Plans for SuperNEMO

A next generation experiment
to search
for neutrino-less double beta decay

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On behalf of the NEMO Collaboration

The ANDES Laboratory
First International Workshop
for the Design of the
ANDES Underground Laboratory
Centro Atómico Constituyentes
Buenos Aires, Argentina
11-14 April 2011

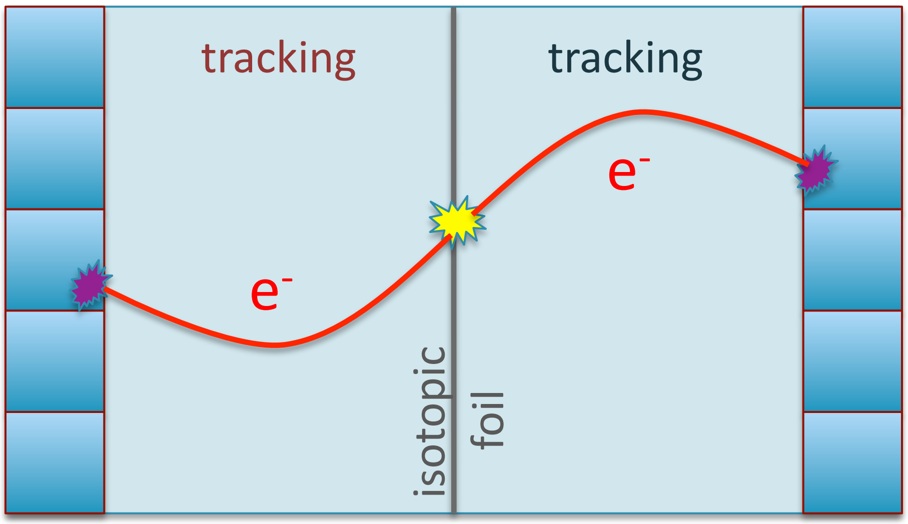
Outline:

- NEMO-3 → SuperNEMO
- R&D program highlights
- Outlook

SuperNEMO: use NEMO-3 principles

NEMO-3 well-proven principles:

Topology and kinematics



Plastic scintillator calorimeter

Plastic scintillator calorimeter

+

Radio-pure materials and a lot of shielding

Need good CR shielding like Fréjus Underground Laboratory : 4800 m.w.e.

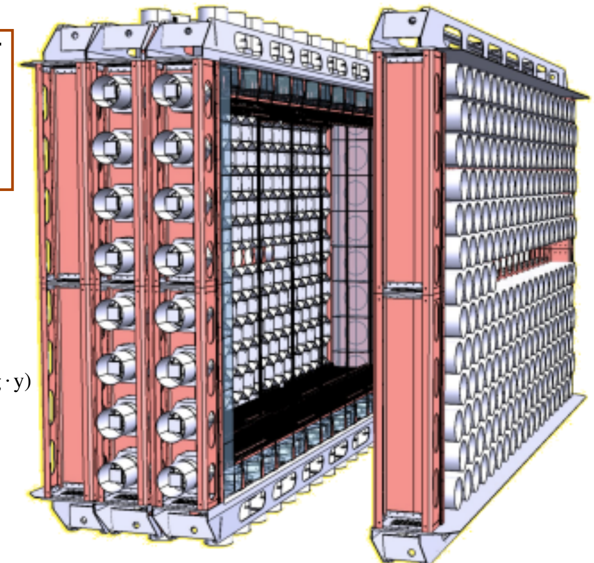
SuperNEMO R&D program:

- Isotope selection
  - ^{82}Se
  - R&D on ^{48}Ca and ^{150}Nd
- Calorimeter improvements
  - Goal: 7-8%/sqrt(E)
  - Larger blocks and PMTs
  - Radio-pure and uniform
- Tracking optimization
  - Cell size
  - Cell distribution
- Radiopurity improvements
  - Isotopic foil
  - Screening for radiopurity
  - Radon-monitoring concentration line
- Calibration system upgrades
  - ^{207}Bi
  - Light-injection
  - Embedded alpha sources

NEMO-3 → SuperNEMO

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times 10^{26}\,y}{n_\sigma}\left(\frac{\varepsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta E}}$$

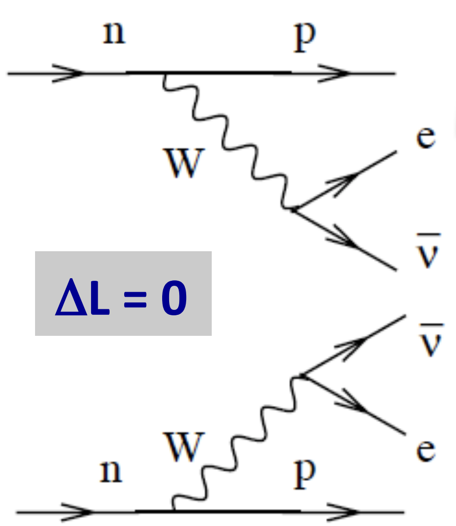
n_σ – number of std. dev. for a given C.L.
a – isotopic abundance
ε – detection efficiency
W – molecular weight of the source
M – total mass of the source (kg)
t – time of data collection (y)
b – background rate in counts $(\mathrm{keV\cdot kg\cdot y})$
ΔE – energy resolution (keV)



NEMO-3	R&D since 2005	SuperNEMO
^{100}Mo	isotope	^{82}Se (maybe also ^{150}Nd or ^{48}Ca)
7 kg	mass	**100 kg**
A(^{208}Tl) < 20 μBq/kg A(^{214}Bi) < 300 μBq/kg Rn ~ 5-6 mBq/m^3	Radio-purity of the foil Radon in the tracker	A(^{208}Tl) < 2 μBq/kg A(^{214}Bi) < 10 μBq/kg Rn < 0.1 mBq/m^3
18%	efficiency	30%
8% FWHM @ 3 MeV	Energy resolution	4% FWHM @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 1.4 \times 10^{24}$ y **$\langle m_n \rangle < 390 – 810$ meV**	sensitivity	**$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y** **$\langle m_n \rangle < 40 – 140$ meV**
1 module	modularity	>20 modules (new lab)

Neutrino questions and $0\nu\beta\beta$

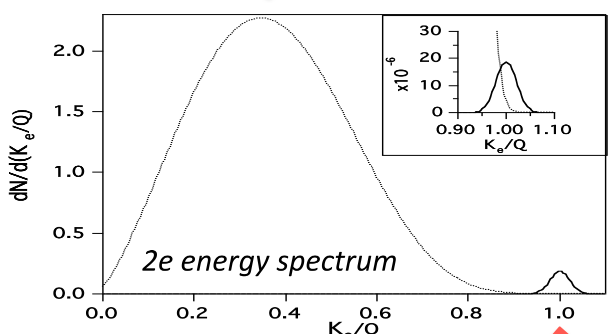
- ✓ What is the absolute mass scale?
- ✓ What is the mass ordering (“mass hierarchy”)?
- ❑ How strong is the subdominant mixing (angle θ_{13} in the PMNS matrix) ?
- ❑ Do neutrinos violate CP symmetry (angle δ in the PMNS matrix)?
- ✓ Are neutrinos Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu \equiv \bar{\nu}$) particles?
- ❑ Are there sterile neutrinos?

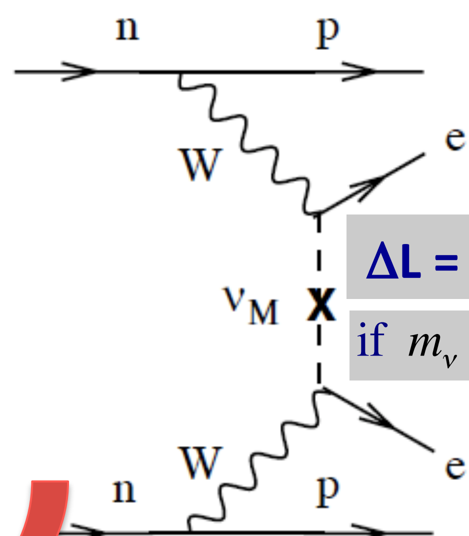


ΔL = 0

$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}$

$(2\nu\beta\beta)$





ΔL = 2

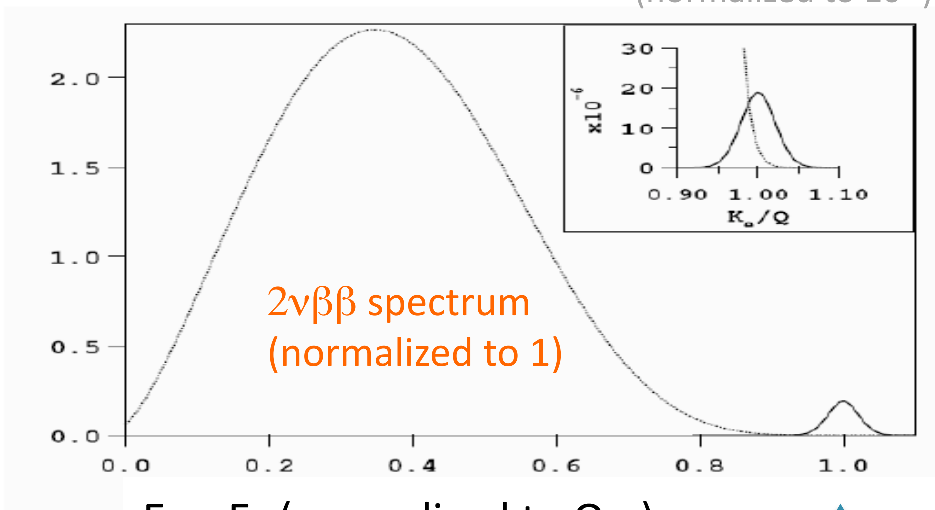
if $m_\nu \neq 0$

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

$(0\nu\beta\beta)$

Choice of an isotope

$0\nu\beta\beta$ spectrum
(5% FWHM)
(normalized to 10^{-6})



$2\nu\beta\beta$ spectrum
(normalized to 1)

$E_1 + E_2$ (normalized to $Q_{\beta\beta}$)

$0\nu\beta\beta$ spectrum
(5% FWHM)
(normalized to 10^{-2})

from S. Elliott and P. Vogel

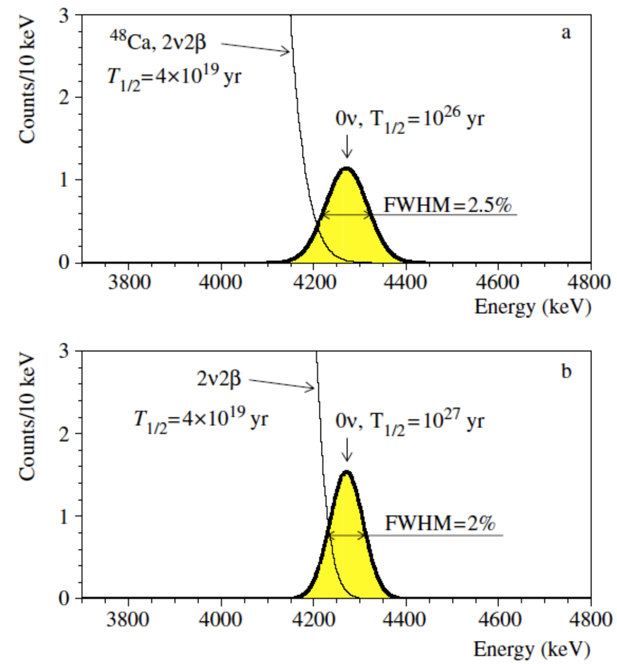


Figure 21. A demonstration of the impact of energy resolution of $|Q_{\beta\beta}|$ on the interference from $2\nu\beta\beta$-decay events.

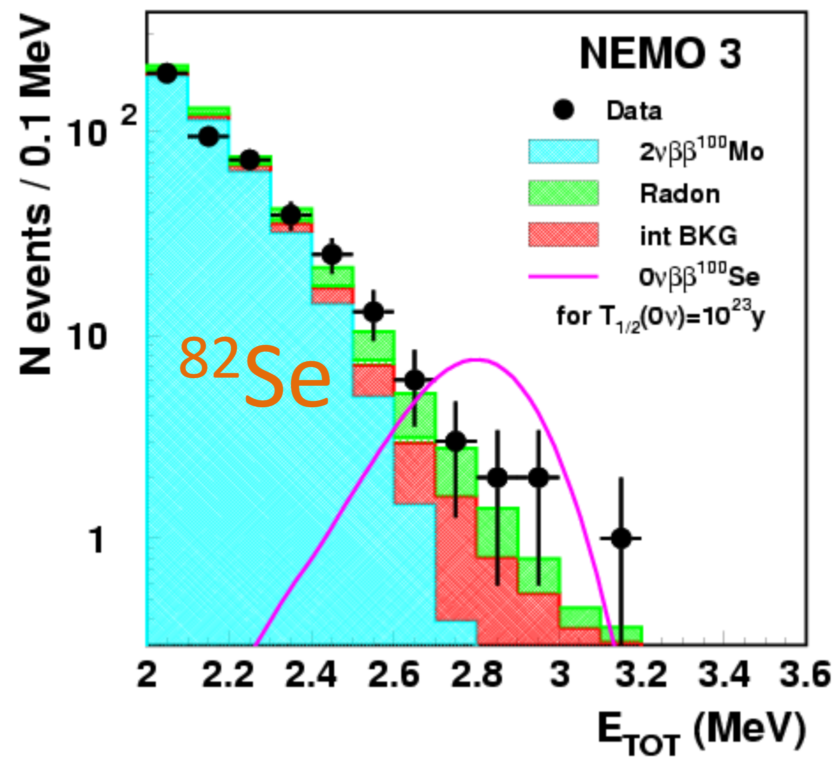
F. T. Avignone, G. S. King and Yu. G. Zdesenko,
``Next generation double-beta decay experiments: Metrics for their evaluation,'' New J. Phys. 7, 6 (2005).

Choice of ^{82}Se

NEMO-3

	$Q_{\beta\beta}$ (MeV)	Natural abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

(11) $\beta\beta$ emiters with $Q_{\beta\beta}$ > 2 MeV



$T_{1/2}$ ($0\nu\beta\beta$) > 3.2×10^{23} y @ 90% C.L.

$\langle m_\nu \rangle$ < 0.9 – 2.5 eV

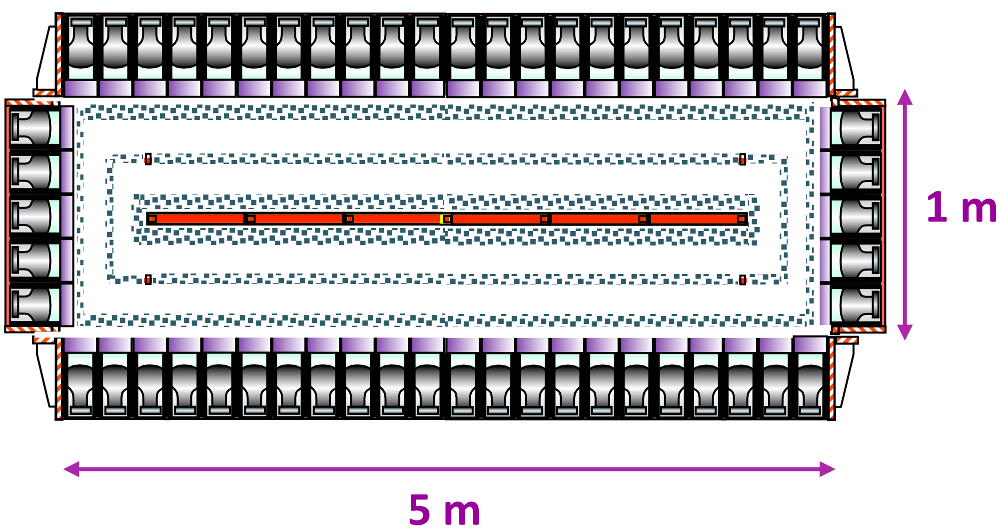
Phase 1+2 exposure: 4.51y*0.932 kg = **4.20 kg*y**

Borrowed from:
F. T. Avignone, S. R. Elliott and J. Engel,
``Double Beta Decay, Majorana Neutrinos, and Neutrino Mass,''
Rev.\ Mod.\ Phys.\ {\bf 80}, 481 (2008) [arXiv:0708.1033 [nucl-ex]].

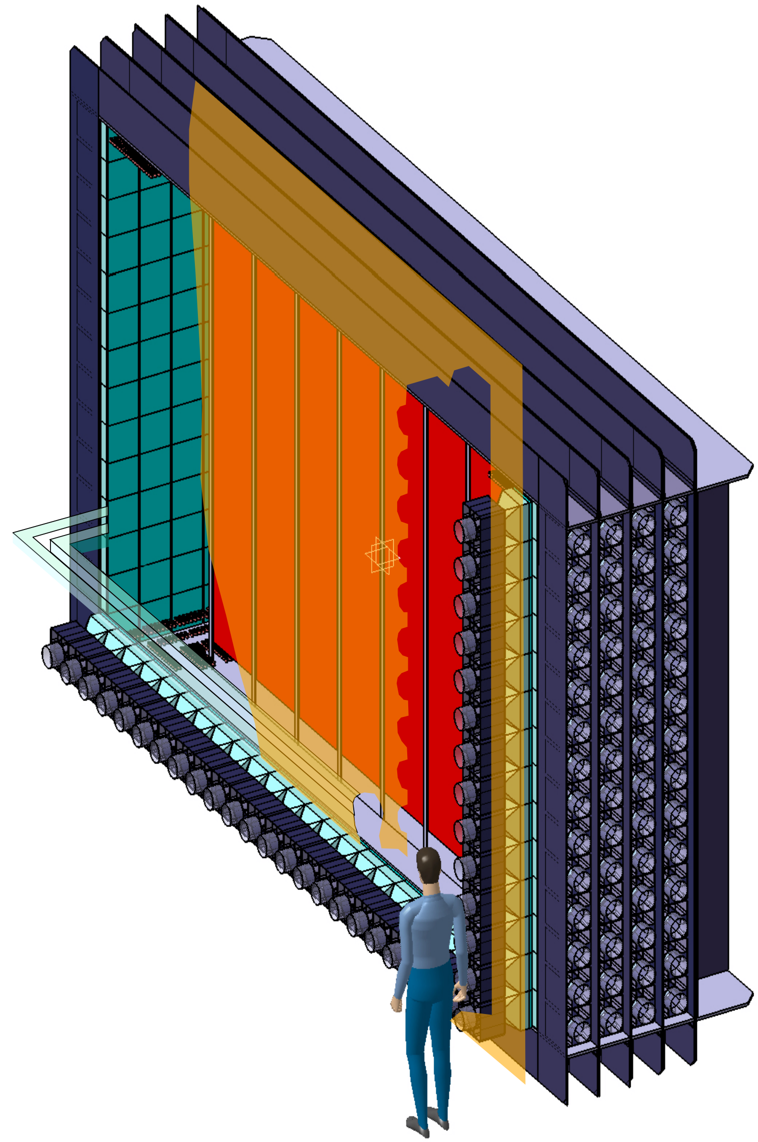
SuperNEMO - conceptually

20 modules for 100 kg

Source: ~ 5kg (4 0 mg/cm², 12m²)
Tracking: ~2,100 drift cells).
Calorimeter: ~600 blocks

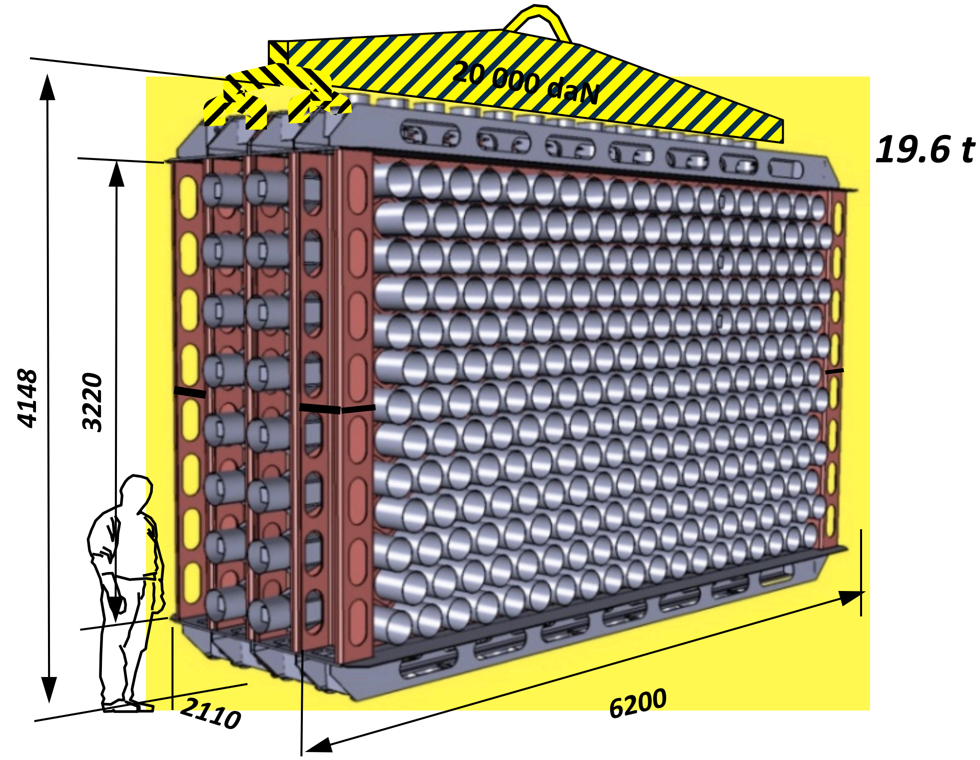


Top view

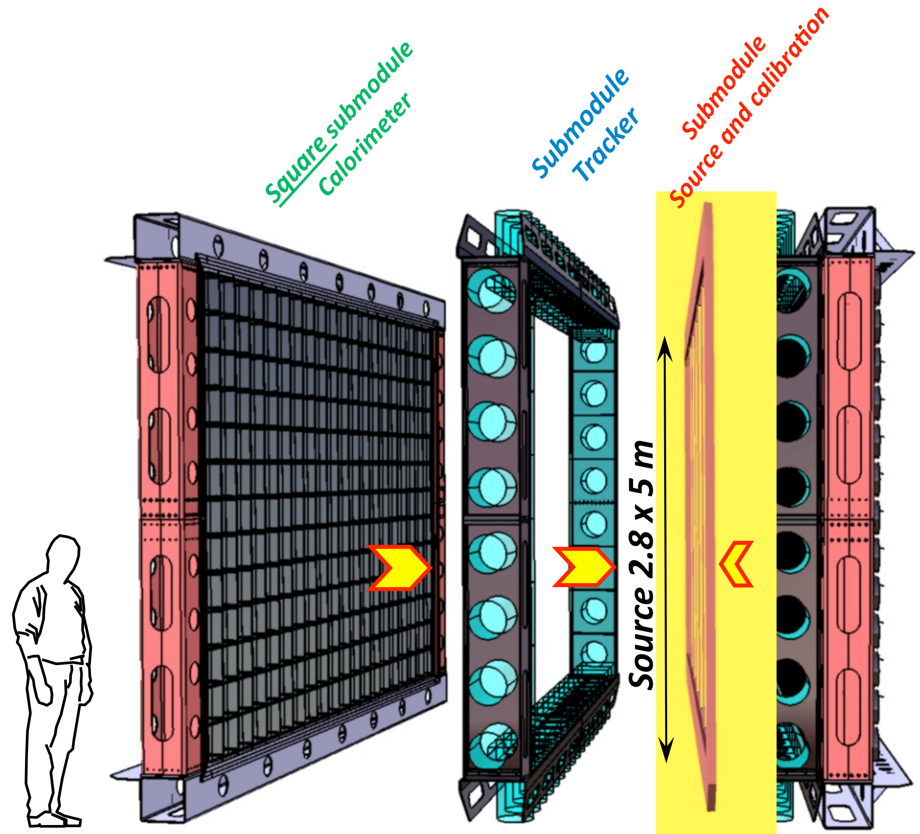


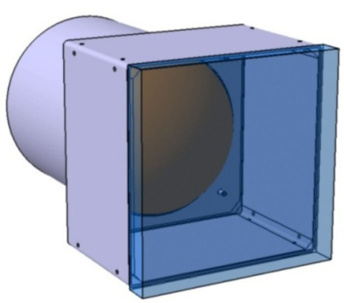
SuperNEMO Demonstrator module

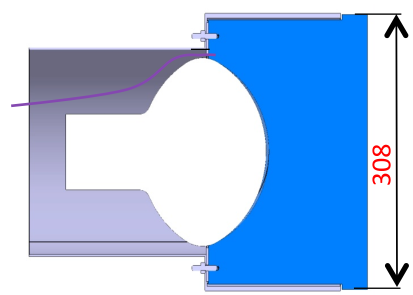
(to be built in the *existing* LSM)



Source Se: 6.3kg

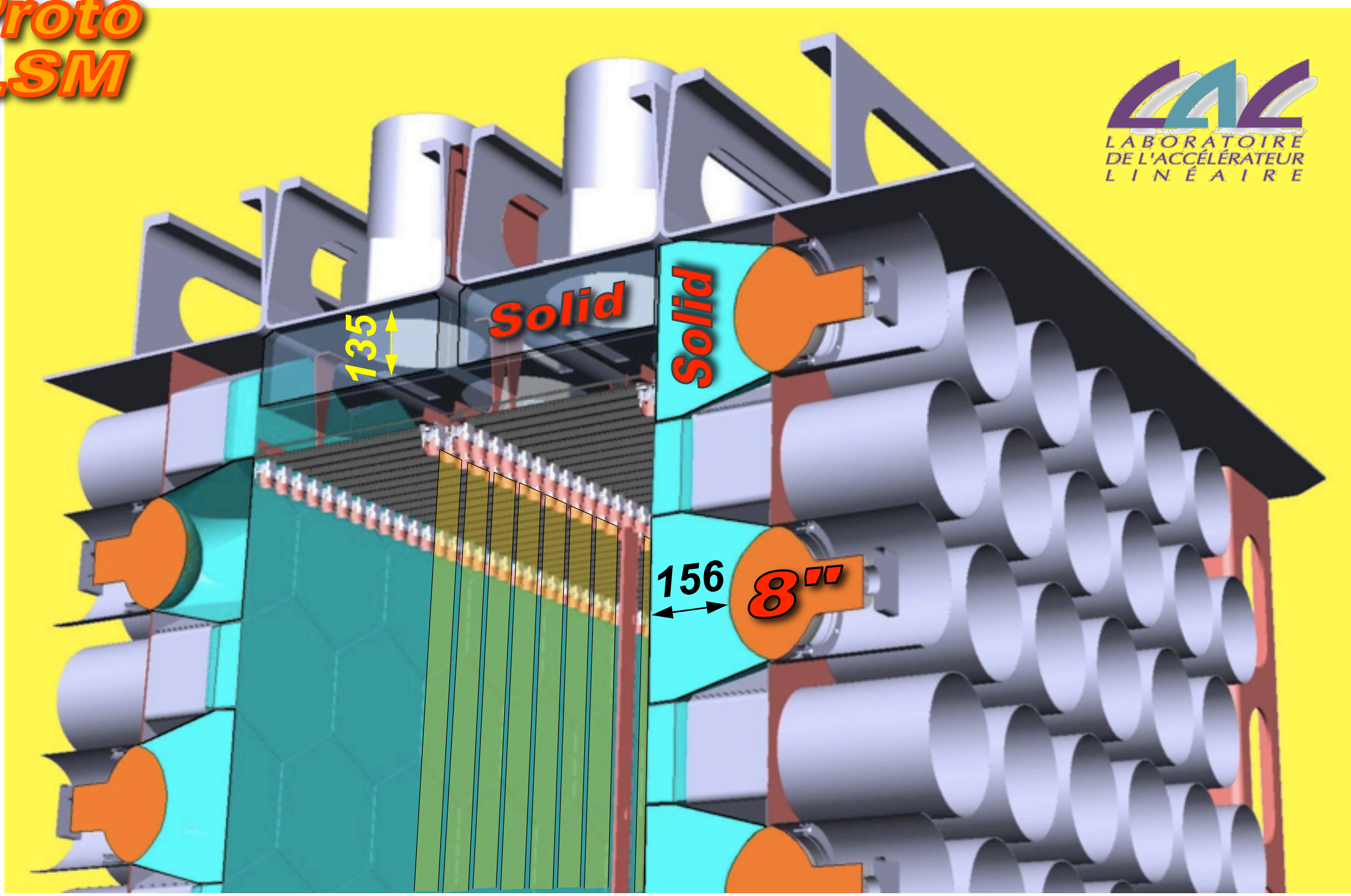




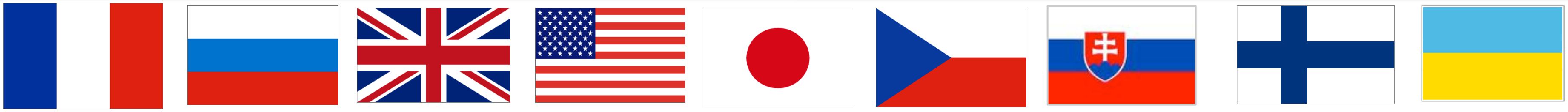


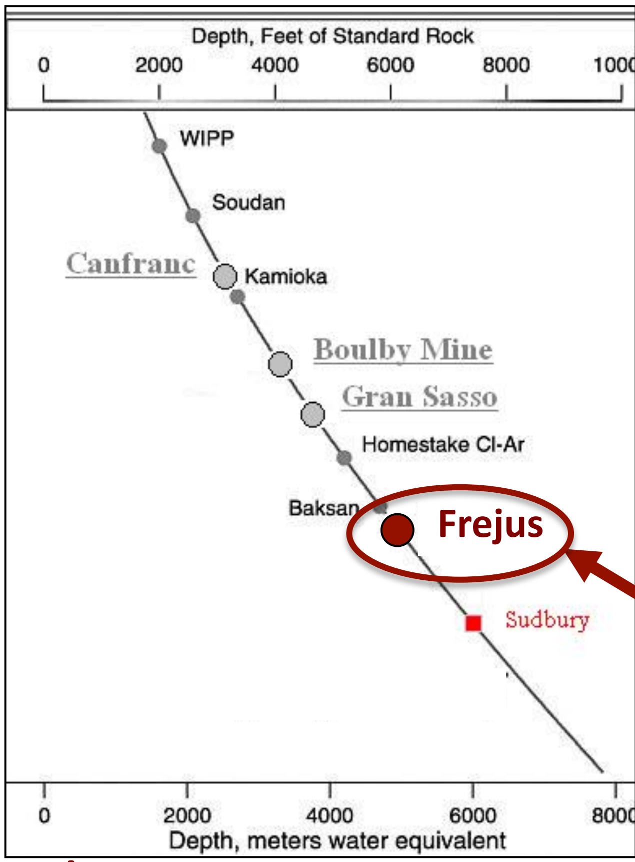
« Calorimeter square design »

Proto LSM


Solid
Solid
135
156
8"
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Laboratoire Souterrain de Modane
(Frejus tunnel)





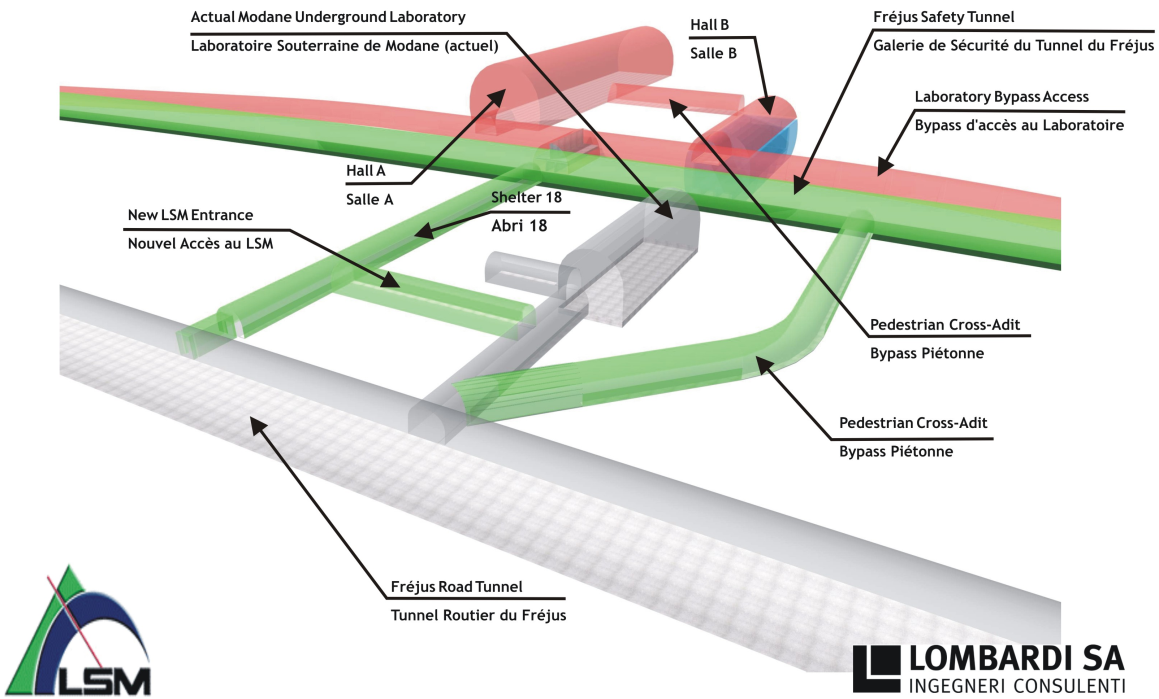
NEMO Collaboration

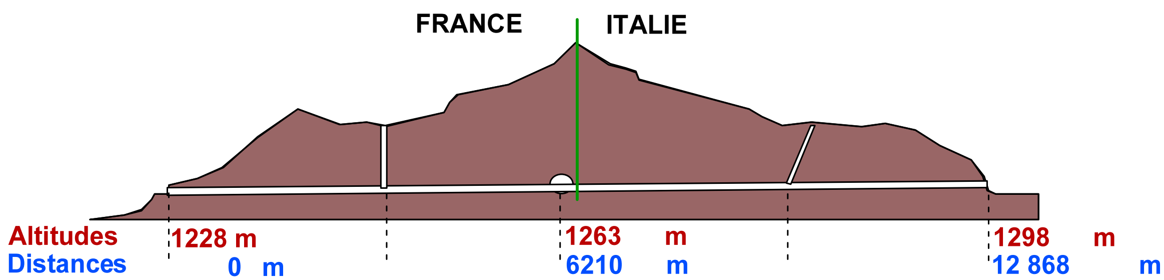
LAL (Orsay), IPHC (Strasbourg), INL (Idaho Falls), ITEP (Moscow), JINR (Dubna), LPC (Caen), CENBG (Bordeaux), UCL (London), U. of Manchester, Tokushima U., Cornelius U. (Bratislava), Osaka, IEAP & Charles U. (Prague), UAB (Barcelona), Saga U., Imperial College (London), Mount Holyoke Coll. (South Hadley), Fukui U., INR (Kiev), CPPM (Marseilles), U. Warwick, Texas (Austin)

LSM Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

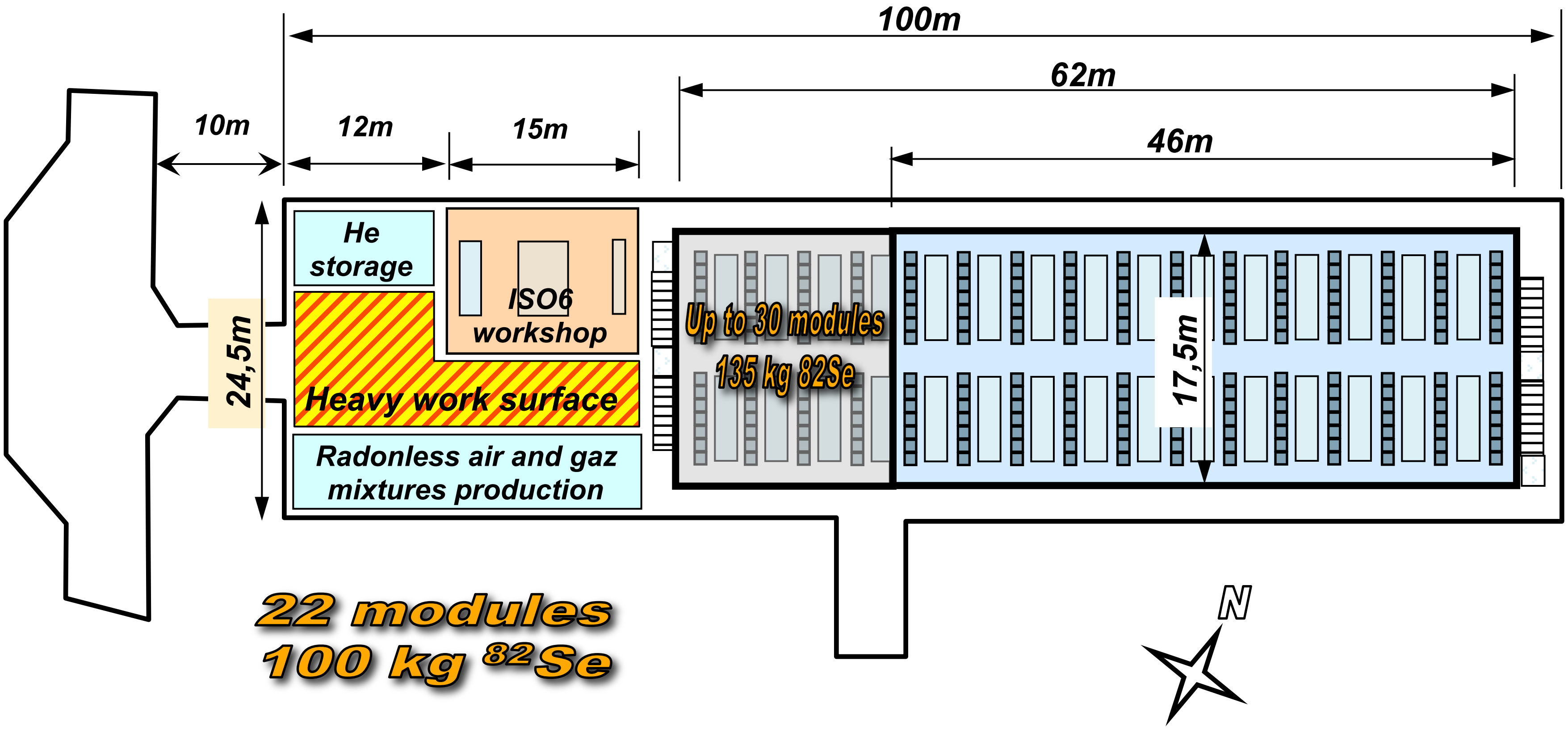
MODANE UNDERGROUND LABORATORY 60'000 m^3 EXTENSION

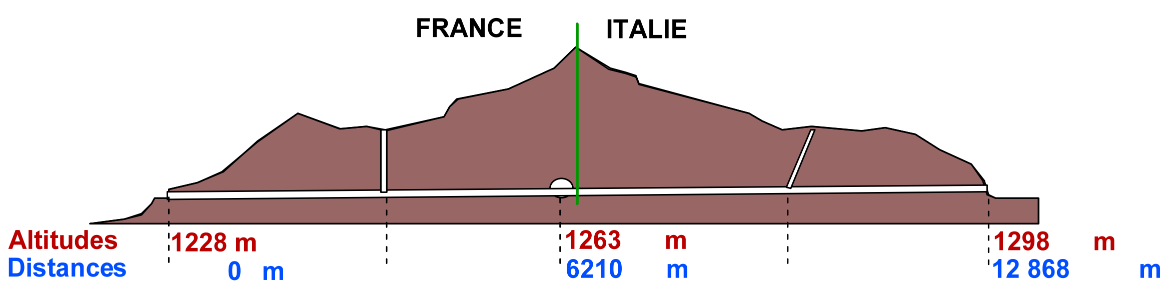
LABORATOIRE SOUTERRAINE DE MODANE AGRANDISSEMENT 60'000 m^3



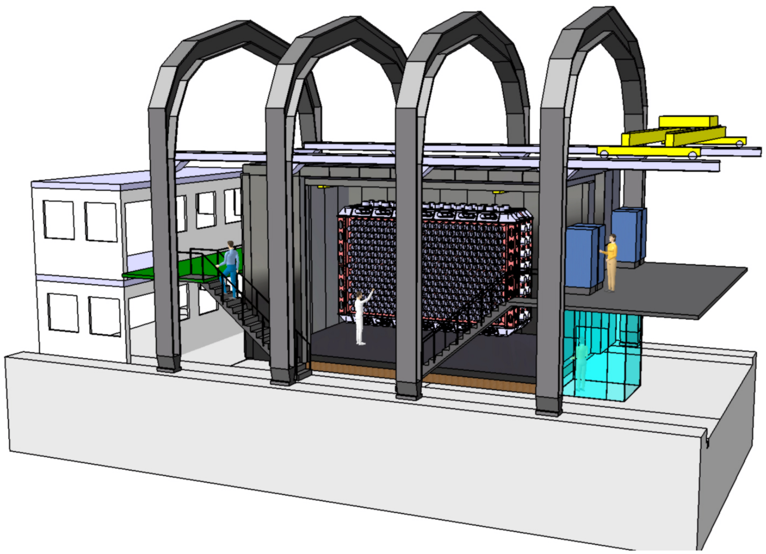


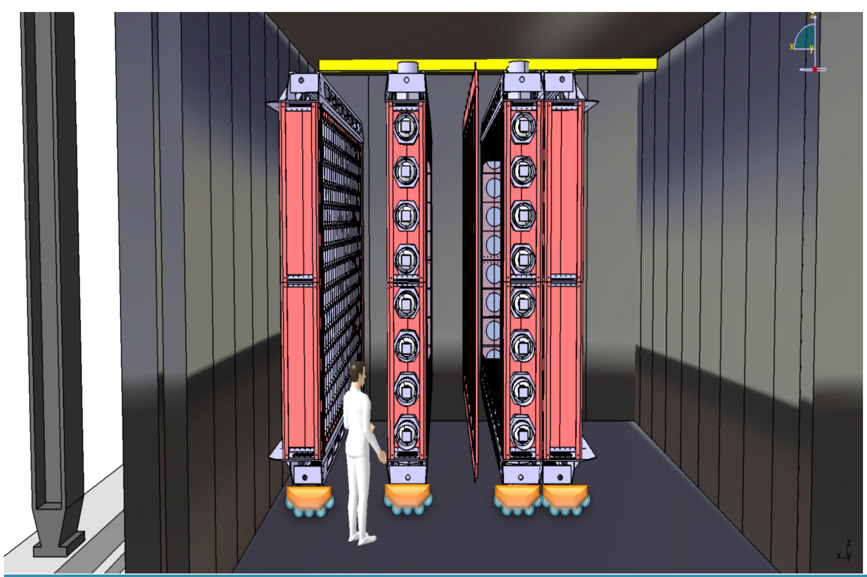
Future LSM Hall A

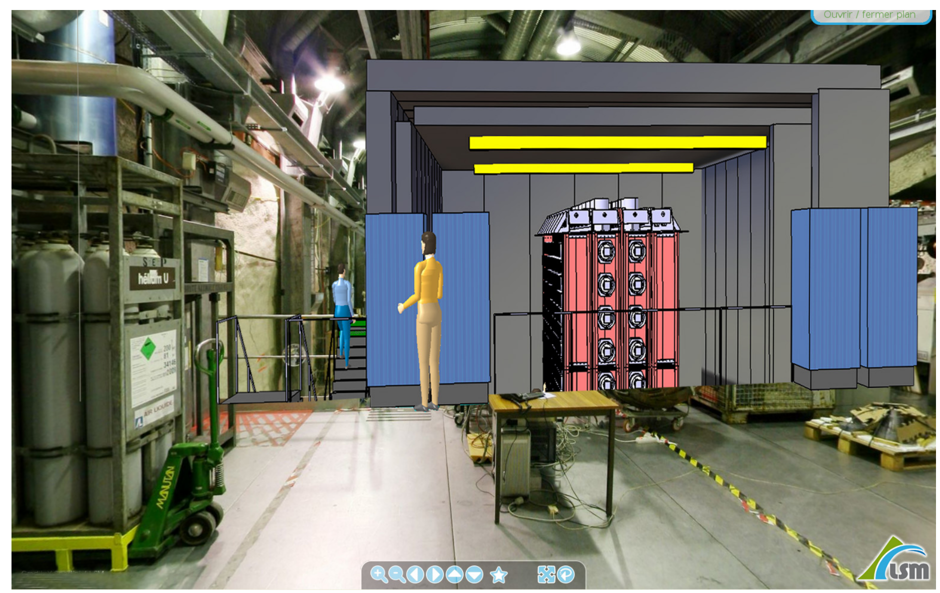




Demonstrator in LSM (Frejus tunnel)

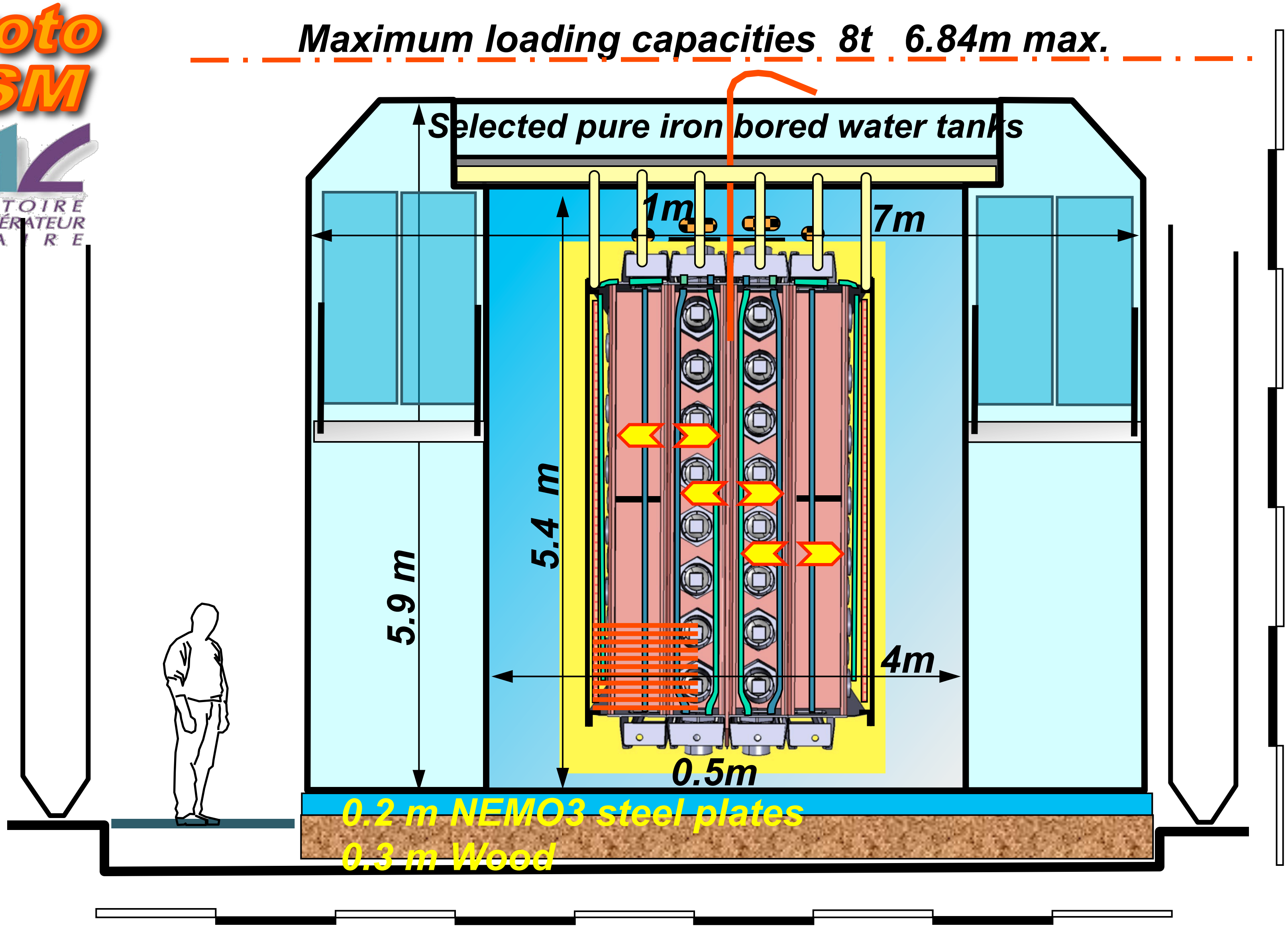






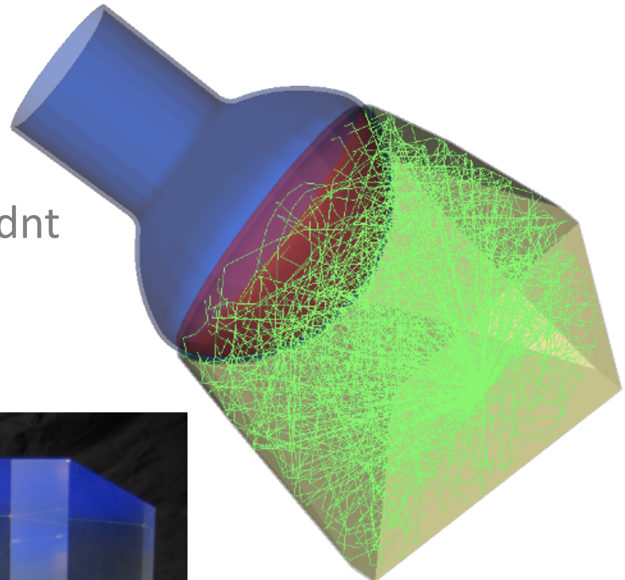
Proto LSM

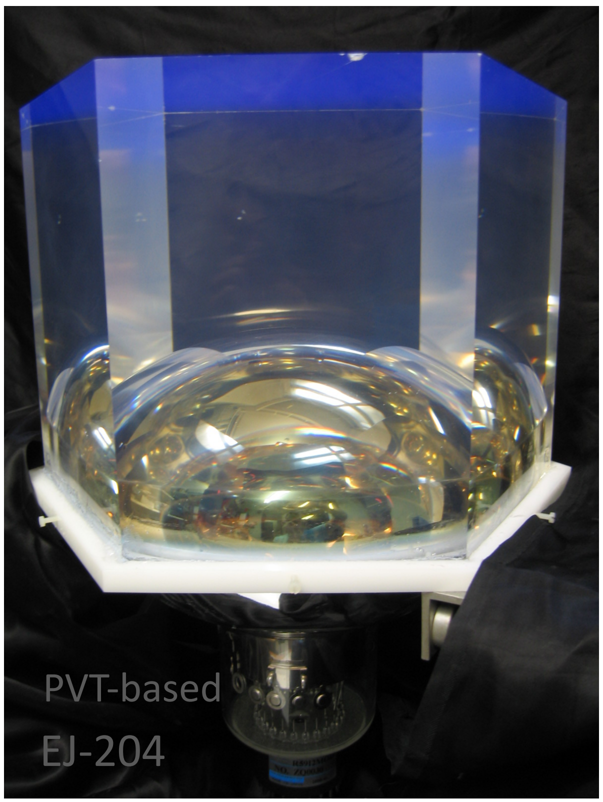
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

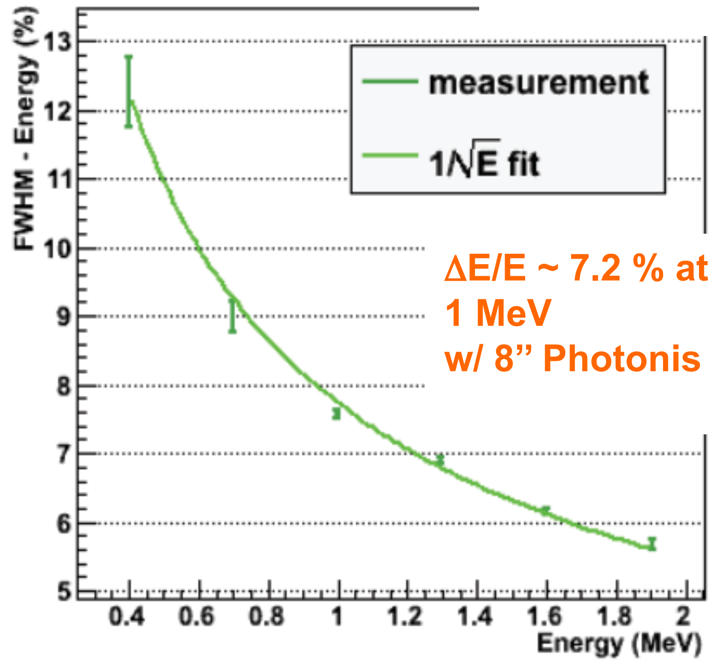


SuperNEMO: Calorimeter R&D

GEANT4 simulations accounting for all wavelength-dependednt properties







ΔE/E ~ 7.2 % at 1 MeV w/ 8" Photonis

8" Hamamatsu R5912-MOD
Super-Bialkali 8 Dynodes

Or

~~8" Photonis "35% QE"~~

Scintillator-PMT response simulations

- Developed GEANT-4 photon-transport simulations which account for all spectral properties of all materials
  - ✓ Bullk PVT or PS, scintillators and shifters, reflections, PMT QE
  - ✓ Reproduce NEMO-3 (MINOS and bench tests), predict and reproduce SuperNEMO tests

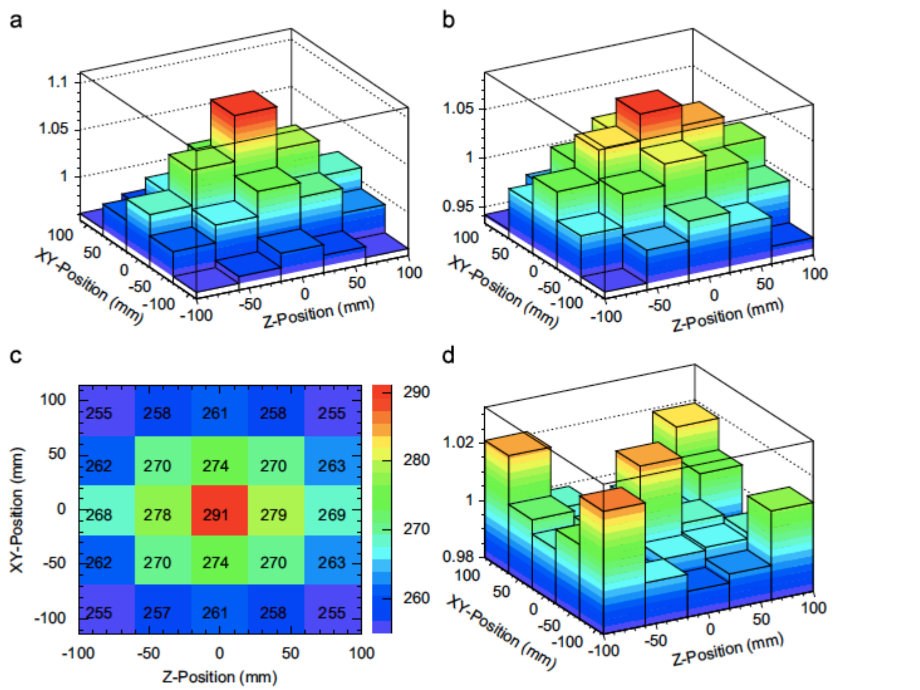


Fig. 5. Results from 1 MeV electrons incident on the EC block. Simulated (a) and measured (b) response, normalized to the mean response. (c) The mean number of photoelectrons collected in each sub-region. (d) The ratio of simulation to measurement.

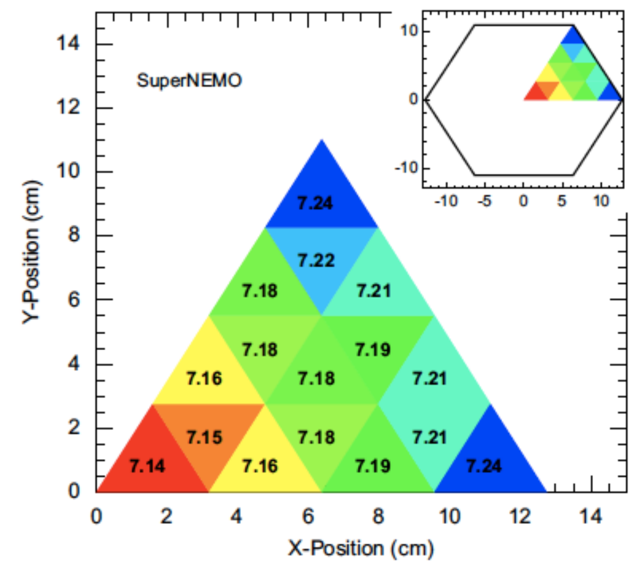
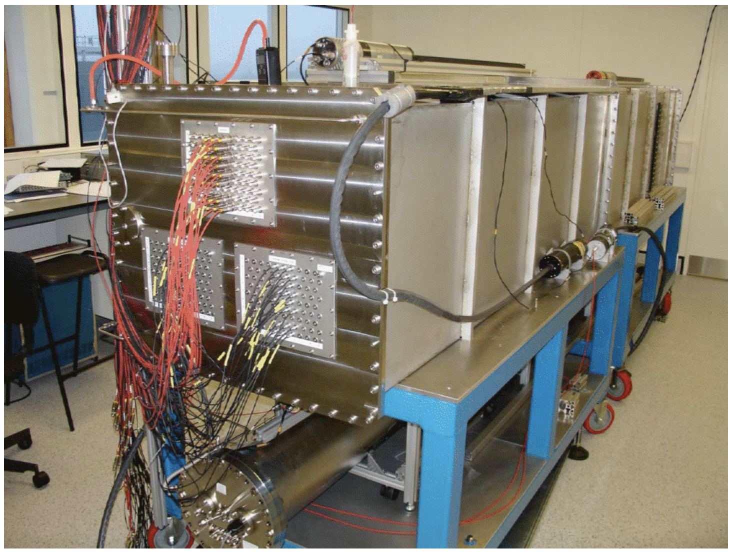


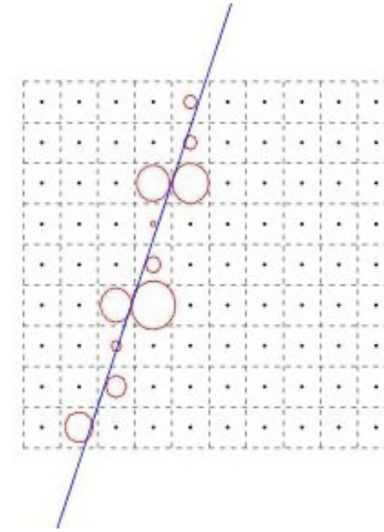
Fig. 10. Spatial dependence of energy resolution (FWHM at 1 MeV) for one sixth of a SuperNEMO scintillator block.

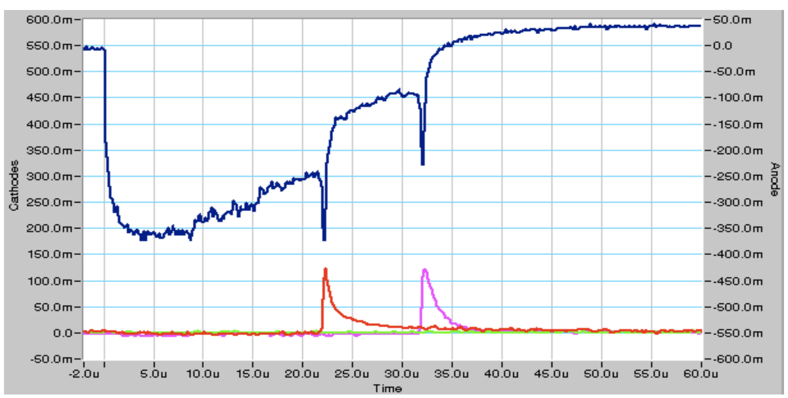
Spectral modeling of scintillator for the NEMO-3 and SuperNEMO detectors. Nucl.Instrum.Meth.A625:20-28,2011

SuperNEMO tracker R&D

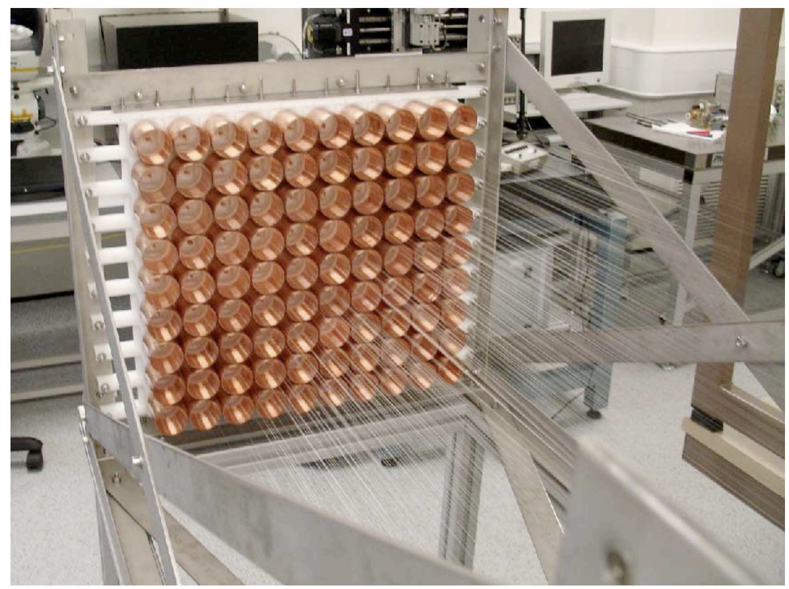
- Optimize length, wire material and diameter, read-out, gas mixture etc
- Several 1-cell and two 9-cell prototypes built and tested
- 90-cell prototype: **r – resolution 0.7 mm**
  z – resolution 1.3 cm





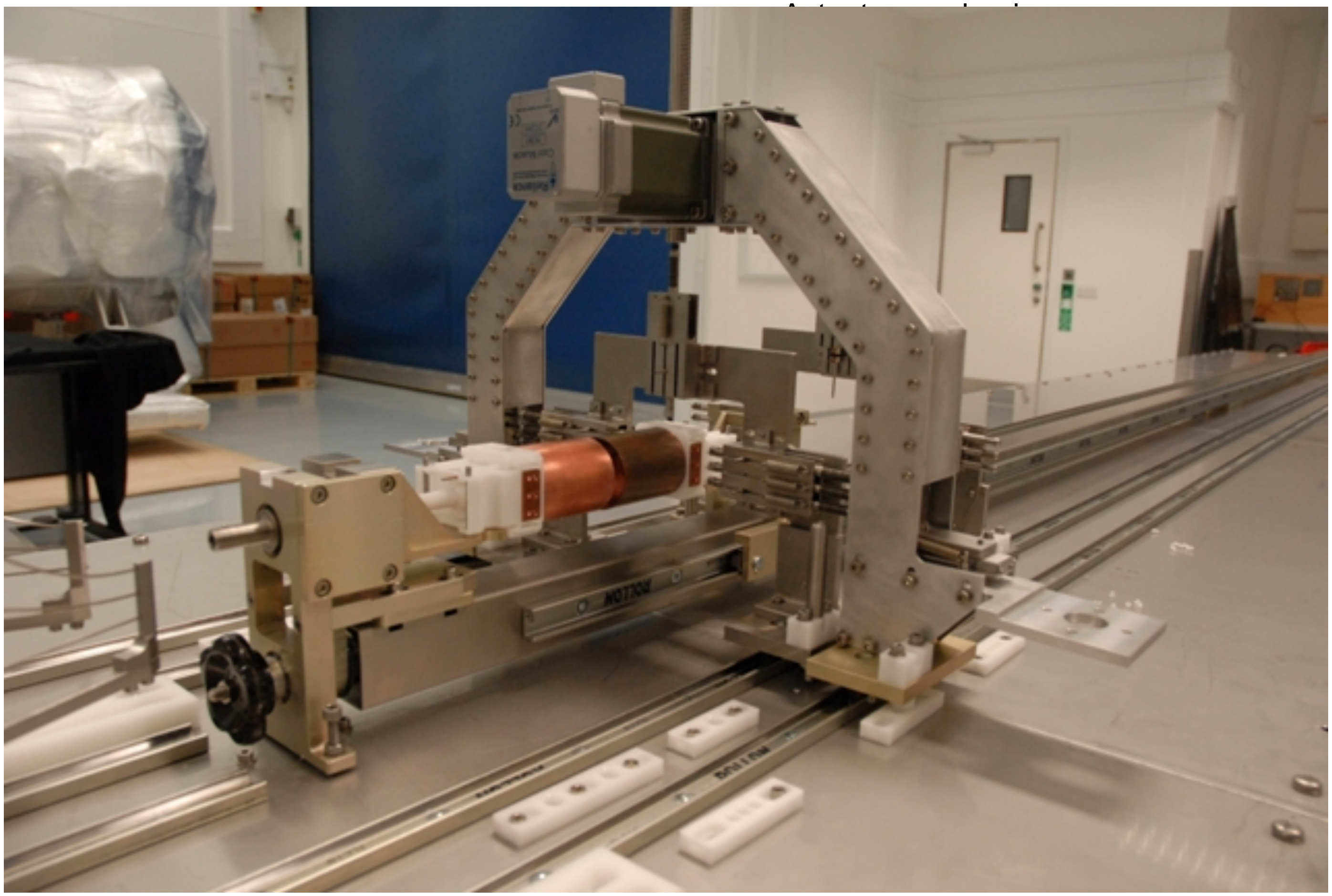


90-cell prototype
Manchester



Tracker: fully automated wiring

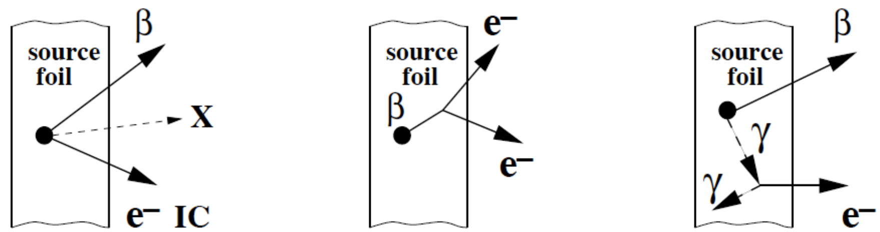
- ~500,000 wires to be strung, crimped, terminated
- Wiring robot being developed in collaboration with Mullard Space Science Lab (UCL)



SuperNEMO's NEMO-3-like backgrounds?

1. Internal background (in addition to a potential $2\nu\beta\beta$ tail)

(due to ^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) radio-impurities of the isotopic source foil)

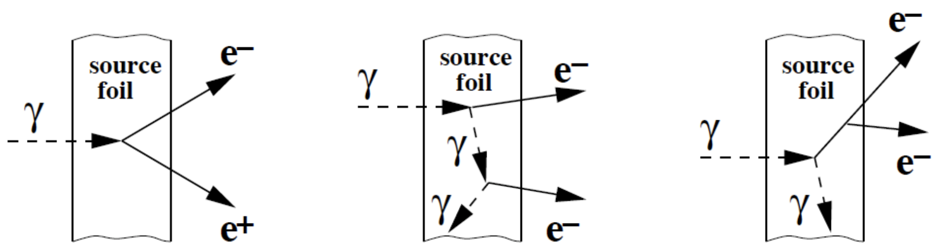


beta + IC (dominant) | beta + Möller | beta + Compton

● = radioisotope   β = electron from beta decay   IC = internal conversion

2. External background (if the γ is not detected)

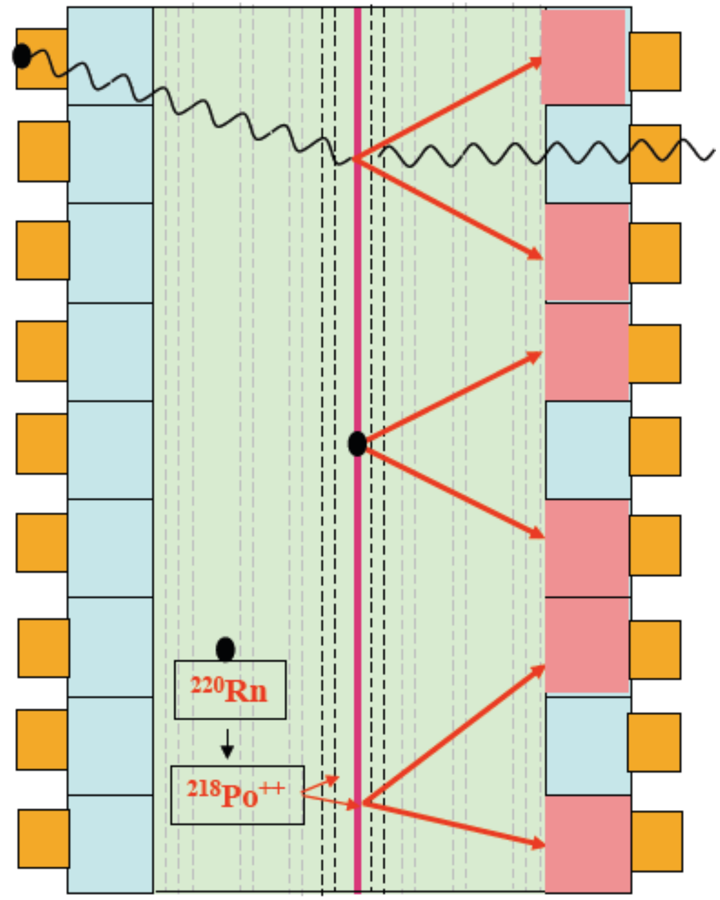
(due to radio-impurities of the detector)



pair creation | Compton + Compton | Compton + Möller

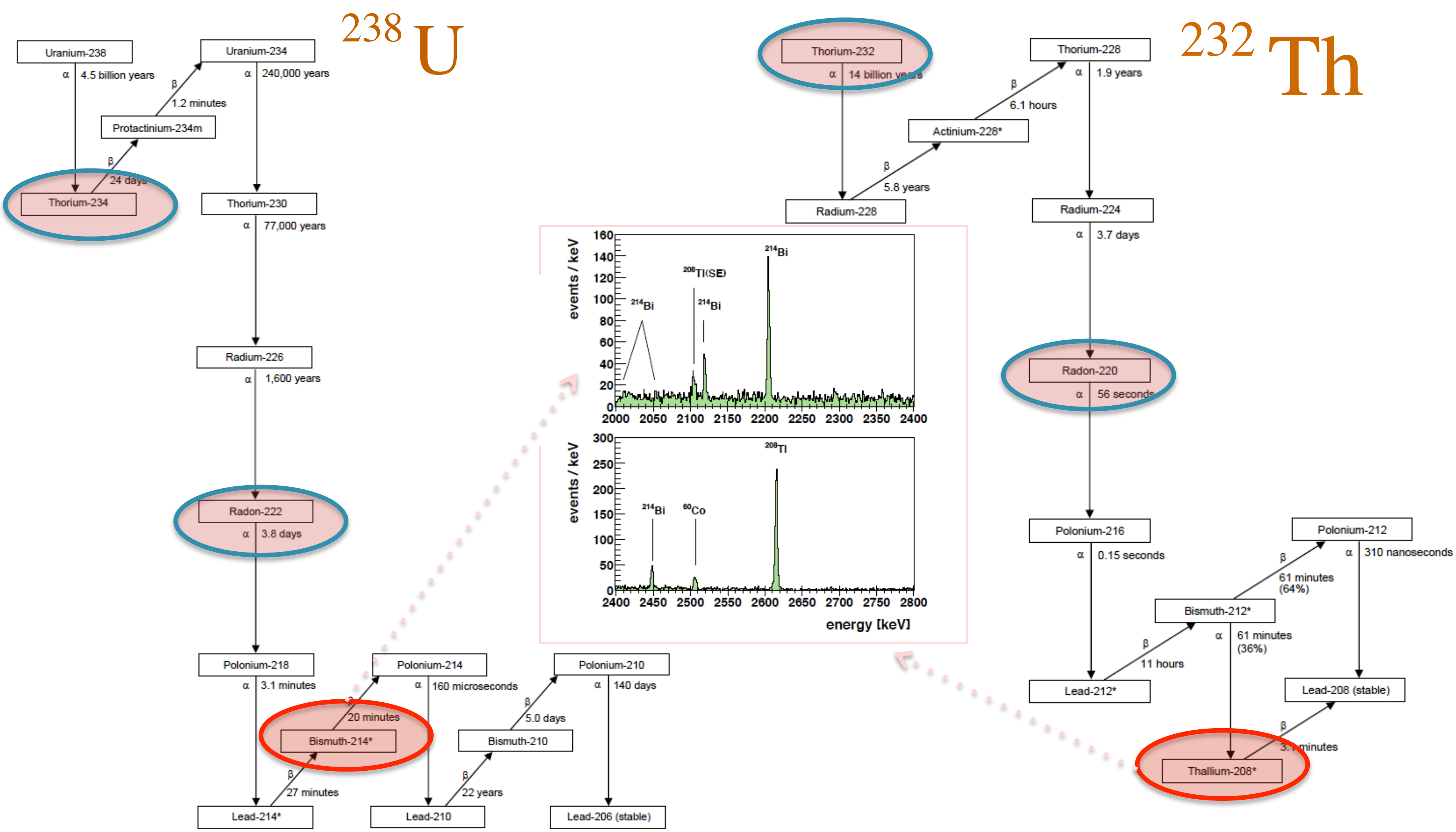
3. Radon (^{214}Bi) inside the tracking detector

- deposits on the wire near the $\beta\beta$ foil
- deposits on the surface of the $\beta\beta$ foil



Each bkg is measured using the NEMO-3 data

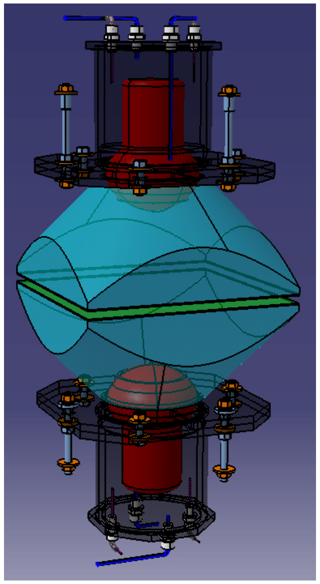
Perennial problem – natural radioactivity

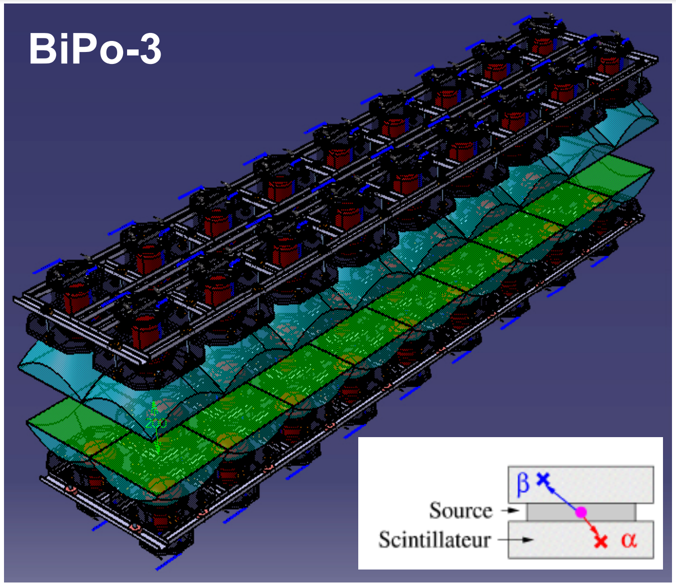


Thorium and radon are diffusive radioactive isotopes out-gased into the air from the rock.

Results of the BiPo-1 prototype for radiopurity measurements for the SuperNEMO double beta decay source foils.
Nucl.Instrum.Meth.A622:120-128,2010.

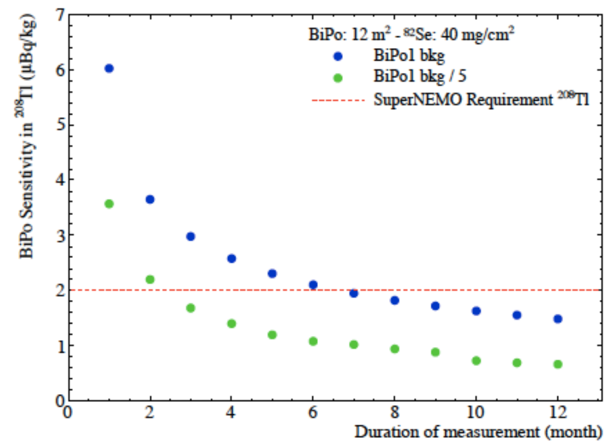
BiPo R&D
(for measuring foil radio-purity)





Objectives :
to mesure ^{208}Tl < 2 μBq/kg & ^{214}Bi < 10 μBq/kg
in ββ source foil (5kg/month)

Sensitivity of the BiPo detector

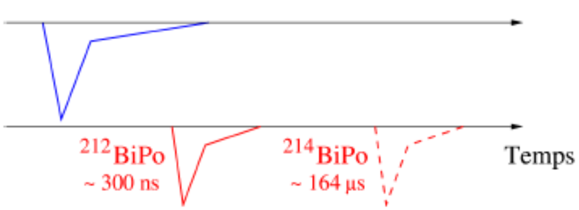


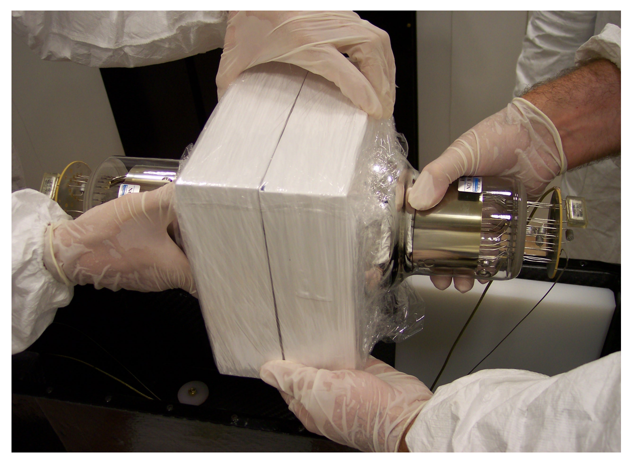
^{238}U → ^{214}Bi (19.9 mn) —β→ ^{214}Po (164 μs) —α→ ^{210}Pb 22.3 y

^{214}Bi —0.021%→ ^{210}Tl (1.3 mn) → ^{210}Pb

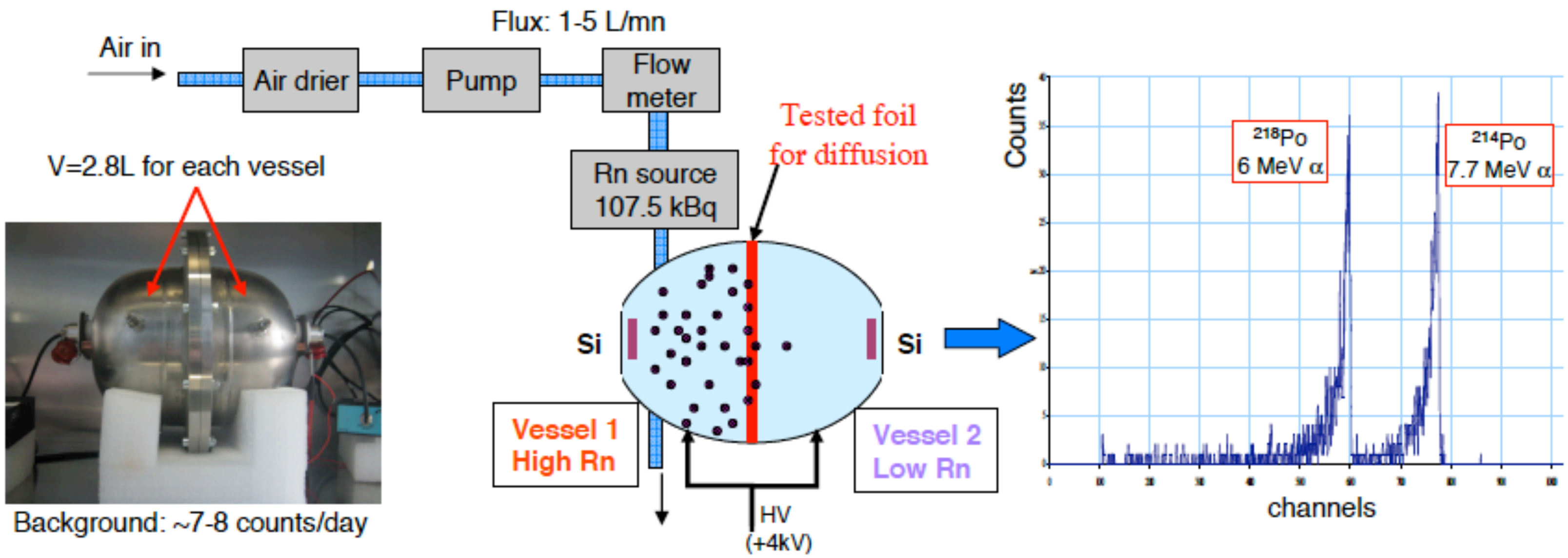
^{232}Th → ^{212}Bi (60.5 mn) —β→ ^{212}Po (300 ns) —α→ ^{208}Pb (stable)

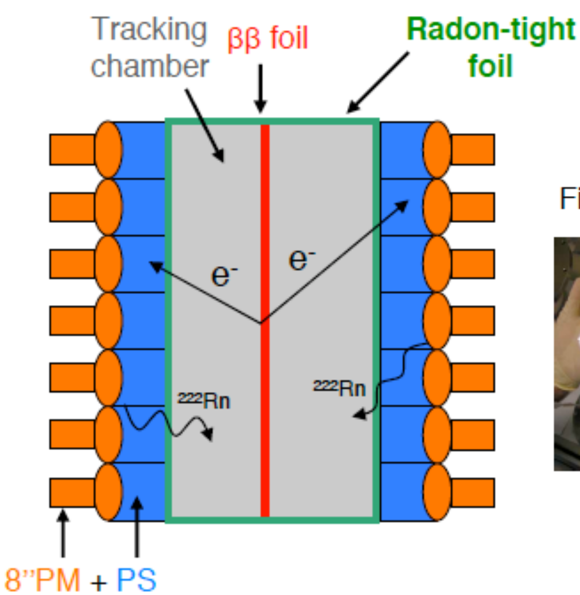
^{212}Bi —36%→ ^{208}Tl (3.1 mn) → ^{208}Pb





Radon emanation and isolation R&D



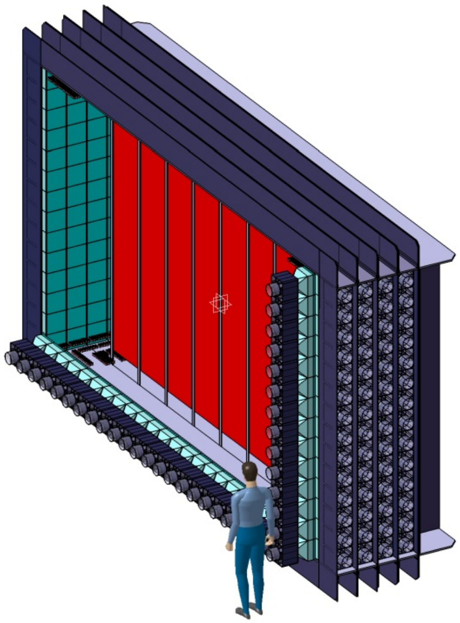


First test on energy resolution with a foil of EVOH (ethylene vinyl alcohol used for food)

8"PMT + Plastic scintillator +	No EVOH	EVOH (15 μm)	EVOH (20 μm)	EVOH (25 μm)
Energy resolution FWHM at 1 MeV (%)	8.5 ± 0.1	8.7 ± 0.1	8.8 ± 0.1	8.7 ± 0.1

→ small effect on energy resolution (no difference between 15 and 25μm)

Concept (borrowed from Borexino/GERDA)



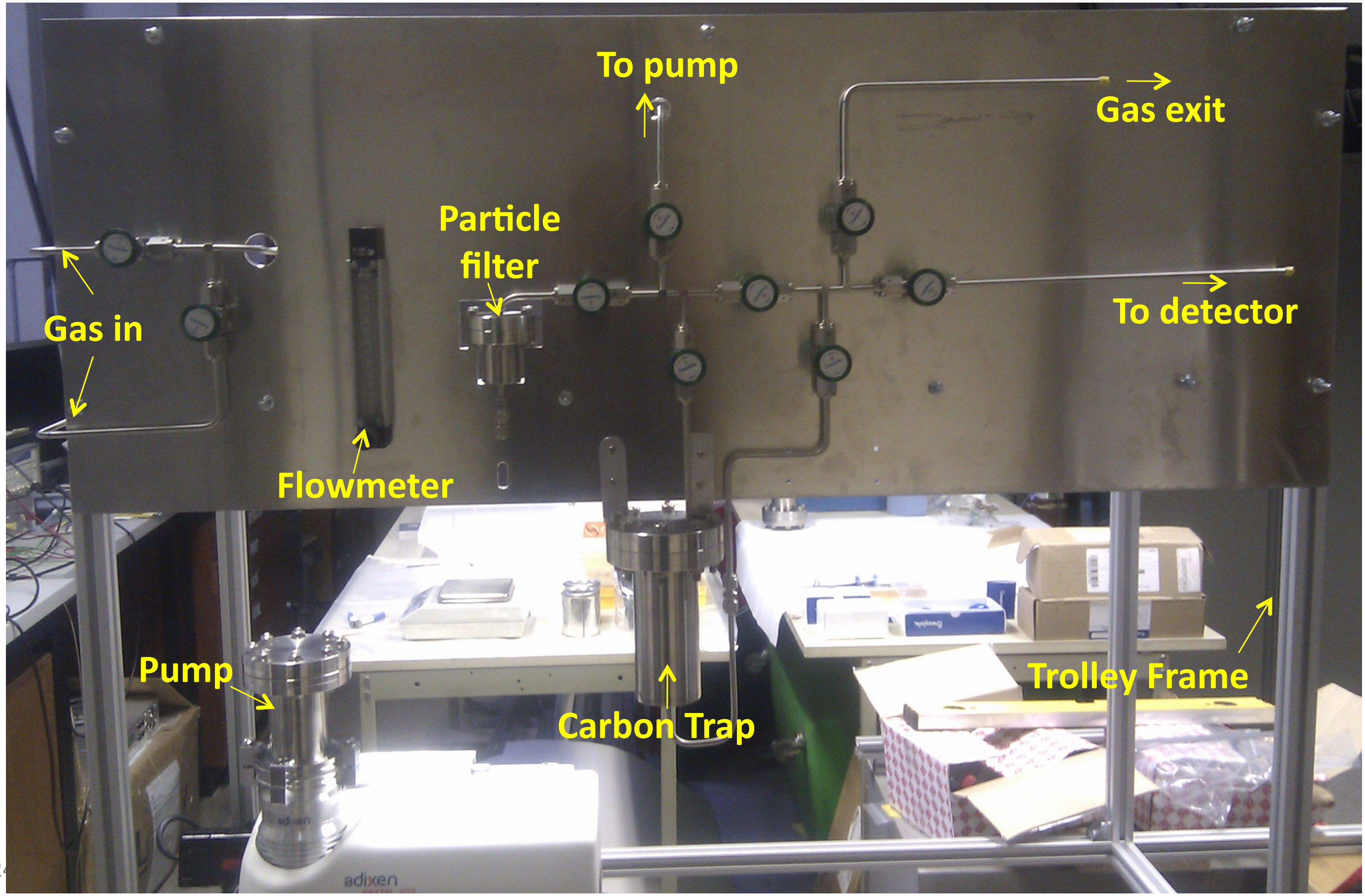
SuperNEMO tracker sub-module (~ $4m^3$)

Radon concentration line

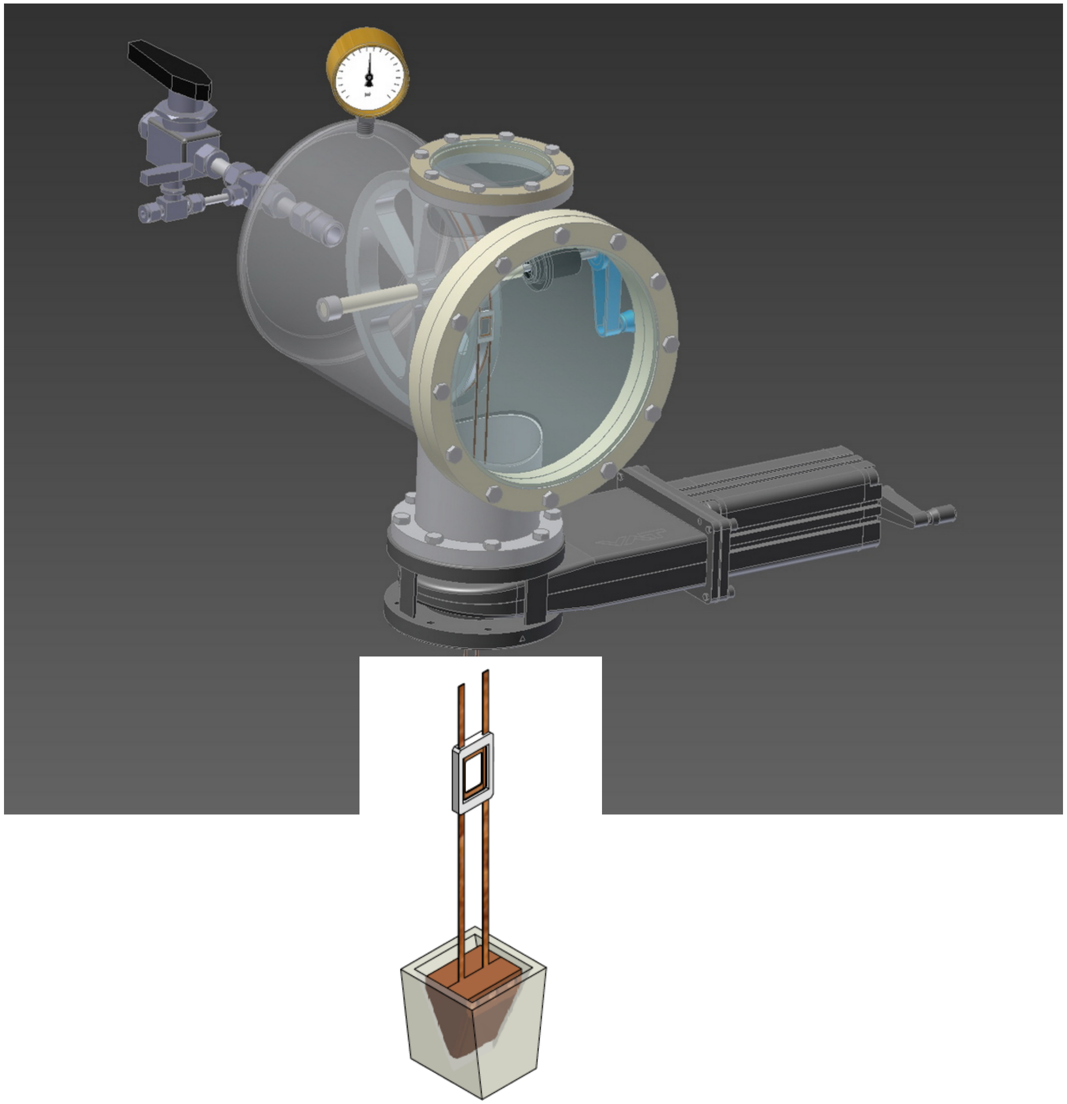
Electrostatic detector

- Gas from the tracker is pumped through a cooled ultra-pure carbon trap and the ^{222}Rn in the gas is adsorbed.
- The concentrated sample is then heated and transferred to an electrostatic detector via helium purge.

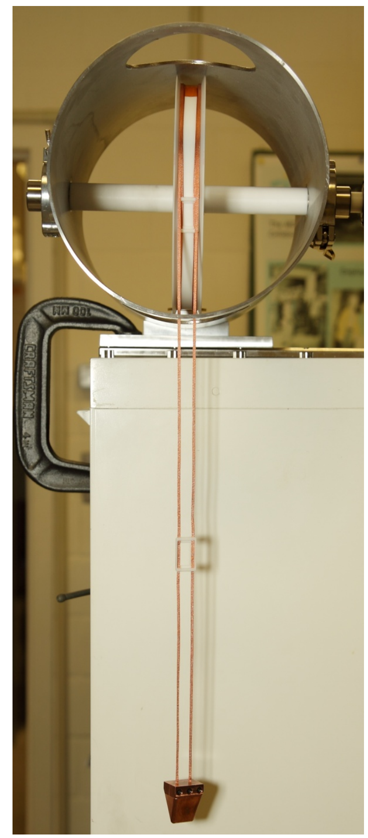
Under development



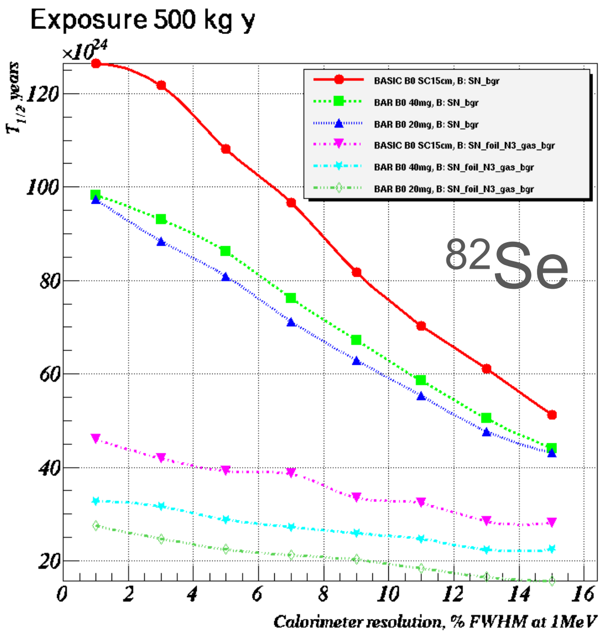
^{207}Bi calibration source improvements



- Hermetic deployment of 207Bi source
- No permanent source tubes
- Design being finalized

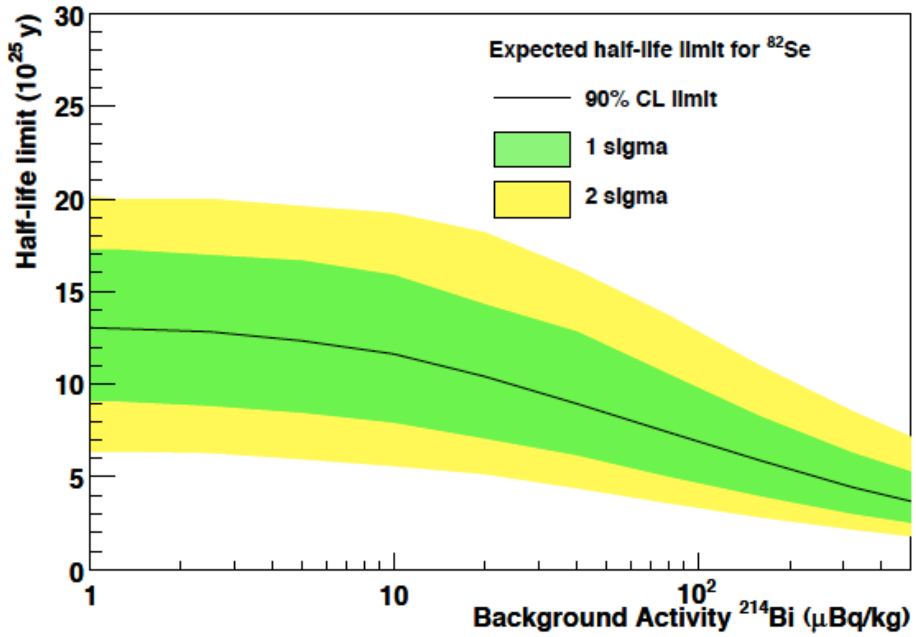


Sensitivity



Calorimeter resolution
(% FWHM at 1 MeV)

GEANT-4 based model of the detector combined with NEMO-3 experience.

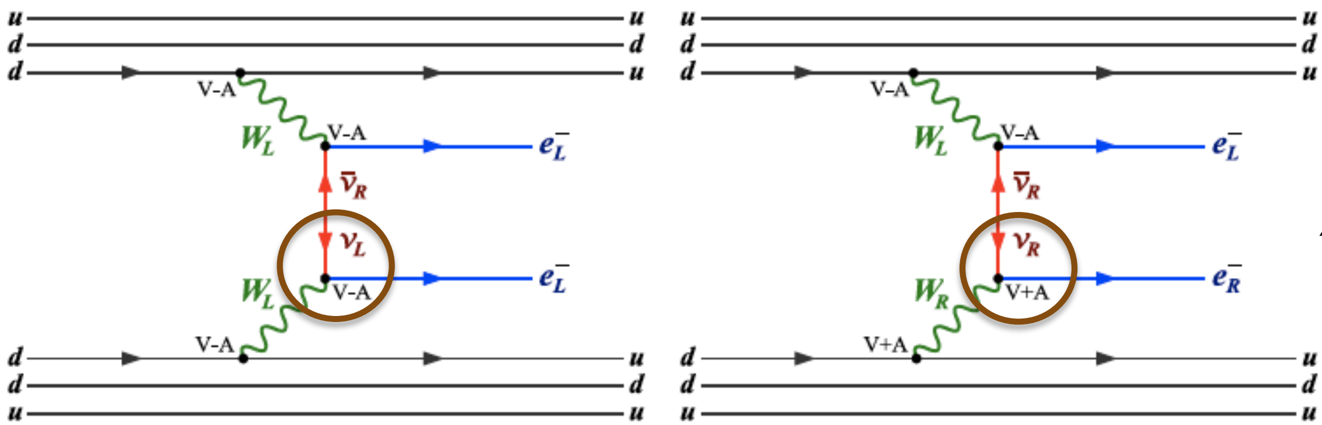


^{82}Se → 5yrs with 100 kg

✓ $T_{1/2}(0\nu\beta\beta)$ > 1-2 x 10^{26} y

✓ $\langle m_\nu \rangle$ < 0.04 - 0.11 eV

"Probing new physics models of neutrinoless double beta decay with SuperNEMO"; R. Arnold et al. , Eur. Phys. Jr. C DOI 10.1140/epjc/s10052-010-1481-5



$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}$$

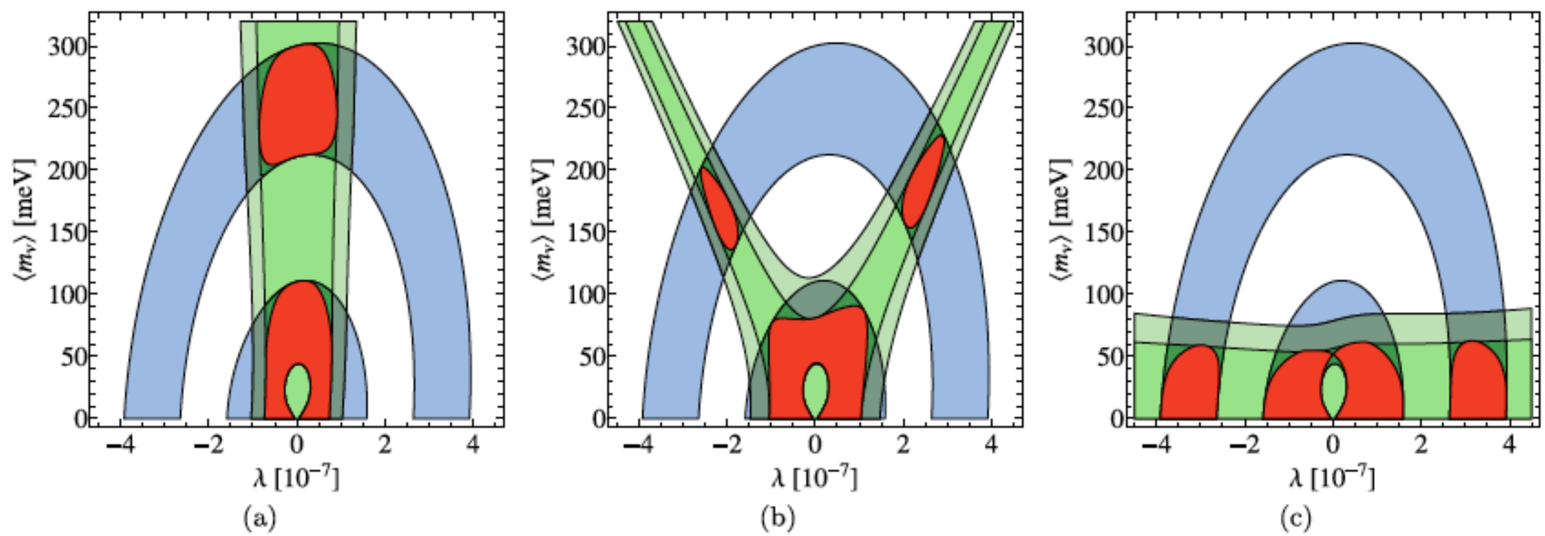


Fig. 11 (Color online) Constraints at one standard deviation on the model parameters m_ν and λ for ^{82}Se from: (1) an observation of $0\nu\beta\beta$ decay half-life at $T_{1/2} = 10^{25}$ y (*outer blue elliptical contour*) and 10^{26} y (*inner blue elliptical contour*); (2) reconstruction of the angular (outer, lighter green) and energy difference (inner, darker green) distribution shape; (3) combined analysis of (1) and (2) using decay rate and energy distribution shape reconstruction (*red contours*). The admixture of the MM and RHC$_\lambda$ contributions is assumed to be: **a** pure MM contribution; **b** 30% RHC$_\lambda$ admixture; and **c** pure RHC$_\lambda$ contribution. NME uncertainties are assumed to be 30% and experimental statistical uncertainties are determined from the simulation

$0\nu\beta\beta$ search is a very dynamic field

Experiment	Isotope(s)	Technique	Main characteristics
SuperNEMO	^{82}Se, ^{150}Nd	Tracking + calorimeter	Bckg rejection, isotope choice
CUORE	^{130}Te	Bolometers	Energy resolution, efficiency
GERDA	^{76}Ge	Ge diodes	Energy resolution, eficiency
Majorana	^{76}Ge	Ge diodes	Energy resolution, efficiency
EXO	^{136}Xe	TPC ionisation + scintillation	Mass, efficiency, final state signature
CANDLES	^{48}Ca	CaF_2 scintillating crystals	Efficiency, Background
SNO++	^{150}Nd	Nd loaded liquid scintillator	Mass, efficiency
XMASS	^{136}Xe	Liquid Xe	Mass, efficiency
KamLAND-Zen	^{136}Xe	Xenon balloon	Mass, efficiency

SuperNEMO's "philosophy"

- Lesson learned from the Klapdor-Kleingrothaus *et al.* "claim"
  - >1 isotope with $0\nu\beta\beta$ desired
  - Topological signature should be demonstrated
- NEMO technique
  - "Low tech", "popular" and robust to control bkg
  - Distributed production
  - May use different isotopes
  - May use several sites
  - May be produced at many institutions
- SuperNEMO is looking for new collaborators
  - Starting Demonstrator construction, operational in 2013
  - More modules soon after
- Frejus expansion is not necessarily the only location…

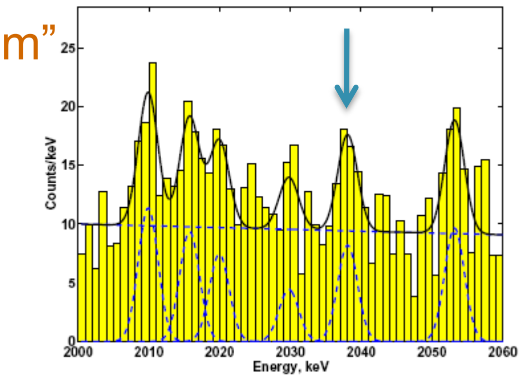
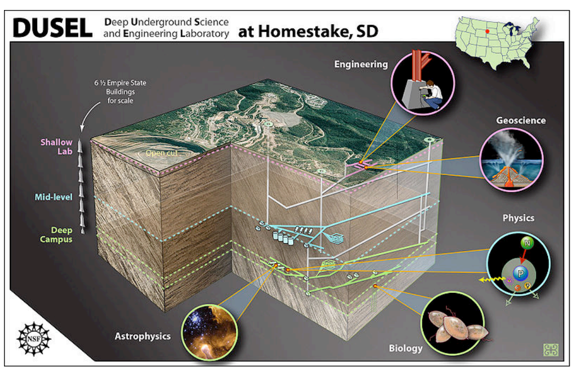
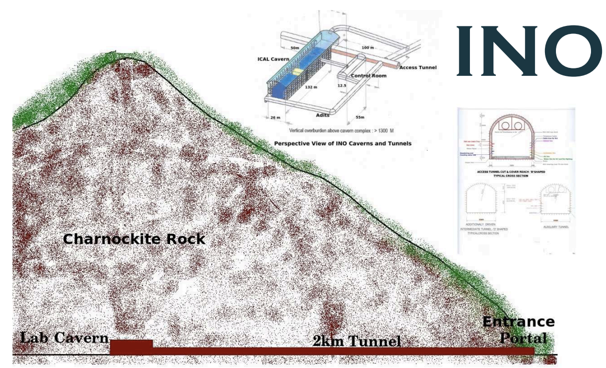


Figure 1. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), in the range 2000 - 2060 keV and its fit, for the period: August 1990 to May 2003 (71.7 kg y) (see [3]).





NEMO Collaboration

Summer 2010 at UCL