- Double Beta Decay
- NEMO-3 Experiment
- The SuperNEMO Experiment

# Latest Results from NEMO-3 and Development of SuperNEMO

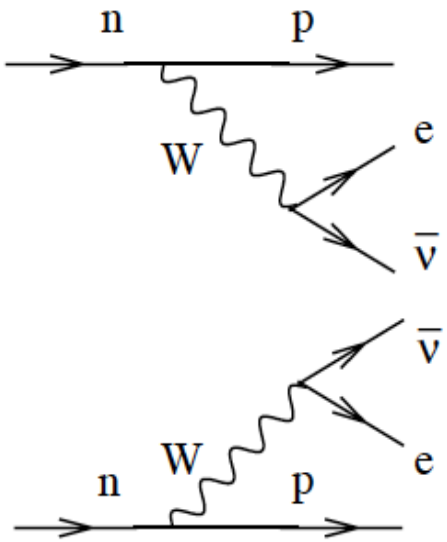
Zachary Liptak
UT Austin Center for Particles and Fields
On behalf of the NEMO Collaboration
INFO13 Workshop

- Double Beta Decay
- NEMO-3 Experiment
- The SuperNEMO Experiment

# Motivating NEMO: Double Beta Decay

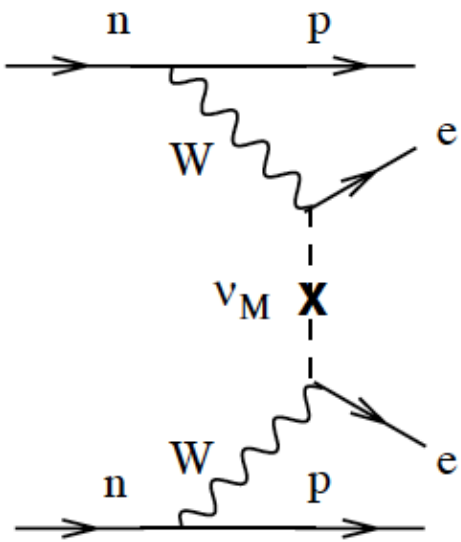
# Double Beta Decay Theory

## $2\nu\beta\beta$ Decay




- $\Delta L = 0$
- Allowed in Standard Model

## $0\nu\beta\beta$ Decay

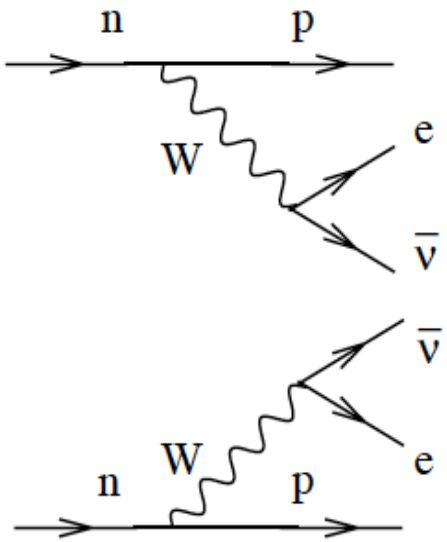



- $\Delta L = 2$
- Forbidden in Standard Model

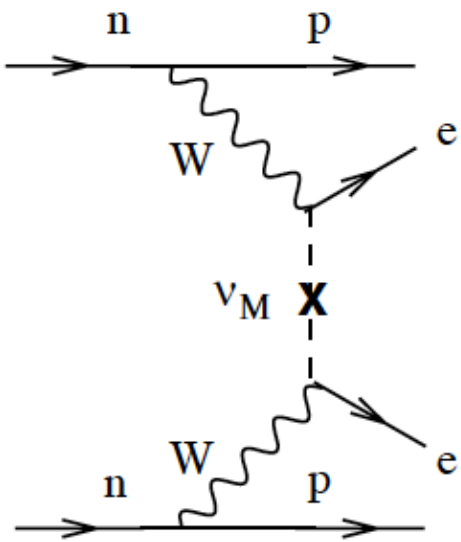
***$0\nu\beta\beta$ decay is only possible if neutrinos are massive Majorana particles***

# Double Beta Decay Theory

2νββ Decay




0νββ Decay

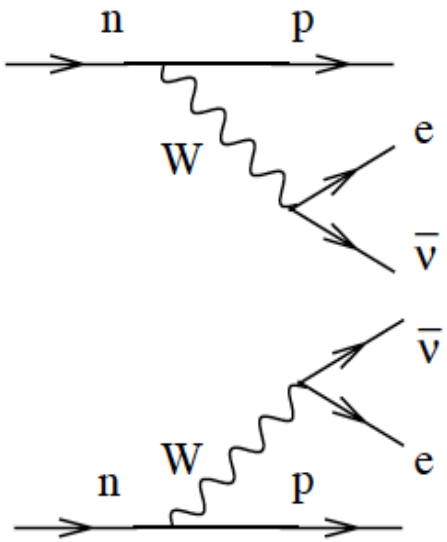



$$\frac{1}{T_{1/2}^{2n}} = G_{2n}(Q_{bb},Z)\cdot\left|M_{2n}\right|^2 \qquad \frac{1}{T_{1/2}^{0n}} = G_{0n}(Q_{bb},Z)\cdot\left|M_{0n}\right|^2\cdot\left\langle m_{bb}\right\rangle^2$$

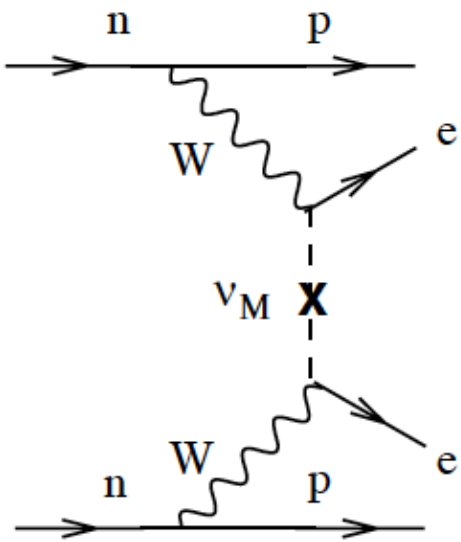
- G(Q,Z) is a well-known phase-space element
- M is complicated nuclear matrix element

# Double Beta Decay Theory

2νββ Decay




0νββ Decay

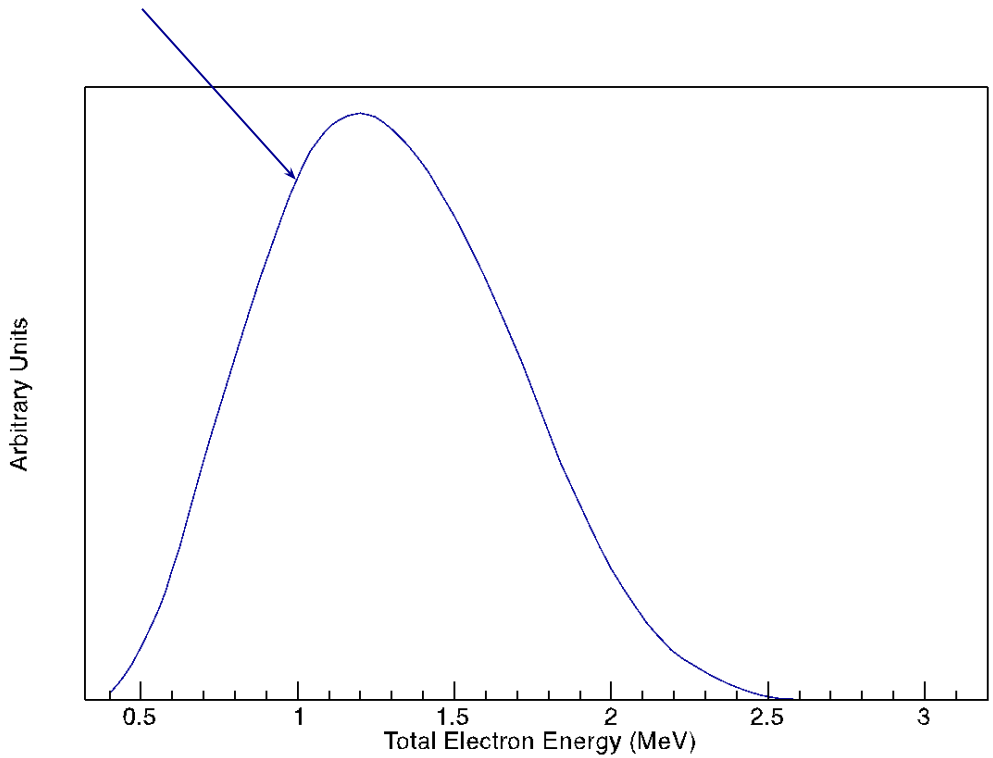



$$\frac{1}{T_{1/2}^{2n}} = G_{2n}(Q_{bb}, Z) \cdot |M_{2n}|^2 \qquad \frac{1}{T_{1/2}^{0n}} = G_{0n}(Q_{bb}, Z) \cdot |M_{0n}|^2 \cdot \langle m_{bb} \rangle^2$$

**Neutrinoless decay allows for measurement of effective neutrino mass**

# Double Beta Decay Phenomenology

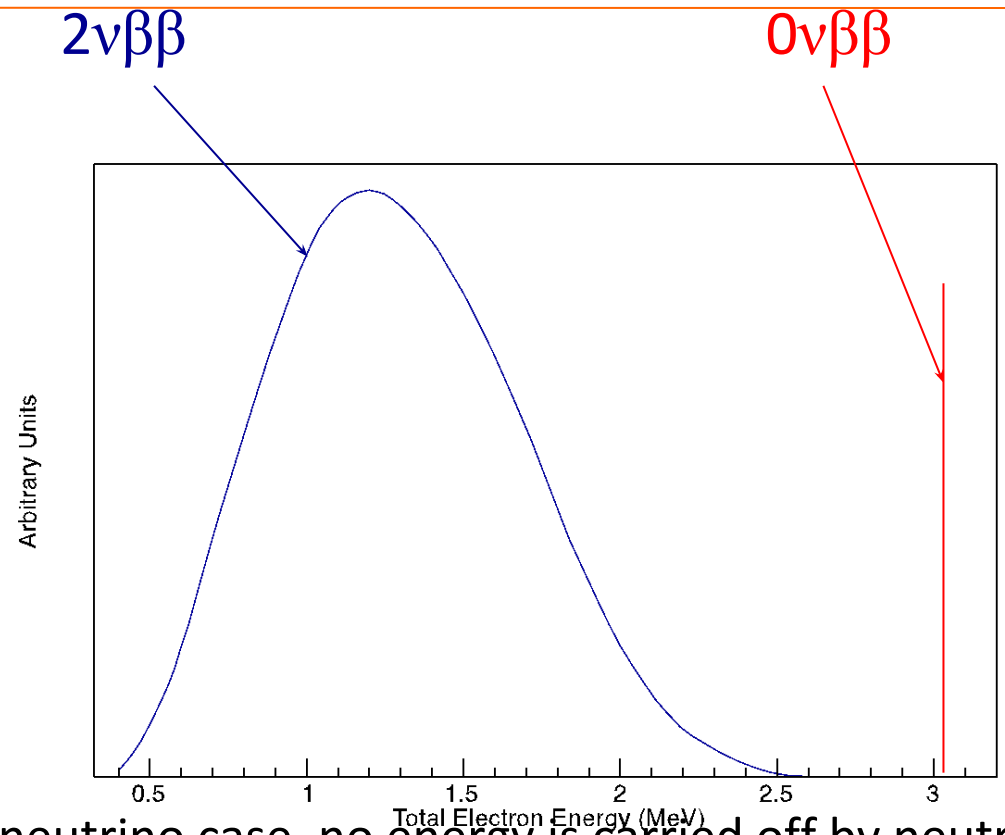
## $2\nu\beta\beta$ total electron energy spectrum




$2\nu\beta\beta$ total electron energy spectrum for $^{100}$Mo ($Q_{\beta\beta}$ = 3.034 MeV)

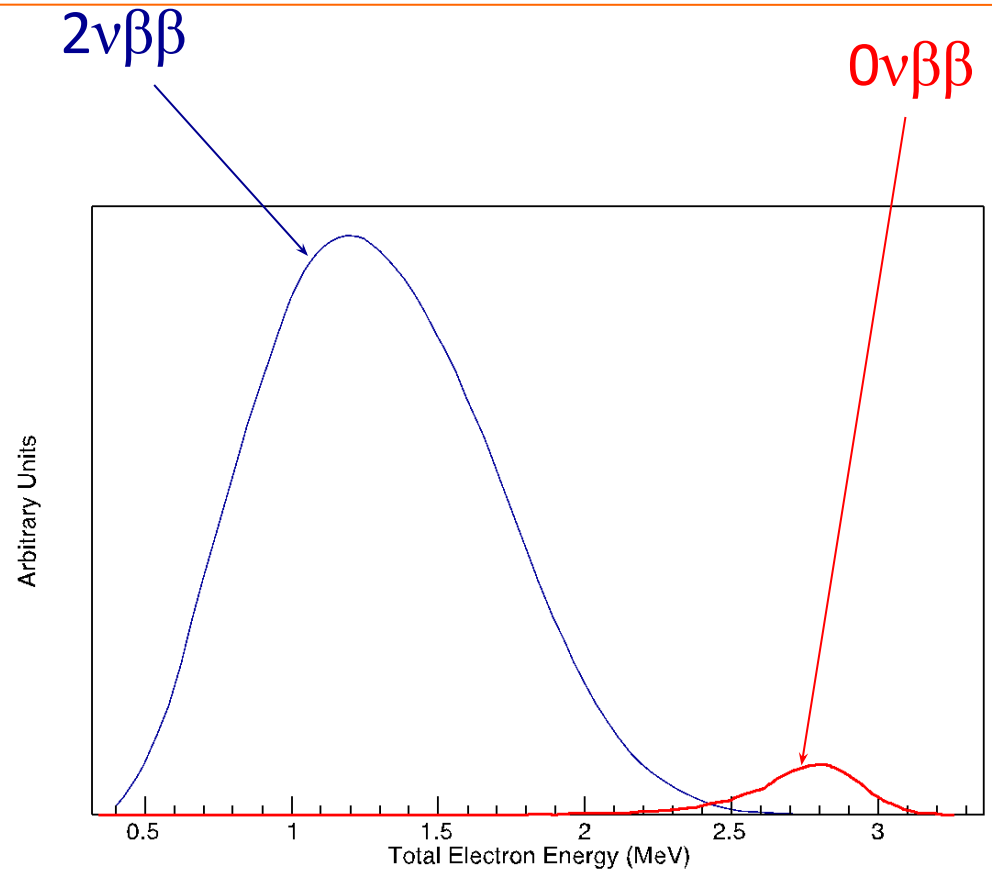
Neutrinos ejected in double beta decay are not readily detectable, so we rely on observables from the two electrons.

# Double Beta Decay Phenomenology




In the zero neutrino case, no energy is carried off by neutrinos and the two-electron energy should approximate a δ-function at the Q-value.

# 2ν Tail Resolution




However… detector effects cause a "smearing" of the 0ν signal, leading to inevitable background from the 2ν tail.

- Double Beta Decay
- **NEMO-3 Experiment**
- The SuperNEMO Experiment

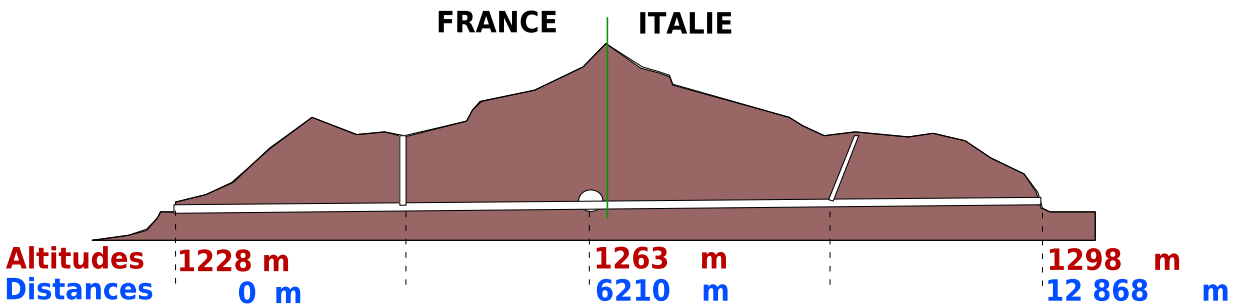
# The NEMO-3 Experiment

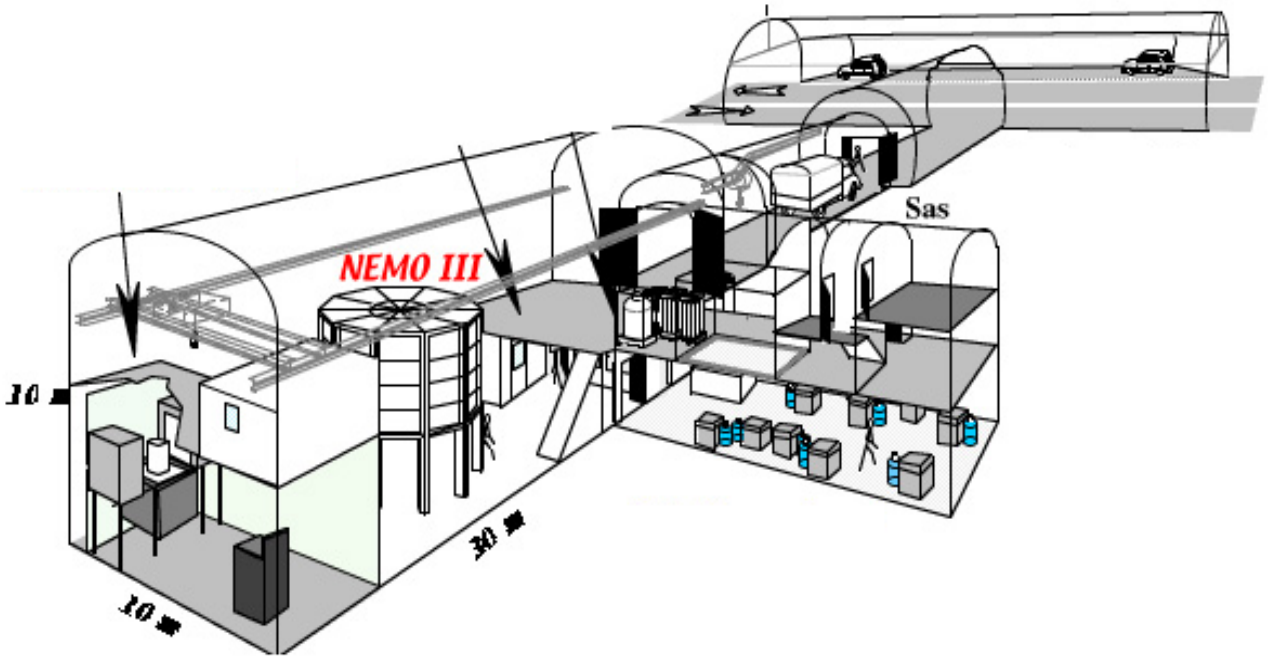
# The NEMO-3 Collaboration

- NEMO-3 detector operated in the LSM at Modane, France (4,800 m.w.e.)
- Data collection from 2003 – 2010
- Collaboration of researchers from 9 different countries:

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

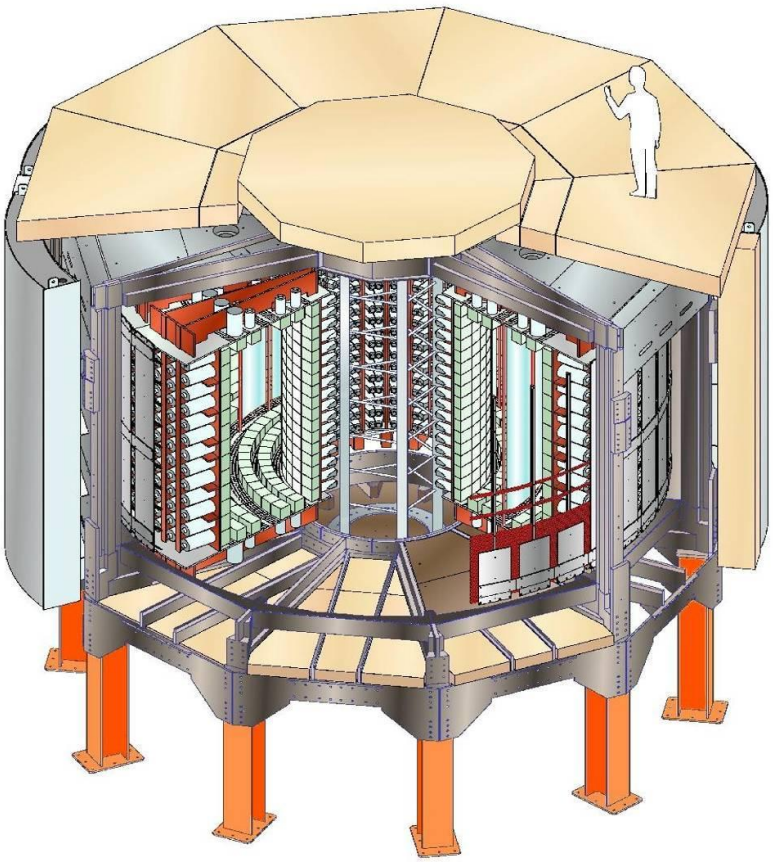
# Laboratoire Souterrain de Modane (LSM)




**NEMO-3/SuperNEMO housed in the Fréjus Tunnel (4800 m.w.e.)**

# The NEMO-3 Detector



- 10 kg source material
  (approx. 80 kg yr exposure)

- Drift wire tracking chamber:
  - 6180 cells in Geiger mode
  - 25 Gauss magnetic field

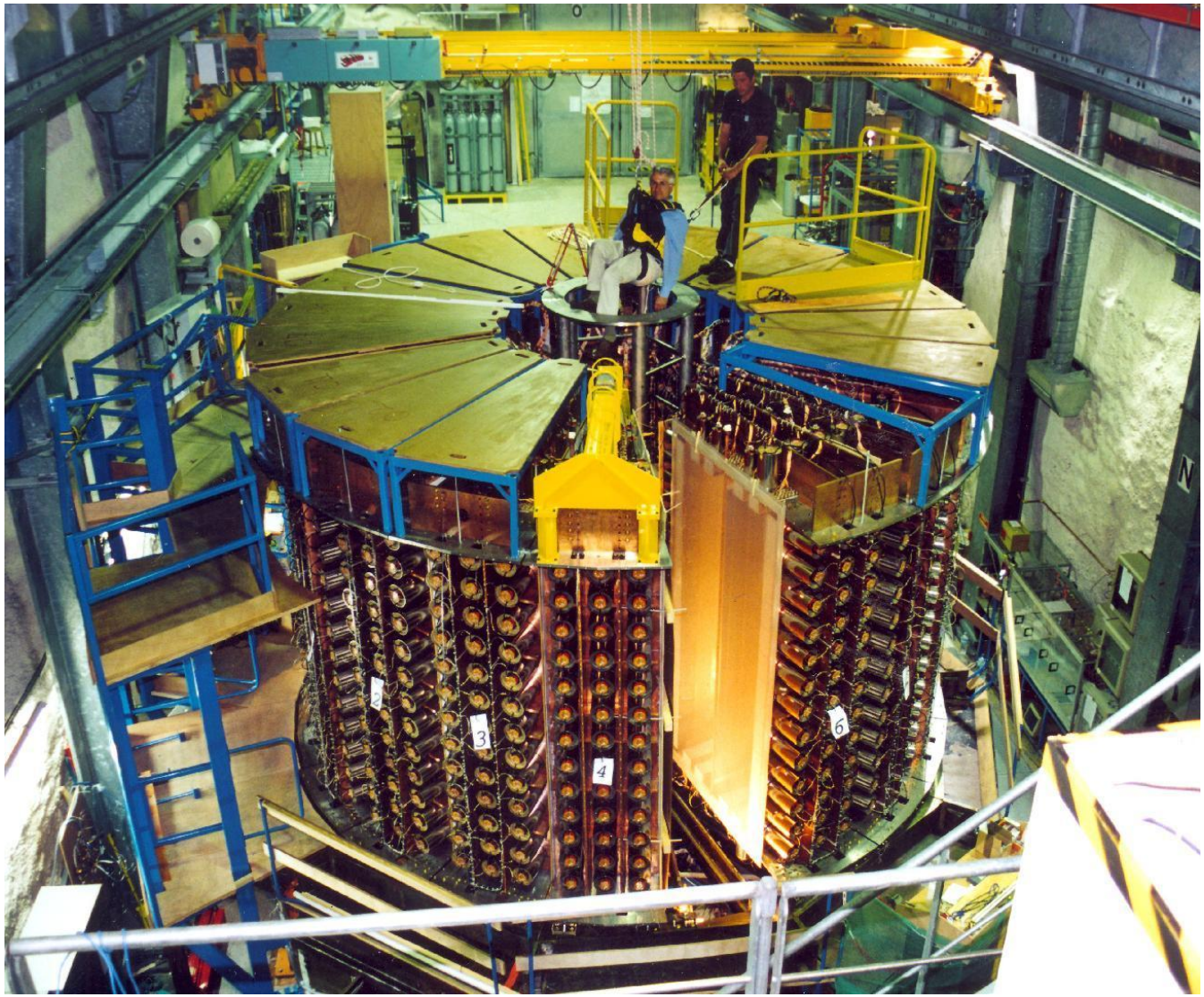
- Calorimeter:
  - 1940 plastic scintillators
  - Low-radioactivity PMTs

- Gamma shield:
  - 18 cm pure iron
- Neutron Shield:
  - Borated Water + Wood
- 4700 m.w.e.

- Data Collection:

Phase I: Feb. 2003 – Sep. 2004
Phase II: Dec. 2004 - Nov. 2010 (Low radon)

# The NEMO-3 Detector



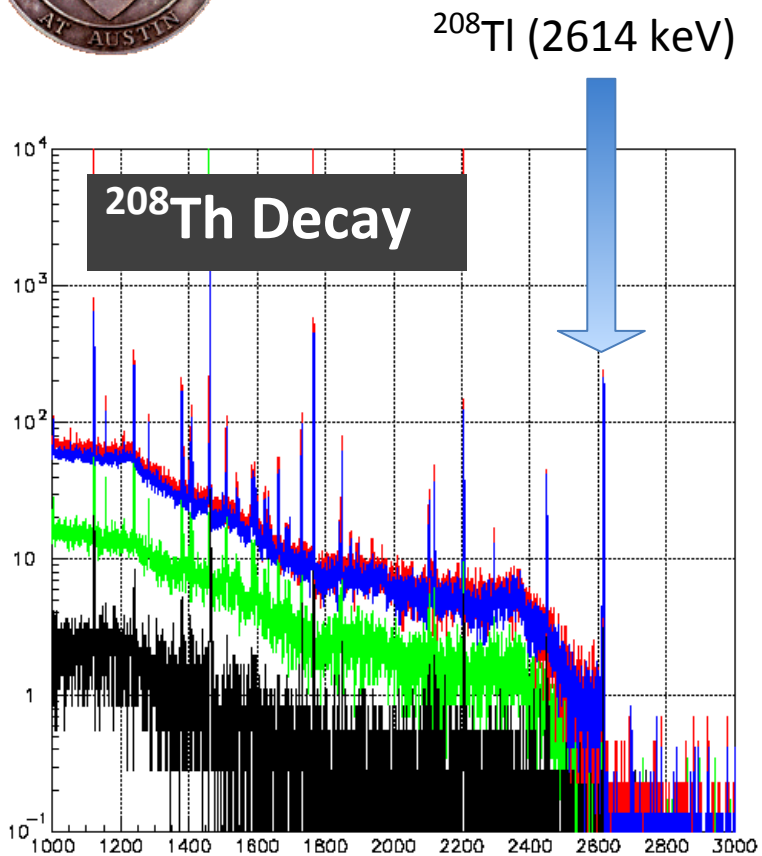
# Choice of Isotope

Choice of isotope dependent on:

- Isotopic abundance
- Phase space factor ($G_{0\nu}$)
- Nuclear matrix elements
- $Q_{\beta\beta}$/Background at Q-value

| Isotope | $Q_{\beta\beta}$ (MeV) | Isotopic Abundance (%) | $G_{0\nu}$ x $10^{-25}$ ($y^{-1}$) |
|---|---|---|---|
| $^{48}Ca$ | 4.271 | 0.187 | 2.44 |
| $^{76}Ge$ | 2.040 | 7.8 | 0.24 |
| $^{82}Se$ | 2.995 | 9.2 | 1.08 |
| $^{96}Zr$ | 3.350 | 2.8 | 2.24 |
| $^{100}Mo$ | 3.034 | 9.6 | 1.75 |
| $^{116}Cd$ | 2.804 | 7.5 | 1.89 |
| $^{130}Te$ | 2.528 | 33.8 | 1.70 |
| $^{136}Xe$ | 2.479 | 8.9 | 1.81 |
| $^{150}Nd$ | 3.367 | 5.6 | 8.00 |

# Background Radiation

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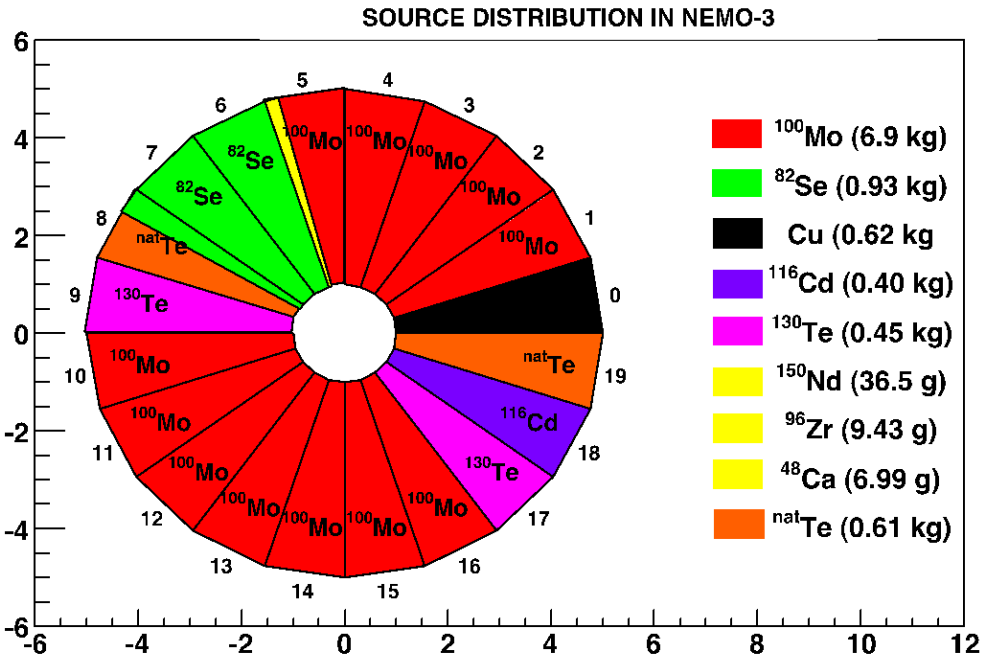
- Natural radioactivity and cosmic rays dominate backgrounds.
- $Q_{\beta\beta}$ above 2.6 MeV are desirable in order to avoid natural $\gamma$s in the signal range

# NEMO-3 Source Distribution

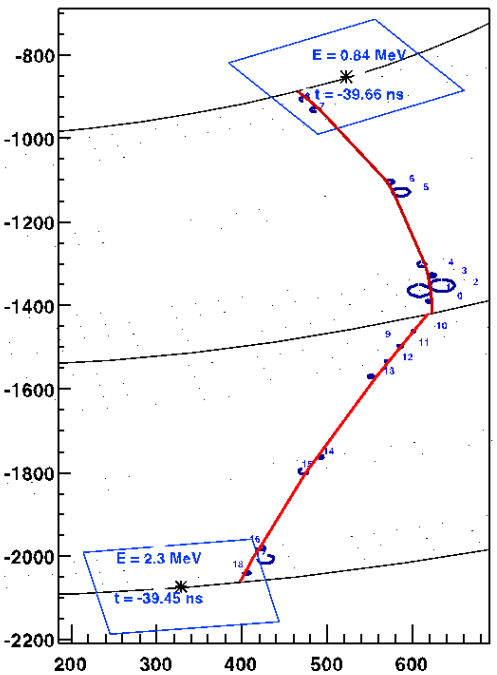



Top-down view of the source distribution in the NEMO-3 detector.

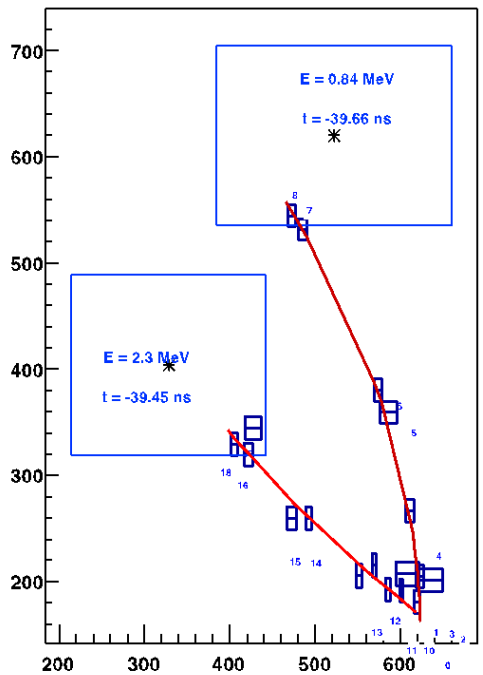
- 20 sectors total
- 7 $0\nu\beta\beta$ candidate isotopes
- Cu and $^{nat}$Te foils for testing background model
- $^{207}$Bi calibration sources between sectors

# Event Topology in NEMO-3

Top-down View




Side View

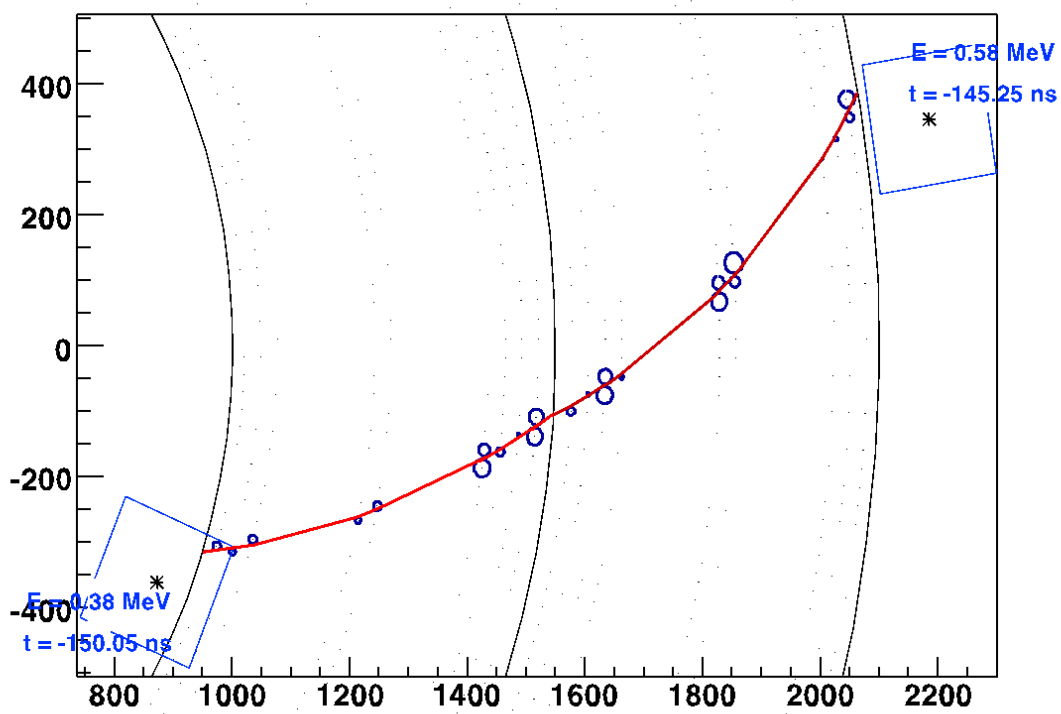



One candidate $2\nu\beta\beta$ event in NEMO-3.

- Event reconstruction from collected data allows for viewing of individual events in the NEMO-3 detector.
- Tracking information allows for identification of electrons, positrons, $\alpha$'s, and $\gamma$'s, and thus background rejection.

# Background Identification

Top-down View




Simulated background event in NEMO-3
(Crossing electron from $^{40}$K in PMT glass)

Several systems in place for *in situ* identification and rejection of background events:

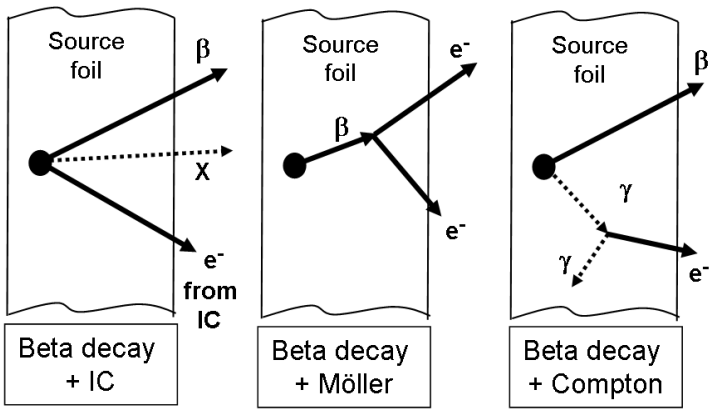
- Time-of-flight probability
- Track curvature
- Particle energy

- Background model based on extensive HPGe measurements
- Testable against data from natural Cu and Te foils

# Backgrounds

## Internal Source Foil Backgrounds

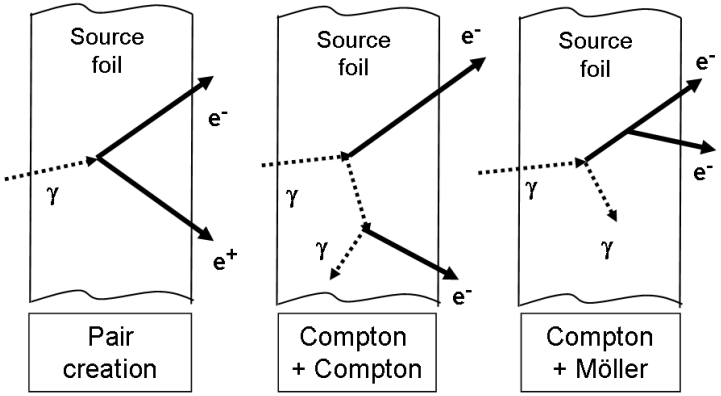
- Result of impurities in the foil
- $2\nu\beta\beta$ tail mimicking $0\nu$ signal



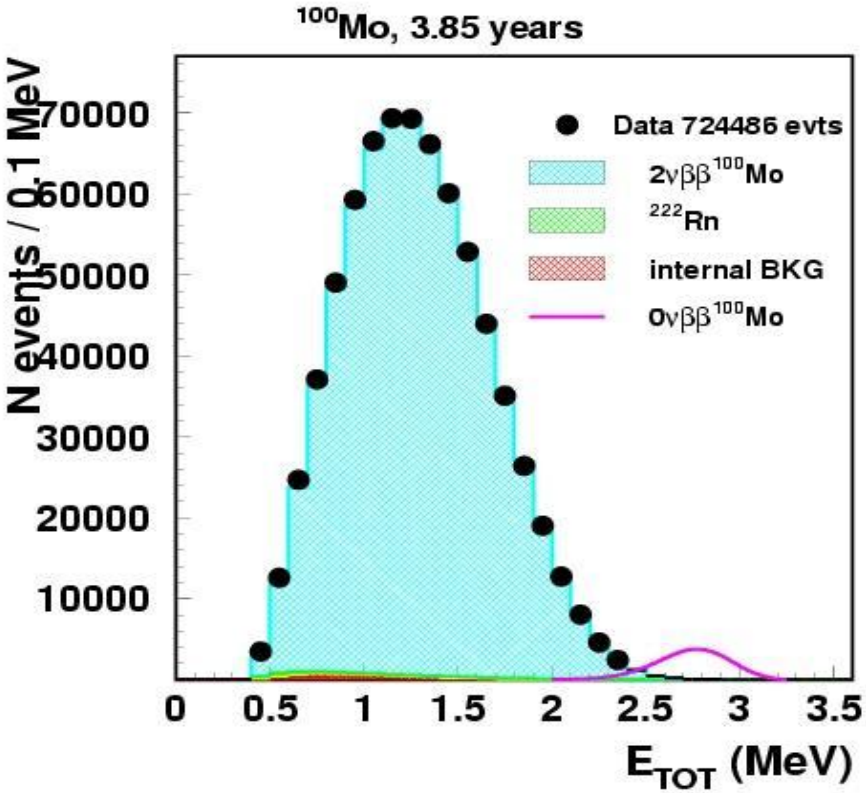

## External Backgrounds

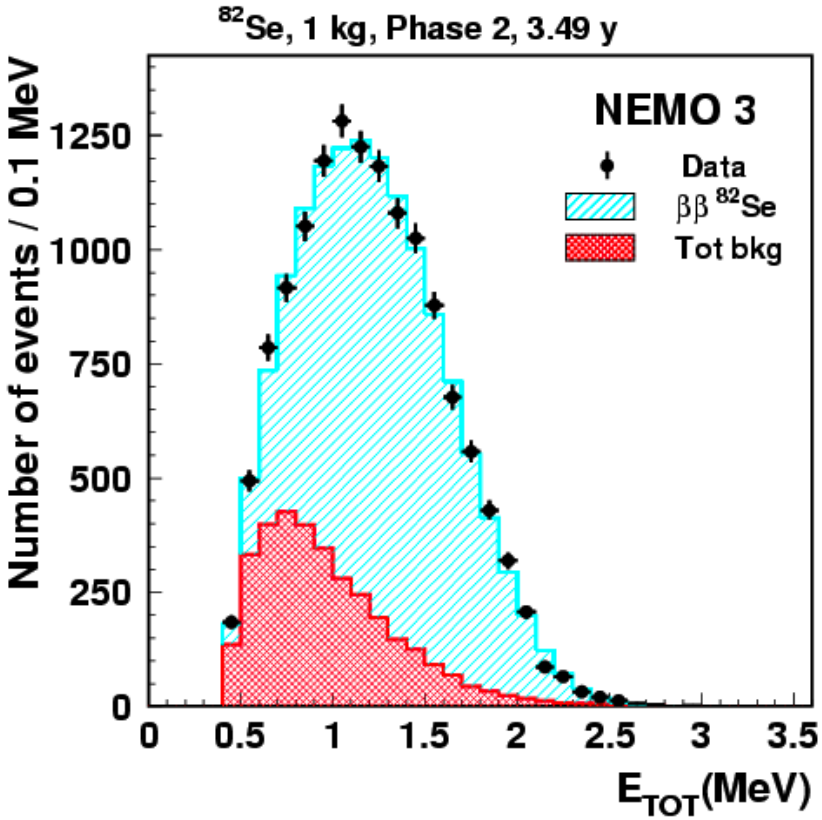
:

- PMTs
- Shielding
- Wires
- Copper support structure
- Outside the detector



# NEMO-3 Flagship Results

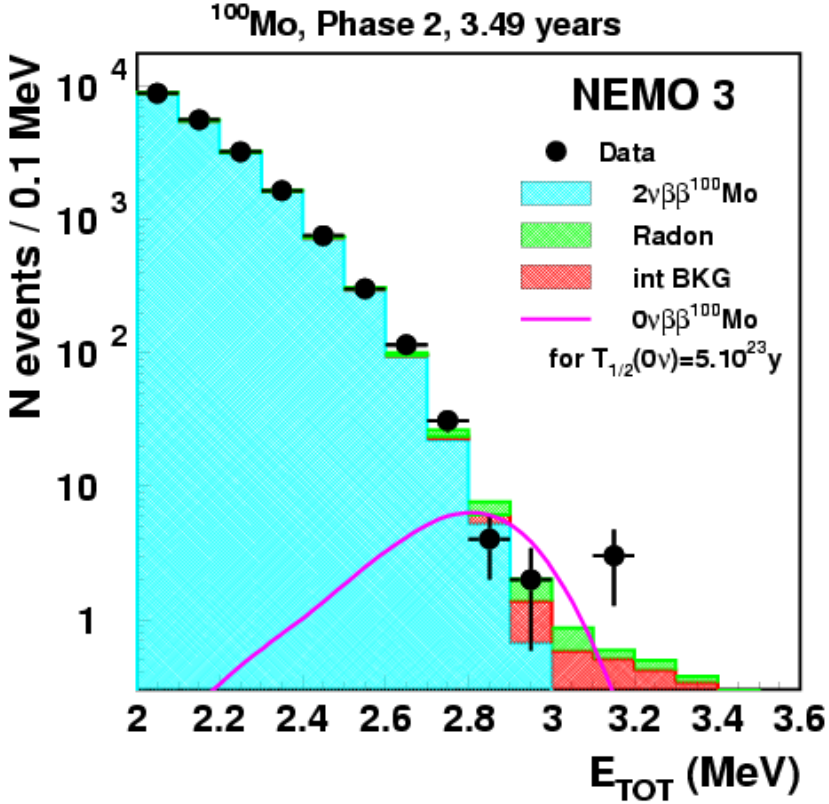


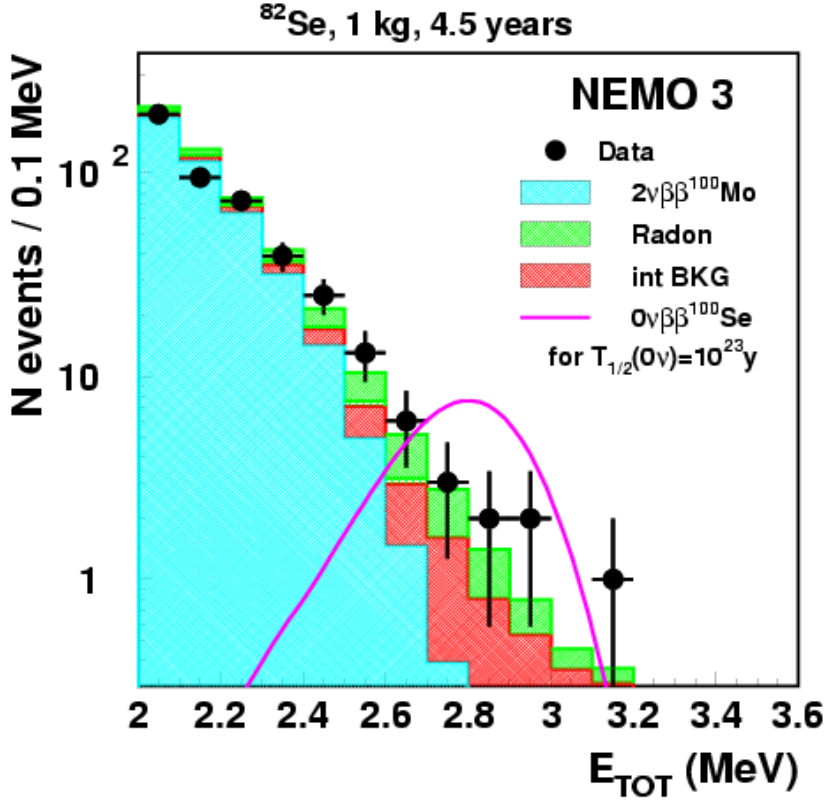




**$^{0}$Mo: $T_{1/2}(2\nu\beta\beta)$ =(7.16 ± 0.01(stat) ± 0.54 (syst)) x $10^{18}$ y**

**$^{82}$Se: $T_{1/2}(2\nu\beta\beta)$ = (9.6 ± 0.1 (stat) ± 1.0 (syst)) x $10^{19}$ y**

# NEMO-3 0νββ Results



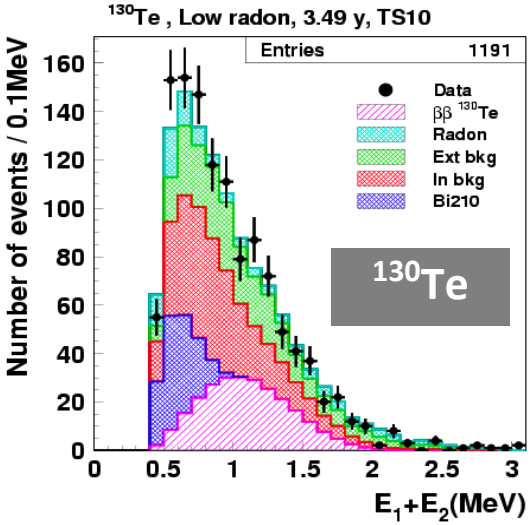

$T_{1/2}(0\nu\beta\beta) > 1.0 \times 10^{24}$ y @ 90% CL

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

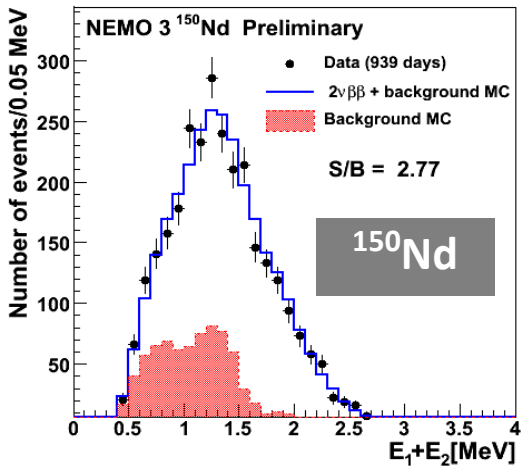
$T_{1/2}(0\nu\beta\beta) > 3.2 \times 10^{23}$ y @ 90% CL

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

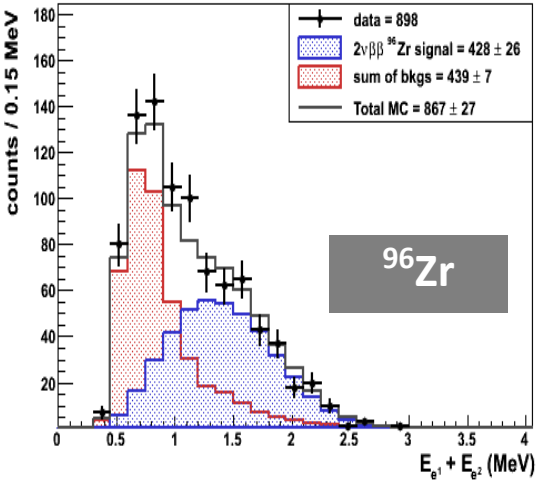
# NEMO-3: Other 2β2ν Results



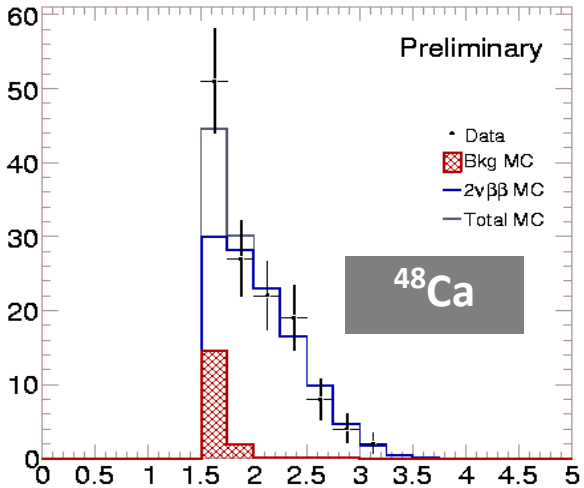

[7.0 ± 0.9 (stat) ± 1.1 (sys)] x $10^{20}$ y



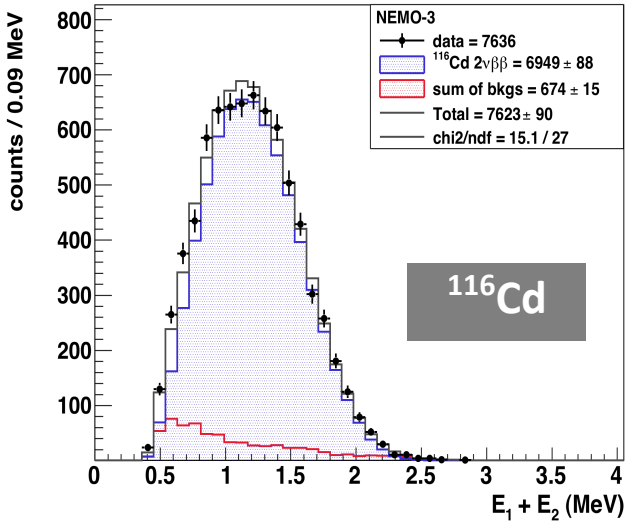

[9.11 $^{+0.25}_{-0.22}$ (stat) ± 0.63 (sys)] x $10^{18}$ y




[2.35 ± 0.14 (stat) ± 0.16 (sys)] x $10^{19}$ y




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




[2.88 ± 0.04 (stat) ± 0.16 (sys)] x $10^{19}$ y

# NEMO-3 Results

So far there is no evidence of neutrinoless double-beta decay, but limits have been established for all seven isotopes:

| Isotope | Exposure (kg y) | $T_{1/2}(0\nu\beta\beta)$, y | $\langle m_\nu \rangle$ eV |
|---|---|---|---|
| $^{100}Mo$ | 26.6 | **$> 1.0 \times 10^{24}$** | < 0.31 – 0.96 |
| $^{82}Se$ | 3.6 | **$> 3.2 \times 10^{23}$** | < 0.94 – 2.6 |
| $^{150}Nd$ | 0.095 | **$> 1.8 \times 10^{22}$** | < 1.5 – 6.8 |
| $^{130}Te$ | 1.4 | $> 1.3 \times 10^{23}$ | < 1.3 – 3.6 |
| $^{96}Zr$ | 0.031 | **$> 9.2 \times 10^{21}$** | < 7.2 – 19.5 |
| $^{48}Ca$ | 0.017 | $> 1.3 \times 10^{22}$ | < 29.6 |

Values in **bold** are the current best upper limit for this process.

NME references:


- [1] M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
- [2] M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
- [3] F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503
- [4] V.A. Rodin et al. Nucl.Phys. A 793 (2007) 213
- [5] V.A. Rodin et al. Nucl.Phys. A 766(2006) 107
- [6] J.H.Hirsh et al. Nucl.Phys. A 582(1995) 124
- [7] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

- Double Beta Decay
- NEMO-3 Experiment
- **The SuperNEMO Experiment**

# Moving into the Future: Development of the SuperNEMO Experiment

# The SuperNEMO Detector

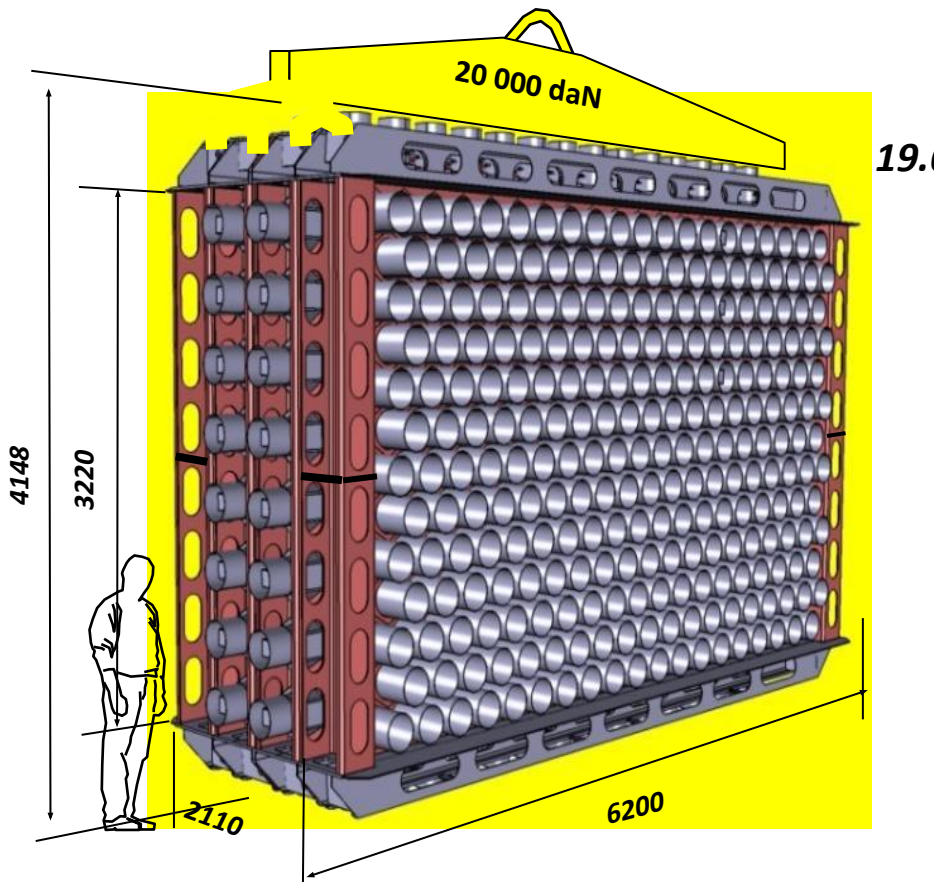
- SuperNEMO is the next-generation double-beta decay detector.

- It will be built on the site of NEMO-3, but will be a significant upgrade:

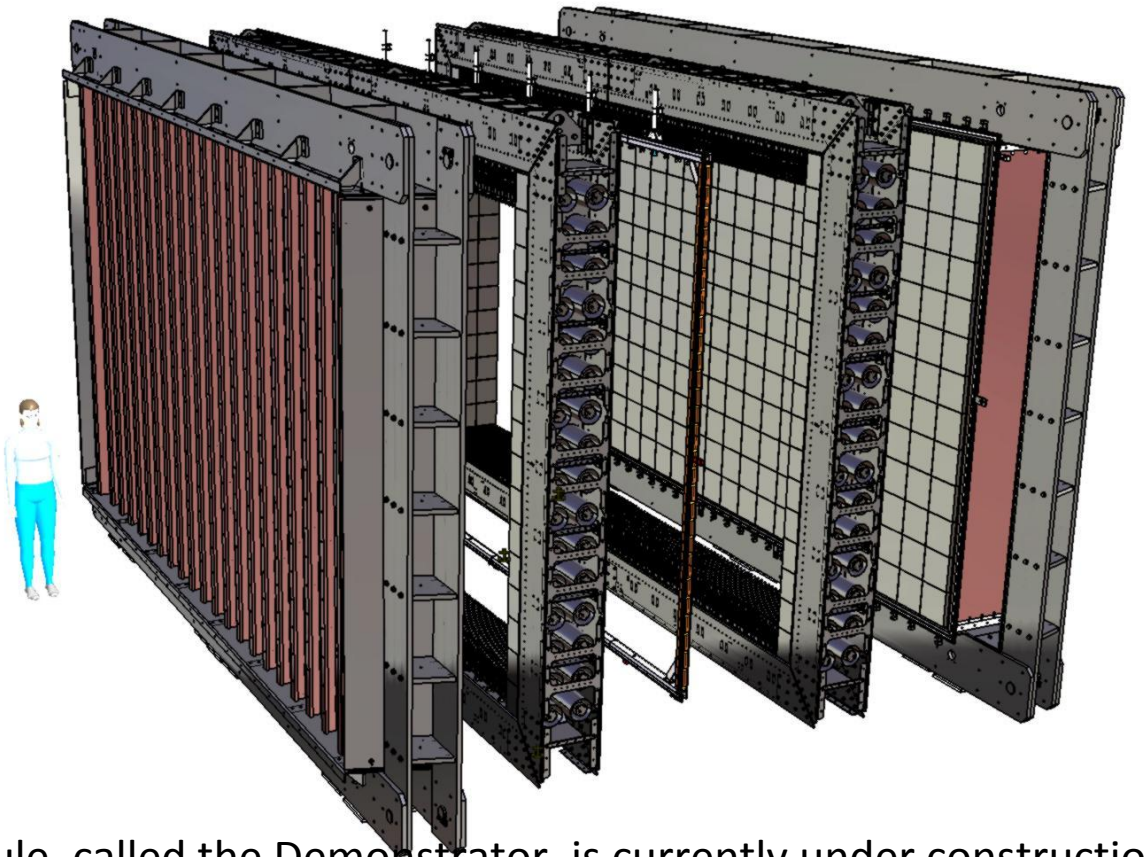
  - > 100 Kg of $0\nu\beta\beta$ candidate isotopes (Mainly $^{82}Se$) in 20 modules

  - Aim to increase sensitivity to $10^{26}$ yr – an improvement of 2 orders of magnitude compared to NEMO-3

- Construction of a demonstrator module has already begun – full construction of remaining SuperNEMO modules to follow



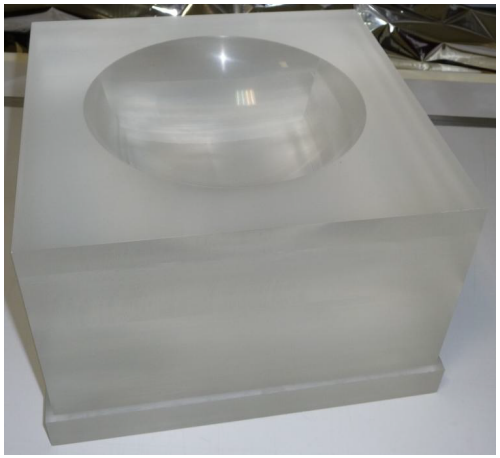
# The SuperNEMO Demonstrator

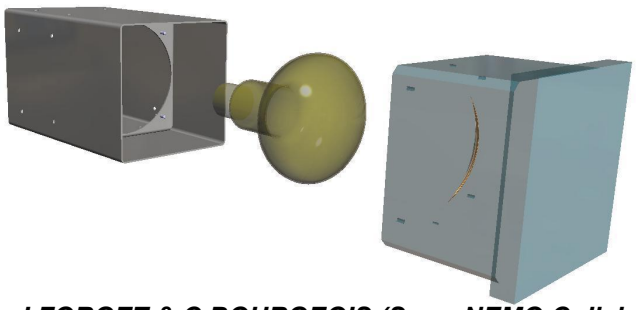


- The first module, called the Demonstrator, is currently under construction.
- Will house ~7kg of $^{82}Se$ (more than future modules)
- Set to be commissioned in 2014.
- Expected to reach $T_{1/2}$ sensitivity of $10^{25}$ y over 2 year exposure.

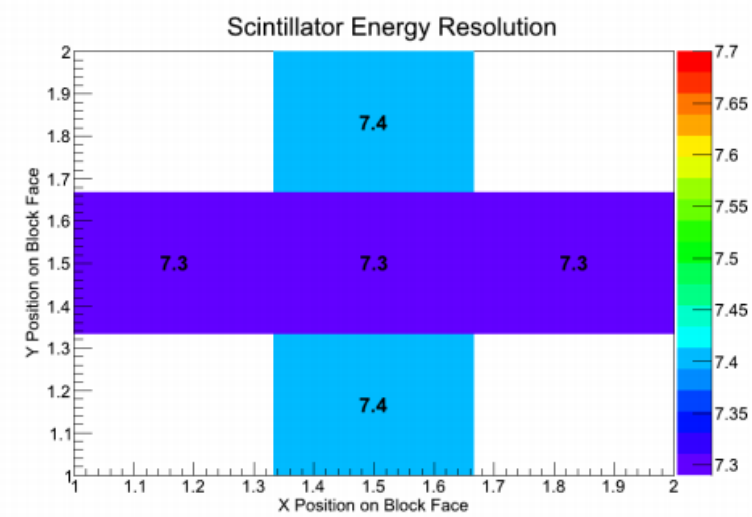
# Calorimetry Development

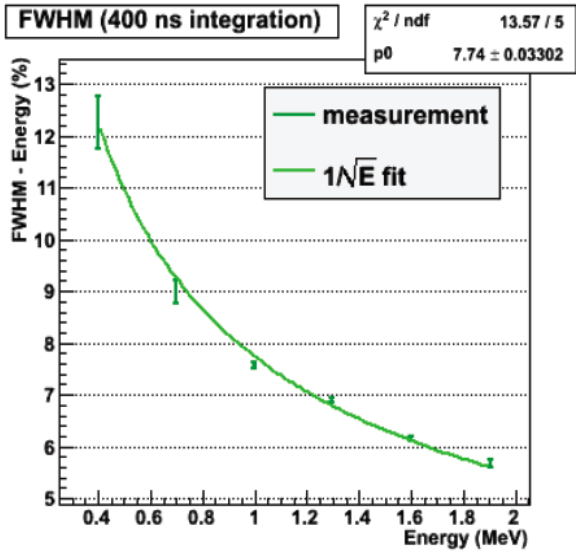
- Final designs: Hamamatsu 8” PMTs, 256 x 256 x 150 $mm^3$ scintillators
- Demonstrated $\Delta E/E < 8\%$ at 1 MeV (➔ 4% at 3MeV)
- GEANT4 Simulations agree with measurements





*Courtesy of: J.FORGET & C.BOURGEOIS (SuperNEMO Collaboration)*



# Improvements to NEMO-3

| NEMO-3 | | SuperNEMO |
|---|---|---|
| $^{100}$Mo, $^{82}$Se $^{150}$Nd, $^{130}$Te, $^{116}$Cd, $^{96}$Zr, $^{48}$Ca | Isotopes | $^{82}$Se ($^{150}$Nd, $^{48}$Ca possible) |
| 10 | Mass (kg) | 100 – 200 |
| $^{208}$Tl: ~100<br>$^{214}$Bi: < 300 | Source Contamination (μBq/kg) | $^{208}$Tl: < 2<br>$^{214}$Bi: < 10 |
| 5 | Radon level (mBq/m$^3$) | <0.15 |
| 8% at 3 MeV | Energy Resolution | 4% at 3 MeV |
| 1.4 x $10^{24}$ y | $T_{1/2}$ Sensitivity | 1 x $10^{26}$ y |
| < 390 – 810 | $\langle m_\nu \rangle$ sensitivity (meV) | < 40 – 140 |

# Summary

- NEMO-3 has produced a unique spectrum of results for $0\nu\beta\beta$ and $2\nu\beta\beta$
  - Preliminary results for all 7 candidate isotopes
  - Final results to be published

- SuperNEMO currently in production
  - Demonstrator to begin taking data in 2015
    - Intend to show zero-background is achievable
  - Modularity to allow addition of mass and other isotopes
    - 20 Modules intended
  - Sensitive to $T_{1/2}$ of $10^{26}$ y (40 – 140 meV $<m_\nu>$)

# Thank You!

**NEMO Collaboration**
**Prague, Czech Republic**
**March 2013**

# Backup slides

# $^{100}$Mo Half-Life

Signal half-life is given by

$$T_{1/2} = \frac{e}{N_s - N_b} \frac{N_A \times m}{m_{molar}} \ln(2) \times t$$

Where

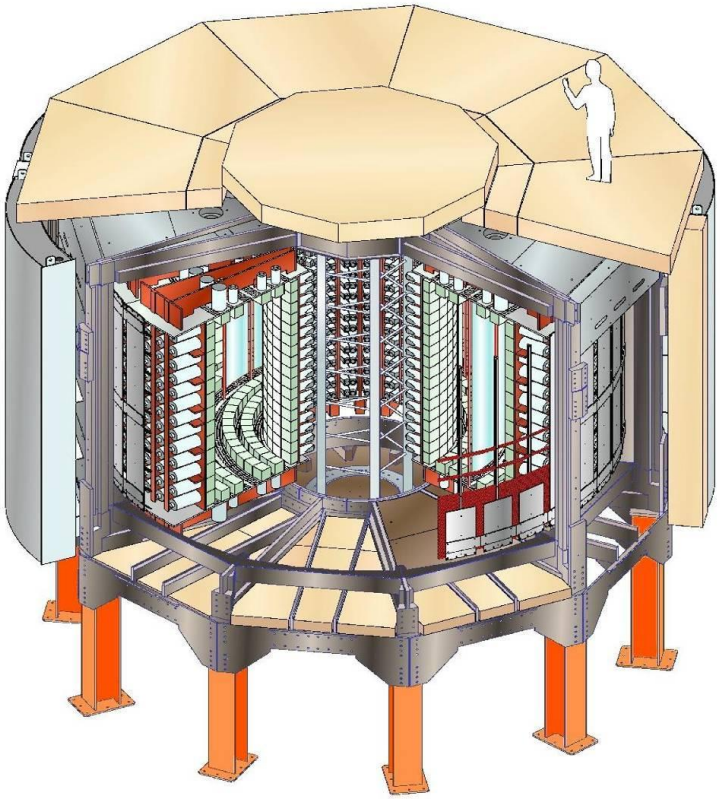
$N_A$ = Avogadro's Number

m = total mass

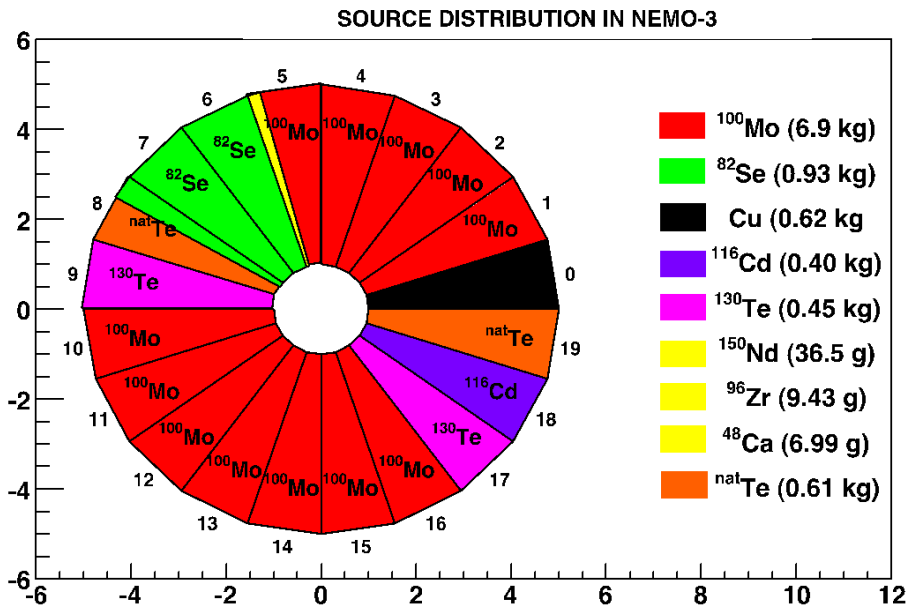
$N_s$ = signal events

$N_b$ = background events

# The NEMO-3 Detector



- 10 kg of source material in 20 sectors
- 7 candidate isotopes
- Cu and $^{nat}$Te foils for testing background model
- $^{207}$Bi calibration sources




- Tracking: 6180 Drift cells
- Calorimetry: 1940 scintillators
- 25 Gauss magnetic field

# $^{100}$Mo Half-Life

Signal half-life is given by

$$T_{1/2} = \frac{e}{N_s - N_b} \frac{N_A \times m}{m_{molar}} \ln(2) \times t$$

This is a fixed constant for a given mass…

Where

$\varepsilon$ = Signal Efficiency

$N_A$ = Avogadro's Number

m = total mass

$N_s$ = signal events

$N_b$ = background events

# $^{100}$Mo Half-Life

Signal half-life is given by

$$T_{1/2} = \frac{e}{N_s - N_b} \frac{N_A \times m}{m_{molar}} \ln(2) \times t$$

This is a fixed constant for a given mass…

…so analysis focuses on improving this ratio.

# Nuclear Matrix Elements

NME calculation is highly non-trivial:

- Complicated nuclear structure for heavy open shell nuclei
- Requires complete set of states for intermediate nucleus
- Many-body problem requiring accurate approximations