Search for the neutrinoless double-beta decay with ***SuperNEMO*** and its radiopurity control with the ***BiPo*** detector.

Héctor Gomez

hgomez@apc.univ-paris7.fr

A BRIEF SELF – PRESENTATION...

- 2009: ***PhD*** at ***Universidad de Zaragoza*** (Spain)
  - Title of the Thesis: Sensitivity study of an double-beta decay experiment using new generation Ge detectors.
- 2009 – 2011: ***Postdoc*** at National Centre of Particle Physics (***CPAN – Spain***)
  - NEXT experiment
    - Coordination of the construction, commissioning and operation of the NEXT-μM prototype
    - Coordination of the NEXT – Vessel Working Group
- 2011 – 2014: ***Postdoc*** (CDD Chercheur) at ***LAL – Orsay***
  - SuperNEMO experiment
    - Coordination of the construction, commissioning and operation of the BiPo detector
    - BiPo data analysis responsible → SuperNEMO source foils Working Group
- From September 2014: ***Postdoc*** at ***APC – Paris*** (Neutrino group)
  - Double – Chooz and WA-105 experiments
    - Muon and muon-induced events characterization for the Double – Chooz near detector
    - Performance of a new self - calibration method for the Double – Chooz detectors

A BRIEF SELF – PRESENTATION...

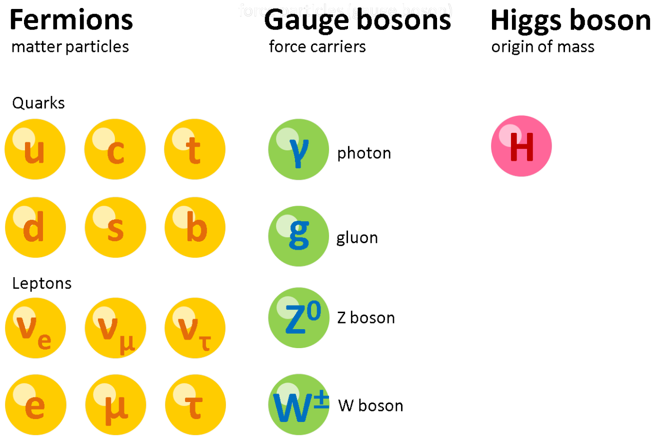
- Summarizing:
  - 10 years of research activities related with ***neutrino physics***, mainly double-beta decay.
  - Expertise on different ***detection techniques***
    - Ge diodes
    - High Pressure gaseous Time Projection Chamber (HP – TPC) readout with microMegas detectors
    - Light detection produced in plastic and liquid scintillators
  - Development of ***analysis tools*** focused on the Rare Event searches
    - Background discrimination techniques
  - ***Radiopurity*** screening and control

OUTLINE

- Neutrinos and their properties
  - Where are we?
- Neutrino nature and mass: The neutrinoless double-beta decay
  - Experimental Issues
- The SuperNEMO experiment
  - Its predecessor: NEMO-3
  - Description
    - The BiPo detector and the source foils radiopurity control
  - Present status
  - Prospects
- Perspectives
  - Where are we going?
- Summary and conclusions

NEUTRINOS AND THEIR PROPERTIES

- The ***Standard Model*** of Particles defines neutrinos as:
  - Massless
  - With no electrical charge
  - Only sensitive to weak interactions
  - With 3 different flavours: ν_e, ν_μ and ν_τ (+ antineutrinos)



- But:
- ***1970*** Chlorine (Homestake) measured the neutrinos coming from the Sun
  - Only 1/3 of the expected neutrinos were detected ...
- ***1988*** Super – Kamiokande (Kamioka) studied the atmospheric neutrinos (interaction cosmic rays – atmosphere)
  - ν_μ,s crossing the Earth seemed to disappear ...

NEUTRINOS AND THEIR PROPERTIES

- Neutrinos those propagate ***(ν_1, ν_2, ν_3)*** are a ***mixture*** of the different neutrino flavours ***(ν_e, ν_μ, ν_τ)***, which interact

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- What does it means?
  - ***Neutrinos*** are ***massive*** particles → ***Physics beyond the Standard Model***

    → ***Possibility of new sources of matter – antimatter asymmetry***

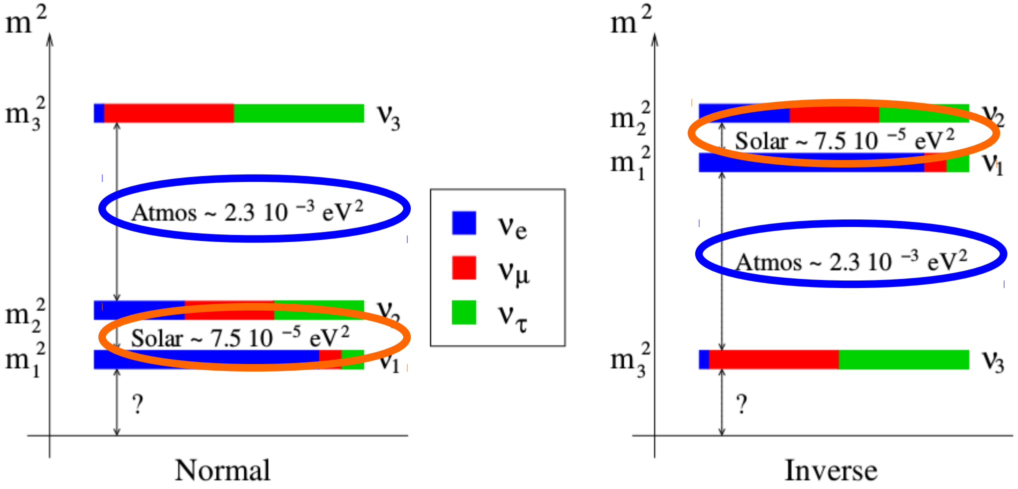
    → ***CP – violation***
  - This physics has been studied over the last decades with a continuous improvement...

NEUTRINOS AND THEIR PROPERTIES: ***WHERE ARE WE?***

- ***Neutrino oscillation*** experiments have answered several questions based on the study of the appearance / disappearance probabilities:

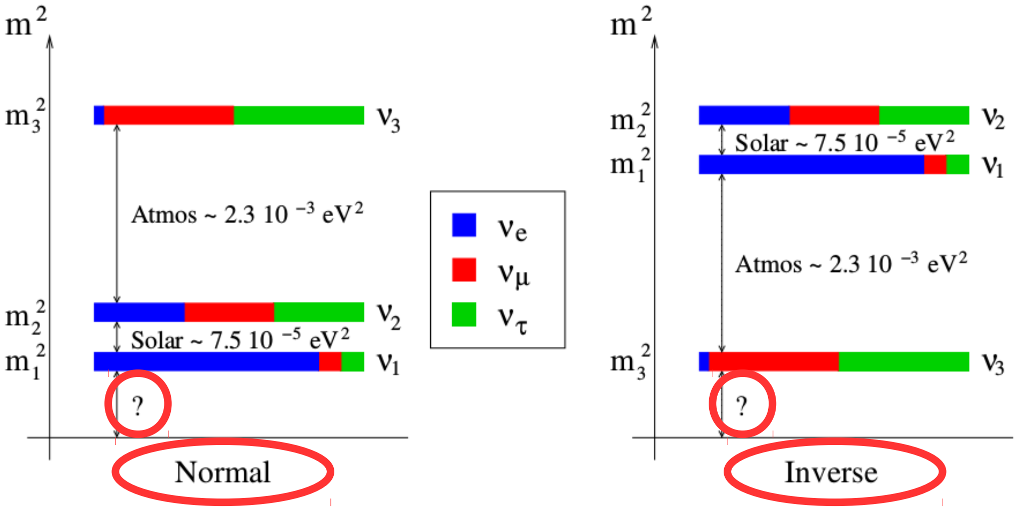
$$P_{\nu_\alpha \to \nu_\alpha}(L,E) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\textbf{Solar } \nu \textbf{ 's} \\ P(\nu_e \to \nu_x) \\ \theta_{12} \sim 33^\circ - \Delta m^2_{12}}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\substack{\textbf{Reactor } \nu \textbf{ 's} \\ P(\nu_e \to \nu_e)\ \&\ P(\nu_\mu \to \nu_e) \\ \theta_{13} \neq 0^\circ - \Delta m^2_{13}\ \&\ \text{“dirac” } \delta_{CP}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\substack{\textbf{Atmospheric } \nu \textbf{ 's} \\ P(\nu_\mu \to \nu_\mu) \\ \theta_{23} \sim 45^\circ - \Delta m^2_{23}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



NEUTRINOS AND THEIR PROPERTIES: ***WHERE ARE WE?***

- But there are still some fundamental open questions:



- ***What are the absolute values of the neutrino masses?***
- ***How the neutrino mass states are ordered?***
- Why the oscillation parameters take the values that have been measured?
- Why neutrino masses are so much smaller than any other fundamental matter particles in the SM?
- ***Could neutrinos be their own anti-particle? Could this be related to the fact that neutrino masses are so small?***
- Do the extremely small neutrino masses tell us something about physics at the very high energy scales of Grand Unified Theories as suggested in so-called “see-saw” mechanisms?
- Could lepton number violation in neutrino interactions help to explain the present asymmetry between matter and antimatter at the Universe?

NEUTRINO NATURE AND MASS: ***THE NEUTRINOLESS DOUBLE BETA DECAY***

- How can we measure the ***neutrino mass***? (and by extension get information about neutrino nature and mass hierarchy)
  - Cosmological measurements (Planck)

    $$M=\sum_i^{n_\nu} m_{\nu,i}$$

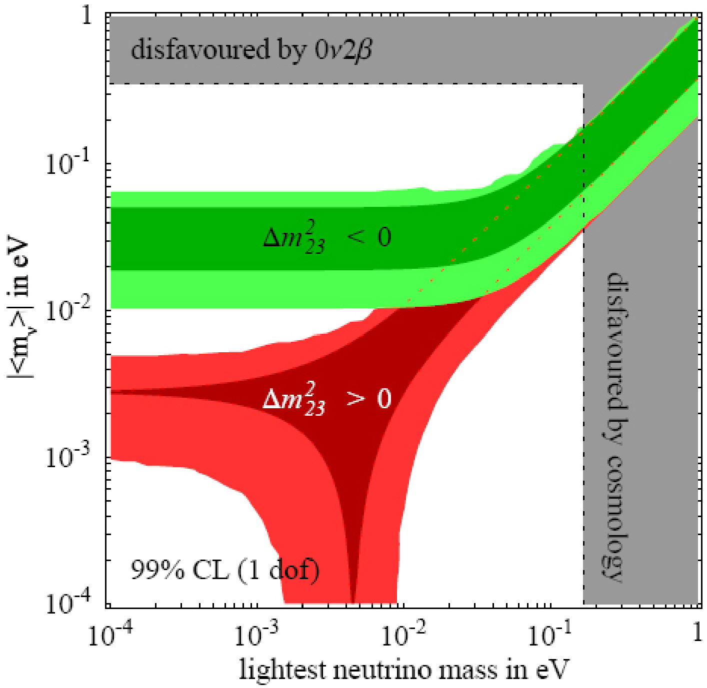
  - Beta decay measurements (Katrin, further Mare – Holmes, Project 8)

    $$\langle m_\beta \rangle^2=\sum_i^{n_\nu} |U_{ei}|^2 m_{\nu,i}^2$$

  - ***Neutrinoless double-beta decay measurements (mass mechanism)***

    $$\langle m_{\beta\beta} \rangle^2=|\sum_i^{n_\nu} U_{ei}^2 m_{\nu,i}^2|$$

    - Majorana nature of the neutrino
    - Neutrino mass absolute value
    - Neutrino mass hierarchy



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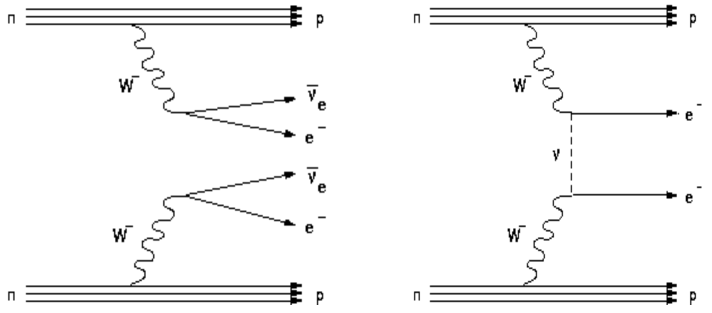


$$2\nu\beta^-\beta^-:(A,Z)\rightarrow(A,Z+2)+2e^-+2\bar{\nu}_e; \qquad (\Delta L=0)$$

$$0\nu\beta^-\beta^-:(A,Z)\rightarrow(A,Z+2)+2e^-; \qquad (\Delta L=2)$$

May have more particles emitted (Majoron, …)

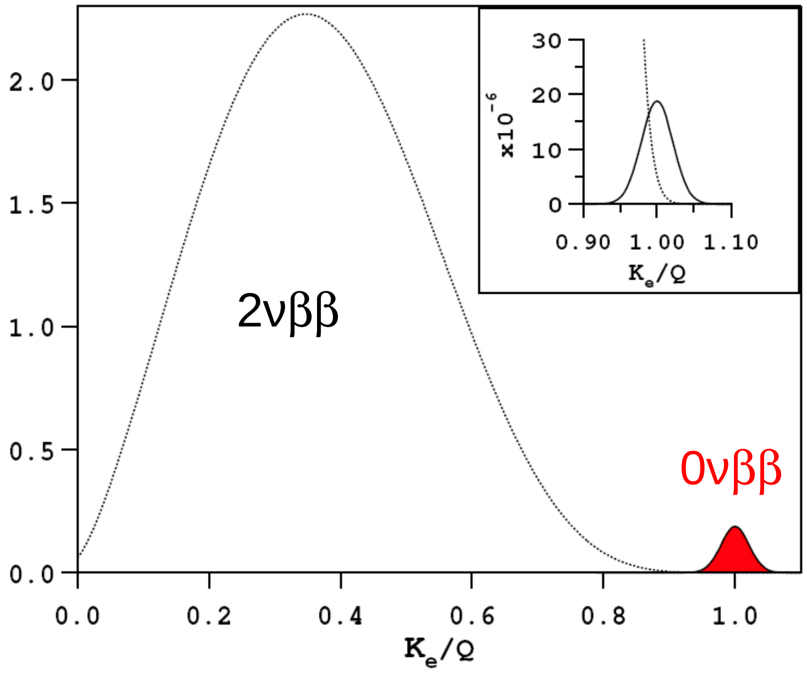
- ***0νββ*** process detection

$$\left(T_{1/2}^{0\nu}\right)^{-1}=G_{0\nu}\underbrace{\left|M_{GT}^{0\nu}-\frac{g_V^2}{g_A^2}M_F^{0\nu}\right|^2}_{F_N}\chi^2$$

where χ $\rightarrow \frac{\boxed{\langle m_\nu\rangle}}{m_e}$ Mass Mechanism

$\rightarrow\langle\lambda\rangle,\langle\eta\rangle$ Right handed currents

$\rightarrow\langle g_M\rangle$ Majoron emission



Supposing the ***mass mechanism***:

No other particles emitted but ***2 electrons*** sharing all the available transition energy (***$Q_{\beta\beta}$***)

NEUTRINO NATURE AND MASS: *THE NEUTRINOLESS DOUBLE BETA DECAY*

- The ***sensitivity*** of a ***0νββ*** experiment (if no significant signal is found) can be expressed as the achievable limit to $T_{1/2}$ as:

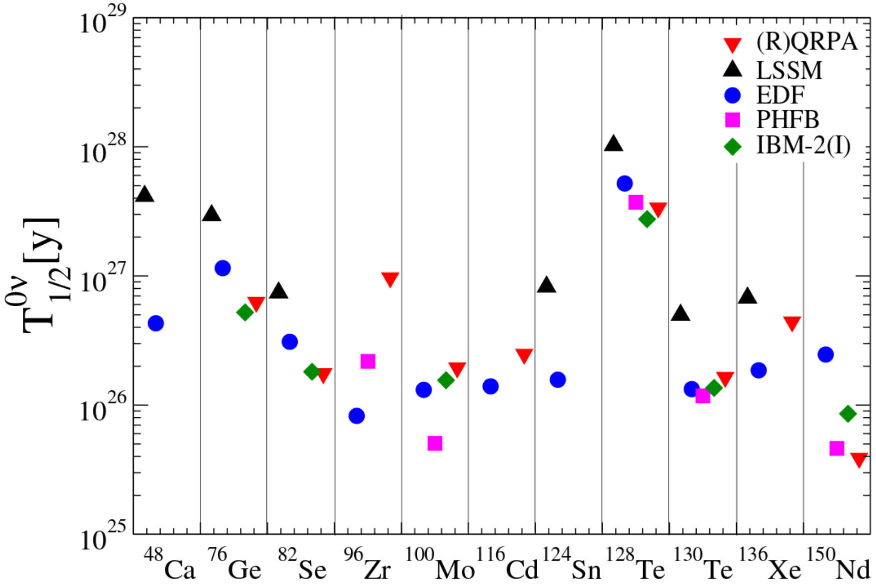
$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{N_{source}\, t}{b(t)\, \Delta E}} \longrightarrow$$

[ε]	Detection efficiency	↑↑
[N_{source}]	*0νββ* nuclei	↑↑
[t]	Measurement time	↑↑
[$b(t)$]	Background level	↓↓
[ΔE]	Energy resolution	↓↓

- In order to improve the sensitivity, experiments must pay attention to different issues:
  - Optimize the exposure
  - Adequate isotope choice (naturally abundant, with “slow” *2νββ* mode...)
  - Good detector performance (in terms of efficiency and energy resolution)
  - Background control
    - Radiopure materials and environment (Underground location)
    - Active and passive background rejection techniques application

NEUTRINO NATURE AND MASS: ***THE NEUTRINOLESS DOUBLE BETA DECAY***

- But in addition, the accuracy of the result is nowadays limited by the uncertainties in the Nuclear Matrix Elements (NME, included in the previously defined F_N)



RPP 75 (2012) 106301, for <m_ν> = 50 meV

- The estimation of the NME is a challenge itself because:
    - Relevant $\beta\beta$ nuclei are heavy (mostly A > 75) and complicated to model
    - The NME have been never measured → Nothing to calibrate with
    - Structures of the initial and final nucleus ground state are quite different → NME are small and sensitive to variations

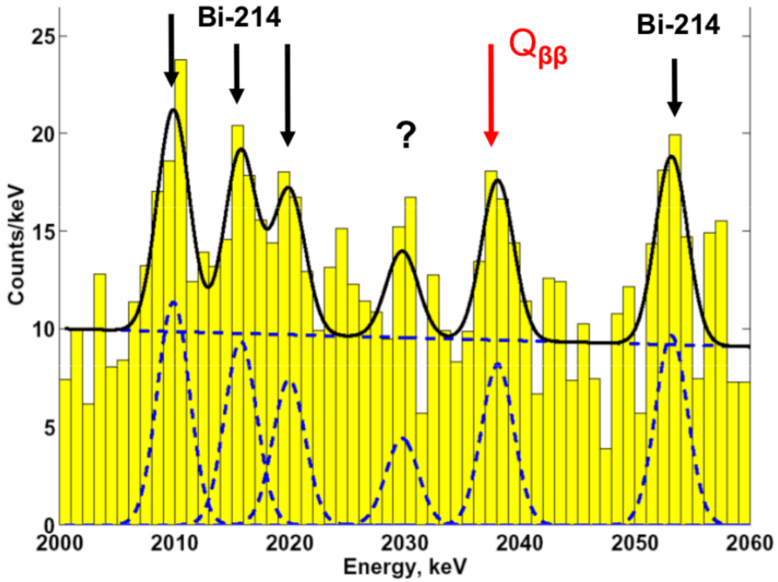
- Measurement of the **$0\nu\beta\beta$** process for ***various isotopes*** would reduce the uncertainty induced by the NME's
    - The detection of the $0\nu\beta\beta$ process in different isotopes reveals mandatory to claim a significant result
- The measurement of the **$2\nu\beta\beta$** mode could provide ***useful information*** for the NME estimation

NEUTRINO NATURE AND MASS: *THE NEUTRINOLESS DOUBLE BETA DECAY*

- ***ββ experiments*** have been running from more than 20 years. This is a (personal) summary.

Experiment	***Isotope***	***Technique***	***Laboratory***	***Results***		
				$T_{1/2}^{2\nu}$ (y)	***$T_{1/2}^{0\nu}$ (y)***	***$<m_\nu>$ (eV)***
CUORICINO	^{130}Te	Bolometers	Gran Sasso	-	> 3.0 10^{24}	< 0.19 – 0.68
Heidelberg – Moscow*	^{76}Ge	Ge diodes	Gran Sasso	1.6 ± 0.2 10^{21}	> 1.6 10^{25}	< 0.35
IGEX	^{76}Ge	Ge diodes	Canfranc	-	> 1.6 10^{25}	< 0.33 – 1.35
NEMO - 3	^{100}Mo	Tracking + Calorimetry	Modane	7.2 ± 0.6 10^{18}	> 1.1 10^{24}	< 0.33 – 0.87

- Experiments ***already finished***. Some of them, as NEMO-3, still have the best limits for several isotopes...
- Part of H-M collaboration claimed for a positive signal
  Mod. Phys. Lett. A 16 (2001) 2409 – 2420
  - $T_{1/2}^{0\nu} = 1.2\ 10^{25}$ y → $<m_\nu> = 0.44$ eV
  - Further experiments were needed to corroborate / refuse this claim



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- ***First phases*** of some new generation experiments, specially based on ^{76}Ge and ^{136}Xe, provides encouraging results
    - GERDA results have ***refused the H-M claim***
    - Combination of ^{76}Ge and ^{136}Xe results, improve the limits and reduce the uncertainties

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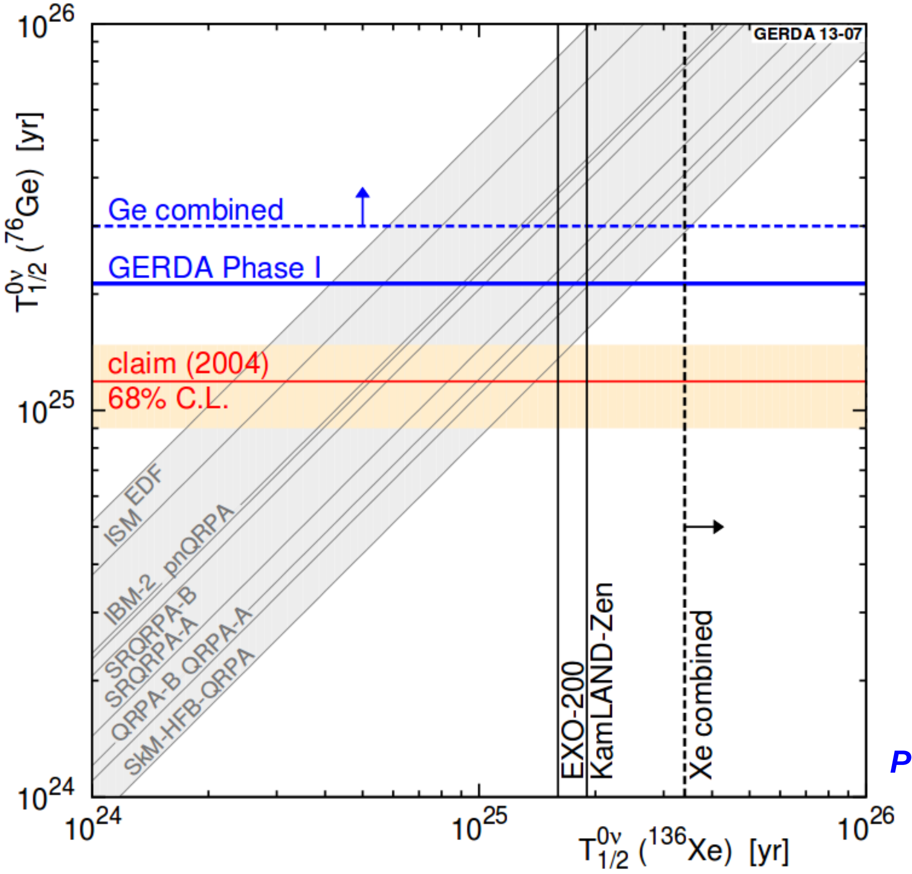

Phys. Rev. Lett. 111 (2013) 122503

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SNO+	^{130}Te	Scintillation	SNO Lab	Isotope mass, Efficiency		
SuperNEMO	^{82}Se	Tracking + Calorimetry	Modane	Background rejection, Isotope selection		

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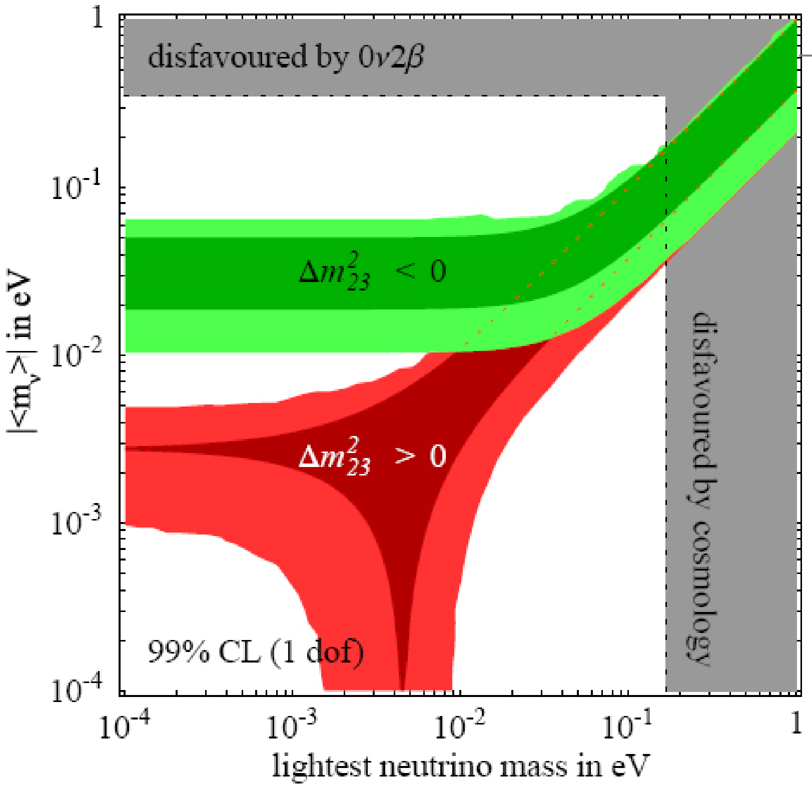

First *ββ* experiments: IGEX, H-M ...

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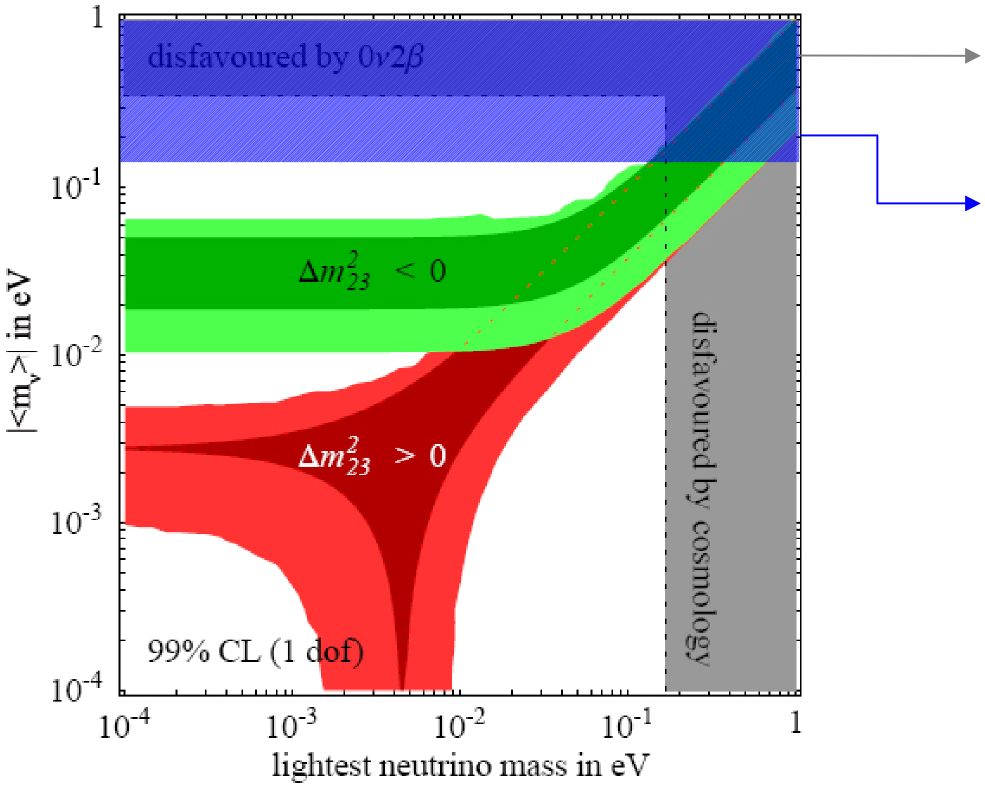

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Current best limits: Ge + Xe combination

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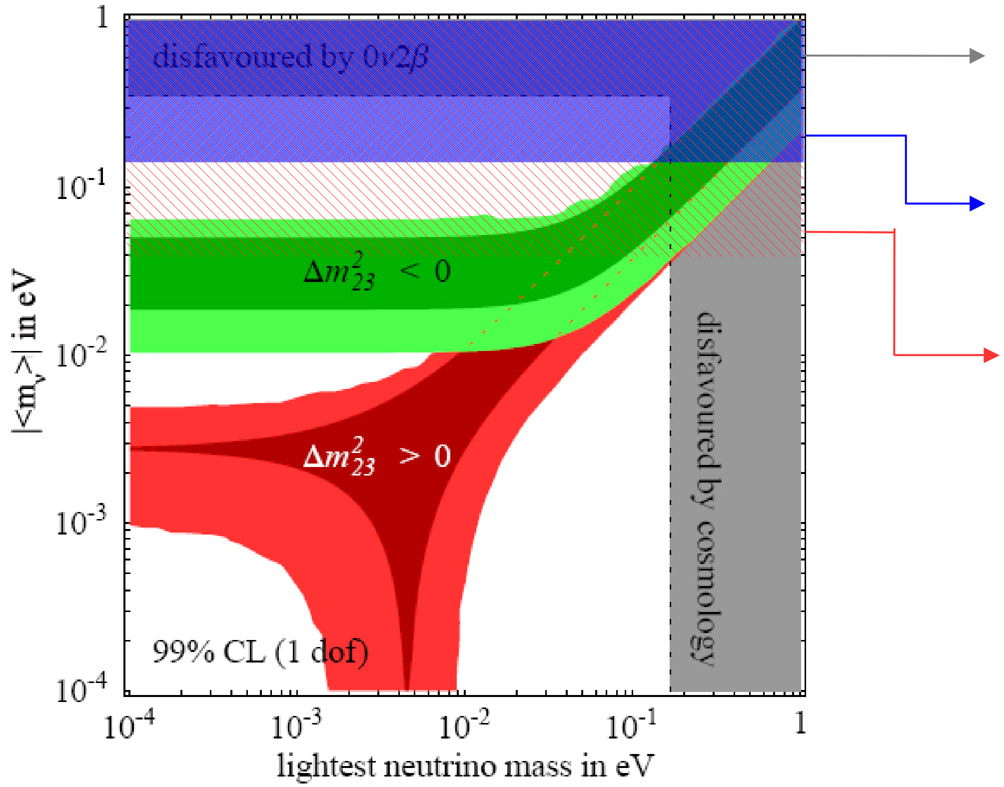

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New Generation experiments expected sensitivity:

$\langle m_\nu \rangle$ < 40 – 50 meV

Exploring the inverted hierarchy region

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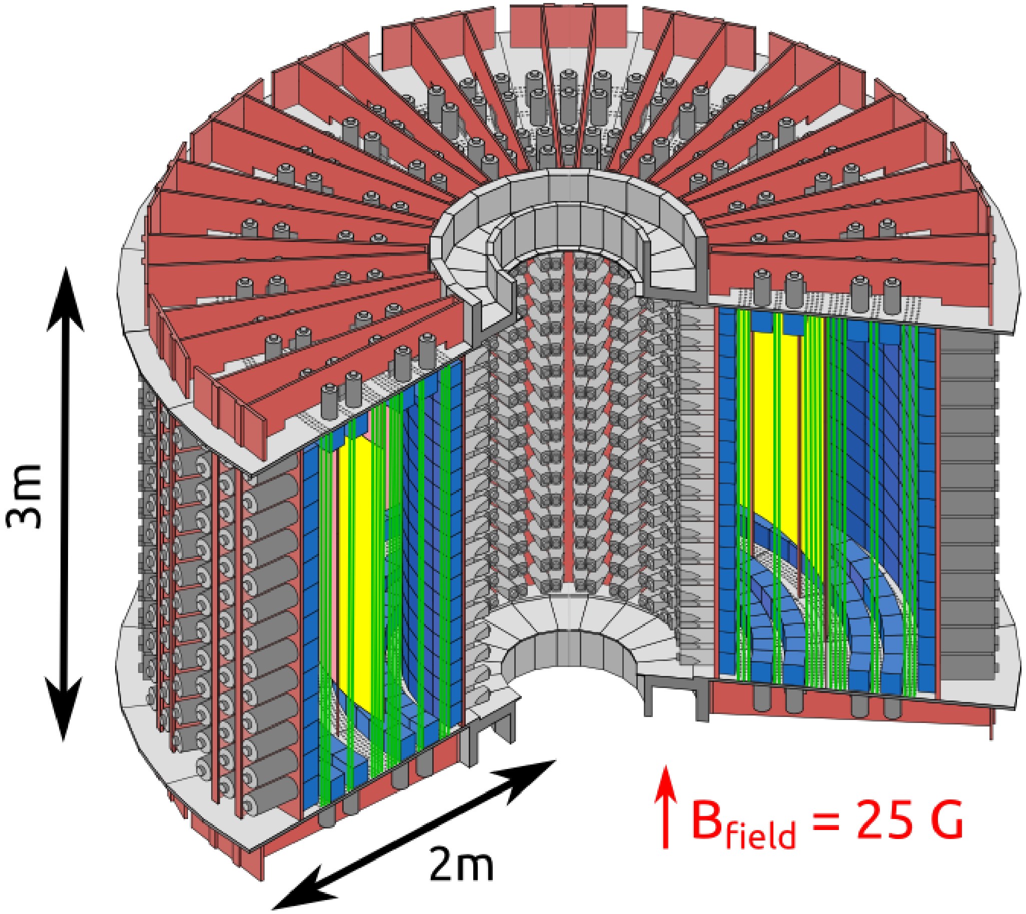
THE SuperNEMO EXPERIMENT: ITS PREDECESSOR **NEMO-3**

- SuperNEMO is conceived based on the ***NEMO-3*** experimental technique
- Combining the measurement of the particles energy with the reconstruction of their tracks
- ββ study fo different isotopes (mainly ^{100}Mo and ^{82}Se)
- Located at the Modane Underground Laboratory (~4800 m.w.e.)
- Data taking (2 phases) from February 2003 to January 2011 → Currently decommissioned



sources
60 mg/cm² foils
10 kg of ββ isotopes

tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

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

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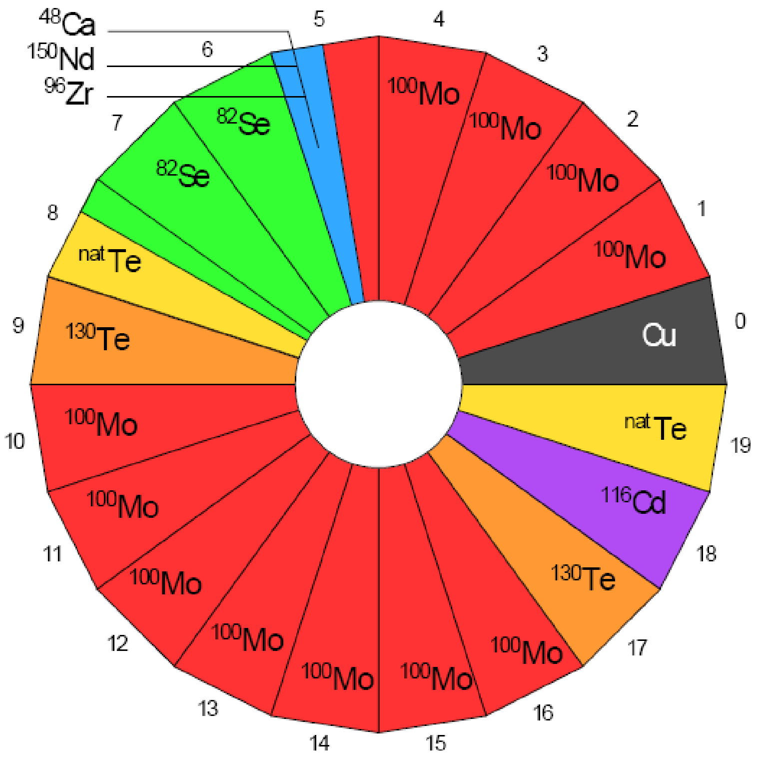
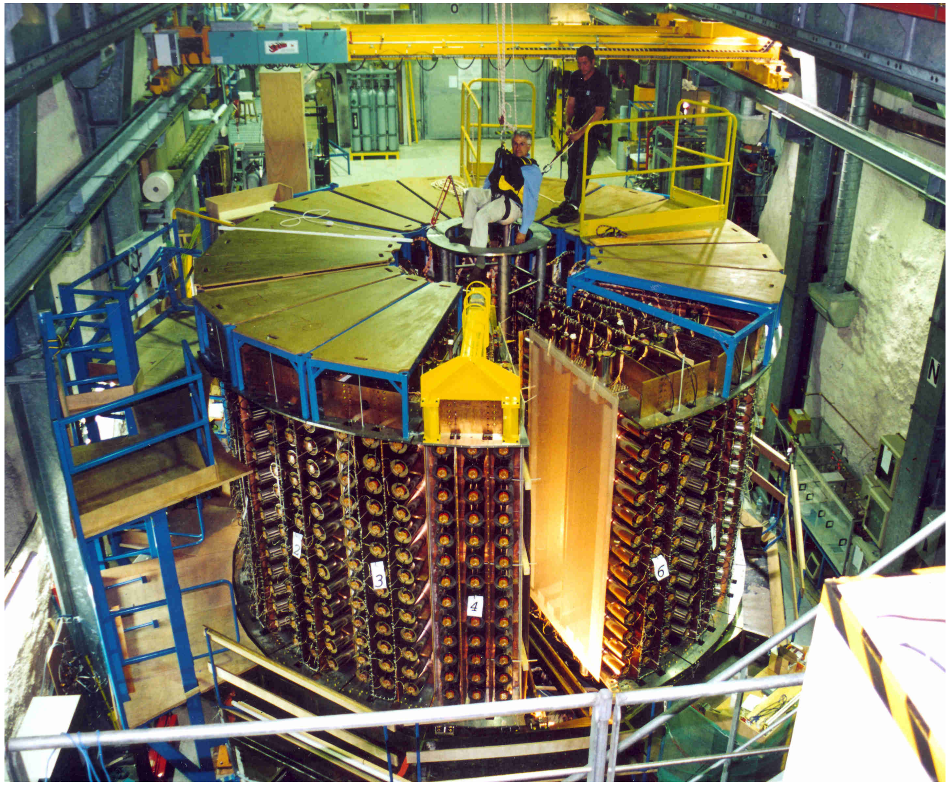


🟥 ^{100}Mo	6,9 kg
🟩 ^{82}Se	0,93 kg
🟧 ^{130}Te	0,45 kg
🟪 ^{116}Cd	0,40 kg
🟦 ^{150}Nd	36,5 g
🟦 ^{96}Zr	9,43 g
🟦 ^{48}Ca	6,99 g



*THE SuperNEMO EXPERIMENT: ITS PREDECESSOR **NEMO-3***

NEMO-3 capability to register simultaneously energy and tracks of the particles of an event, gave him unique advantages inside the ββ experiments:

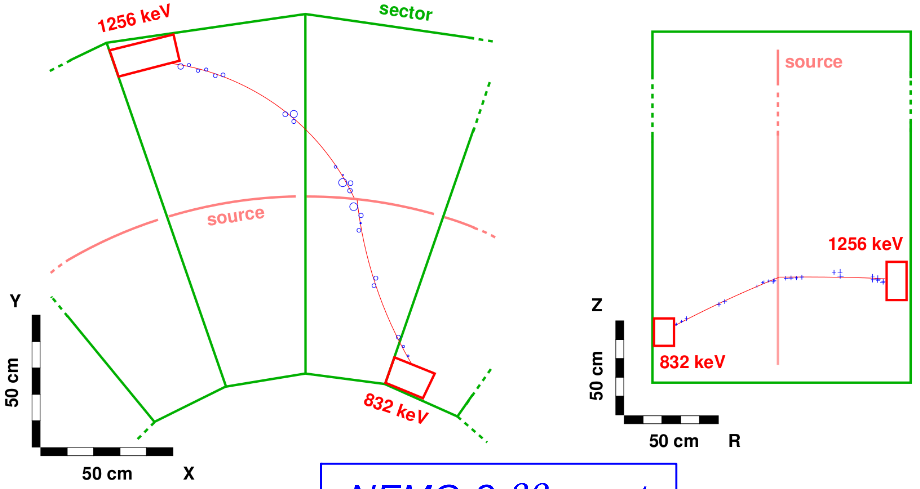
Full reconstruction of the 2 electrons present in a ***ββ decay event***:

Electrons energies (E_1, E_2)

Electrons arrival time (t_1, t_2)

Emission vertex and angle ($\cos\theta$)

Particle curvature inside the magnetic field → particle charge **±**



NEMO-3 ββ event

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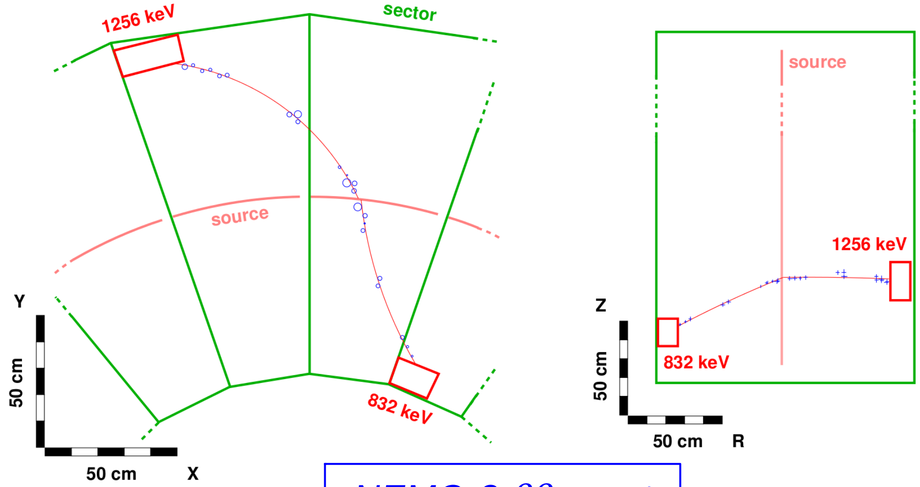
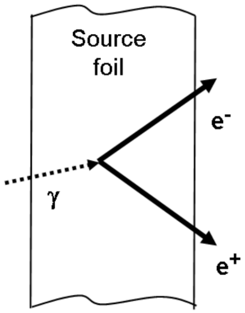


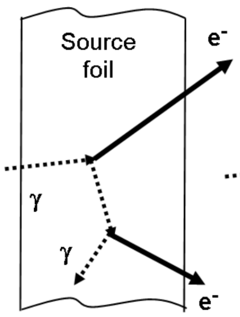
NEMO-3 ββ event

External Backgrounds:

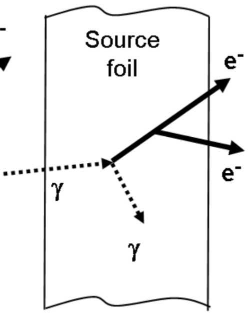
- Natural radioactivity from detector components (PMTs mainly)



Pair creation



Compton + Compton



Compton + Möller

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NEMO-3 capability to register simultaneously energy and tracks of the particles of an event, gave him unique advantages inside the ββ experiments:

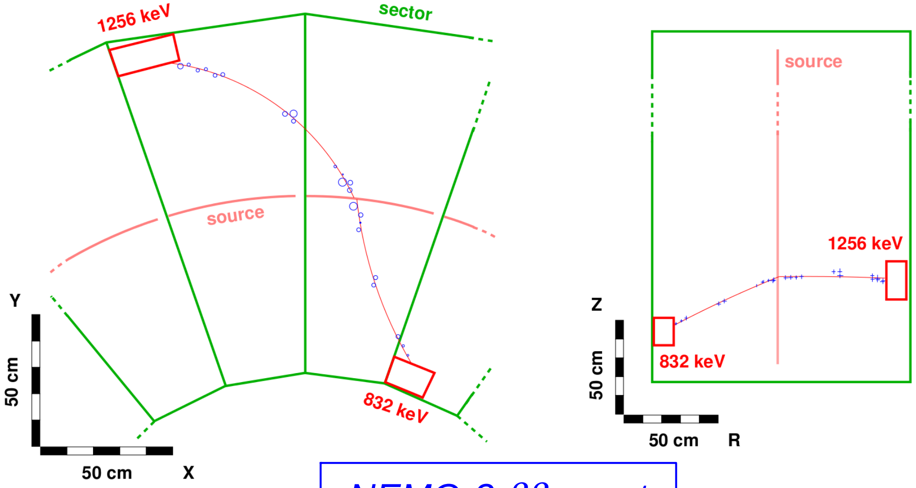
Full reconstruction of the 2 electrons present in a ββ decay event:

Electrons energies (***E_1, E_2***)

Electrons arrival time (***t_1, t_2***)

Emission vertex and angle (***cos θ***)

Particle curvature inside the magnetic field → particle charge **±**



NEMO-3 ββ event

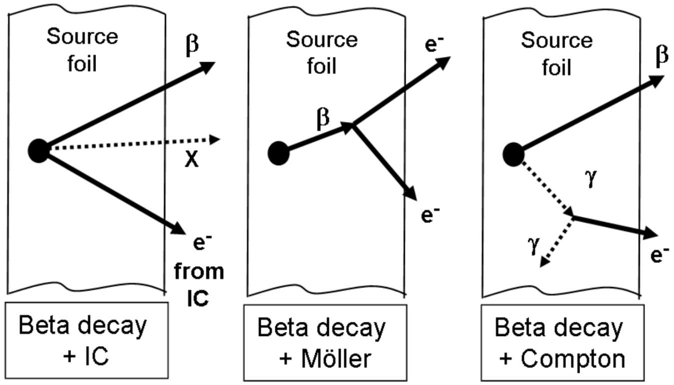
External Backgrounds:

Natural radioactivity from detector components (PMTs mainly)

Internal Backgrounds:

Radioactive contamination of the source foils (^{208}Tl, ^{214}Bi, ^{40}K)

Rn daughter deposition (source foils or tracker wires)



• = radioisotope ; β = electron from beta decay ; IC = internal conversion

Analysis of the different background channels: (γe^-)$_{ext}$, $e^-_{crossing}$, ($e^-\alpha$), ($e^-\alpha_{delayed}$), ($e^-N\gamma$), ($2e^-N\gamma$), ($2e^-\alpha$) ...

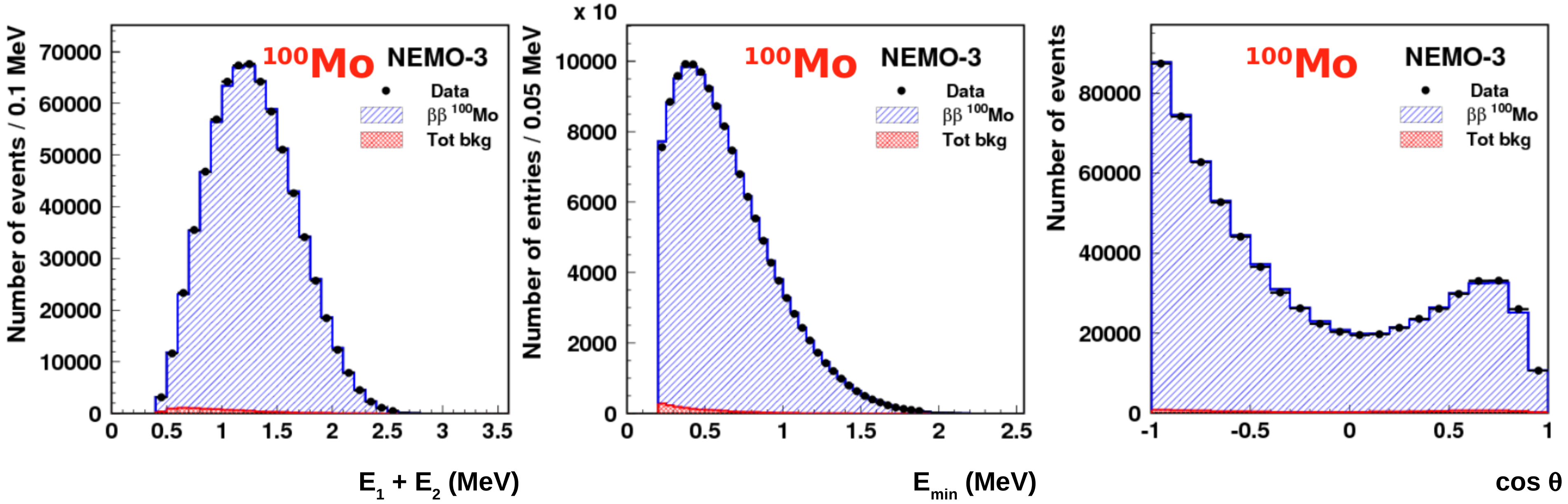
NIM A 606 (2009) 449 - 465

THE SuperNEMO EXPERIMENT: ITS PREDECESSOR **NEMO-3**

- ***$2\nu\beta\beta$ main results***

Isotope	Mass	$T^{2\nu}_{1/2}$(years)	Ref.
^{100}Mo	**6.9 kg**	**7.16 ± 0.01 (stat) ± 0.54 (sys) 10^{18}**	***PRL 95 (2005) 182302***
^{82}Se	0.93 kg	9.6 ± 1.0 10^{19}	*PRL 95 (2005) 182302*
^{150}Nd	36.5 g	9.1 ± 0.7 10^{18}	*Phys. Rev. C 80 (2009) 032501*
^{96}Zr	9.43 g	2.35 ± 0.21 10^{19}	*Nucl. Phys. A 847 (2010) 168*
^{130}Te	0.45 kg	7.0 ± 1.4 10^{20}	*PRL 107 (2011) 062504*

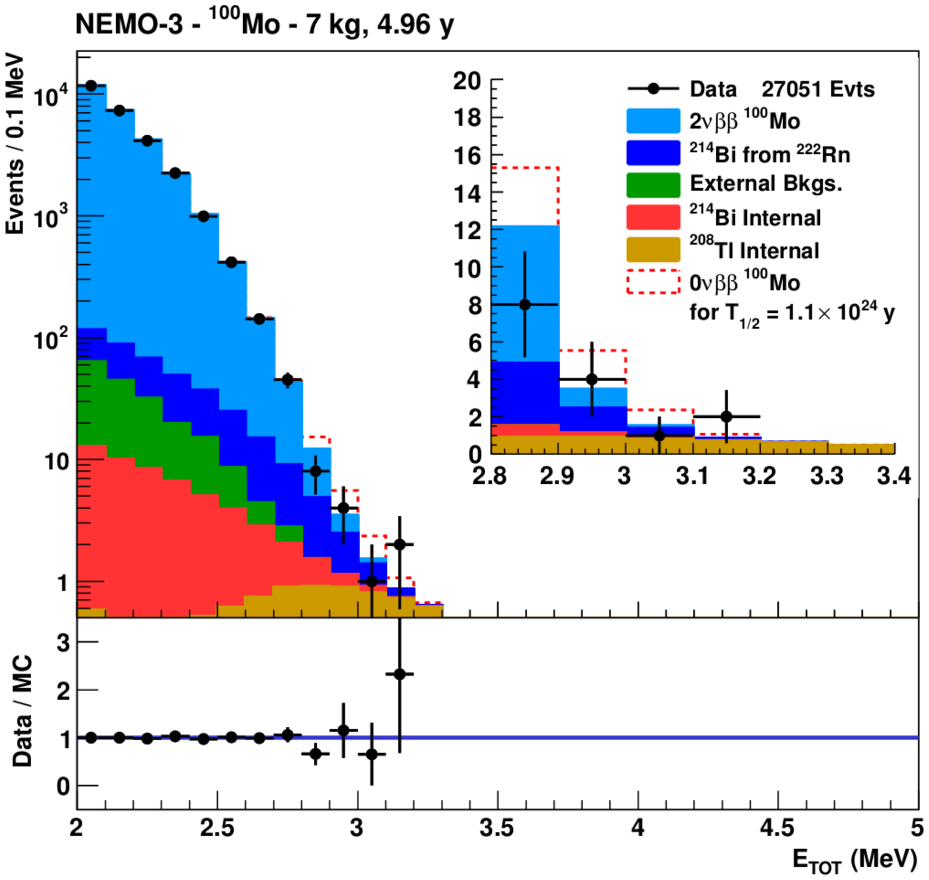
Analysis in other isotopes (^{48}Ca, ^{116}Cd ...) in progress



*THE SuperNEMO EXPERIMENT: ITS PREDECESSOR **NEMO-3***

- ***0νββ main results and High Energy Background***

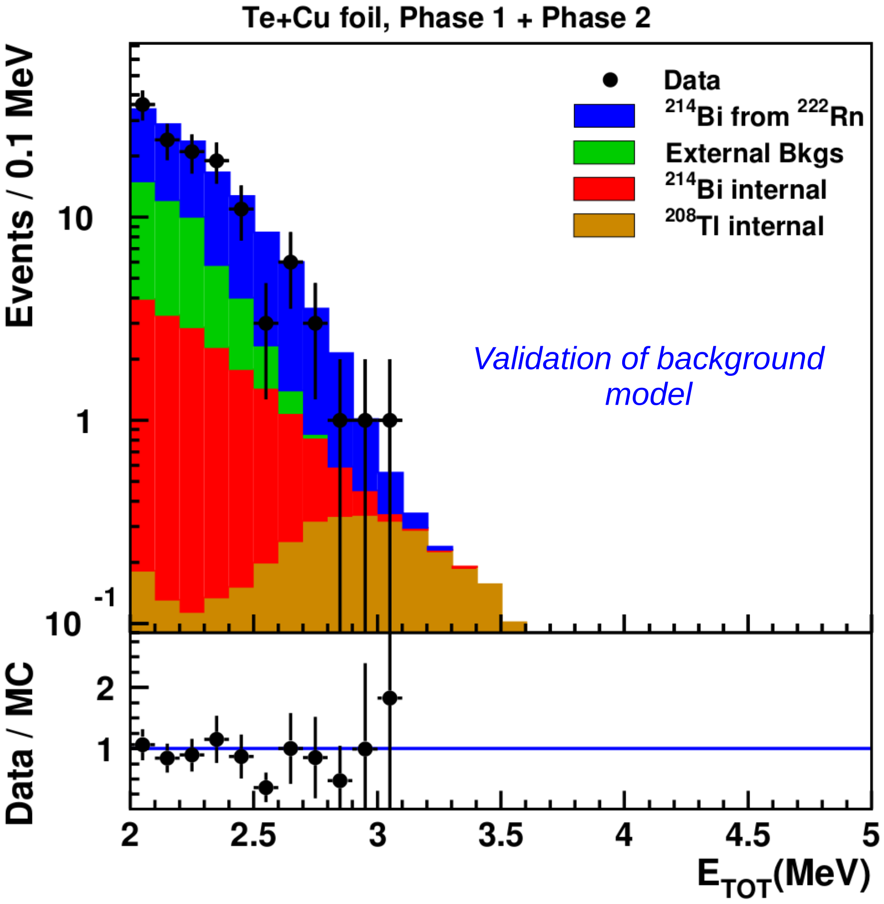
Phys. Rev. D 89 (2014) 111101



No event excess for ^{100}Mo after 34.3 kg y exposure

$T^{0\nu}_{1/2} > 1.1\ 10^{24}$ y (90 % C.L.) → $\langle m_{\beta\beta}\rangle < 0.3 – 0.9$ eV

No events above 3.2 MeV



Validation of background model

No event in Cu and ^{nat}Te after 13.5 kg y exposure above 3.1 MeV

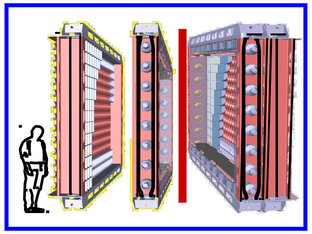
Background free technique for high $Q_{\beta\beta}$ isotopes:

^{48}Ca (4.272 MeV), ^{150}Nd (3.368 MeV), ^{96}Zr (3.350 MeV)

THE *SuperNEMO* EXPERIMENT

NEMO 3

From NEMO 3 to SuperNEMO



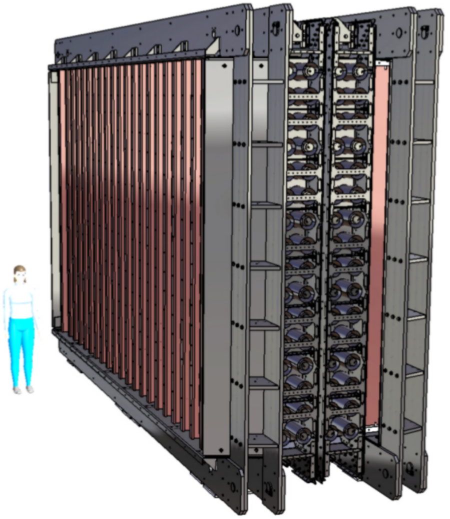
SuperNEMO

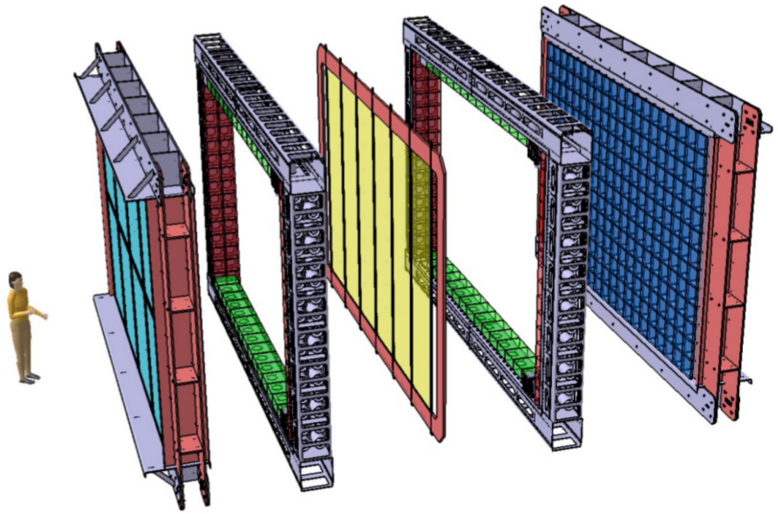
^{100}Mo, ^{82}Se and others	*Isotope*	^{82}Se (^{150}Nd or ^{48}Ca?)
7 kg	*Mass*	~100 kg
60 mg/cm^2	*Foil Density*	40 mg/cm^2
15 % FWHM @ 1 MeV	*Energy Resolution*	7 % FWHM @ 1 MeV
8 % FWHM @ 3 MeV		4 % FWHM @ 3 MeV
~ 100 µBq/kg	*^{208}Tl source radiopurity*	< 2 µBq/kg
< 300 µBq/kg	*^{214}Bi source radiopurity*	< 10 µBq/kg
~ 5 mBq/m^3	*Rn level in Tracker*	~ 0.1 mBq/m^3
6180	*Tracking cells*	20 x 2034
1940	*Calorimeter Blocks*	20 x 712
1.3 10^{-3}	*Total Background (c/keV/kg/y)*	5 10^{-5}
$T^{0\nu}_{1/2} > 1.1\ 10^{24}$ y	*Sensitivity*	$T^{0\nu}_{1/2} > 1\ 10^{26}$ y
$\langle m_{\beta\beta} \rangle < 0.3 – 0.9$ eV		$\langle m_{\beta\beta} \rangle < 0.04 – 0.1$ eV

THE **SuperNEMO** EXPERIMENT

- ***Demonstrator***
  - First phase of SuperNEMO: One module with the final features
    - 6.2 x 2.1 x 4.1 m^3 (32 tons)
    - 7 kg of ^{82}Se (distributed in 53 mg/cm^2 foils)
  - Physics case
    - NEMO-3 sensitivity after 5 months of measurement
      - $T_{1/2}^{0\nu} > 1.1\ 10^{24}$ y → $<m_\nu> < 0.3 – 0.9$ eV
    - If no background after 2.5 years of data taking
      - $T_{1/2}^{0\nu} > 6.5\ 10^{24}$ y → $<m_\nu> < 0.2 – 0.4$ eV

Construction and Commissioning expected from September 2015





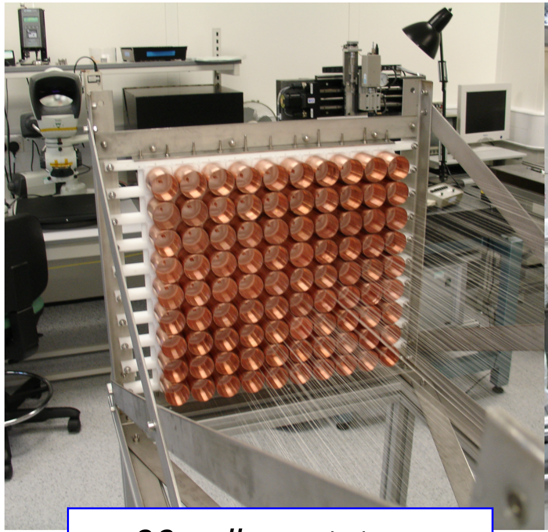
THE **SuperNEMO** EXPERIMENT

Calorimeter:

- Hamamatsu R9512
  - 8” and high quantum efficiency
  - Improved HV divider (less noise)
- Direct coupling PMT – Polystyrene Scintillator Block
  - Optimized geometry for the scintillator
- Tested with DAQ equivalent to the SuperNEMO one
  - ~2 GS/s for pulse sampling
- Energy resolution tests
  - 7.8 % FWHM @ 1 MeV

Tracker:

- 2034 Geiger cells distributed in 18-cells cartridges
- Installed inside a Rn tight tracker chamber
  - Done in 4 quarters (C0-C1-C2-C3)
  - Surrounded by Optical Modules (veto)
- Tracking resolution (tested in prototypes)
  - $\sigma_{xy} \sim 0.7$ mm
  - $\sigma_{z} \sim 10$ mm



90 cells prototype

General View

THE **SuperNEMO** EXPERIMENT

Radon studies:

It is necessary to reduce internal Radon background to 0.15 mBq/m^3

Control the Radon emanation of the materials

Assure the Radon tightness of the sensitive volume

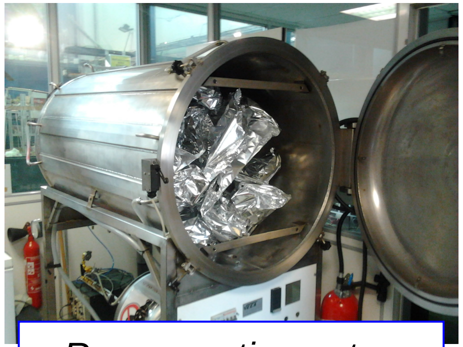
Reliable measurements of such a low level of Radon concentration

Detection limits:

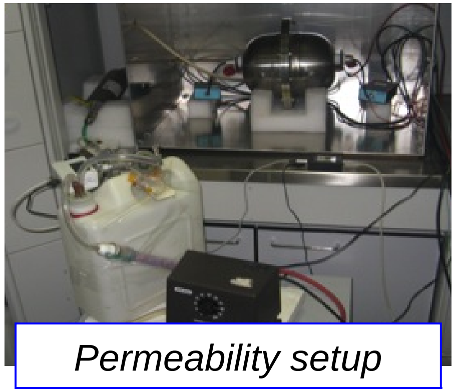
~ µBq/s for emanation

~ µBq/m^3 for Rn concentration

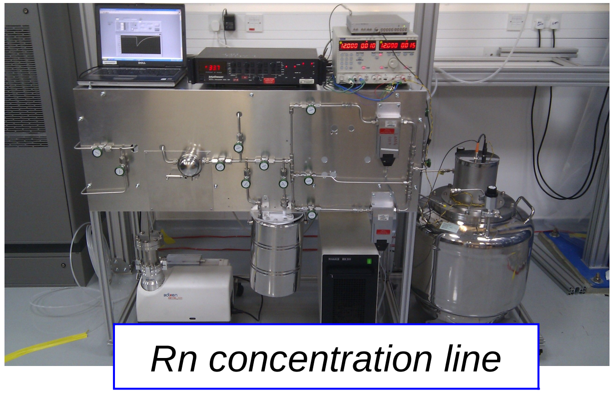
~ 10^{-15} m^{-2}s^{-1} for permeability



Rn emanation setup



Permeability setup



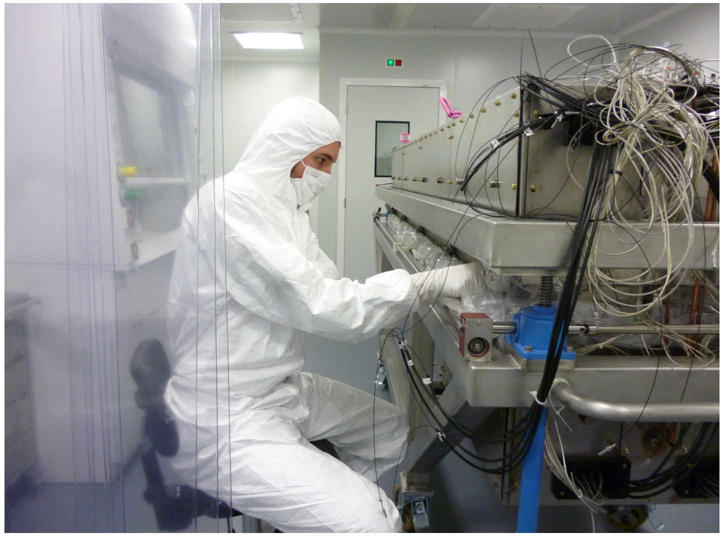
Rn concentration line

Radiopurity measurements:

Routine materials screening with HPGe detectors → Radiopurity budget

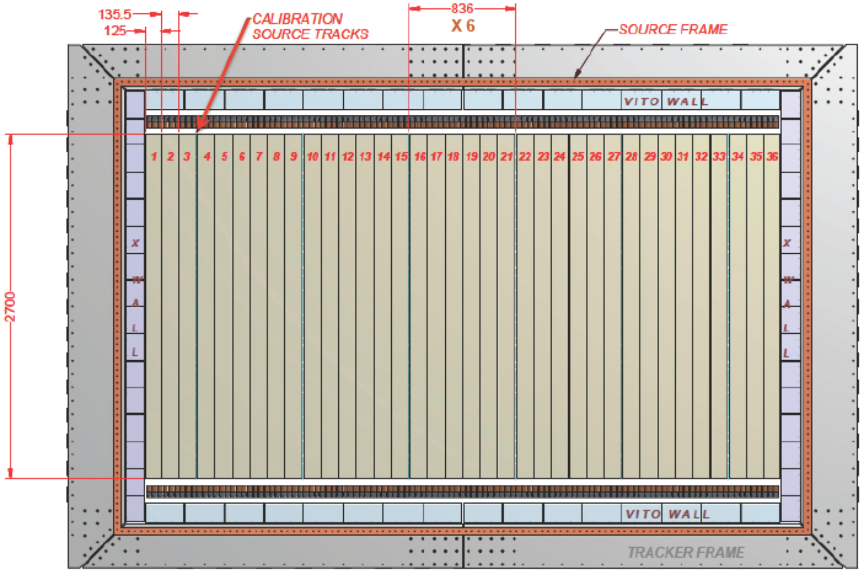
Source foils: < 2 (< 10) µBq/kg in ^{208}Tl (^{214}Bi) required

Dedicated setup to reach this sensitivity level → ***BiPo detector***



THE BiPo DETECTOR

- Each SuperNEMO module (as the demonstrator) will hold ~7 kg of ^{82}Se
    - 36 strips ~ 135 x 2700 mm^2 and ~ 150 μm thick
    - Contamination of these strips must not exceed
        - A(^{208}Tl) < 2 μBq/kg
        - A(^{214}Bi) < 10 μBq/kg
    - Most sensitive HPGe detectors reach the 100 μBq/kg sensitivity for ^{208}Tl

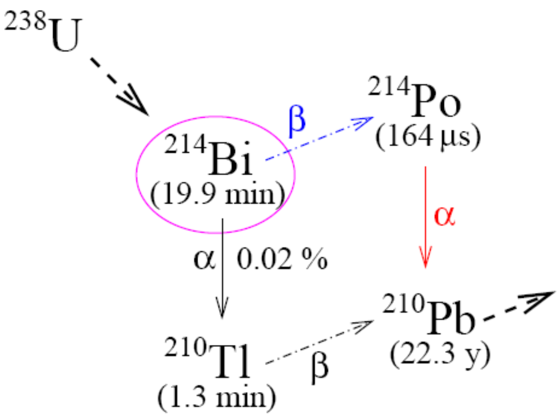


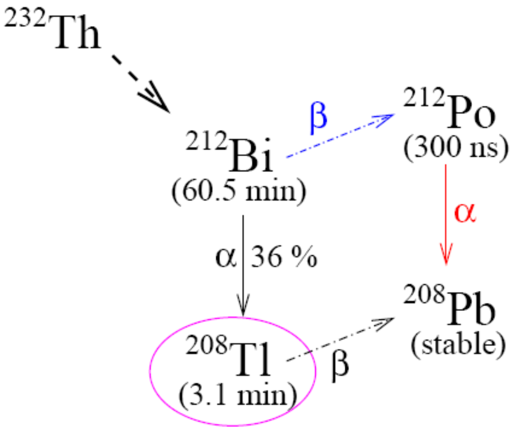
2 Source Foils 125mm x 2700mm (1&36)
34 Source Foils 135.5mm x 2700mm (2-35)
TOTAL SOURCE SURFACE = 131139cm^2

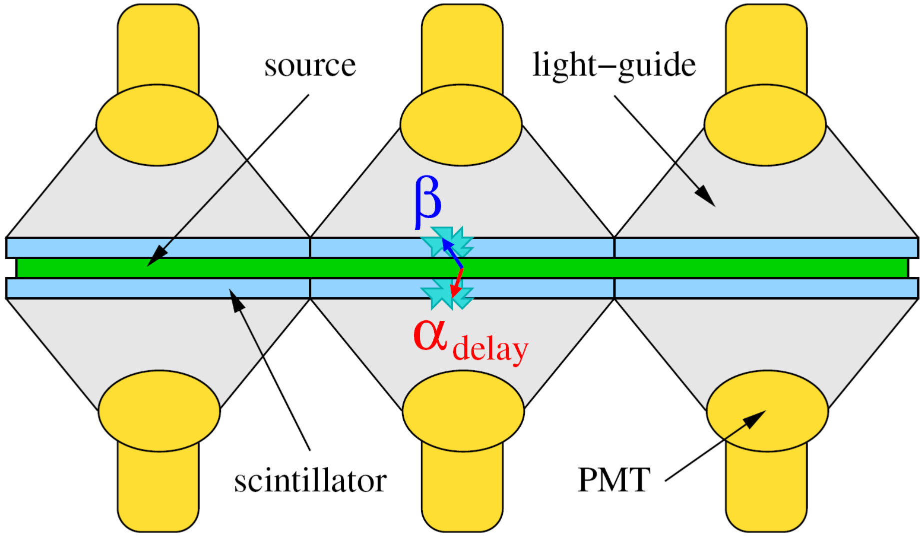
- SuperNEMO requires a way to measure the source foils
    - In a non – destructive way
    - Allowing to measure the foils in their final geometry
    - With the required sensitivity

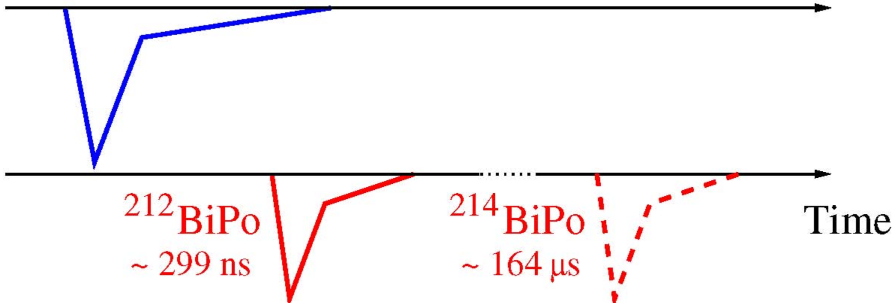
*THE **BiPo** DETECTOR*

- BiPo is based on the detection of the e$^-$ - α delayed coincidence produced in the ^{212}Bi → ^{212}Po and ^{214}Bi → ^{214}Po cascades









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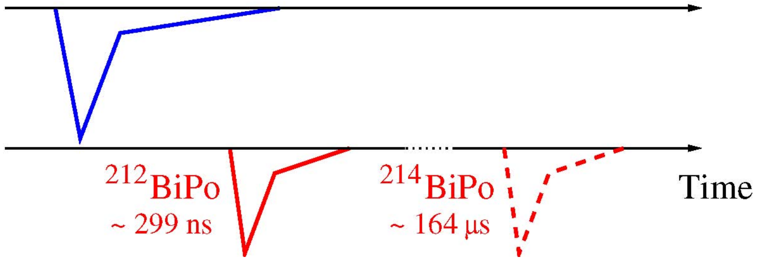
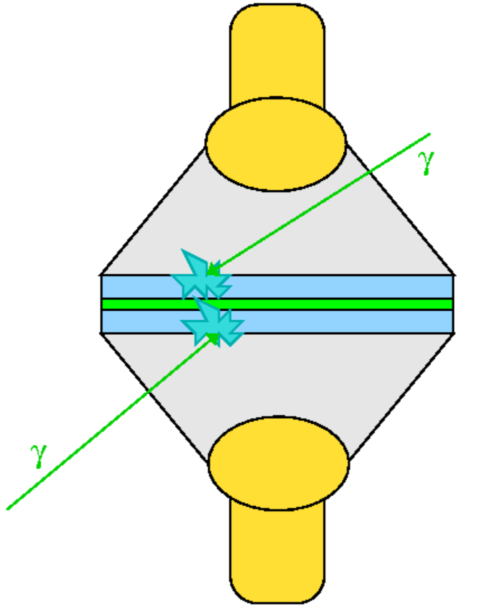
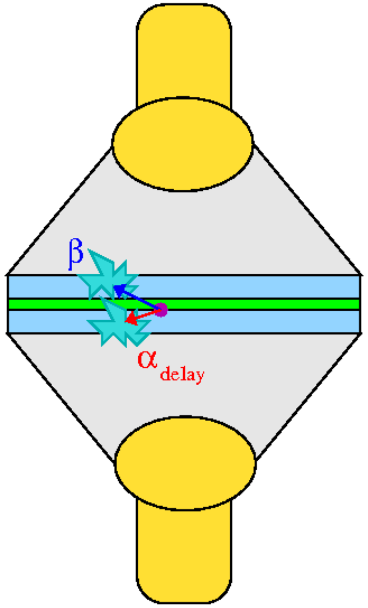


- Based on this detection techniques, background sources are limited:

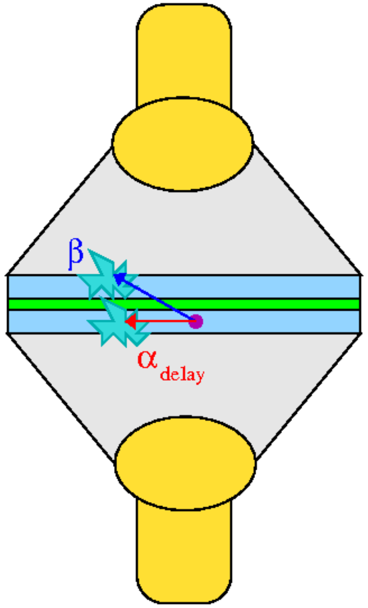


γ – induced random coincidence



Scintillator surface contamination

Rn in the sensitive volume



Scintillator bulk contamination

Shielding

Radiopure Materials

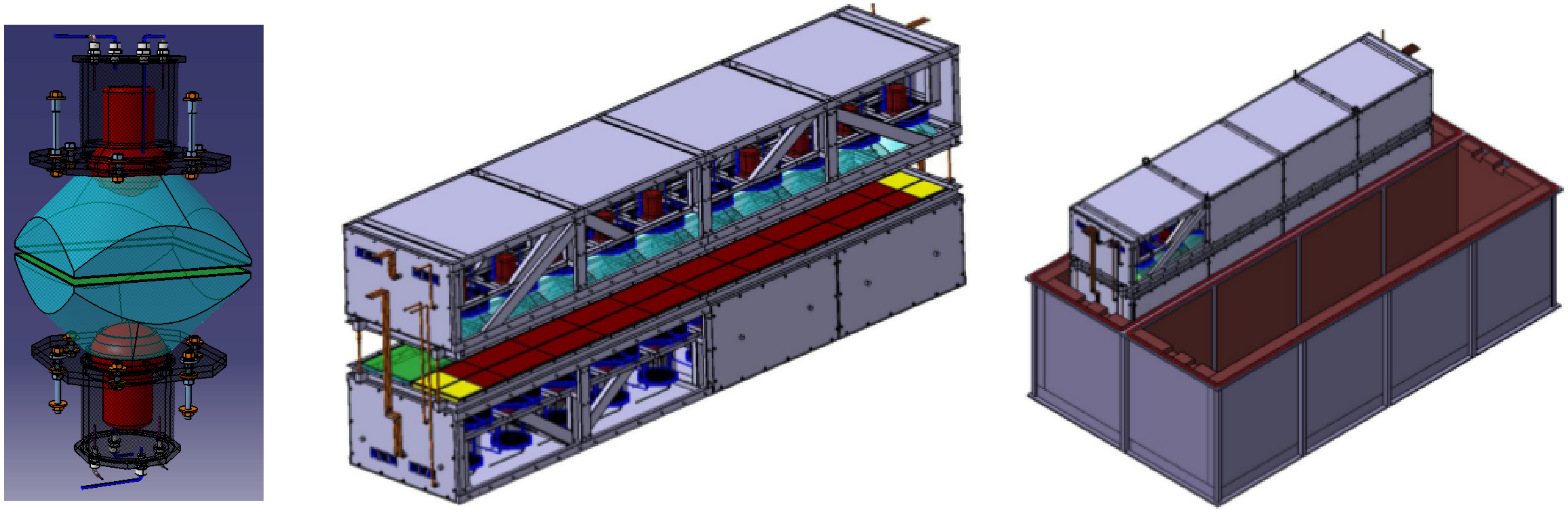
Ultrapure Scintillator

Rn removal (LN_2 flushing)

Ultrapure Scintillator

*THE **BiPo** DETECTOR*

- ***BiPo final setup (@ Canfranc Underground Laboratory):***
  - 2 Modules detector (3.0 x 0.6 m^2 each)
    - 3.6 m^2 sensitive surface → Possibility to measure up to 8 source foils at the same time (1 SuperNEMO Module = 36 foils)
  - 20 optical sub-modules per module independently registered → Possibility of “hot-spots” detection
    - 30 x 30 cm^2, 2 mm thick aluminized polystyrene plates
    - 5” Hamamatsu lox radioactivity PMTs
    - Coupled by PMMA light guides (optimized geometry for light collection)
  - Shielding: 10 cm Lead, Stainless Steel Rn-tight tank + 20 cm iron
    - Inner volumes separation to optimize the nitrogen flushing for Rn suppression



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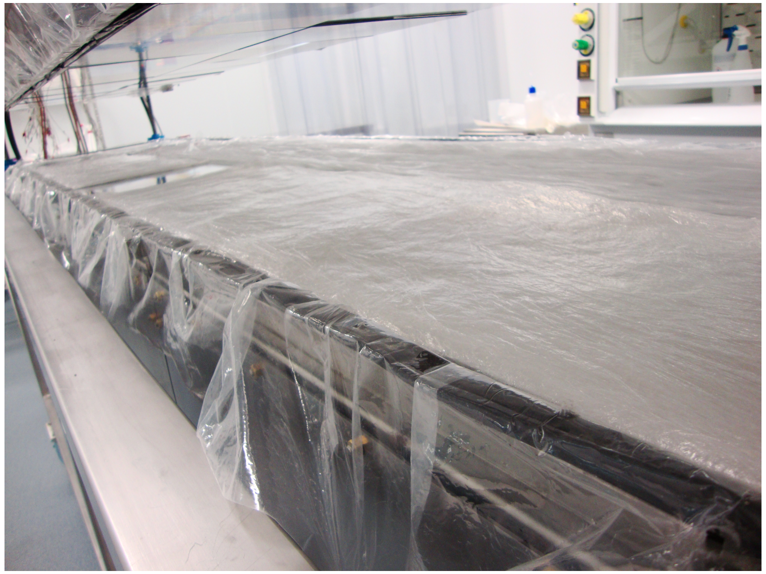


THE **BiPo** DETECTOR

- ***BiPo working timeline:***
- Design & Construction
- Characterization of the optical lines
    - ^{207}Bi absolute calibration (gain and energy resolution)
    - ^{241}Am calibrations (aluminization quality and light collection efficiency)
- Assembly tests
    - Alignment and planarity of the detector (at 0.1 mm accuracy)

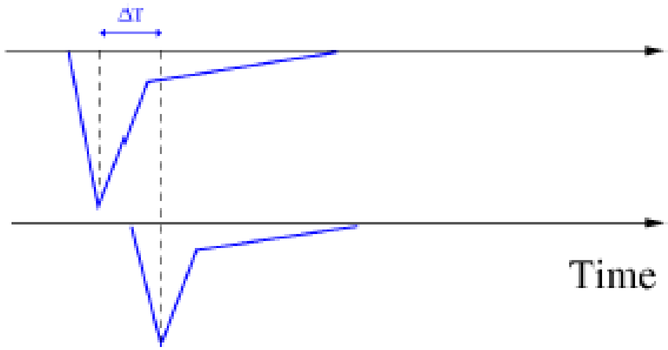
@ LAL

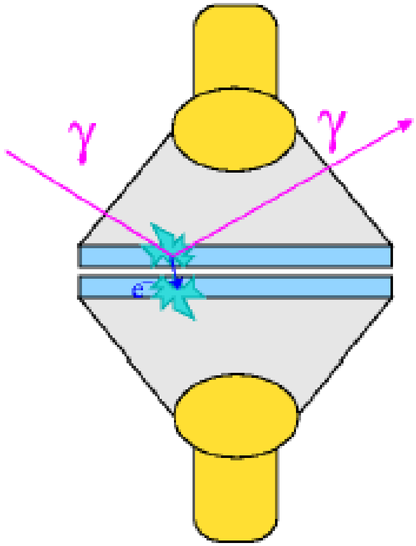
- Detector installation and commissioning
    - ^{22}Na and ^{54}Mn calibrations to check the good performances
    - Over 10 weeks, fully operative since February 2013
- Detection validation with a calibrated sample
- Background measurement → Sensitivity estimation
- SuperNEMO samples measurement

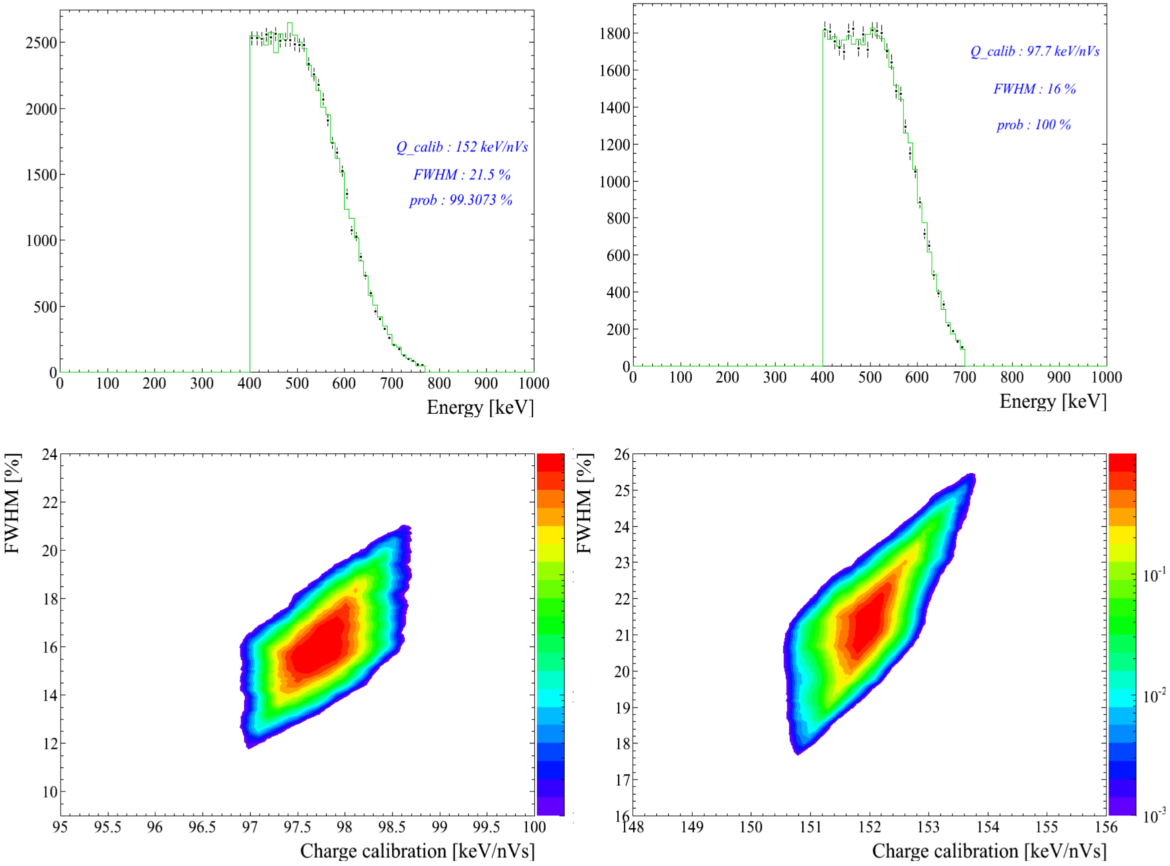
@ LSC

THE **BiPo** DETECTOR

- ***BiPo systematic calibrations:***
- For the identification of the BiPo events the energy calibration of each scintillator and the time calibration of all the optical lines is needed:
- ^{22}Na and ^{54}Mn sources provide 3 gamma lines (511, 1274 and 835 keV respectively) to make the calibration
- The calibration is done by studying the Compton edge → Kolmogorov Test (Gain & FWHM)

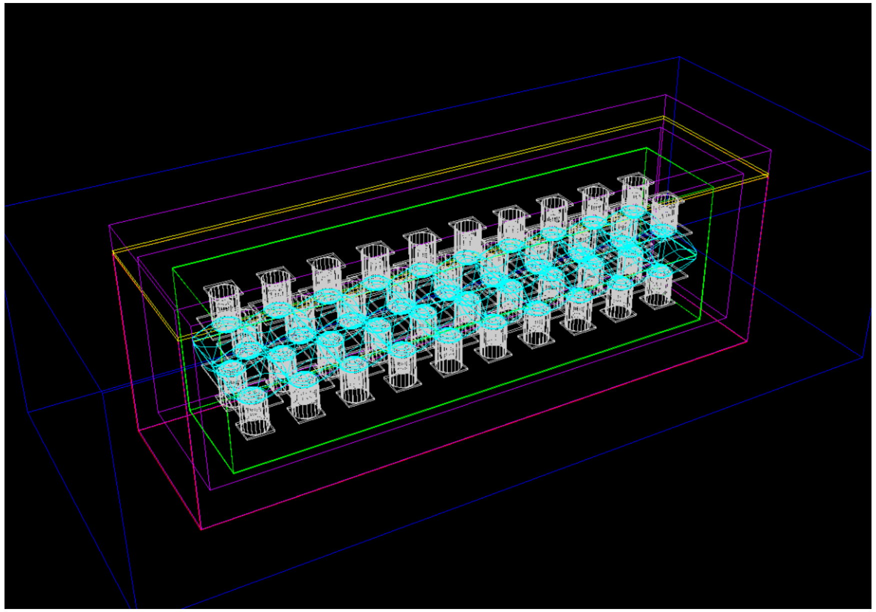






THE **BiPo** DETECTOR

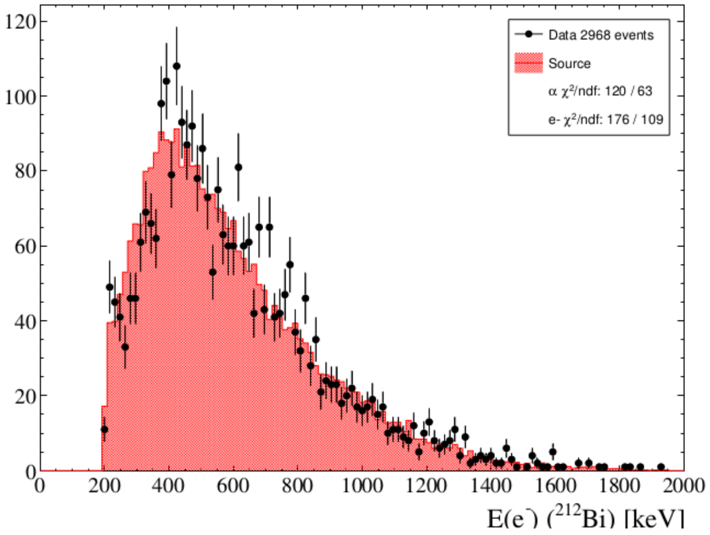
- ***Al foil calibration, validation of the detection principle and efficiency:***
- To check the detector performance, and validate the detection efficiency estimation
  - Two aluminium foils → Equivalent geometry than the further source foils
  - Two different thickness: 85 and 170 µm
    - Sample thickness is the main concern regarding efficiency (probability α escapes from the sample)
  - Efficiency simulation is done with the same framework used for SuperNEMO simulations
    - First cross-check simulation – real data

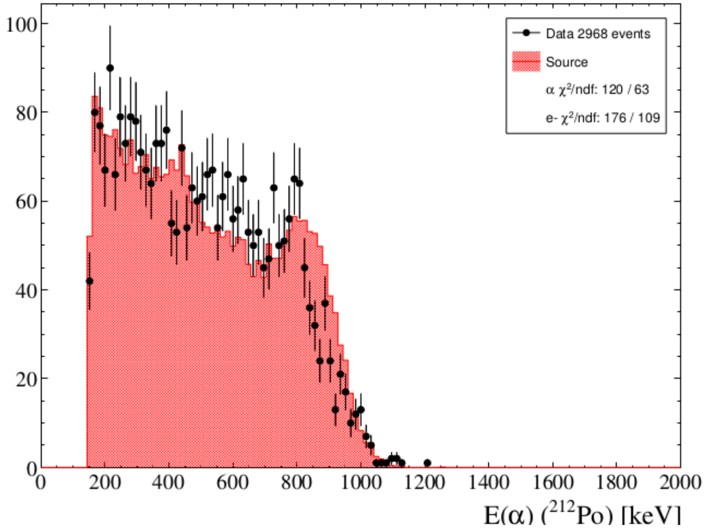


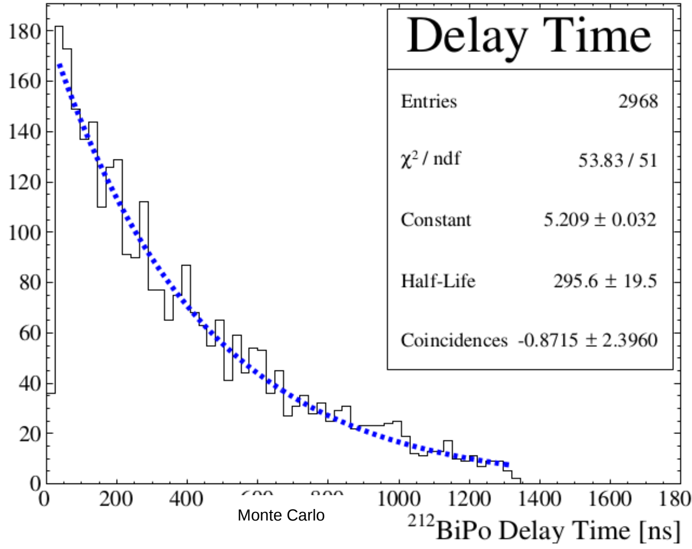
*THE **BiPo** DETECTOR*

- ***Al foil calibration, validation of the detection principle and efficiency:***
- ^{212}BiPo channel (^{208}Tl activity)
    - 2968 ^{212}BiPo events registered in 24.1 days
    - Monte-Carlo gives an efficiency ε(^{212}BiPo) = 5.3 %
    - Reconstructed activity: A(^{208}Tl) = 130 ± 26 mBq/kg

85 μm thick Al foil (224 g)







- Match data – simulation by Likelihood method
- Expected time delay distribution
- Validation of polystyrene a quenching
- Light collection efficiency

Measured at LAL test bench

THE **BiPo** DETECTOR

- ***Al foil calibration, validation of the detection principle and efficiency:***

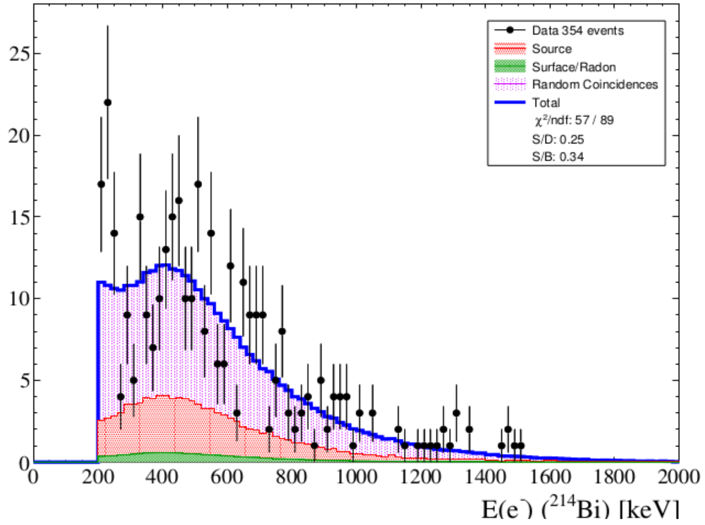
- ^{214}BiPo channel (^{214}Bi activity)

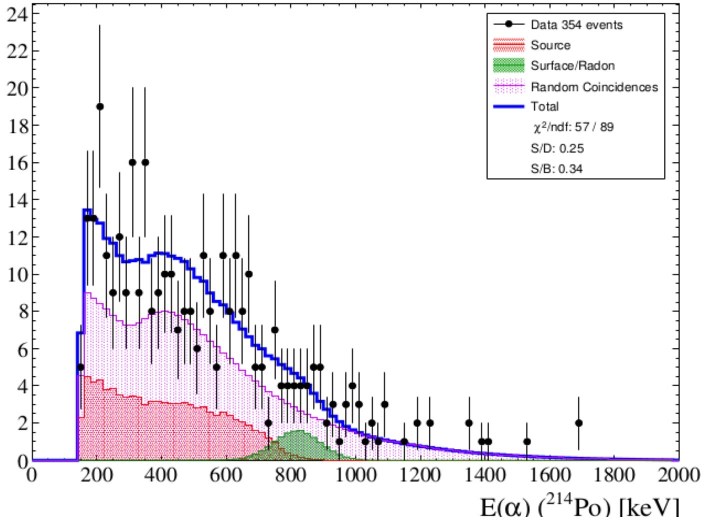
  - 354 ^{214}BiPo events registered in 11.9 days

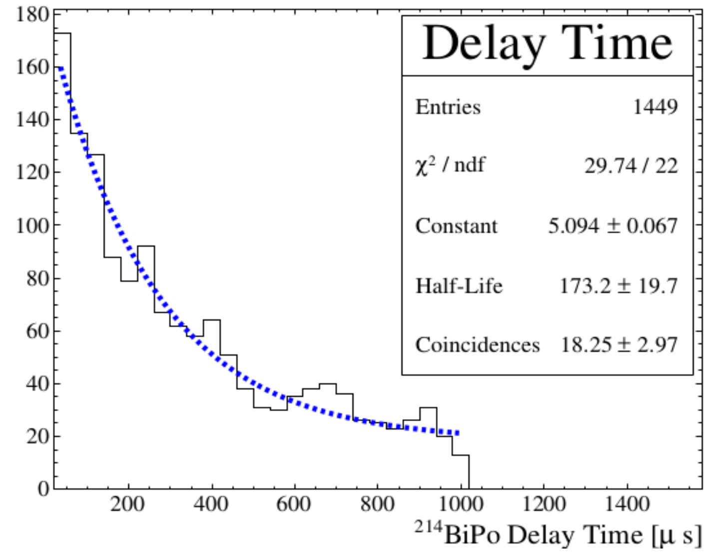
  - Monte-Carlo gives an efficiency $\varepsilon(^{214}\mathrm{BiPo}) = 3.3$ %

  - Reconstructed activity: $A(^{214}\mathrm{Bi}) = 12.7 \pm 2.1$ mBq/kg

85 µm thick Al foil (224 g)







- Match data – simulation by Likelihood method (***Radon + Random Coinc***)

- Expected time delay distribution

- Validation of polystyrene a quenching

- Light collection efficiency

} Measured at LAL test bench

THE **BiPo** DETECTOR

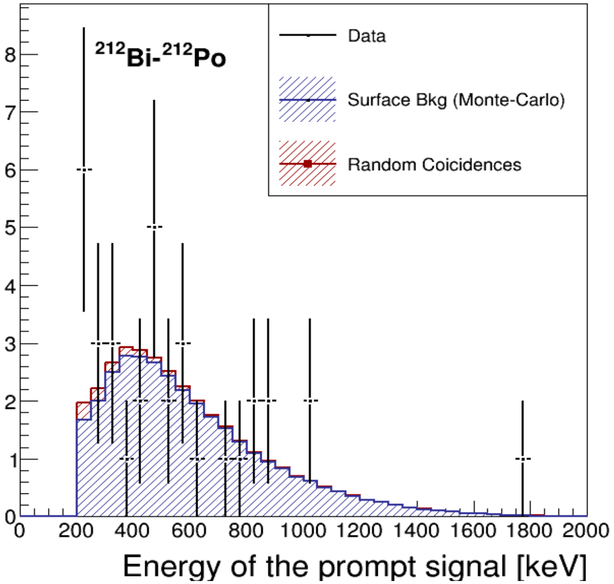
- ***Al foil calibration, validation of the detection principle and efficiency:***

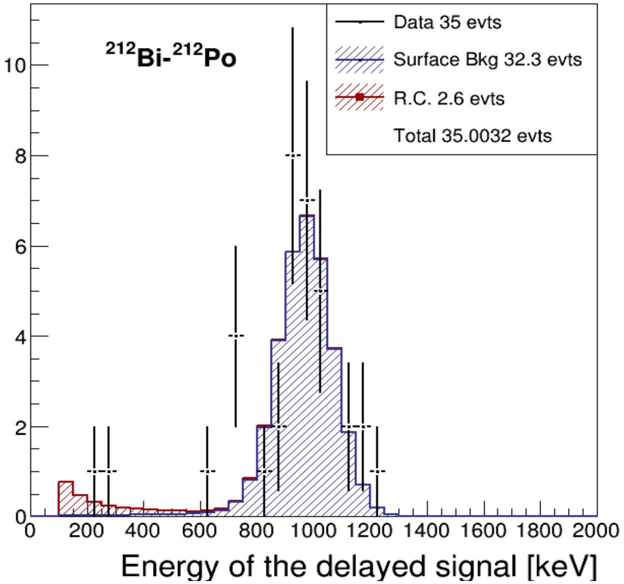
	A(^{208}Tl) [mBq/kg]	A(^{214}Bi) [mBq/kg]
HP-Ge	109 ± 10	13.2 ± 3.6
BiPo	130 ± 26	10.4 ± 3.3

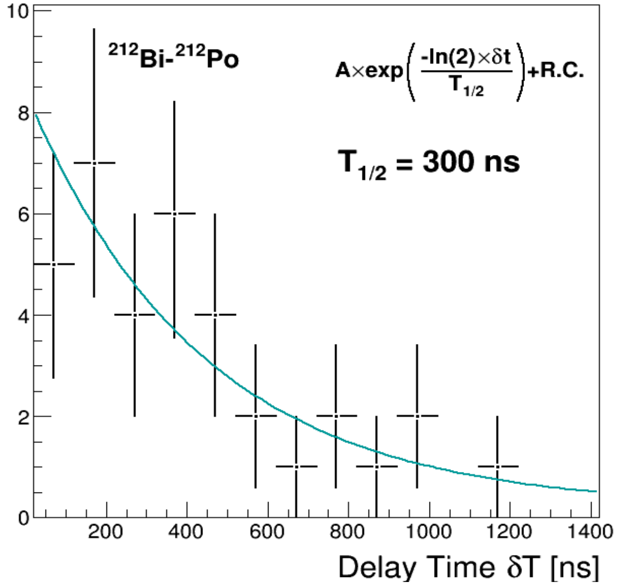
- The compatibility of the results leads to validate the detection principle and the simulation framework
- By simulation + likelihood analysis is possible not only to determine the activity but also to have an idea of their origin (an advantage for the samples measurement...)

THE ***BiPo*** DETECTOR

- ***Background measurements and detector sensitivity:***
- Three background measurements performed
- ***^{212}BiPo***
    - 717 days x m^2 scintillator exposure (200 days of measurement)
    - Estimated detection efficiency ε(^{212}BiPo) = 30 %
    - 35 ^{212}BiPo candidates observed (homogeneously distributed in the different measurements)





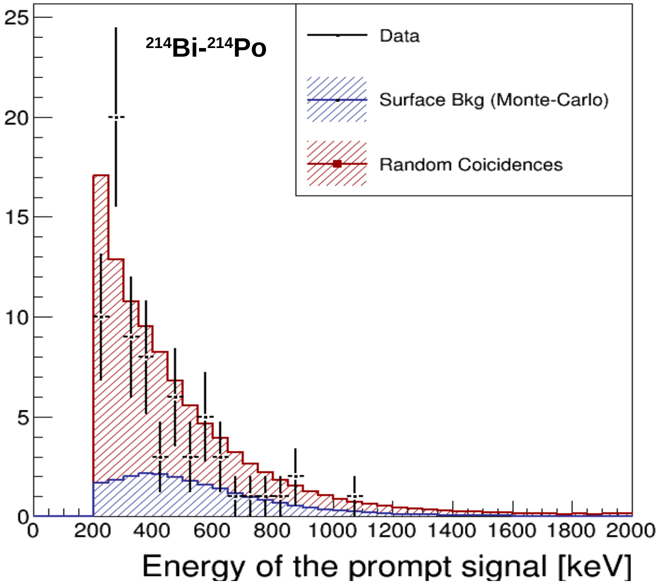


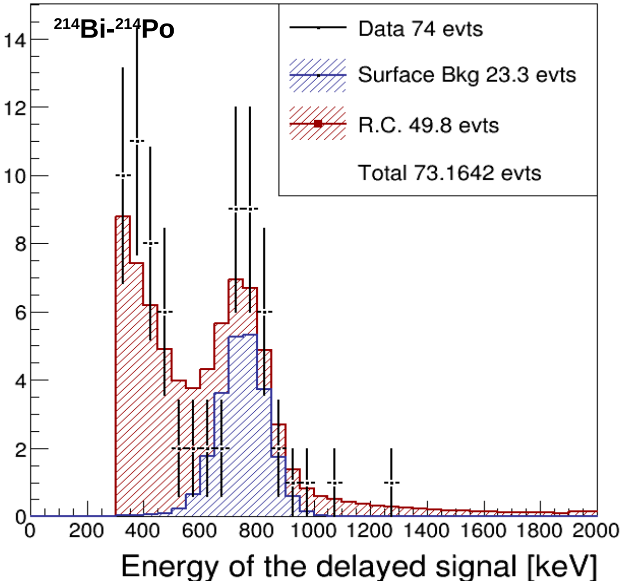
A (^{208}Tl) = 1.09 ± 0.20 μBq/m^2 scintillator (90 % C.L.)

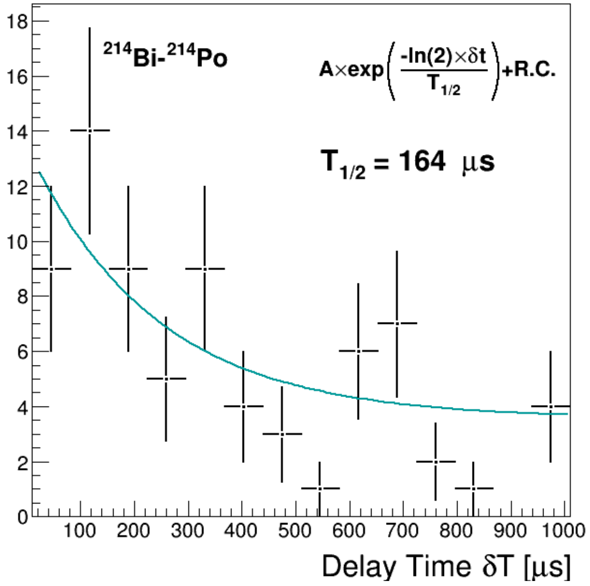
An additional cut at E_{delay} > 700 keV → No Random Coincidences

*THE **BiPo** DETECTOR*

- ***Background measurements and detector sensitivity:***
- Three background measurements performed
- ***^{214}BiPo***
    - 576 days x m^2 scintillator exposure (184 days of measurement)
    - Estimated detection efficiency $\varepsilon(^{214}\mathrm{BiPo}) = 27$ %
    - 74 ^{214}BiPo candidates observed (homogeneously distributed in the different measurements)







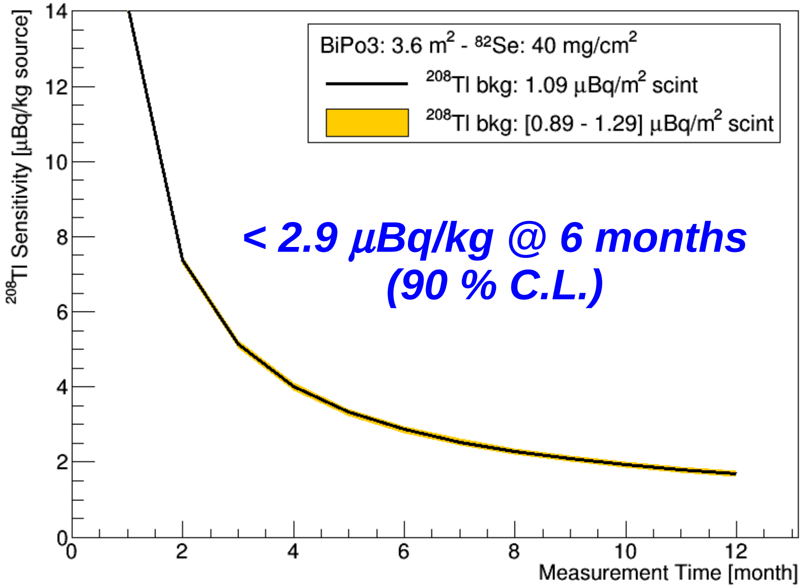
A (^{214}Bi) = 1.54 ± 0.32 µBq/m^2 scintillator (90 % C.L.)

Surface Contamination / Random Coincidences (30 / 70)

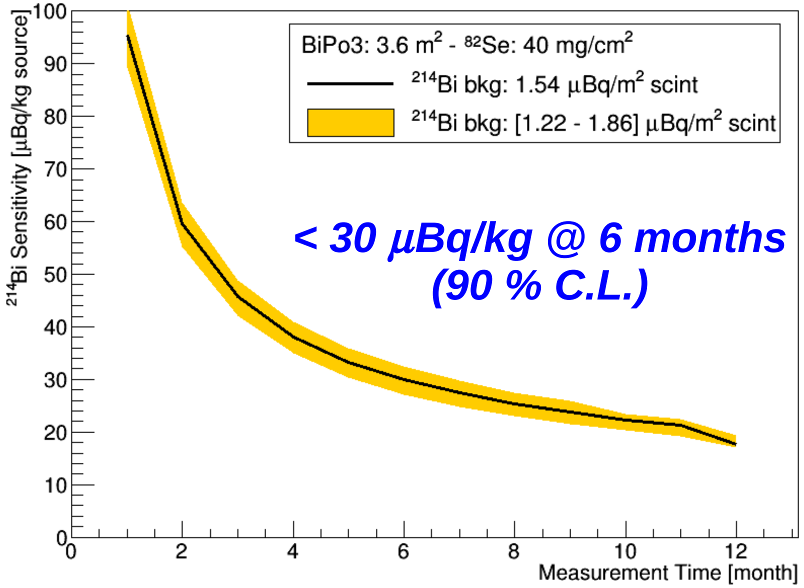
An additional cut in E_{delay} → Removal of the external Rn – induced Background or Random coincidences

THE ***BiPo*** DETECTOR

- ***Background measurements and detector sensitivity:***



< 2.9 µBq/kg @ 6 months (90 % C.L.)

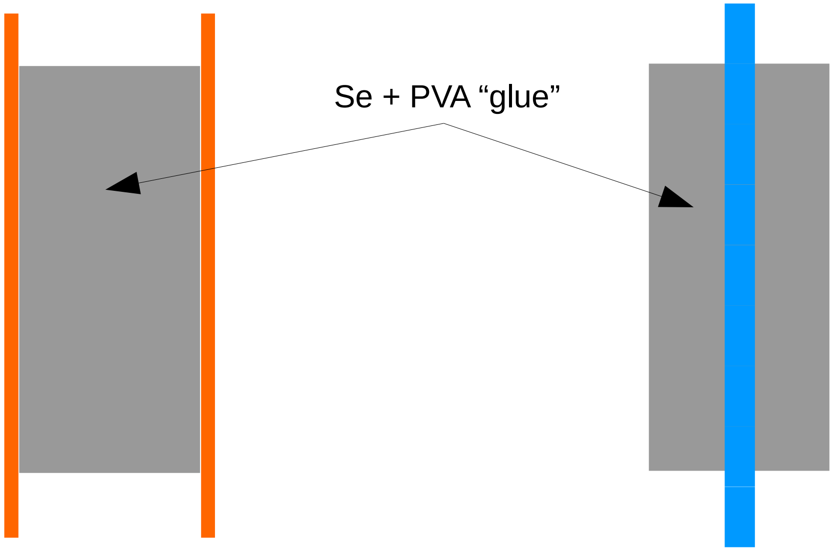


< 30 µBq/kg @ 6 months (90 % C.L.)

- BiPo is at the level of the SuperNEMO required sensitivity
  - It improves any other non-destructive technique sensitivity
- It is an important test-bench with real data for the SuperNEMO collaboration
  - Data Transfer (LSC → CC-Lyon) and automated processing and analysis
  - Simulation cross-check
  - DAQ testing (same pulse-digitization technique than for the SuperNEMO calorimeter)
  - SuperNEMO analysis tools development based on the Pulse Analysys
- Construction of a radiopure detector (it is the ***most sensitive*** detector in the world for radiopurity screening)
  - CUORE Bolometers: A(^{208}Tl) = 7 µBq/m^2, A(^{214}Bi) = 17 µBq/m^2

THE **BiPo** DETECTOR

- ***Samples measurement, ^{82}Se source foils:***
- Since the radiopurity is a must, BiPo is a crucial tool to determine the suitability of a potential component of the source foil
- Based on the analysis method, it is possible to determine the origin of an eventual contamination
  - Useful during the R&D process
- All the source components has been measured independently concluding with the measurement of the source foils
- Due to the BiPo potential, measurements of materials of other experiments have been measured
  - CUORE reflector film, CAST Micromegas detectors...



Sandwich Foil Backing Film

Central Mesh Foil

THE **BiPo** DETECTOR

- ***Samples measurement, ^{82}Se source foils:***

- Since the radiopurity is a must, BiPo is a crucial tool to determine the suitability of a potential component of the source foil

- Based on the analysis method, it is possible to determine the origin of an eventual contamination
  - Useful during the R&D process

- All the source components has been measured independently concluding with the measurement of the source foils

- Due to the BiPo potential, measurements of materials of other experiments have been measured
  - CUORE reflector film, CAST Micromegas detectors...

First 2 ^{82}Se source foils installed (August 2014)

No contamination evidences

$A(^{208}Tl) < 18\ \mu Bq/kg$

$A(^{214}Bi) < 1\ mBq/kg$

Best HP-Ge limit (82Se)

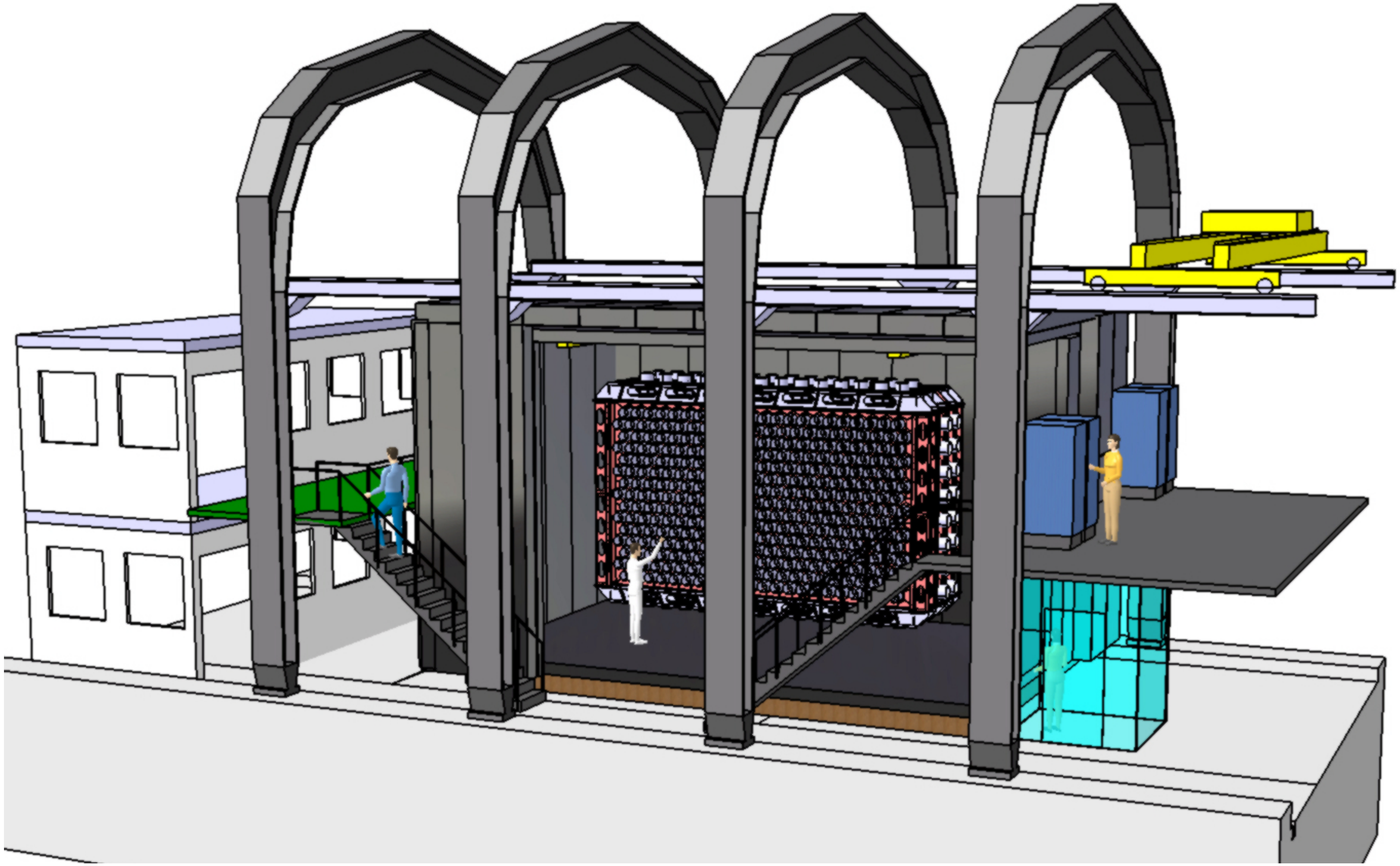
$A(^{208}Tl) < 300\ \mu Bq/kg$

NEMO-3 (^{100}Mo)

$A(^{208}Tl)$ 128 µBq/kg

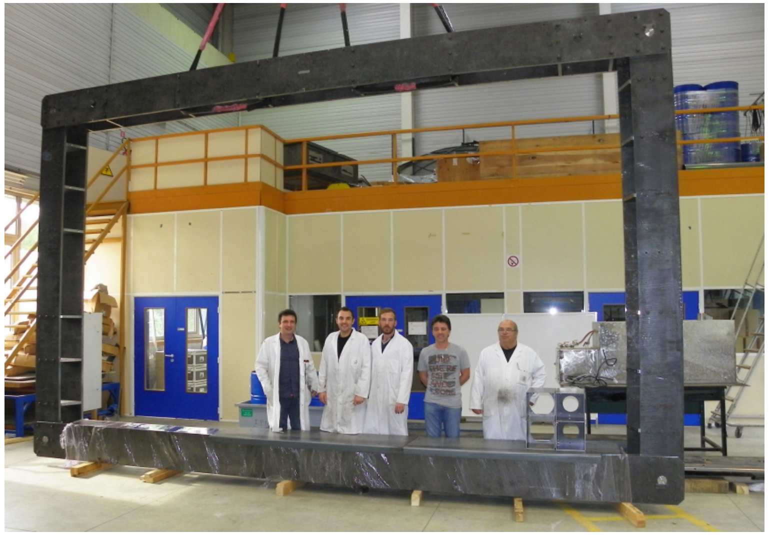
THE ***SuperNEMO*** *EXPERIMENT*

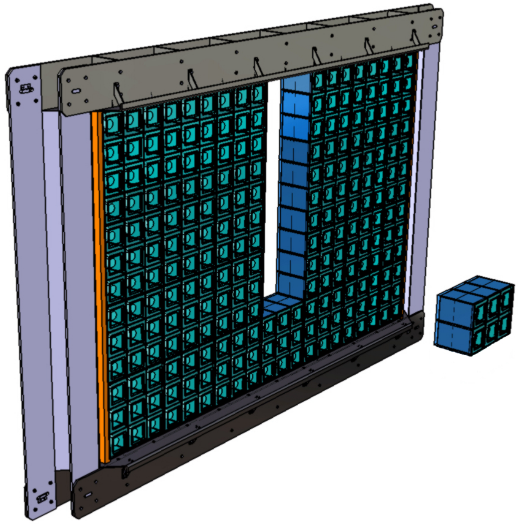
- ***Present Status***
  - ***Demonstrator*** construction started in 2012:
    - It will be installed at the Modane Underground Laboratory, where NEMO-3 operated

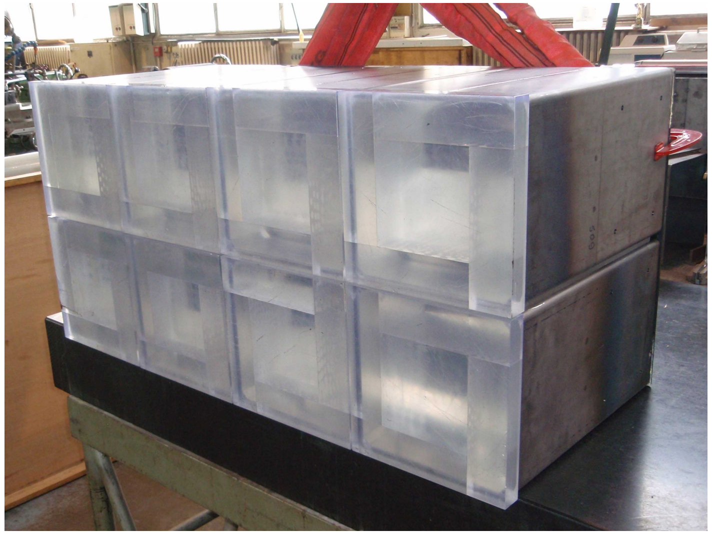


THE **SuperNEMO** EXPERIMENT

- ***Present Status***
  - ***Demonstrator*** construction started in 2012:
    - It will be installed at the Modane Underground Laboratory, where NEMO-3 operated
  - ***Calorimeter***
    - Optical modules: 5” under assembly (almost finished) and 8” under construction
    - FE digitizer boards built, control and trigger boards under development
    - DAQ components already done or under development
    - Construction of the calorimeter blocks magnetic shields and mechanical structure started

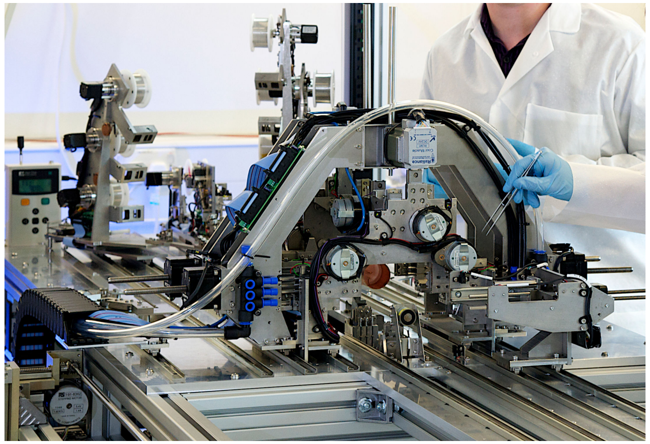


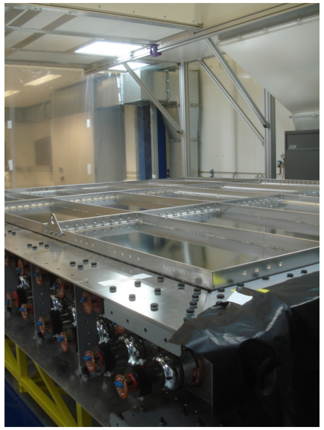


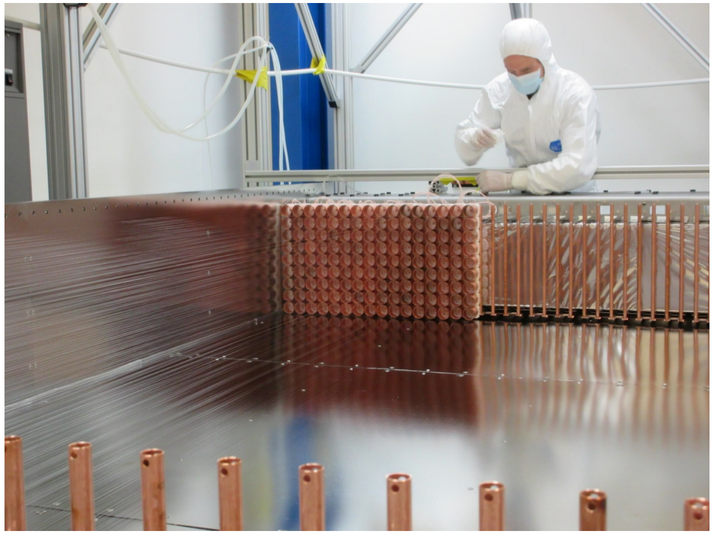


THE *SuperNEMO* EXPERIMENT

- ***Present Status***
  - ***Demonstrator*** construction started in 2012:
    - It will be installed at the Modane Underground Laboratory, where NEMO-3 operated
  - ***Tracker***
    - Wiring robot developed or automated drift cells production
    - First quarter of the C0 (tracker chamber) constructed and checked for Radon emanation (OK!)
      - Population of the Geiger drift cells finished
    - Commissioning of the full C0: shortly at sea-level







THE **SuperNEMO** EXPERIMENT

- ***Present Status***
  - ***Demonstrator*** construction started in 2012:
    - It will be installed at the Modane Underground Laboratory, where NEMO-3 operated
  - ***Sources***
    - 5.5 kg of ^{82}Se available with 0.5 kg already purified
    - Screening of potential source components (mesh, glue) with BiPo and HPGe
    - First 4 source foils "NEMO-3 type" (~10 %) already assembled and being screened in BiPo
    - R&D for alternative source foils manufacturing processes

THE **SuperNEMO** EXPERIMENT

- ***Prospects***
  - Installation and operation of the Demonstrator in Modane
    - Experimental site conditioning (ongoing)
    - Arrival of detector components (mid – 2015)
    - Starting of the commissioning phase (calorimeter commissioning at the beginning 2016)
    - Fully commissioning and starting of data taking (summer 2016)
      - ^{222}Rn background measurement
      - Internal ^{208}Tl and ^{214}Bi measurement
      - ββ run measurement
  - Experience taken from the demonstrator physics run could help to improve the features of the full SuperNEMO modules

THE **SuperNEMO** EXPERIMENT

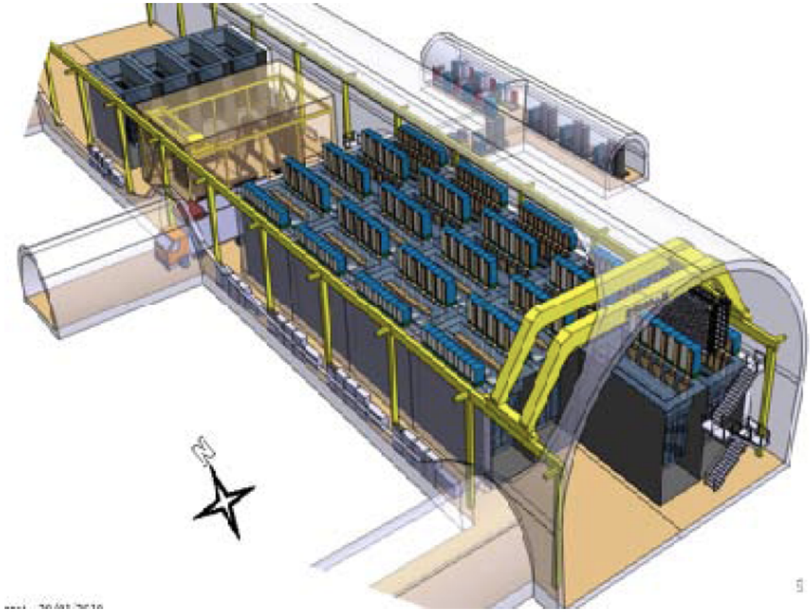
- ***Summary***
- ***NEMO-3***
  - Unique experiment to reconstruct energy and tracks of the 2 electrons expected as signal
    - Signature of the ββ events with high background rejection capabilities
  - ^{100}Mo data have not excess after 34.7 kg y exposure
    - $T_{1/2}^{0\nu} > 1.1\ 10^{24}$ y → $<m_{\nu}> < 0.3 – 0.9$ eV
  - Other results in $2\nu\beta\beta$ processes for several isotopes and other LNV measurements with ^{100}Mo
    - Phys. Rev. D 89 (2014) 111101
  - It showed the potential of developing a new generation experiment using this detection technique

THE **SuperNEMO** EXPERIMENT

- ***Summary***
- ***NEMO-3***
    - $T_{1/2}^{0\nu} > 1.1\ 10^{24}$ y → $<m_\nu> < 0.3 – 0.9$ eV
- ***SuperNEMO Demonstrator***
  - ~ 7 kg ^{82}Se
  - Start of data taking in mid – 2016
  - No background in the *0νββ* region after 2.5 years of data taking
    - $T_{1/2}^{0\nu} > 6.5\ 10^{24}$ y → $<m_\nu> < 0.2 – 0.4$ eV
  - Demonstrate the background free possibility for the SuperNEMO construction
  - Easiest (almost the only one) way to measure the ββ process in eventual favourable isotopes
    - High $Q_{\beta\beta}$ as ^{48}Ca or ^{150}Nd

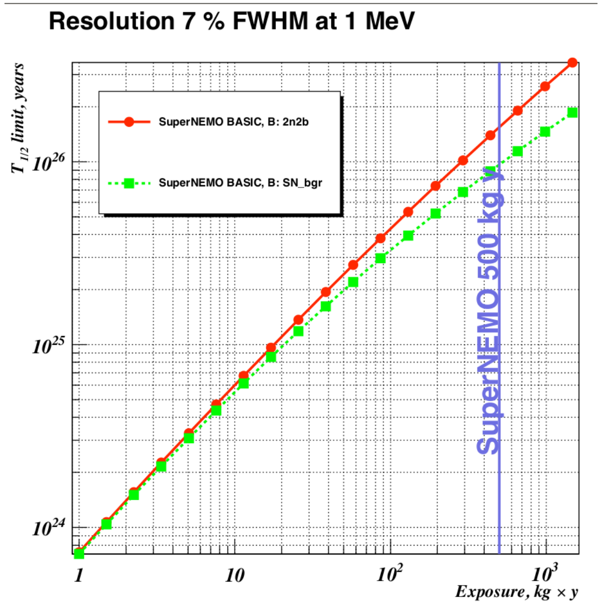
THE **SuperNEMO** EXPERIMENT

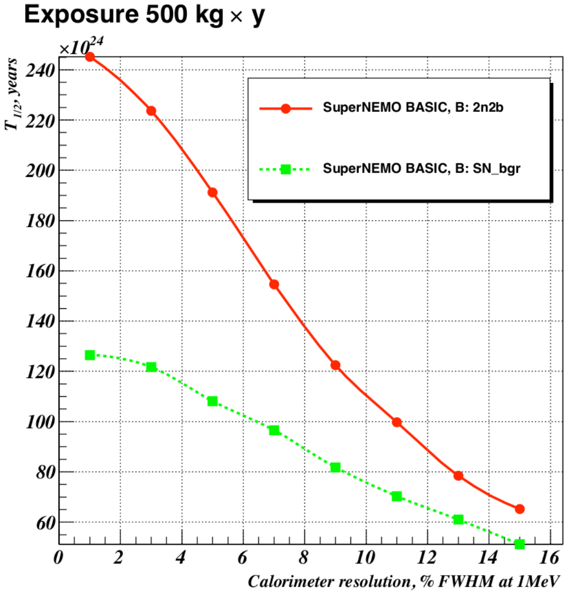
- ***Summary***
- ***NEMO-3***
    - $T_{1/2}^{0\nu} > 1.1\ 10^{24}$ y → $\langle m_\nu \rangle < 0.3 – 0.9$ eV
- ***SuperNEMO Demonstrator***
    - $T_{1/2}^{0\nu} > 6.5\ 10^{24}$ y → $\langle m_\nu \rangle < 0.2 – 0.4$ eV
- ***Full SuperNEMO***
    - 100 kg of ^{82}Se (or other isotope if better)
    - $T_{1/2}^{0\nu} > 1.0\ 10^{26}$ y → $\langle m_\nu \rangle < 0.04 – 0.1$ eV



20 "Demonstrator" modules

To be installed at the Modane extension





THE ***SuperNEMO*** EXPERIMENT

- ***Summary***

- ***NEMO-3***
  - $T_{1/2}^{0\nu} > 1.1\ 10^{24}$ y → $<m_\nu> < 0.3 – 0.9$ eV

- ***SuperNEMO Demonstrator***
  - $T_{1/2}^{0\nu} > 6.5\ 10^{24}$ y → $<m_\nu> < 0.2 – 0.4$ eV

- ***Full SuperNEMO***
  - $T_{1/2}^{0\nu} > 1.0\ 10^{26}$ y → $<m_\nu> < 0.04 – 0.1$ eV

Results with a third isotope different from ^{76}Ge and ^{136}Xe

PROSPECTS IN NEUTRINO PHYSICS: ***WHERE ARE WE GOING?***

- ***Double-beta decay:***
- Projects based on ^{76}Ge and ^{136}Xe ongoing and producing first results
  - GERDA, EXO, KamLAND-Zen already → MAJORANA, NEXT
- The study of other isotopes is assured with some reliable projects
  - ^{130}Te: CUORE, SNO+
  - ^{82}Se: SuperNEMO

Experiment	**Isotope**	**Mass [kg]**	**$T_{1/2}^{0\nu}$ sensitivity [y]**	**$\langle m_\nu \rangle$ sensitivity [eV]**
CUORE	^{130}Te	200	$1\ 10^{26}$	0.04 – 0.1
EXO	^{136}Xe	200	$5\ 10^{25}$	0.08 – 0.3
GERDA	^{76}Ge	40	$2\ 10^{26}$	< 0.1
KamLAND-Zen	^{136}Xe	400	$4\ 10^{26}$	< 0.06
MAJORANA	^{76}Ge	40	$2\ 10^{26}$	< 0.1
NEXT	^{136}Xe	100	$5\ 10^{25}$	< 0.1
SNO+	^{130}Te	200	$1\ 10^{26}$	0.04 – 0.1
SuperNEMO	^{82}Se	7	$6.5\ 10^{24}$	0.2 – 0.4
		100	$1\ 10^{26}$	0.04 – 0.1

- If ***no positive signal*** is found, it is necessary to go to ***1 ton*** projects (some collaborations have already propose that)

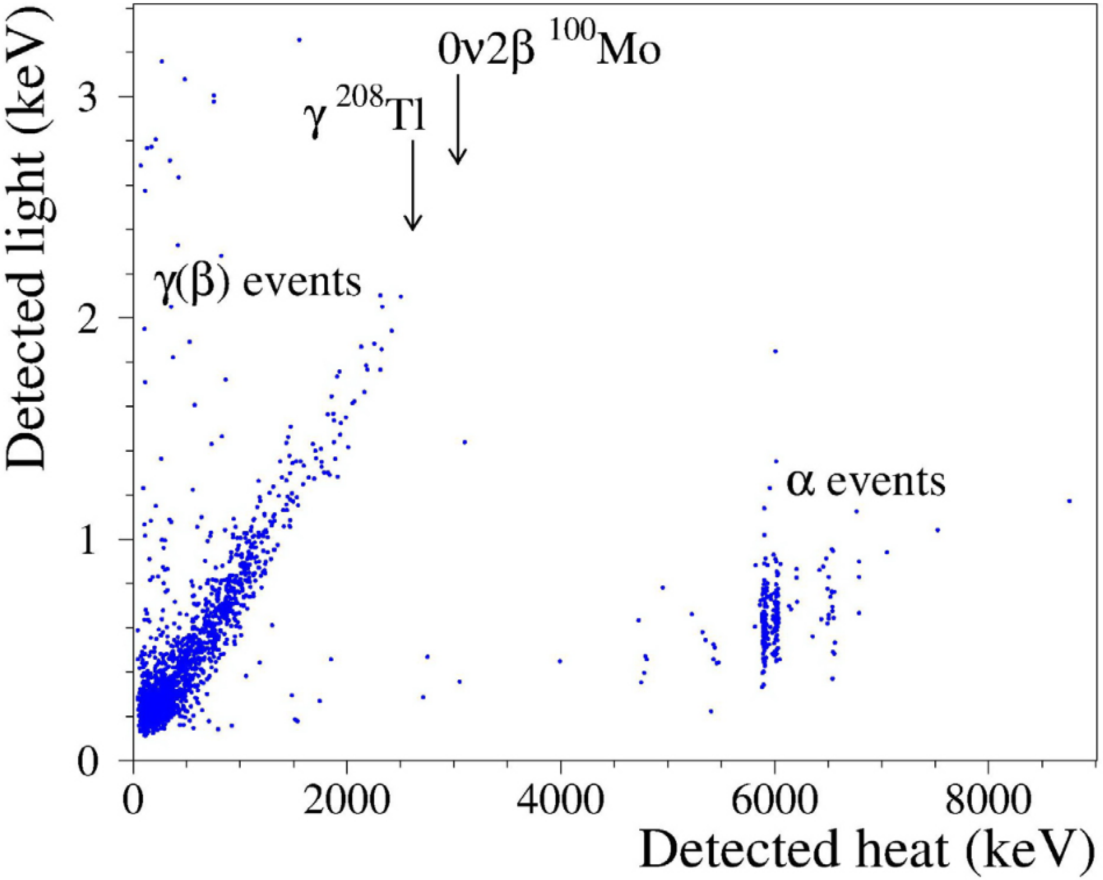
PROSPECTS IN NEUTRINO PHYSICS: WHERE ARE WE GOING?

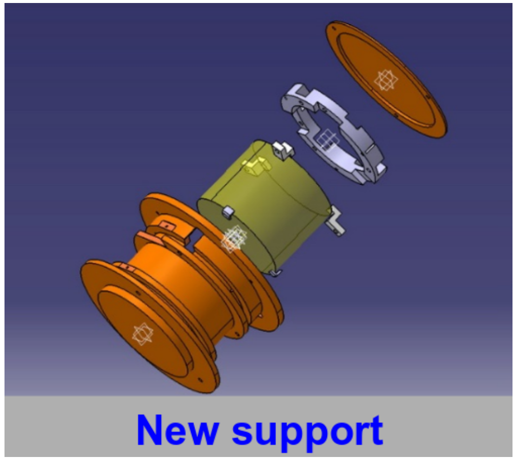
- ***Double-beta decay:***
- Projects based on ^{76}Ge and ^{136}Xe ongoing and producing first results
  - GERDA, EXO, KamLAND-Zen already → MAJORANA, NEXT
- The study of other isotopes is assured with some reliable projects
  - ^{130}Te: CUORE, SNO+
  - ^{82}Se: SuperNEMO
- Other interesting isotopes should be always under consideration
  - High $Q_{\beta\beta}$ (easier to have zero background) as ^{48}Ca, ^{96}Zr or ^{150}Nd
  - SuperNEMO could be the best (almost the only one) option to test them
- Continuous R&D looking for new detection techniques
  - France has a really interesting line → LUMINEU

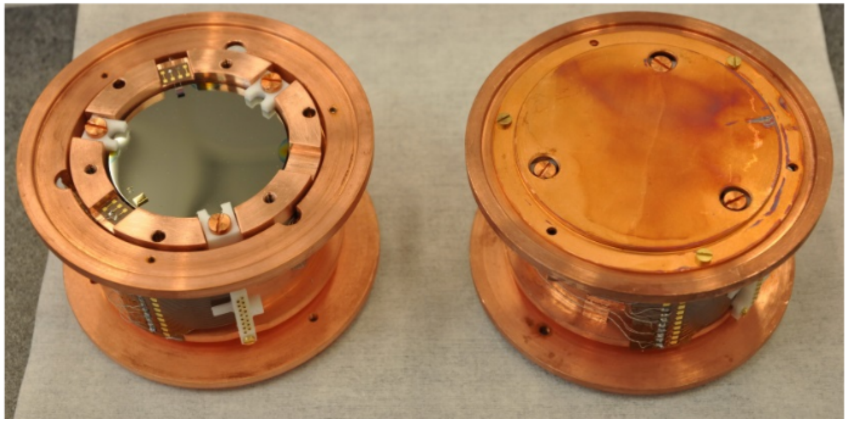
- ***Double-beta decay:***

- LUMINEU: study of the ^{100}Mo $\beta\beta$ decay using $ZnMoO_4$ scintillating bolometers

- High capabilities of background rejection techniques based on the combined light/heat detection
  - Zero background




New support



From LUMINEU Collaboration, Talk @ ICHEP 2014

PROSPECTS IN NEUTRINO PHYSICS: *WHERE ARE WE GOING?*

- ***Neutrino oscillations, mass hierarchy, CP - violation:***
  - Different projects to measure with better accuracy the neutrino oscillation parameters

Parameter	Best Fit	Precision(%)
$\sin^2 \theta_{12}$	0.304 ± 0.012	4
$\sin^2 \theta_{23}$	$0.451 \pm 0.001 \;\|\|\; 0.577^{+0.027}_{-0.035}$	7.5
$\sin^2 \theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	5
Δm^2_{21}	$7.50^{+0.19}_{-0.17}\ 10^{-5}\ eV^2$	2.3
Δm^2_{31}	$2.458 \pm 0.002\ 10^{-3}\ eV^2$	2
Δm^2_{32}	$-2.448 \pm 0.047\ 10^{-3}\ eV^2$	2
$\delta_{CP}\|^{0}$	251^{+67}_{-59}	-

Status at Mid-2014 (ICHEP 2014)

- Other questions as mass hierarchy, CP – violation, θ_{23} octant has to be still explored

PROSPECTS IN NEUTRINO PHYSICS: ***WHERE ARE WE GOING?***

- ***Neutrino oscillations, mass hierarchy, CP - violation:***

	θ_{12}, Δm^2_{12}	**θ_{23}, Δm^2_{23}**	**θ_{13}, Δm^2_{13}**	**δ_{CP}**	**Mass Hierarchy**	**CP-violaion**
Daya-Bay, Double-Chooz, Reno			▨			
Solar / KamLAND	▨		▨			
MINOS / MINOS+		▨				
T2K		▨	▨		▧ **Significantly?**	▧
NOVA		▨		▧	▧ **Significantly?**	▧
JUNO	▨	▨	▨		▨	
LBNE / LBNO	▨	▨	▨	▨	▨	▨
HyperK, INO, Pingu					▨	

SUMMARY AND CONCLUSIONS

- Neutrino Physics is one of the most interesting topics in particle physics since many of its fundamental properties are still unknown
    - Absolute mass, mass hierarchy, Dirac – Majorana nature
- Study of the neutrinoless double – beta decay can solve some of these questions
- Nowadays worldwide efforts are devoted to the detection of this process, combining the study of several isotopes and detection techniques
    - A significant result will come by the combination of the results from some of these projects
- SuperNEMO plays a key role in this challenge
    - Unique tracking + calorimetry technique
    - Study of $\beta\beta$ emitters not studied by any other collaboration
- SuperNEMO R&D program has allowed the construction of outstanding detectors
    - BiPo has become the most sensitive detector in the world for non-destructive radiopurity measurements
    - The measurement of samples not only for SuperNEMO indicates the importance of this detector
- SuperNEMO is at present in a crucial phase with the upcoming construction and operation of the demonstrator

Search for the neutrinoless double-beta decay with ***SuperNEMO*** and its radiopurity control with the ***BiPo*** detector.

Héctor Gomez

hgomez@apc.univ-paris7.fr