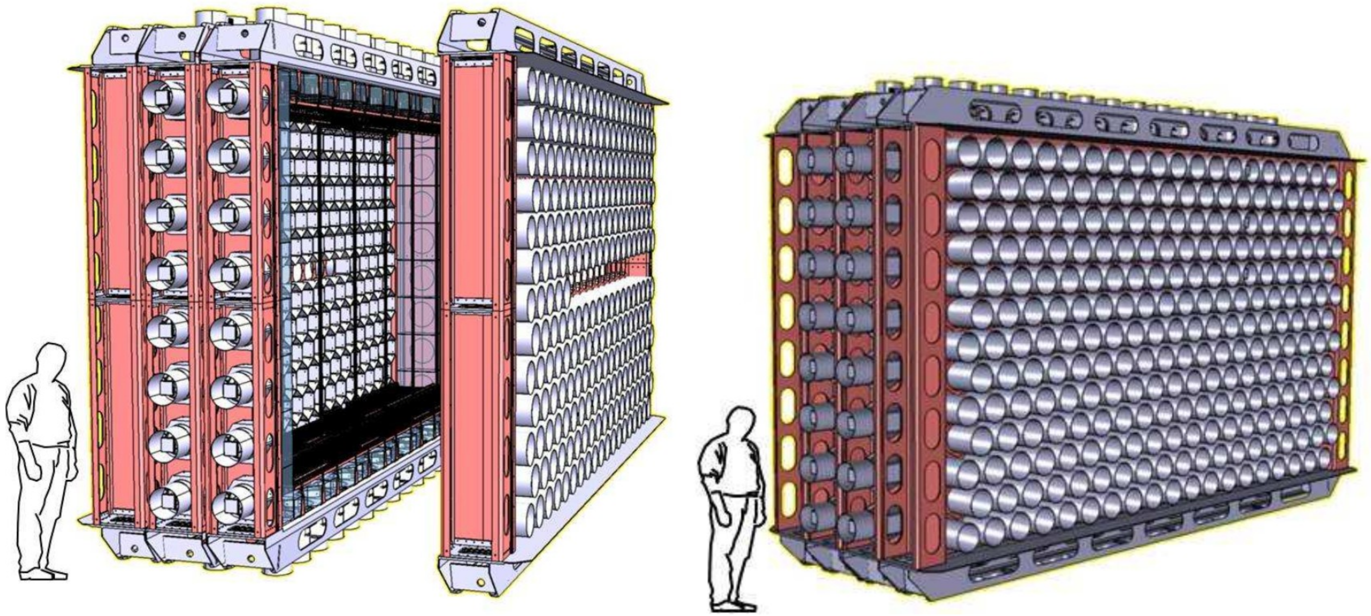
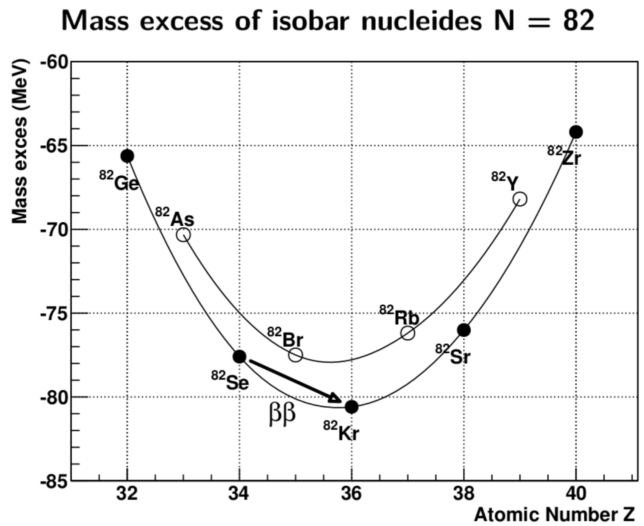
Radon emanation studies in the SuperNEMO double beta decay experiment



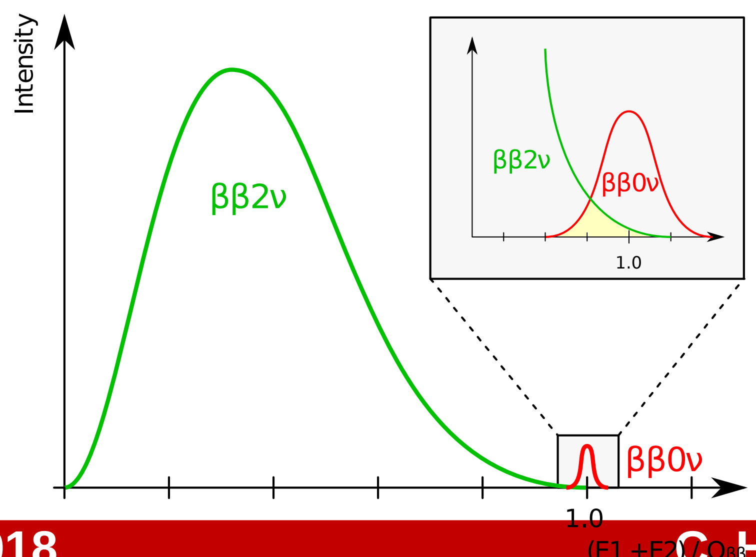
Hugon Christophe
Université Aix-Marseille, CPPM, IN2P3/CNRS
on behalf of the SuperNEMO collaboration

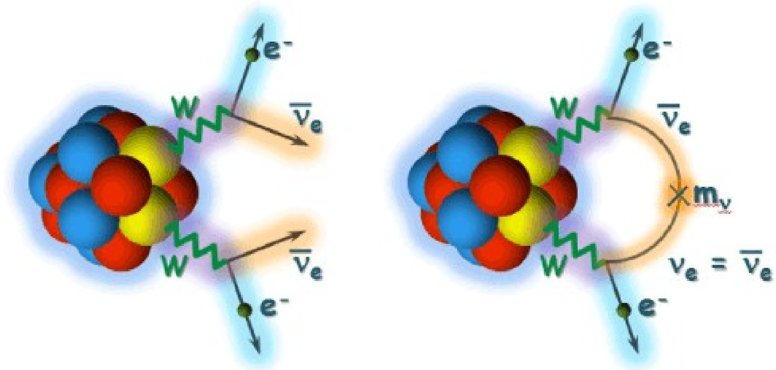
supernemo collaboration

The double beta decay



For some isotopes as the ^{82}Se only the ββ decay is allowed





Gives an access to 3 fundamental informations

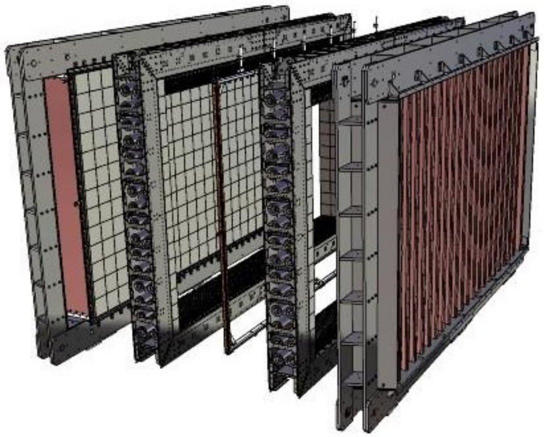
- Neutrino nature (Dirac or Majorana)
- Effective mass ν_{ee}
- Neutrino mass hierarchy

The both decays have a different energy spectrum

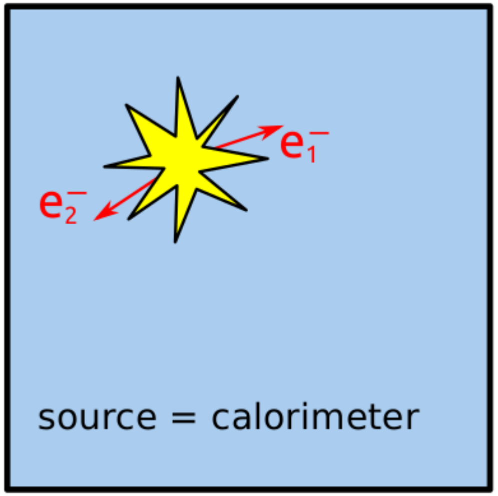
$$T^{1/2}(2\beta 0\nu) \propto \frac{1}{|M|^2 |m_{\beta\beta}|^2}$$

The calorimetry/tracking technology From NEMO-3 to SuperNEMO

NEMO-3 (2003 - 2011)



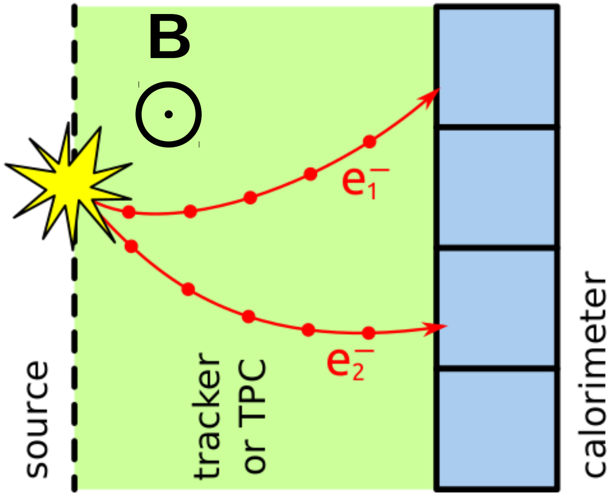
SuperNEMO démonstrateur (≥ 2016)



→ GERDA, KamLAND-Zen, CUORE, ...

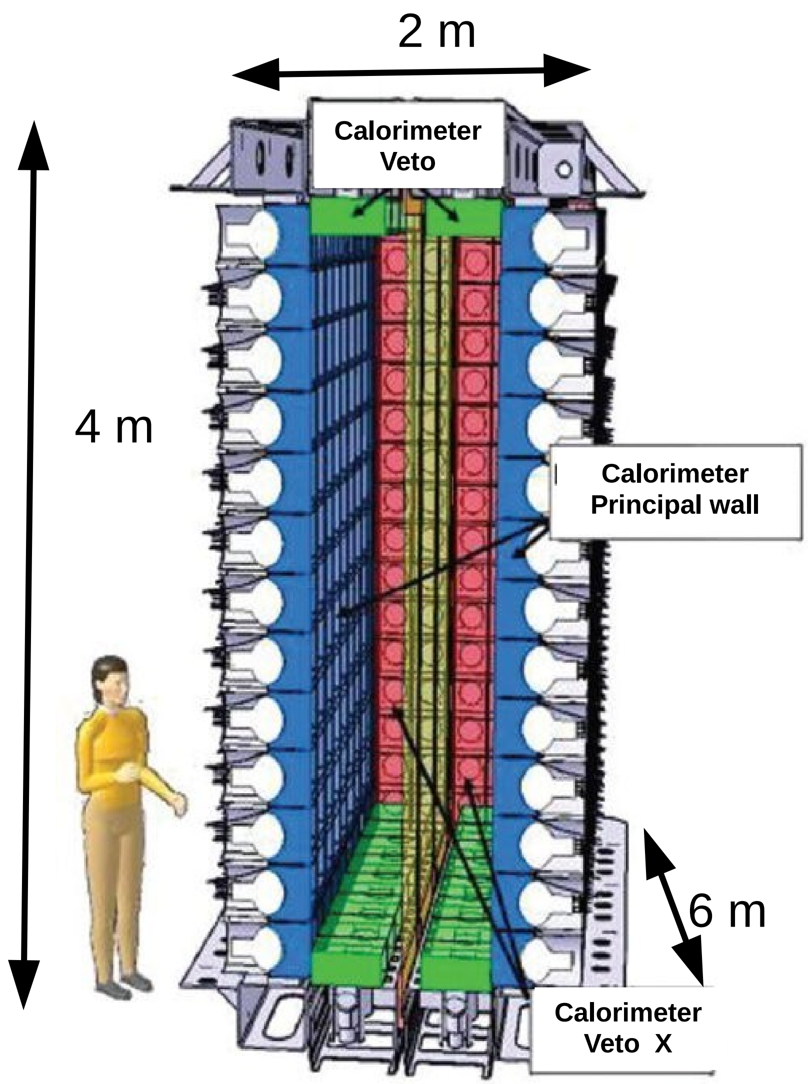
The calorimetry/tracking technology
- Has a lower efficiency
- Poor energy resolution (8%@1MeV for SuperNEMO)

But
- It has a good electron identification and ββ kinematics
- It can identify other particles ($\alpha,\gamma,\beta^+,\beta^-$)
- It can be multi-sources
- Background identification an rejection
- Multi-channel study ββ0ν, ββ2ν, ββ*, ...



→ EXO, NEMO-3, SuperNEMO

The new generation: SuperNEMO

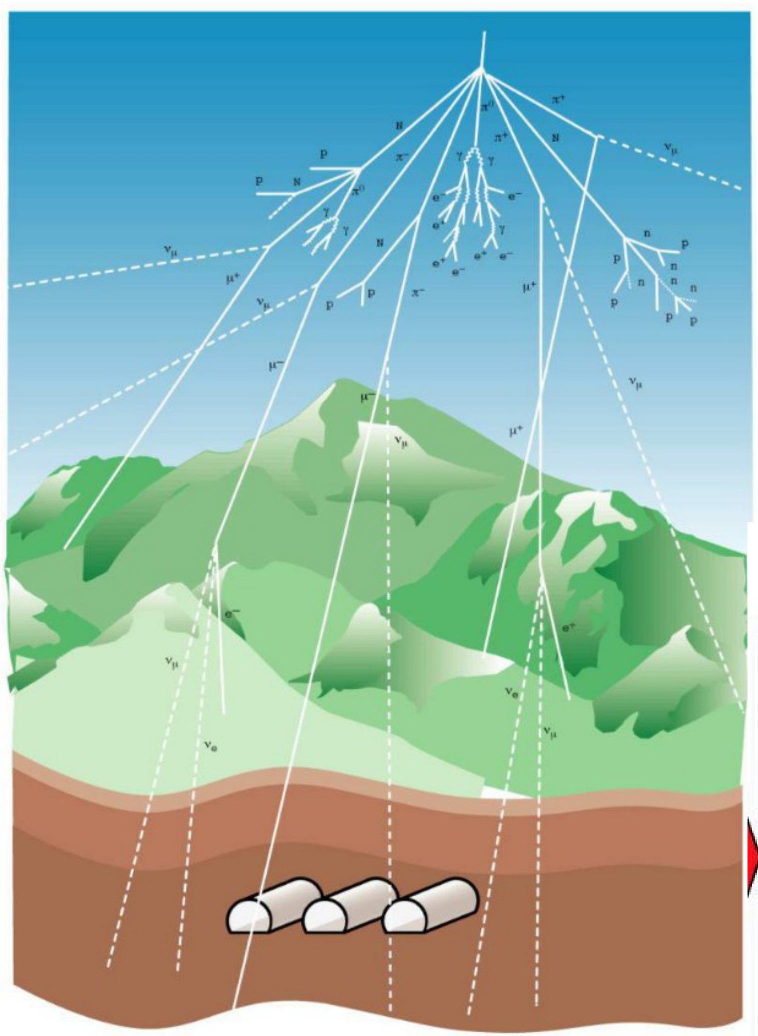


- Installed at the Frejus lab. 4,800 mwe depth
- The full detector will be composed by 20 modules
- For a total source mass of 100 kg (mainly ^{82}Se and ^{150}Nd)
- The calorimeter will be composed by scintillator+PMTs walls
  - 8% of energy resolution @ 1MeV
  - 250 of time spread
  - <1% of linearity divergence from 200 keV to 3 MeV
- The tracking will be done by a wire chamber of 2000 cells at Geiger mode
- 25 G field for particles identification

ββ0ν lifetime objective:
$T_{12}(\beta\beta0\nu) > 10^{26}$ years

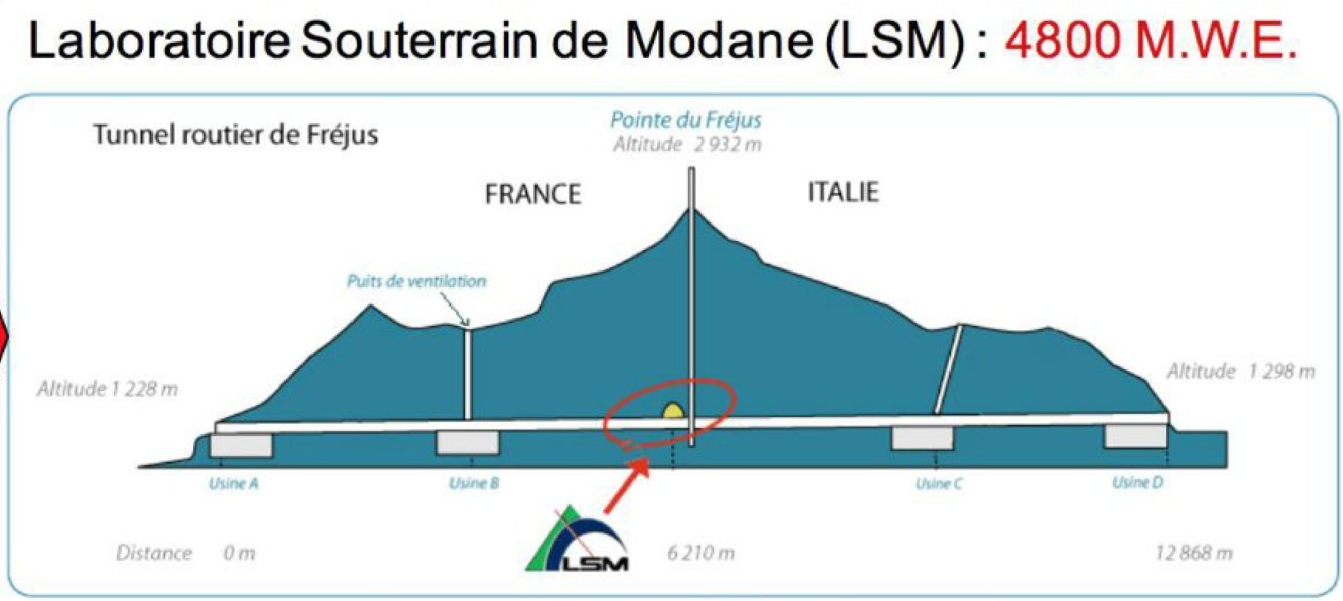
The background reduction and control are essential to reach this goal

Underground laboratories and muon flux

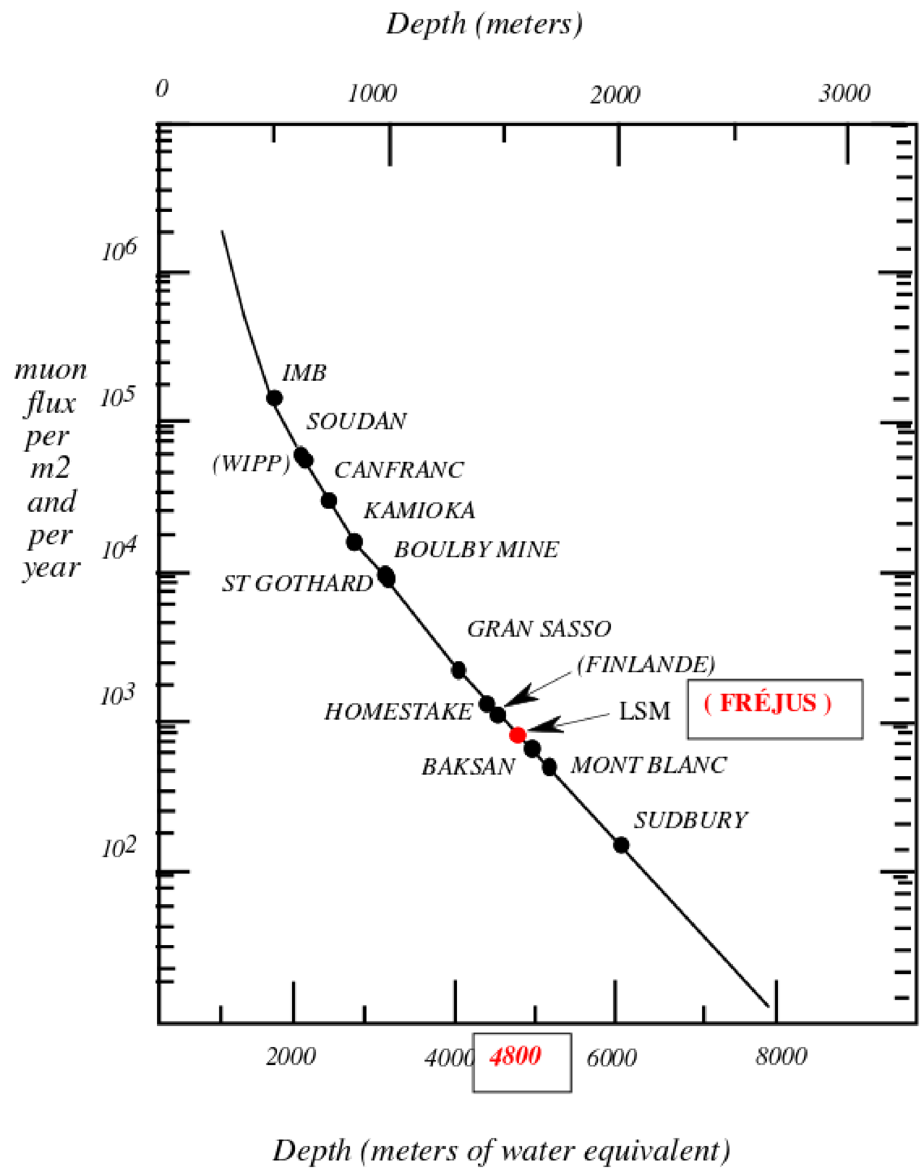


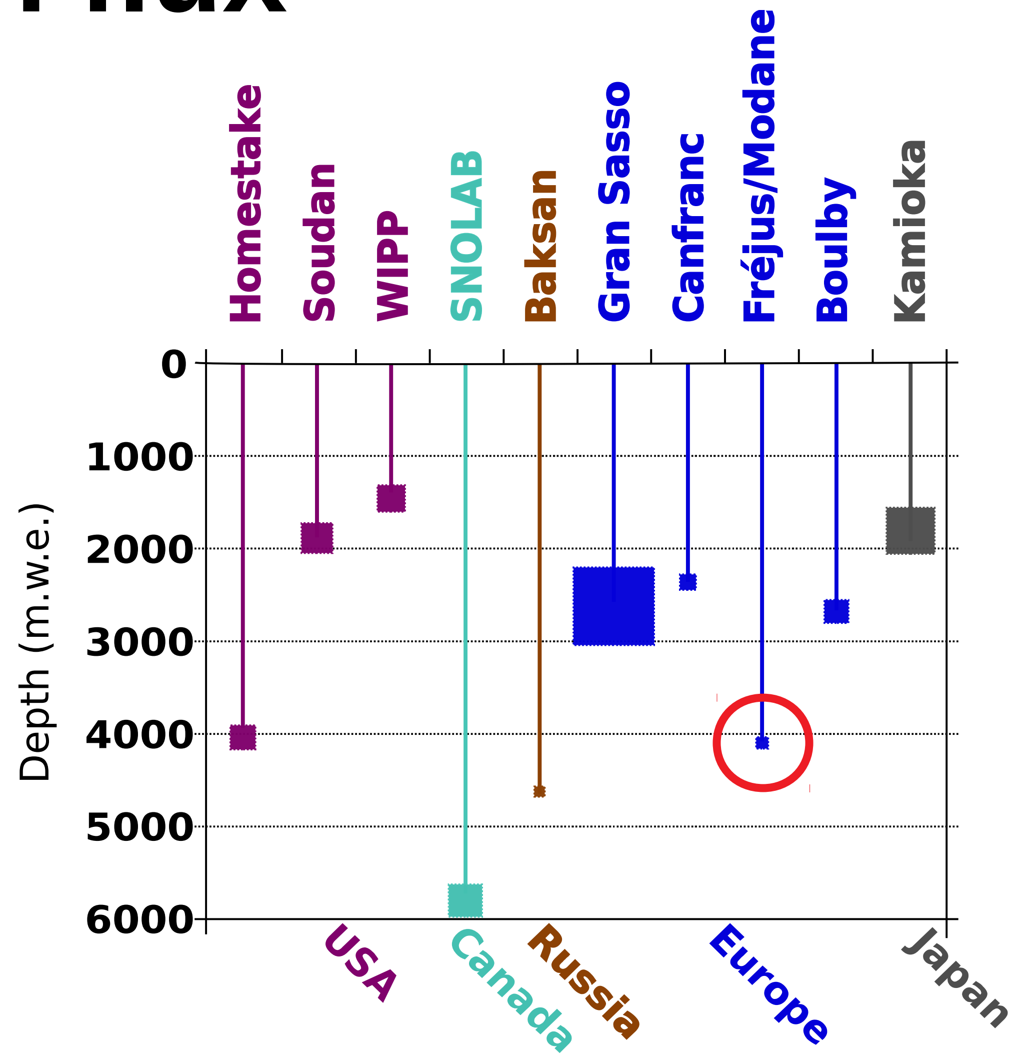
- Very rare events → needs a very low background
- “Laboratoire souterrain de Modane”
  - In the frejus tunnel
  - Dug in 1983 for the proton decay research
  - 1780 m underground, 4800 m MWE

Reduction of muon flux by a factor of 10^6



Underground laboratories and muon flux





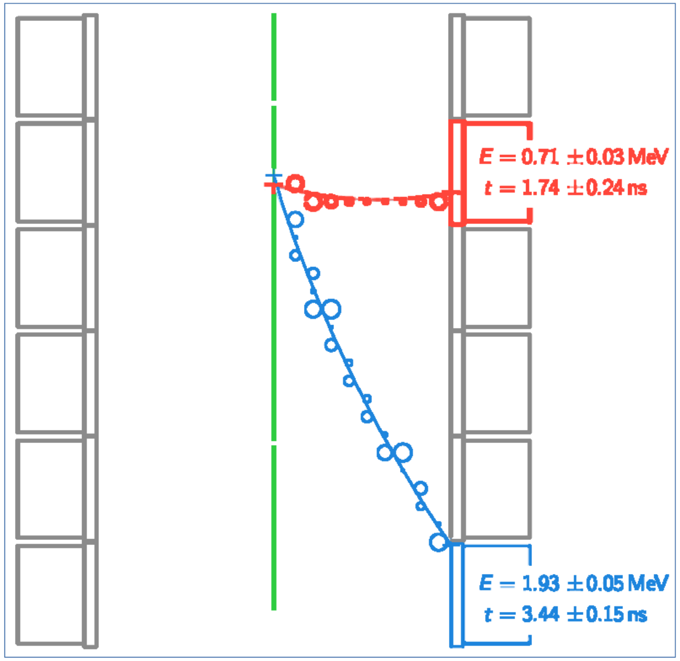
Deepest in Europe

The SuperNEMO international collaboration

SuperNEMO demonstrator sources

- Source
  - 7 kg of ^{82}Se ⇄ 17.5 kg.yr
  - ~40 mg/cm^2
  - $T_{1/2}(2\nu\beta\beta) = 10.3 \pm 0.3$ (stat) $\pm$ 0.7 (syst) 10^{19} y
  - $Q_{\beta\beta}$ = 2,966 MeV

SuperNEMO demonstrator tracker



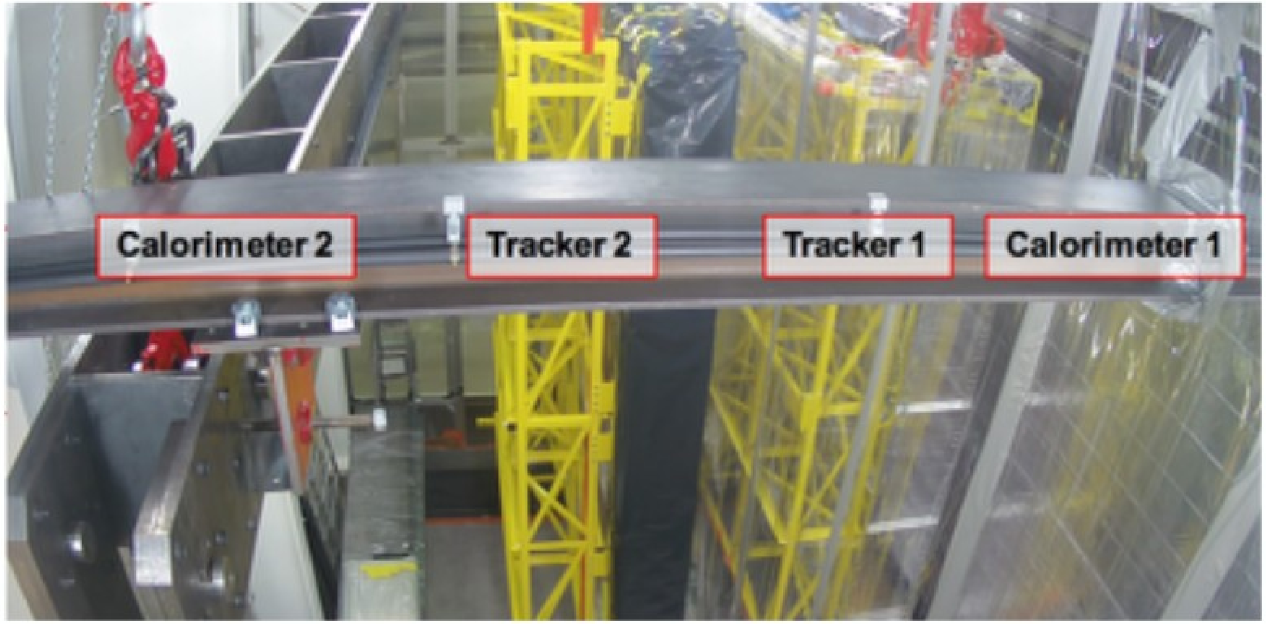
- 2034 wires in Geiger mode in each module (~45 km of wires)
- Ultra pure material (copper, steel, duracon, HPGe tested)
- 3d track reconstruction

SuperNEMO demonstrator calorimeter walls

- Calorimeter
  - 520 x 8” PM + 192 x 5” PMs coupled with polystyrene scintillators
  - Energy resolution: 8% FWHM @ 1 MeV
  - Time resolution: σ = 400 ps @ 1MeV

SuperNEMO demonstrator status

- Calorimeter on site, under final commissioning
- Cabling ongoing at the LSM
- The demonstrator data taking will start by the half of 2018



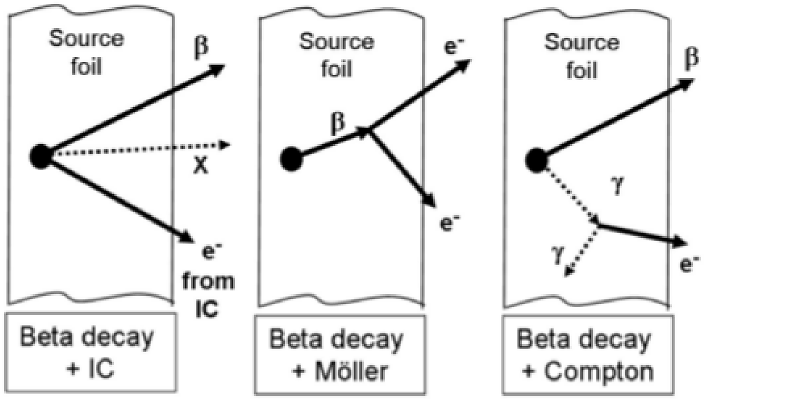
The Background noise: Internal background

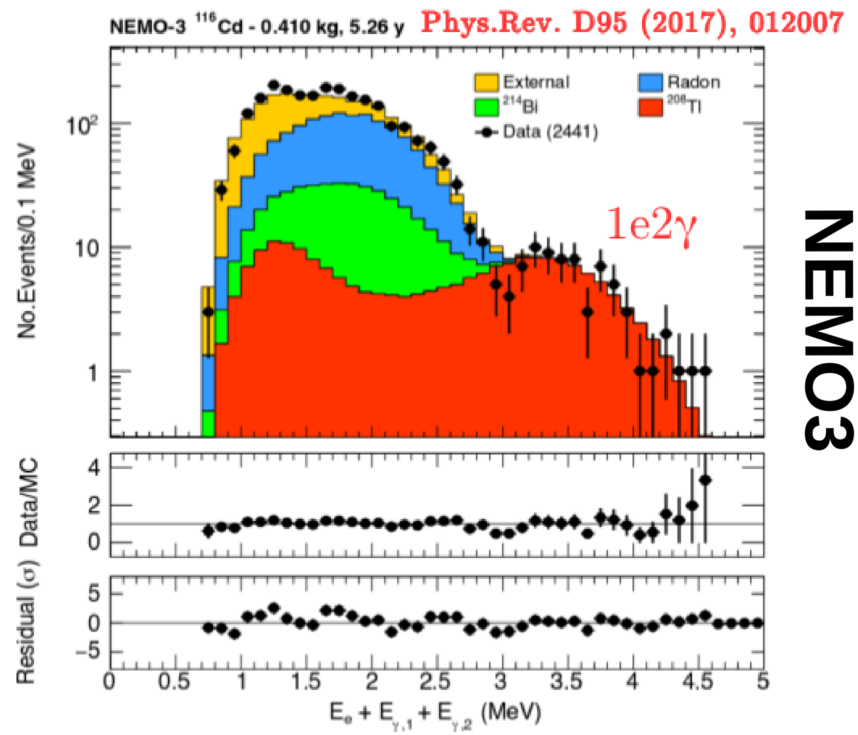
Regroups the backgrounds coming from the source foil, mainly come from :

- Radio-impurities inside the source foil
  - ^{208}Tl (from ^{232}Th), ^{214}Bi (from ^{238}U)
  - Single beta emitter (^{40}K, ^{234m}Pa, ^{210}Bi)
- ^{214}Bi from radon decay in tracker volume

Backgrounds are measured through different background channels using event topologies

- ^{208}Tl in 1e1γ, 1e2γ and 1e3γ
- ^{40}K, ^{210}Bi, ^{234m}Pa in 1e channel
- ^{210}Bi, ^{222}Rn in 1e1α and 1e1γ channel





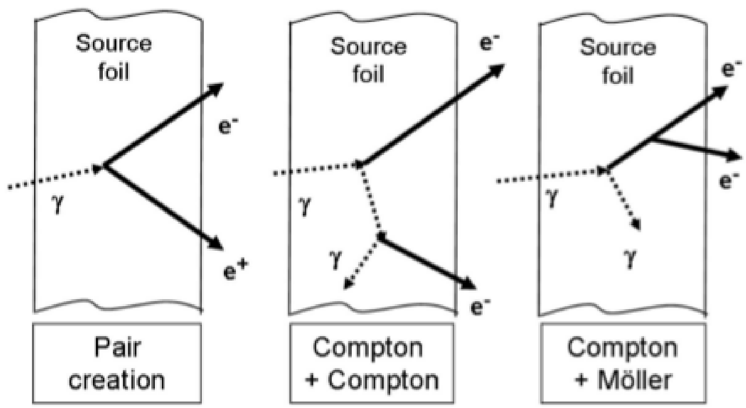
Example: Internal Background from NEMO-3 (^{116}Cd)

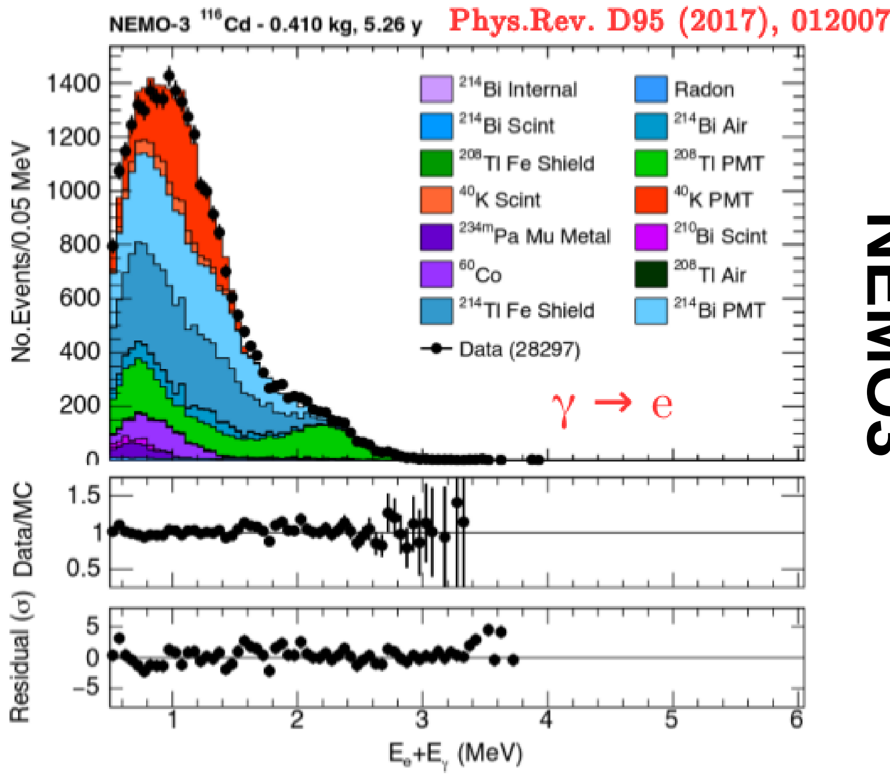
The background noise: External background

- Regroups the backgrounds not coming from the source foil, come from :
- Radio-impurities in detector material (208 Tl, 214 Bi)

- γ from (n,γ) reactions
- μ from Bremsstrahlung

- Are measured in 2 main channels, requiring the timing informations :
  - external crossing electron
  - external γ → e

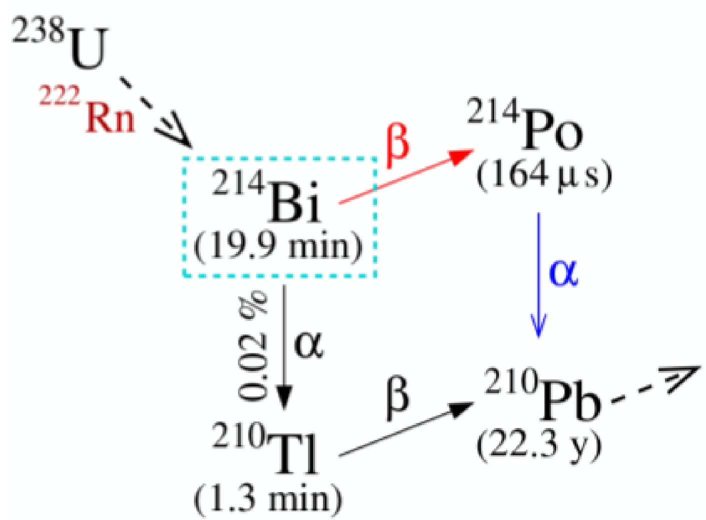




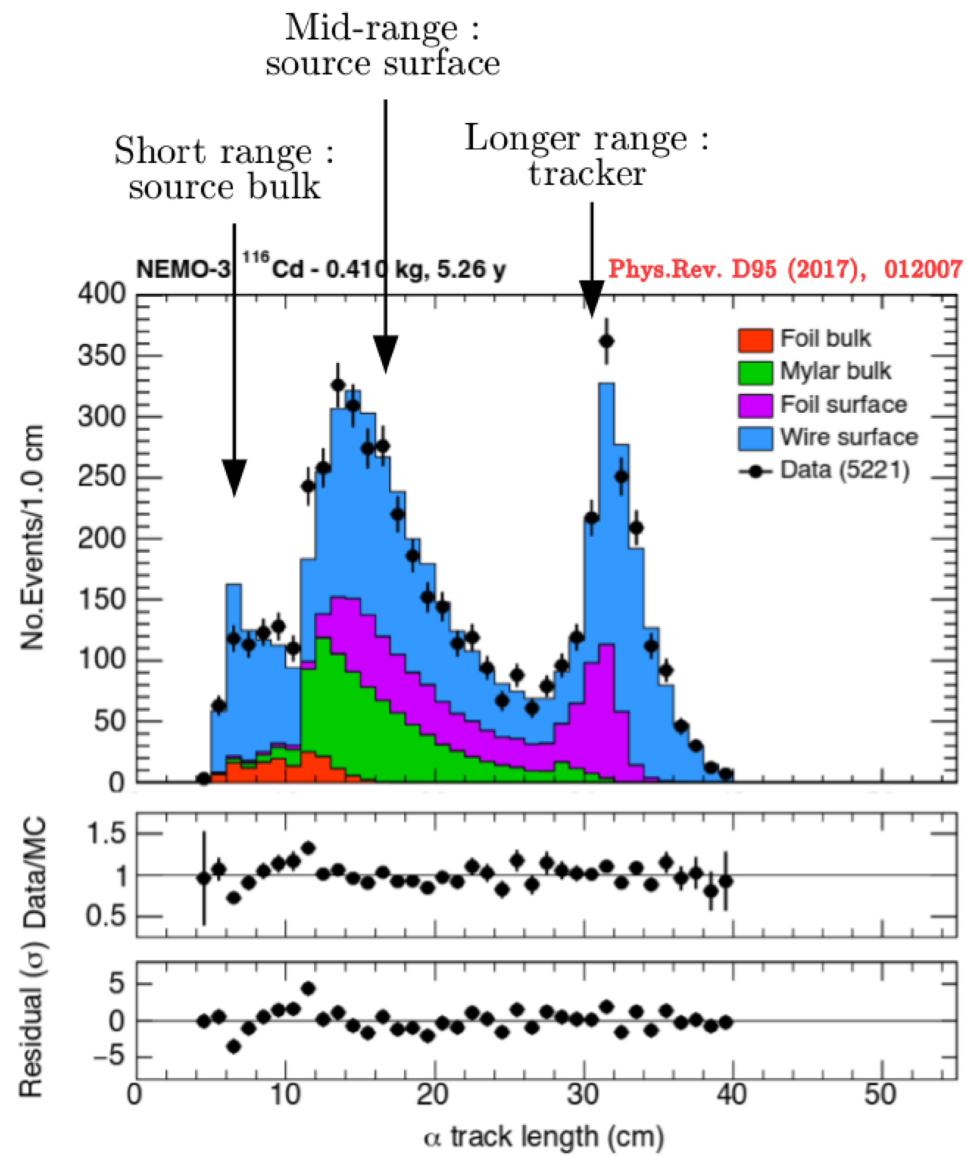
NEMO3

Example: External background from NEMO-3 (^{116}Cd)

The background noise: The radon in the wire chamber



- ^{214}Bi is an important background with a Q_β=3,3 MeV
- Arise from ^{238}U chain or ^{222}Rn emanation
- Measured in 1e1α channel → Background free measurement
- Alpha track length provide information on contamination origins

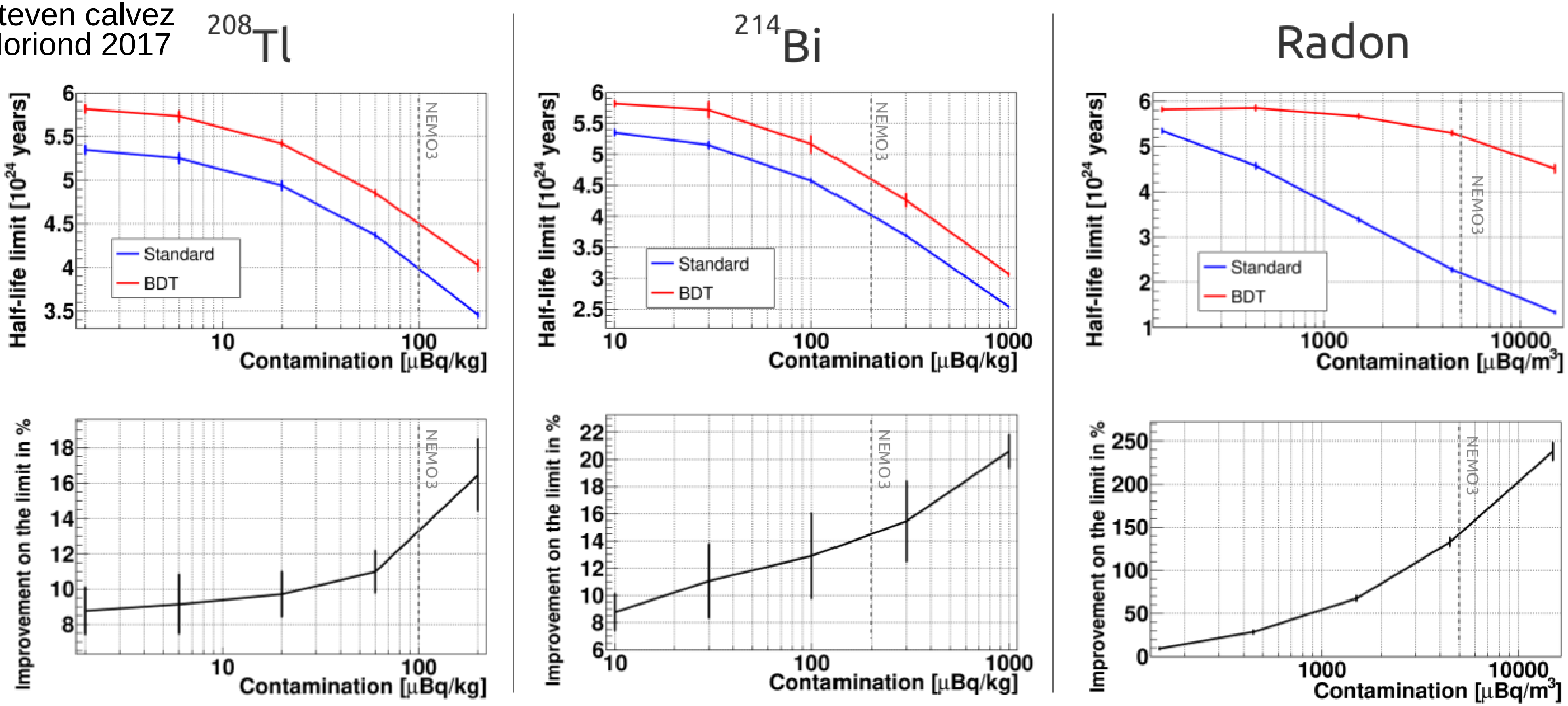


NEMO3

SuperNEMO demonstrator sensitivity

- Train BDTs to discriminate signal events from background events
- Radiopurity requirements : A(^{208}Tl) = 2 µBq/kg, A(^{214}Bi) = 10 µBq/kg
- and A(Radon) = 150 µBq/m^3
- Half-life limit as a function of the background contamination levels :

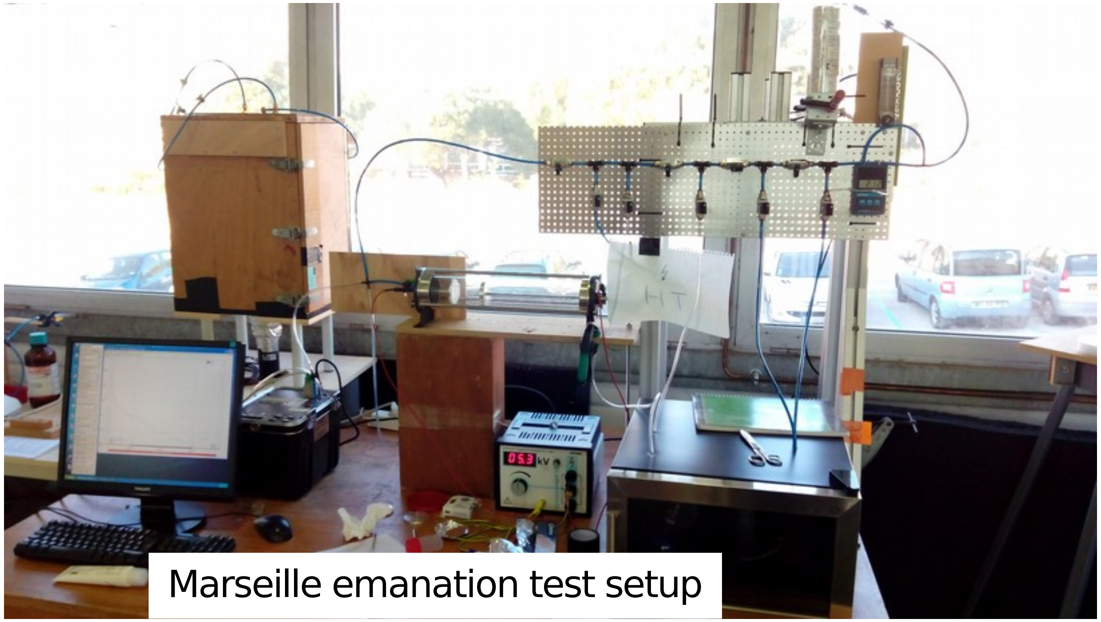
Steven calvez
Moriond 2017



The radon measurements among the SuperNEMO collaboration

- CENBG Bordeaux
- UCL London
- IEAP CTU Prague
- **CPPM Marseille**


Bordeaux emanation setup


Marseille emanation test setup


London concentration line

Radon studies at CPPM

CPPM is in charge of radon background

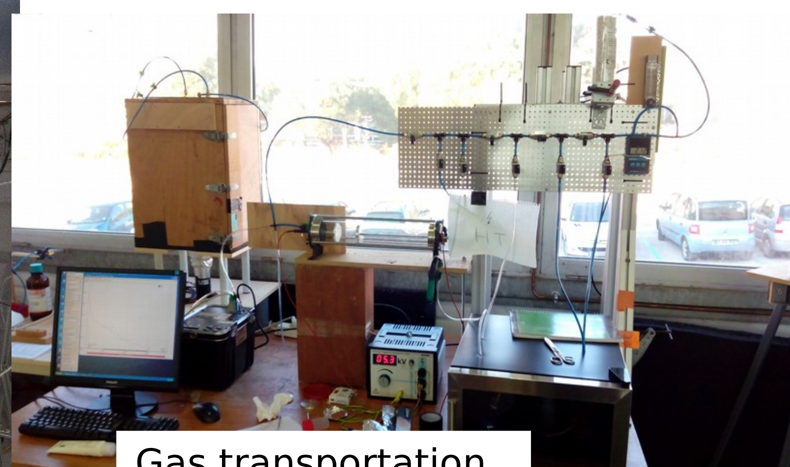
- gas purificaton

- radon background transport simulatons and measurements

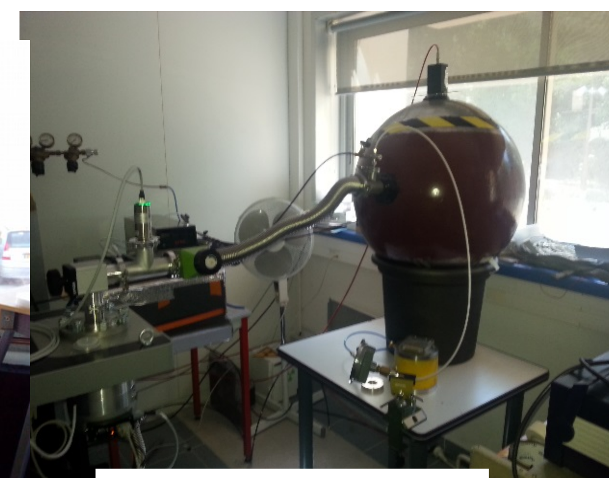
- radon concentraton measurement

We need less than 50 atoms of radon on 3.10^{25} atoms of He

Radon trap



Gas transportation studies



Spherical detector

R&D on low background studies in the SuperNEMO CPPM group

- Proportional spherical detector for continuous survey of radon rate in SuperNEMO gas
- Charcoal radon trap testing for the SuperNEMO gas purification
- **Radon transportation in the SuperNEMO gas studies**
- **Radon Emanation of material depending on the gas nature (helium, humidity, ethanol...)**

Instrumentation SuperNEMO
Post-doctorat CPPM : études radon

Problematic: E_{trans} ^{214}Bi close to the E_{trans} β

SuperNEMO Objective : 150 µBq/m³

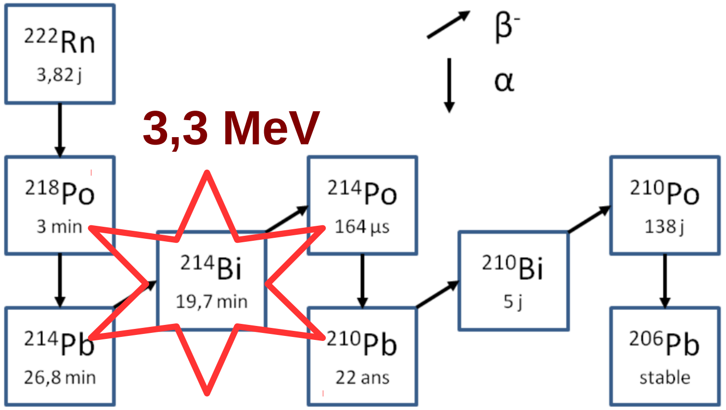
- Hard to reach
- **Hard to measure**

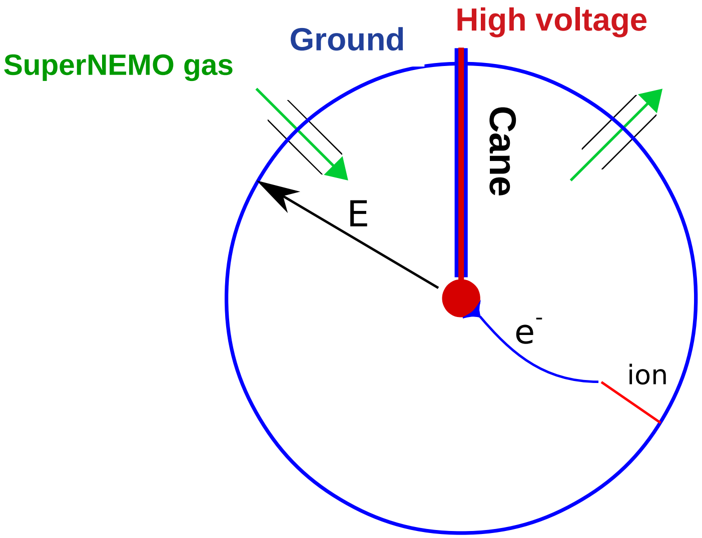
The idea:

1) Direct usage of the SuperNEMO gas for measurements

→ Spherical proportional detector

- Big volume
- Good noise/background discrimination
- High purity and low material quantity (copper)
- Simple:
  - To integrate: directly on the gas cycle
  - only one output channel!



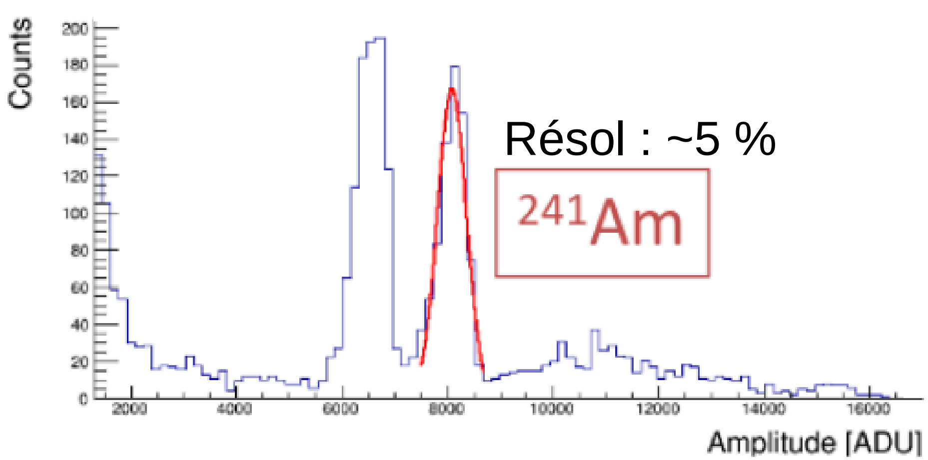


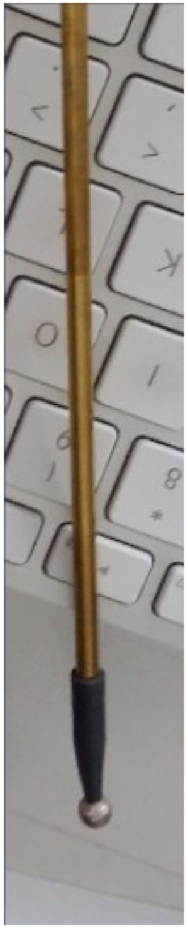
Travaux de post-doctorat

Instrumentation SuperNEMO
Post-doctorat CPPM : études radon

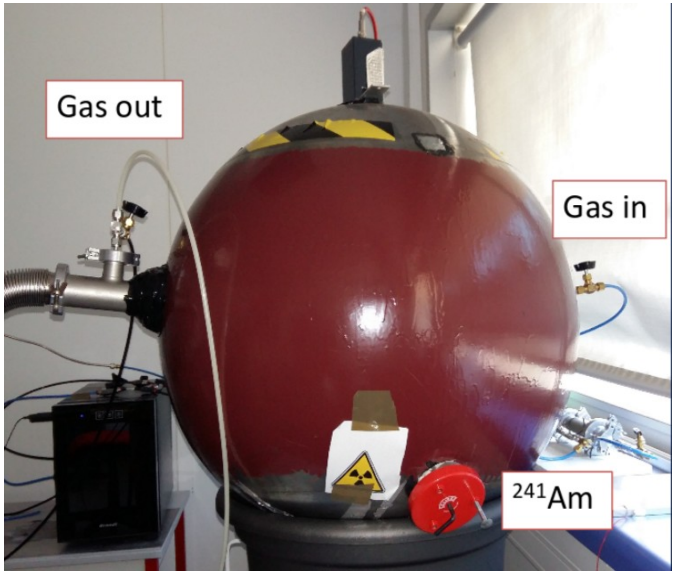
Ongoing works:
- Experimental detector (iron) at the CPPM
- Simulations « finite elements method »
  → electric fields and fluid mechanics
- Development and construction of new "canes"
- Measurements of radon and sources

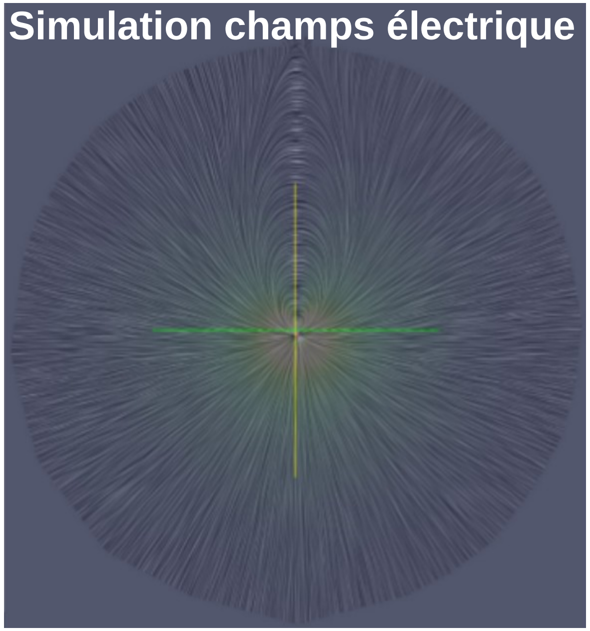
Measurement with ^{241}Am source on the surface





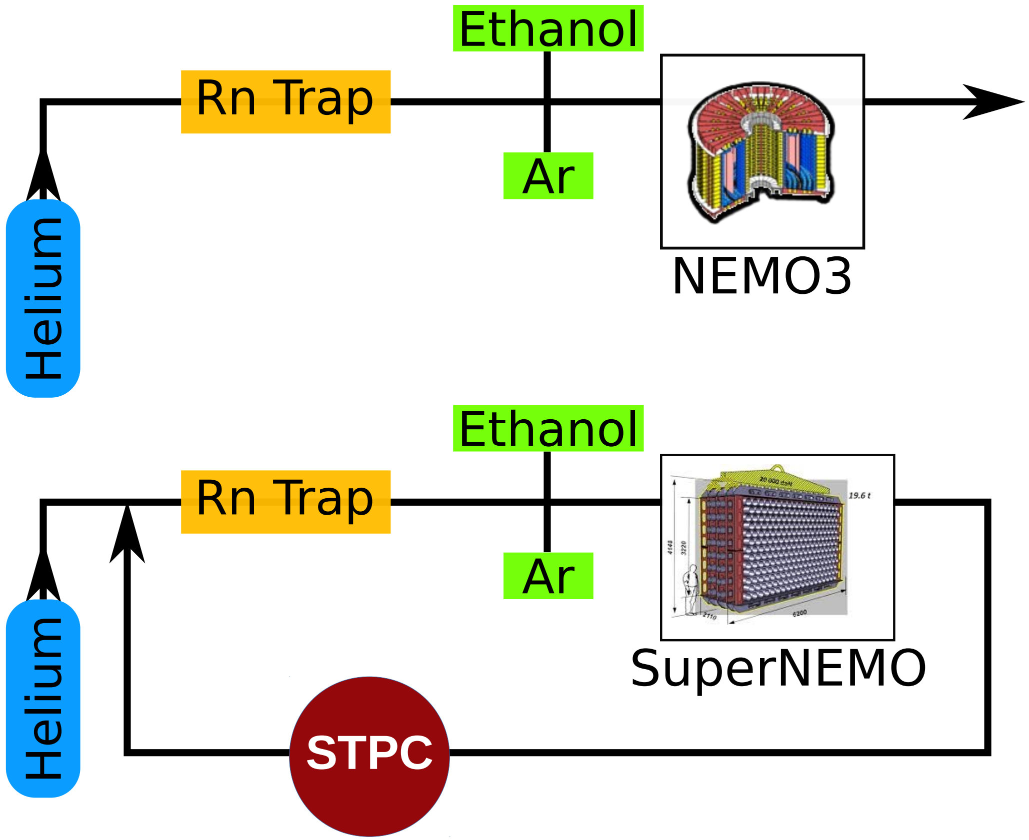
Anode (canne)





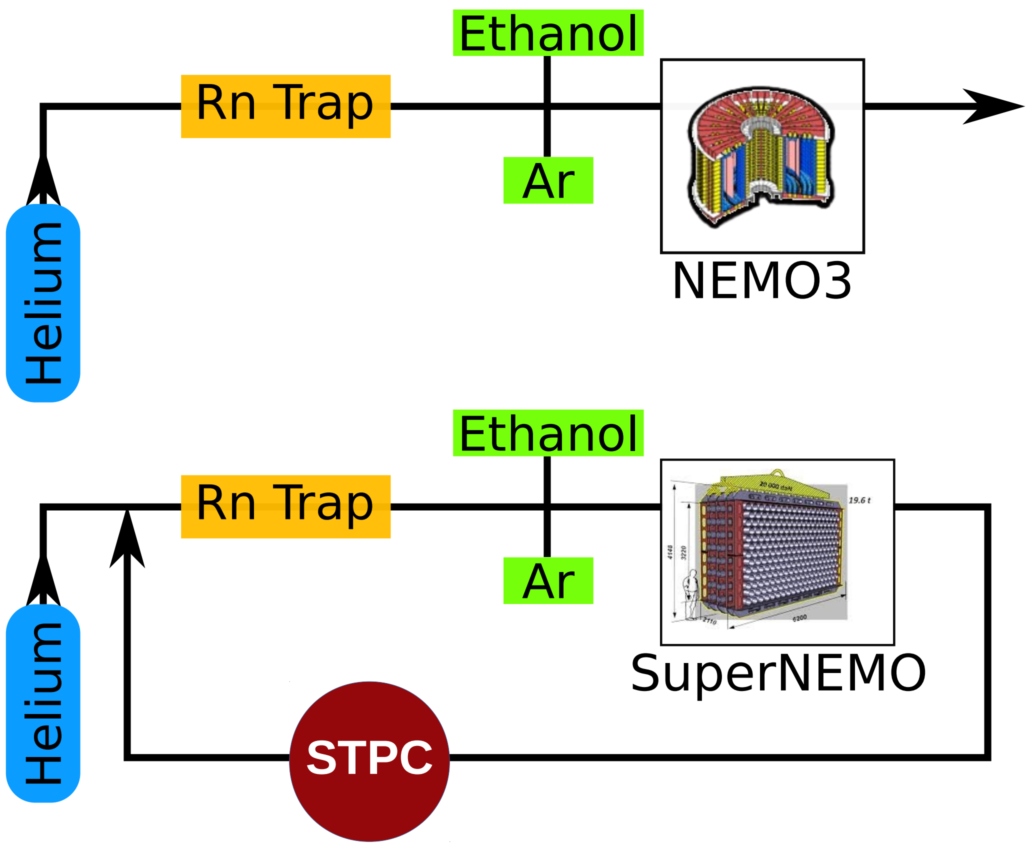
Travaux de post-doctorat ANIMMA 2017

Where is it in the gas cycle?



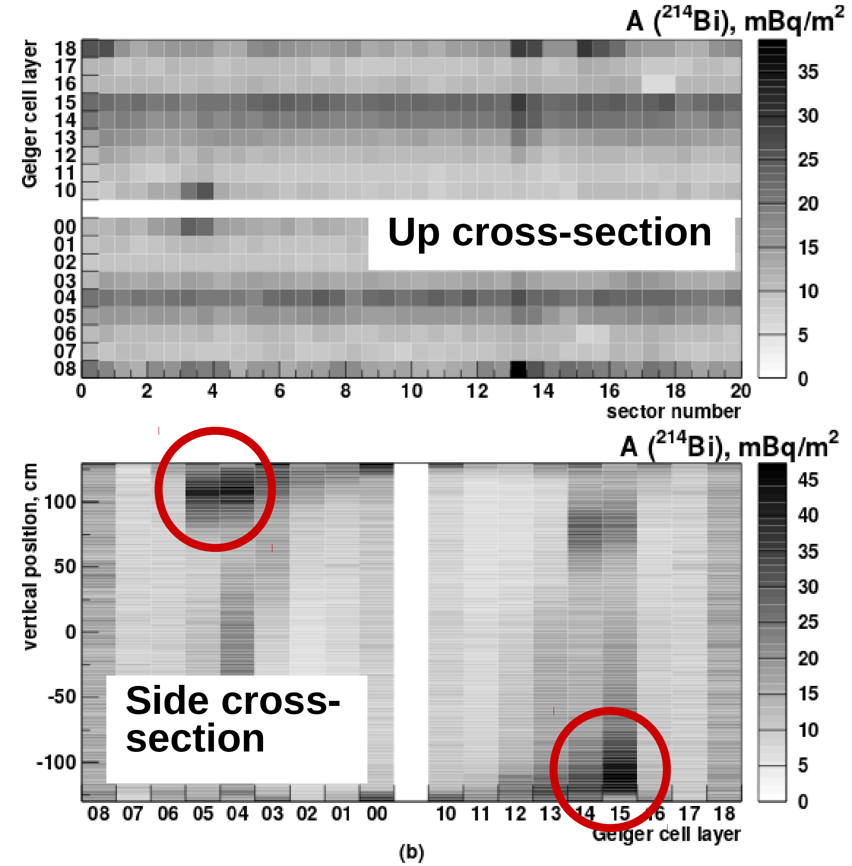
- Principle:
  - Continuous purified gas flushing in the detector wire chamber
  - Order of magnitude 1 m^3/h
  - ^{222}Rn goal for SuperNEMO 150 $\mu Bq/m^3$
  - Gas recycling system for SuperNEMO

The radon transportation in the detector



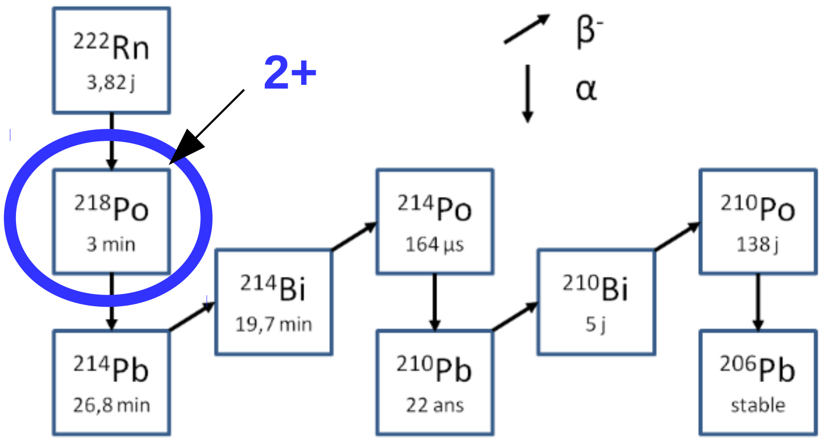
A better knowledge of the radon distribution in the detector would improve the total sensitivity

Radon hot spots in NEMO-3 wire chamber



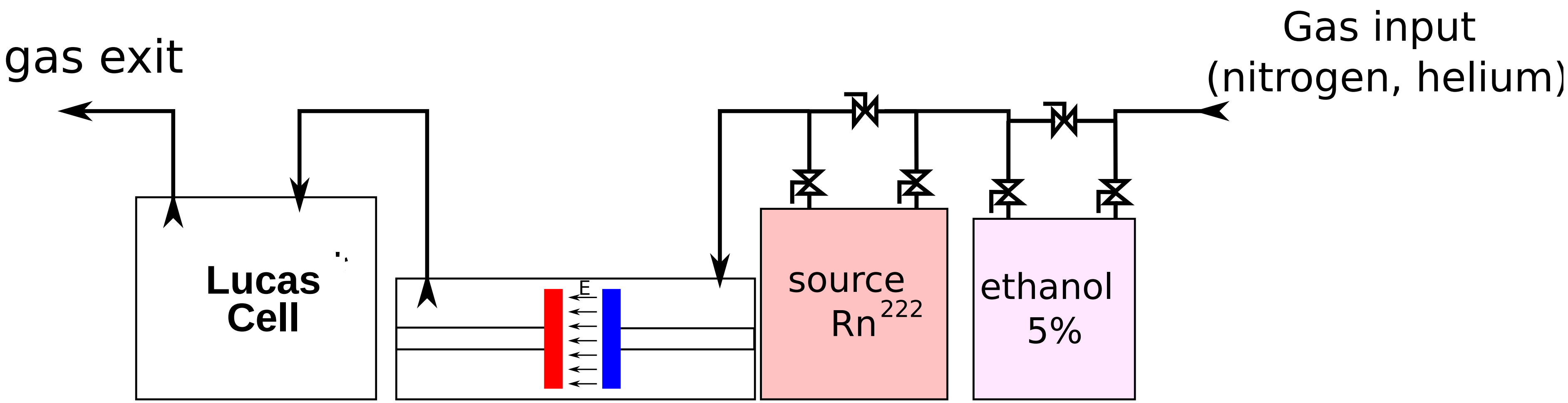
⇒ Fluid mechanics, electrostatic and neutralization/decays simulation to estimate the radon transportation in the wire chamber

The experimental setup of radon transportation measurements

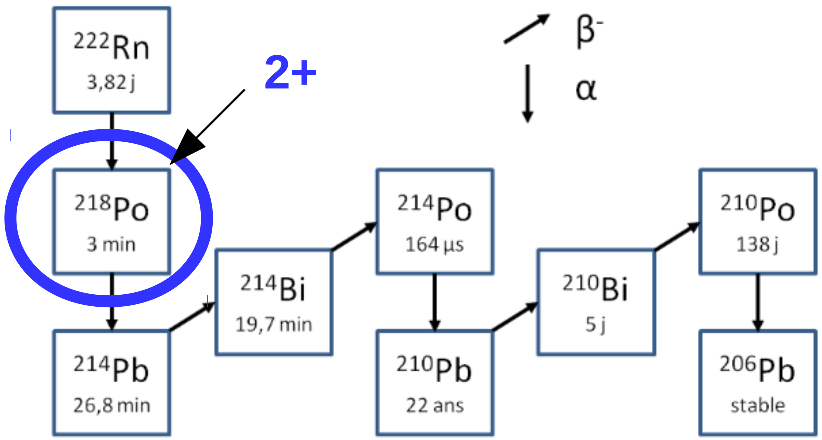


- Objective: Estimation of deposit of $^{218}Po^{2+}$ in the SuperNEMO chamber wires → simulation FEM and experimental measurements
- Simpler setup for calibration/validation of simulation and measurements
- Measurement of ethanol role transportation/**neutralization**

- kBq/m³ of radon in the input gas
- 1 kV/cm between electrodes
- The deposit on the anode is measured with an Ge detector



The experimental setup of radon transportation measurements



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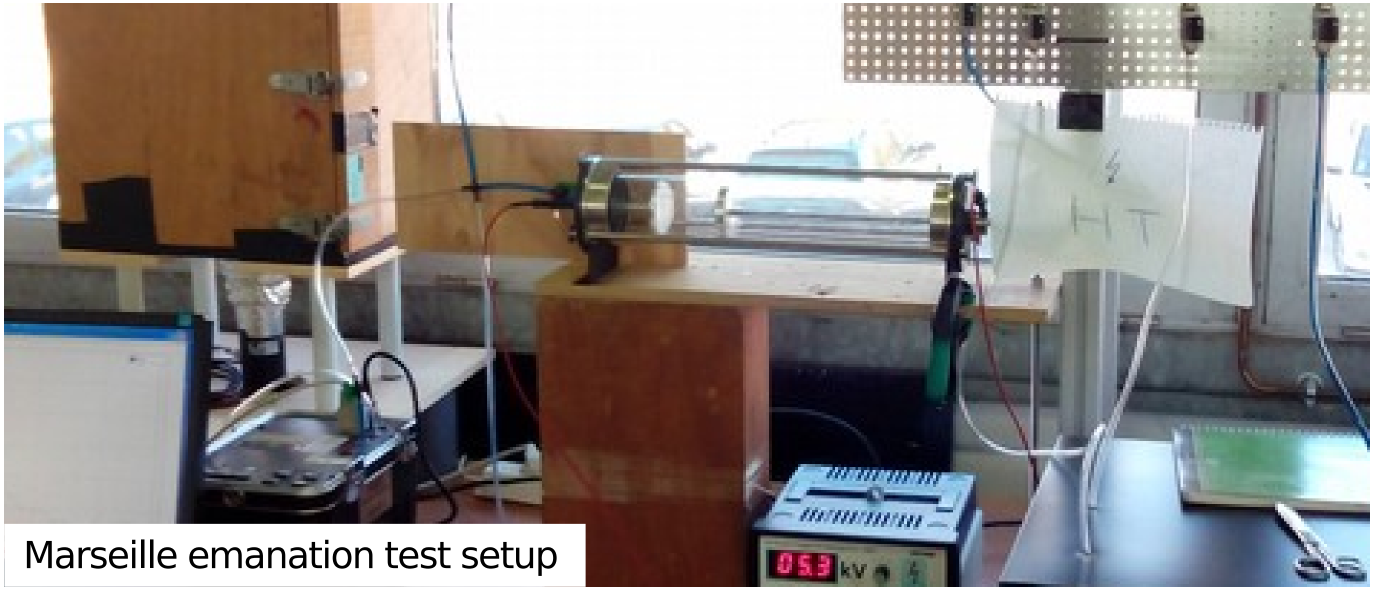
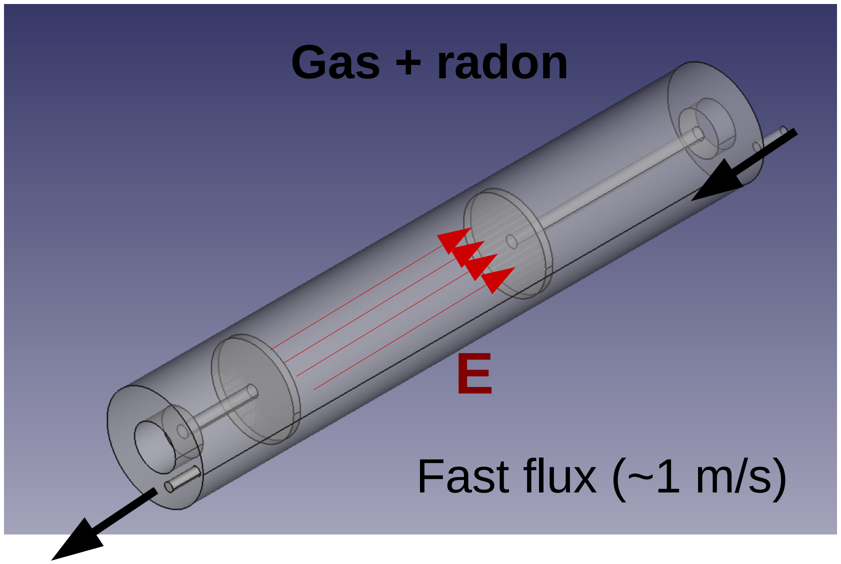
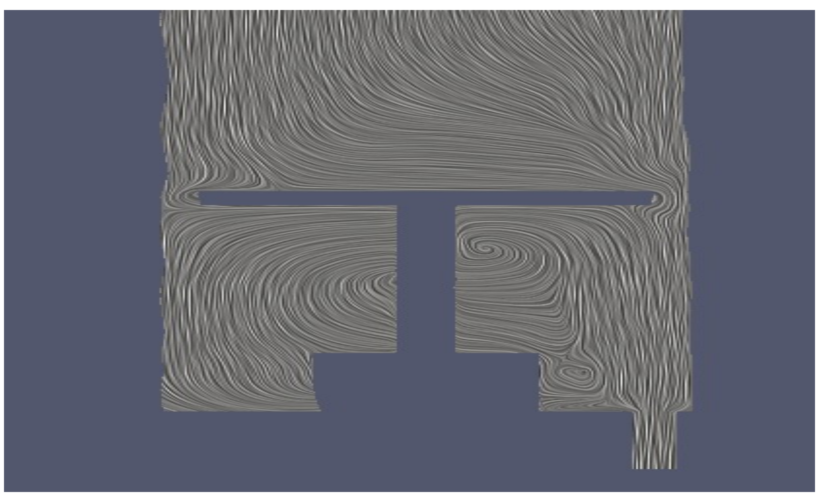
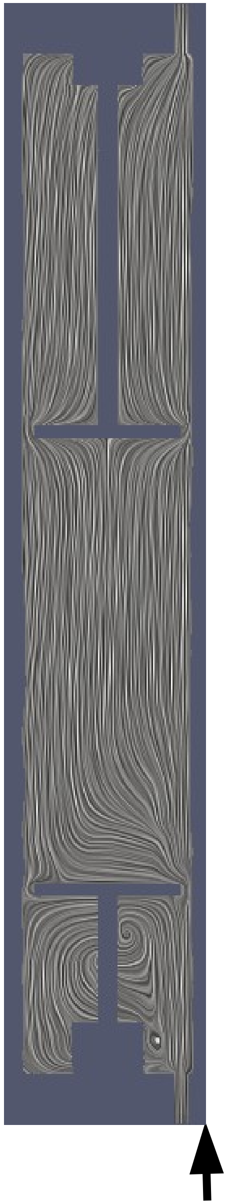


Marseille emanation test setup

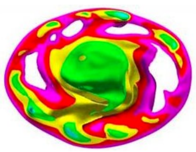
The fluid mechanics simulation





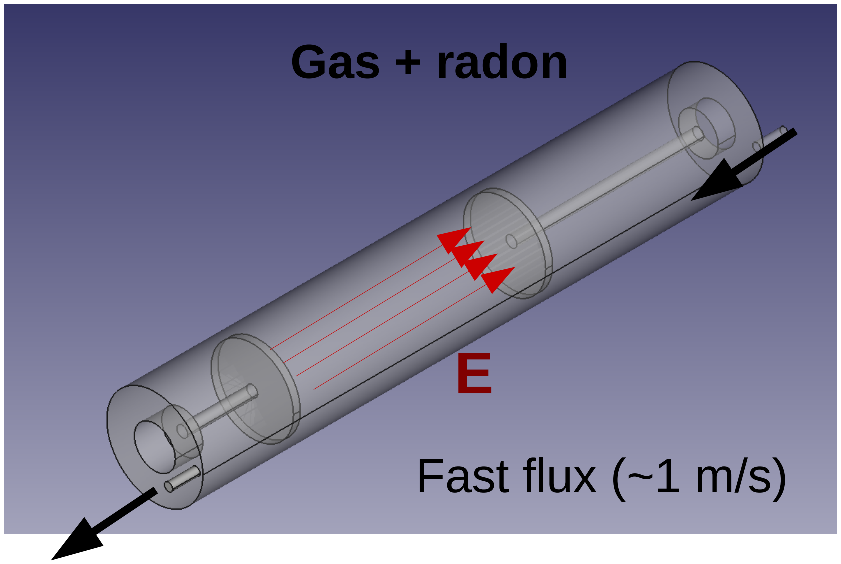


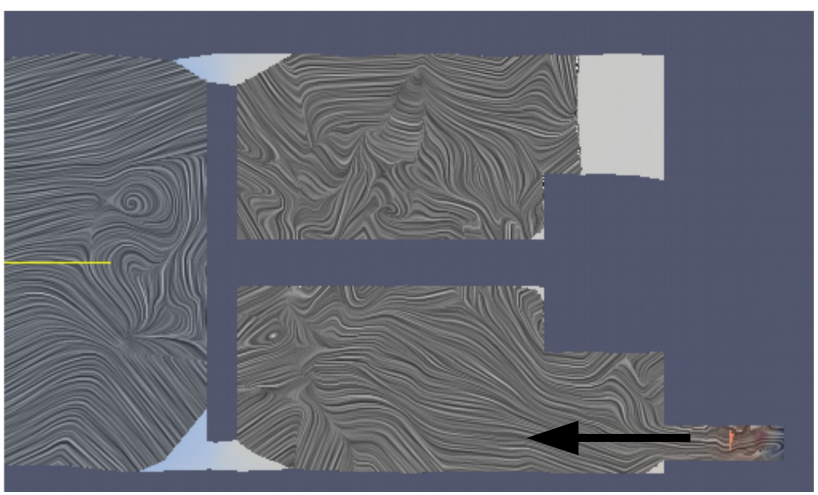
- Finite Element Method: ElmerFEM
  - Electrostatic
  - Fluid Mechanics
  - Time dependence

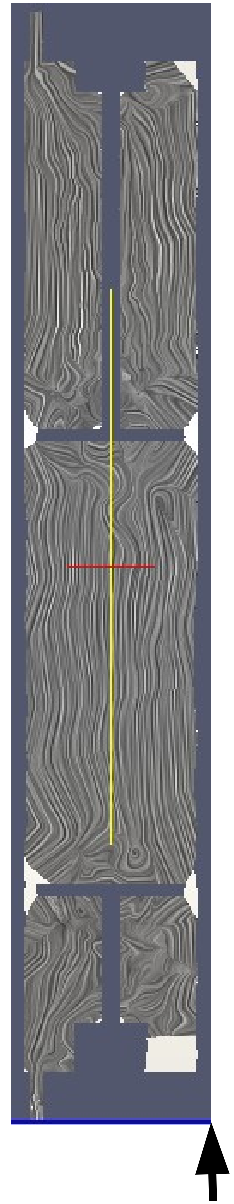


- Custom step-by-step simulation
  - Taking elmer data as input
  - Transportation of $^{222}rn/^{218}po^{2+}$ in in the flux
  - Decays/neutralization based on the half-life time
- Experimental measurement and simulation done with 0% and 4% of ethanol in the gas.
- Once validated and calibrated, it will be applied to the SuperNEMO volume

The fluid mechanics simulation







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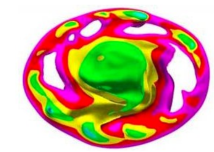

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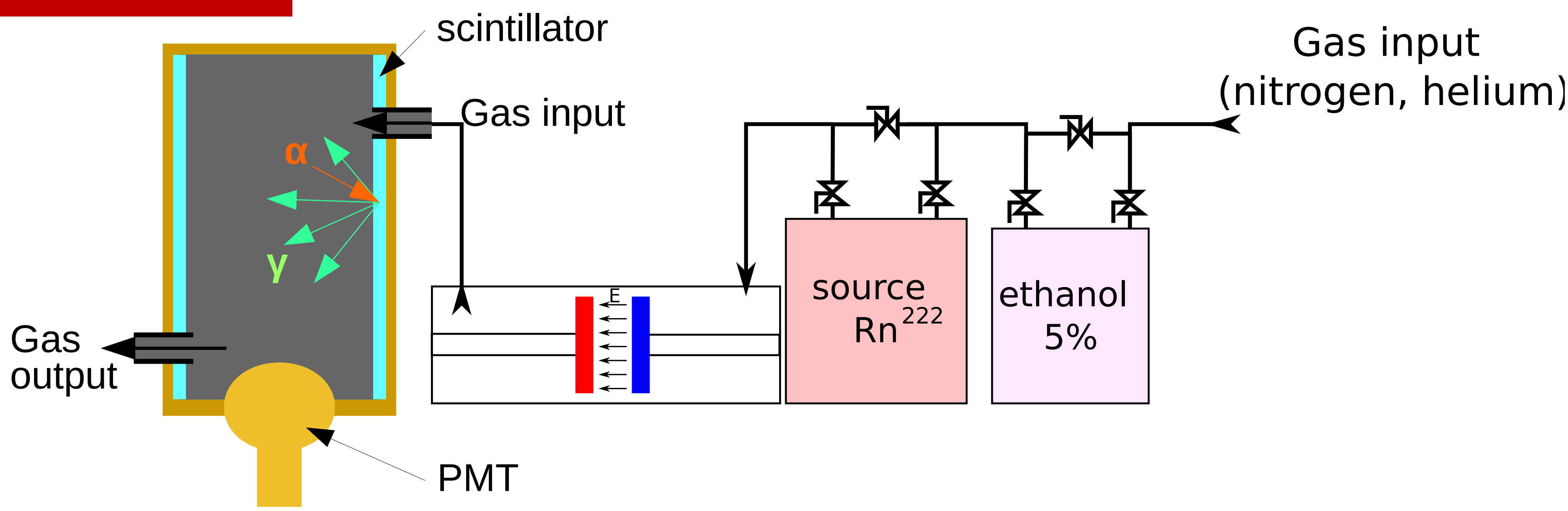
The first results and by-product

- **The first results showed an disagreement between the experimental data and simulation! (roughly 2 times experimental excess in the 4% ethanol case)**
- Hypothesis:
  - There's a known humidity effect that increase the emanation rate (IJSR, ISSN (Online): 2319-706)
  - The radon emanation from the source material is also dependent to the rate of ethanol in the gas?
- Inverting the source and ethanol in the circuit suppressed this effect
- **By-product measurement: emanation rate of the source with and without ethanol in the gas**

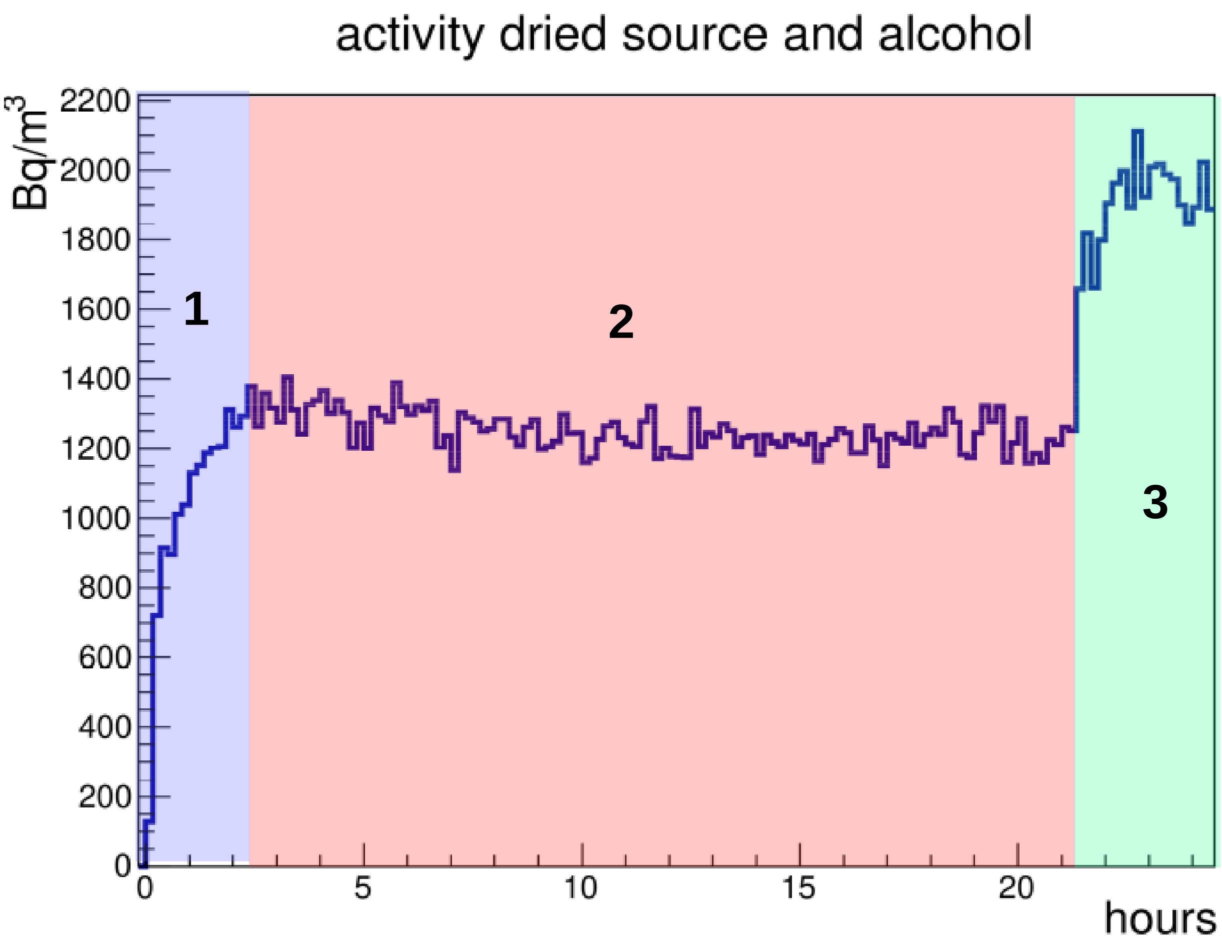
Measurment of the radon emanation with of ethanol exposure



- The common radon detector is based on the detection of $^{218}Po^{2+}$ thanks to a electrostatic collection of alpha-emitters.
- The presence of alcohol **neutralize the $^{218}Po^{2+}$** and make the measurements unreliable.

A Lucas cell has been used instead.

Measurement with “dried” source then exposed to ethanol



The measurement has 3 zones:

1) Rising until the equilibrium of the source activity and the Lucas cell volume
2) Flushing with dry nitrogen: stable (slow decrease)
3) Ethanol (4%): activity multiplied by **~2**

The source emanation measurements showed increase mean of 1,7!

A different setup based on sample injection and germanium detector indirect measurement validated this result at 3σ.

There is a strong dependence on ethanol rate and source emanation
The radio-purity should be measured taking this effect in account

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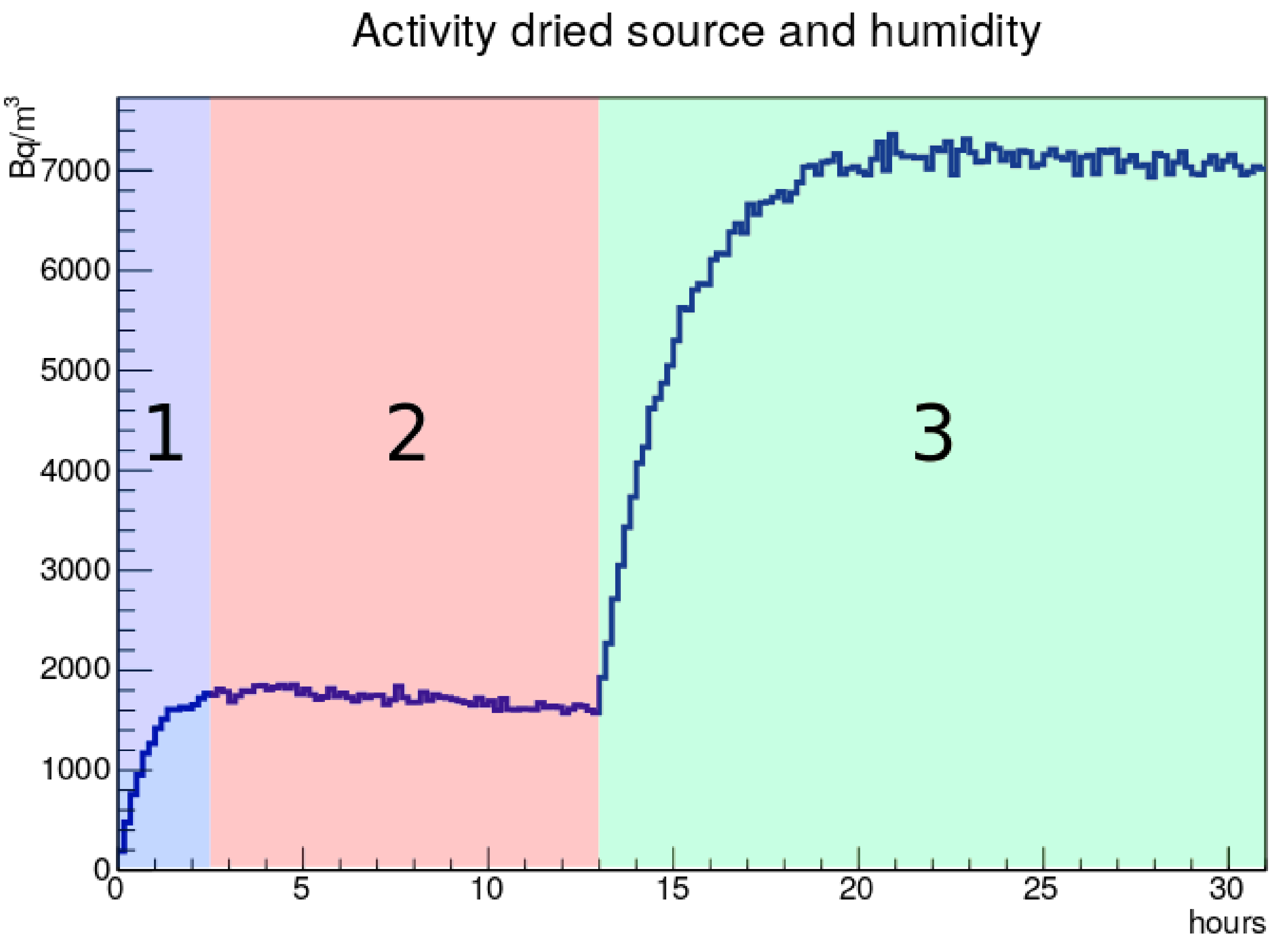

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Summary, conclusions and perspectives

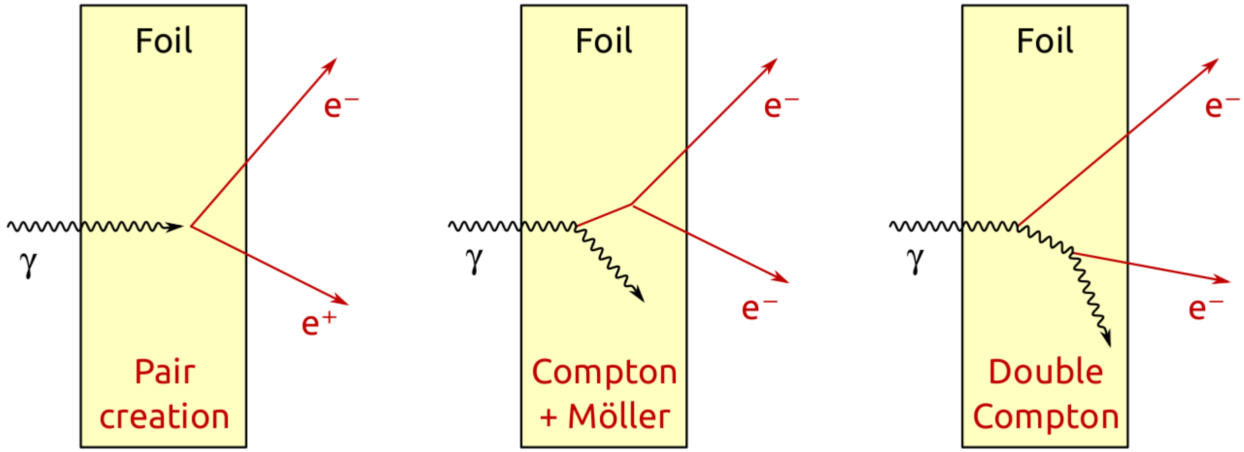
- SuperNEMO detector
  - Calorimeter/tracking technology validated by NEMO-3, used by SuperNEMO
  - The data taking should start by this year
  - Sensitivity $T_{1/2}^{0v} \sim 10^{24}$ years ($T_{1/2}^{0v} \sim 10^{26}$ years for full detector)

- Radon measurement R&D
  - Expertises from the NEMO-3 experiment (emanation chambers, gas circulation etc.)
  - New innovative radon studies (transportation) for very low background experiments
  - Evidences for material emanation in function of the nature of gas (ethanol rate)
    - Essential for very low background experiment! New ^{222}Rn detector under development
    - The material radio-purity measurements have to be done in the experimental gas
    - Work still under progress (humidity, helium, nitrogen etc...)

backup

The background noise

- External γ, if not tagged
  - Origin : detector radioactivity, neutrons and cosmics
  - Underground (Modane, 4800 m e.w.), shielding (steel and water), E < 2.6 MeV
    ⇒ background for ββ2ν
- Internal contamination in β emitter with $Q_\beta \geq Q_{\beta\beta} \sim 3$ MeV
  - ^{214}Bi in ^{238}U chain ($Q_\beta = 3.3$ MeV)
  - ^{208}Tl in ^{232}Th chain ($Q_\beta = 4.9$ MeV)
- Radon inside tracking detector
  - decay then deposit of daughter on wire and foil surfaces
  - feed internal contamination in ^{214}Bi



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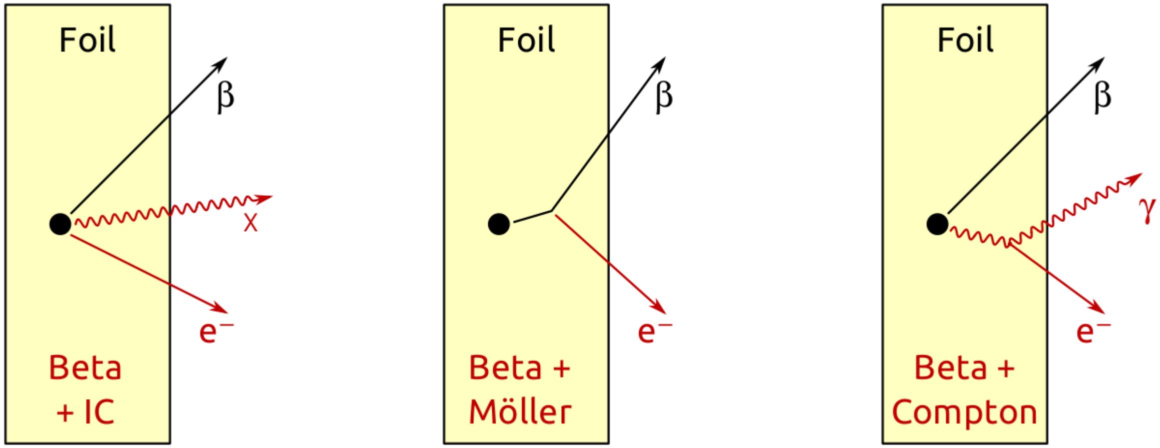

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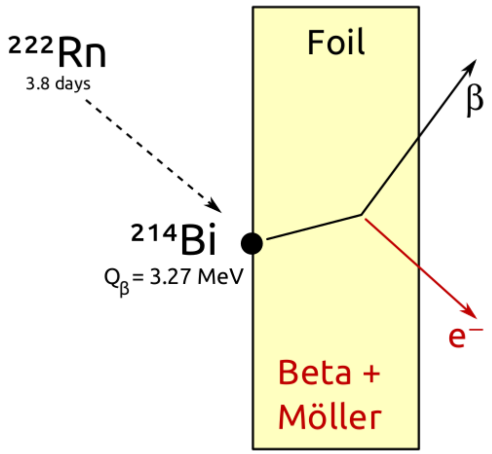

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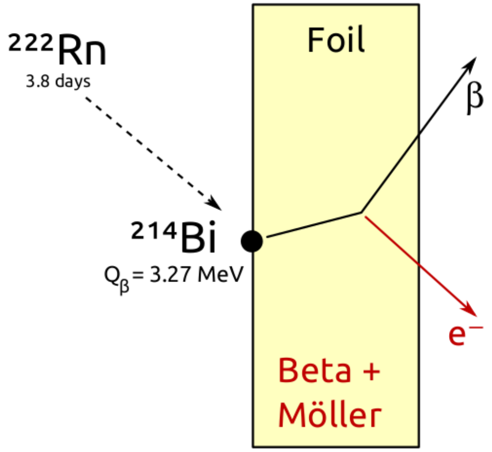
- **Radon inside tracking detector**
  - **decay then deposit of daughter on wire and foil surfaces**
  - **feed internal contamination in ^{214}Bi**

Under construction demonstrator
- **7 kg of ^{82}Se**
- **BG 10^{-4} evt/keV/kg/y**
- **$|m_{\beta\beta}|$ < 0.2-0.4 eV in 2,5 years**



^{222}Rn is a major BG
The 150µBq/m^3 goal is hard to reach, but also to control: Radon contamination measurements

The Double beta decay and the mass hierarchy

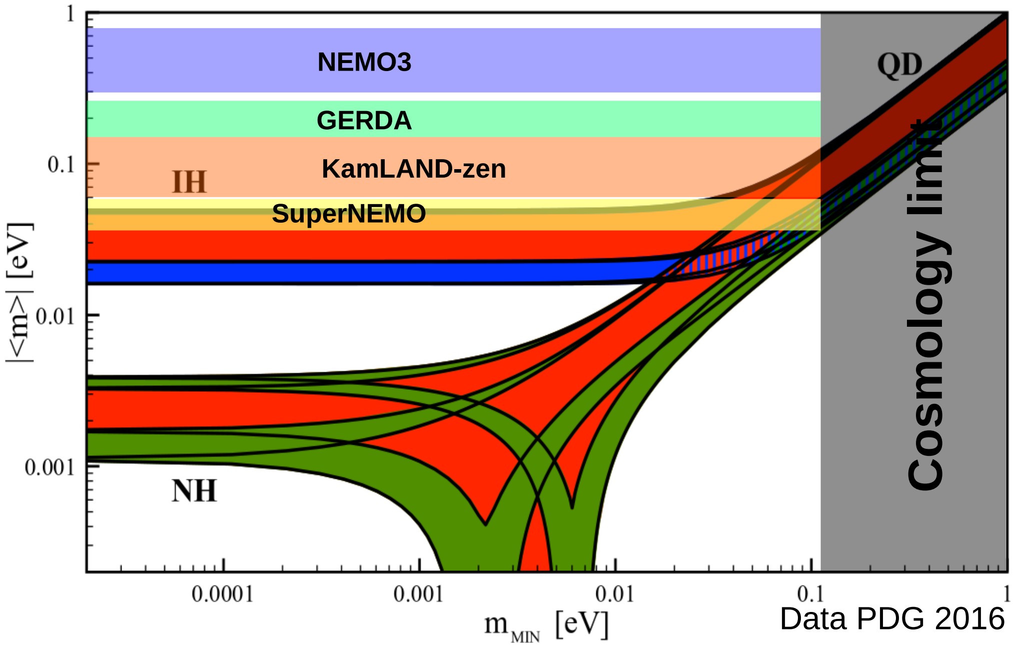
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle \equiv |\sum_k m_k U^2_{ek}|$$

$$m_{\nu_e} = \left(\sum_i |V^2_{ei}|\ m^2_i\right)^{1/2}$$

The measurement of the double beta decay lifetime and the PMNS angle values gives an access to the hierarchy:

- NH: <m$_{ee}$> = [4;0] meV
- IH: <m$_{ee}$> = [60;15] meV & m$_{\nu e}$ ~ 40 meV

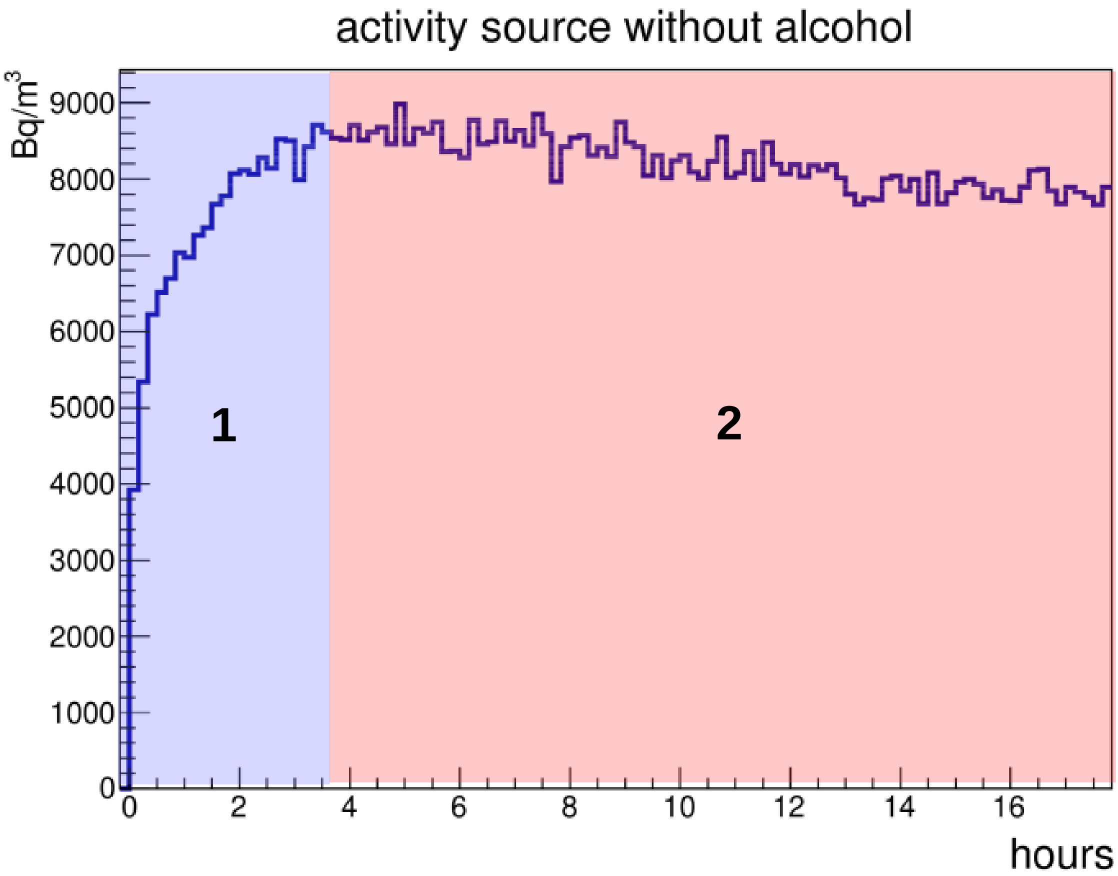


Data PDG 2016

Nemo-3 ^{100}Mo result: 300-900 meV

SuperNEMO goal: 50-100 meV

Results with source, no alcohol



The source has been directly used, from ambient air (and “normal” humidity)

The flushing gas is dried nitrogen, at 10 l/h

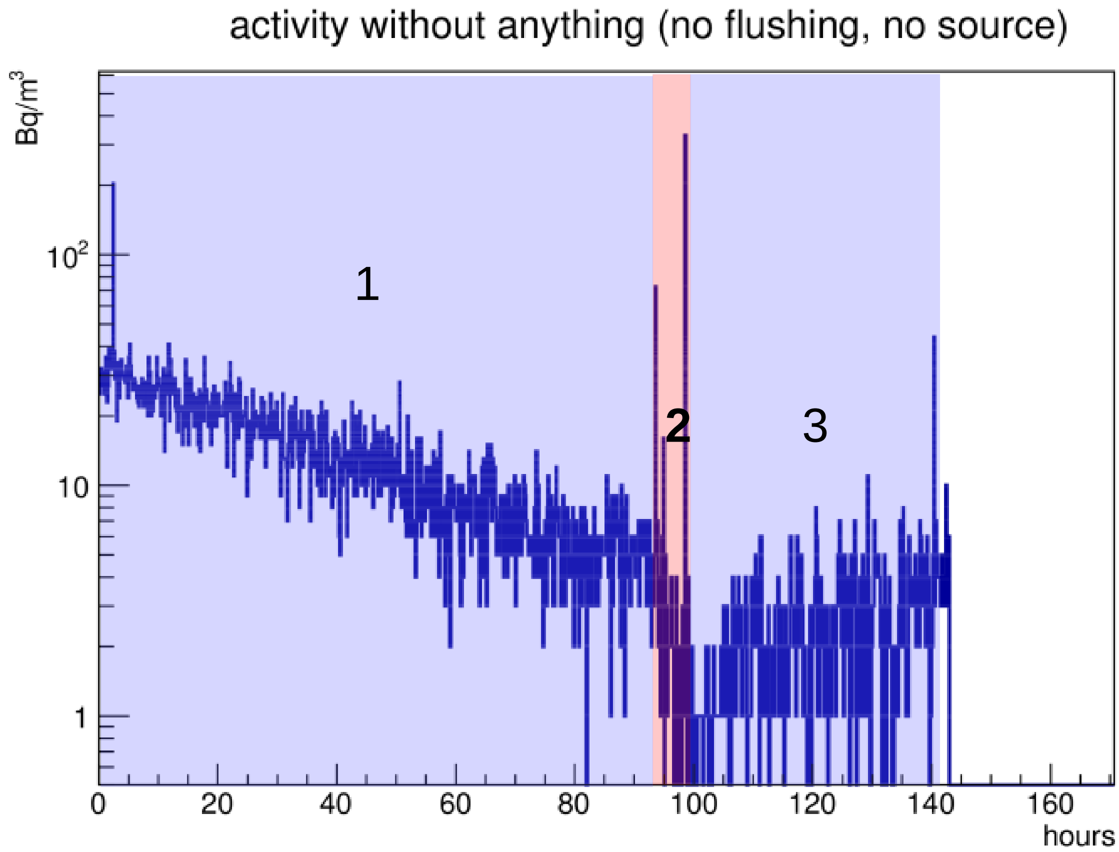
The preparatory measurement has been done for 17 hours. 2 zones are observed:

1) Flushing period: the radon come to equilibrium between the source and the Lucas cell,
2) The “stable” zone

The measurement seems stable and reliable

The slow decreasing will be explained later.

Test of the Lucas cell stability and alcohol sensitivity



To test the Lucas cell (PMT gain fluctuations, noise fluctuations) the Lucas was left without gas flushing, with and without alcohol injection:

1) No flushing, we see the decreasing of the ^{222}Rn decay rate (3.8 days) from the previous measurement
2) ~5 hours of 5% alcohol nitrogen flushing
3) No flushing (the alcohol remains inside the cell)

No counting rate fluctuations
No alcohol impact

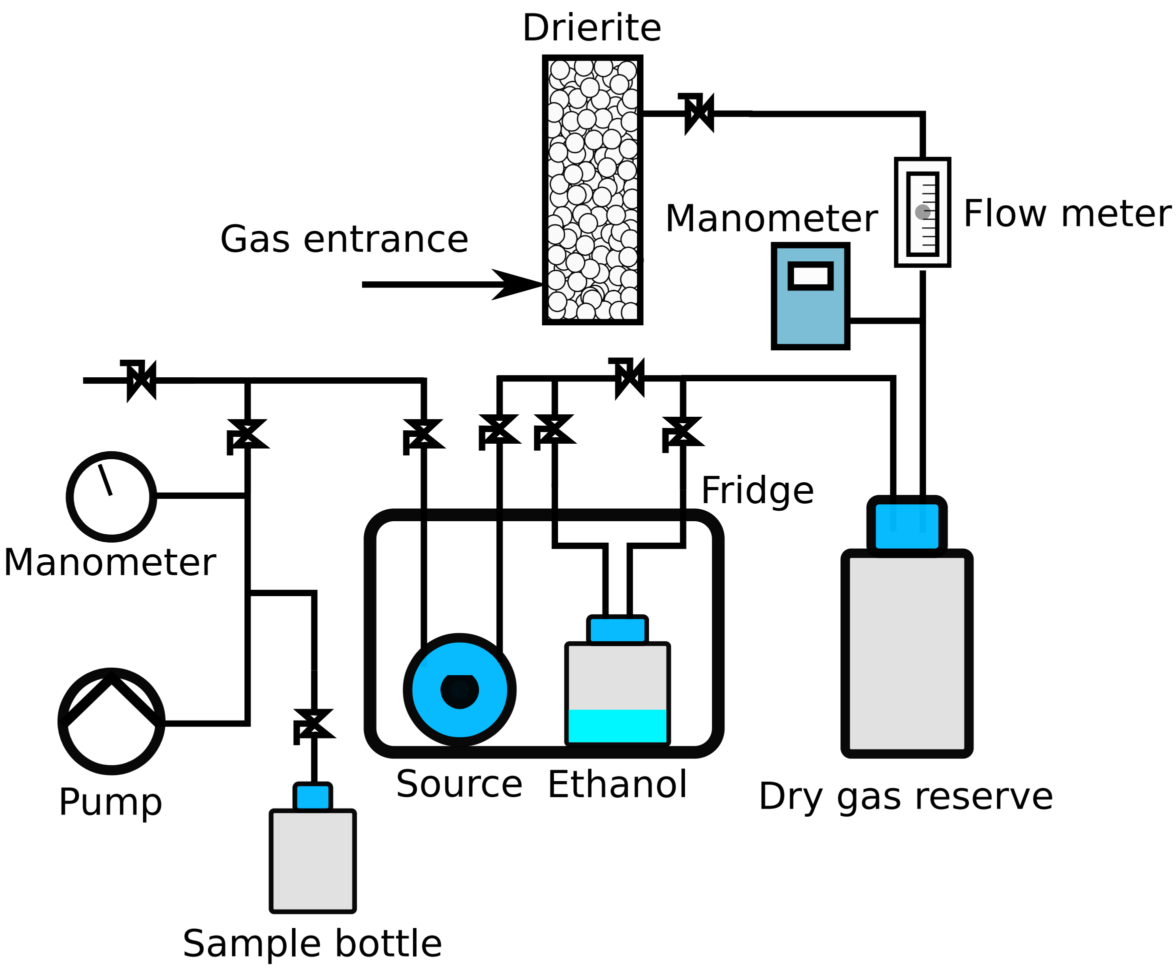
A word about the source and its preparation

- We have two kinds of source
  - Rocks
    - Centimeter sized
    - Porous ?
    - The recipient contains smaller rocks (mm) and dust
  - Clock hands
    - Millimeter sized
    - Less porous than rock?
- The drying out process has been automatized
  - At 150°
  - The recipient is emptied and fill back each minutes during 15 min cycles
  - A cycle each 30 min during a full night
- We are thinking to do it with the tested gas (now using ambient air)

Why a different setup

- To have a detector that is not exposed to the gas mixture (totally independent to the ethanol/humidity rates)
- To cross check the result with another way to measure it
- Idea:
  - Injection in a small bottle of source gas
  - Measurements done thanks to a germanium detector (^{214}Bi 609 keV gamma rays)

Summary of the new setup



- The setup is mostly the same:
  - The source is exposed to the gas during one hour
  - The sample bottle is under vacuum (50 mbar)
  - The vans are open such a way that the sample bottle fill itself with the gas from the source
  - Then the bottle is closed and placed in a germanium detector to measure the gas activity

The result is given in “hit”, the interesting point is to get a relative result with and without ethanol

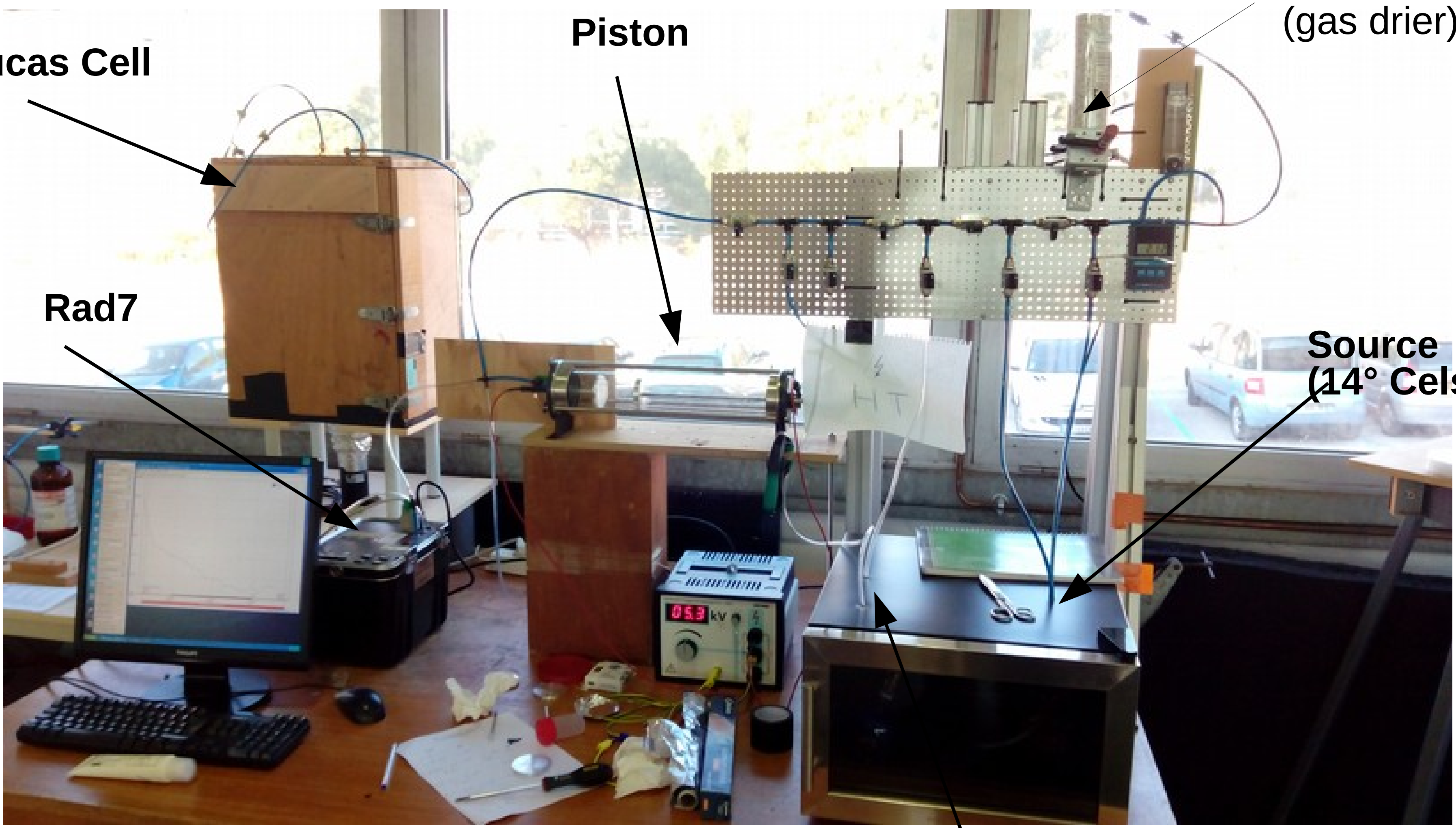
Summary of the first results and remarks

	Dried out source	5% ethanol + source	Totals, difference & sigma total
Nb Measurements	32	15	Total: 47
609 keV γ hits mean	359	578	Difference: 219
Errors	+/-52	+/-51	+/-73

- The measurements gave a relative difference of **~1.6 at 3σ** between dried out and ethanol exposed sources
- This setup much harder to manage (complex protocole) so it has bigger systematics errors
- Even if during the measurement protocol weakness has been identified, few measurement has been excluded (only them with clearly identified errors)

It validates previous measurements at 3σ
Need to reach 5σ?

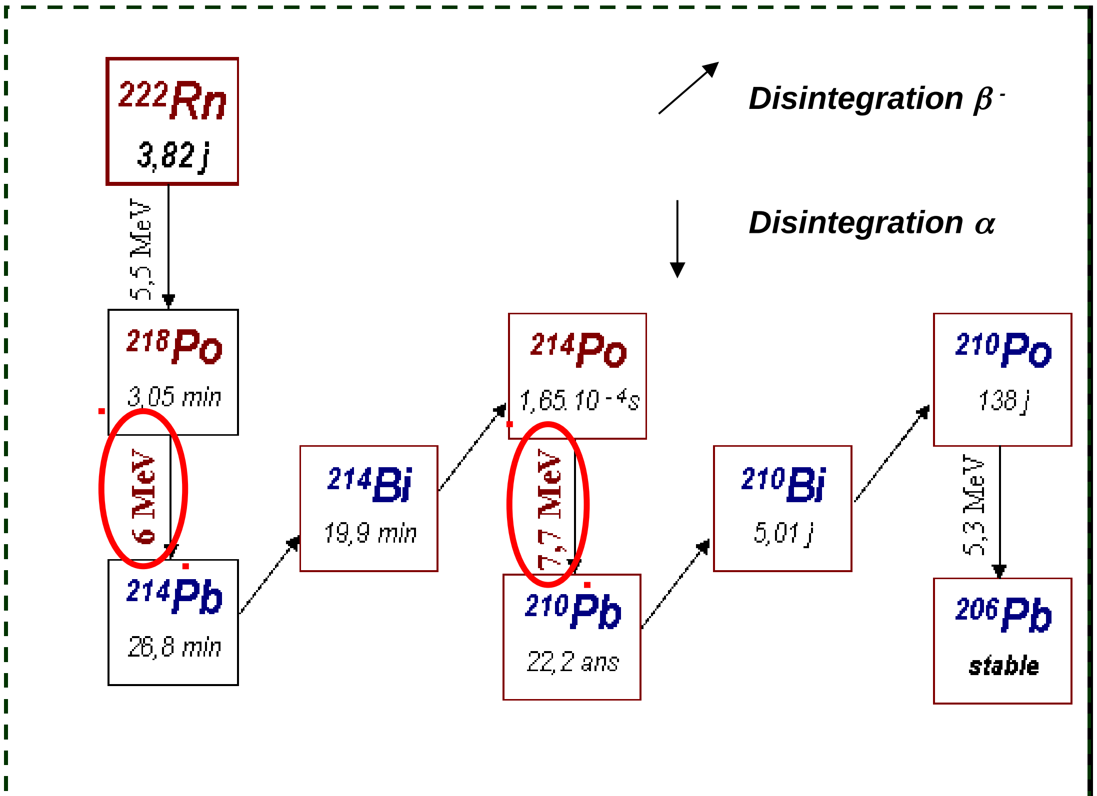
What it looks like?



Radon and thoron decay chains

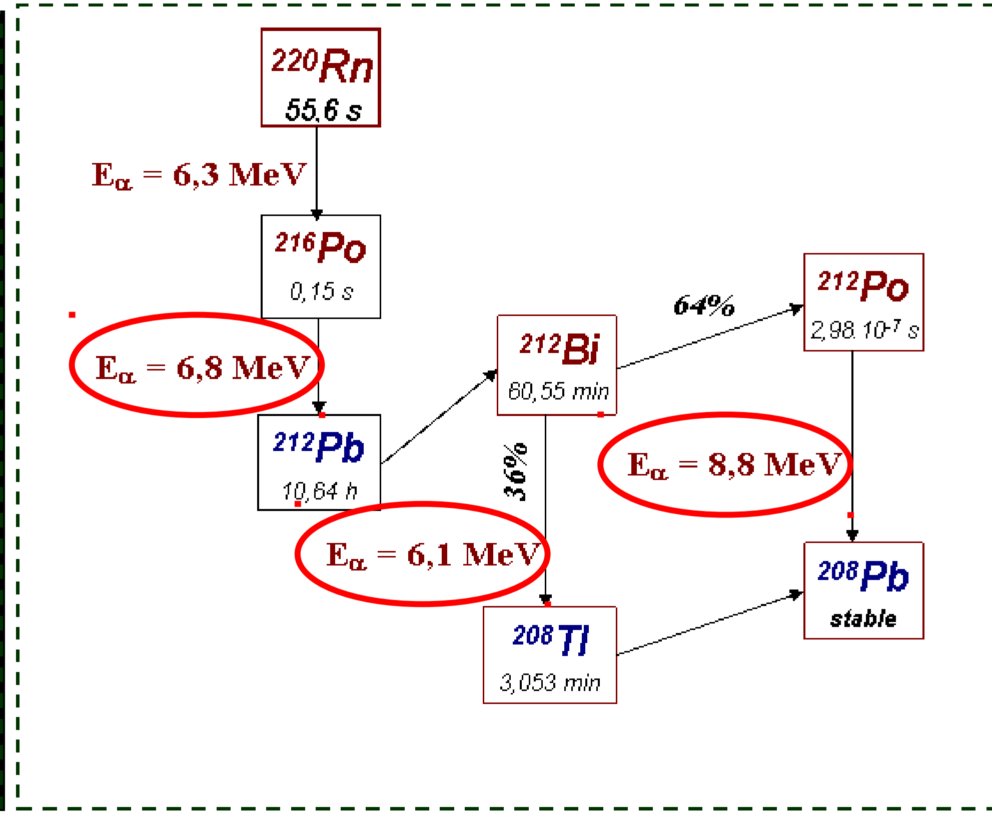
Radon

(Chain of l'^{238}U)



Thoron

(Chain of ^{232}Th)



- Remarks :

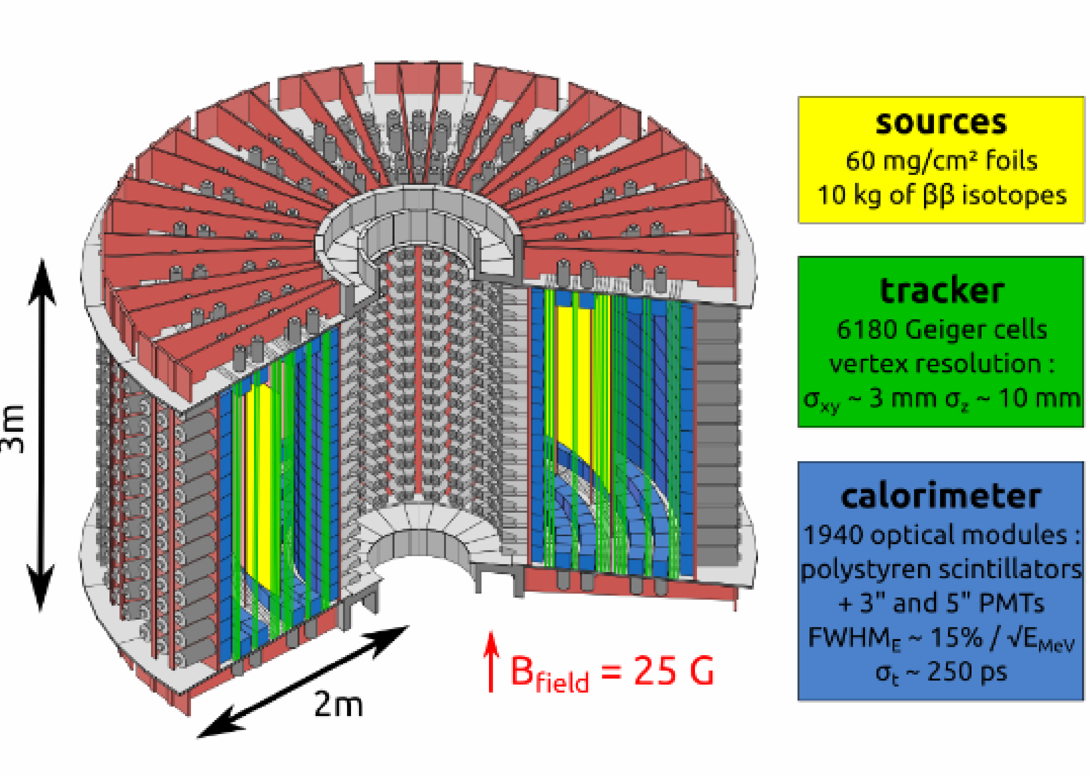
- The two decay chains are identical in the chemical point of view
- The main difference comes from the periods : 56 seconds for the thoron
  3.8 days for the radon

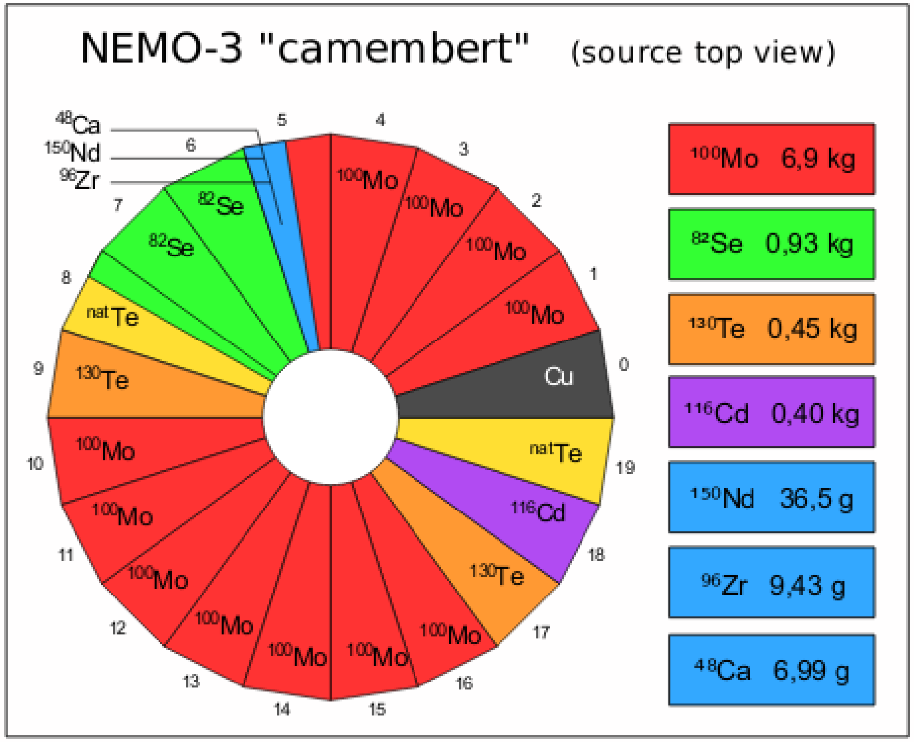
Some experimental results (from Roger Abou-Khalil thesis):

			time,s	humidity	
Renoux (1965)	^{218}Po	air	-	air ambiant	81,5% positive 18,5% neutre
Raabe (1968)	^{218}Po	air	330	13 33	Neutre
Porstendörfer (1979)	^{218}Po	air	au moment de formation	≥ 95	88% positive 12% négative
Dua (1981)	Descendants du ^{222}Rn	air	0,046	16 - 19	90,8% positive 3,9% négative 5,3% neutre
Dankelmann et al. (2001)	^{218}Po	air	-	air ambiant	49% chargé 51% neutre
Porstendörfer (2005)	^{218}Po	air	-	30 - 95	48% positive 52% neutre
	^{214}Pb	air	-		45% positive 55% neutre

- In most cases positively charged, ~80%
- Exact conditions of measurement are important!
- Typical voltage in these experiments ~ 500 V/cm

From NEMO-3 to SuperNEMO

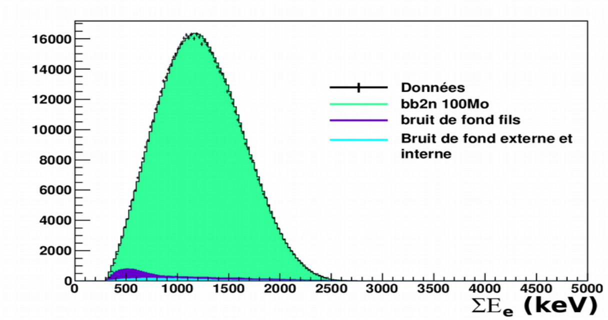


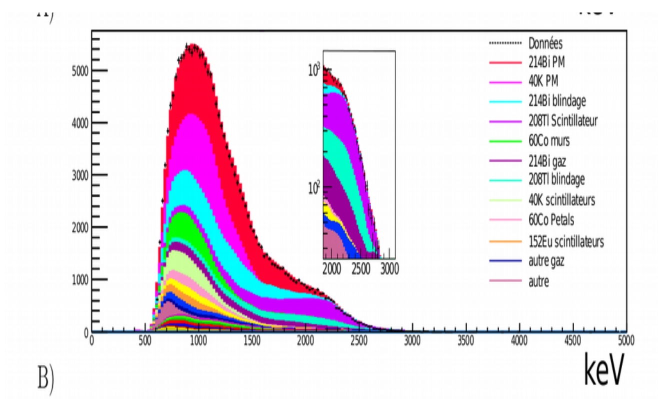


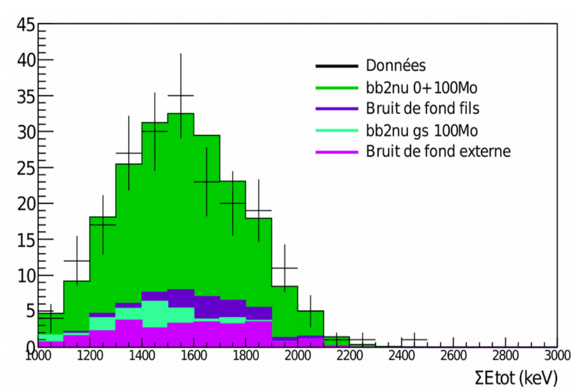
- Tracker + calorimetric experiment searching for 0νββ decay
- Located at Modane underground laboratory from Feb. 2003 to Jan. 2011
- 5 years of effective data taking
- 10 kg total of different ββ isotopes

reconstruction

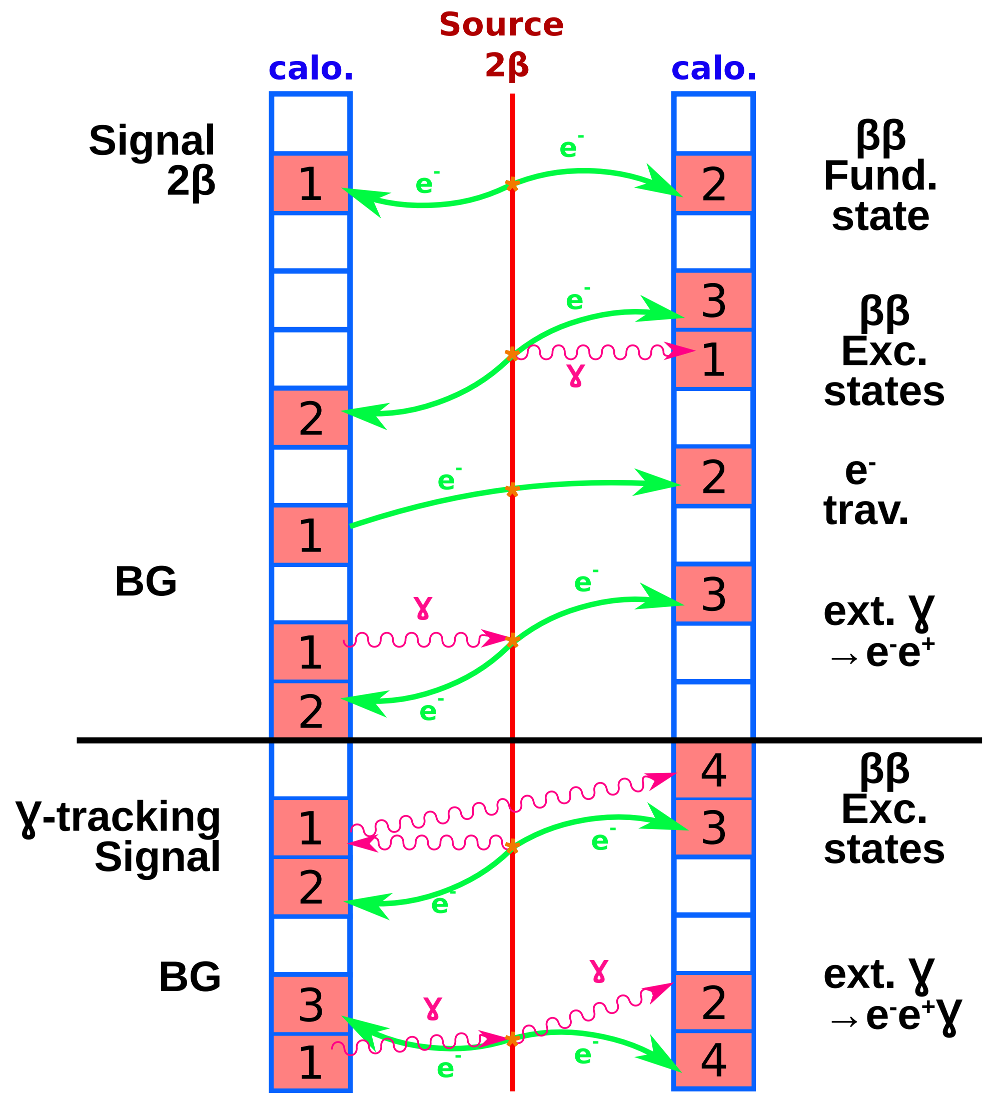
The reconstruction of the events and NEMO3 spectrums





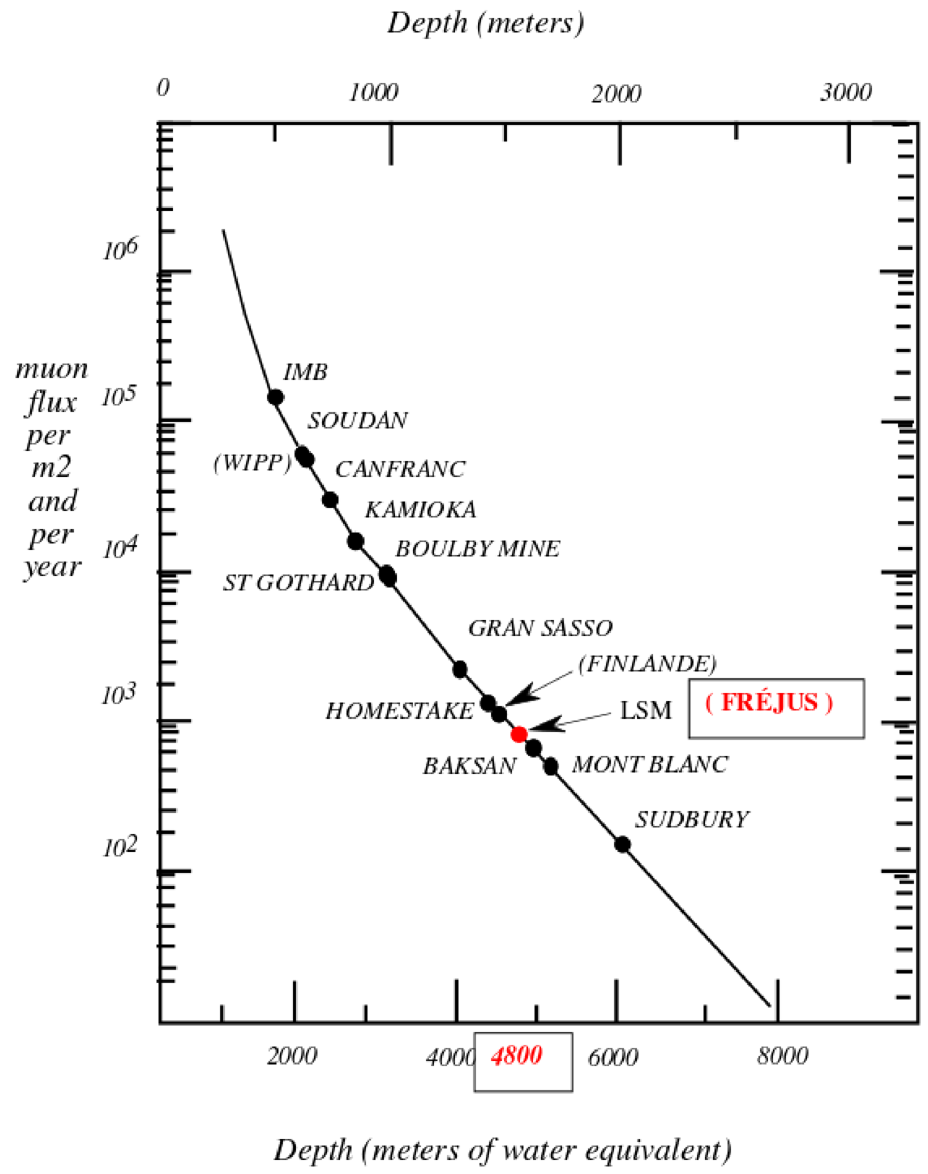


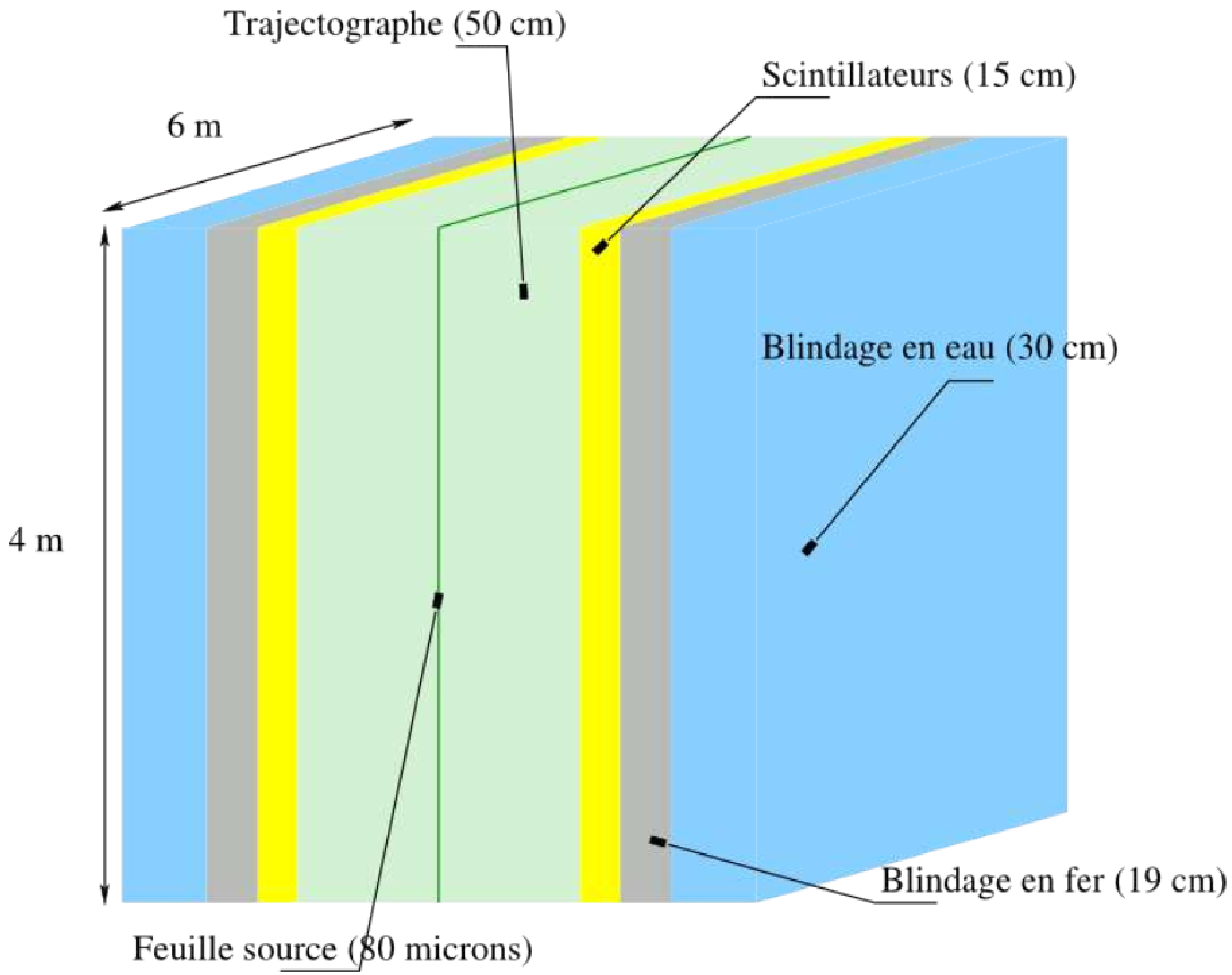
Event reconstruction
C. Hugon Ph.D (NAT++)



Muon flux per depth

Mwe ~ 2.5 – 3 x depth




Trajectographe (50 cm)
Scintillateurs (15 cm)
6 m
4 m
Blindage en eau (30 cm)
Blindage en fer (19 cm)
Feuille source (80 microns)