NEMO-3 latest results

Thibaud Le Noblet - LAPP
On behalf of the NEMO collaboration

GdR neutrino 29-30 mai 2017 - APC

Laboratoire d'Annecy-le-Vieux de Physique des Particules

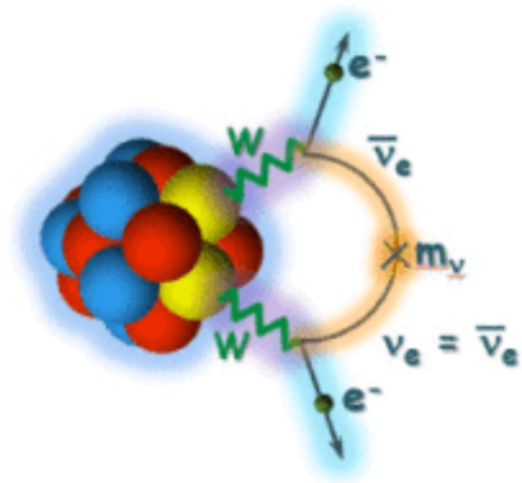
supernemo collaboration

Outline

- Neutrinoless double beta decay
- Tracker-calorimeter technique – NEMO-3 detector
- Latest results from NEMO-3
- Some exotic searches

Neutrinoless double beta decay

- Process forbidden in the SM
- Test Dirac/Majorana nature of neutrinos
- Half-life strongly suppressed



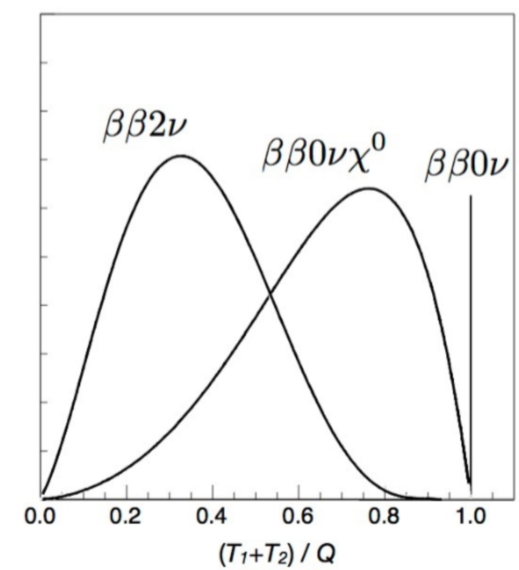
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

Phase space (well known)

Nuclear matrix elements (challenging to compute)

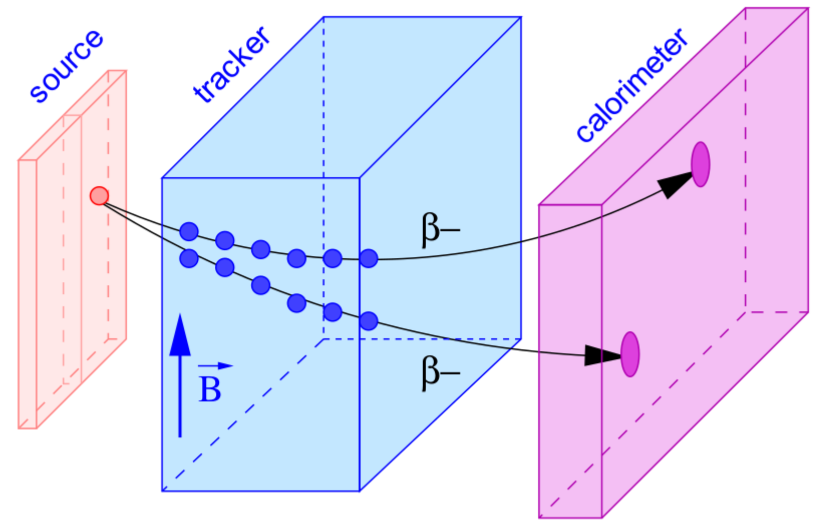
Take into account the mechanism underlying the $0\nu\beta\beta$ process

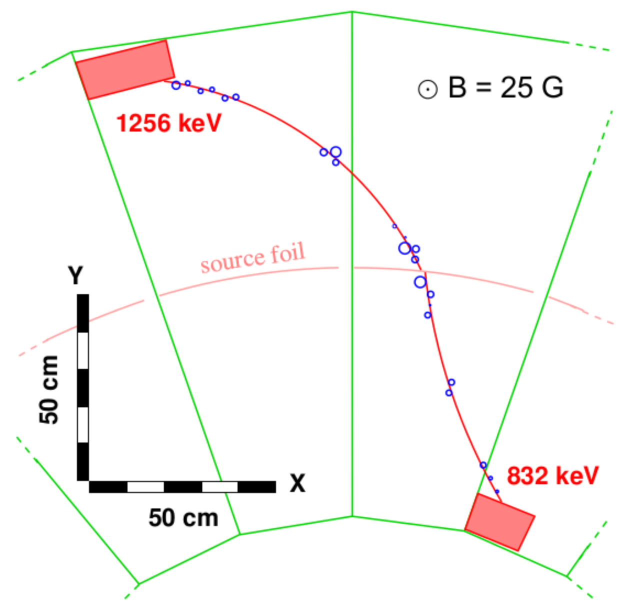
- Few different mechanisms may induce $0\nu\beta\beta$:
  - Light Majorana exchange
  - Right-handed current (V+A), Majoron, SUSY etc.
- Different topology in the final state



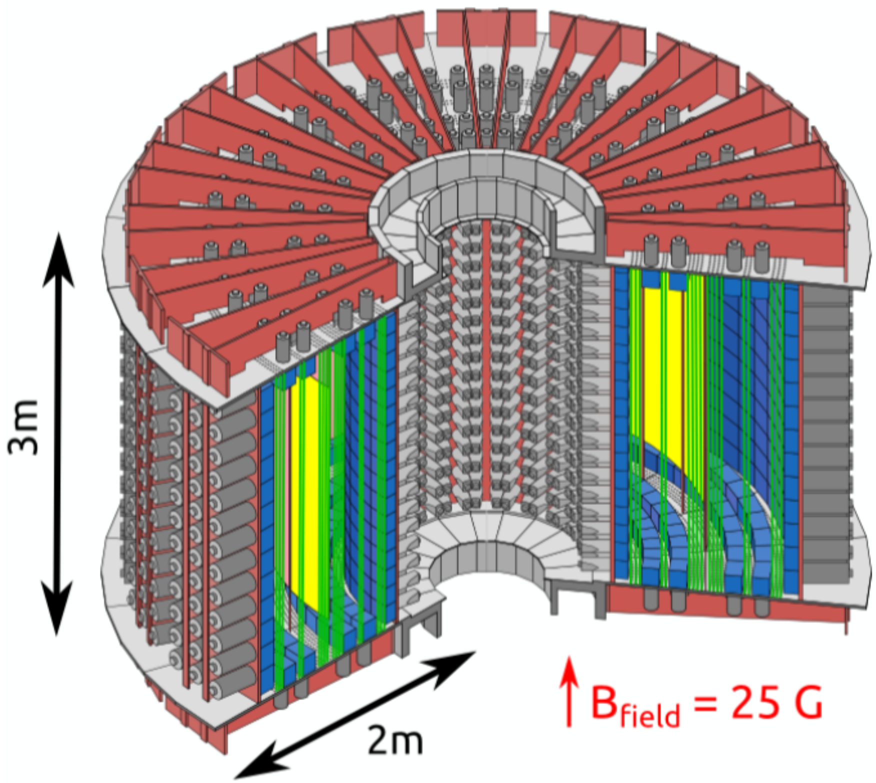
The tracker-calorimeter technique

- Source separated from detector : many ββ isotopes can be investigated
- Reconstruction of the final state topology and particle identification :
  - Excellent background suppression
  - Possible discrimination of mechanism behind 0νββ process
- Generally poorer energy resolution and detection efficiency than homogeneous detector (HPGe and bolometers)



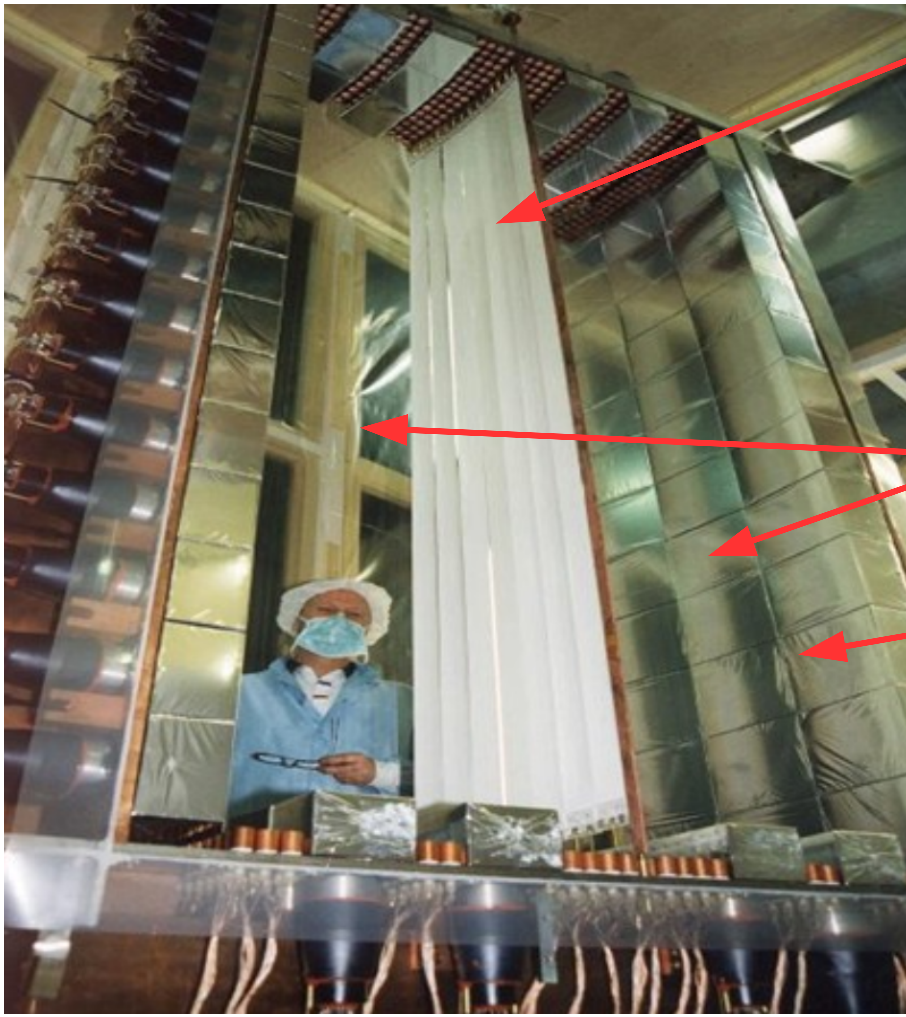


The NEMO-3 detector



- ββ decay experiment which combines both tracker and calorimetric measurements
- Took data from February 2003 to January 2011
- Located in the Modane underground laboratory (LSM) at ~4800 m.w.e
- Investigated 7 different ββ isotopes
- Divided into 20 identical sectors

The NEMO-3 detector – a sector

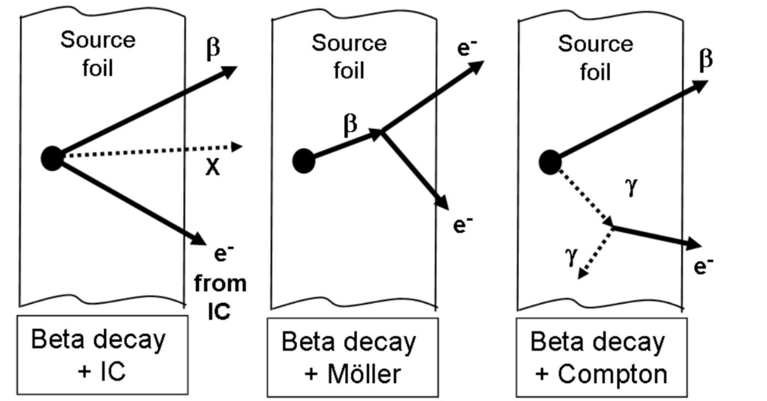


- Central ββ source plane made of 7 different isotopes : ^{100}Mo (7 kg), ^{82}Se (1 kg), ^{130}Te, ^{116}Cd, ^{150}Nd, ^{96}Zr, ^{48}Ca
- Ultra-pure Cu and very pure ^{nat}Te blank foils to cross check background measurements
- Wire drift chamber made of 6180 Geiger cells, σ_{vertex} = 3 mm (XY), 10 mm (Z)
- Calorimeter made of 1940 polystyrene scintillators coupled with low radioactivity PMTs, FWHM ~15 % at 1 MeV
- 25 Gauss magnetic field for the charge identification
- Gamma and neutron shields, anti-radon tent

Internal Backgrounds

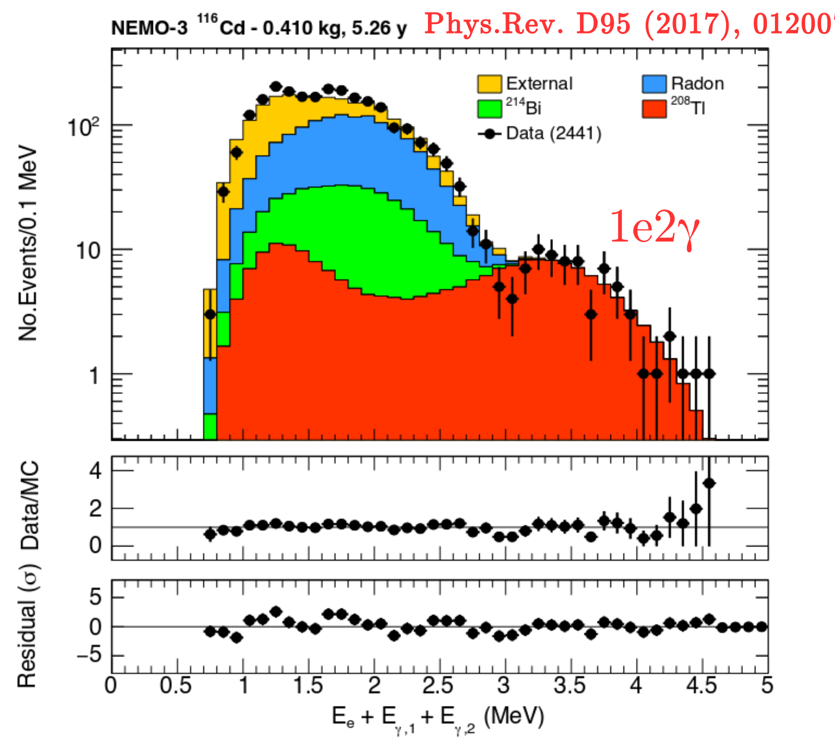
Regroups the backgrounds coming from the source foil, mainly come from :

- Radio-impurities inside the source foil
  - ^{208}Tl (from ^{232}Th), ^{214}Bi (from ^{238}U)
  - Single beta emitter (^{40}K, ^{234m}Pa, ^{210}Bi)
- ^{214}Bi from radon decay in tracker volume



Backgrounds are measured through different background channels using event topologies

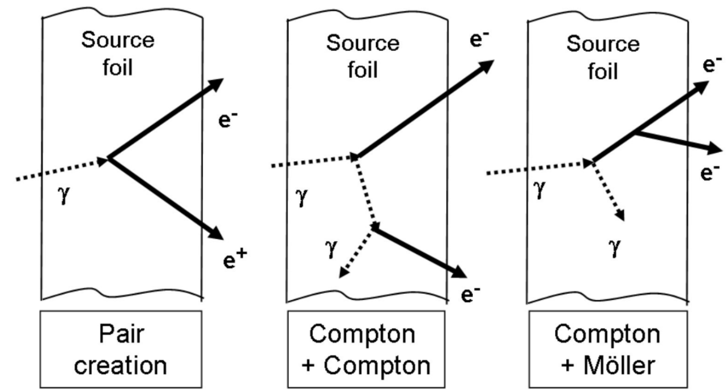
- ^{208}Tl in 1e1γ, 1e2γ and 1e3γ
- ^{40}K, ^{234m}Pa, ^{210}Bi in 1e channel
- ^{214}Bi – ^{222}Rn in 1e1α and 1e1γ channel



External Backgrounds

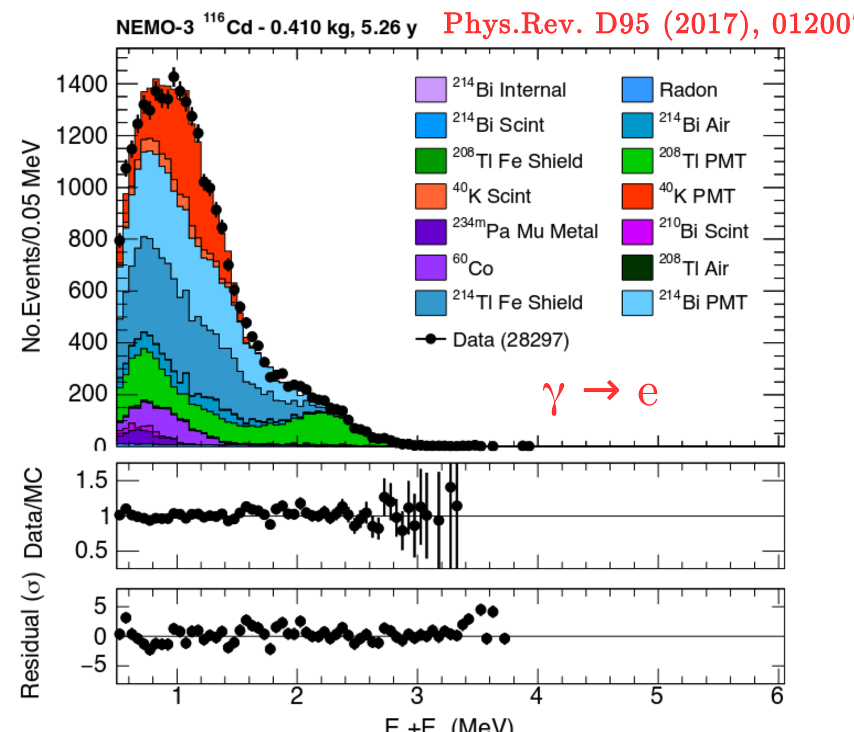
Regroups the backgrounds not coming from the source foil, come from :

- Radio-impurities in detector material (^{208}Tl, ^{214}Bi)
- γ from (n,γ) reactions
- μ Bremsstrahlung



Are measured in 2 main channels, requiring the timing informations :

- external crossing electron
- external γ → e

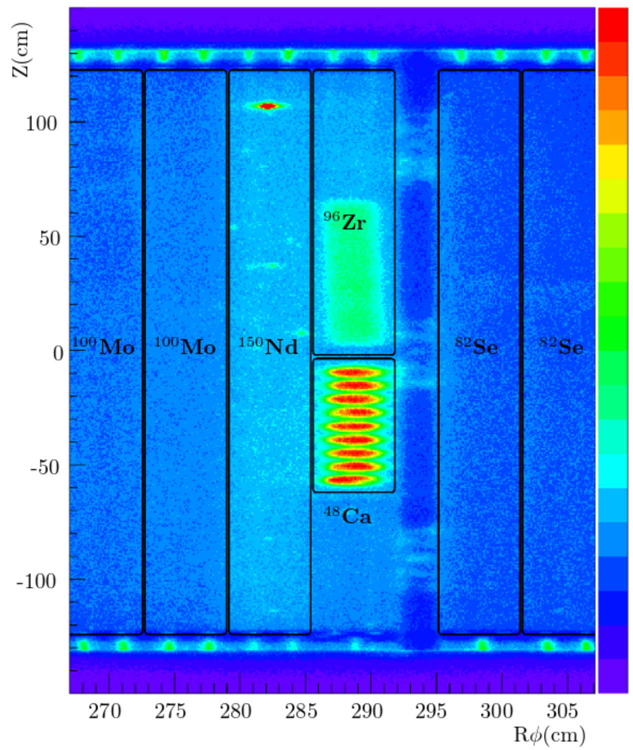


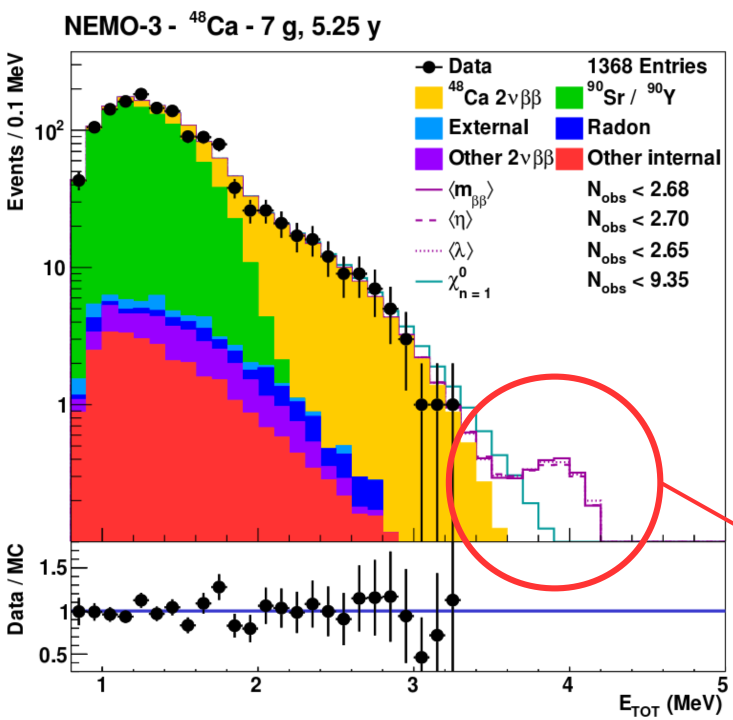
^{48}Ca results

Phys.Rev. D93 (2016), 112008

- 7 g distributed in 9 CaF2 disks
- ^{48}Ca: highest $Q_{\beta\beta} = 4.3$ MeV above almost all backgrounds
- Most precise measurement of the $2\nu\beta\beta$ decay rate to date :

$$T_{1/2}^{2\nu\beta\beta} = 6.4^{+0.7}_{-0.6}(\text{stat.})^{+1.2}_{-0.9}(\text{syst.}) \times 10^{19}\ \text{yr}$$





- Limits set for different $0\nu\beta\beta$ mechanisms

$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{22}\ \text{yr}\ (90\%\ \text{C.L.})$$

$$\langle m_\nu \rangle < 6.0 - 26\text{eV}$$

No events observed for E > 3.4 MeV, promising for background free searches with SuperNEMO

^{150}Nd results

Phys.Rev. D94 (2016), 072003

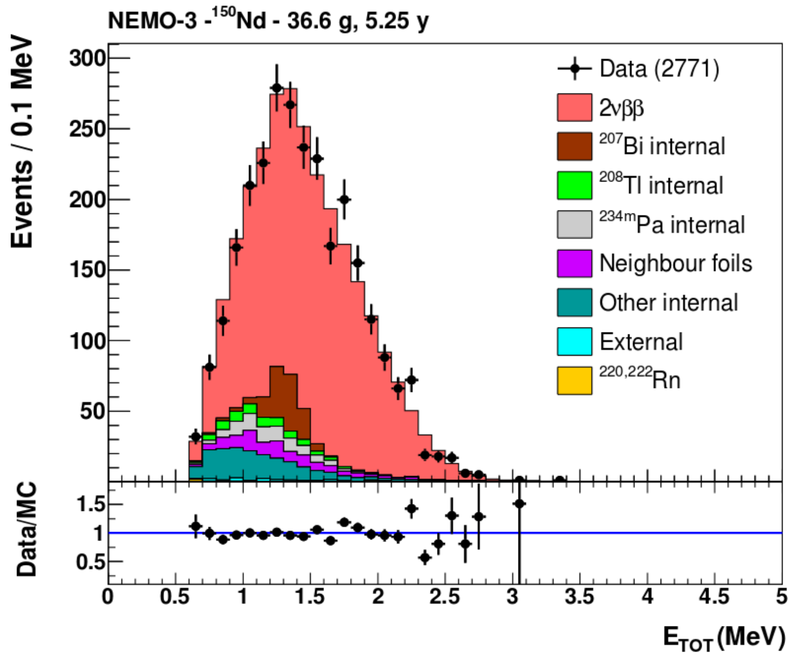
- 36.6 g contained in a strip
- ^{150}Nd : $Q_{\beta\beta} = 3.4$ MeV and the largest phase space of any isotope
- Most precise measurement of the 2νββ decay rate to date :

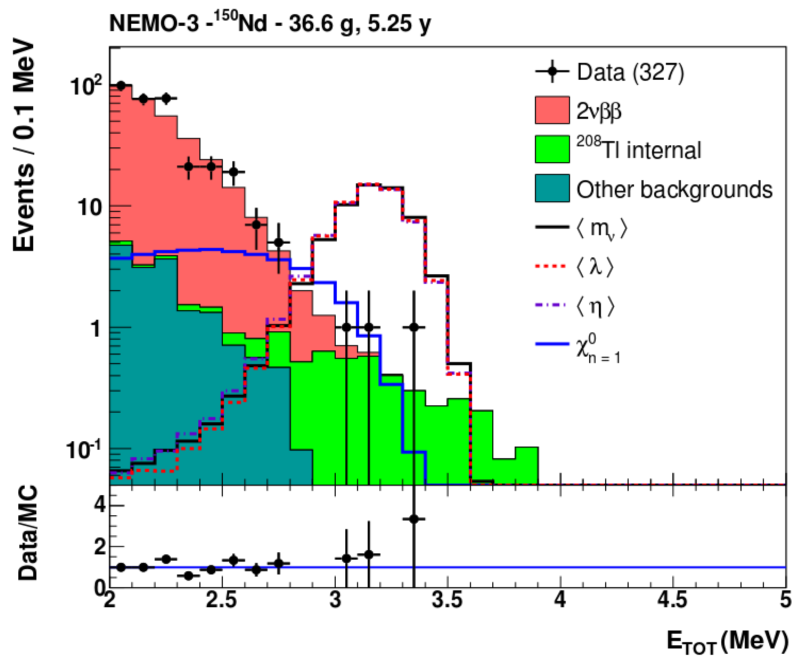
$$T^{2\nu}_{1/2} = [9.34 \pm 0.22\,(\text{stat.})\,^{+0.62}_{-0.60}(\text{syst.})] \times 10^{18}\,\text{yr}$$

- 0νββ :
  - First use of BDT to increase sensitivity by 10 %
  - Limits set for different mechanisms

$$T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{22}\,\text{yr}\,(90\%\,\text{C.L.})$$

$$\langle m_\nu \rangle < 1.6 - 5.3\ \text{eV}$$





^{116}Cd results

Phys.Rev. D95 (2017), 012007

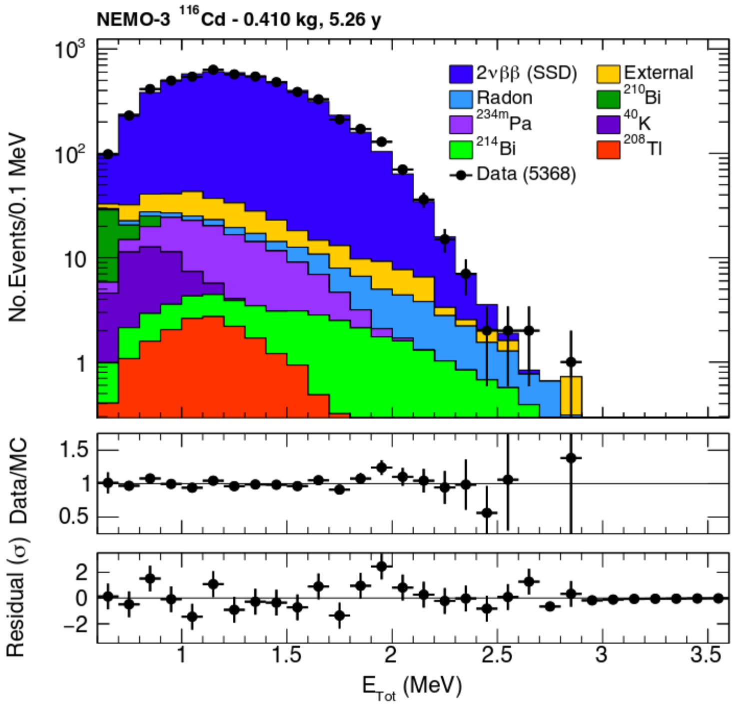
- 410 g distributed in 5 five strips
- ^{116}Cd : $Q_{\beta\beta}$ = 2.8 MeV and is a candidate isotope for futur 0νββ experiments (CdZnTe pixels)
- High precision measurement of the 2νββ decay rate :

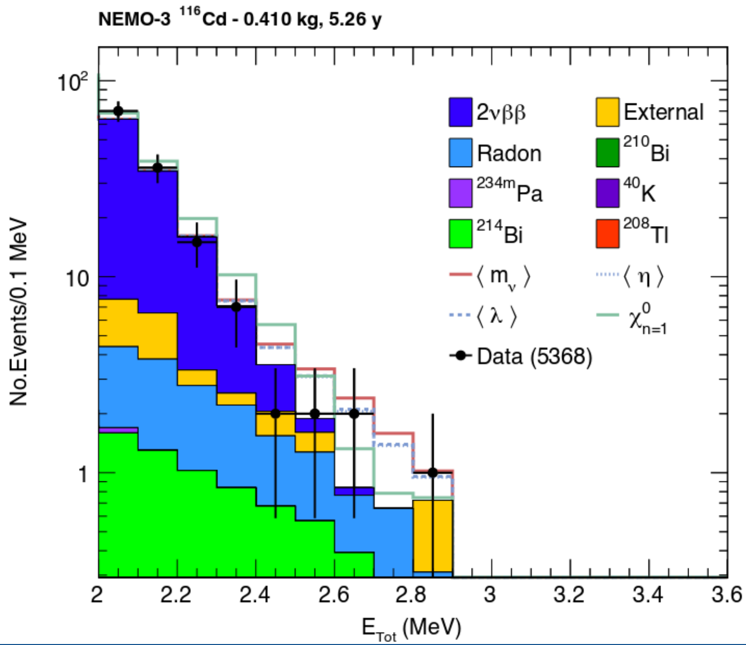
$$T_{1/2}^{2\nu} = [2.74 \pm 0.04\,(\text{stat.}) \pm 0.18\,(\text{syst.})] \times 10^{19}\,\text{yr}$$

- 0νββ :
  - Use of a multivariate analysis
  - Limits set for different mechanisms

$$T_{1/2}^{0\nu\beta\beta} > 1.0 \times 10^{23}\ \text{yr (90\% C.L.)}$$

$$\langle m_\nu \rangle < 1.4 - 2.5\text{eV}$$

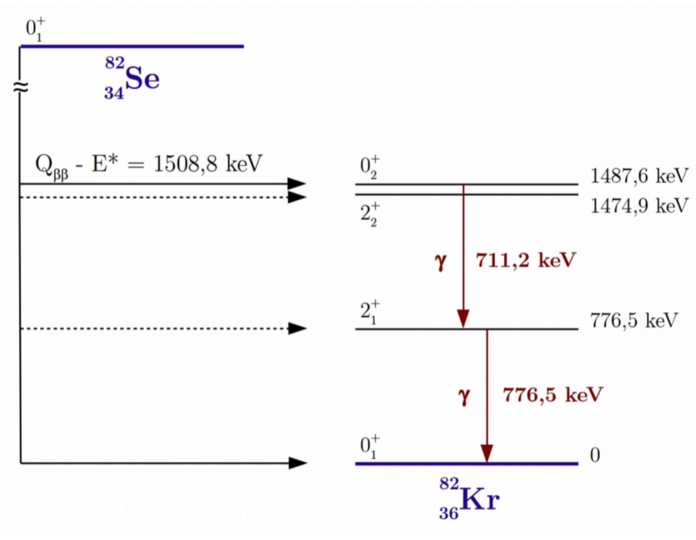


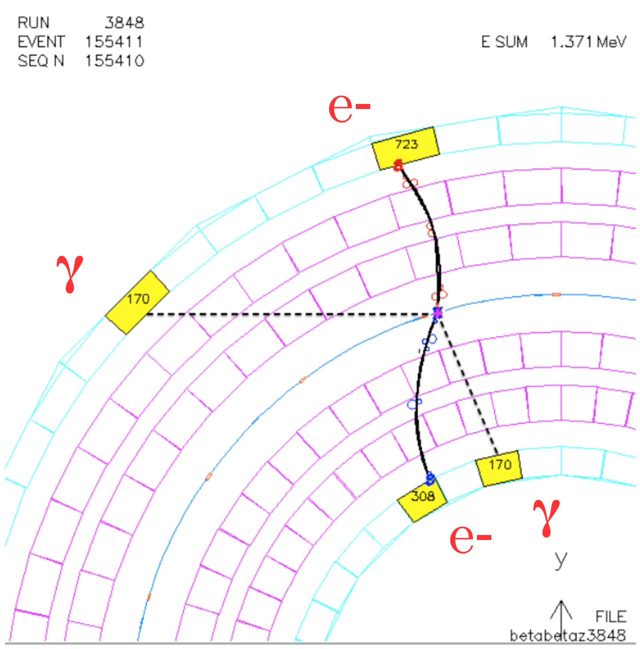


Searches for exotic processes

Decay via the excited states

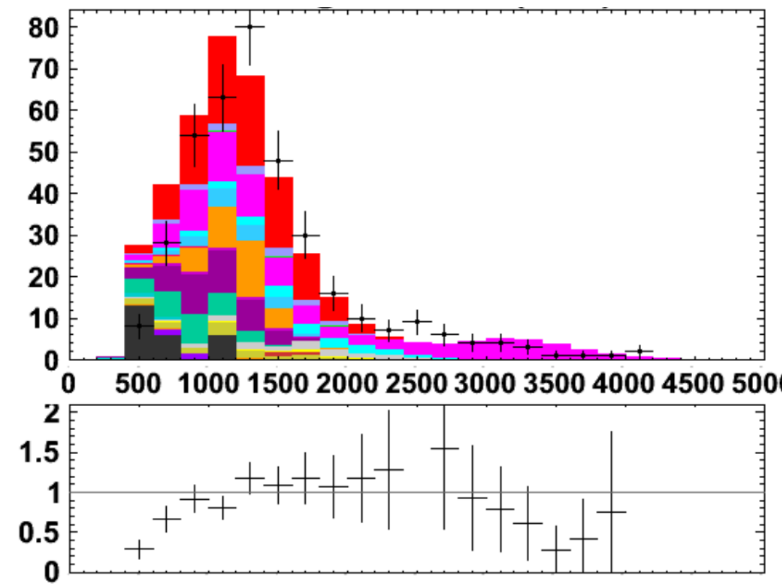
- The double beta decay can also occurs via the excited state of the daughter nucleus
- Provide additional handle for NME calculations
- Alternative channel to study an hypothetical $0\nu\beta\beta$ signal
- Might help to distinguish alternative $0\nu\beta\beta$ decay mechanisms
- Signature : 2e + one or more mono-enertic γ in coincidence
- Background is highly suppressed





Decay via the excited states

- Several isotopes have already been investigated
  - ^{150}Nd (S. Blondel Ph.D. thesis 2013)



$$T_{1/2}(^{150}\mathrm{Nd}_{0^+\to 0_1^+}) = [7,12 \pm 1,28\ (\mathrm{stat.}) \pm 0,91\ (\mathrm{syst.})] \times 10^{19}\ \mathrm{ans}$$

$$T_{1/2}^{2\beta 0\nu}(^{150}\mathrm{Nd}_{0^+\to 0_1^+}) > 1,6 \times 10^{21}\ \mathrm{ans}$$

$$T_{1/2}^{2\beta 2\nu}(^{150}\mathrm{Nd}_{0^+\to 2_1^+}) > 2,4 \times 10^{20}\ \mathrm{ans}$$

  - ^{96}Zr (G. Eurin Ph.D. thesis 2015)

$$T_{1/2}^{2\nu 2\beta}(^{96}\mathrm{Zr} \to ^{96}\mathrm{Mo}, 0_1^+) > 5.85 \times 10^{19}\ \mathrm{y}\ @\ 90\%\ \mathrm{C.L}$$

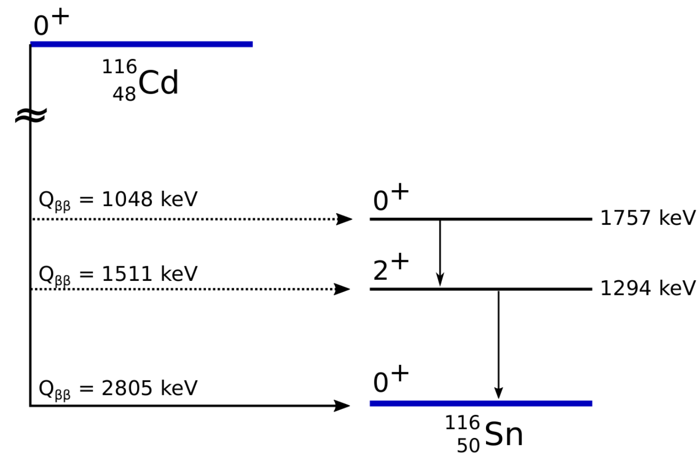
  - ^{82}Se (B. Soulé Ph.D. thesis 2015)

$$T_{1/2}^{2\nu}(^{82}Se, 0_1^+ \to 0_1^+) = (10{,}87 \pm 0{,}15(stat.) \pm 0{,}80(syst.)) \times 10^{19}\ \mathrm{ans}$$

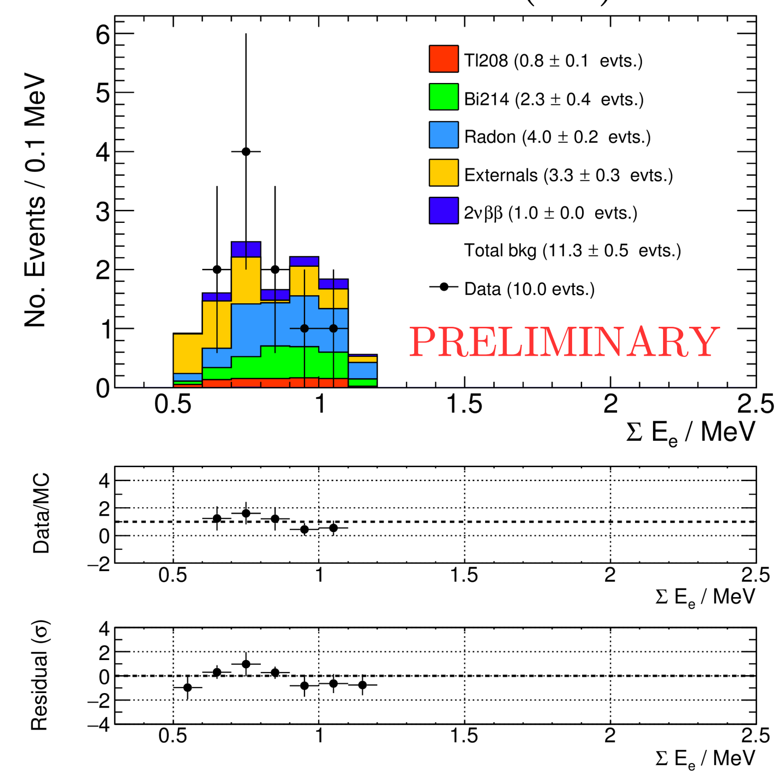
$$T_{1/2}^{0\nu}(^{82}Se, 0_1^+ \to 0_2^+) > 2{,}31 \times 10^{22}\ \mathrm{ans}$$

Decay via the excited states

- ^{116}Cd → ^{116}Sn analysis via the excited states (2+) and (0+) are on going in 2ν and 0ν decay modes :
  - Use the same background model implemented for ^{116}Cd decay to the ground state.
  - Use the rich informations provided by full event reconstruction to perform a multi-variate analysis.
  - According to the excited states 7 or 8 variables are used such as electron energy, photon energy, angle, TOF…



Excited state (2+) 2ν

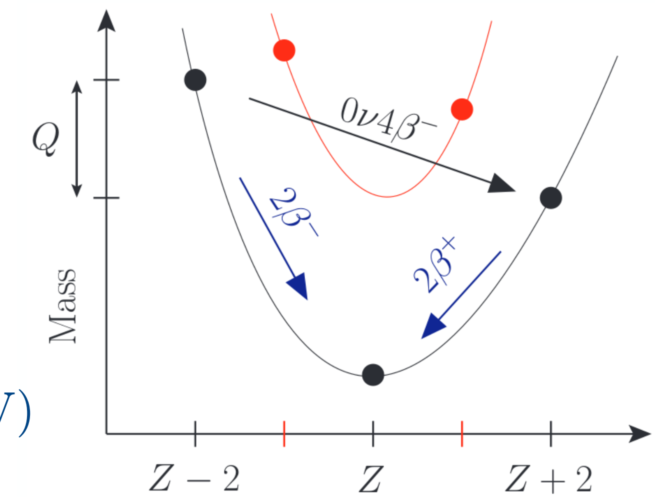


For the excited state (2+) 2ν, a sensitivity of $T_{1/2} > 5.7 \times 10^{20}$ y is expected

Quadruple beta decay

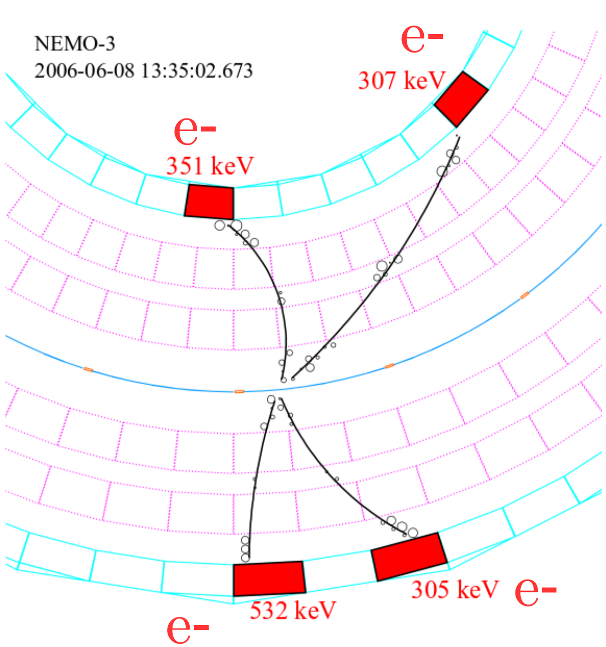
Neutrinoless quadruple beta decay

- Proposed by Heeck and Rodejohann [1]
- Lepton number violating process
- Neutrinos are Dirac particle and $0\nu\beta\beta$ is forbidden
- The best candidate is $^{150}Nd \rightarrow {}^{150}Gd + 4e$ ($Q_{4\beta} = 2.079$ MeV)

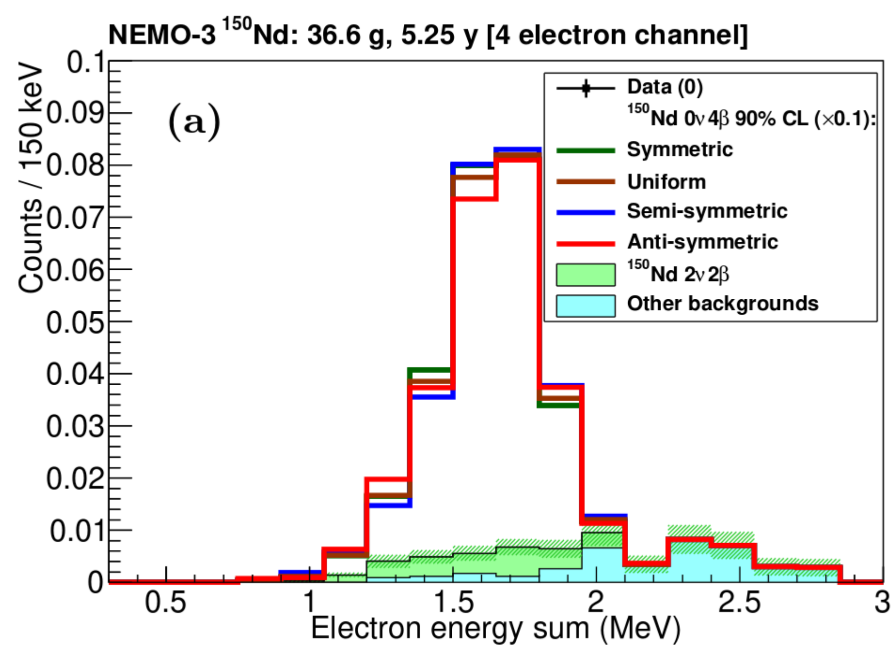


Exploit the unique ability of NEMO-3 to reconstruct the kinematics of each e-

- Paper submitted to PRL
- World's first limit on this process

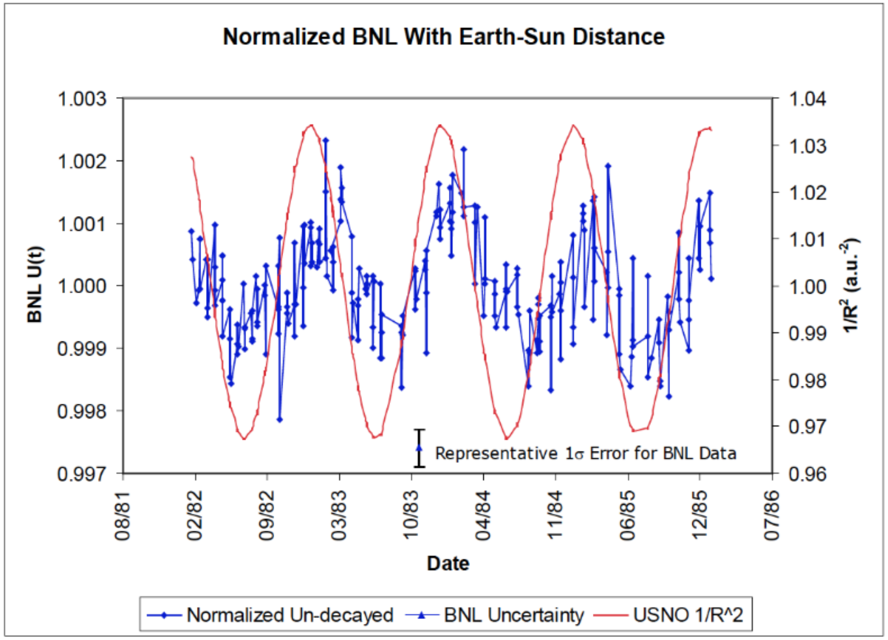


arXiv:1705.08847v1



Searches for periodic modulation in decay rate

- Nuclear decays are governed by various fundamental forces and are considered unaffected by the external temporal or environmental effects.
- Modulations in nuclear decay rate may point toward physics beyond standard model.
- Some experiments claim the observation of modulation of decay rate (BNL : ^{32}Si)



BNL experiment Astropart.Phys. 32 (2009) 42-46

- NEMO-3 ran during over 7 years.
- Use the ^{100}Mo sample (largest and cleanest ββ sample in NEMO-3)
- First search for periodic variation in the 2νββ decay rate
- No evidence of periodic modulations has been found (publication soon)

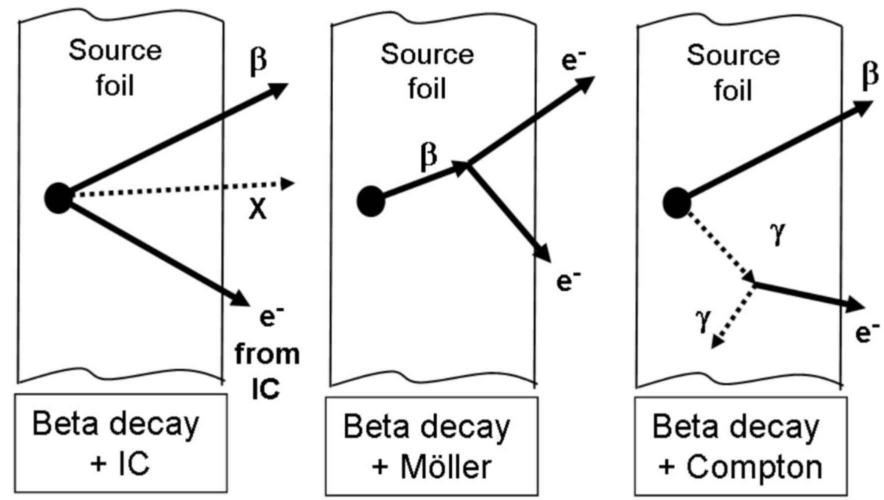
Conclusion

- Final searches to $0\nu\beta\beta$ have been published : ^{100}Mo, ^{116}Cd, ^{150}Nd, ^{48}Ca
- Most precise measurement of $2\nu\beta\beta$ decay rate for ^{116}Cd and ^{150}Nd published so far
- Non competitive limits on $0\nu\beta\beta$ (due to limited exposure), but proof of concept for SuperNEMO.
- First use of multivariate techniques to enhance signal/background discrimination and sensitivity
- Some exotic searches have also been performed
  - Study of $\beta\beta$ decay to excited state performed over ^{150}Nd, ^{82}Se, ^{96}Zr and ^{116}Cd
  - Searches for $0\nu4\beta$ on going : arXiv:1705.08847v1
  - Searches for periodic modulation of ^{100}Mo $2\nu\beta\beta$ decay rate : publication soon
- Final search for ^{82}Se is under finalisation ($2\nu\beta\beta$ and $0\nu\beta\beta$)
- Future : SuperNEMO is currently under construction (more details S. Calvez's presentation)

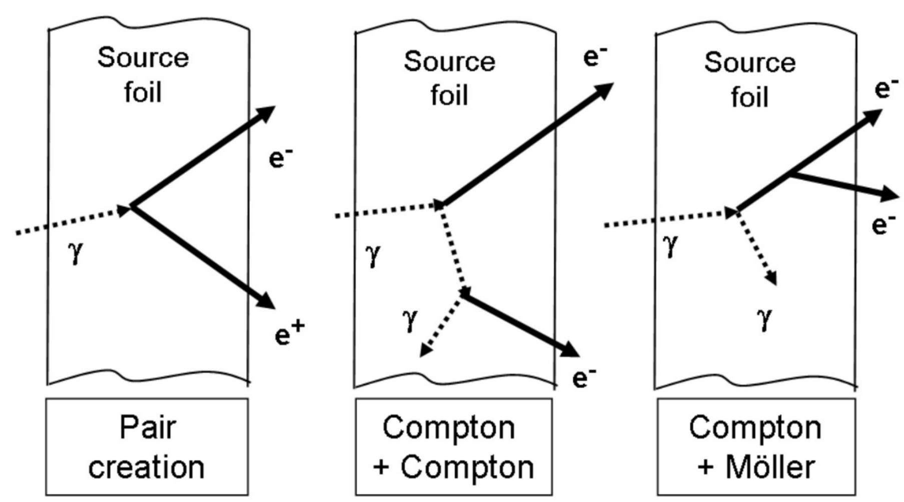
Back -up

The backgrounds

- Internal backgrounds :
  - ^{208}Tl (from ^{232}Th), ^{214}Bi (from ^{238}U) contamination in foil source
  - ^{214}Bi from radon decay in tracker volume
  - Single beta emitter (^{40}K, ^{234m}Pa, ^{210}Bi)

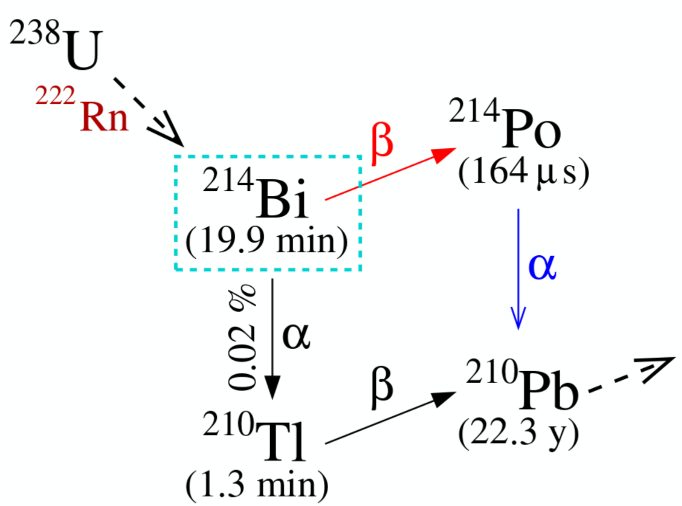


- External backgrounds :
  - Radio-impurities in detector material (^{208}Tl, ^{214}Bi)
  - γ from (n,γ) reactions
  - μ Bremsstrahlung

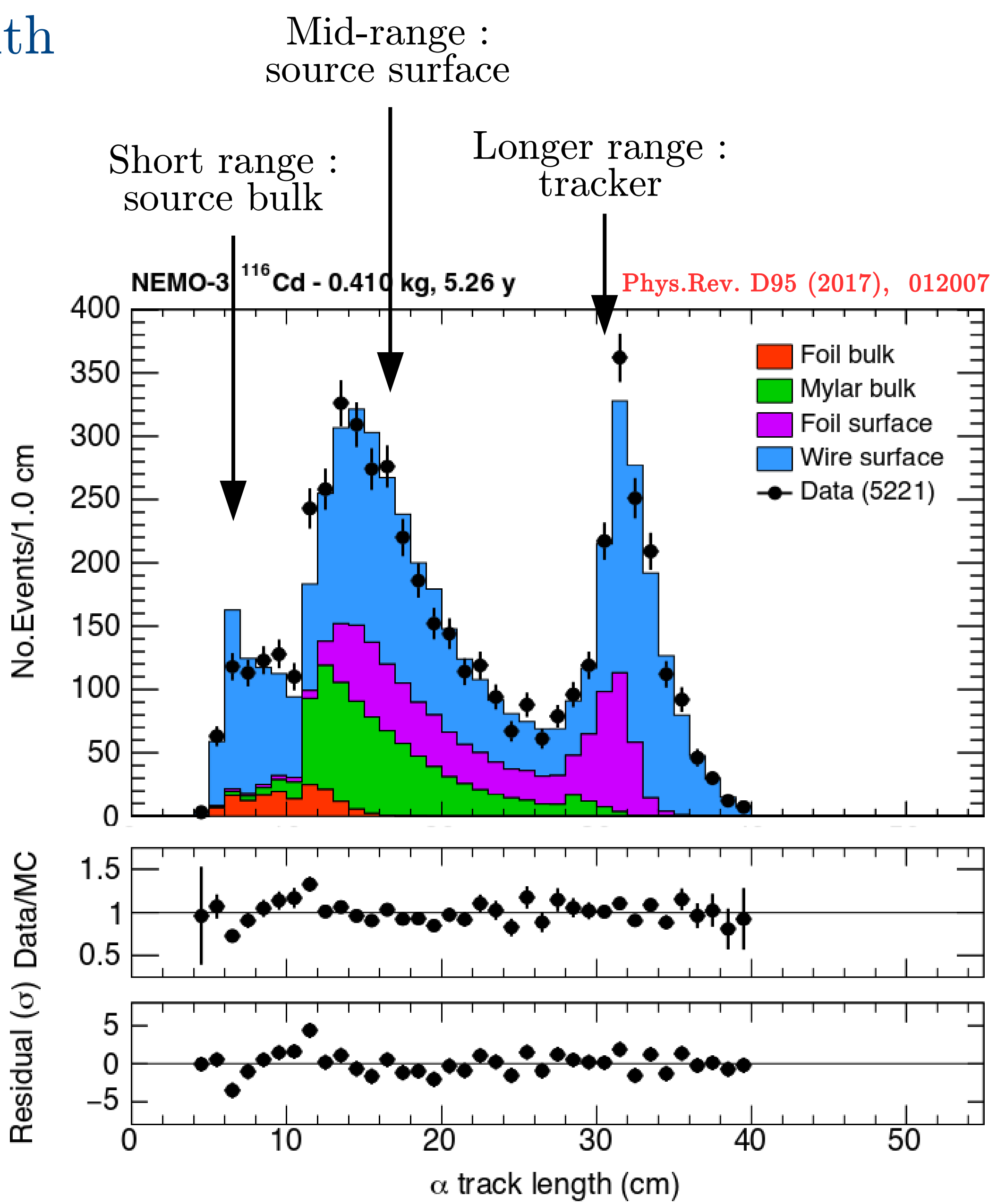


^{214}Bi and Radon

- ^{214}Bi is a dangerous background with $Q_\beta = 3.3$ MeV
- Arise from ^{238}U-chain or ^{222}Rn emanation
- Measured in 1e1α channel



- Background free measurement
- Alpha track length sensitive to different contamination origin



Searches for periodic modulation in decay rate

- In their *Radiations from Radioactive Substances*, E. Rutherford, J. Chadwick and Charles Ellis concluded :

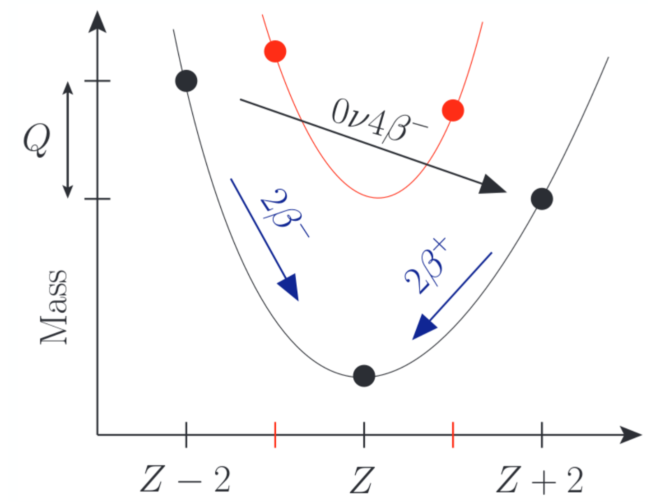
« the rate of transformation [...] is a constant under all conditions »

- Is the decay « constants » are influenced by the Sun ? By which phenomena ? Influence of solar neutrino ? arXiv:0808.3283
- An experiment performed at Brookhaven National Laboratory (BNL), between 1982 and 1986, by studying silicon-32, found that its half-life modulated around its usual value (172 y) by the order of 0.1 %.
- The modulation appeared to be almost in phase with the varying distance of the Earth to the Sun: in January, when the Earth is closest, the decay rate was faster; in July, when the Earth is farthest, it was slower.
- The variation of the decay rate have also been claimed for Manganese-54 arXiv:0808.3156
- The results are controversial, and the physics community is skeptical. Very small deviation and what about the stability of the detectors ?

Quadruple beta decay 1

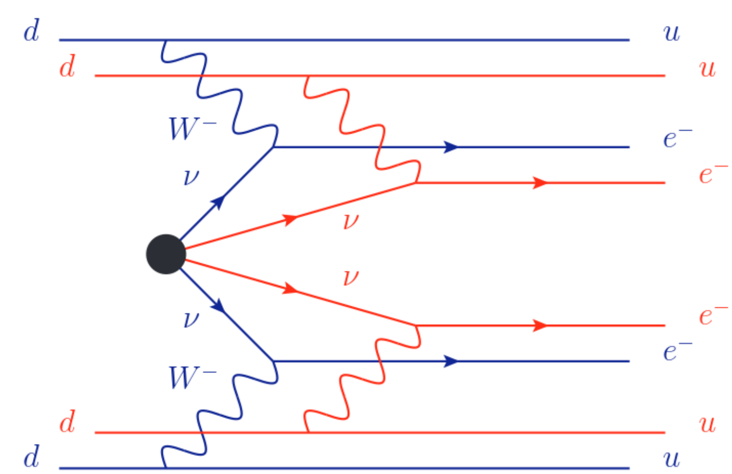
Only 3 candidates

	$Q_{0\nu4\beta}$	Other decays	NA
$^{96}_{40}Zr \rightarrow ^{96}_{44}Ru$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}Xe \rightarrow ^{136}_{58}Ce$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}Nd \rightarrow ^{150}_{64}Gd$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6



Estimated life-time :

$$\frac{\tau_{0\nu4\beta}}{\tau_{2\nu2\beta}} \simeq 10^{46} \left(\frac{\Lambda}{\text{TeV}}\right)^4$$



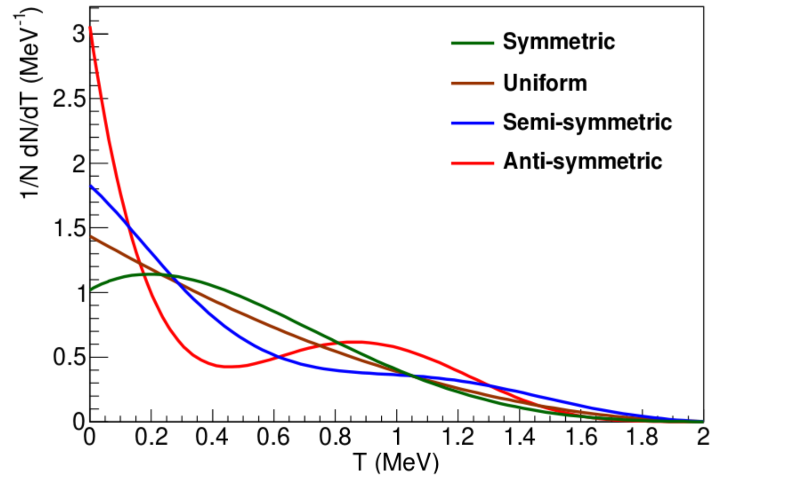
4n4b is killed by the Q-dependance of the eight-particle phase space ~ Q^{23} (compared to Q^{11} for 0n4b)

Quadruple beta decay 2

Very uncertain and little phenemenoly in the literature

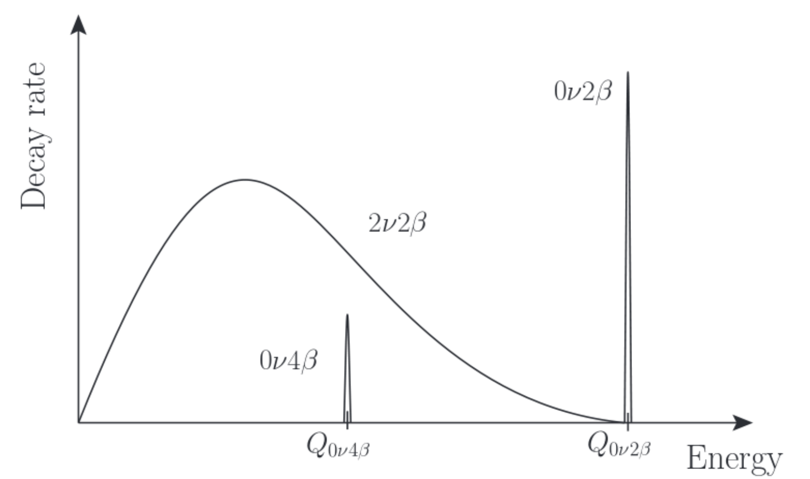
Due to the absence of a complete theoretical treatment of the kinematics of 0n4b decays, 4 models of the electron energy distribution have been tested

- Uniform $Q_{0n4b} = E_1+E_2+E_3+E_4$ (distributed uniformly)
- Symmetric $A_m = \mathcal{S}\{1 \times 1\}$
- Semi-symmetric $A_m = \mathcal{S}\{1 \times (T_k - T_l)^2\}$
- Anti-symmetric $A_m = \mathcal{S}\{(T_i - T_j)^2 \times (T_k - T_l)^2\}$



$$\frac{d^4N}{\prod_{i=1}^{4} dT_i} \propto A_m \delta\left(Q_{4\beta} - \sum_{i=1}^{4} T_i\right) \cdot \prod_{i=1}^{4} (T_i + m_e) p_i F(T_i, Z),$$

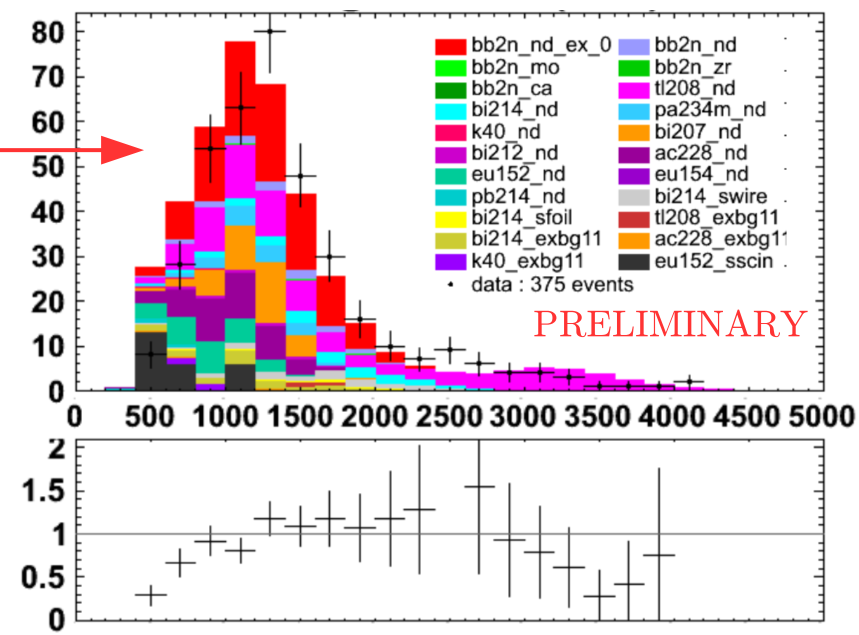
S{…} is a sum over the symmetric interchange of label i,j,k,l of the four electrons



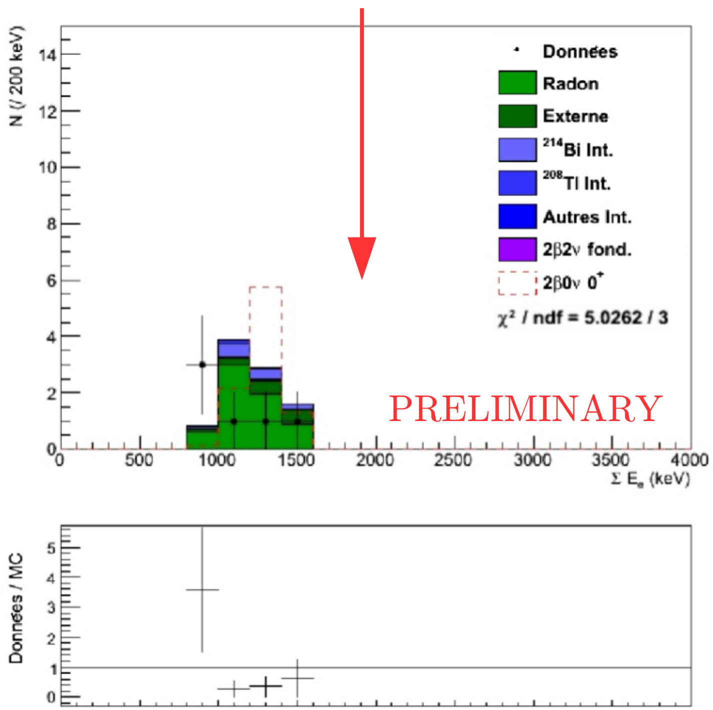
Decay via the excited states

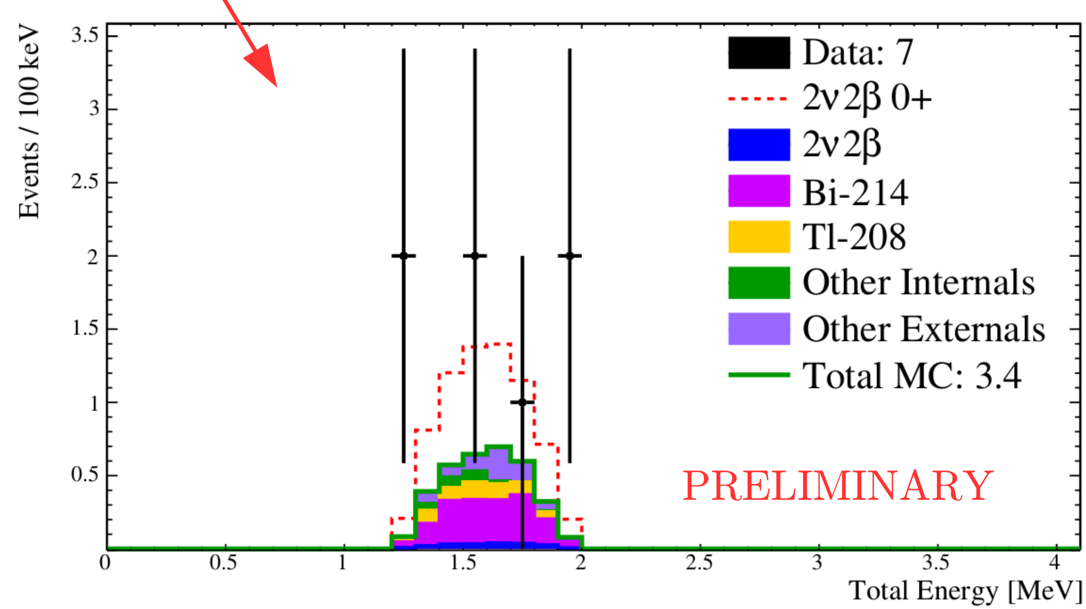
- Several isotopes have been investigated :
  - ^{150}Nd (S. Blondel Ph.D. thesis 2013)

$$T_{1/2}(^{150}\mathrm{Nd}_{0^+\to 0_1^+}) = [7,12 \pm 1,28\ (\mathrm{stat.}) \pm 0,91\ (\mathrm{syst.})] \times 10^{19}\ \mathrm{ans}$$



  - ^{96}Zr (G. Eurin Ph.D. thesis 2015)
  - ^{82}Se (B. Soulé Ph.D. thesis 2015)





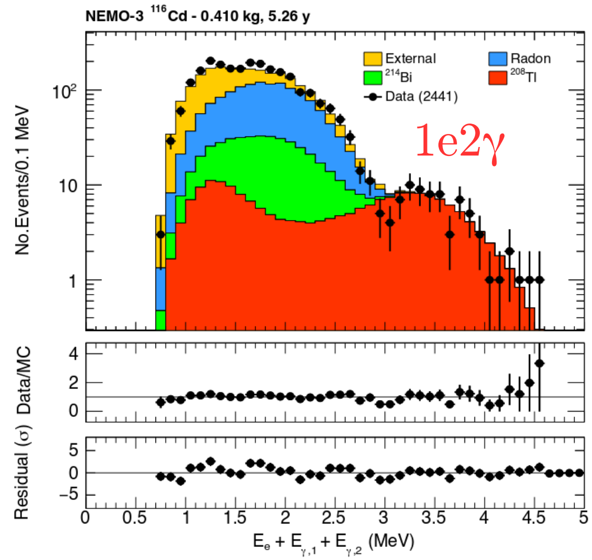
Background measurements

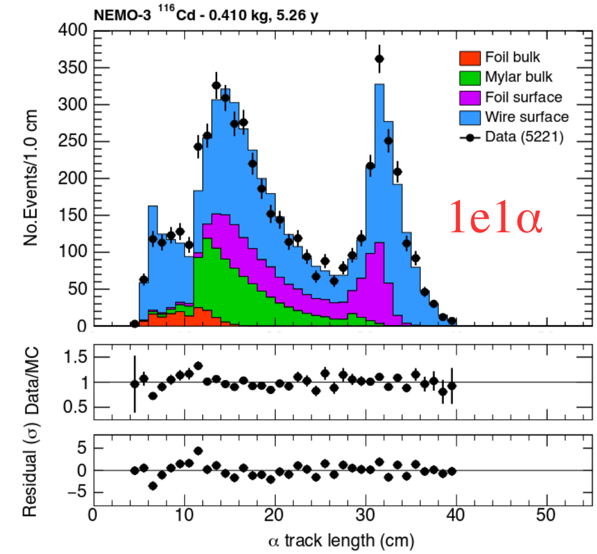
Backgrounds are measured through different background channels using event topologies

Figures from Phys.Rev. D95 (2017), 012007

Internal backgrounds are measured in 5 channels :

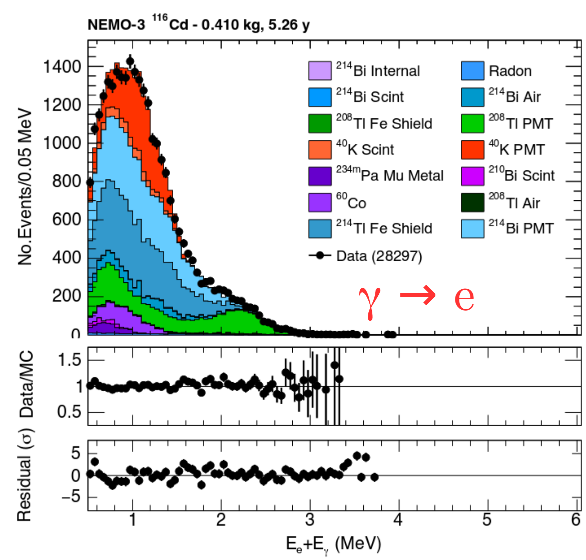
- 1e (^{40}K, ^{234m}Pa, ^{210}Bi)
- 1e1α (^{214}Bi - ^{222}Rn)
- 1e1γ (^{214}Bi and ^{208}Tl)
- 1e2γ (^{208}Tl)
- 1e3γ (^{208}Tl)

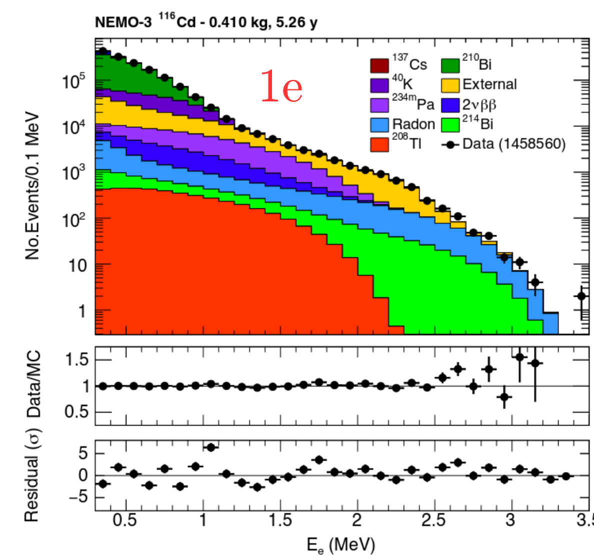




External backgrounds are measured in 2 main channels :

- external crossing electron
- external γ → e





Decay via the excited states

- Several isotopes have already been investigated

Decays	$T_{1/2}$ [y] at 90 % C.L.		
	^{82}Se B. Soulé Ph.D. thesis 2015	^{96}Zr G. Eurin Ph.D. thesis 2015	^{150}Nd S. Blondel Ph.D. thesis 2013
$(g.s \rightarrow 0^+)$ $2\nu\beta\beta$	$> 1.29 \times 10^{21}$	$> 5.85 \times 10^{19}$	$(7.12 \pm 1.28 \pm 0.91) \times 10^{19}$
$(g.s \rightarrow 0^+)$ $0\nu\beta\beta$	$> 2.31 \times 10^{22}$	-	$> 1.6 \times 10^{21}$
$(g.s \rightarrow 2^+)$ $2\nu\beta\beta$	-	-	$> 2.4 \times 10^{20}$
$(g.s \rightarrow 2^+)$ $0\nu\beta\beta$	-	-	-