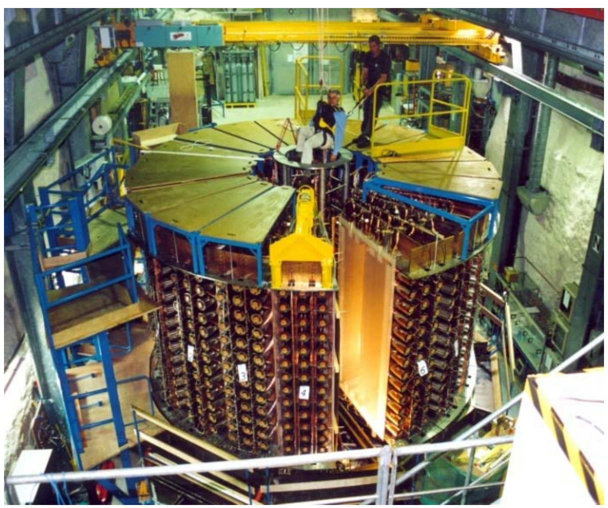
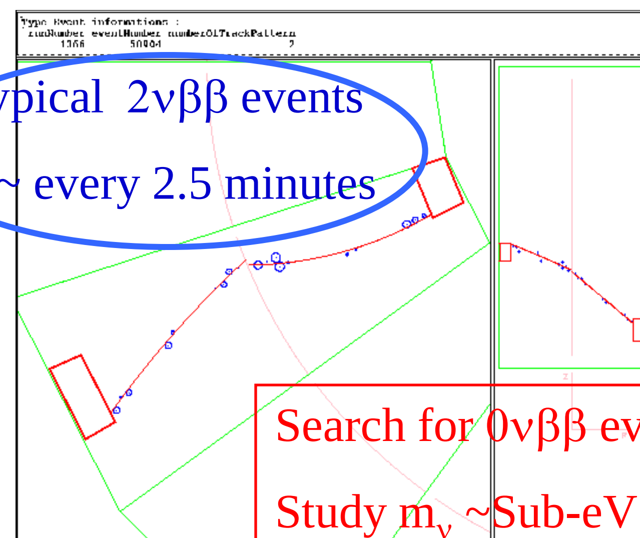
# NEMO 3 double beta decay experiment and SuperNEMO project

**Hideaki OHSUMI (Saga Univ.)**
**(NEMO 3/SuperNEMO Collaboration)**



**NEMO 3 is running at LSM**



Typical 2νββ events

~ every 2.5 minutes

Search for 0νββ events !

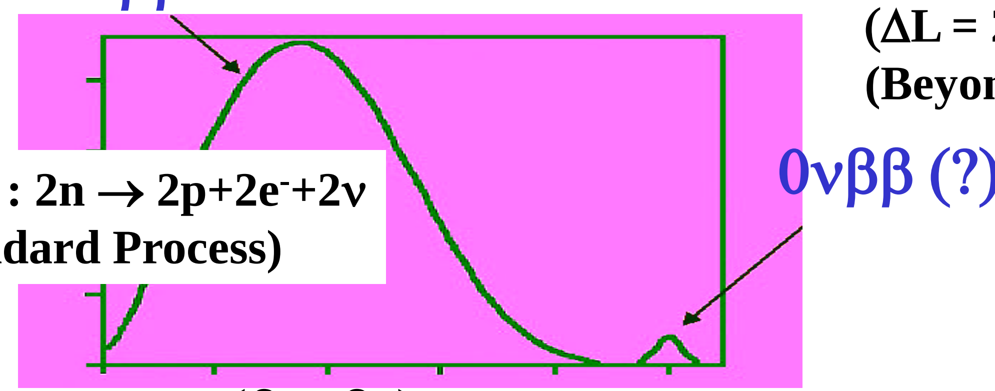
Study $m_\nu$ ~Sub-eV

# Philosophy of the NEMO 3/SuperNEMO experiment

- **Neutrinoless Double Beta Decays ($0\nu\beta\beta$)**
  - **Majorana $\nu$ and effective mass $<m_\nu>$ ? or new physics (SUSY) ?**
- **Measure almost all isotopes ($0\nu\beta\beta$, $2\nu\beta\beta$) @NEMO3**
  - **$^{100}Mo$(~7kg), $^{82}Se$(~1kg), $^{130}Te$, $^{116}Cd$, $^{96}Zr$, $^{48}Ca$, $^{150}Nd$ (no $^{76}Ge$, $^{136}Xe$)**
- **Tag and measure all the BG events with Track-Calo detector**
  - **$e^-$, $e^+$, $\gamma$, $\alpha$, neutron**
  - **Tracking chamber+Calorimeter+($\vec{B}$-field)+Shields**

**Understand all background !!**

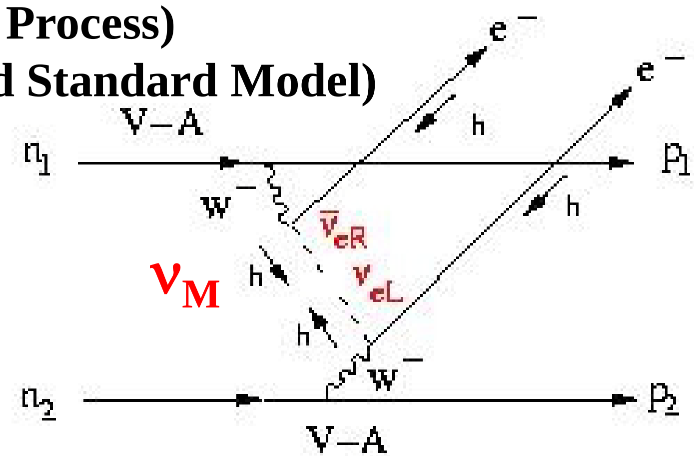
$2\nu\beta\beta$




**$2\nu\beta\beta$ : $2n \rightarrow 2p+2e^-+2\nu$**
**(Standard Process)**

$E(\beta_1+\beta_2)$ $Q_{\beta\beta}$

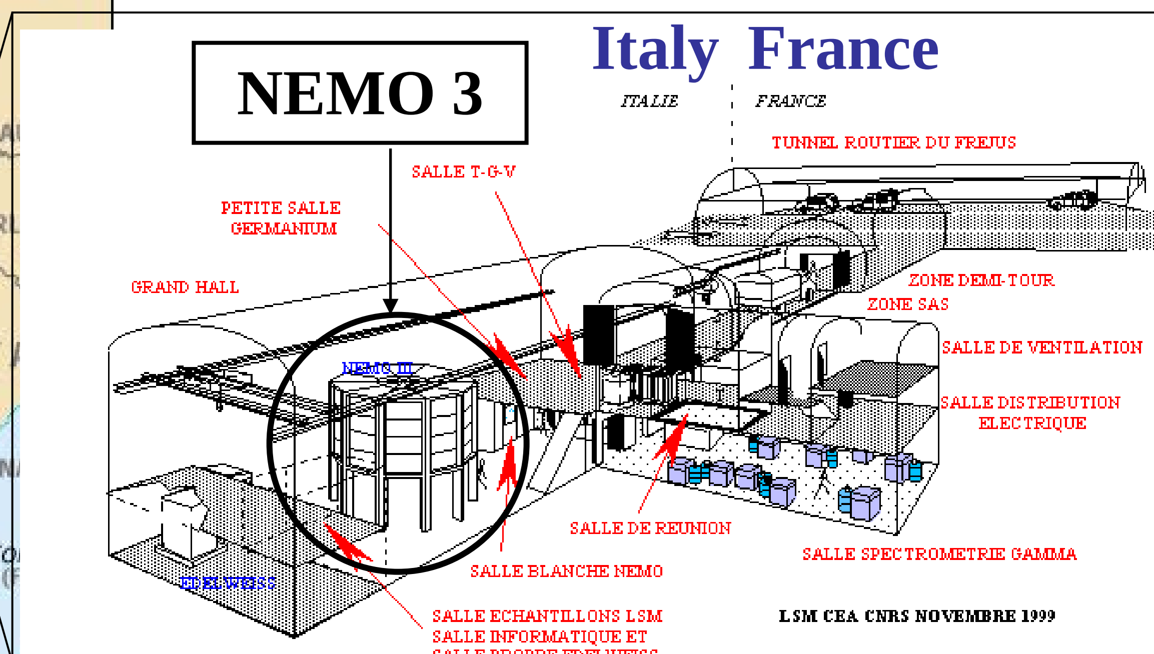
**$0\nu\beta\beta$ : $2n \rightarrow 2p+2e^-$**
**($\Delta L$ = 2 Process)**
**(Beyond Standard Model)**



# The Location of NEMO3

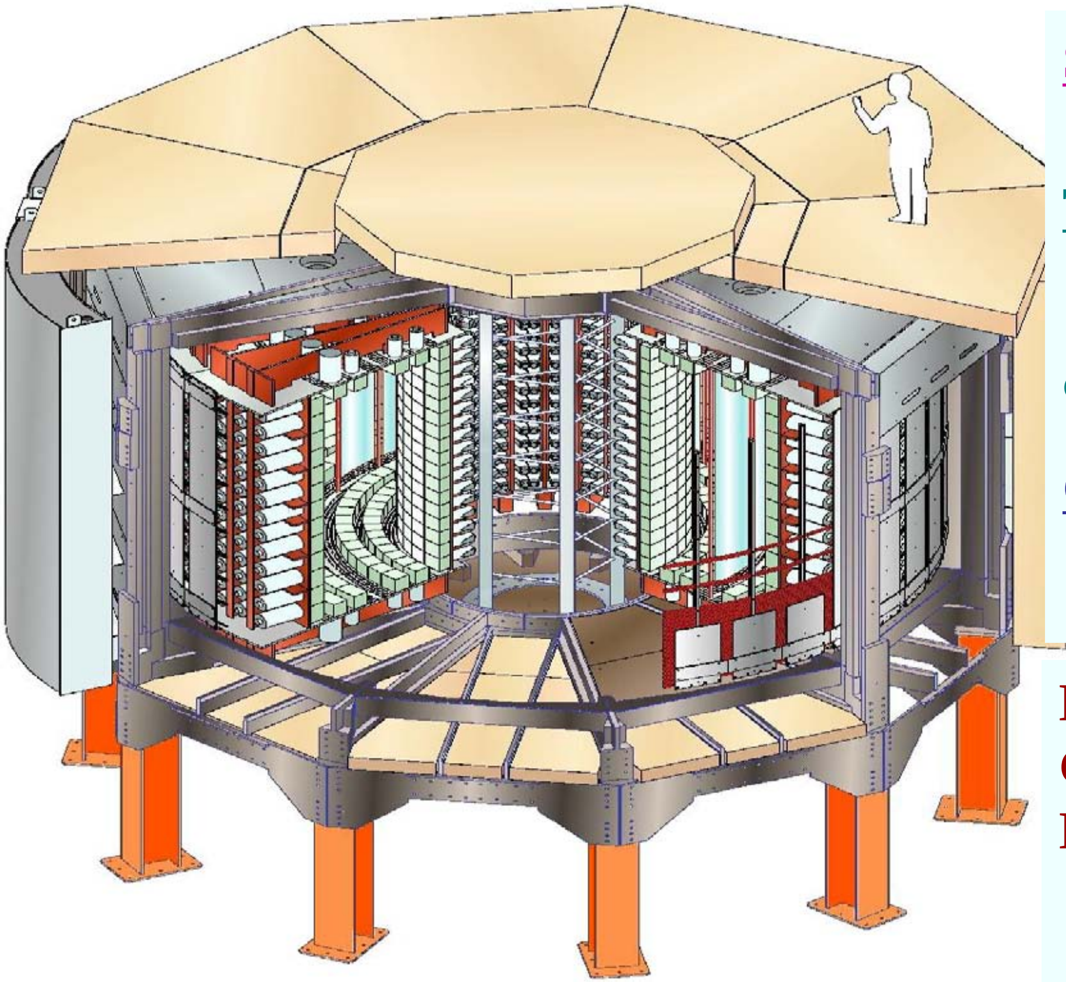
**Frejus Underground Laboratory**
**Laboratoire Souterraine de Modane(LSM)**
**(4800 m.w.e.)**

**NEMO 3 is here !**

# The NEMO3 detector

**Fréjus Underground Laboratory : 4800 m.w.e.**



**Source: 10 kg of ββ isotopes**
**cylindrical, S = 20 m², e ~ 60 mg/cm²**

**Tracking detector:**
**drift wire chamber operating**
**in Geiger mode (6180 cells)**
**Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% $H_2O$**

**Calorimeter:**
**1940 plastic scintillators**
**coupled to low radioactivity PMTs**

**Magnetic field: 25 Gauss**
**Gamma shield: Pure Iron (e = 18cm)**
**Neutron shield:**
**30 cm water + boron**
**40 cm wood (top and bottom)**

**Able to identify $e^-$, $e^+$, γ and α**

**Cathodic rings**
**Wire chamber**

**PMTs**

**Calibration tube**

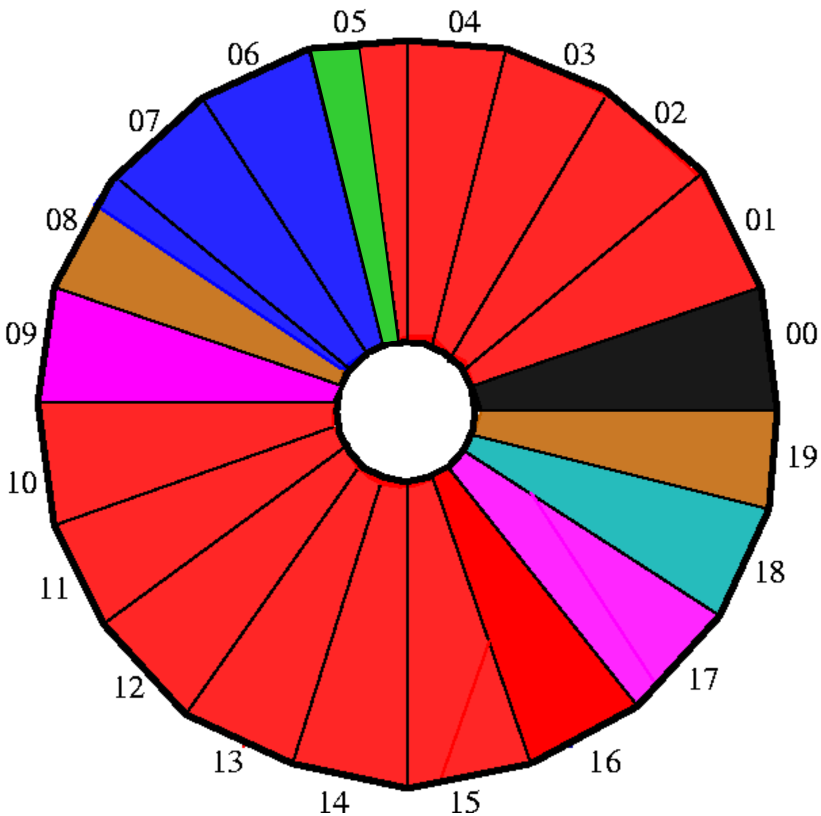
**scintillators**

Calibration Source

$^{207}$Bi
2e$^{-}$ (IC) lines
~0.5 ,~1 MeV
$^{90}$Sr
$^{60}$Co

**ββ isotope foils**

# ββ decay isotopes in NEMO-3 detector




$^{100}$Mo 6.914 kg
$Q_{\beta\beta}$ = 3034 keV

$^{82}$Se 0.932 kg
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

$^{116}$Cd 405 g
$Q_{\beta\beta}$ = 2805 keV

$^{96}$Zr 9.4 g
$Q_{\beta\beta}$ = 3350 keV

$^{150}$Nd 37.0 g
$Q_{\beta\beta}$ = 3367 keV

$^{48}$Ca 7.0 g
$Q_{\beta\beta}$ = 4272 keV

$^{130}$Te 454 g
$Q_{\beta\beta}$ = 2529 keV

$^{nat}$Te 491 g

Cu 621 g

External bkg measurement

# How to detect the signals and the tag the background ?

**Identification of e, γ, α**

- **Tracking** (Identification e/others)

  Delayed (<700μs) α track

- **Calorimeter** ε(γ)~50% (@0.5MeV)

  Possible for tagging eγ, eγγ, eγγγ, …

- **Time of flight** $\sigma_t$~300ps(@1MeV)

  External Background rejection

- **Magnetic Field** (Identification $e^-/e^+$)

  3~5% $e^-/e^+$ confusion @ 1~7MeV

**Study of Background Process**

- $^{214}$Bi Tagged by e(γ)α (~164μs)

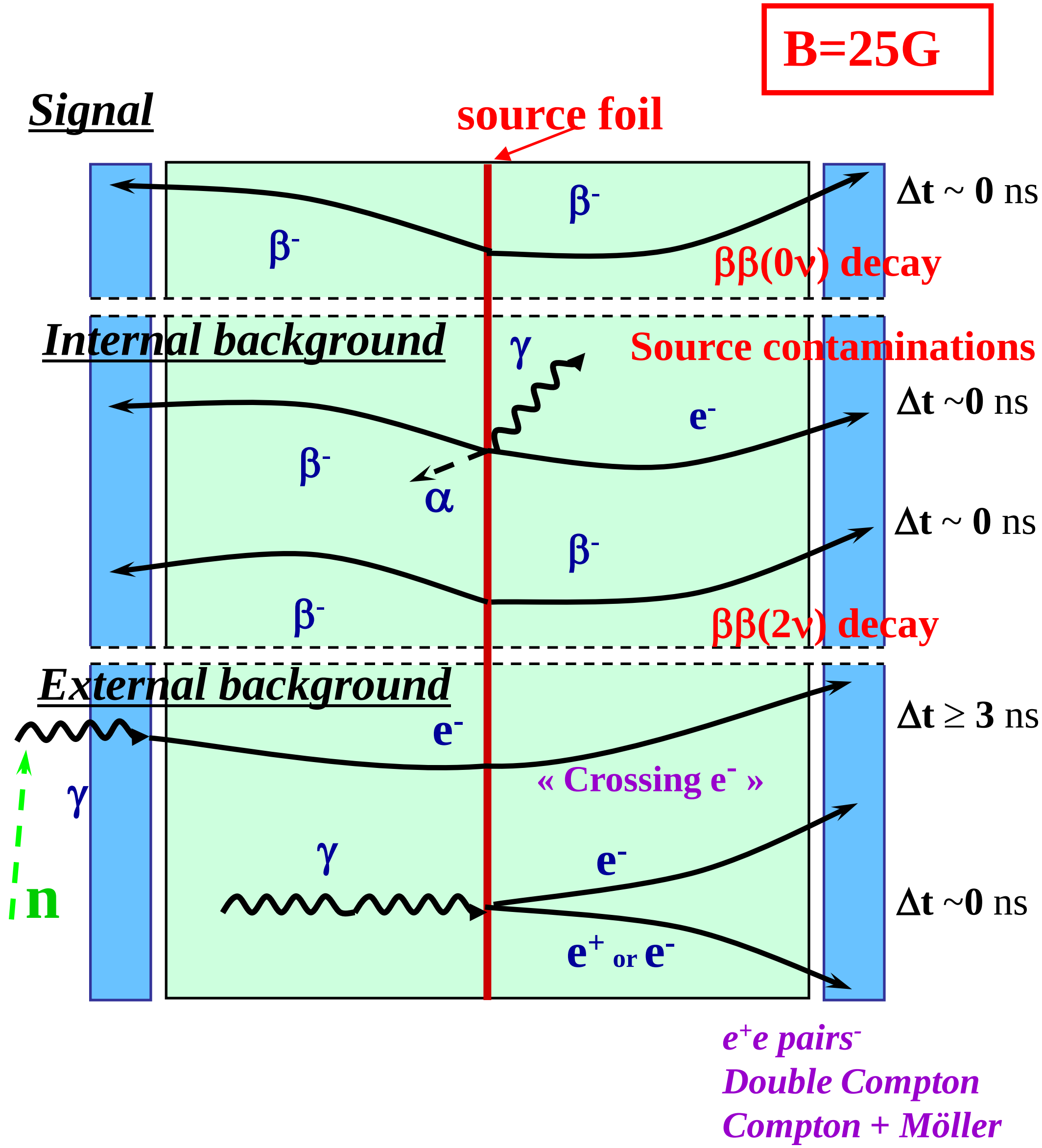
  ( $^{214}$Bi->$^{214}$Po->$^{210}$Pb)

- $^{208}$Tl eγ, eγγ, eγγγ, with γ (2.6MeV)

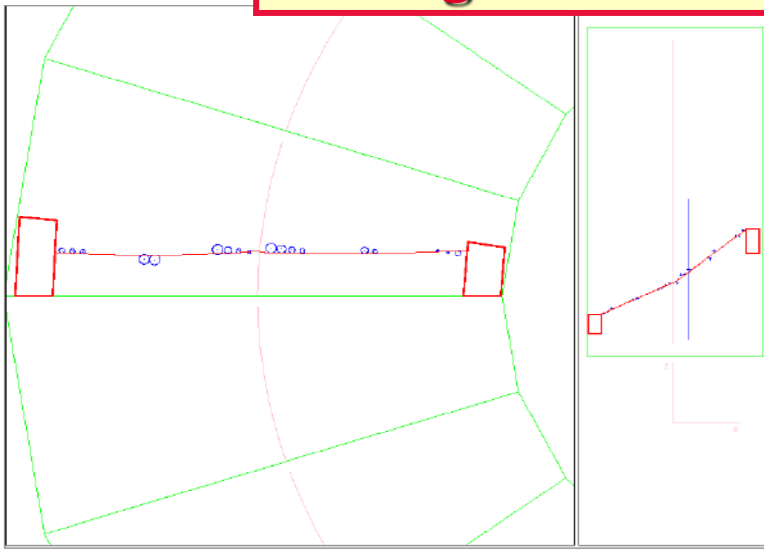
  or Tagged by e(γ) α (~300ns)

  ( $^{212}$Bi->$^{212}$Po->$^{208}$Pb)

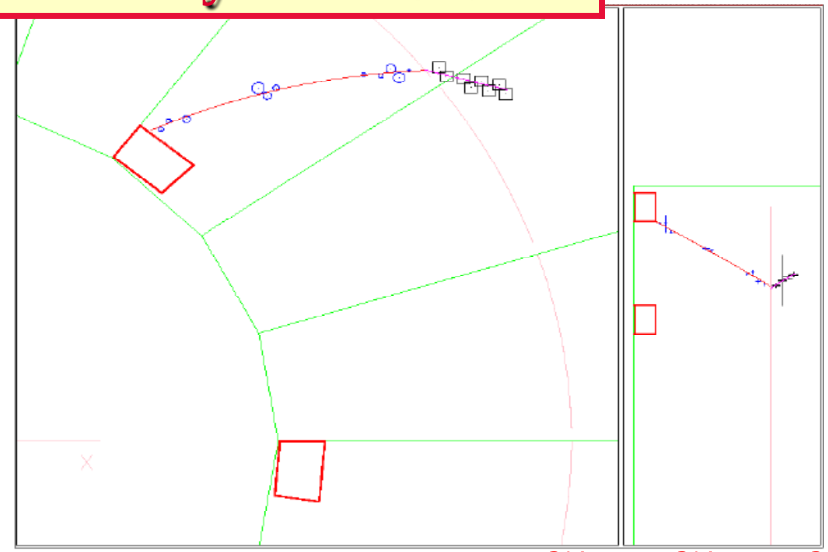
- **Neutron** Crossing e (4~8MeV)



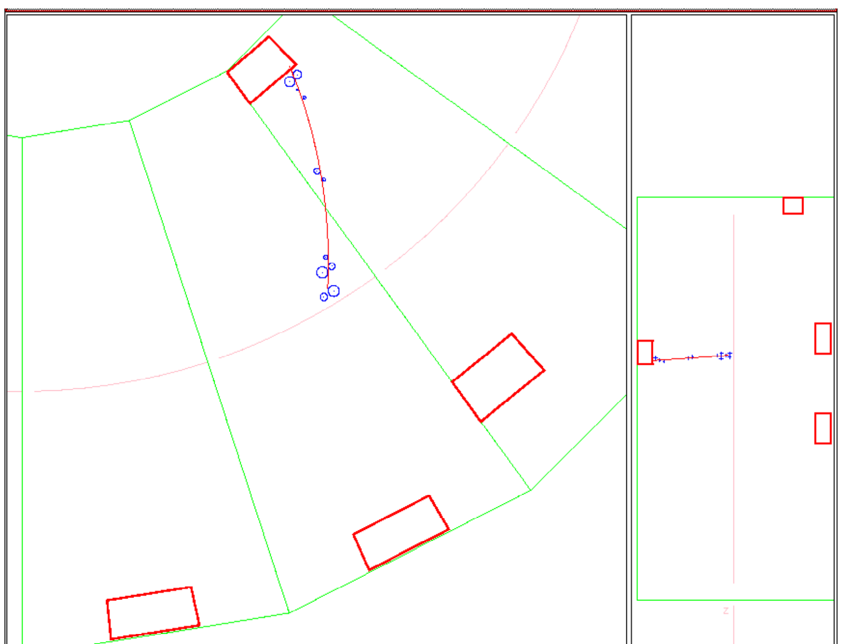
# Background events observed by NEMO-3…



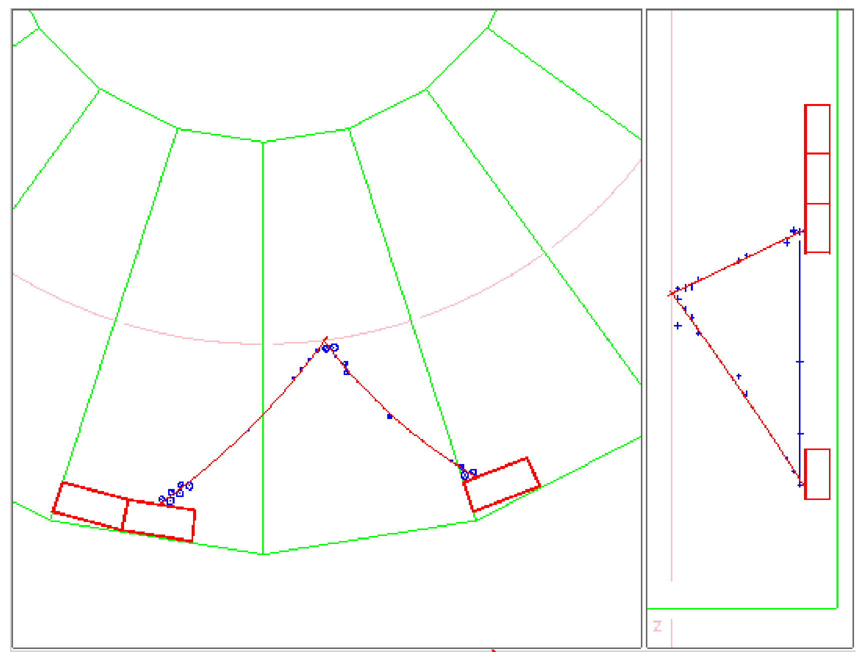
Electron crossing > 4 MeV   Neutron capture



Electron + α delay track (164 μs)   $^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$



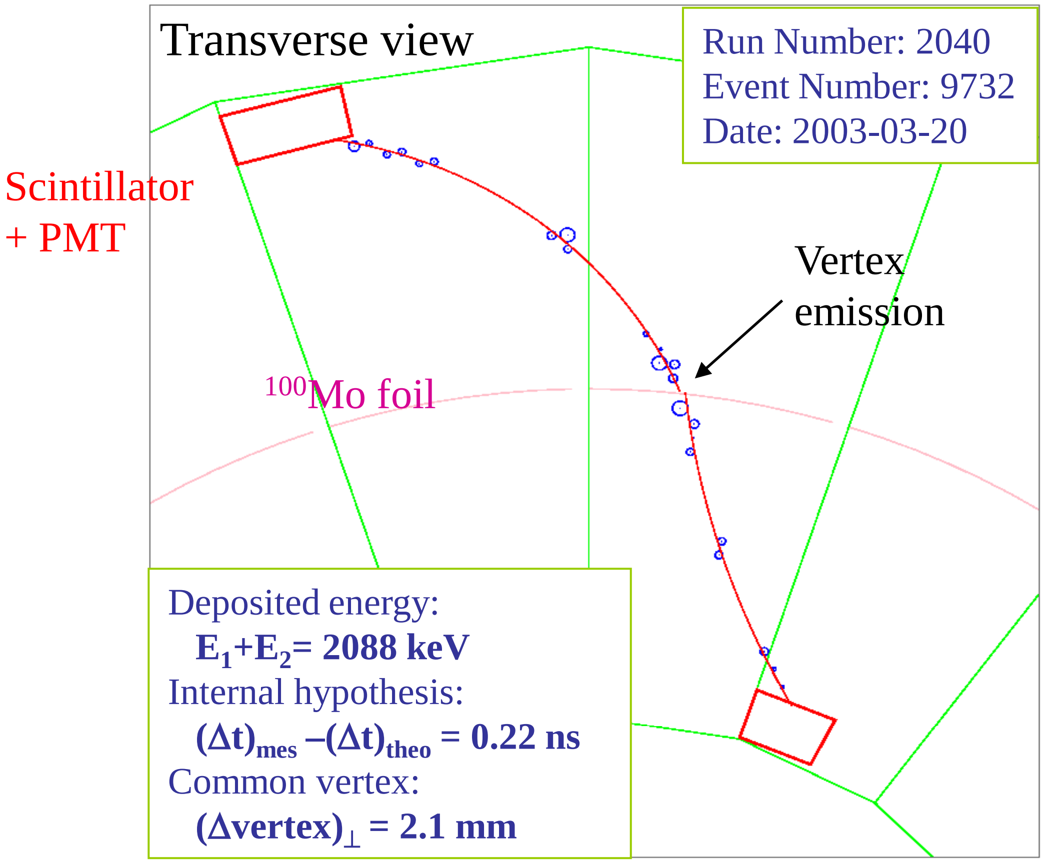
Electron + N γ's   $^{208}Tl$ (Eγ = 2.6 MeV)

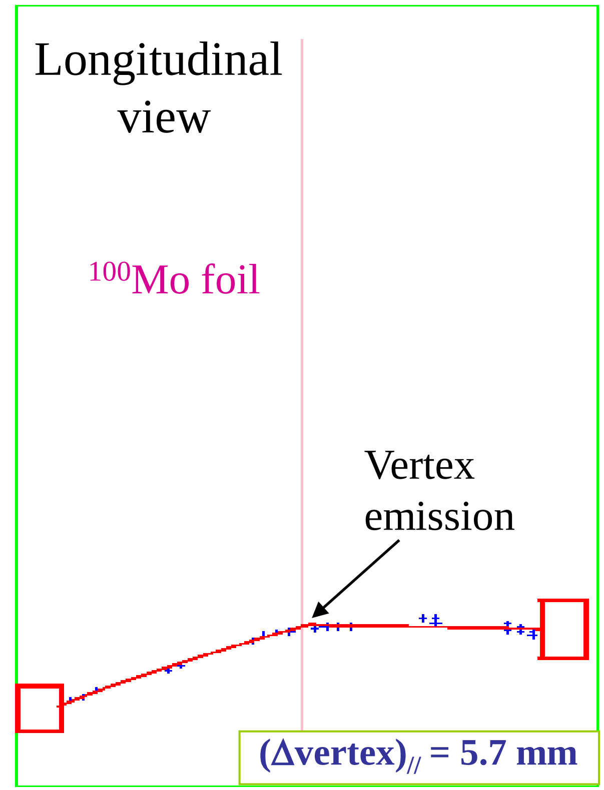


Electron – positron pair   $\vec{B}$ rejection

# ββ events selection in NEMO-3

## Typical ββ2ν event observed from $^{100}Mo$




**Criteria to select ββ events:**

- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track ($^{214}$Bi rejection)

**Trigger**:

at least 1 PMT > 150 keV

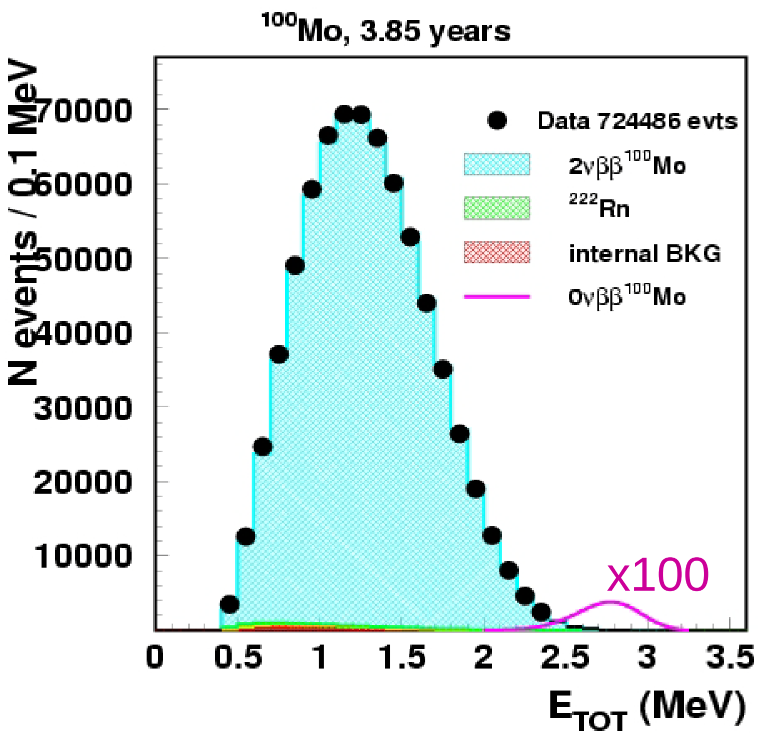
≥ 3 Geiger hits (2 neighbour layers + 1)

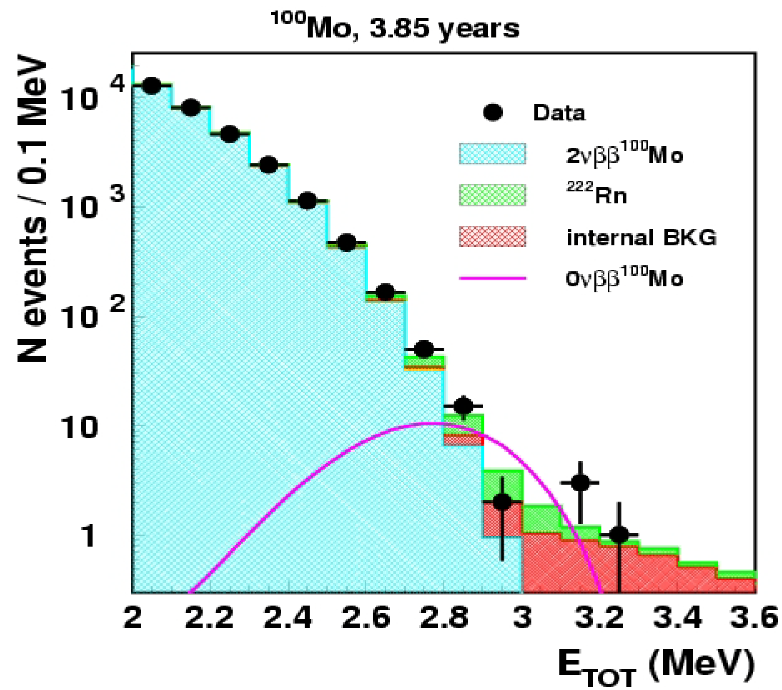
Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

# 0νββ of $^{100}$Mo

(Data at the end of 2008)
Phase 1 + Phase 2



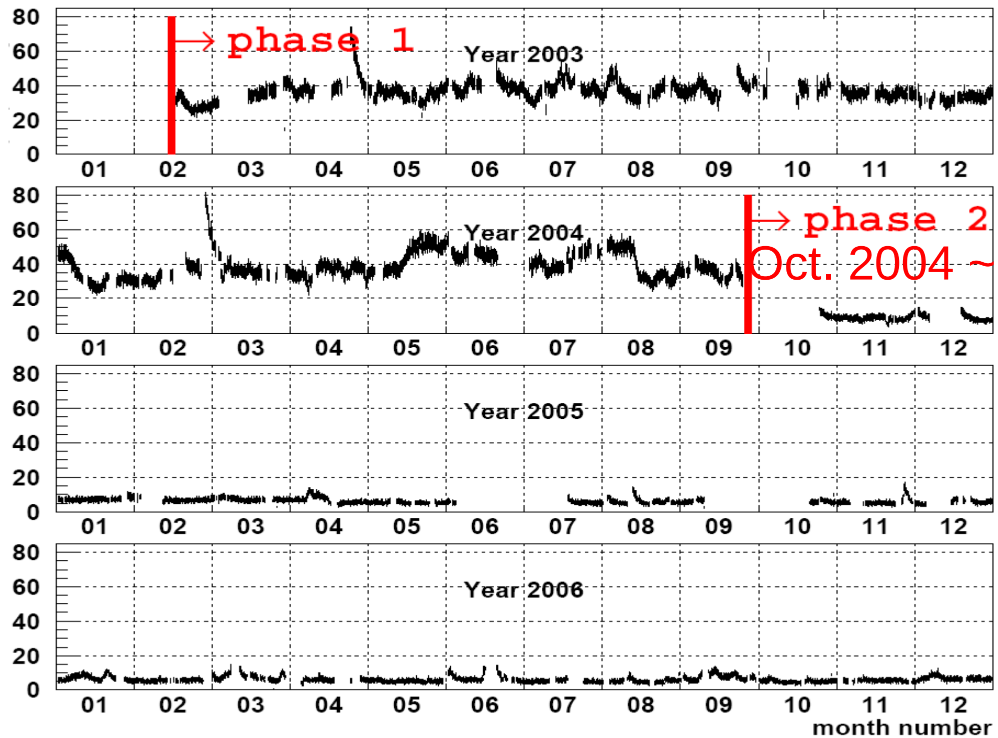

Simple counting

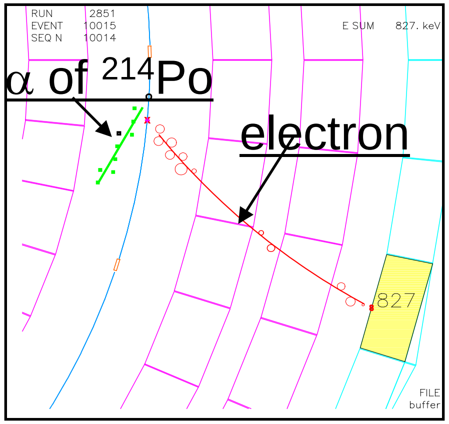
[2.8 , 3.2] MeV:
Data: 20 events, Expected: 18.6 events
Excluded at 90% C.L. 9.6 events
Efficiency ε= 0.0726

Likelihood method

MCLIMIT : [2.0, 3.2] eV
18 events excluded
Total mean 0ν efficiency ε = 0.174
**$T_{1/2}$ (0νββ) > 1.1 · $10^{24}$ y @90% C.L.**
$\langle m_\nu \rangle$ < 0.45 – 0.93 eV

# (Phase 1 → Phase 2) NEMO 3 have been done
# Radon BG. reduction




$^{214}$Bi -> $^{214}$Po -> $^{210}$Pb

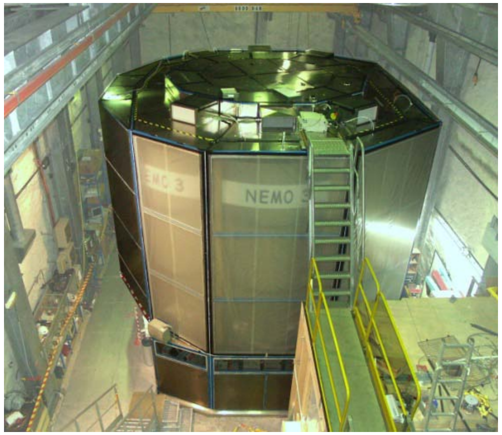
NEMO 3 itself can measure Radon BG.

Radon Monitor


Free-Radon Air Factory
(15Bq/m$^3$→ <15mBq/m$^3$)

Inside NEMO 3
Reduction factor of ~6

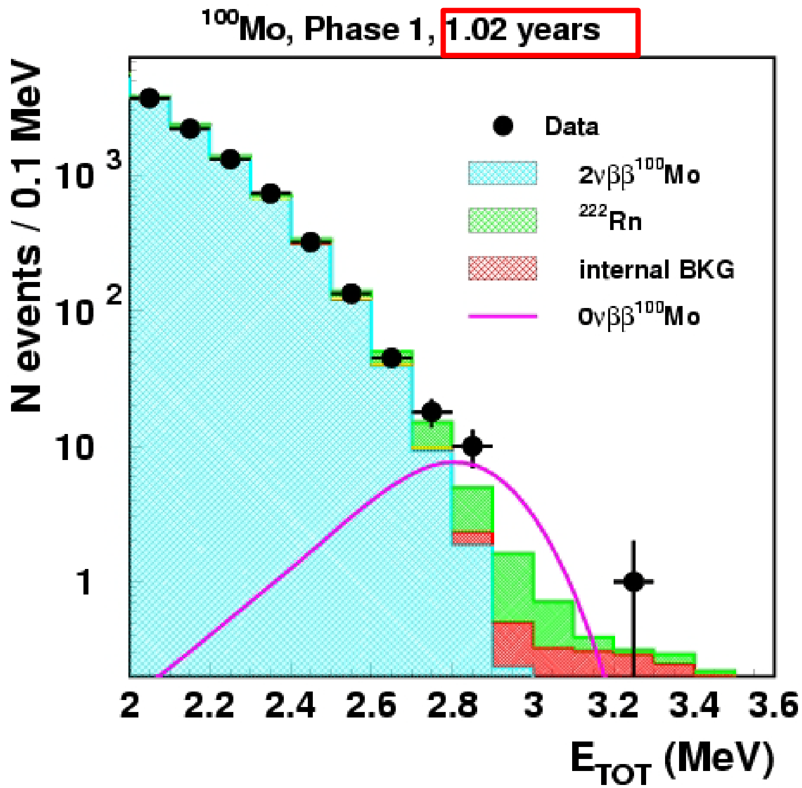
(Average)
(Phase 1 → Phase 2)
37.7 → 6.5 mBq/m$^3$

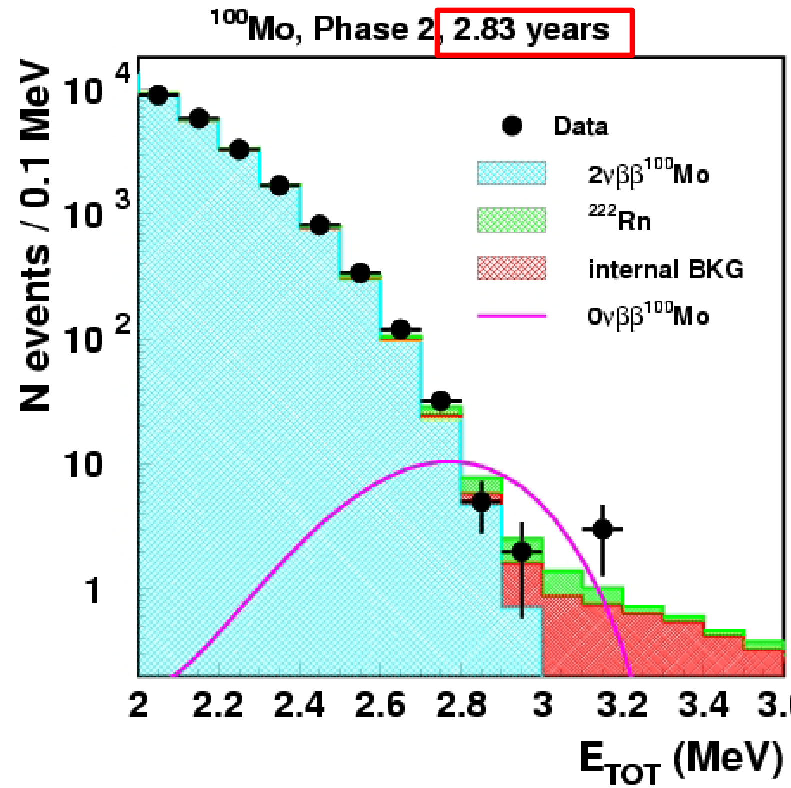



NEMO 3 Tent

# (Phase 1 → Phase 2)

## Radon BG. reduction in 0νββ energy region ($^{100}Mo$)




[2.8 , 3.2] MeV:
Data: 10 events, Expected: 7.4 events
Excluded at 90% C.L. 8.3 events
BG. < 1.5 events/y/kg (~1 events/y/kg, radon)

[2.8 , 3.2] MeV:
Data: 10 events, Expected: 11.2 events
Excluded at 90% C.L. 6.1 events
BG. < 0.7 events/y/kg (<0.2 events/y/kg, radon)

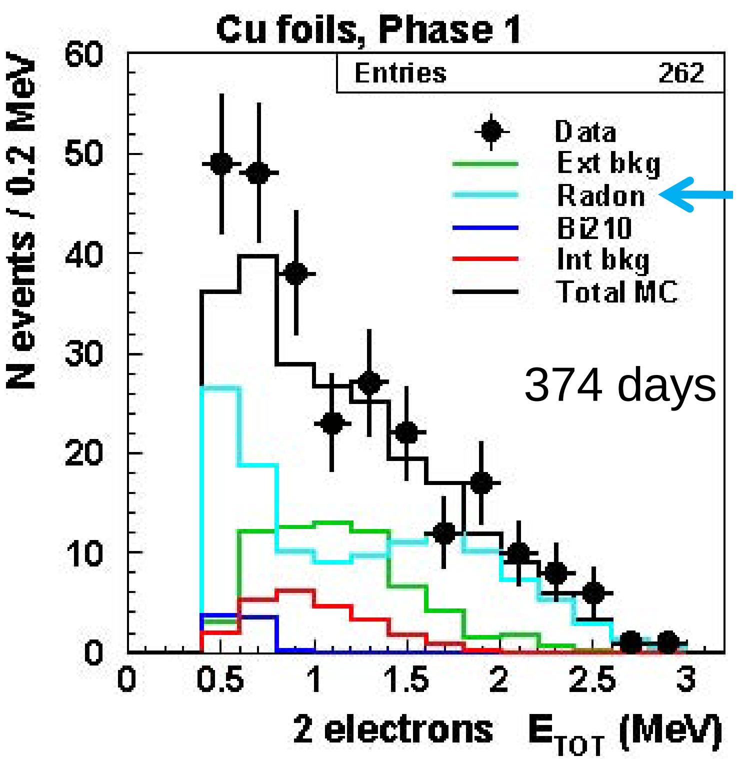
# Good proof of NEMO 3 high quality data from Cu foils

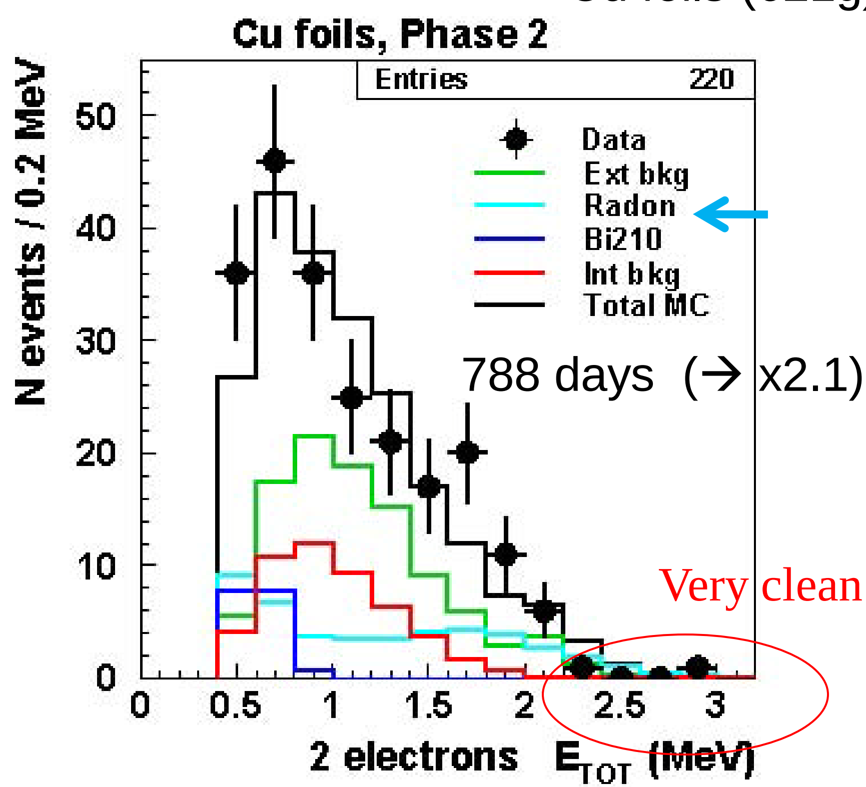
→ No unknown ee signals (like ββ decay) from Cu foils !

→ Background events are perfectly understood.

(Good examples of the background study in NEMO 3 )

Cu foils (621g)



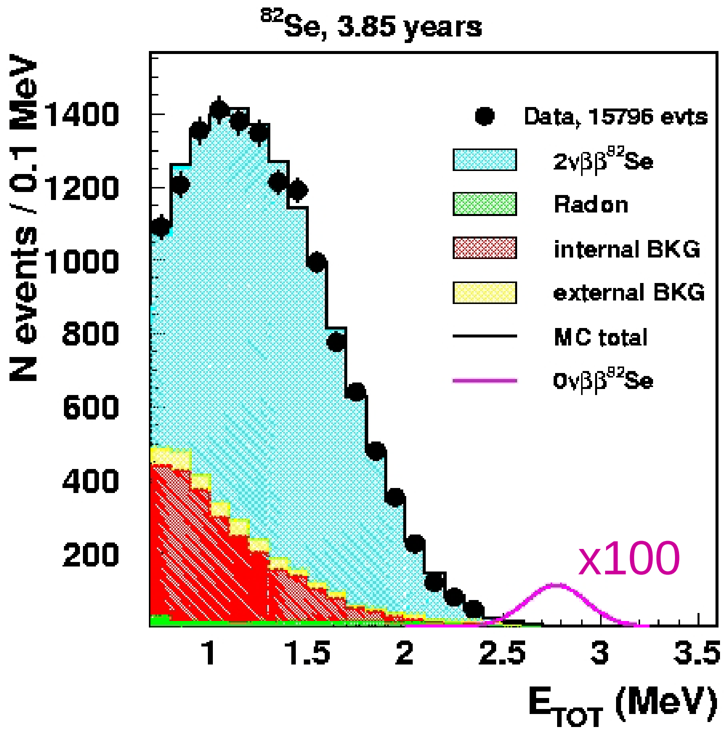

Radon Contributions → 1/6

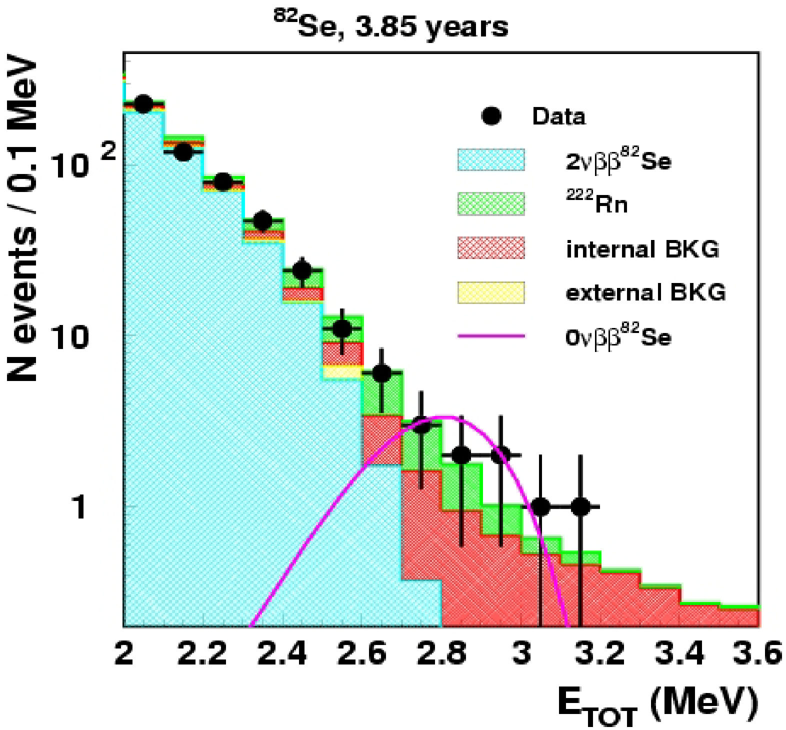
Other BG Components unchanged.

NEMO measures all background contributions itself using various channels (e, ee, eα, eγ, eγγ…. ) NIM A606(2009) pp. 449-465.

# 0νββ of $^{82}Se$

(Data at the end of 2008)
Phase 1 + Phase 2




[2.6 , 3.2] MeV:
Data: 15 events, Expected: 13.2 events
Excluded at 90% C.L. 8.9 events
Efficiency ε= 0.151

MCLIMIT : [2.0, 3.2] MeV
9.8 events excluded
Total mean 0ν efficiency ε = 0.182
**$T_{1/2}$ (0νββ) > 3.6 · $10^{23}$ y @90% C.L.**
$\langle m_\nu \rangle$ < 0.89 – 1.61 eV

# Summary of 0νββ results

- No evidence for 0νββ decay
- Current limits on 0νββ (at 90% C.L.):

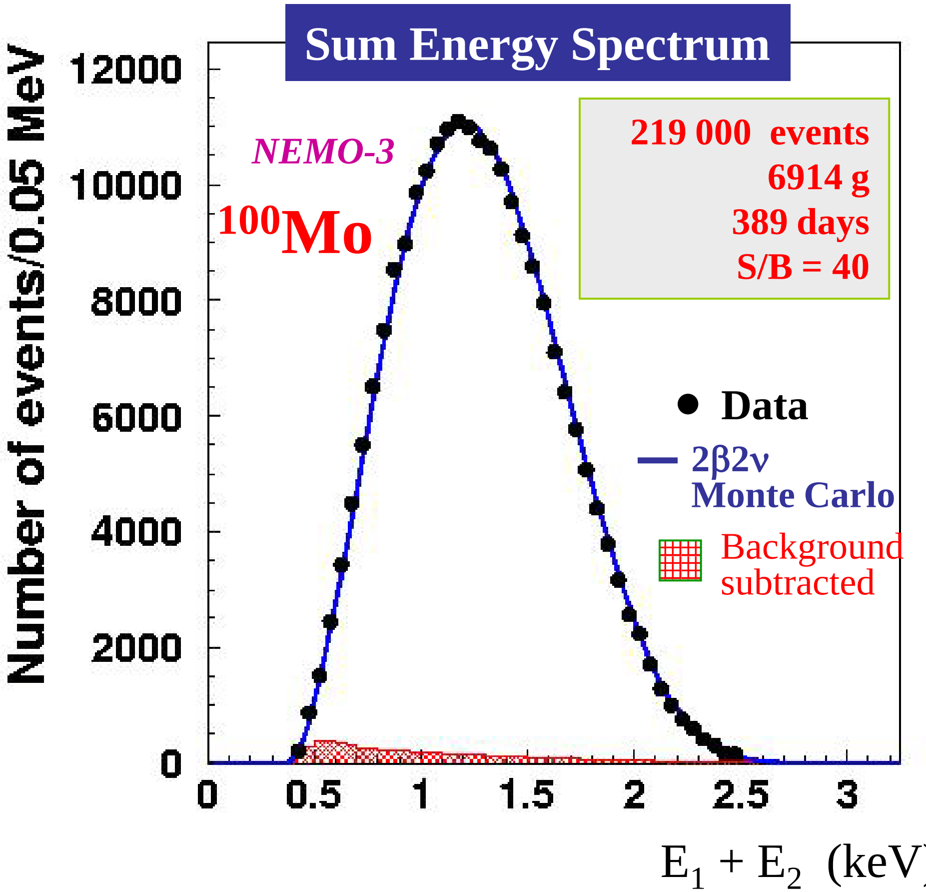
| Isotope | Exposure (kg·y) | $T_{1/2}(0\nu\beta\beta)$, y | $\langle m_\nu \rangle$, eV [NME ref.] |
|---|---|---|---|
| $^{100}$Mo | 26.6 | $> 1.1 \cdot 10^{24}$ | < 0.45 – 0.93 [1-3] |
| $^{82}$Se | 3.6 | $> 3.6 \cdot 10^{23}$ | < 0.9 – 1.6 [1-3]; < 2.3 [7] |
| $^{150}$Nd | 0.095 | $> 1.8 \cdot 10^{22}$ | < 1.7 – 2.4 [4,5] ;< 4.8 – 7.6 [6] |
| $^{130}$Te | 1.4 | $> 9.8 \cdot 10^{22}$ | < 1.6 – 3.1 [2,3] |
| $^{96}$Zr | 0.031 | $> 9.2 \cdot 10^{21}$ | < 7.2 – 19.5 [2,3] |
| $^{48}$Ca | 0.017 | $> 1.3 \cdot 10^{22}$ | < 29.6 [7] |

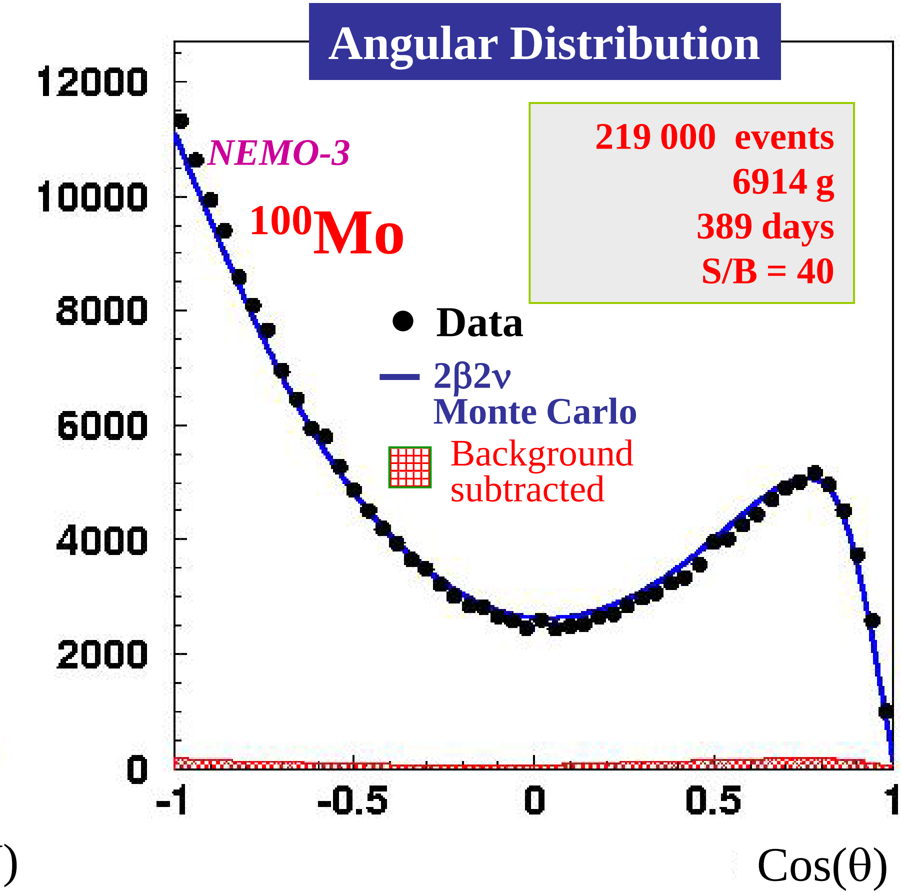
- NME references:


  - [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

# $^{100}$Mo 2β2ν results (Phase I)

(Data Feb. 2003 – Dec. 2004) → (Phase I)



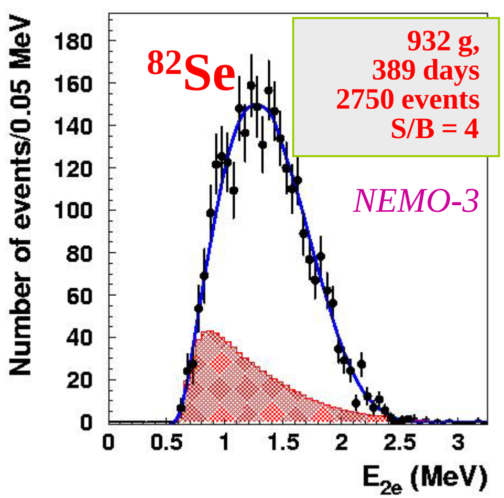

**7.37 kg.y**

**$T_{1/2} = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y**

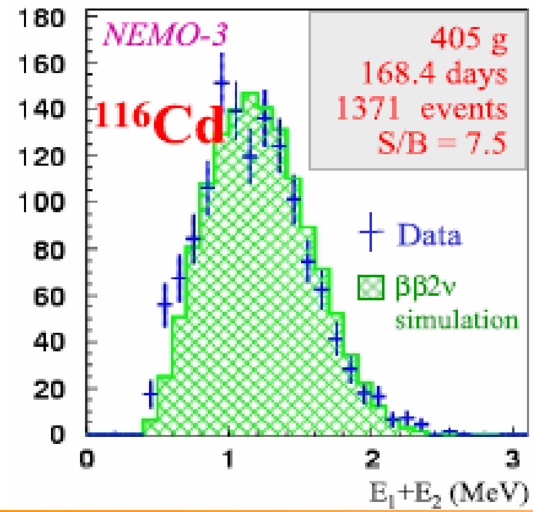
***Phys Rev Lett 95, 182302 (2005)***

**No Significant discrepancy → 2νββ is really standard process!**

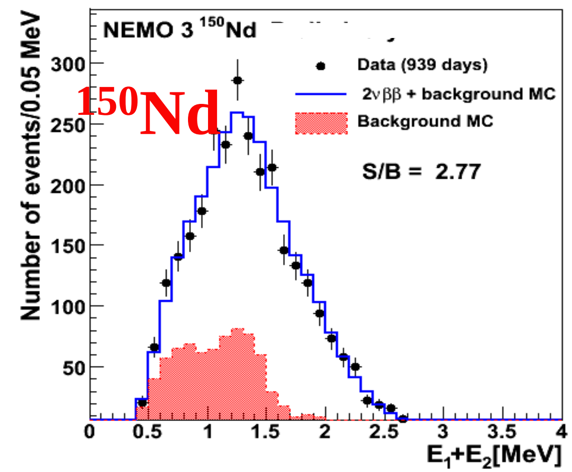
# Other nuclei: results of the ββ2ν measurements



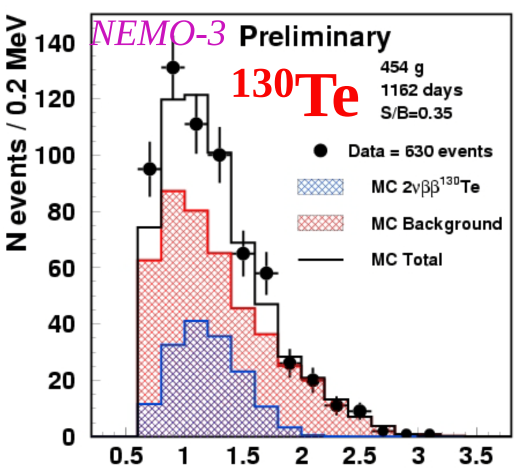

9.6 ± 0.3 (stat) ± 1.0 (sys) $10^{19}$ y



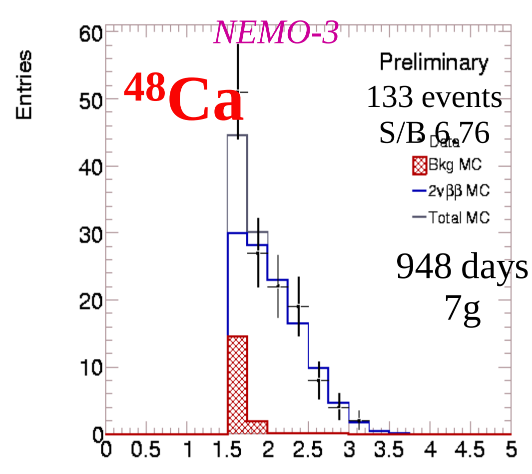

2.8 ± 0.1 (stat) ± 0.3 (sys) $10^{19}$ y



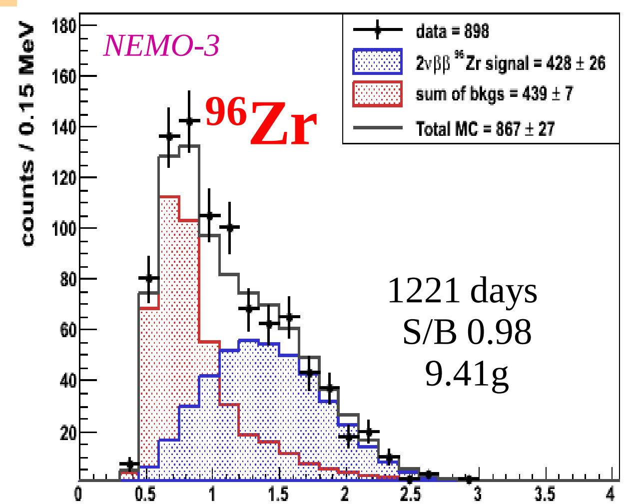

9.11 $^{+0.25}_{-0.22}$(stat) ± 0.63 (sys) $10^{18}$




6.9± 0.9 (stat) ± 1.0 (sys) $10^{20}$ y

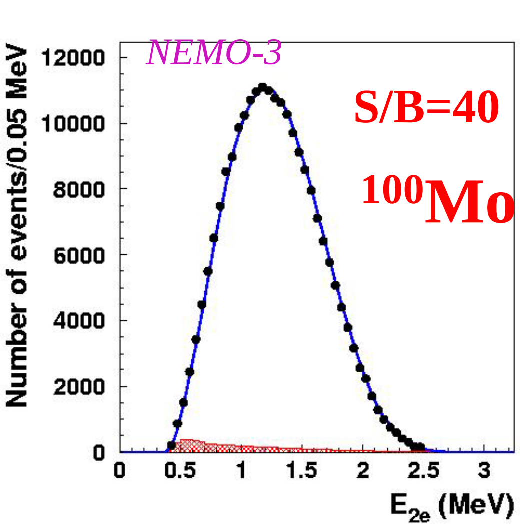


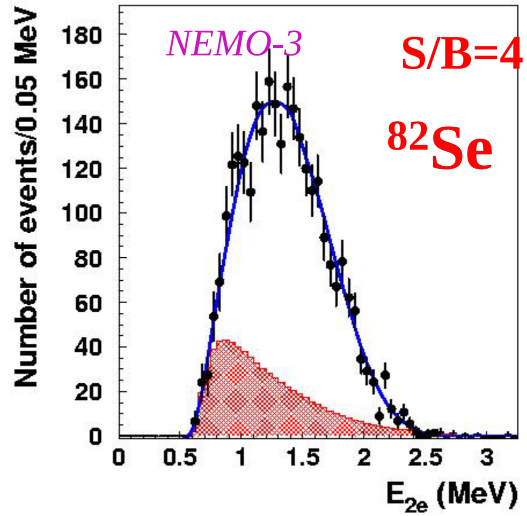

4.4 $^{+0.5}_{-0.4}$ (stat)± 0.4 (sys) $10^{19}$ y

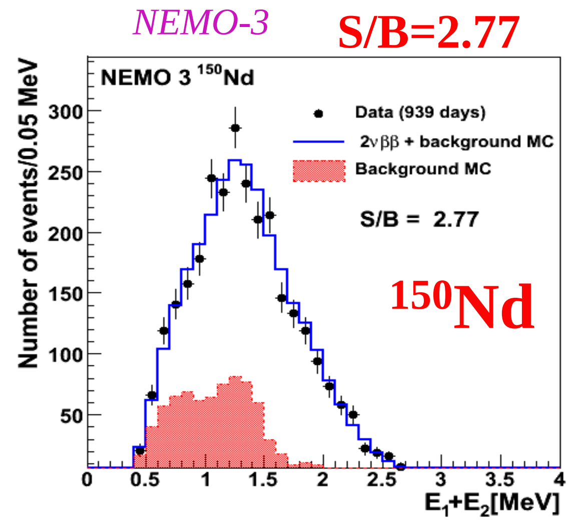


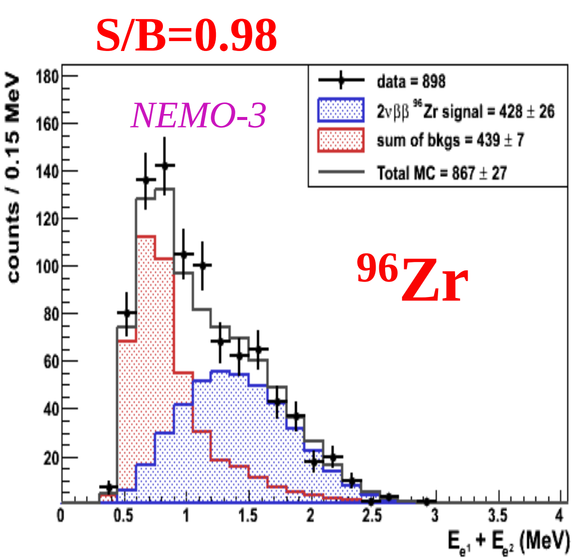

2.35 ± 0.14 (stat) ± 0.16 (sys) $10^{19}$ y

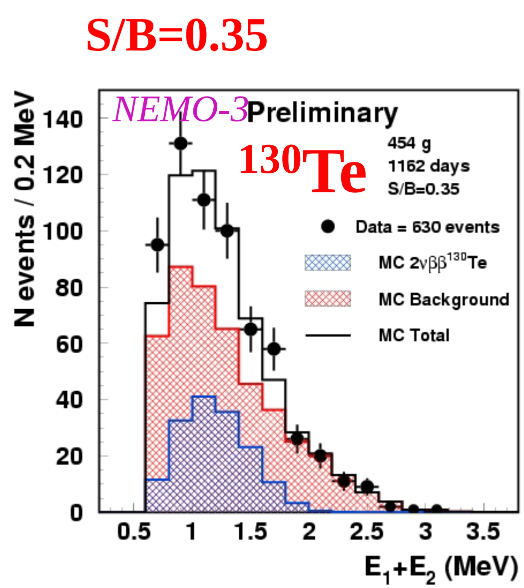
# It is interesting to arrange the data according to S/B ..

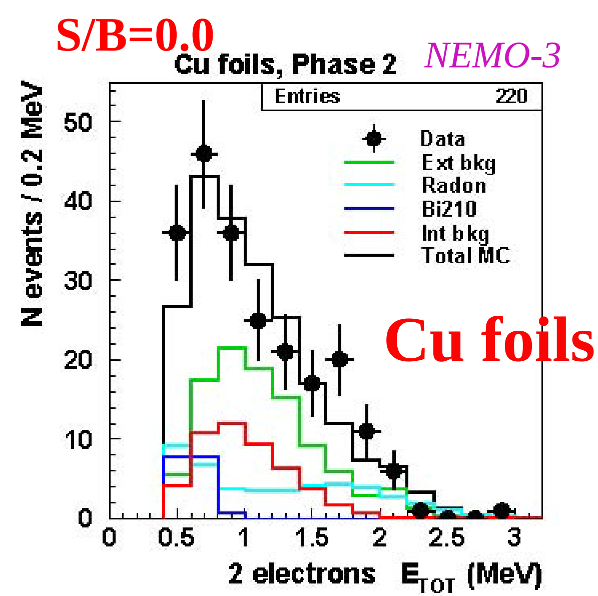


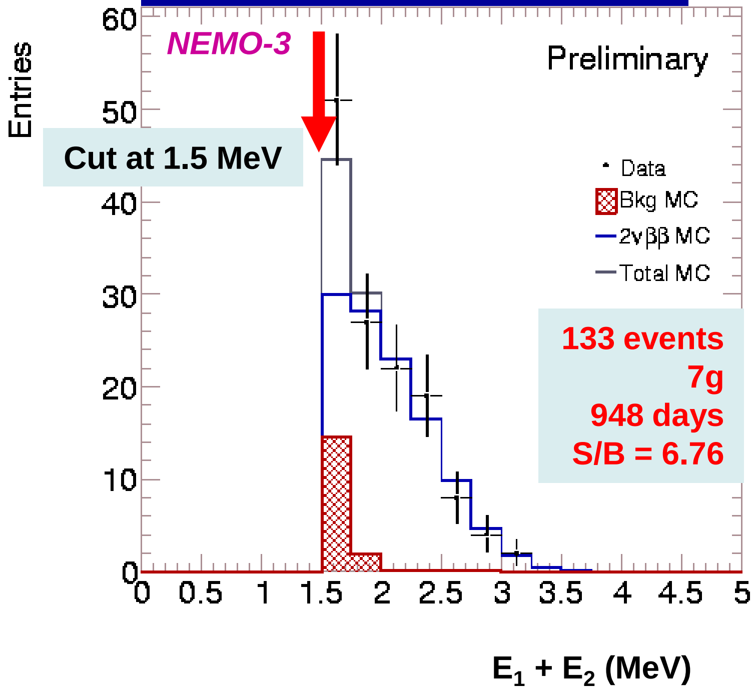




No unknown ee signals !

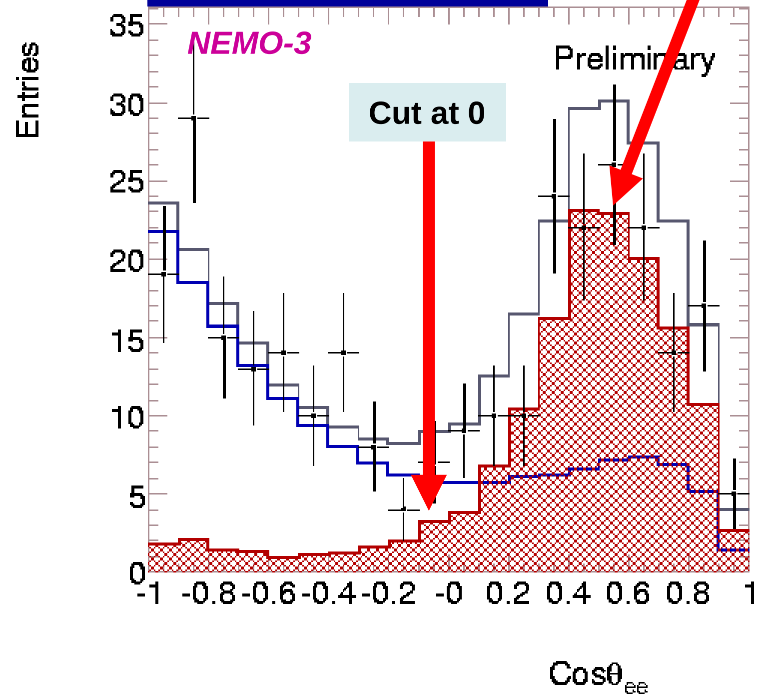
# $^{48}$Ca (Preliminary)

High bkg here due to contamination with $^{90}$Sr

**Energy sum of the electrons**




**Angular distribution**




**Preliminary results:**

$T_{1/2}$ (2νββ) = [4.4 $^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst)] × $10^{19}$ y

$T_{1/2}$ (0νββ) > 1.3 × $10^{22}$ y (90% C.L.) → ⟨$m_\nu$⟩ < 29.6 eV (90% C.L.), eff. 22%

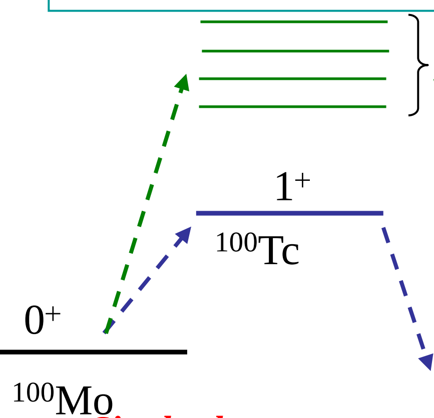
NME: E. Caurrier et al., Phys. Rev. Lett. 100 (2008) 052503.

# Single electron spectum $2\nu\beta\beta$ ($^{100}$Mo)

SSD simulation

$T_{1/2} = 7.11 \pm 0.02$ (stat) $\pm$ 0.54 (syst) $\times 10^{18}$ y
***Phys. Rev. Lett. 95 (2005) 182302***

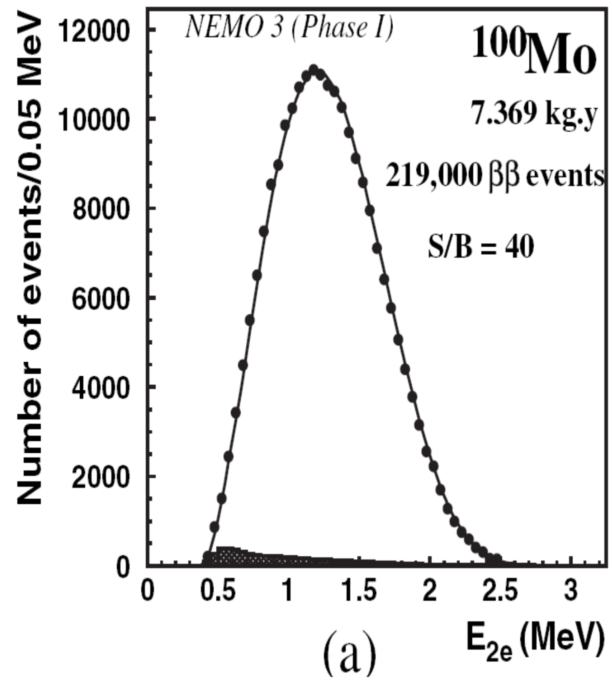
SSD model confirmed

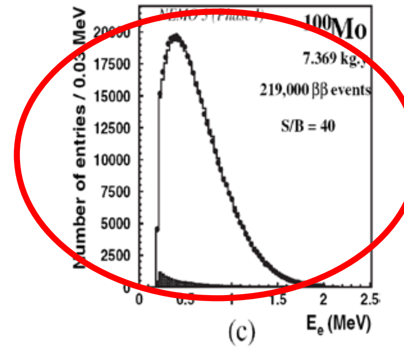


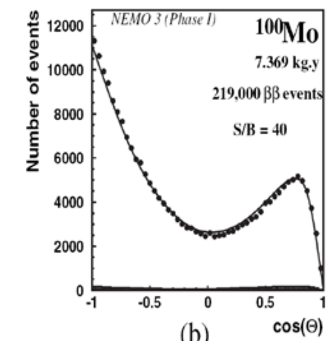

**HSD**, **higher levels contribute to the decay**

**SSD**, **$1^+$ level dominates in the decay**

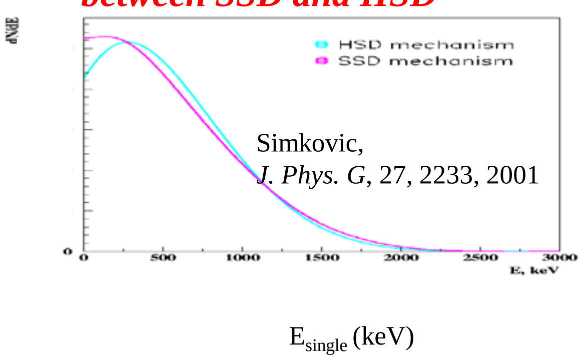
(Abad et al., 1984, *Ann. Fis.* A 80, 9)

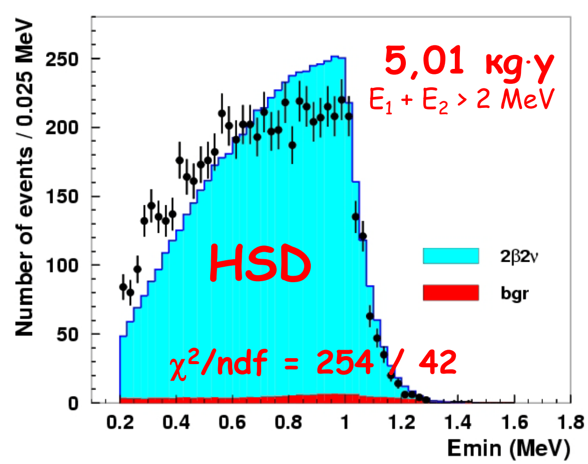


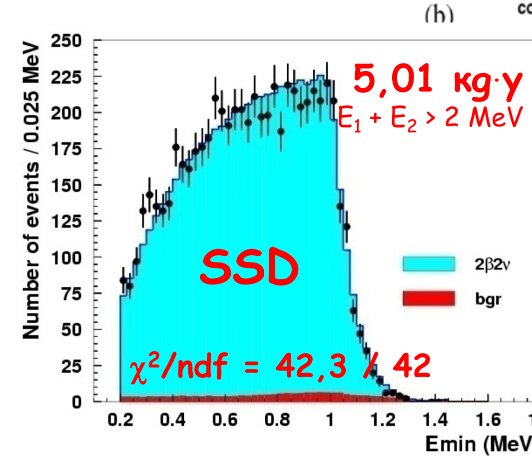




***Single electron spectrum different between SSD and HSD***



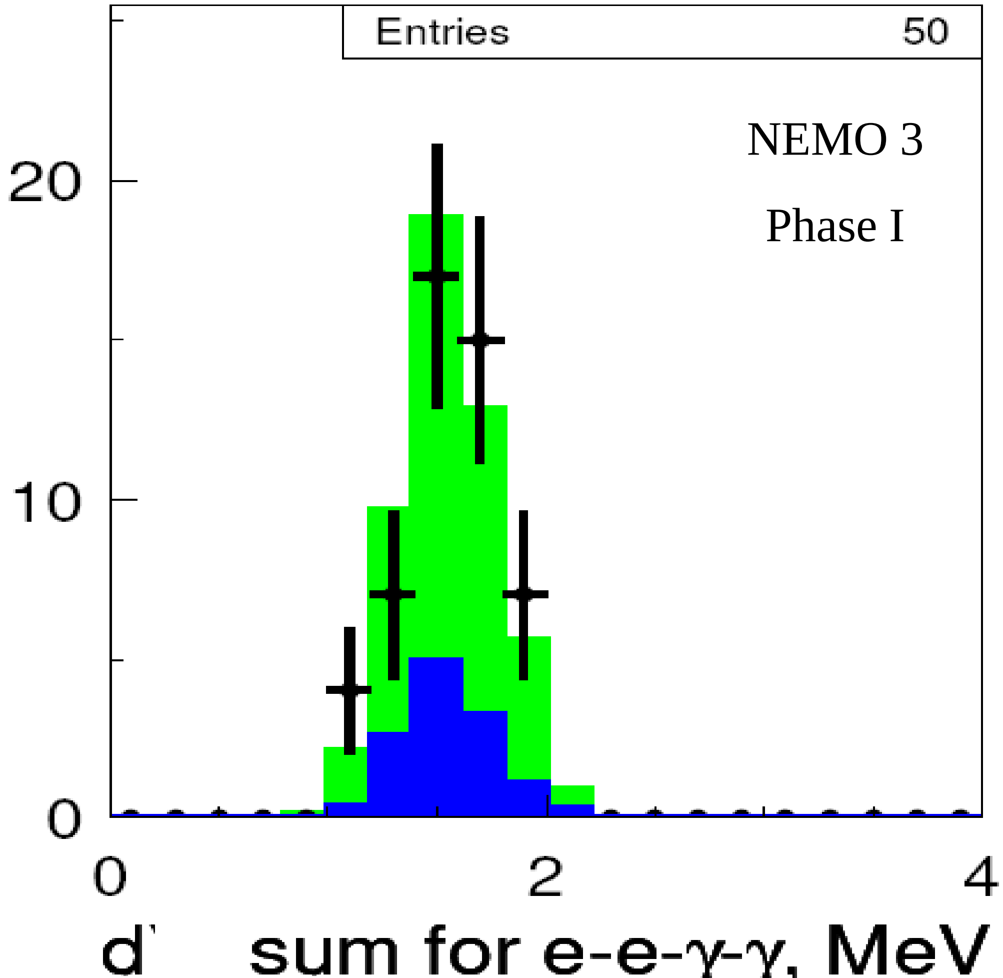



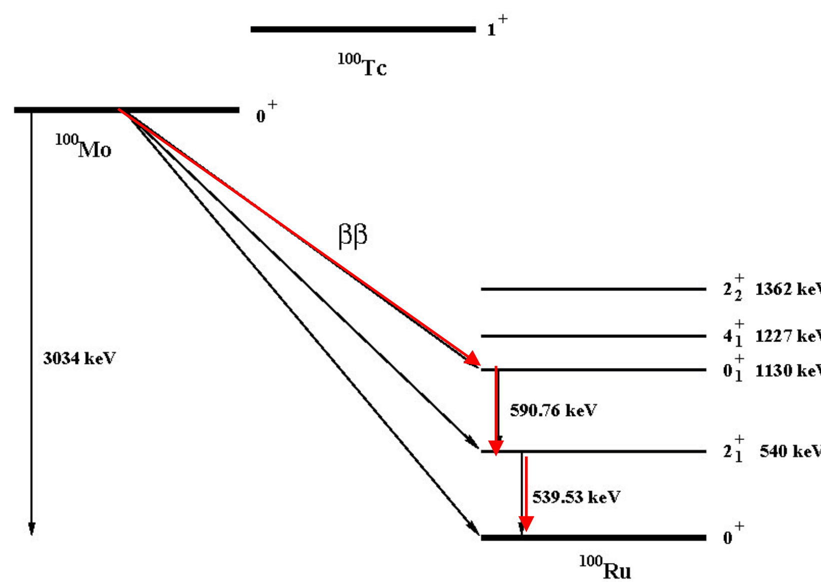
# Decay to the excited $0^+$ ($^{100}$Mo $2\nu\beta\beta$ )

Decay to the excited $0^+$ state (1130keV) of $^{100}$Ru
$T_{1/2} = 5.7^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (syst) $\times 10^{20}$ y
***Nuclear Physics A781 (2006) 209-226.***

Direct Observation

With all the particles detected on the final state



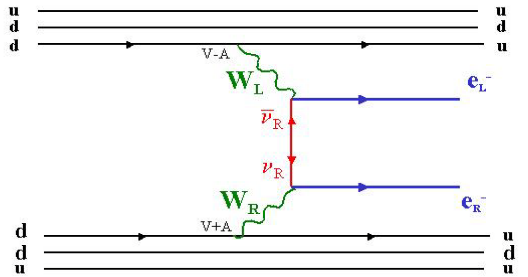



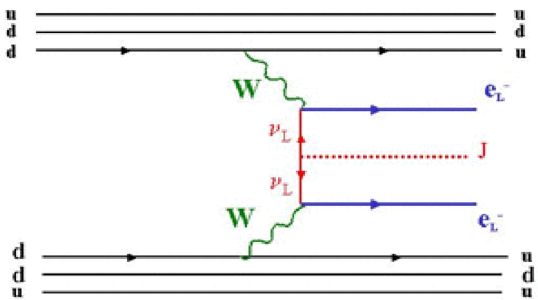
# Summary of 2νββ results

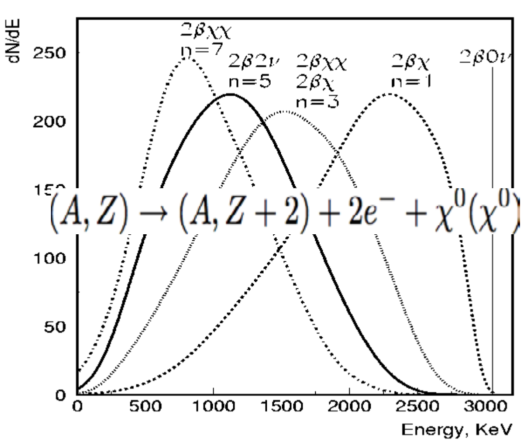
| Isotope | S/B | $T_{1/2}$(2νββ), y (NEMO 3) |
|---|---|---|
| $^{100}$Mo | 40 | $(7.11 \pm 0.02(stat) \pm 0.54(syst)) \cdot 10^{18}$ (SSD favoured) [1] |
| $^{100}$Mo($0^+_1$) | 3 | $(5.7^{+1.3}_{-0.9}(stat)) \pm 0.8(syst)) \cdot 10^{20}$ [2] |
| $^{82}$Se | 4 | $(9.6 \pm 0.3(stat) \pm 1.0(syst)) \cdot 10^{19}$ [1] |
| $^{116}$Cd | 7.5 | $(2.8 \pm 0.1(stat) \pm 0.3(syst)) \cdot 10^{19}$ [3] |
| $^{130}$Te | 0.35 | $(6.9 \pm 0.9(stat) \pm 1.0(syst)) \cdot 10^{20}$ [6] |
| $^{150}$Nd | 2.8 | $(9.11^{+0.25}_{-0.22}(stat) \pm 0.63(syst)) \cdot 10^{18}$ [4] |
| $^{96}$Zr | 1.0 | $(2.35 \pm 0.14(stat) \pm 0.16(syst)) \cdot 10^{19}$ [5] |
| $^{48}$Ca | 6.8 | $(4.4^{+0.5}_{-0.4}(stat) \pm 0.4(syst)) \cdot 10^{19}$ [6] |

[1] Phase 1 data, Phys. Rev. Lett. 95 (2005) 182302. Additional statistics are being analysed, to be published soon.
[2] Phase 1 data, Nuclear Physics A781 (2006) 209-226.
[3] Phase 1 data.
[4] Phase 1 and 2, Physcal Review C80 (2009) 032501(R)
[5] Phase 1 and 2, arXiv:0906,2694[nucl-ex] (2009)
[6] Phases 1 and 2, preliminary.

# V+A currents and Majoron




**V+A currents:**

$(T_{1/2})^{-1} = C_{mm}\langle m_\nu\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{m\eta}\langle m_\nu\rangle\times\langle\eta\rangle + C_{m\lambda}\langle m_\nu\rangle\times\langle\lambda\rangle + C_{\eta\lambda}\langle\eta\rangle\times\langle\lambda\rangle$ , $C_{xx}$ - $F\cdot|M|^2$

$\langle\lambda\rangle,\langle\eta\rangle$ - right currents coupling constants

**Majoron emission:**

$$(A, Z) \to (A, Z+2) + 2e^- + \chi^0(\chi^0)$$

| Isotope | V+A * | Majoron(s) emission ** | | | |
|---|---|---|---|---|---|
| | $T_{1/2}(0\nu\beta\beta)$ y | n=1 | n=2 | n=3 | n=7 |
| $^{100}Mo$ | >5.7·10^23 <br> λ<1.4·10^-6 | >2.7·10^22 <br> $g_{ee}$<(0.4-1.8)·10^-4 | >1.7·10^22 | >1.·10^22 | >7·10^19 |
| $^{82}Se$ | >2.4·10^23 <br> λ<2.·10^-6 | >1.5·10^22 <br> $g_{ee}$<(0.7-1.9)·10^-4 | >6·10^21 | >3.1·10^22 | >5·10^20 |

n: spectral index, limits on half-life in years

* Phase I+Phase II data

** Phase I data, *R.Arnold et al. Nucl. Phys. A765 (2006) 483*

# Summary of NEMO 3

- ββ decay for $^{48}Ca$, $^{96}Zr$, $^{82}Se$, $^{100}Mo$, $^{116}Cd$, $^{130}Te$ and $^{150}Nd$ has been investigated, accurate measurement of half-lives has been performed.
- New limits on 0νββ decay
  - $^{100}Mo > 1.1 \cdot 10^{24}$ y
  - $^{82}Se > 3.6 \cdot 10^{23}$ y

have been obtained.

- NEMO-3 continues taking data up to end 2010, 0ν sensitivity will be improved.

# From NEMO3 to SuperNEMO

$$T_{1/2}(\beta\beta0\nu) > \ln 2 \times \frac{N_{avo}}{A} \times \frac{M \times \varepsilon \times T_{obs}}{N_{exclu}}$$

| NEMO-3 | | SuperNEMO |
|---|---|---|
| $^{100}$Mo<br>$T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y | Choice of isotope | $^{150}$Nd or $^{82}$Se<br>$T_{1/2}(\beta\beta2\nu) = 10^{20}$ y |
| 7 kg | Isotope mass M | 100 - 200 kg |
| $\varepsilon(\beta\beta0\nu)$ = 8 % | Efficiency $\varepsilon$ | $\varepsilon(\beta\beta0\nu) \sim$ 30 % |
| $^{214}$Bi < 300 μBq/kg<br>$^{208}$Tl < 20 μBq/kg<br>($^{208}$Tl, $^{214}$Bi) ~ 1 evt/ 7 kg /y<br>ββ2ν ~ 2 evts / 7 kg / y<br>FWHM(calo)=8% @3MeV | $N_{exclu}$ = f(BKG)<br>*Internal contaminations*<br>*$^{208}$Tl and $^{214}$Bi in the ββ foil*<br>*ββ(2ν)* | $^{214}$Bi < 10 μBq/kg<br>$^{208}$Tl < 2 μBq/kg<br>($^{208}$Tl, $^{214}$Bi) ~ 1 evt/ 100 kg /y<br>ββ2ν ~ 1 evt / 100 kg/ y<br>FWHM(calo)=4% @3MeV |
| $T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y<br>$<m_\nu> < 0.3 – 0.7$ eV | SENSITIVITY | $T_{1/2}(\beta\beta0\nu) > 10^{26}$ y<br>$<m_\nu> < 50$ meV |

**Main R&D tasks:**

**1) ββ source production** **2) Energy resolution**

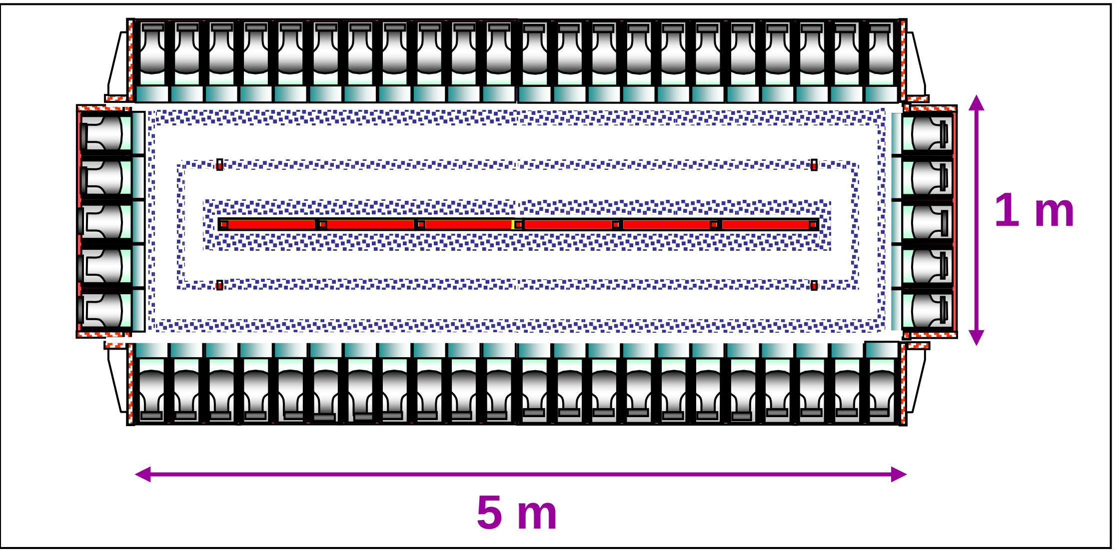
**3) Radioprurity** **4) Tracking**

# SuperNEMO conceptual design

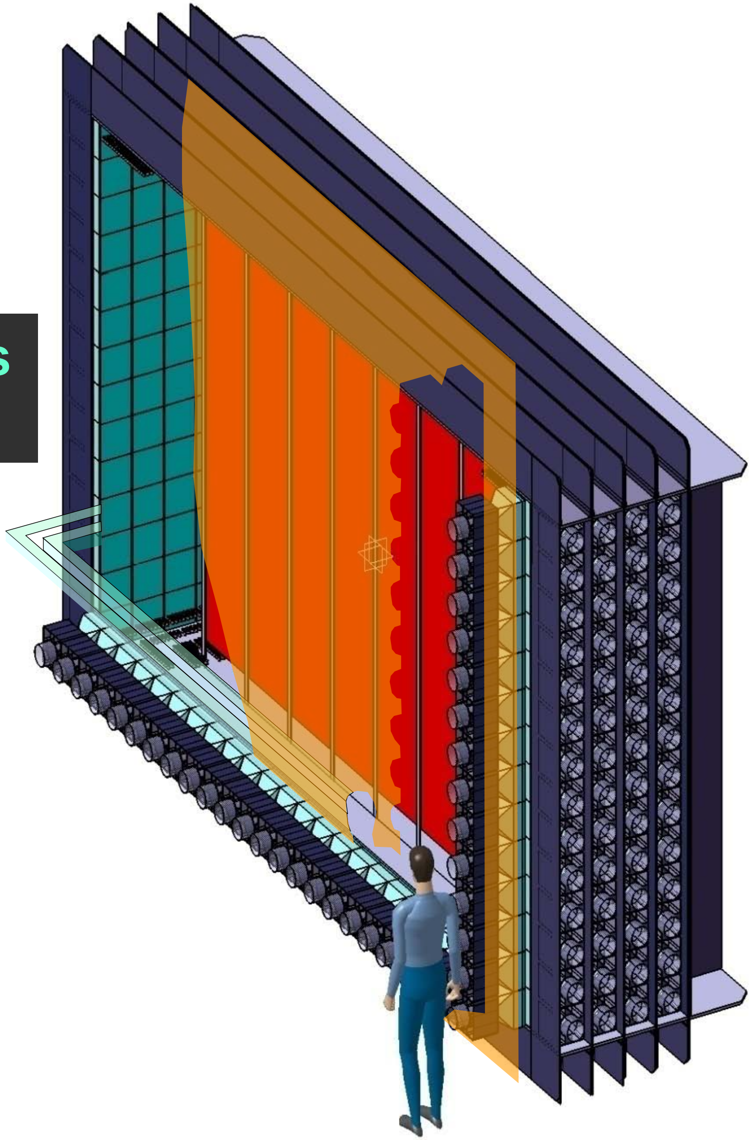
**20 modules for 100 kg**

**Source (40 mg/cm²) 12m²**
**Tracking (~2-3000 Geiger cells).**
**Calorimeter (600 channels)**

**Total:~ 40 000 – 60 000 geiger cells channels**
**~ 12 000 PMT**




Top view



# SuperNEMO Status

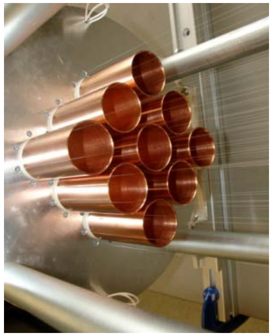
Calorimeter: ΔE/E < 8% at 1 Mev reached

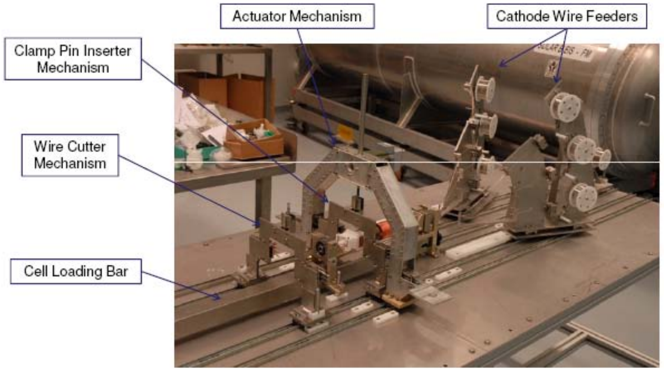
Tracking (UK) : 90 cells prototype
Wiring robot built

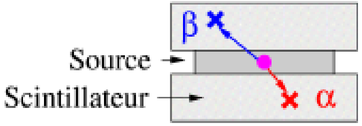
Low radioactivity measurement:
BiPo detector $^{208}$Tl < 5 µBq/kg

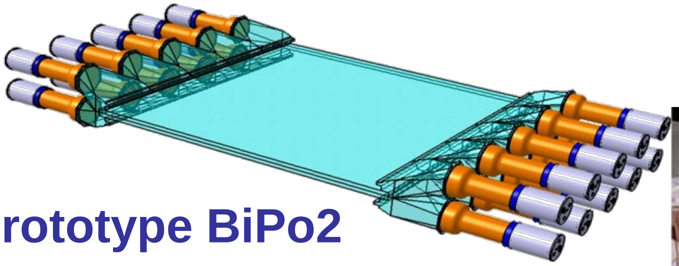
Mechanical design : in progress

Source purification: 2 methods

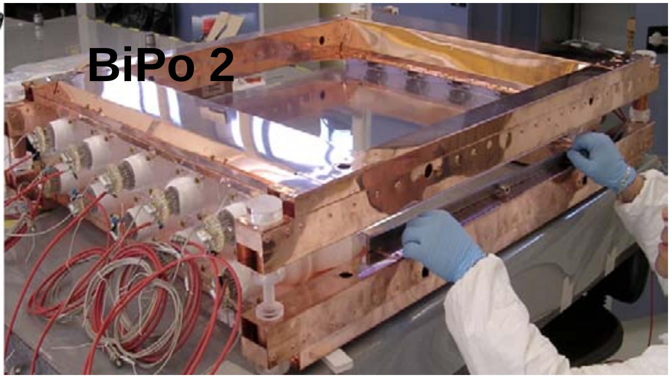




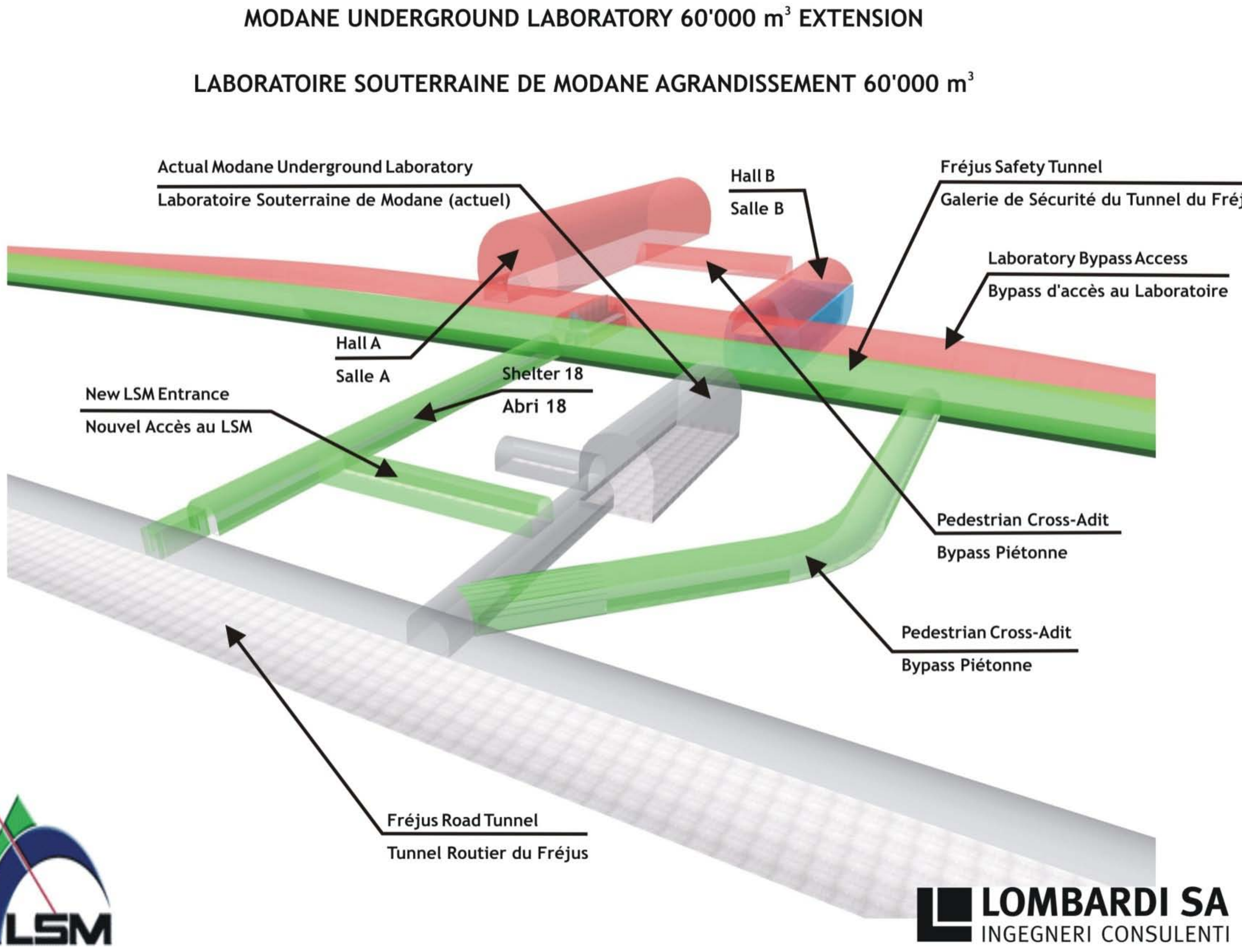



Prototype BiPo2

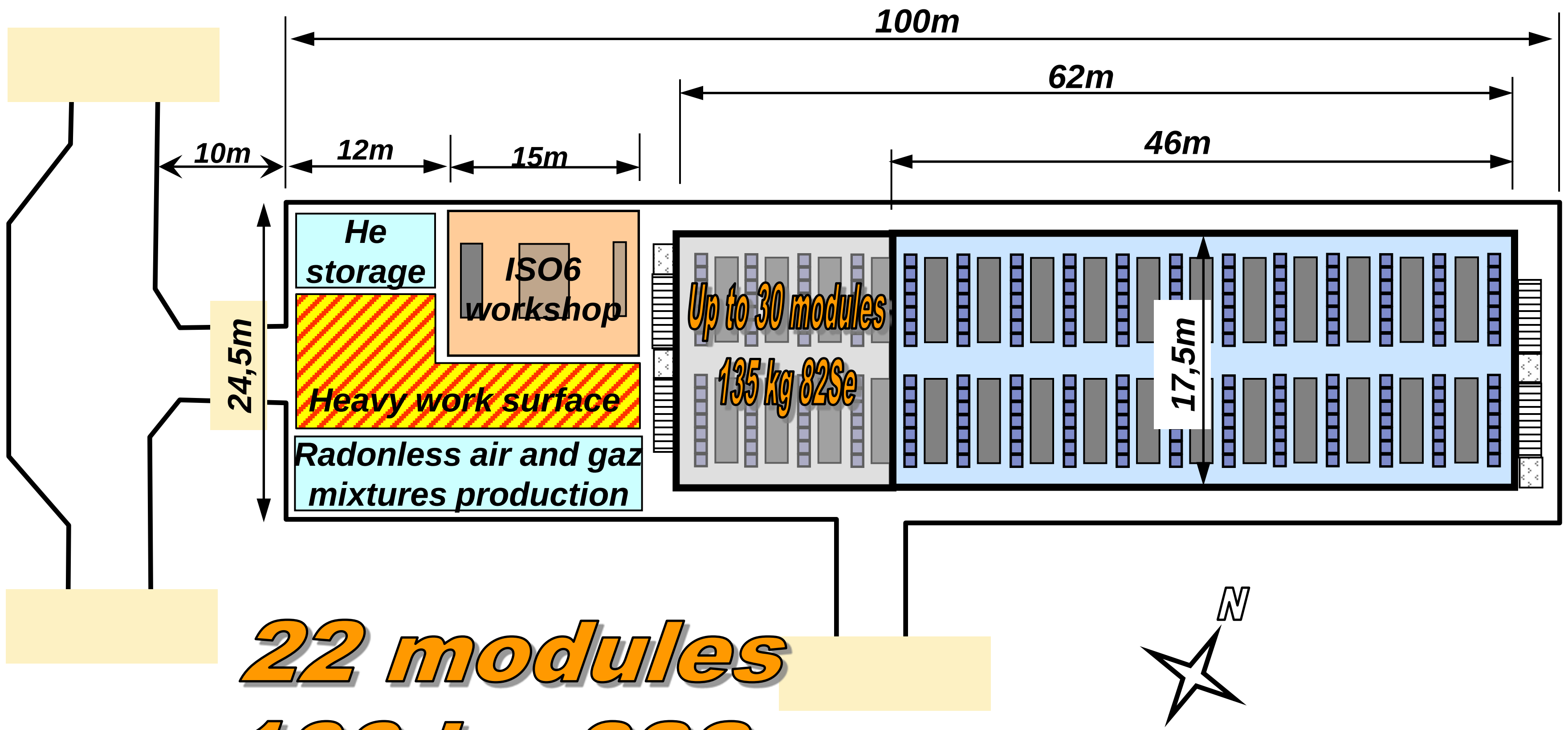



SuperNEMO prototype module at LSM end 2011

# Extension project



# SuperNEMO in LSM




**22 modules**
**100 kg 82Se**

Source (40 mg/cm$^2$) 12m$^2$

*J.FORGET SuperNEMO all 8inch general design june 2008*

# Concluding remarks

- NEMO 3 succeeded to reach the required level of background (proposal).
- All backgrounds in NEMO 3 are completely understood.
- NEMO 3 is a good lesson for SuperNEMO to explore next goal of inverted hierarchy neutrino mass region (~50 meV).
- NEMO / SuperNEMO collaboration
  (80 physicists, 29 labs., 11 countries)
- SuperNEMO R&D's are going on …..
  next step: 1st prototype module at LSM (2011).