Searching for the neutrinoless double beta decay with the SuperNEMO experiment : Development of reconstruction algorithms and analysis tools. Integration and commissioning of the demonsrator

Steven Calvez PHENIICS days 2016, 05/10/16

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Outline

- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning

Brief reminder

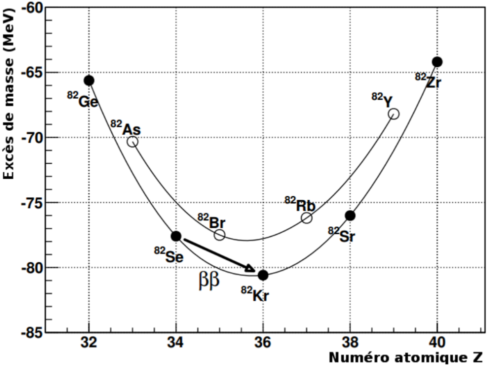
- The neutrino is the only neutral fundamental fermion
- Mass and nature unknown :

$$\textbf{Dirac particle} \Leftrightarrow \nu \neq \overline{\nu}$$
$$\textbf{Majorana particle} \Leftrightarrow \nu \equiv \overline{\nu}$$

- If neutrinos are Majorana particles :
  - Lepton number violation
  - See-Saw mechanism (small neutrino masses)
  - Leptogenesis (matter/antimatter asymmetry)
- Best known experimental way :
  search for the neutrinoless double beta decay

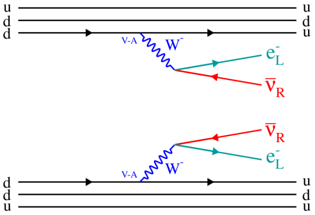
Double beta decay

- Radioactive decay naturally occuring in a few even-even nuclei where the single beta decay is energetically impossible (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd, ...)



Double beta decay

$2\nu 2\beta$



- Allowed in the Standard Model and already observed
- Second order process :

$$T^{2\nu 2\beta}_{1/2} \sim 10^{18} \text{ - } 10^{21} \text{ years}$$

$0\nu 2\beta$

- Forbidden by the Standard Model
- Only if Majorana neutrinos

$$T^{0\nu 2\beta}_{1/2} > 10^{24} \text{ - } 10^{25} \text{ years}$$

Double beta decay

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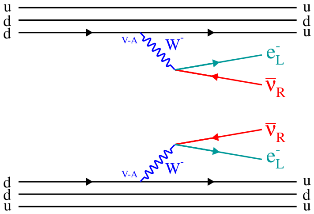

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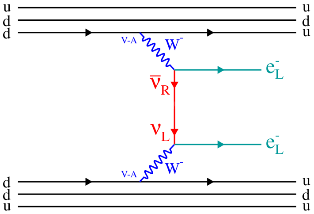

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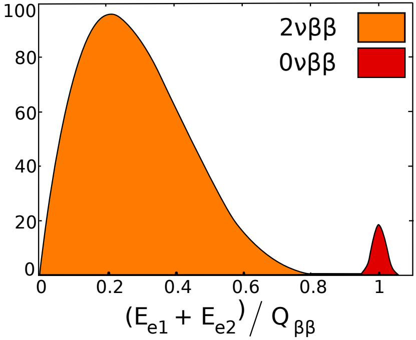
$T_{1/2}^{0\nu 2\beta} > 10^{24}$ - 10^{25} years

Double beta decay : Experimental signature

- Two different energy spectra

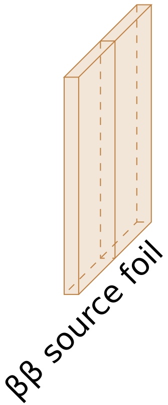


- $2\nu 2\beta$: continuous β-like spectrum, the neutrinos escape the detection
- $0\nu 2\beta$: peak at the transition energy $Q_{\beta\beta}$, all the energy is carried by the two electrons

The SuperNEMO experiment

- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning

NEMO experimental principle



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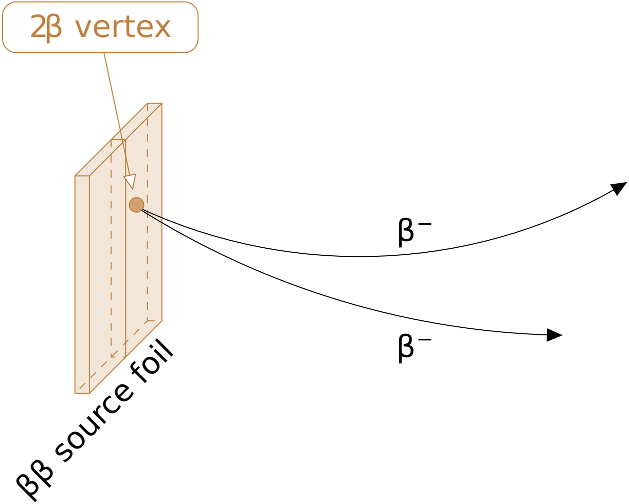

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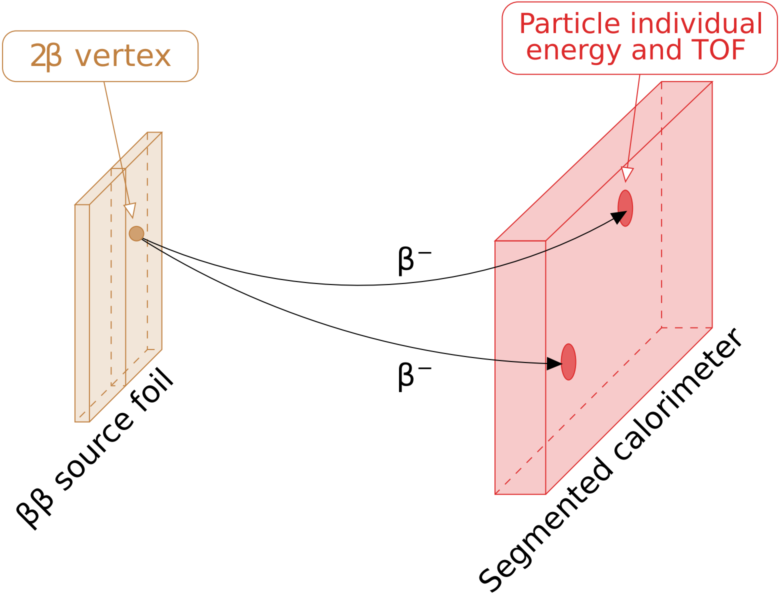

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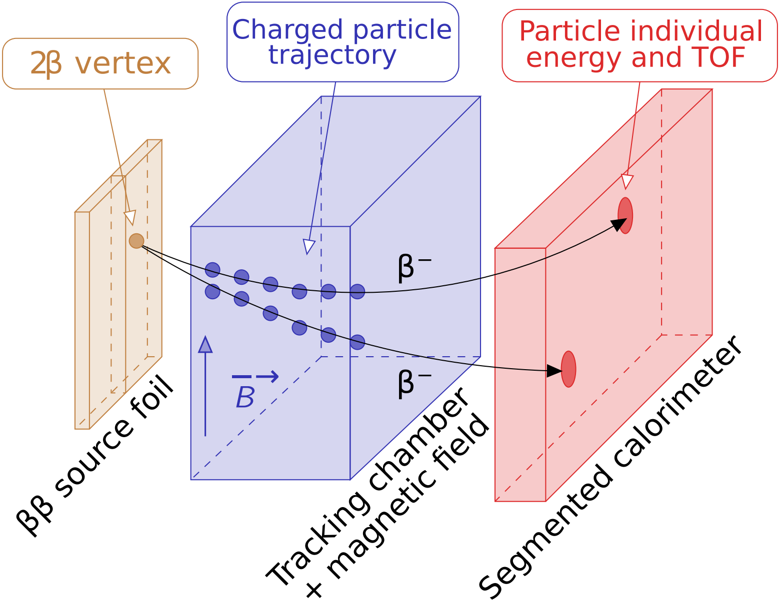
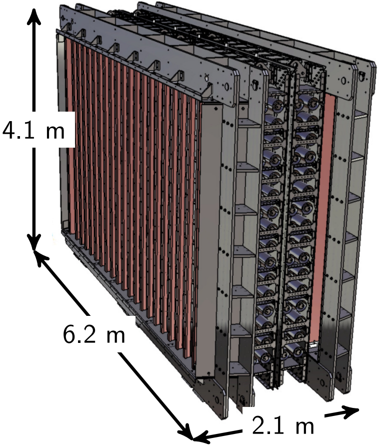


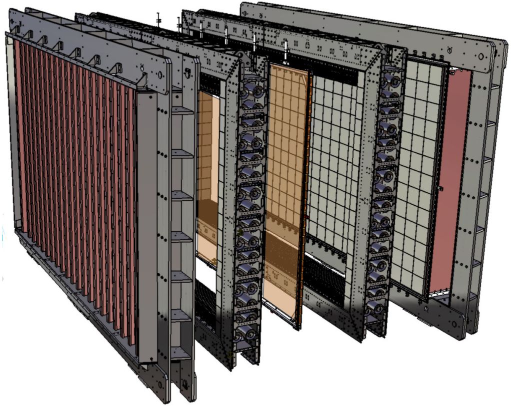
The SuperNEMO experiment



x 20 = SuperNEMO

Located in Modane (LSM)
under 4200 m.w.e.

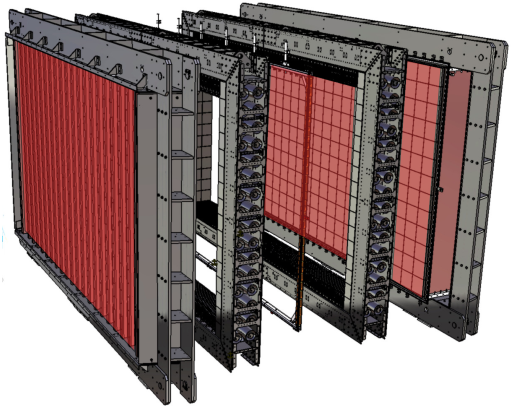
SuperNEMO demonstrator



$\beta\beta$ source foil :

7 kg of ^{82}Se (d = 53 mg/cm^2)

SuperNEMO demonstrator



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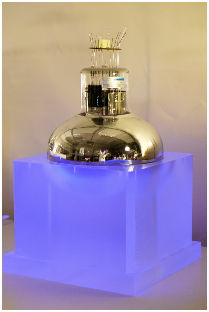
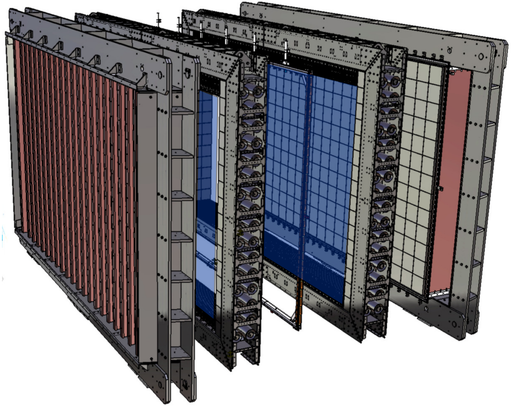


Calorimeter :

520 x 8" PM + 192 x 5" PM

coupled to polystyrene scintillators

SuperNEMO demonstrator



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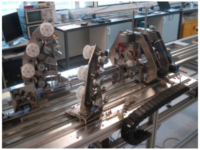
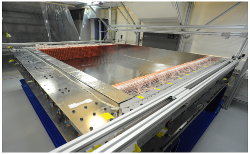
Tracking chamber :

2034 wires in Geiger regime





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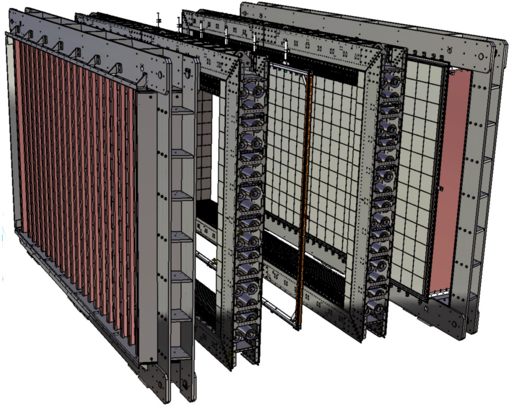

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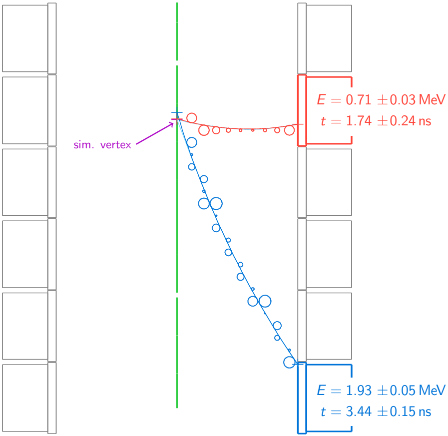
$\rightarrow$ **Commissioning and data taking by the end of 2016**

γ reconstruction algorithms

- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning

Software : simulation and reconstruction

- Use SN@ilWare software developped by and for the SuperNEMO collaboration : relies on GEANT4 and Genbb (event generator).

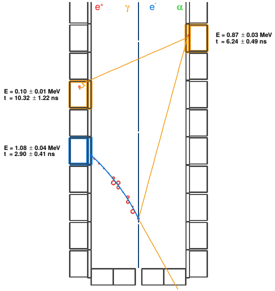


SN@ilWare — Top view

- Visualization of a $0\nu2\beta$ event from the source foil

γ detection and reconstruction in SuperNEMO

- The NEMO experiments are able to look for $0\nu2\beta$ <u>and</u> to measure the backgrounds thanks to a variety of event topology : $1e^-$, $2e^-$, $1e^-1e^+$, $1e^-1\alpha$, $1eN\gamma$, $2eN\gamma$...

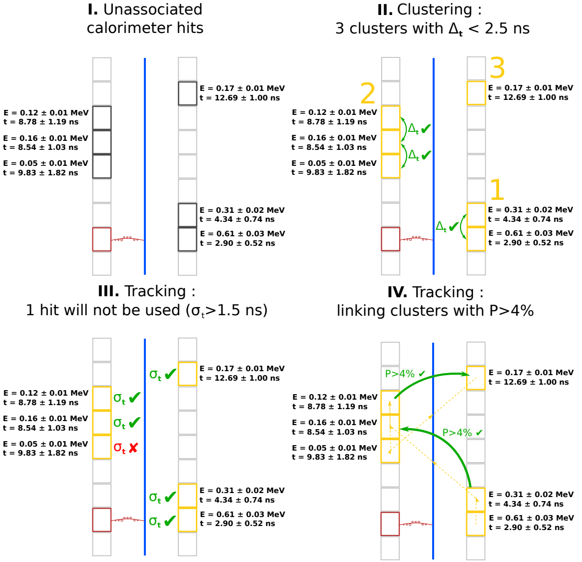


$\rightarrow$ Look for ^{208}Tl and ^{214}Bi events in the $1eN\gamma$ channels

- The γ reconstruction is important for :
  - background identification
  - study of double beta decay towards the excited states of the daughter nucleus.

γ-tracko-clustering

- **Clustering** : Gather the neighbouring calorimeter hits into clusters
- **Tracking** : Compute the probability a γ flew from one cluster to another based on Time-Of-Flight
- Better reconstruction efficiency and fidelity



Analysis software development

- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Demonstrator integration and commissioning.

Analysis software development

- Implement the end of the event reconstruction chain and provide the analysis tools to the collaboration :
  - Particle identification according to the user definitions
  - Perform relevant topological measurement (energy, vertices separation, TOF probabilities, angle, etc...)
  - Event selection and construction of the final analysis channels
  - Serialize the event model into a more user-friendly and analysis-oriented framework (ROOT TTrees for instance)

Sensitivity studies

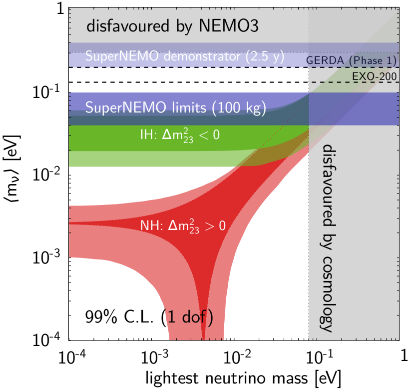
- Neutrinoless double beta decay
- The SuperNEMO experiment
- γ reconstruction algorithms
- Analysis software development
- Sensitivity studies
- Demonstrator integration and commissioning.

Analysis overview

- Simulate and reconstruct Monte-Carlo datasets for signal and backgrounds (several years of CPU hours)
- Select $\beta\beta$-like events
- Perform cuts to optimize the signal selection and background rejection (machine learning tools like Boosted Decision Trees...)
- Evaluate the demonstrator sensitivity for the neutrinoless double beta decay search, assuming the target background contributions

Demonstrator performance

- Should reach the NEMO3 sensitivity in less than a year.
- Less than one background count in total in the energy region of interest in the demonstrator.
- Demonstrator with 17.5 kg.y should reach $\langle m_{\beta\beta} \rangle < 0.2$ - 0.4 eV

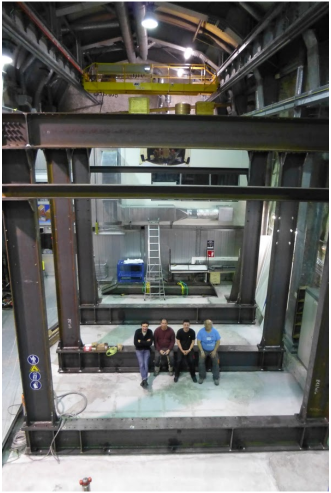


Demonstrator integration and commissioning

- The demonstrator is under construction in Laboratoire Souterrain de Modane, in the Frejus tunnel under the Alps.

Demonstrator integration and commissioning

- Mechanical structure and clean tent in LSM



Demonstrator integration and commissioning

- Integration and commissioning of the calorimeter

The end

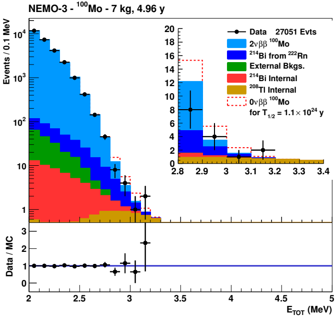
Thank you for your attention !

Backup

BACKUP

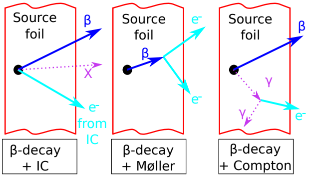
Experimental challenges

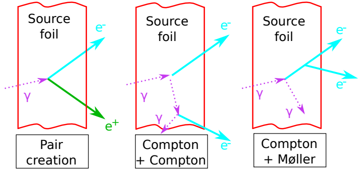
- Find a peak at the end of the $2\nu2\beta$ spectrum
- $2\nu2\beta$ irreducible background $\rightarrow$ improve energy resolution
- High $Q_{\beta\beta}$ isotope to rise above natural radioactivity
- Radiopure source and materials



Internal (source contamination, Radon on source surface, ...)

External (PMT glass, ...)





● = radioisotope; β = electron from β-decay; IC = internal conversion

Comparison NEMO3 SuperNEMO

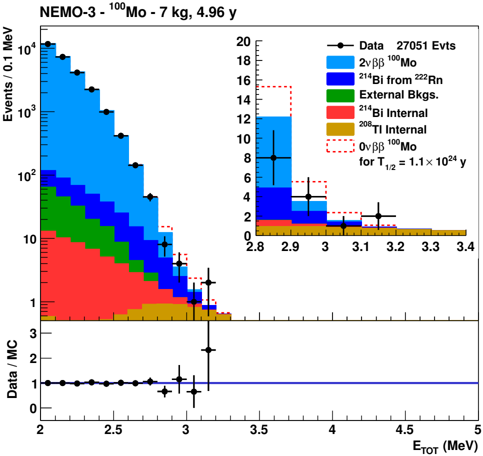
	NEMO3	SuperNEMO
Mass	7 kg	100 kg
Isotopes	^{100}Mo 7 isotopes	^{82}Se, ^{150}Nd
Energy resolution @3MeV FWHM - σ	8 % - 3.4 %	4 % - 1.7 %
Source contaminations		
A(^{208}Tl)	$\sim$ 100 μBq/kg	$\leq$ 2 μBq/kg
A(^{214}Bi)	$\sim$ 300 μBq/kg	$\leq$ 10 μBq/kg
Radon in tracker		
A(^{222}Rn)	$\sim$ 5 mBq/m^3	$\leq$ 0.15 mBq/m^3
0ν efficiency	18 %	30 %
Exposure	35 kg.y	500 kg.y
Sensitivity		
$T_{1/2}^{0\nu2\beta}$ (90% C.L.)	$>$ 1.1 10 ^{24}	$>$ 1 10 ^{26}
$\langle m_{\beta\beta}\rangle$	$<$ 0.33 - 0.87 eV	$<$ 0.04 - 0.1 eV

$$\textbf{Sensitivity :} \quad T_{1/2}^{0\nu2\beta} \propto \begin{cases} \epsilon mt & \text{without background.} \\ \epsilon\sqrt{\frac{mt}{b\Delta E}} & \text{with background.} \end{cases}$$

$$(T_{1/2}^{0\nu2\beta})^{-1} = G^{0\nu}\ |M_{0\nu}|^2\ \langle\ m_{\beta\beta}\rangle^2 \text{ (for Mass Mechanism)}$$

NEMO-3 results

NEMO3 results for the $0\nu2\beta$ search in ^{100}Mo (*Phys. Rev. D 92, 072011*):

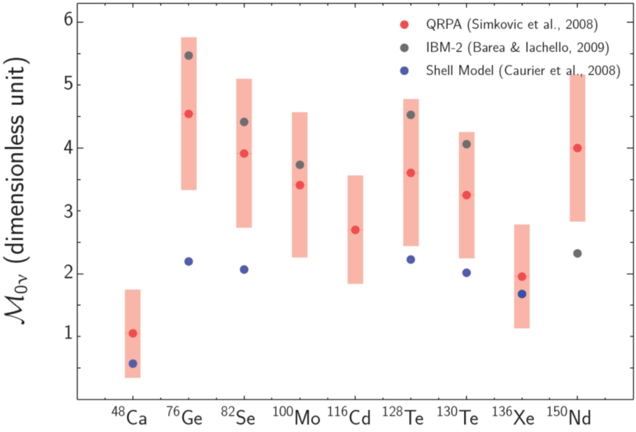


Isotope choice

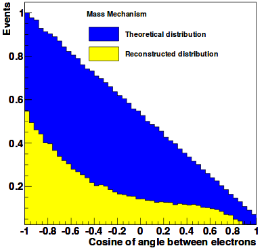
$$(T_{1/2}^{0\nu 2\beta})^{-1} = G^{0\nu}\ |M_{0\nu}|^2\ \langle\ m_{\beta\beta}\rangle^2 \text{ (for Mass Mechanism)}$$

2β	$Q_{\beta\beta}$ [MeV]	$G_{0\nu}$ $[10^{-14}\ y^{-1}]$	$\mathcal{T}_{1/2}^{2\nu}$ [y]	NA [%]
^{48}Ca	**4.274**	6.35	$4.3\ 10^{19}$	**0.187**
^{76}Ge	**2.039**	**0.62**	**$1.3\ 10^{21}$**	7.61
^{82}Se	2.996	2.70	$9.2\ 10^{19}$	8.73
^{96}Zr	**3.348**	5.63	$2.0\ 10^{19}$	2.8
^{100}Mo	3.035	4.36	**$7.0\ 10^{18}$**	9.63
^{116}Cd	2.805	4.62	$3.0\ 10^{19}$	7.49
^{130}Te	2.530	4.09	**$6.1\ 10^{20}$**	**34.1**
^{136}Xe	2.462	4.31	**$2.1\ 10^{21}$**	8.9
^{150}Nd	**3.368**	**19.2**	$7.9\ 10^{18}$	5.6

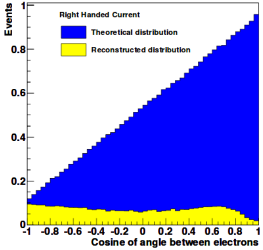
Nuclear matrix elements



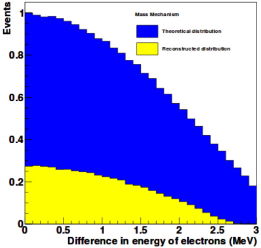
Underlying mechanisms



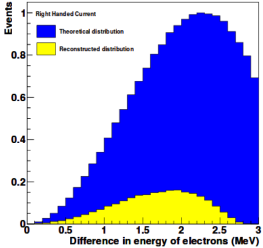
(a)



(b)



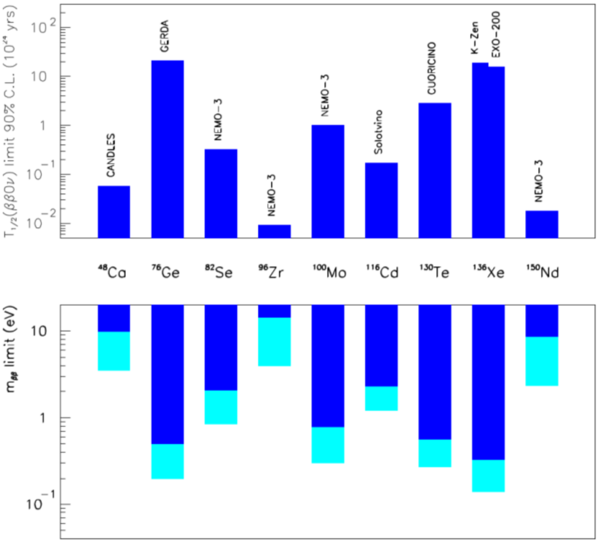
(c)



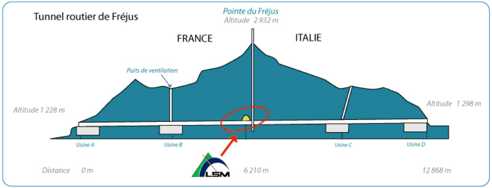
(d)

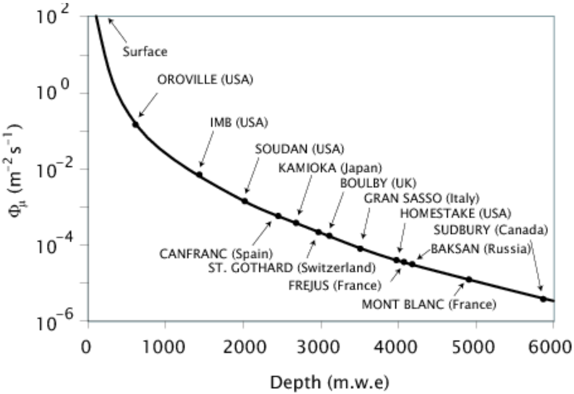
Current experiments sensitivities

ββ experiments current sensitivities



Underground laboratory





Time-of-Flight probability

TOF and internal probability

$$\chi^2_{int} = \frac{\left((t_2^{exp} - t_1^{exp}) - (\frac{l_2}{\beta_2 c} - \frac{l_1}{\beta_1 c})\right)^2}{\sigma^2_{t_1} + \sigma^2_{t_2}}$$

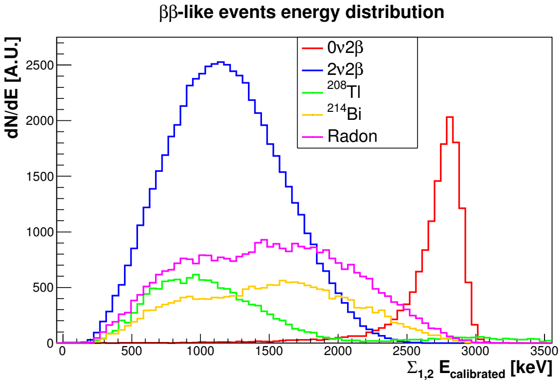
$$\sigma^2_{t_i} = (\frac{\partial t_{int}}{\partial t_i^{meas}})^2 \sigma^2_{t_i^{meas}} + (\frac{\partial t_{int}}{\partial E_i})^2 \sigma^2_{E_i}$$

with $\sigma_{t_i^{meas}} = 400$ ps and energy FWHM = 8 % (at 1 MeV). For two electrons, the track length uncertainty is negligeable.
Then,

$$P(\chi^2_{int}) = 1 - \frac{1}{\sqrt{2\pi}} \int_0^{\chi^2_{int}} x^{-\frac{1}{2}} e^{-\frac{x}{2}} dx$$

Energy spectra

- Simulate and select $\beta\beta$-like events :
  - 0ν : signal
  - 2ν : irreducible background
  - ^{208}Tl and ^{214}Bi : source contamination
  - Radon : gas in tracker



- $Q_{\beta\beta}(^{82}Se) = 2.996$ Mev
- $Q_{\beta}(^{214}Bi) = 3.272$ Mev
- $Q_{\beta}(^{208}Tl) = 5.001$ Mev