NEMO3 results and status of SuperNEMO

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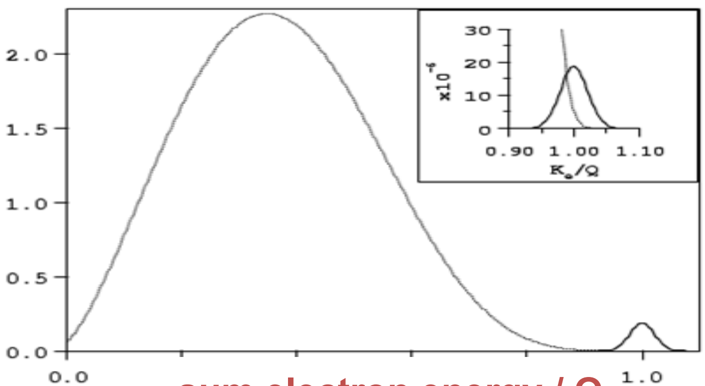
for SuperNEMO collaboration

16th Lomonosov conference
22-28 August 2013, Moscow

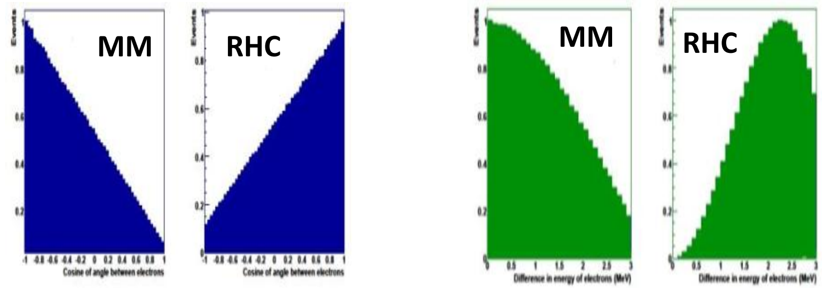
Double beta decay observables

$$(A,Z) \longrightarrow (A,Z+2) + 2e^-$$

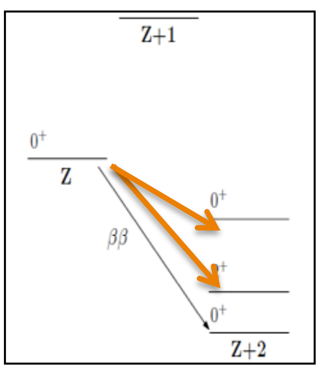


sum electron energy / Q

Angular distribution **$Ee_1 - Ee_2$ distribution**



Mass vs Right-Handed Current mechanism



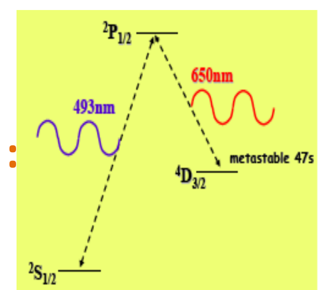
Decay to Excited States

$(A,Z) \rightarrow (A, Z+2) + 2e^- + 1,2\,\gamma$

1 or 2 additonnal γ-rays

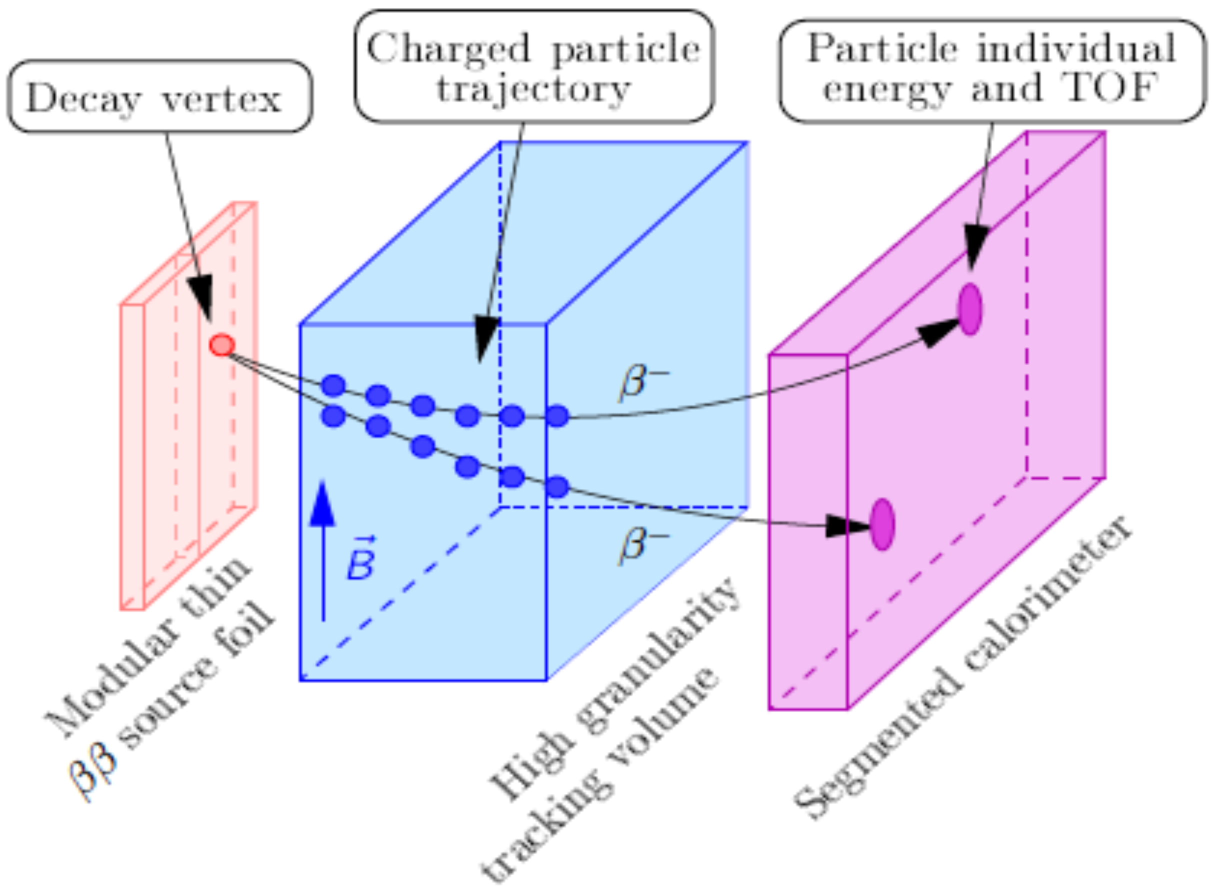
Identification of daugther nucleus :

$Xe \rightarrow Ba^{++} + 2e^-$



NEMO detector principle

Particle physic approach: **to measure all kinematic parameters**



Avantages of the tracko-calo technique

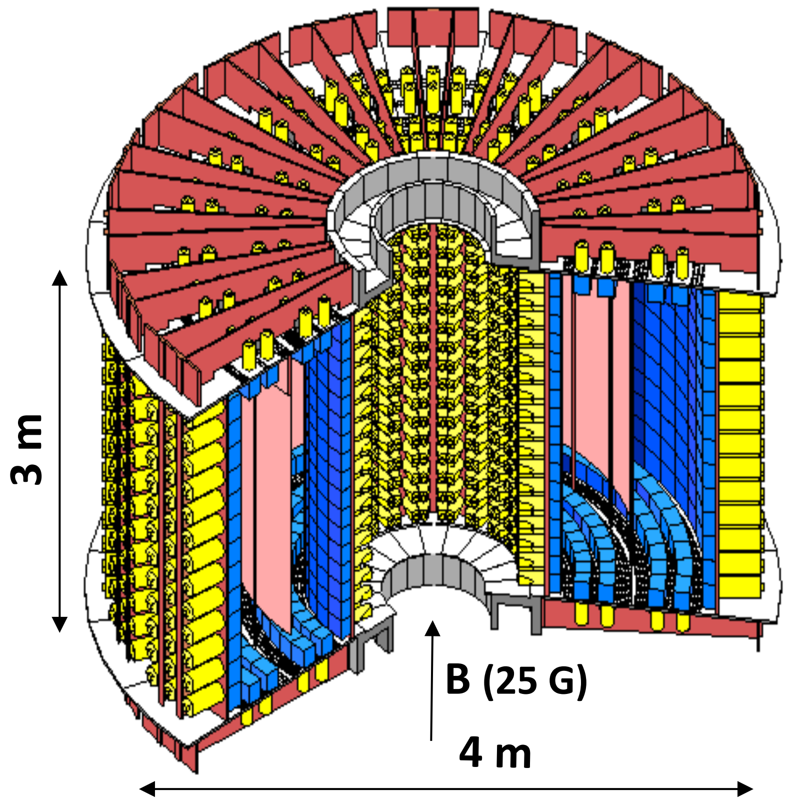
- Identification of electrons
- Identification of e+, g, a particles
- High background rejection
- Vertex emission: possible identification of « hot spot » on the source foil
- Cross-check of background with several topologies
- Multi-isotopes
- Mesurement of all kinematics parameters: possibility to determine the process in case of signal
- Reliable techniques

The NEMO 3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

<u>Source</u>: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

20 sectors



<u>Tracking detector</u>:

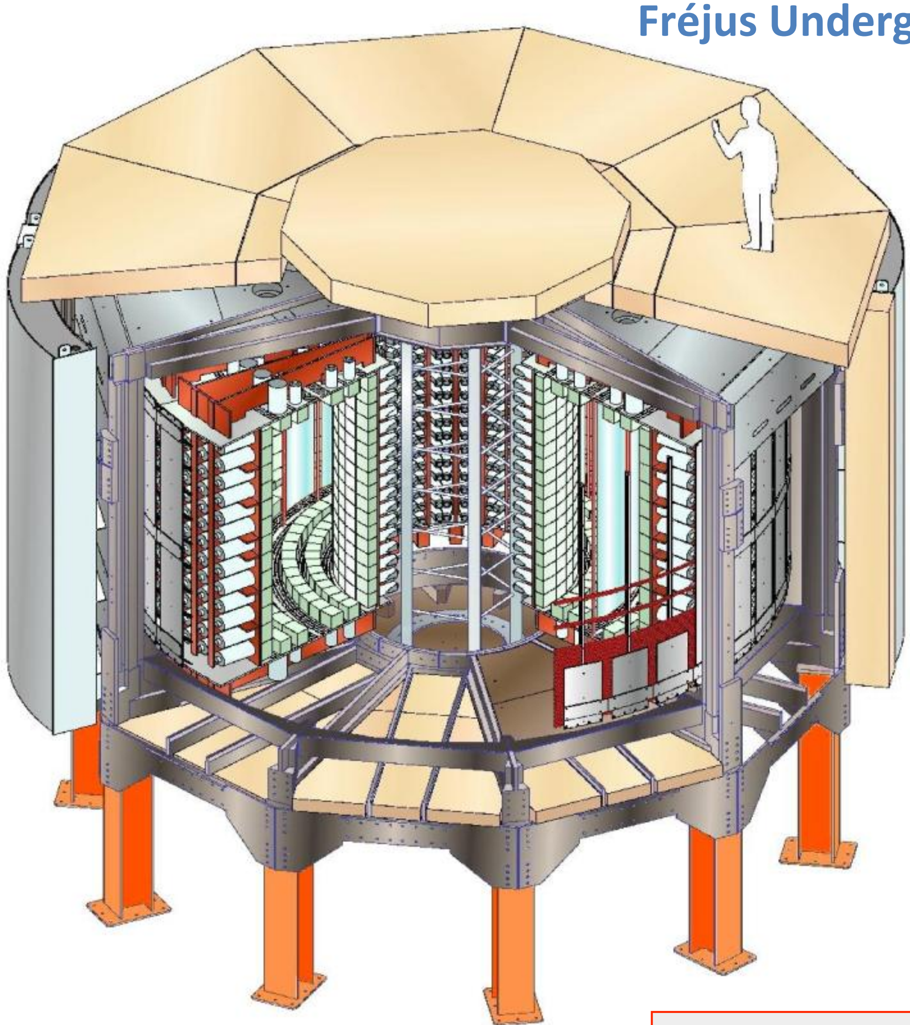
drift wire chamber operating
in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

<u>Calorimeter</u>:

1940 plastic scintillators
coupled to low radioactivity PMTs

The NEMO 3 detector



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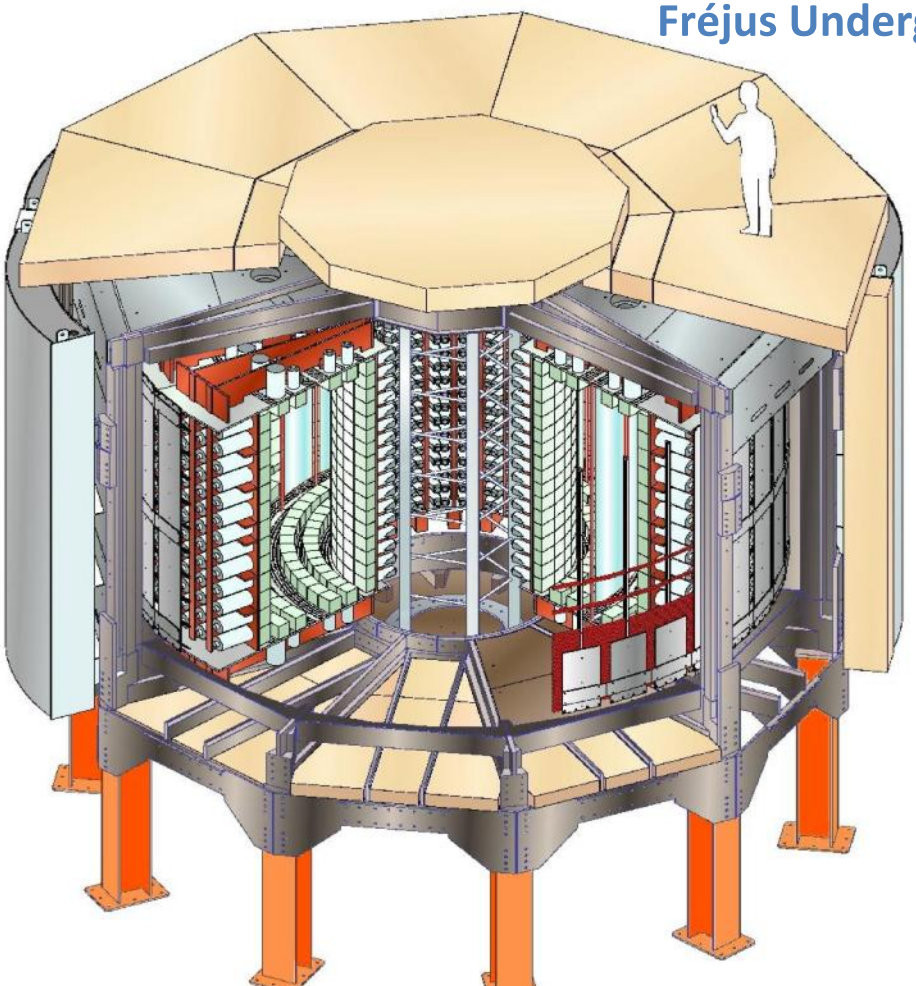
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

Able to identify e^-, e^+, γ and α

The NEMO 3 detector



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+ Wood

Background: natural radioactivity, mainly ^{214}Bi et ^{208}Tl (γ 2.6 MeV)
Radon, neutrons (n,γ), muons, ββ(2ν)

A sector of the NEMO 3 detector

Anneau cathodique de la chambre à fils

PM

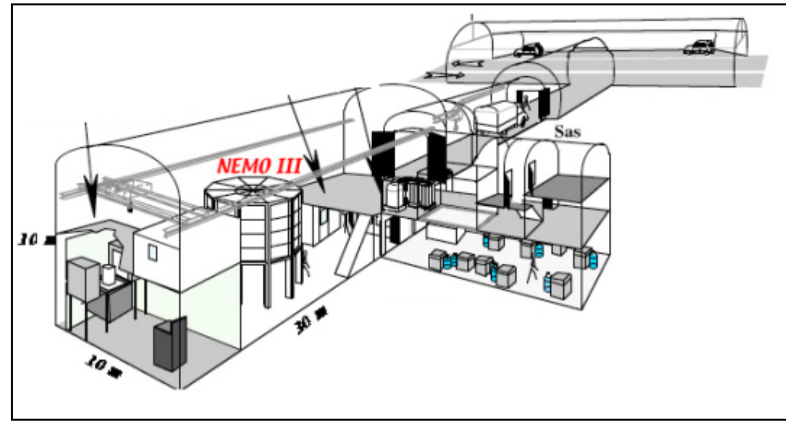
Tube d'étalonnage

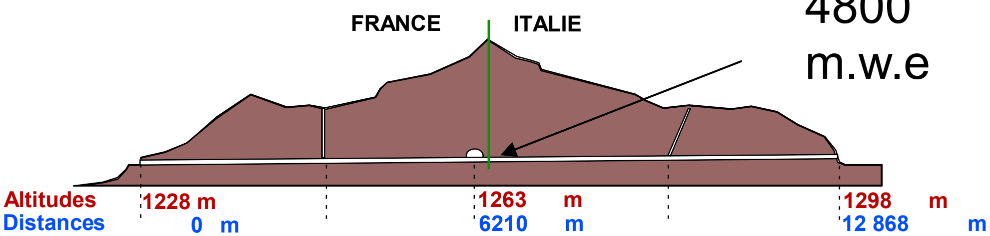
Scintillateurs

Feuilles Sources ββ

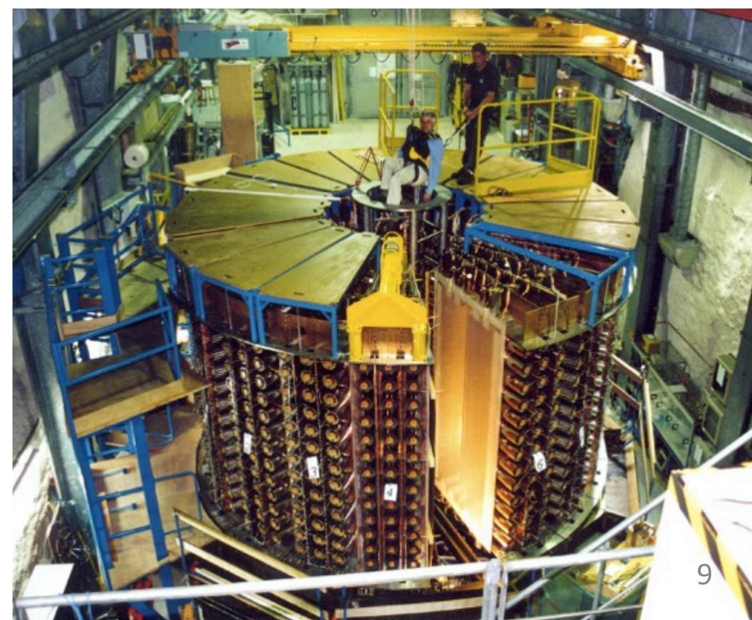
NEMO 3 detector at LSM (France)

Modane Underground Laboratory
(Laboratoire Souterrain de Modane, LSM, CNRS and CEA)





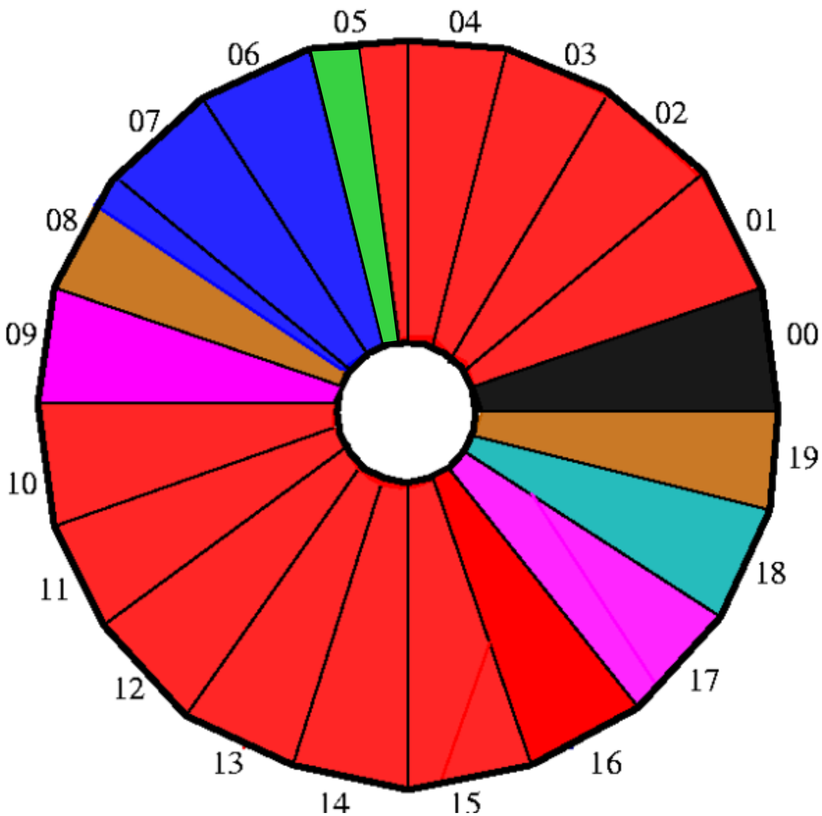
4800 m.w.e



1700 m (4800 m.w.e. under Fréjus mountain

Agreement of International Associated Laboratory
with JINR Dubna (Russia and CTU Prague (Czech Republic)

The NEMO 3 sources



^{100}Mo **6.914 kg**
$Q_{\beta\beta}$ = 3034 keV

^{82}Se **0.932 kg**
$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

ββ2ν measurement

^{116}Cd **405 g**
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr **9.4 g**
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd **37.0 g**
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca **7.0 g**
$Q_{\beta\beta}$ = 4272 keV

^{130}Te **454 g**
$Q_{\beta\beta}$ = 2529 keV

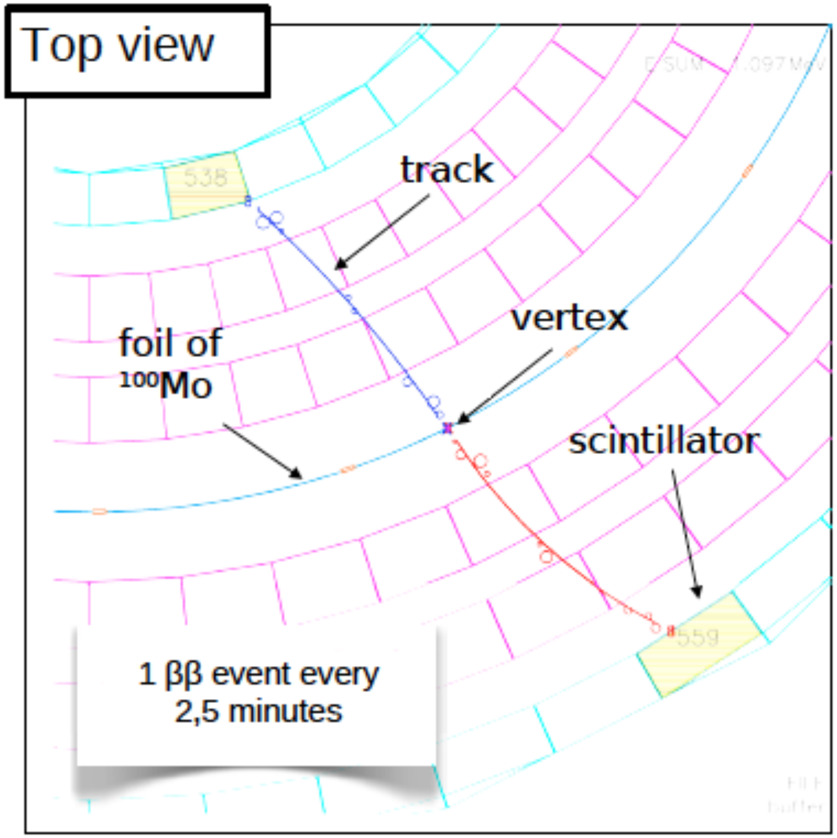
^{nat}Te **491 g**

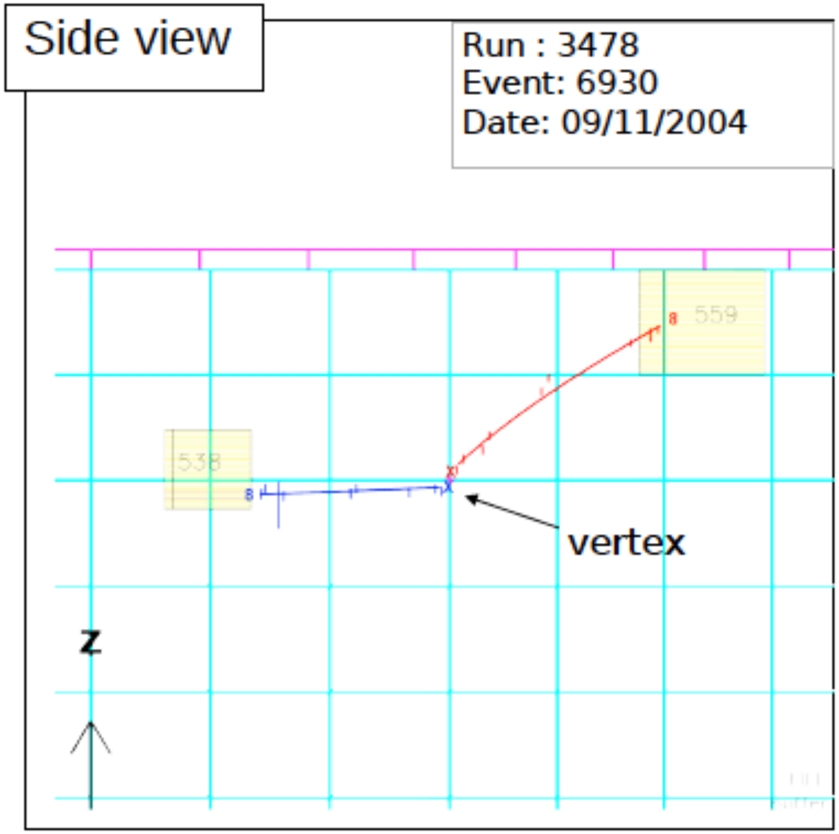
Cu 621 g

External bkg measurement

(All enriched isotopes produced in Russia)

A typical ββ event in NEMO 3



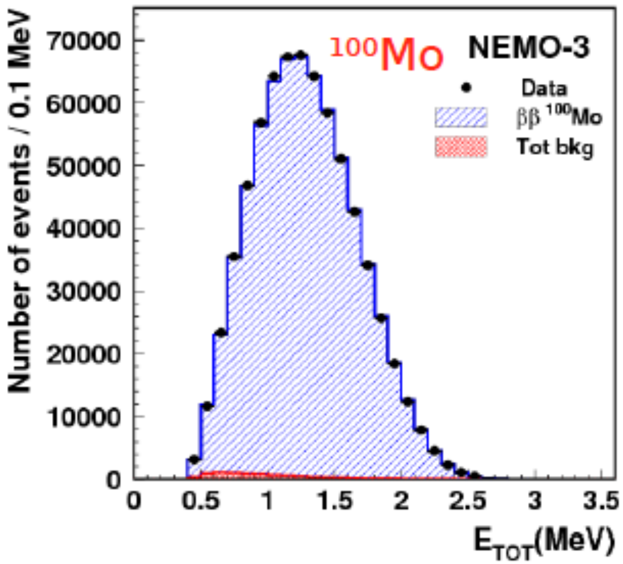


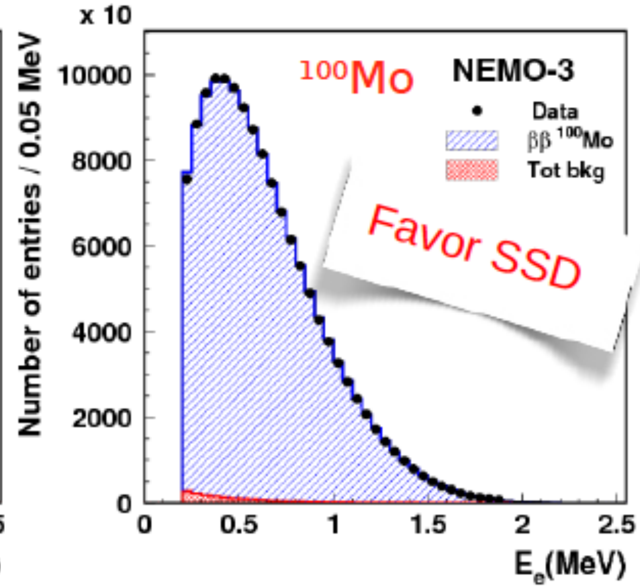
Criteria to select ββ events

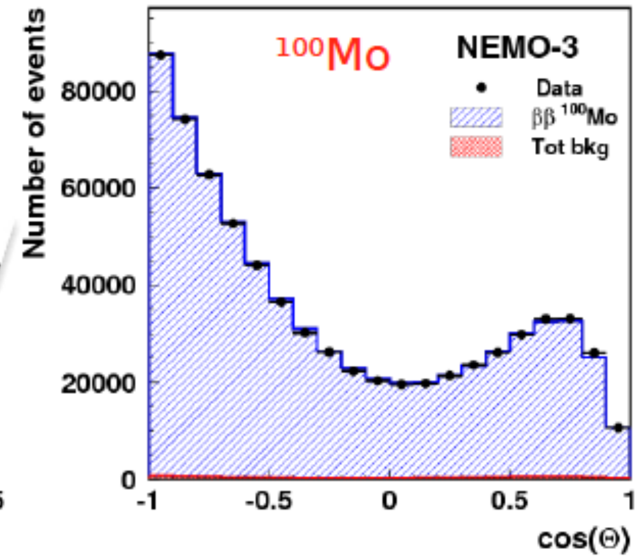
- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex

- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

^{100}Mo ββ(2ν) results







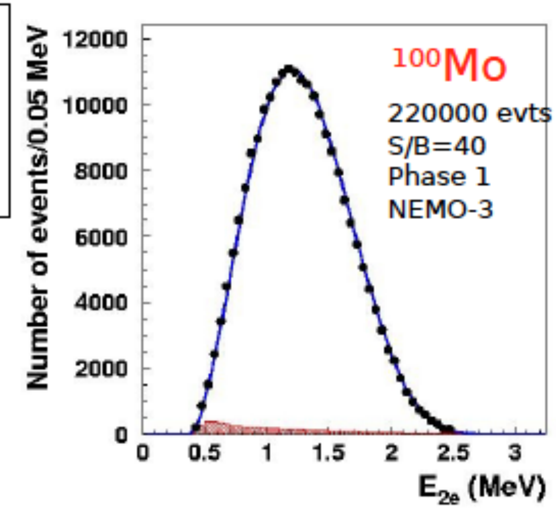
- 700000 two-electron events from ^{100}Mo foils
- S/B = 76
- ε(2ν2β) = 0.043

  $T_{1/2}(2\nu2\beta)$ = [7.16 ± 0.01 (stat) ± 0.54(syst)] 10^{18} y PRELIM.

Consistent with the published NEMO-3 result obtained with Phase 1 data:

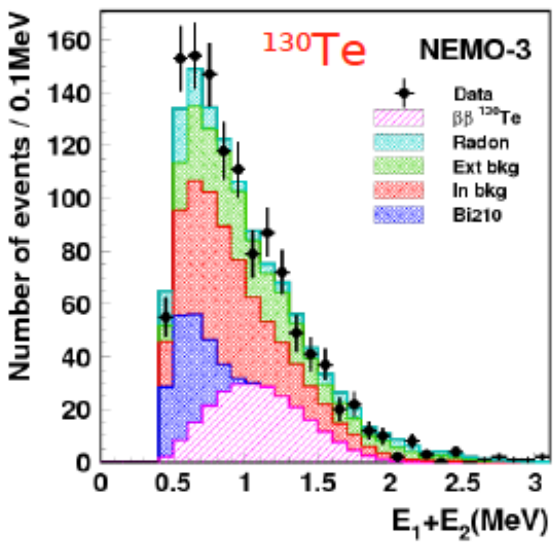
$T_{1/2}$ = [7.11 ± 0.02(stat) ± 0.54(syst)] 10^{18} y

Phys.Rev.Lett. 95(2005)483



^{100}Mo $\beta\beta(2\nu)$ results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)	S/B	Comment	Reference
^{82}Se	932	2998	9.6 ± 1.0	4	World's best!	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2813	2.8 ± 0.3	10	World's best!	
^{150}Nd	37	3371	0.91 ± 0.07	2.7	World's best!	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best!	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4263	4.4 ± 0.6	6.8 (h.e.)	World's best!	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best!	Phys.Rev.Lett. 95(2005) 483
^{130}Te	454	2527	70 ± 14	0,5	First direct detection!!!	Phys. Rev. Lett. 107, 062504 (2011)



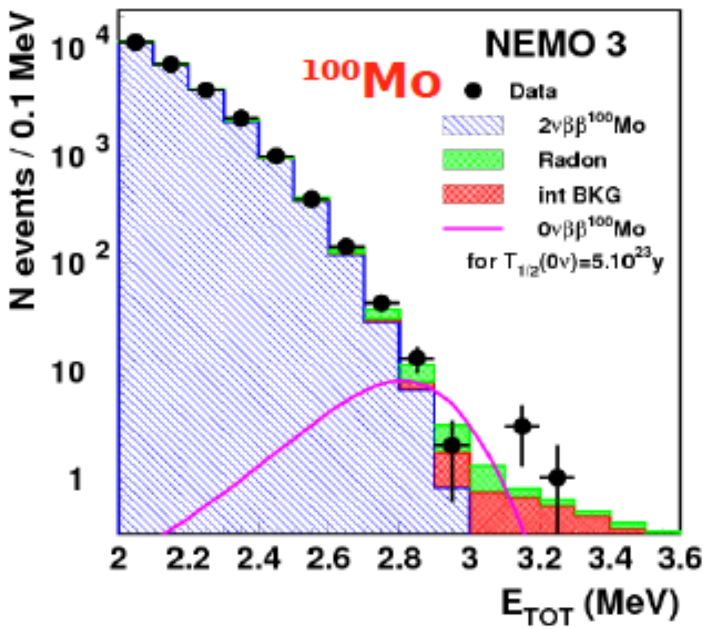
First direct observation: 7.7σ stat significance

Indirect observations:
- ~2.7 x 10^{21} yrs in 10^9 yr old rocks
- ~8 x10^{20} yrs in 10^7-10^8 yr old rocks

Result from MIBETA Coll in isotopically enriched crystals:
6.1 ± 1.4(st) $^{+2.9}_{-3.5}$(sy) x10^{20} yrs

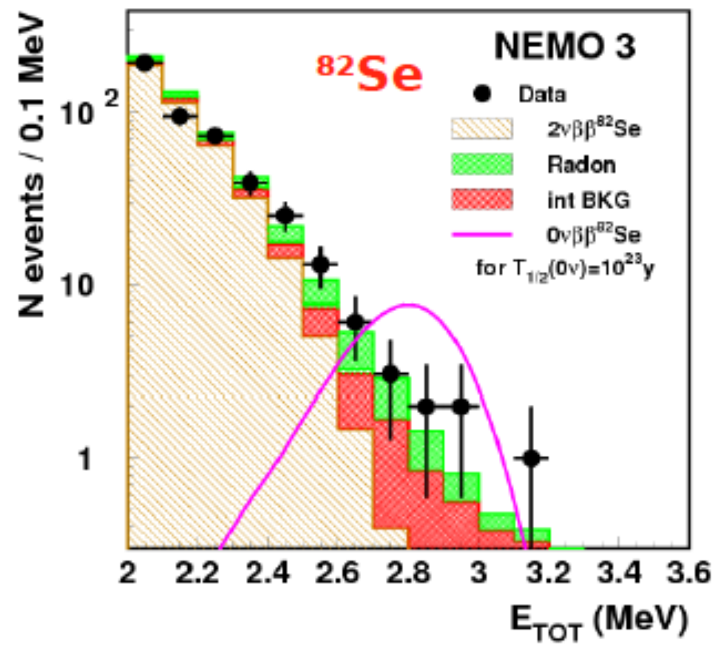
^{100}Mo ββ(0ν) preliminary results

^{100}Mo : 7kg × 4.5 years



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

^{82}Se : 1kg × 4.5 years



[2.6 – 3.2] MeV 14 observed events, 11.3 ± 1.3 expected

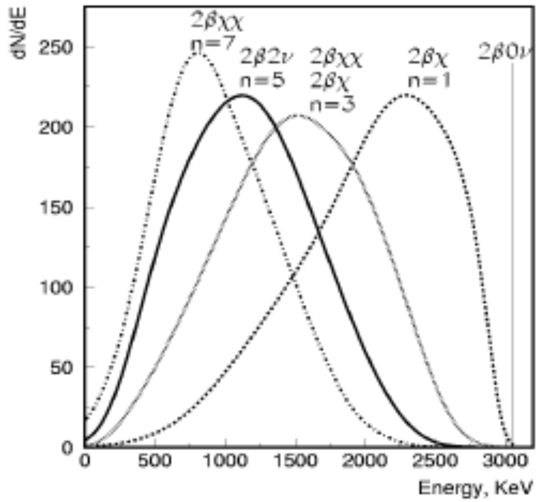
Total mean 0ν efficiency [2.0,3.2]MeV ε = 0.13
^{100}Mo $T_{1/2}(0\nu)$ > 1.0 · 10^{24} y @90% C.L.
$<m_\nu>$ < 0.31 – 0.79 eV NME [1-5]

Total mean 0ν efficiency [2.0,3.2]MeV ε = 0.14
^{82}Se $T_{1/2}(0\nu)$ > 3.2 · 10^{23} y @90% C.L.
$<m_\nu>$ < 0.94 – 1.71 eV NME [1-4]
$<m_\nu>$ < 2.6 eV NME [6]

[1] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)
[2] QRPA M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315
[3] QRPA F.Simkovic, et al. Phys.Rev. C 79 (2009) 055501
[4] IBM2 J.Barrea and F.Iachello Phys.Rev.C 79(2009)044301

NME
PHFB [5] P.K. Rath et al., Phys. Rev. C 82 (2010) 064310
SM [6] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

$^{100}Mo\ \beta\beta(0\nu)$ preliminary results

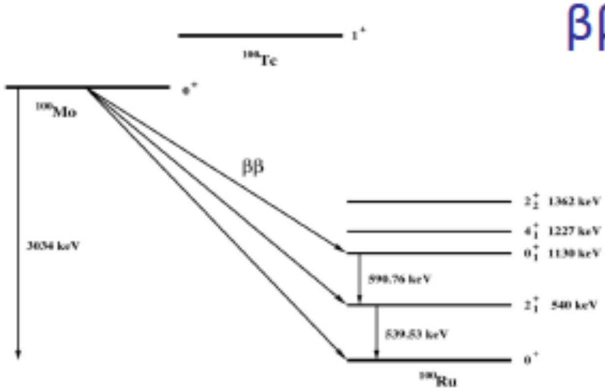


Majoron emission would distort the shape of the energy sum spectrum

	V+A*	n=1**	n=2**	n=3**	n=7**
Mo	$>5.7\cdot10^{23}$ $\lambda<1.4\cdot10^{-6}$	$>2.7\cdot10^{22}$ $G_{ee}<(0.4-1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>2.4\cdot10^{23}$ $\lambda<2.0\cdot10^{-6}$	$>1.5\cdot10^{22}$ $G_{ee}<(0.7-1.9)\cdot10^{-4}$	$>6\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5\cdot10^{20}$

n: spectral index, limits on half-life in years
* Phase I+Phase II data (including 2008)
** Phase I data, R.Arnold et al. Nucl. Phys. A765 (2006) 483

$\beta\beta$ decay to excited states with detection of $2e^-$ and γ(s)



$T_{1/2}^{2\nu}(0^+ \rightarrow 0^+_1) = 5.7^{+1.3}_{-0.9}$ (stat) $\pm$ 0.8 (syst) $\times 10^{20}$ y

$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.

$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @90% C.L.

$T_{1/2}^{0\nu}(0^+ \rightarrow 2^+_1) > 1.6 \times 10^{23}$ y @ 90% C.L.

Nuclear Physics A781 (2006) 209-226.

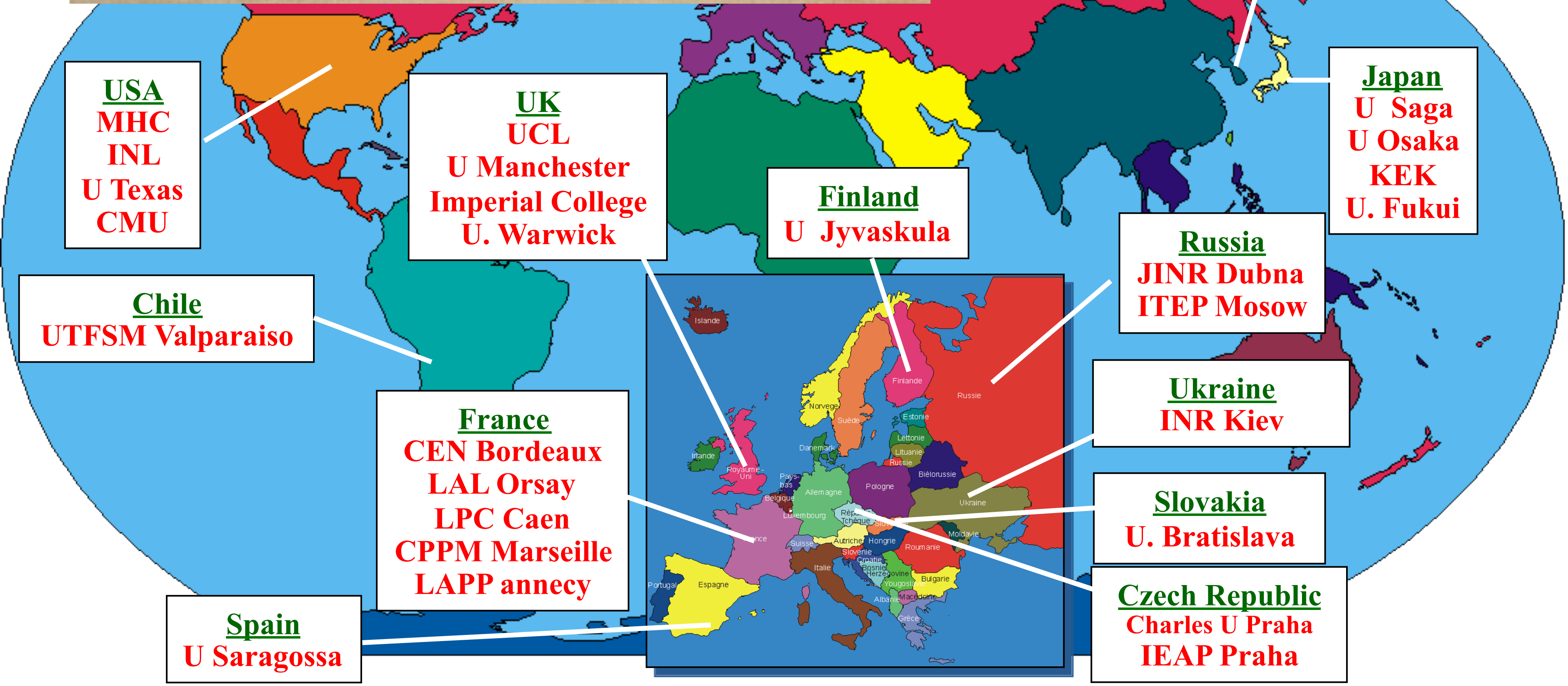
From NEMO3 to SuperNEMO

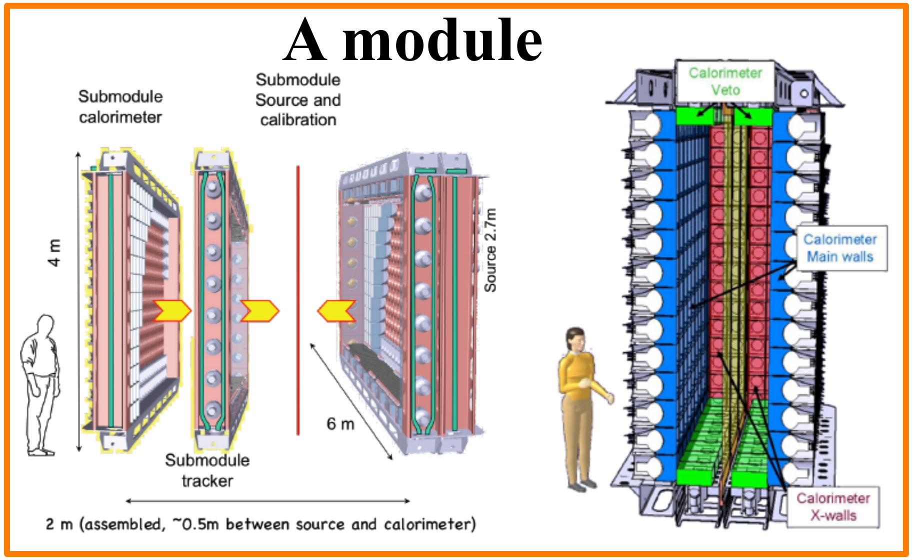
$$T_{1/2}(\beta\beta0\nu) > \ln 2 \times \frac{N_A}{A} \times \frac{M \times \varepsilon \times T_{obs}}{N_{90}}$$

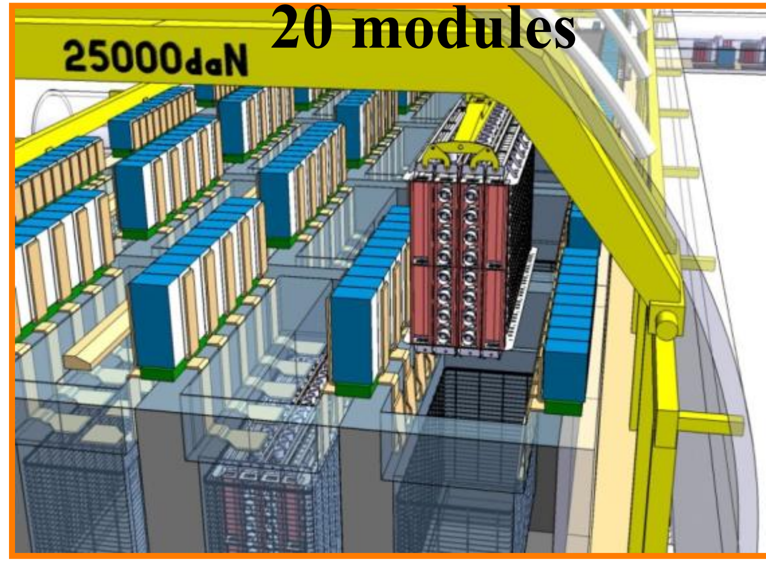
NEMO-3		SuperNEMO
^{100}Mo	isotope	^{82}Se (baseline) or 150Nd or ^{48}Ca
7 kg	isotope mass M	100 kg
8 %	efficiency ε	~ 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil	^{208}Tl < 2 μBq/kg *if ^{82}Se*: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

NEMO-3	SuperNEMO
$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 1.3$ eV	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < 40 - 100$ meV

SuperNEMO collaboration





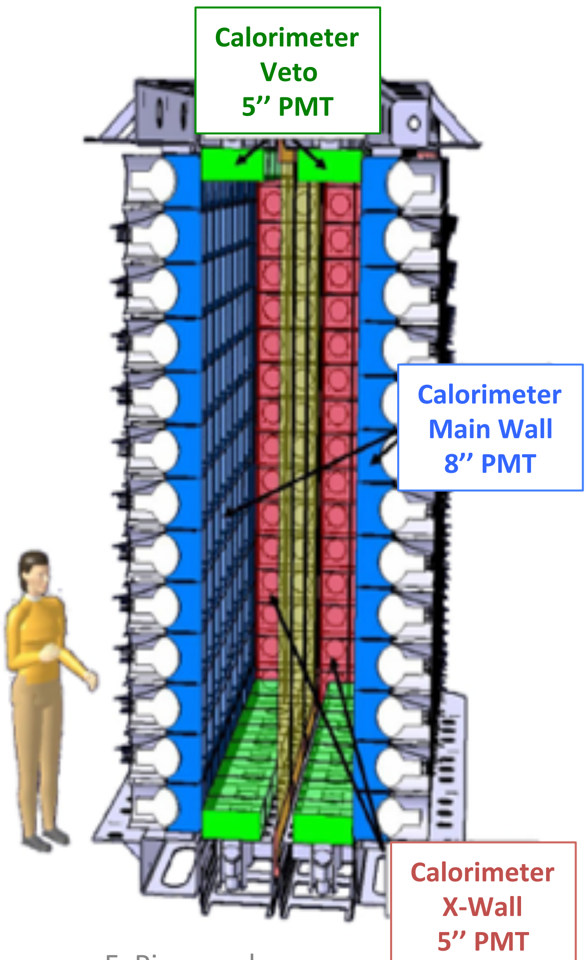


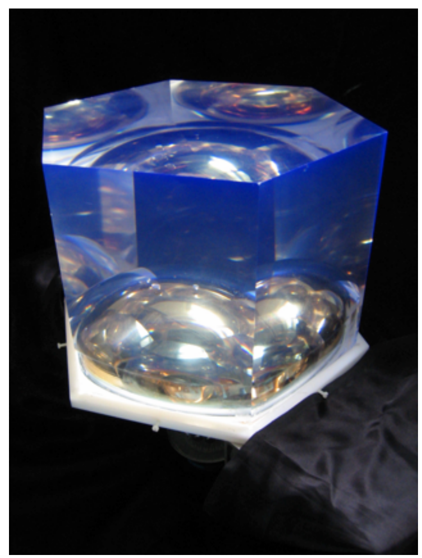
	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	100 kg
Drift chambers for tracking	2 0000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$<m_\nu>$ sensitivity	200 – 400 meV	40 – 100 meV

Demonstrator module (7 kg) under construction

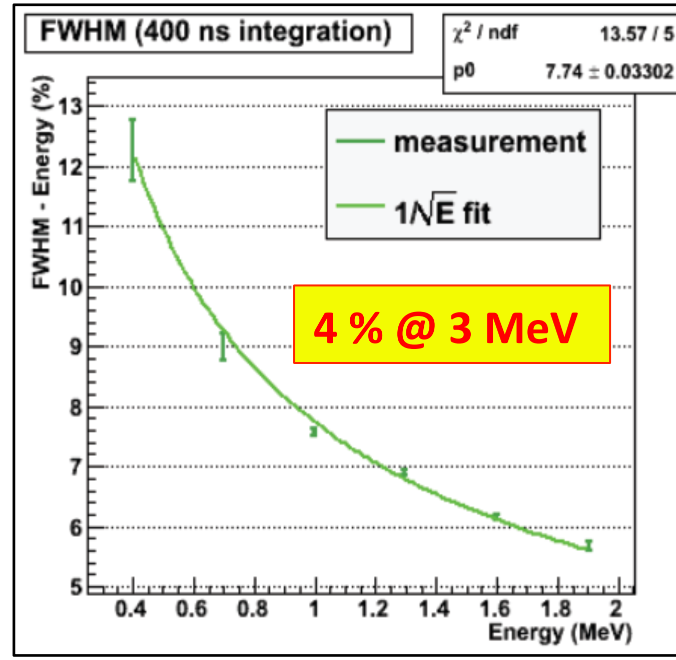
Calorimeter

- To measure electrons energy
- To detect γ-rays for excited state decay search
- To measure and reject backgrounds





8'' PMT
\+ Plastic Scintillator

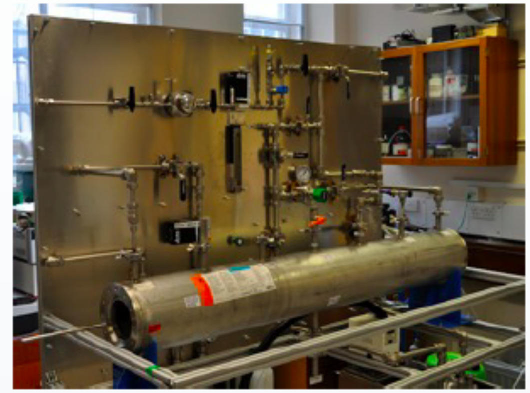


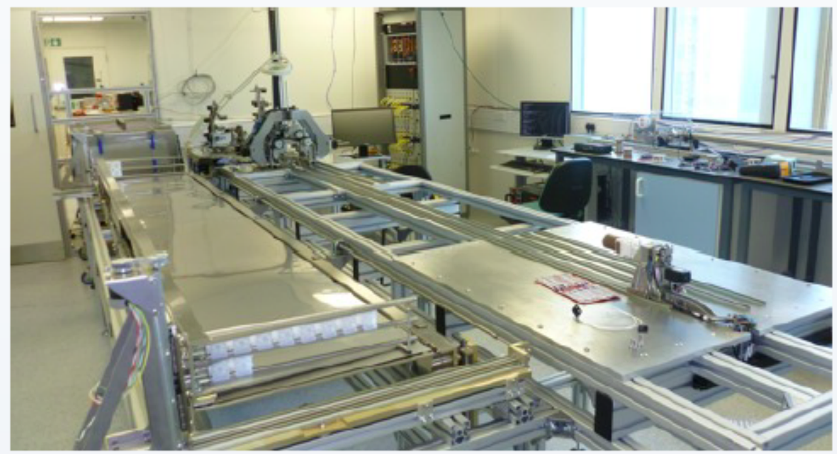
- Improvement of PMT QE
- Use of PVT instead of PS
- Optimization geometry
- Optimization electronics

Tracker

Tracker Construction and R&D

- Automated wiring robot design to mass produce at ultra low background condition
- First cartridge with 18 cells produced and tested
- NEMO3 Gas system refurbished with low Rn emanation materials
  - for commissioning and running of Demonstrator





Main challenge Radon < 150 μBq/m^3 →

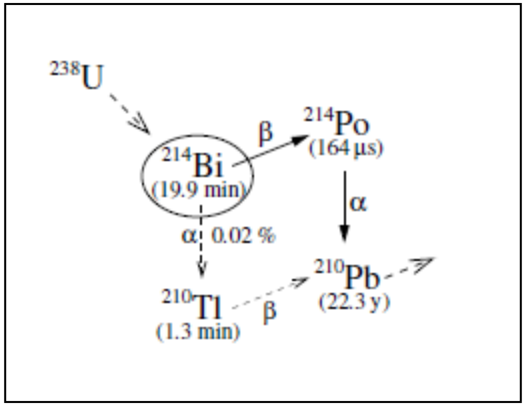
- Material selection
- Control of emanation
- Radiopurity of gas

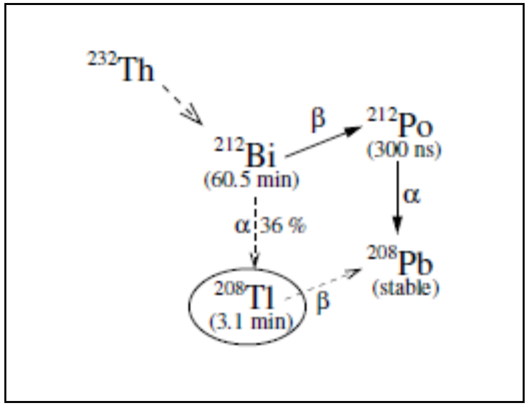
BiPo detector

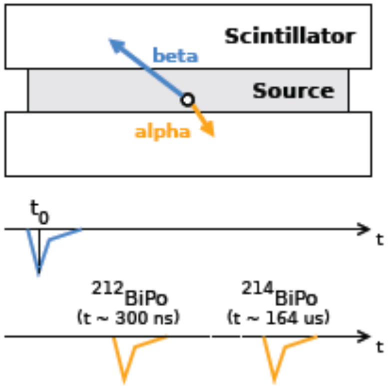
< 2 μBq/kg for ^{208}Tl

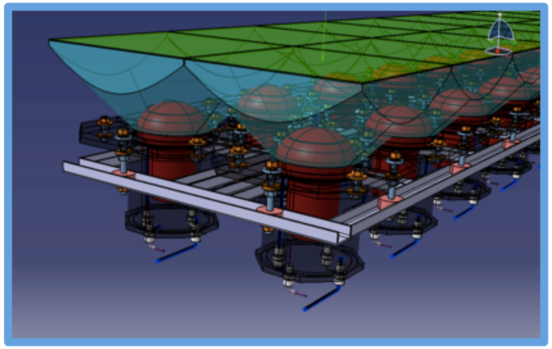
< 10 μBq/kg for ^{214}Bi

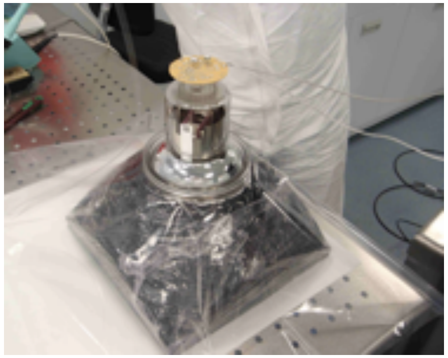
Bi – Po delayed coincidence in U and Th chains







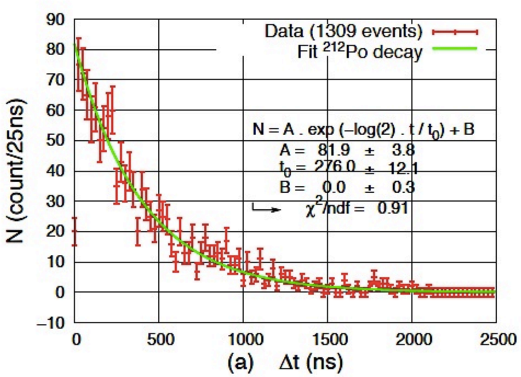


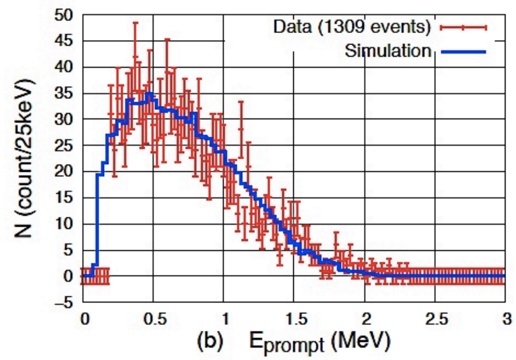


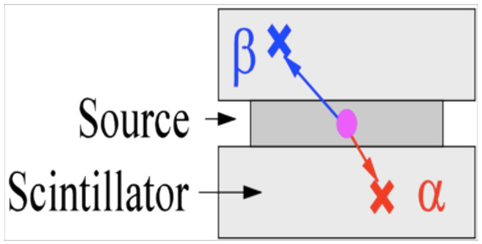
BiPo installed in Canfranc Underground Laboratory (Spain) since 2012

BiPo Results

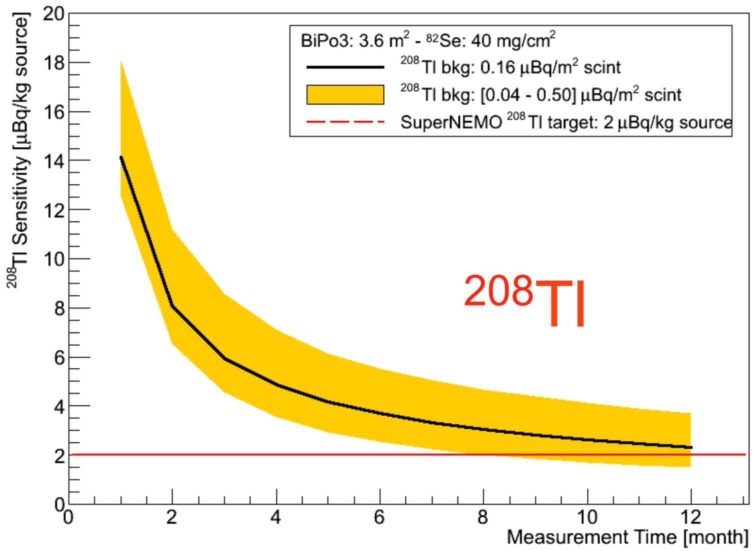
Test with Al foil contaminated in $^{212}Bi \rightarrow {}^{212}Po$

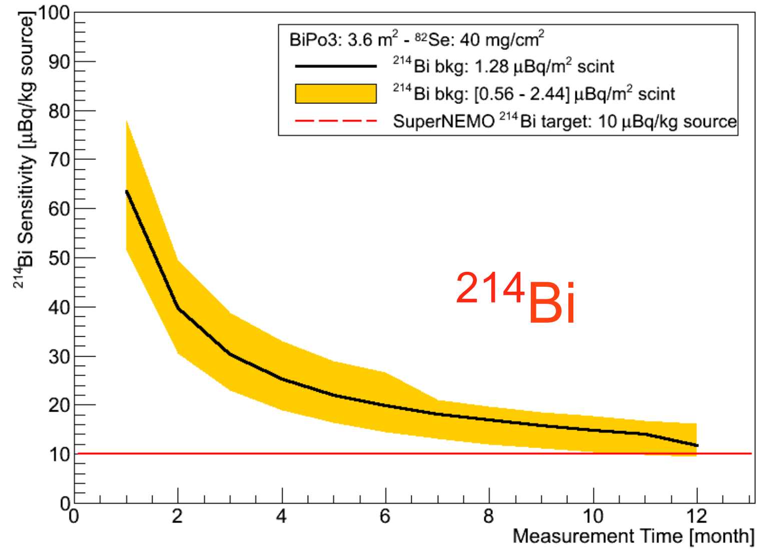




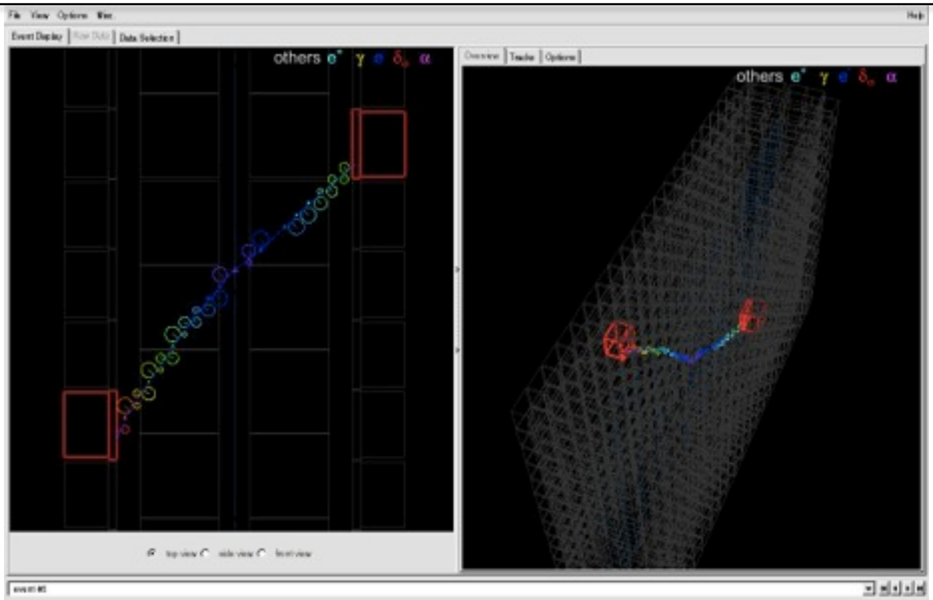


BiPo Sensitivity

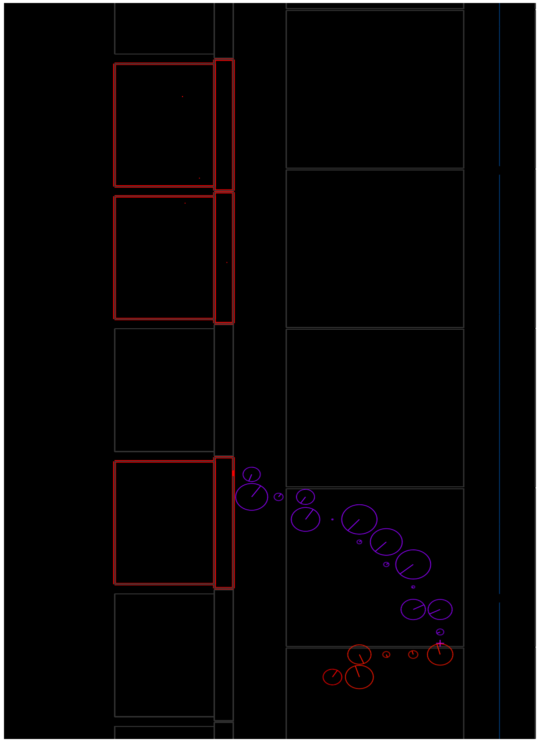




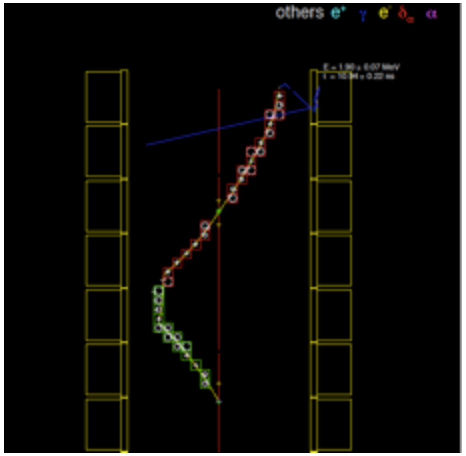
Simulations



A simulated $\beta\beta(0\nu)$ event

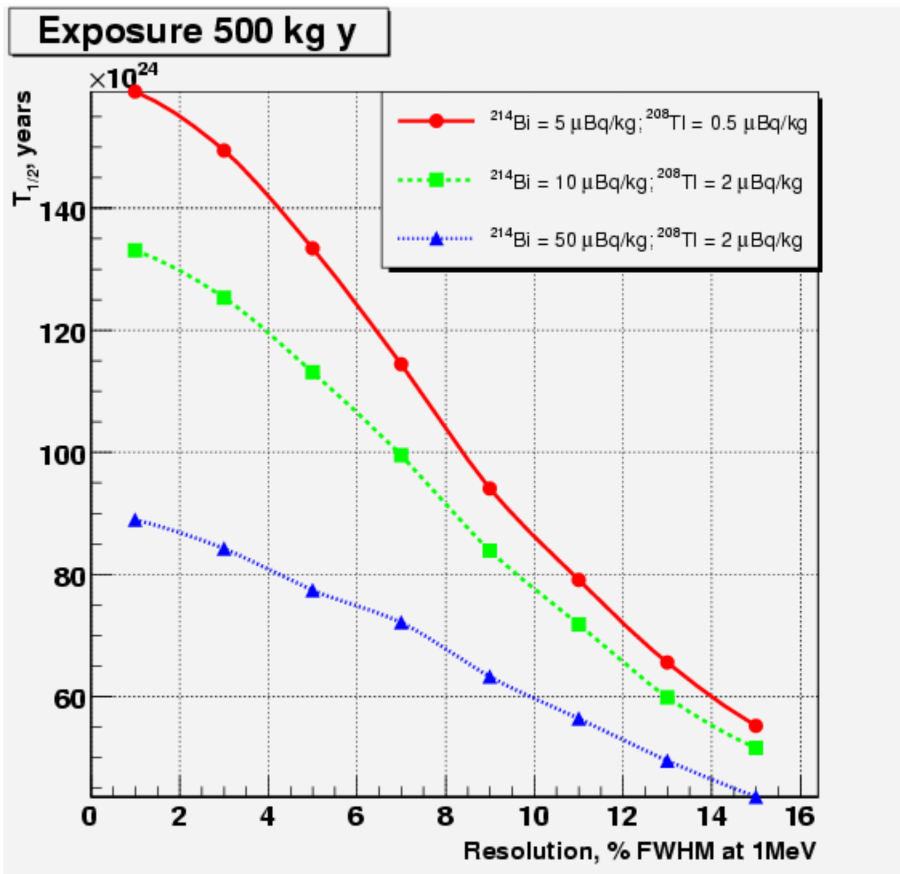


e^-, α, $\gamma\gamma$ background event

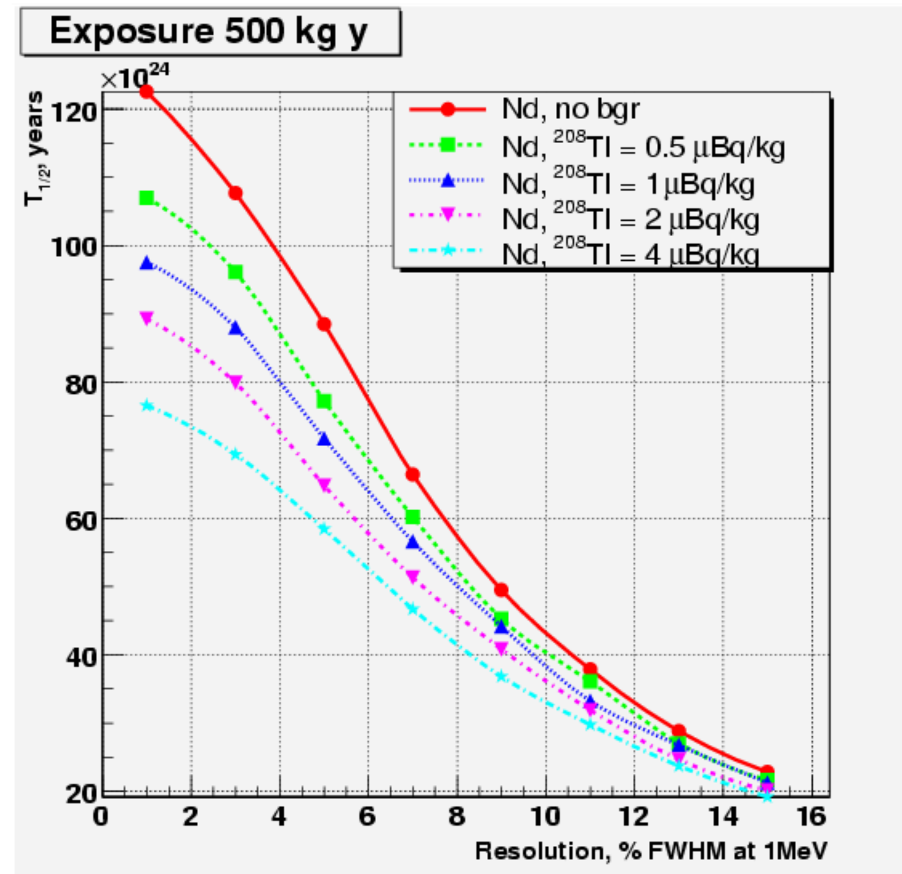


SuperNEMO sensitivity for 5 years

^{82}Se

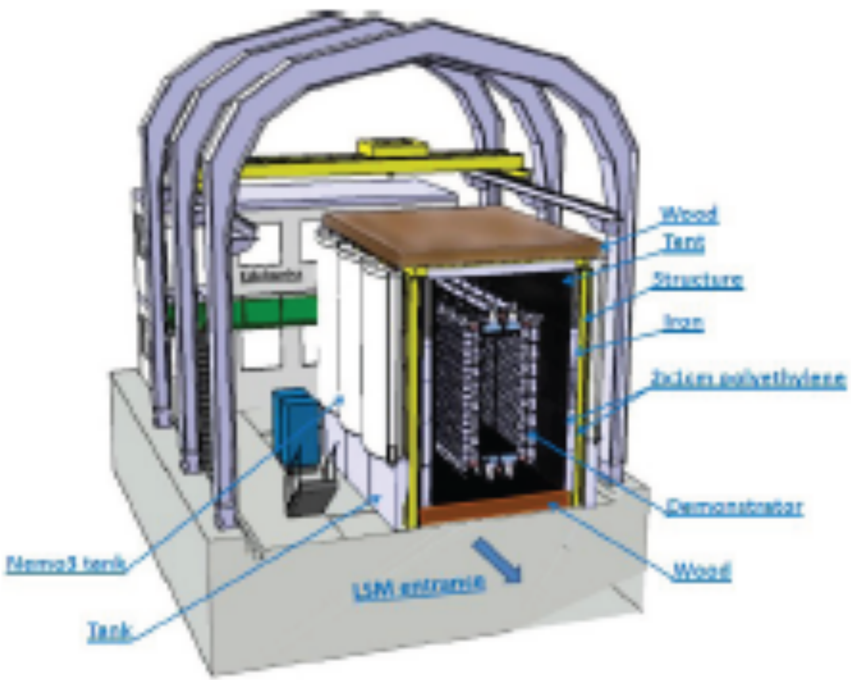


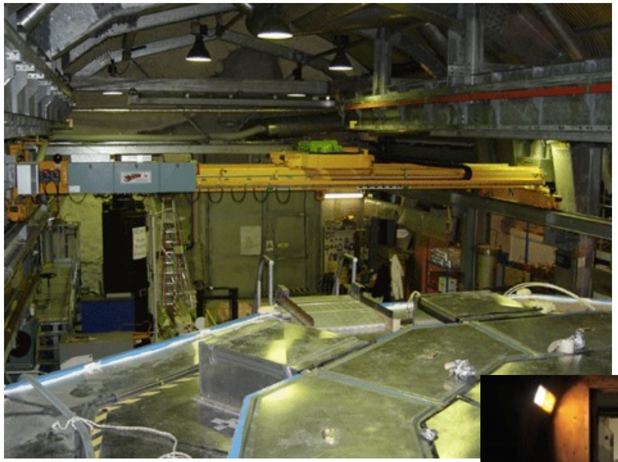
^{150}Nd



$\langle m_\nu \rangle < 40 - 100$ meV

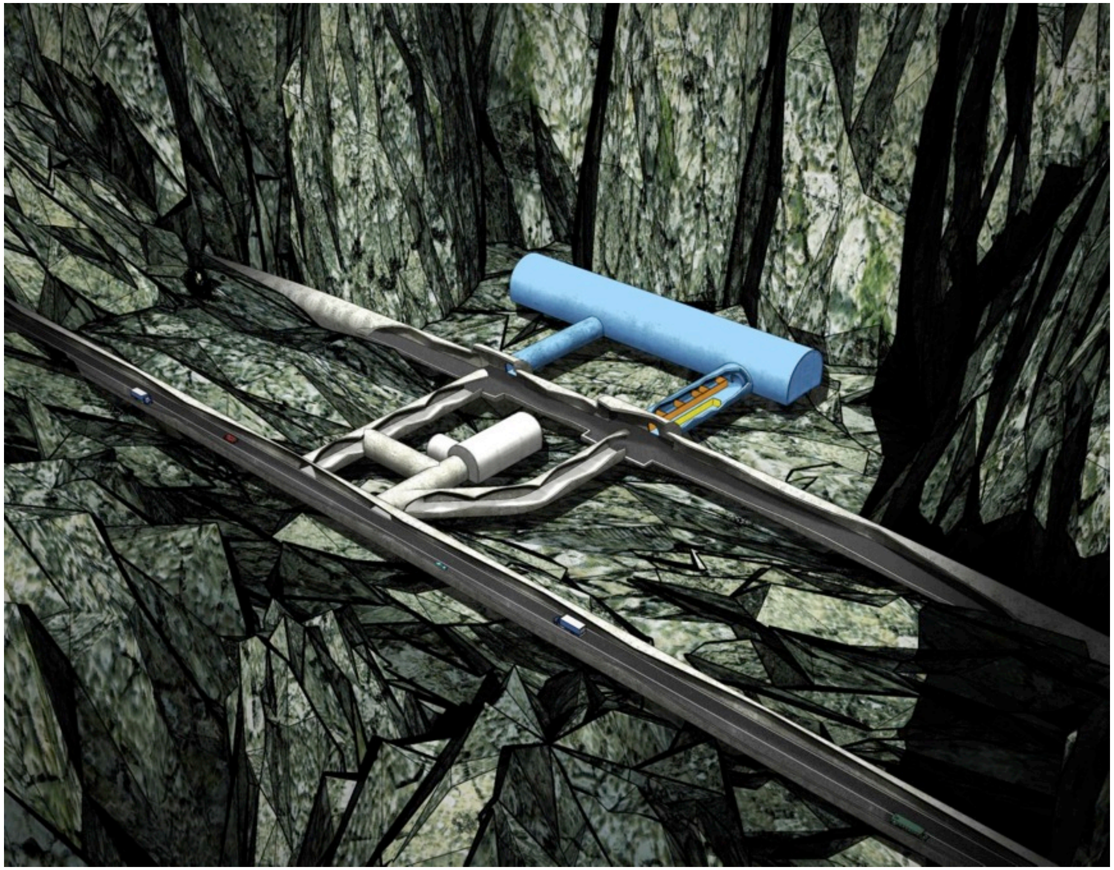
SuperNEMO demonstrator at present LSM

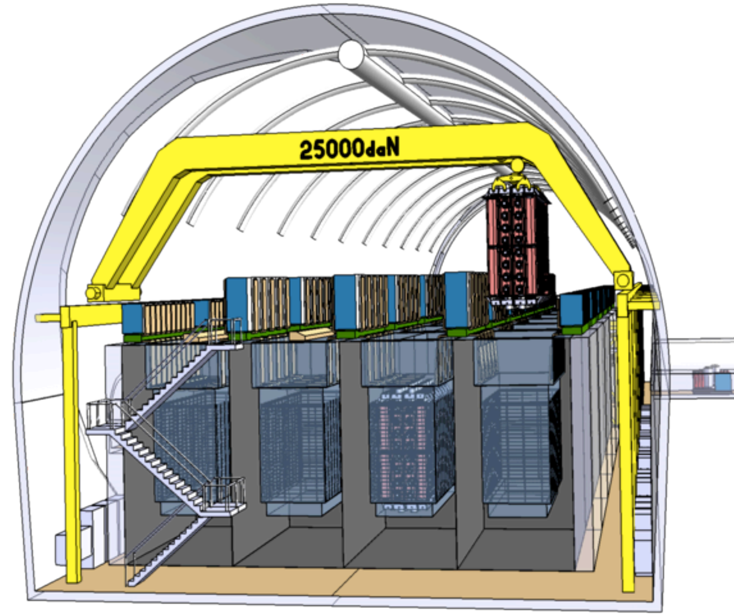


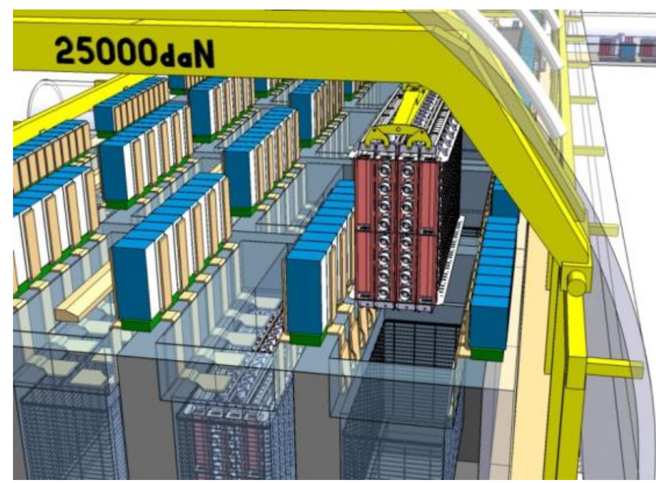


- ❑ Construction started in the laboratories
- ❑ Installation and commissioning @ Modane Underground Laboratory
- ❑ Data taking in 2014 - 2015
- ❑ No background expected for 7 kg of ^{82}Se and 2 years of data
- ❑ Sensitivity after 2 years : $T_{1/2} > 6.6\ 10^{24}$ y and $<m_{\nu}> < 0.2$ -0.4 eV

SuperNEMO and Modane extension







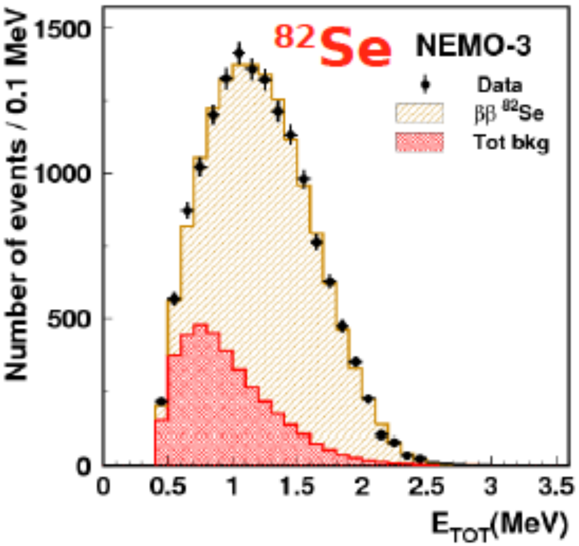
- ✓ 5 times the present LSM
- ✓ Digging in 2014 -2015
- ✓ In Operation 2016

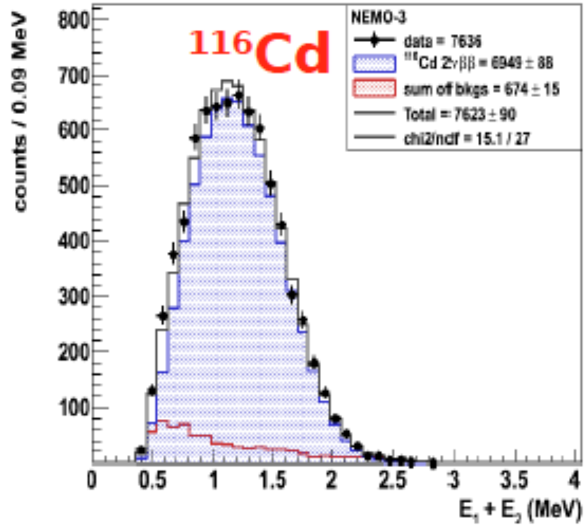
Summary

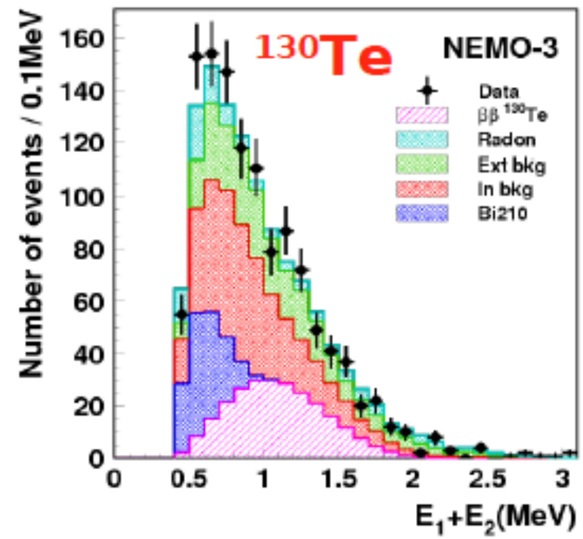
- The NEMO detectors have the unique feature to track the electrons and to measure all kinematic parameters
- Publication of final NEMO3 results for 30 kg.an of ^{100}Mo soon
- Possibility to use different double beta decay isotopes
- Construction of the demonstrator in progress
- Installation at present LSM
- Data taking 2014 – 2015 with 7 kg of ^{82}Se
  No background expected in 2 years $\langle m_\nu \rangle < 0.2 - 0.4$ eV
- Possibility to share the full SuperNEMO detector (20 modules) in different underground laboratories (LSM extension, ANDES,…)

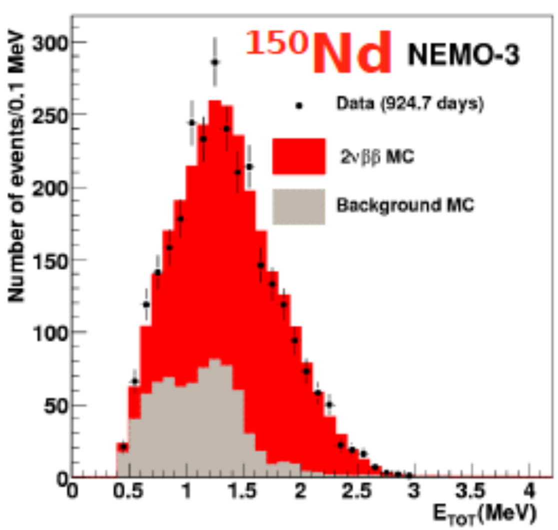
Backup

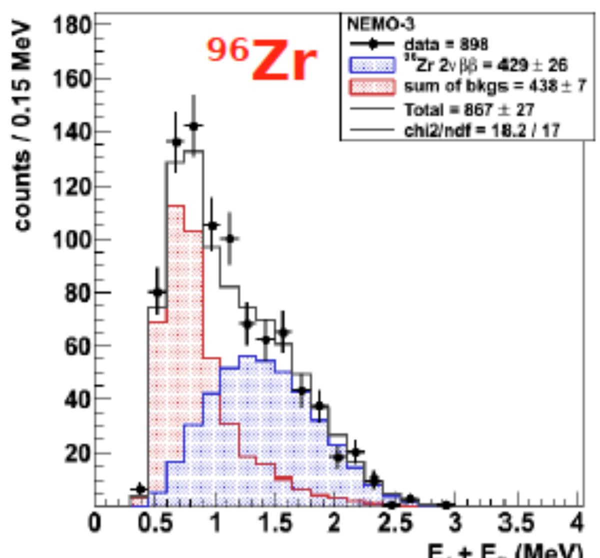
ββ(2ν) results for other isotopes

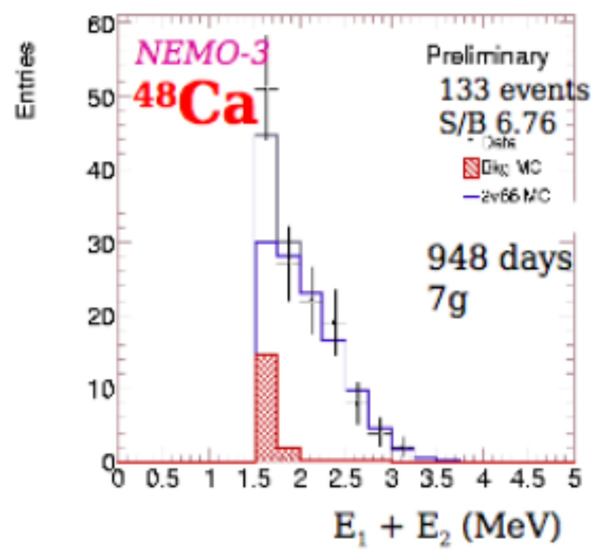












Laboratoire Souterrain de Modane

Depth: **4800 m.w.e.**

Surface: **400 m2**

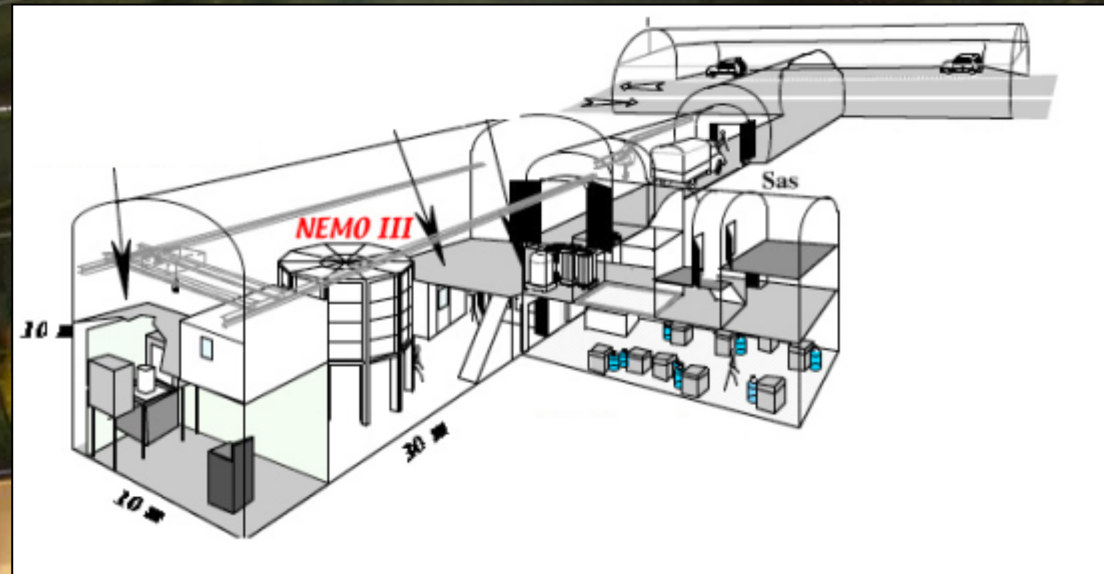
Volume : **3500 m^3**

Muon flux: **4 10^{-5} $\mu.m^{-2}.s^{-1}$**

Neutrons:
Fast flux: 4 10^{-2} $n.m^{-2}.s^{-1}$
Thermal flux: 1.6 10^{-2} $n.m^{-2}.s^{-1}$

Radon: **15 Bq/m^3**

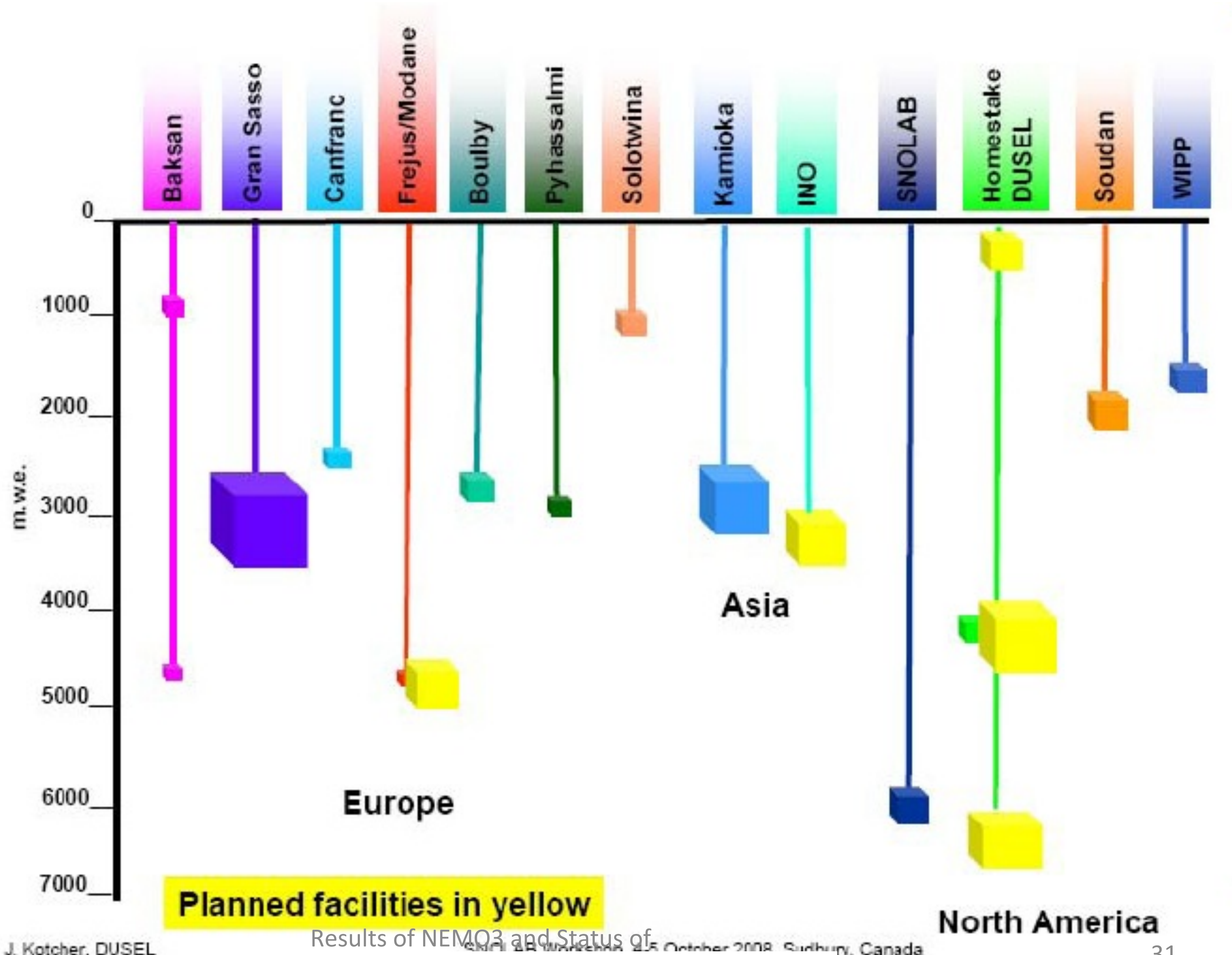
Access : **horizontal**



Budget (full cost): **1 M€/yr**
Staff: **3 Physicists**
3 Engineers
7 Technicians

International associated laboratory agreement with JINR Dubna (Russia) and CTU Prague (Czech Republic)

Comparison of Underground Labs



Remark on $\Delta E \times N_{bckg}$

Experiment	ΔE (keV)	N_{bckg} (cts/ keV/kg/y	$\Delta E \times N_{bckg}$	
H-M	4.5	0.06	0.3	CALO
Cuoricino	6	0.13	0.8	CALO
NEMO3	260	0.003	0.8	TRACKING
KamLAND-Zen	250	0.0028	0.7	CALO
EXO-200	120	0.0015	0.2	CALO
GERDA Phase I Phase 2	4 4	0.01 0.001	0.04 0.004	CALO CALO
CUORE	6	0.01	0.06	CALO
Majorana	4	0.003	0.01	CALO
SuperNEMO	120	0.0001	0.01	TRACKING

Experimental techniques

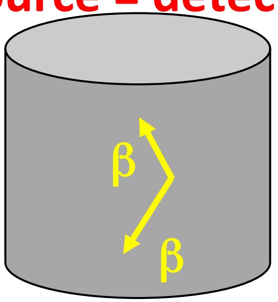
With background:

$$T^{0\nu}_{1/2}(y) > \frac{\ln 2 \, . \, \mathcal{N}}{k_{C.L.}} \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \, . \, t}{N_{Bckg} \, . \, \Delta E}}$$

M: masse (g)
ε : efficiency
$K_{C.L.}$: Confidence level
$\mathcal{N}$: Avogadro number
t: time (y)
N_{Bckg}: Background events ($keV^{-1}.g^{-1}.y^{-1}$)
ΔE: energy resolution (keV)

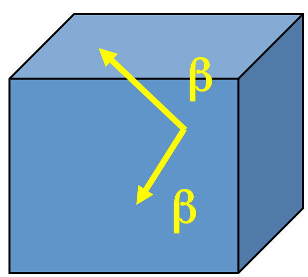
Today, no technique able to optimize all the parameters

Calorimeter
Semi-conductors
Bolometers
Source = detector



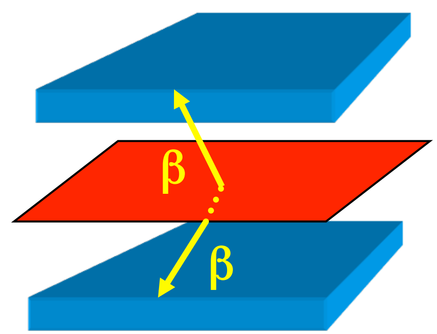
ε, ΔE

Calorimeter
(Loaded) Scintillator
Source = detector



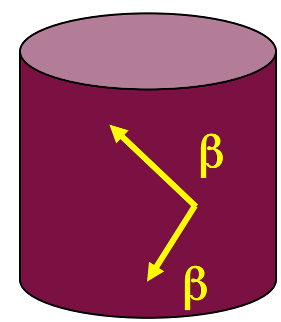
ε, M

Tracko-calo
Source ≠ detector



NBckg, isotope choice

Xe TPC
Source = detector



ε,M, (N_{Bckg})

Double beta decay background

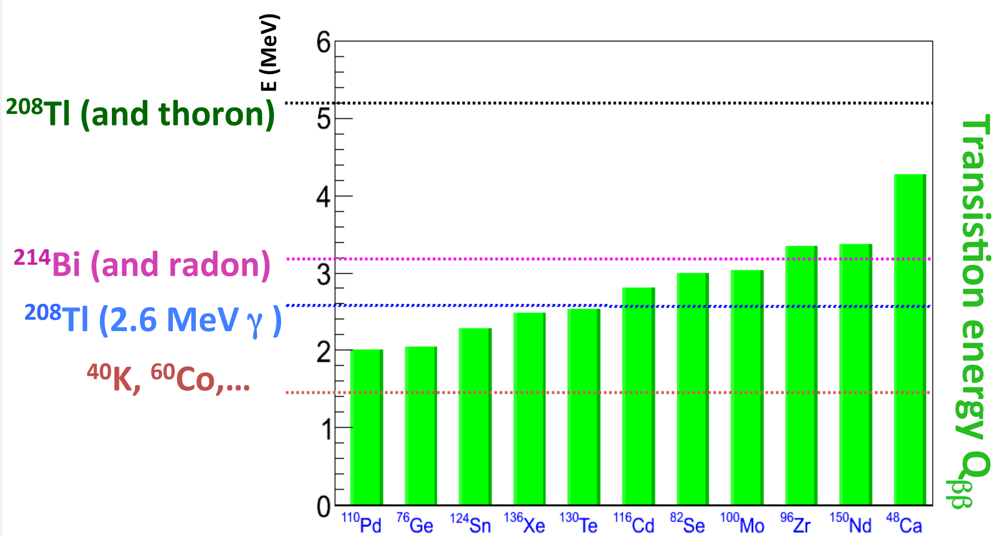
WITH Background

$$T^{0\nu}_{1/2}(y) \propto \frac{\varepsilon}{A}\sqrt{\frac{M\ .\ t}{N_{Bckg}\ .\ \Delta E}} \qquad \langle m_\nu \rangle \propto \sqrt[4]{M}$$

ε :efficiency, M: Mass, t: time, N_{bckg}: Background events, ΔE: energie resolution, A: isotope mass

Background origins

Natural radioactivity



Other sources of background:

- Muons (underground labs)
- γ from ((n,γ) reactions , μ bremstrahlung
- Muon spallation products
- α emitters from bulk or surface contaminations for calorimeters
- ββ(2ν) if modest energy resolution

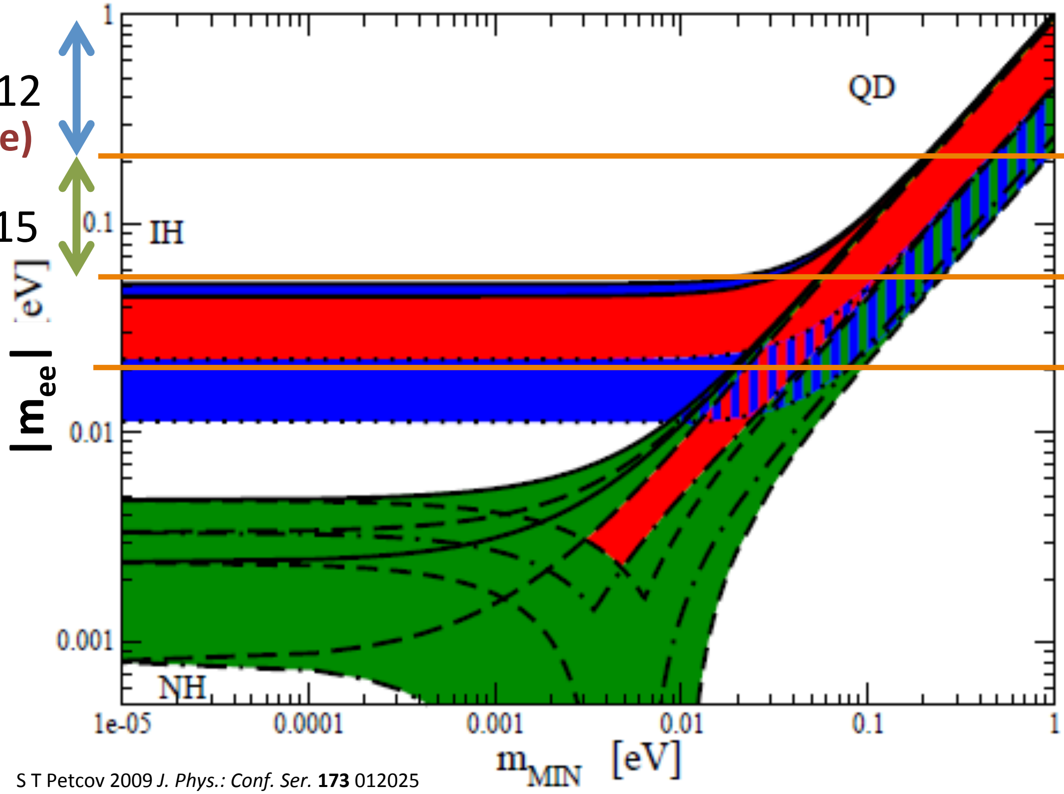
Goal of the next generation

Isotope mass

~ 10 kg 2012
(200 – 400kg ^{136}Xe)

~ 100 kg 2015

~ 1000 kg



S T Petcov 2009 *J. Phys.: Conf. Ser.* **173** 012025

Required background level in the ROI

100 – 1000 cts/yr/ton

1 – 10 cts/yr/ton

0.1 – 1 cts/yr/ton

Next generation will use ≥ 100 kg (started with Xe experiments)

Improvements of background needed

Next generation of experiments

Calorimeter

Ge diode
ε, ΔE
^{76}Ge
→ GERDA, MAJORANA

Bolometers
ε, ΔE
^{130}Te, ^{82}Se, ^{100}Mo
→ CUORE, LUCIFER, ZnMo4

Liquid Xe
ε, M, (N_{bckd})
^{136}Xe
→ EXO

Scintillator
ε, M
^{136}Xe, ,^{48}Ca, ^{150}Nd, ^{100}Mo
→ KamLAND-Zen, CANDLES, SNO+, Borexino, CdWO4, AMoRE

Tracker

Tracko-calo
N_{Bckg}, isotopes
^{82}Se (^{150}Nd, ^{48}Ca)
→ SuperNEMO

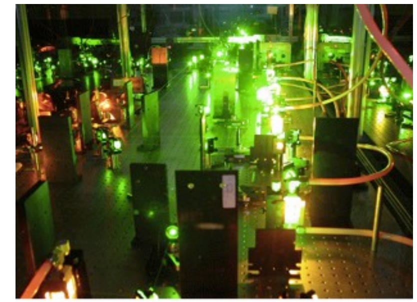
Pixellized CdZnTe
ε, N_{Bckd}
^{116}Cd
→ COBRA

TPC
ε, N_{Bckd}
^{136}Xe, ^{150}Nd
→ MTD, EXO-gas, NEXT

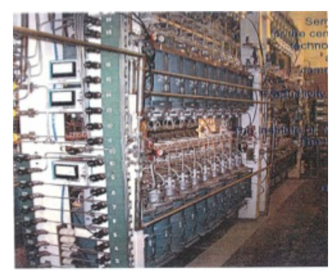
Source enrichment

Nucleus	Existing method	R&D
^{48}Ca		Laser separation, gazeous diffusion
^{76}Ge	Centrifugation	
^{82}Se	Centrifugation	
^{96}Zr		Laser separation
^{100}Mo	Centrifugation	
^{116}Cd	Centrifugation	
^{130}Te	Centrifugation	
^{136}Xe	Centrifugation	
^{150}Nd		Centrifugation, Laser

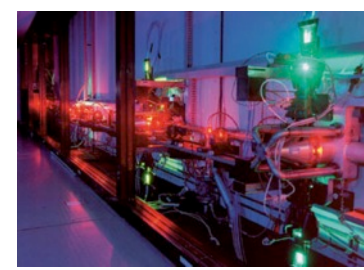
R&D in KAERI (Korea) for ^{48}Ca enrichment by laser



R&D in Russia for ^{150}Nd enrichment by centrifugation



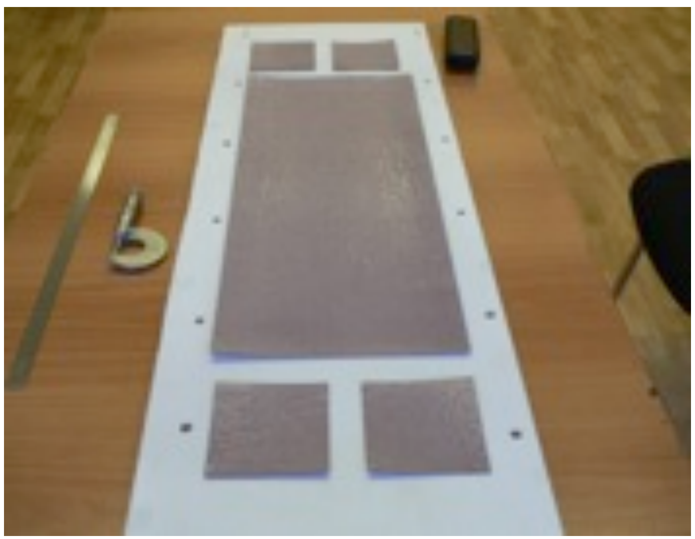
R&D in France for ^{150}Nd enrichment by laser



Double beta decay Sources

- Radiopurity of source foil < 2 μBq/kg in ^{208}Tl and < 10 μBq/kg in ^{214}Bi
- Thickness of source foil 40 mg/cm^2

Enriched ^{82}Se already
5,5 kg in the collaboration

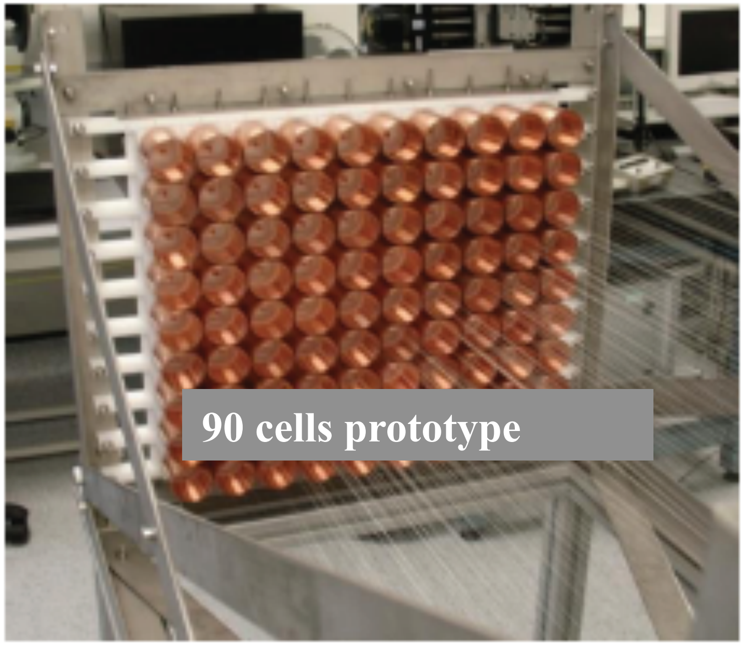


Source production R&D @ ITEP

Chemical purification @INL

- ❑ Chemical purification (INL)
- ❑ Physical purification (ITEP)
- ❑ Reverse method (JINR,LSM)

Tracker

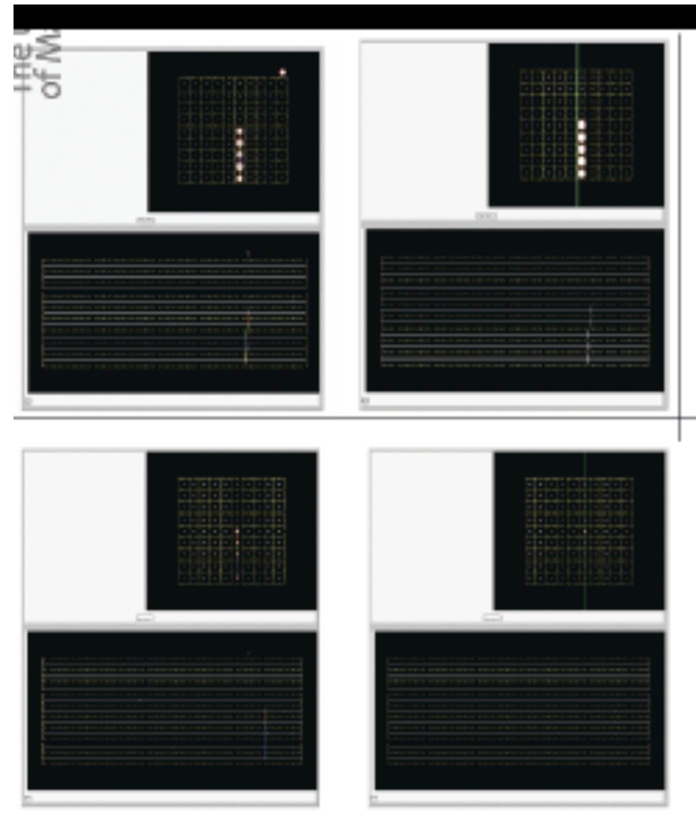


- Cells: Diameter= 44 mm
  Length = 3.7 m

- Basic 90 cells prototype demonstrated:

  σ_{trans} = 0.7 mm σ_{long} = 1 cm

  Efficiency > 98%



90 cells prototype : data with cosmic rays

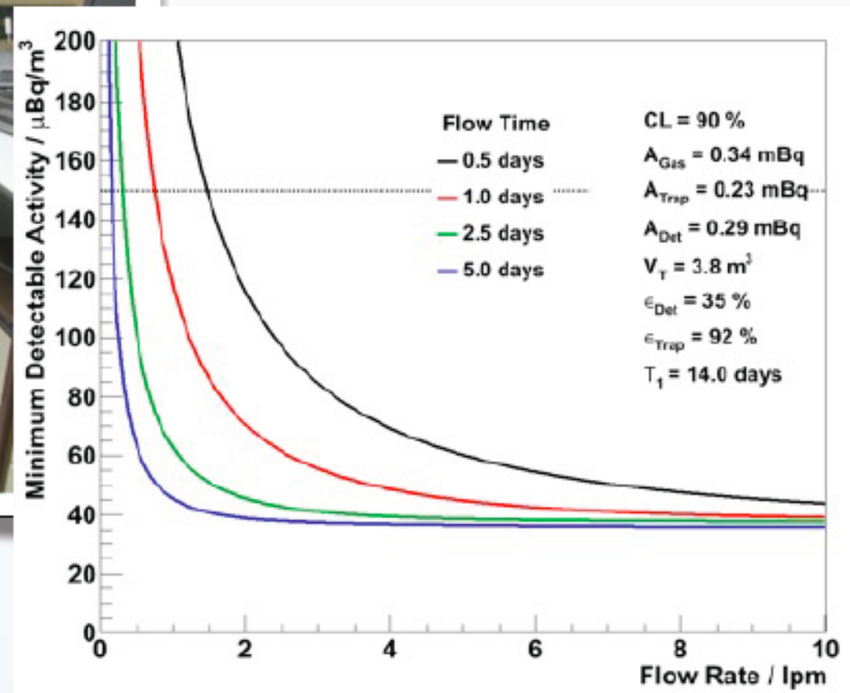
Measurement of Rn activity in tracker

Vacuum Pump

Carbon Trap

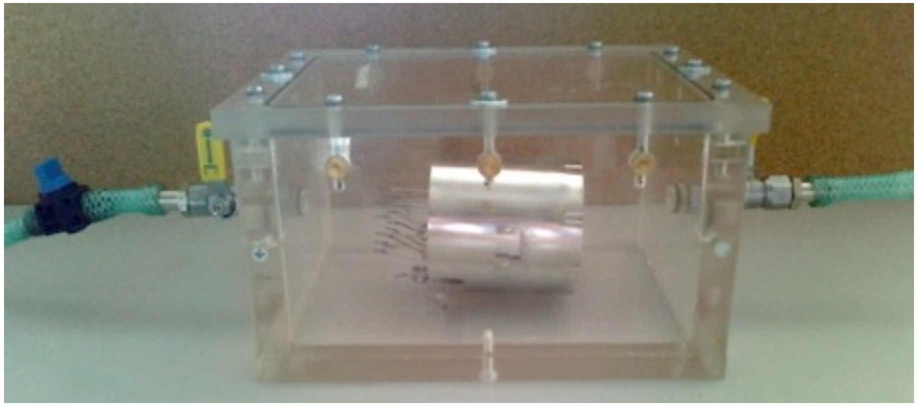
Radon Detector (Electrostatic & Pin Diode)

Measurement of emanation from quarter sub-section of SuperNEMO tracker



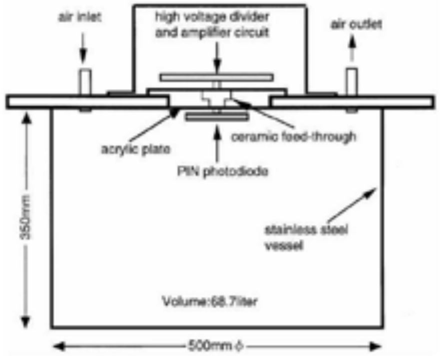
Radon measurements

Prague : setup to measure permeability of materials



Bratislava:emanation setup

CENBG:emanation setup



Saga U, JINR, CENBG, Marseille, Prague:
Electrostatic detectors for gas measurements