Topological detection of $\beta\beta$-decay with NEMO-3 and SuperNEMO

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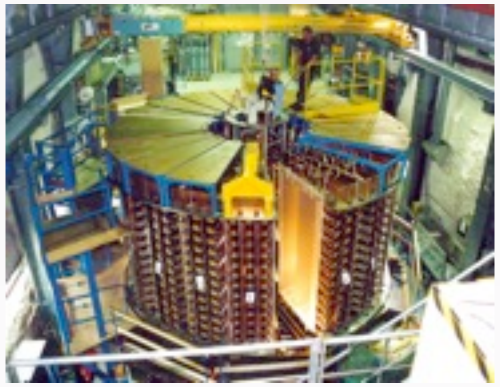
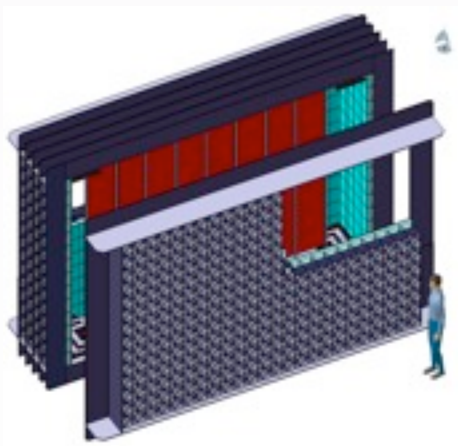
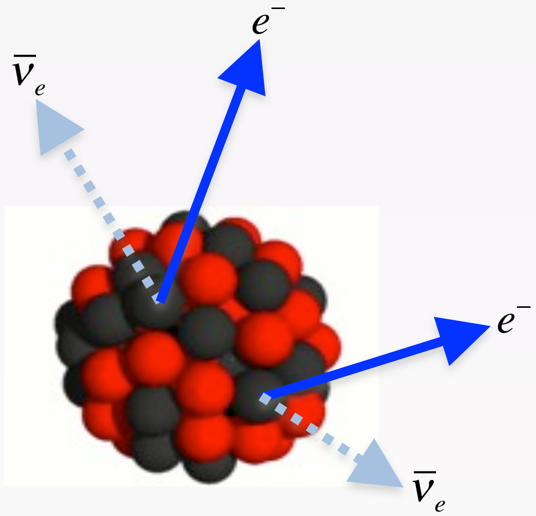
ANDES Workshop
Valparaiso, Chile
11 January 2012

- Motivation and Concept
- NEMO-3
  - Detector
  - Results
- SuperNEMO
  - Physics reach
  - R&D results
  - Demonstrator
  - Schedule







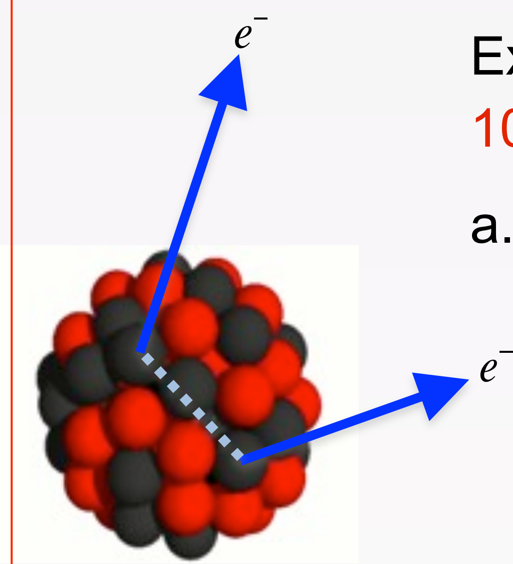
with 2ν's - allowed in Standard Model but still very rare

Observed for 11 nuclei with

$\tau \sim 10^{19}$-10^{21} yr

For comparison the age of Universe is $\sim 10^{10}$ yr.

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$



without ν's (0ν) - forbidden in SM, lepton number violation.

So far not observed $\tau > 10^{25}$ yr

Except one claim at 10^{25} yr level ⇒ $\langle m_\nu \rangle \approx 0.4$ eV!

a.k.a "Klapdor" claim

$$2n \rightarrow 2p + 2e^-$$

IF 0ν observed

- Neutrino identical to its anti-particle (Majorana particle)
- Access to absolute ν mass
- Origin of mass (not Higgs in case of ν?)
- Origin of matter-antimatter asymmetry in Universe
- Other new physics: SUSY, V+A, Majoron etc

⇨

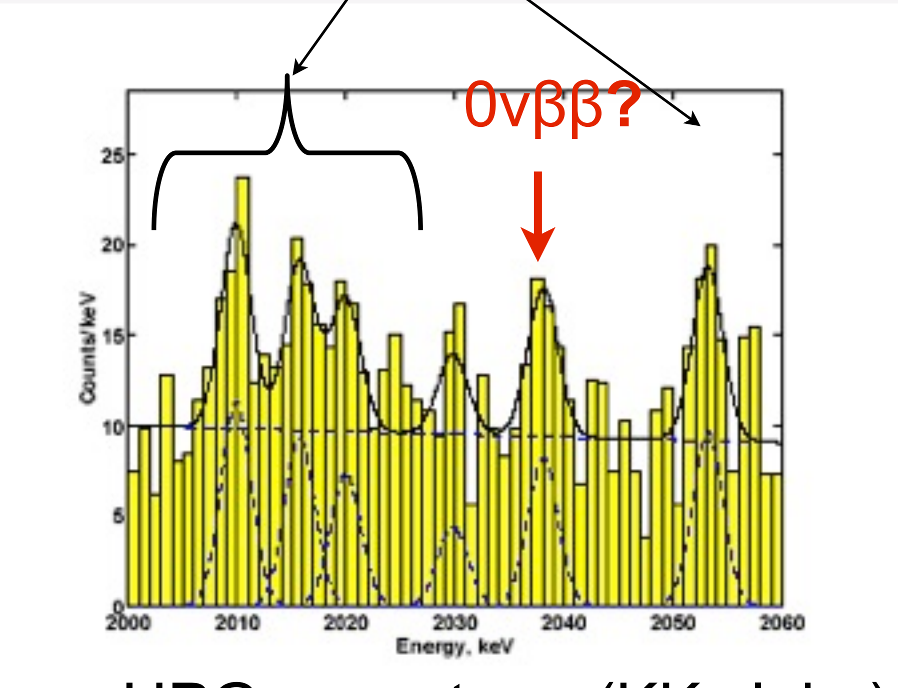
- Questions as fundamental as those addressed by LHC
- Many can only be addressed by 0νββ

How do we know it is ββ?

☑ $E_{e1} + E_{e2} = Q_{\beta\beta}$ (for 0ν)

Calorimeter only

Background γ lines

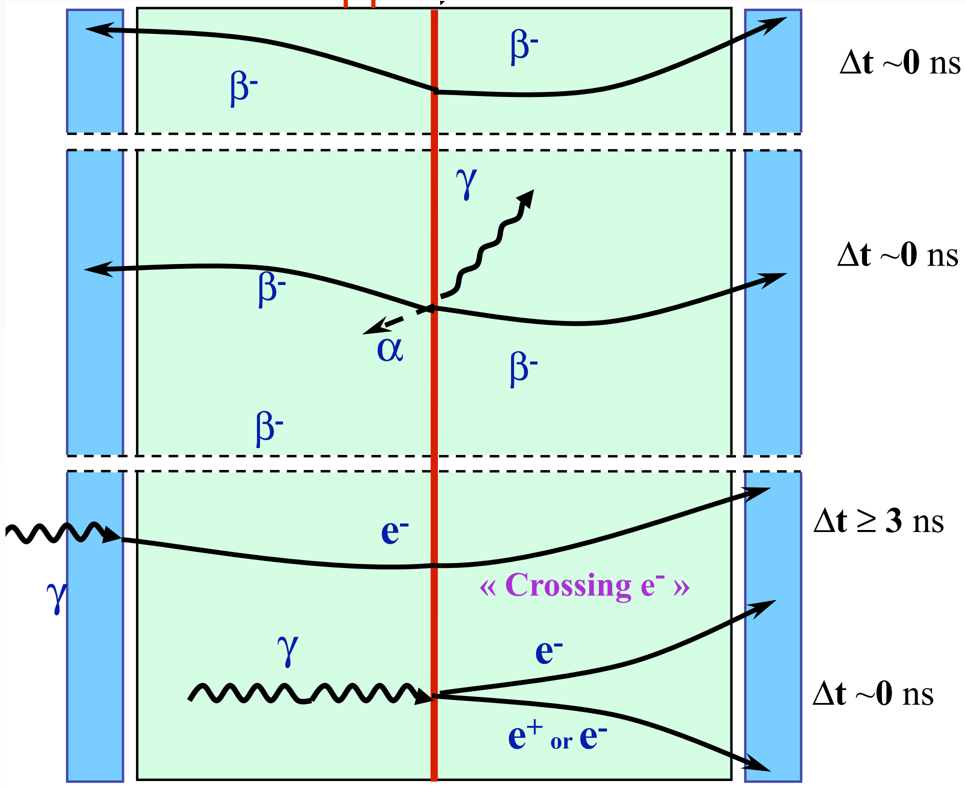


HPGe spectrum (KK claim)

- ☑ **Several** observables
- ☑ Two **electrons**
- ☑ **Coincident**
- ☑ From the **same vertex**
- ☑ **Angular** distributions between two electrons

Tracking

ββ source

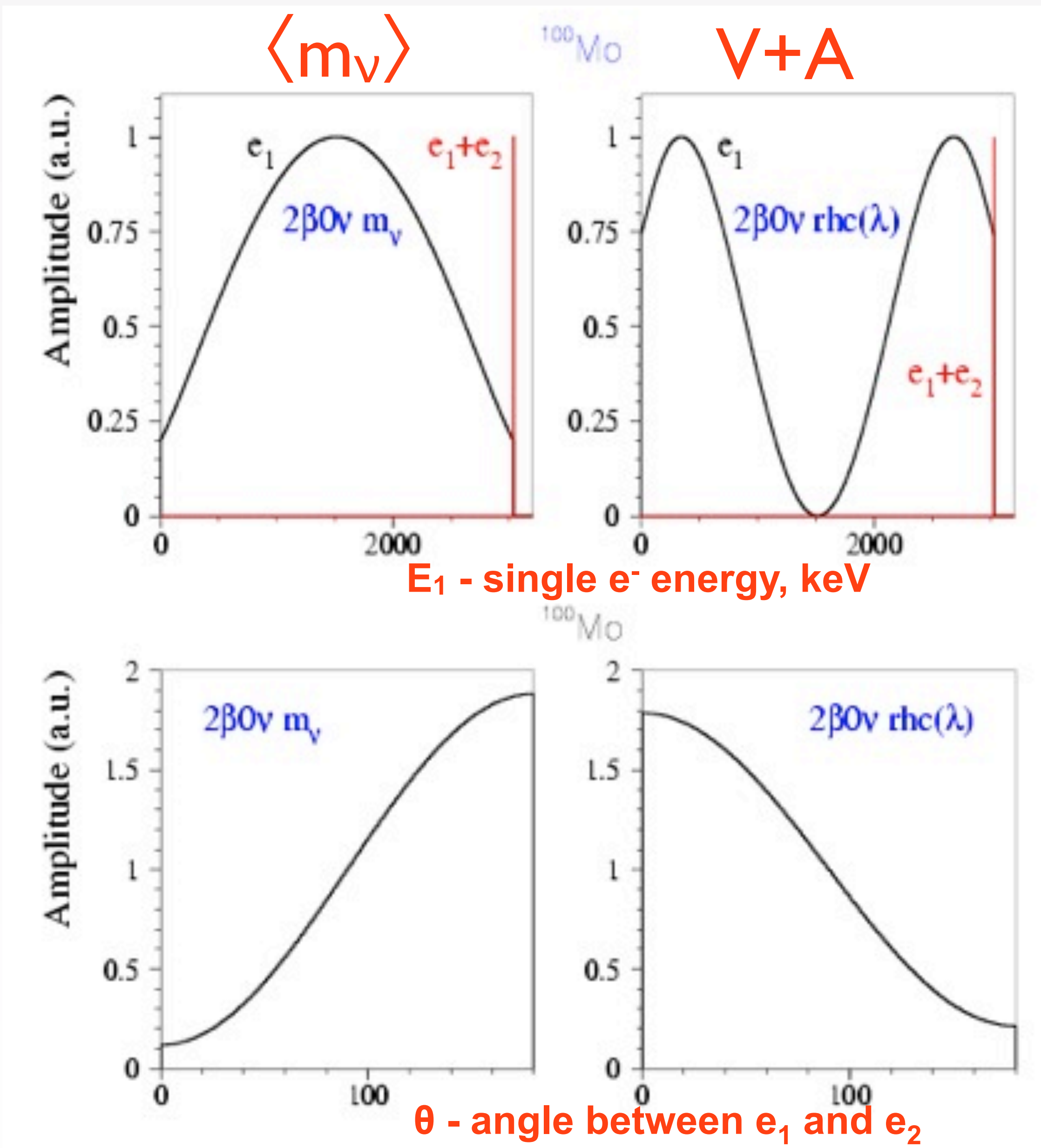


Tracko-Calo, e.g. NEMO3/SuperNEMO

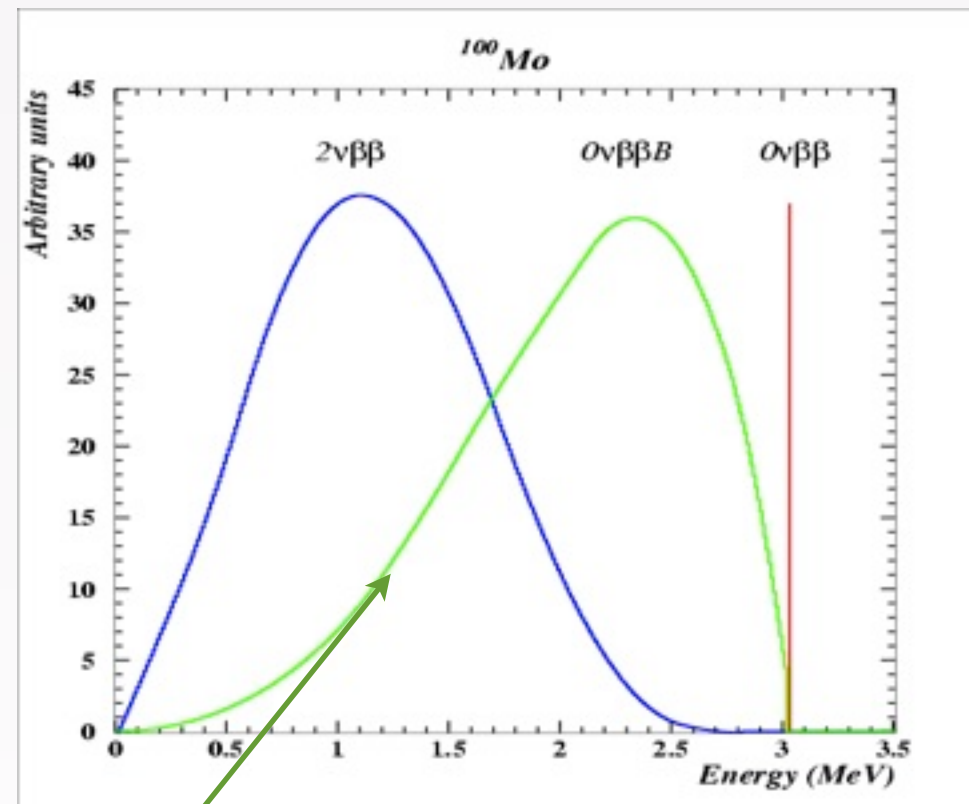
Open-minded search for any 0νββ mechanism

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \eta^2$$

η can be due to $\langle m_\nu \rangle$,V+A, Majoron, SUSY, H^- or a combination of them



Topology can be used to disentangle underlying physics mechanism

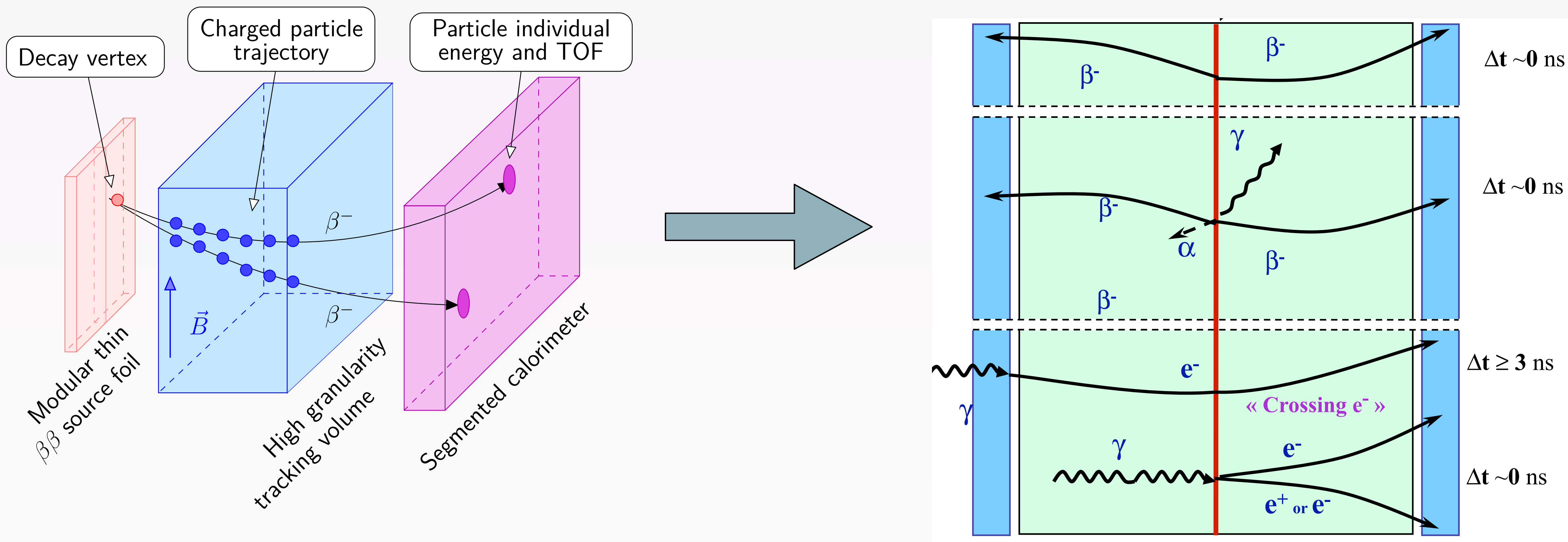


Majoron

Topology detection is a more sensitive method for phenomena with continuous spectra, e.g. 2νββ, 0νββB (Majoron)

NEMO-3 and SuperNEMO

Unique Detection principle: reconstruct topological signature

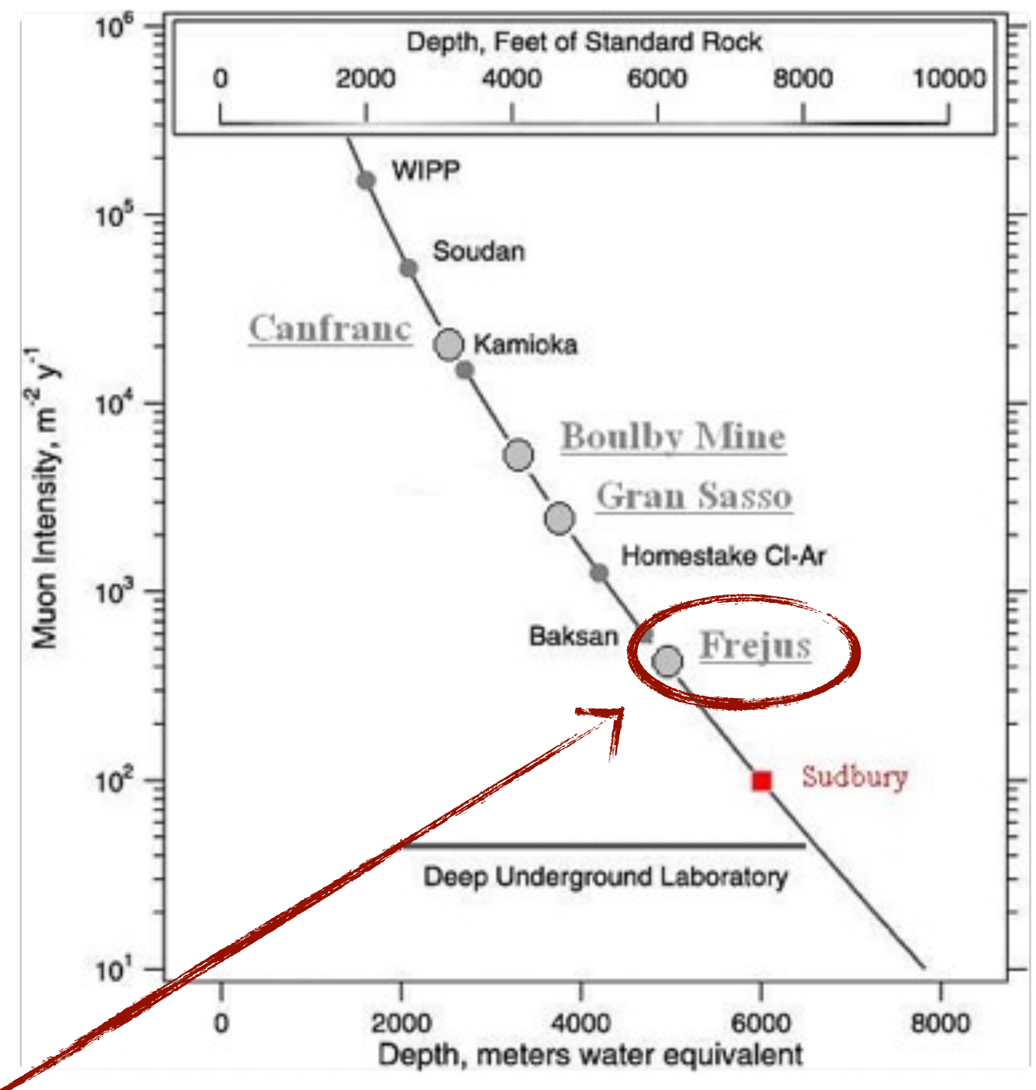


- **Reconstruct two electrons in the final state ($E_1+E_2 = Q_{\beta\beta}$)**
- **Measure several final state observables**
  - **Individual electron energies**
  - **Electron trajectories and vertices**
  - **time of flight**
  - **Angular distribution between electrons**
- **Powerful Background rejection through particle ID: e^-, e^+, α, γ**

➡ **"Smoking gun"** evidence for 0νββ
➡ **Open-minded** search for **any** lepton violating process
➡ Possibility to **disentangle** underlying **physics mechanism**

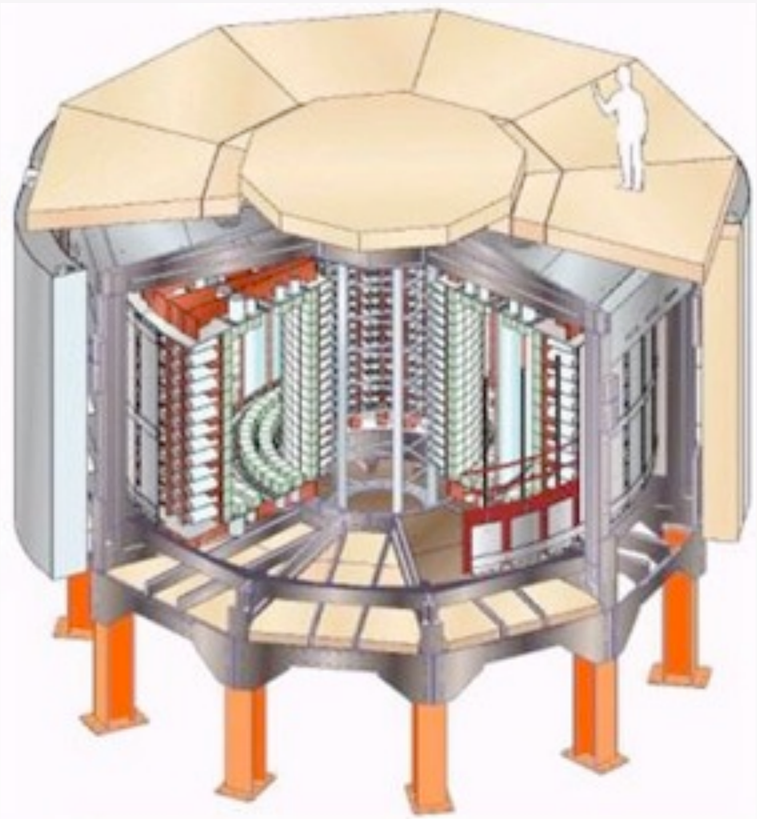
Neutrino Ettore Majorana Observatory 3

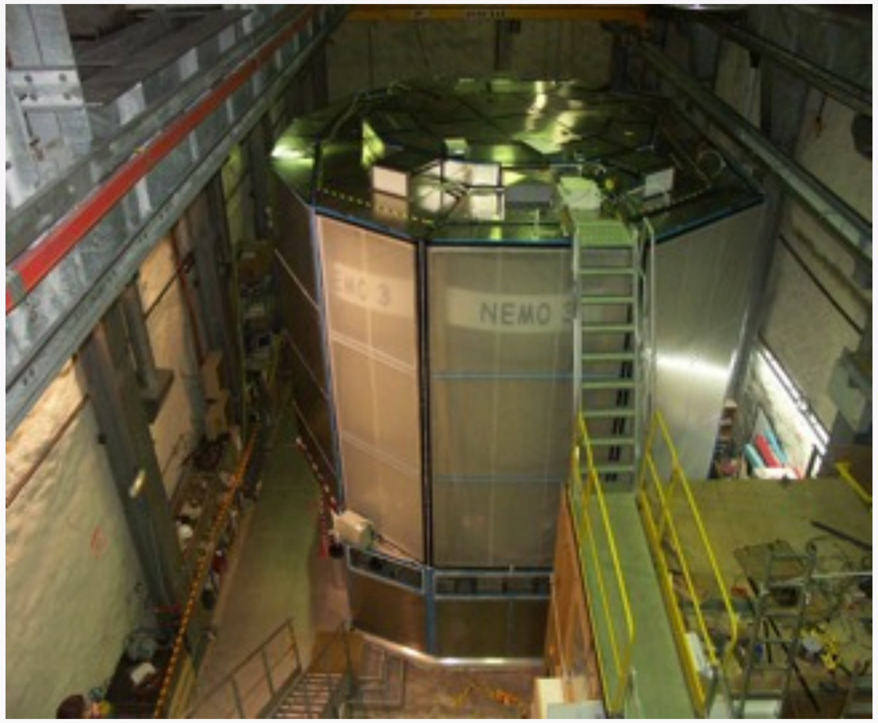
Data taking: Feb'03 - Jan'11



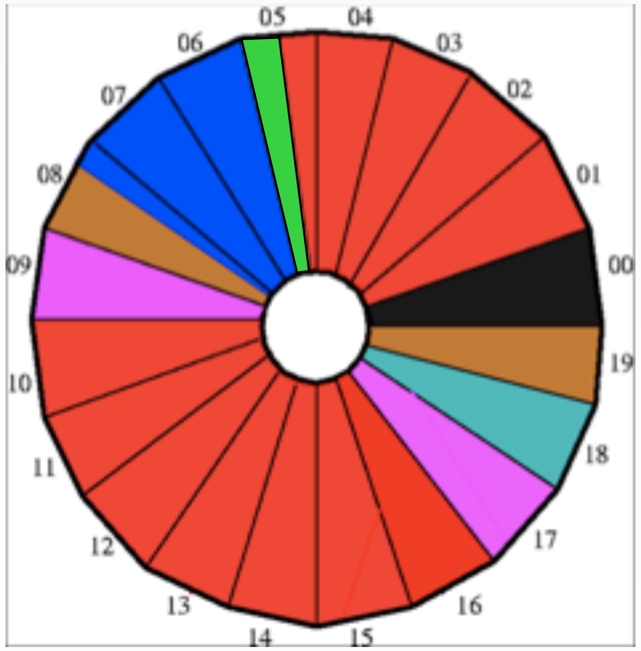
Laboratoire Souterrain de Modane (LSM)
Modane, France
(Tunnel Frejus, depth of ~4,800 mwe)

NEMO-3 - 20 sectors with ~10 kg of isotopes





- Magnetic field: 25 Gauss
- Gamma shield: 18 cm of pure iron
- Neutron shield:
  - 30cm borated water (external wall)
  - 40cm wood (top and bottom)
- Anti-Radon "factory" and "tent"



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

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

^{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

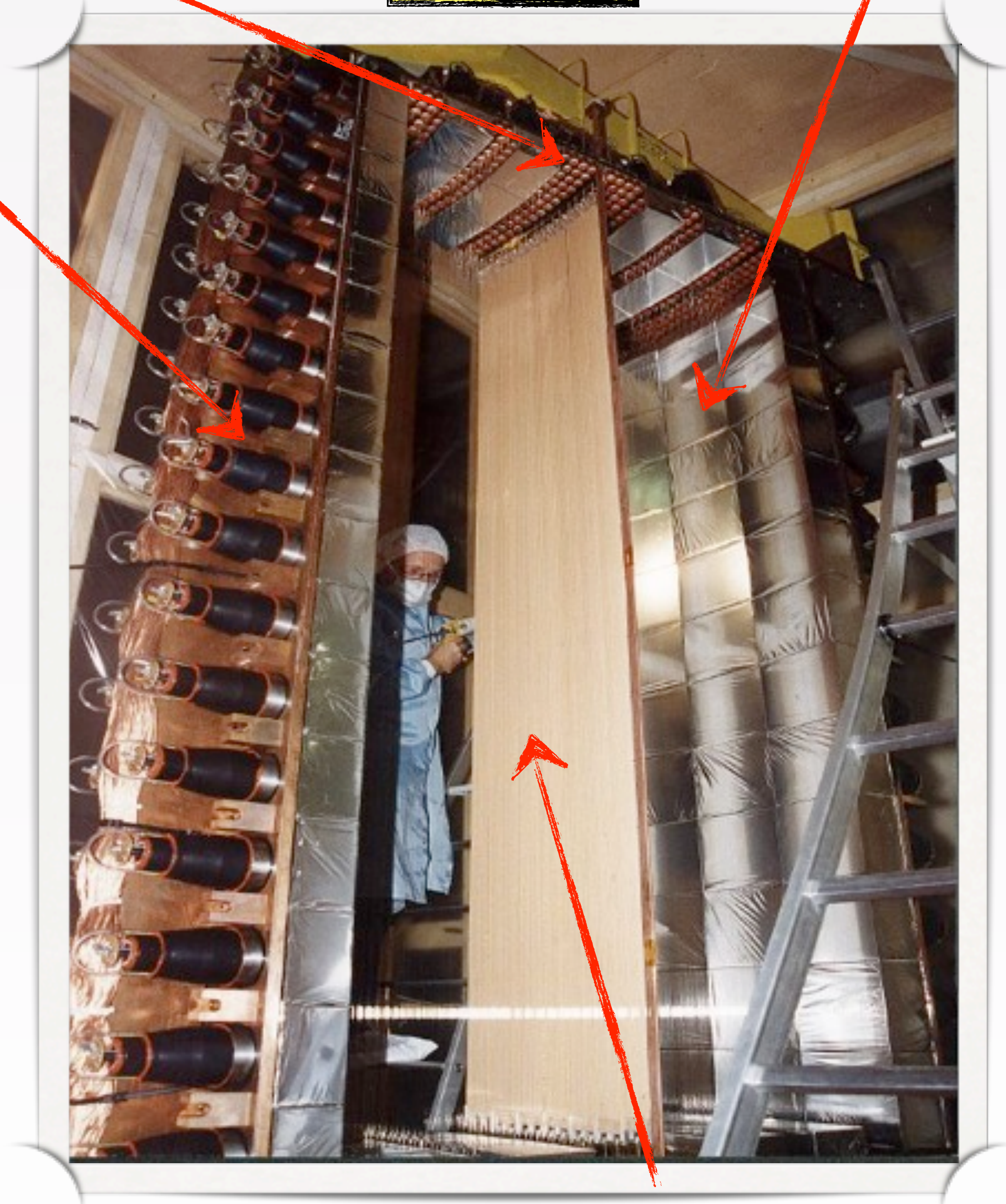
^{130}Te 454 g
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te 491 g

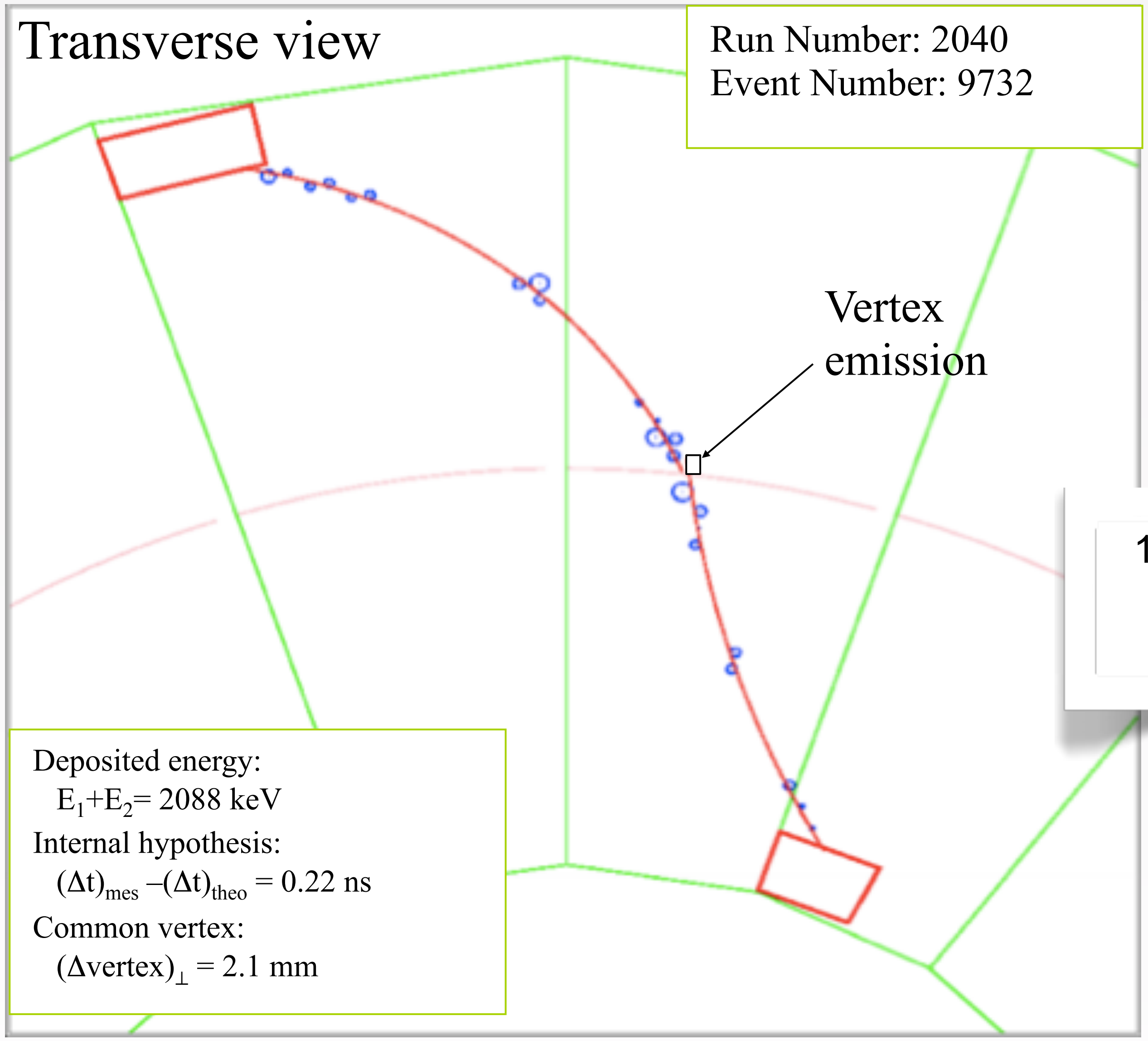
Cu 621 g

NEMO-3 design

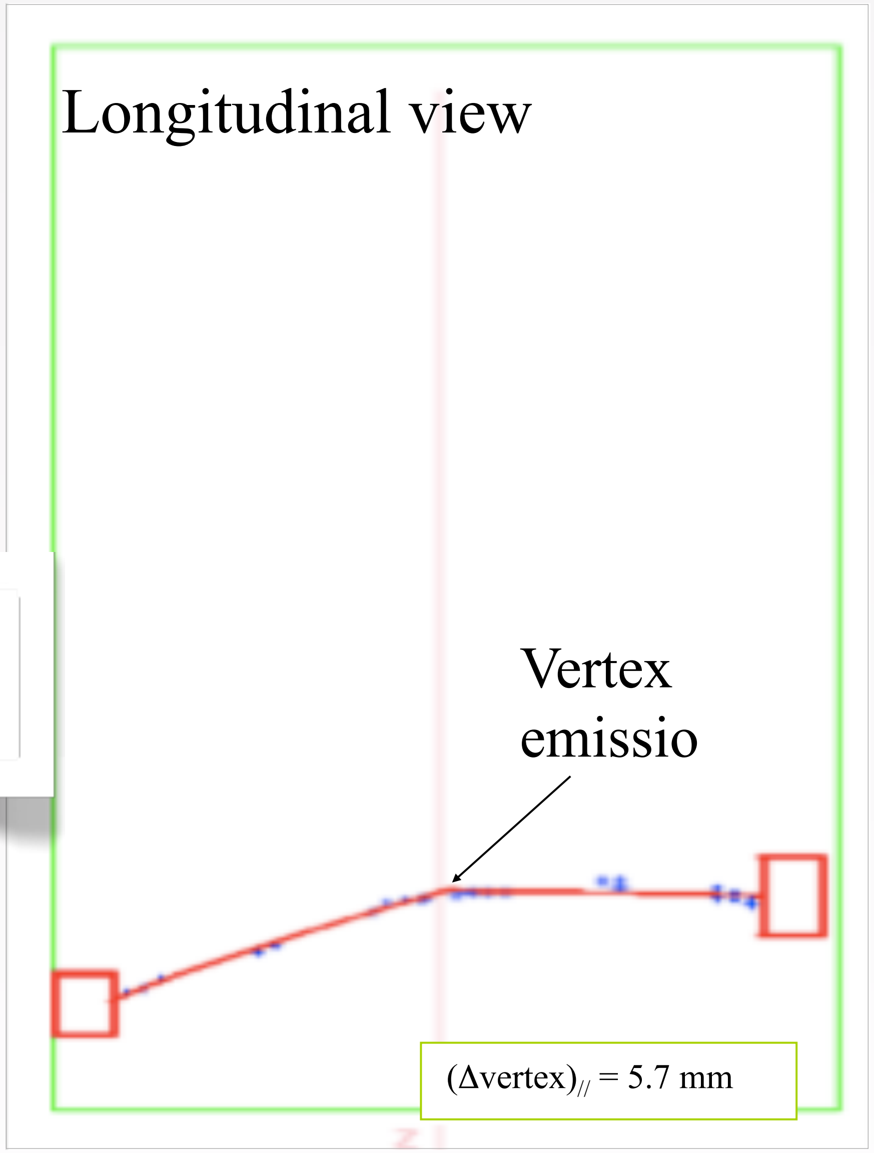
- Tracker for full event reconstruction
  - 6180 drift cells in Geiger mode: Helium + 4% ethyl alcohol + 1% Ar + 0.1% H_2O
- Calorimeter for energy and time measurement
  - 1940 scintillator blocks coupled to low radioactivity PMTs
- Identify e^-, e^+, γ, α
- Identify external and internal events



NEMO-3 ββ event selection

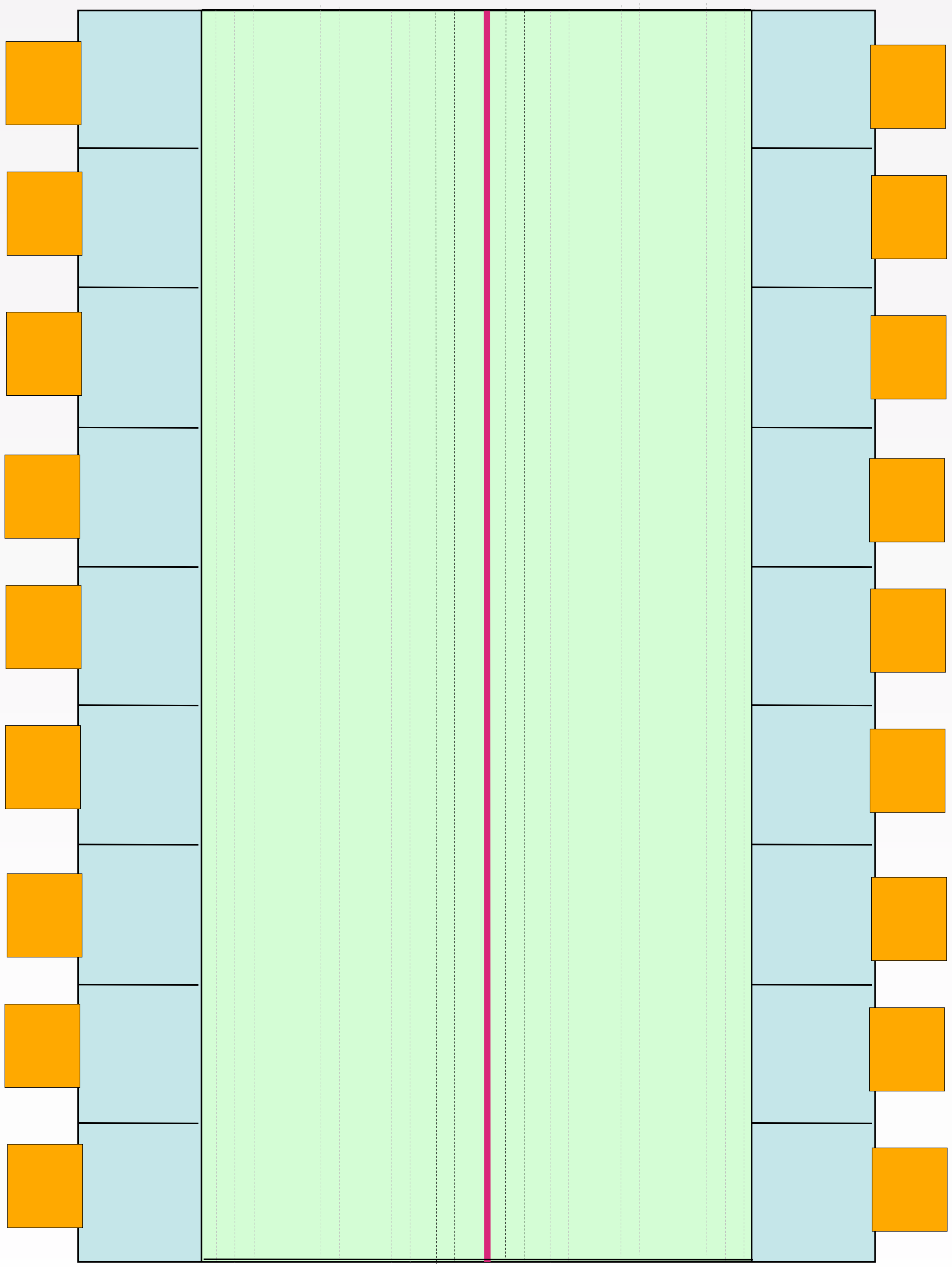


1 ββ event every 2,5 minutes!
(in ^{100}Mo)



- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

Background: The Enemy and how to fight it

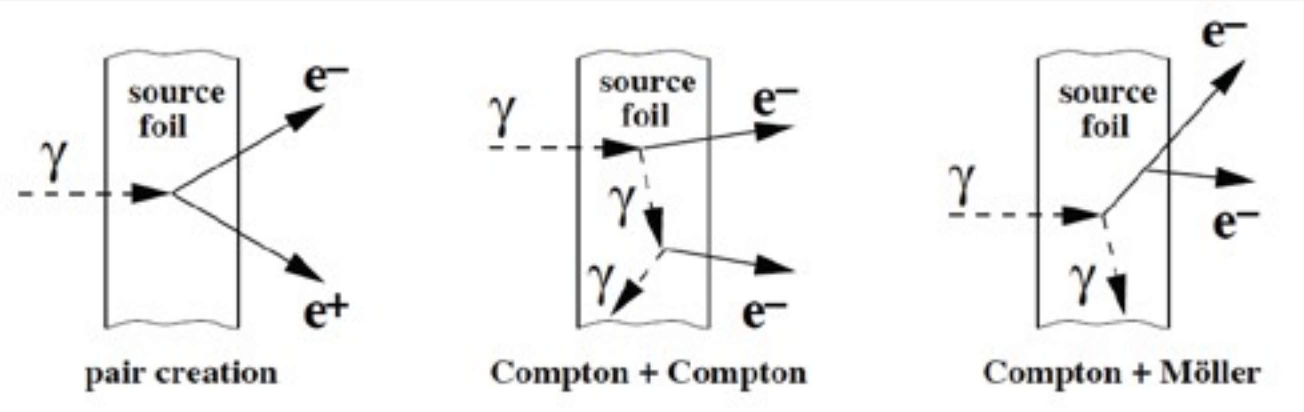


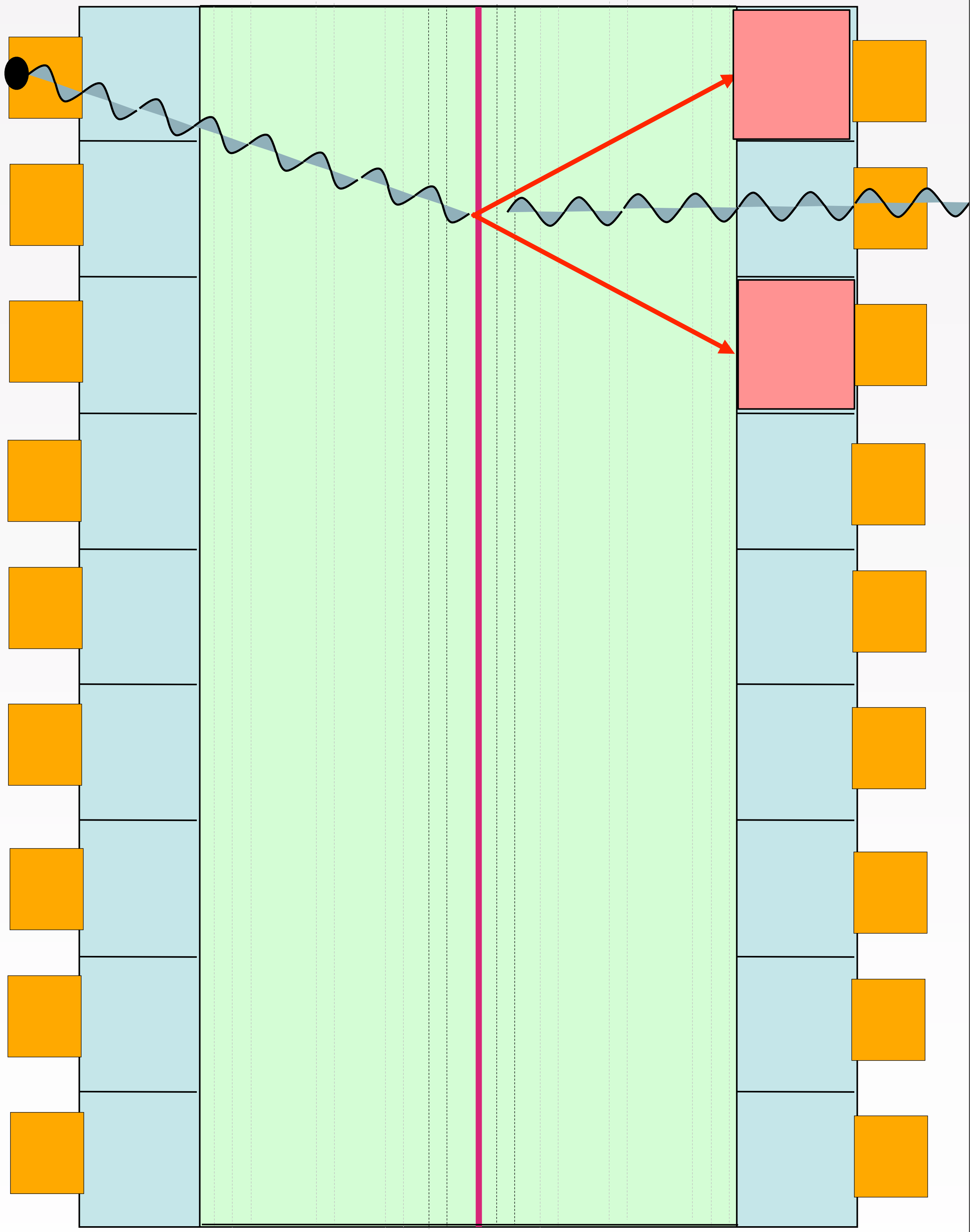
- **External** γ (if the γ is not detected in the scintillators)

  Origin: natural radioactivity of the detector or neutrons

  Major bkg for $2\nu\beta\beta$ but small for $0\nu\beta\beta$

  (^{100}Mo and ^{82}Se $Q_{\beta\beta}$~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)





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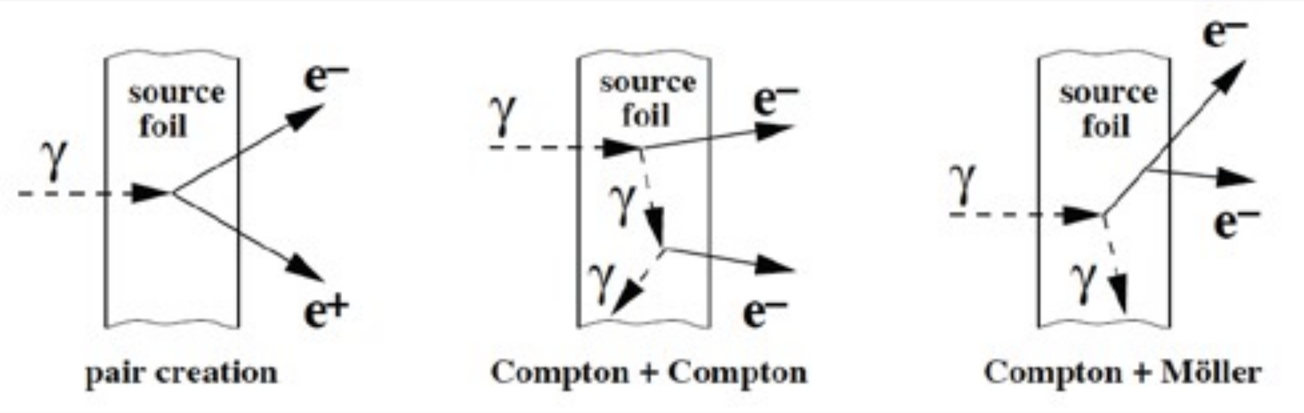
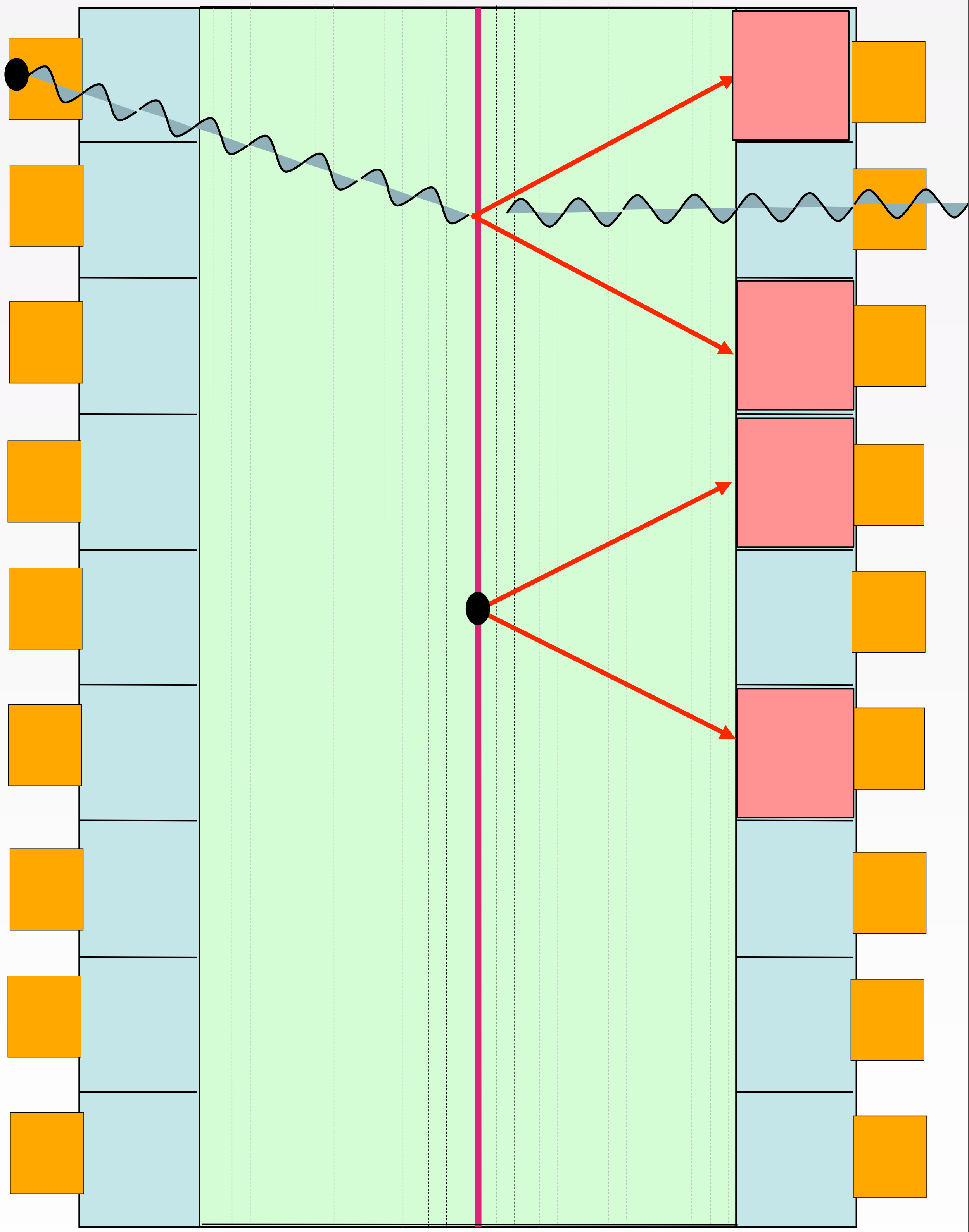
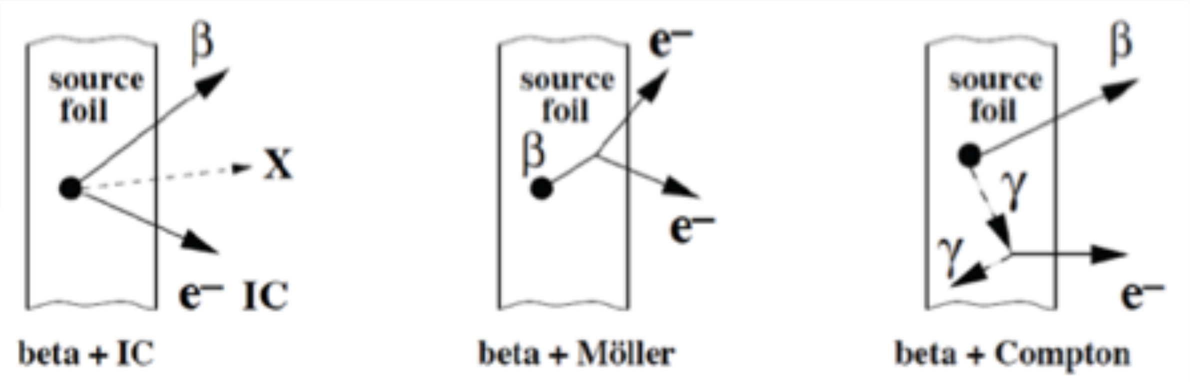




- **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi) contamination inside the ββ source foil**



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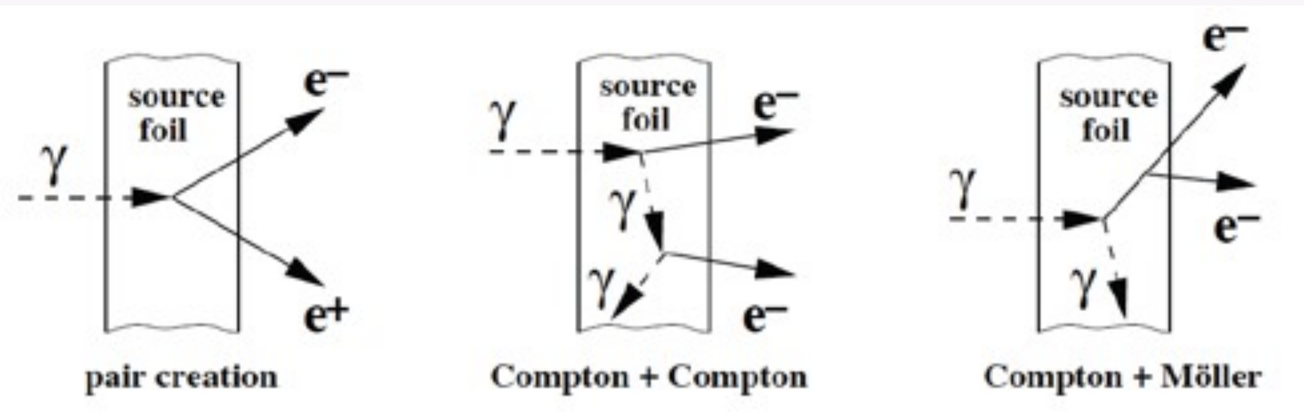

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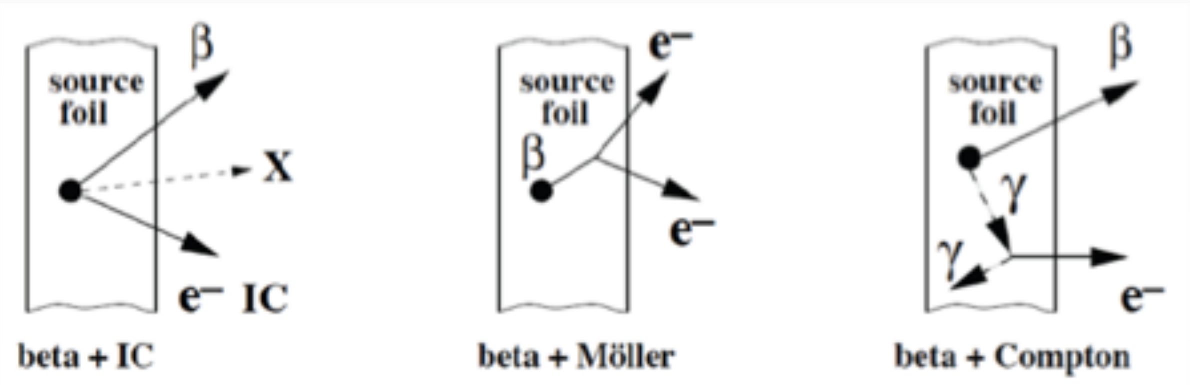
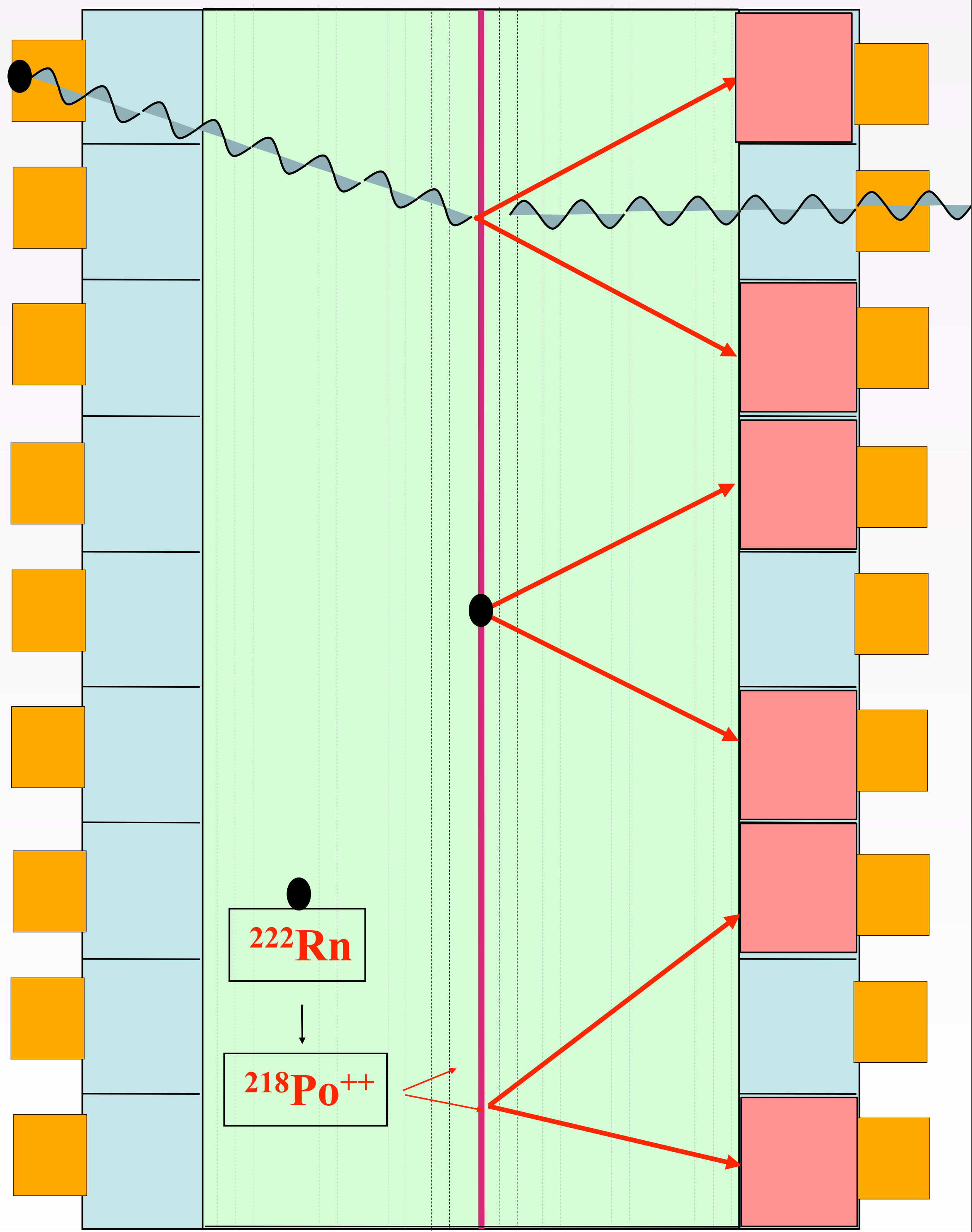


- **Radon (^{214}Bi) inside the tracking detector**
  - deposits on the wire near the $\beta\beta$ foil
  - deposits on the surface of the $\beta\beta$ foil



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Major bkg for 2νββ but small for 0νββ

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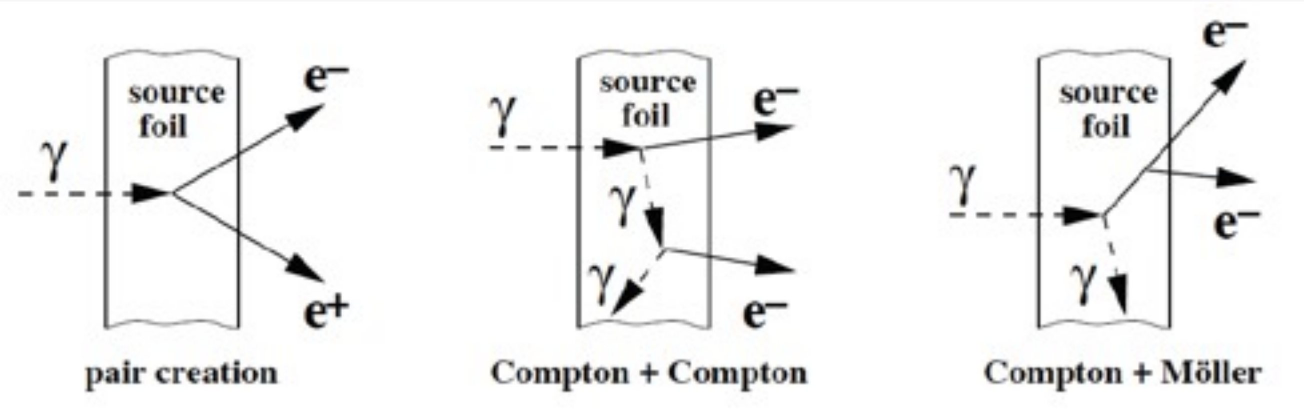

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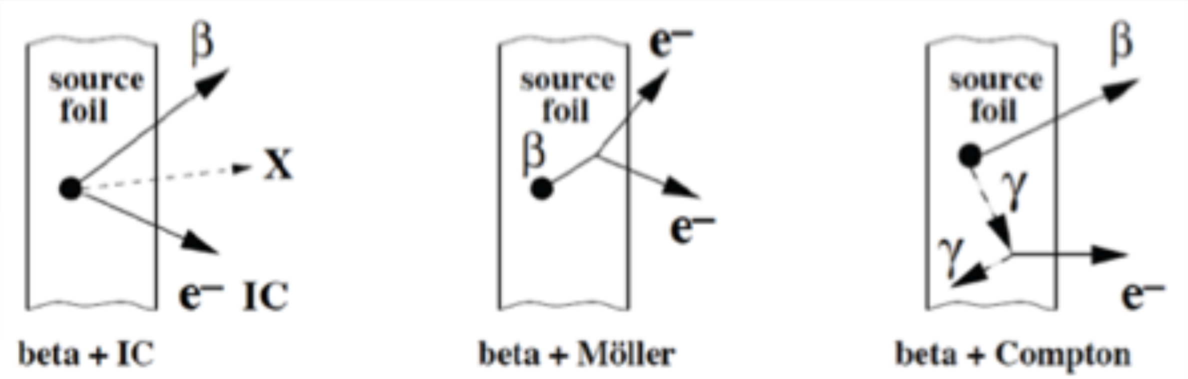
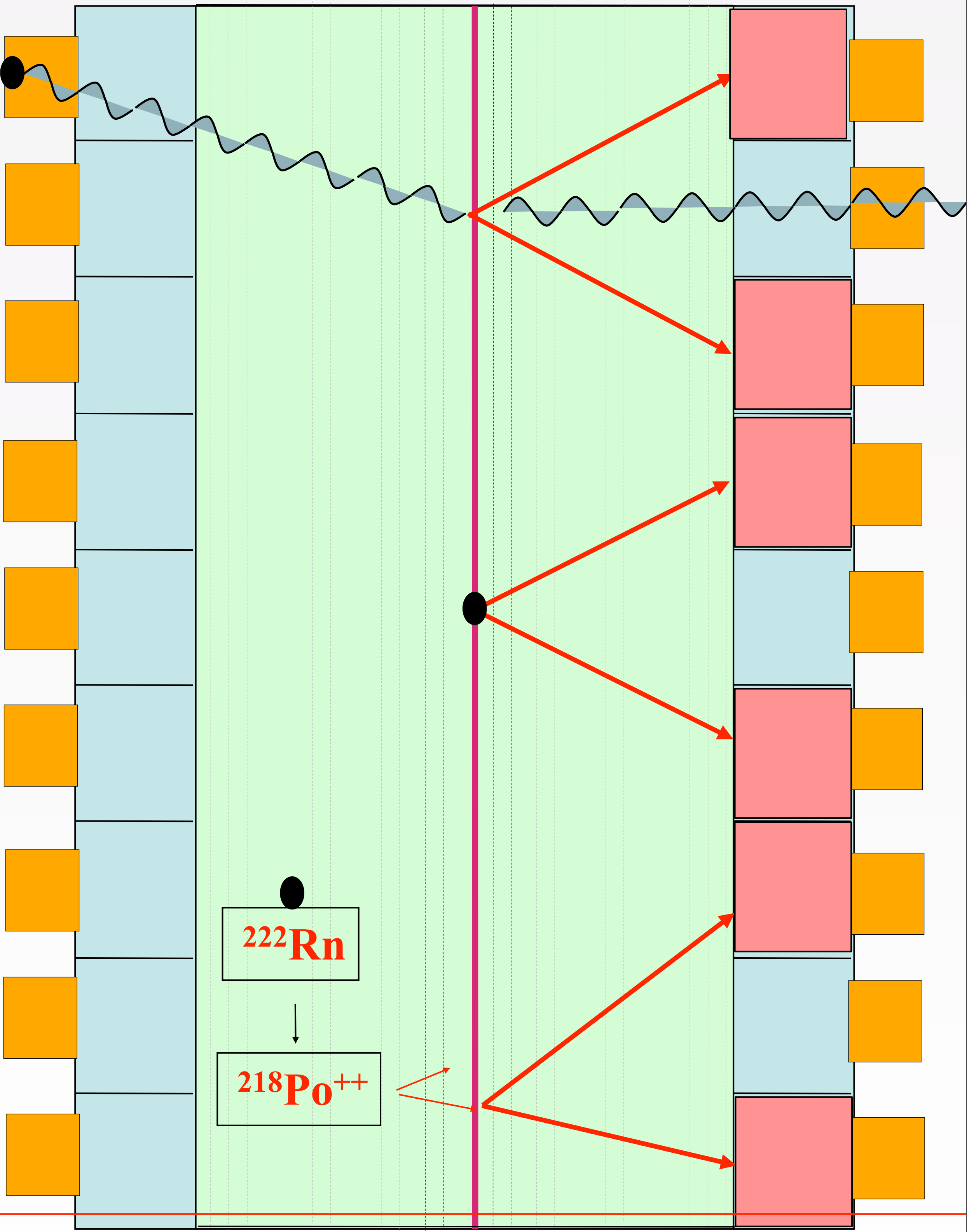
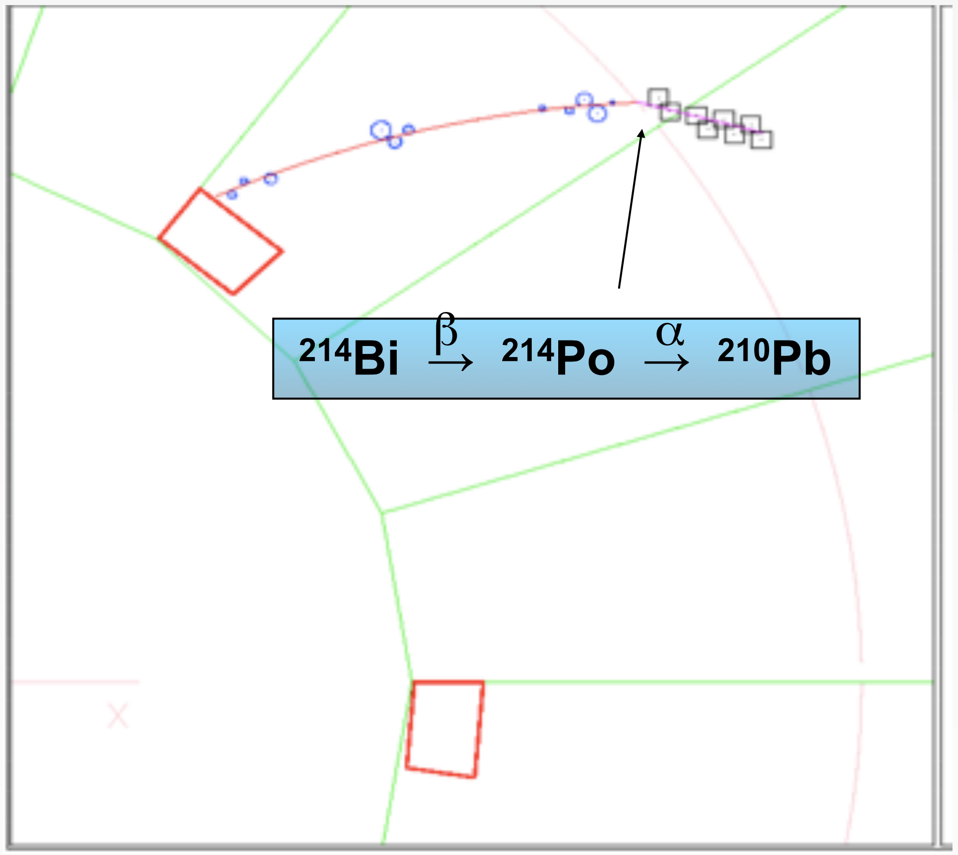


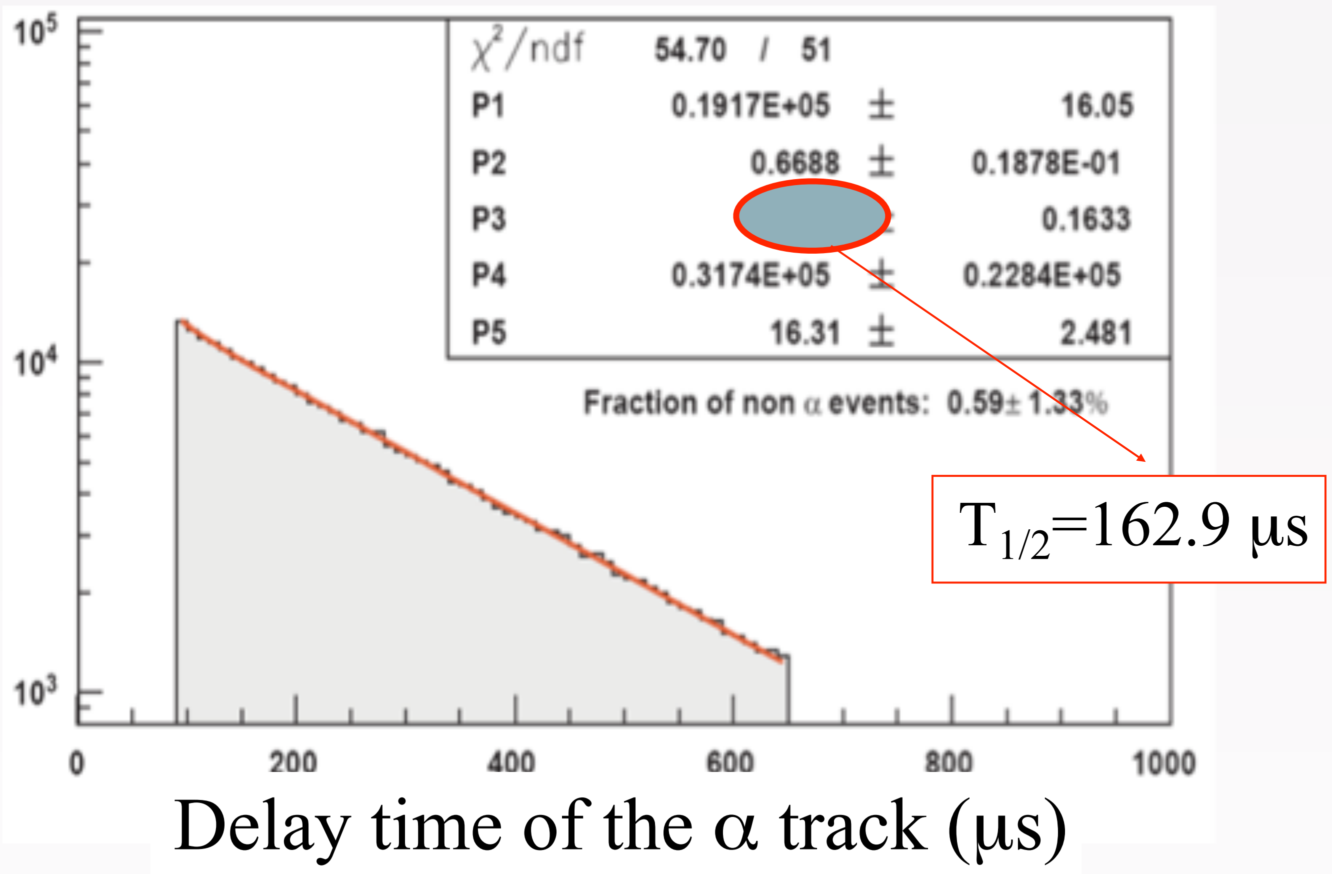
- **Radon (^{214}Bi) inside the tracking detector**
  - deposits on the wire near the ββ foil
  - deposits on the surface of the ββ foil



Each bkg is measured using the NEMO-3 data

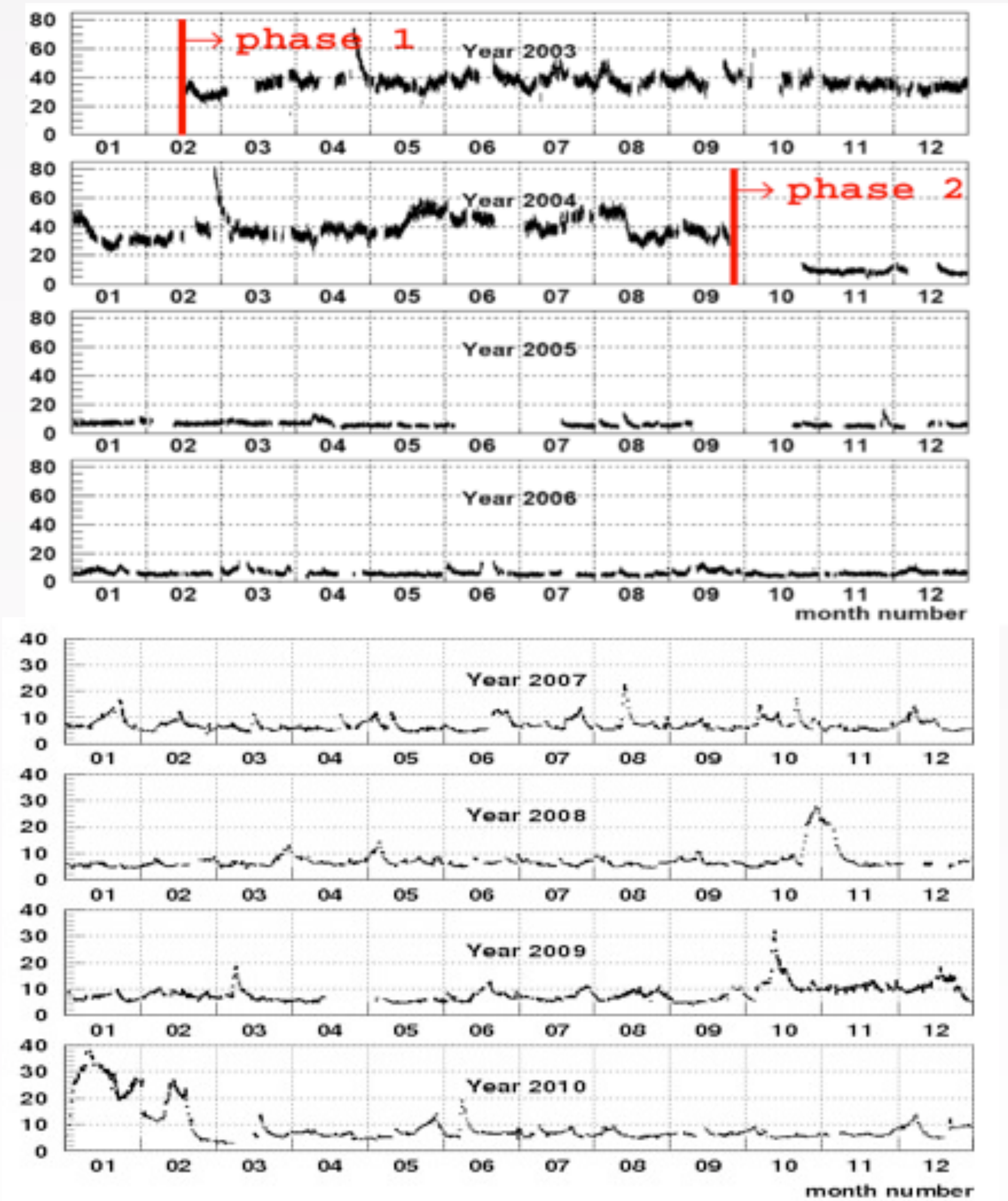


Pure sample of ^{214}Bi – ^{214}Po events



Anti-radon "factory" - trapping Rn in cooled charcoal. A must for a low-background lab.

Measurements of ^{222}Rn activity in the gas of tracker (mBq/m^3)



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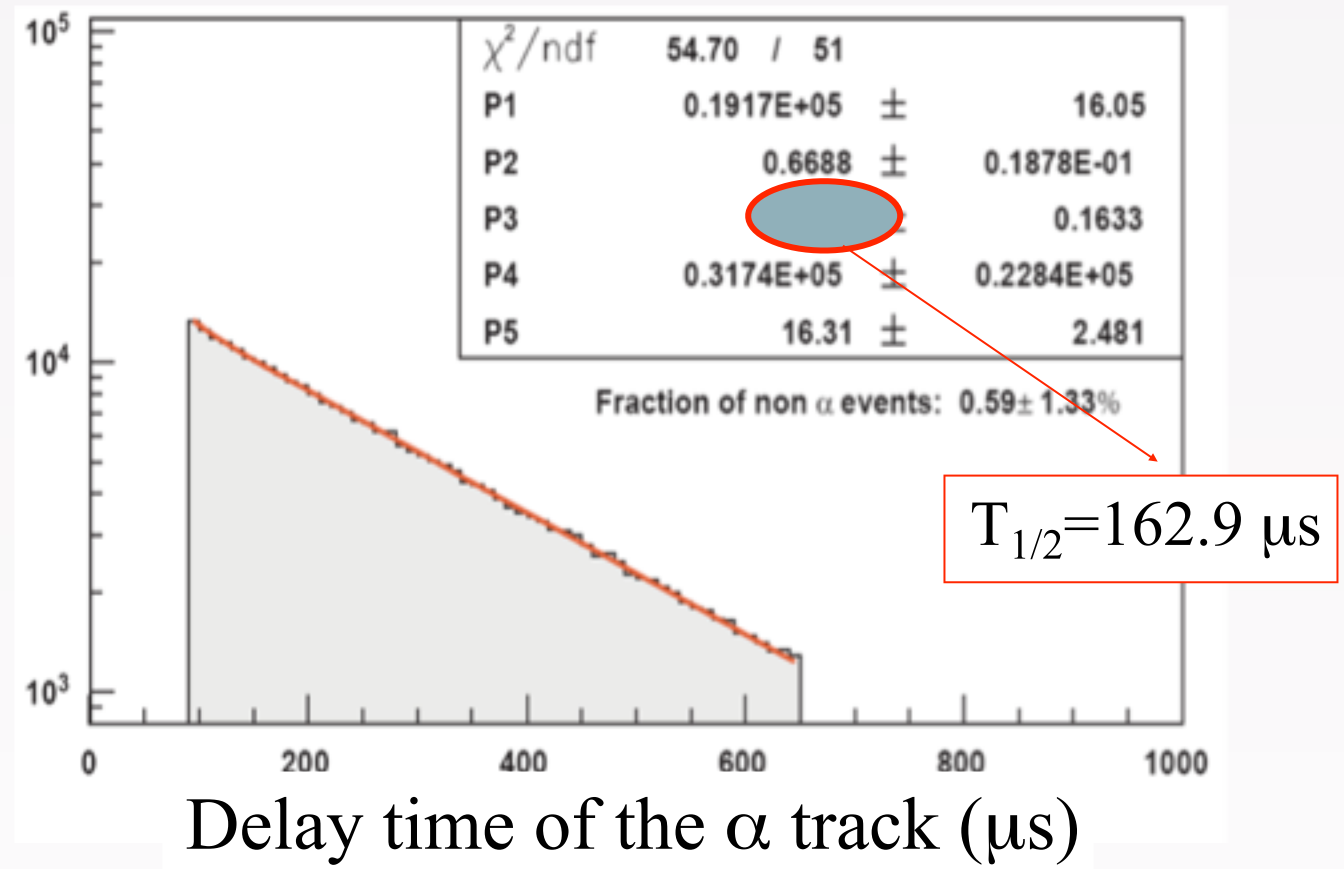

Anti-Rn factory: Input=15Bq/m^3 →Output 15mBq/m^3

Inside the detector:

- Phase 1: Feb'03 → Sep'04
  A(Radon) ≈ 40 mBq/m^3
- Phase 2: Dec. 2004 → Jan'11
  A (Radon) ≈ 5 mBq/m^3

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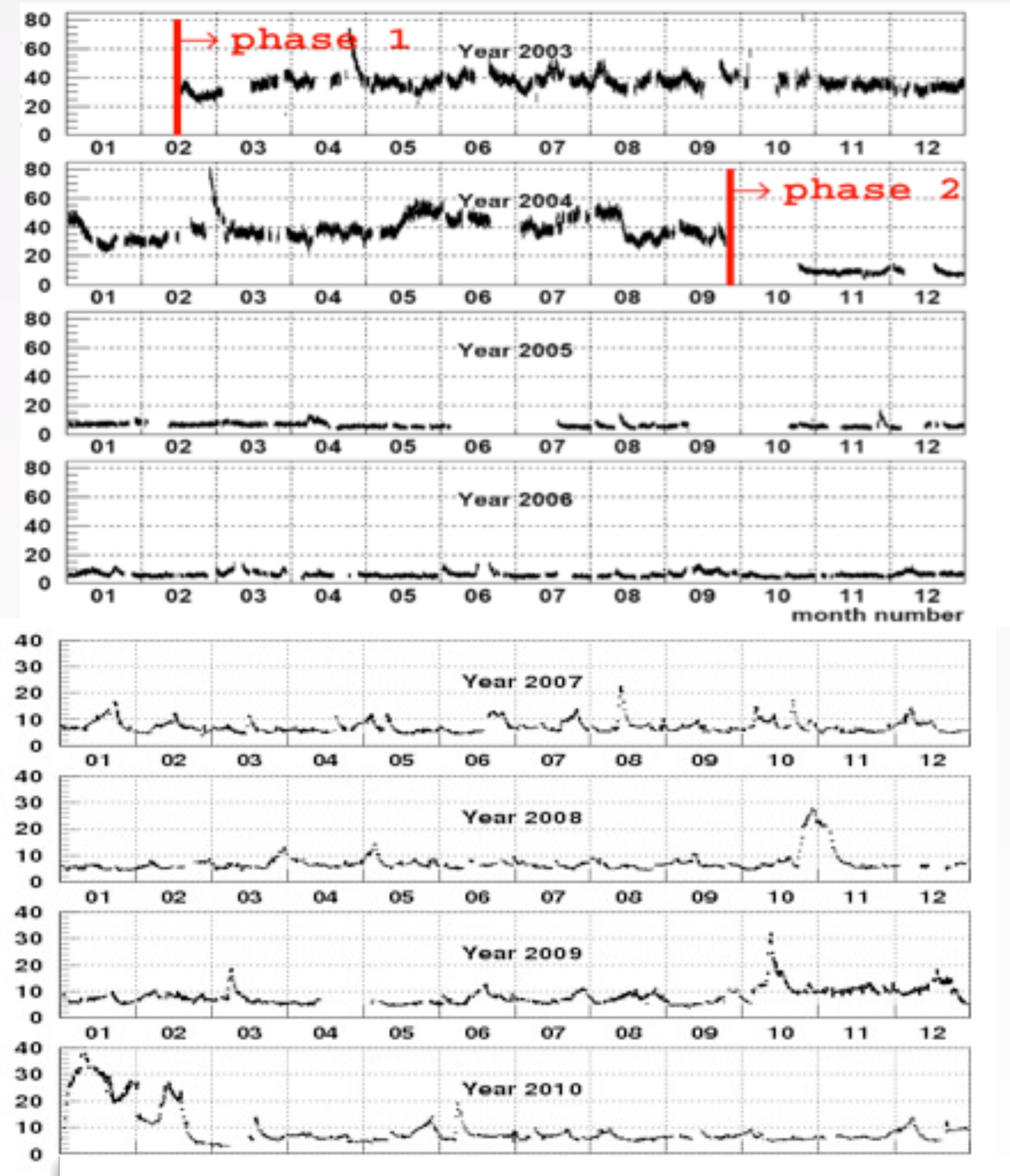
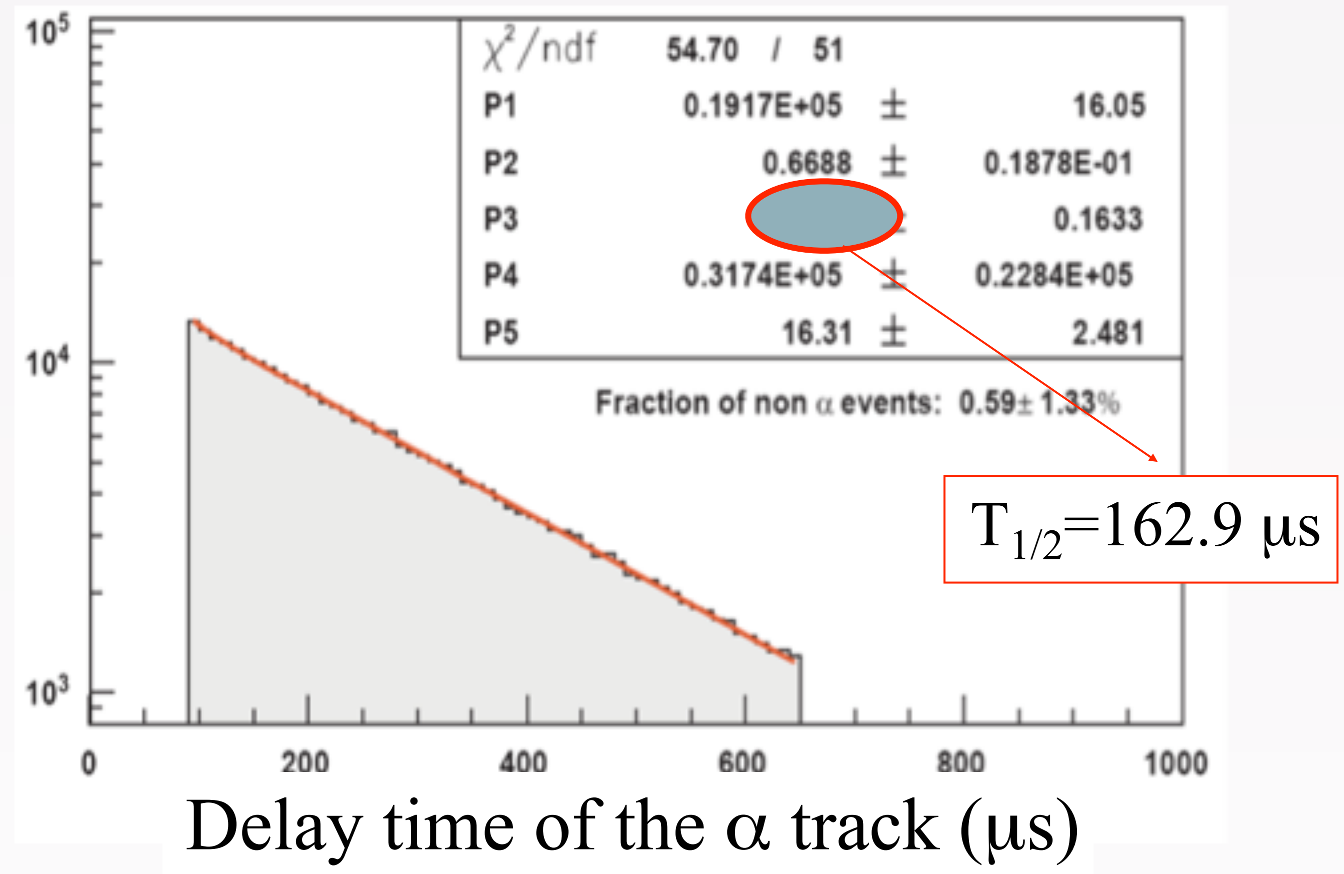


"Handbook" on backgrounds for ββ experiments:
Background measurement in NEMO3:
NIM A 606 (2009) pp. 449-465.

Pure sample of ^{214}Bi – ^{214}Po events



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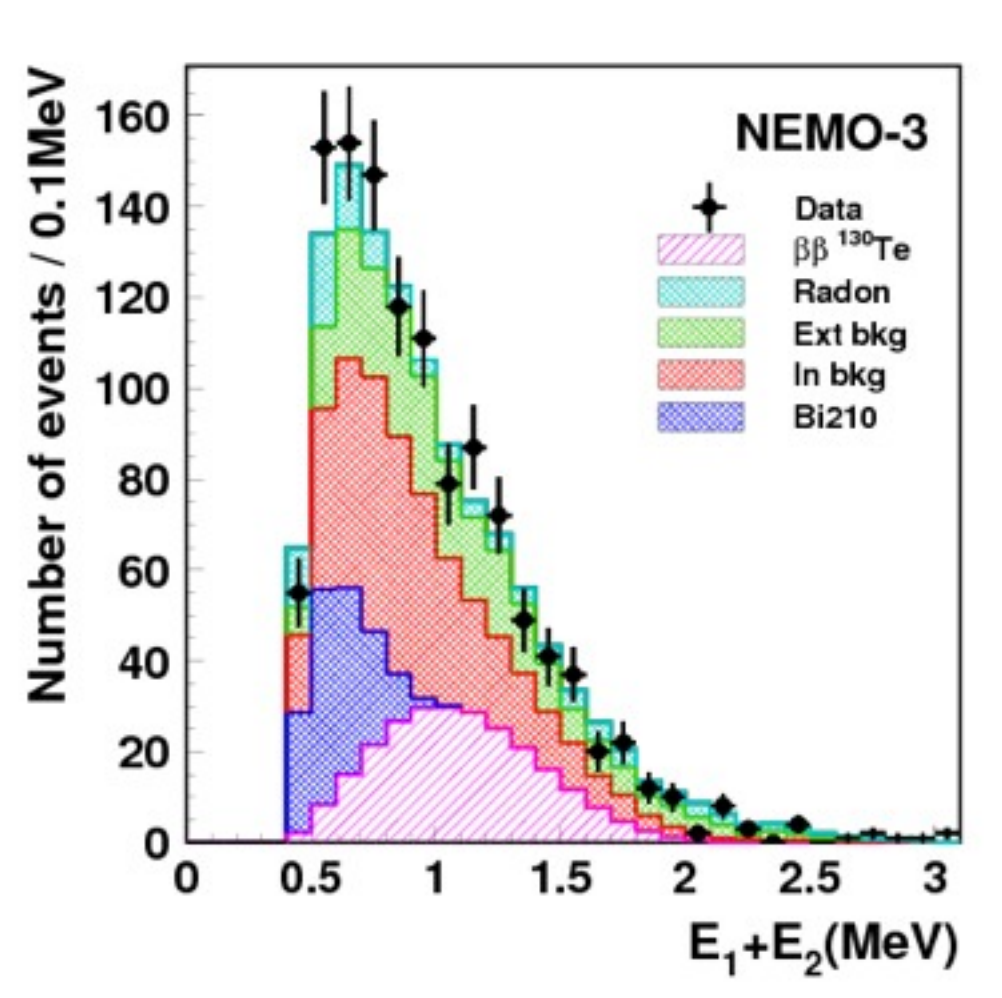
NEMO-3 latest results (2011)

661 g of ^{130}Te



1275 days

N(2νββ) = 178 ± 23

$$T_{1/2}^{2\nu} = [7.0 \pm 0.9(stat) \pm 1.1(syst)] \times 10^{20} \text{ yr}$$

Phys. Rev. Lett. 107, 062504 (2011)

c.f.

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

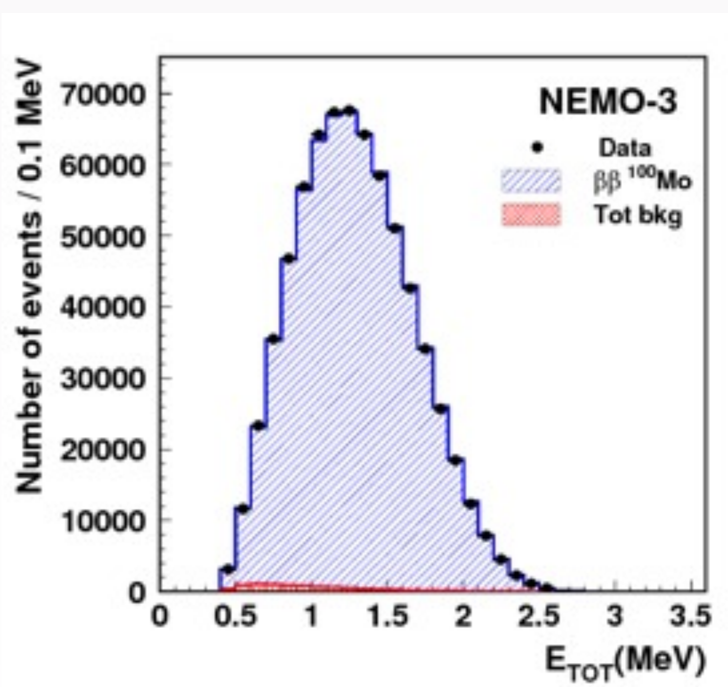
Indication from MIBETA

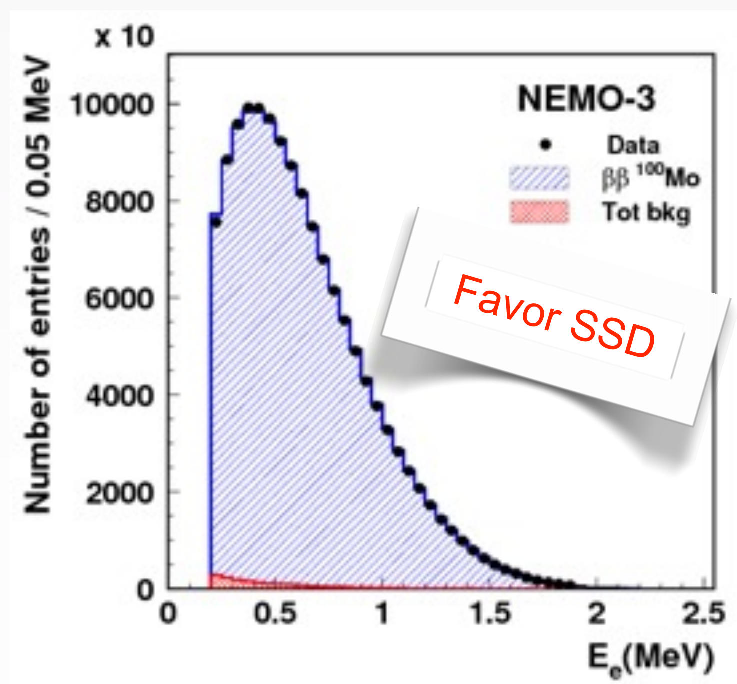
$$T_{1/2}^{2\nu} = [6.1 \pm 1.4(stat)^{+2.9}_{-3.5}(syst)] \times 10^{20} \text{ yr}$$

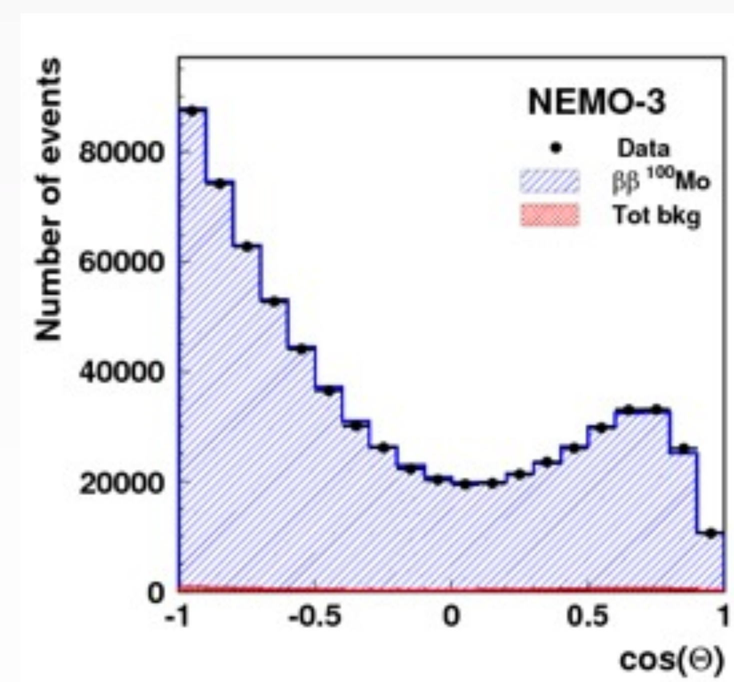
$2\nu\beta\beta$ Results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2809	2.8 ± 0.3	10	World's best	
^{150}Nd	37	3367	0.9 ± 0.07	2.7	World's best	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best	Phys.Rev.Lett. 95(2005) 483
^{130}Te	454	2533	70 ± 14	0.5	First direct detection	Phys. Rev. Lett. 107, 062504 (2011)

Unprecedented accuracy with ^{100}Mo







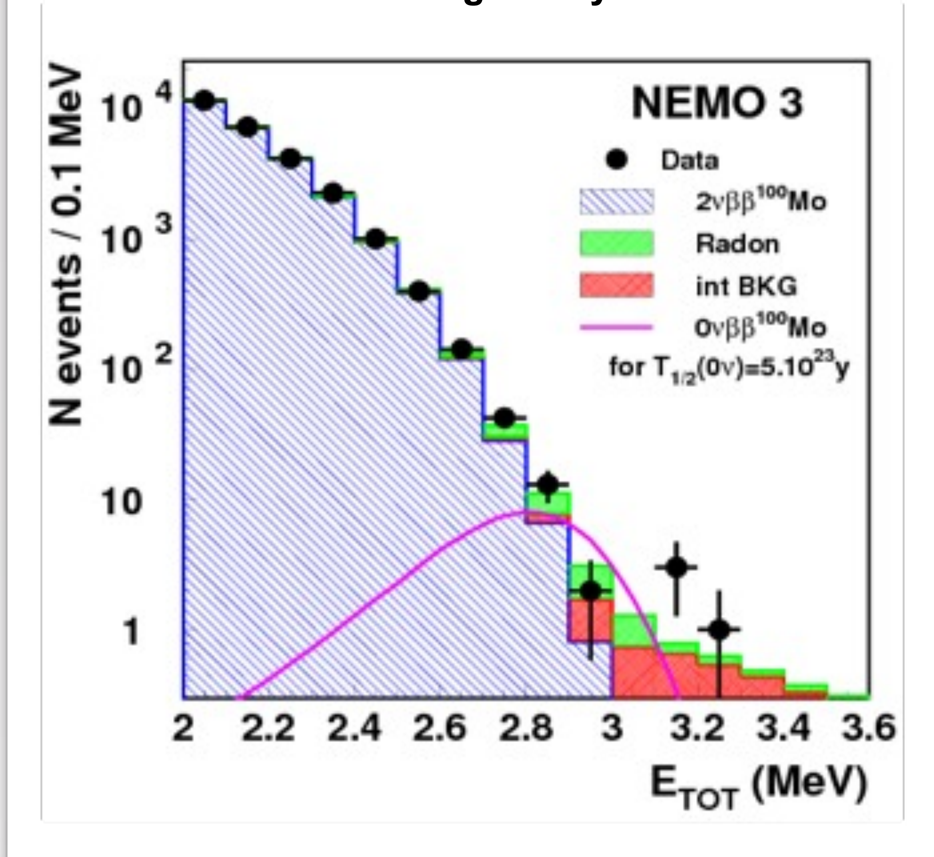
Crucial experimental input for 1) NME calculations

2) Ultimate background characterisation for 0ν

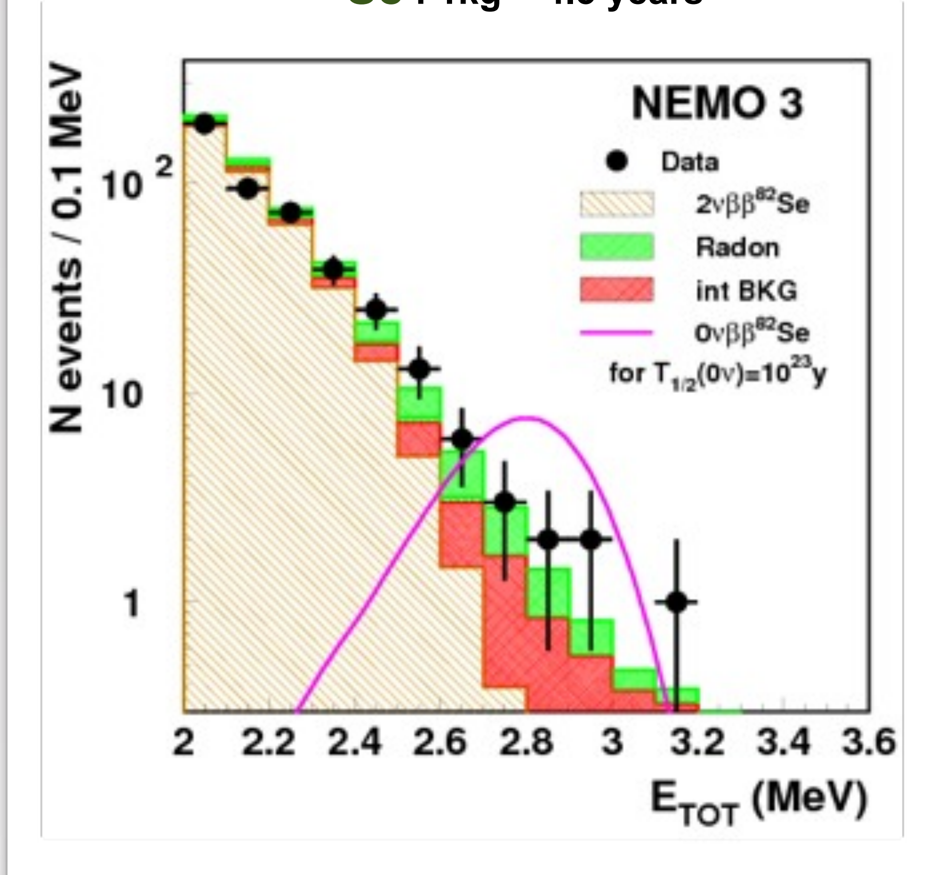
Search for 0νββ

Data period: Feb'03 - Dec'09

^{100}Mo : 7kg × 4.5 years



^{82}Se : 1kg × 4.5 years



[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

$<m_\nu> <$ (0.31 - 0.96) eV

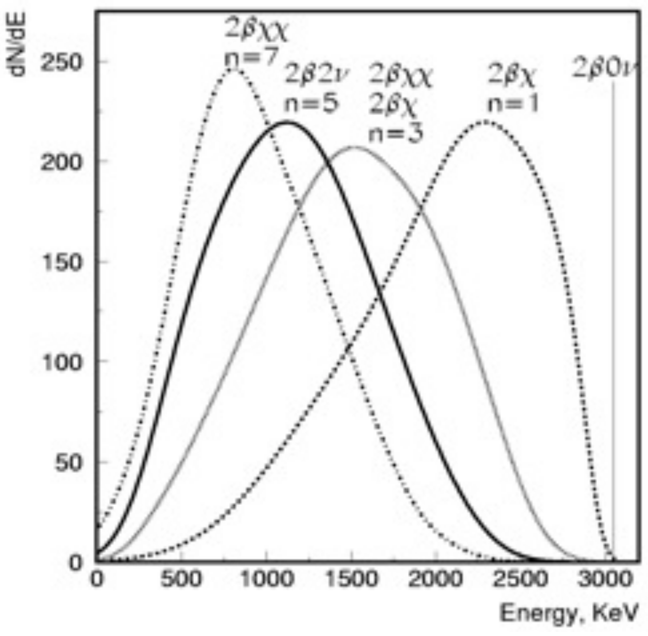
[2.6-3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

$<m_\nu> <$ (0.94 - 2.6) eV

c.f. CUORICINO: $<m_\nu> <$ (0.3 - 0.7) eV; Combined H-M/IGEX $<m_\nu> <$ (0.22 - 0.41) eV

Other 0νββ modes



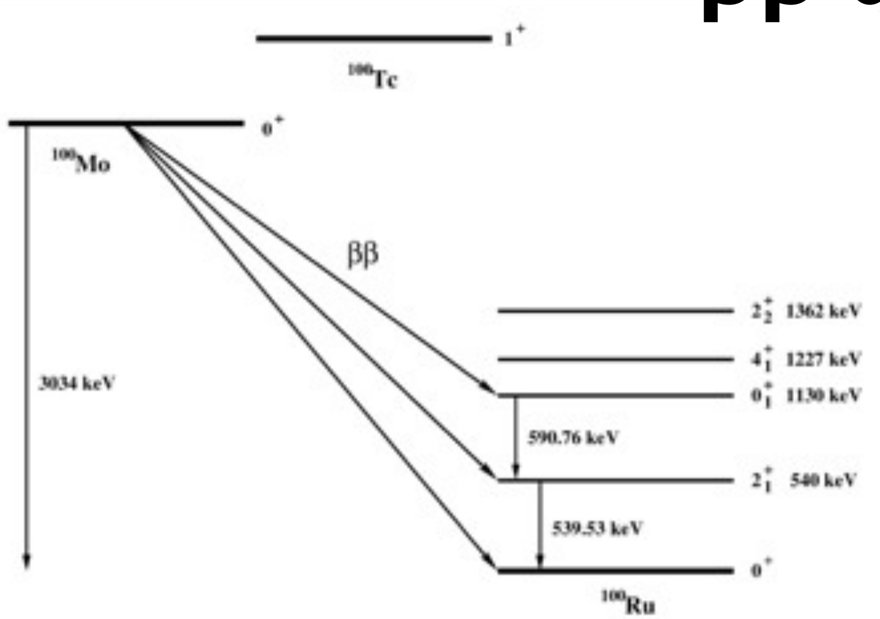
Majoron emission would distort the shape of the energy sum spectrum

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

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

World's best

ββ decays to excited states



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

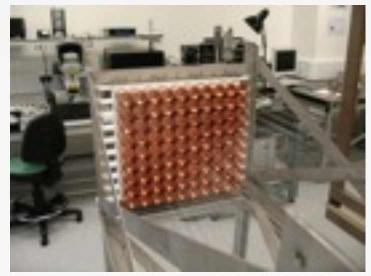
$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+_1) > 8.9 \times 10^{22}$ y @ 90% C.L.

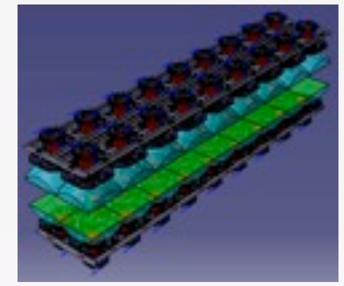
$T_{1/2}^{2\nu}(0^+ \rightarrow 2^+_1) > 1.1 \times 10^{21}$ y @90% C.L.

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

Nuclear Physics A781 (2006) 209-226.

From NEMO-3 to SuperNEMO

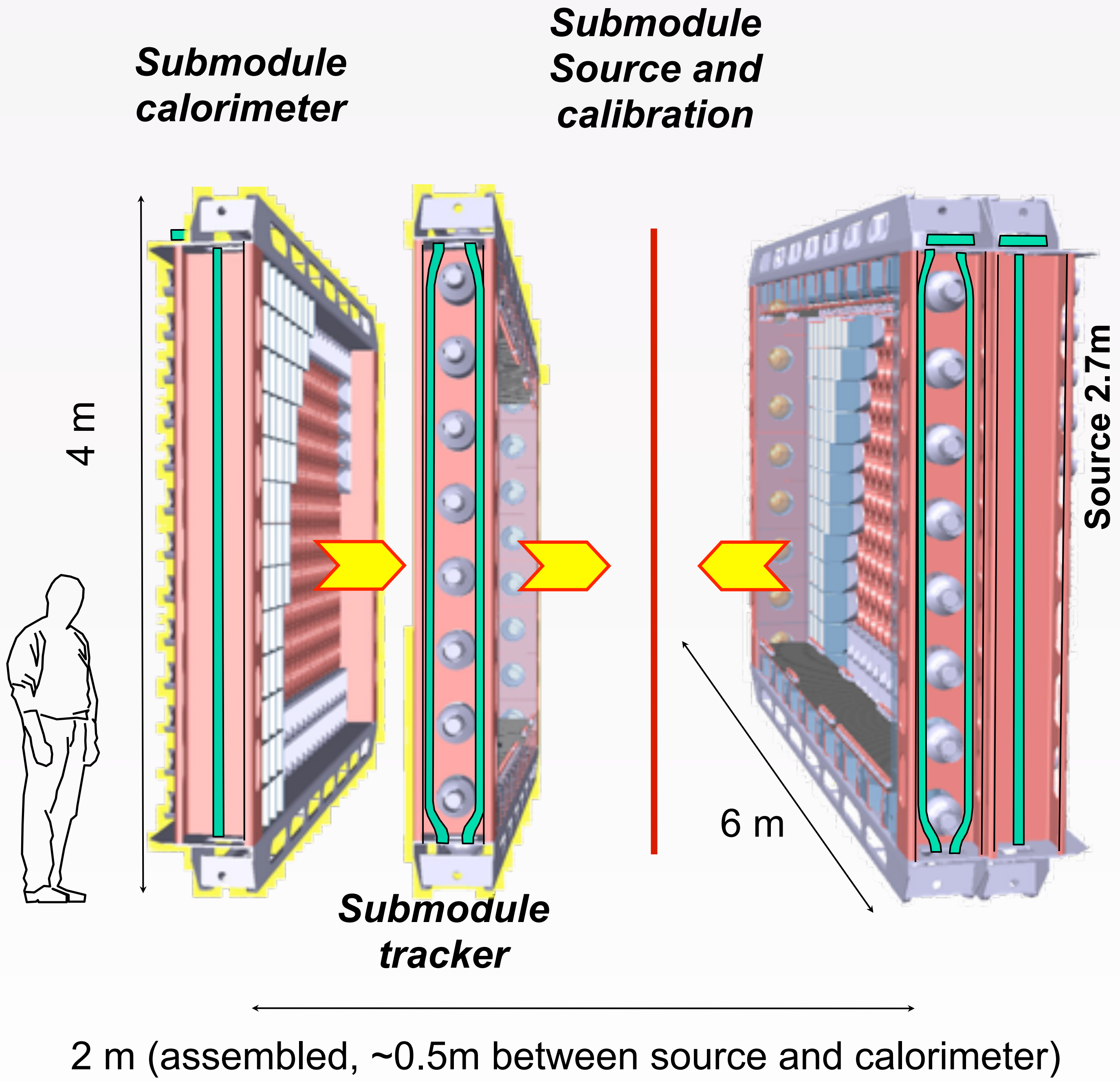




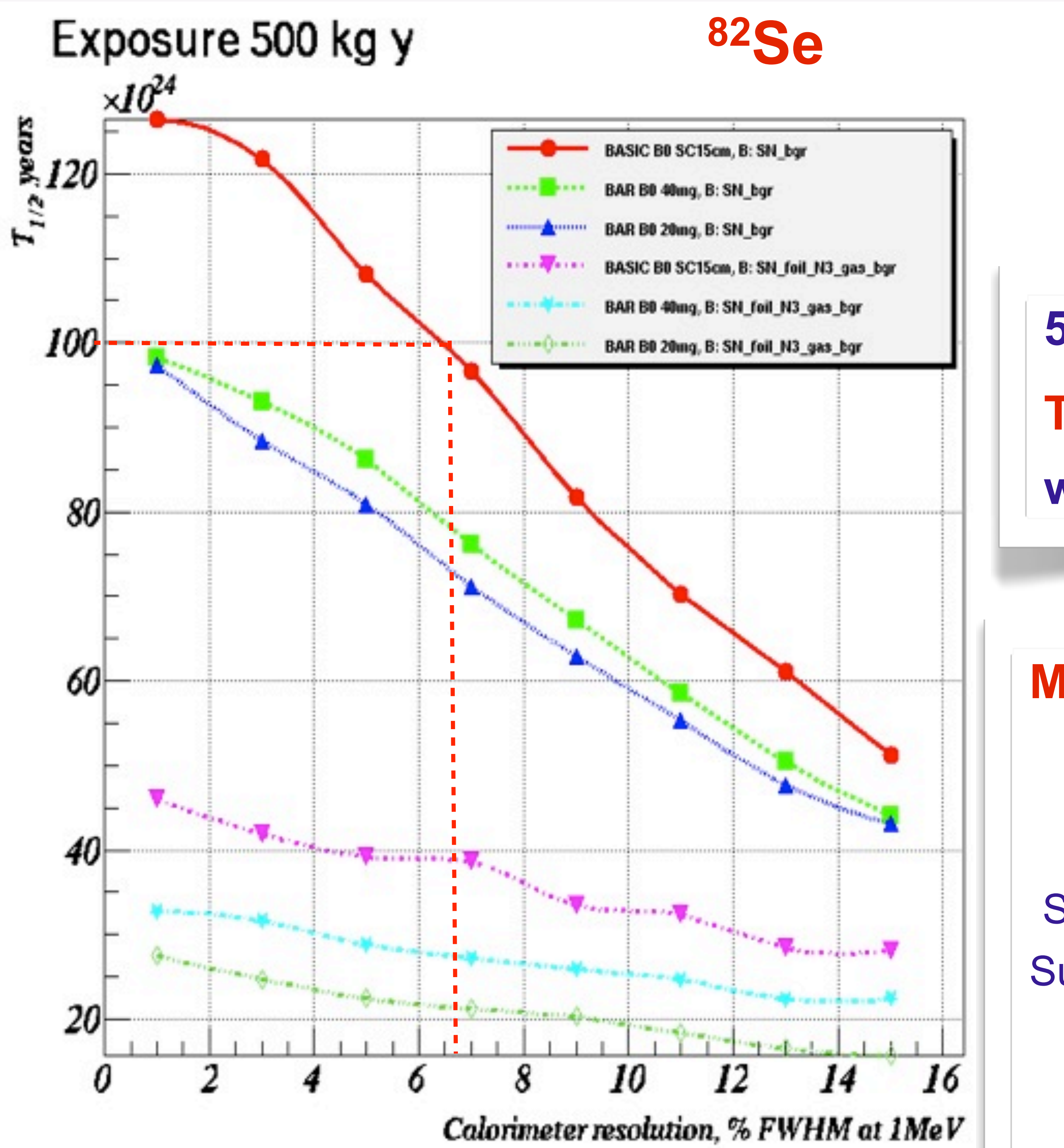
R&D since 2006 →

NEMO-3		SuperNEMO
^{100}Mo	Isotope	^{82}Se (or ^{150}Nd or ^{48}Ca)
7 kg	Isotope mass M	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: < 300 μBq/kg	Contaminations in the ββ foil	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg
Rn: 5 mBq/m^3	Rn in the tracker	Rn ≤ 0.15 mBq/m^3
8% @ 3MeV	Calorimeter energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(\beta\beta0\nu) > 1 \div 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 0.9$ eV	Sensitivity	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $\langle m_\nu \rangle < 0.04 - 0.1$ eV

- Modular design
  - 20 modules, each with 5kg of isotope
- Each Module:
  - Source: (40mg/cm^2) 4x2.7m^2
    - ^{82}Se (High $Q_{\beta\beta}$, long $T_{1/2}(2\nu)$, proven enrichment technology)
    - ^{150}Nd, ^{48}Ca being looked at
  - Tracking
    - drift chamber ~2000 cells in Geiger mode
  - Calorimeter:
    - 550 PMTs + scintillators
  - Module surrounded by water passive shielding (water)



SuperNEMO Physics Studies



Full chain of GEANT-4 based software + detector effects + backgrounds + **NEMO3 experience**

5 yr with 100kg of ^{82}Se:

$T_{1/2} > 10^{26}$ yr, $\langle m_\nu \rangle < 50\text{-}100$ meV at 90%CL with target detector parameters

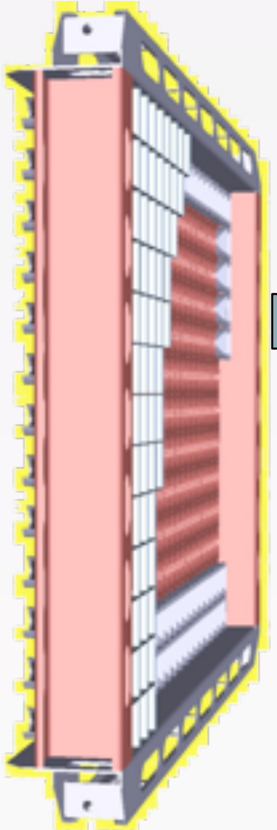
Much more than 1 result!

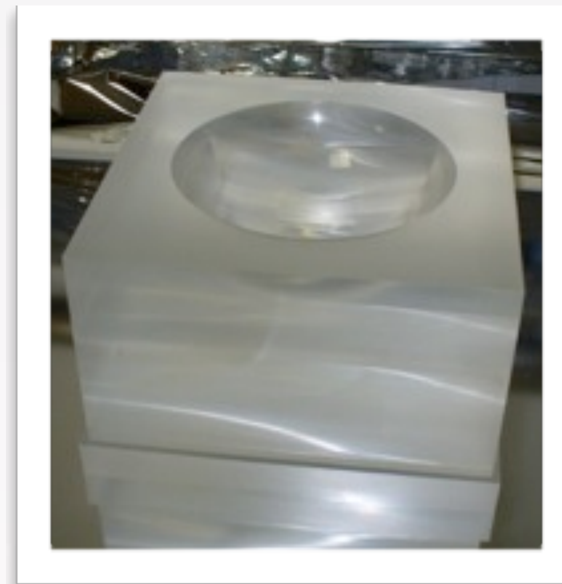
- **Other mechanisms: V+A, Majoron, etc**
- **Disentangling $\langle m_\nu \rangle$ and V+A**

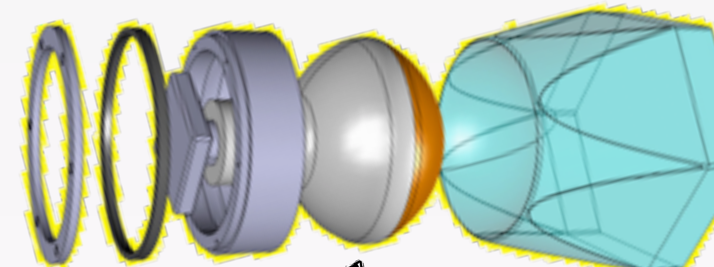
See "Probing new physics models of 0νββ with SuperNEMO", EPJ C (2010) 70, 972-943.

- **ββ0ν(and 2ν) to excited states**
- **Other isotopes**

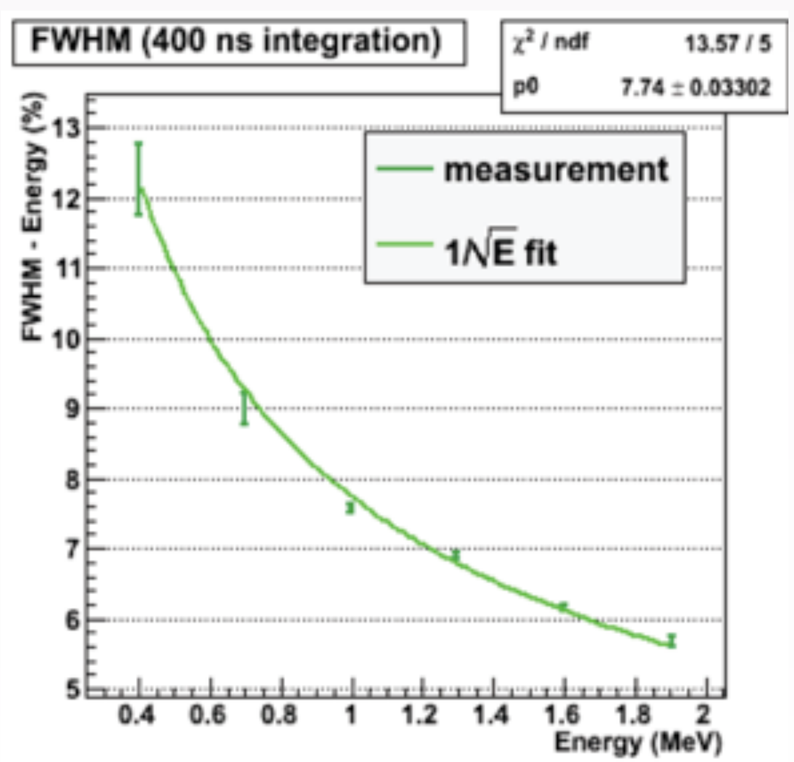
Main Calorimeter Wall







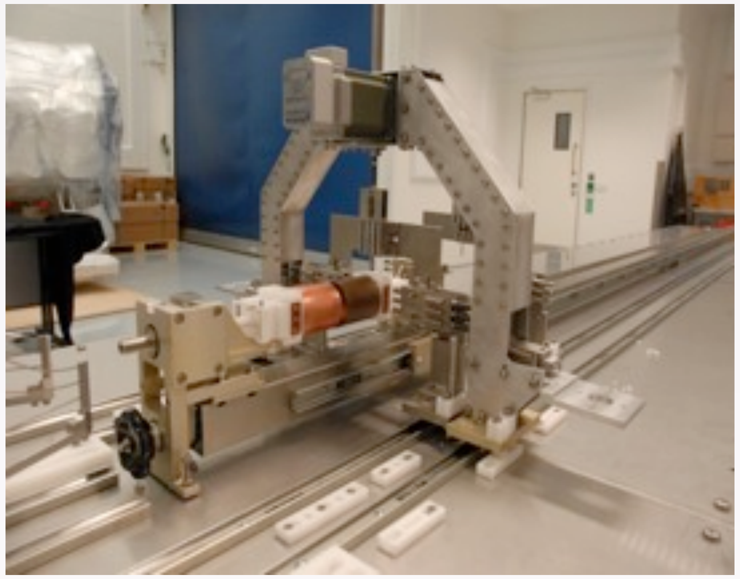
8" High-QE PMT:
Hamamatsu R5912MOD

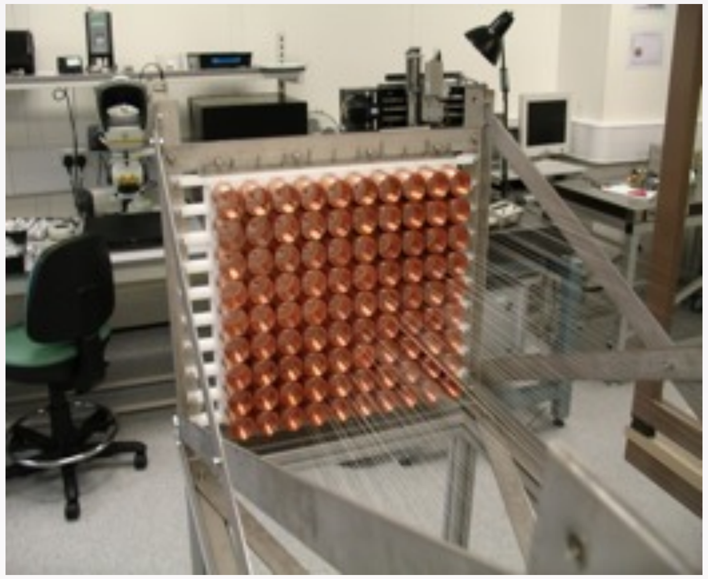


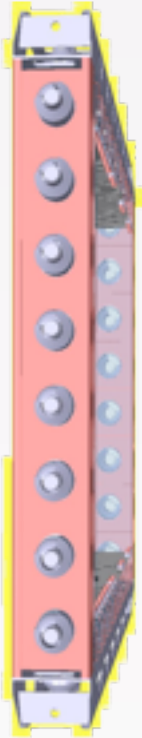
$\Delta E/E$ ~ 7.2% (FWHM) at 1 MeV equiv. to 4% @ $Q_{\beta\beta}$ = 3 MeV

Target resolution has been reached with hexagonal and cubic blocks

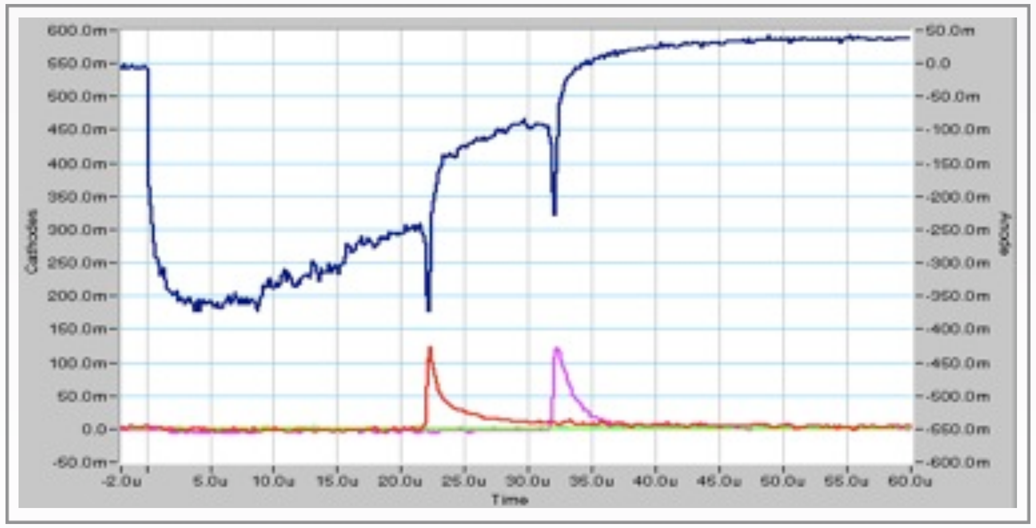
SuperNEMO Tracker







- Automated wiring robot design to mass produce under ultra low background conditions
  - 500,000 wires to be strung, crimped and terminated
- Basic design developed and verified with several prototypes
  - Resolution: 0.7mm transverse, 1cm longitudinal
  - Cell efficiency > 98%
- Readout electronic being developed:
  - Allow for single and double-cathode readout
  - Differentiate anode signal

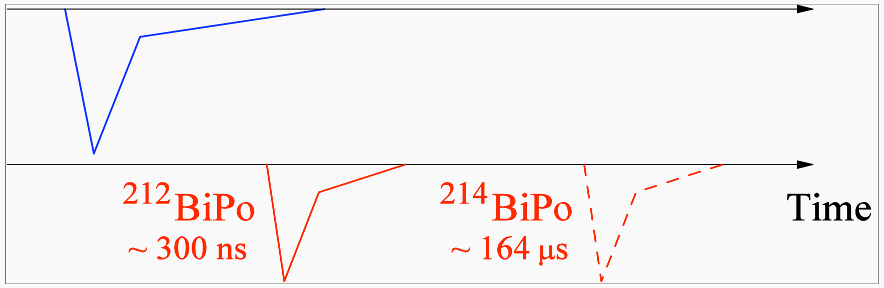


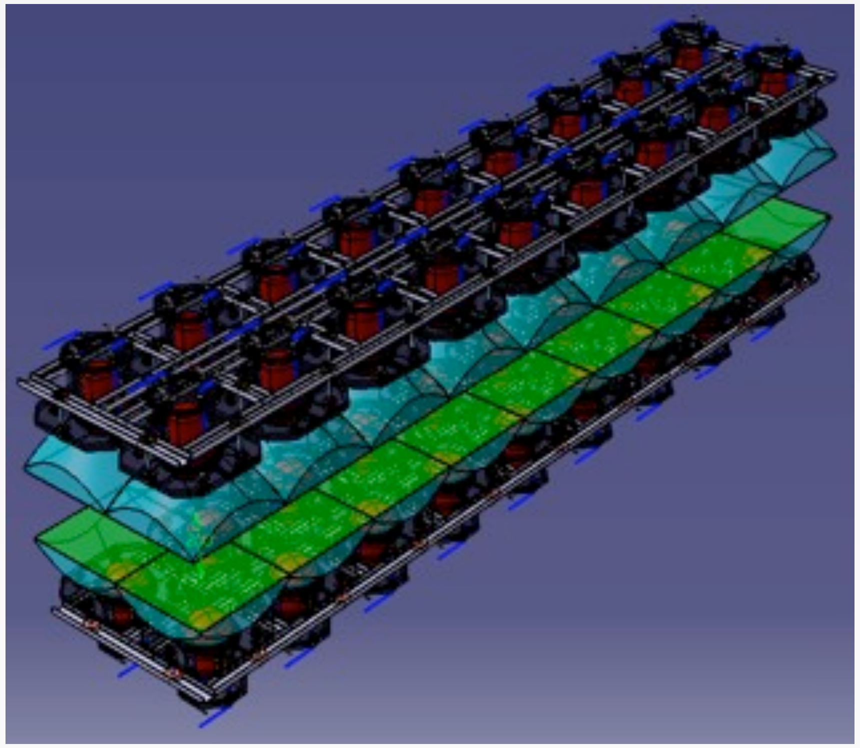
Source Radiopurity

- ~2.7m "composite" foil strips of 40-50 mg/cm^2 (~80 μm)
- Radiopurity (^{82}Se)
  - ^{208}Tl < 2 μBq/kg
  - ^{214}Bi < 10 μBq/kg

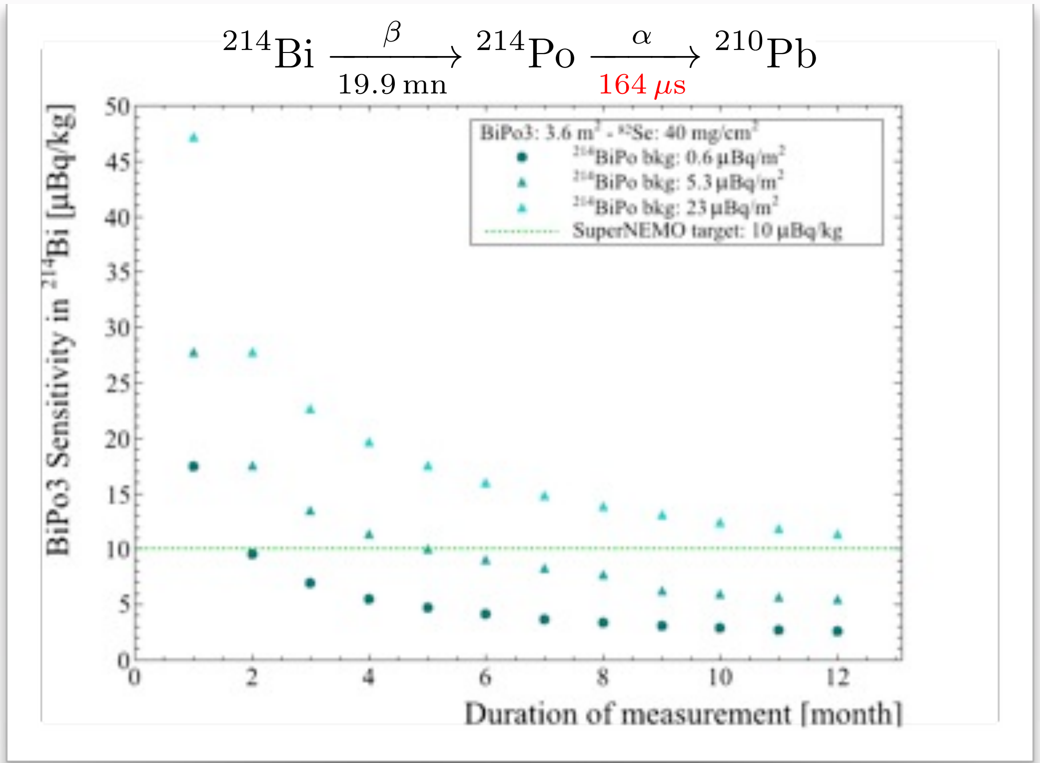
→ HPGe detectors are used for screening but not sufficient to reach required levels

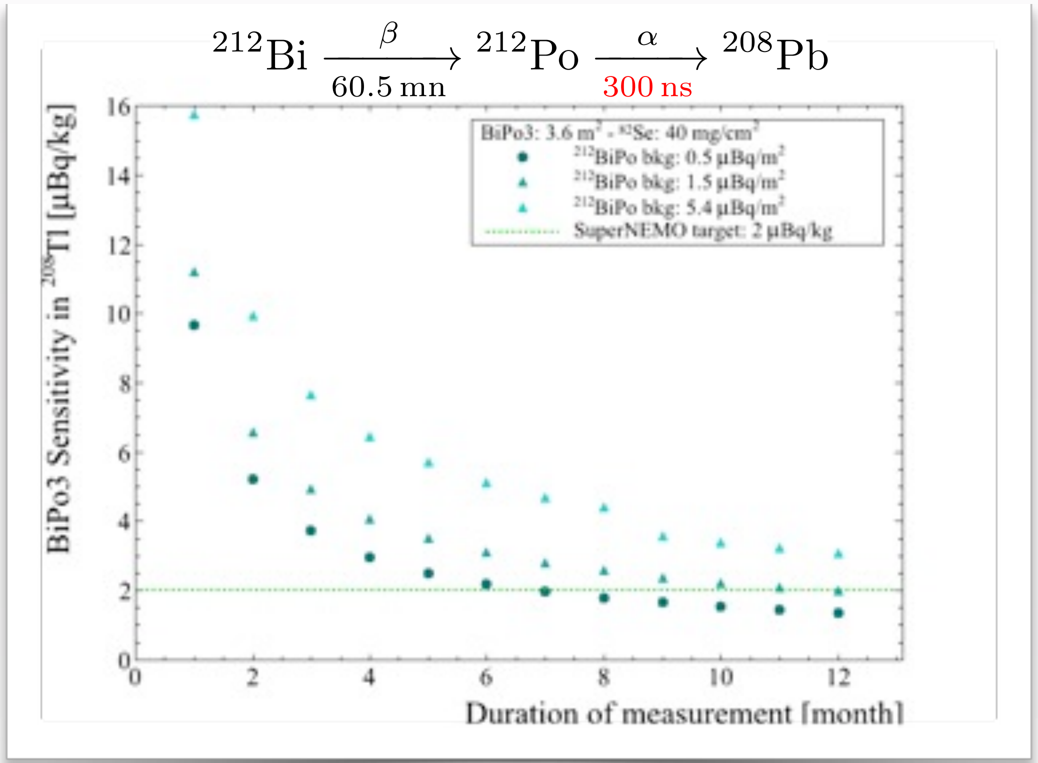
BiPo signature





Dedicated **BiPo** detector developed and installed in Canfranc (running in 2012)

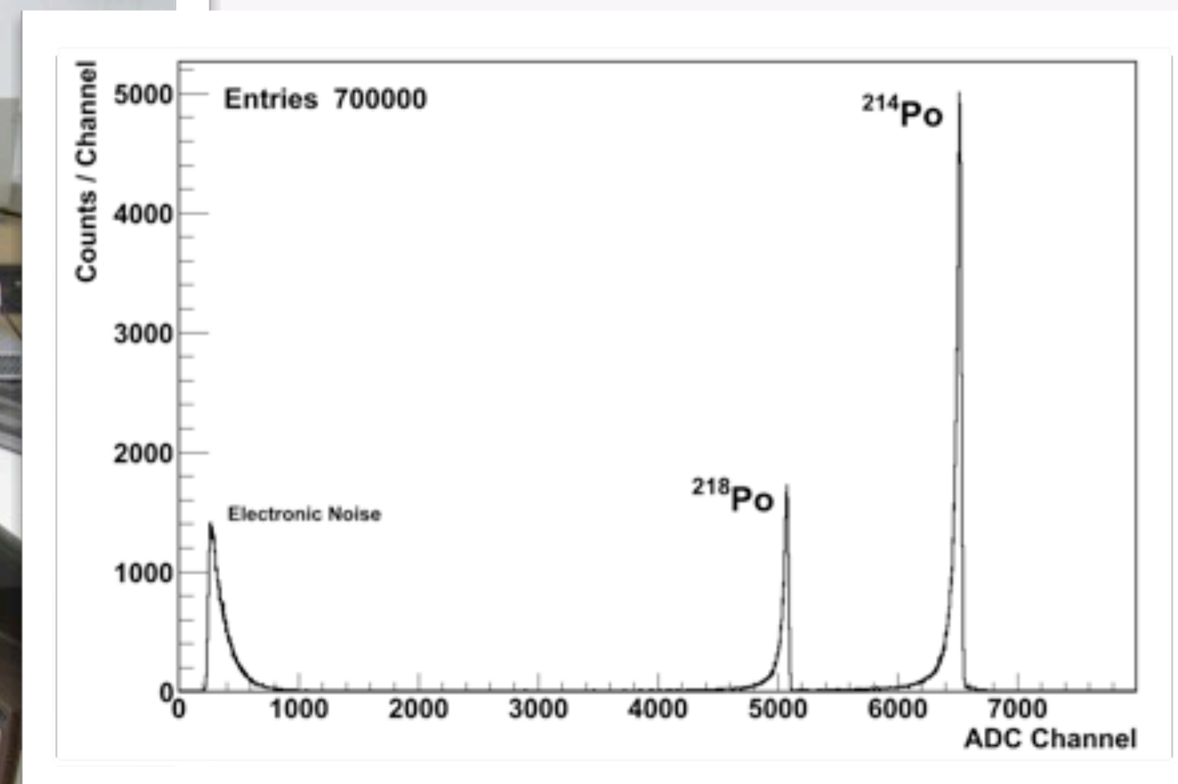




Radon activity measurement

Requirement: Rn activity inside tracker < 150 μBq/m^3

Radon Concentration Line sensitivity < 50 μBq/m^3 (90%CL)



Vacuum Pump

Carbon Trap

Radon Detector (Electrostatic & Pin Diode)

- Measurements of Rn emanation from materials
- Rn permeability measurements through membranes/seals

SuperNEMO Demonstrator

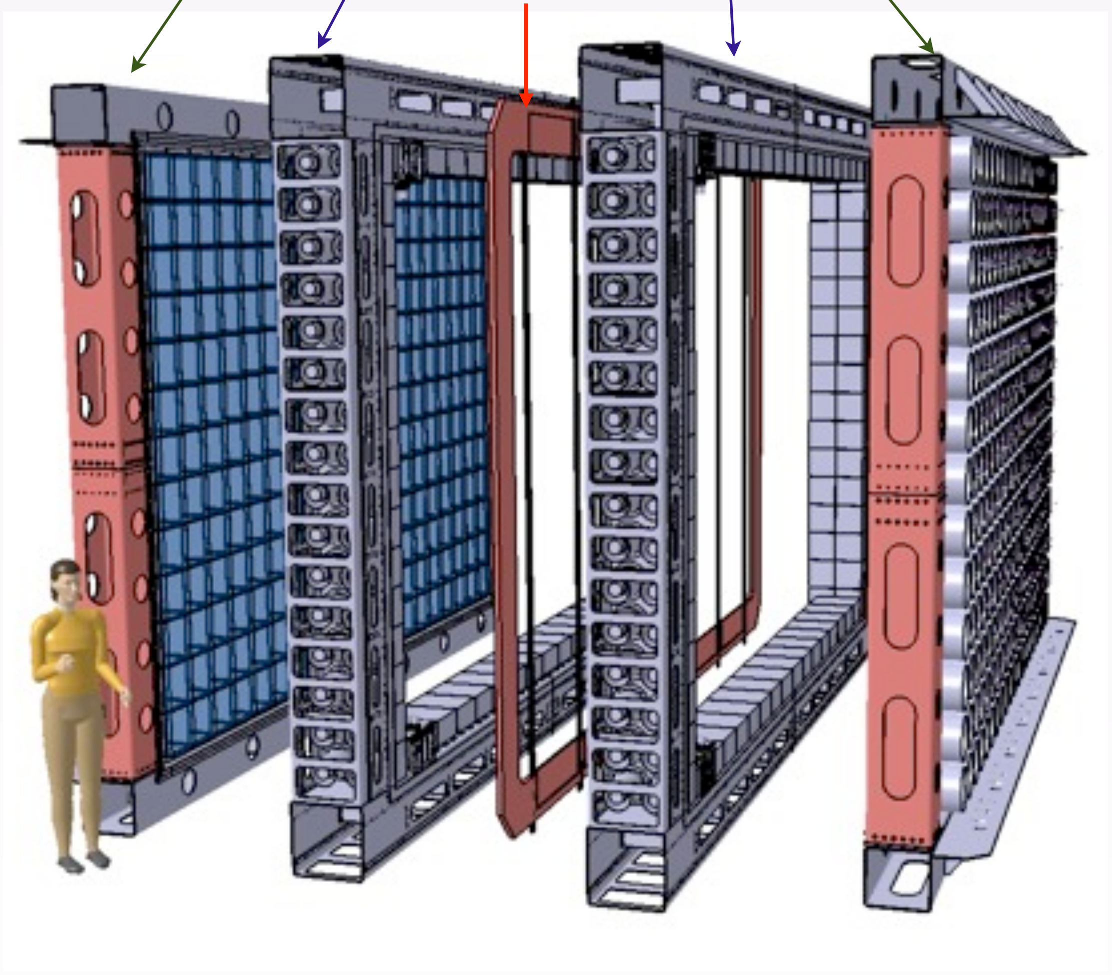
Technology
Ultimate proof of BG levels
Physics
Sensitive to K-K claim

7kg of ^{82}Se
Bgrd ≤ 0.06 events/yr in the RoI

A Zero-Background Experiment

$$T_{1/2}^{0\nu}(90\%CL) = 2.56\times10^{24}\times t \text{ yrs}$$

Gerda-I sensitivity in 2.5 years -
6.5×10^{24} yr (equivalent to 3×10^{25}yr with ^{76}Ge)



SuperNEMO Demonstrator Construction has started

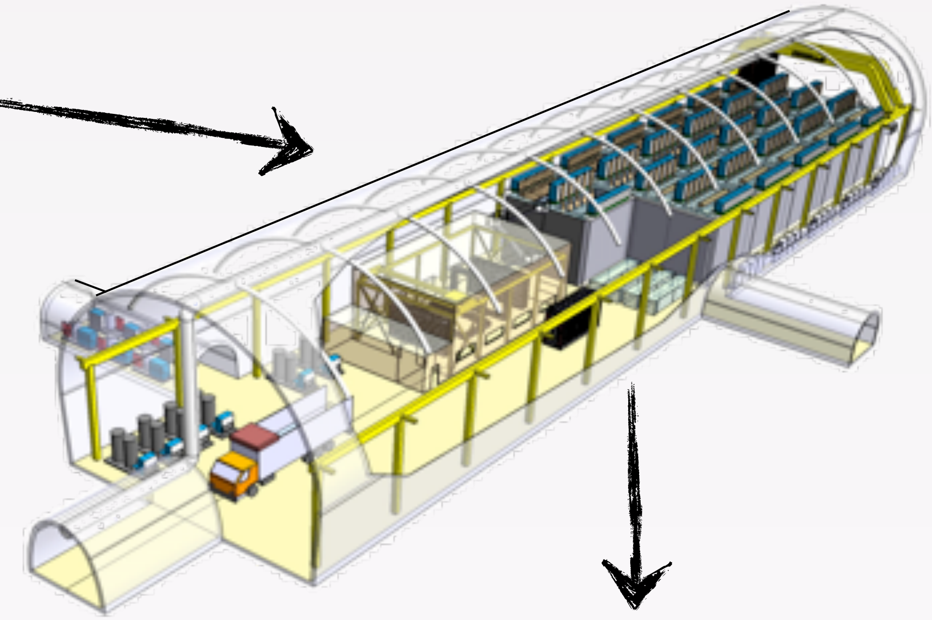
Construction of optical modules for tracker frame

Assembly hall prepared for tracker integration and commissioning

NEMO3 dismantled and removed to free underground space at LSM for Demonstrator

SuperNEMO Schedule

SuperNEMO in planned LSM extension



Modularity of SuperNEMO makes distributed location in different underground labs possible and even beneficial (provided resources availability).

Demonstrator Module construction and commissioning

Demonstrator running

K-K claim probed

2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021

Installation in LSM

Construction, deployment and running successive SuperNEMO modules

Continuous operation of ≥1 SuperNEMO module

Summary

- NEMO-3 has **finished running**
  - ^{100}Mo: $T_{1/2} > 1.0 \times 10^{24}$ yr, $\langle m_\nu \rangle < 0.31-0.96$ eV, 90%CL. Other lepton violating mechanisms probed.
  - Unprecedented **2νββ measurements**: input for **NME** calculations
  - Improved analysis ongoing. More results in 2012.
  - Invaluable **test bench** for SuperNEMO and other **ββ experiments**
- SuperNEMO is capable of probing **new physics at 50-100 meV** neutrino mass scale
- First module (**Demonstrator**) will **start** taking data in **2014**
- SuperNEMO approach is **unique**
  - **Event topology** fully reconstructed - **smoking gun** signature and comprehensive **background characterisation**
  - Isotope **flexibility**
  - **Modularity.** Possible distributed location in different underground labs.
- Target sensitivity (**50-100 meV**) to be reached in **2019/20**