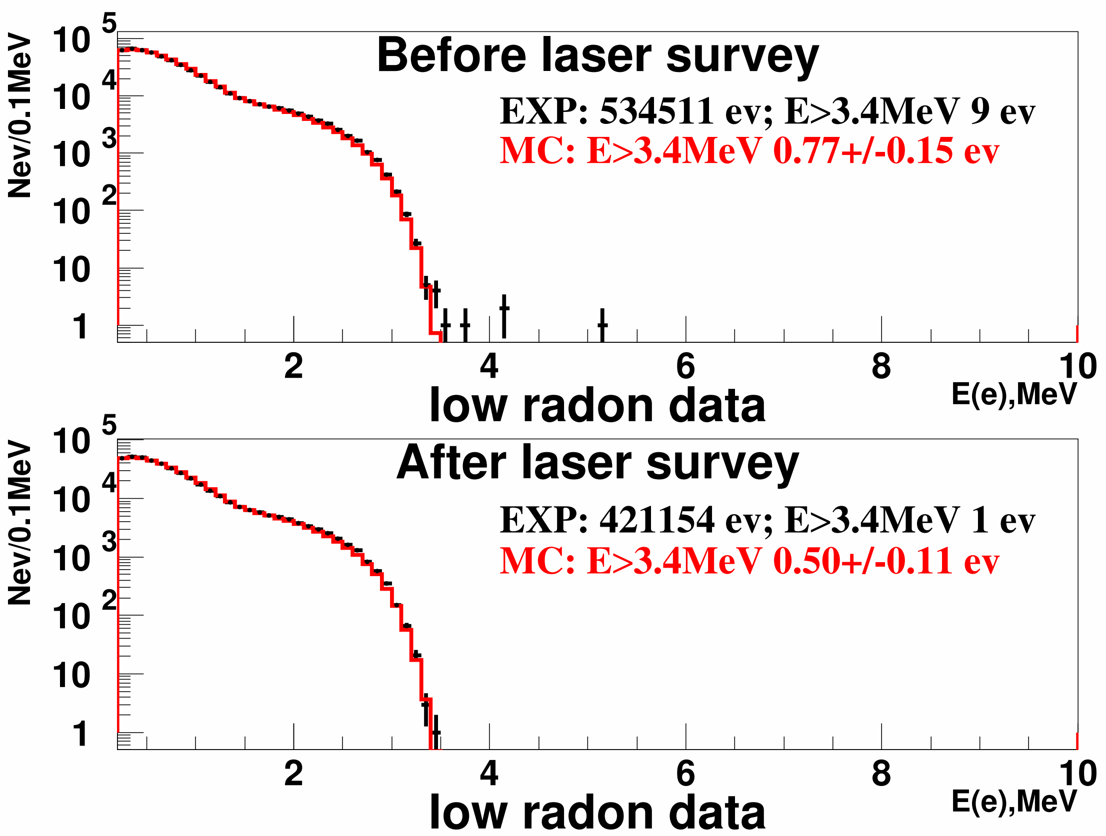
Isotopes enrichment and $T^{2\nu}_{1/2}$ from respective experiment

Isotope	$Q_{\beta\beta}$ [keV]	Nat. abund. (enrich.) [%]	$G_{0\nu}$ [10^{-14} y^{-1}]$^{(*)}$	$T^{2\nu}_{1/2}$ [10^{19} y]	Experiment
^{48}Ca	4270	0.187 (73)	6.35	$4.2^{+2.1}_{-1.0}$	NEMO3
^{76}Ge	2039	7.8 (86)	0.62	150±10	GERDA
^{82}Se	2995	8.7 (97)	2.70	9.0±0.7	NEMO3
^{96}Zr	3350	2.8 (57)	5.63	2.0±0.3	NEMO3
^{100}Mo	3034	9.6 (99)	4.36	0.71±0.04	NEMO3
^{116}Cd	2802	7.5 (93)	4.62	3.0±0.2	NEMO3
^{130}Te	2527	34.5 (90)	4.09	70±10	NEMO3
^{136}Xe	2480	8.9 (80)	4.31	238±14	KamlandZEN
^{150}Nd	3367	5.6 (91)	19.20	0.78±0.7	NEMO3

What is the status?

		Light Majorana neutrino exchange		Right handed current		SUSY: neutralino or gluino exchange	Majoron emission
Isotope	Exposure (kg·y)	Half life (10^{25} y) published	$\langle m_\nu \rangle$ (eV) published	$\langle \lambda \rangle$ (10^{-6}) published	$\langle \eta \rangle$ (10^{-8}) published	λ'_{111}/f (10^{-2}) published	$\langle g_{ee} \rangle$ (10^{-5}) published
^{100}Mo [1] (NEMO-3)	34.7	0.1	0.33 - 0.87	0.9 - 1.3	0.5 - 0.8	4.4 - 6.0	2 - 5
^{130}Te [2][3] (CUORICINO)	19.75	0.3	0.31 - 0.71	1.6 - 2.4	0.9 - 5.3		17 - 33
^{136}Xe [4][5] (KamLAND-Zen)	89.5	1.9	0.14 - 0.34				
^{136}Xe [9] (KamLAND-Zen)	109.4 + 89.5	2.6	0.14 - 0.28				
^{136}Xe [6] (EXO-200)	99.8	1.1	0.19 - 0.45				
^{76}Ge [7][8] (GERDA)	21.6	2.1	0.2 - 0.4				3.4 - 8.7
^{76}Ge [9] (HdM)	35.5	1.9	0.4	1.1	0.6		8.1

NEMO-3: Laser survey



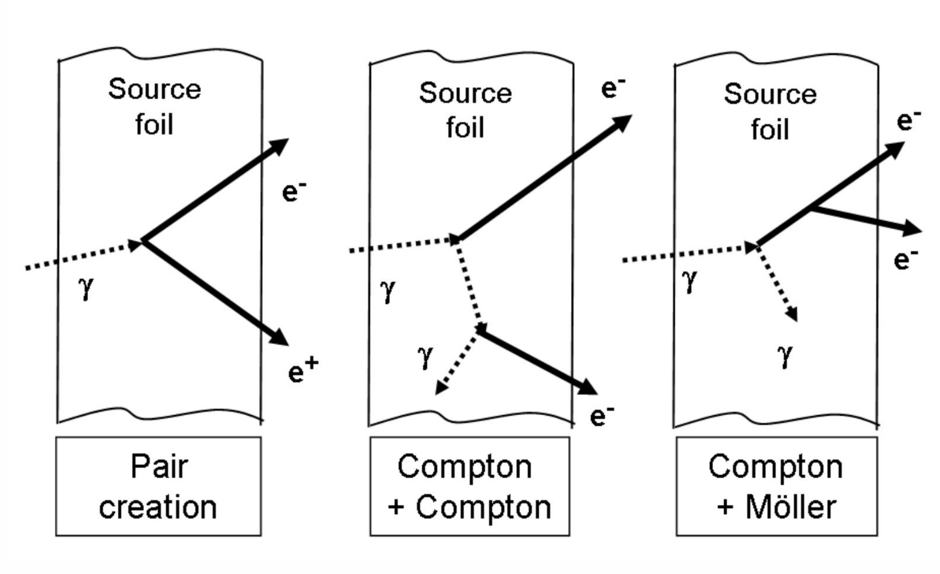
Laser inter-calibration system:

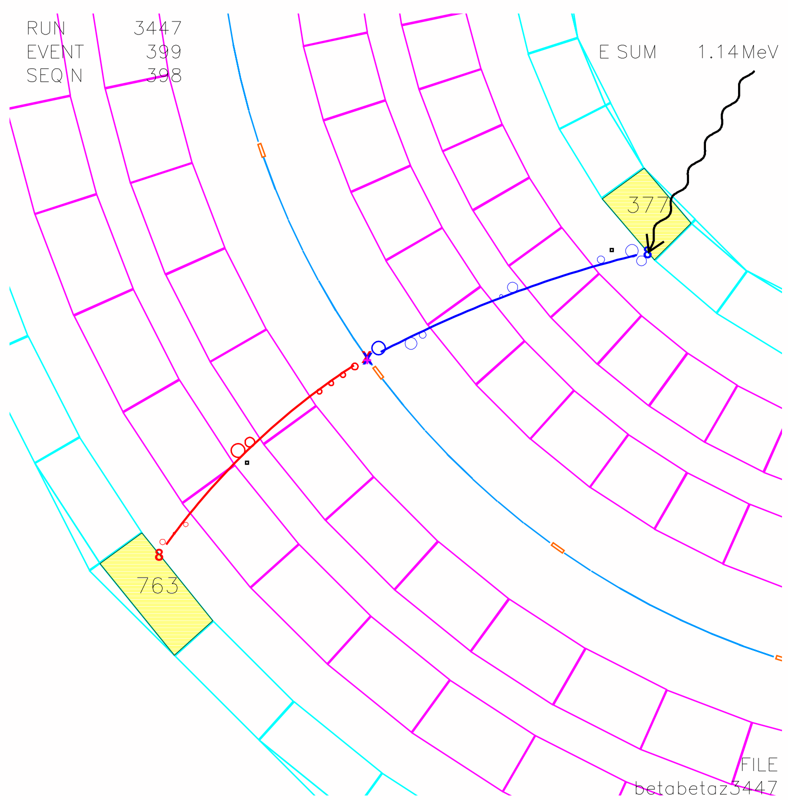
- Gain and time survey twice a day PMTs linearity < 1% for E < 4 MeV
- 82% of PMTs stable < 5% over the whole data taking
- Validate PMT stability with the ^{214}Bi β-decay end point (3270 keV) background free channel

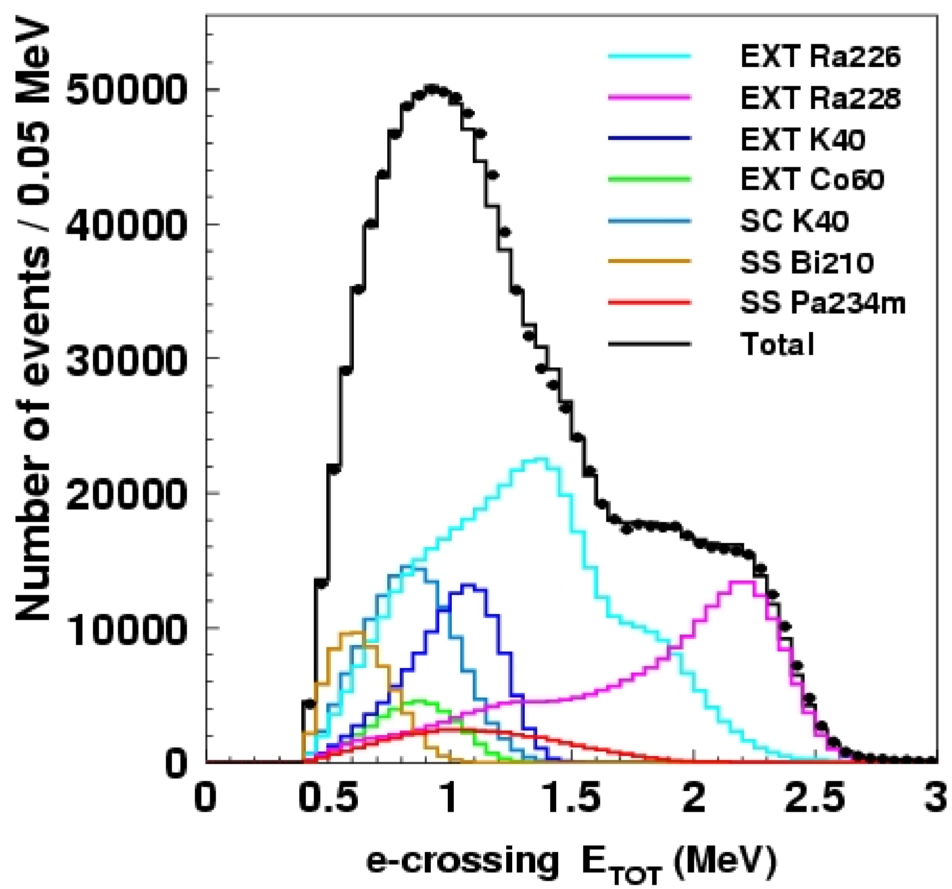
NEMO-3: external backgrounds

Radio-impurities in material, γ from (n,γ) and μ bremsstrahlung

e-γ and one-crossing-e channels

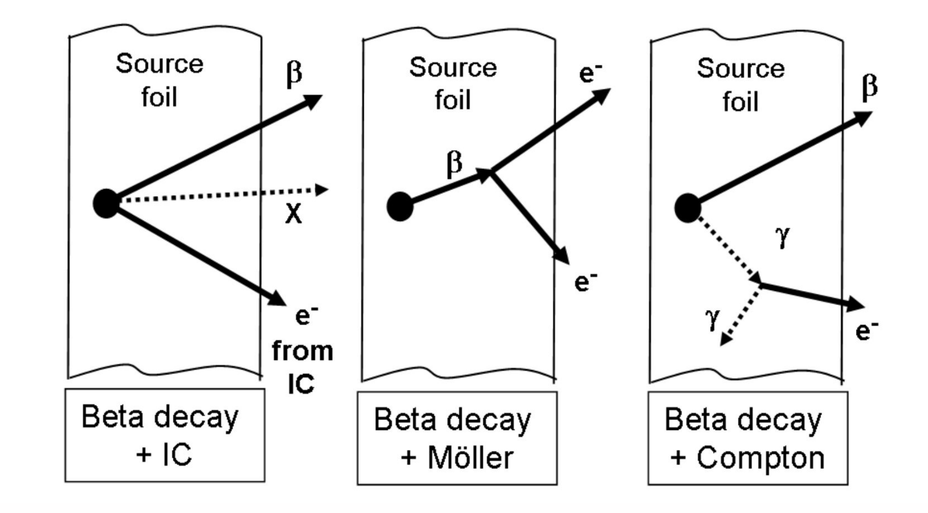




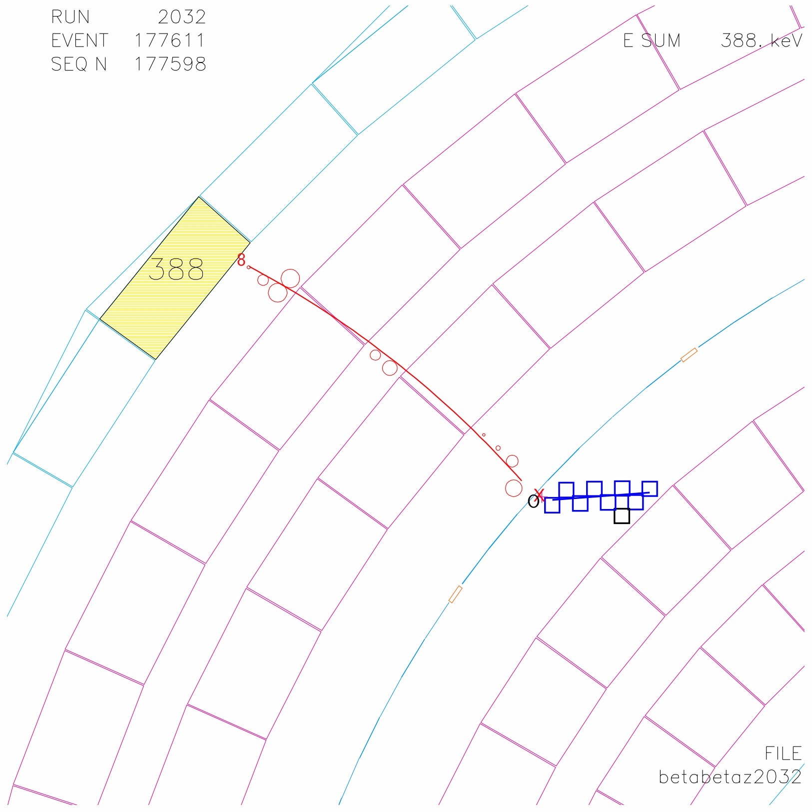


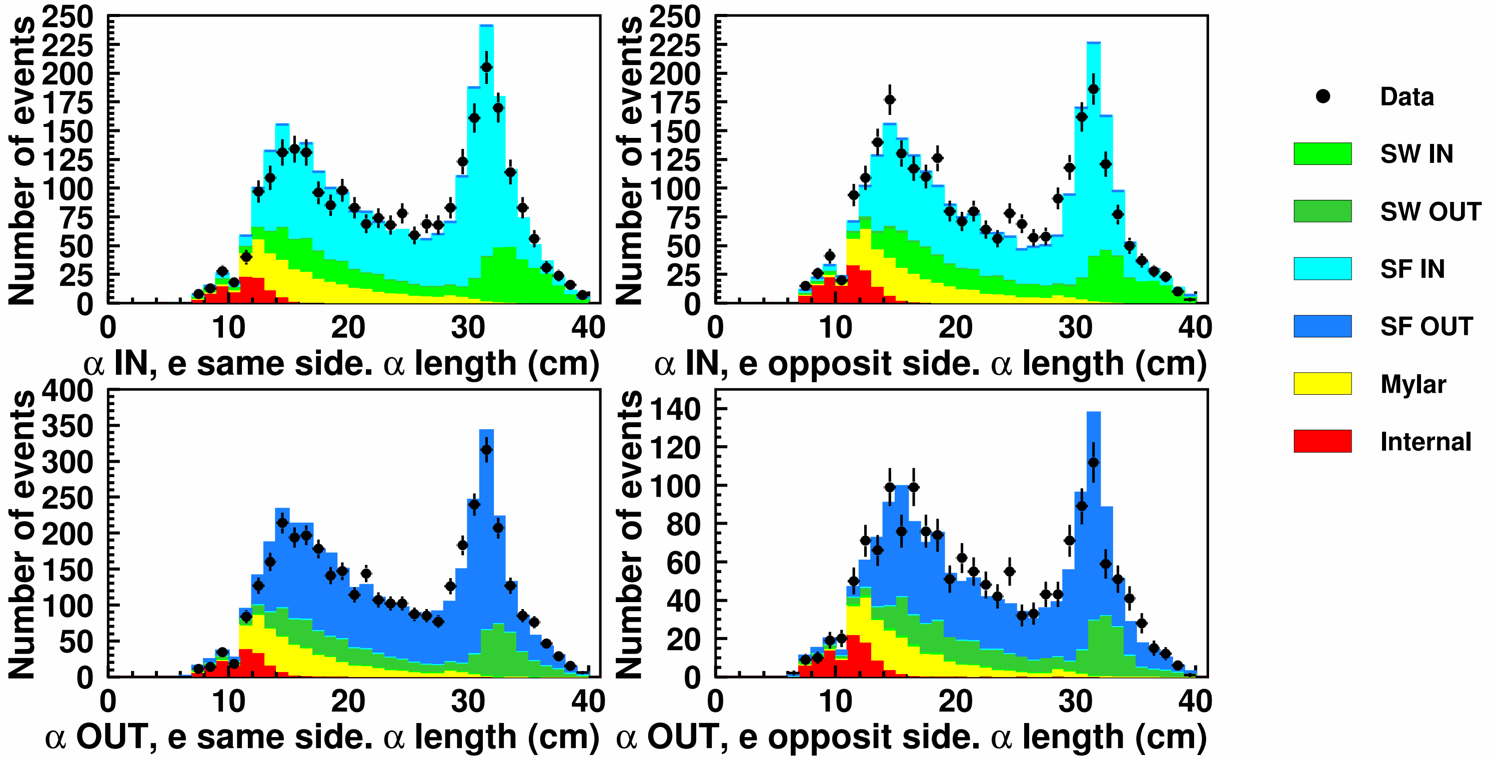
NEMO-3: internal backgrounds

^{208}Tl (from ^{232}Th) and ^{214}Bi (from ^{238}U) contamination in foil source and ^{214}Bi from Rn decay in tracker volume



1eNγ (^{208}Tl) and 1e1α (^{214}Bi) channels

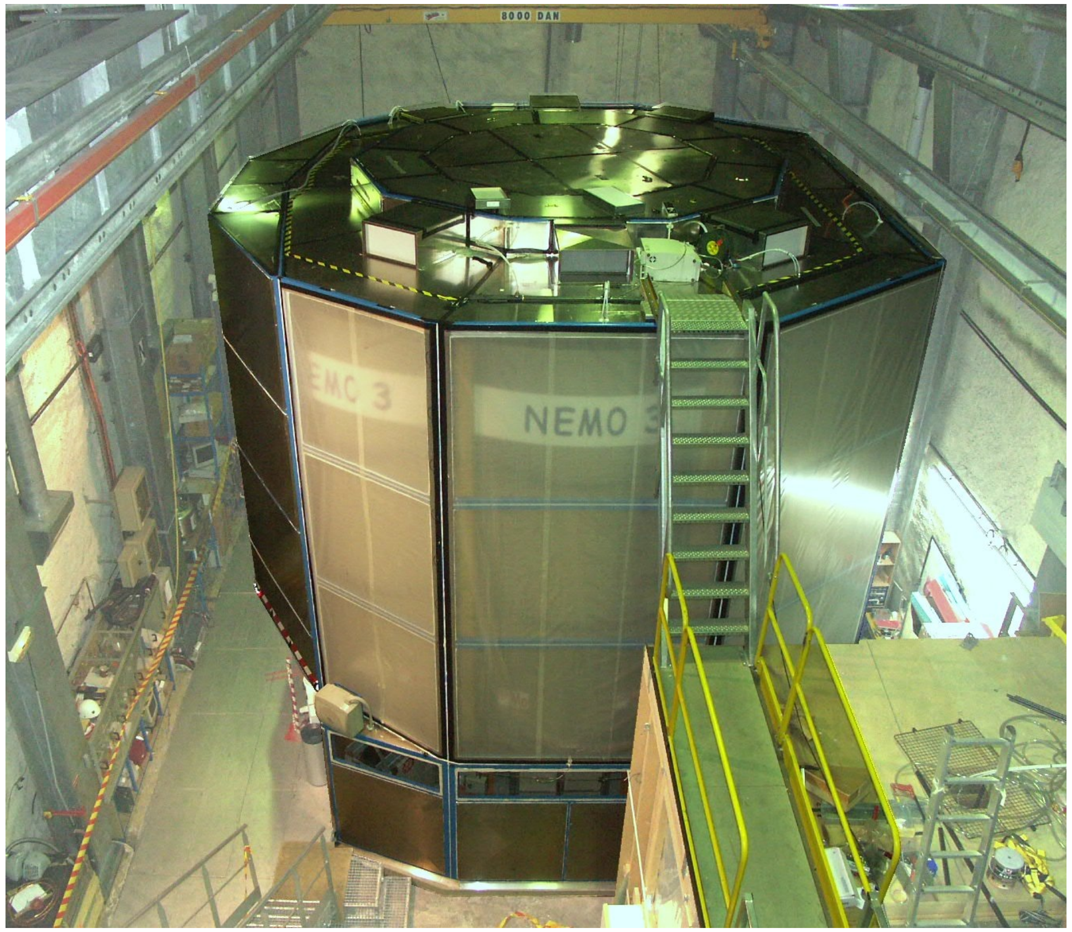


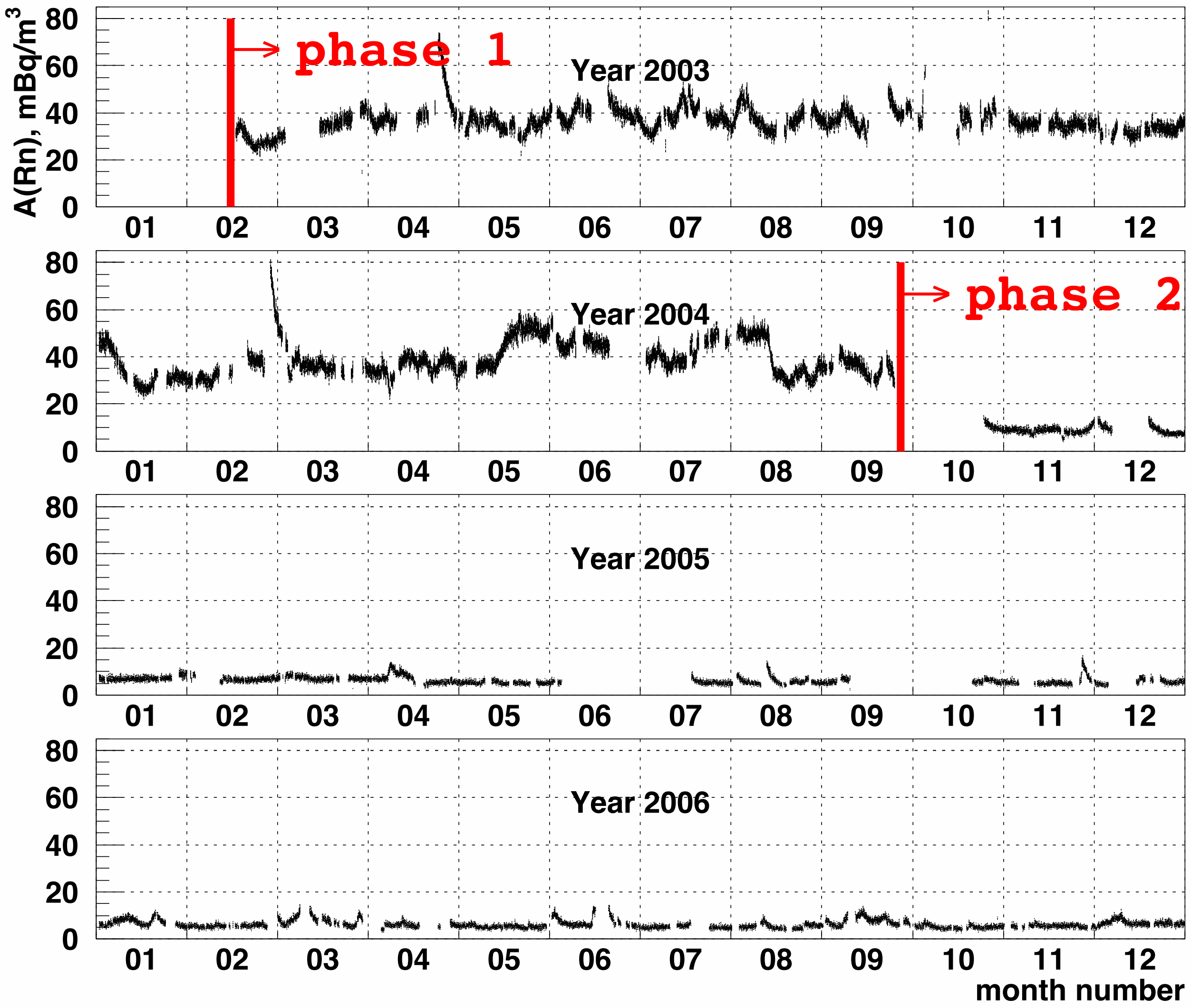


NEMO-3: ^{222}Rn background

^{222}Rn in the gas of the tracking chamber monitored through the 1e1a channel

Strongly suppressed upon flushing Rn-free air into a dedicated tent surrounding the detector

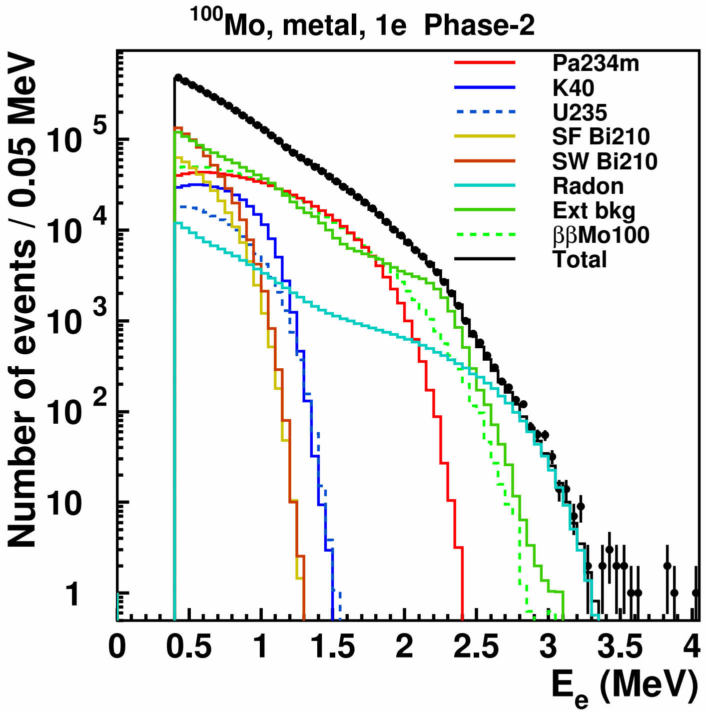


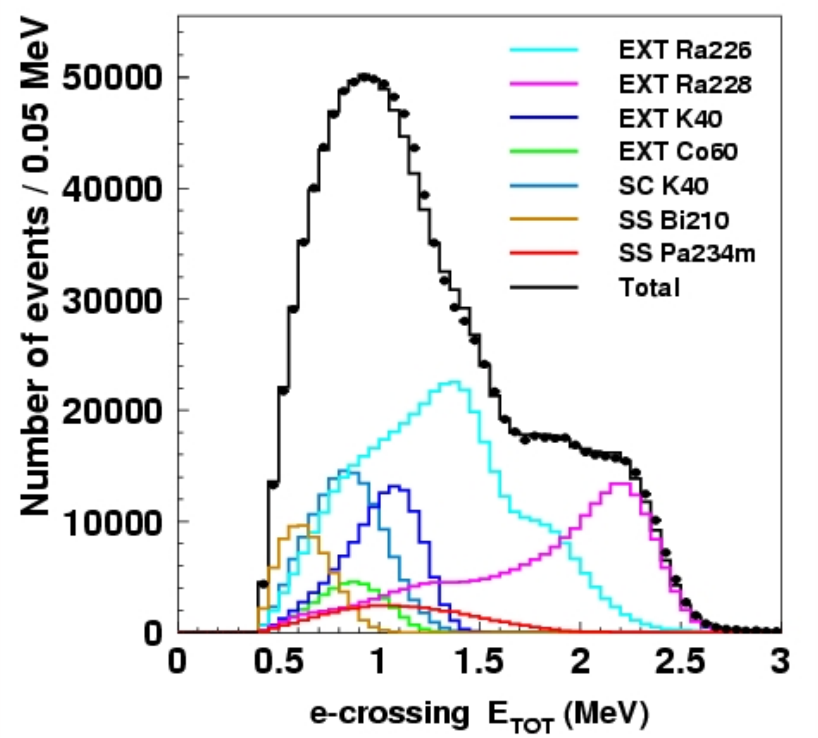


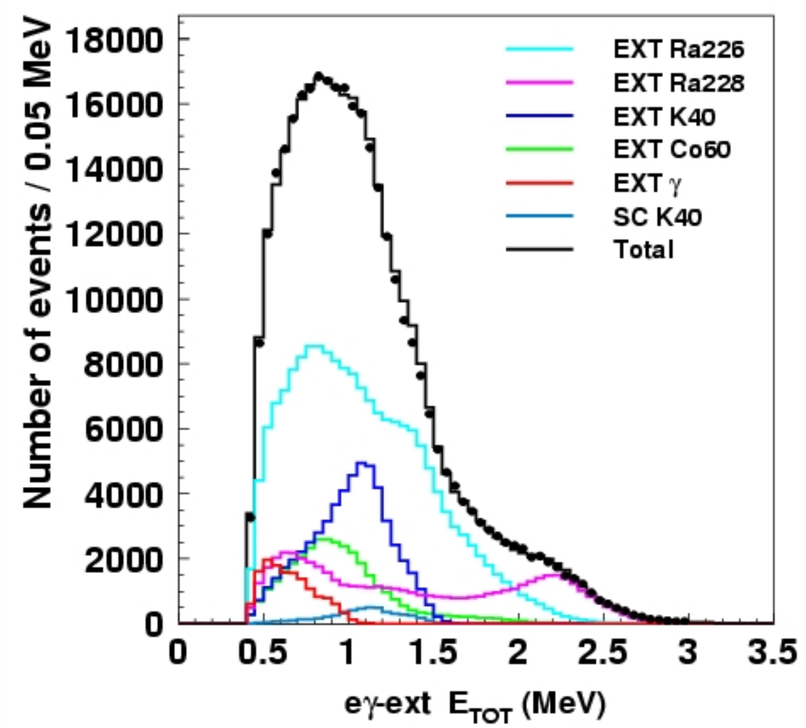
Phase 1: 37.7±0.1 mBq/m^3

Phase 2: 6.46±0.02 mBq/m^3

NEMO-3: Background measurement







NEMO-3: Systematic uncertainties

Systematics

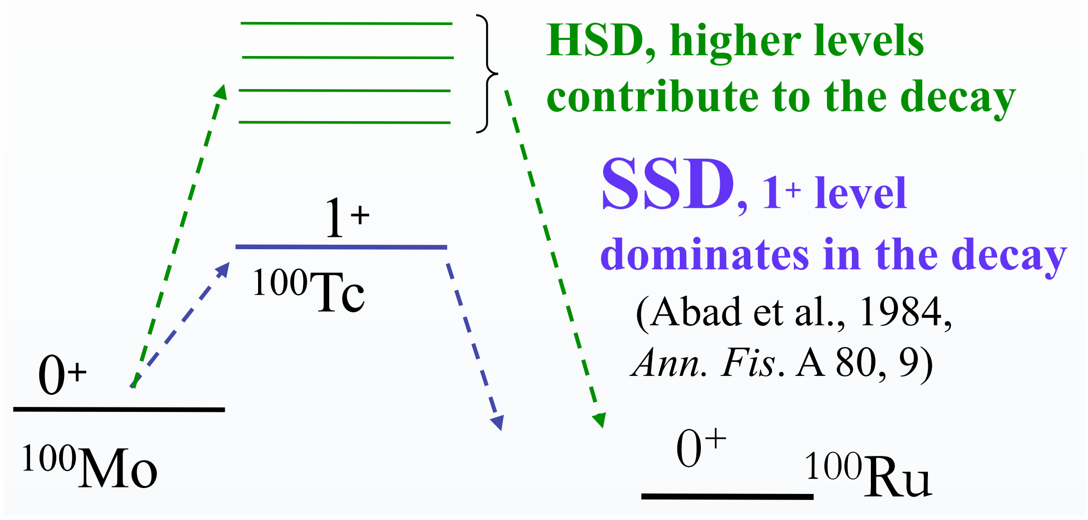
$0\nu\beta\beta$ detection efficinecy	7.0%	Measure activity of known ^{207}Bi source
$2\nu\beta\beta$ events in window	0.7%	$2\nu\beta\beta$ energy spectrum fit for $E > 2$ MeV
^{214}Bi contamination	10.0%	^{214}Bi measurement in $1e1\alpha$ and $1e1\gamma$ channel
^{208}Tl contamination	10.0%	Measure activity of known ^{238}U source

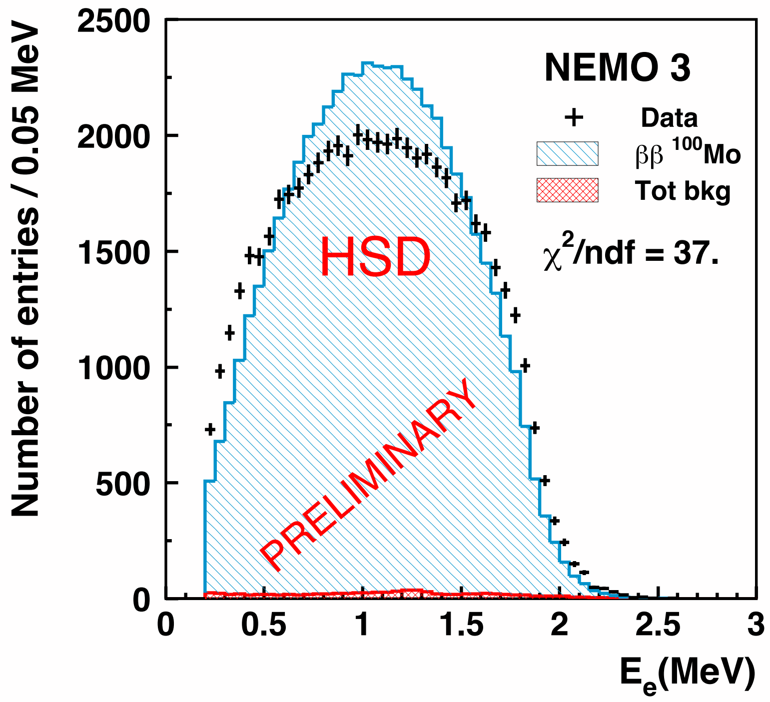
NEMO-3: 2νββ of ^{100}Mo SSD/HSD

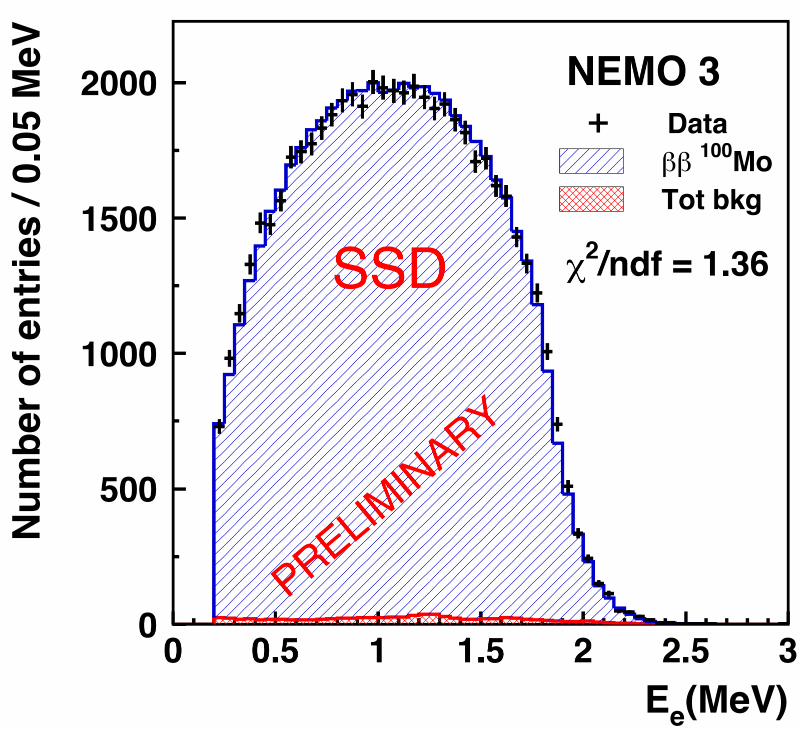
If the intermediate nucleus is a J^{π}=1+ state, the NME could be dominated by GT transitions through this state.

If the SSD hypothesis is confirmed

- 2νββ half-life could be determined from single-β and electron capture (EC) measurements.
- simplification in the theoretical description of the intermediate nucleus



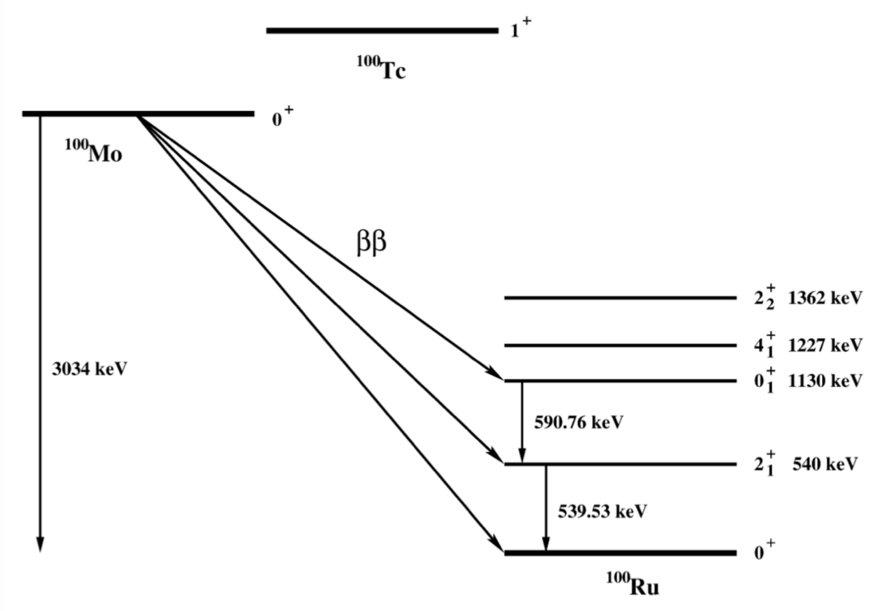




Electron energy distribution in 2νββ decay of ^{100}Mo is in favour of SSD

NEMO-3: excited states

^{100}Mo decays to excited states: constrain model for NME calculation



With NEMO3 after 7kg · yr of exposure (Phase1):

$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) ± 0.8 (syst) × 10^{20} y

$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.

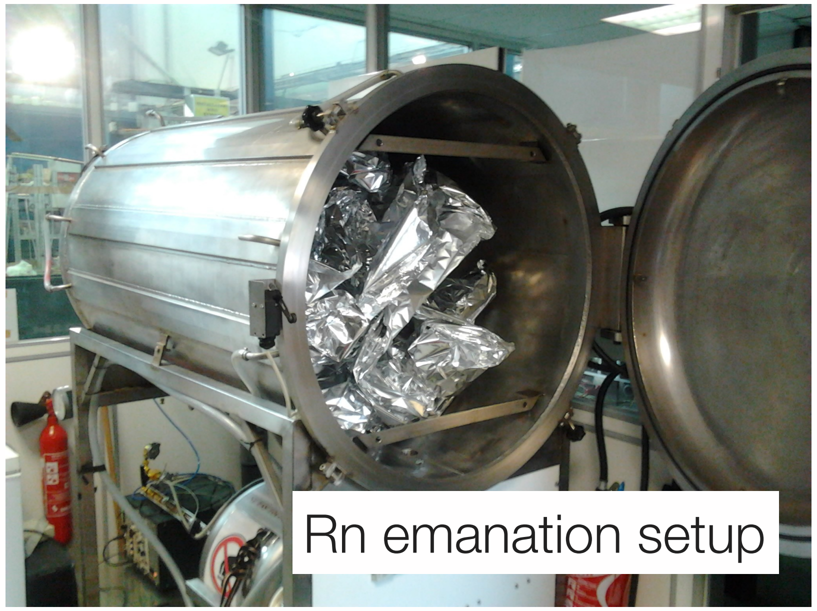
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @ 90% C.L.

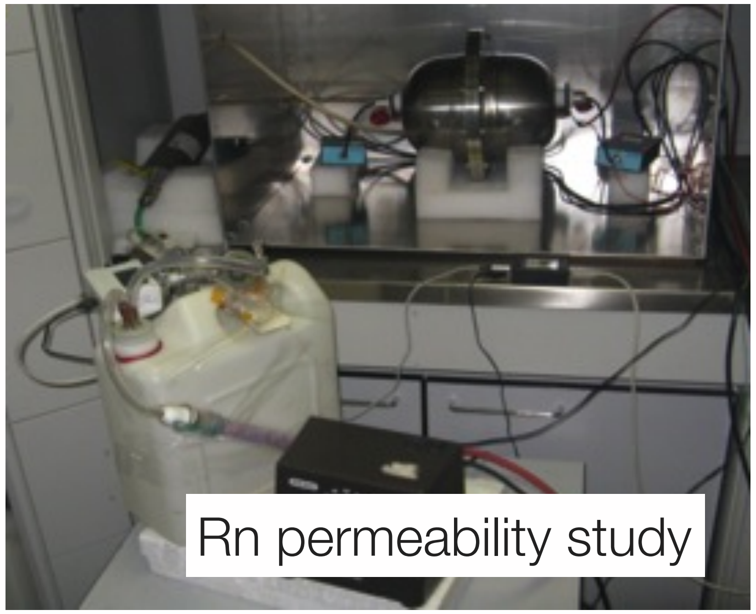
$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.

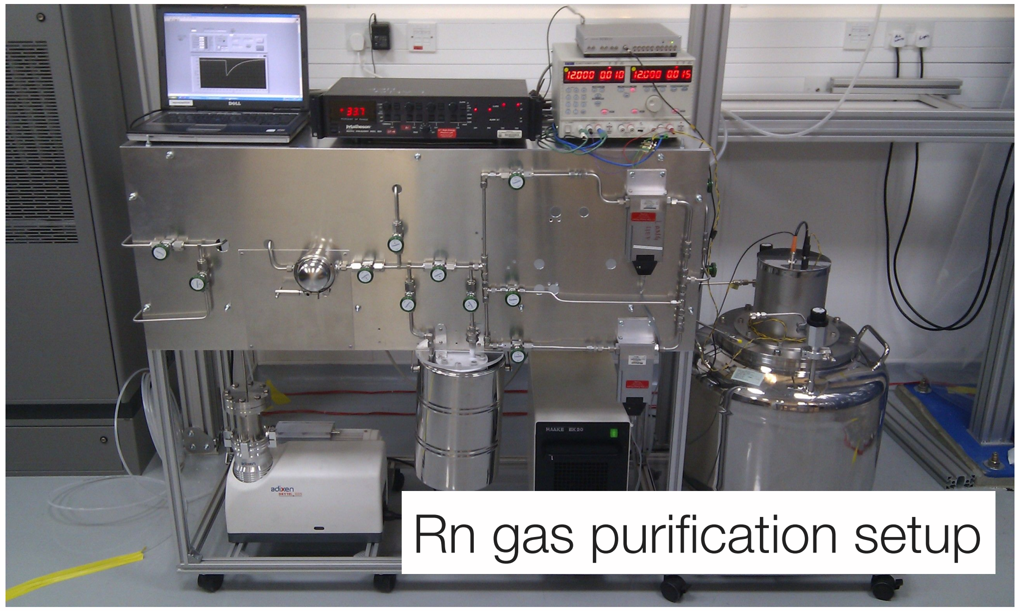
[Nuclear Physics A781 (2007) 209-226]

SuperNEMO: Radon measurements

- The Rn gas in the tracker volume was the dominant background in NEMO-3
- Reduce Rn contamination to 0.15 mBq/m^3
- Control the Radon emanation of the materials
- Radon purification/absorption with dedicated setup
- Preliminary radon emanation of C0 = 0.236 ± 0.035 mBq/m^3 — limits is close!


Rn emanation setup


Rn permeability study


Rn gas purification setup

SuperNEMO: radio-purity measurements

Detector radio-purity budget:

- Materials validation with HPGe detectors (sensitivity ~ mBq)

Source foils:

- HPGe not sensitive enough for SuperNEMO requirement
- Dedicated setup operating since February 2013 @ LSC (Canfranc): BiPo
- Detecting delayed β—α coincidence from Bi—Po chain
- First two ^{82}Se foils currently under measurement