Searching for $0\nu\beta\beta$ decay with the SuperNEMO demonstrator
A sensitivity study

Cloé Girard-Carillo

Laboratoire de l'Accélérateur Linéaire

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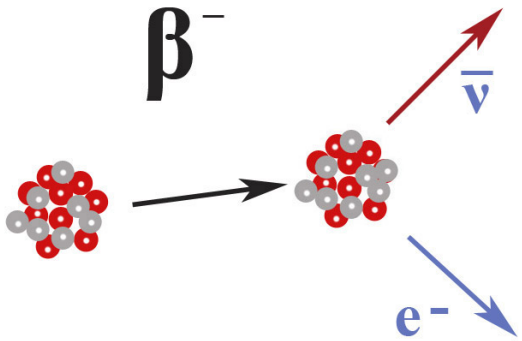
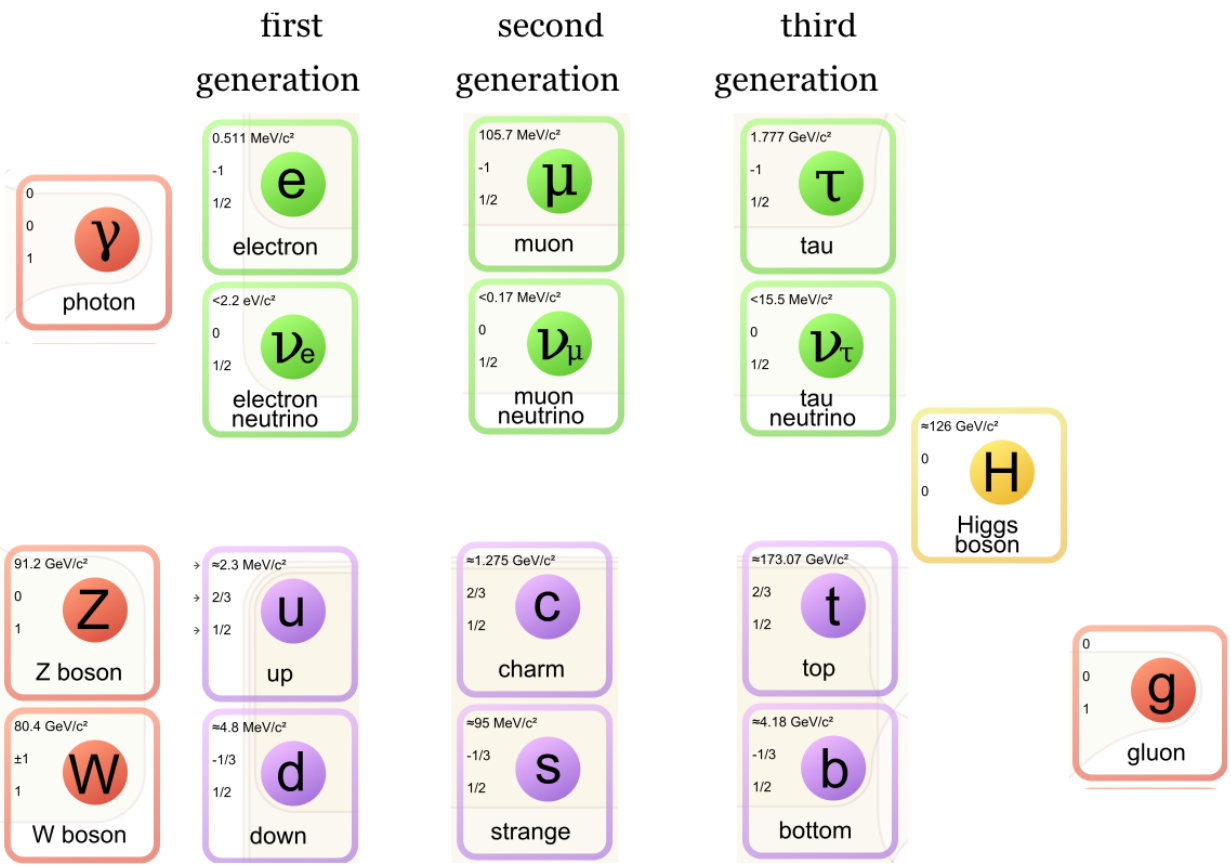


"I have done a terrible thing, I have postulated a particle that cannot be detected."
Pauli, 1930.

- H.Becquerel 1896 : Discovery of radioactivity
  Only electron observed $\rightarrow$ non conservation of total energy
- W.Pauli 1930 : Solution to conserve total energy $\Rightarrow$ "Neutrino"
  - $\rightarrow$ neutral
  - $\rightarrow$ spin $1/2$
  - $\rightarrow$ small or null mass
  - $\rightarrow$ small interaction probability
- E.Fermi 1934 : Effective theory : foundation stone of weak interaction
- C.Cowan & F.Reines 1956 : Neutrino discovery

The Standard Model of Particle Physics

Succeeds to describe particles and interactions



SM $\longrightarrow$ neutrinos are massless

Pontecorvo, 1957 : neutrino oscillations ?
Oscillation probability (2 flavours) :

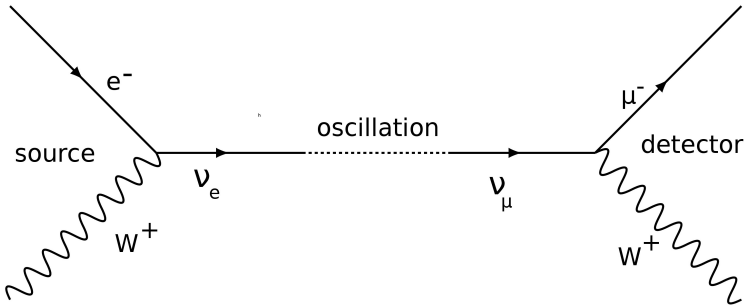
$$\mathcal{P}_{e\to\mu}(t) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{2E} L$$

- possible only if neutrinos are massive particles

SuperKamiokande, 1998

Observation of neutrino oscillations

- considering three flavours : at least 2 massive neutrinos



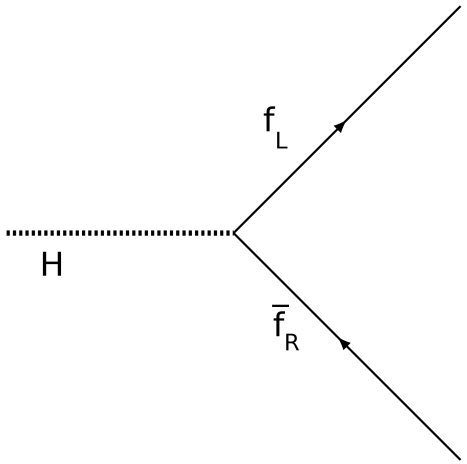
Which mechanism for the mass generation ?

$\rightarrow$ depends on neutrino nature

Dirac particles

Same mass mechanism as other fermions :
Higgs field coupling : $g_{Hf\overline{f}} \propto \frac{m_f}{v}$
Neutrino Dirac mass term in the Lagrangian :

$$\mathcal{L}_l^{mass} = -\frac{v}{\sqrt{2}}\bar{l}_L Y^l l_R + h.c.$$



SM extended with right-handed neutrino

Which mechanism for the mass generation ?

$\rightarrow$ depends on neutrino nature

$m_\nu \ll m_l \Rightarrow$ origin of neutrino masses different from those of charged fermions ?

Majorana particles : The neutrino is its own antiparticle

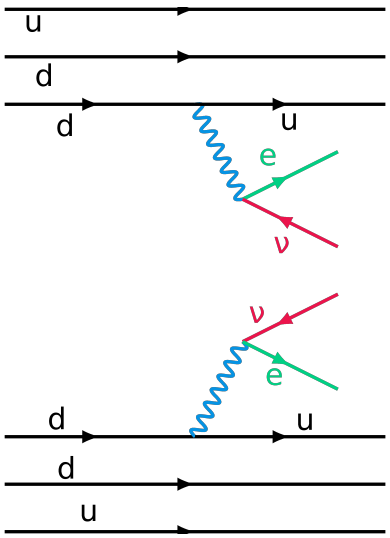
Majorana mass term in the Lagrangian with no extra particle

- leads to Lepton Number Violation (LNV) with $\Delta L = 2$ (forbidden in the SM)
  $\rightarrow$ could explain matter/antimatter asymmetry in the universe
- Seesaw mechanisms : heavy ν_R mixes with ν_L and generates light Majorana masses for the observed active neutrinos
  $\rightarrow$ could explain smallness of neurino masses

Probe : Neutrinoless double beta decay

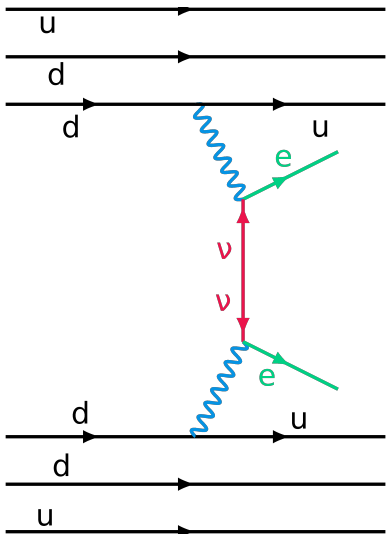
Double beta decay $= 2$ simultaneous neutron decays inside the nucleus

$2\nu\beta\beta$



- Allowed in SM
- Has been observed in several isotopes
- $\tau_{1/2}^{2\nu\beta\beta} \sim 10^{18} - 10^{21}$ years

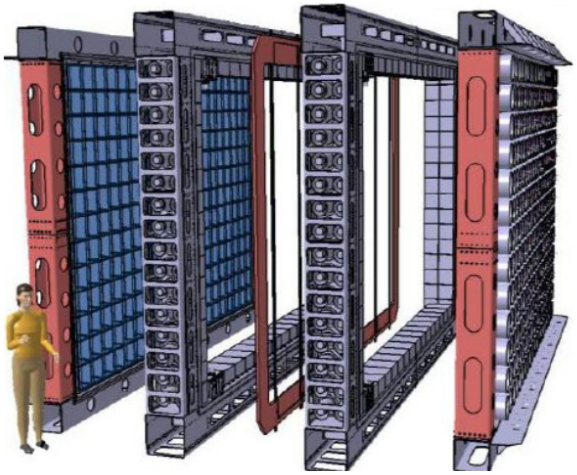
$0\nu\beta\beta$

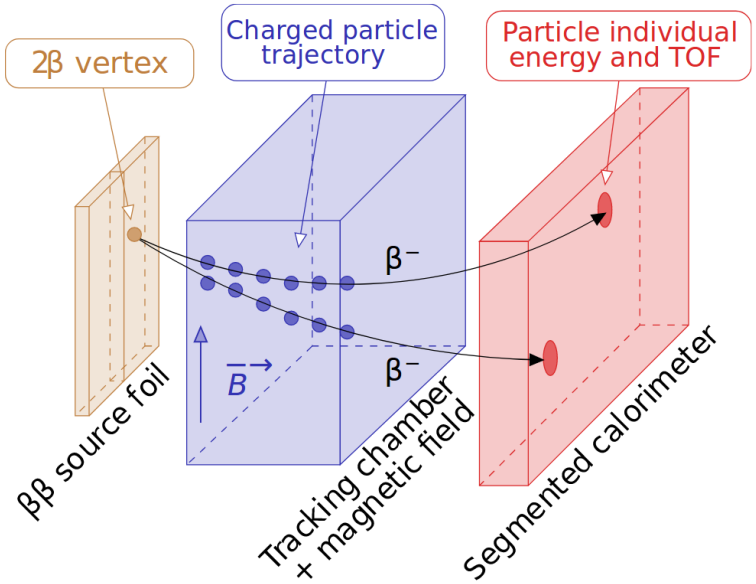


- Forbidden in SM
- Possible only if neutrinos are Majorana partciles
- $\tau_{1/2}^{0\nu\beta\beta} > 10^{24} - 10^{26}$ years

The SuperNEMO experiment

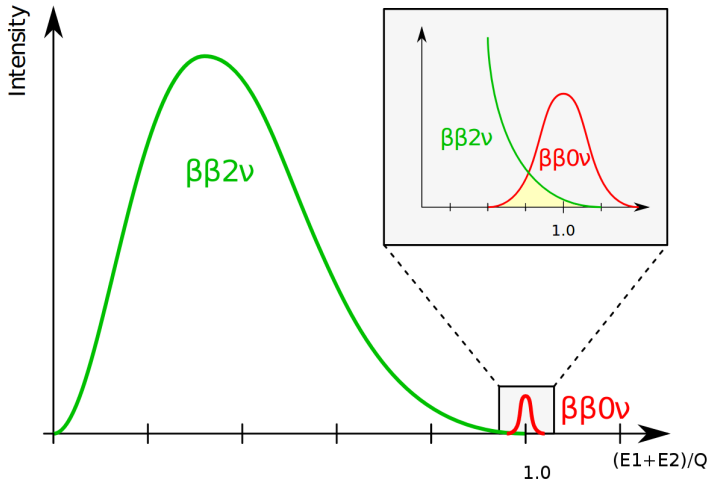
SuperNEMO demonstrator in installation at LSM





The SuperNEMO demonstrator :

- Searching for $0\nu\beta\beta$ decay
- Tracker + calorimeter
  $\Rightarrow$ unique experiment : reconstruction of the tracks of the particles AND measurement of the deposited energies
- Magnetic field 25 G



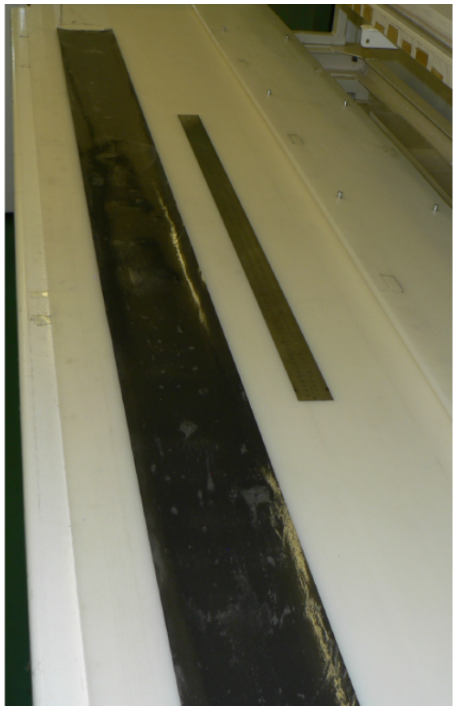
The source foils

The choice of isotope

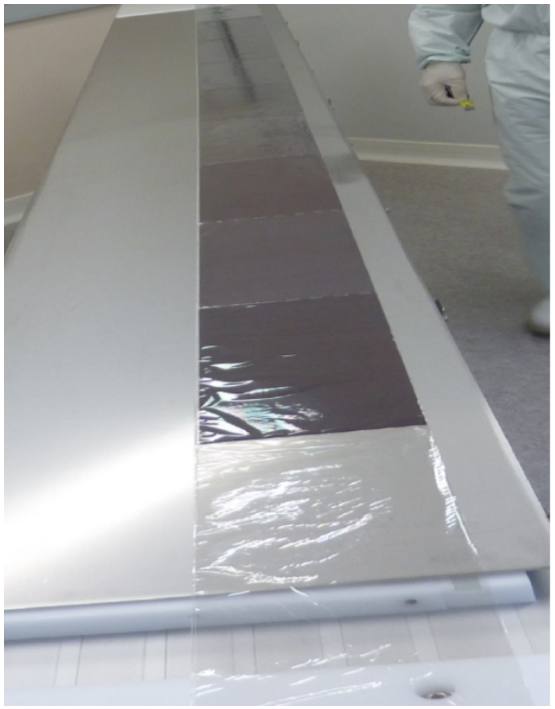
- High $Q_{\beta\beta}$ to reduce natural radioactivity background
  $Q_{\beta\beta} > 2.615$ MeV
- $(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$
  High phase space factor $G^{0\nu}$ and matrix elements $M^{0\nu}$ to minimise $0\nu\beta\beta$ half life
- Isotopic abundance
- Highest $T^{2\nu}_{1/2}$ to reduce the $2\nu\beta\beta$ background contribution

...

Isotope	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (10^{-15} y^{-1})	$T^{2\nu}_{1/2}$ (y)	η (%)
^{48}Ca	4.273	24.81	6.37×10^{19}	0.187
^{76}Ge	2.039	2.363	1.926×10^{21}	7.8
^{82}Se	2.995	10.16	9.6×10^{19}	9.2
^{96}Zr	3.350	20.58	2.35×10^{19}	2.8
^{100}Mo	3.035	15.92	6.93×10^{18}	9.6
^{116}Cd	2.809	16.70	2.8×10^{19}	7.6
^{130}Te	2.530	14.22	6.9×10^{20}	34.5
^{136}Xe	2.458	14.58	2.165×10^{21}	8.9
^{150}Nd	3.367	63.03	9.11×10^{18}	5.6



ITEP style foils

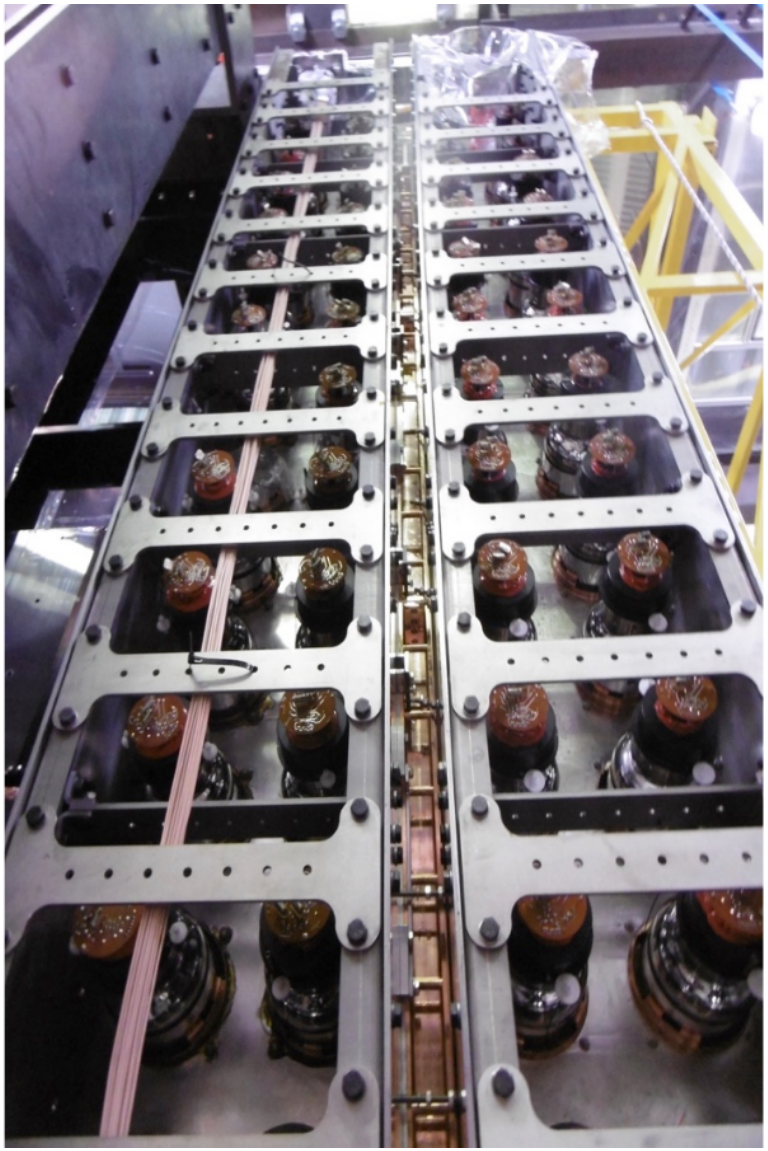


LAPP style foils

- ^{82}Se 6.23 kg in thin source foils
- Expected sensitivity $\tau_{1/2}^{0\nu\beta\beta} > 5 \times 10^{24}$ years
- ~ 7 kg of ^{82}Se for ~ 2.5 years taking data ($= 17.5$ kg.y exposure)

The SuperNEMO demonstrator

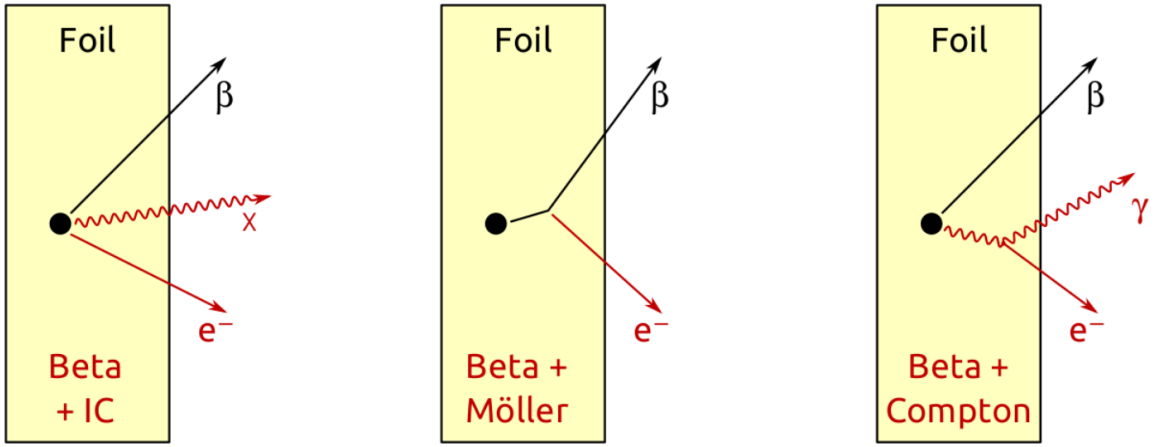
Source foils installed ! !



The background for SuperNEMO experiment

Main backgrounds for the SuperNEMO experiment

- External γ from natural radioactivity
  - Origin : detector PMs
  - $E_\gamma < 2.6$ MeV
- Internal contamination of Radon in the tracker
- **Internal contamination in the source foils**
  - **^{208}Tl from ^{232}Th decay chain**
  - **^{214}Bi from ^{238}U decay chain**



Ultra-low background specifications :

$\mathcal{A}(^{208}\text{Tl})$	$\leq 2\mu\text{Bq/kg}$
$\mathcal{A}(^{214}\text{Bi})$	$\leq 10\mu\text{Bq/kg}$
$\mathcal{A}(^{222}\text{Rn})$	≤ 0.15 mBq/m^3

Goal

Study the sensitivity of SuperNEMO to the half life of the $0\nu\beta\beta$ decay and influence of internal backgrounds

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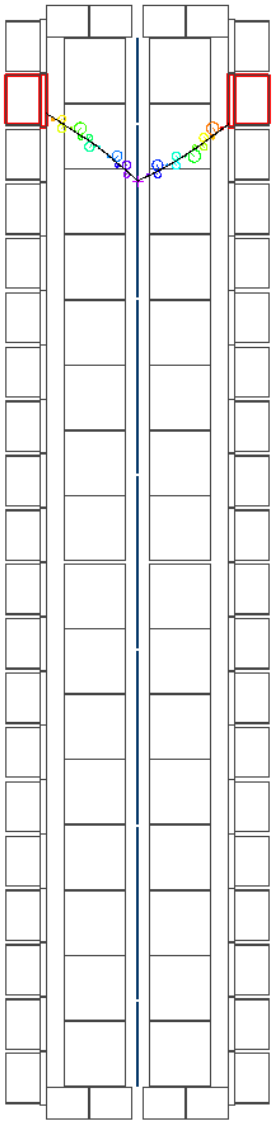
Goal

Study the sensitivity of SuperNEMO to the half life of the $0\nu\beta\beta$ decay and influence of internal backgrounds

Event simulations & reconstruction with the Falaise software



Event simulation & reconstruction :

- Simulate particles through the detector (GEANT4)
- Record and write informations in an output file
- Reconstruct events (energy and time resolutions, tracker response, ...)

Simulation of internal backgrounds :
$0\nu\beta\beta$, $2\nu\beta\beta$, ^{208}Tl, ^{214}Bi in the source foils

Selection of 2e topologies
1 electron is defined as :

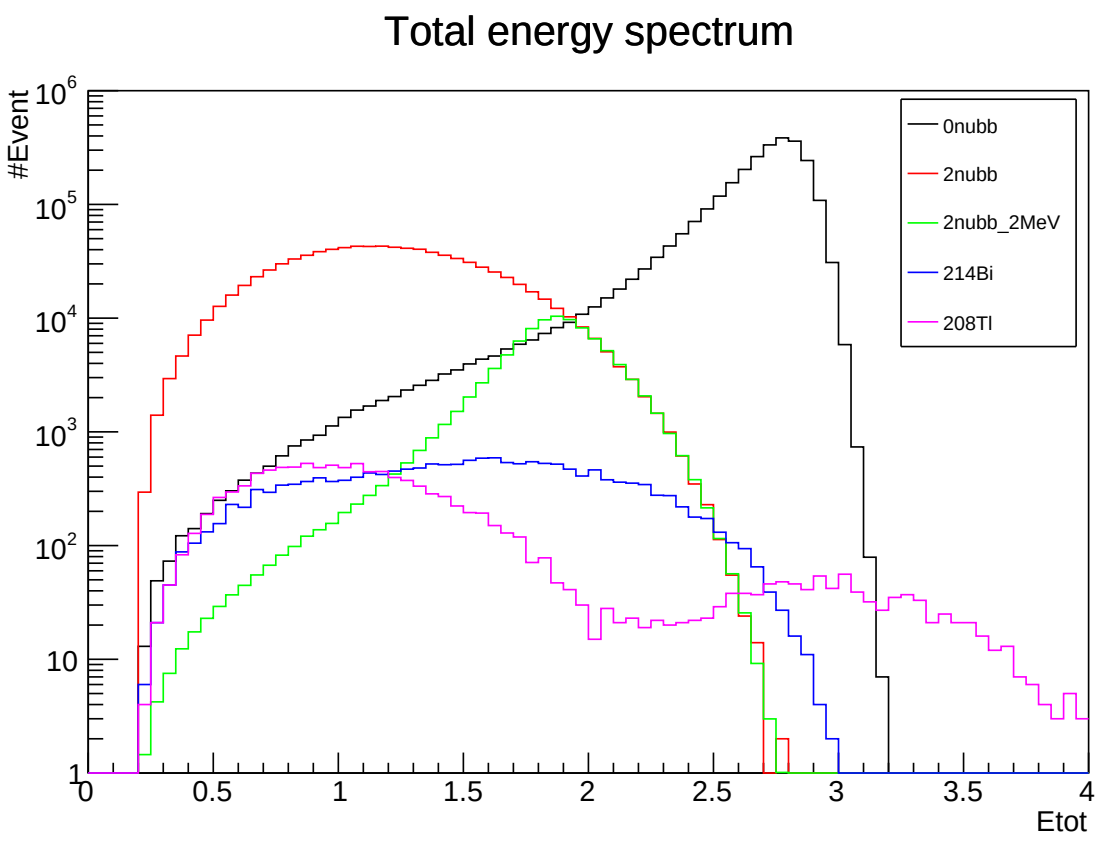
- Vertex on source foil
- 1 calorimeter $+$ 1 tracker trajectory
- 1 negative curve

Limit on $0\nu\beta\beta$ half life

$$T_{1/2}^{0\nu} > \frac{N_A \ln 2}{W} \times \frac{\epsilon \times M \times T}{N_{exclus}}$$

ϵ - selection efficiency of $0\nu\beta\beta$ events

N_{exclus} - number of excluded signal events calculated with $N_{background}$



Selection efficiency and expected number of background events

Selection efficiencies for $0\nu\beta\beta$ and backgrounds :

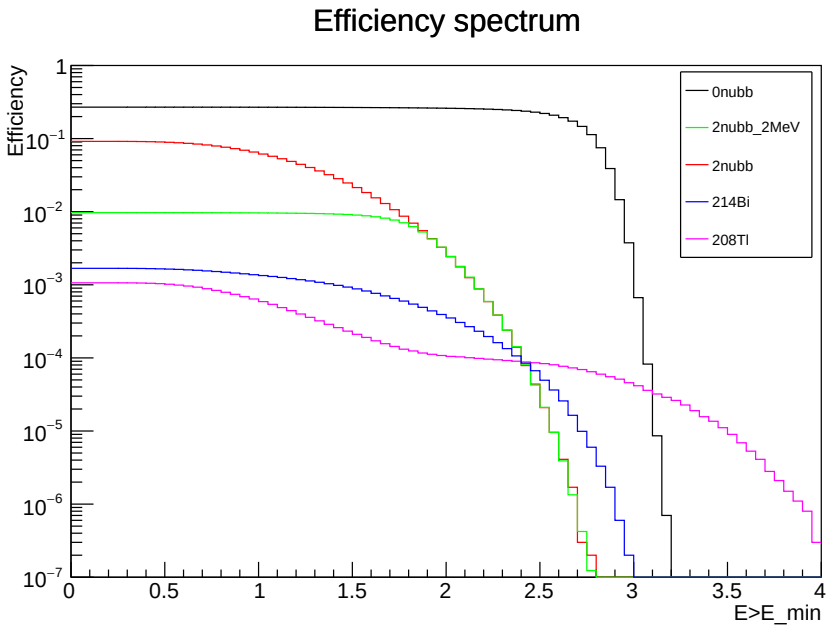
$$\epsilon(E_{\text{inf}}, E_{\text{sup}}) = \frac{1}{N}\int_{E_{\text{inf}}}^{E_{\text{sup}}} \frac{\partial E}{\partial N} dE$$

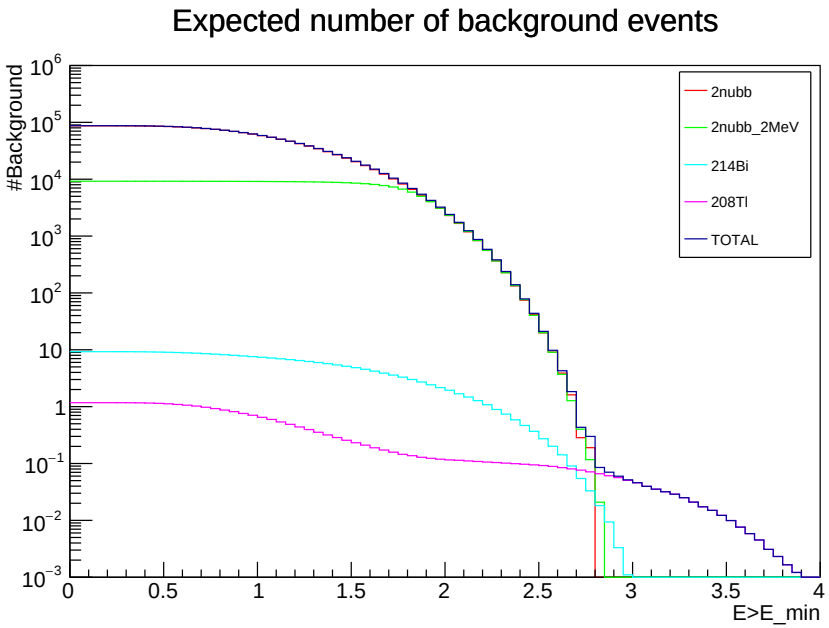
Expected number of background events in the correponding ROI :

$$N_{2\nu} = \frac{N_A \ln 2}{W} \frac{\epsilon_{2\nu} \times M \times T}{T_{1/2}^{2\nu}}$$

$$N_{^{208}\text{Tl}} = A_{^{208}\text{Tl}} \times \epsilon_{^{208}\text{Tl}} \times M \times T$$

$$N_{^{214}\text{Bi}} = A_{^{214}\text{Bi}} \times \epsilon_{^{214}\text{Bi}} \times M \times T$$



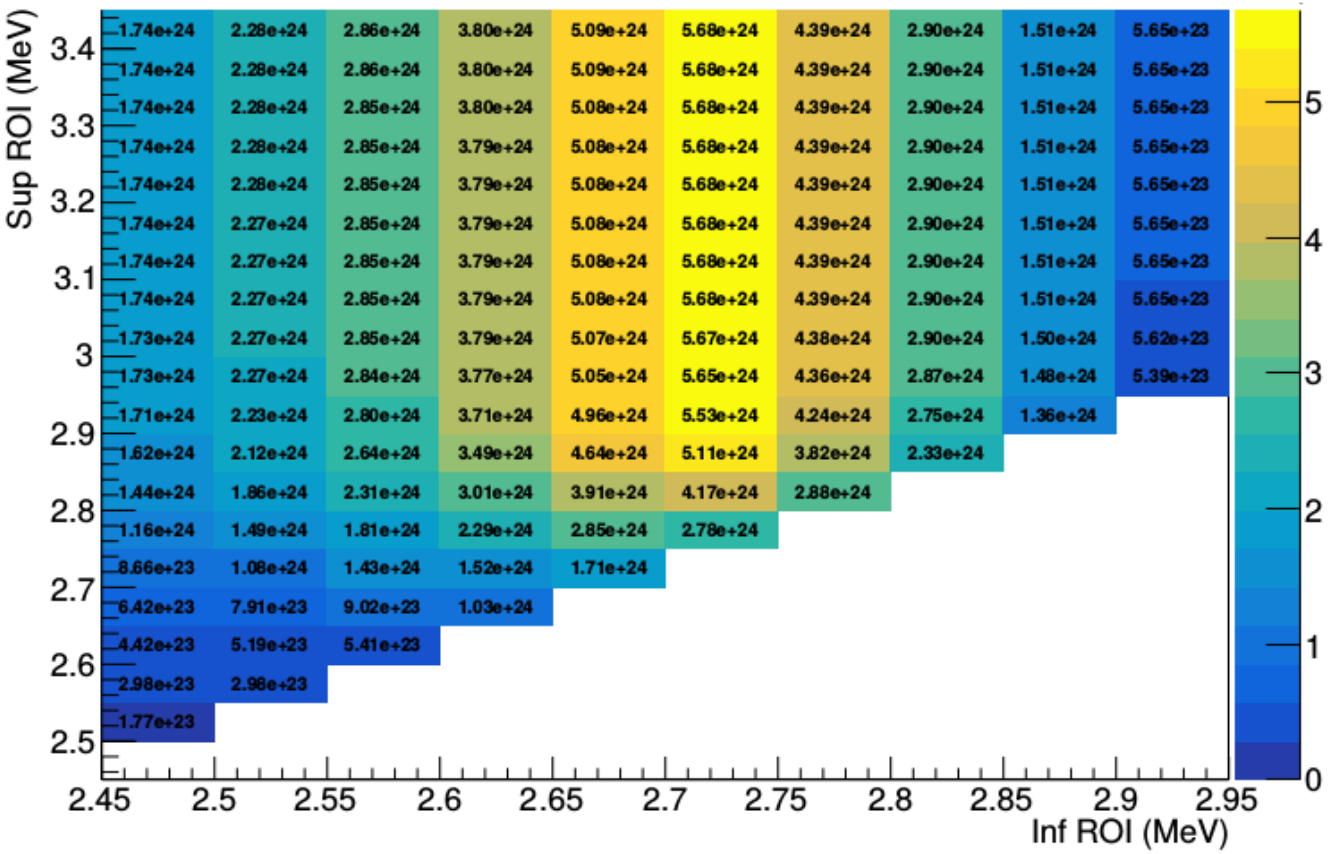


Exposure 17.5 kg.y
Source foils material : ^{82}Se

Background specifications

Sensitivity of SuperNEMO on the half life with E_{inf} and E_{sup}

$T^{0\nu}_{1/2}$ depends on $[E_{\text{inf}}, E_{\text{sup}}]$

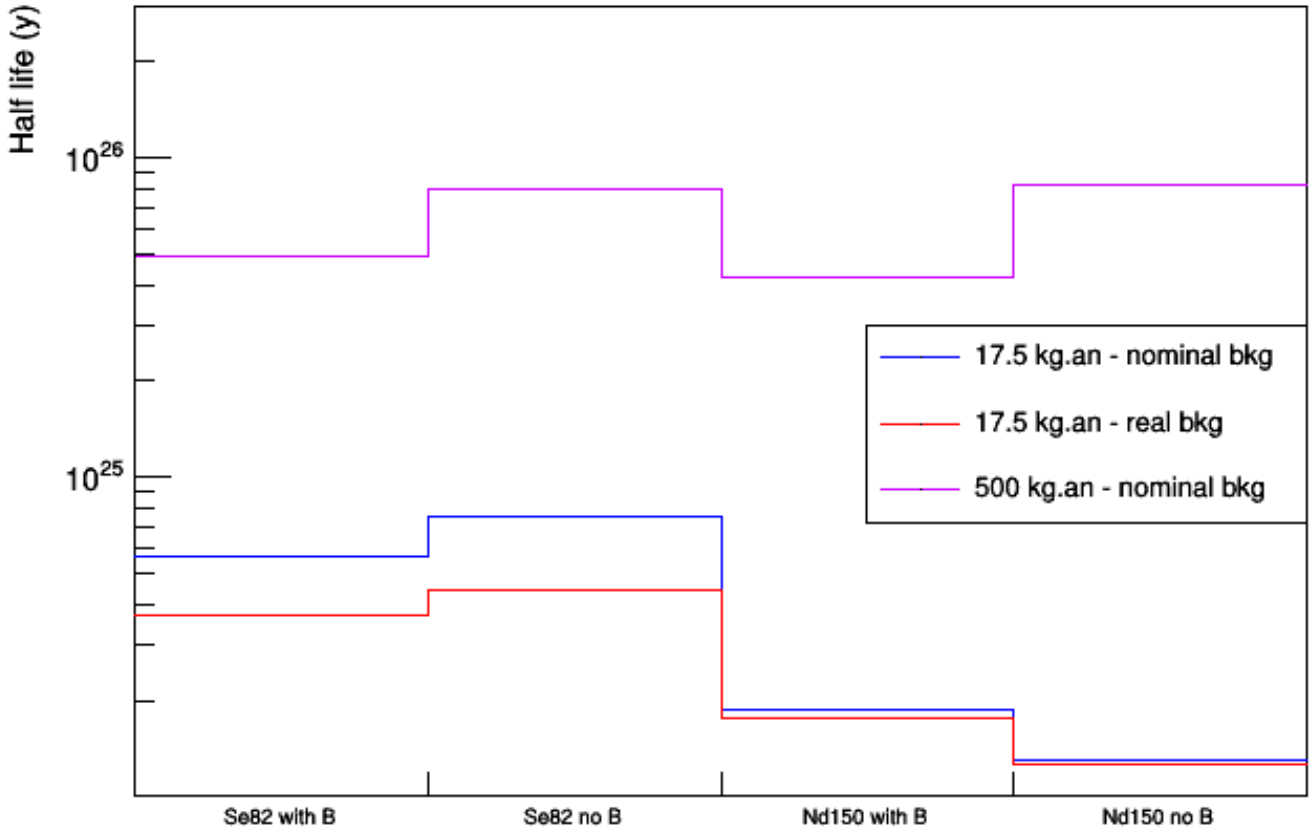


Exposure 17.5 kg.y
Source foils material : ^{82}Se

Background specifications

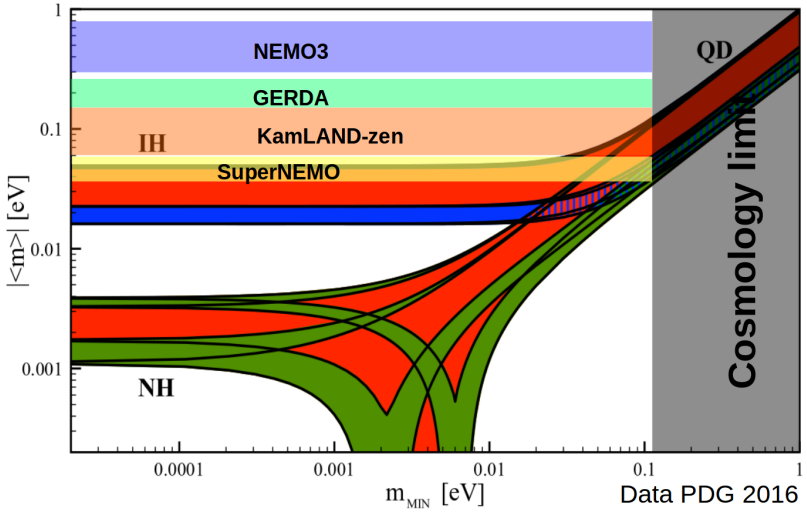
The complete sensitivity study

- Source material : ^{82}Se or ^{150}Nd
- Magnetic field
- Background specifications
- *HyperNEMO* : 500 kg.y



Neutrino effective masses

$$(T^{0\nu}_{1/2})^{-1} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left| \frac{m_{\beta\beta}}{m_e} \right|^2$$



^{82}Se source foils :

		B = 25 G	B = 0 G
17.5 kg.y	Nominal background	[0.23 - 0.46] eV	[0.20 - 0.41] eV
	Measured background	[0.37 - 0.70] eV	[0.28 - 0.52] eV
	No internal background	[0.23 - 0.46] eV	[0.20 - 0.41] eV
500 kg.y	Nominal background	[0.08 - 0.16] eV	[0.06 - 0.13] eV

^{150}Nd source foils :

		B = 25 G	B = 0 G
17.5 kg.y	Nominal background	[0.15 - 0.50] eV	[0.13 - 0.44] eV
	Measured background	[0.15 - 0.50] eV	[0.20 - 0.65] eV
	No internal background	[0.15 - 0.50] eV	[0.13 - 0.44] eV
500 kg.y	Nominal background	[0.046 - 0.15] eV	[0.04 - 0.14] eV

Conclusion

SuperNEMO in installation at LSM

- Neutrinoless double beta decay is the best known process to probe LNV
- SuperNEMO is a tracko-calorimeter detector searching for $0\nu\beta\beta$
- Source foils installed and tracker closed ! !
- First data early 2019

PhD work

- Continue the sensitivity study with 2nd order cuts
- Study influence of external background

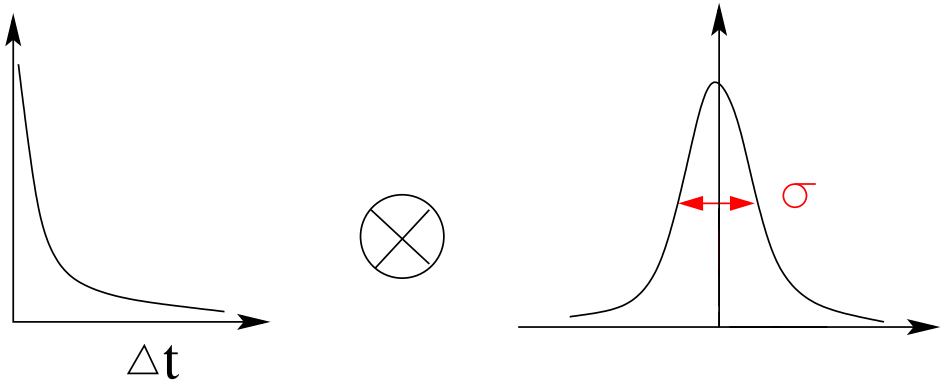
Back up

Exponentially modified gaussian

Convolution of an exponential and a gaussian function :

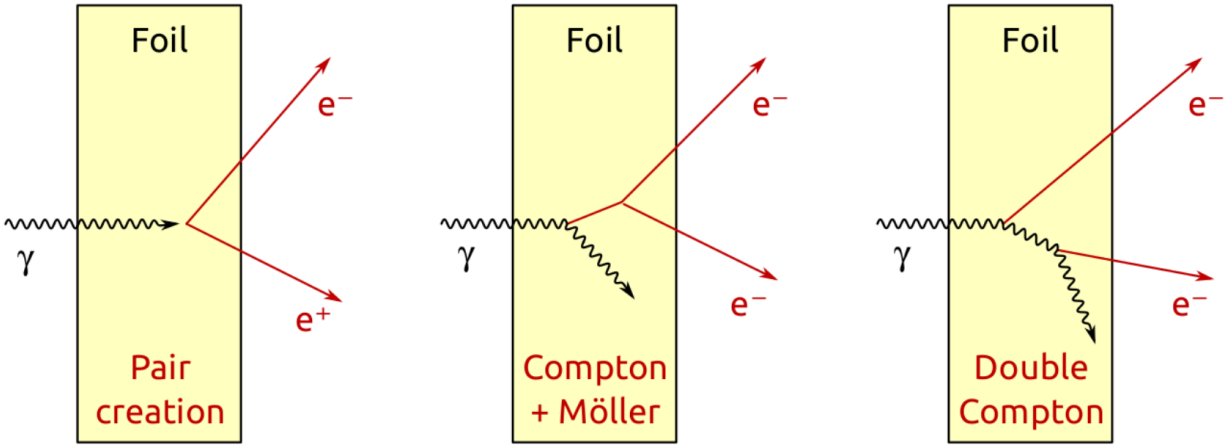
$$f(x,\mu,\sigma) = \frac{\lambda}{2}\exp^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)}\,\text{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

with $\mu = 0, \sigma = \sqrt{\sigma_t^2 + \sigma^2_{(\frac{L}{\beta c})} + \sigma_T^2}$ and $\tau = 294$ps

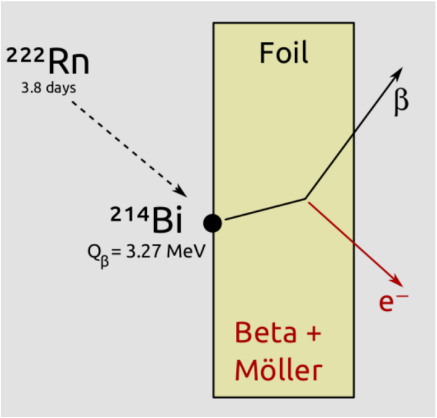


Background scheme for external gammas and Radon

External gamma background :

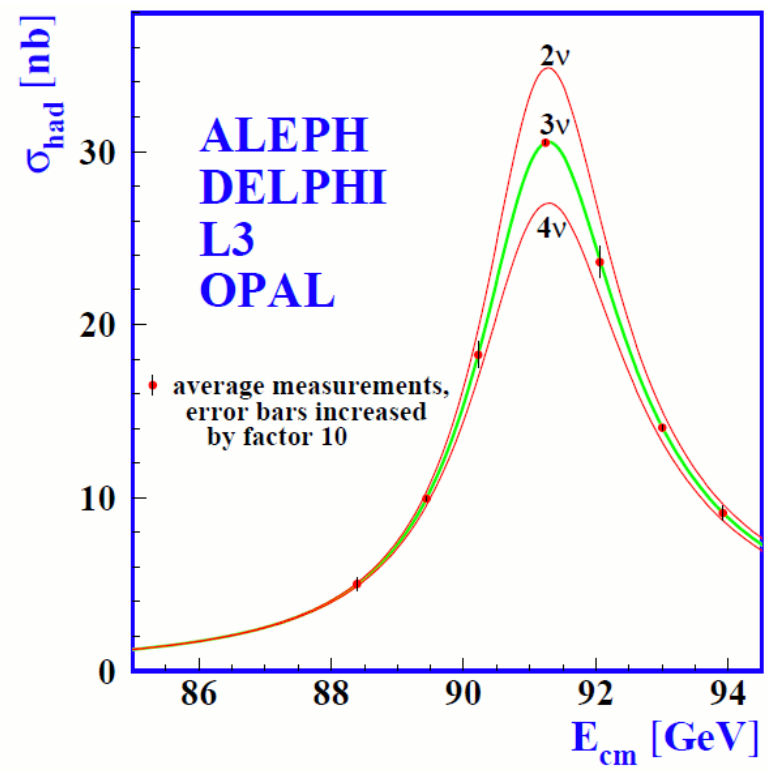


Internal Radon background :



Active light neutrino number with the total Z width

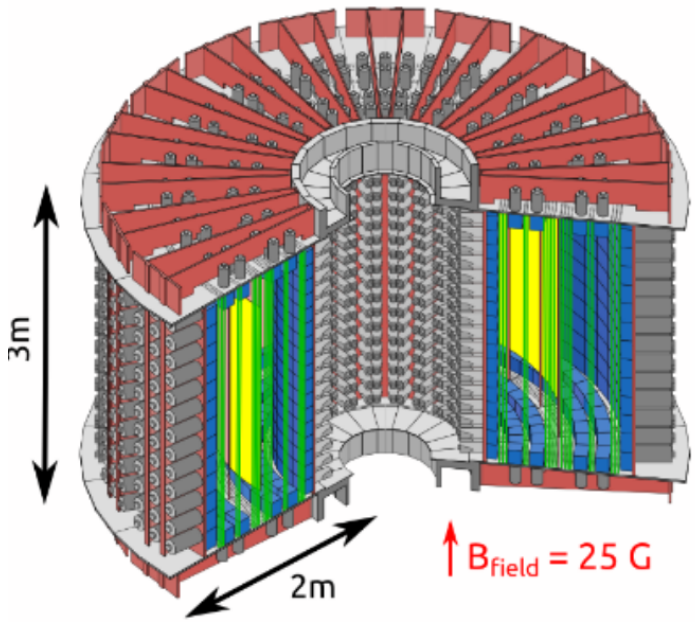
The most precise measurements of the number of light neutrino types come from studies of Z production in e^+e^- collisioners.



$N_\nu = 2,984 \pm 0,012$ light neutrinos

From NEMO3 to SuperNEMO

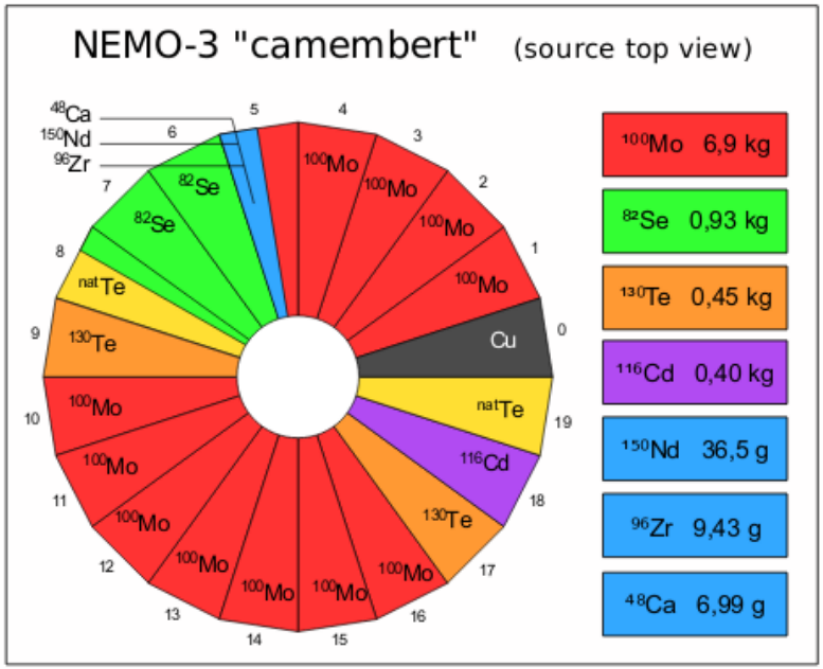
(Pour Laurent : je voudrais mettre ici un tableau comparatif NEMO3/SuperNEMO, est-ce que tu aurais ça quelque part en stock ?)



sources
60 mg/cm² foils
10 kg of ββ isotopes

tracker
6180 Geiger cells
vertex resolution :
σ_{xy} ~ 3 mm σ_z ~ 10 mm

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



$0\nu\beta\beta$ sensitivity

Neutrinoless double beta decay sensitivity :

$$\tau_{1/2}^{0\nu\beta\beta} \propto \frac{a\epsilon}{m_{\text{mol}}}\sqrt{\frac{M \times t}{N_{bkg} \times \Delta E}}$$

a - abundance of isotope
ϵ - efficiency of the detector
$M \times t$ - exposure
N_{bkg} - the background rate (counts.keV^{-1}.kg^{-1}.y^{-1})
ΔE - energy resolution

To have a better sensitivity :

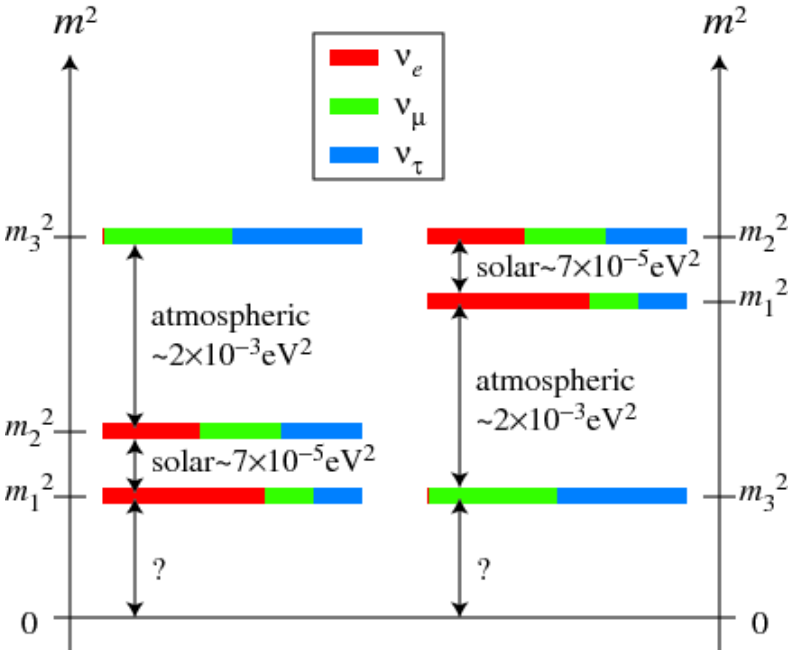
- High detection efficiency
- Long period data taking
- Big quantity of isotope
- Low background level

SuperNEMO gas composition

Gas proportions chosen to have the wire chamber functioning at optimal performances

- 95% He : low atomic number $\Rightarrow$ low energy losses for incoming particles (1 MeV electron : 50 keV energy loss)
- 4% ethanol : absorption of UV photons generated by Geiger plasma
- 1% Ar : ionisable $\Rightarrow$ ease the Geiger plasma propagation

Neutrino mass ordering



Majorana mass term

Weinberg operator :

$$\mathcal{L}_W = \frac{1}{2}\frac{g_{eff}v^2}{\mathcal{M}}\bar{\nu}_L^c\nu_L + \text{h.c.}$$

with $\quad m_\nu = \dfrac{g_{eff}v^2}{\mathcal{M}}$

New physics