Recent results from NEMO-3

A search for neutrino-less double beta decay

Karol Lang

The University of Texas at Austin

On behalf of the NEMO Collaboration

The ANDES Laboratory
First International Workshop
for the Design of the
ANDES Underground Laboratory
Centro Atómico Constituyentes
Buenos Aires, Argentina
11-14 April 2011

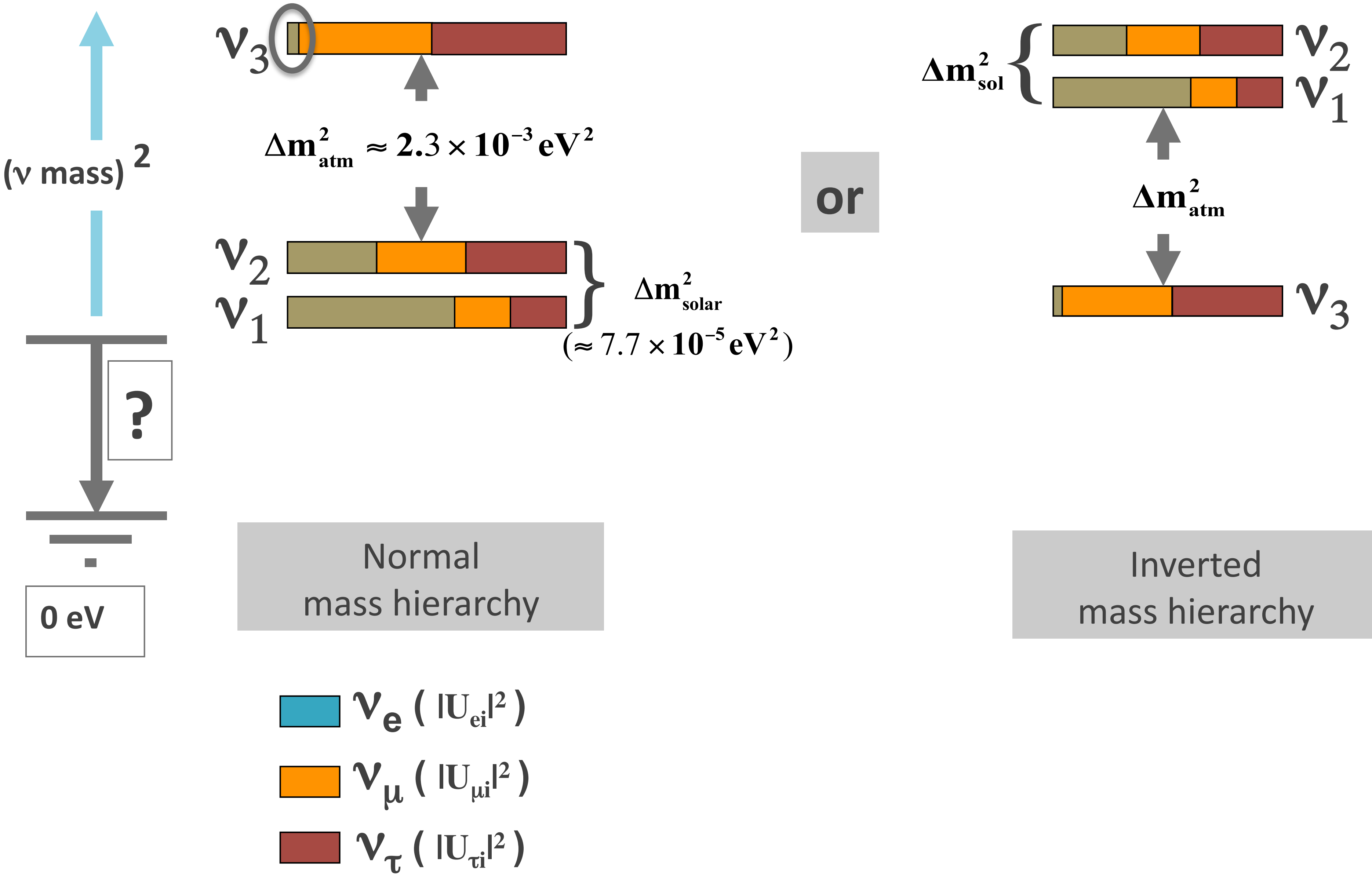
Outline:

- Context for $0\nu\beta\beta$
    - State of neutrinos
    - Neutrino oscillations
- Practical factors
- NEMO-3 results
- Outlook

"You can observe a lot just by watching."

Yogi Bera

In summary…



ν_3
$\Delta m^2_{atm} \approx 2.3 \times 10^{-3}\, eV^2$
ν_2
ν_1
Δm^2_{solar}
$(\approx 7.7 \times 10^{-5}\, eV^2)$
(ν mass) 2
?
0 eV
Normal
mass hierarchy
or
Δm^2_{sol}
ν_2
ν_1
Δm^2_{atm}
ν_3
Inverted
mass hierarchy
ν_e ($|U_{ei}|^2$)
ν_μ ($|U_{\mu i}|^2$)
ν_τ ($|U_{\tau i}|^2$)

Neutrino questions

- What is the absolute mass scale?
- What is the mass ordering (“mass hierarchy”)?
- How strong is the subdominant mixing (angle θ_{13} in the PMNS matrix) ?
- Do neutrinos violate CP symmetry (angle δ in the PMNS matrix)?
- Are neutrinos Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu \equiv \bar{\nu}$) particles?
- Are there sterile neutrinos?
- …

Neutrino questions and $0\nu\beta\beta$

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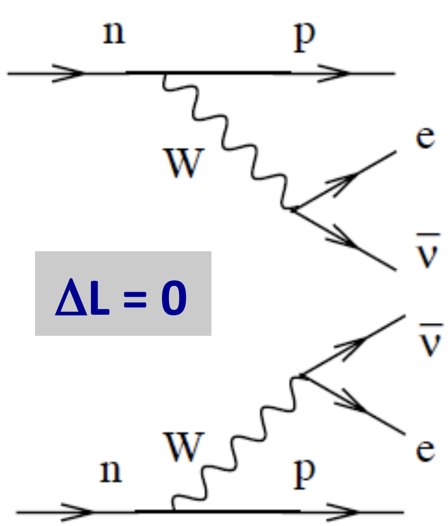
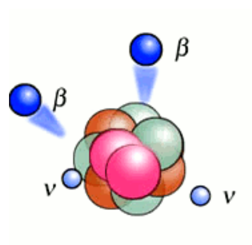
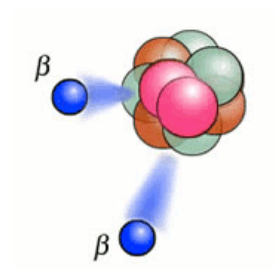


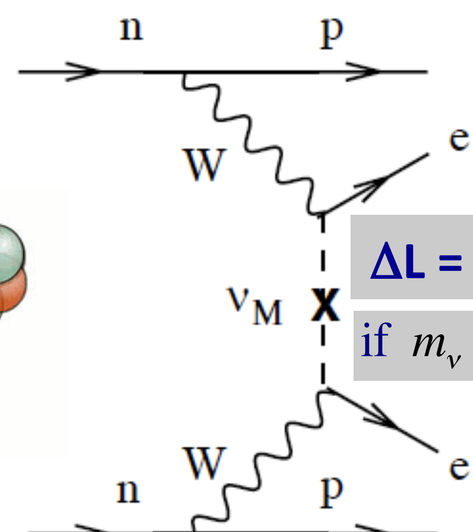
ΔL = 0

$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$

$(2\nu\beta\beta)$







ΔL = 2

if $m_\nu \neq 0$

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

$(0\nu\beta\beta)$

Neutrino questions and $0\nu\beta\beta$

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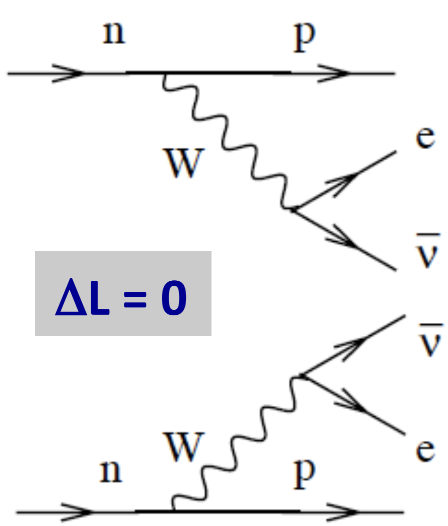

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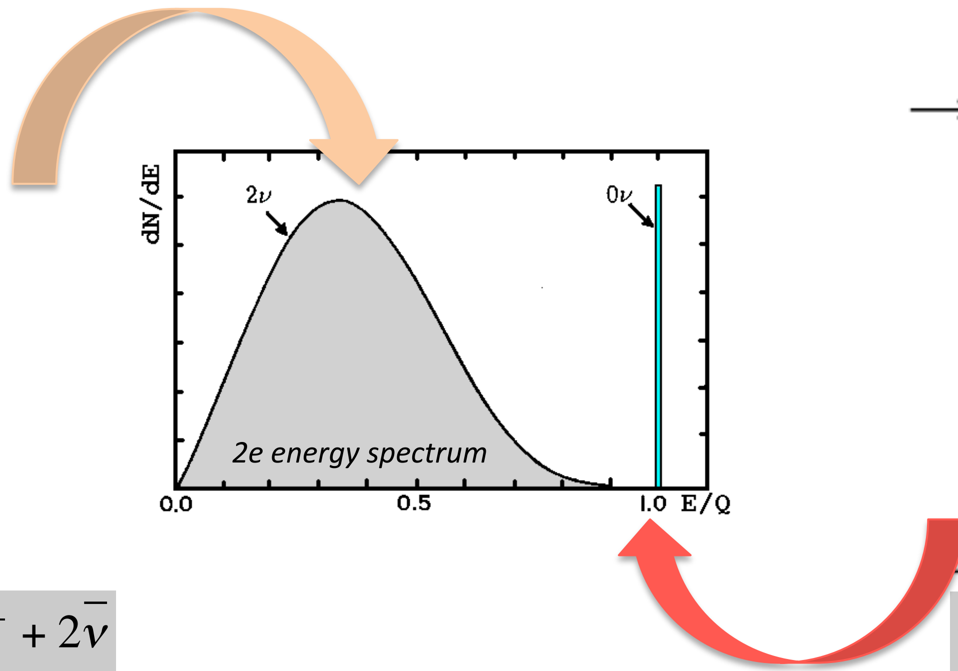

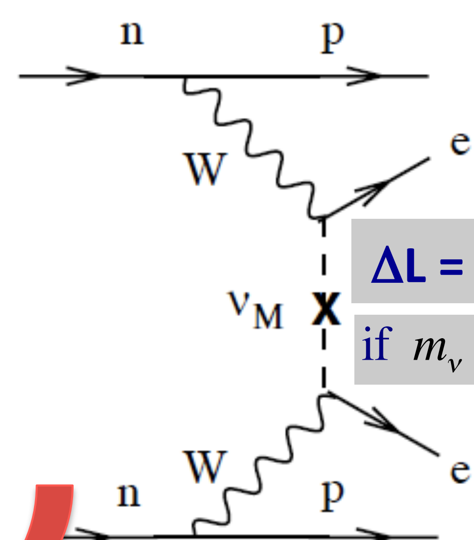

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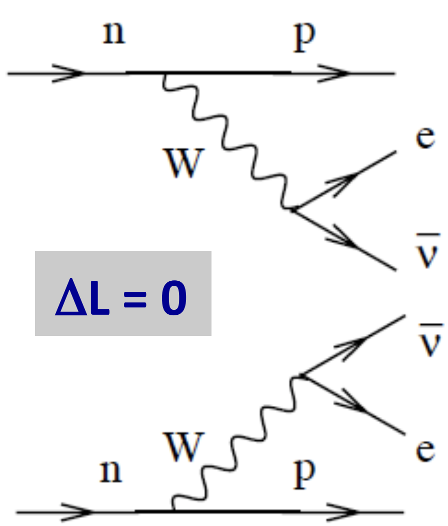

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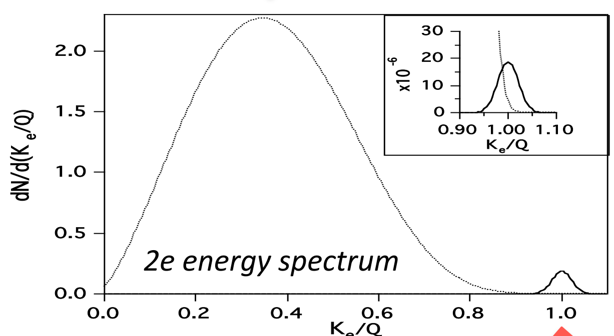
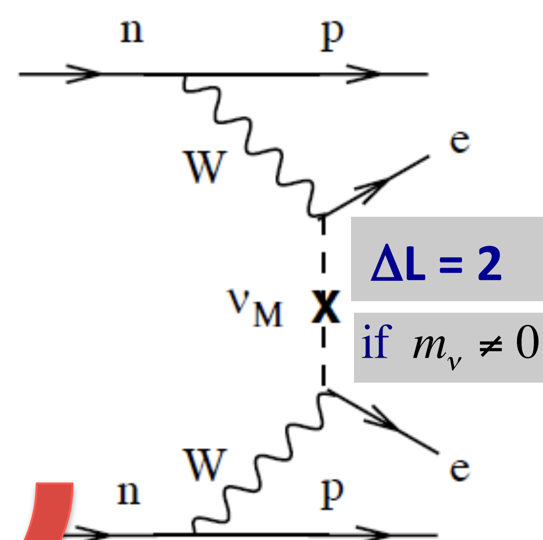




$(Z,A) \rightarrow (Z+2,A) + 2e^-$
$(0\nu\beta\beta)$

Why are neutrino masses so small?

Answer (?): Majorana mass and the see-saw mechanism

With massive neutrinos, we need to add a right-handed neutrino field

$$e_R \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \nu_R$$

$$L_{m_\nu} = m_D \phi \bar{\nu}_R \nu_L + M_R \phi \bar{\nu}^c_R \nu^c_R + m_D \phi \bar{\nu}^c_L \nu^c_R \qquad [\bar{\nu}^c_L, \bar{\nu}_R] \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu^c_R \end{bmatrix} + \text{h.c.}$$

$$D_\nu = \begin{bmatrix} \frac{m_D^2}{M_R} & 0 \\ 0 & M_R \end{bmatrix}$$

$$m_1 \simeq \frac{m_D^2}{M_R} \quad \text{and} \quad m_2 \simeq M_R$$

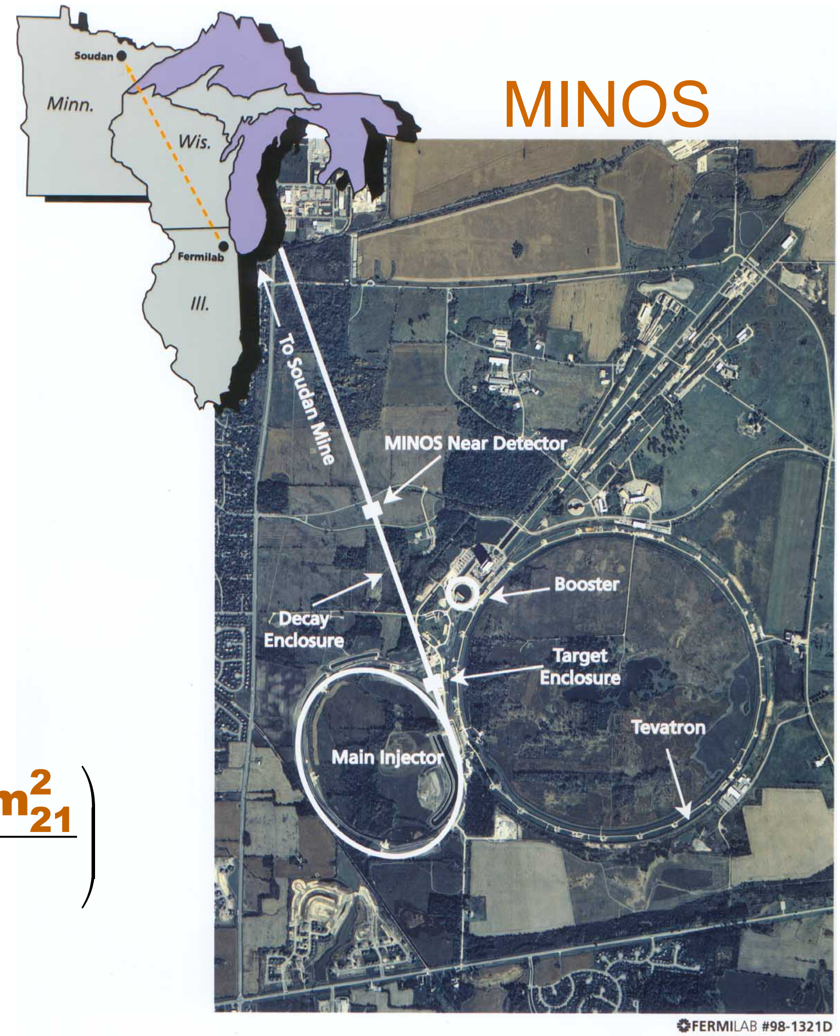
$$L_{m_\nu} = m_1 \bar{\nu}_1 \nu_1 + M_R \bar{\nu}_2 \nu_2$$

$$\nu_1 = -i(1 - \frac{1}{2}\rho^2)(\nu_L - \nu^c_L) + i\rho(\nu^c_R - \nu_R)$$

$$\nu_2 = \rho(\nu_L + -\nu^c_L) + (1 - \frac{1}{2}\rho^2)(\nu_R + \nu^c_R)$$

Neutrino oscillations

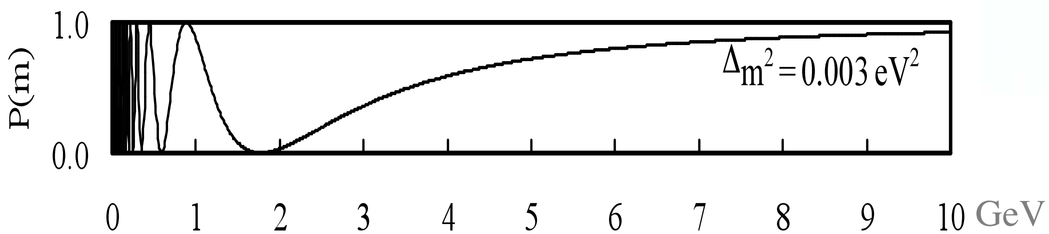
- Two-detector measurement
  - long baseline (735km)
- High intensity beam
  - (120 GeV from Main Injector)



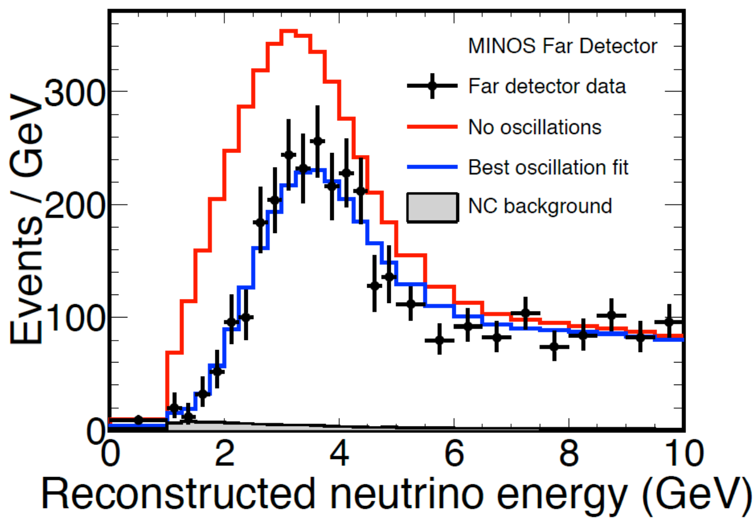
$$|\nu(t=0)\rangle = |\nu_a\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

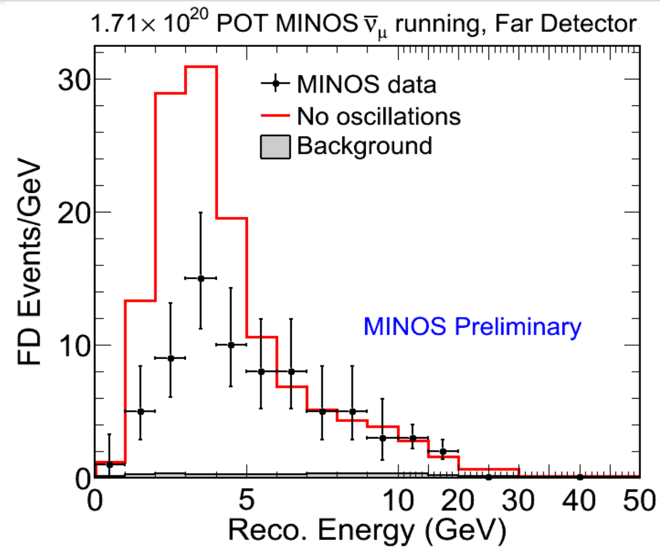
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix}_{weak} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}_{mass}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2(2\theta) \cdot \sin^2\left(\frac{1.27 \cdot L \cdot \Delta m^2_{21}}{E}\right)$$



Oscillations of neutrinos versus anti-neutrinos



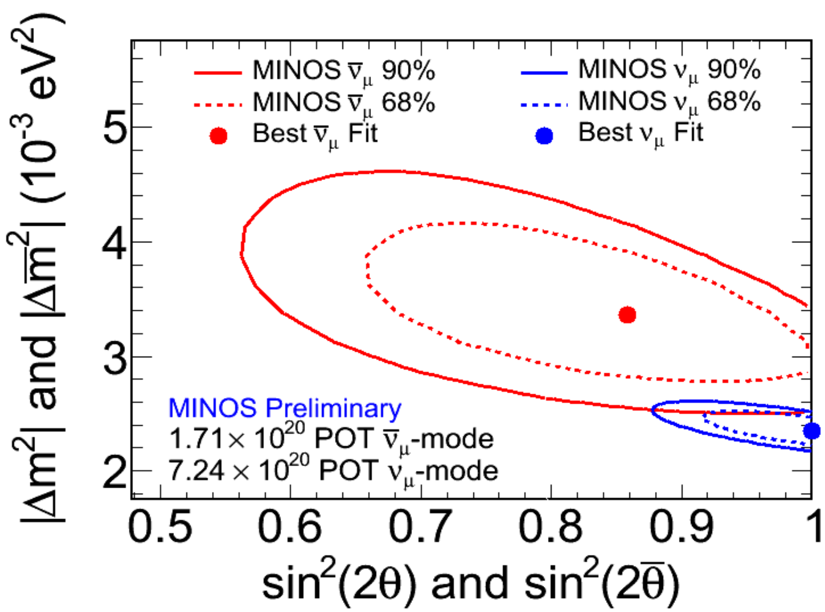


$\left|\Delta m^2\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\theta) > 0.90$ (90% C.L.)

Measurement of the neutrino mass splitting and flavor mixing by MINOS, **arXiv:1103.0340** [hep-ex]

First direct observation of muon antineutrino disappearance. **arXiv:1104.0344** [hep-ex]



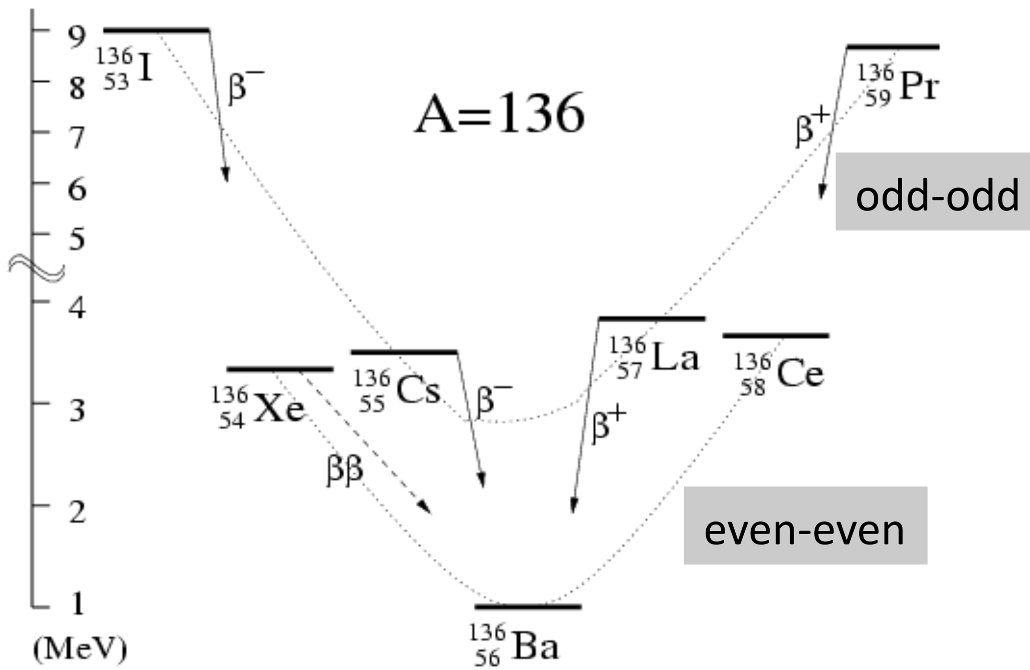
$\left|\overline{\Delta m}^2\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\overline{\theta}) = 0.86 \pm 0.11$

It could happen in 2% experiments with such statistics

Phenomenology of 0νββ and 2νββ

- Pairing interaction between nucleons (even-even nuclei more bound than the odd-odd nuclei)
- e.g., ^{136}Xe and ^{136}Ce are stable against β decay, but unstable against ββ decay ($\beta^-\beta^-$ for ^{136}Xe and $\beta^+\beta^+$ for ^{136}Ce)



There are 35 $\beta^-\beta^-$ emitters
6 $\beta^+\beta^+$

Phenomenology of 0νββ and 2νββ (2)

$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta}^{11}, Z) \bullet \left| M_{2\nu}^{GT} \right|^2$$

G = phase space (well known)

M = nuclear matrix element (challenging)

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left| M_{0\nu}^{GT} \right|^2 \bullet \left\langle m_{\beta\beta} \right\rangle^2$$

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

α^*, β^* = linear combinations of α and β

Phenomenology of 0νββ and 2νββ (2)

$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}(Q_{\beta\beta}^{11}, Z) \bullet \left| M_{2\nu}^{GT} \right|^2$$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q_{\beta\beta}^{5}, Z) \bullet \left| M_{0\nu}^{GT} \right|^2 \bullet \langle m_{\beta\beta} \rangle^2$$

G = phase space (well known)

M = nuclear matrix element (challenging)

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

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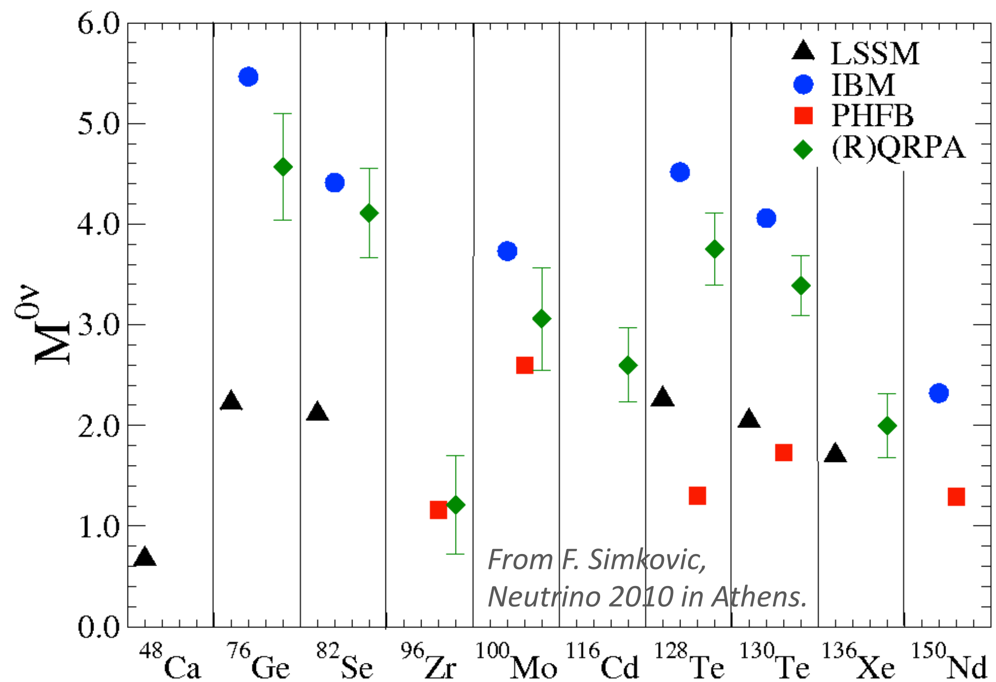


NME models differences:

i) mean field;

ii) residual interaction;

iii) size of the model space;

iv) many-body approximation

NSM *(Madrid-Strassbourg)*

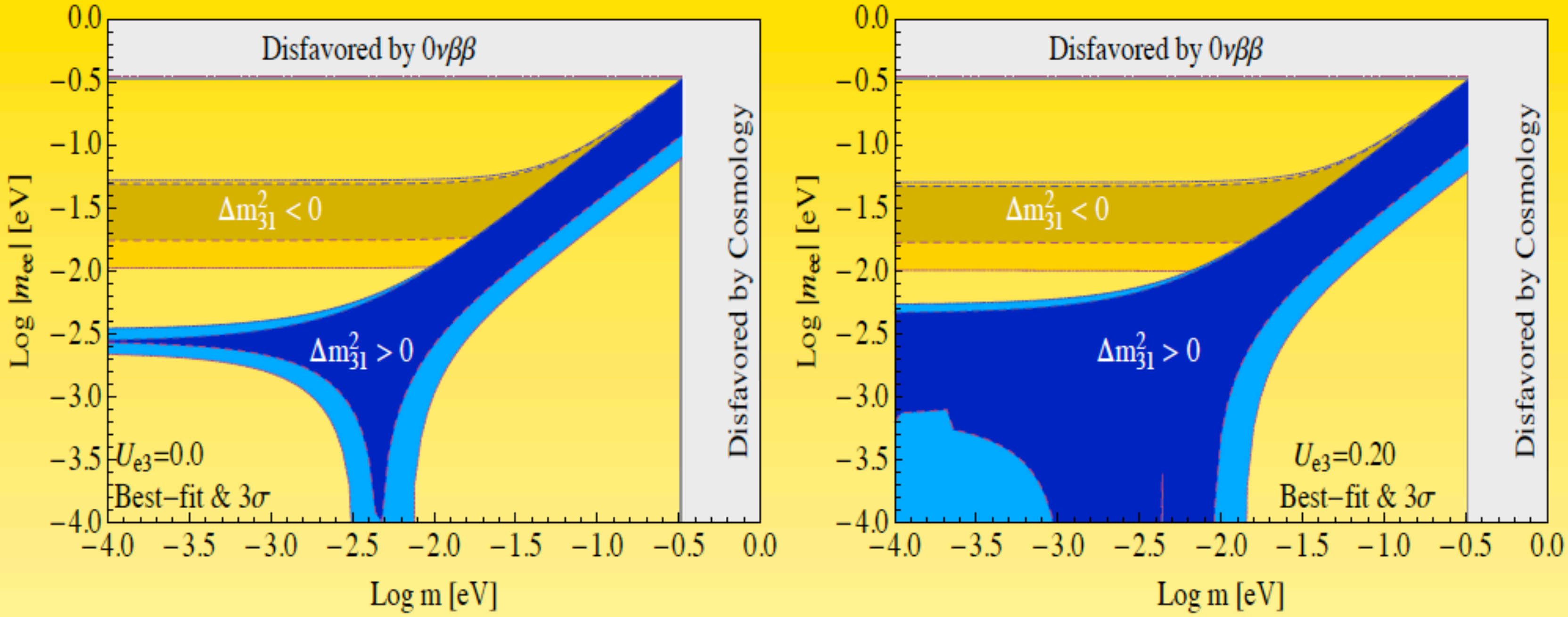
QRPA *(Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata)*

IBM *(Iachello, Barea)*

PHFB *(India/Mexico)*

"The gauge"

$$|m_{ee}| = |\cos^2\theta_{13}(\cos^2\theta_{12} m_1 + \sin^2\theta_{12} e^{2i\alpha} m_2) + \sin^2\theta_{13} e^{2ib} m_3|$$



Lightest neutrino mass

Note: importance of U_{e3}

WERNER RODEJOHANN (MPIK, HEIDELBERG) ATHENS, 16/06/10

parameter	best-fit$^{+1\sigma}_{-1\sigma}$	2σ	3σ
Δm^2_{21} [10^{-5} eV^2]	$7.59^{+0.23}_{-0.18}$	7.22 – 8.03	7.03 – 8.27
$\|\Delta m^2_{31}\|$ [10^{-3} eV^2]	$2.40^{+0.12}_{-0.11}$	2.18 – 2.64	2.07 – 2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29 – 0.36	0.27 – 0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39 – 0.63	0.36 – 0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	$\leq$ 0.039	$\leq$ 0.053

Schwetz, Tortola, Valle, 0808.2016v3 (Feb 2010)

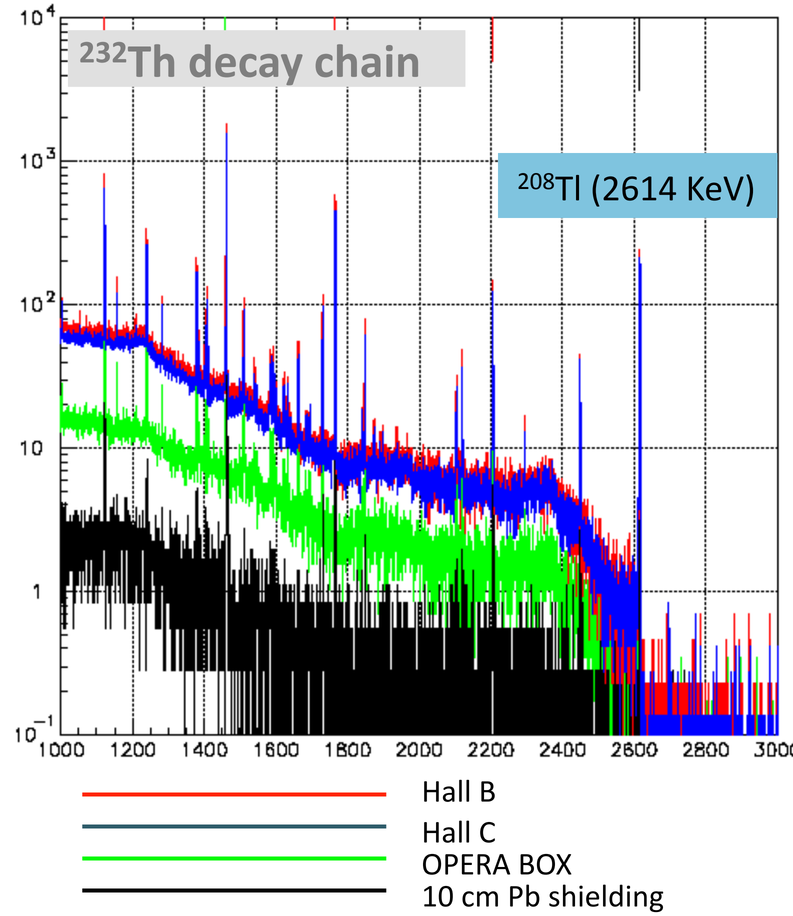
$$|m_{ee}| = |\cos^2\theta_{13}(\cos^2\theta_{12} m_1 + \sin^2\theta_{12} e^{2i\alpha} m_2) + \sin^2\theta_{13} e^{2ib} m_3|$$

Practical matters

NEMO-3	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

(11) $\beta\beta$ emiters with $Q_{\beta\beta} > 2$ MeV

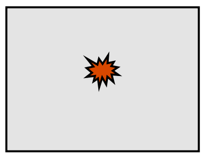
- Natural radioactivity and cosmic rays dominate the source of backgrounds → need to go underground + lots of local shielding
- ^{238}U and ^{232}Th decay chains produce the most troubling gammas (highest energies):
  - ^{214}Bi
  - ^{208}Tl



Borrowed from:
F. T. Avignone, S. R. Elliott and J. Engel,
``Double Beta Decay, Majorana Neutrinos, and Neutrino Mass,''
Rev.\ Mod.\ Phys.\ {\bf 80}, 481 (2008) [arXiv:0708.1033 [nucl-ex]].

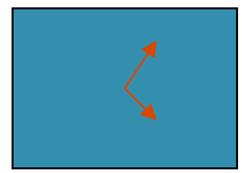
Experimental techniques

Calorimeter / bolometer
Source=detector



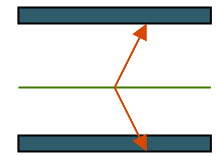
Resolution, efficiency

TPC (Xe), Liquid Sc.



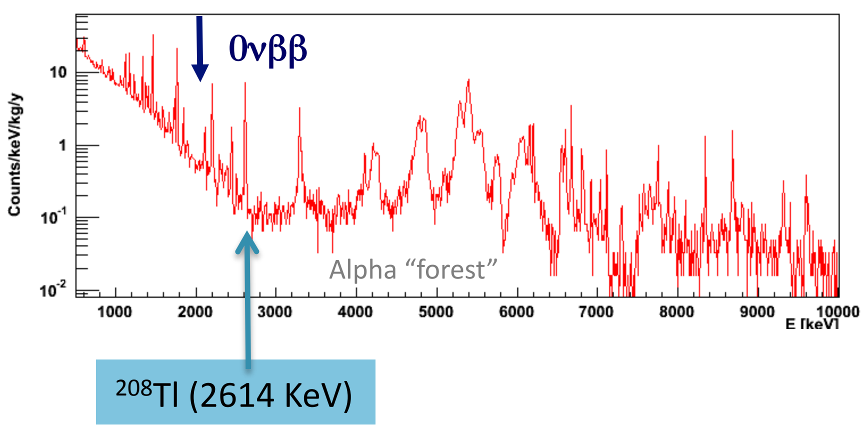
Efficiency, Mass

Tracking and calorimeter
Source ≠ detector



Background, isotope choice

Main features:
- **Exquisite energy resolution**
- **Modest background rejection**



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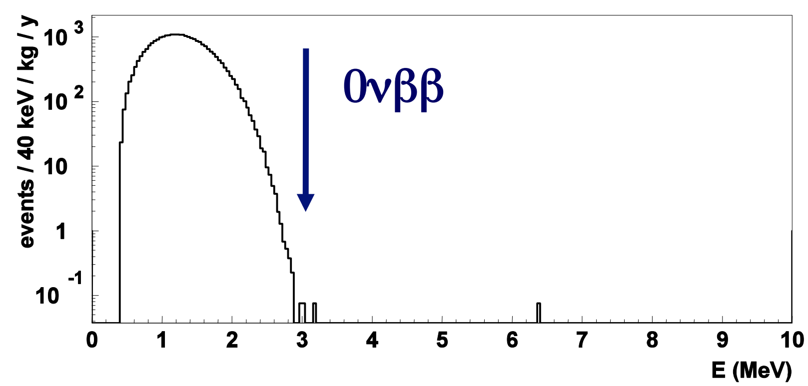
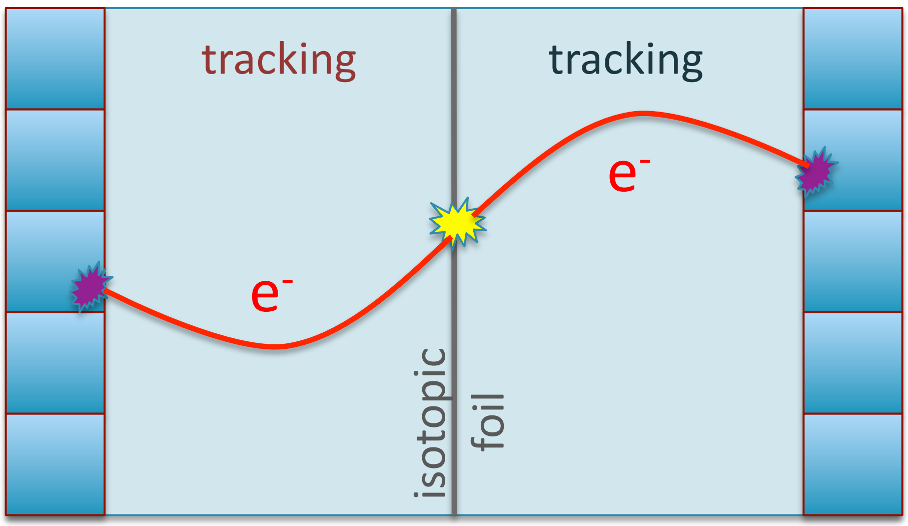


NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

The principle:

Topology and kinematics



Plastic scintillator calorimeter

Plastic scintillator calorimeter

+

Radio-pure materials and a lot of shielding

Source: 10 kg of ββ isotopic foils
area = 20 m^2, thickness ~ 60 mg/cm^2

Tracking detector:
drift wire chamber operating (9 layers) in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

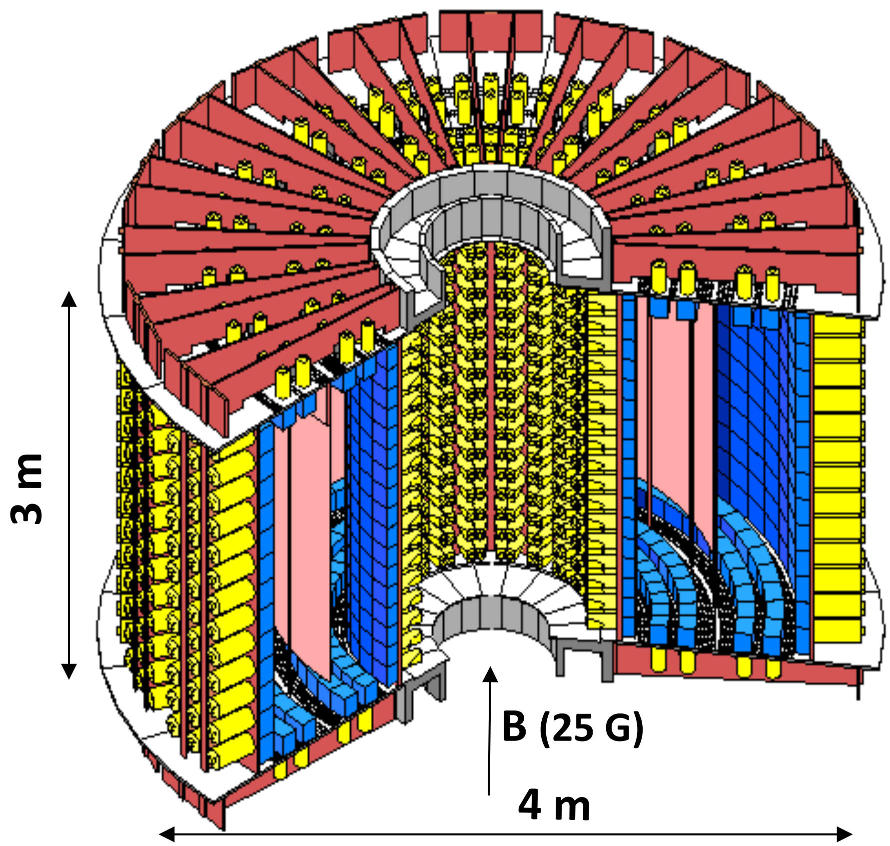
Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: pure iron (d = 18cm)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since March 2004: water + boron)

NEMO-3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

20 sectors



Particle ID: e^-, e^+, γ and α

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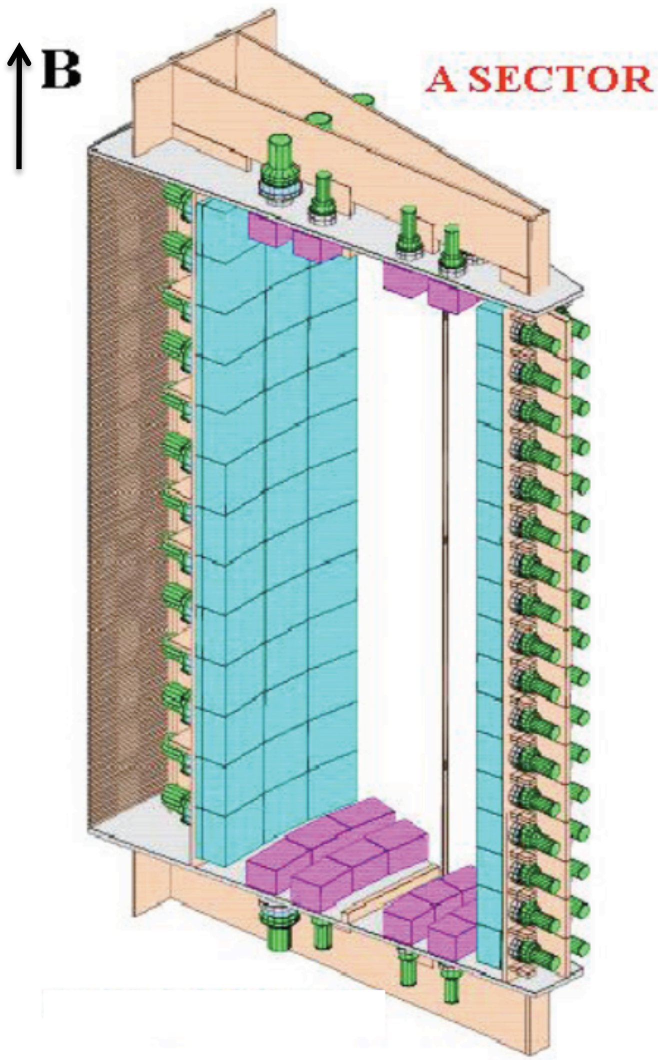

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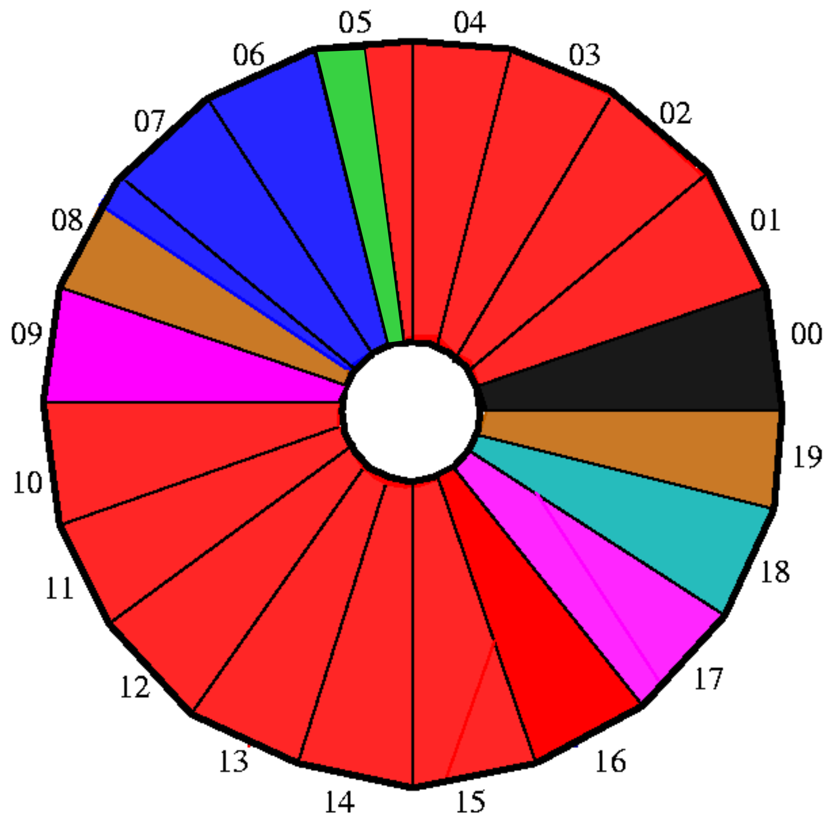
ββ decay isotopes NEMO-3



^{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

(All enriched isotopes produced in Russia)

Cathod rings
Wire chamber

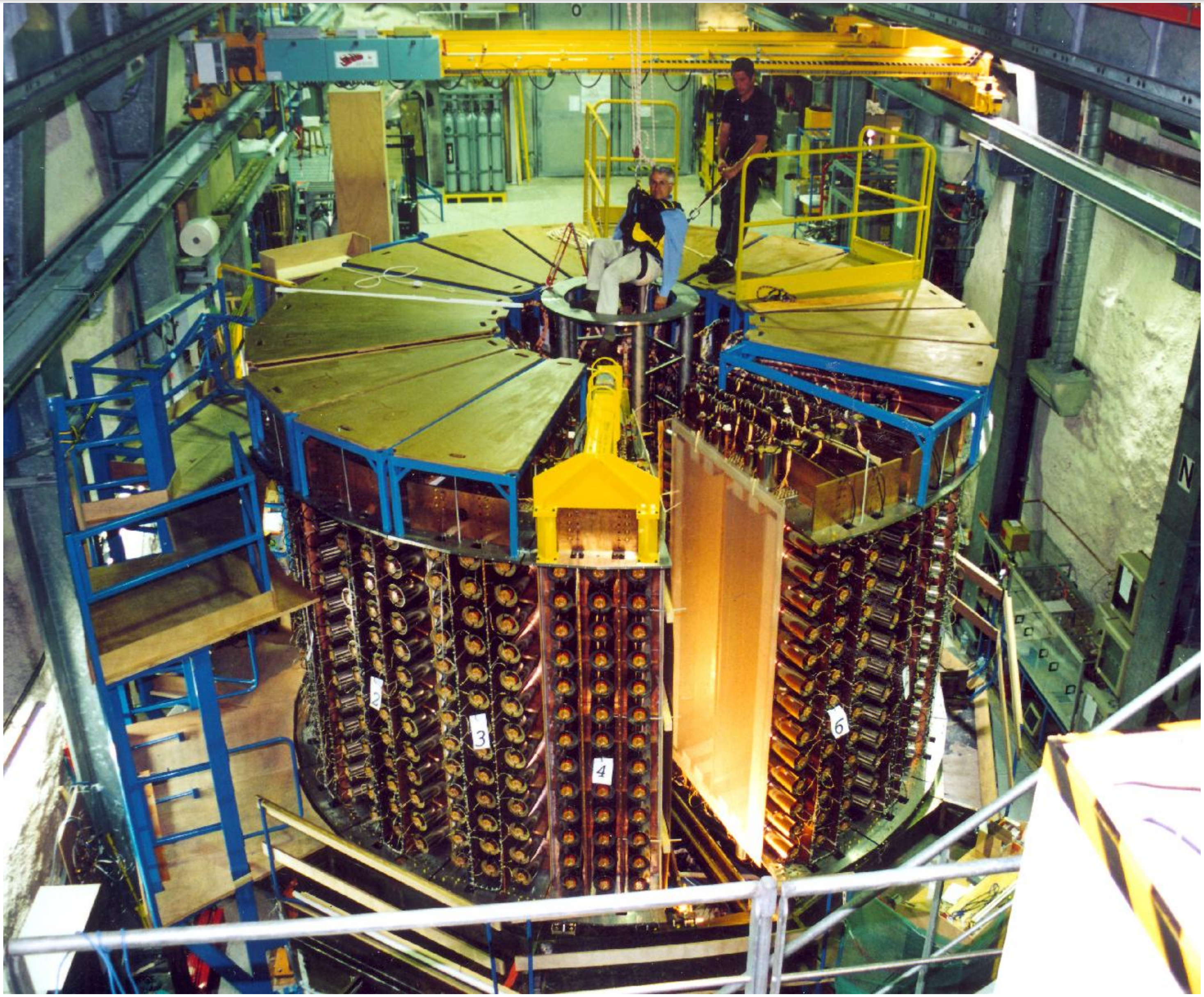
PMTs

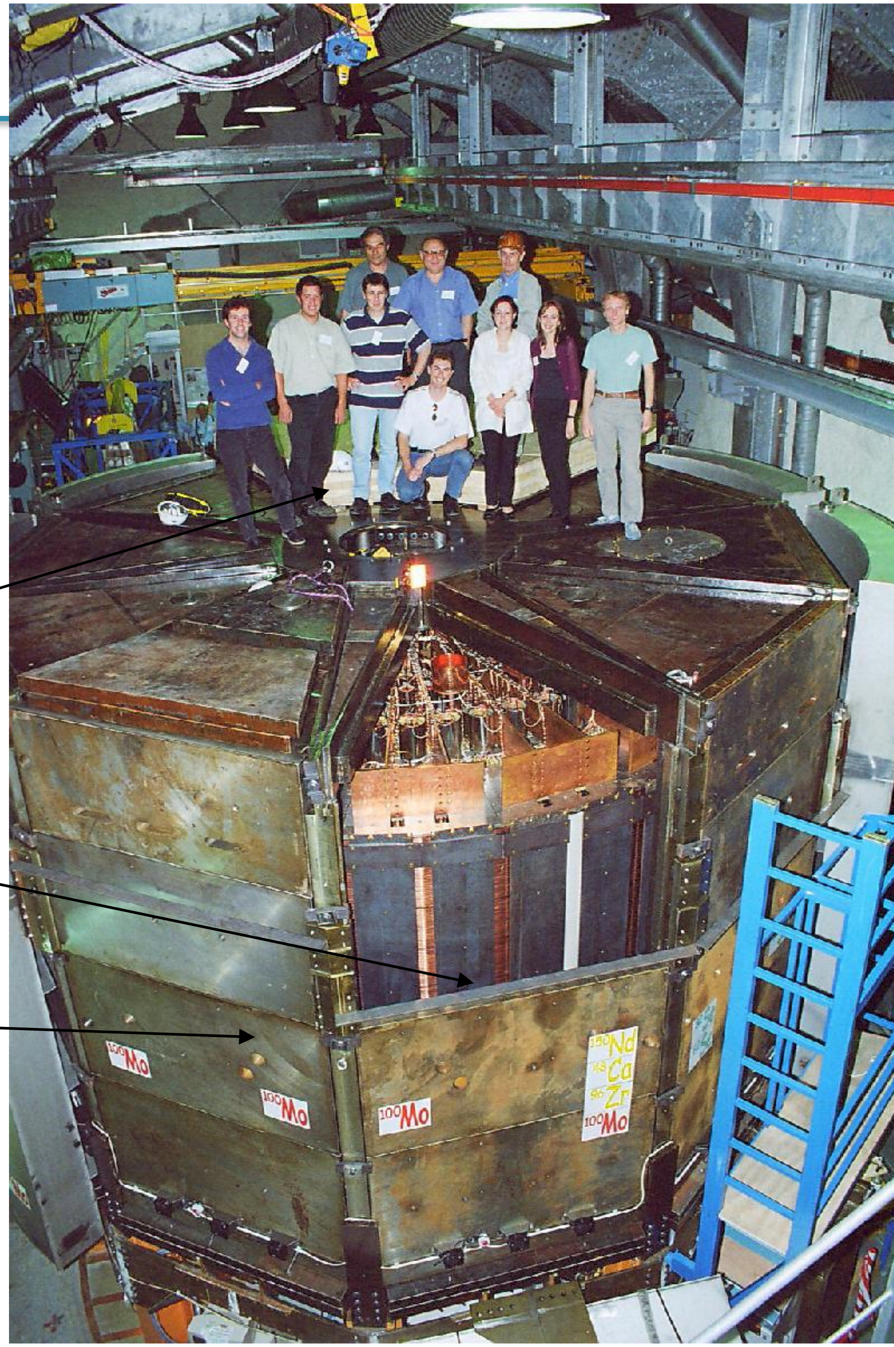
Calibration tube

scintillators

ββ isotope foils

NEMO-3 detector during installation in 2001





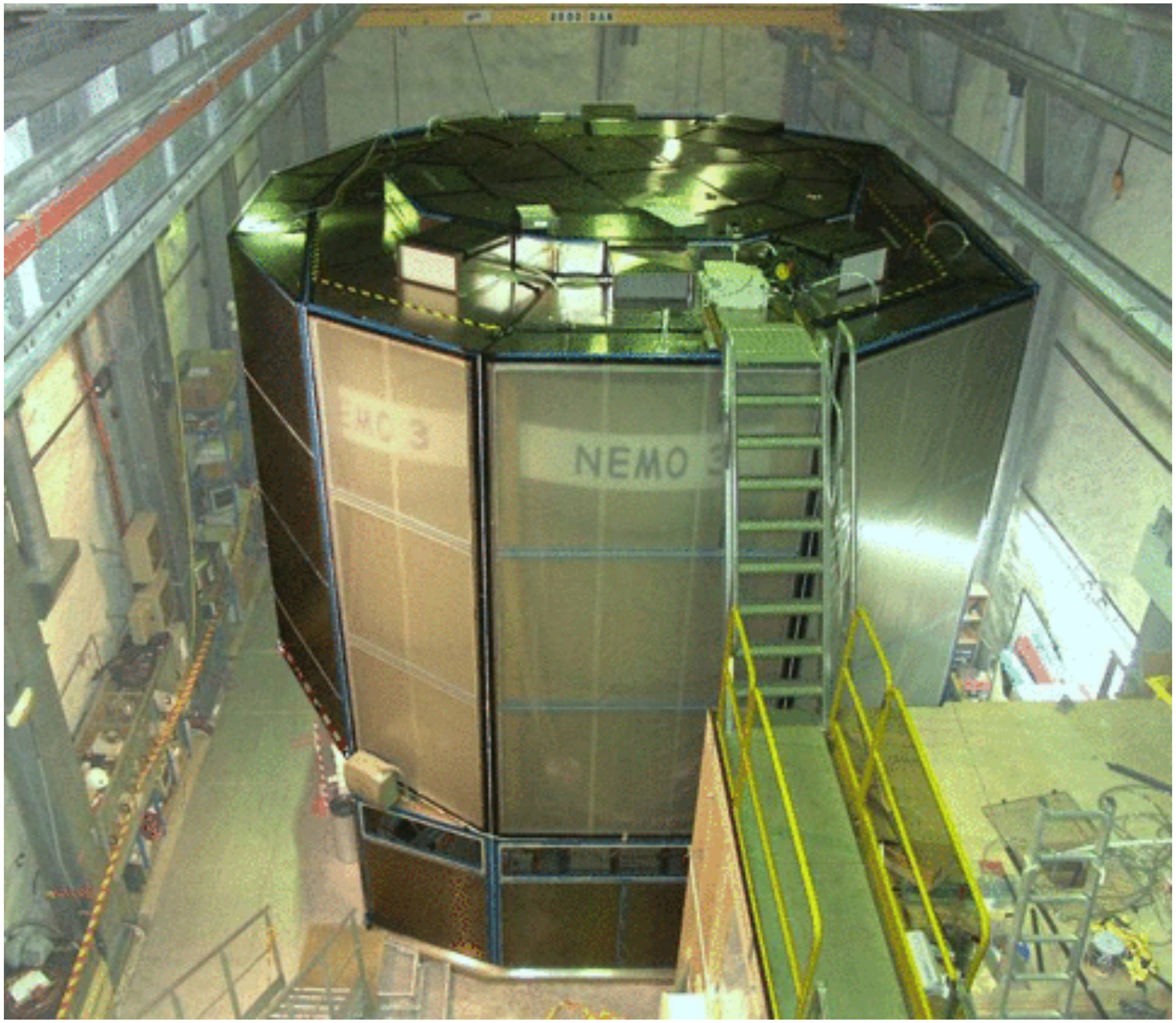
Water tank

wood

coil

Iron shield

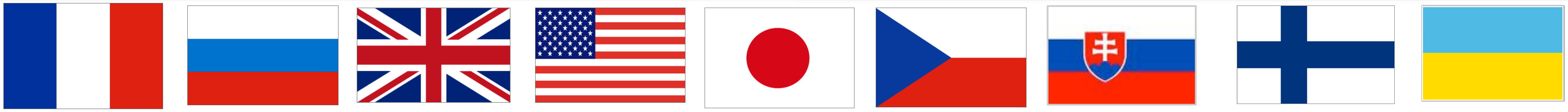
Completed detector

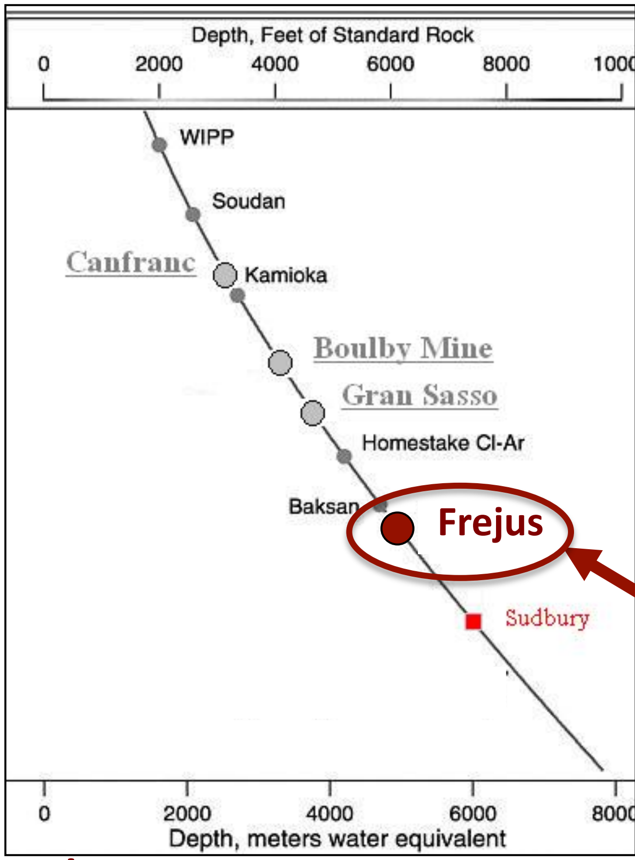


NEMO-3 Opening Day, July 2002

Started taking data 14 February 2003

Laboratoire Souterrain de Modane
(Frejus tunnel)





NEMO Collaboration

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)

LSM Modane, France

(Tunnel Frejus, depth of ~4,800 mwe)

Laboratoire Souterrain de Modane

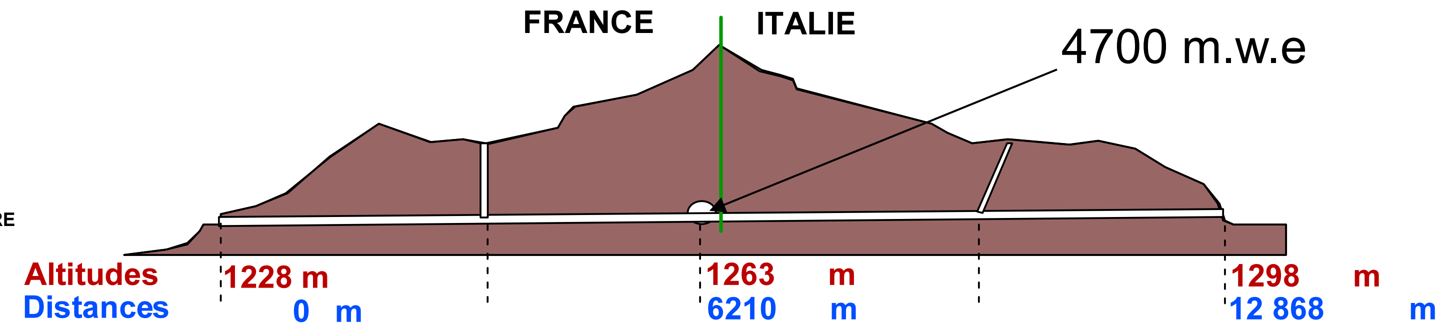
LSM
LABORATOIRE SOUTERRAIN DE MODANE

cea
COMMISSARIAT À L'ÉNERGIE ATOMIQUE

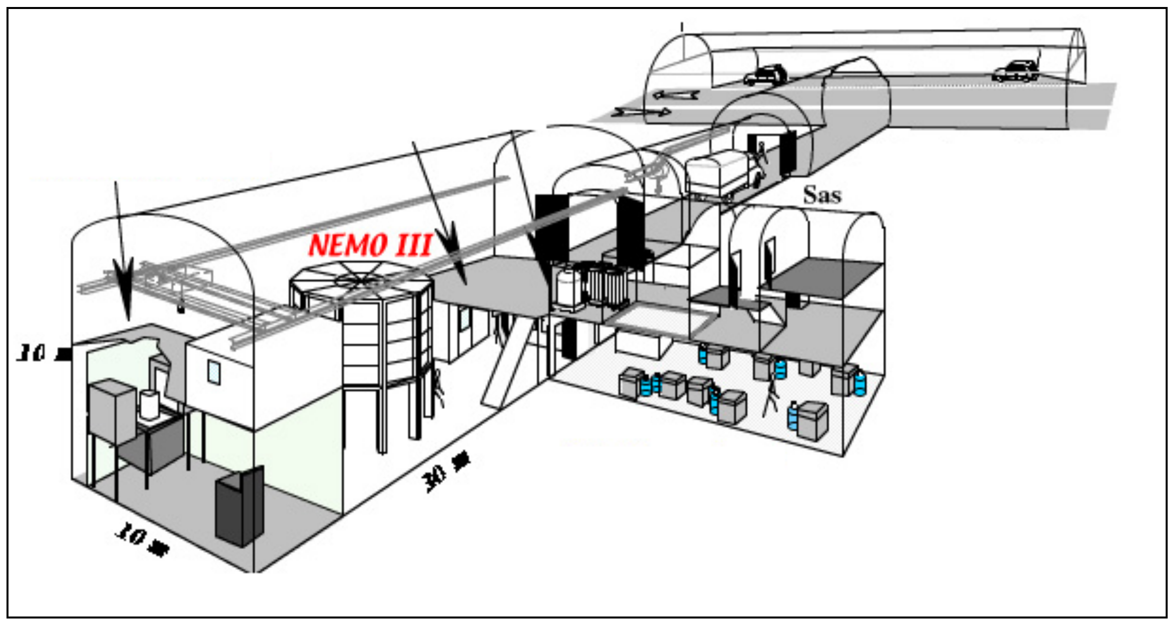
DSM
DIRECTION DES SCIENCES DE LA MATIÈRE

CNRS
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IN2P3
Institut National de Physique Nucléaire et de Physique des Particules

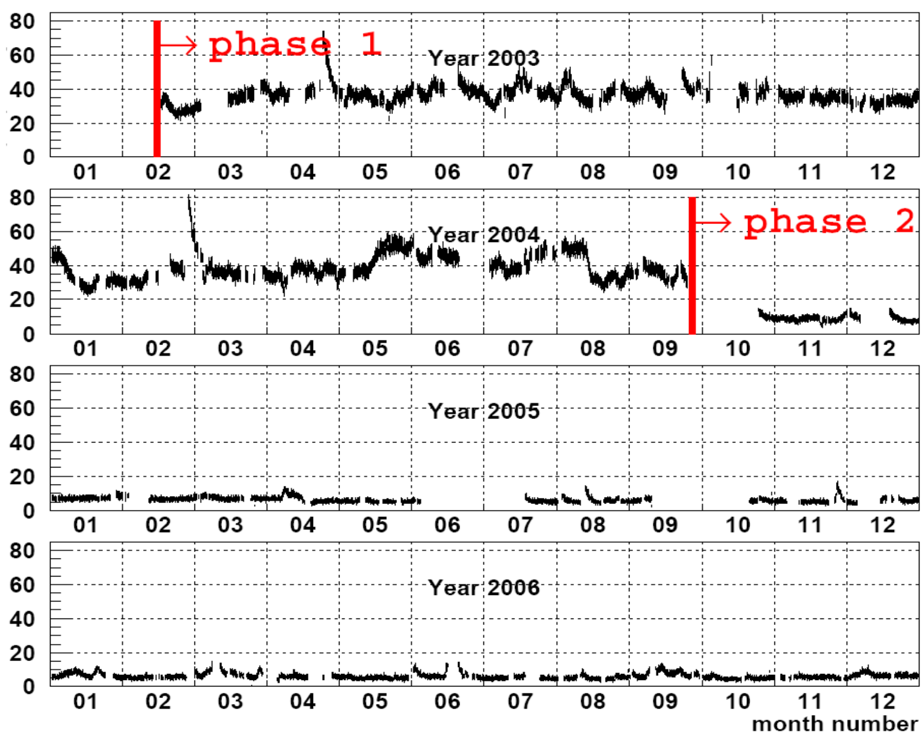


Built for Taup experiment (proton decay) in 1981-1982



Radon Trapping Facility

- Radon trapping facility installed in September 2004.
- The trapping time in activated charcoal longer than ^{222}Rn half-life of 3.8 days.
- Radon level reduced by almost factor of 10 in the detector by installing radon trapping facility

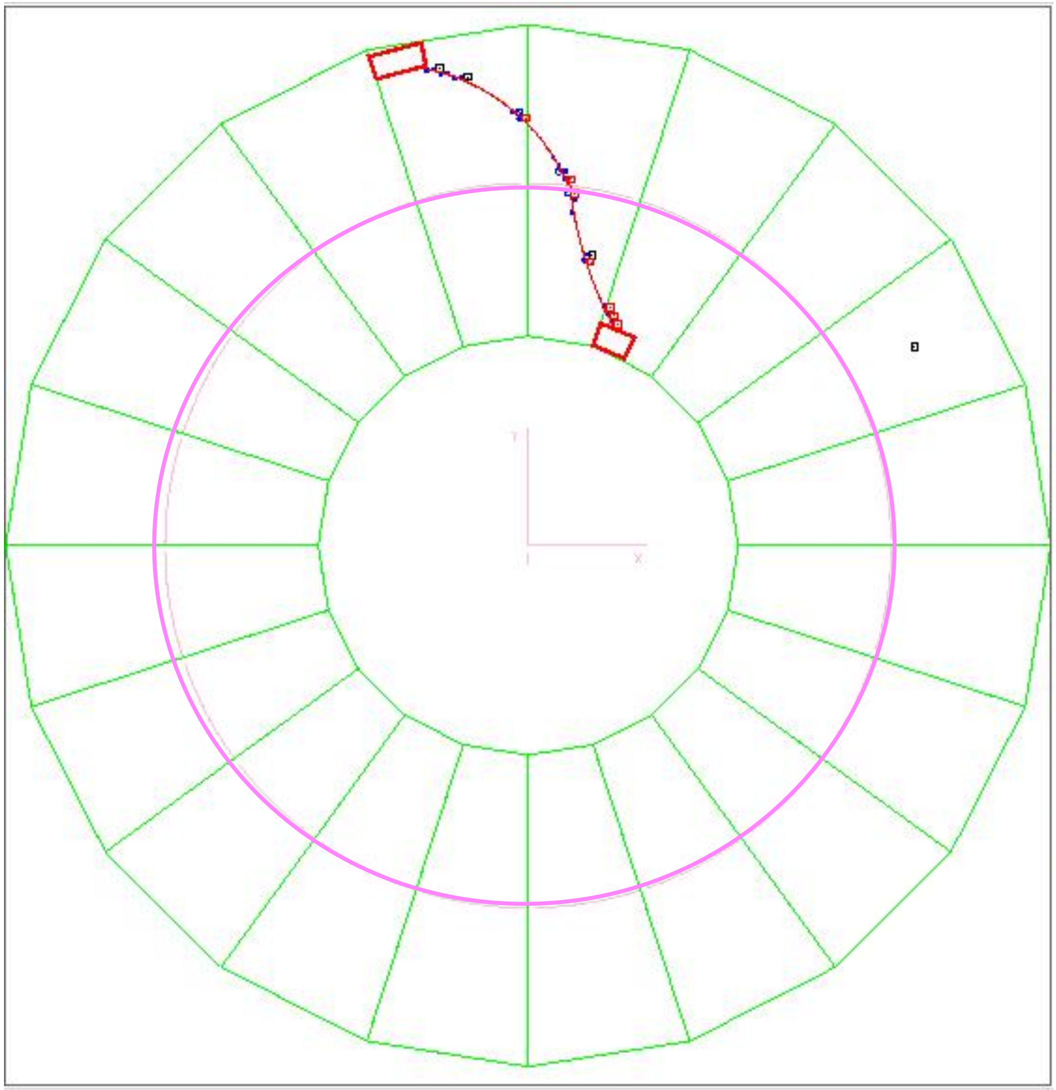


Adsorption unit @-50°C

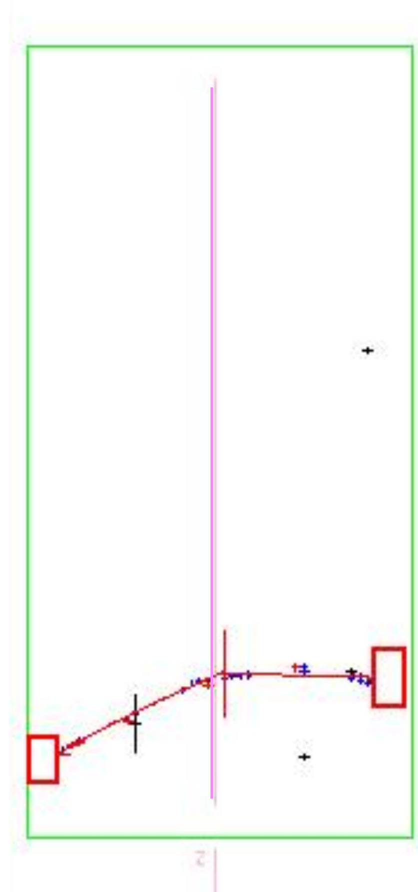
Input: A(^{222}Rn) 15 Bq/m^3

Output: A(^{222}Rn) < 15 mBq/m^3 !!
reduction factor of 1000

$\beta\beta$ events selection in NEMO-3



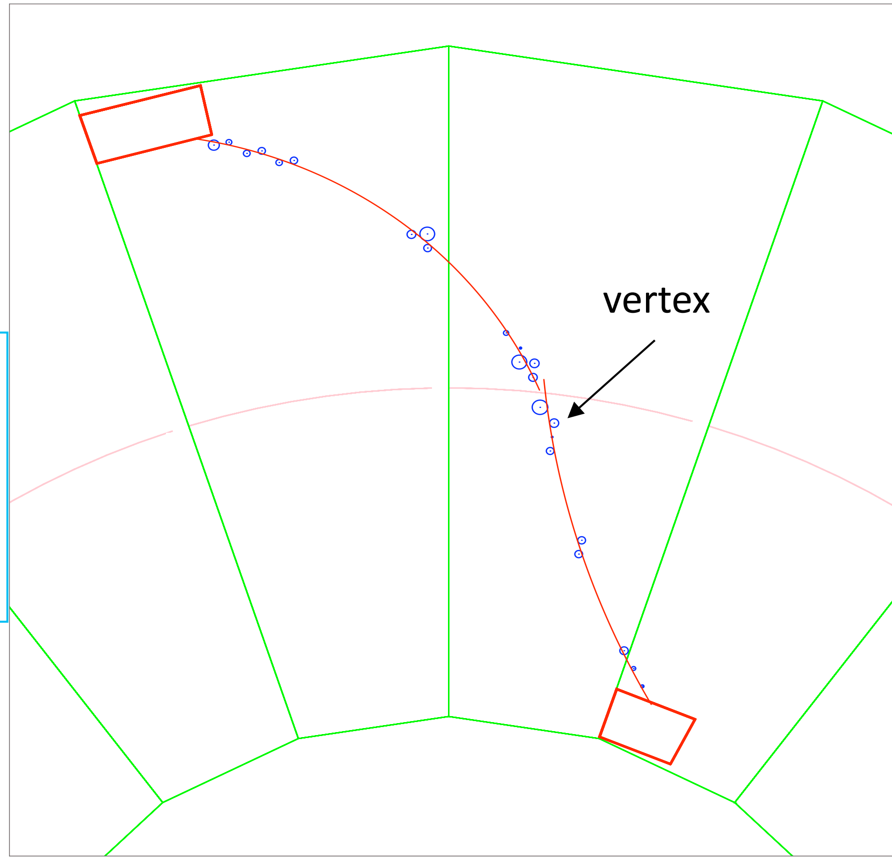
Top view



Side view

Typical $\beta\beta2\nu$ event observed from ^{100}Mo

Typical $\beta\beta2\nu$ event observed in ^{100}Mo



Run Number: 2040
Event Number: 9732
Date: 2003-03-20

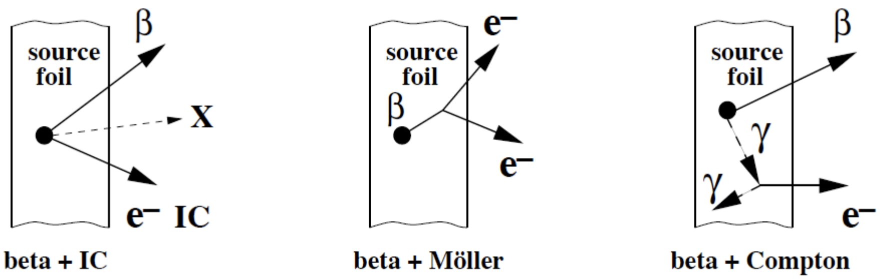
Deposited energy:
E_1+E_2= 2088 keV
Internal hypothesis:
$(\Delta t)_{mes} - (\Delta t)_{theo}$ = 0.22 ns
Common vertex:
$(\Delta vertex)_{\perp}$ = 2.1 mm

Trigger: **at least 1 PMT > 150 keV**
≥3 Geiger hits (2 neighbouring layers+1)
Trigger rate = 7 Hz
25 $\beta\beta$ events per hour

NEMO-3 backgrounds

1. Internal background (in addition to a potential $2\nu\beta\beta$ tail)

   (due to ^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) radio-impurities of the isotopic source foil)

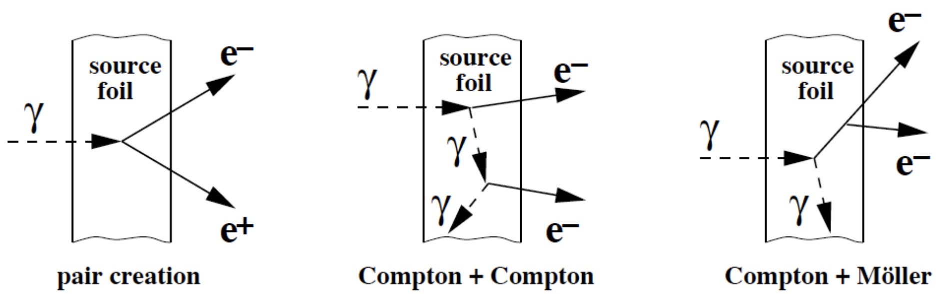


(dominant)

● = radioisotope   β = electron from beta decay   IC = internal conversion

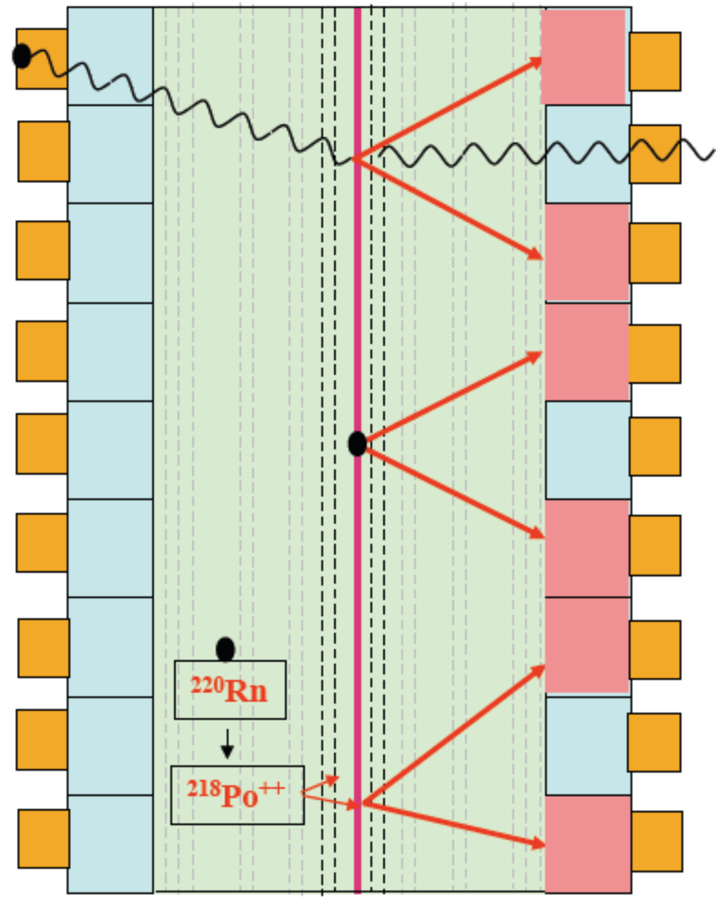
2. External background (if the γ is not detected)

   (due to radio-impurities of the detector)



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

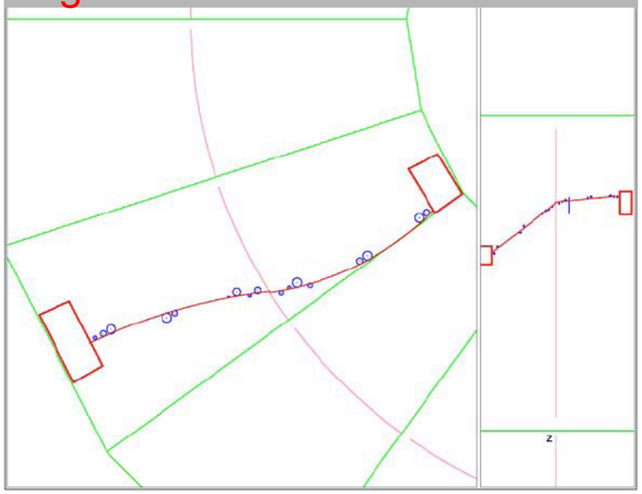
   - deposits on the wire near the $\beta\beta$ foil
   - deposits on the surface of the $\beta\beta$ foil



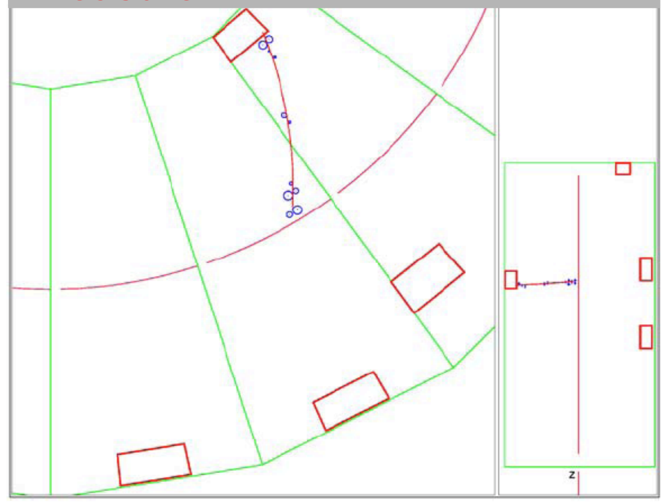
Each bkg is measured using the NEMO-3 data

Signal and background signatures

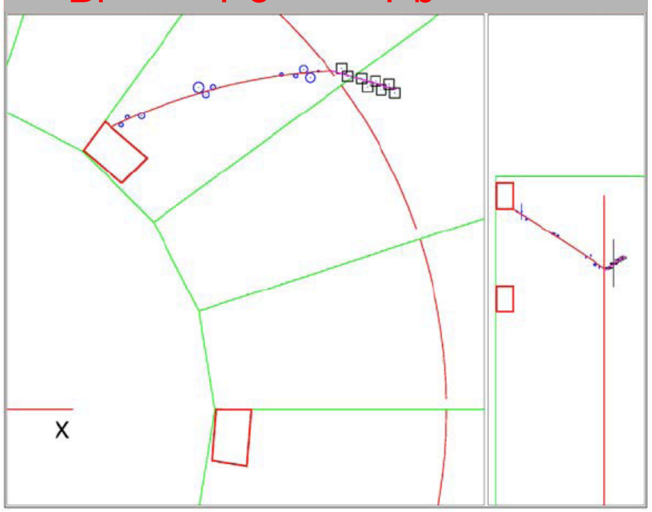
2e⁻ event
signal



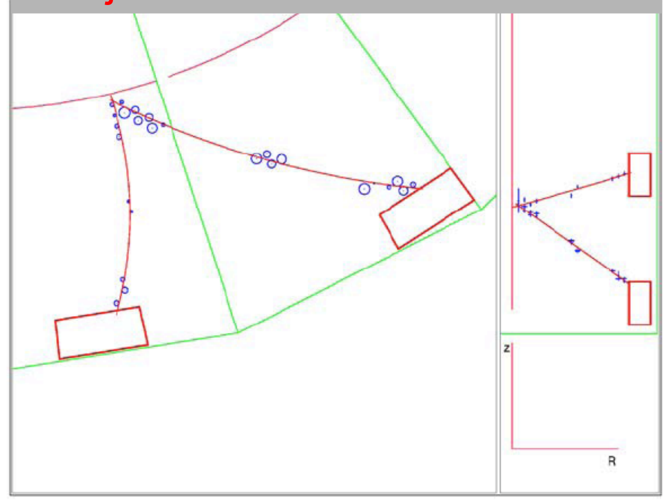
e⁻ γγγ event
measure ^{208}Tl



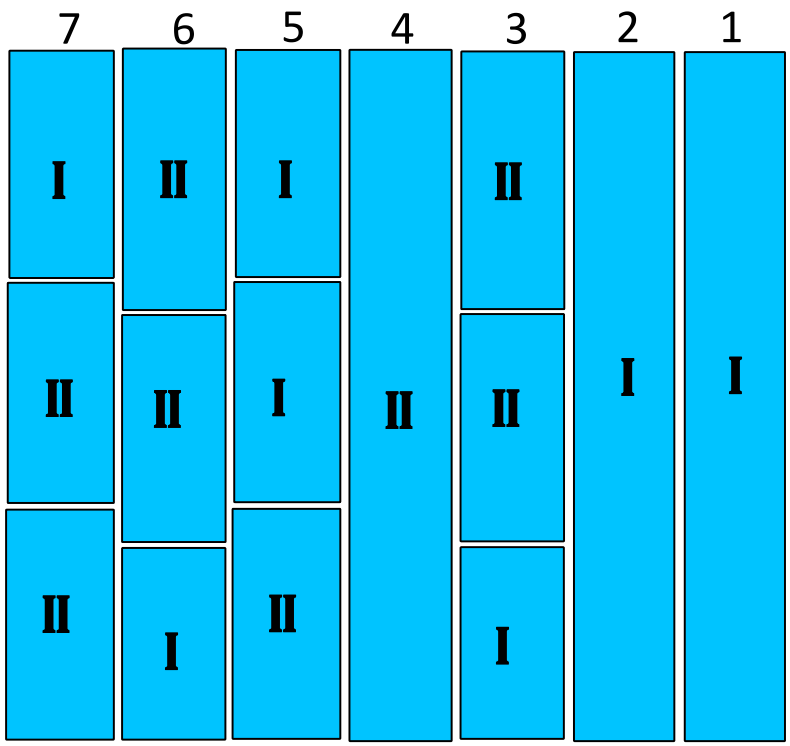
β - α (delay track) event
^{214}Bi → ^{214}Po → ^{210}Pb



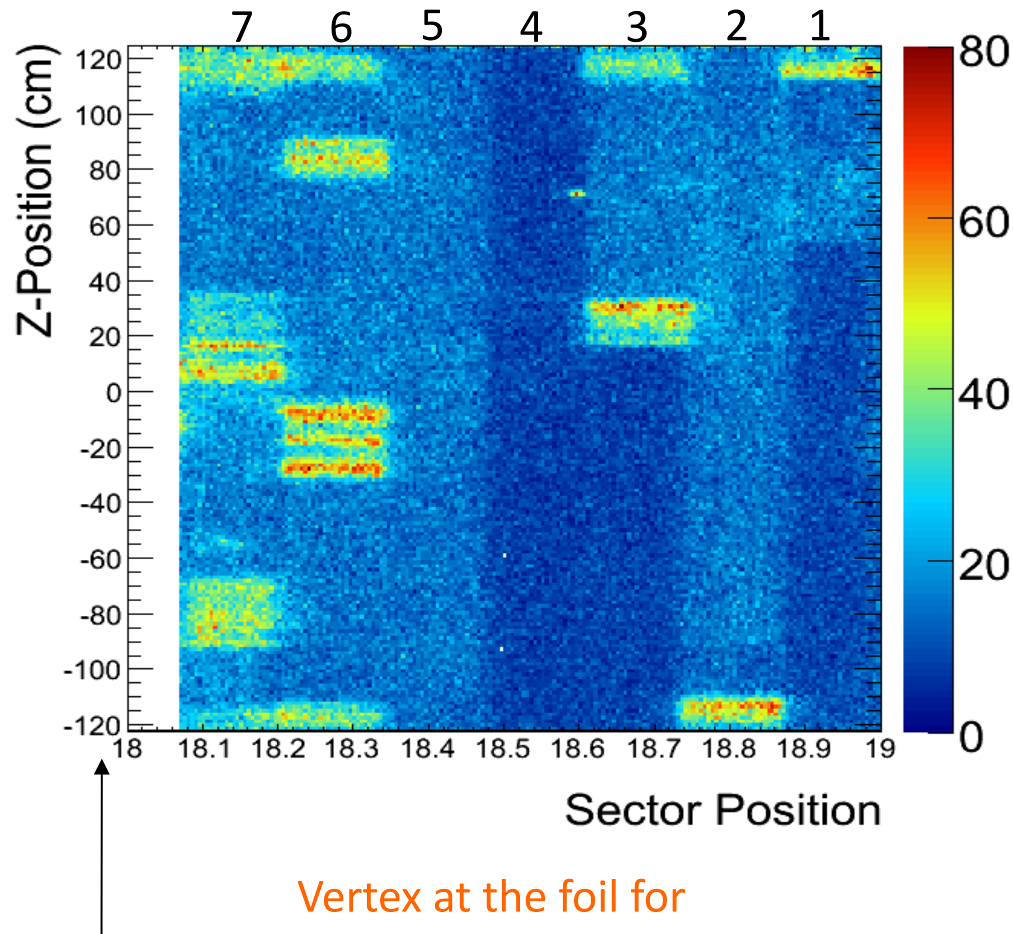
e⁺ – e⁻ pair event
B rejection



Cadmium Foil
Activity and Hot Spots



Production foil parts

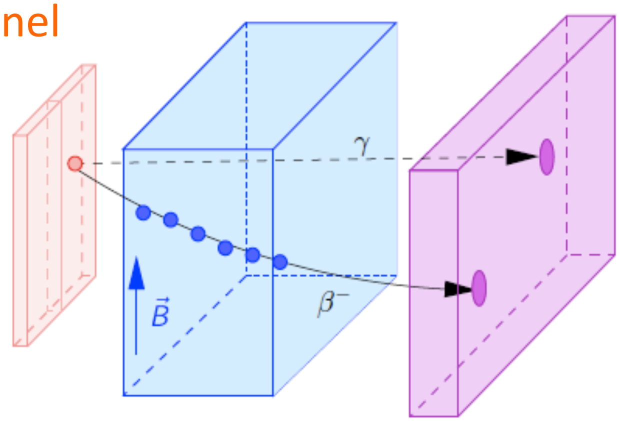


calibration tube

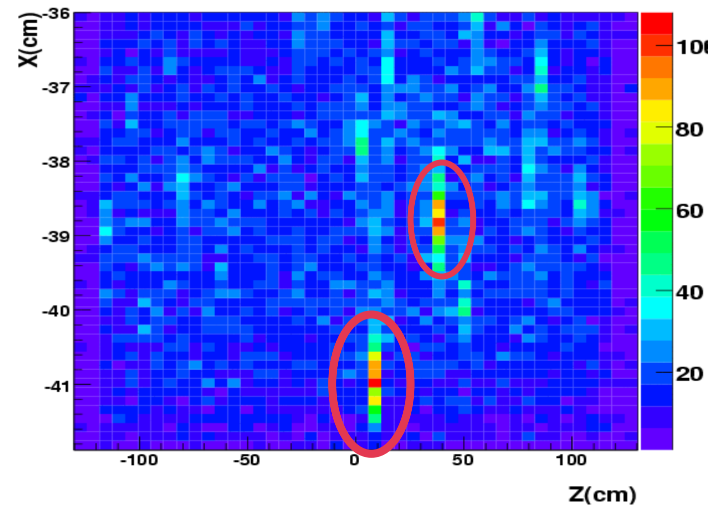
Vertex at the foil for
1 electron data

Background: control channels

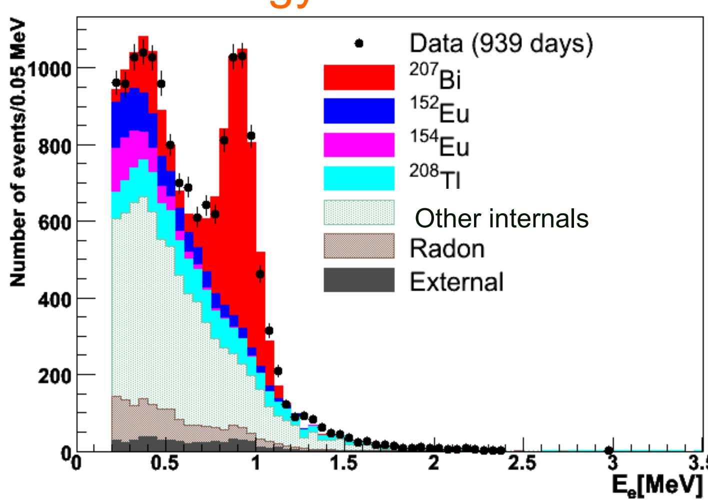
Example:
eγ control channel



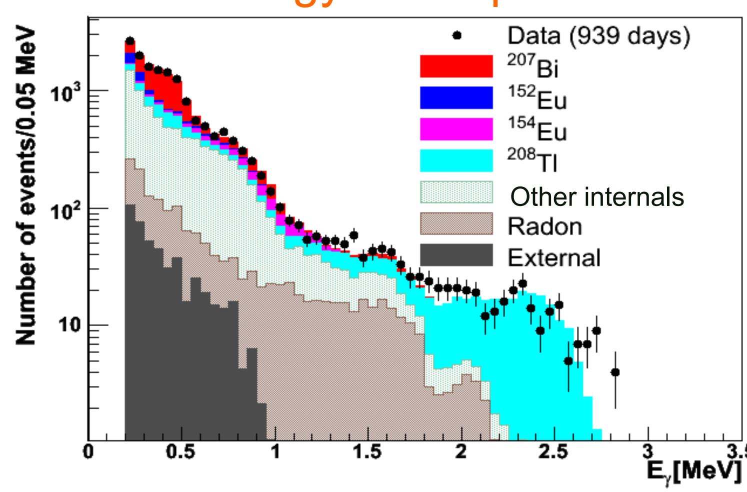
150-Nd foil



Energy of the electron

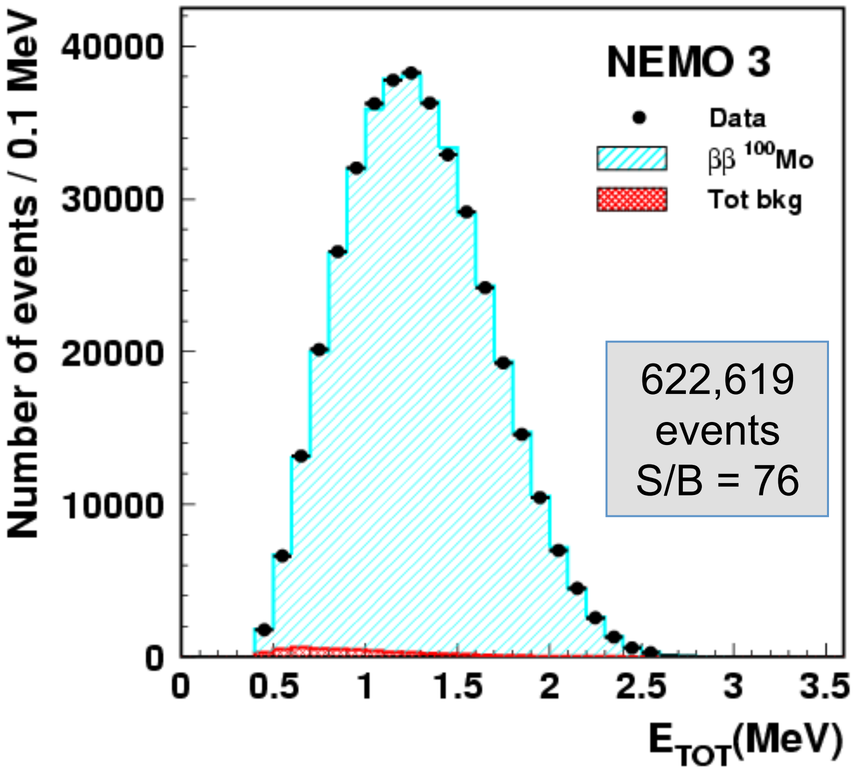


Energy of the photon



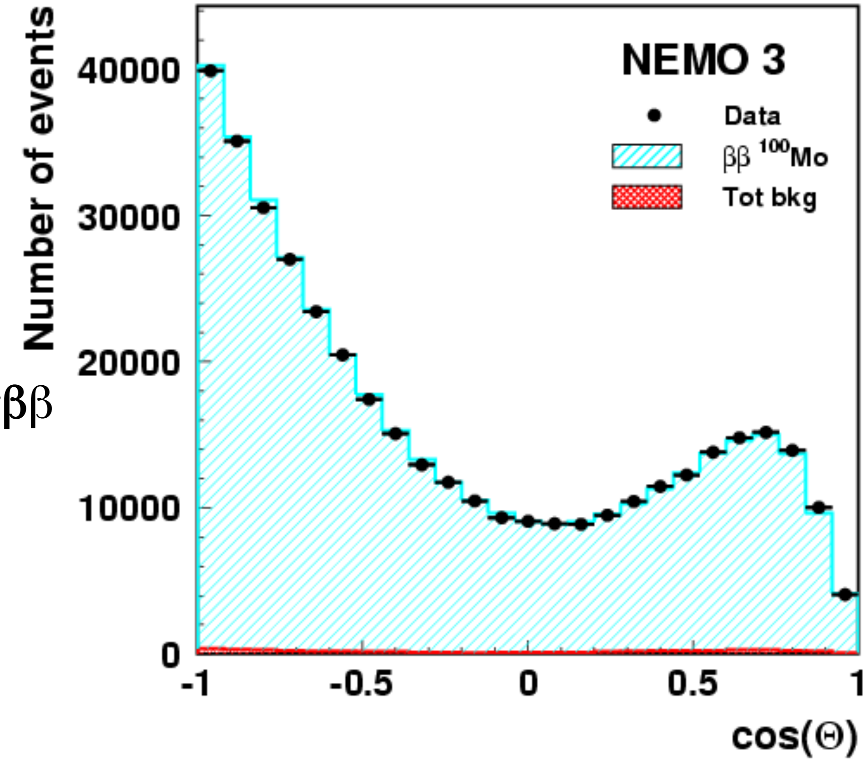
^{100}Mo 2νββ results (Phase 2, low Rn)

Sum energy spectrum



0νββ

Angular distribution

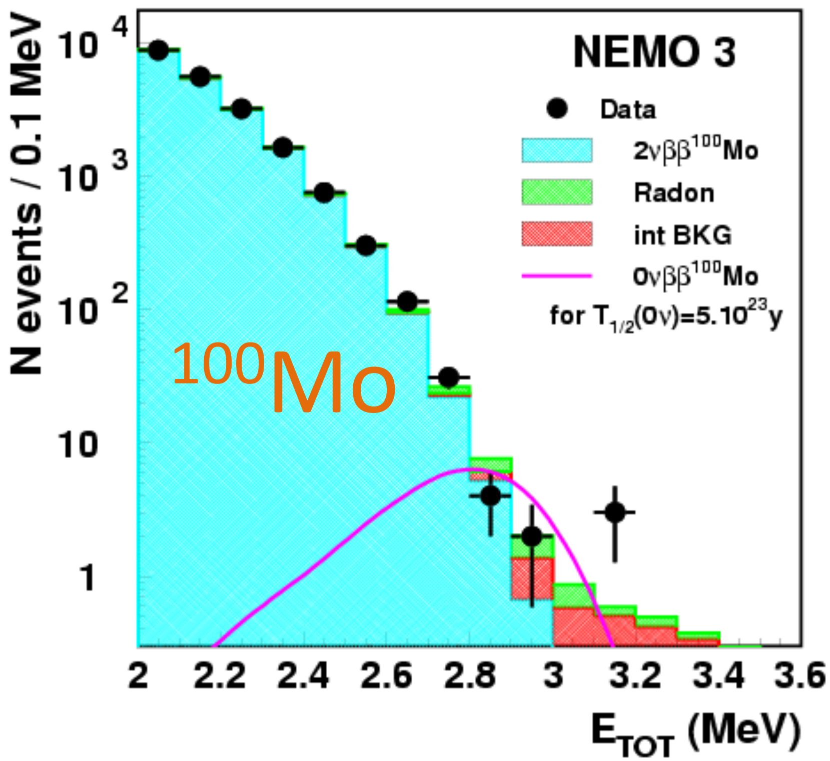


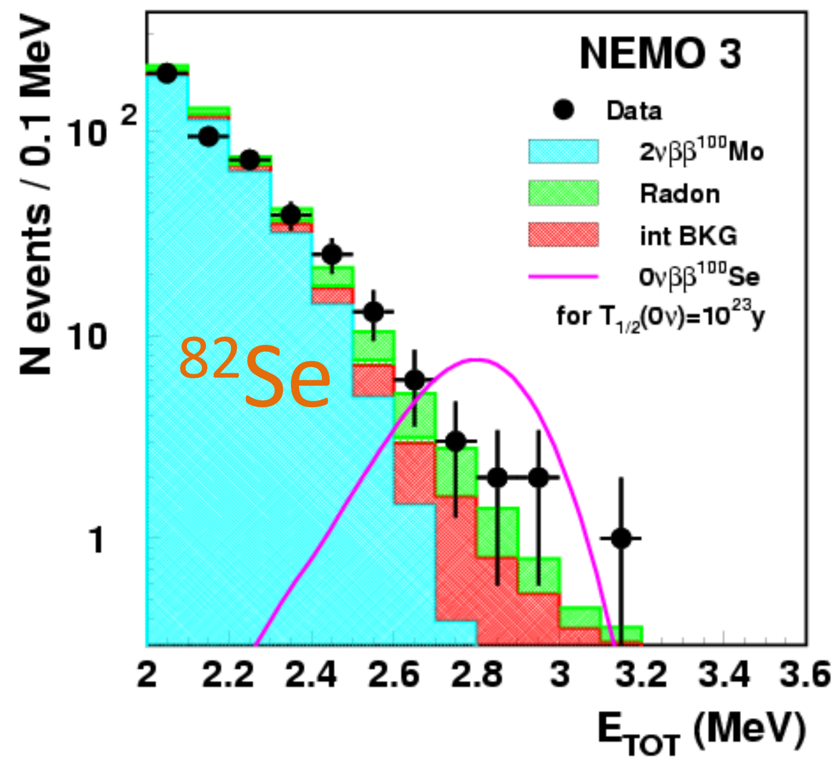
$T_{1/2}(2\nu\beta\beta) = (\,7.17 \pm 0.01_{(stat)} \pm 0.54_{(syst)}) \times 10^{18}$ years

Phase 2 exposure: 3.49 y*6.914 kg = 24.13 kg*y

$0\nu\beta\beta$: ^{100}Mo and ^{82}Se (Phase 1+2)

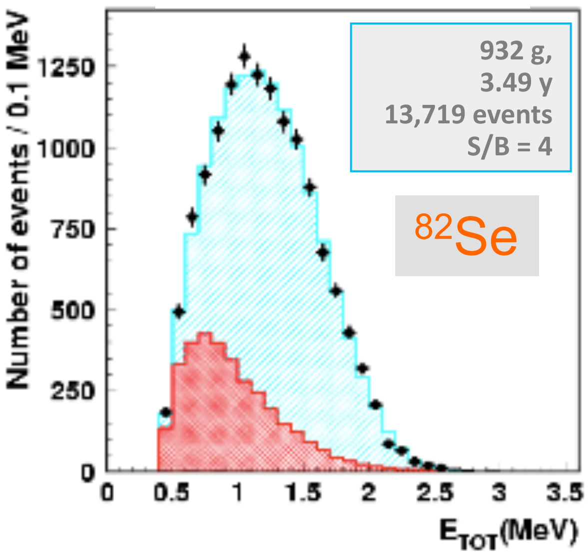
End-point energy spectrum



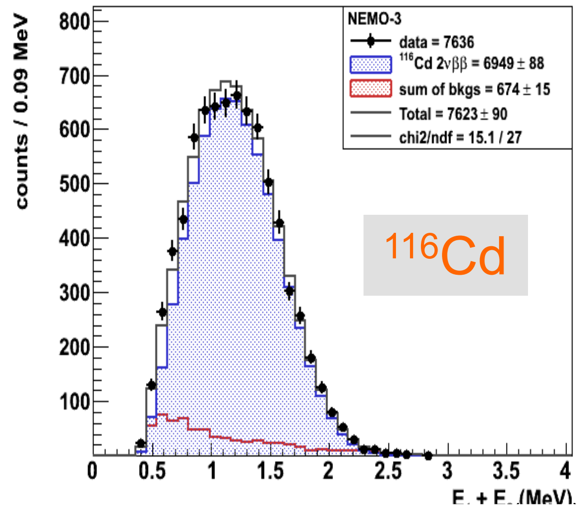


$T_{1/2}$ ($0\nu\beta\beta$) > 1.0×10^{24} y @ 90% C.L.	$T_{1/2}$ ($0\nu\beta\beta$) > 3.2×10^{23} y @ 90% C.L.
$\langle m_\nu \rangle$ < 0.47 – 0.96 eV	$\langle m_\nu \rangle$ < 0.9 – 2.5 eV
Phase 1+2 exposure: 4.51y*6.914 kg = **31.18 kg*y**	Phase 1+2 exposure: 4.51y*0.932 kg = **4.20 kg*y**

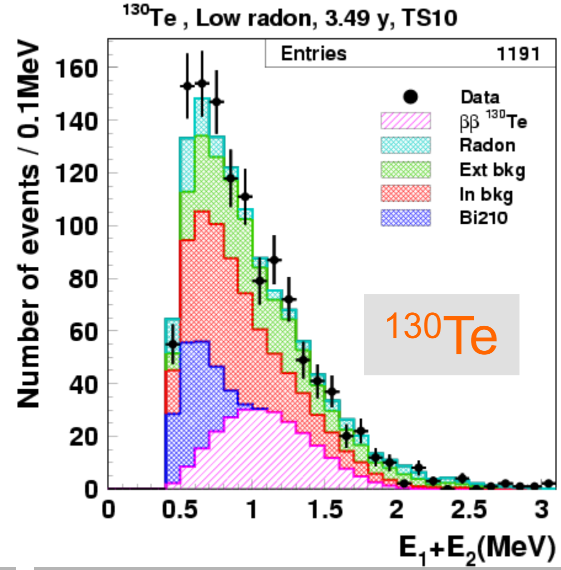
Results of $2\nu\beta\beta$ measurements
Summer 2010



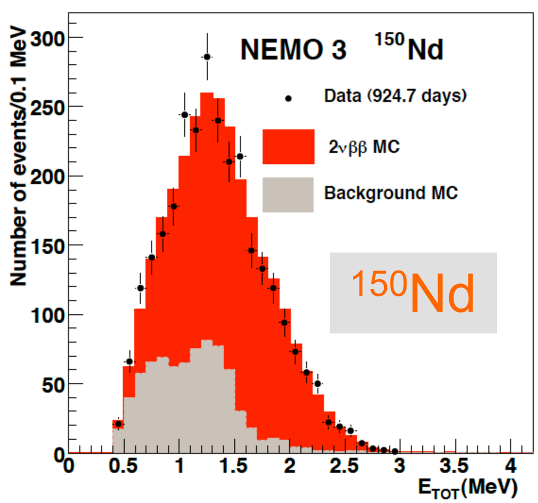
[$9.6 \pm 0.1_{(stat)} \pm 1.0_{(syst)}$] x 10^{19} y



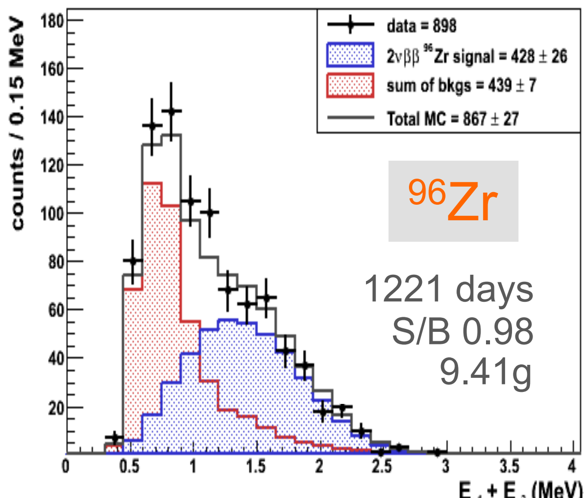
[$2.88 \pm 0.04_{(stat)} \pm 0.16_{(syst)}$] x 10^{19} y



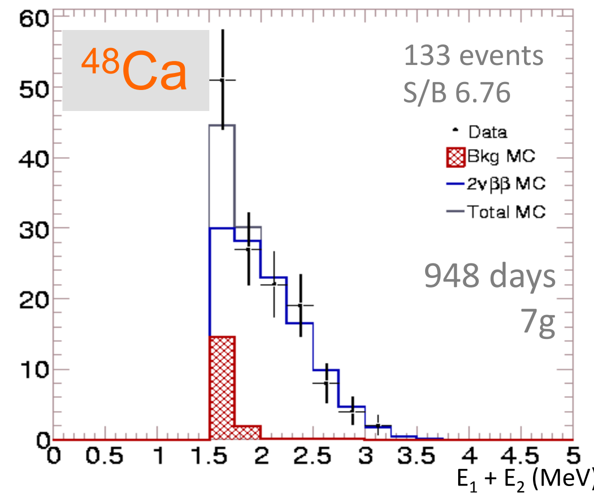
[$7.0^{+1.0}_{-0.8}$ (stat) $^{+1.1}_{-0.9}$ (syst)] x 10^{20} y



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

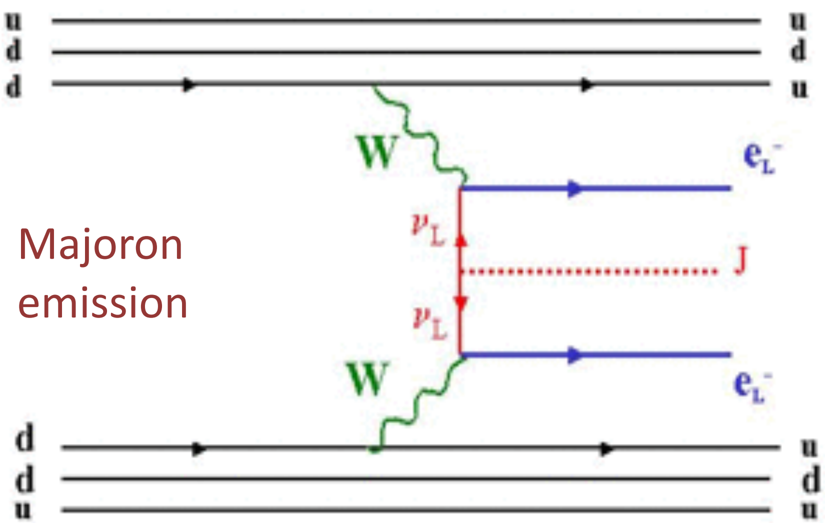


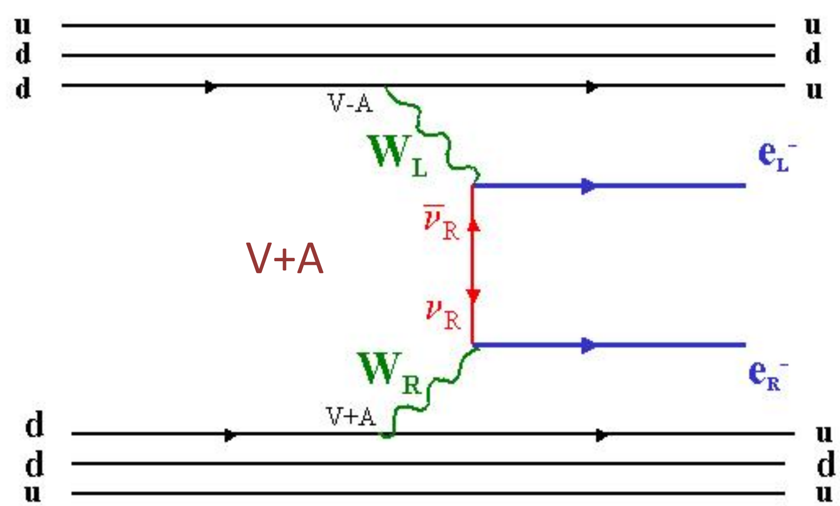
[$2.35 \pm 0.14_{(stat)} \pm 0.16_{(syst)}$] x 10^{19} y

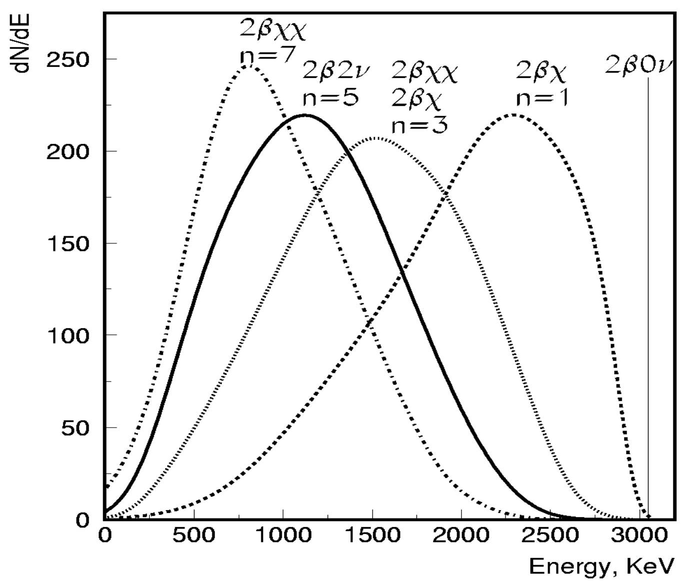


[$4.4^{+0.5}_{-0.4}$ (stat) ± 0.4 (syst)] x 10^{19} y

Other physics







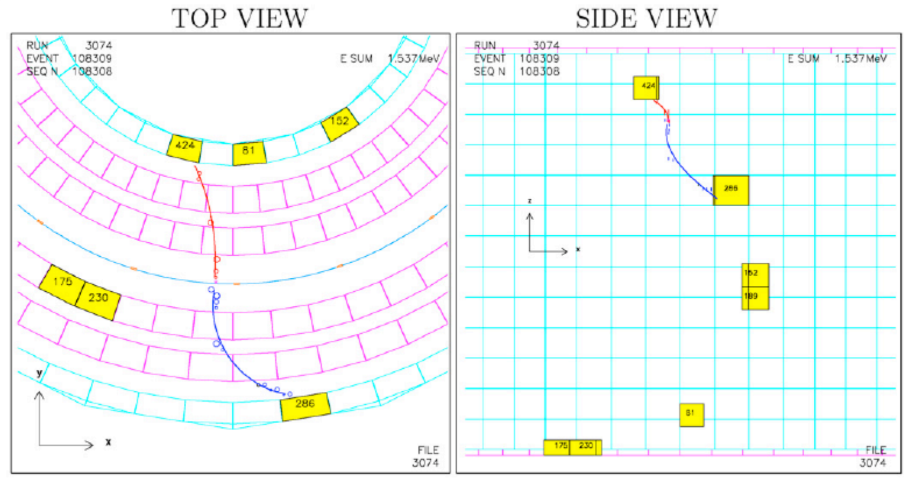
	V+A *	Majoron(s) emission (n=spectral index)**			
	$T_{1/2}(0\nu\beta\beta)$ [years]	n=1	n=2	n=3	n=7
^{100}Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $g_{ee}<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1\cdot10^{22}$	$>7\cdot10^{19}$
^{82}Se	$>2.4\cdot10^{23}$ $\lambda<2.\cdot10^{-6}$	$>1.5\cdot10^{22}$ $g_{ee}<(0.7\text{-}1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{22}$	$>5\cdot10^{20}$

* Phase I+Phase II data

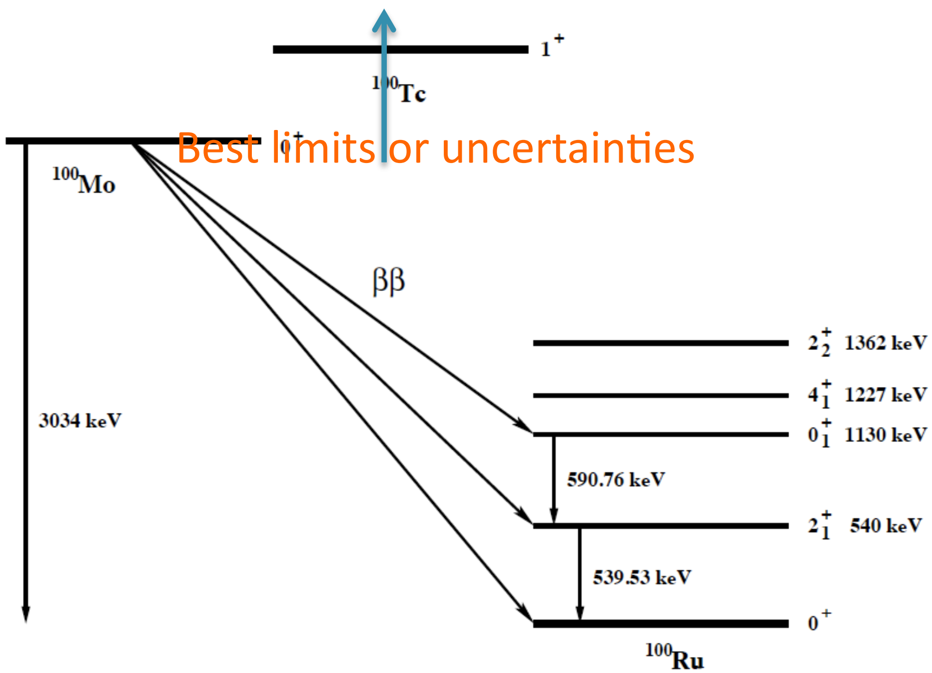
** Phase I data, *R. Arnold et al. Nucl. Phys. A765 (2006) 483*

NEMO-3: ββ of ^{100}Mo to excited states

Transition	$T_{1/2}$ (y) (this work)	Theory
0νββ $0^+ \to 2^+_1$	> 1.6 * 10^{23}	6.8 * 10^{30} $<m_\nu>$ 2.1 * 10^{27} $< \lambda >$
2νββ $0^+ \to 2^+_1$	> 1.1 * 10^{21}	2.1 * 10^{21} - 5.5* 10^{25}

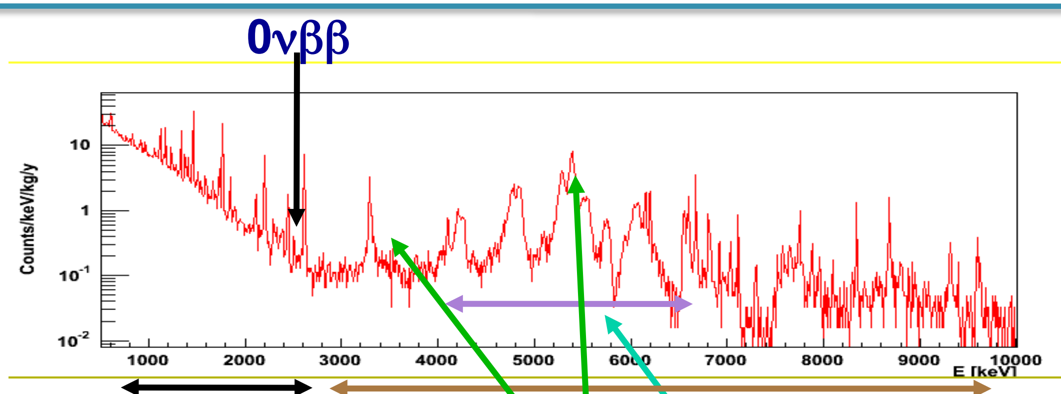


Best limits or uncertainties



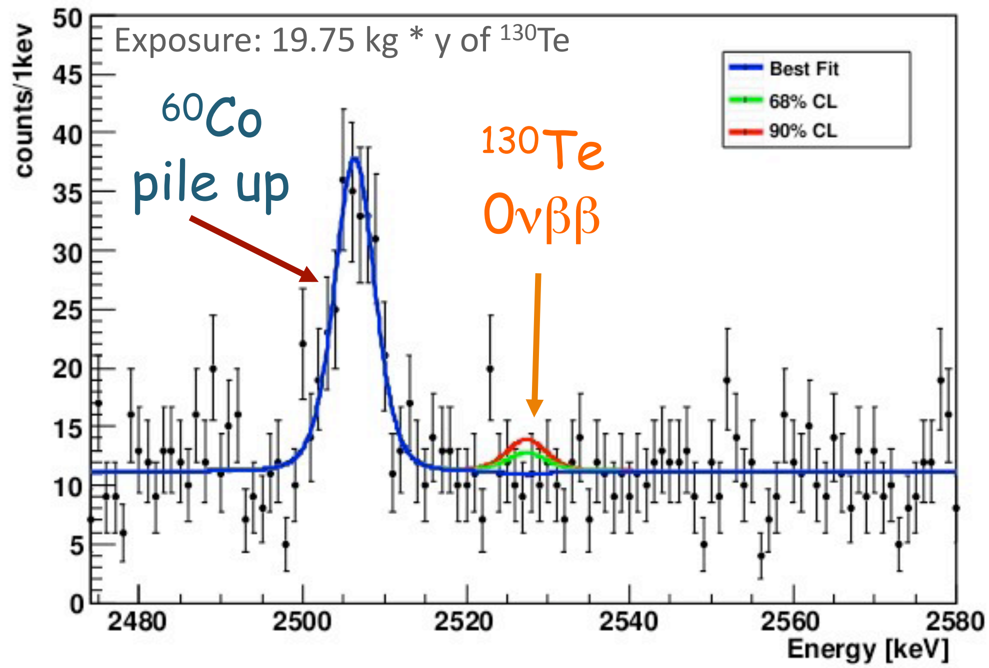
NEMO Collaboration / Nuclear Physics A 781 (2007) 209–226

CUORICINO results



Gamma region, dominated by gamma and beta events,

Alpha region, dominated by alpha peaks (internal or surface contaminations)



$T_{1/2}$ > 2.8 x 10^{24} yr

$\langle m_\nu \rangle < 0.3 - 0.7$ eV

Cannot fully refute the Klapdor-Kleingrothaus *et al.* ``claim''

From M. Pavan, Neutrino 2010 (Athens)

Summary and outlook

- Very active experimental program worldwide

- NEMO-3 produces unique results
  - ✓ many best results in $0\nu\beta\beta$ and $2\nu\beta\beta$

    ^{100}Mo (2009): $T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{24}$ y (90% CL) $\langle m_\nu \rangle < (450 - 930)$ meV

    ^{82}Se (2009): $T_{1/2}^{0\nu\beta\beta} > 3.6 \times 10^{23}$ y (90% CL) $\langle m_\nu \rangle < (900 - 2300)$ meV

  - ✓ results for 5 other isotopes: ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{130}Te, ^{150}Nd
  - ✓ results on transitions to excited states, V+A, Majorons, SSD vs HSD, …

- Full data set 2003-2011 currently being analyzed

- Next: SuperNEMO (first module in 2013)
  - ✓ sensitivity $T_{1/2}(0\nu) = (1 - 2) \times 10^{26}$ y (500 kg*y exposure)

    $\langle m_\nu \rangle \leq$ 40 – 140 meV (NME uncertainty QRPA + SM)