How to build a radiopure detector ?

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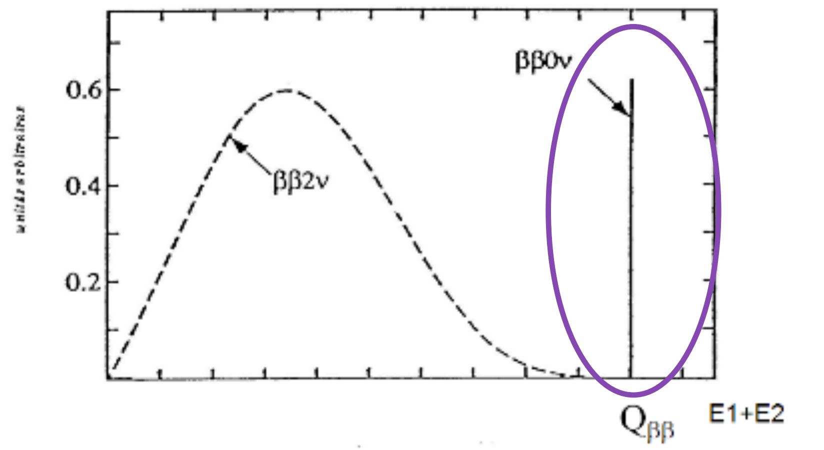
Outline

- ✓ NEMO experiments: tracko-calorimeter technique and main backgrounds
- ✓ Radiopurity strategies in SuperNEMO and related techniques used for material screening
- ✓ Illustration of some issues than may happen during the production. Quality procedures to track all the samples.
- ✓ Installation of the detector in a clean environment
- ✓ Conclusion

Main ingredients of a ββ experiment

- ✓ Mass of ββ isotopes and time
  → exposure in kg.year
- ✓ Efficiency
- ✓ Energy resolution
- ✓ **Level of background**
- ✓ Particle discrimination
- ✓ Time resolution

Region of interest
~2-4 MeV

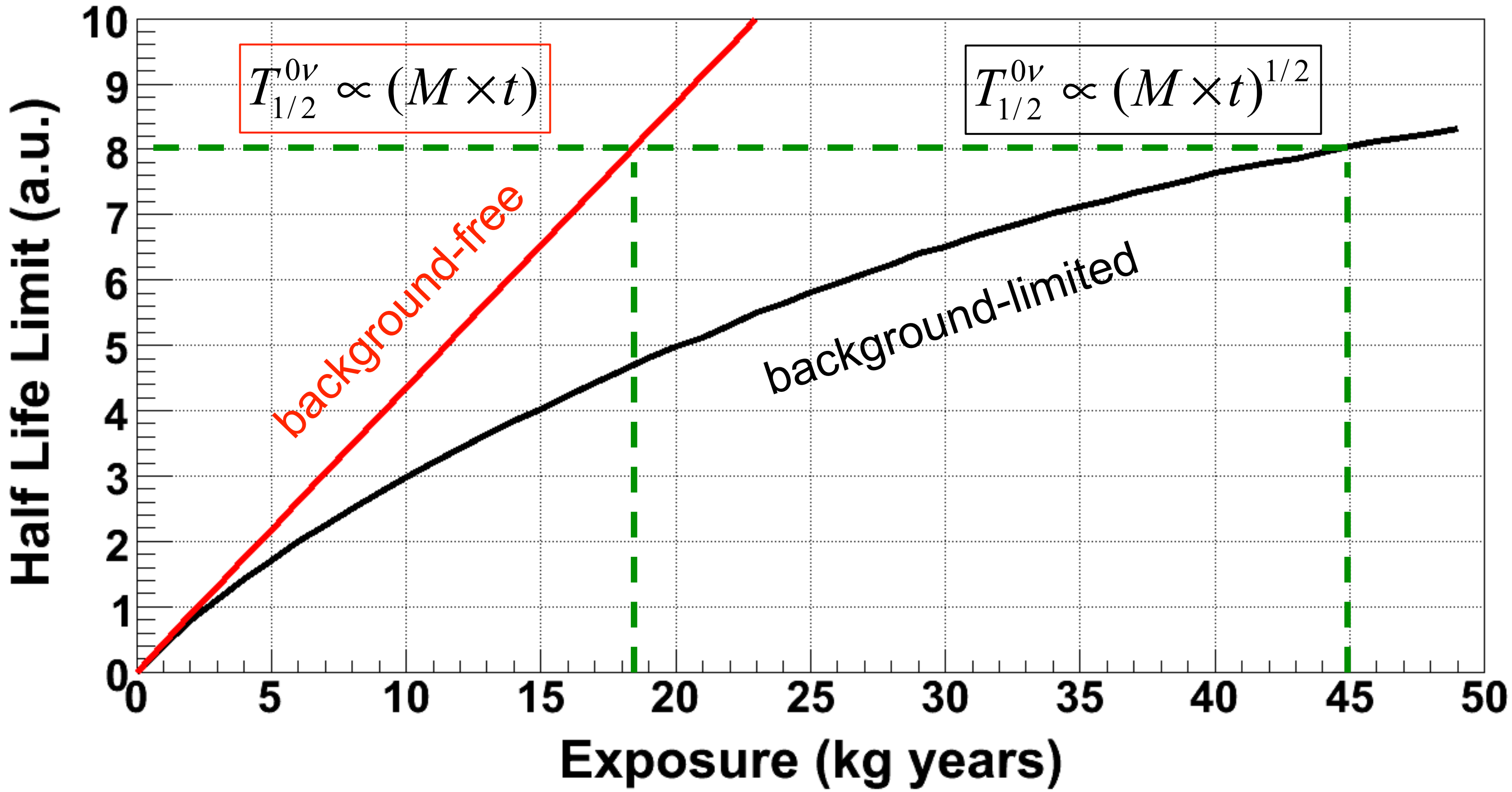


Efficiency
Exposure

$$T_{1/2}^{0\nu} > \frac{Ln(2)\times N_A}{W} \times \boxed{\varepsilon_{0\nu}} \times \left(\frac{\boxed{M\times t}}{\boxed{b}\times\boxed{\Delta E}}\right)^{1/2}$$

Background
Energy resolution

Sensitivity vs background

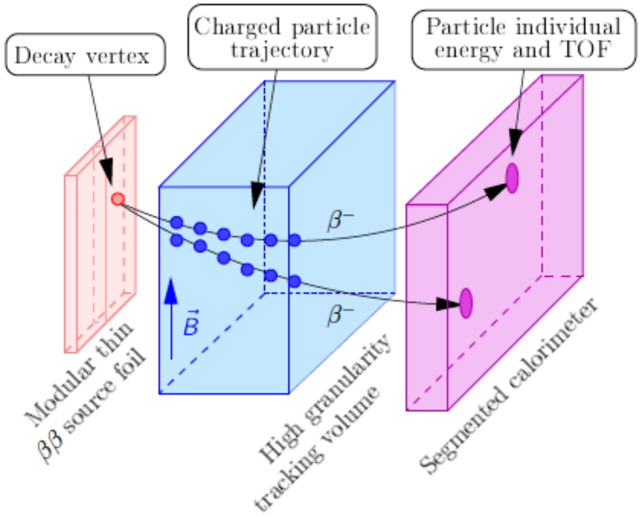


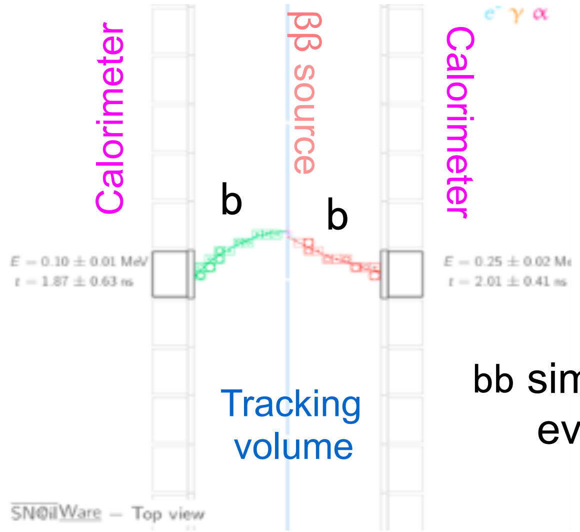
Effective neutrino mass $< m_\nu > \propto (M \times t)^{1/2}$ $< m_\nu > \propto (M \times t)^{1/4}$

→ Sensitivity to half-life and even more to the effective neutrino mass is dramatically depending on the level of background

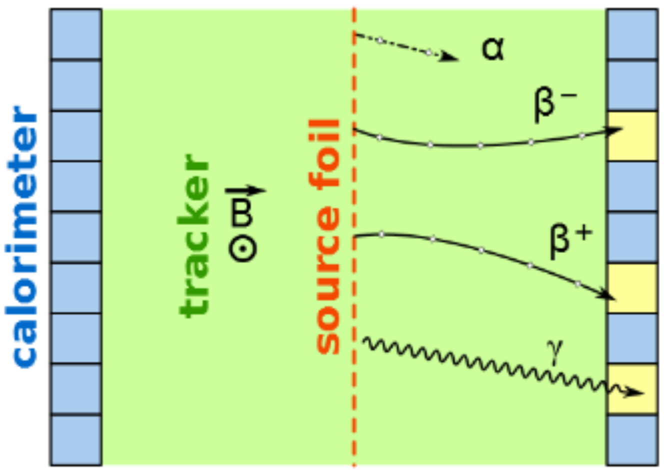
NEMO: tracko-calorimetric technique

Principle: source ≠ detector





Particle identification capability



ββ event : 2 negative curved tracks
+ 2 hits in the segmented calorimeter
→ **unique feature to identify the 2electrons !**

- Full topological event reconstruction (vertex, energy, time of flight)
- Identification of α-particle, $e^{\pm}$ and γ-ray

→ **strong background suppression**
→ **alpha particles are not a problem**

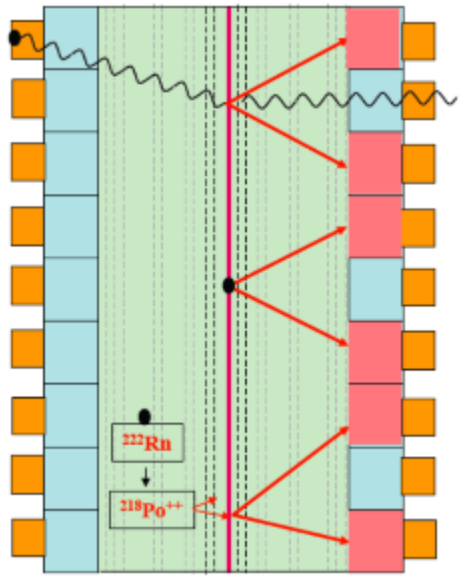
Main backgrounds for ββ0ν

Internal background (coming from the ββ source foil)

From ^{232}Th chain: **^{208}Tl (Q_β=5.00 MeV)**
From ^{238}U chain: **^{214}Bi (Q_β =3.27 MeV)**

> $Q_{\beta\beta}(^{82}$Se)=3 MeV

^{82}Se ββ foil



Scenario:

- β + electron from internal conversion
- β + electron from Möller diffusion
- β + electron from γ Compton

2 electrons emitted from the ββ foil

Radon in the tracking chamber

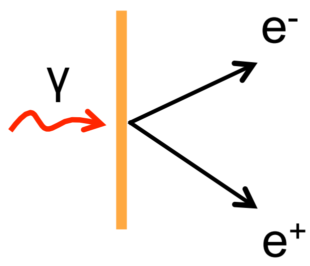
Internal background-like (mother nucleus of **^{214}Bi**) when deposited on the source foil or on the first plan wires

External background (coming from the detector materials)

Scenario:

- ~~double Compton from the same γ in the foil~~ **Not a problem @3 MeV**
- Radiative neutron capture on Cu/Fe and pair production e^+/e^- in the foil from the high energy γ

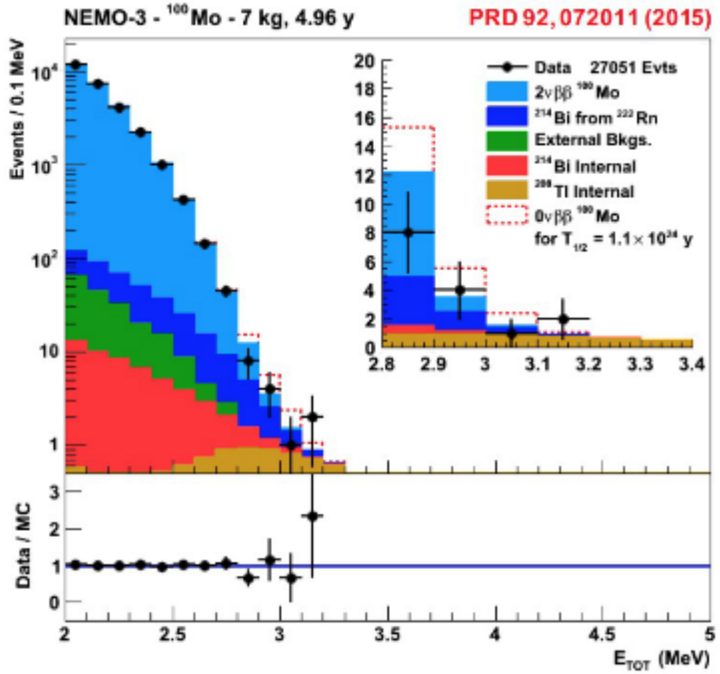
^{82}Se foil



From NEMO-3 to SuperNEMO

In NEMO-3, main backgrounds for ^{100}Mo were :

- **2vββ from ^{100}Mo**
- Internal foil contamination (**^{208}Tl**, **^{214}Bi**)
- **^{214}Bi from Radon**



	NEMO-3		SuperNEMO
ββ sources radiopurity			
A(^{208}Tl)	~100 μBq/kg	X 1/50	<2 μBq/kg
A(^{214}Bi)	60 - 300 μBq/kg		<10 μBq/kg
Radon in Tracker			
A(^{222}Rn)	5.0 mBq/m³	X 1/30	< 0.15 mBq/m³
Total background			
cts.keV^{-1}.kg^{-1}.y^{-1}	1.3 ×10^{-3}		5.0 × 10^{-5}

Radiopurity strategies in SuperNEMO and related screening techniques

SuperNEMO radiopurity strategies

- Goal : to reach a **« 0-background » level** for the Demonstrator module

- Strategies :

  ✓ Purification and measurement of the ^{82}Se ββ foil internal radiopurity at the **level of 2-10 μBq/kg**
  → **development of the BiPo3 detector** (+ ICP-MS)

  ✓ Selection of radiopure internal materials to reach **a Radon level of 150 μBq/m^3** in the Tracker
  → **development of several Radon facilities**

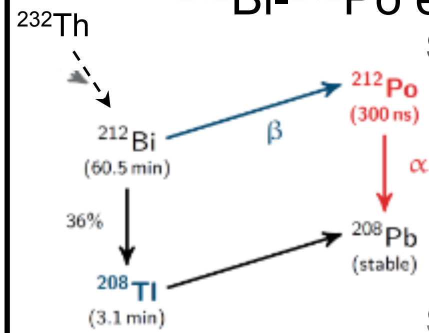
  ✓ Selection of radiopure materials at level of 0.2 to 200 mBq/kg
  → **large screening process using low-background γ spectrometry with HPGe detectors**

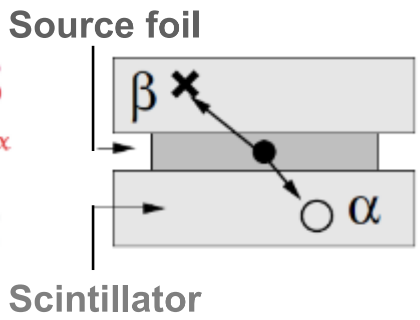
BiPo-3 detector

Goal: to measure ^{82}Se ββ foils at 2 µBq/kg level for ^{208}Tl

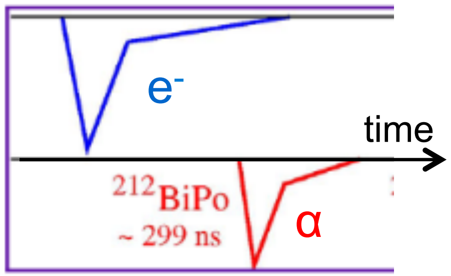
Principle : ^{82}Se foil placed between two PS scintillators + 5”PMTs

^{212}Bi-^{212}Po effect

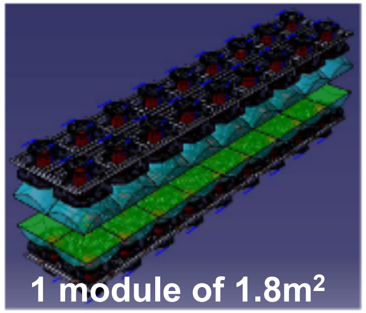


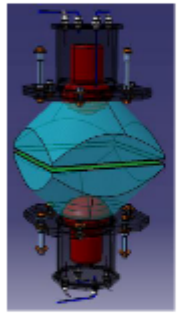


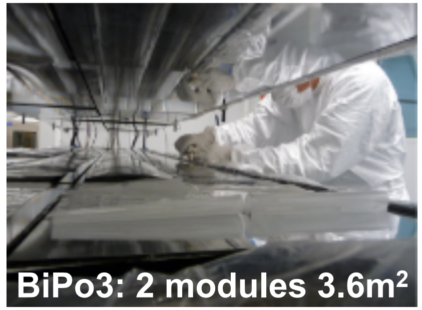
^{208}Tl measured by electron-alpha coincidence from ^{212}BiPo cascade with ΔT~300 ns



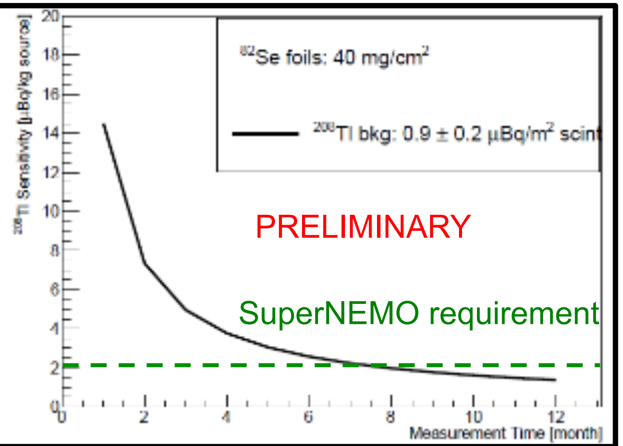
In operation in Canfranc lab. since 2013







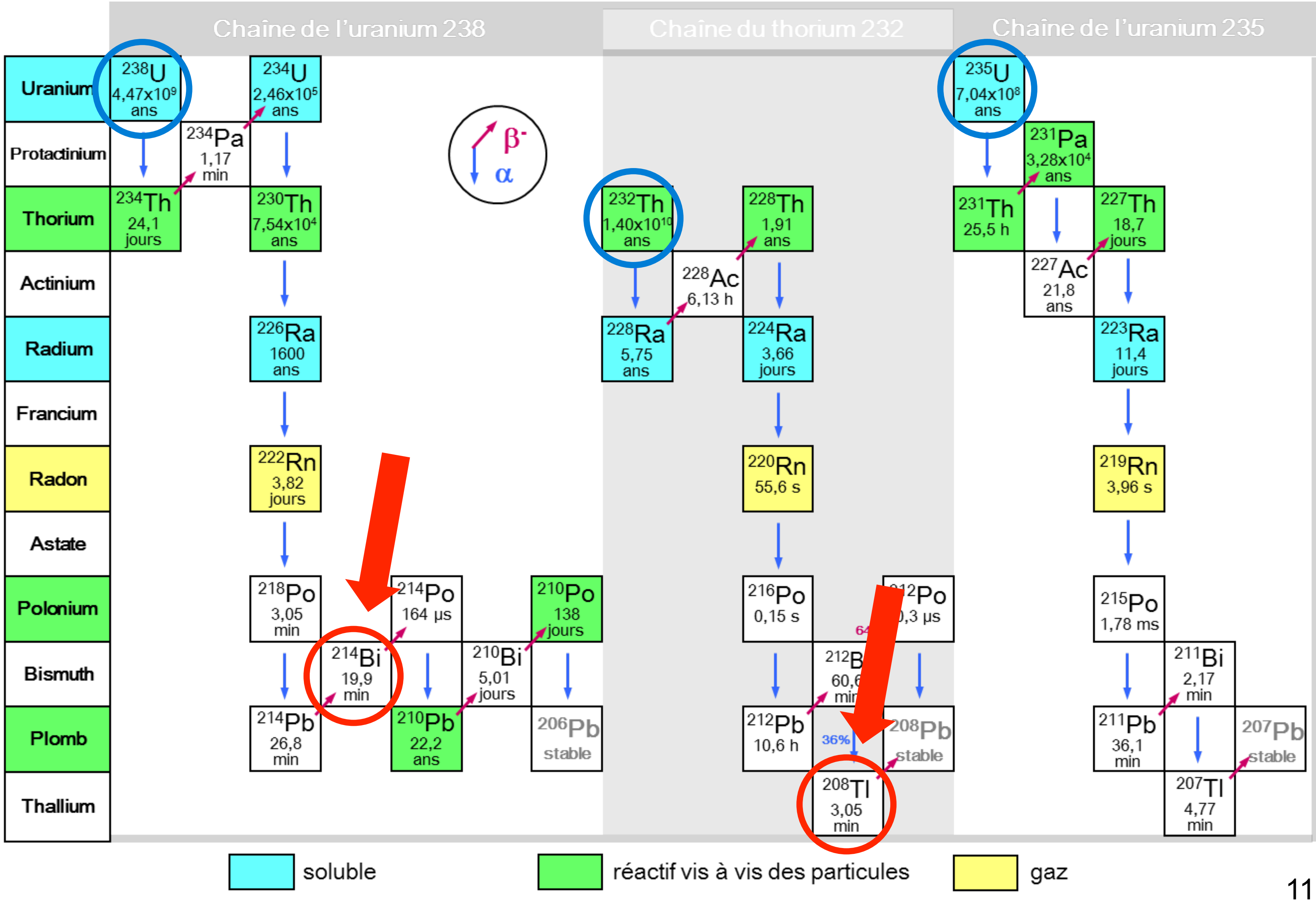
^{208}Tl sensitivity is achieved in 6-8 months for a 3.6 m^2 ββ foil



→ well-adapted to measure ^{208}Tl and ^{214}Bi activity in very thin materials

Natural radioactivity : our main ennemy!

- ✓ Primordial radioactivity: ^{238}U, ^{232}Th, ^{235}U chains (+^{40}K)



Techniques for radiopurity screening

✓ Pro and cons of three well-known techniques for radiopurity screening

Techniques	Mass sample	Sensitivity For U/Th (g/g)	Advantages	Limitations
ICP-MS*	Few mg	10^{-10}-10^{-12}	High sensitivity, small mass	Limited to the head of the U/Th chains
Neutron Activation Analysis	10g to 1kg	10^{-12} -10^{-15}	Highest sensitivity	Limited to the head of the U/Th chains
Low-background γ spectrometry	10g to 1kg	10^{-9}-10^{-10}	Multi-radionuclides analysis, full screening of the U/Th chains	Limited to γ emitters, Less sensitive

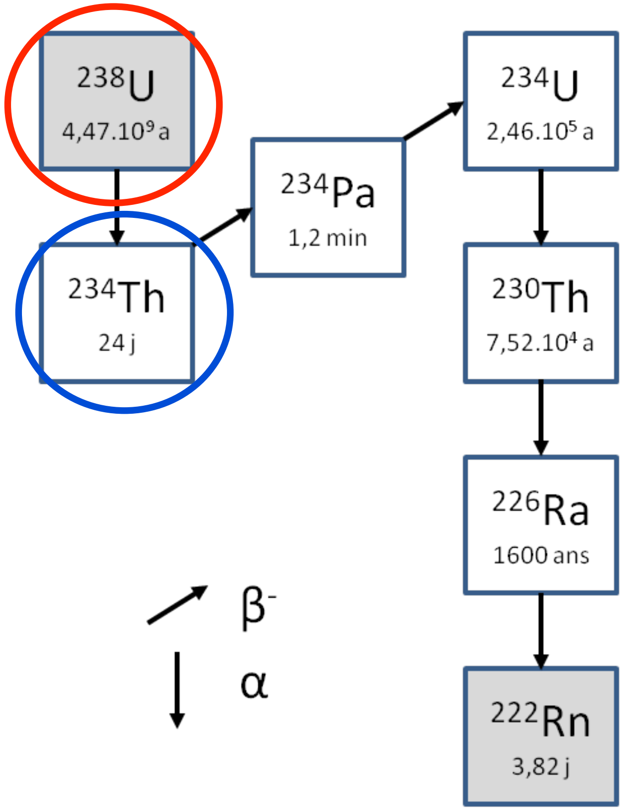
Unique technique to measure the activity of several radionuclides in the same chain → allow to check if there is secular equilibrium in a given material

* Inductively Coupled Plasma Mass Spectrometry

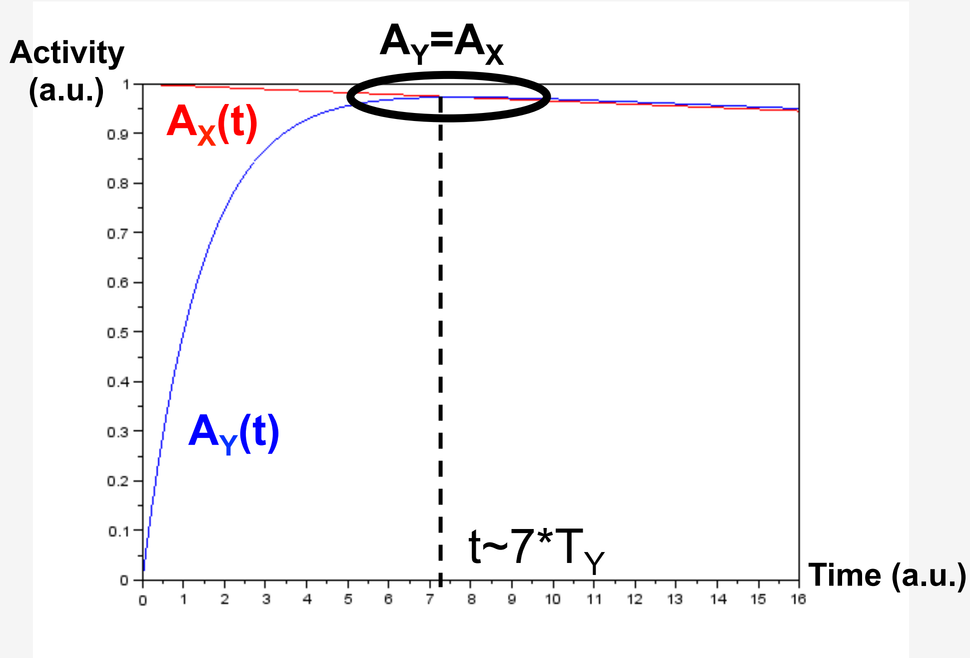
Secular equilibrium: example of ^{238}U chain

✓ In some cases**, the ^{238}U chain is not be in secular equilibrium**, i.e. ^{238}U, ^{226}Ra and $^{210}Pb/^{210}Po$ have not the same activity

→ Need to measure several radionuclides along the Uranium chain



Example: $X \rightarrow Y \rightarrow ...$ With $T_X >> T_Y$

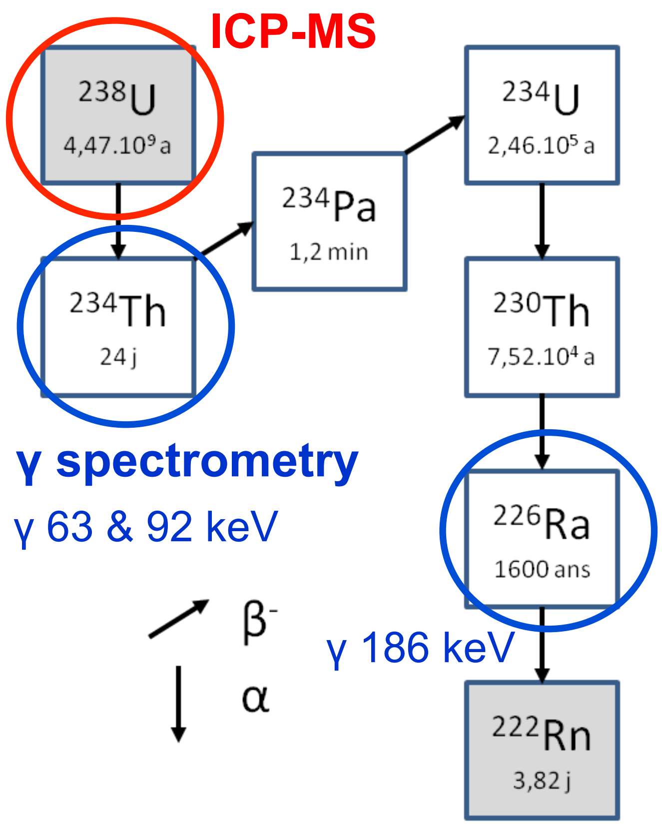


→ Secular equilibrium reached after ~7 times the half-life of the daughter nucleus

Secular equilibrium: example of ^{238}U chain

- ✓ In some cases**, the ^{238}U chain is not be in secular equilibrium**, i.e. ^{238}U, ^{226}Ra and $^{210}Pb/^{210}Po$ have not the same activity

→ Need to measure several radionuclides along the Uranium chain

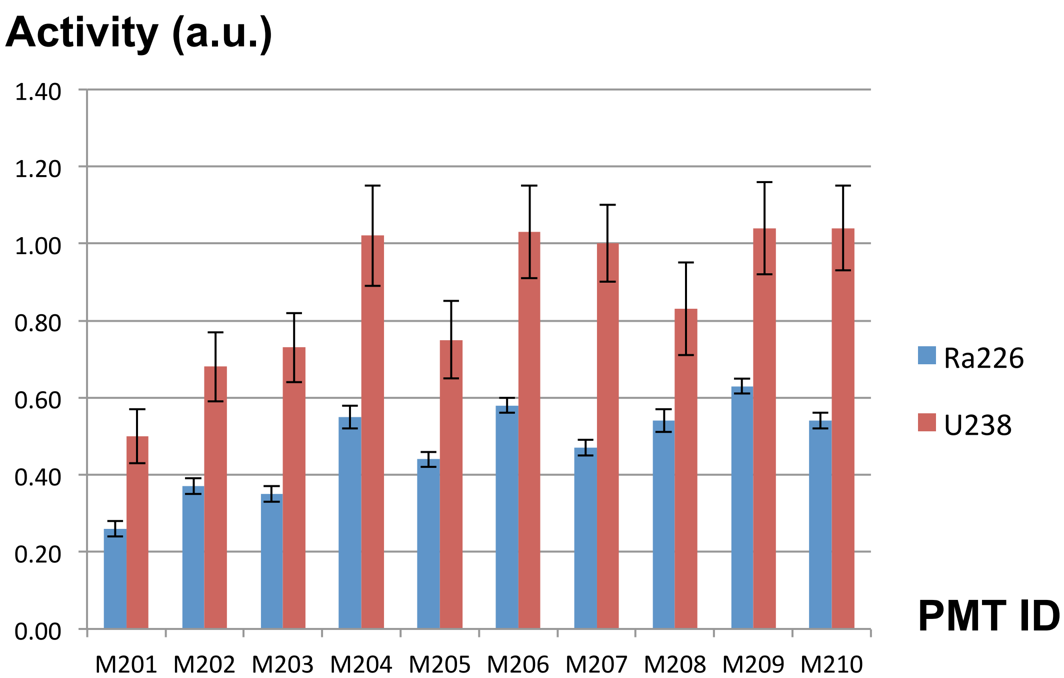


- ✓ ICP-MS: direct measurement of ^{238}U activity
- ✓ Gamma spectrometry: indirect measurement of ^{238}U activity using gamma's from ^{234}Th because of secular equilibrium
- ✓ Gamma spectrometry: indirect measurement of ^{238}U activity using gamma from ^{226}Ra

→ γ spectrometry able to measure the ratio $A(^{234}Th)/A(^{226}Ra)$ and to check the secular equilibrium

Example : glass of 8'' PMTs

- ✓ 10 glass bulbs from 8'' Hamamatsu PMT have been crushed and measured for SuperNEMO (among 440 x 8''PMTs in total)



- ✓ factor of 2 between ^{238}**U activity** and ^{226}**Ra activity**

→ no secular equilibrium in the Uranium chain

→ need to be controlled precisely (could have been the opposite)

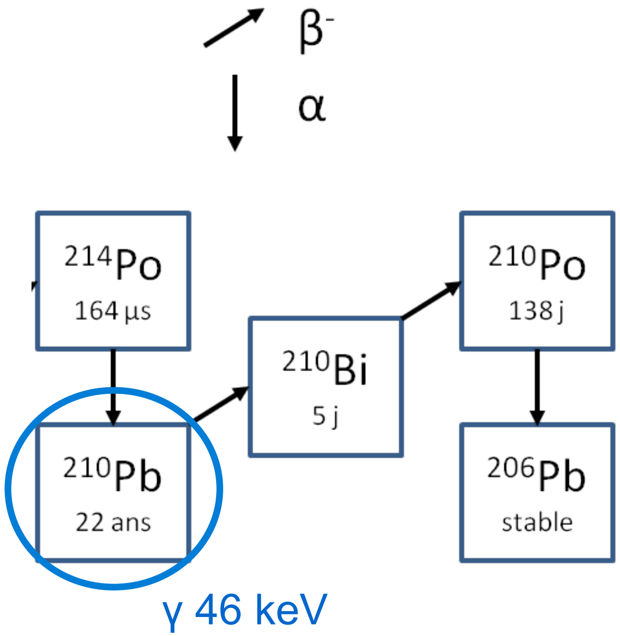
Secular equilibrium: example of ^{238}U chain

- ✓ Bottom part of the **^{238}U chain** starting from ^{226}Ra to ^{210}Pb

  - ✓ Ratio of A(^{226}Ra)/A(^{210}Pb) using the γ's from ^{226}Ra & ^{214}Pb (186, 295 and 352 keV) and the low energy γ from ^{210}Pb (46 keV)

→ also possible to control the secular equilibrium

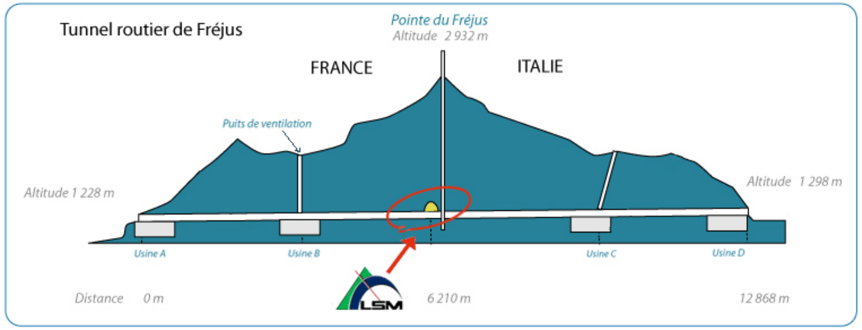
γ 186keV



- ✓ Part of ^{210}Pb chain is not a problem for ββ0ν decay with SuperNEMO:
  - ^{210}Pb: Q_β=63 keV
  - ^{210}Bi: Q_β =1.16 MeV
  - ^{210}Po: Q_α=5.4 MeV

→ may be an issue for ββ0ν using a calorimetric approach and for dark matter searches

Facilities for low-background γ spectrometry



PRISNA platform (Bordeaux)

- Building with **6 m.w.e**
- Coaxial and well-type HPGe detectors

→ sensitivity for $^{238}U/^{226}Ra$ ~ 50 mBq/kg

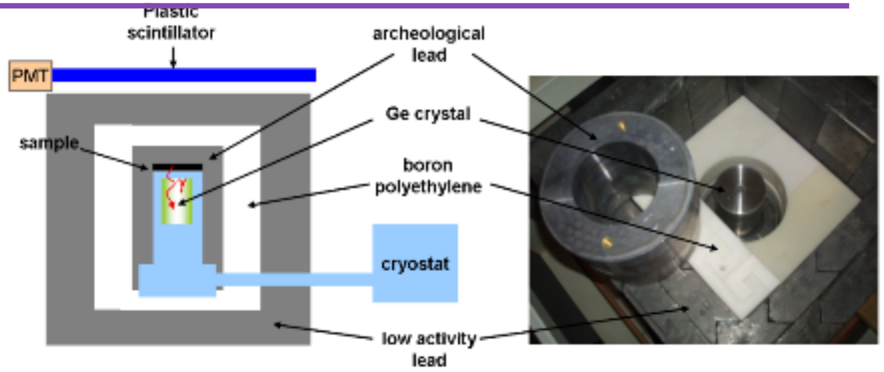
LSM platform (Modane)

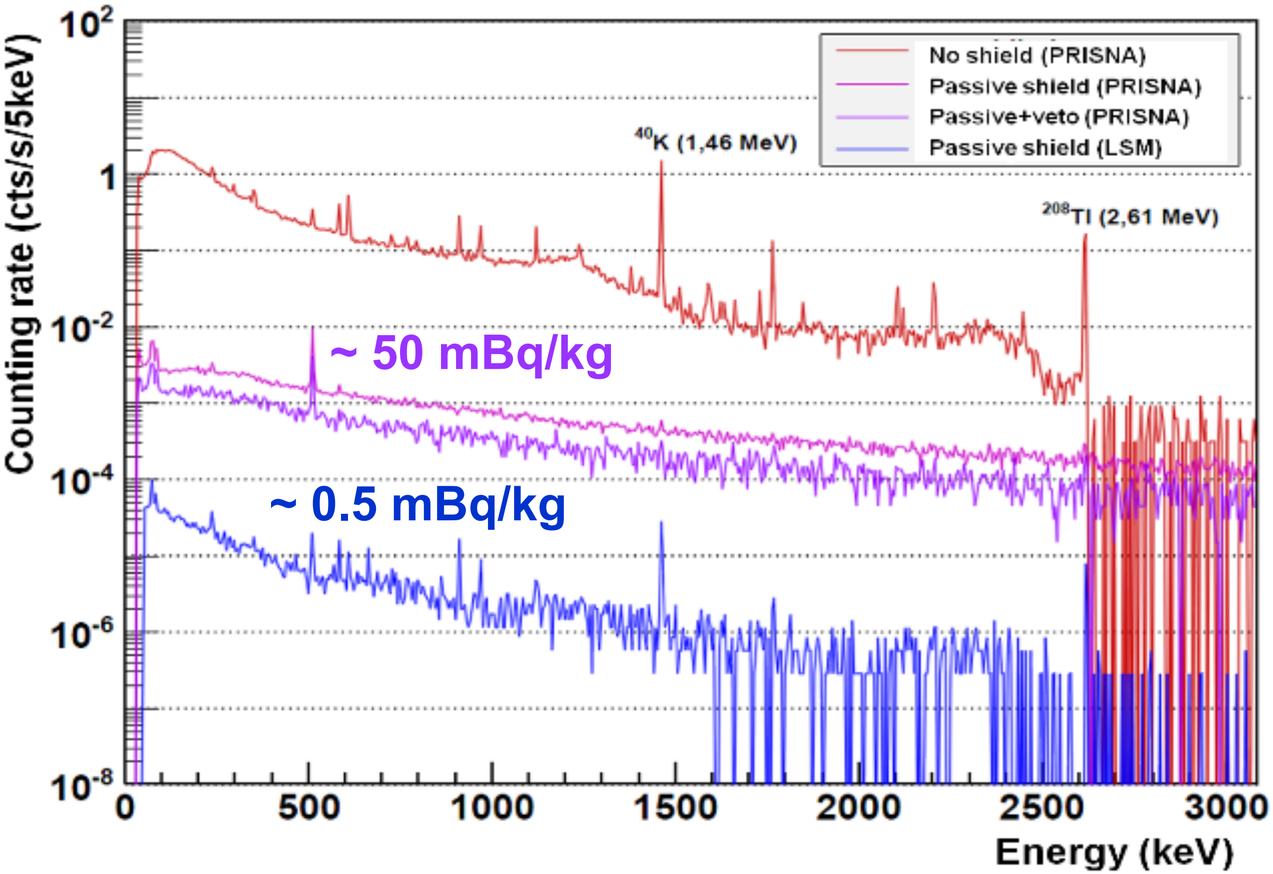
- Underground lab. with **4800 m.w.e**
- Coaxial and planar HPGe detectors

→ sensitivity for $^{238}U/^{226}Ra$ ~ 0.5 mBq/kg

Facilities for low-background γ spectrometry

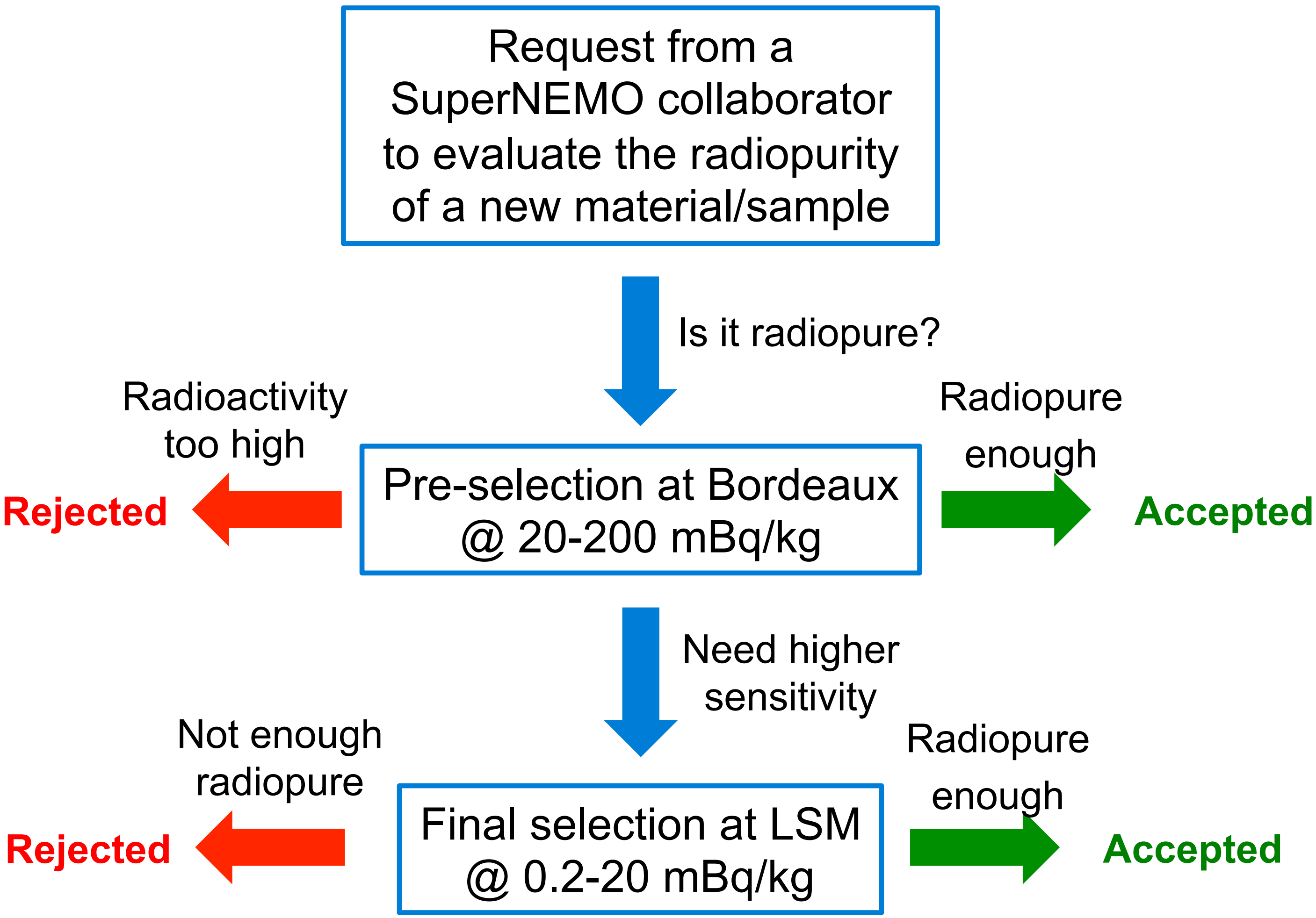
- ✓ At sea level (Bordeaux), muon flux is ~10^6 higher than at LSM, inducing a constant background
- ✓ Partially removed with concrete and muon veto





From sample to final decision-making

- ✓ Every material has to be screened at least by γ spectrometry
- ✓ There is no *a priori* safe radiopure material !

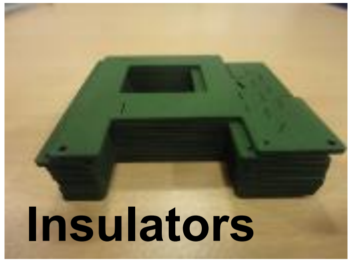


PMT activity: our candle to make a decision

- ✓ SuperNEMO: external background is be dominated by the radioactivity of the 440 x 8''PMTs and 232 x 5''PMTs

PMT	^{40}K	^{226}Ra	^{232}Th
232x5''+ 440x8''PMTs	~550 Bq	~200 Bq	~125 Bq

~ 4kg of bananas

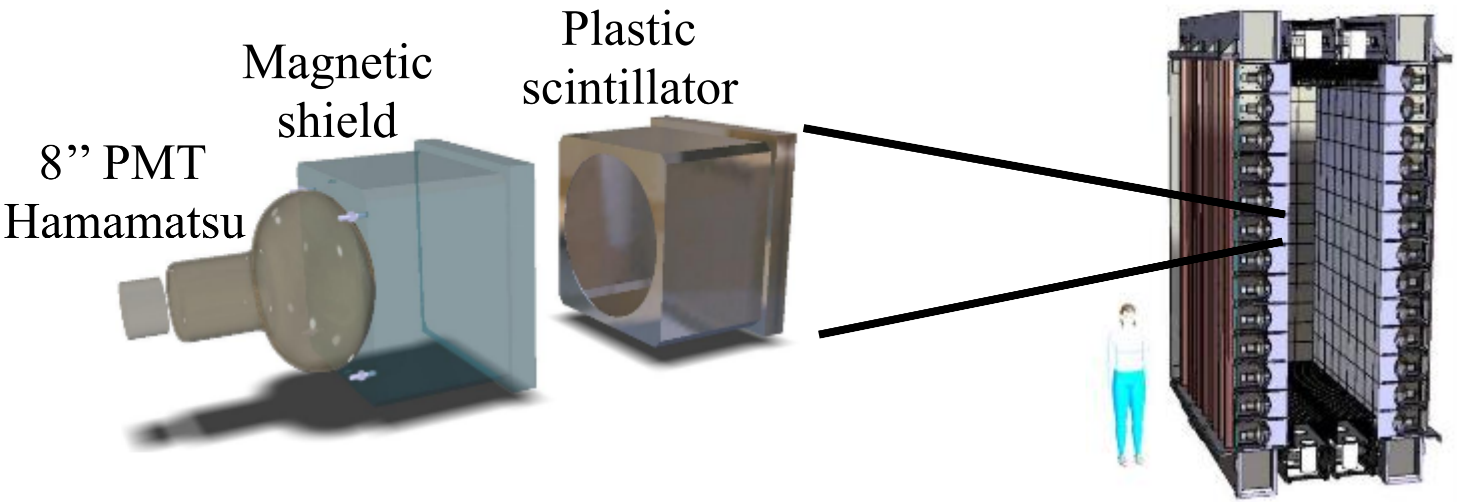


- ✓ For all the materials screened by gamma spectrometry, their activity have been compared to the PMTs activity
- ✓ The radiopurity budget of a subsystem in SuperNEMO must be negligible or at least not exceed 10% of the PMT budget

- ✓ For critical materials, simulations have been performed to evaluate their contribution

Example of pure iron for magnetic shield

✓ Example: 7 tons of pure iron used for PMT magnetic shield



✓ To fulfill the <10% activity PMT requirement, this lead to following limits :

$A(^{40}K) < A_{PMTs}/(\text{Iron mass}) \times 1/10 = 550.10^3 / 7000 \times 0.1 = 7.9$ mBq/kg

$A(^{226}Ra) < 200.10^3 / 7000 \times 0.1 = 2.9$ mBq/kg

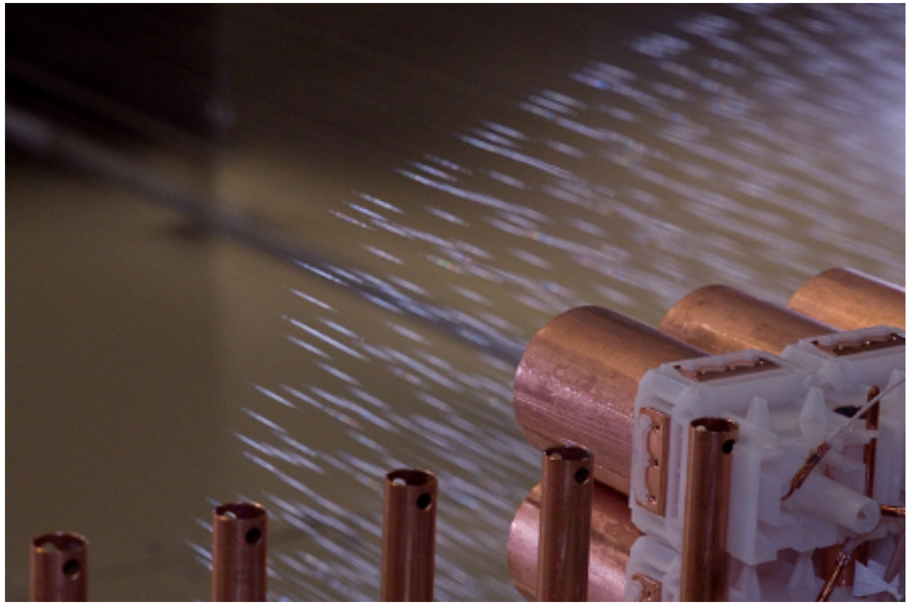
$A(^{232}Th) < 125.10^3 / 7000 \times 0.1 = 1.8$ mBq/kg

→ these limits can be (and have been) easily reached with HPGe detectors at LSM with selected radiopure iron

Example of critical materials for Tracker

Cathodic wires for tracking chamber

Copper rings for tracker cells

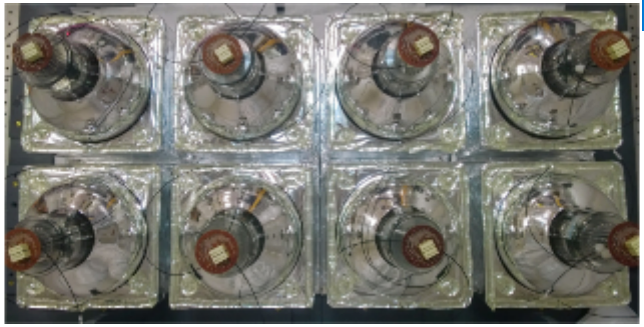


Critical materials for the calorimeter

Nylon film betwee tracker and calorimeter (Radon barrier)

Aluminized mylar for wrapping optical modules

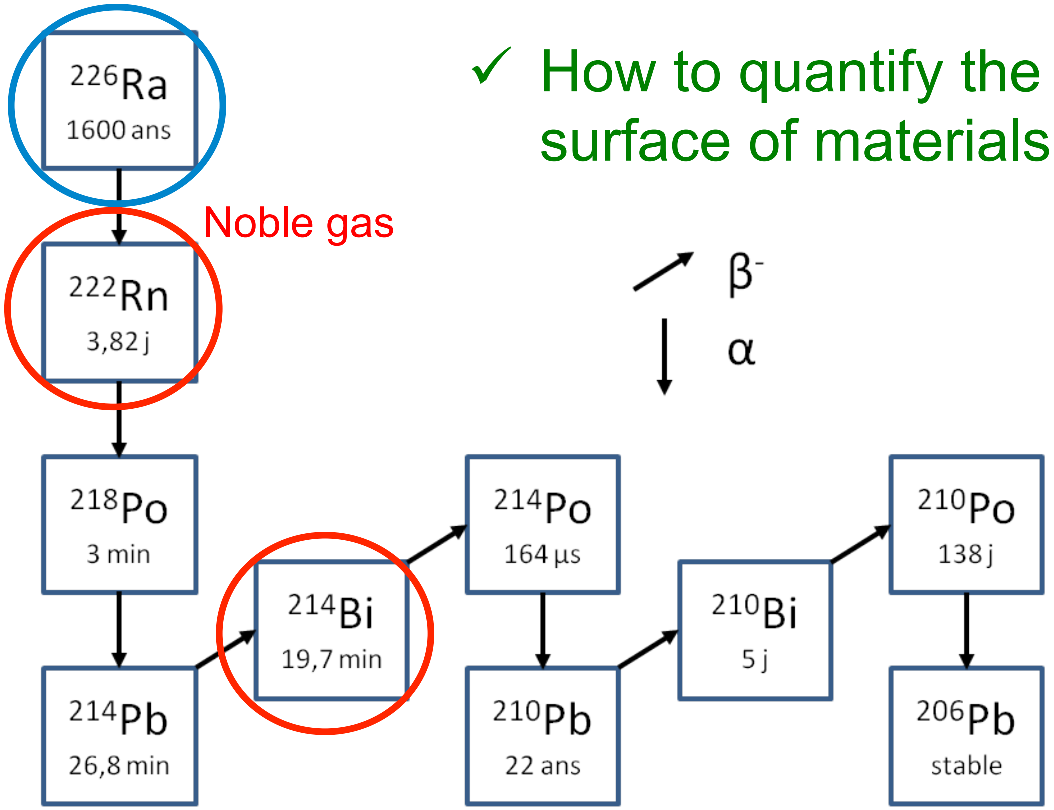
Components for PMT base



The Radon 222 issue

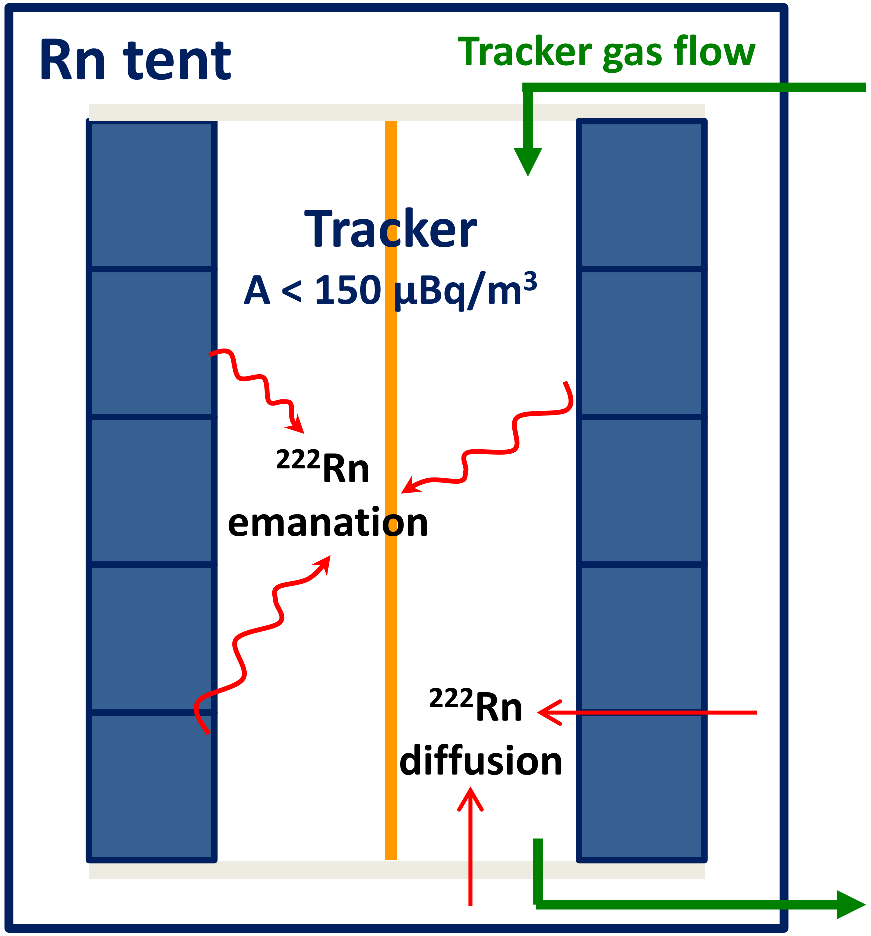
- ✓ Radon 222 (^{222}Rn) is a noble gas with a relative long half-life (3.8 days) which decays into ^{214}Bi (Q_{β}=3.27 MeV)
- ✓ For samples with large surface and/or low density, there is a risk of ^{222}Rn emanation/diffusion even if the ^{226}Ra activity is low (not observed by gamma spectrometry)

- ✓ How to quantify the ^{222}Rn escaping from bulk or surface of materials ?



Radon origin in SuperNEMO

Goal : maximum activity of 0.15 mBq/m^3 in the tracking chamber



Radon may have several origins:

- Rn impurities in the Tracker gas

→ purification with a Rn trap

- Rn diffusion from the outside

→ selection of tight and radiopure sealants

→ installation of a Rn tent with flow of radon-free air (LSM facility)

- Rn emanation from internal materials

→ Rn barrier between Calo and Tracker (nylon film)

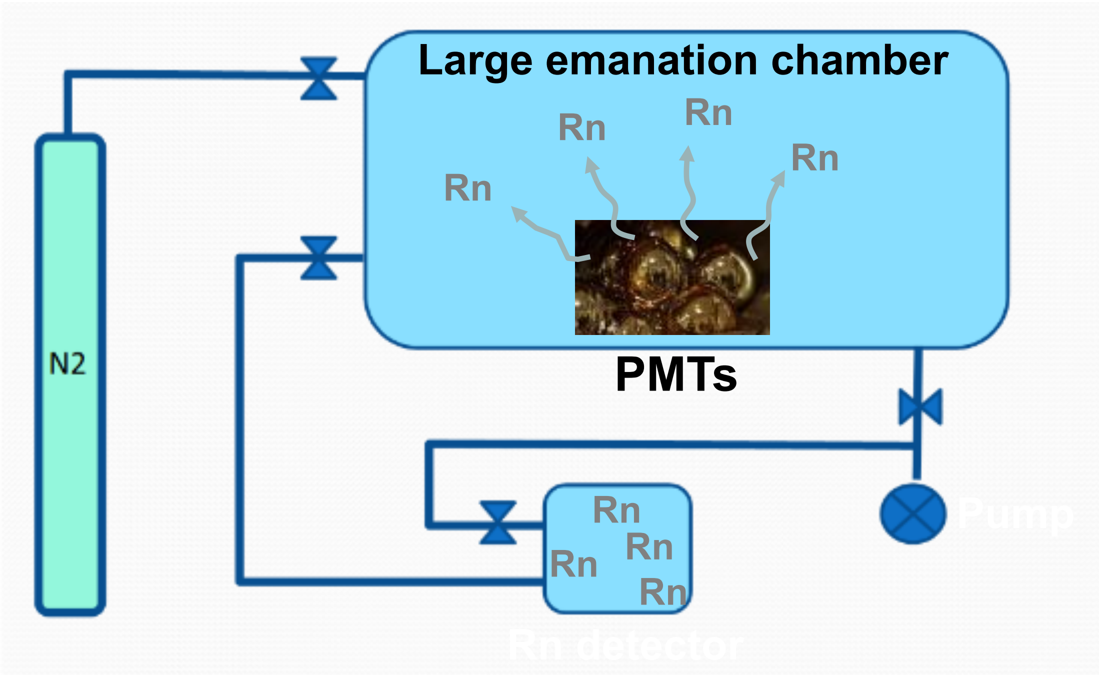
→ Selection of radiopure materials

Facility for Rn emanation measurements

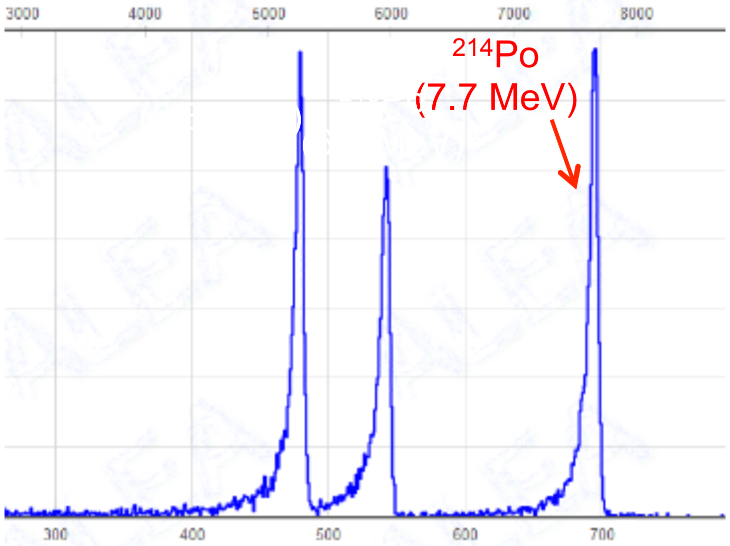
- Development of a Rn emanation setup in order to screen the large material in contact with the tracking chamber
- A 710L large chamber in stainless steel for large samples to be qualified
- An electrostatic detector using a 70L stainless steel vessel and a PIN Si diode to perform alpha-spectrometry (sensitivity ~1-3 mBq/m^3)

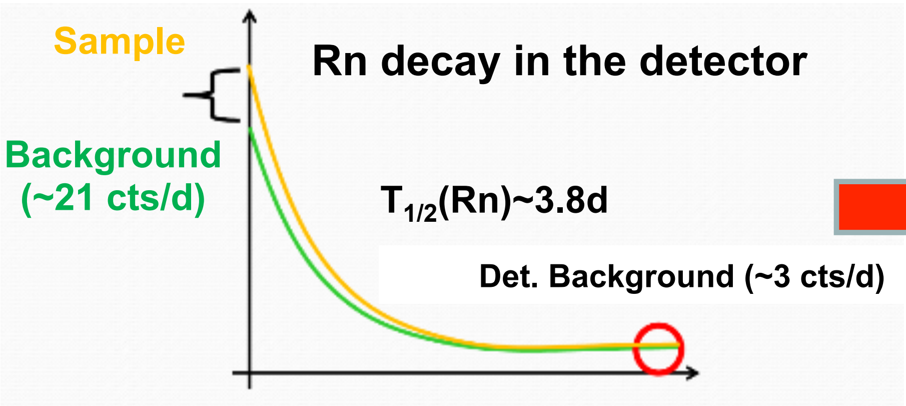
→ **Low background setup in operation since 2012**

Principle of the measurement



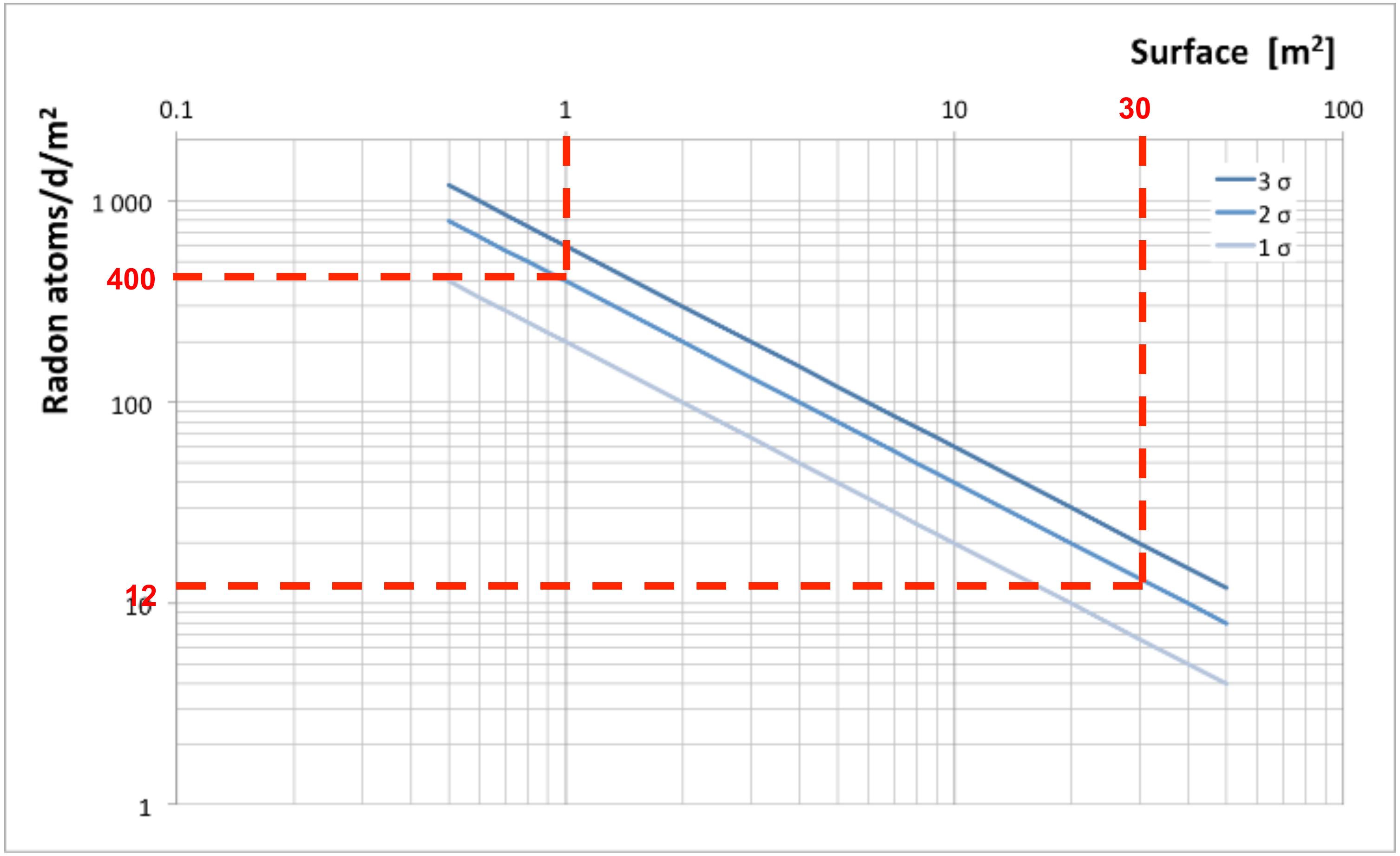
Alpha spectrum





Determination of the Radon emanation rate from the sample

Sensitivity of the Rn emanation setup



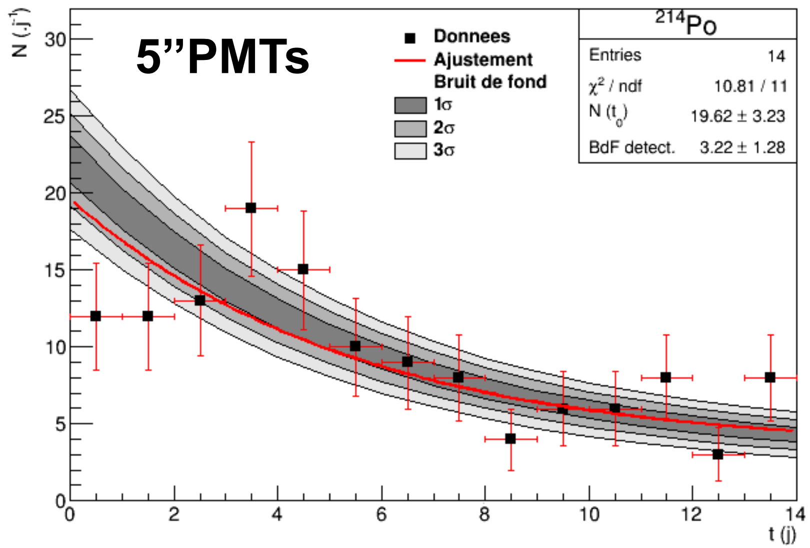
For 1 m^2 surface sample → emanation rate < 400 Rn atoms/day (95% C.L.)

For 30 m^2 surface sample → emanation rate < 12 Rn atoms/day (95% C.L.)

→ Sensitity of the measurement improved with the surface of the sample

Examples of Radon emanation screening

Emanation of 30 x 5”PMTs



Emanation of 30 x 8”PMTs

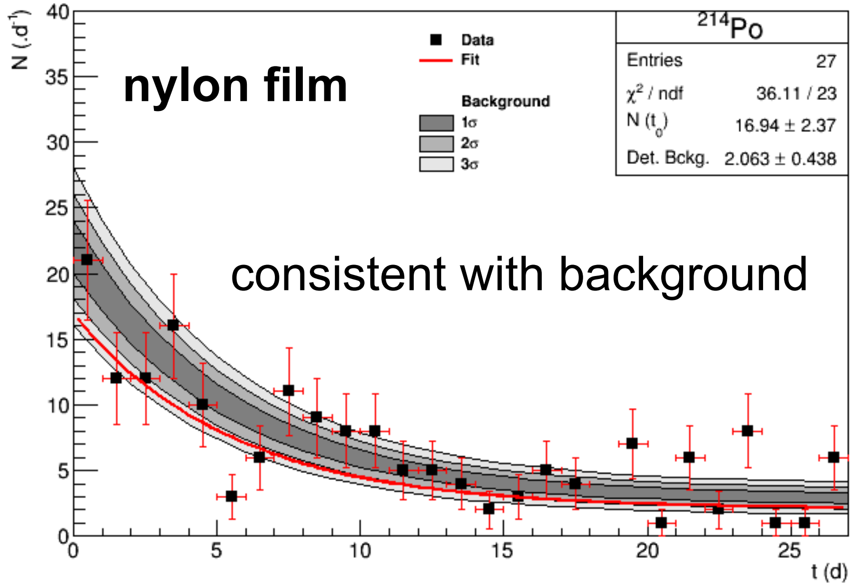
Radon emanation rate is consistent with the background level of the setup and below 0.16 mBq/PMT for 5”PMTs and 8”PMTs

→ totally negligible for SuperNEMO

→ not the origin of the remaining Radon in NEMO-3

Examples of Radon emanation screening

45 m^2 of nylon film (radon barrier between Tarcker and Calorimeter)



→ Radon emanation from nylon is negligible

→ nylon foil is a safe material for SuperNEMO

Other facilities for Radon studies

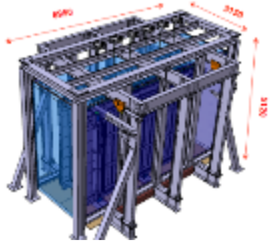
Radon emanation of critical materials

Large emanation facility with V~700L well-adapted to large volume or surface samples (films, PMTs…)

Small emanation facilities with V~3L well-adapted to smaller samples with a higher sensitivity

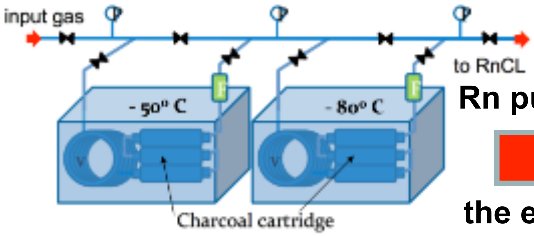
Radon diffusion in the Tracker

Rn diffusion facility to select ultra tight barriers (nylon film, sealing) to prevent Radon diffusion in the Tracker



Rn tent and 'Rn-free' air to prevent diffusion into the Demonstrator module from normal air in the lab.

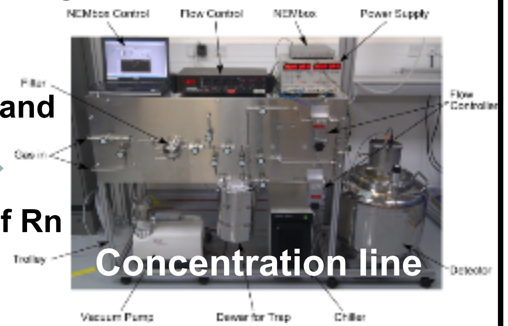
Radon Concentration Line to measure the final volumic activity in the Tracker



Rn trapping system

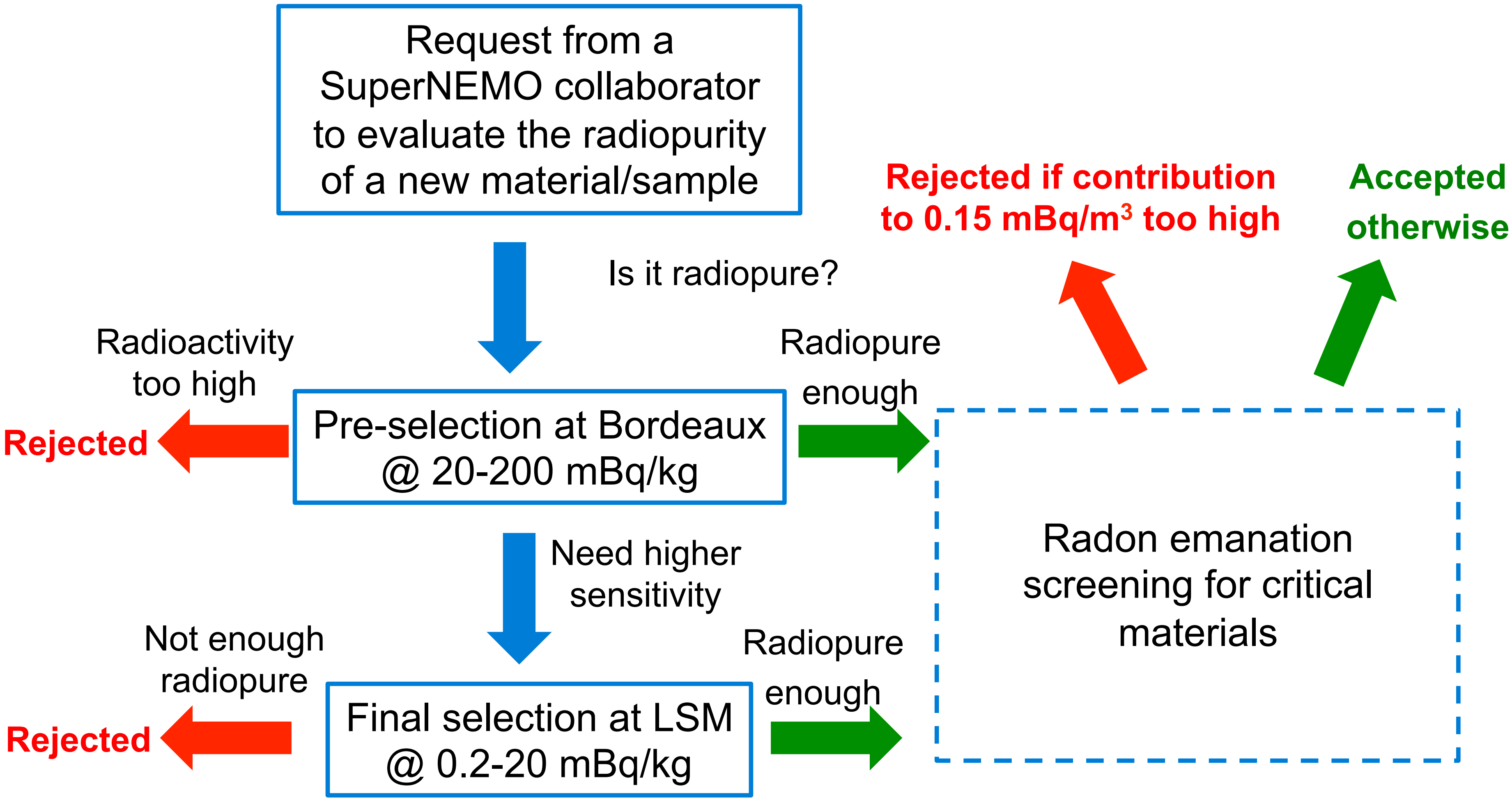
Rn purification of the entrance gas

Concentration and Measurement of Rn



→ for 2 m³/h flow rate, the 150 µBq/m³ level is achievable !

From sample to final decision-making

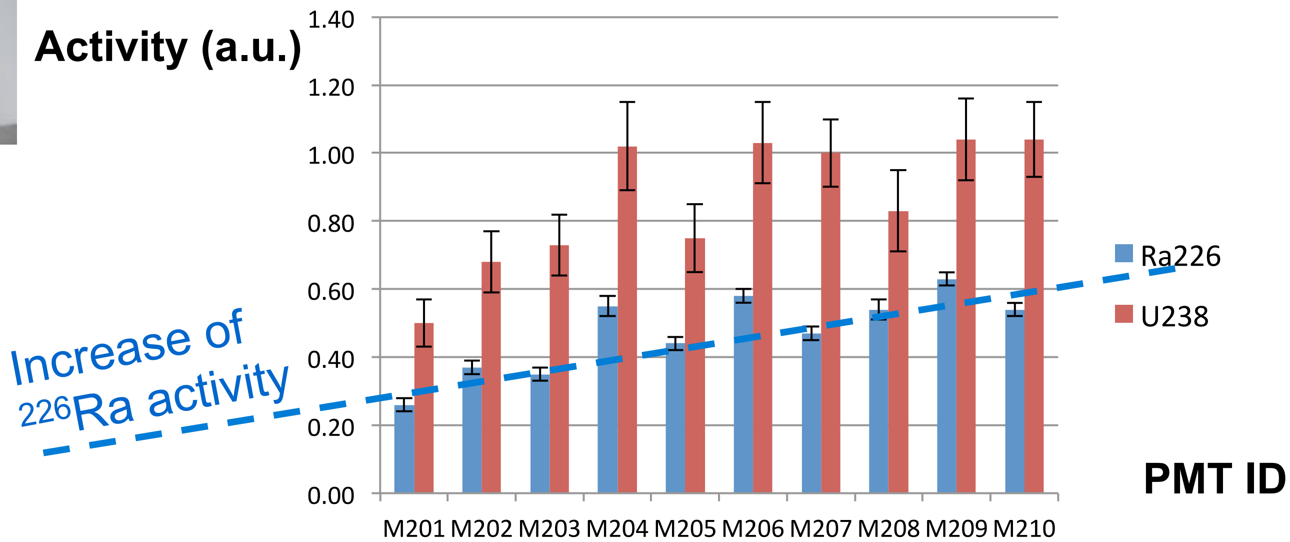


✓ More than 300 samples measured by gamma spectrometry and few tens of samples by Radon emanation measurement !

Illustration of some issues than may happen during the production

Radiopurity of the glass for 8'' PMTs

- ✓ 10 glass bulbs from 8'' Hamamatsu PMT measured



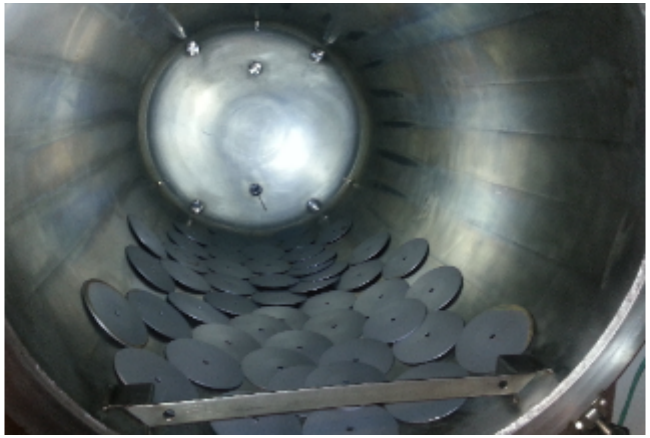
- ✓ The 10 PMTs are ranked according to the date of production: an increase of the ^{226}Ra activity is observed
- ✓ After discussion with Hamamatsu, it appears that:
  - The glass manufacturer has changed during the production !! → very important to control all the batches of glass during production
  - In addition, it is possible that the oven or crucible may have been slightly polluted during the production of the glass bulbs → very important to be in close contact with the company (if possible)

Sand blasting of iron beams

- ✓ In order to remove the roughness of the surfaces of Tracker beams, it has been decided by UK colleagues (researcher and engineers) to blast the iron beams with sand

- ✓ But the sand used (as it is often the case) was very radioactive, about 8 Bq/kg in ^{226}Ra with a risk of Radon emanation : 180 mg/m^2 of this sand would have reached the limit of SuperNEMO requirement…

- ✓ We checked the Rn emanation on iron plates that were treated with the same sand blasting and the same cleaning procedure



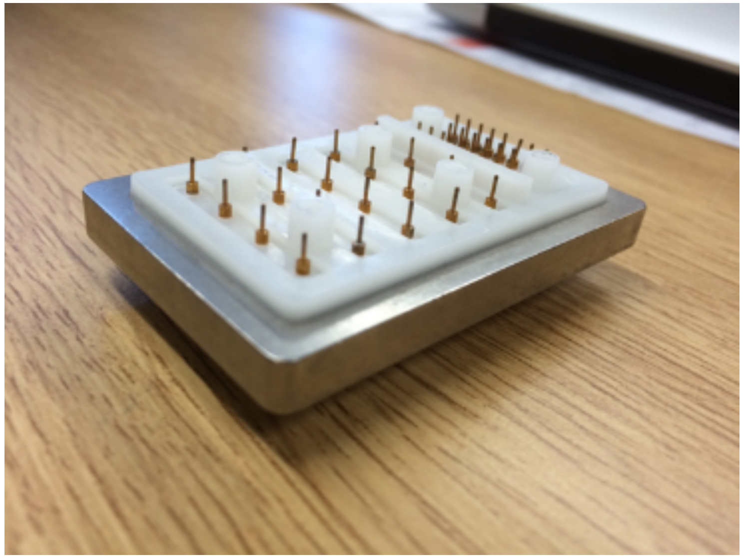
→ Fortunately, Rn was in limit of detection

→ It is very important to have the maximum number of people in a low background collaboration aware of the radiopurity issues

Pin connectors: brass ou BeCu?

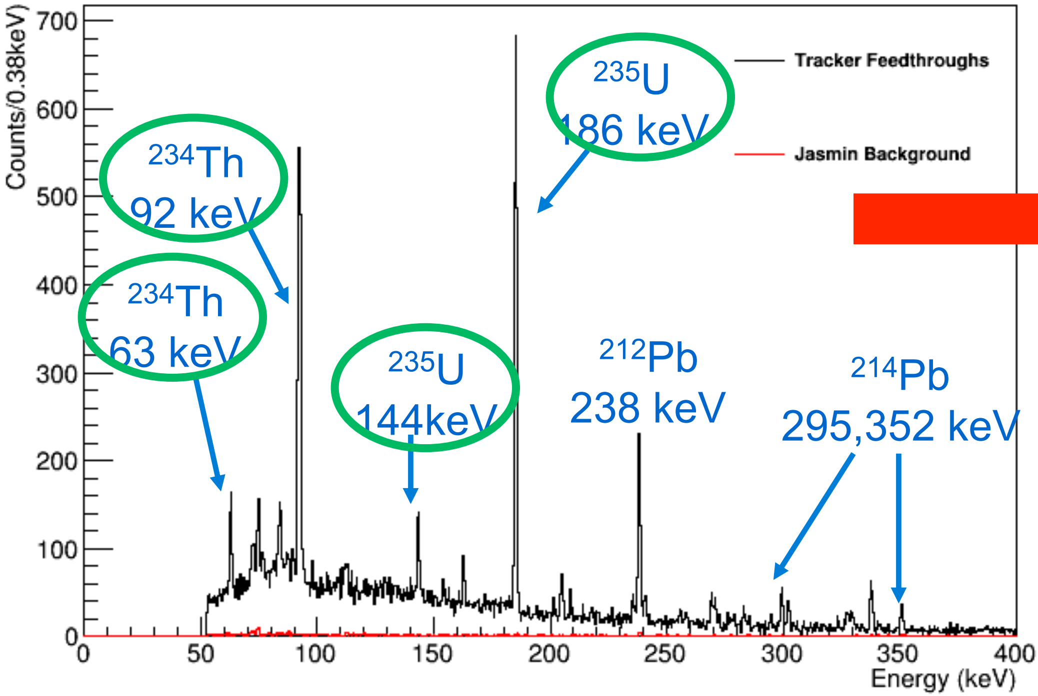
- ✓ Pin connectors have been screened during the production and not before the production of Tracker feedthroughs

- ✓ A priori safe material with brass pins, delrin and stainless steel



24 pieces have been measured by gamma spectrometry at LSM

Results: U contamination and BeCu pins



the main γ lines are coming from ^{235}U and ^{238}U chains

✓ Uranium is coming from pins at the level of ~10 mBq/g

✓ Pins are not in brass but in copper-beryllium (CuBe) !! Material has not been carefully choosen…

→ **risk of neutron production with high energy gamma emission**

Neutrons and gamma issues

- The neutrons will have 2 origins here :
  1) **Spontaneous fission SF** of ^{238}U (produces about 2 n/fission)

  2) **(Alpha,n) reactions on ^{9}Be** which is used to produce neutrons with isotopic sources (AmBe or PoBe)

$$\alpha + {}^{9}Be \rightarrow {}^{12}C^{*} + n$$

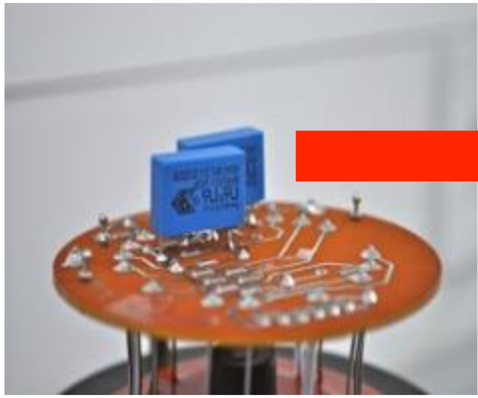
  This reaction also generates high energy gamma rays mainly at 4.44 which may be a major background for ββ0ν
- Neutrons are thermalized and captured by ^{56}Fe producing gamma rays of 7-9 MeV. They will produced e^-/e^+ pair in the foil and mimic a ββ event if the curvature of the positron is not well-reconstructed

→ simulations have shown that the gamma and neutrons background will not affect the sensitivity of the demonstrator

→ but it would have been an issue for full SuperNEMO (100 kg)

Capacitors for PMT base

✓ Huge efforts have been put to screen and to finally select radiopure capacitors for 8''PMTs and 5''PMTs bases



Capacitors removed from 5''PMT base because too much radioactive

→ It takes time to build a radiopure detector…

Quality procedure: traceability of a sample (1/3)

- A request form for HPGe measurement has been established in the SuperNEMO collaboration : the goal is to have a well-identified sample with all the needed information

- When, who ?
  - Date of submission:
  - Submitter:

- Description and reference of the sample/material
  - Sample description/ Commercial name:
  - Chemical composition:
  - Manufacturer:
  - Supplier:
  - Reference (manufacturer):
  - Batch number:

Quality procedure: traceability of a sample (2/3)

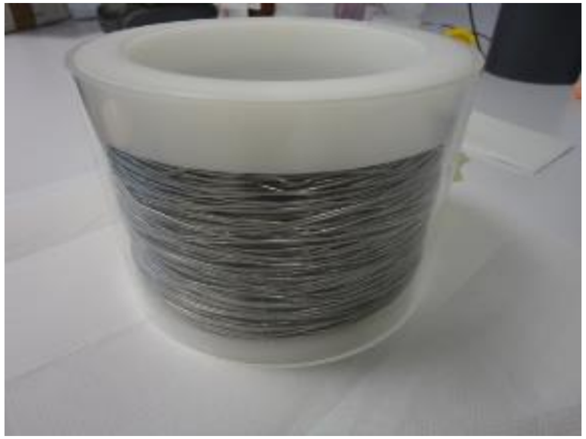
- Where in the demonstrator? Total mass/surface?
  - System:
  - Sub-system:
  - Total expected mass/number in SN demonstrator:
  - Total expected surface in the SN demonstrator (critical for Rn emanation):

- Which geometry/mass available for HPGe measurement?
  - Sample mass:
  - Sample geometry :
  - Already cleaned:
  - Already conditioned (in a Marinelli, plastic box, others):

  If yes: precise

Quality procedure: traceability of a sample (3/3)

- Comments
  - If sample was cleaned: could be a brief description of the cleaning process
  - Other informations
- How it looks like?
  - A picture of the sample before or (better) after conditioning if it is still visible can be also attached to this file (can help for geometry considerations and to be sure that we are talking about the same sample!)



Examples

Tracker wires

Request for a HPGe radiopurity measurement

Date of submission: 16.07.2014
Submitter: J.Pater

Sample description/ Commercial denomination: 50u diameter tracker cathode wire
Chemical composition: stainless steel: 1.4301 X5crNi18-10 AISI304
Manufacturer: Trakus, Bergneustadt Koelner Str. 113, 51647 Gummersbach, Germany
Supplier: steel supplied to Trakus from French source
Reference (manufacturer): Trakus delivery no 2399011
Batch number: N/A

Sample mass: 794g
Sample geometry: 50u-diameter (cathode) wire
Already cleaned: yes
Already conditioned (in a Marinelli, plastic box, others): Yes – wound onto small Marinelli bobbin No.4. Thickness of wire layer is about 3.8mm; see attached photograph.

System: tracker
Sub-system: cathode and anode wires
Total expected mass/number in the SN demonstrator: 0.57 kg
Total expected surface in the SN demonstrator (critical for Rn emanation): 6.65m^2

Comments :
Expected mass in demonstrator taken from R.Thompson notes, Oct-2011.
Expected surface area:

- anode wires : 18 * 113 wires, 2.92m long, diameter 40u=0.75m^2
- cathode wires: 114 *113 wires, diameter 50u=5.9m^2

Nylon foil

Request for a HPGe radiopurity measurement

Date of submission: 7/01/2014
Submitter: Mathieu Bongrand (LAL)

Sample description/ Commercial denomination: Nylon Film OPA25
Chemical composition: nylon
Manufacturer: MF-Folien GmbH
Supplier: MF-Folien GmbH - Kempten - Germany
Reference (manufacturer): OPA25
Batch number:

Sample mass: 1106.7 g
Sample geometry: strips between 80-90 mm wide and about 2 m long
Already cleaned: produced in clean environment
Already conditioned (in a Marinelli, plastic box, others): Delrin Bobbin - Marinelli 40

System: Calorimeter
Sub-system: Radon tightness between calorimeter and tracker
Total expected mass/number in the SN demonstrator: 3.5 kg
Total expected surface in the SN demonstrator (critical for Rn emanation): ~ 120 m^2

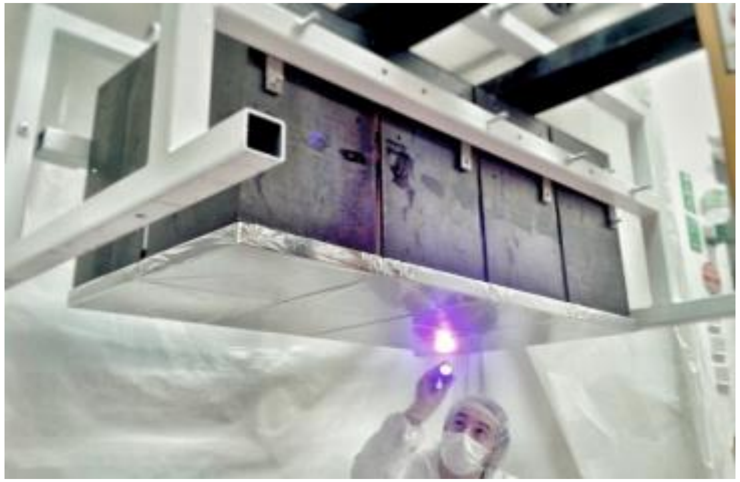
Comments :

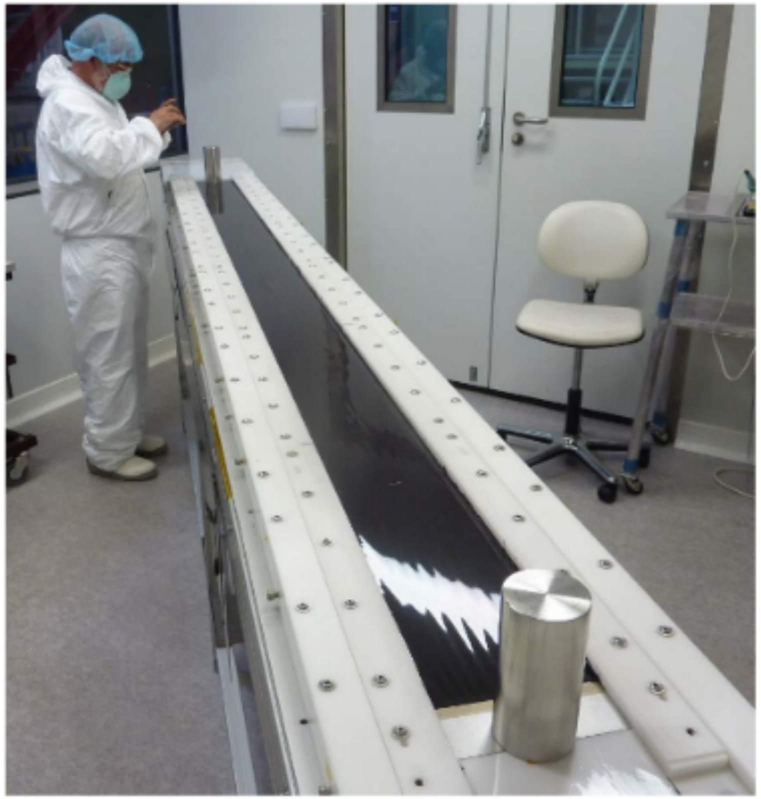
The Delrin bobbin was previously cleaned by Manchester group.
The nylon strips were cut in LAL clean room with a PMMA ruler and a cutter and rolled by pack of around 50 g around the bobbin.
The bobbin is wrapped in PE film for transportation : to be removed for measurement.

Final installation of the detector in a clean environment

During the assembling of the detector

- ✓ Once the materials have been selected, they must be assembled in clean conditions/ clean environment in the different labs





- ✓ The final installation must be also performed in a clean environment

During the installation of the detector

- ✓ For the installation of SuperNEMO, a home-made cleanroom has been built and installed at LSM
- ✓ Use of 12 laminar flow hoods, each flushing 680 m^3/h of purified air from top to bottom to remove the dusts
- ✓ Renewing of the air once every 2 mn for a 300m^3 cleanroom !

During the installation of the detector

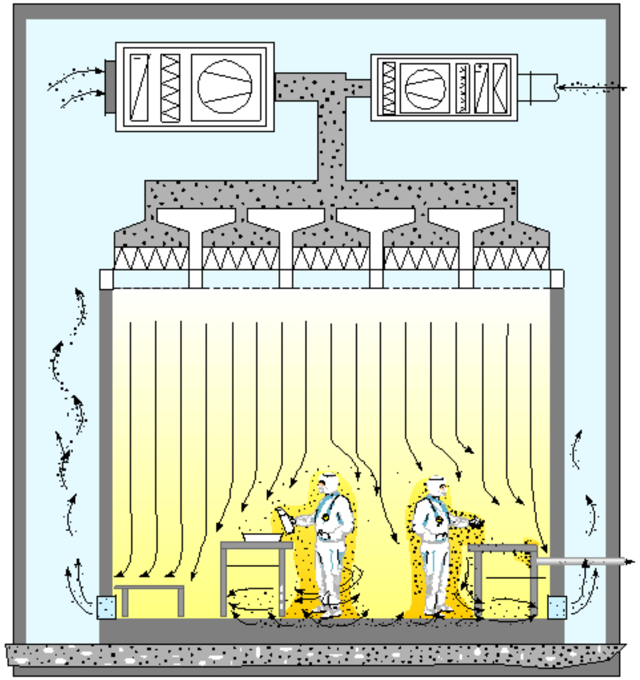

Top of the cleanroom with 12 laminar Flow hoods


Integration of the first calorimeter wall

ISO Cleanroom Standards

Airborne Particulate Cleanliness Classes (by cubic meter):

CLASS	Number of Particles per Cubic Meter by Micrometer Size					
	0.1 micron	0.2 micron	0.3 micron	0.5 micron	1 micron	5 microns
ISO1	10	2				
ISO2	100	24	10	4		
ISO3	1,000	237	102	35	8	
ISO4	10,000	2,370	1,020	352	83	
ISO5	100,000	23,700	10,200	3,520	832	29
ISO6	1,000,000	237,000	102,000	35,200	8,320	293
ISO7				352,000	83,200	2,930
ISO8				3,520,000	832,000	29,300
ISO9				35,200,000	8,320,000	293,000

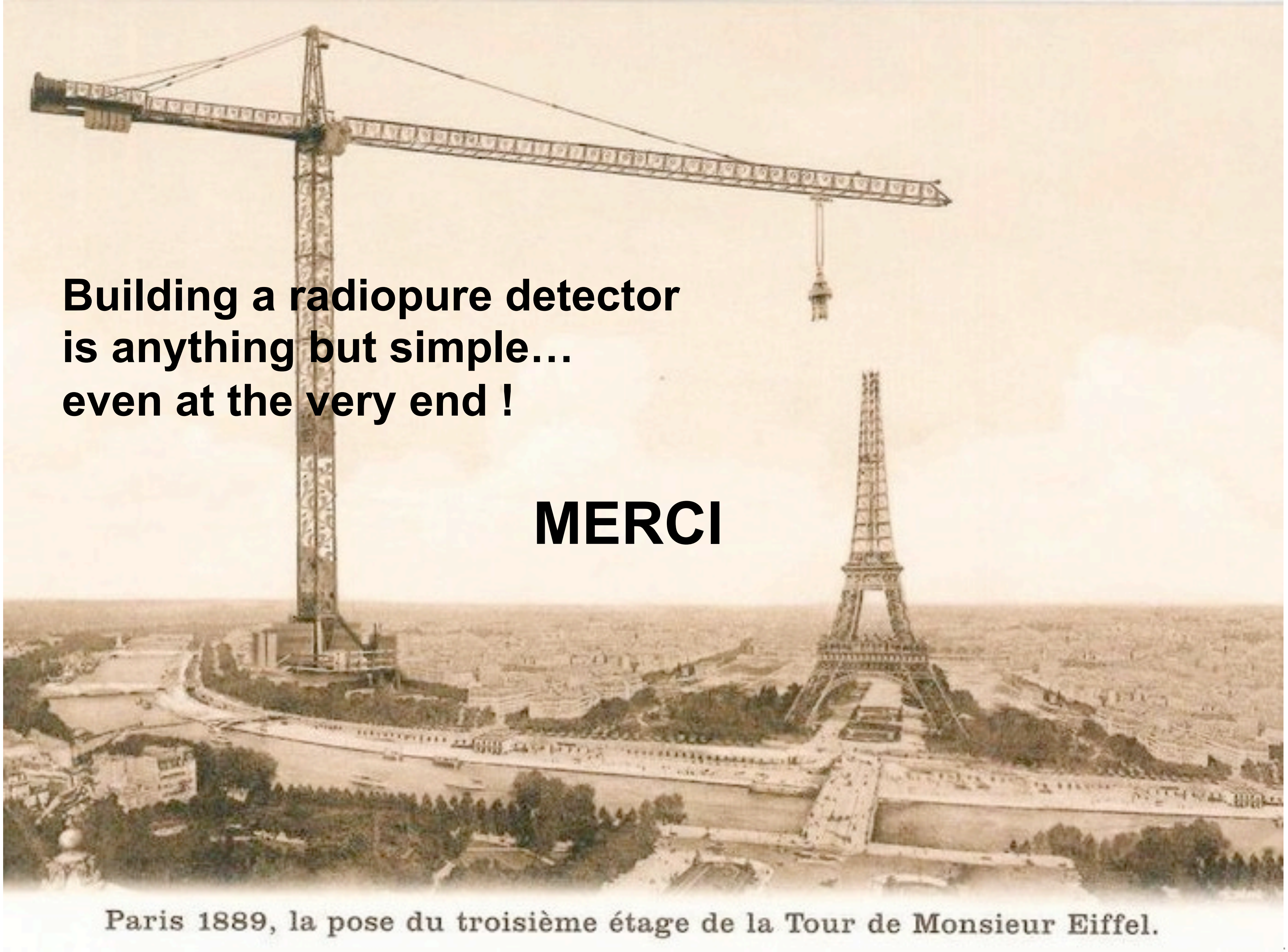


Conclusions

- ✓ The SuperNEMO tracko-calorimetric technique (source≠detector) is very powerful to identify and reject most of the backgrounds around 3 MeV → only ^{208}Tl and ^{214}Bi (^{222}Rn) are dangereous
- ✓ Radiopurity strategy in SuperNEMO has consisted in developing a dedicated technique for each of the critical material (BiPo, radon emanation, gamma spectrometry)
- ✓ There is no safe material and ALL the materials entering in the construction has to be screened by low background gamma spectrometry : more than 300 samples measured
- ✓ Some issues always happen during the construction: every people involved in a low background experiment has to be aware of the radiopurity issues

Building a radiopure detector is anything but simple… even at the very end !

MERCI



Paris 1889, la pose du troisième étage de la Tour de Monsieur Eiffel.

SuperNEMO strategy

Ultra-critical materials: ββ ^{82}Se source foils
→ dedicated detector called BiPo3 to qualify their radiopurity at the level of few tens μBq/kg

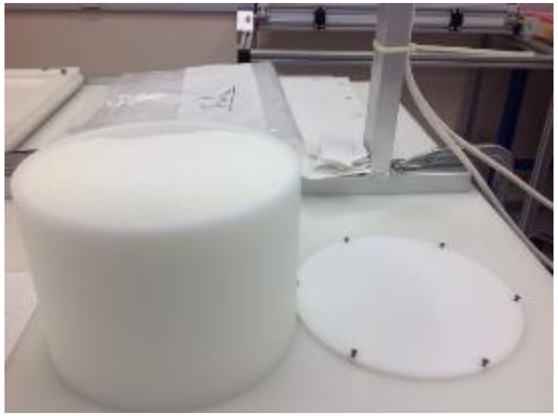
Critical materials: tracker and source frame materials in contact with the gas
→ dedicated techniques to qualify their radiopurity by low-background gamma spectrometry and Radon emanation at the level of 0.2-20 mBq/kg

Nylon film (Radon barrier)

« Less » critical materials: calorimeter and surroundings materials
→ dedicated techniques to qualify their radiopurity by low-background gamma spectrometry and Radon emanation at the level of 1-1000 mBq/kg

Critical materials for the source

PVA powder to be mixed with ^{82}Se powder



Acetron rollers for source foils holding (medical grade quality)

From sample to decision

- ✓ Reception and conditionning of the sample
- ✓ Depending on the mass of the sample and the sensitivity to be achieved, you choose the best container and the more sensitive HPGe detector
- ✓ Cleaning procedure and conditionning in clean bags
- ✓ Traceability: provider/batch number/reference code
- ✓ Measurement at Bordeaux or LSM
- ✓ Pre-analysis during the measurement
- ✓ Is it radiopure enough?