The 47th regular meeting of the JINR PAC for Nuclear Physics, 17/01/2018, Dubna, Russia

Investigation of the 2β-decay processes of ^{82}Se with the SuperNEMO detector

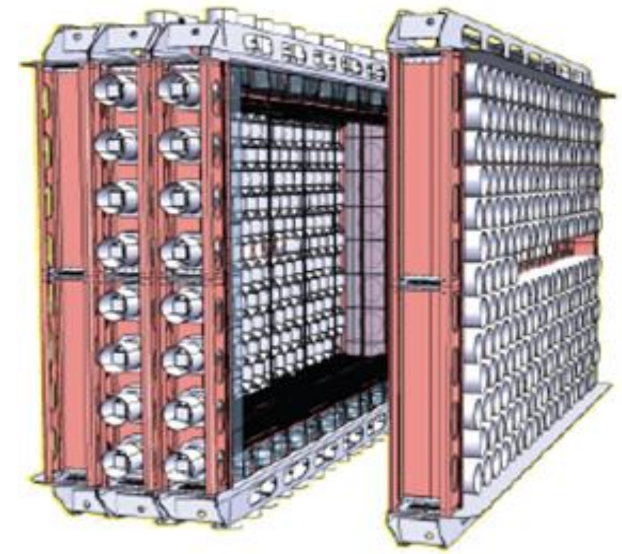
Theme 03 – 2 - 1100 - 2010/2018
“Non-accelerating neutrino physics and astrophysics”

Extension of the SuperNEMO project
for the period 2019-2021

Speaker: **Yuri Shitov** (DLNP, JINR)

From NEMO-3 to SuperNEMO: R&D since 2006

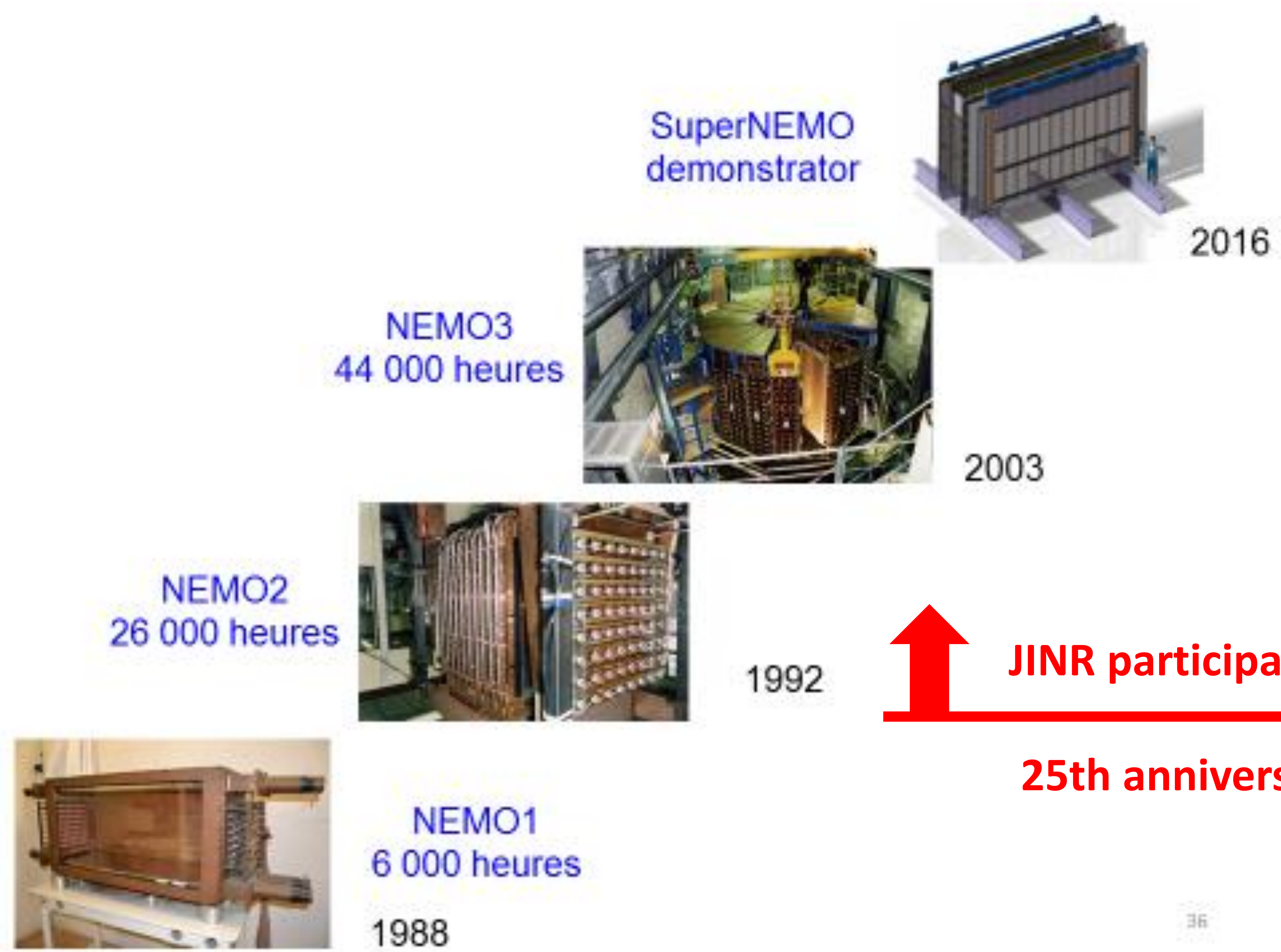
$$T_{1/2}^{0\nu}(y) \propto \frac{a\varepsilon}{W} \times \sqrt{\frac{M \times t}{N_{BGR} \times \Delta E}}$$



NEMO-3	⇒	SuperNEMO
^{100}Mo, 7kg	Isotope, mass	^{82}Se,100-200 kg
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	Background in ββ-foil	^{208}Tl: < 2 μBq/kg ^{214}Bi: < 10 μBq/kg
8%	Efficiency	30%
8% @ 3 MeV	Energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}$ > 2 x 10^{24} y $<m_\nu>$ < 0.3 – 0.6 eV	Sensitivity	$T_{1/2}$ > 1-2 x 10^{26} y $<m_\nu>$ < 40 – 110 meV

NEMO-3 successful experience allows to extrapolate tracko-calo technique on larger mass next generation detector to reach new sensitivity level.

The NEMO/SuperNEMO road map



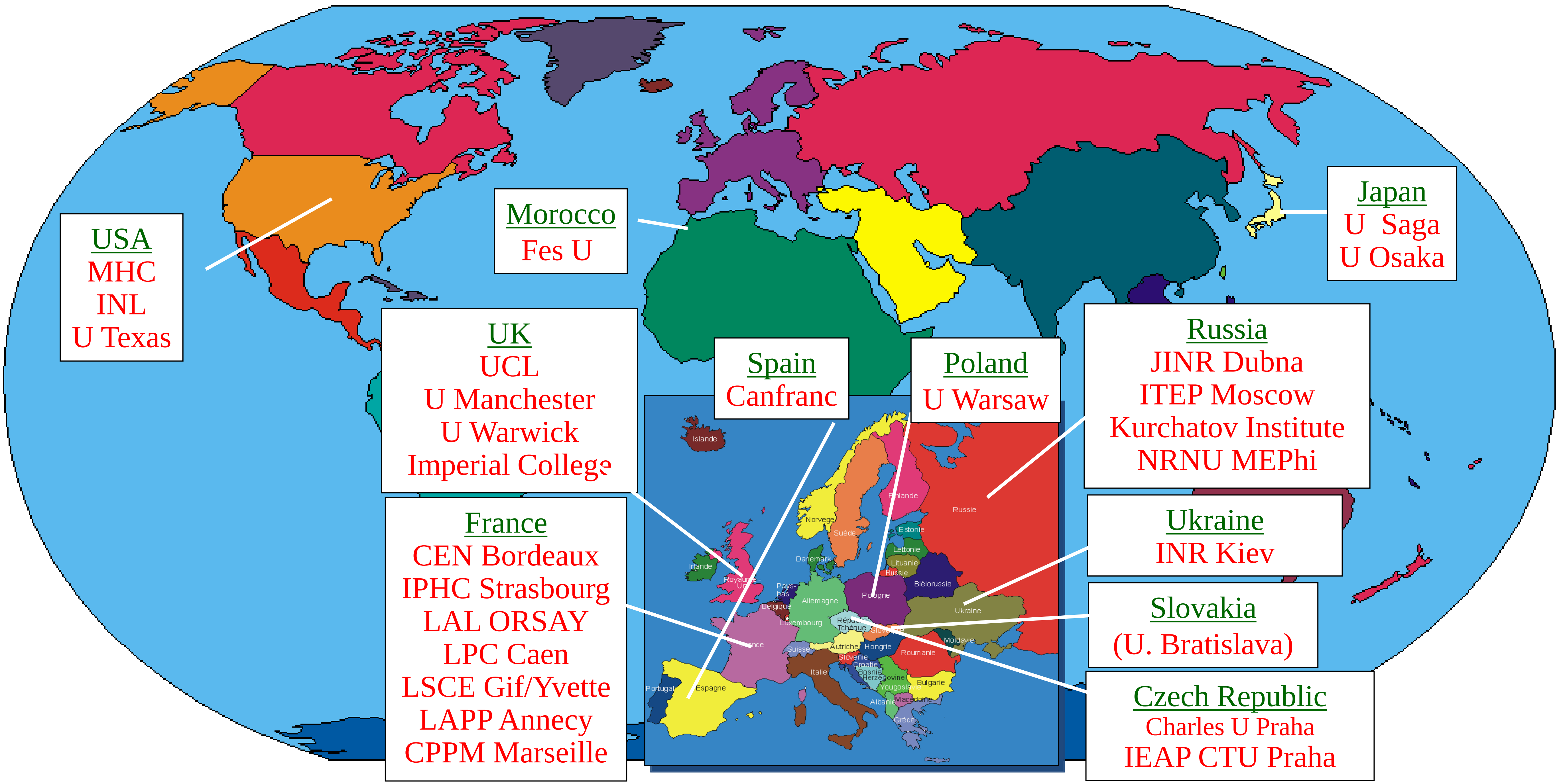
JINR participation

25th anniversary!

The NEMO/SuperNEMO collaborations

Neutrino **E**ttore **M**ajorana **O**bservatory

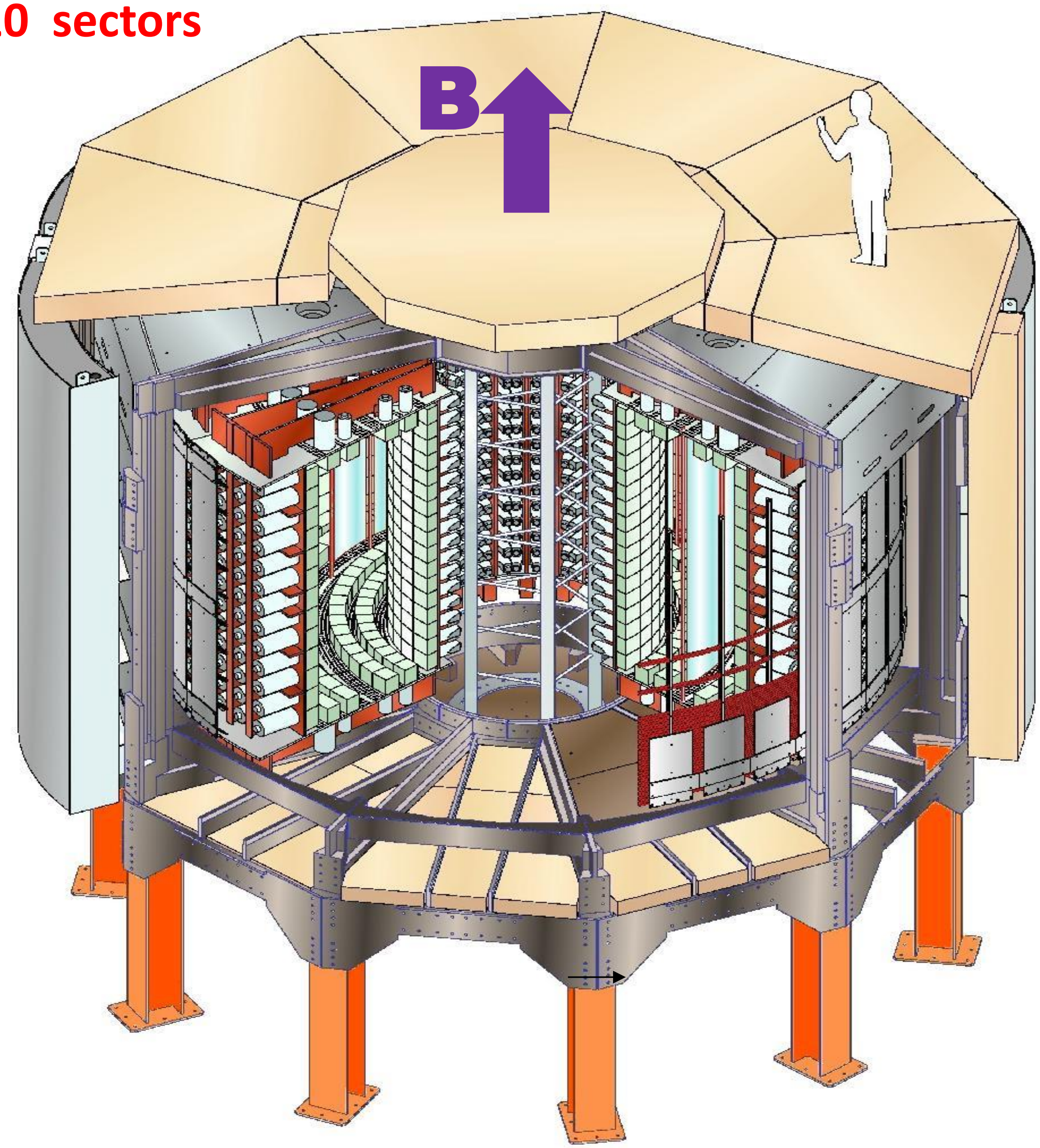
(**N**eutrino **E**xperiment on **MO**lybdenum – historical name)



~ 80 physicists, 11 countries, 25 laboratories

The NEMO-3 detector

Modode (Fréjus) Underground Laboratory (LSM) : 4800 m.w.e.



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 60 mg/cm²

Tracking detector:
drift wire chamber operating in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

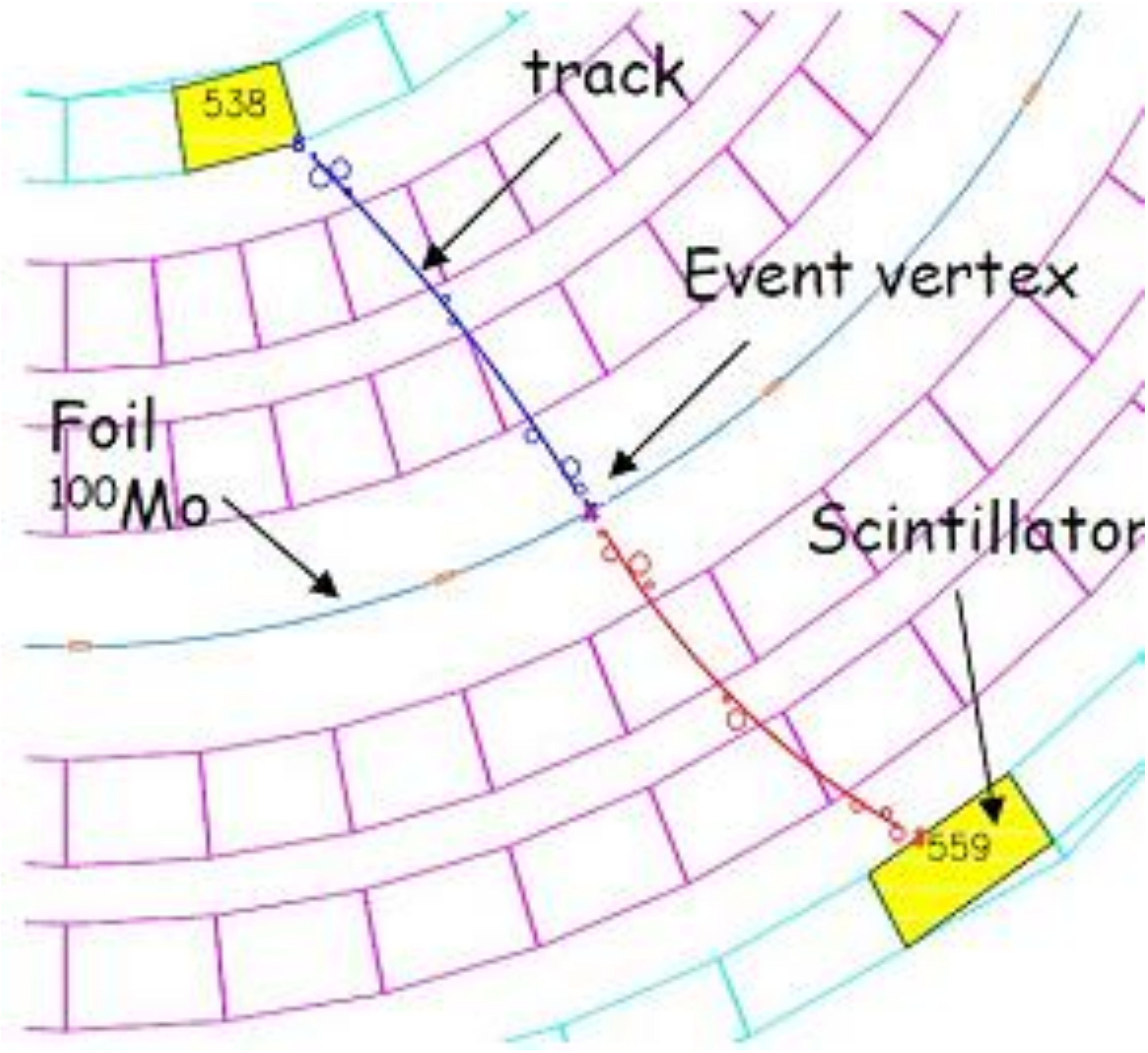
Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

Data taking: February 2003 – January 2011
7 ββ-isotopes have been measured:
^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd

Able to identify e^-, e^+, γ and α–delayed

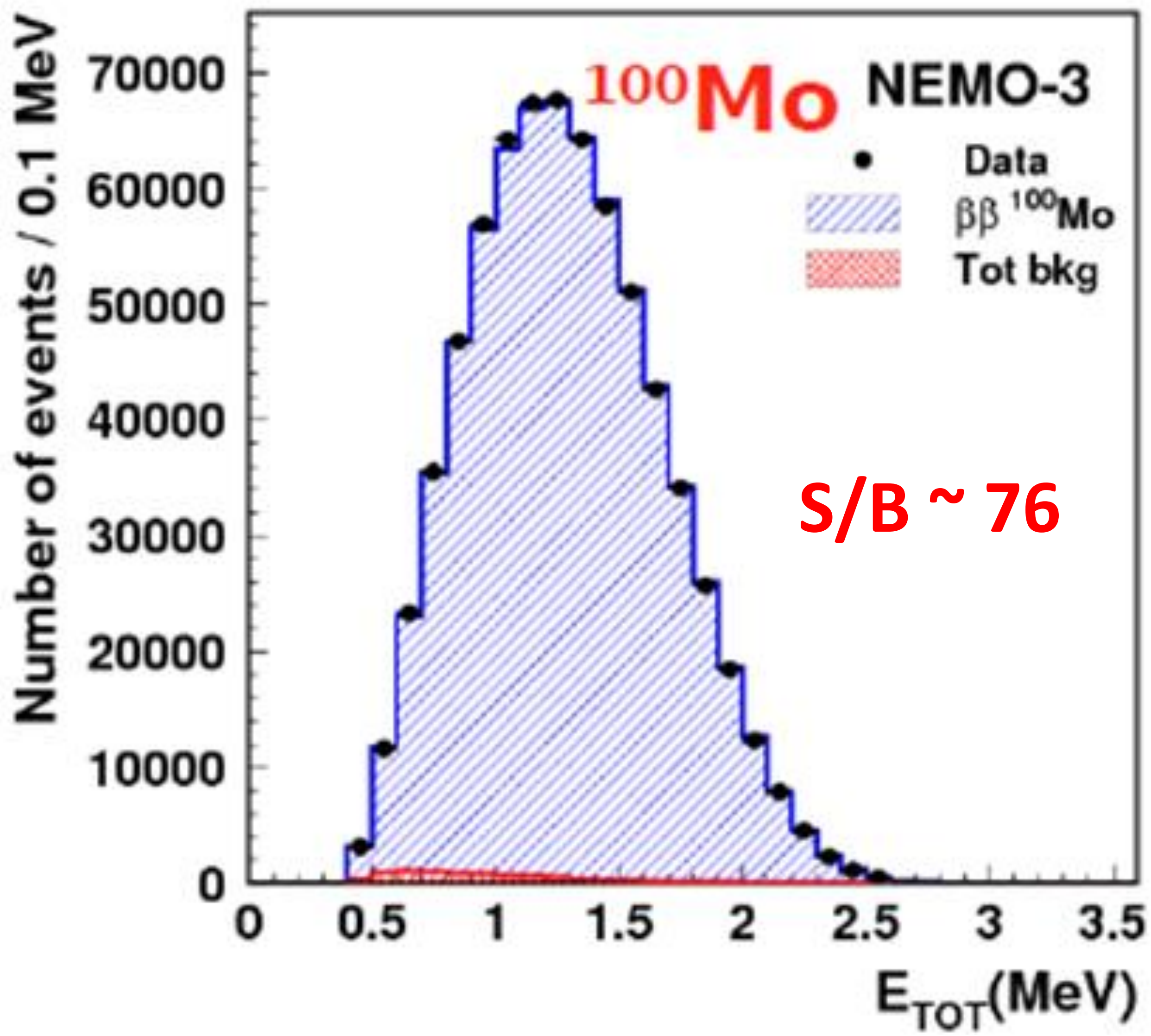
Self-detection of all own background channels

The ββ-decay pattern in the NEMO-3 detector

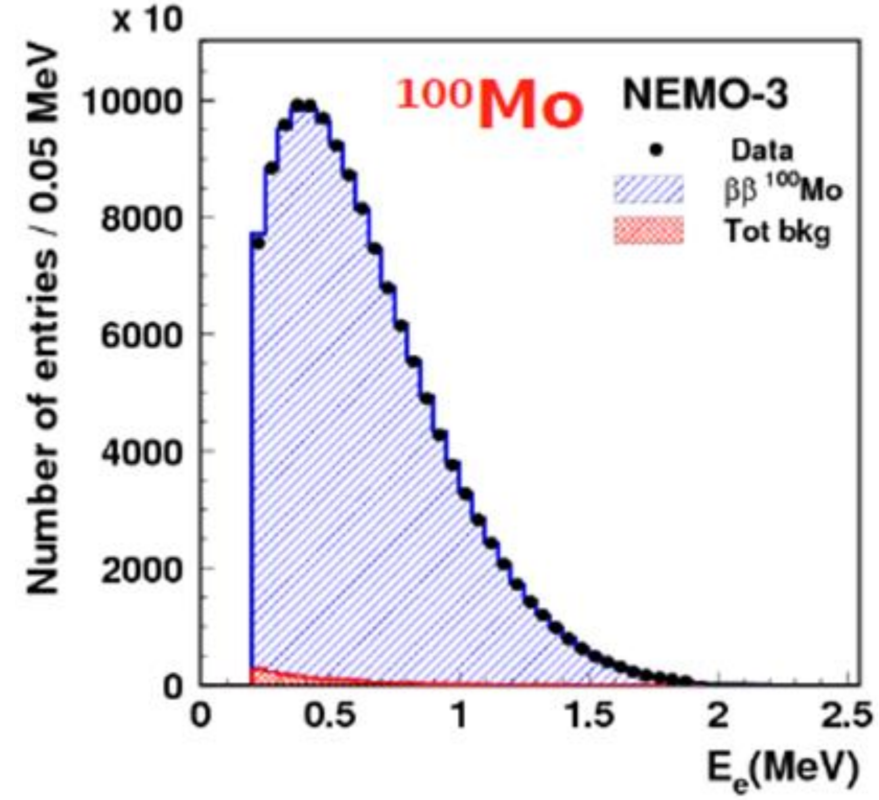


The NEMO-3: $2\nu\beta\beta$-spectra of ^{100}Mo

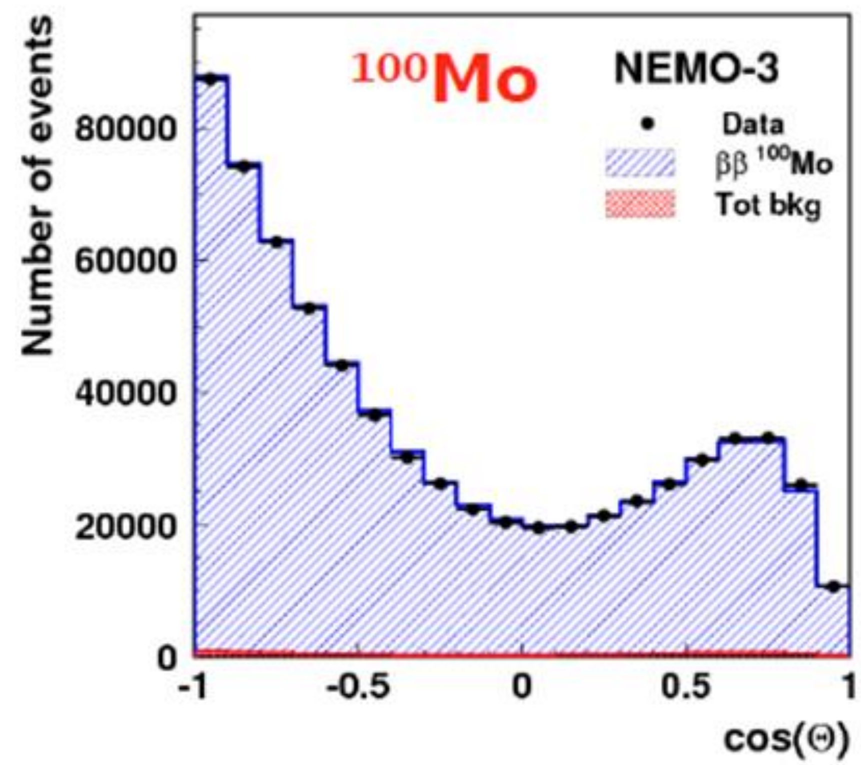
Sum energy spectrum



Single electron spectrum



Angle between electrons

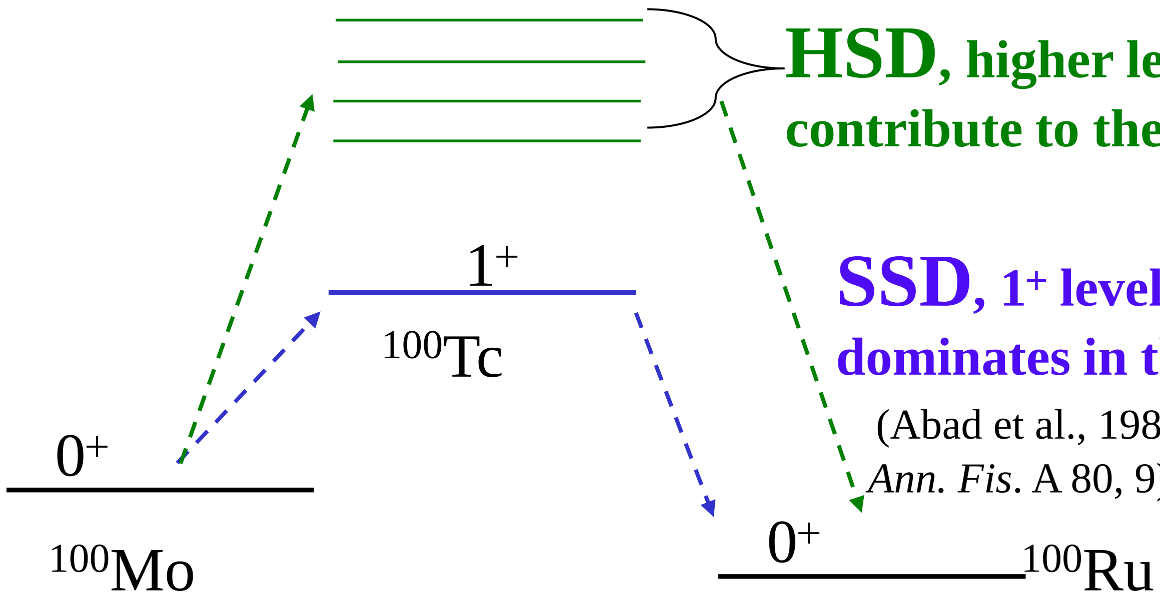


«ββ-decay factory»

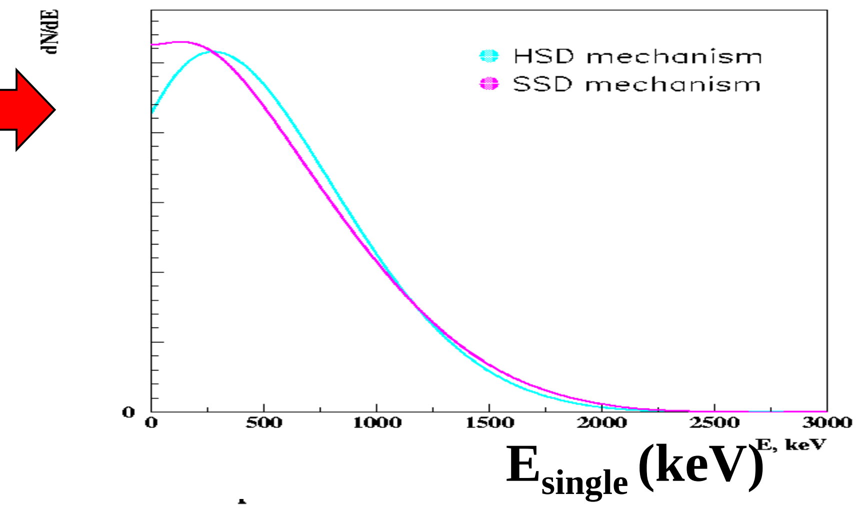
One ββ-event each 2.5 minutes,
~1M registered ββ-events

Unique data for precision test!s!

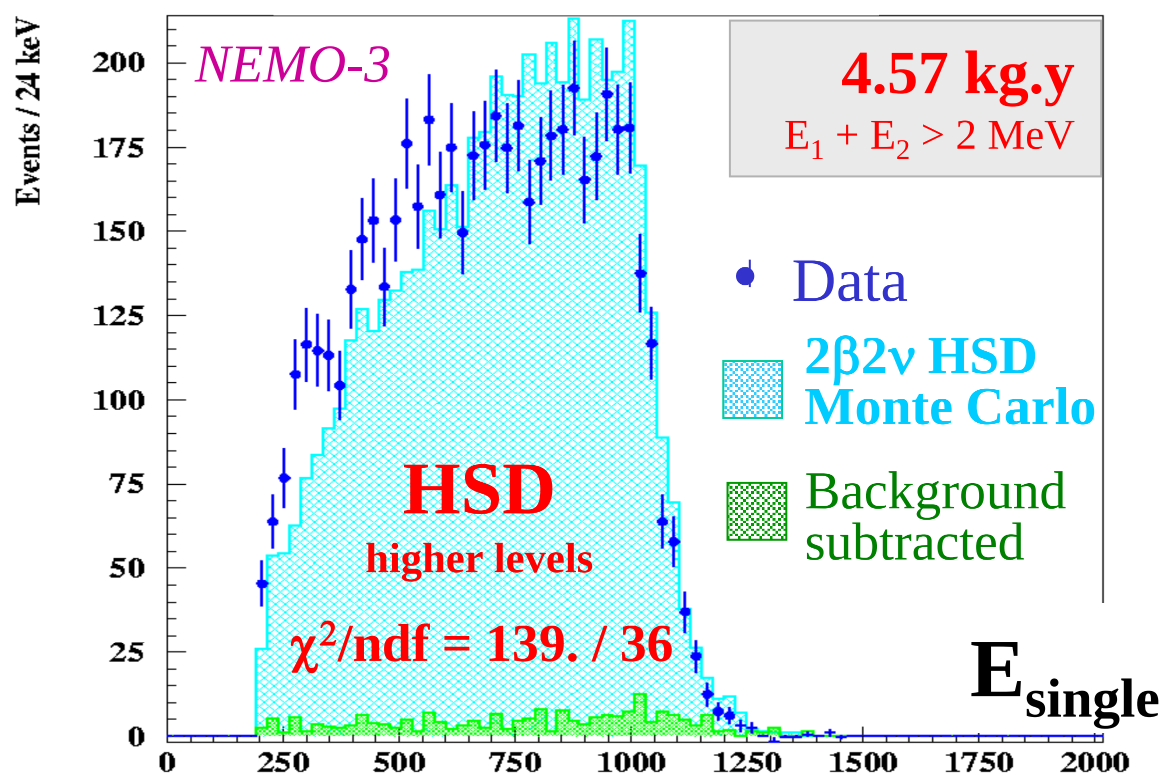
Probe of 2νββ-mechanism in ^{100}Mo

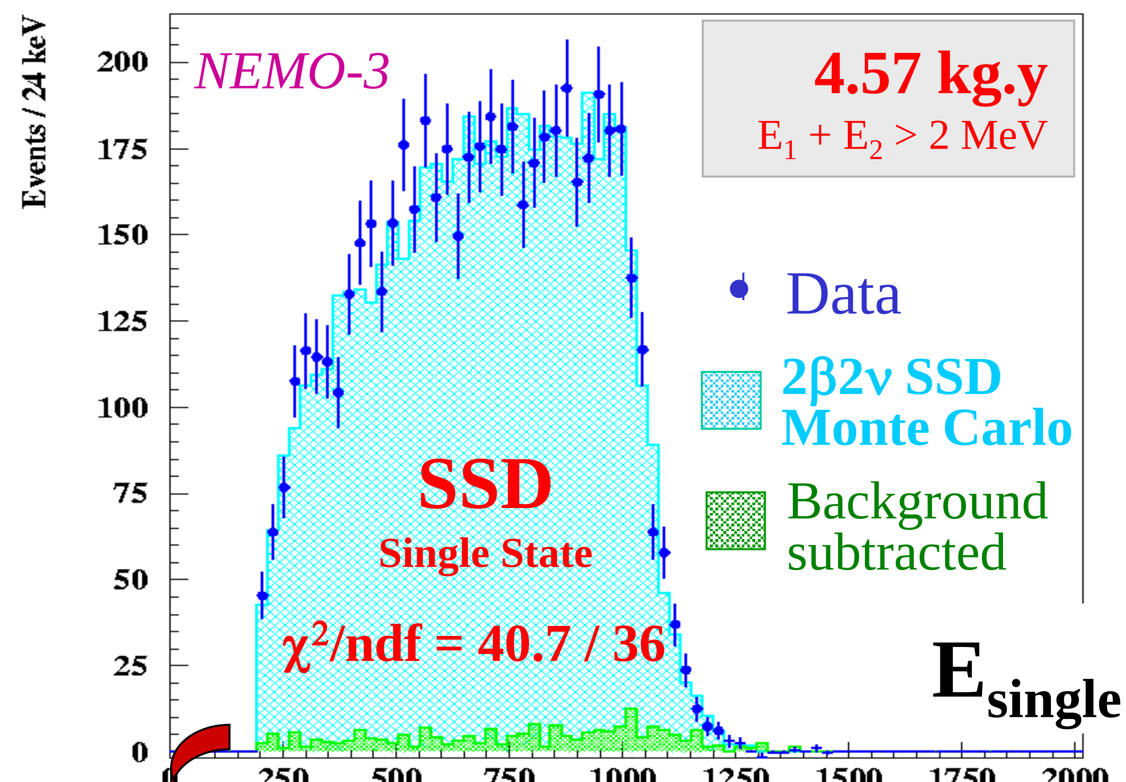


Single electron spectrum different between SSD and HSD



Simkovic, *J. Phys. G*, 27, 2233, 2001





HSD: $T_{1/2} = 7.76 \pm 0.01\ (stat) \pm 0.52\ (syst) \times 10^{18}$ y

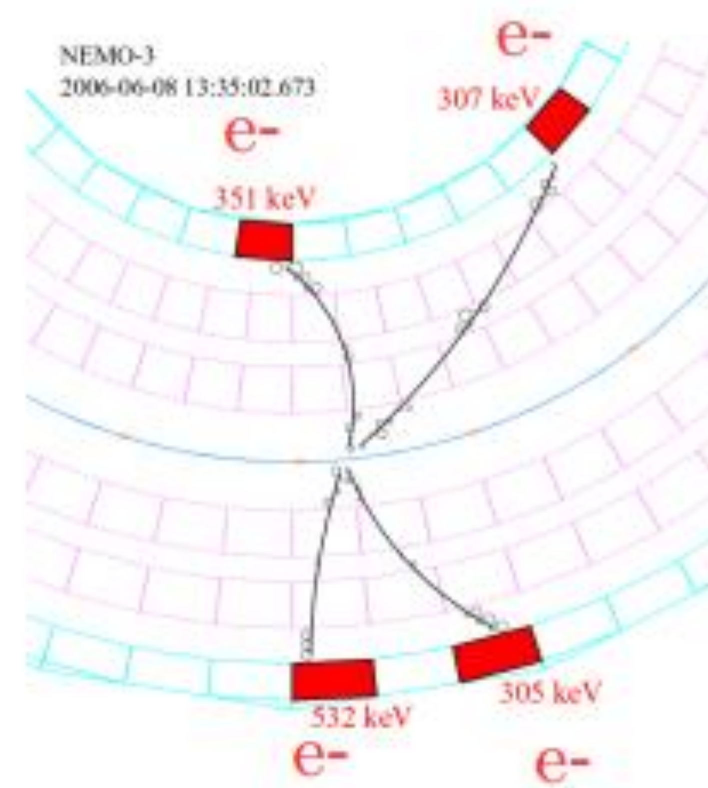
SSD: $T_{1/2} = 6.81 \pm 0.01\ (stat) \pm 0.46\ (syst) \times 10^{18}$ y

^{100}Mo 2β2ν single energy distribution in favour of Single State Dominant (SSD) decay

Method is sensitive to 2νββ-mechanism: first demonstration!

Quadruple neutrinoless 0ν4β-decay

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

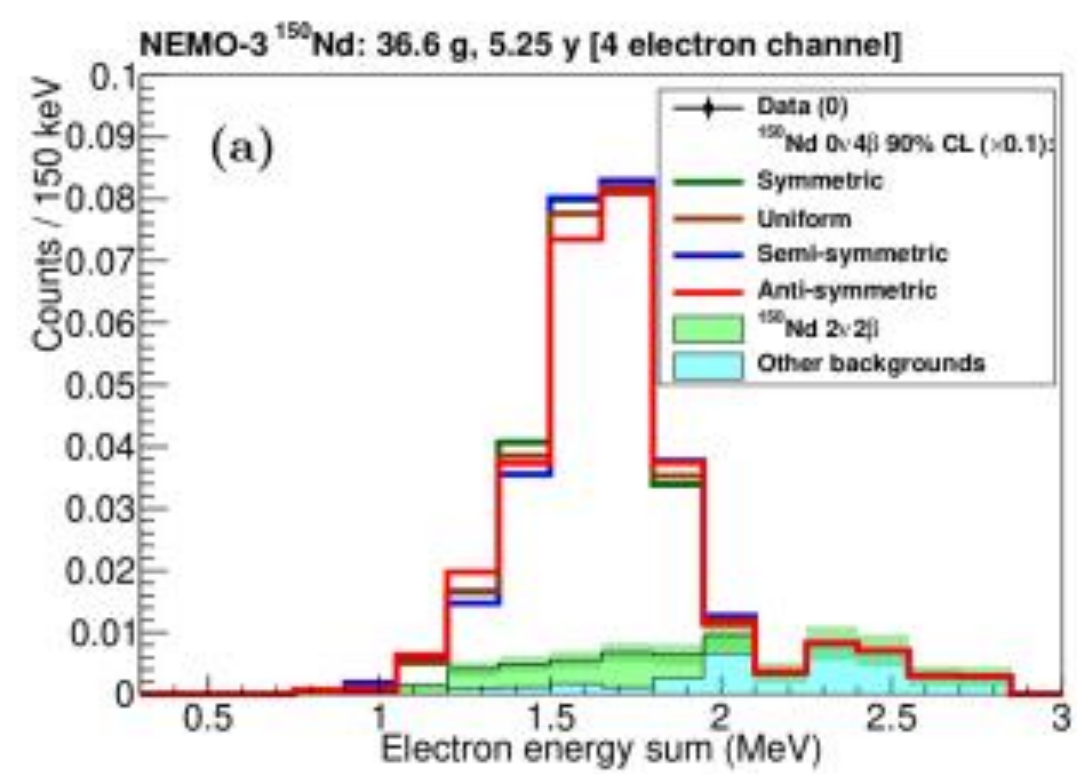


- Exploit the unique ability of NEMO-3 to reconstruct the kinematics of each e-

- No evidence of this decay

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

According the model



- World's first limit on this process

R. Arnold *et al.* Phys. Rev. Lett. 119, 041801 (2017) – PRL Editor's selection!

The SuperNEMO Demonstrator

Source: 7kg of ^{82}Se

Calorimeter R&D

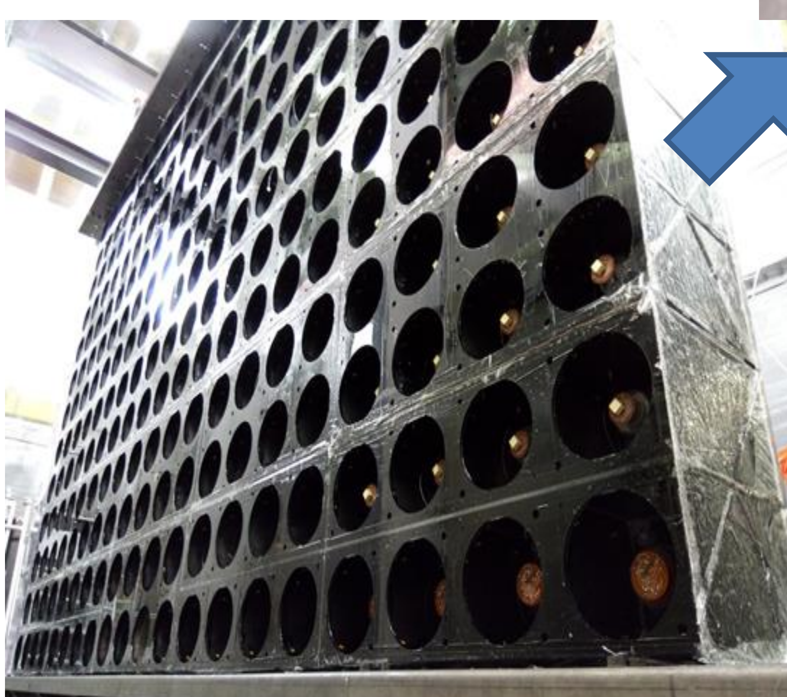
Optical unit

Tracker R&D:

Wiring robot

C0: 1 quarter of tracker

Calorimeter wall

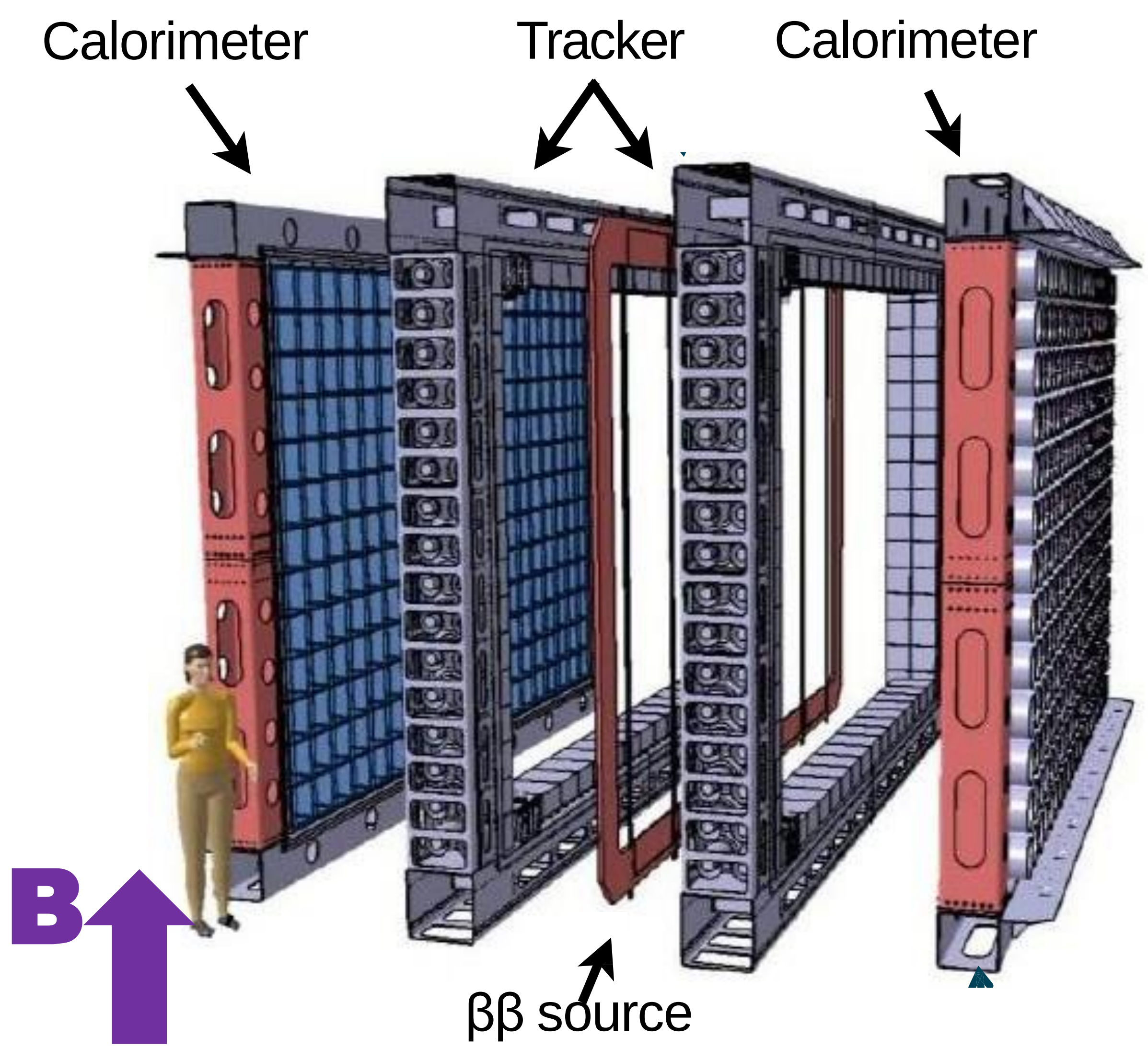


The current goal: the start of the first module, which should achieve the claimed background conditions.

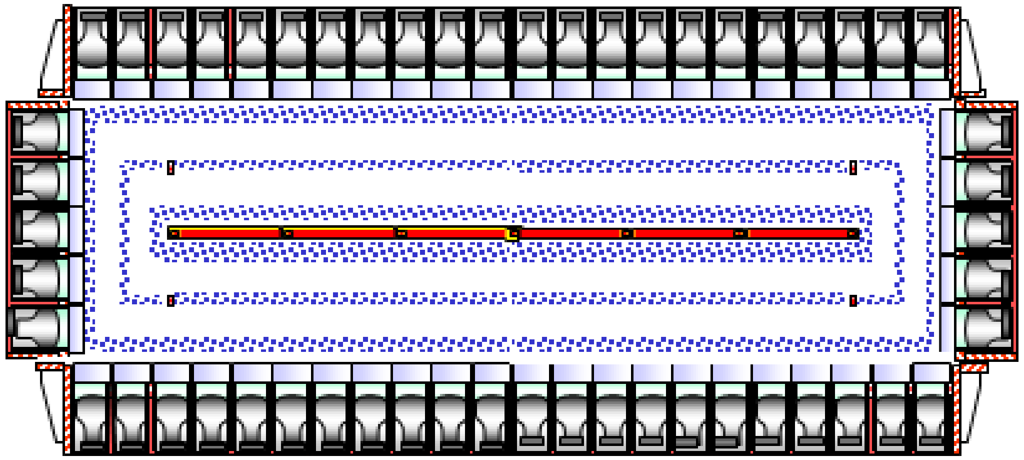
Low background R&D: BiPo-3

The SuperNEMO Demonstrator

Modane (Fréjus) Underground Laboratory (LSM) : 4800 m.w.e.



Top view



Source: 7 kg of ^{82}Se, 36 strips
planar geometry, S ~ 15 m^2, 40-80 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (2034 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
520 plastic scintillators in 2 main walls
+ PMTs: 8" R5912-03 HAMAMATSU
200 PS in side walls (X-walls)
+ PMTs: 5" R6594 HAMAMATSU

Magnetic field: 25 Gauss.

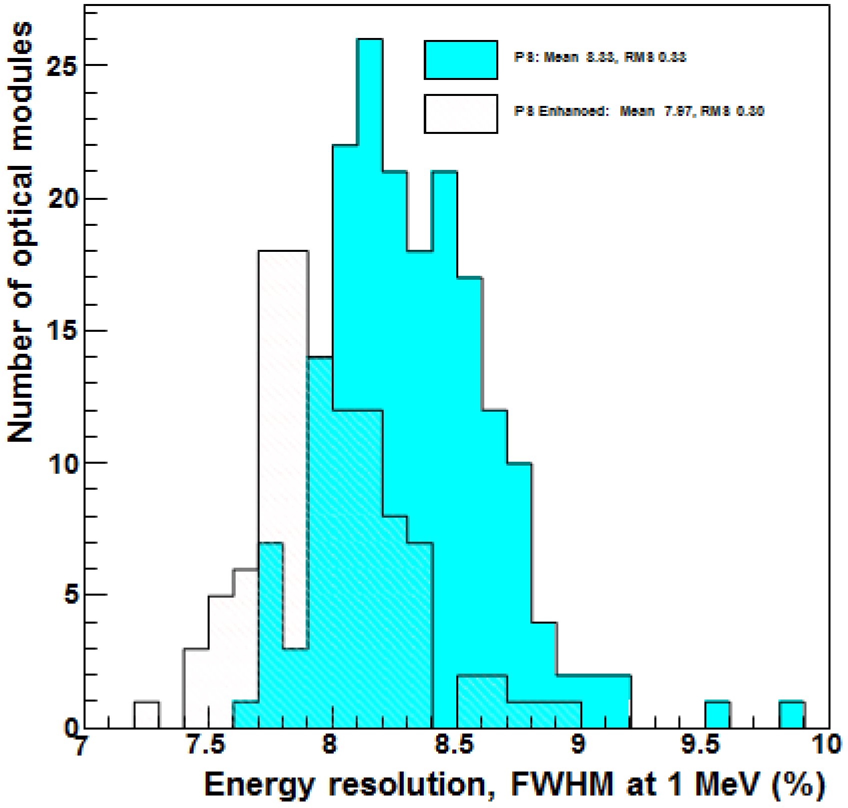
VETO:
60 plastic scintillators in top/bottom walls
+ PMTs: 5" R6594 HAMAMATSU

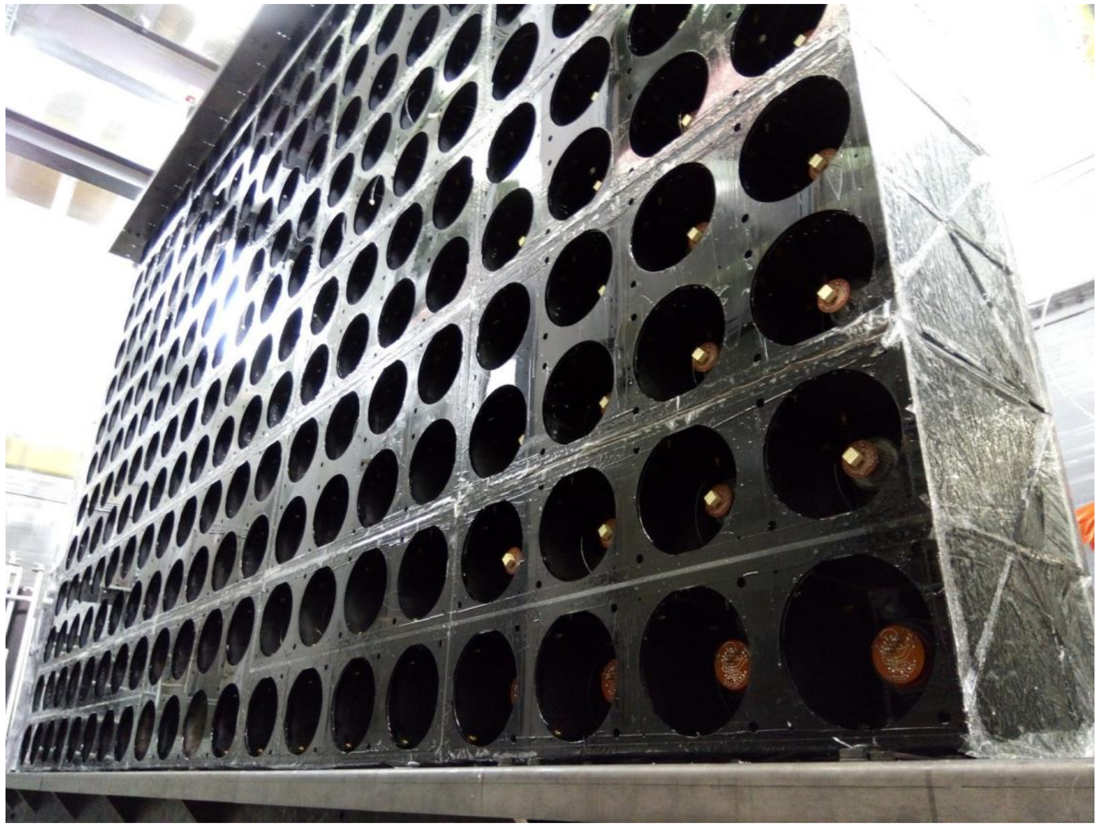
PASSIVE SHIELD:
To be built. Planned: 20 cm of iron + 30 cm of borated polyethylene.

The SuperNEMO calorimeter

- 520 main optical modules
- 8” high QE radiopure PMTs
- σ_t = 400 ps at 1 MeV
- Energy resolution 8%/√E(MeV)
- Calibration system allows stability to < 1%

Nucl.Instrum.Meth. under publication (2017)





The SuperNEMO tracker

Nucl.Instrum.Meth. A824 (2016)

- Multi-wire drift chamber in Geiger mode
- Ultrapure materials: copper, steel, duracon .
- Robotic production of 2034 drift cells
- Radiopure gas flow, anti-radon sealing
- <1% dead channels

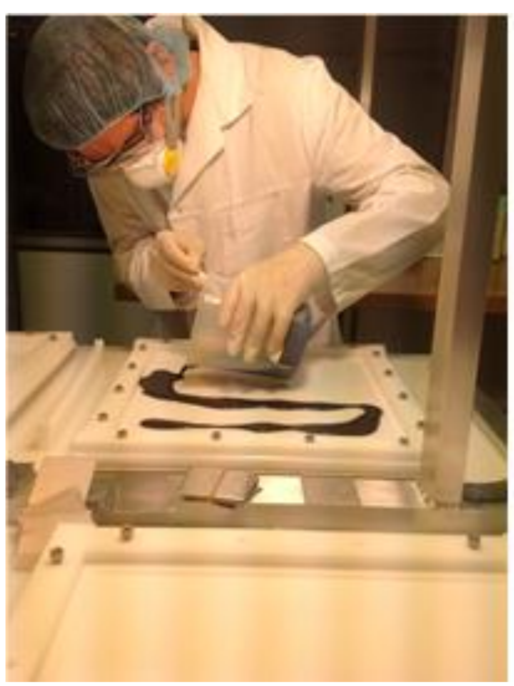
The SuperNEMO foil-sources

- 36 foils made of ^{82}Se powder mixed with PVA glue + mylar mechanical support (200 um thick)
- 7 kg of ^{82}Se ($Q_{\beta\beta}$=2.996 MeV)
- Target limits (challenging) on foil contamination:
  - $^{208}Tl \leq 2$ μBq/kg
  - $^{214}Bi \leq 10$ μBq/kg

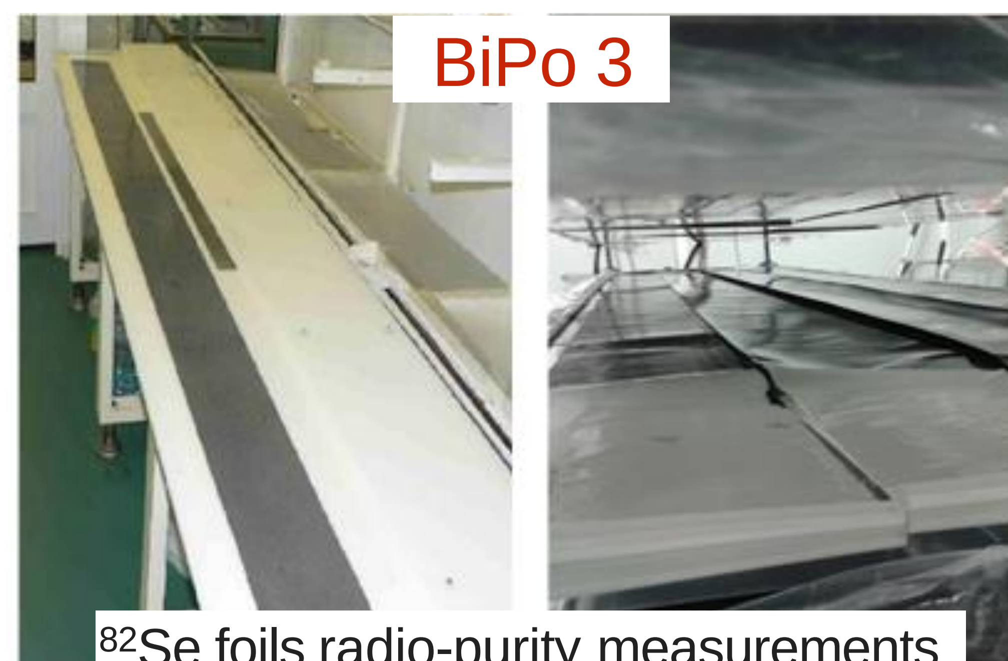
1 μBq/kg = 1 decay in 1 kg per 11.5 days!

- BiPo detector in Canfranc laboratory to measure source foil contamination: preliminary results indicate levels of ^{208}Tl [10-30] μBq/kg (90% C.L.)

JINST 12 (2017) no.06



Training foil production technique

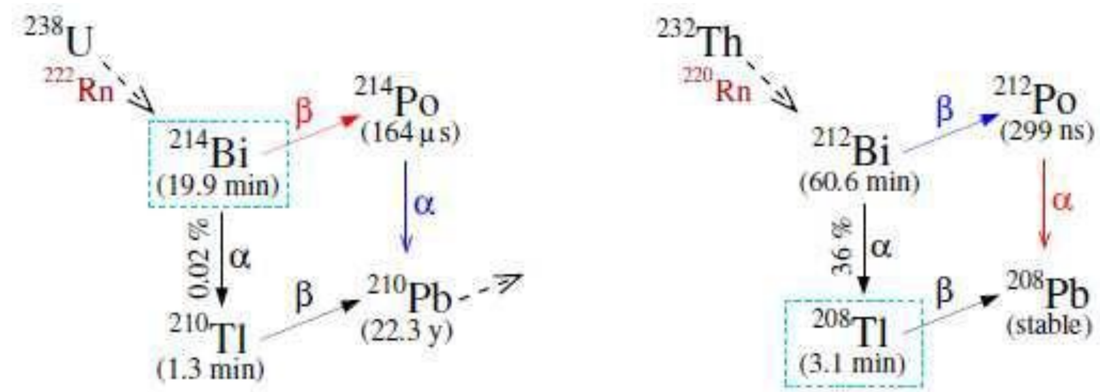


BiPo 3

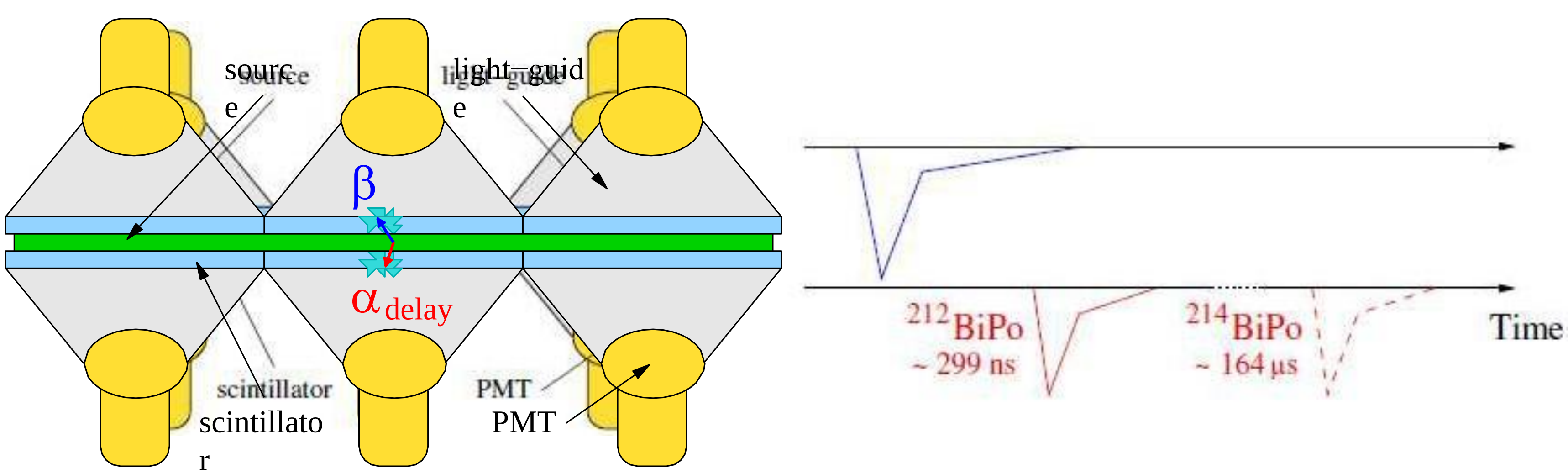
^{82}Se foils radio-purity measurements

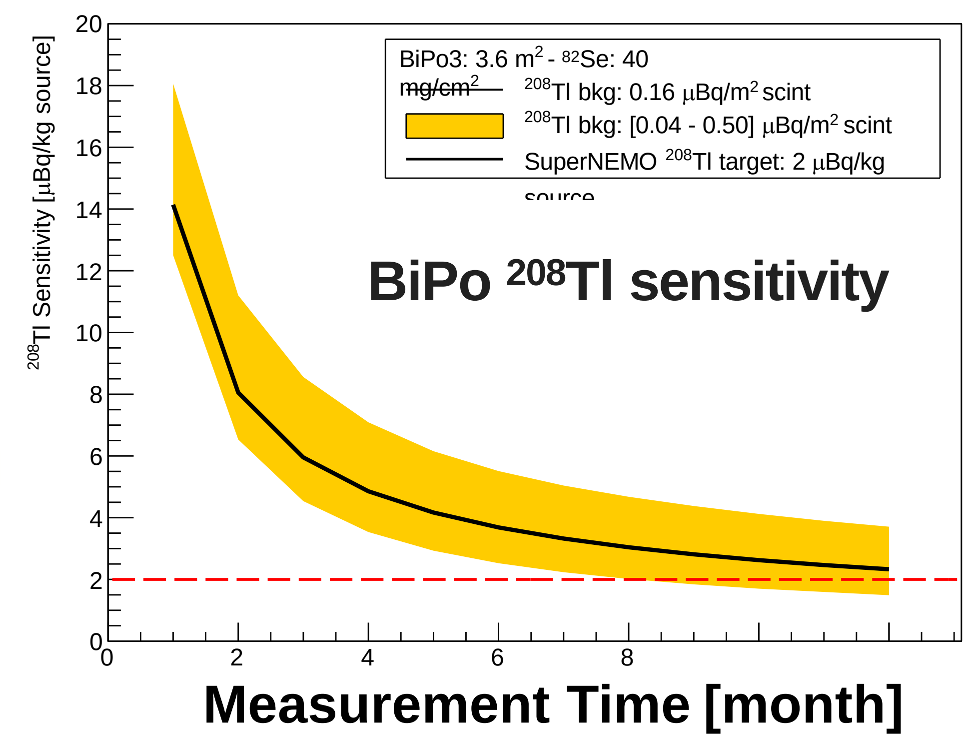
The Bi-Po 3 detector

- HPGe spectroscopy not sensitive enough to reach few μBq/Kg: BiPo-3 dedicated setup at Canfranc underground lab

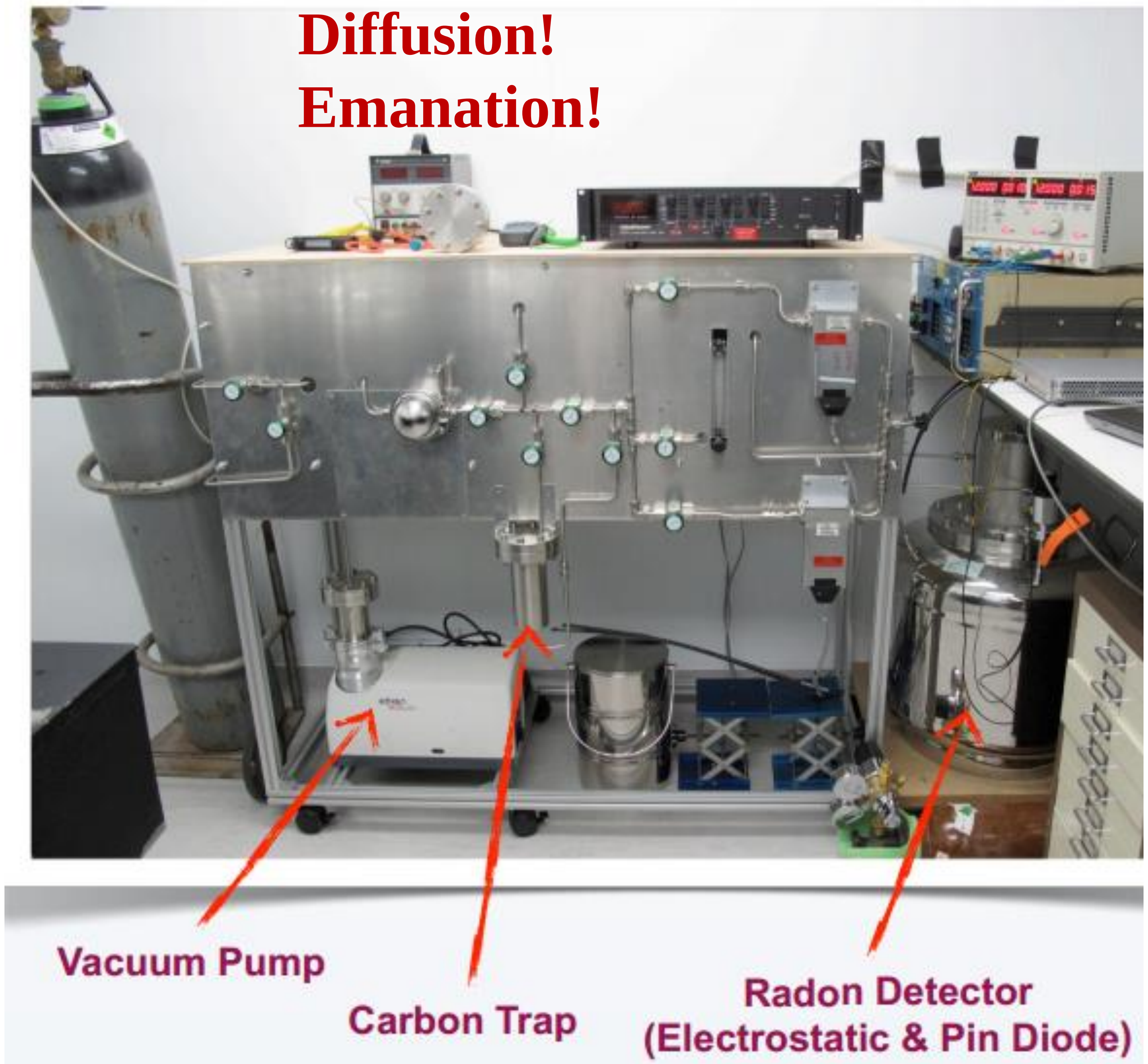


- 2 modules of 3.0x0.6 m^2 can measure up to 1.4 kg of ^{82}Se foil with thickness of 40 mg/cm^2
- ^{214}Bi and ^{208}Tl measured trough process from natural radioactivity chain
- Thin radiopure plastic scintillators coupled to lightguides and low radioactivity PTMs



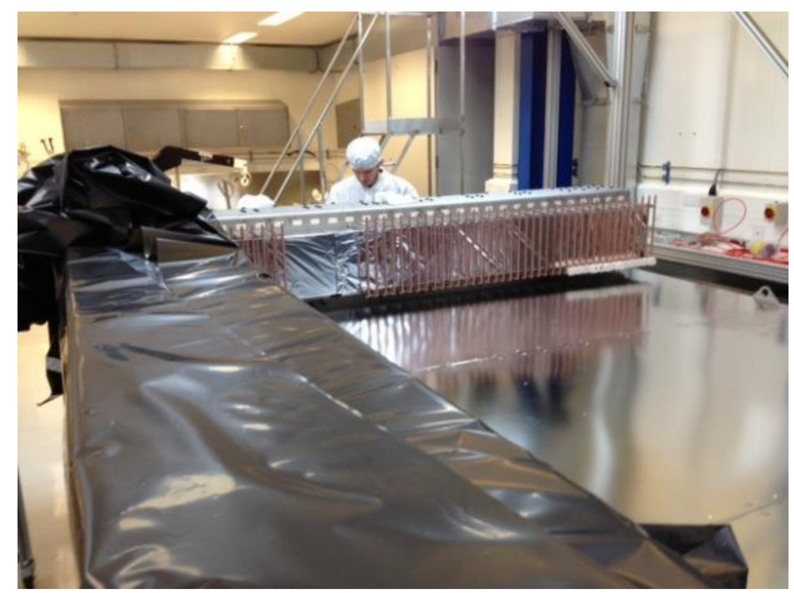


The fight against radon



Radon line to work with tracker

Radon emanation setup.

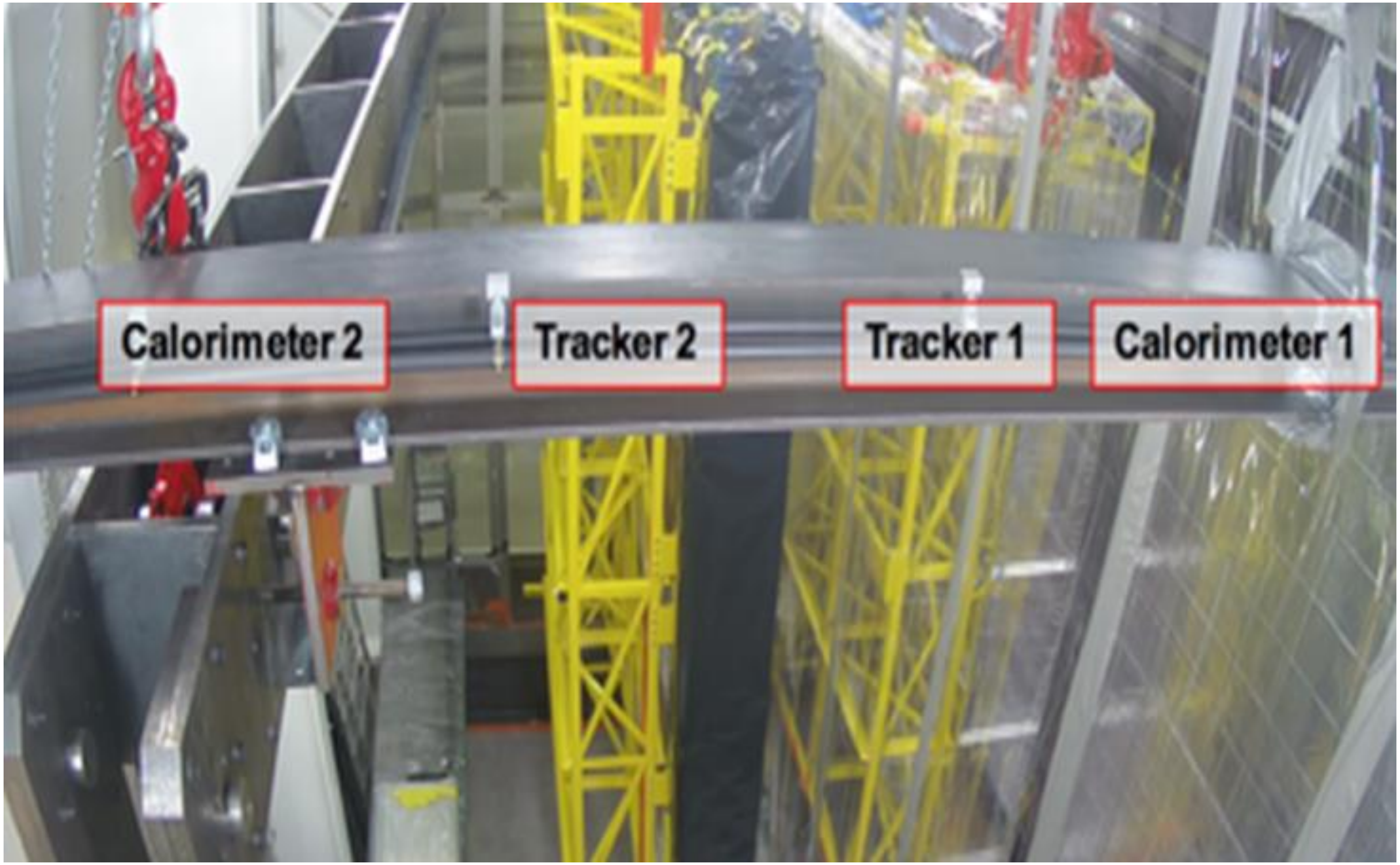


Tracker module under Rd measurement

Very time and labour consuming: 10 days spent for one basic measurement, big tanks, sealing, sealing, and sealing

SuperNEMO collaboration has a unique experience and a database on radon measurements for various materials.

The current status of the Demonstrator



SuperNEMO The demonstrator is almost completely assembled in the LSM (except for a few source foils and a calibration system). The closure and start in full configuration is planned for the spring of 2018.

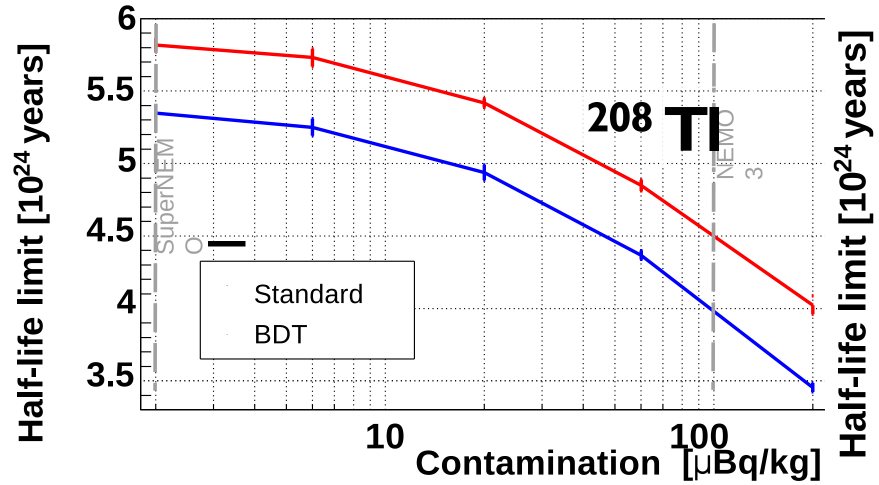
JINR contribution

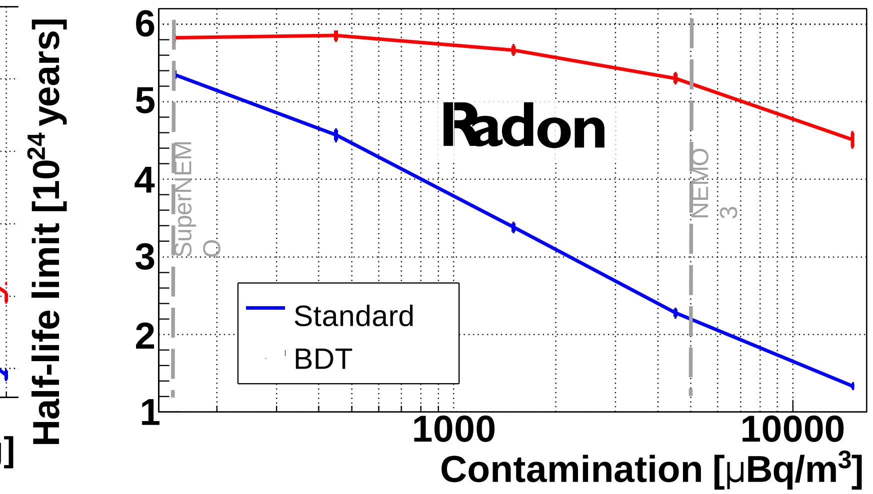
- Production of 720 plastic scintillator blocks for the Demonstrator calorimeter (in cooperation with the University of Prague).
- Manufacturing of 60 optical modules for the VETO system (scintillator + PMN 5“ R6594 HAMAMATSU).
- Acquisition of 100 PMT 8“ R5912-03 HAMAMATSU for the calorimeter.
- Purchase of 7 crates for the electronics of the calorimeter.
- Purchase 1.5 kg of enriched ^{82}Se to create sources.
- A unique ^{82}Se purification technique has been developed and implemented. A clean room has been built , and 3.5 kg of ^{82}Se has been purified, used to create the sources of the Demonstrator.
- Manufacturing of signal and HV cables for the tracker.
- Acquisition, creation and maintenance of equipment for low-background measurements: germanium, radon, neutron detectors in LSM.
- Participation in software development, simulations, and data analysis.

Clean room for ^{82}Se purification (DLNP JINR)

The SuperNEMO sensitivity

	SuperNEMO	Status
isotope	^{82}Se (or other, e.g. ^{150}Nd)	82Se
isotope mass	7 –+ 100 kg	7 kg
radon	0.15 mBq/m^3	in progress
internal contamination	$^{208}Tl \leq 2$ μBq/kg $^{214}Bi \leq 10$ μBq/kg	in progress
FWHM	8% @ 1 MeV	ok





In [2.8-3.2] MeV:

- Efficiency: 27.5%
- Total number of bkg events: 0.21
- Background index: 3 x 10^{-5} cts/(keV kg yr)

1 module

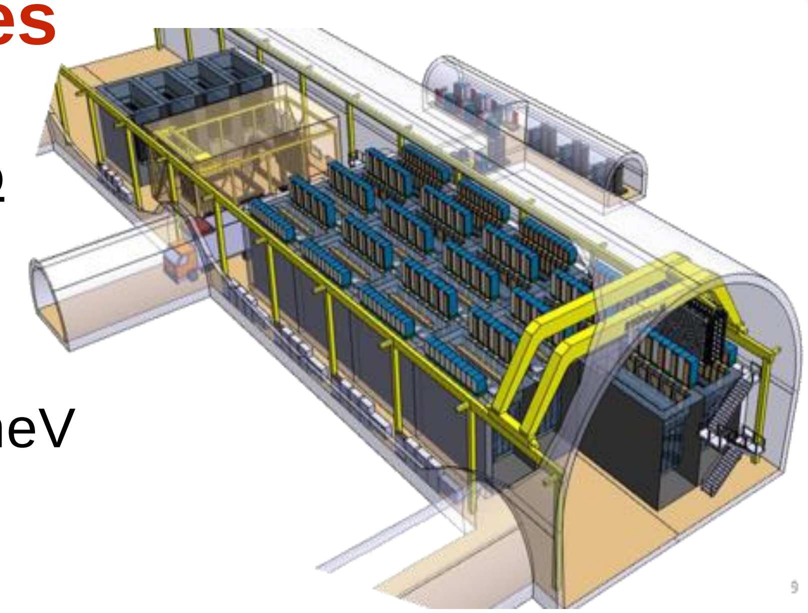
Demonstrator Module

17.5 kg.yr :

$T^0_{1/2} > 6 \times 10^{24}$ yr

m < 0.20 - 0.55 eV

20 modules



Full SuperNEMO

500 kg.yr :

$T^0_{1/2} > 10^{26}$ yr

m < 40 - 110 meV

Working schedule

- Spring 2018 - completion of assembly and launch of the Demonstrator without neutron protection.
- The summer of 2018 - the calibration of the Demonstrator, the launch of data taking in a configuration without neutron protection
- The first half of 2019 - the creation of neutron shield of the Demonstrator.
- The second half of 2019 - calibration and run of data collection in the full configuration of the Demonstrator.
- 2020-2021 - data taking, data analysis, background assessment, control of backgrounds, publication of results if required.
- During the whole period - the continuation of the R&D program on the methods of enrichment of other isotopes: ^{150}Nd, ^{96}Zr, ^{48}Ca. Improvement of the cleaning procedure for ^{82}Se. Further development of PS production technique.

Schedule proposal and resources (form №26)

List of parts and devices; Resources; Financial sources			Cost of parts (K US$), resources needs	Allocation of resources and money		
				1st year	2nd year	3rd year
Main parts and equipment	1. Materials for a calorimeter (styrene, aluminum, P-terphenyl, POPOP)		24	8	8	8
	2. Spectroscopic electronics for test stands of PS&PMTs		10	10	0	0
	3. Borated polystyrene for neutron shielding of the Demonstrator		40	30	10	0
	4. Materials&equipment for Demonstrator maintenance under JINR responsibility (2 Radon detectors, HPGe spectrometer,) and carrying out calibrations, including creation of calibration sources. Radiochemical equipment.		45	15	15	15
	Total		**119**	**63**	**33**	**23**
Resources	Norm-hours	JINR workshop	0	0	0	0
		DLNP workshop	1800	600	600	600
Financial sources	JINR budget	Budget spending	119	63	33	23
	Off-budget sources	Grants; Other sources (these funds are not currently guaranteed)	*30*	*10*	*10*	*10*

Estimated expenditures (form №29)

#	Designation for outlays	Total cost	1 year	2 year	3 year
	Direct expenses for the project				
1.	Networking	6.0K US$	2.0	2.0	2.0
2.	DLNP workshop	1500 norm-h	500	500	500
3.	JINR workshop	0	0	0	0
4.	Materials	64.0K US$	38.0	18.0	8.0
5.	Equipment	55.0K US$	25.0	15.0	15.0
6.	Collaboration fee	60.0K US$	20.0	20.0	20.0
7.	Travel expenses	60.0K US$	30.0	15.0	15.0
	Total	**245.0K US$**	**115.0K US$**	**70.0K US$**	**60.0K US$**

The SuperNEMO publications in 2016-2018

1. R. Arnold, O. Kochetov et.al., "Measurement of the double beta-decay half-life and search for the neutrinoless double beta-decay of Ca-48 with NEMO-3 detector", Phys. Rev. D93 (2016) 112008-1 – 112008-9.
2. R. Arnold, O. Kochetov et.al., "Measurement of the double beta-decay half-life and search for the neutrinoless double beta-decay of Cd-116 with the NEMO-3 detector",
3. arXiv: 1610.03226v2[hep-ex], Phys. Rev. D95 (2017) 012007-1 – 012007-12.
4. R. Arnold, O. Kochetov et.al., "Measurement of the double beta-decay half-life of Nd-150 and a search for neutrinoless double beta-decay processes with the full exposure from the NEMO-3 detector", Phys. Rev. D94 (2016) 072003.
5. S. Blot from NEMO-3&SuperNEMO Collaborations, "Investigating bb decay with NEMO-3 and SuperNEMO experiments", Journal of Physics: Conference Series 718 (2016).
6. H. Gomes from NEMO-3&SuperNEMO Collaborations, "Latest results of NEMO-3 experiment and present status of SuperNEMO", Nuclear and Particle Physics Proceedings (2016) 1765-1770.
7. P.Povinec SuperNEMO Collaboration, "SuperNEMO – a new generation of underground experiments for double beta-decay investigations", The 14th Vienna Conference on Instrumentation 15-16 Feb., 2016.
8. A.S. Barabash, O. Kochetov et. al.,"Calorimeter development for the SuperNEMO double beta-decay experiment", NIM A868 (2017) 98-108.
9. R. Arnold, O. Kochetov et al. from NEMO-3 Collaboration, "Search for neutrinoless quadrupole-b decay of the Nd-150 with the NEMO-3 detector" Phys. Rev. Lett. 119 (2017) 041801.
10. A.S. Barabash, O. Kochetov et al.,"The BiPo-3 detector for the measurement of ultra low natural radioactivities of thin materials" JINST 12 (2017) P06002.
11. P. Loazia, O.Kochetov et al., "The BiPo-3 detector", Applied Radiation and Isotopes 123 (2017) 54-59.

Human resources

N	Person	Status	Subjects	FTE
1	O.I Kochetov	Project Leader	calorimeter	0.9
2	Yu.A.Shitov	Deputy Leader	software, data analysis	0.5
3	V.B.Brudanin	Participant	calorimeter	
4	V.G.Egorov	Participant	calorimeter, data analysis	
5	3. A.A. Smolnikov	Participant	calorimeter, data analysis	0.3
6	4. A.A. Klimenko	Participant	software, data analysis	0.35
7	5. V.I. Tretyak	Participant	software, data analysis	0.9
8	7. D.V. Karaivanov	Participant	radiochemistry, Se-82 purification, sources	0.35
9	8. A.V. Rahimov	Participant	radiochemistry, Se-82 purification, sources	0.35
10	9. D.V. Filosofov	Participant	radiochemistry, Se-82 purification, sources	0.3
11	10. N.A. Mirzaev	Participant	radiochemistry, Se-82 purification, sources	0.4
12	11. Yu.V. Yushkevich	Participant	electromagnetic mass separation, calibration	0.25
13	12. A.V. Salamatin	Participant	electronics,cables	0.3
14	13. V.V. Timkin	Participant	calorimeter, VETO system and cables	0.9
15	14. I.B. Nemchenok	Participant	PS production, calorimeter and VETO system	0.2
16	15. I.I. Kamnev	Participant	PS production, calorimeter and VETO system	0.3
17	16. O.I. Vagina	Participant	PS production, calorimeter and VETO system	0.3
In total				**5.2**

Conclusion

- The NEMO/SuperNEMO experiments are based on a unique track-calorimetric method for the investigation of ββ-processes, which has been successfully developed for decades. It allows to reconstruct the complete pattern of ββ-decay and to test its mechanism.
- R&D project SuperNEMO have been running since 2006, and the Demonstrator (the first module) of the SuperNEMO detector was developed as a result. Its main task is to validate the technique of background suppression, as well as physical measurements. At 7 kg ^{82}Se in 2.5 years, it is planned to achieve sensitivity to the effective neutrino mass at level of 0.20 - 0.55 eV.
- The demonstrator is almost completely assembled in the LSM, its start is planned for the spring of 2018.
- The creation of the Demonstrator became possible with the decisive contribution of JINR to a number of working tasks: a calorimeter, a tracker, sources, etc.
- At this stage of the project (the phase of data taking) the required costs are small with guaranteed benefits - participation in coming publications.
- The success of the Demonstrator opens the opportunity for the full SuperNEMO detector: measurement of 100 kg of the source in 20 modules with a sensitivity of 40-110 meV to the effective Majorana neutrino mass.

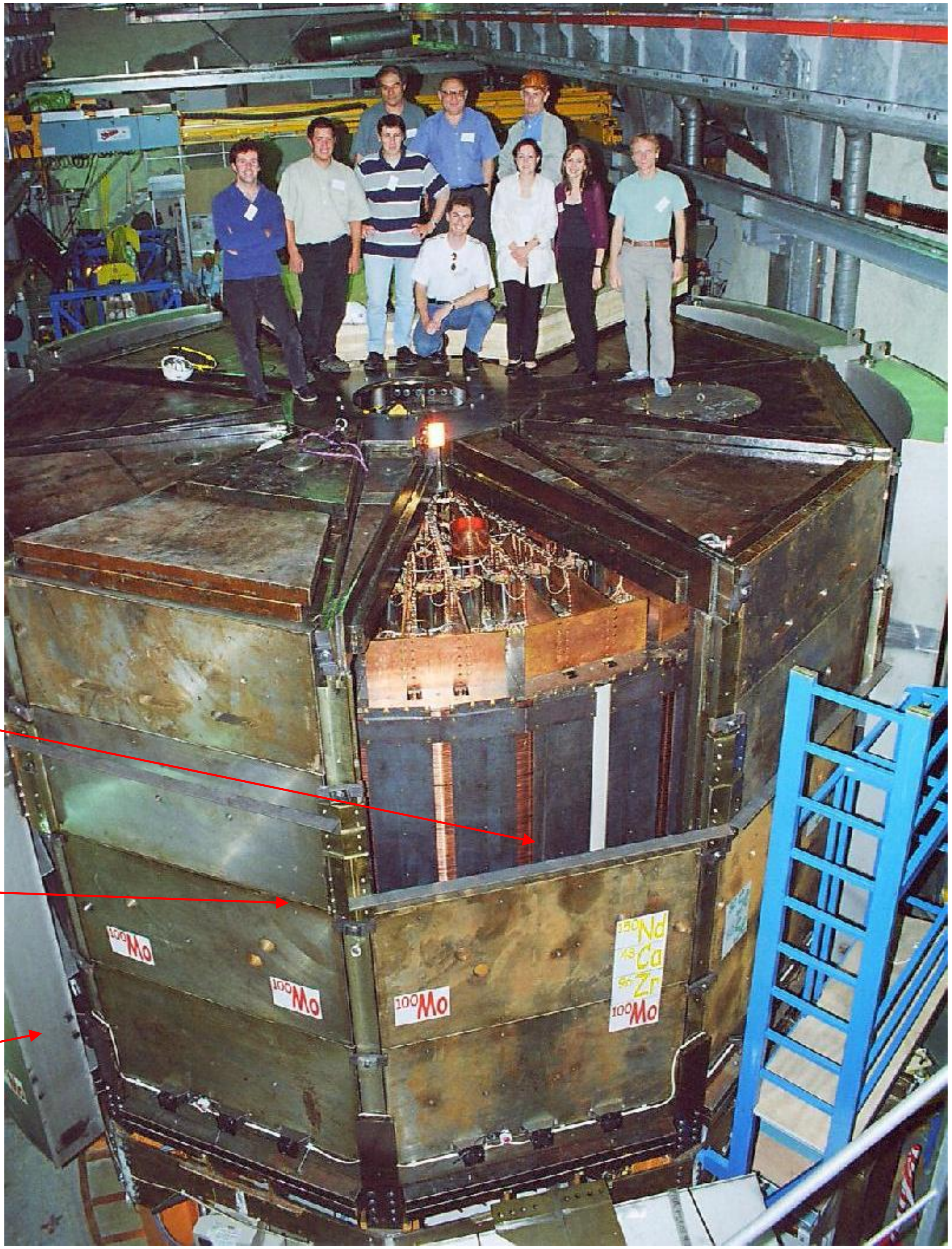
Backup slides

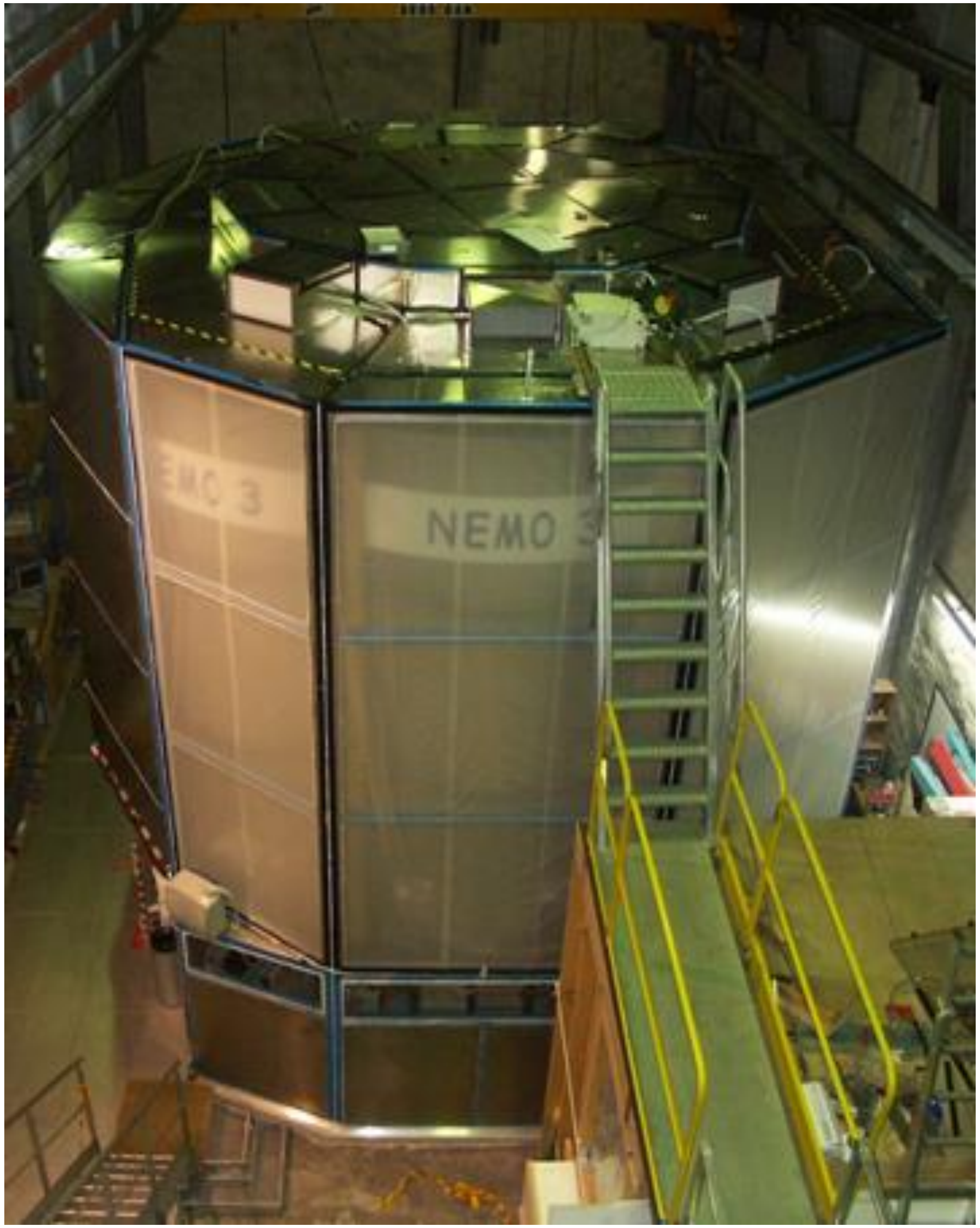
NEMO-3 shielding and anti-radon tent

coil

iron shield

Water + B tank





NEMO3 sector

Cathodic rings
Wire chamber

PMTs

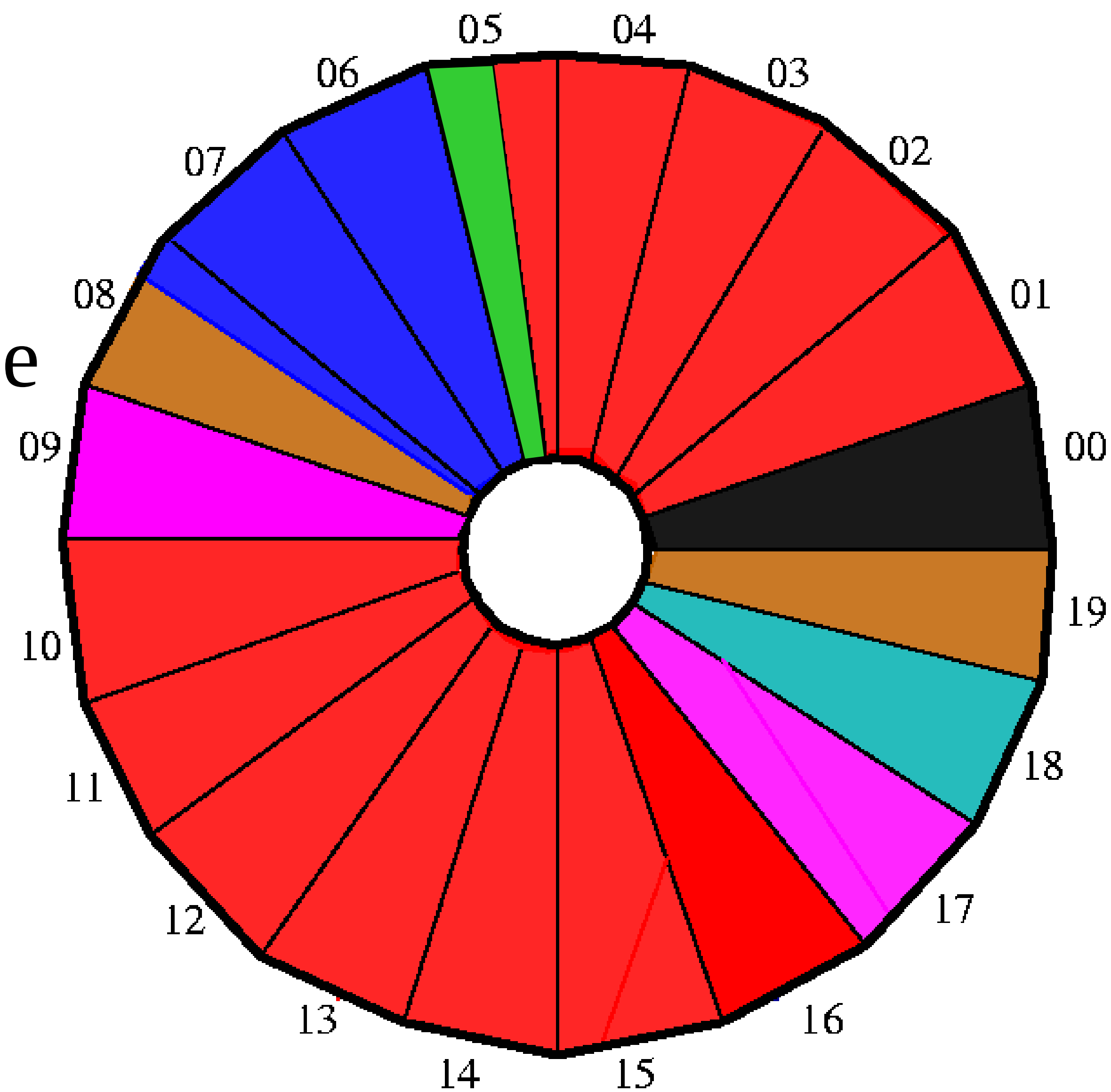
Calibration tube

scintillators

ββ isotope foils

Camembert of ββ-sources in NEMO-3 detector

France



Italy

Camembert

^{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

NEMO-3: final results for 2β2ν и 2β0ν modes

Table 1: 2β2ν-results obtained in the NEMO-3

Isotope	Mass [g] β	Qββ [keV]	Sig/Bkg	T(1/2) [years]
Mo-100	**6914**	**3034**	**76**	**$7.16 \pm 0.01(\text{stat}) \pm 0.54(\text{syst}) \times 10^{18}$**
Se-82	**932**	**2995**	**4**	**$10.07 \pm 0.14(\text{stat}) \pm 0.54(\text{syst}) \times 10^{19}$**
Te-130	**454**	**2529**	**0.25**	**$7.0 \pm 0.9 \pm 1.1(\text{syst})\ 10^{20}$**
Cd-116	**405**	**2805**	**10.3**	**$2.74 \pm 0.04(\text{stat}) \pm 0.18(\text{syst}) \times 10^{19}$**
Nd-150	**37.0**	**3368**	**2.8**	**$9.27 \pm 0.22(\text{stat}) \pm 0.60(\text{syst}) \times 10^{18}$**
Zr-96	**9.43**	**3350**	**1.0**	**$2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst}) \times 10^{19}$**
Ca-48	**6.99**	**4274**	**6.99**	**$6.4 \pm 0.7\ (\text{stat}) \pm 1.2\ (\text{syst}) \times 10^{19}$**

Table 2: 2β0ν-limits obtained in the NEMO-3

Isotope	T(1/2) [years]	<mββ> eV
Mo-100	1.1×10^{24}	0.3–0.6
Se-82	2.5×10^{23}	1.2 – 3.0
Te-130	1.3×10^{23}	1.4 – 3.5
Cd-116	1.0×10^{23}	1.4 − 2.5
Nd-150	2.0×10^{22}	1.6 − 5.3
Zr-96	9.2×10^{21}	7.2 – 20
Ca-48	2.0×10^{22}	6.0 − 26

Calorimetry vs. tracko-calo

Calorimetric | Tracko-calo

Experimental advantages

Calorimetric:

- **Larger mass**
- **Better resolution**
- **high (~ 100%) efficiency**

Tracko-calo:

- **Real ββ-observation.**
- **Any ββ-source can be measured**
- **Potentially zero-background exp.**
- **Test of different ββ0ν mechanisms in the case of observation**

Experimental drawbacks

Calorimetric:

We don’t see electrons, just energy released - no absolute proof, that we see ββ0ν-peak and not something else (γ-line)!

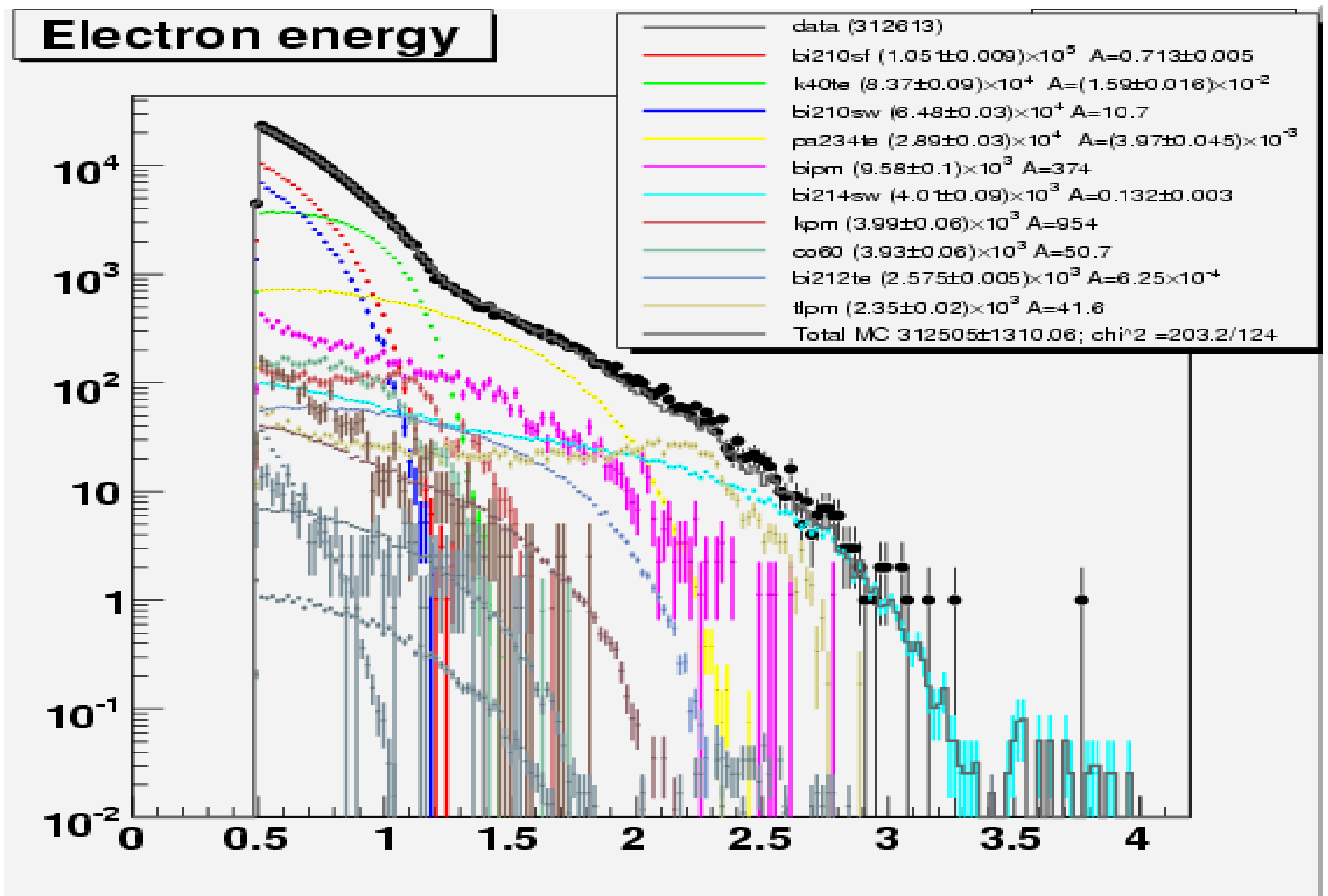
Tracko-calo:

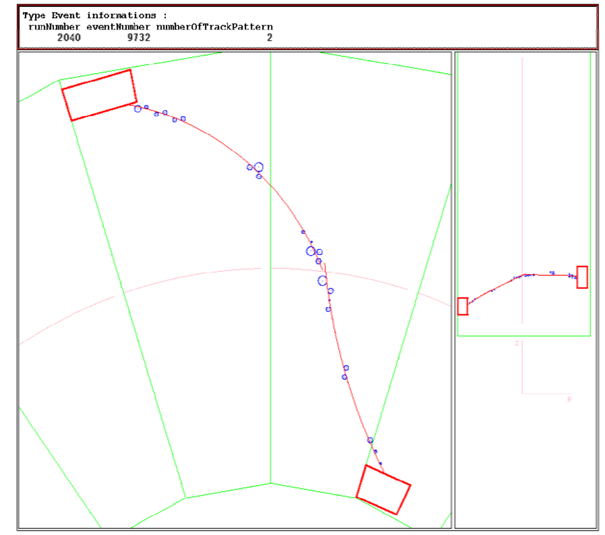
- **difficult to accept large mass**
- **smaller efficiency**
- **worth resolution**

NEMO-3 background

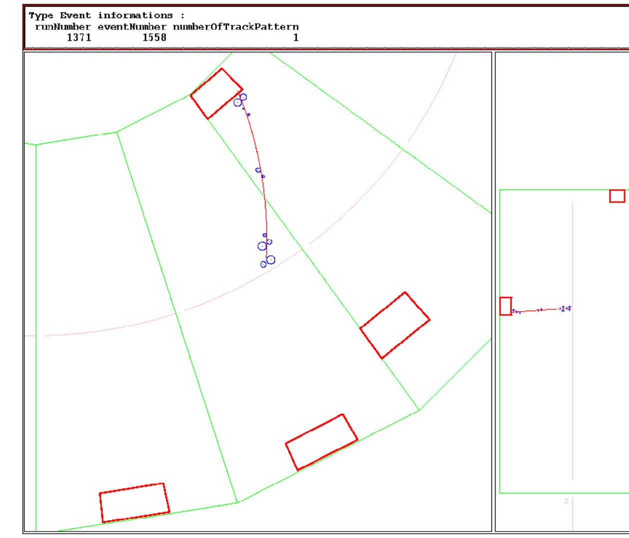
External events rejection by
TOF – time of flight method

Single electron channel

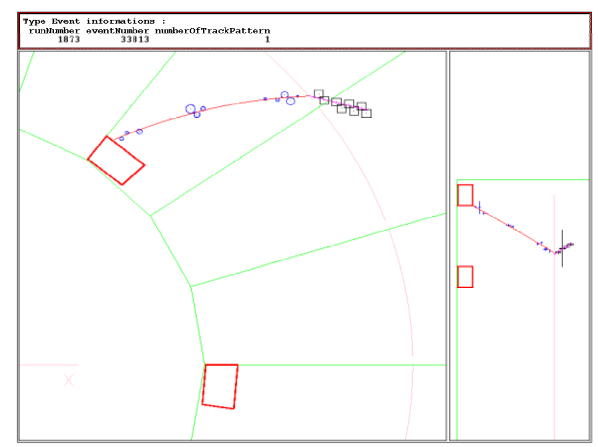




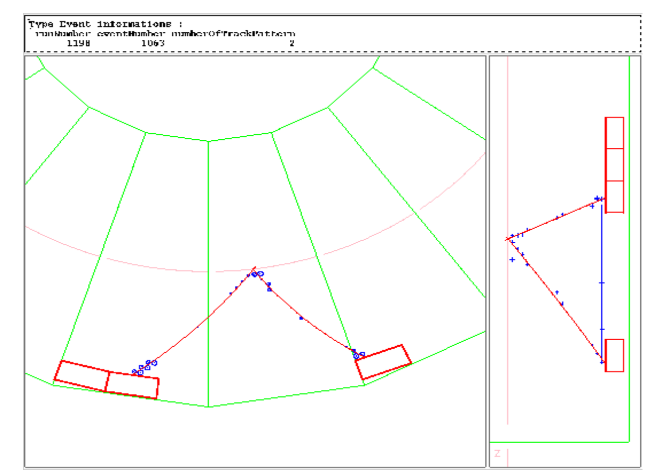
$2e^-$ event



$e^-N\gamma$ event to measure ^{208}Tl



β-α-delayed event
$^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$



$e^+ - e^-$ pair event
B rejection

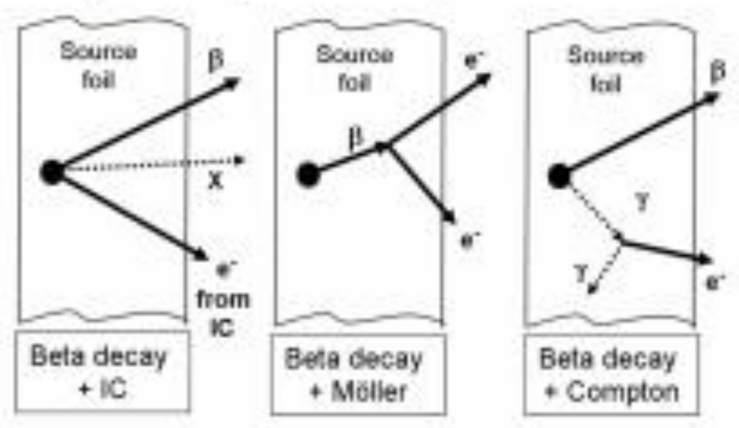
Unprecedented understanding, self-measuring, control, and rejection of all background components

The SuperNEMO backgrounds

- Internal backgrounds

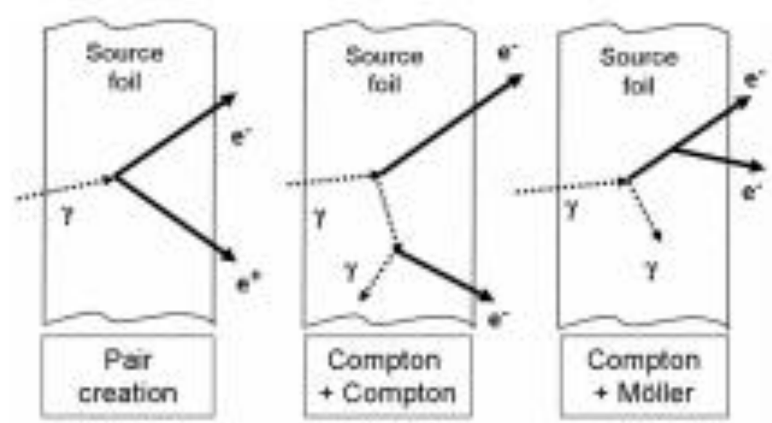
  $2\nu\beta\beta$ tail and radio-impurities inside the source foil

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



- External backgrounds

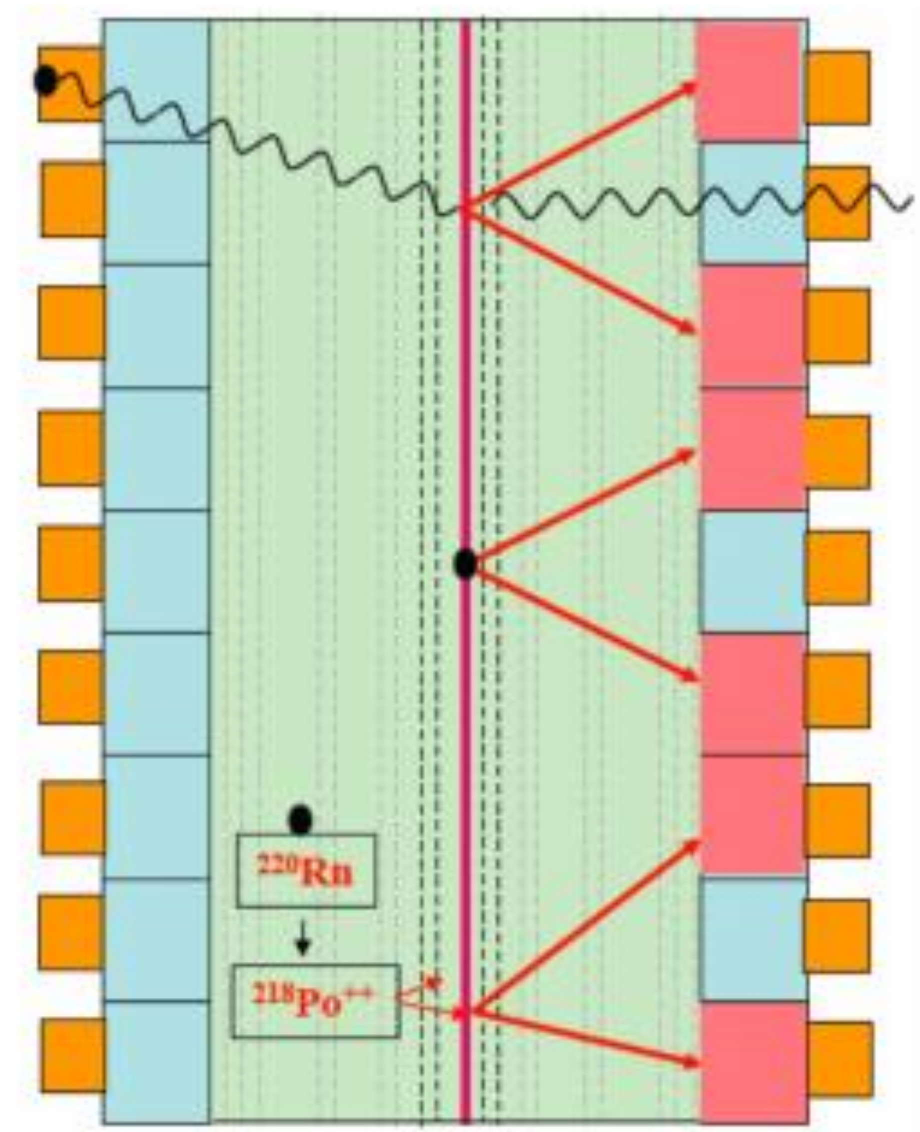
  Radio-impurities of the detector



- Radon inside the tracking detector

  Deposits on the wire near the $\beta\beta$ foil

  Deposits on the surface of the $\beta\beta$ foil



Backgrounds are measured through different background channels using event topologies

^{82}Se enrichment

ECP (Electro-Chemical Plant, Svetlana)
Zelenogorsk (Siberia)