Latest results from NEMO-3 and commissionning status of the SuperNEMO demonstrator

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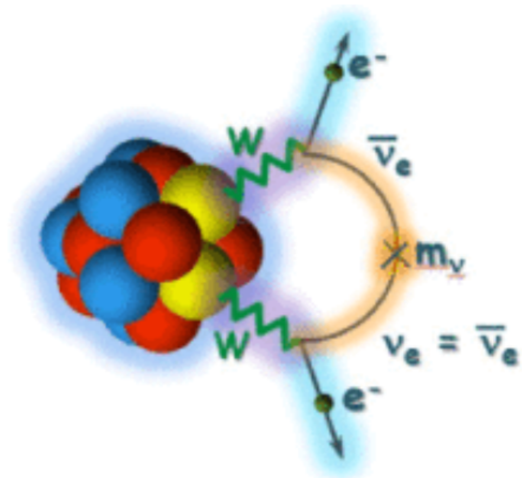
On behalf of the NEMO collaboration

Neutrinoless double beta decay

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



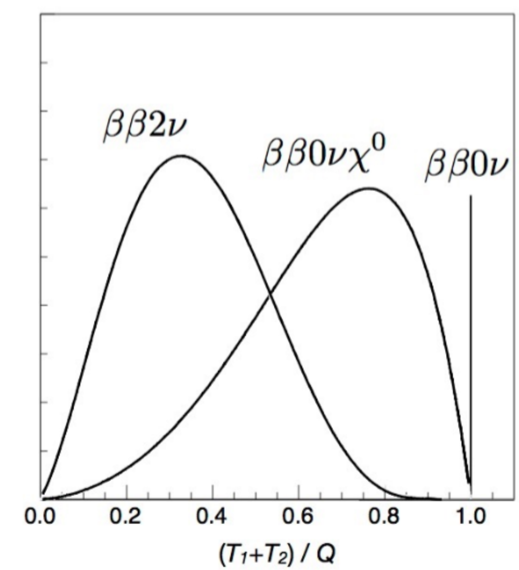
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

Phase space (well known)

Nuclear matrix elements (challenging to compute)

Take into account the mechanism underlying the 0νββ process

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

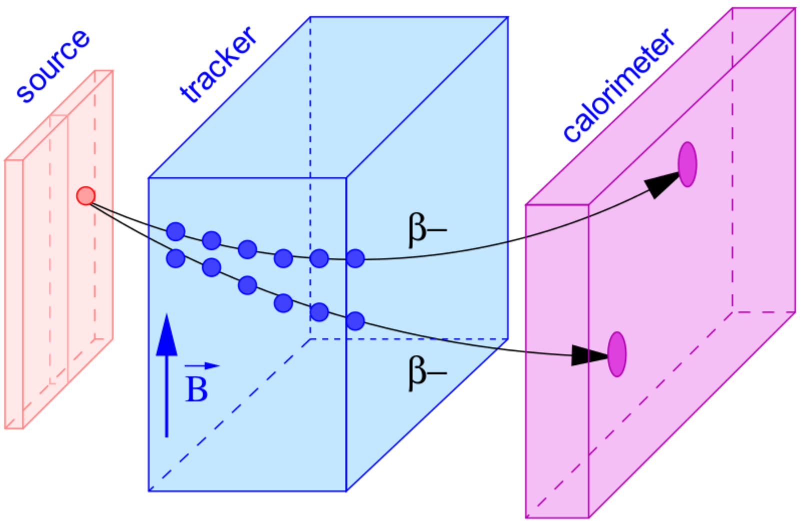


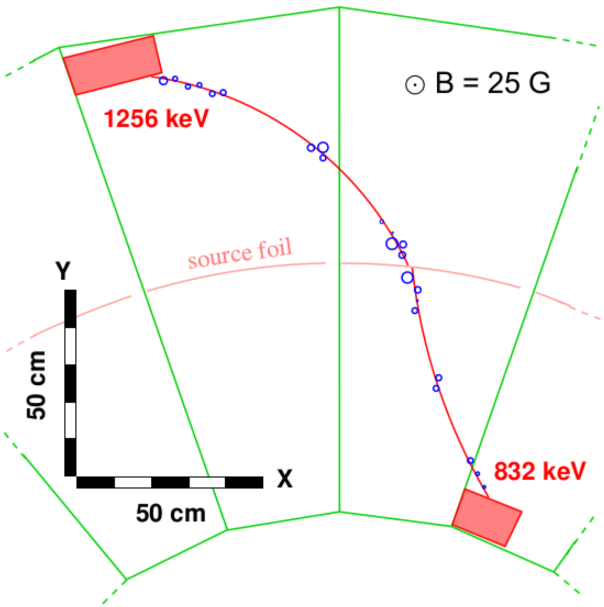
The tracker-calorimeter technique

- Source separated from detector : many $\beta\beta$ isotopes can be investigated

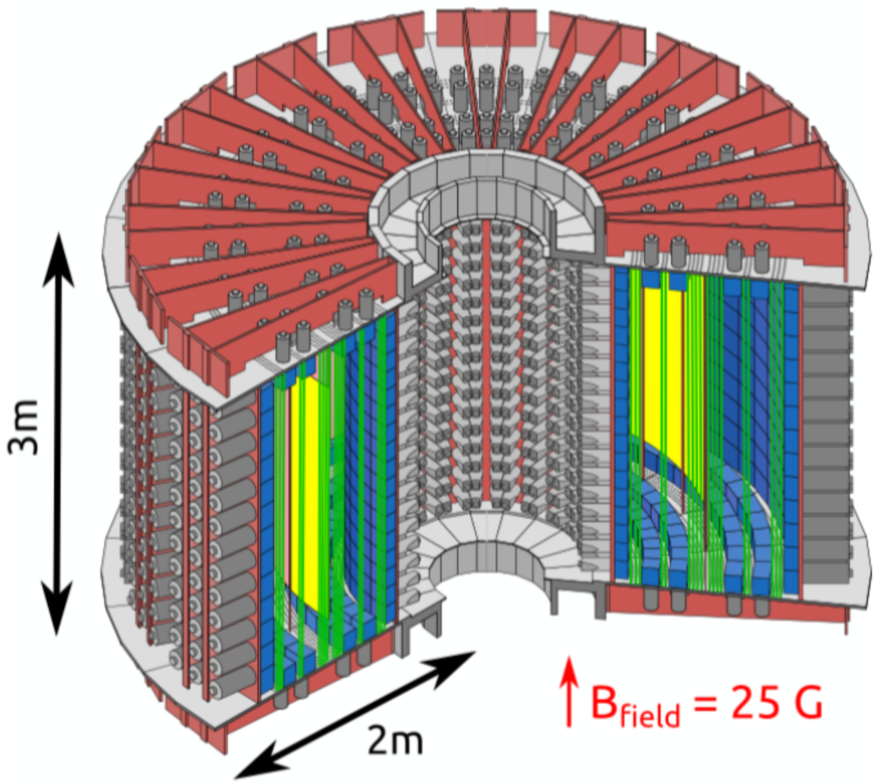
- Reconstruction of the final state topology and particle identification :
  - Precise background identification and measurement
  - Possible discrimination of mechanism behind $0\nu\beta\beta$ process

- Generally lower energy resolution and detection efficiency than homogeneous detector (HPGe and bolometers)



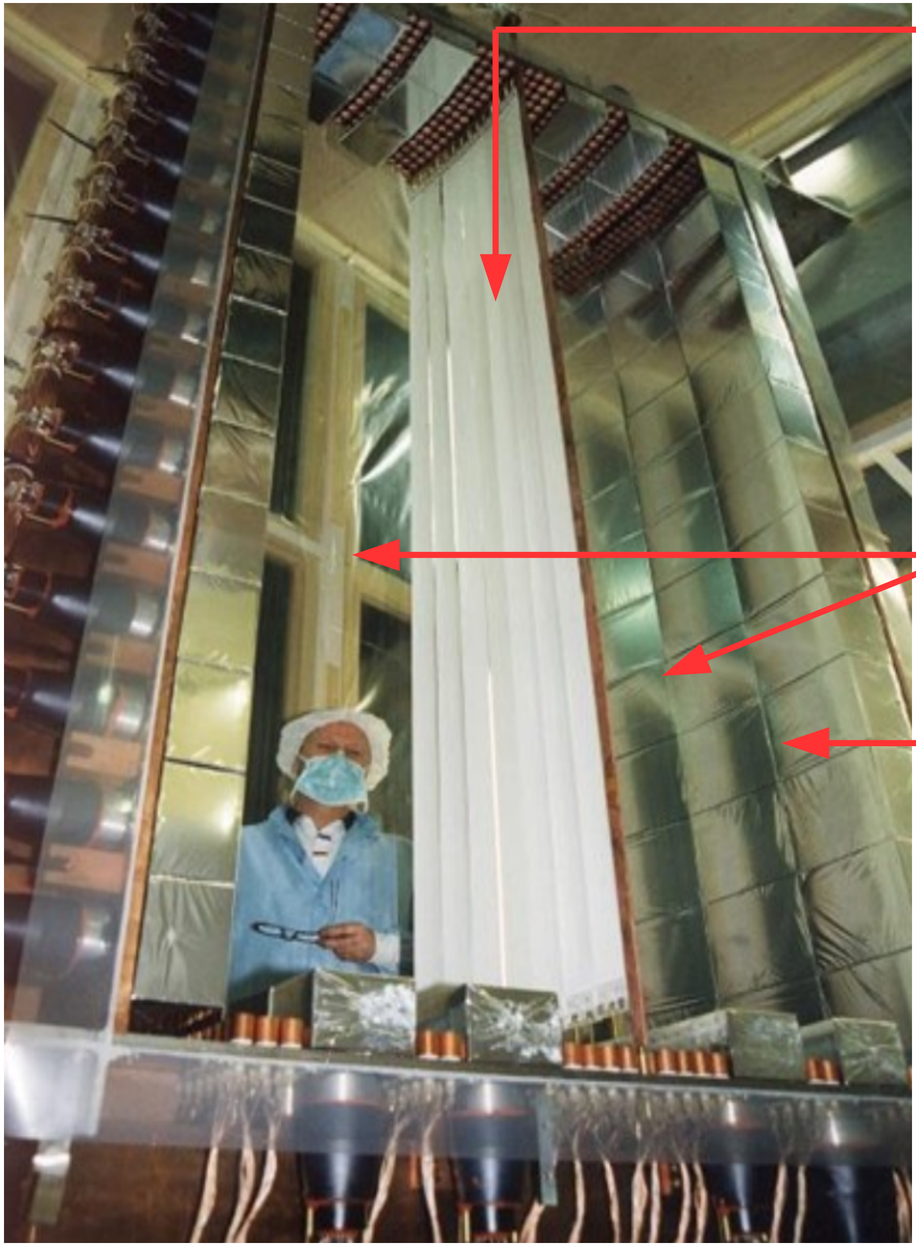


The NEMO-3 detector



- 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

  → Latest results presented in this talk

  + Ultra-pure Cu and very pure ^{nat}Te blank foils to cross check background measurements

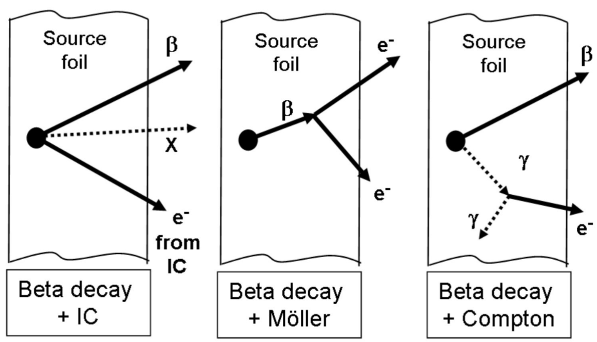
- **Wire drift chamber** made of 6180 Geiger cells, σ_{vertex} = 3 mm (XY), 10 mm (Z)
- **Calorimeter** made of 1940 polystyrene scintillators coupled with low radioactivity PMTs, FWHM ~15 % at 1 MeV
- 25 Gauss magnetic field for the charge identification
- Gamma and neutron shields, anti-radon tent

Backgrounds

- ## Internal backgrounds

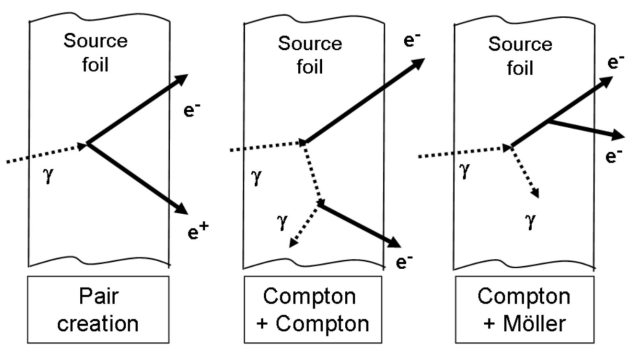
  2νββ tail and radio-impurities inside the source foil

  ^{208}Tl (from ^{232}Th), ^{214}Bi (from ^{238}U)



- ## External backgrounds

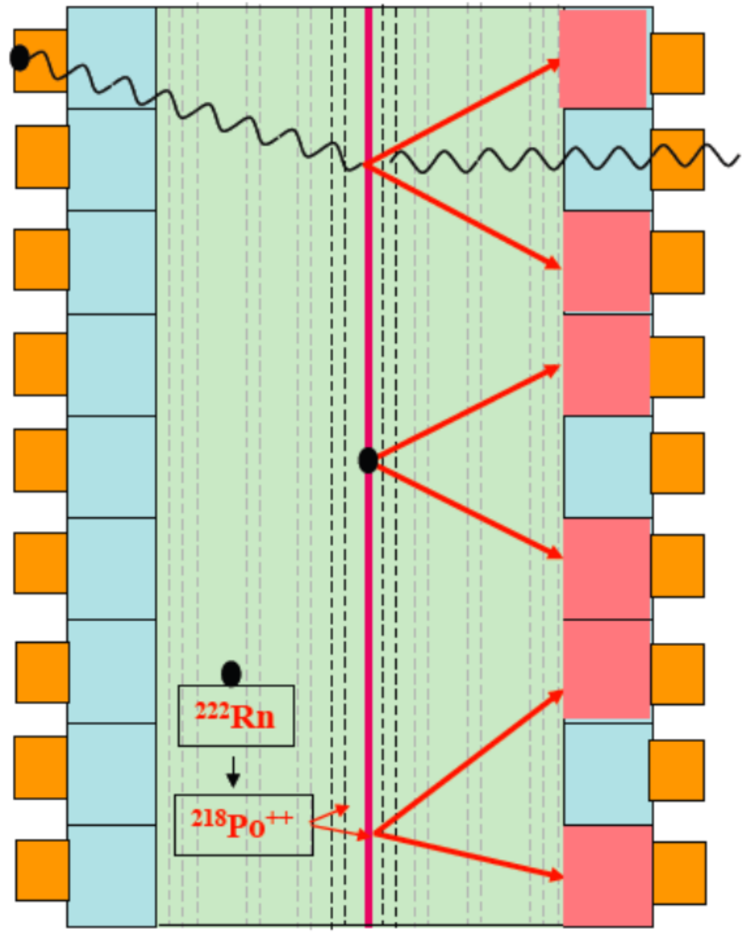
  Radio-impurities of the detector



- ## Radon inside the tracking detector

  Deposits on the wire near the ββ foil

  Deposits on the surface of the ββ foil



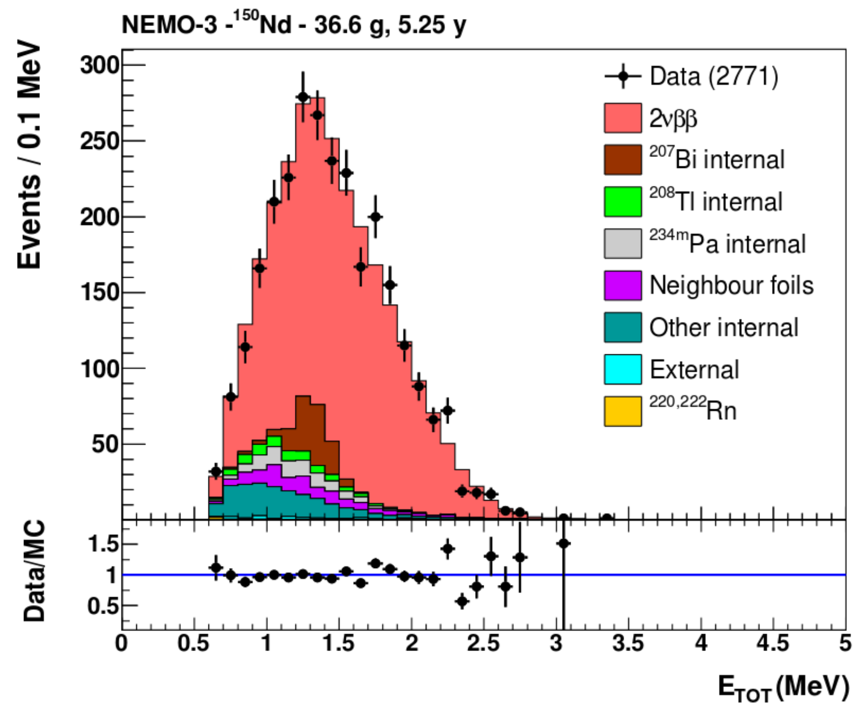
Backgrounds are measured through different background channels using event topologies

^{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 :

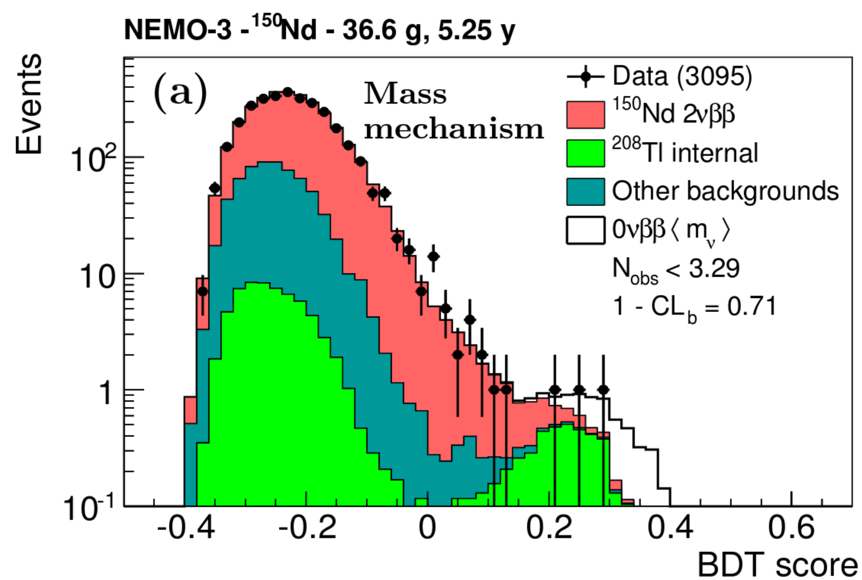
$$T^{2\nu}_{1/2} = [9.34 \pm 0.22\,(\text{stat.})\,^{+0.62}_{-0.60}(\text{syst.})] \times 10^{18}\,\text{yr}$$



- 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

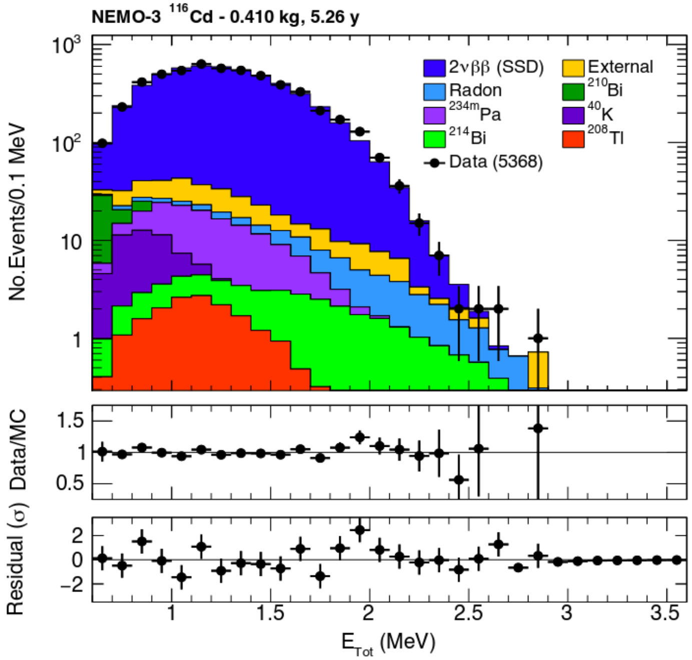
- 410 g distributed in 5 strips
- ^{116}Cd : $Q_{\beta\beta} = 2.8$ MeV and is a candidate isotope for future 0νββ experiments (CdZnTe pixels)
- High precision measurement of the 2νββ decay rate :

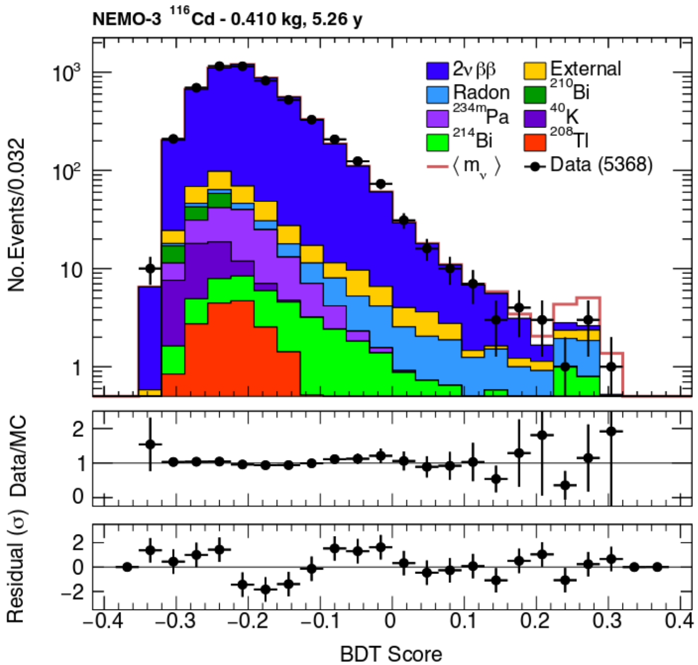
$$T_{1/2}^{2\nu} = [2.74 \pm 0.04\,(\text{stat.}) \pm 0.18\,(\text{syst.})] \times 10^{19}\,\text{yr}$$

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

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

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

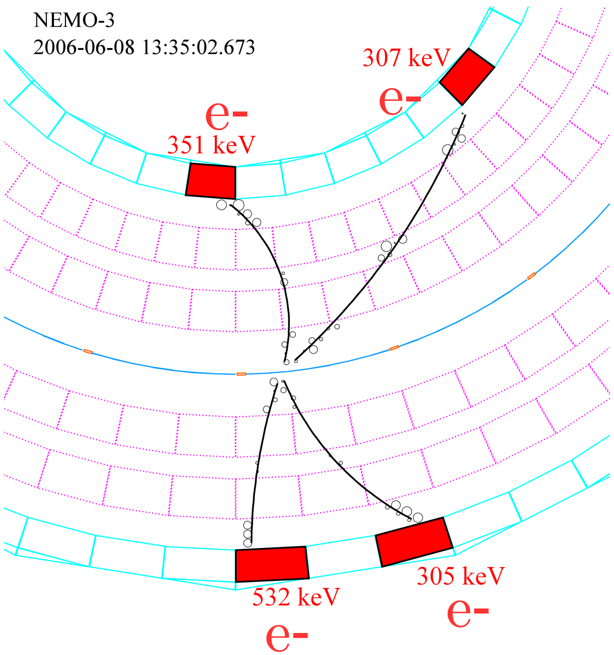




0ν4β results

Accepted by PRL arXiv: 1705.08847

- Neutrinoless quadruple beta decay
  - Proposed by Heeck and Rodejohann Europhys. Lett. 103, 32001 (2013)
  - Lepton number violating process
  - Neutrinos are Dirac particles and 0νββ is forbidden in this model
  - The best candidate is $^{150}Nd \rightarrow {}^{150}Gd + 4e$ ($Q_{4\beta} = 2.079$ MeV)



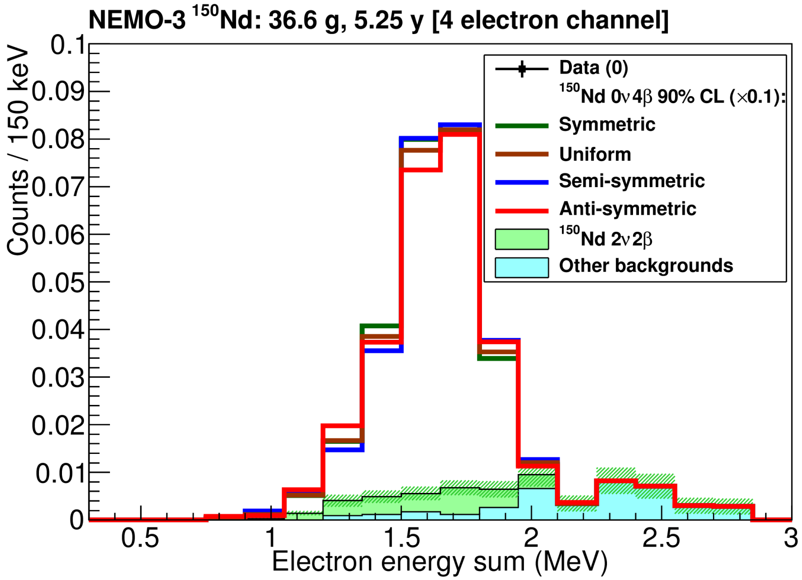
- Exploit the unique ability of NEMO-3 to reconstruct the kinematics of each e-

- No evidence of this decay

$$T_{1/2}^{0\nu4\beta} > (1.1 - 3.2) \times 10^{21} \text{ y}$$

Depending on the model

- World's first limit on this process

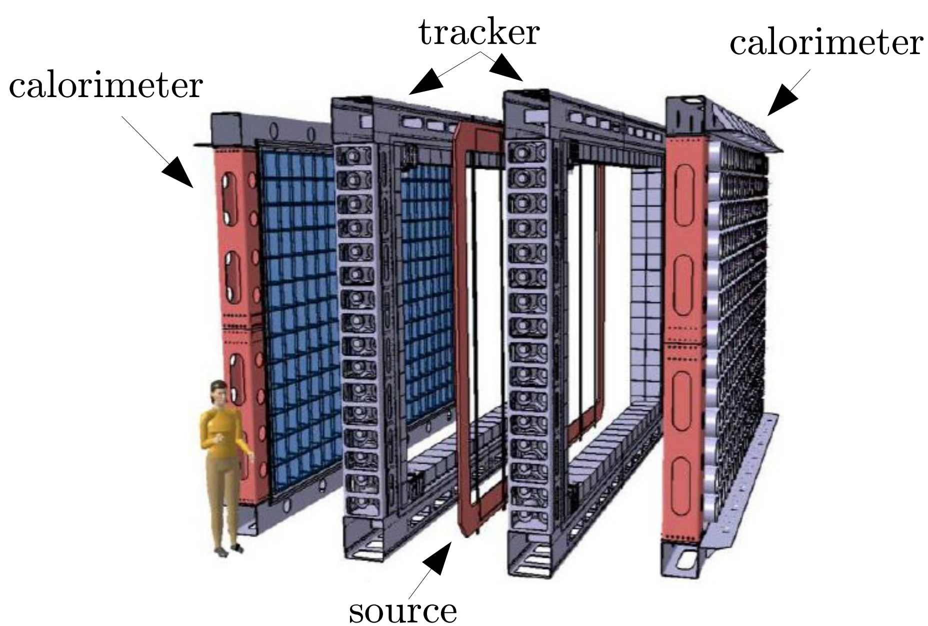


Installation and Commissionning status of the SuperNEMO demonstrator

SuperNEMO demonstrator module

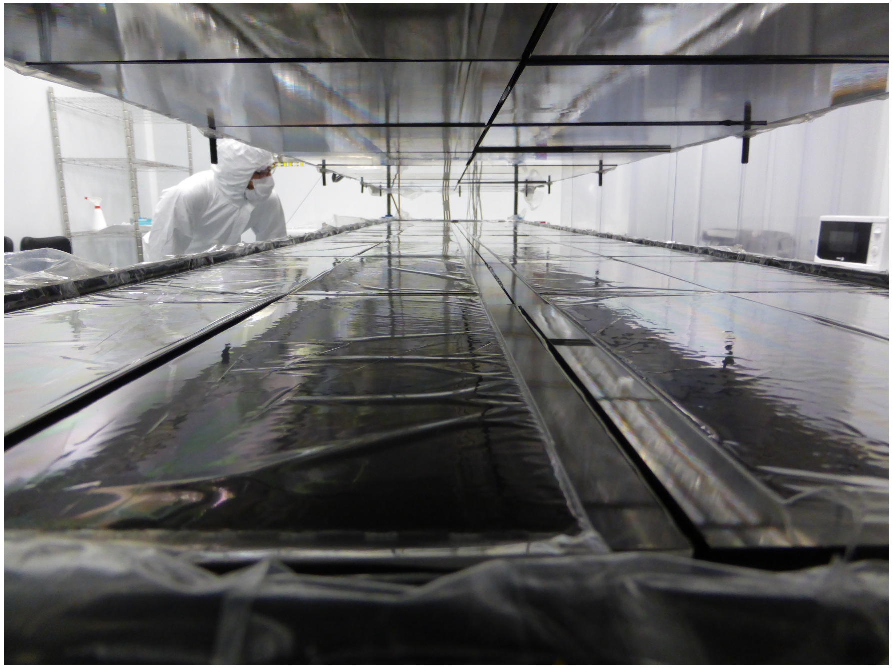
	NEMO-3	SuperNEMO demonstrator
Mass [kg] (main isotopes)	7 (^{100}Mo)	7 (^{82}Se)
$T^{2\nu}_{1/2}$ [y]	7.2×10^{18}	9.9×10^{19}
Energy resolution		
FWHM at 1 MeV	15 %	8 %
FWHM at 3 MeV	8 %	4 %
Source radiopurity		
A(^{208}Tl)	$\sim 100\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
A(^{214}Bi)	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg
Level of radon A(^{222}Rn)	~ 5.0 mBq/m^3	< 0.15 mBq/m^3
Sensitivity after 5 y of data taking	$T^{0\nu}_{1/2} > 10^{24}$ y	$T^{0\nu}_{1/2} > 6 \times 10^{24}$ y

- Goal of the demonstrator
  - Run for 2.5 y with 7 kg of ^{82}Se
    → $T_{1/2} > 6 \times 10^{24}$ y $m_{\beta\beta} < 0.2 – 0.55$ eV
  - Prove SuperNEMO module can be a background free experiment in the region of interest



SuperNEMO source foils

- 7 kg of ^{82}Se ($Q_{\beta\beta}$ = 2.998 MeV) distributed in 36 foils
- Made of ^{82}Se + PVA glue + mylar (mechanical support)
- Different purification methods tested : distillation, chromatography, chemical precipitation
- Very challenging requirements on foil contamination :
  - A(^{208}Tl) < 2uBq/kg and A(^{214}Bi) < 10uBq/kg
- Radiopurity measured in a dedicated detector BiPo



JINST 12 (2017), P06002

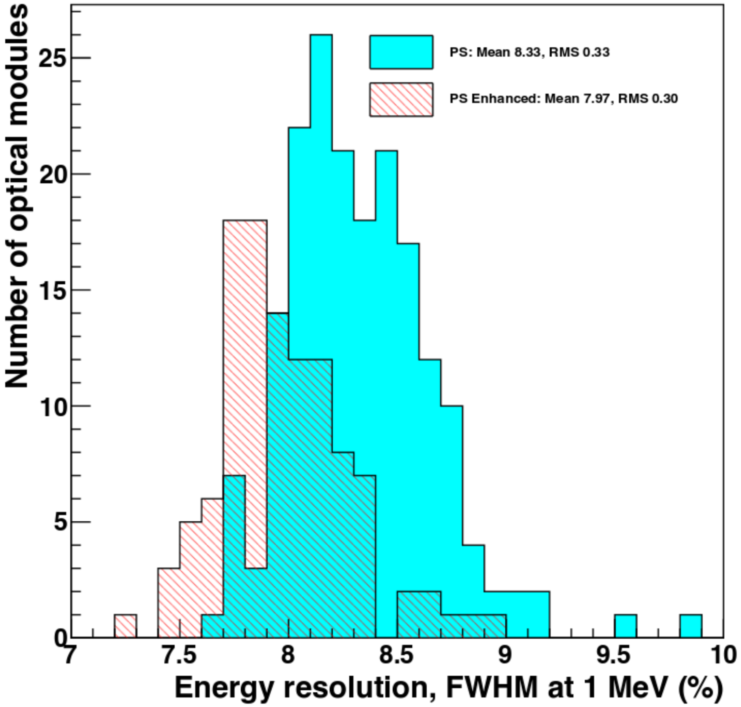
SuperNEMO tracker

- 2034 drift cells working in Geiger mode
- Ultrapure materials : copper, steel, duracon. HPGe and radon tested.
- Robotic construction
- Radiopure gas flow, anti-radon sealing
- < 1 % of dead channels

SuperNEMO calorimeter

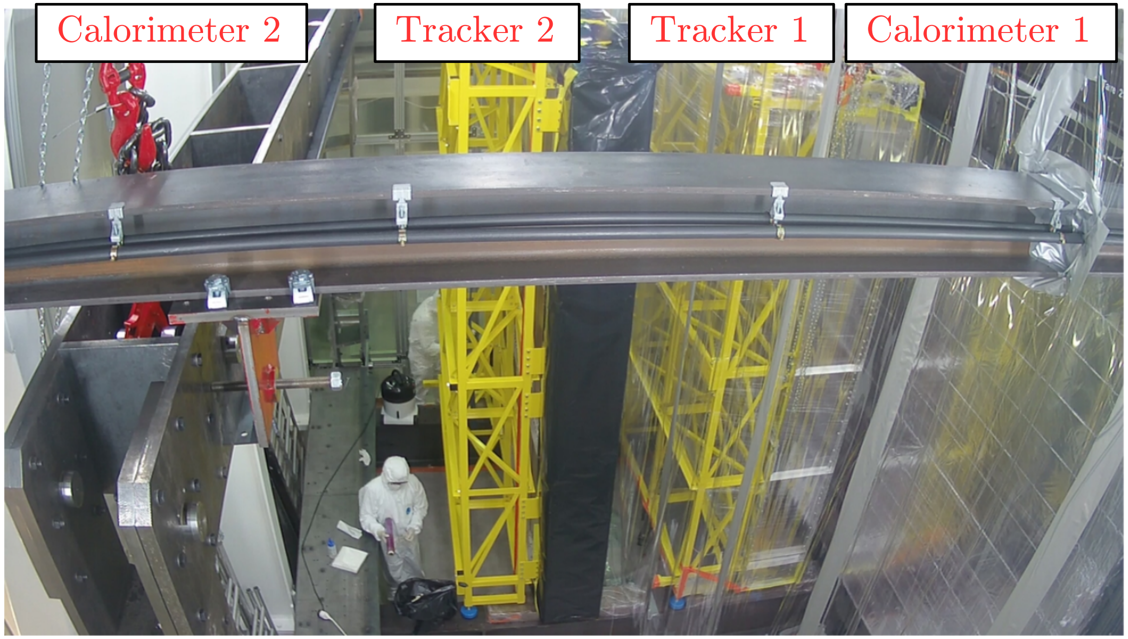
- 440 x 8'' PMT + 272 x 5'' directly coupled to polystyrene scintillators
- Energy resolution : 4 % FWHM at 3 MeV (^{82}Se $Q_{\beta\beta}$)
- Coincidence time resolution : 400 ps at 1 MeV
- Calibration system maintain stability better than < 1 %

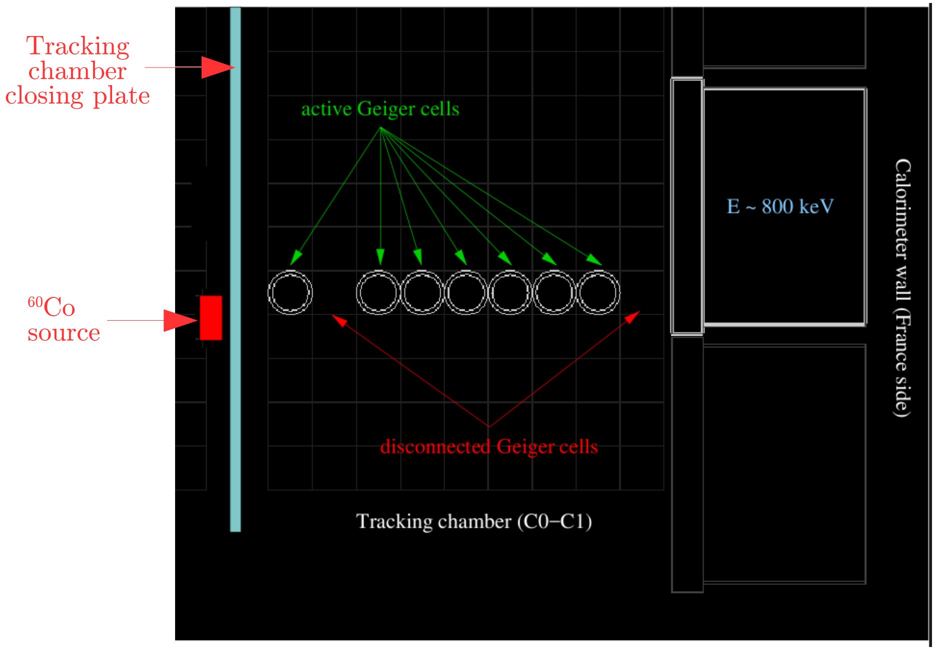
Nucl.Instrum.Meth. under publication (2017)



Status of the installation and commissionning

- The 2 calorimeter frames have been assembled and populated with the calorimeter blocks
- The tracker has been installed
- Installation of the source foil during fall 2017
- Demonstrator module starts data taking at end of 2017





- Commissionning of one half of the demonstrator is underway

First event display showing the tracker and the calorimeter working together

Conclusion

- NEMO 3 :
  - Final searches for $0\nu\beta\beta$ have been published : ^{100}Mo, ^{116}Cd, ^{150}Nd, ^{48}Ca
  - Most competitive $0\nu\beta\beta$ limit obtained with ^{100}Mo, close to the best limits from other experiments, with only 7kg of isotopes $\langle m_\nu \rangle < 0.3 - 0.6$ eV
  - Final search for ^{82}Se, publication is coming up ($2\nu\beta\beta$ and $0\nu\beta\beta$)
  - Many world leading $2\nu\beta\beta$ measurements
  - Unique new physics can be performed (e.g. $0\nu4\beta$)

- SuperNEMO :
  - The SuperNEMO demonstrator module is almost completed :
    - The calorimeter and tracker have been installed
    - Installation of the source foil this fall
  - Demonstrator data taking expected to start at the end of this year

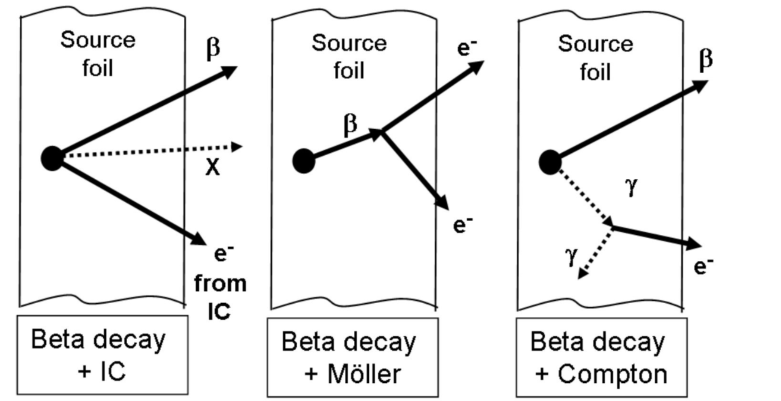
Thank you !

Back -up slides

Internal Backgrounds

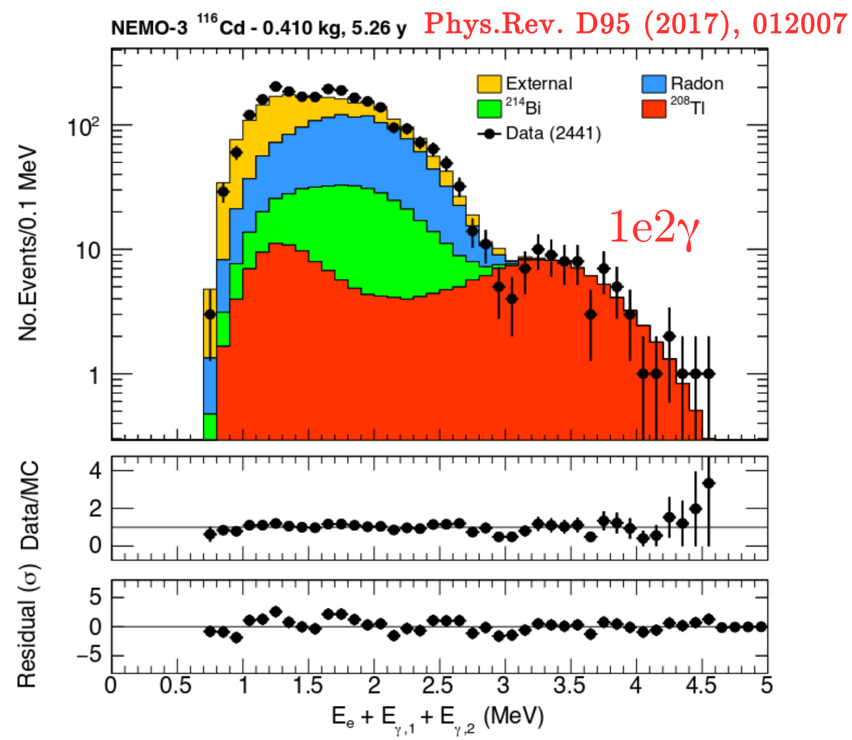
Regroups the backgrounds coming from the source foil, mainly come from :

- 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

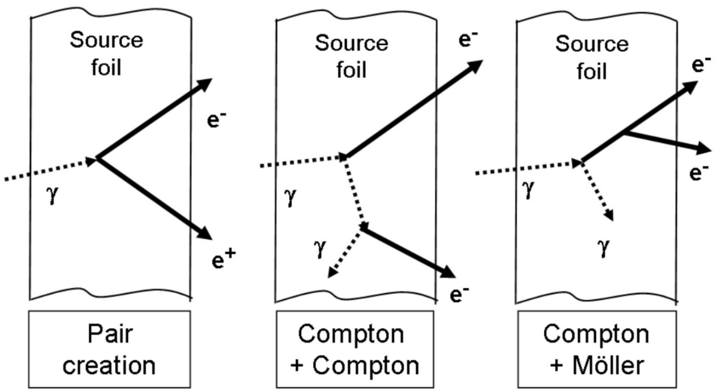
- ^{208}Tl in 1e1γ, 1e2γ and 1e3γ
- ^{40}K, ^{234m}Pa, ^{210}Bi in 1e channel
- ^{214}Bi – ^{222}Rn in 1e1α and 1e1γ channel



External Backgrounds

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

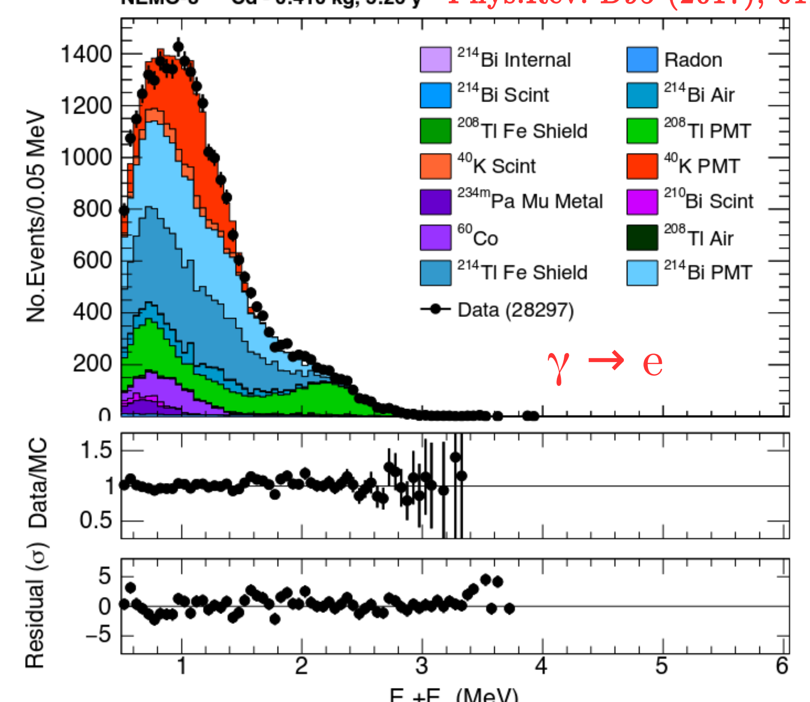
- Radio-impurities in detector material (^{208}Tl, ^{214}Bi)
- γ from (n,γ) reactions
- μ Bremsstrahlung



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

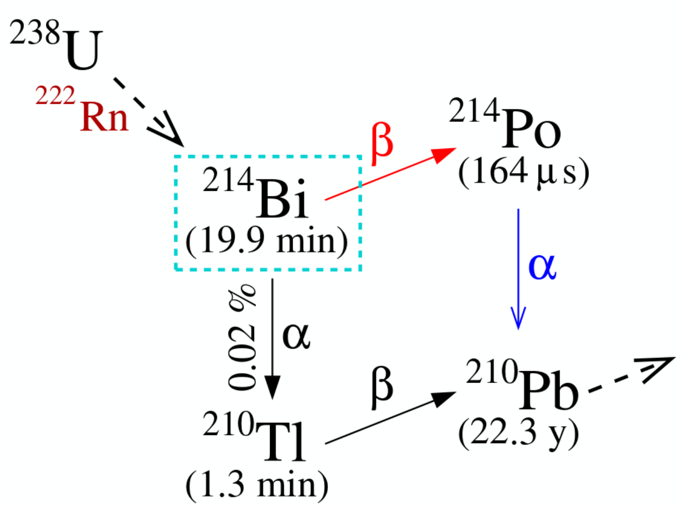
- external crossing electron
- external γ → e

Phys.Rev. D95 (2017), 012007

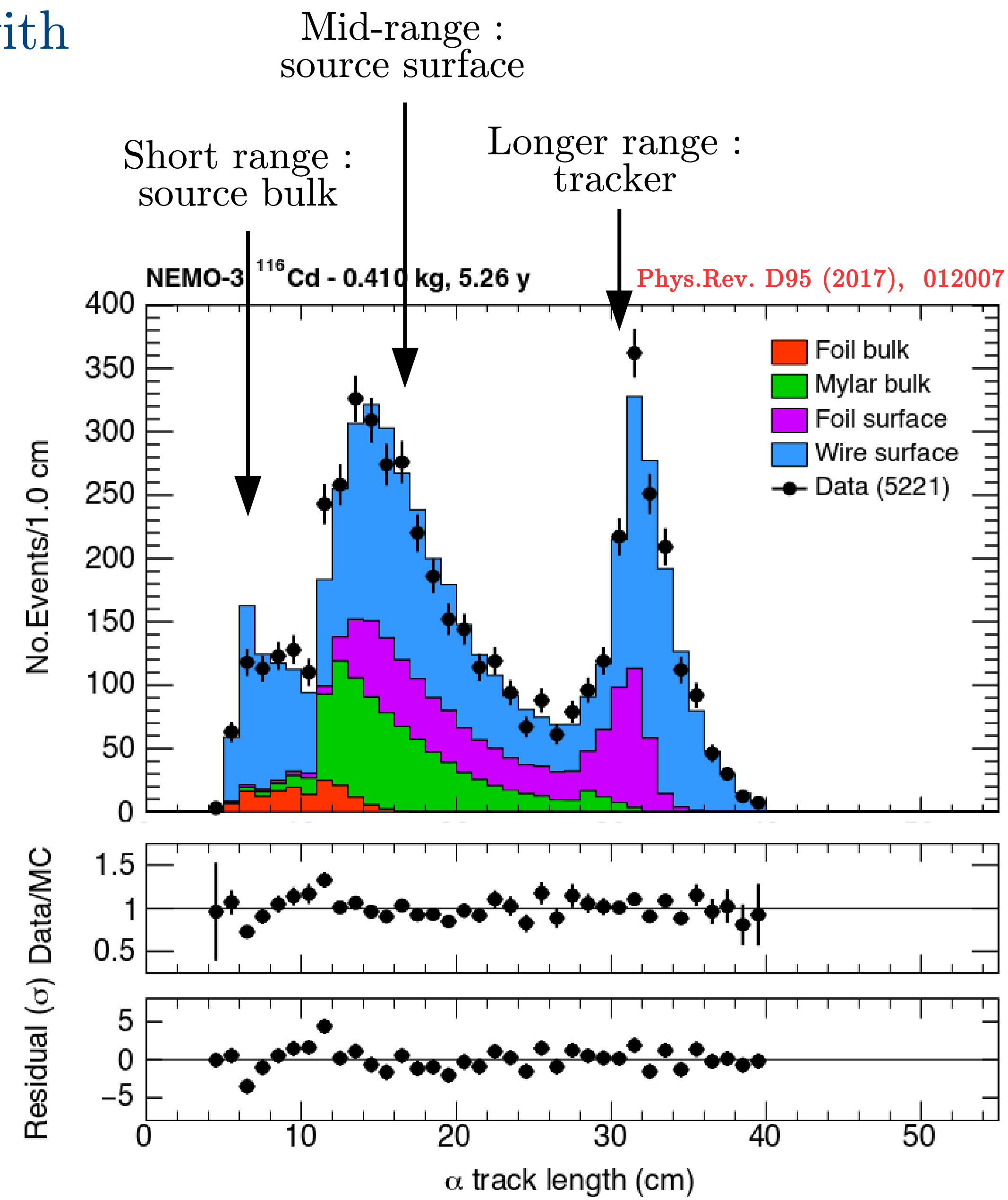


^{214}Bi and Radon

- ^{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



Calibration systems

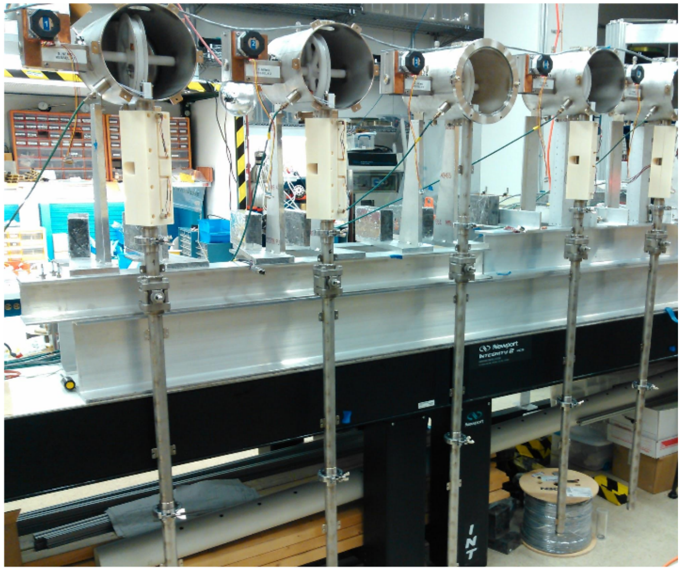
- A two part system has been developed to calibrate the detector

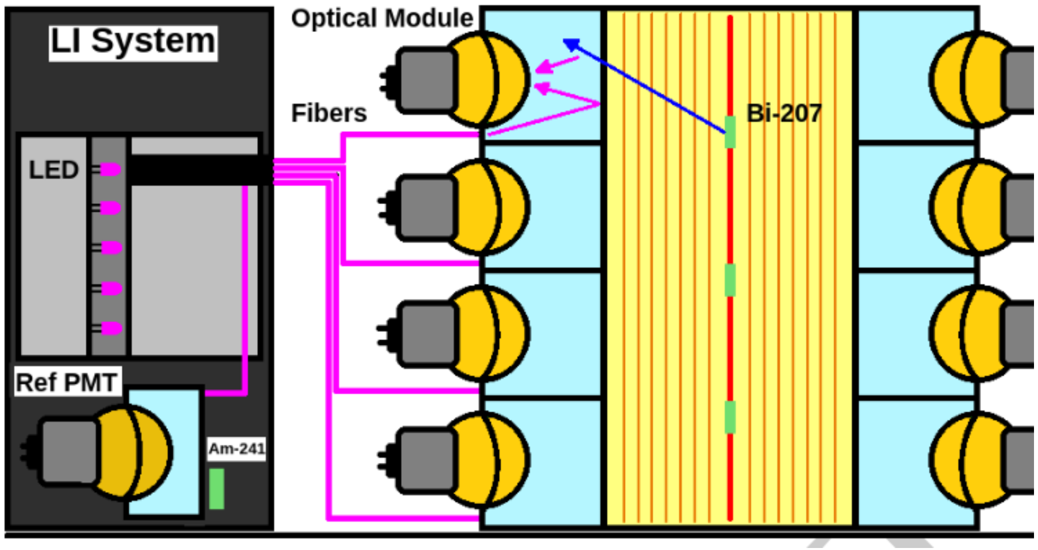
1) Source Deployment system :

  - Introduction of ^{210}Bi sources into the detector via a system of weights and stepper motors to calibrate the energy scale (~ monthly)

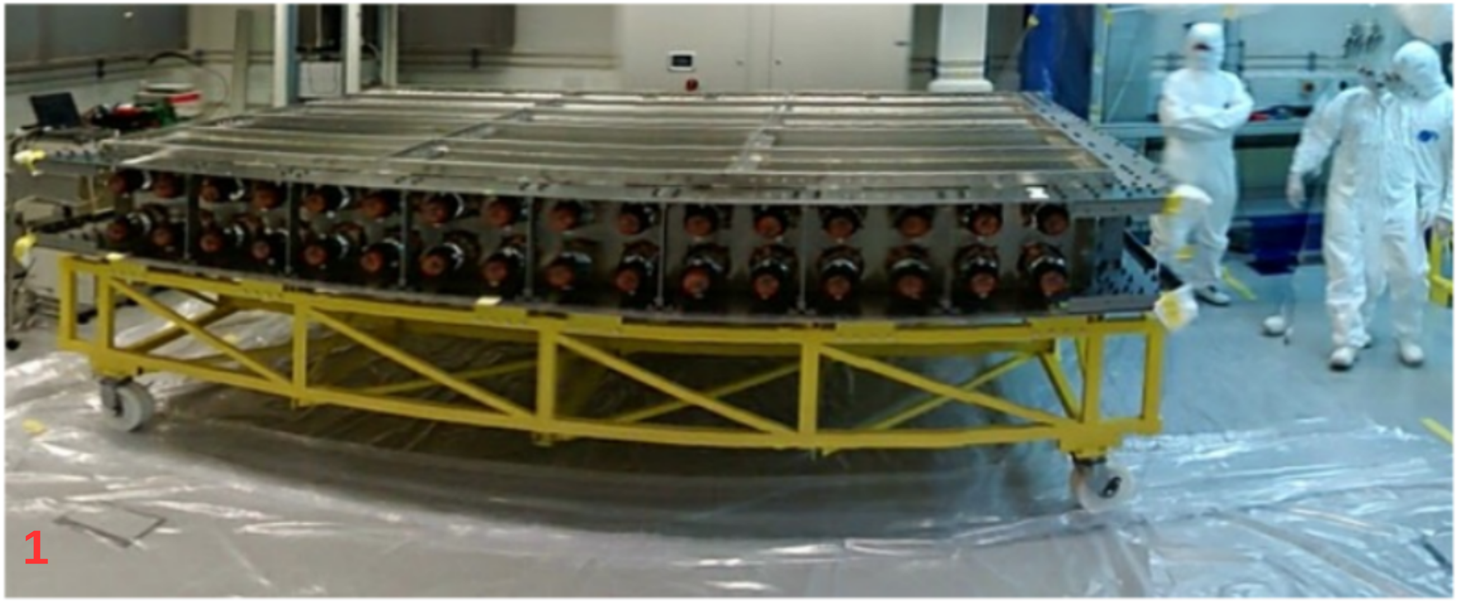
2) Light Injection system :

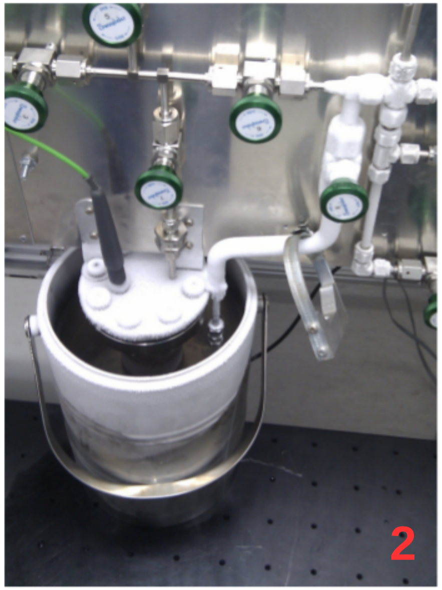
  - Guarantee the stability of the calorimetric response to 1 %.
  - Injection of LED light into each scintillator block via optical fibers (~ daily)



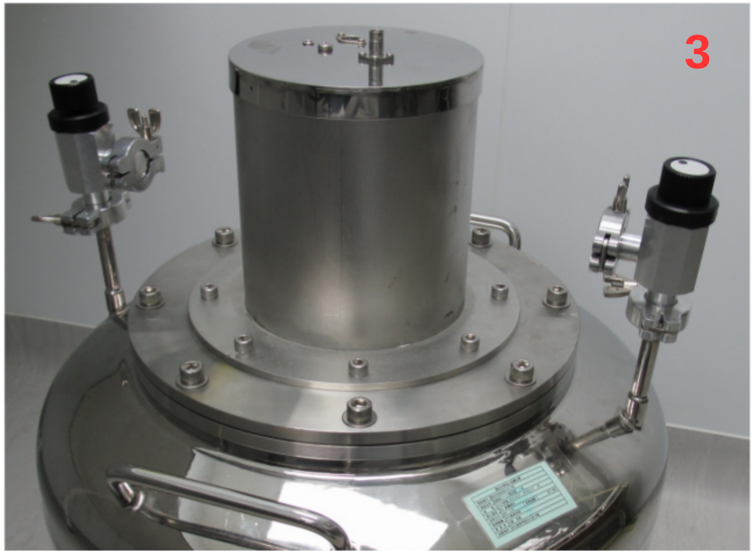


Radon





1. Purge for several $T_{1/2}$
2. Flow through cooled carbon trap
3. Release into electrostatic detector



For reasonable gas flow rates :

$$A\ (^{222}Rn) = 150 uBq/m^3$$

70 atoms per m^3 (30 times better than NEMO-3)

Sensitivity vs Exposure

$$T_{1/2}^{0\nu} > \frac{\ln 2 N_A}{W} \times \epsilon_{0\nu} \times \sqrt{\frac{M \times T}{b \quad \Delta E}}$$

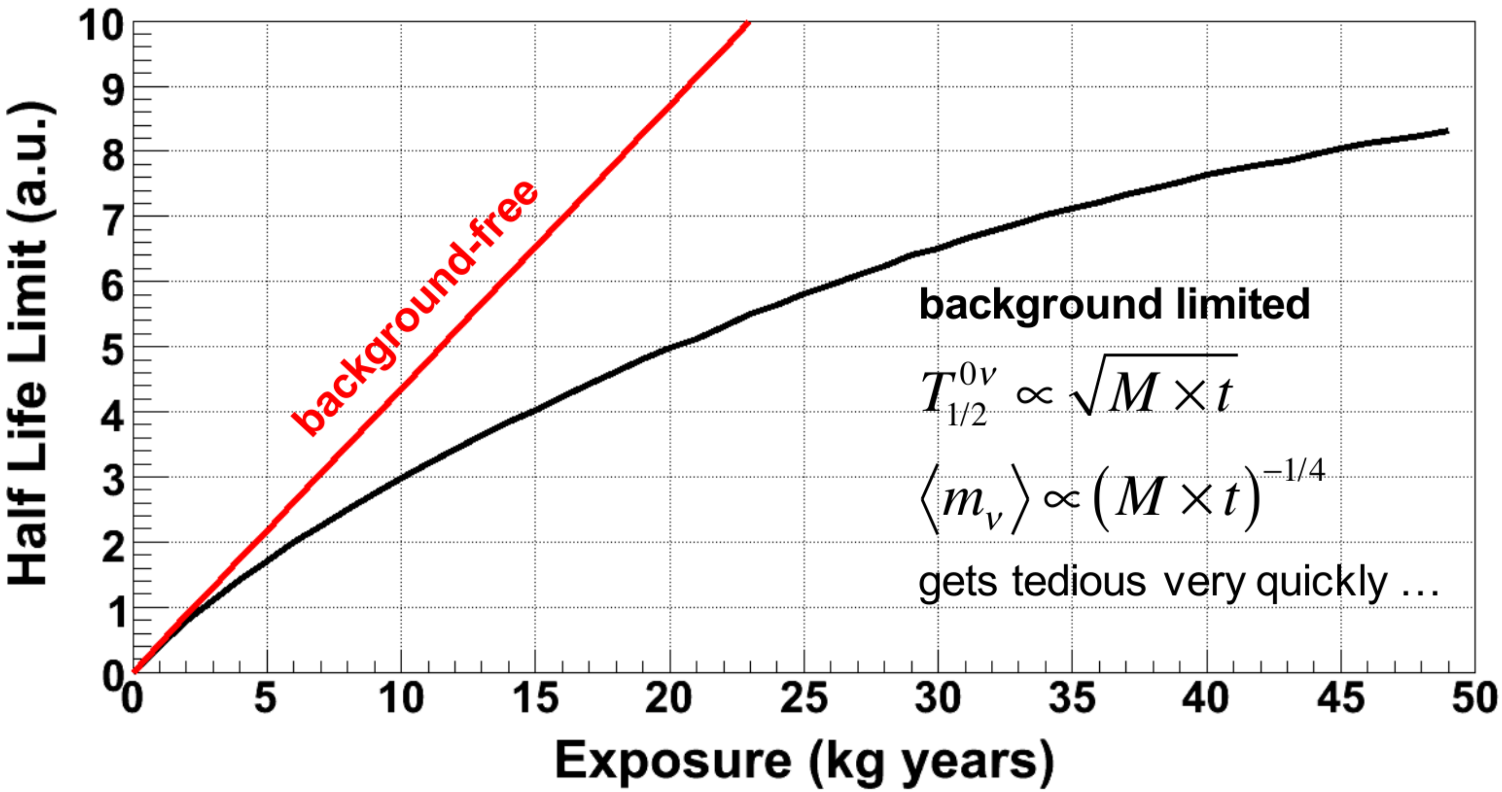
Constant depends of the isotope

Efficiency

Exposure

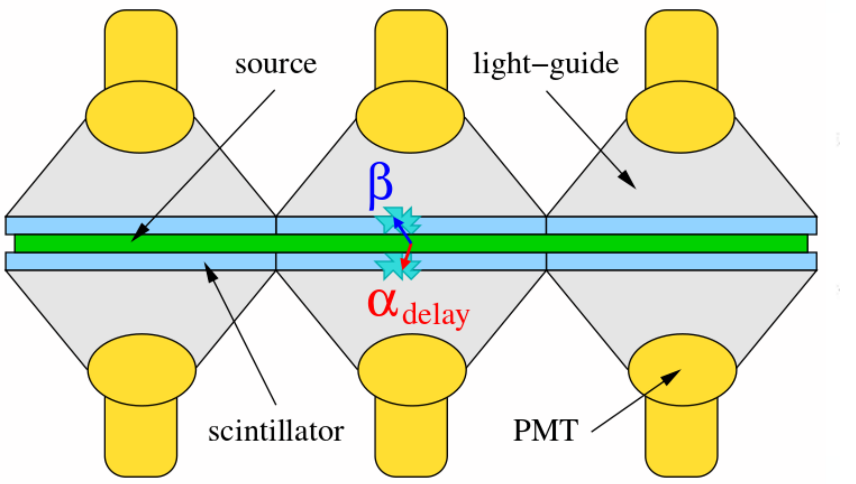
Energy resolution

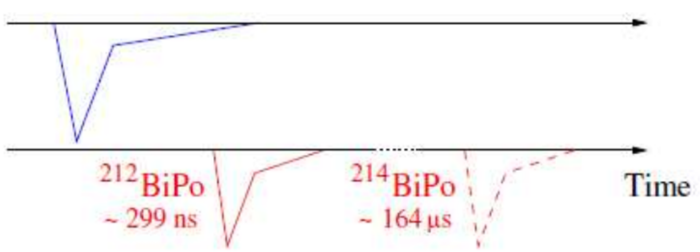
Background

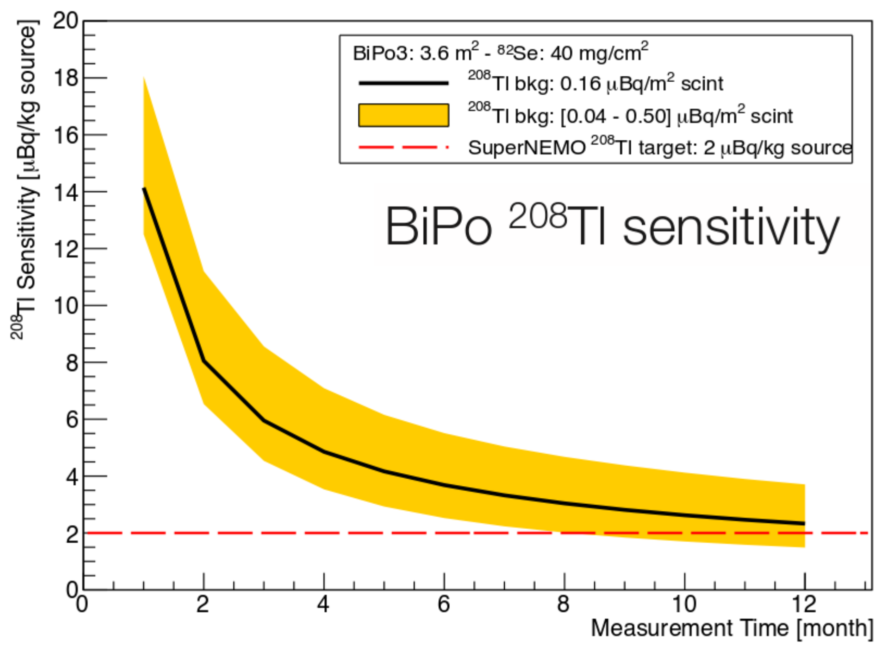


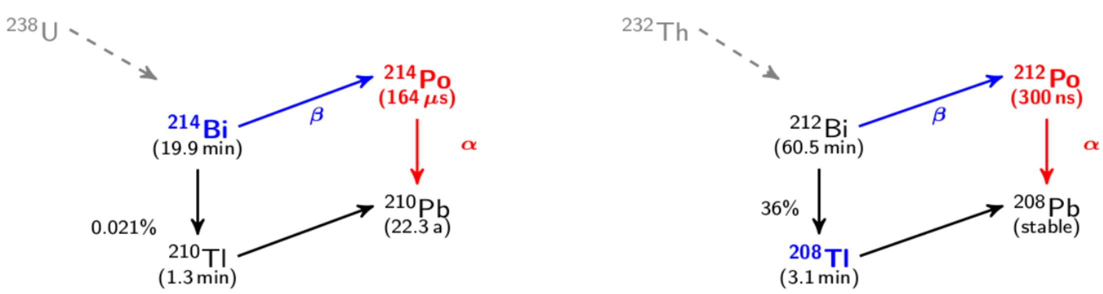
BiPo-3 detector

- HPGe detectors are not sensitive enough to reach few uBq/kg.
- BiPo is a dedicated detector running at Canfran Underground Laboratory to measured very low contaminations.
- ^{214}Bi and ^{208}Tl measured through process from natural radioactivity chain
- Thin radiopure plastic scintillators coupled to light guides and low radioactivity PMTs







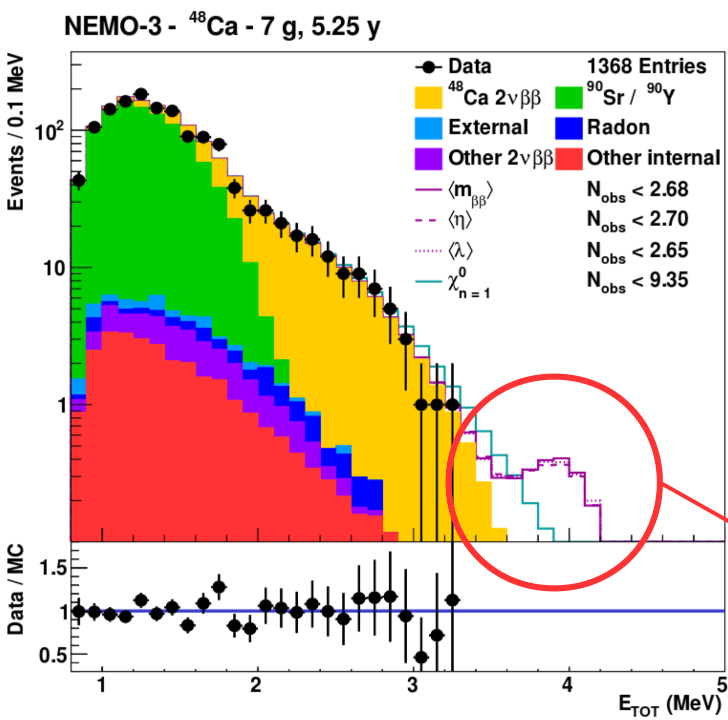


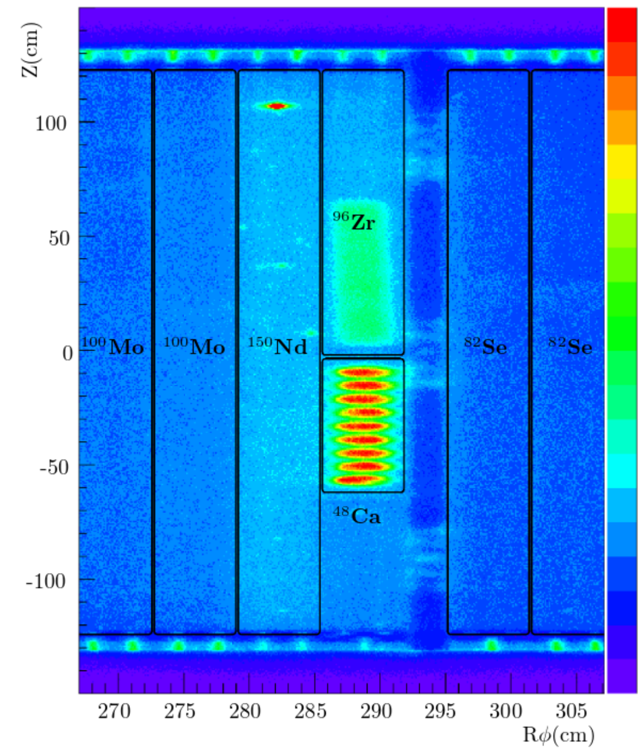
^{48}Ca results

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

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

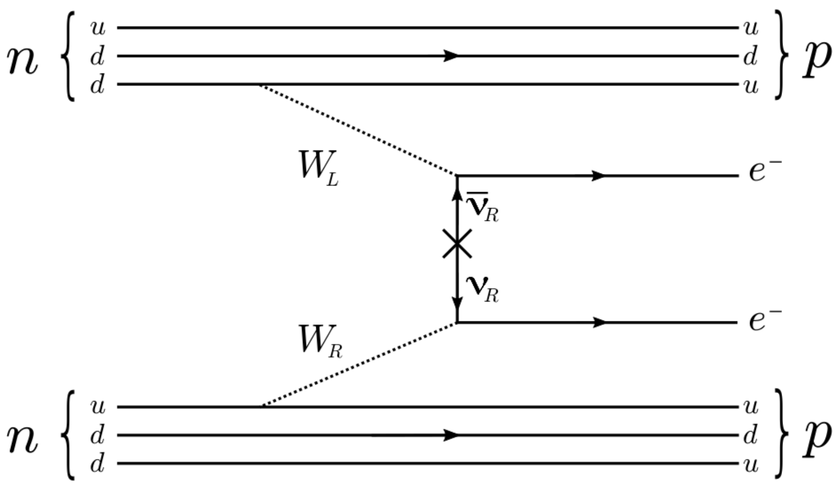
$$\langle m_\nu \rangle < 6.0 - 26\text{eV}$$

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

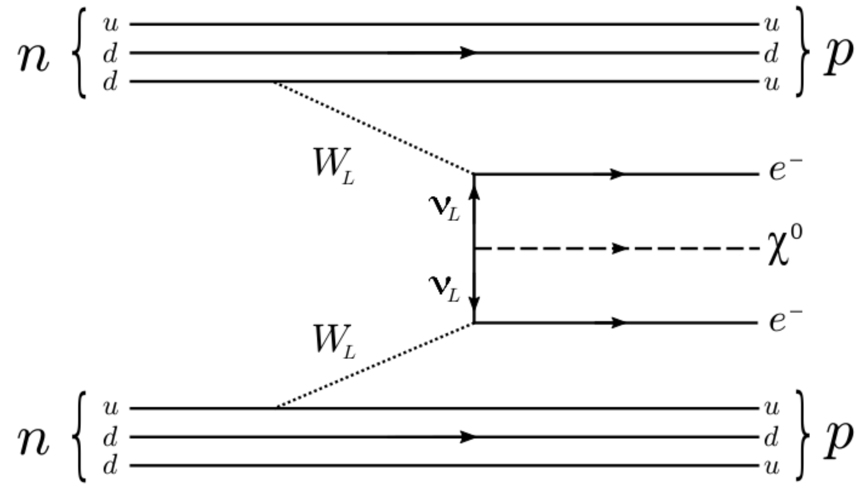
Other physics 1 (example)

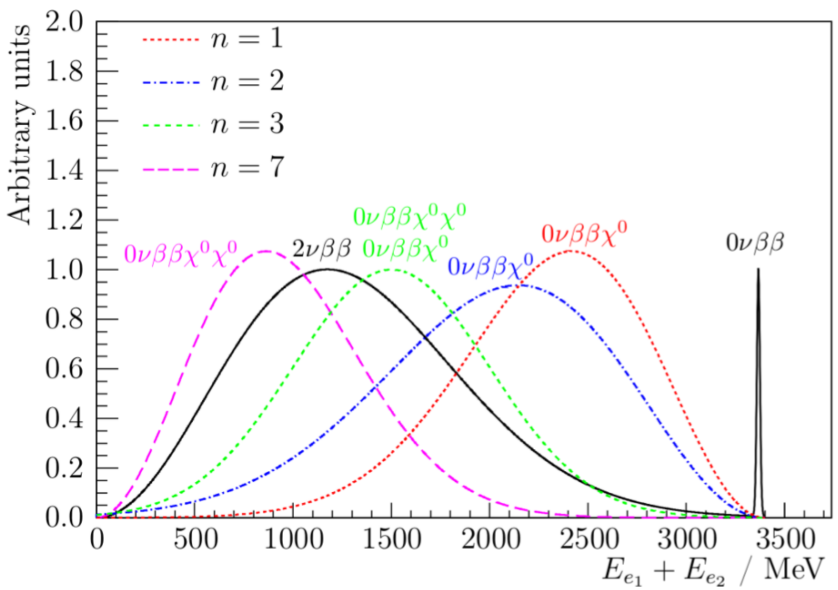
- Many models might mediate neutrinoless double beta decay

Right Handed Current



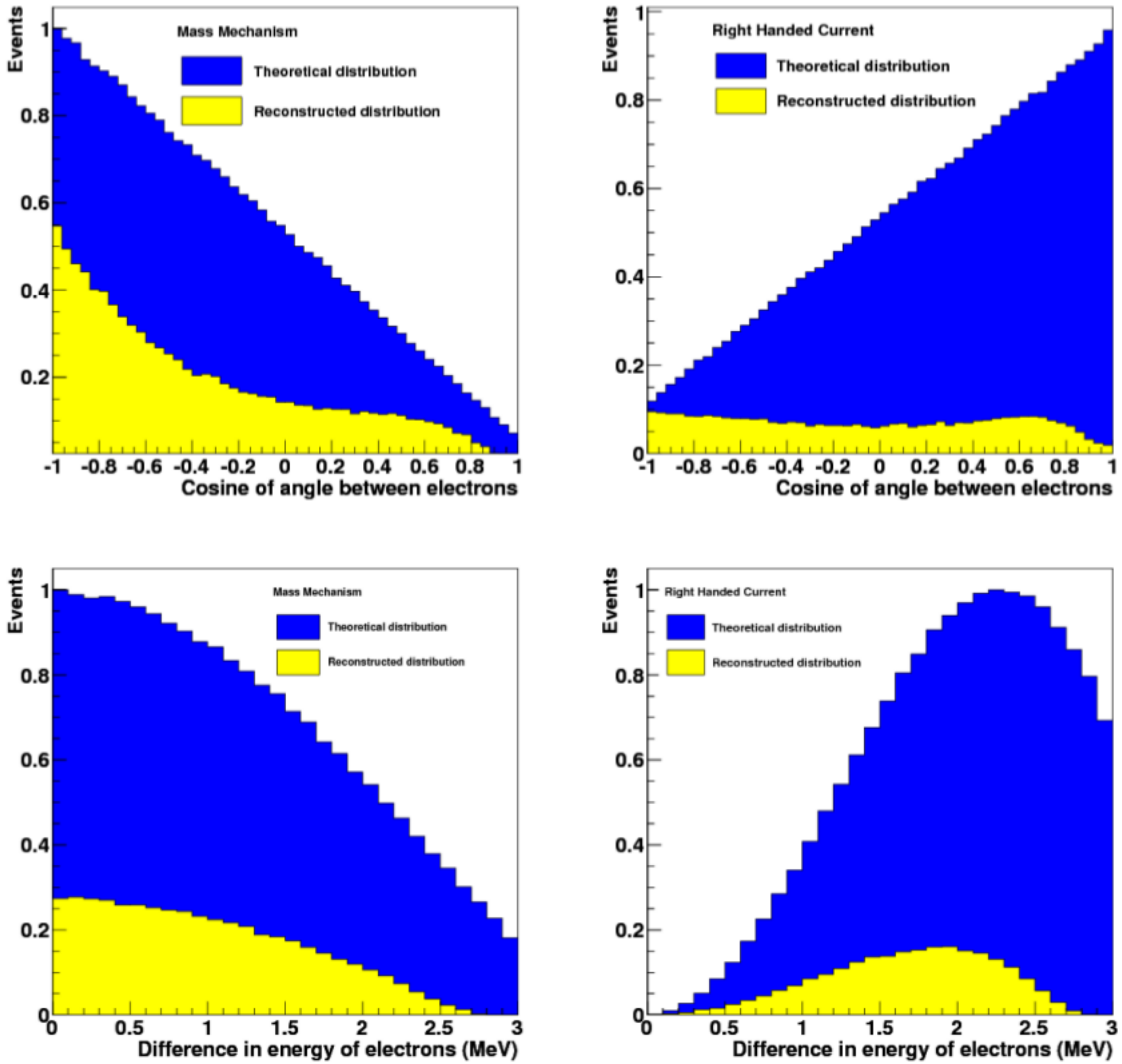
Majoron





Other physics 2 (example)

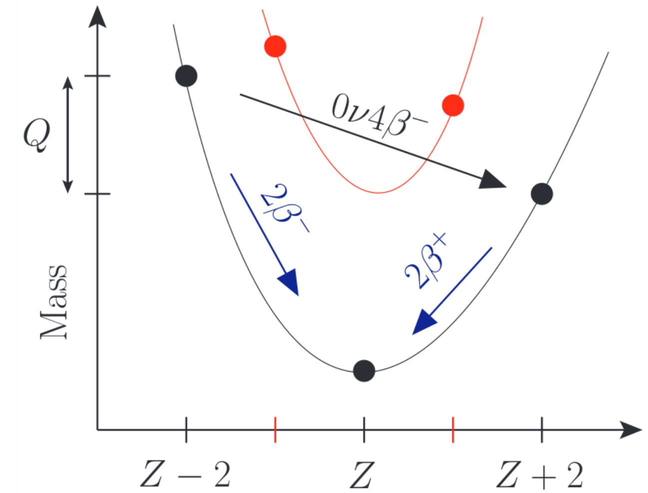
- Many models might mediate neutrinoless double beta decay



Quadruple beta decay 1

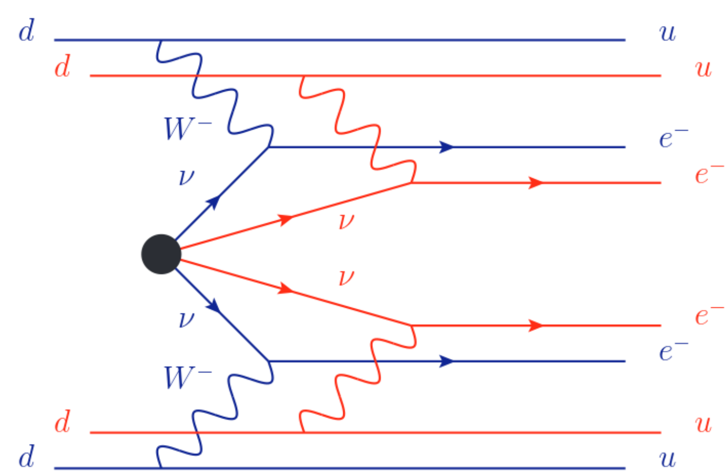
Only 3 candidates

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



Estimated life-time :

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



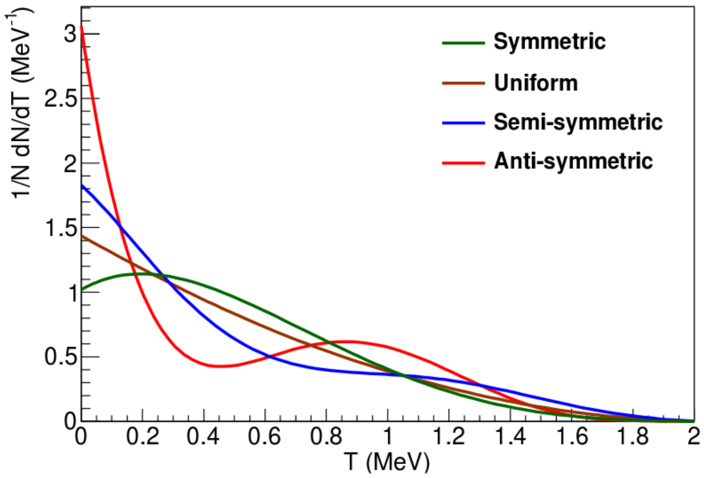
4n4b is killed by the Q-dependance of the eight-particle phase space ~ Q^{23} (compared to Q^{11} for 0n4b)

Quadruple beta decay 2

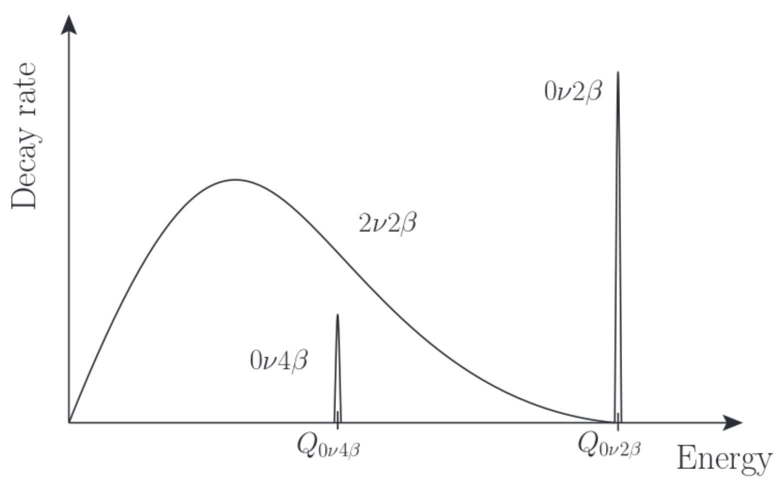
Very uncertain and little phenemenoly in the literature

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 $A_m = \mathcal{S}\{(T_i - T_j)^2 \times (T_k - T_l)^2\}$



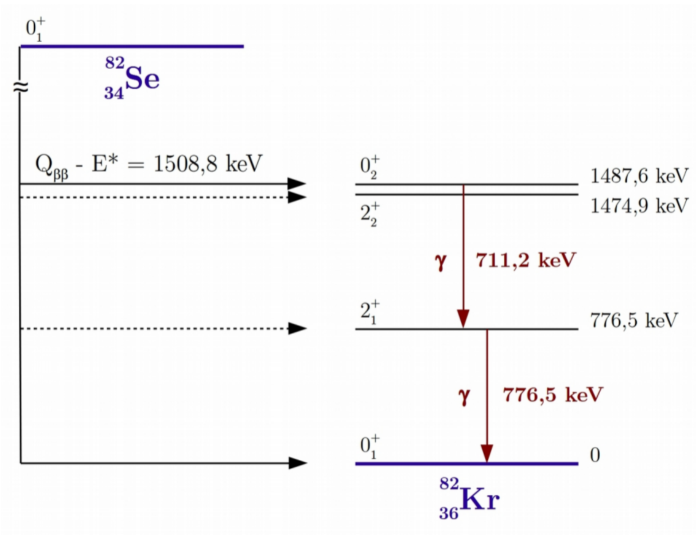
$$\frac{d^4N}{\prod_{i=1}^{4} dT_i} \propto A_m \delta\left(Q_{4\beta} - \sum_{i=1}^{4} T_i\right) \cdot \prod_{i=1}^{4} (T_i + m_e) p_i F(T_i, Z),$$



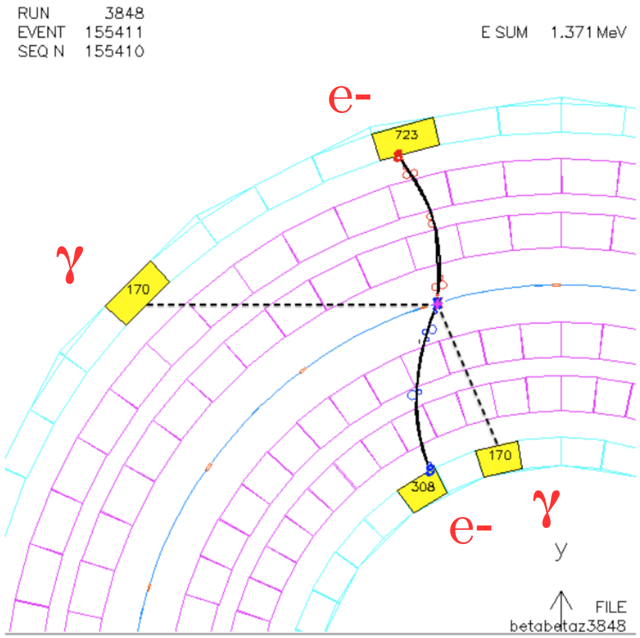
S{…} is a sum over the symmetric interchange of label i,j,k,l of the four electrons

Decay via the excited states 1

- 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



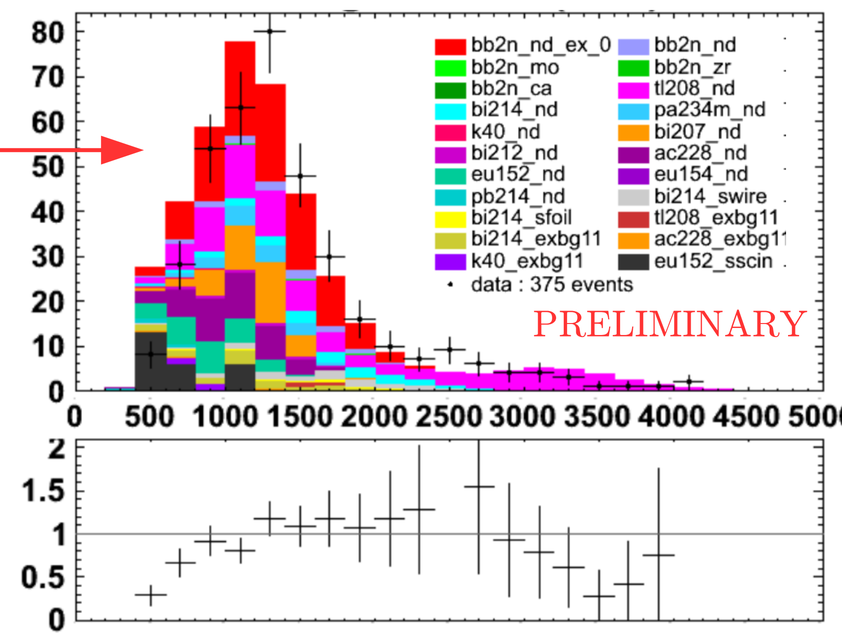
- Signature : 2e + one or more mono-enertic γ in coincidence
- Background is highly suppressed



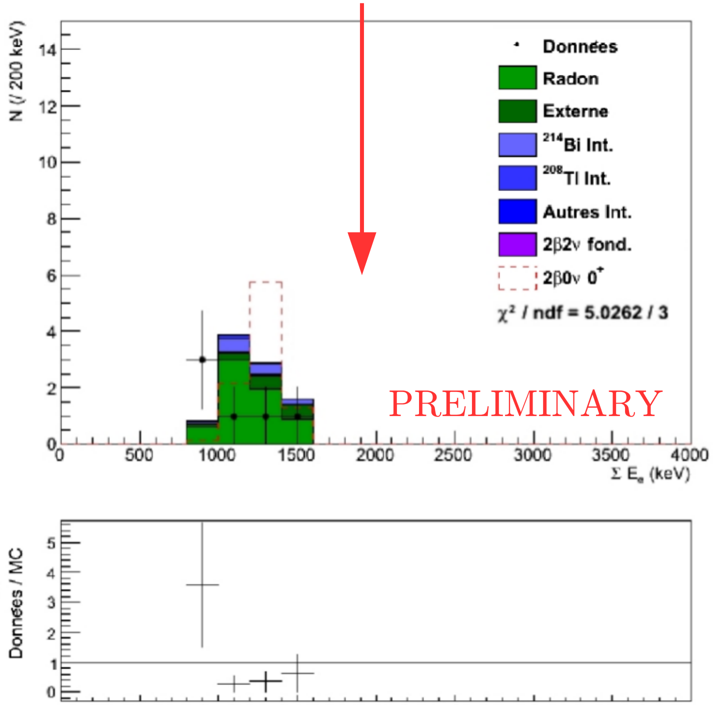
Decay via the excited states 2

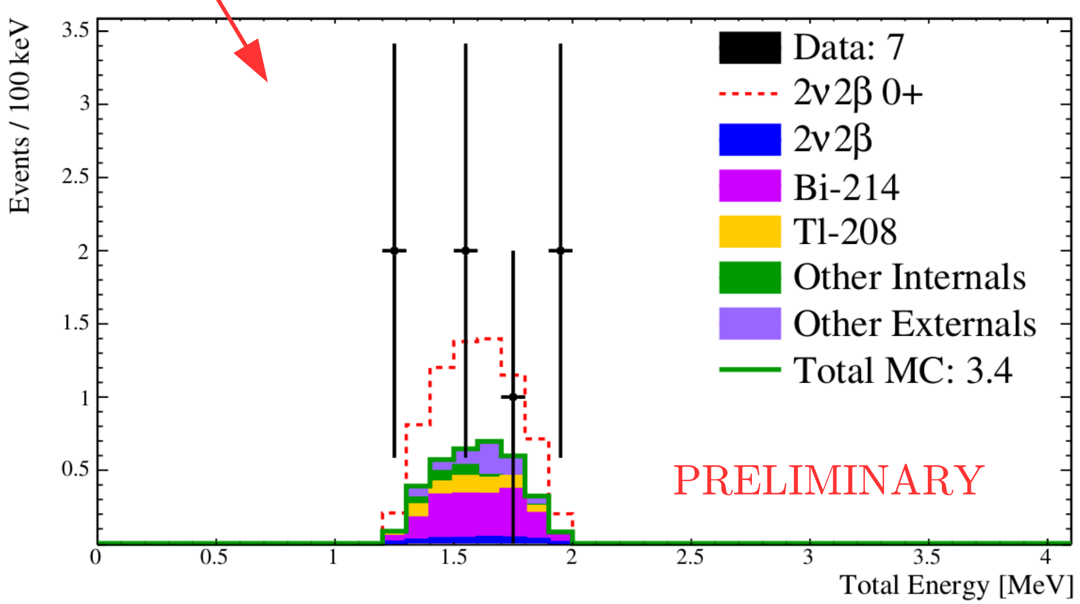
- Several isotopes have been investigated :
  - ^{150}Nd (S. Blondel Ph.D. thesis 2013)

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



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





Decay via the excited states 3

- 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
$(g.s \rightarrow 0^+)$ $2\nu\beta\beta$	$> 1.29 \times 10^{21}$	$> 5.85 \times 10^{19}$	$(7.12 \pm 1.28 \pm 0.91) \times 10^{19}$
$(g.s \rightarrow 0^+)$ $0\nu\beta\beta$	$> 2.31 \times 10^{22}$	-	$> 1.6 \times 10^{21}$
$(g.s \rightarrow 2^+)$ $2\nu\beta\beta$	-	-	$> 2.4 \times 10^{20}$
$(g.s \rightarrow 2^+)$ $0\nu\beta\beta$	-	-	-

Searches for periodic modulation in decay rate

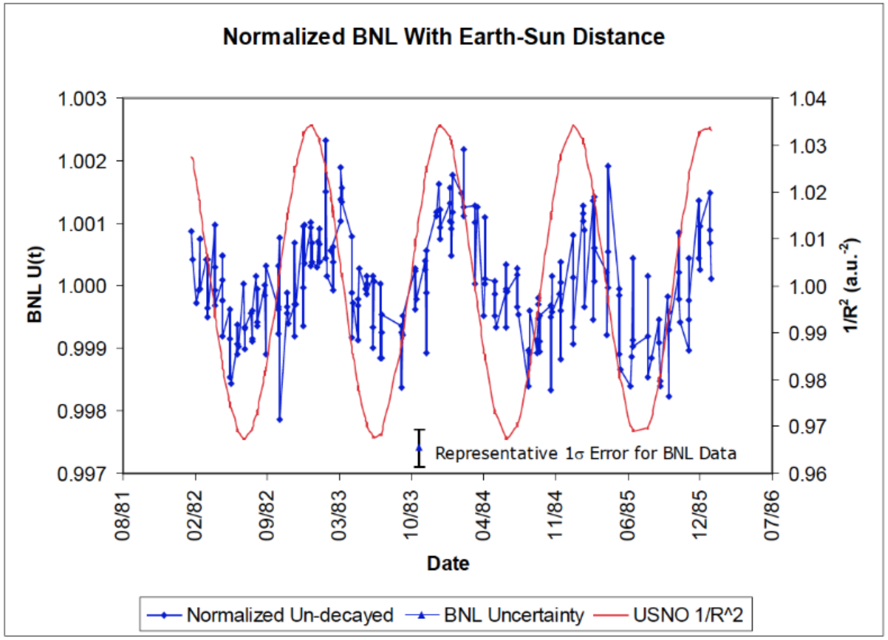
- In their *Radiations from Radioactive Substances*, E. Rutherford, J. Chadwick and Charles Ellis concluded :

« 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 ?

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)

Choice of the isotopes

- Only 35 nuclei can decay by $0\nu\beta\beta$

Isotope	$Q_{\beta\beta}$ [keV]	Nat. abund. (enrich.) [%]	$G_{0\nu}$ [10^{-14} y^{-1}]$^{(*)}$	$T^{2\nu}_{1/2}$ [10^{19} y]	Experiment
^{48}Ca	4270	0.187 (73)	6	$4.2^{+2.1}_{-1.0}$	NEMO3
^{76}Ge	2039	7.8 (86)	1	150±10	GERDA
^{82}Se	2995	8.7 (97)	3	9.0±0.7	NEMO3
^{96}Zr	3350	2.8 (57)	6	2.0±0.3	NEMO3
^{100}Mo	3034	9.6 (99)	4	0.71±0.04	NEMO3
^{116}Cd	2802	7.5 (93)	5	3.0±0.2	NEMO3
^{130}Te	2527	34.5 (90)	4	70±10	NEMO3
^{136}Xe	2480	8.9 (80)	4	238±14	KamlandZEN
^{150}Nd	3367	5.6 (91)	19	0.78±0.7	NEMO3

Isotopes enrichment and $T^{2\nu}_{1/2}$ from respective experiment

NEMO-3 : Physics Highlights (2νββ)

Isotope	Mass [g]	$Q_{\beta\beta}$ [keV]	$T_{1/2}$ [10^{19}] yrs	Comments
^{100}Mo	6914	3034	0.71 ± 0.05	World's Best
^{82}Se	932	2996	10.07 ± 0.56	World's Best
^{130}Te	454	2528	70 ± 14	World's Best & First (Direct)
^{116}Cd	410	2814	2.74 ± 0.18	World's Best
^{150}Nd	37	3371	0.934 ± 0.066	World's Best
^{96}Zr	9.4	3350	2.35 ± 0.21	World's First & Best
^{48}Ca	7	4272	6.4 ± 1.4	World's Best