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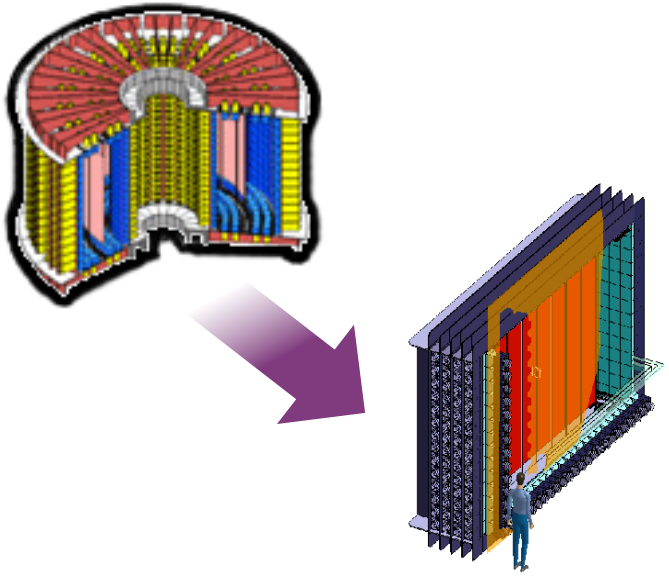
The University of Manchester

supernemo collaboration

Investigating ββ decay with NEMO-3 and SuperNEMO

Summer Blot, on behalf of the NEMO-3 and SuperNEMO experiments

7 September 2015



Outline

Review of double β decay

The NEMO technique

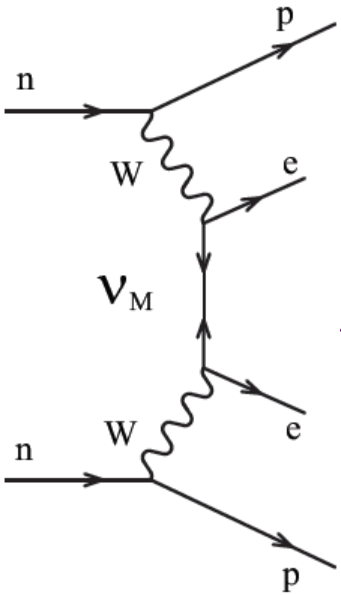
Recent results from NEMO-3

Status of SuperNEMO

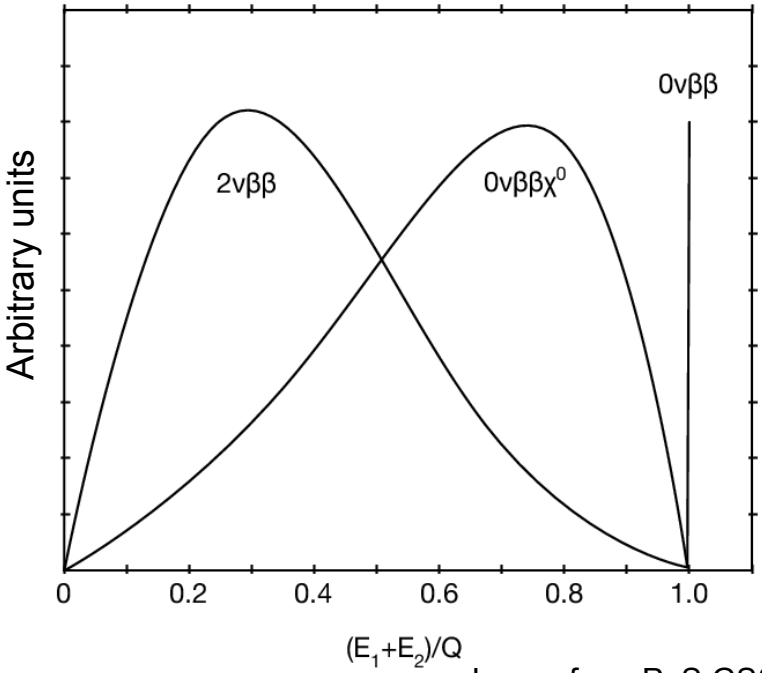
Summary

Neutrinoless double-beta (0νββ) decay

- BSM process that violates lepton number conservation by 2 units
- Can be mediated by: Light Majorana neutrino exchange, (V+A) current, SUSY, ...
- Not yet observed, current limits at $T_{1/2} > 10^{24}$y



"Mass mechanism"



Experiment

New physics

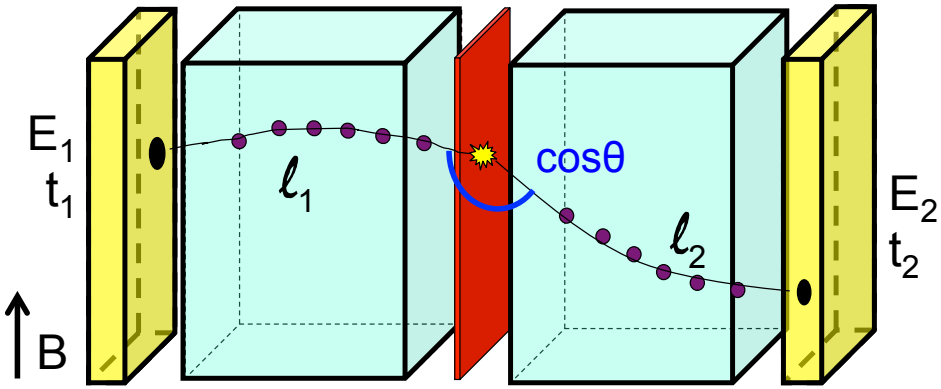
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 \eta^2$$

Theoretical input

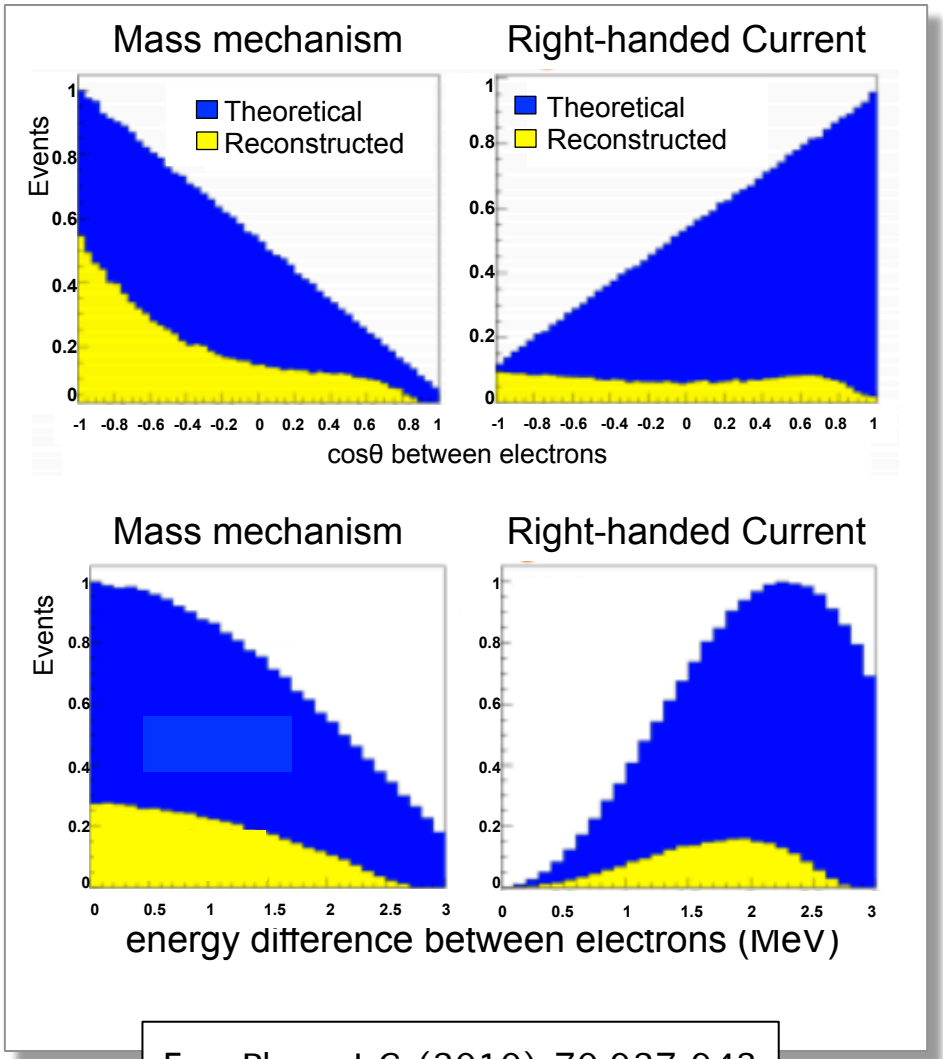
Image from PoS GSSI14 (2015) proceedings, [arxiv:1502.00581]

NEMO detection principle

- Reconstruct the full topology and kinematics of final states
  - Measure backgrounds *in situ* and reject from signal channel
  - Can disentangle underlying 0νββ mechanisms



Source
≠
Active detector



Eur. Phys. J C (2010) 70:927-943

The NEMO-3/SuperNEMO collaboration

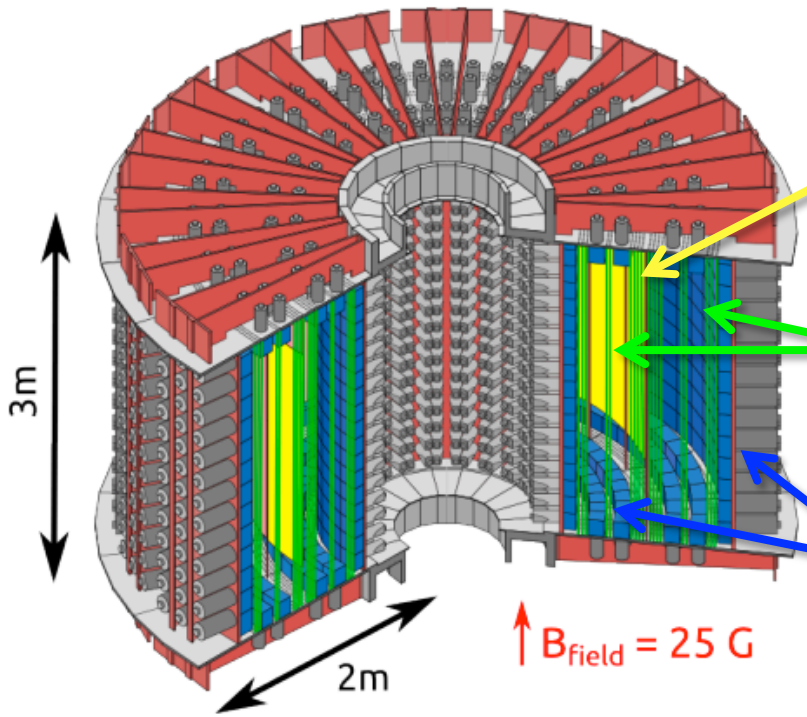
LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., LAPP (Annecy), Comenius U. (Bratislava), Osaka U., IEAP CTU (Prague), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui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

22 Universities & Institutions

9 different countries

Aussois, 2015

The NEMO-3 detector



- ~10 kg of ββ-decay isotopes
  - ^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr and ^{48}Ca
  - Produced as **thin foils** 30-60mg/cm^2
  - Typically 2.5m in height, 63-65 mm wide

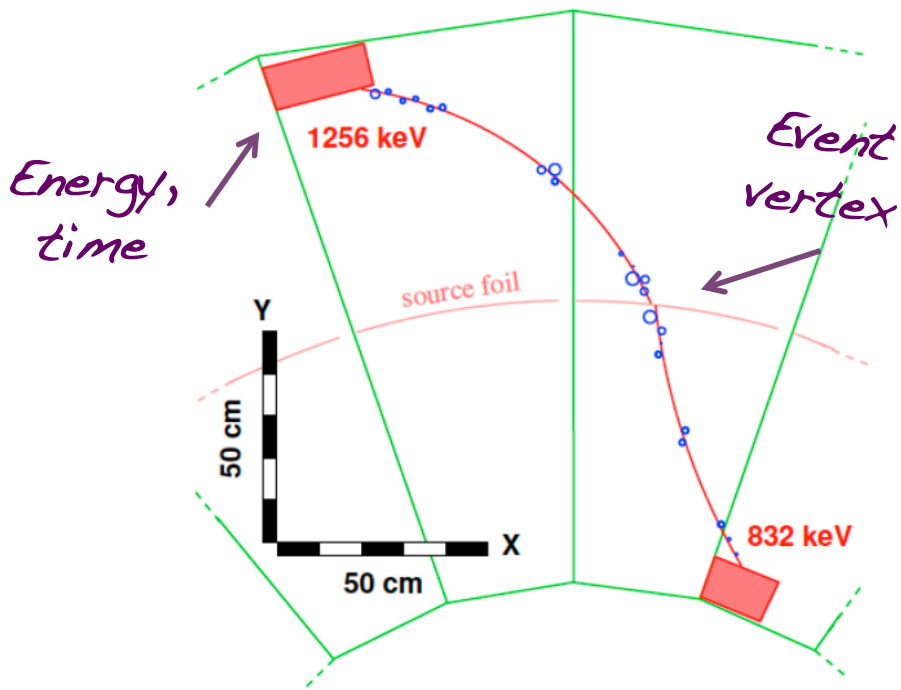
- Tracking chamber (both sides of foil)
  - 6180 Geiger cells operating in gas mixture of 95% He, 4% alcohol, 1% Ar and 0.1% H_2O
  - Vertex resolution σ_{XY}~3 mm, σ_Z~10mm

- Calorimeter (top, bottom, in and out)
  - 1940 optical modules
  - 3" and 5" PMTs + plastic scintillator blocks
  - FWHM 14-17%, σ_t~250 ps for electrons @1MeV

Largest mass/exposure with ^{100}Mo (6.9 kg) and ^{82}Se (0.93 kg)

The NEMO-3 detector

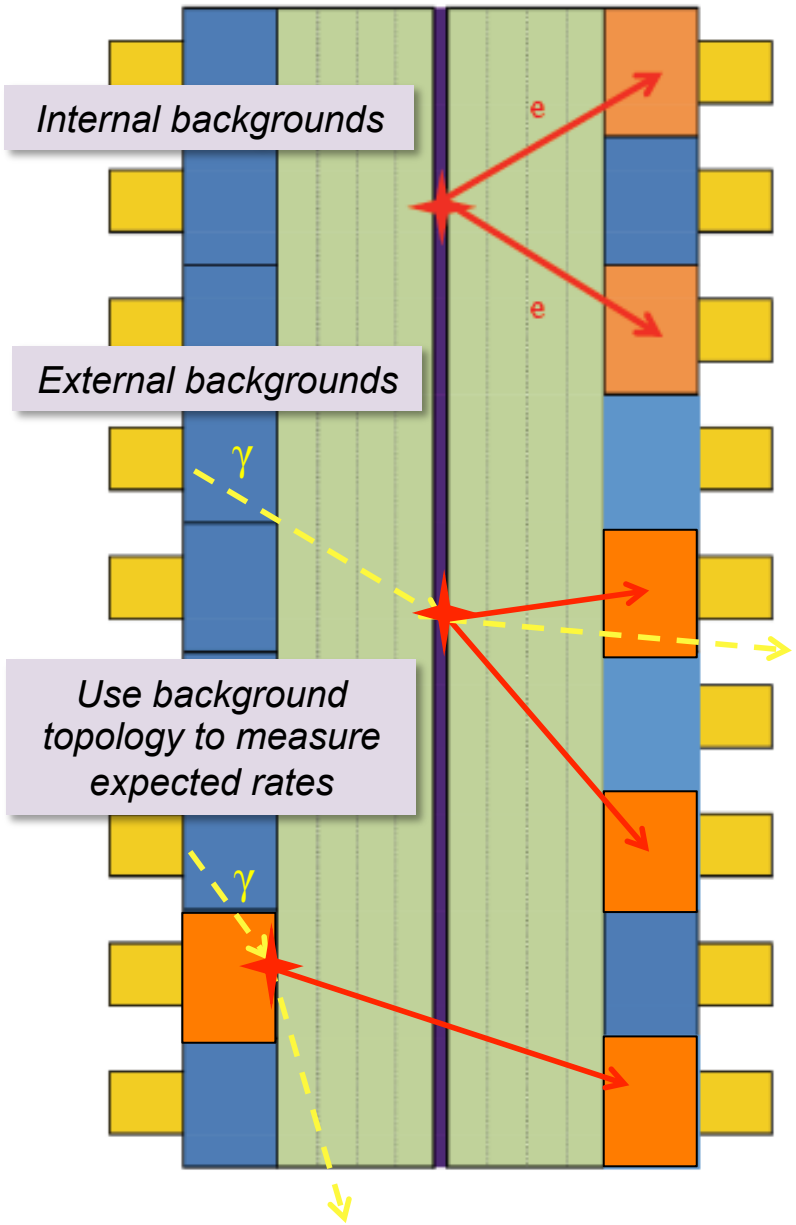
- Operated from Feb 2003–Jan 2011
- Modane Underground Laboratory (LSM)
- Cylindrical geometry (R,ϕ,z)
- 7 different isotopes simultaneously



- Separate tracker-calorimeter systems + *B* Field
- Enables the reconstruction of full kinematics of final state

Backgrounds to 0νββ

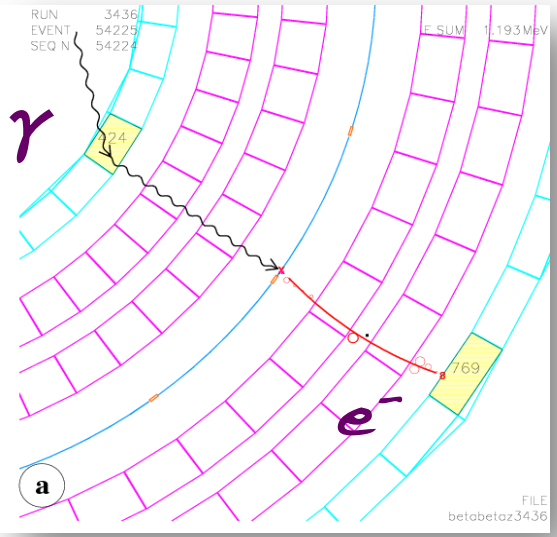
- External backgrounds from neutron capture, producing high energy γ-rays
  - e.g. Pair production e^+e^-
- Radon induced backgrounds
- Internal background decays
  - Impurities in the foil
  - *e.g.* Single β-decay + Møller scattering
- 2νββ decay

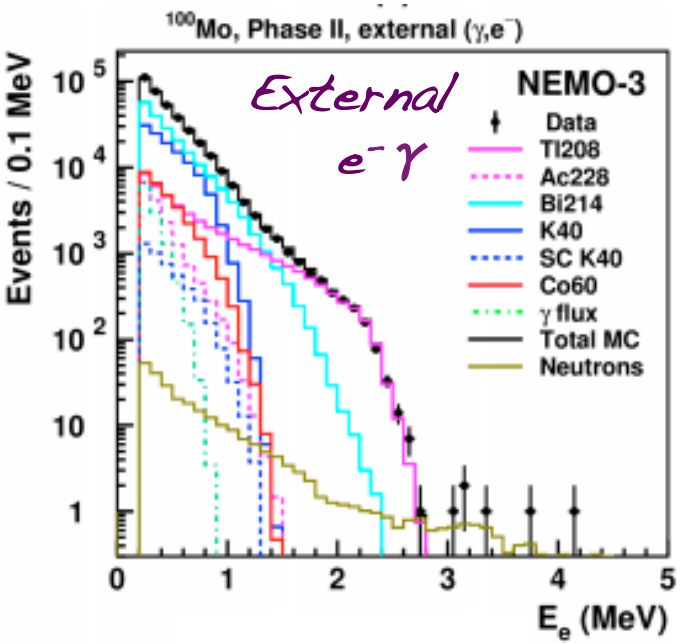


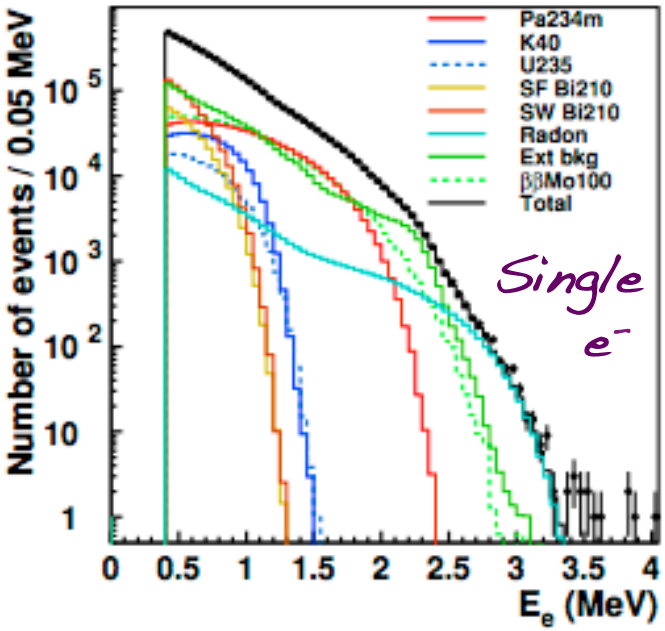
[arxiv:1506.05825]

Background channels

- External background channels identified by distinct time sequence ($t_i << t_j$)







- Measure internal background rates using single β-decay channel

Latest NEMO-3 Results – ^{100}Mo

Phys. Rev D 89, 111101 (2014). [arxiv:1506.05825]

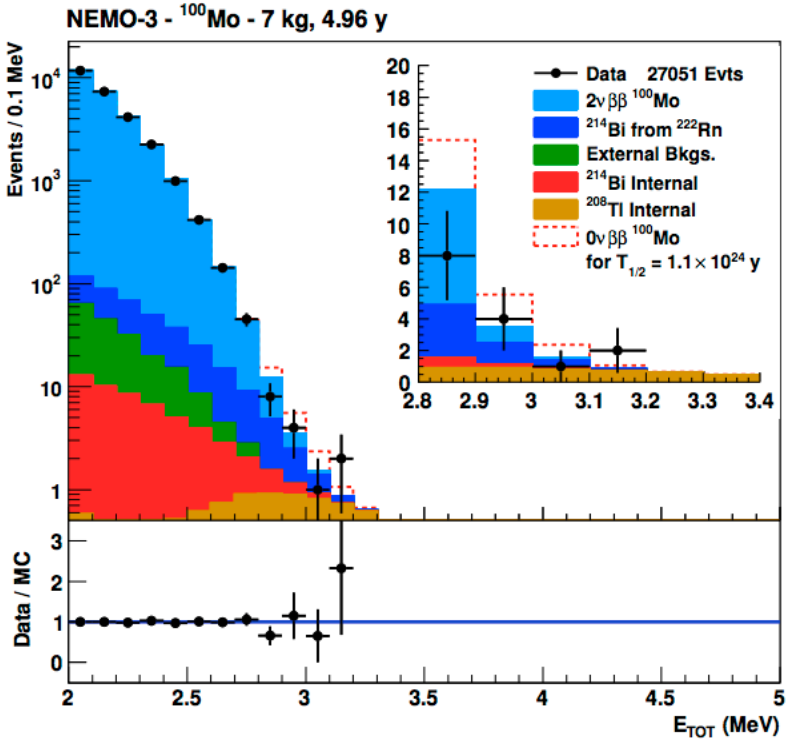
- 34.7 kgy of ^{100}Mo
- No excess of data in region of interest:

  E_{TOT} = [2.8-3.2] MeV

$T_{1/2}^{0\nu} > 1.1 \times 10^{24}$ y

$\langle m_{\beta\beta} \rangle < 0.33\text{-}0.62$ eV

- No events > 3.2 MeV
- Reached background expectations



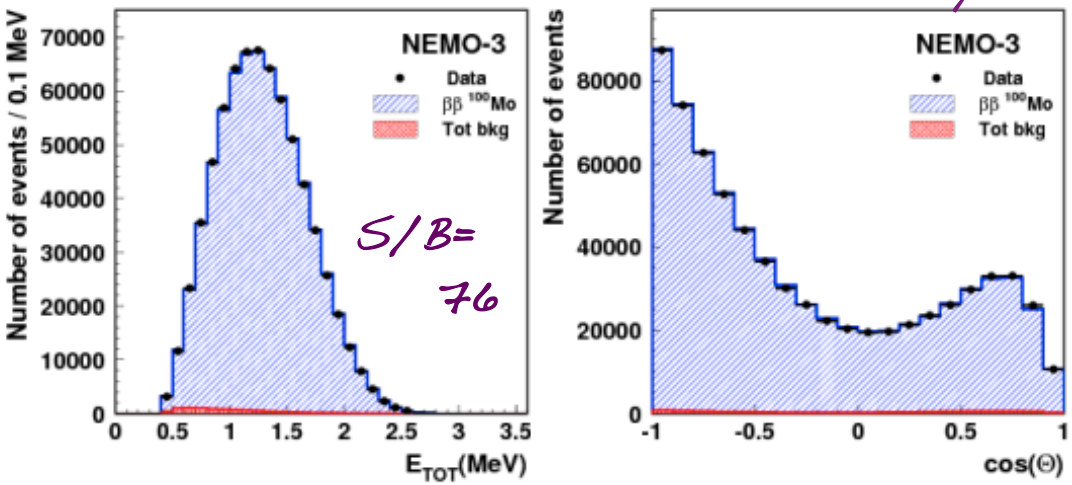
Mass mechanism	$T_{1/2} > 1.1 \times 10^{24}$y	$m_{\beta\beta} < 0.33\text{-}0.62$ eV
RH current $\langle\lambda\rangle$	$T_{1/2} > 0.7 \times 10^{24}$y	$\langle\lambda\rangle < (0.9\text{-}1.3)\times10^{-6}$
RH current $\langle\eta\rangle$	$T_{1/2} > 1.0 \times 10^{24}$y	$\langle\eta\rangle < (0.5\text{-}0.8)\times10^{-8}$
Majoron ($\chi^0_{n=1}$)	$T_{1/2} > 0.05 \times 10^{24}$y	$\langle g_{ee}\rangle < 1.6\text{-}3.0 \times10^{-5}$

Other results from NEMO-3

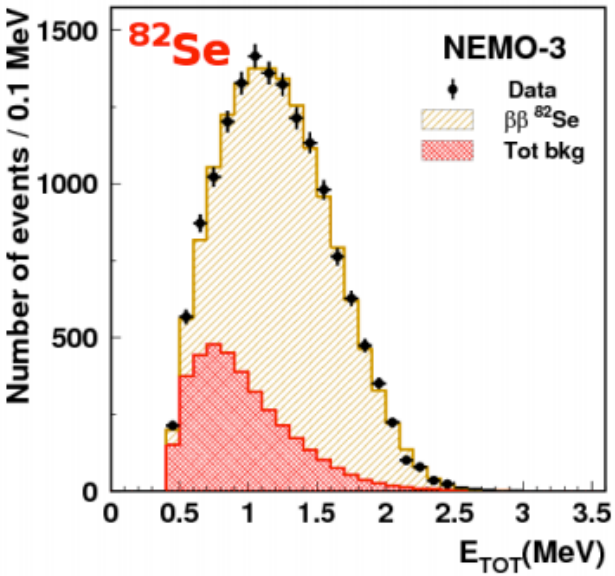
Preliminary

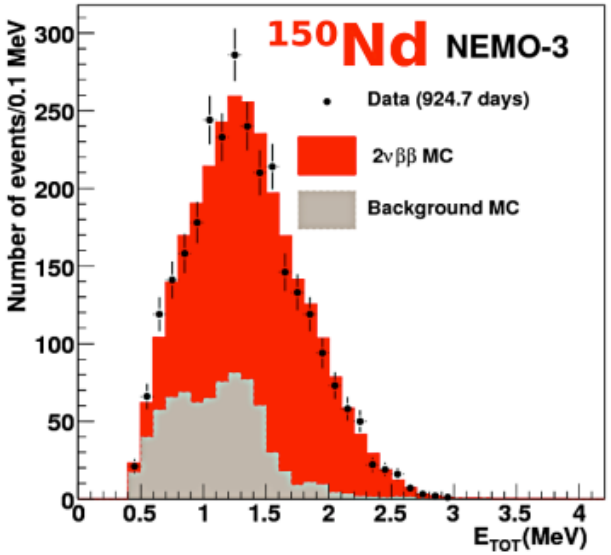
$T_{1/2}^{2\nu}(^{100}Mo) = 7.16 \pm 0.01_{stat} \pm 0.54_{syst}$

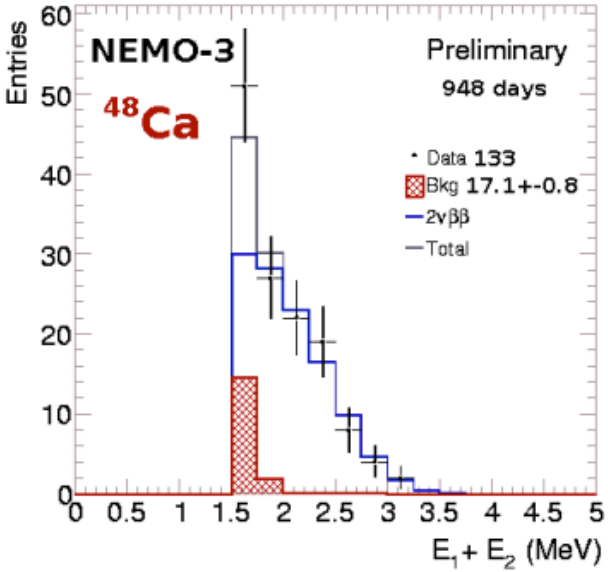
- World best $T_{1/2}^{2\nu\beta\beta}$ measurements for all 7 isotopes investigated
- Best $T_{1/2}^{0\nu\beta\beta}$ decay limits for most



Updated results with full exposure coming soon...





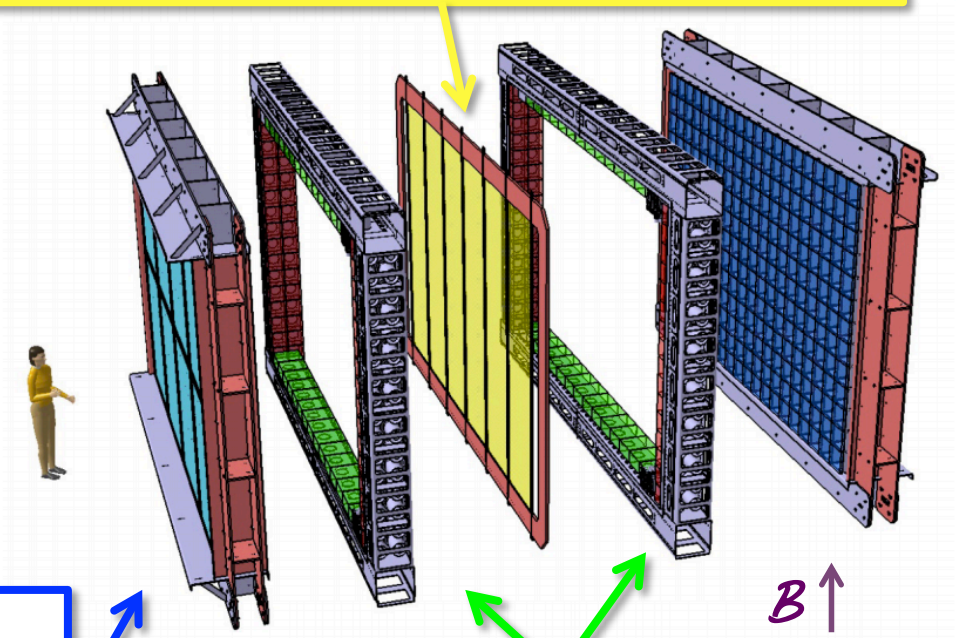


The SuperNEMO detector

- 20 identical Modules with 100 kg total isotope mass
- Demonstrator module (1/20) will house 7kg of ^{82}Se and with 2.5y reach sensitivity of $\langle m_{\beta\beta} \rangle < 0.2 - 0.4$ eV
- Full SuperNEMO to reach sensitivity of $\langle m_{\beta\beta} \rangle < 0.04 - 0.1$ eV

Thin ββ-decay source foils

- 7kg of ^{82}Se in demonstrator module
- Factor of x10 decrease in ^{208}Tl contamination and x30 decrease in ^{214}Bi



Calorimeter walls

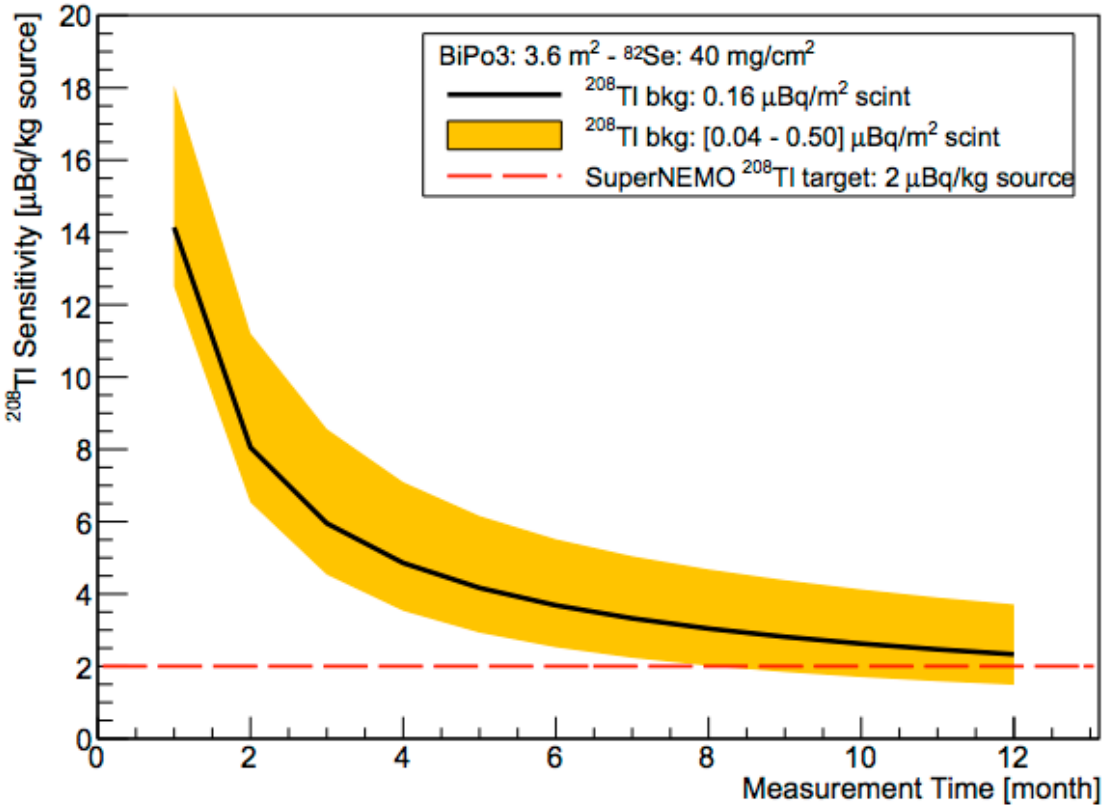
- **5" & 8"** PMTs coupled to **scintillator** blocks
- **FWHM 4% for** electrons @3MeV ($Q_{\beta\beta}$ value)

Tracking chambers

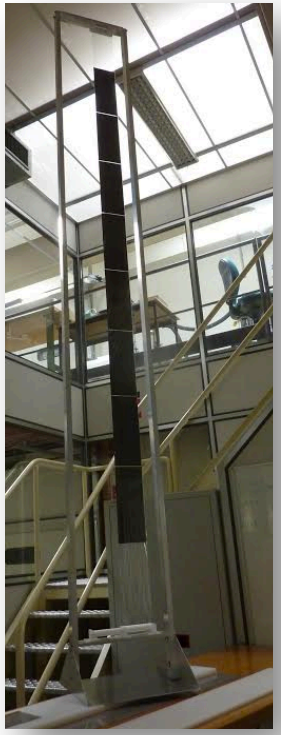
- Wire chambers in Geiger mode

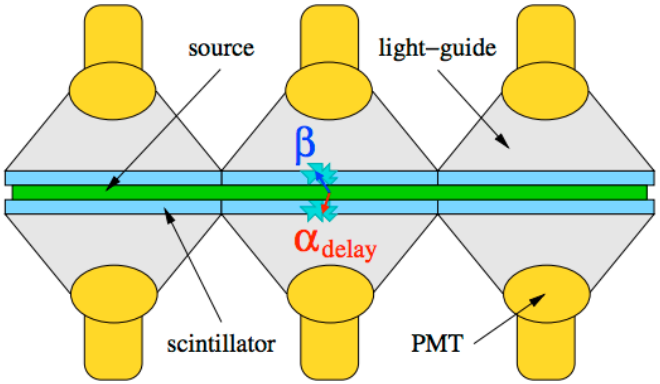
SuperNEMO demonstrator status – source foils

- 25% of source foil produced for demonstrator (^{82}Se)
- Radio-purity measurements underway using the dedicated BiPo detector



Source foil mounting test



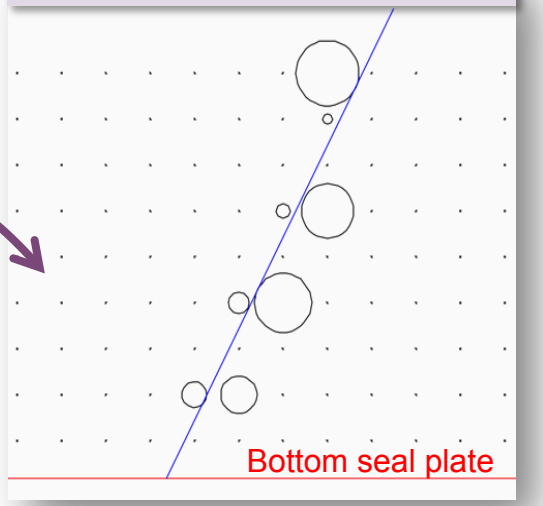


SuperNEMO demonstrator status – tracker

- First half of tracker complete
- First quarter (aka C0) commissioned, ready for shipment from UK to LSM
  - 98.4% of cells fully operational! (504 total)
- Radon tests for C1 underway, commissioning to follow

Populating a tracker section

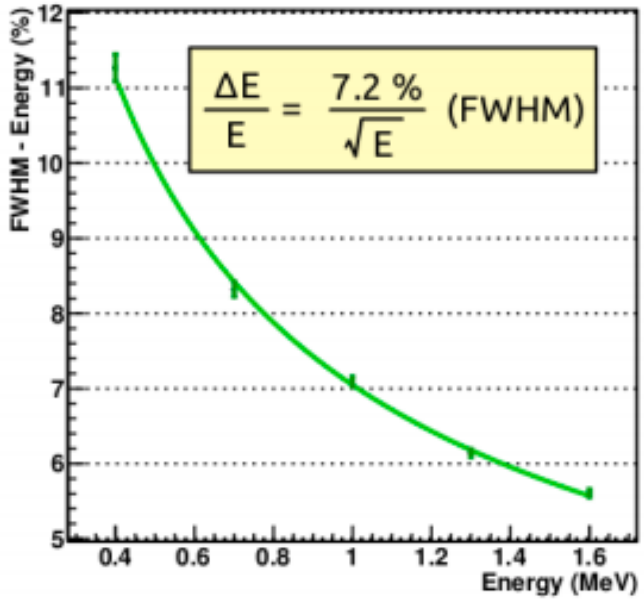
First tracks in C0



Commissioning with cosmics

SuperNEMO demonstrator status – calorimeter

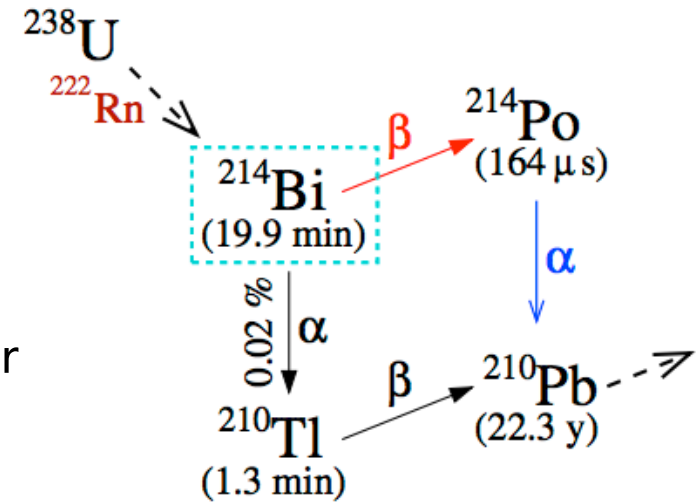
- Production and testing of optical modules is well underway (40% complete)
- Energy resolution meeting design specifications (FWHM 4% @ $Q_{\beta\beta}$)



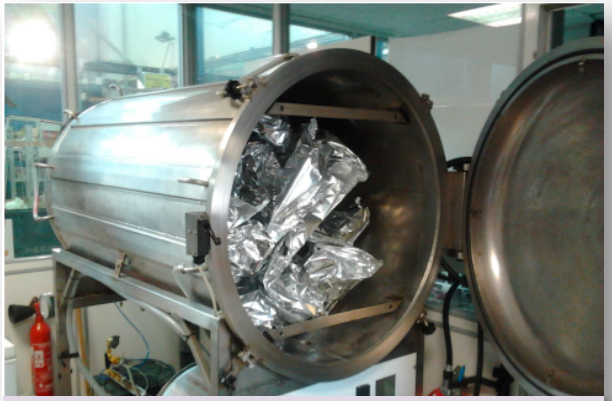
Optical module production and testing

SuperNEMO demonstrator status – radiopurity

- All materials screened for radiopurity with HPGe detectors and radon emanation chamber
- Radon (Rn) concentration line measures Rn in tracker gas (Target < 0.15 mBq/m^3)
- Radon trap will be installed to remove Rn from air
- Preliminary measurements of radon in tracker sections are ***very*** promising!!

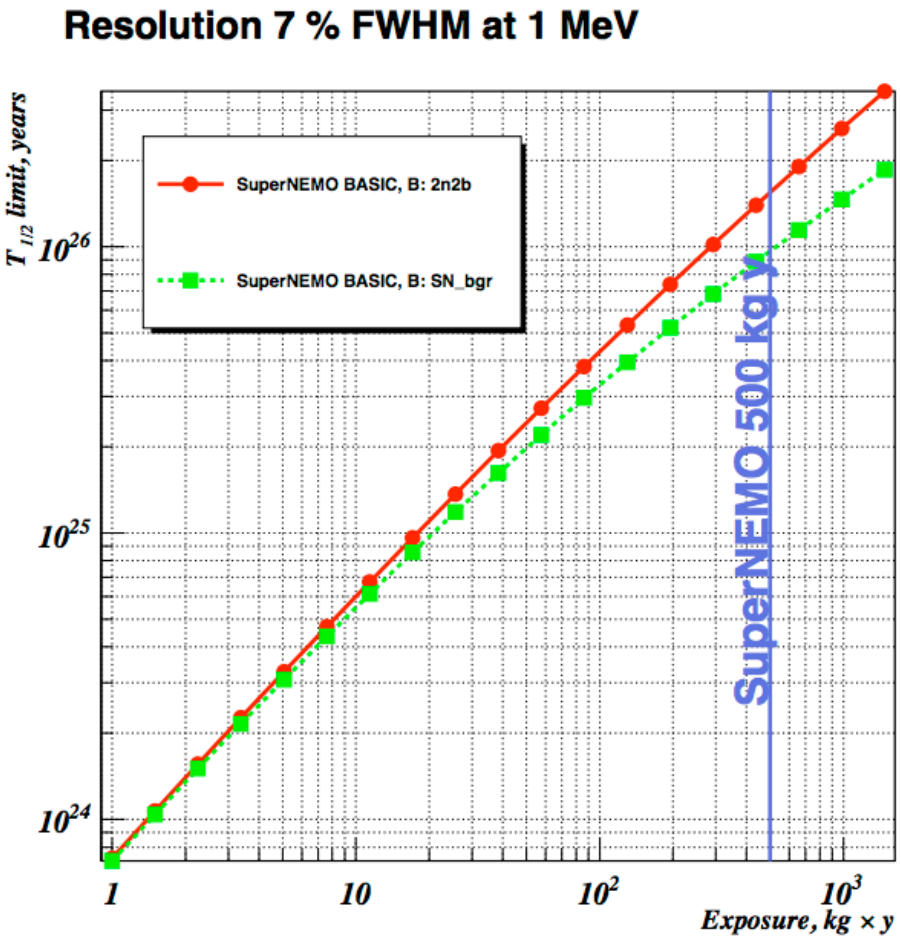


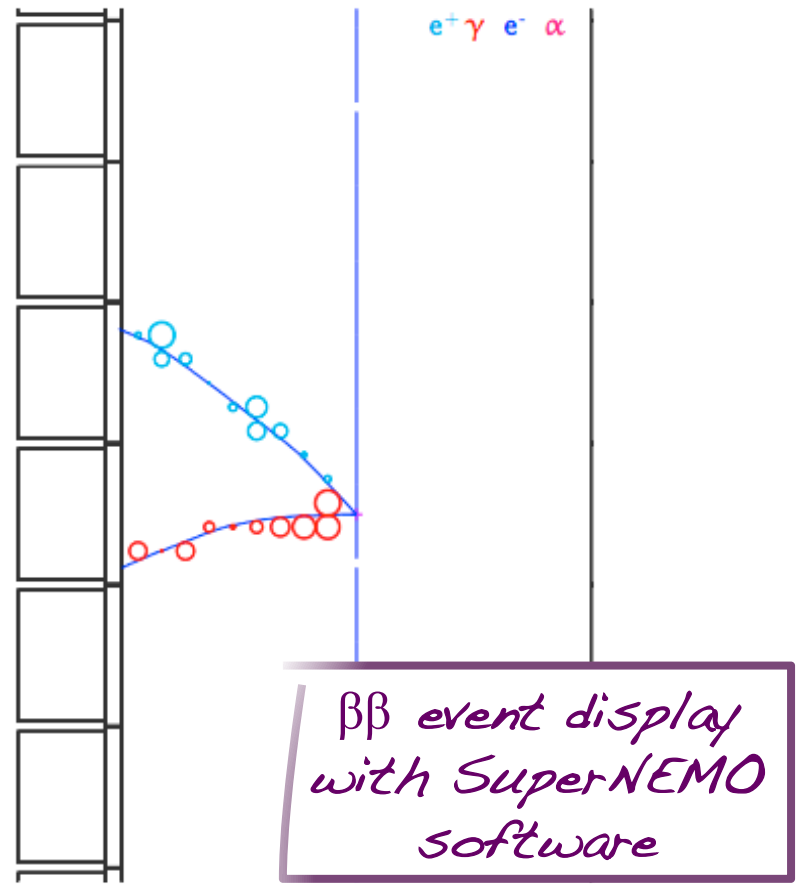
Radon concentration line



Radon emanation chamber

From demonstrator to full SuperNEMO





- Full SuperNEMO to reach sensitivity of $T_{1/2} > 1 \times 10^{26}$ y corresponding to $\langle m_{\beta\beta} \rangle < 0.04 - 0.1$ eV with 500 kg x y

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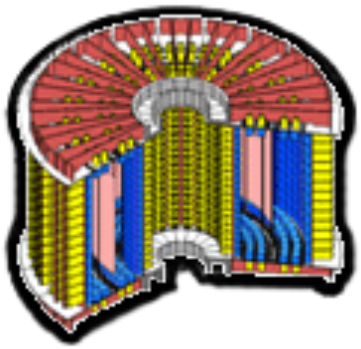
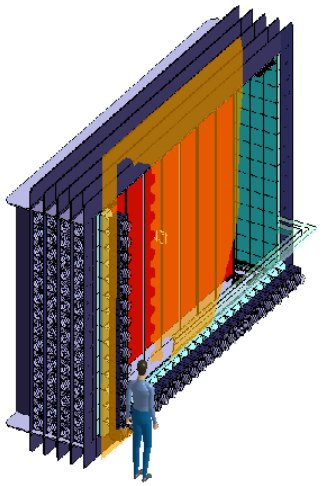
Summary

- NEMO-3/SuperNEMO experiments can reconstruct multiple final state topologies and event kinematics
- Offers a *unique* way to search for 0νββ decay and disentangle underlying mechanisms
- Analysis of full data set from NEMO-3 is ongoing
  - Best limit with 34.7 kgxy of ^{100}Mo is $T_{1/2} > 1.1 \times 10^{24}$ y
    $\langle m_{\beta\beta} \rangle < 0.33 - 0.62$ eV





- Construction of SuperNEMO demonstrator is underway
  - 7kg of ^{82}Se
  - With 2.5 kgxy, will reach $\langle m_{\beta\beta} \rangle < 0.2 - 0.4$ eV
- Commissioning to begin at the end of next year! (2016)

Thank you for your attention!

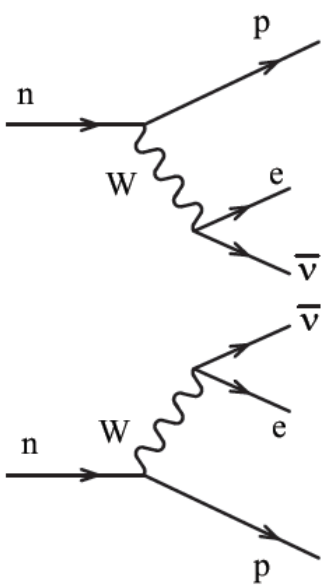
BACKUP SLIDES

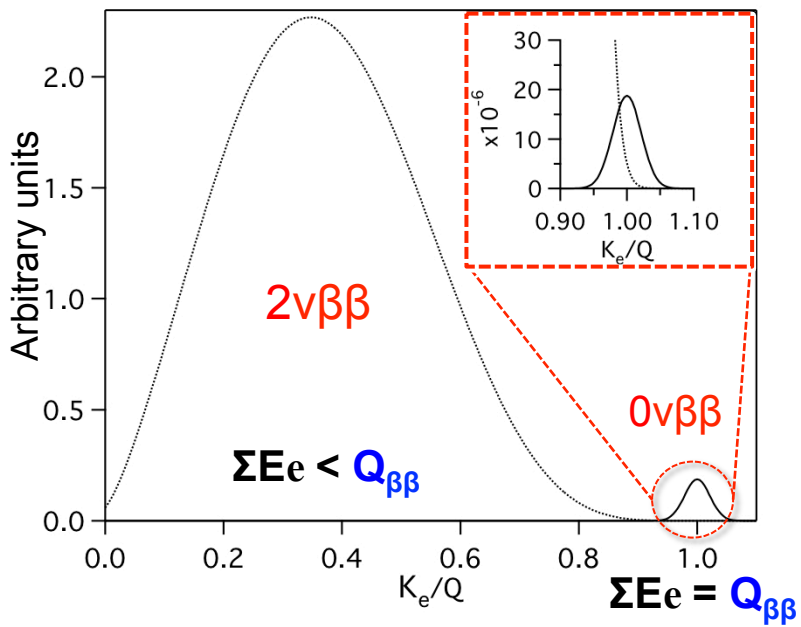
2νββ decay

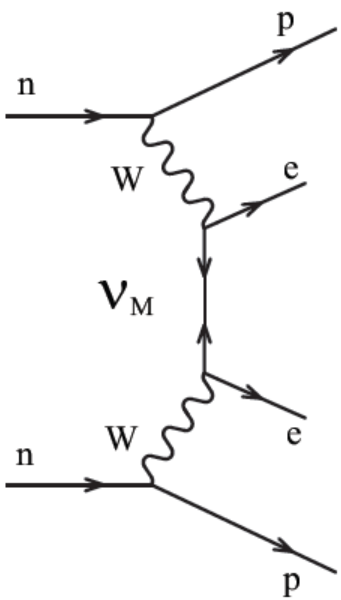
- Occurs if β-decay is forbidden or highly suppressed (35 isotopes)
- 2nd order weak process in the Standard Model (SM) ($T_{½}$ ~10^{18-21} yrs)
- Detect 2 electrons with continuous ΣE_{TOT} ($\bar{\nu}_e$'s escape detection)

0νββ decay

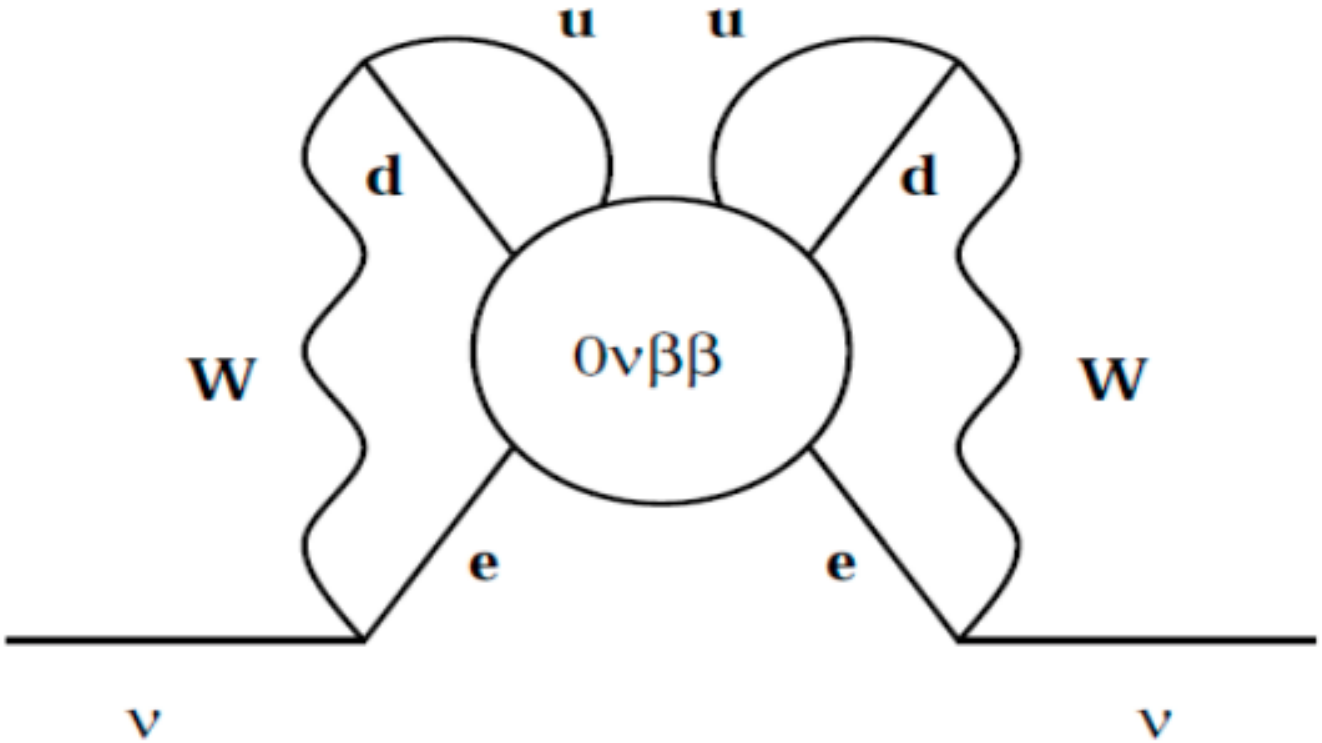
- BSM process that violates ΔL conversation by 2 units
- Can be mediated by: Light Majorana ν, (V+A) current, SUSY
- Observed final state identical to 2νββ







Dirac vs Majorana

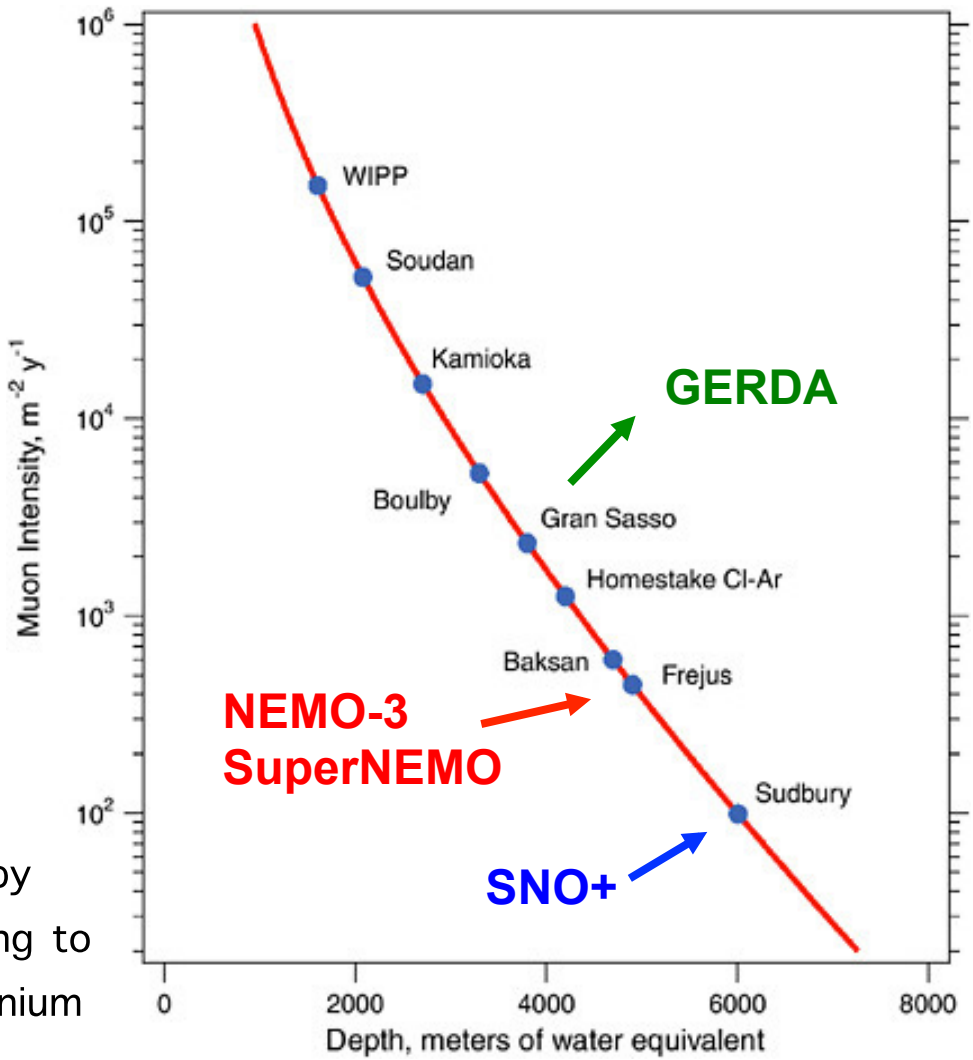


Schechter-Valle theorem

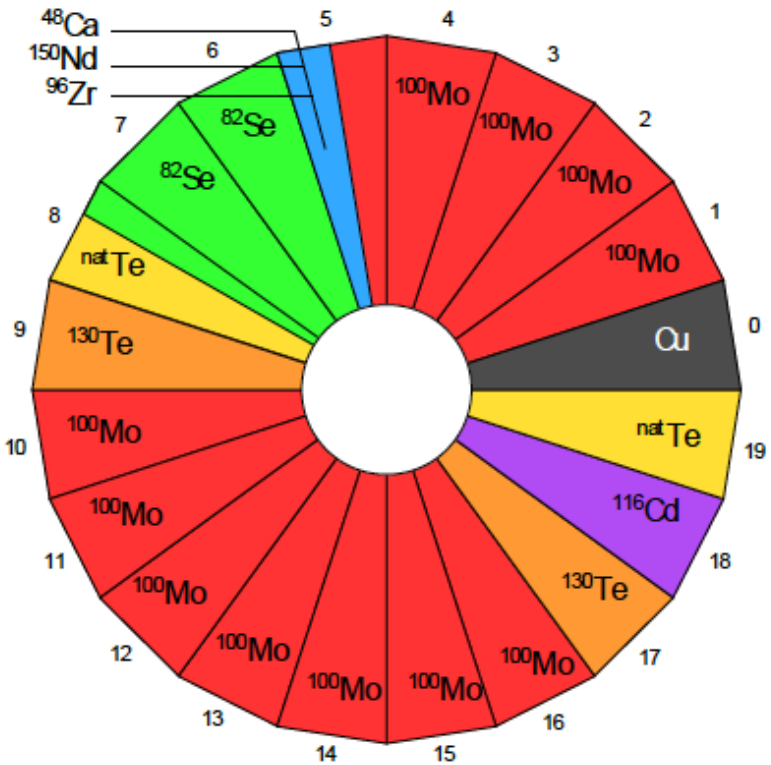
Image from Neutrino Physics Kai Zuber, IoP Publishing 2004

Experimental considerations for 0νββ

- Choice of isotope
  - Large $G^{0\nu}$ and $M^{0\nu}$ for shorter $T_{1/2}$
  - Large $Q_{\beta\beta}$ for background rejection
  - Large mass of isotope of interest
    - Enrichment, purification, abundance
- Detector design
  - Good energy resolution
  - Radio-pure materials
  - Active or passive
- Choice of location
  - Experiments underground and protected by many layers of passive and active shielding to protect from cosmic muon spallation, uranium fission, etc



The NEMO-3 detector – ββ-decay sources



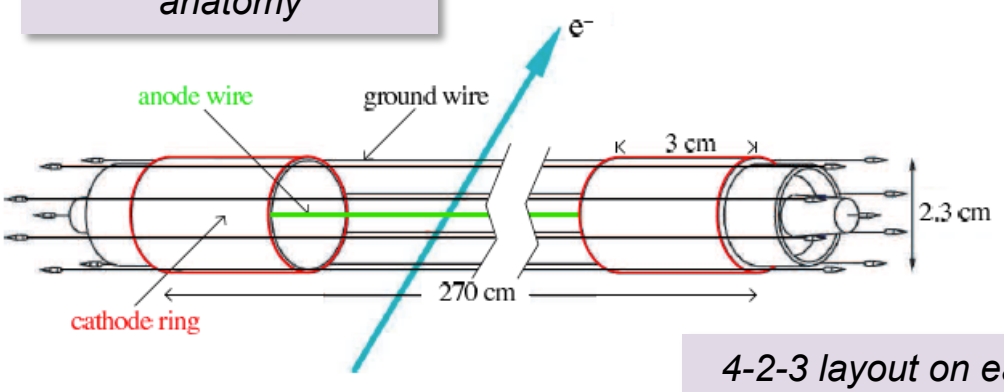
^{100}Mo 6,9 kg	^{150}Nd 36,5 g
^{82}Se 0,93 kg	^{96}Zr 9,43 g
^{130}Te 0,45 kg	^{48}Ca 6,99 g
^{116}Cd 0,40 kg	

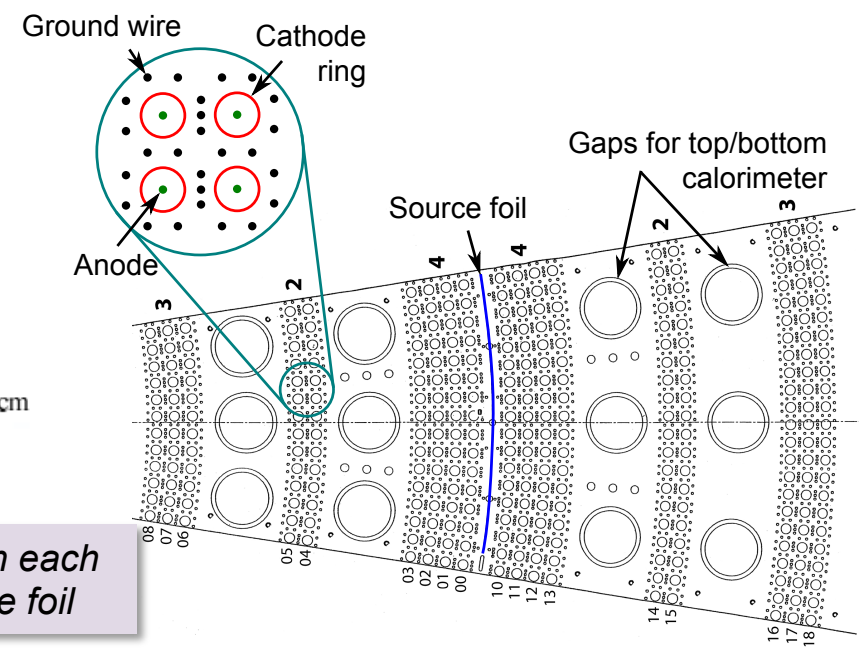
- Only technique that can measure multiple isotopes at the same time
- Largest mass with ^{100}Mo (6.9 kg) and ^{82}Se (0.93 kg)

NEMO-3 *tracker*

- Wire tracking chamber with 6180 cells operating in Geiger mode
  - 95% He, 4% alcohol, 1% Ar, 0.1% H_2O
- Vertex resolution: $\sigma_{XY} \sim 3$ mm, $\sigma_Z \sim 10$ mm
- 25 G magnetic field for discrimination between e^+/e^-

Single tracker cell anatomy



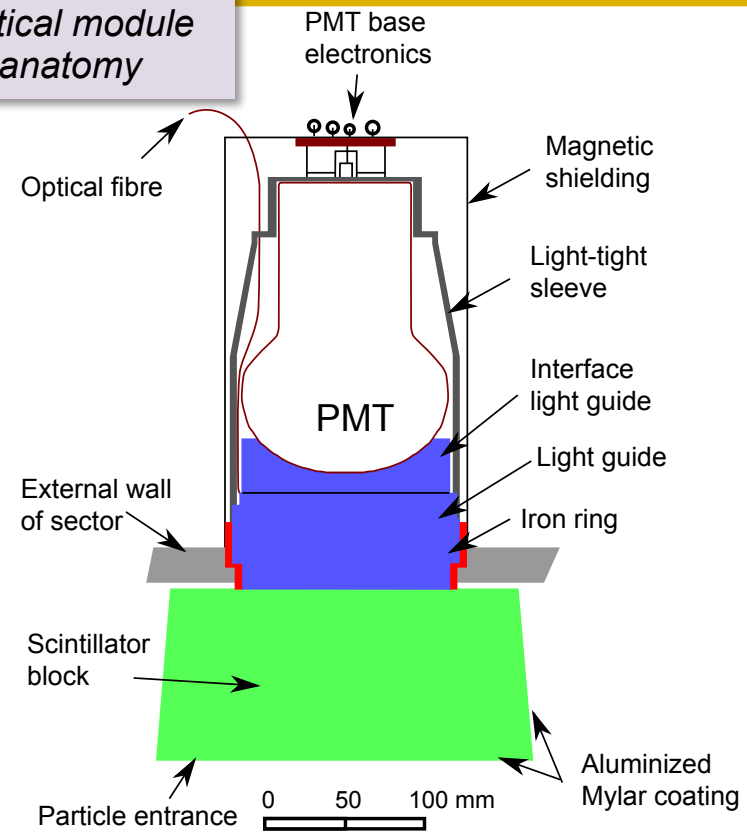


4-2-3 layout on each side of source foil

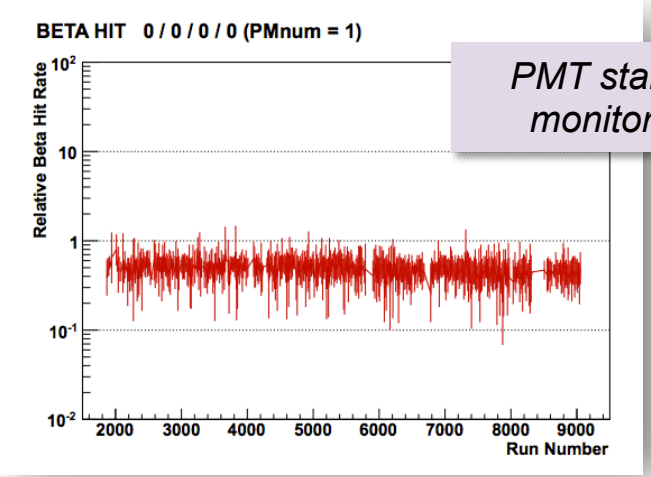
NEMO-3 *calorimeter*

- 1940 optical modules
- 3” and 5” low-radioactivity PMTs coupled to large (10x10x10) scintillator blocks
- ~15% / √E @ 1 MeV
- Dedicated studies for PMT monitoring to ensure high quality modules used in analysis

Optical module anatomy

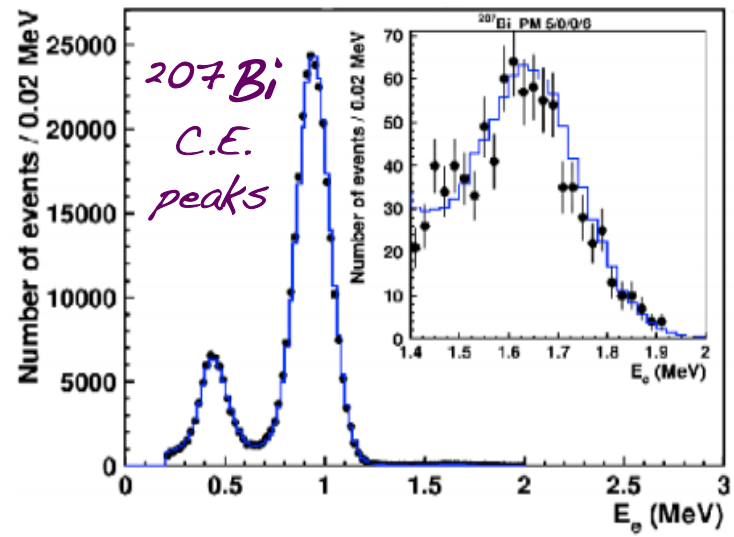


PMT stability monitoring

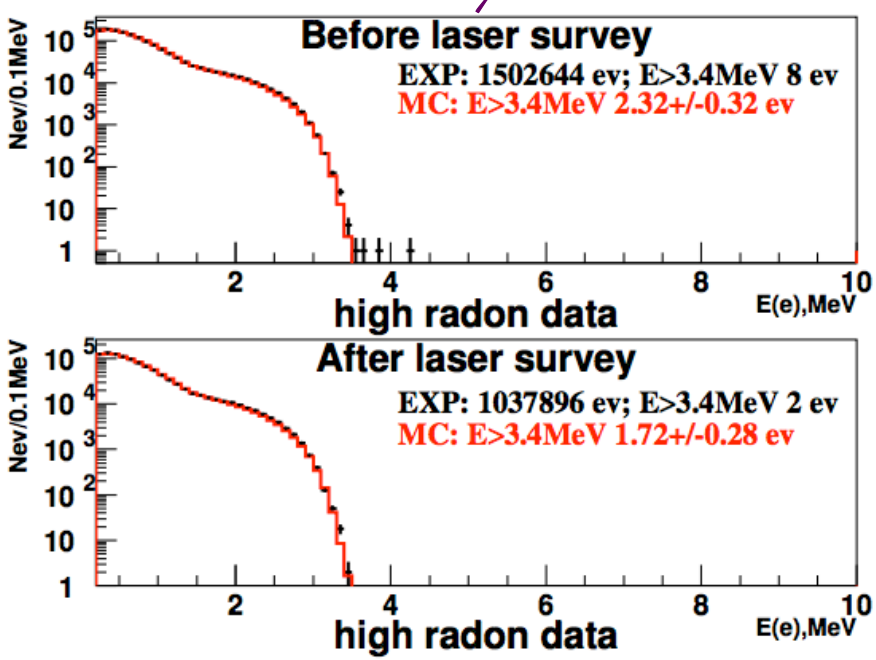


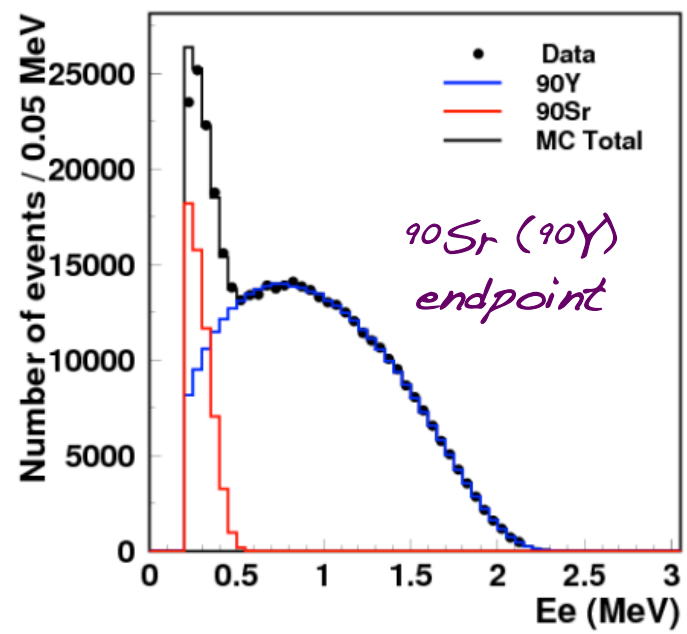
NEMO-3 calibrations

- Monthly absolute calibration runs with ^{207}Bi sources + runs with ^{90}Sr source for calibrating up to 3 MeV
- Check PMT stability with daily laser survey (82% of PMTs stable for entire lifetime of experiment)



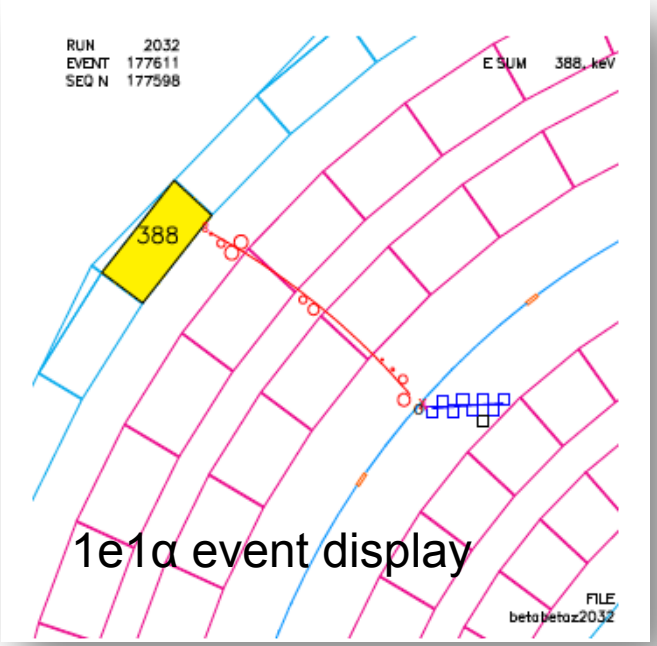
Laser survey validation

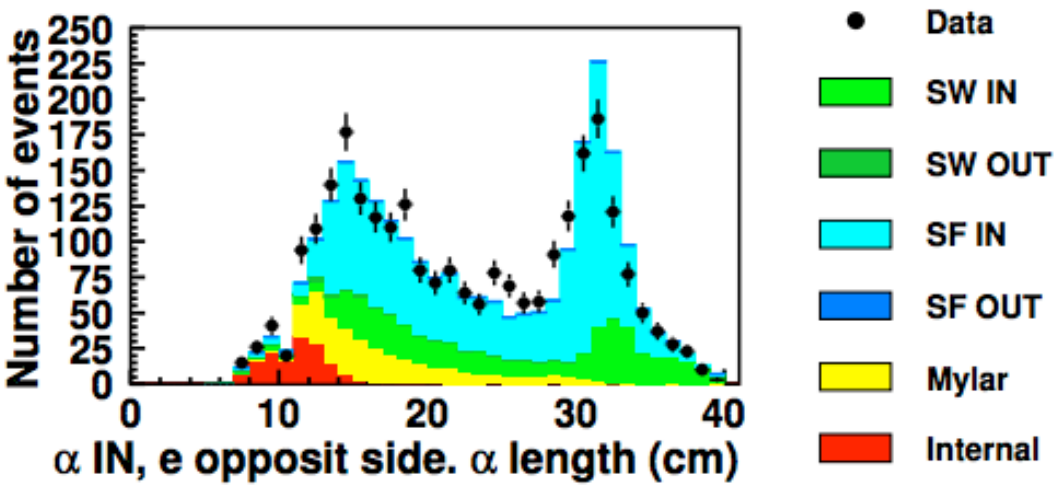




Measuring backgrounds: ^{214}Bi-^{214}Po cascade

- Electronics store Geiger hits information up to 700µs after event trigger
- Tag ^{214}Bi-^{214}Po cascades with one electron and one cluster of delayed Geiger hits (α)



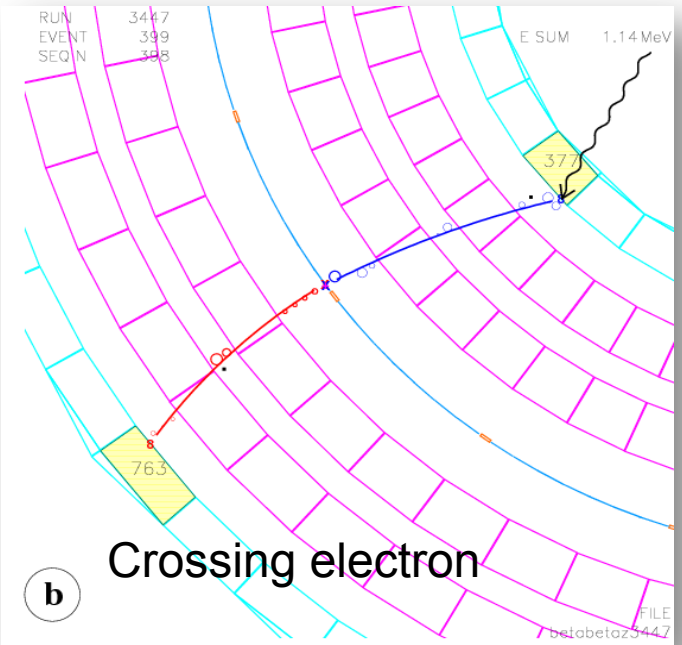


arxiv:1506.05825

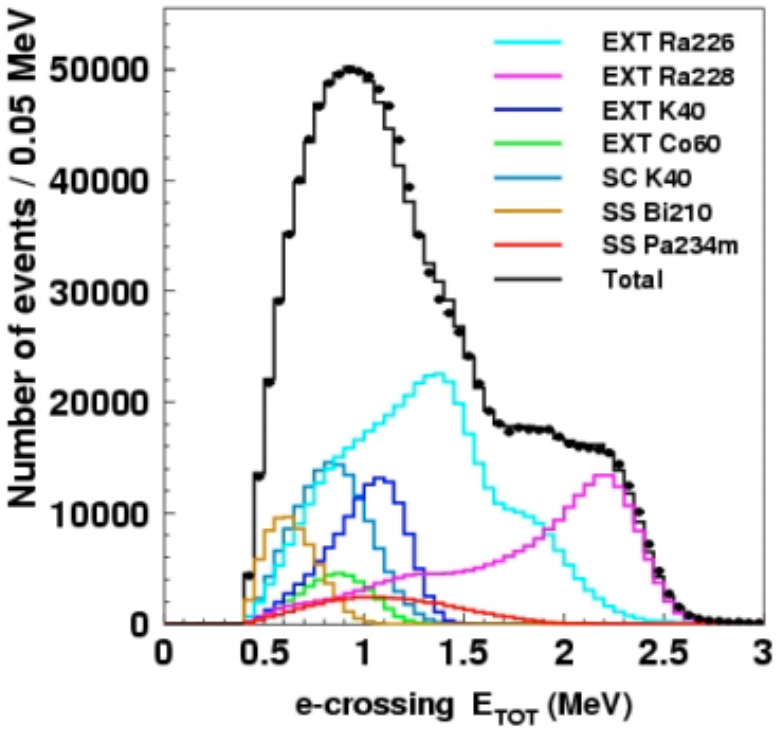
^{214}Po half-life is 164.3µs

Measuring backgrounds: Crossing electrons

- High energy external γ-flux can produce e^+e^- pairs in foil
- Use passive shielding to reject most events (slide 9)
- Use calo timing information to tag and characterize external events

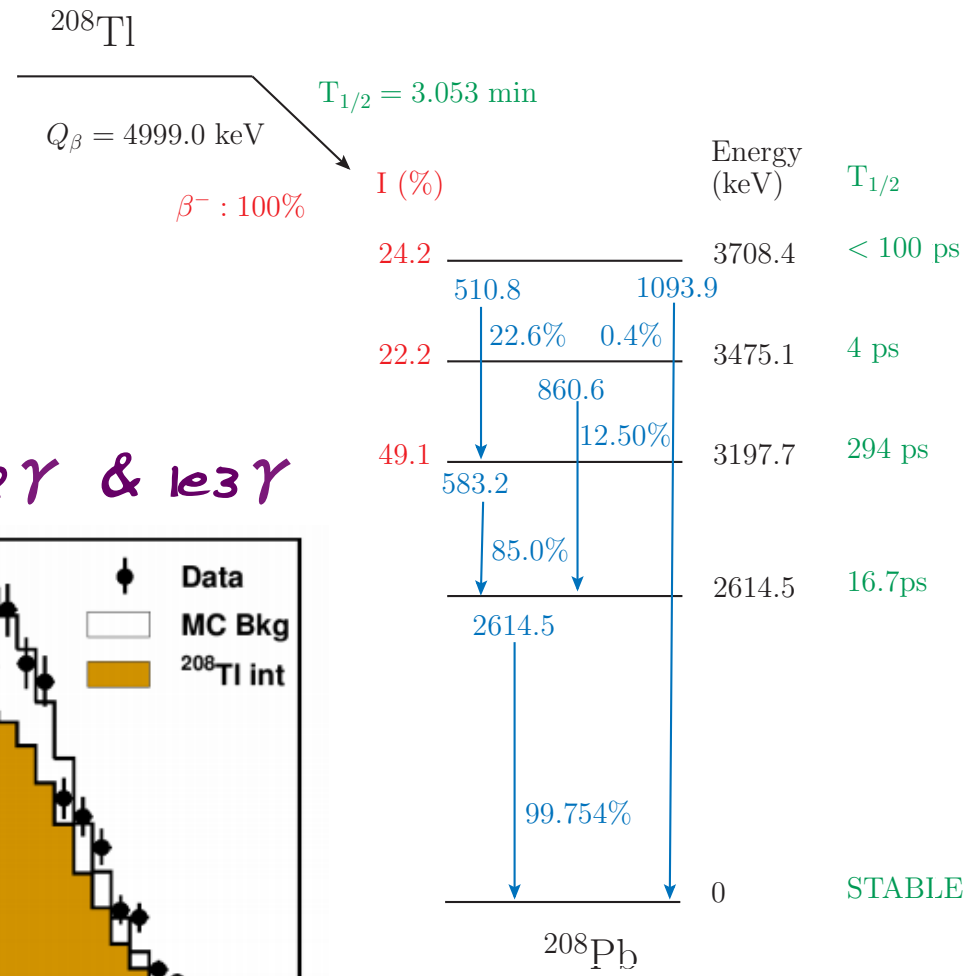


NIM A 606: 449-465, 2009

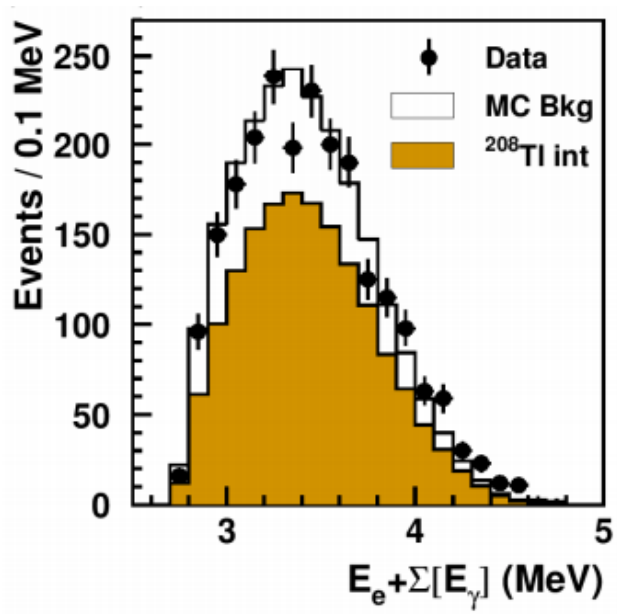


Measuring backgrounds: electron + gammas

- Many internal background decay to excited states of their daughter isotopes
- Tag γ rays emitted in de-excitation to identify these backgrounds
- Channel selects one electron and *N* scintillator hits without tracks pointing to them

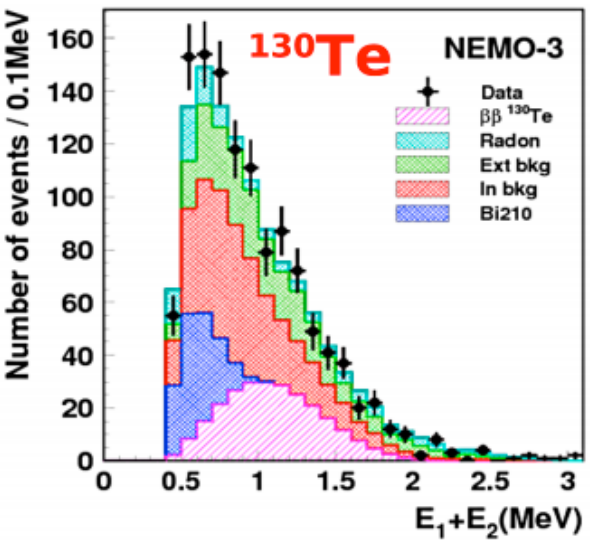


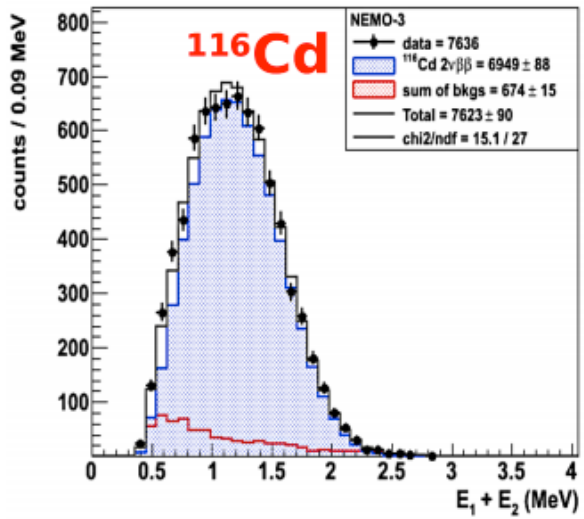
^{100}Mo 1e2γ & 1e3γ

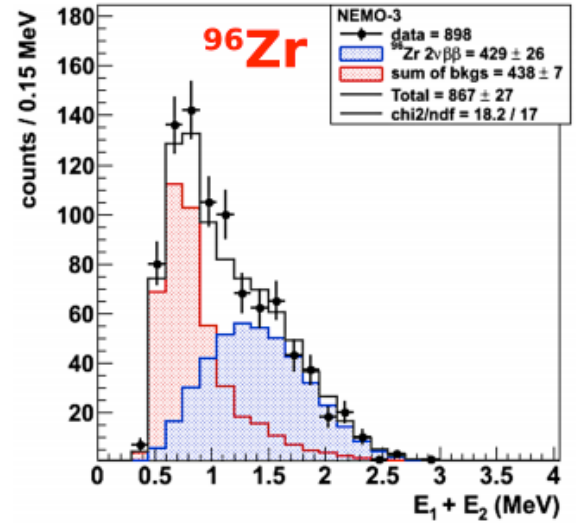


arxiv:1506.05825

Results from NEMO-3





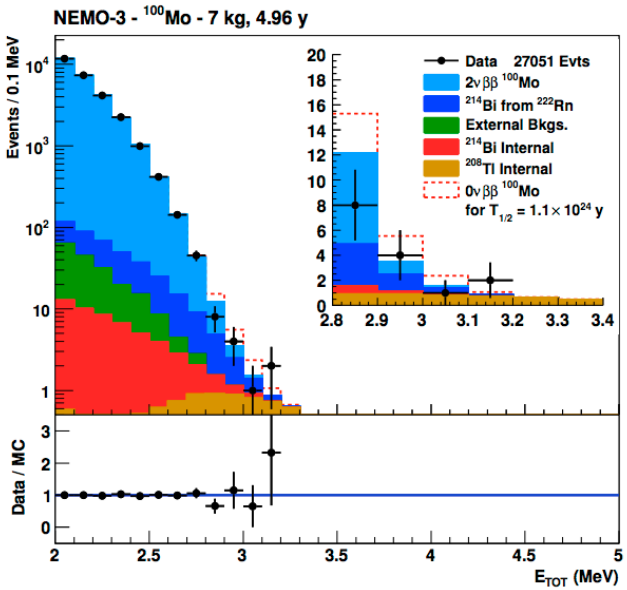


Isotope	Mass (g)	2νββ $T_{1/2}$ ($\times 10^{19}$ y)	0νββ $T_{1/2}$ (90% CL)	Reference
^{82}Se	932	$9.6 \pm 0.1_{stat} \pm 1.0_{syst}$	$> 3.2 \times 10^{23}$	PhysRevLett 95 (2005) 182302
^{150}Nd	37.0	$0.91^{+0.025}_{-0.022}{}^{stat} \pm 0.063_{syst}$	$> 1.8 \times 10^{22}$	PhysRevC 80 (2009) 032501
^{96}Zr	9.4	$2.35 \pm 0.14_{stat} \pm 0.16_{syst}$	$> 9.2 \times 10^{21}$	Nucl.Phys.A847 (2010) 168
^{130}Tl	454	$70 \pm 9_{stat} \pm 11_{syst}$	$> 1.3 \times 10^{22}$	PhysRevLett 107 (2011) 062504

New results soon for ^{150}Nd, ^{48}Ca, ^{116}Cd, ^{96}Zr and ^{82}Se for full exposure!

^{100}Mo 0νββ result

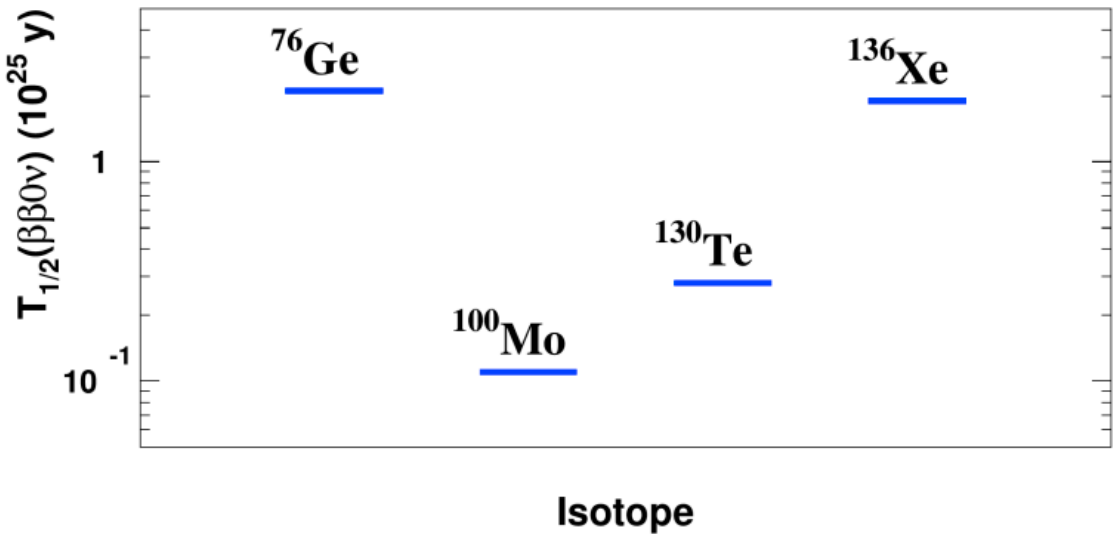
- Event break-down
- Dominant systematic is absolute normalization on 0νββ efficiency

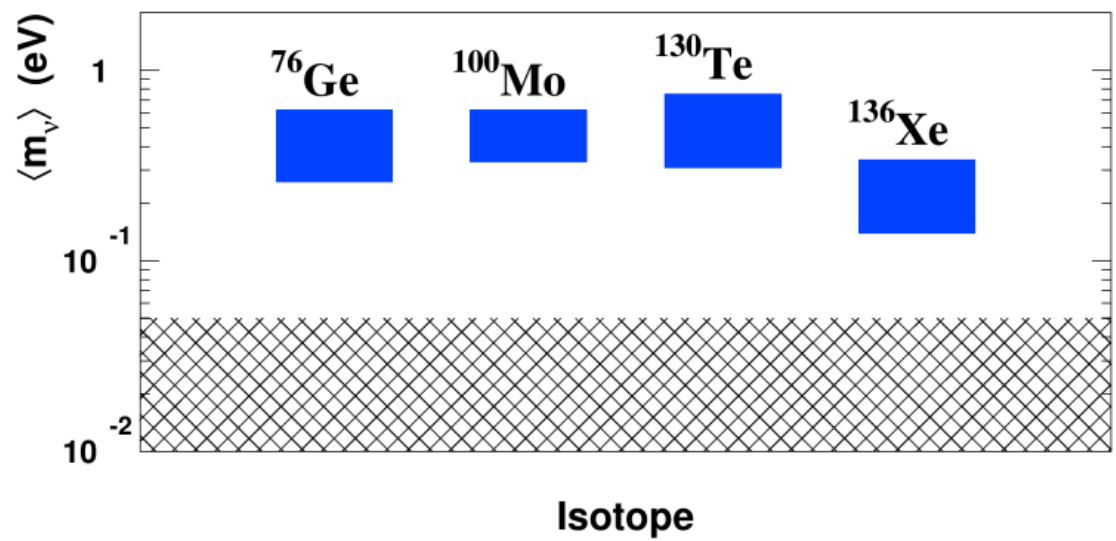


Contribution	N_{2e} events E_{TOT} = [2.8-3.2] MeV
External background	< 0.2
^{214}Bi from radon	5.2 ± 0.5
^{214}Bi internal	1.0 ± 0.1
^{208}Tl internal	3.3 ± 0.3
2νββ	8.45 ± 0.05
Total Expected	18.0 ± 0.6
Data	15

Systematics	%	Estimation method
0νββ efficiency	7.0	Activity of ^{207}Bi calibration sources HPGe v NEMO
^{214}Bi internal	10.0	Variation of activity between bkg. channels
^{208}Tl internal	10.0	Activity of ^{232}U calibration sources HPGe v NEMO
2νββ	0.7	2νββ total energy spectrum fit > 2 MeV

Comparison to other isotopes





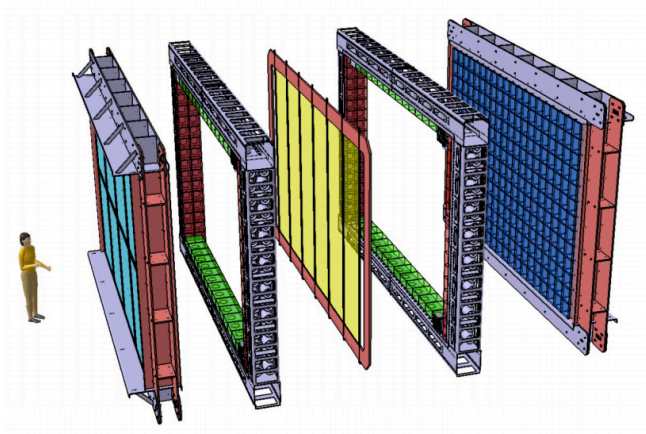
- See [arxiv:1506.05825] for references to other isotope results

Moving towards SuperNEMO

- SuperNEMO shares the same detector design principles as NEMO-3
- Modular in design → first module (of 20 total) is the demonstrator
- Demonstrator will house 7kg of ^{82}Se and with 2.5y will reach sensitivity of $\langle m_{\beta\beta} \rangle \sim 0.2 - 0.4$ eV

Feature	NEMO-3	SuperNEMO
Isotope	^{100}Mo	^{82}Se (^{48}Ca, ^{150}Nd)
Mass	7 kg	100 kg
Radiopurity	A(^{208}Tl) < 20 μBq/kg	A(^{208}Tl) < 2 μBq/kg
(activity)	A(^{214}Bi) < 300 μBq/kg	A(^{214}Bi) < 10 μBq/kg
	A(Rn) < 5 mBq/m^3	**A(Rn) < 0.15 mBq/m^3**
Efficiency	18%	30%
σ_E (FWHM@3MeV)	8%	4%
Sensitivity	$T^{0\nu}_{1/2} > 1 \times 10^{24}$	$T^{0\nu}_{1/2} > 1 \times 10^{26}$
	$m_{\beta\beta} < 0.3 - 0.8$ eV	$m_{\beta\beta} < 0.04 - 0.1$ eV

**Values in table correspond to the full 20 modules of SuperNEMO*



Full SuperNEMO:
$m_{\beta\beta} \sim 0.04 - 0.1$ eV

Considerations for 0νββ sensitivity

- Maximizing exposure (M x t) is important
- Minimizing background counts and improving energy resolution have equivalent effects

$$T_{1/2}^{0\nu} > \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{Z}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

With background

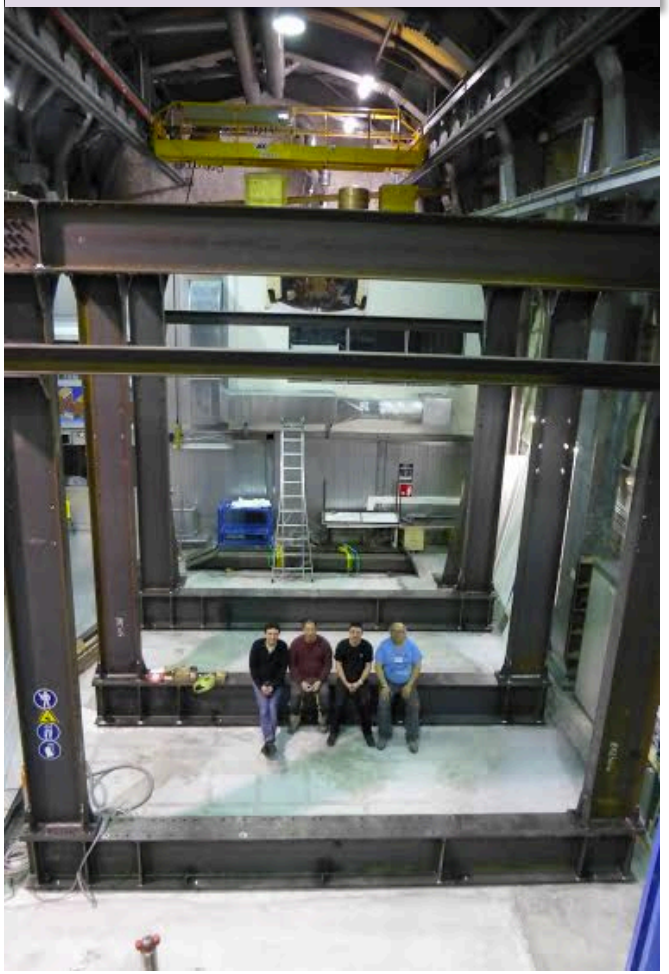
$$T_{1/2}^{0\nu} > \frac{4.16\times10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{Z}\right)M\times t$$

No background

- n_σ – number of standard deviations for a given CL
- ε – detection efficiency
- a – isotopic abundance in source mass
- Z – Molecular weight of source isotope
- Mt – exposure in kg y
- b – background rate in kg^{-1} keV^{-1} y^{-1}
- ΔE – energy resolution in 0νββ signal region in keV
- Z – Molecular weight of source isotope

SuperNEMO demonstrator - integration

Support frame installed at LSM



Tracker section ready for transport to LSM

Optical module production underway

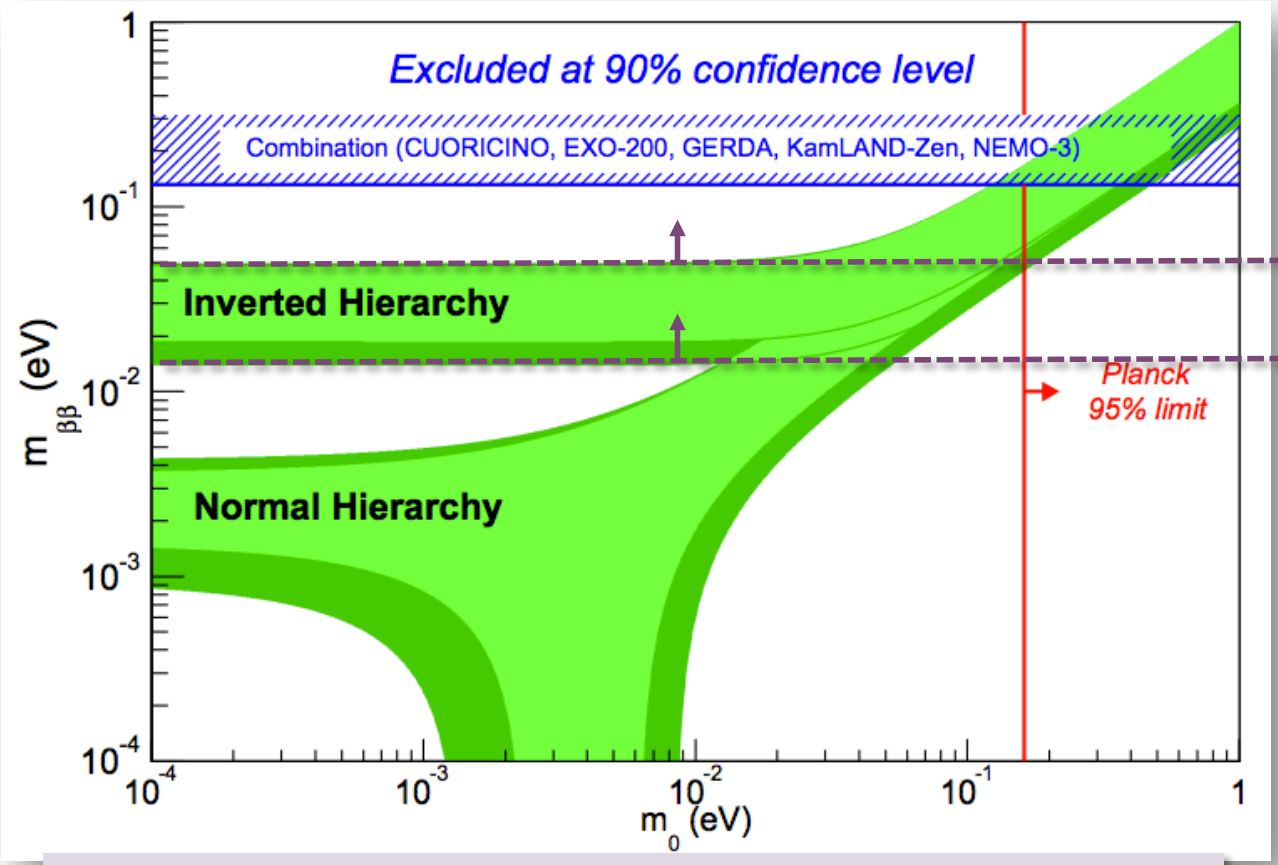
SuperNEMO Demonstrator starting to take shape

Commissioning by 2016

Sensitivity of next generation 0νββ experiments

Current best limit at $m_{\beta\beta}$ < 130 - 310 meV (90% CL)

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



SNO+, SuperNEMO, CURORE< EXO+, GERDA, KAMLAND-Zen+ (2017–)

SNO+ ungraded, nEXO, Super-KamLAND-Zen

Assumes 3 neutrino mixing model

P. Guzowski *et al.*, Phys.Rev.D 92 (2015) 012002. [arXiv:1504.03600 [hep-ex]]

*See talk P. Guzowski's talk later in this session