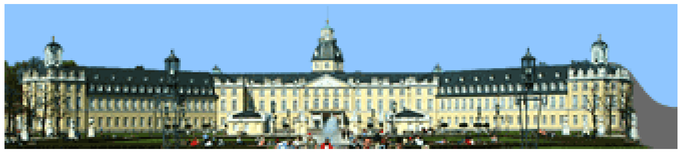
Search for $\beta\beta0\nu$ decay with NEMO 3 and SuperNEMO experiments

Vladimir Vasiliev

UCL, London, UK

on behalf of the NEMO collaboration



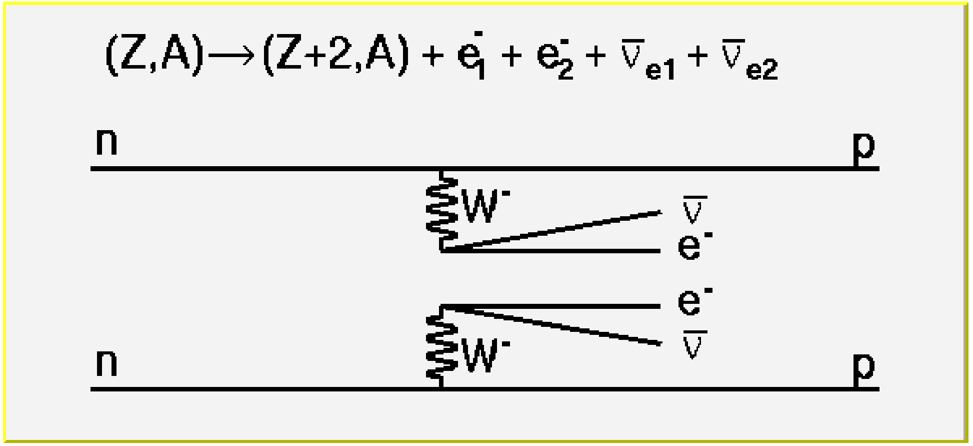
SUSY 2007

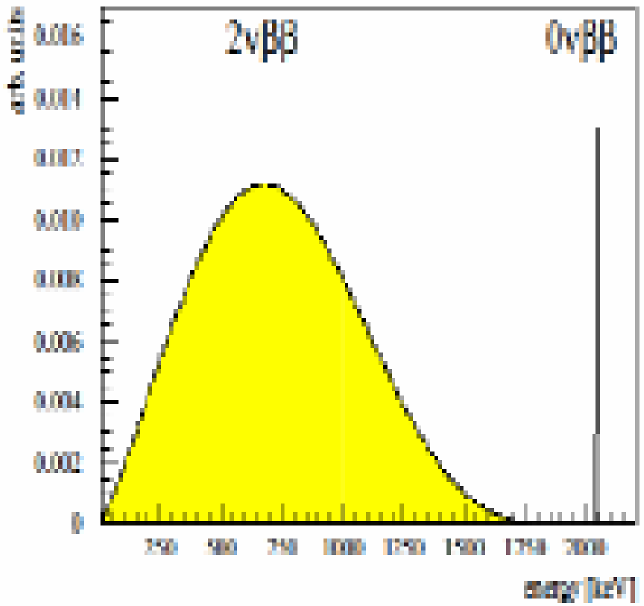
Karlsruhe, 28 July 2007

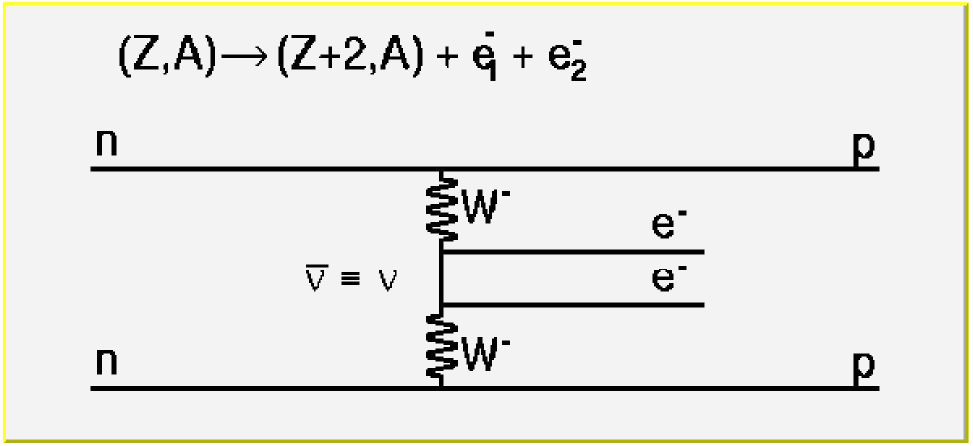
Outline

- ββ decay and SUSY
- NEMO-3 experiment
  – Overview of the NEMO-3
  – Highlights of the main NEMO-3 results
- SuperNEMO project
  – R&D program
  – Current status

ββ0ν decay, ν mass mechanism







$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2\langle m_\nu\rangle^2$$

only possible for
Majorana neutrinos with mass > 0

Beyond the SM:
Lepton Number Violation !

ββ decay and SUSY: threelinear terms

$$L = \lambda_{ijk} LLE + \lambda'_{ijk} LQD + \lambda''_{ijk} UDD$$

lepton number violation

ββ decay amplitude related to $(\lambda'_{111})^2$

$d_R + d_R \rightarrow u_L + u_L + e_L + e_L$

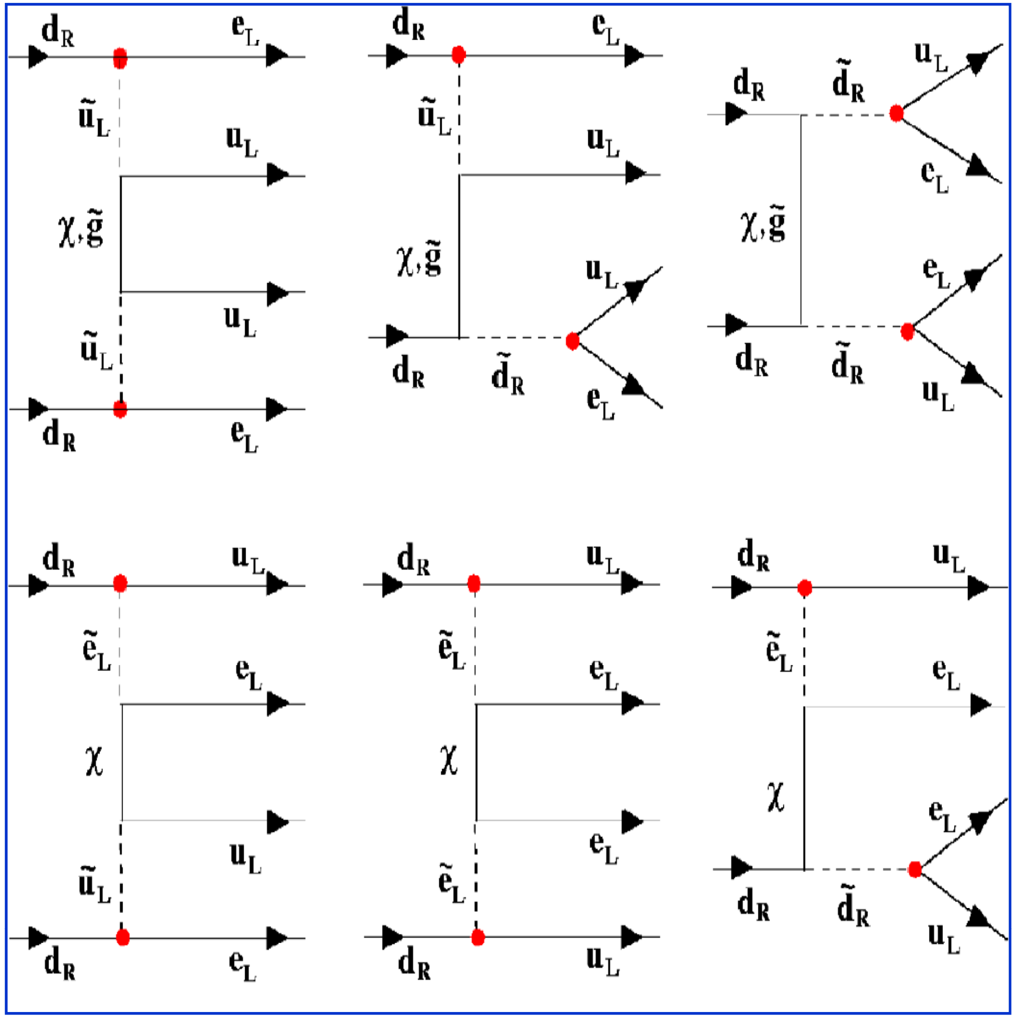
exchange with:

squarks

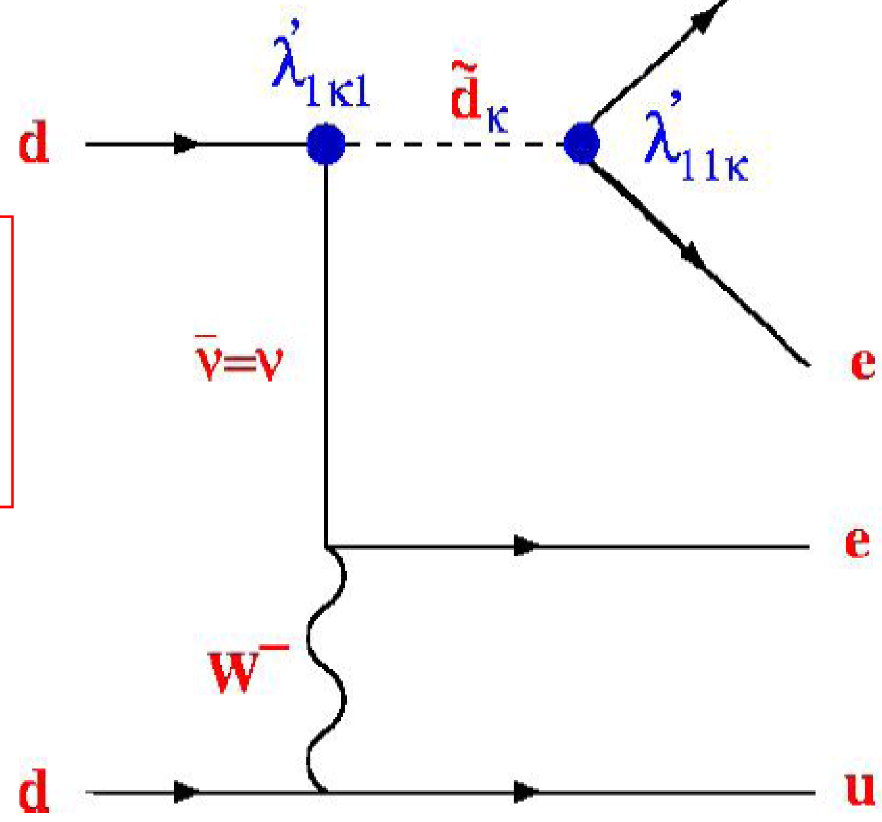
sleptons

neutralinos

gluinos



$$L = \lambda'_{ijk} LQD$$



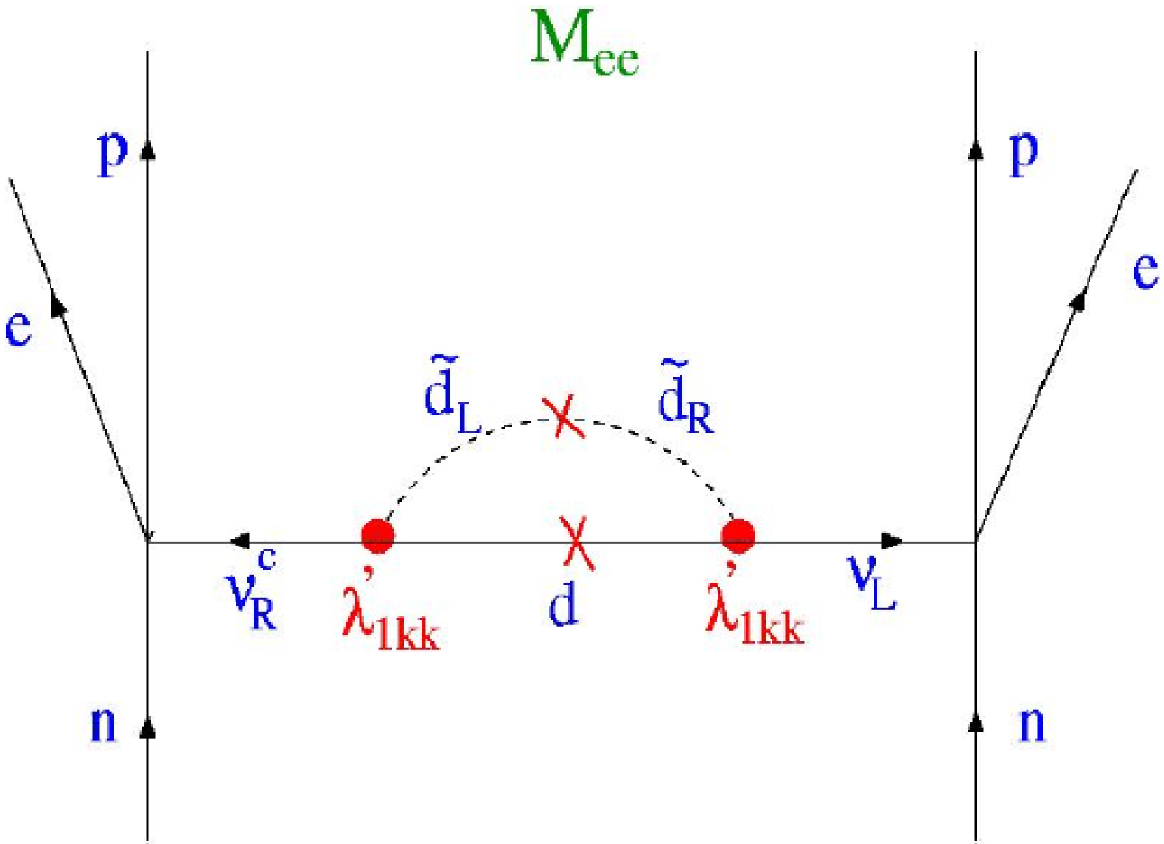
contribution from λ'_{1jk} possible via left- and right- squark mixing

Hirsch,Klapdor-Kleingrothaus, Kovalenko, PLB 372 (1996) 181

Paes, Hirsch,Klapdor-Kleingrothaus, PLB 459(1999) 450

$$L = \lambda'_{ijk} LQD$$

neutrino can acquire mass due to SUSY radiactive corrections, λ'_{1kk}



Gozdz, Kaminski, Šimkovic, PRD 70 (2004) 095005

NEMO 3: Neutrino Ettore Majorana Observatory

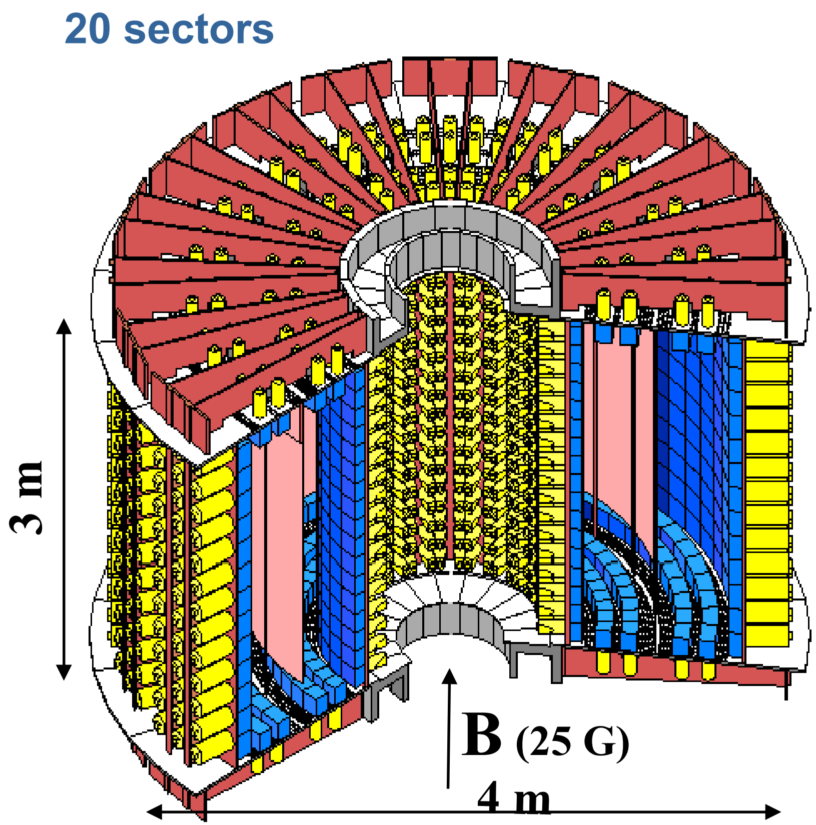
- Czech Republic
- Finland
- France
- Japan
- Russia
- Spain
- UK
- Ukraine
- USA

LS Modane, FR
Tunnel Frejus

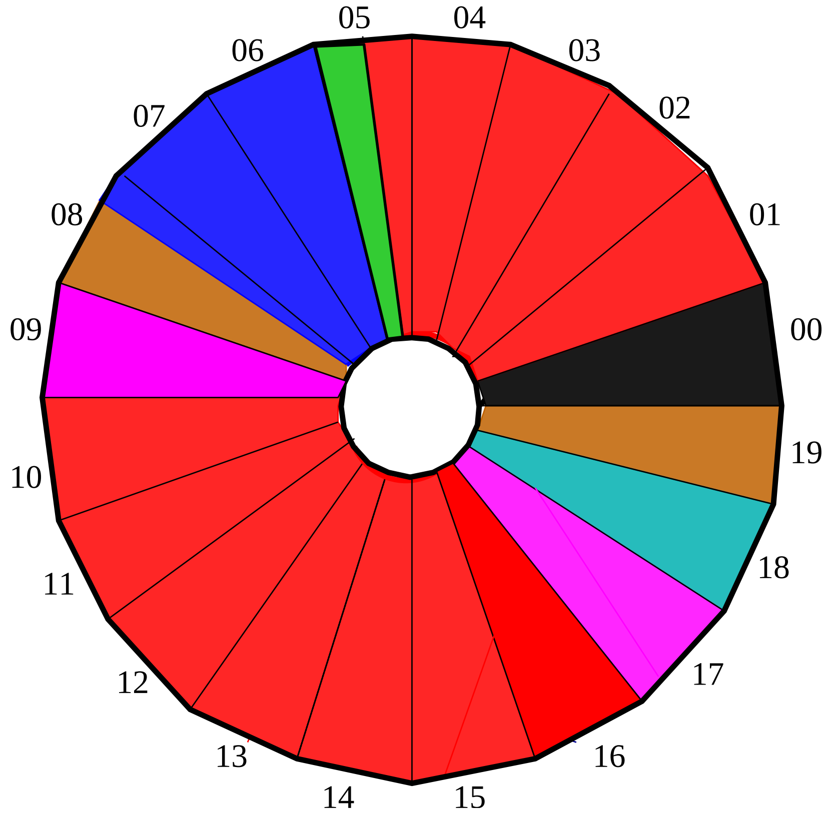
key techniques: tracking, calorimetry, timing

- Goal: reconstruct 2 electrons of the final state
  - $E1 + E2 = Q_{bb}$
- Particle physics - like approach:
  - Measure several observables of the final state
    - Trajectories of 2 electrons
    - Energies of 2 electrons
    - Time
    - Magnetic field curvature ("+" vs "-")
  - Reconstruct the final state topology and kinematics
- Several requirements for candidate events
  - Topology (vertex, track-scintillator correlation)
  - Time coincidence
  - 2-electron invariant mass
  - Identify e^-, e^+, γ, α
  - Able to *measure* backgrounds

NEMO-3



Multi source detector



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

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

ββ0ν search

ββ2ν measurement

^{116}Cd **405 g**
$Q_{\beta\beta}$ = 2805 keV

^{96}Zr **9.4 g**
$Q_{\beta\beta}$ = 3350 keV

^{150}Nd **37.0 g**
$Q_{\beta\beta}$ = 3367 keV

^{48}Ca **7.0 g**
$Q_{\beta\beta}$ = 4272 keV

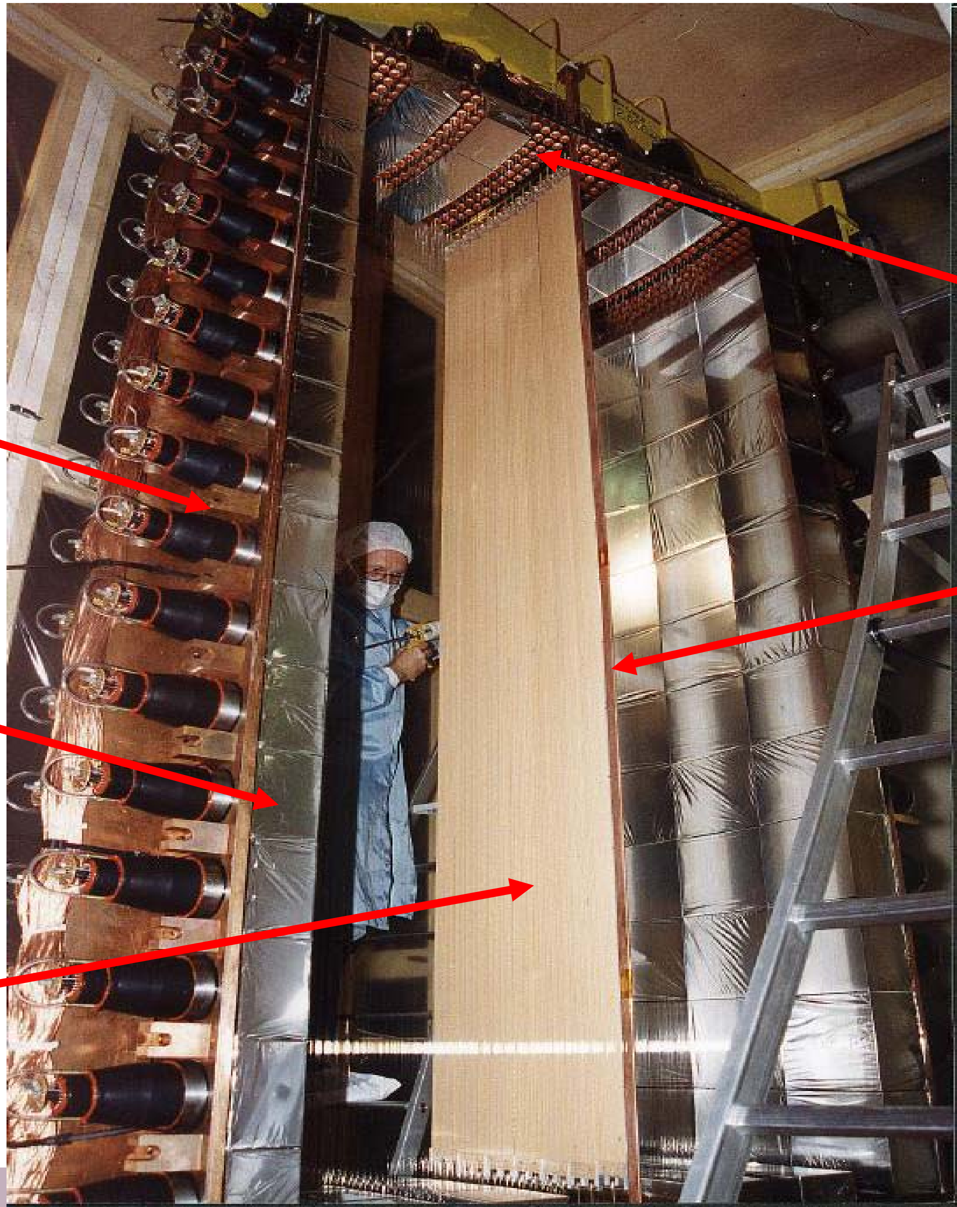
^{130}Te **454 g**
$Q_{\beta\beta}$ = 2529 keV

^{nat}Te **893 g**

Cu **621 g**

Detector bkg measurement

Sector interior view



PMTs

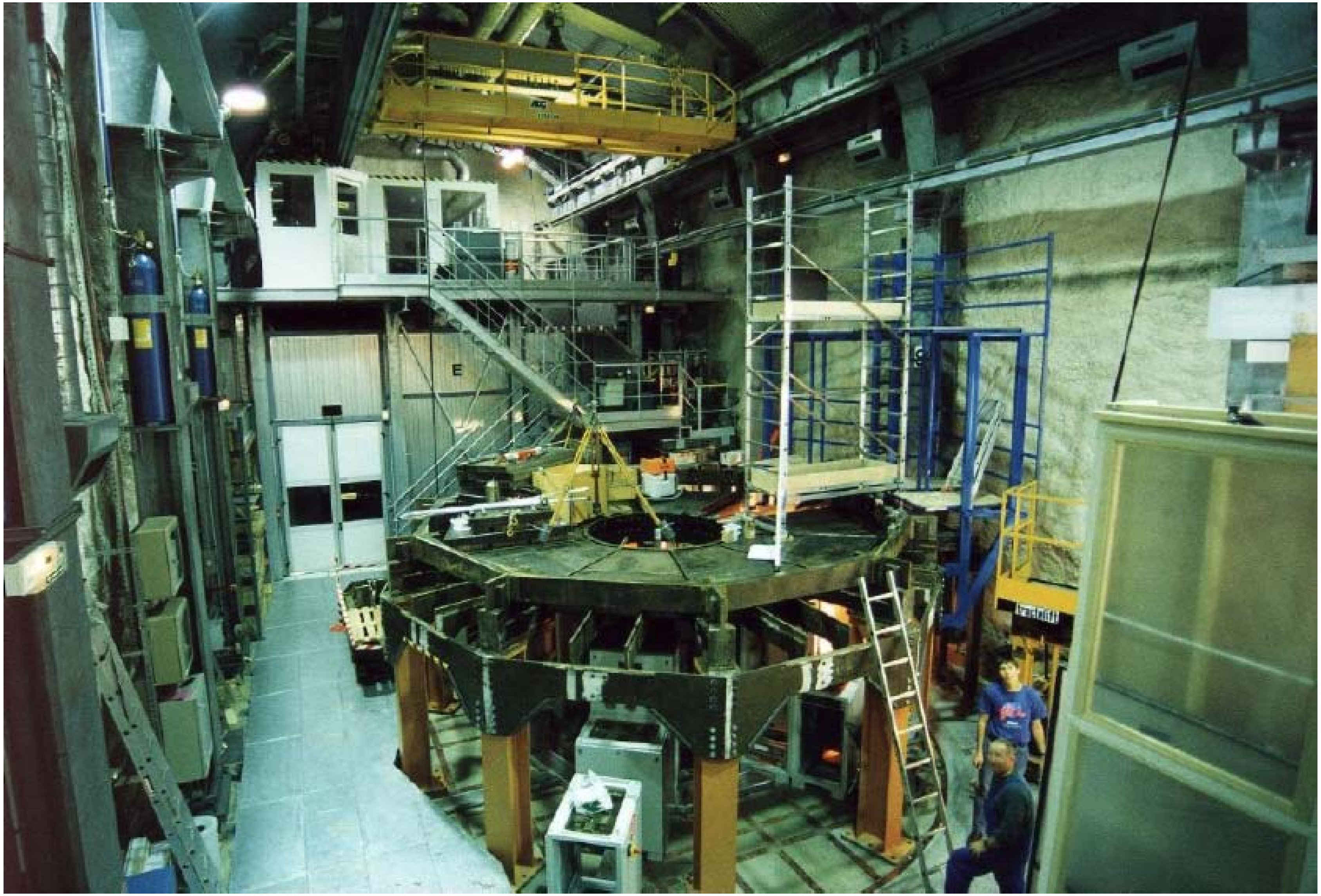
scintillators

ββ isotope foils

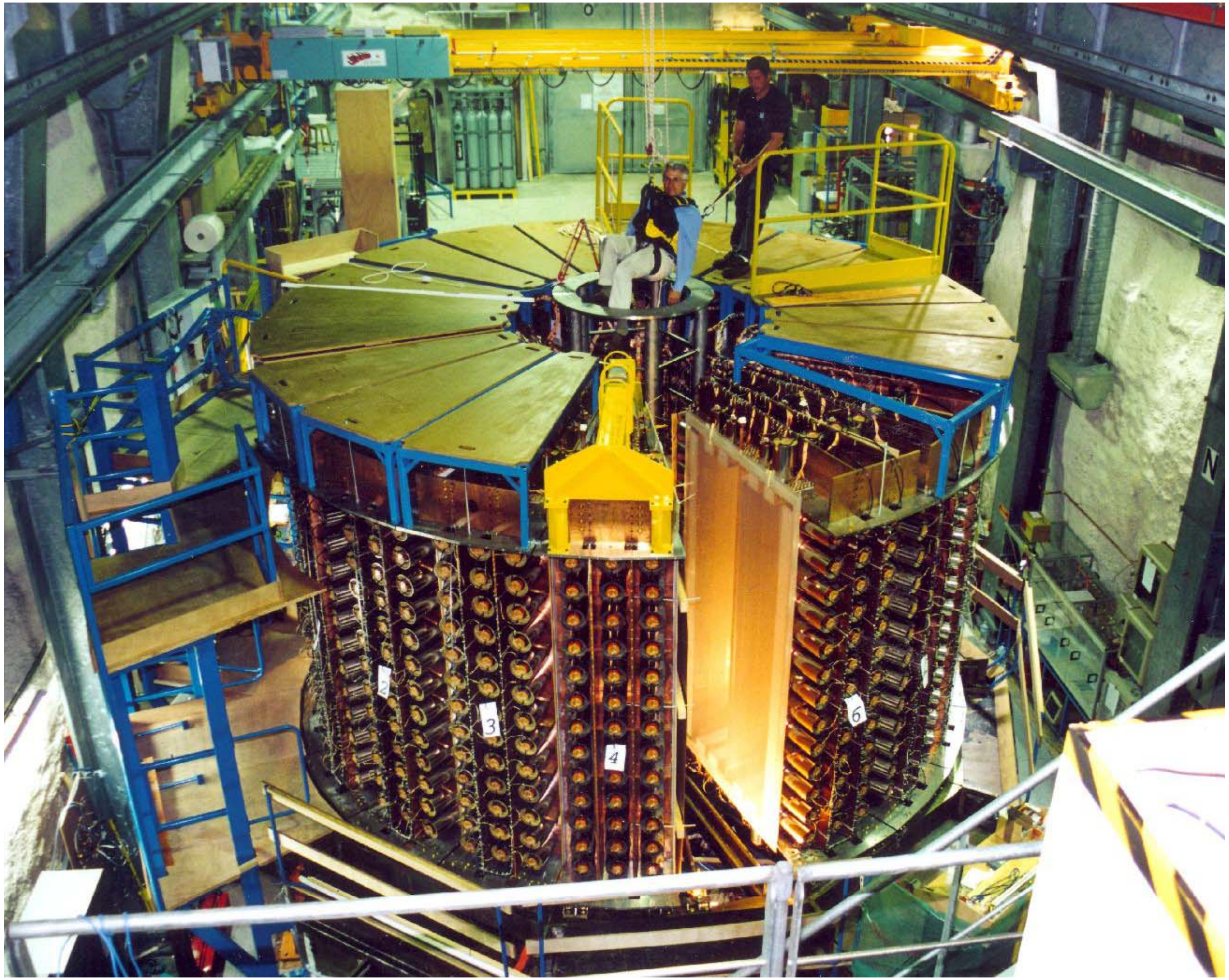
cathode rings
wire chamber

Calibration tube

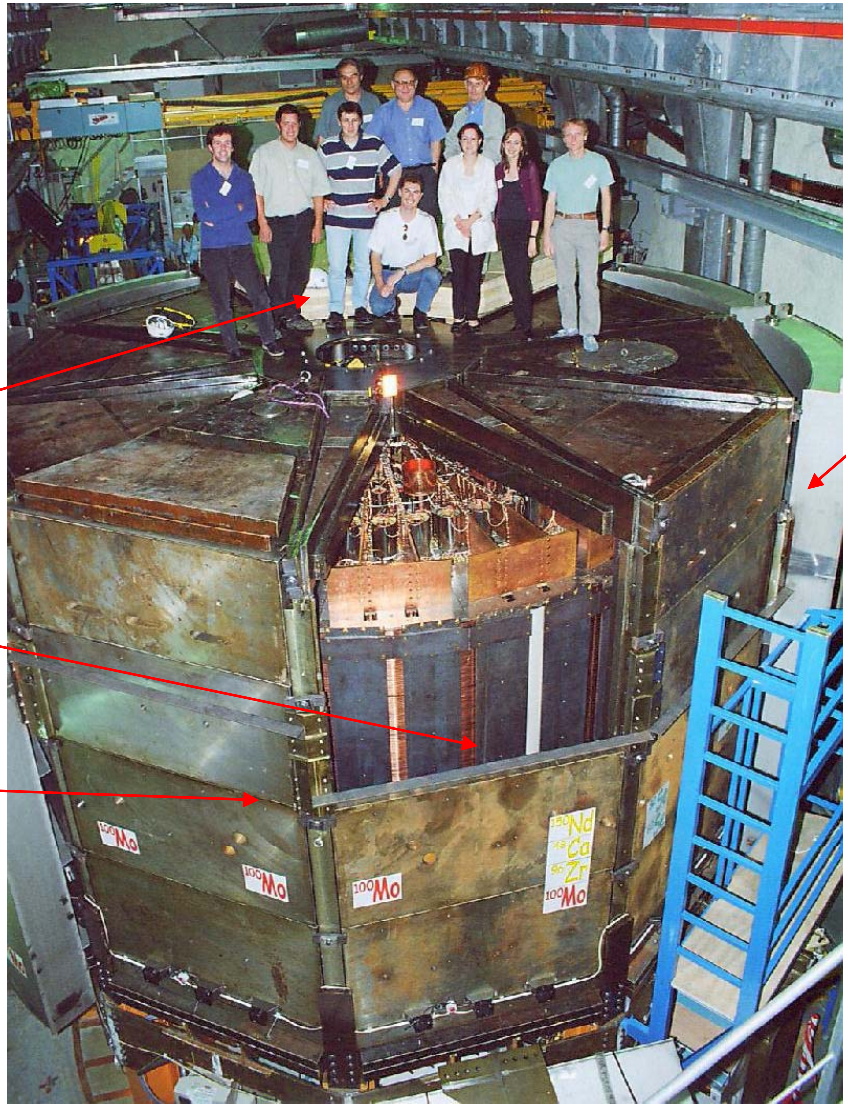
Installation in Modane



Installation in Modane

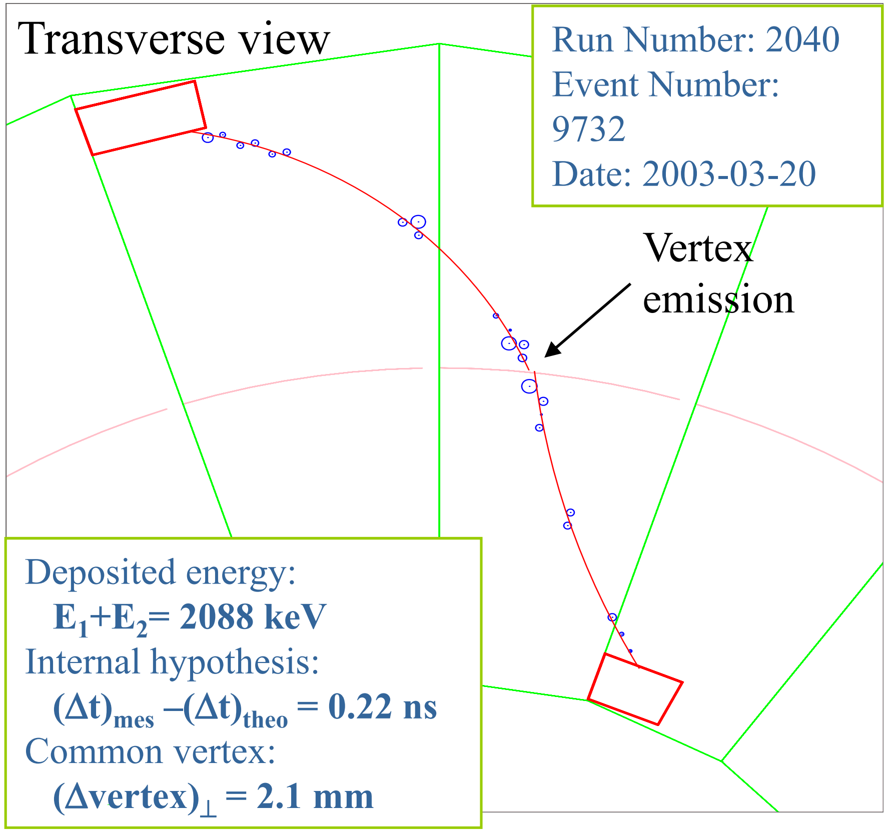


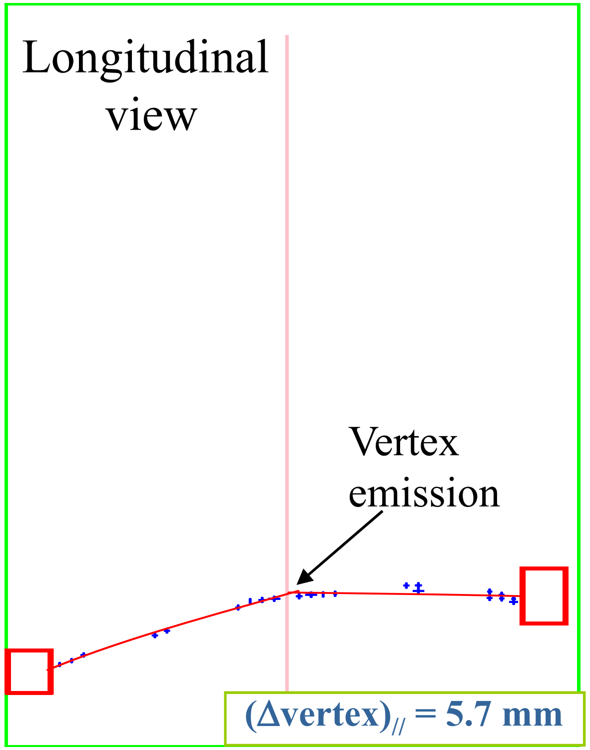
With shielding



Full detector now

Typical $\beta\beta2\nu$ event observed from ^{100}Mo





^{100}Mo 6.914 kg

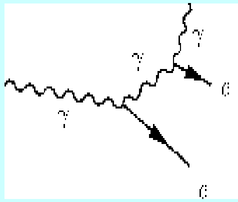
$Q_{\beta\beta}$ = 3034 keV

Criteria to select $\beta\beta$ events:

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

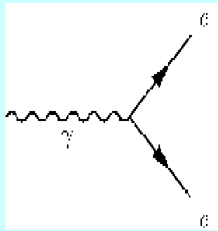
- Natural radioactivity:
  - U/Th chain
  - ^{40}K
  - Radon
- cosmic μ
- neutrons

External



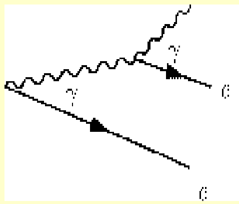
double Compton

Compton + Moller

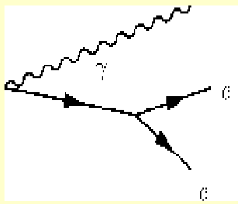


pair production

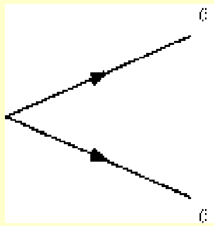
Internal



β^-+Compton



β^-+Moller

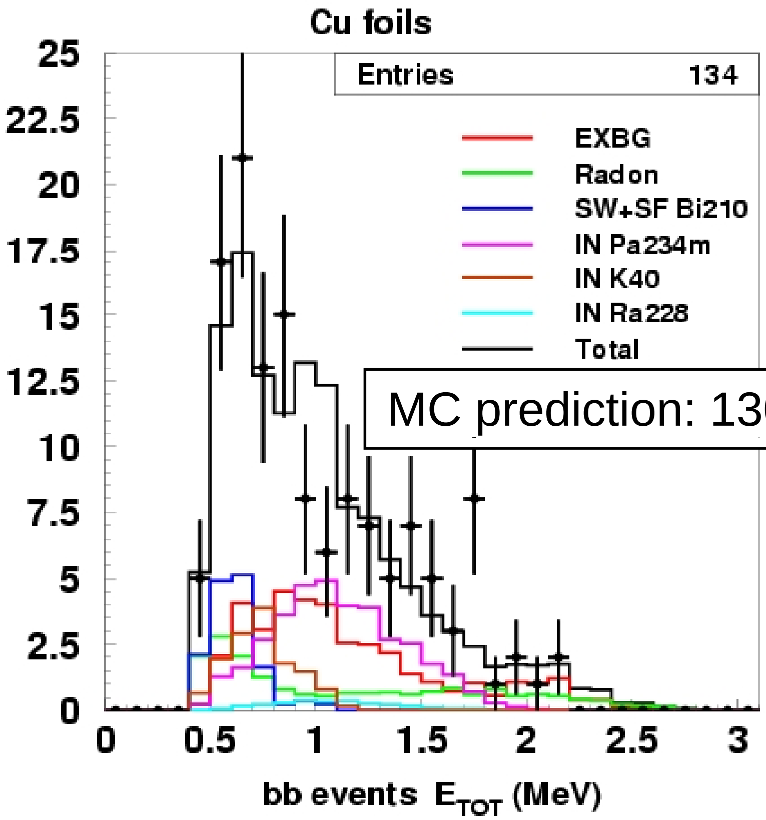


β^-+IC

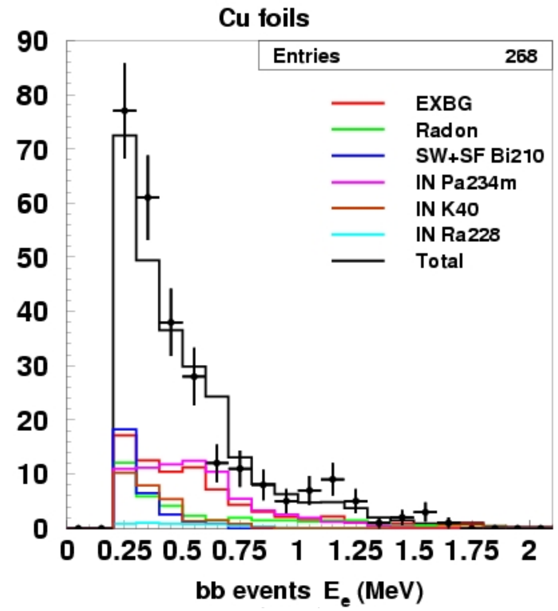
Backgrounds: ββ-like events from Cu

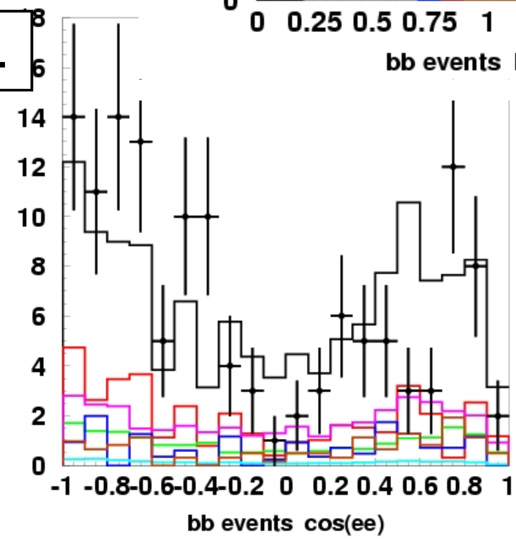
- background sources simulated using Monte Carlo
- radioactivity rates from material tests in HPGe and control channel meas's

Phase II data; 1.5 y x 0.6 kg ~ 1 kg y.



MC prediction: 130 ev.

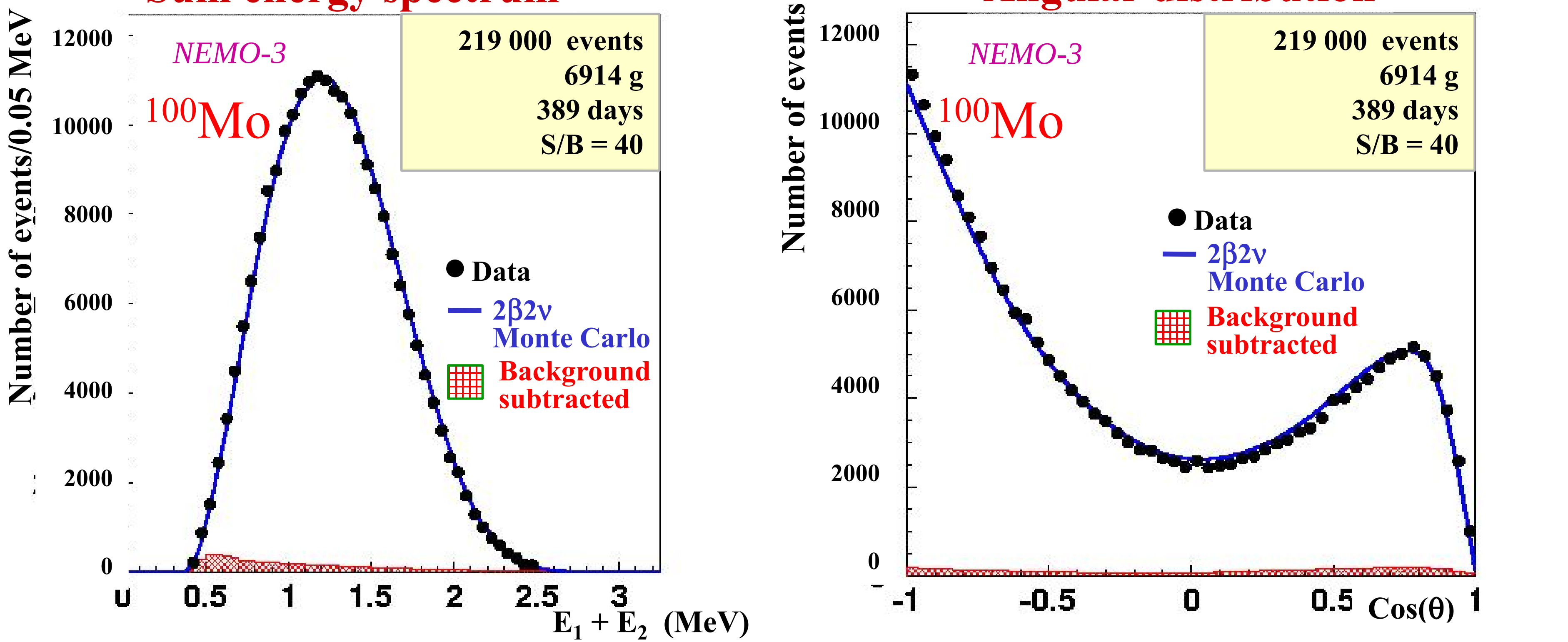




NEMO 3 highlights: $2\beta2\nu$ ^{100}Mo

Sum energy spectrum

Angular distribution

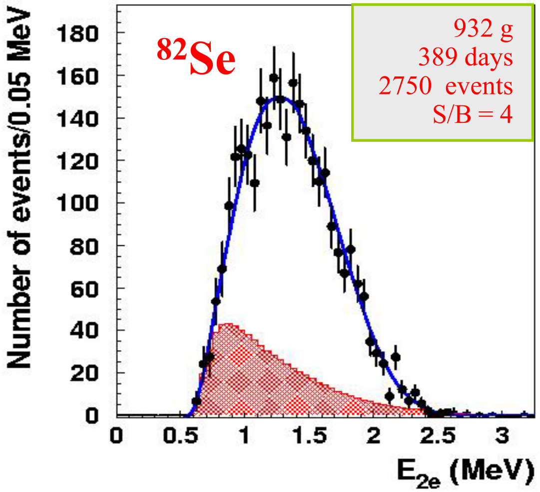


$T_{1/2}(\beta\beta2\nu) = 7.11 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ years

Phys. Rev. Lett. 95 182302 (2005)

«ββ factory» → tool for precision test

NEMO 3 highlights: 2β2ν preliminary



Preliminary results for ~360 d Phase I data. Additional statistics is being analysed and to be published soon.

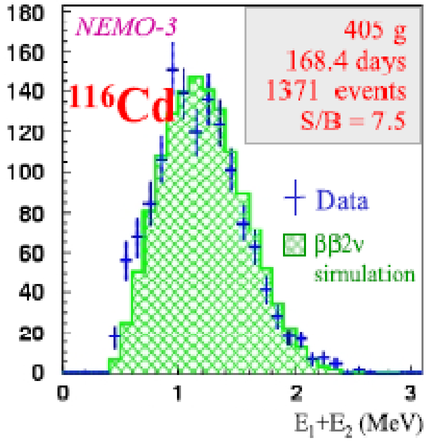
^{82}Se $T_{1/2}$ = 9.6 ± 0.3 (stat) ± 1.0 (syst) × 10^{19} y

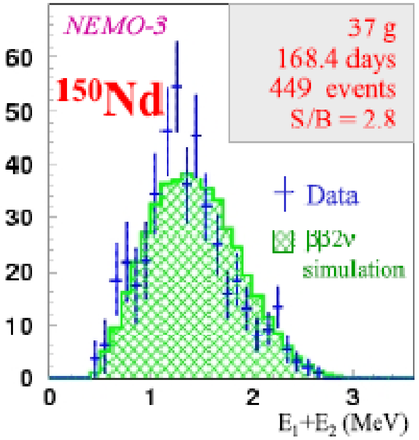
^{116}Cd $T_{1/2}$ = 2.8 ± 0.1 (stat) ± 0.3 (syst) × 10^{19} y

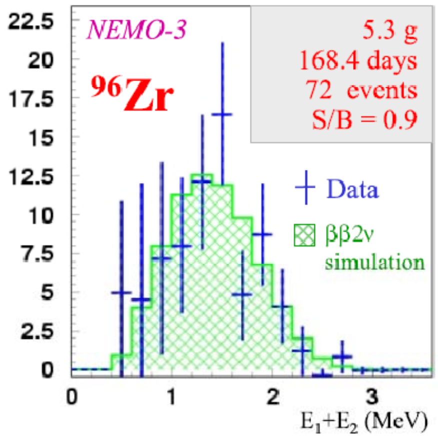
^{150}Nd $T_{1/2}$ = 9.7 ± 0.7 (stat) ± 1.0 (syst) × 10^{18} y

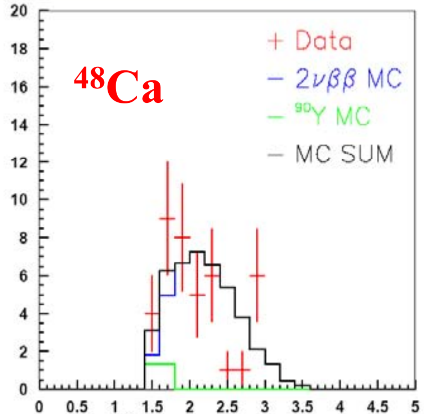
^{96}Zr $T_{1/2}$ = 2.0 ± 0.3 (stat) ± 0.2 (syst) × 10^{19} y

^{48}Ca $T_{1/2}$ = 3.9 ± 0.7 (stat) ± 0.6 (syst) × 10^{19} y









Important ingridient for $M_{0\nu}$ calculation in QRPA

NEW in 2007: direct meas. of ^{130}Te $2\beta2\nu$

The $\beta\beta2\nu$ half-life of ^{130}Te has been a long-standing mystery::

Geochemical:
- $(25 \pm 2) \times 10^{20}$ years (Kirsten 83)
- $(27 \pm 2) \times 10^{20}$ years (Bernatowicz 93)
- $(7.9 \pm 1) \times 10^{20}$ years (Takaoka 96)
- $\sim 8 \times 10^{20}$ years (Manuel 91)

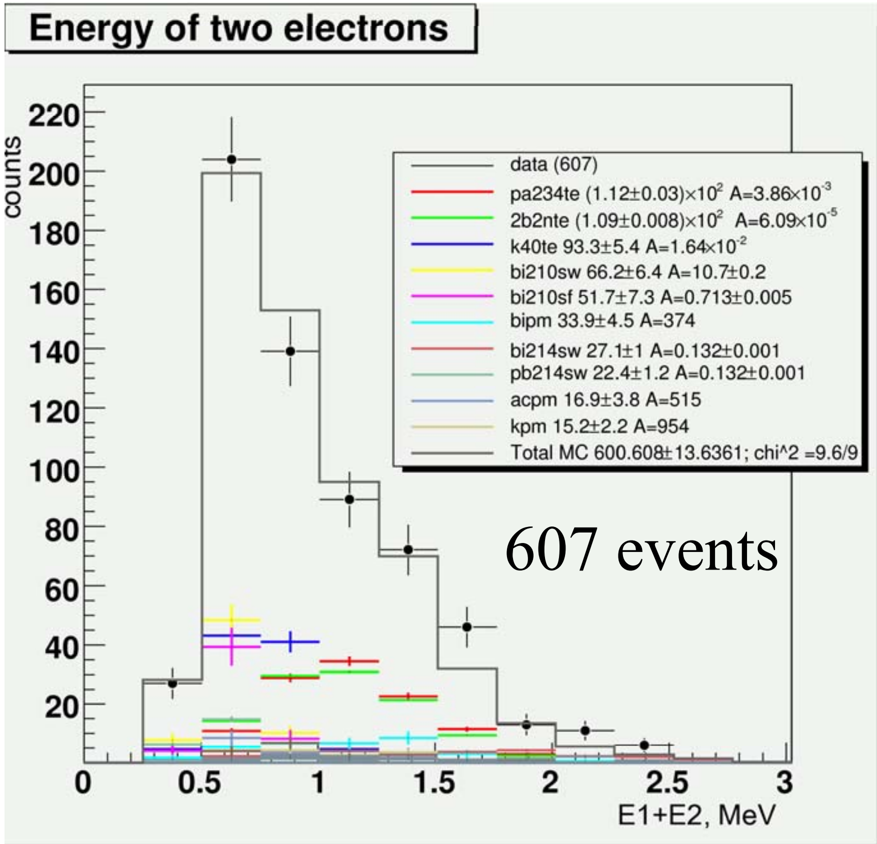
Difference between 'old' and 'young' ores due to time dependence of constants..?

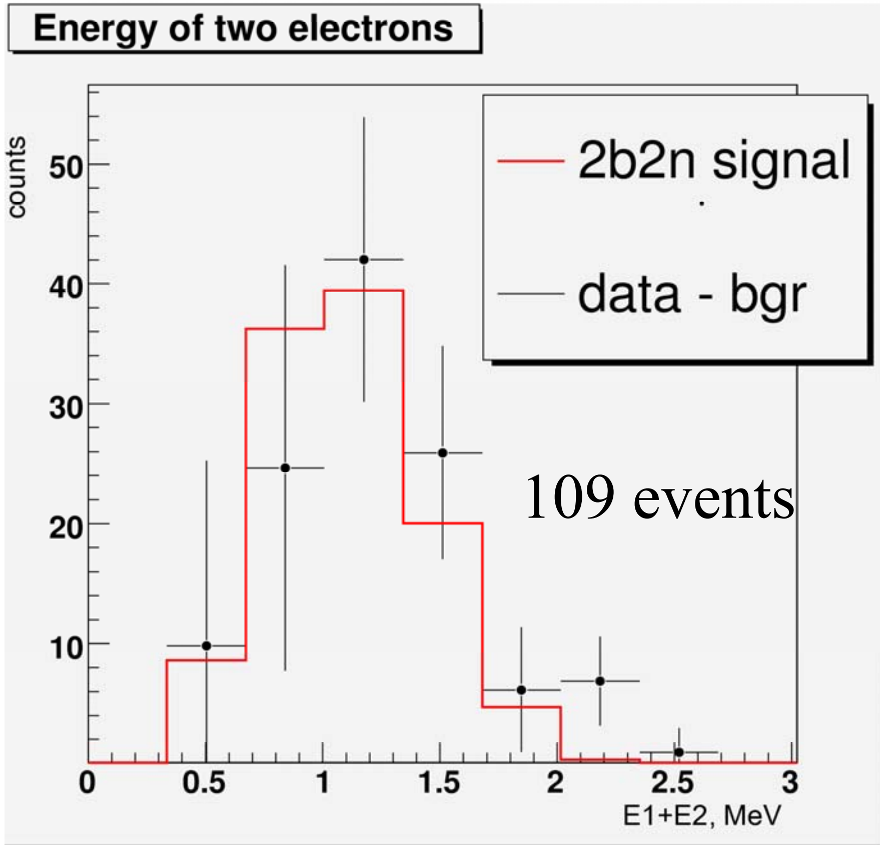
Ratio of $^{82}Se/^{130}Te$ (less systematic):
-$(9 \pm 1) \times 10^{20}$ years (average by A. Barabash)

Direct measurement:
-$(6.1 \pm 1.4\,(syst) \pm^{2.9}_{3.4}(stat)) \times 10^{20}$ years (Arnaboldi 2003)

NEW in 2007: direct meas. of ^{130}Te $2\beta2\nu$

$$T_{1/2}^{2\nu\beta\beta} = (7.6 \pm 1.5(stat) \pm 0.8(syst)) \cdot 10^{20}\ years$$

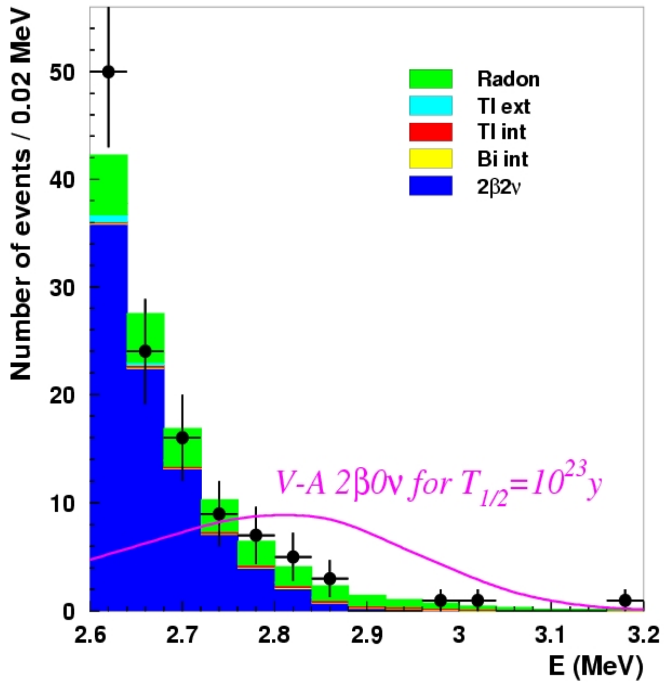


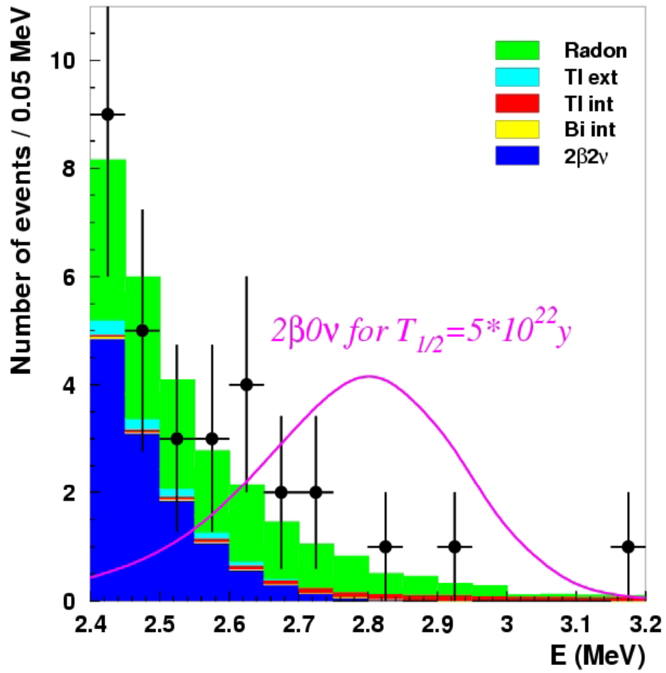


534 days, 454 g of ^{130}Te

background subtracted

NEMO 3 highlights: 2β0ν ^{100}Mo & ^{82}Se





$T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23}$ (90 % CL)
$<m_\nu>^* < 0.8 – 1.3$ eV
$\lambda'_{111} < 1.5\ 10^{-4}$

expected in 2009: $T_{1/2}^{\beta\beta0\nu} > 2 \times 10^{24}$ (90 % CL)
$<m_\nu>^* < 0.4 – 0.7$ eV

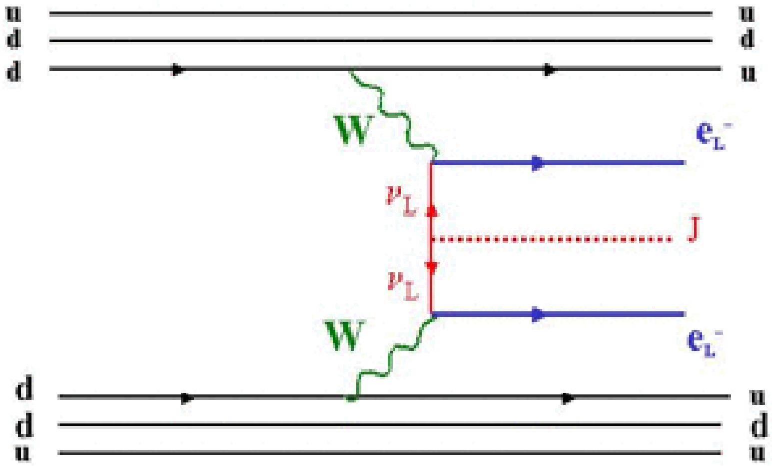
$T_{1/2}^{\beta\beta0\nu} > 2.1 \times 10^{23}$ (90 % CL)
$<m_\nu>^* < 1.4\text{-}2.2$ eV
$\lambda'_{111} < 2.5\ 10^{-4}$

$T_{1/2}^{\beta\beta0\nu} > 8 \times 10^{23}$ (90 % CL)
$<m_\nu>^* < 0.7\text{-}1.1$ eV

- **Collaboration decided to perform blind analysis with mock data**
- **Plan to open the box and update the results ~ summer 2008 and again ~ early 2010.**

* *Recent QRPA NME calculation as in MEDEX'07*

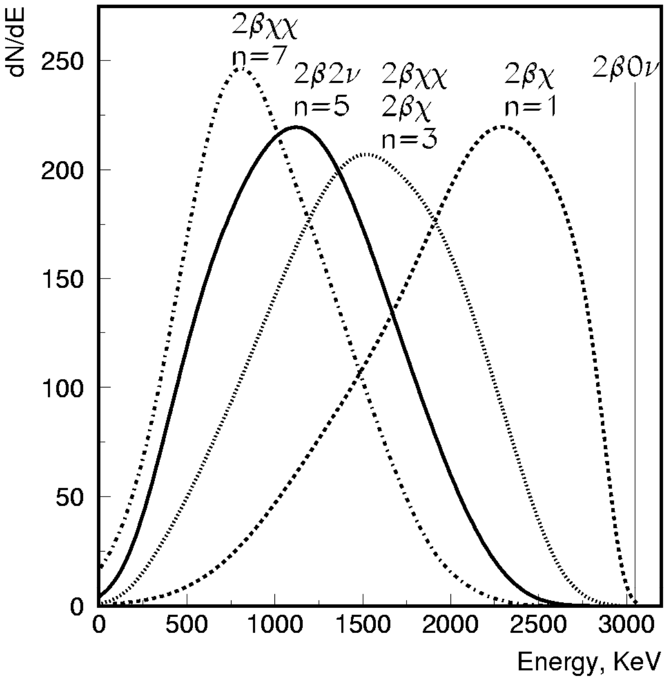
'Majoron' search



Lepton number violation due to local symmetry breaking

Axions χ ('Majorons') with coupling to neutrinos

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + \chi^{0}(\chi^{0})$$



best limits

	n=1 **	n=2 **	n=3 **	n=7 **
Mo	$>2.7\cdot10^{22}$ $g<(0.4\text{-}1.8)\cdot10^{-4}$	$>1.7\cdot10^{22}$	$>1.0\cdot10^{22}$	$>7\cdot10^{19}$
Se	$>1.5\cdot10^{22}$ $g<(0.7\text{-}1.9)\cdot10^{-4}$	$>6.0\cdot10^{21}$	$>3.1\cdot10^{21}$	$>5.0\cdot10^{20}$

n: spectral index, limits on half-life in years

** PI data, ***R.Arnold et al. Nucl. Phys. A765 (2006) 483***

SuperNEMO project

From NEMO-3 to SuperNEMO

$$T_{1/2}(\beta\beta0\nu) > \ln 2 \times \frac{\mathcal{N}_A}{\mathbf{A}} \times \frac{\mathbf{M} \times \varepsilon \times \mathbf{T_{obs}}}{\mathbf{N_{90\%\,CL}}}$$

NEMO-3		SuperNEMO
^{100}Mo	isotope	^{150}Nd or ^{82}Se
7 kg	isotope mass M	100-200 kg
8 %	efficiency ε	~ 30 %
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	internal contaminations ^{208}Tl and ^{214}Bi in the ββ foil	^{208}Tl < 2 μBq/kg if ^{82}Se: ^{214}Bi < 10 μBq/kg
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

NEMO-3	SuperNEMO
$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < 0.4 – 0.7$ eV	$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{26}$ y $\langle m_\nu \rangle < 40 – 70$ meV

Very preliminary SuperNEMO design

<u>Planar</u> and <u>modular</u> design: ~ 100 kg of isotope (~20 modules × 5-7 kg)

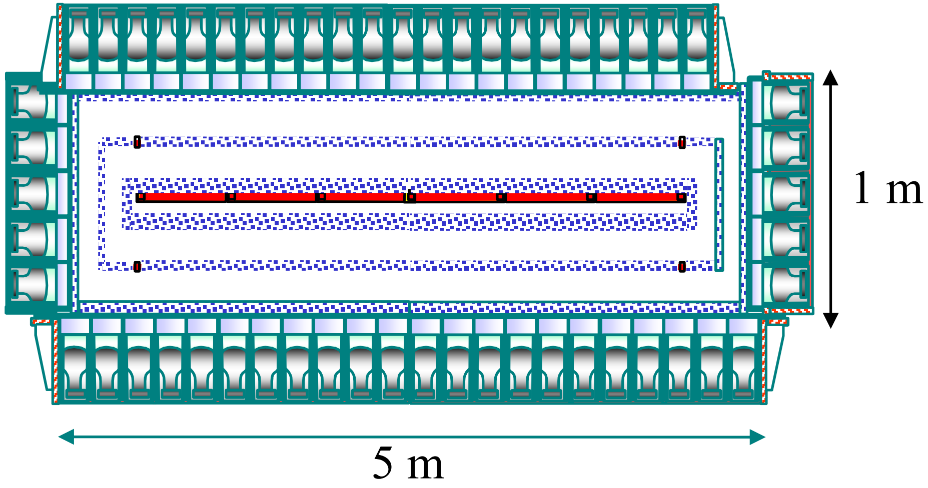
<u>1 module:</u>

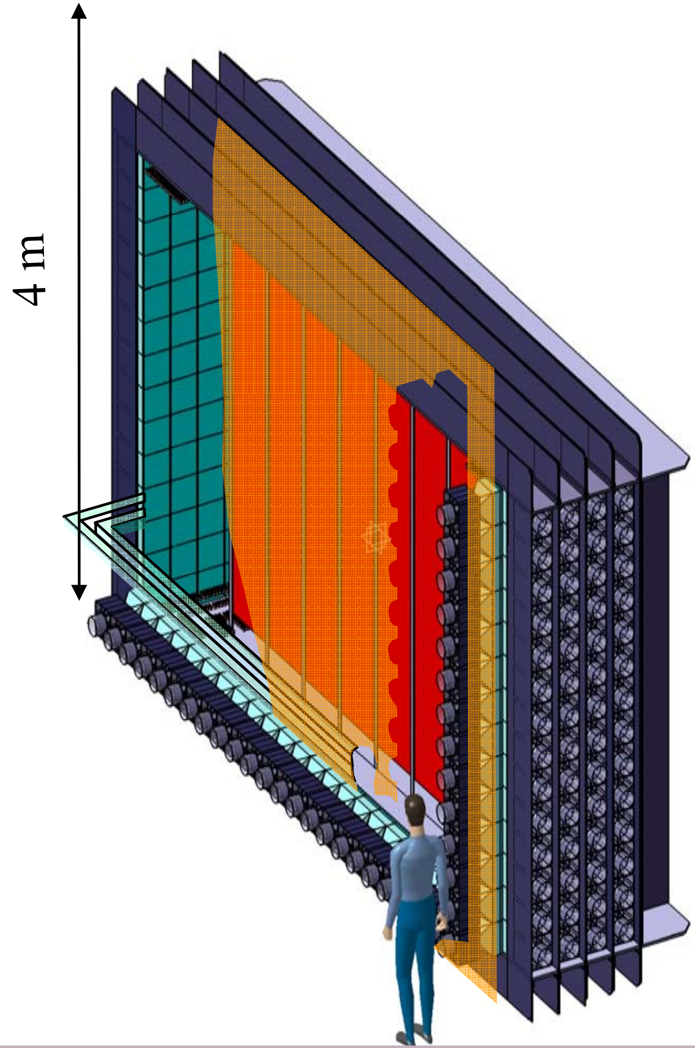
Source (~40 mg/cm^2) 4 (length) x 3(height) m^2

Tracking : drift chamber ~3000 cells in Geiger mode

Calorimeter: scintillators + PM
~1 000 PM if scint. blocks
~ 100 PM if scint. bars

Top view



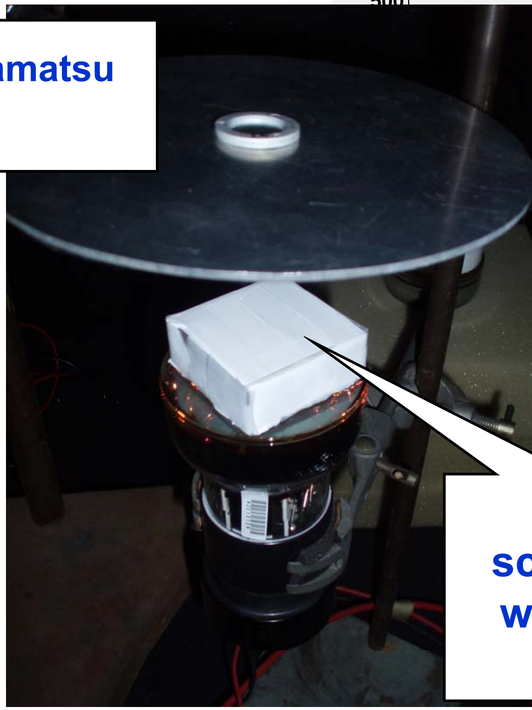


R&D: SuperNEMO calorimeter

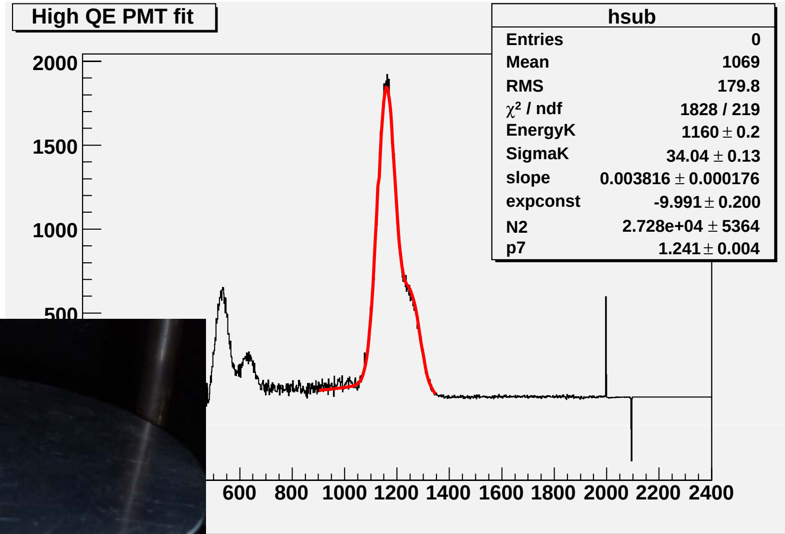
- Goal: FWHM ≈ 7%/√E ⇒ 4% at 3 MeV (Currently 14-16%/√E in NEMO3)
- A combination of energy losses in the foil and calorimeter DE/E
- Studies
  - Organic (plastic or liquid),
  - Shape, size, coating
  - PMTs (Photonis, Hamamatsu, ETL)
  - Light guides, optical contact
  - Chemistry

High QE Hamamatsu tube

\+



BC404 scintillator wraped in teflon



=

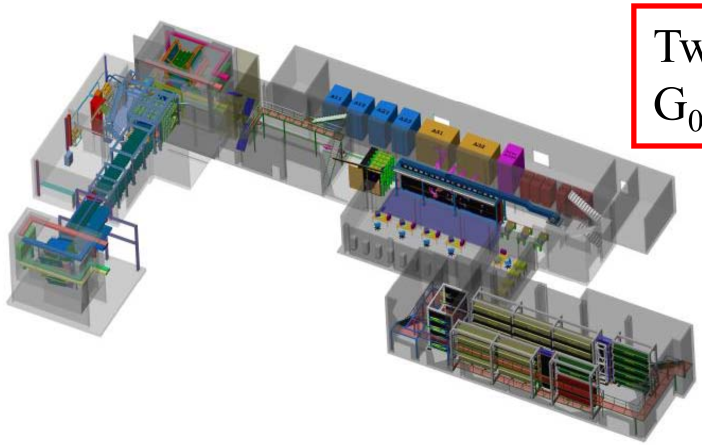
ΔE/E = 6.5% at 1 MeV
⇓
3.8% at 3 MeV if 1/√E

R&D: isotope enrichment/ purification

- 4 kg of ^{82}Se funded by ILIAS have been delivered from Russia.
- purification at ILN (US) underway
- enrichment of Nd possible in France (MENPHIS, currently mothballed)

Choice of nucleus depends on:

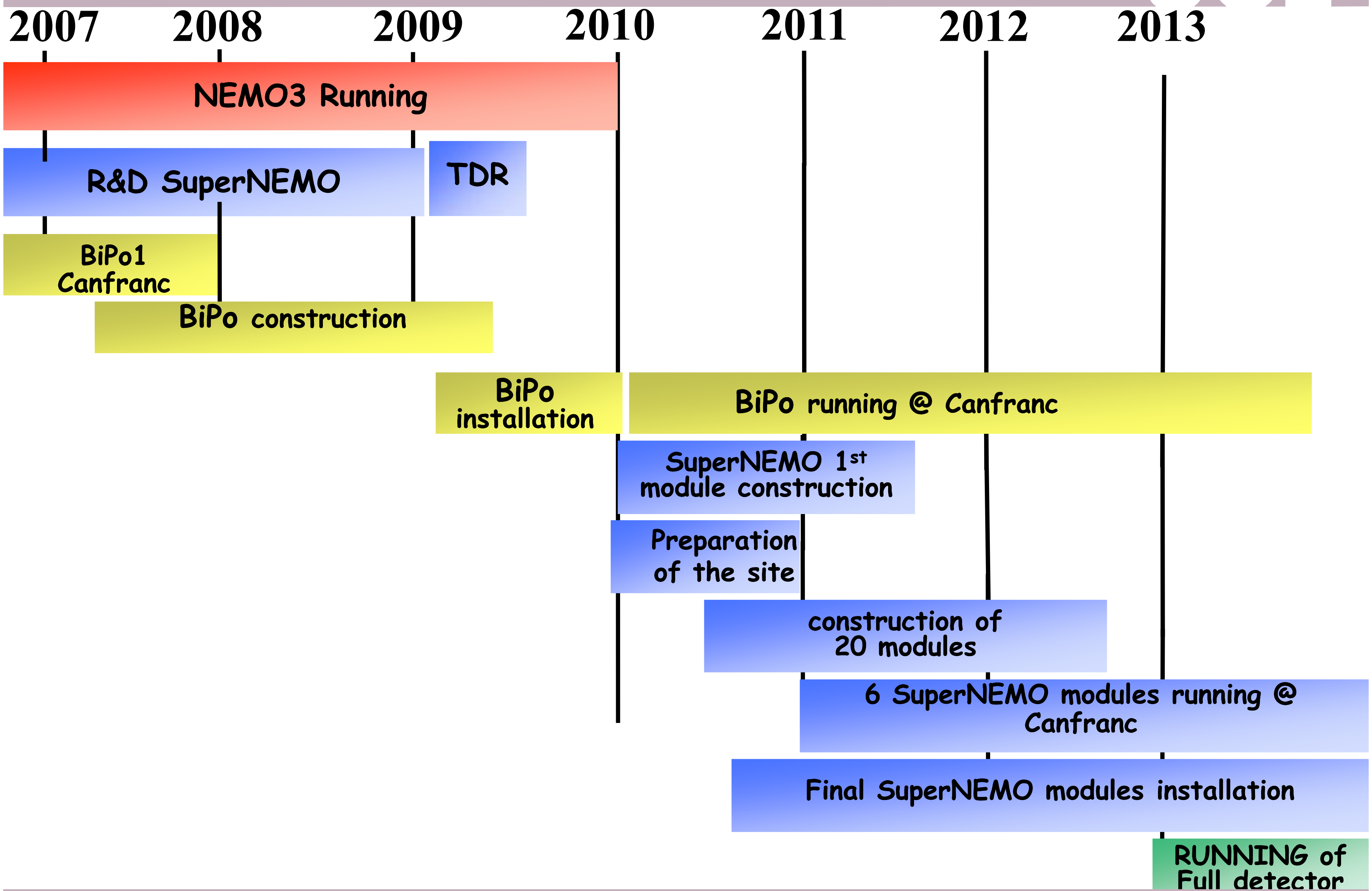
- enrichment possibilities
- high $Q_{\beta\beta}$ value
  - → larger phase space
  - → lower non-ββ background
- small ββ2ν contribution



Two main options:
$G_{0\nu}(150Nd) / G_{0\nu}(82Se) = 8$

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

SuperNEMO schedule summary



Conclusion

NEMO's Tracking+Calorimetry approach is unique:

- high background rejection
- choice of isotopes
- reconstruction of kinematics

NEMO 3 is taking data:

- $\beta\beta2\nu$ factory, important for understanding of backgrounds and NME
- limits on $\beta\beta0\nu$ using different isotopes:
- $T_{1/2}(0\nu) > 5.8 \times 10^{23}$ y @ 90% CL for $^{100}Mo \rightarrow \langle m_\nu \rangle < 0.8\text{-}1.3$ eV (693 days); $\lambda'_{111} < 1.5 \times 10^{-4}$
- limits on Majoron's coupling
- $T_{1/2}(2\nu) = (7.6 \pm 1.5\,(stat) \pm 0.8(syst)) \times 10^{20}$ y for ^{130}Te

SuperNEMO R&D approved in France, the UK and Spain; TDR expected in 2008; full 20 modules in 2012-2013

- choice of isotopes: ^{82}Se or ^{150}Nd

Backup slides

If observed, **how to determine mechanism**: ν *mass, SUSY, V+A ... ???*

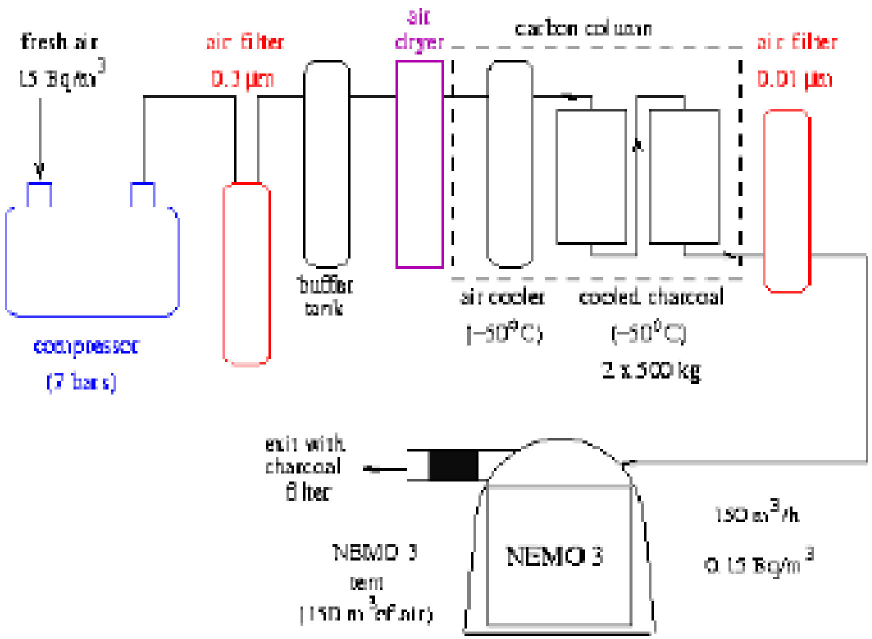
- measure kinematical parameters: angular correlation, individual electron energy!
- measure several isotopes!
- measure $\beta\beta 0\nu$ decay to excited state of final nuclei!

Calorimetry plus tracking approach:

Detection of both electrons, three kinematic observables: individual electron energies; angular correlation; energy sum
Sources separated from the detector: measure $T_{1/2}$ for several isotopes
Particle identification: e^-, γ; good signature for decay to excited states

Unique and complementary

Backgrounds: Radon purification facility



Running since Oct. 4th, 2004 in FréjusUnderground Lab.

1 ton charcoal @ -50°C, 7 bars

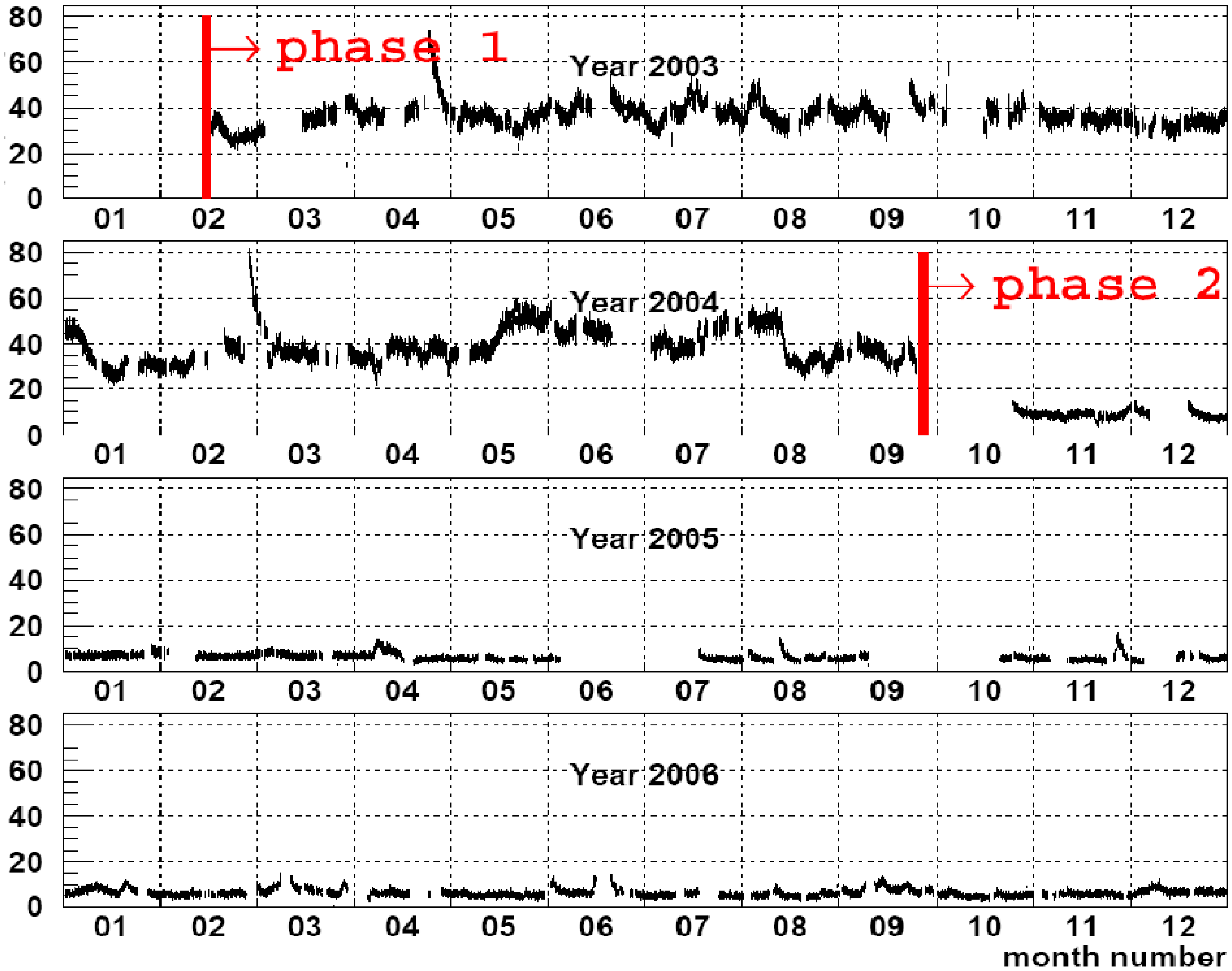
Flux: 150 m^3/h

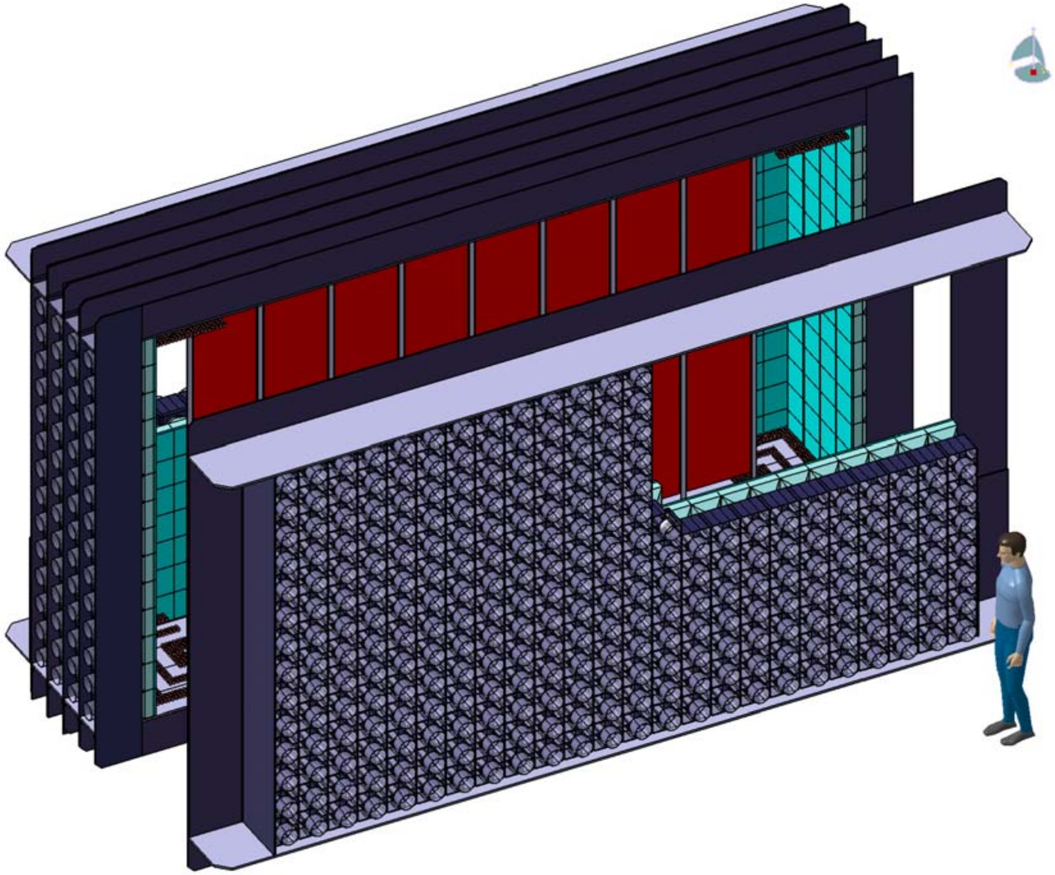
Activity of ^{222}Rn :

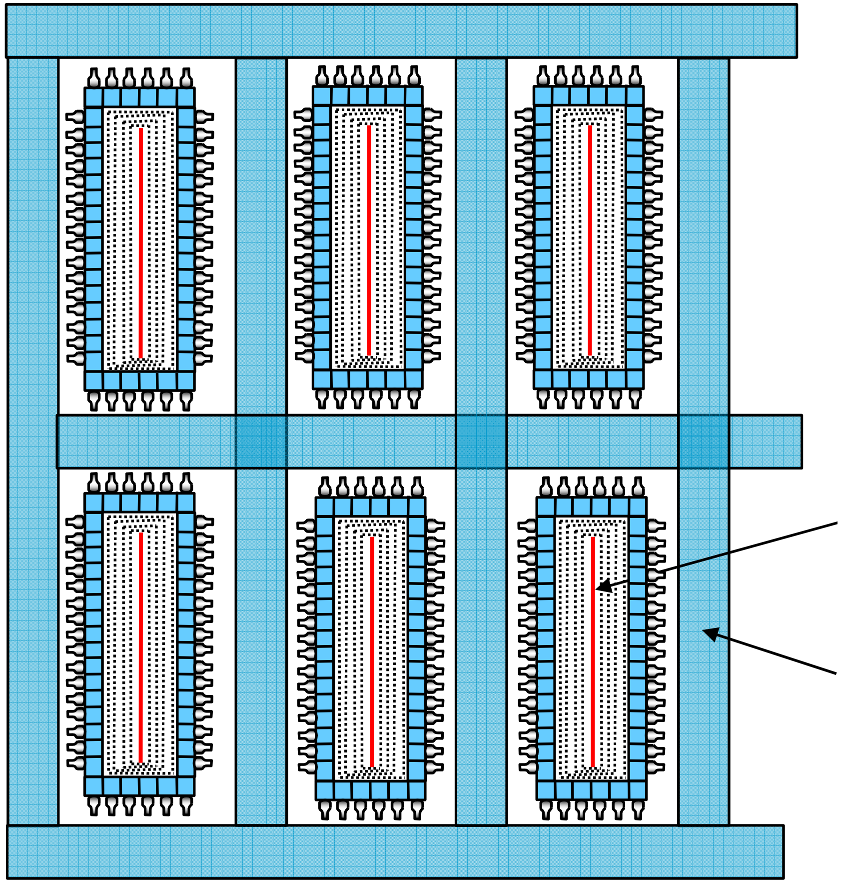
Before Facility = 15 Bq/m^3

After Facility < 15 mBq/m^3

Radon purification facility, effect inside NEMO3





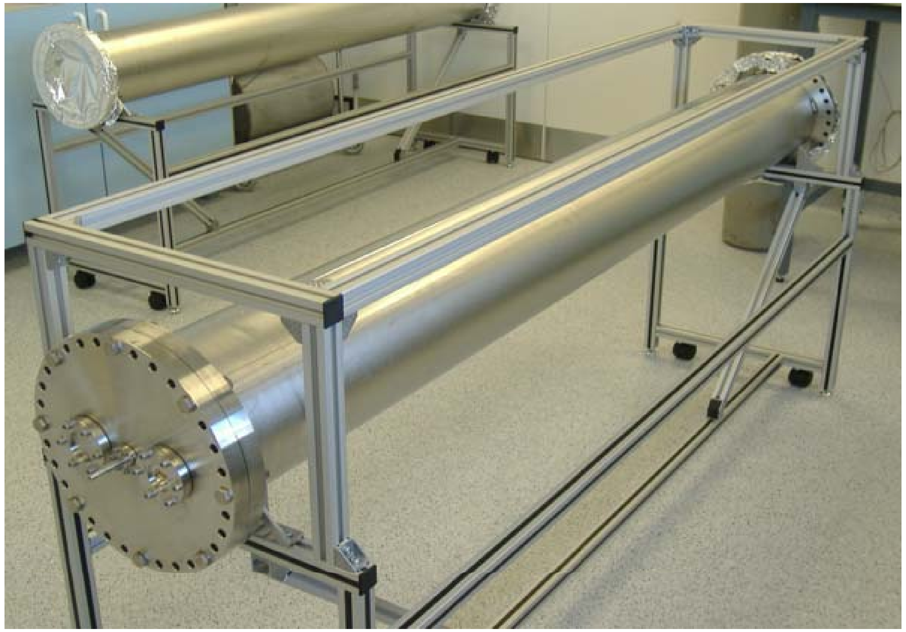


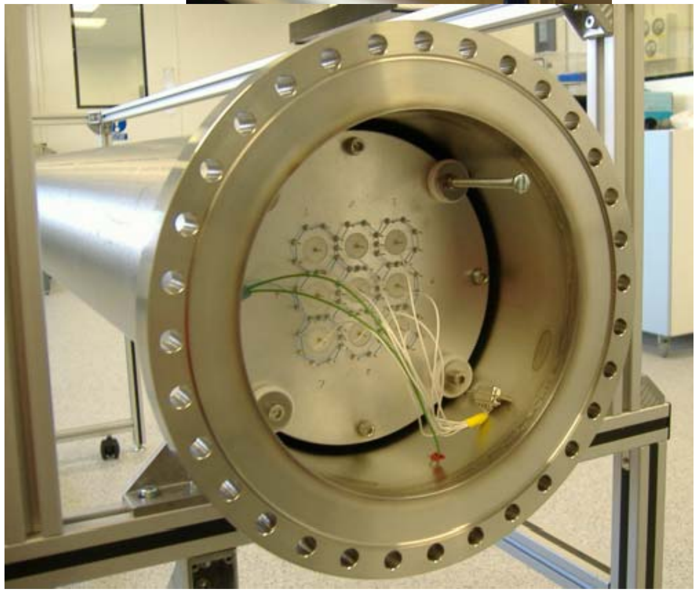
Single sub-module
with ~7 kg of isotope

~20 sub-modules for 100+ kg of isotope
surrounded by shielding

R&D: tracker optimisation

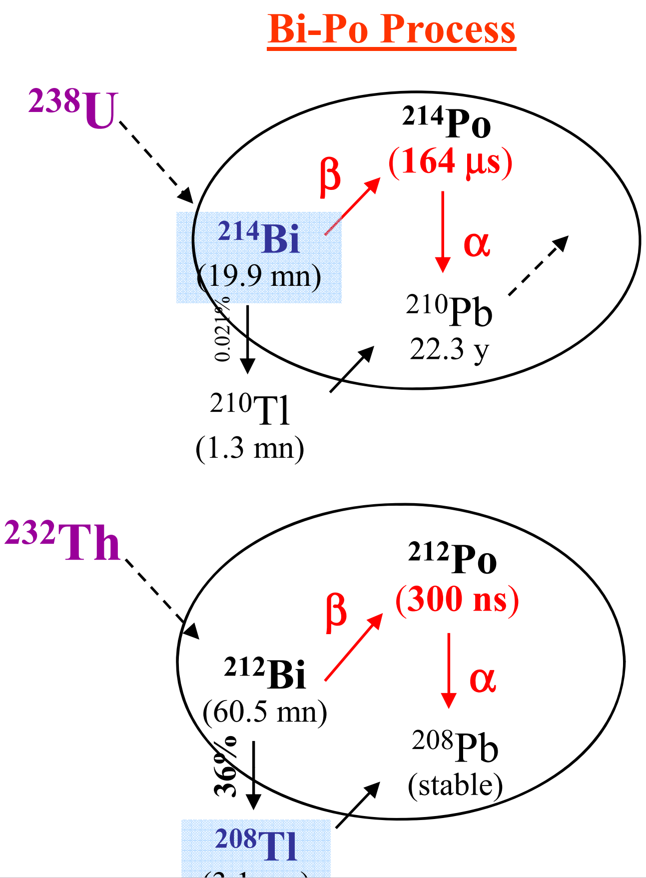
- optimize:
  - wire length and diameter
  - wire material and diameter,
  - read-out, gas mixture etc
- 9-cell prototype built
- 90 cell prototype + 300 cell prototype to be built by Spring 2008
- About 500k wires to be strung, crimped, terminated => wire robot under development

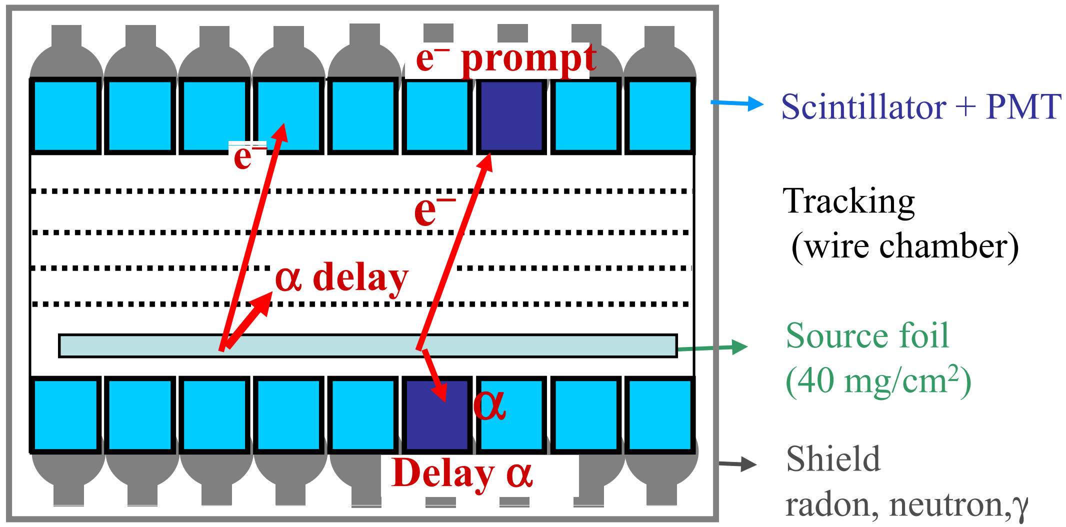




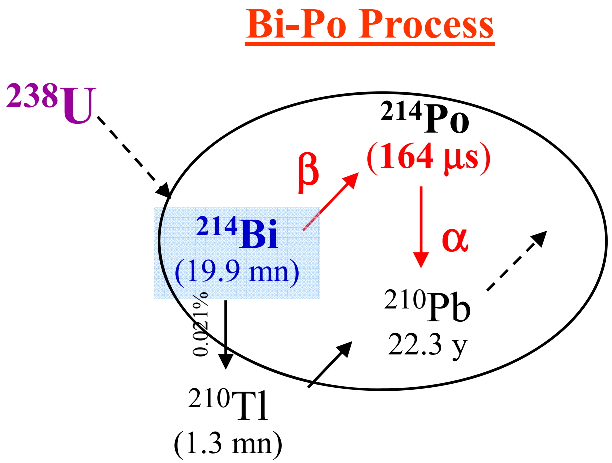
R&D : radio purity and BiPo device

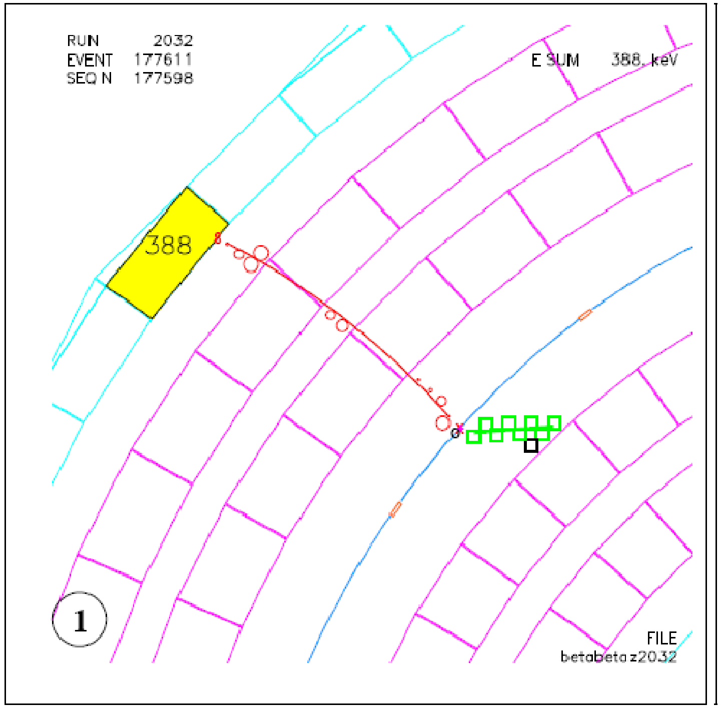
- Need to measure radio purity at a few µBq/kg level
  - Beyond sensitivity of conventional Ge detectors
  - Build new tool, BiPo detector.





Backgrounds: Radon, delayed ^{214}Po α

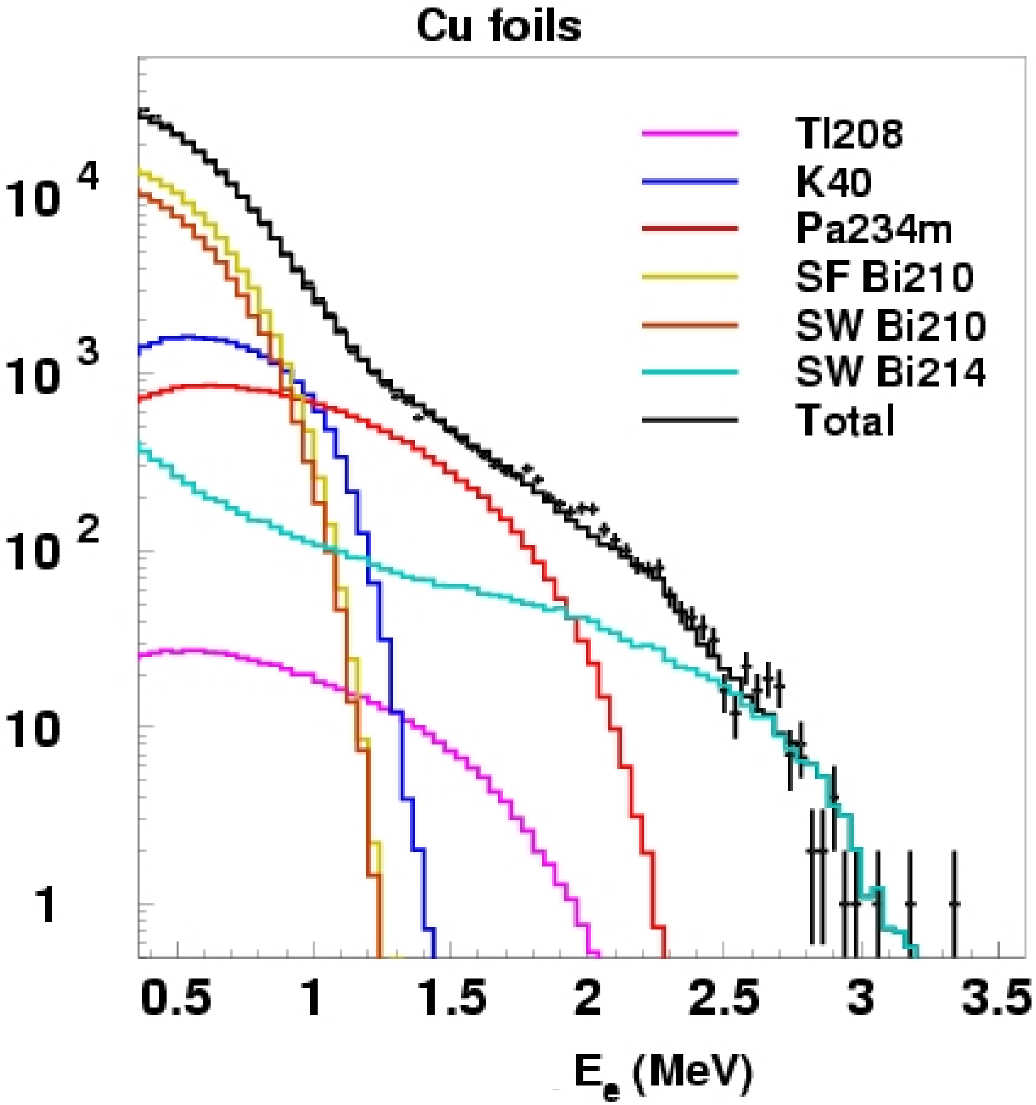




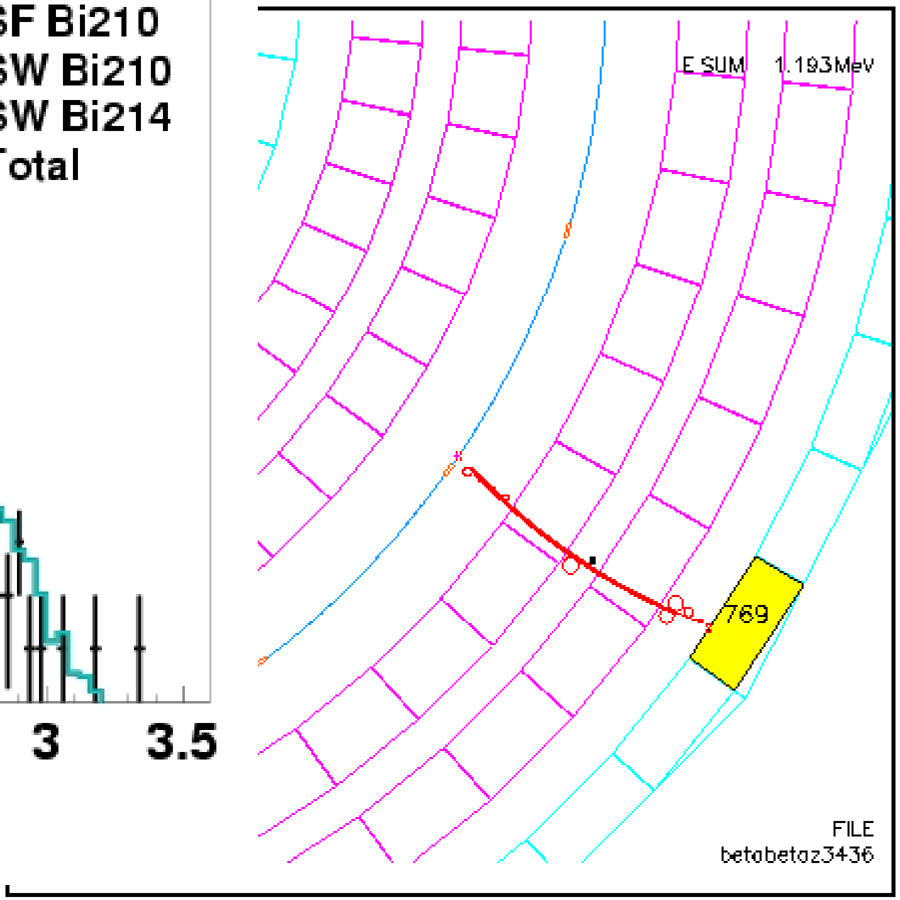
α track length & event topology allows to separate ^{214}Bi on

- **surface of GG wires**
- **tracking gas**
- **surface of the foil**
- **inside the source foil**

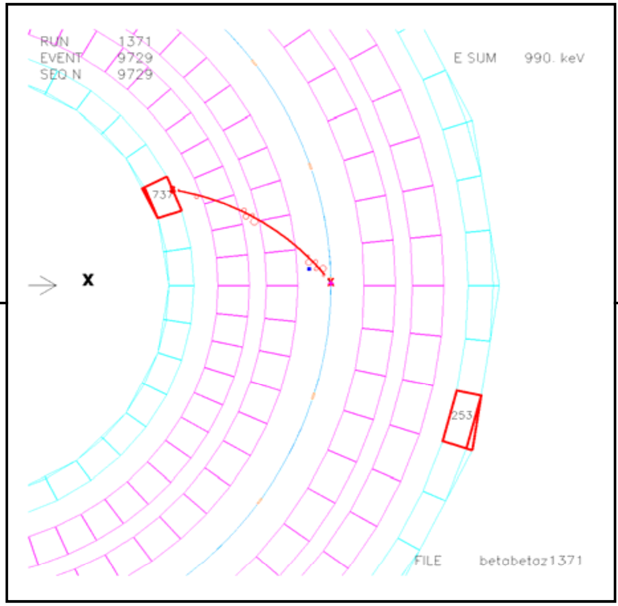
Backgrounds : internal from β^- decay

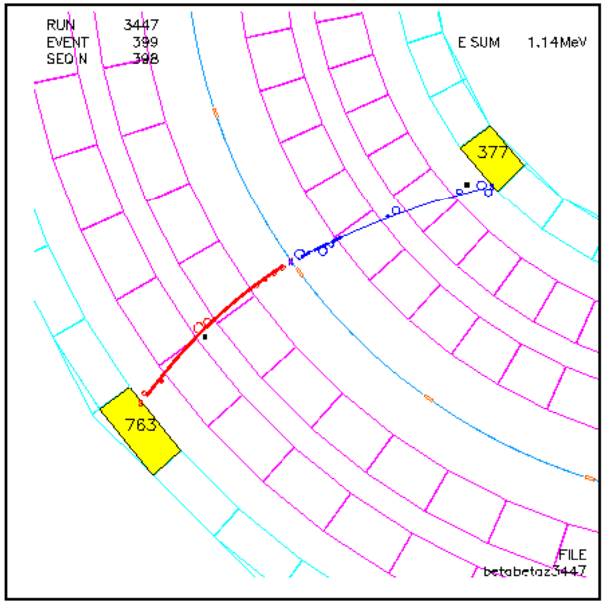


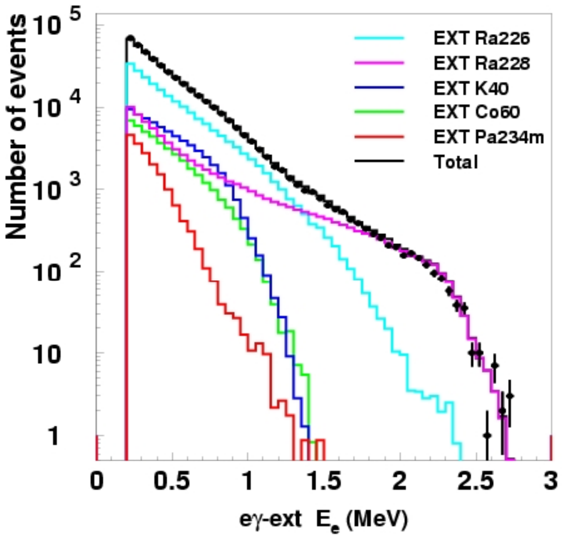
single electron events

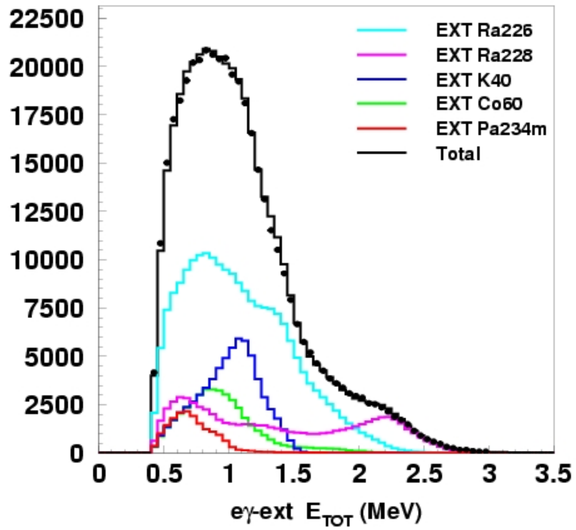


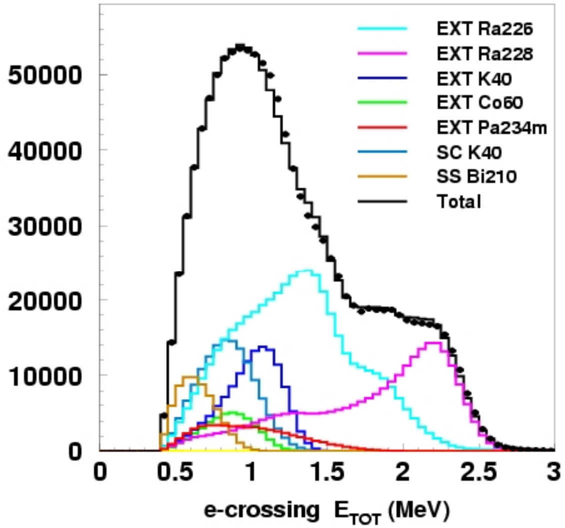
Backgrounds: external γ





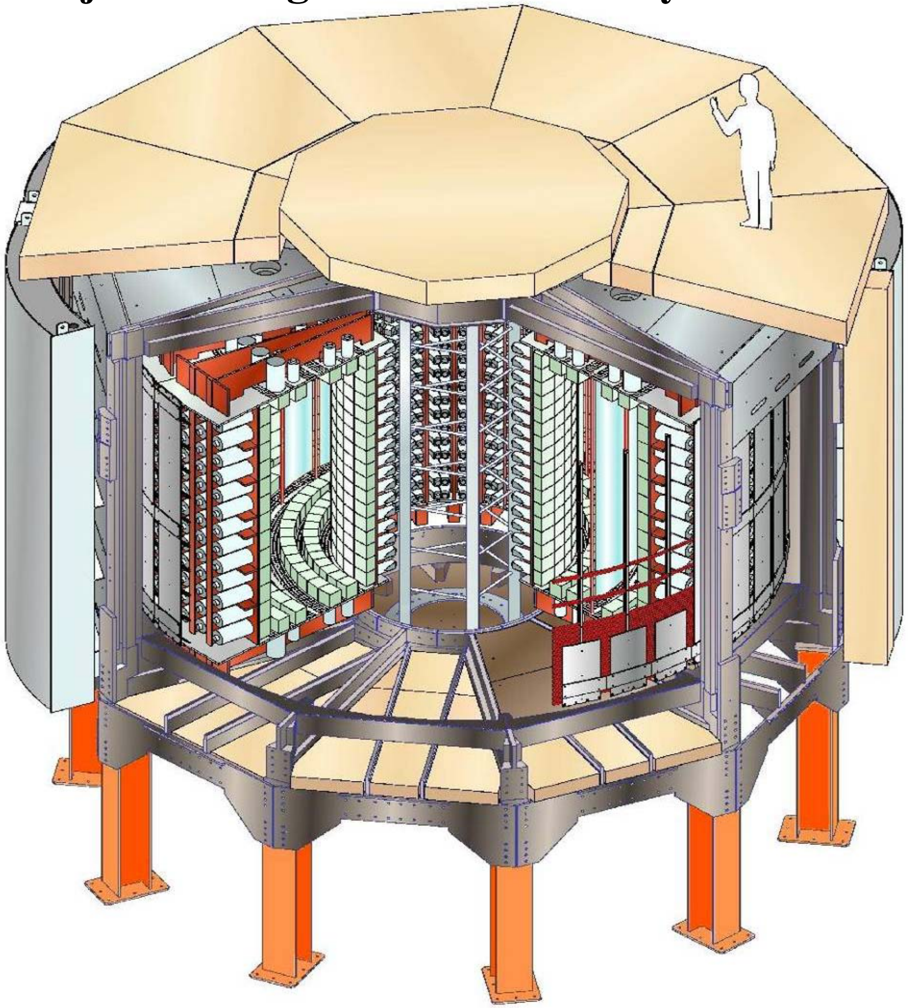






NEMO 3: details

Fréjus Underground Laboratory : 4800 m.w.e.



<u>Source</u>: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

<u>Tracking detector</u>: drift wire chamber operating in Geiger mode (6180 cells)
$\sigma_\perp = 5$ mm, $\sigma_z = 1$ cm (vertex)

<u>Calorimeter</u>: 1940 plastic scintillators coupled to low radioactivity PMTs
- **Energy Resolution FWHM=14% (1 MeV)**
- **Time resolution = 0.25 ns @ 1MeV**
- **γ veto efficiency ≈ 50 %**

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water + Wood

Background: natural radioactivity, mainly ^{214}Bi and ^{208}Tl (γ 2.6 MeV)
Radon, neutrons (n,γ), muons, ββ(2ν)

R&D: ^{150}Nd production at CEA-MENPHIS

No gaseous compuond! need alternative technology.

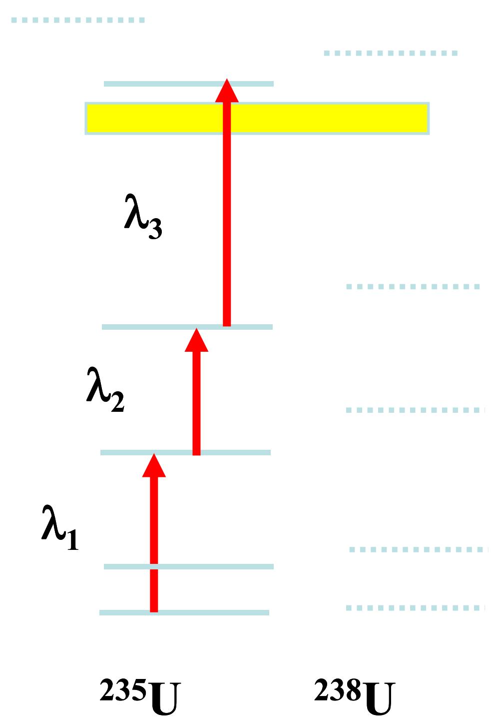
Laser-vapor interaction

SILVA / AVLIS

(Atomic Vapor Laser Ionization S)

2 Isotopes ^{235}U and ^{238}U

5 energy levels (3 transitions)



Photoionization

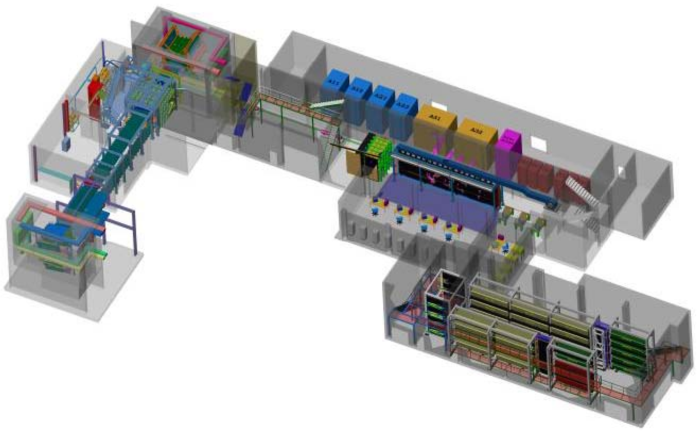
1973 : Atomic isotope separation by laser : initial patent
1980 : Basic research at CEA (spectroscopy, evaporation)
1985 : SILVA/AVLIS selected as advanced process :
USA, France, Japan

1994 : Tens of grams produced at the industrial assay
1994-1998 : Technological demonstrations (by parts)
Mid 1999 : AVLIS shut down in US ; early 2003 in Japan

2000 : Decision for a conclusive 4 years program
2000 - 2003 : MENPHIS construction and preliminary R&D.

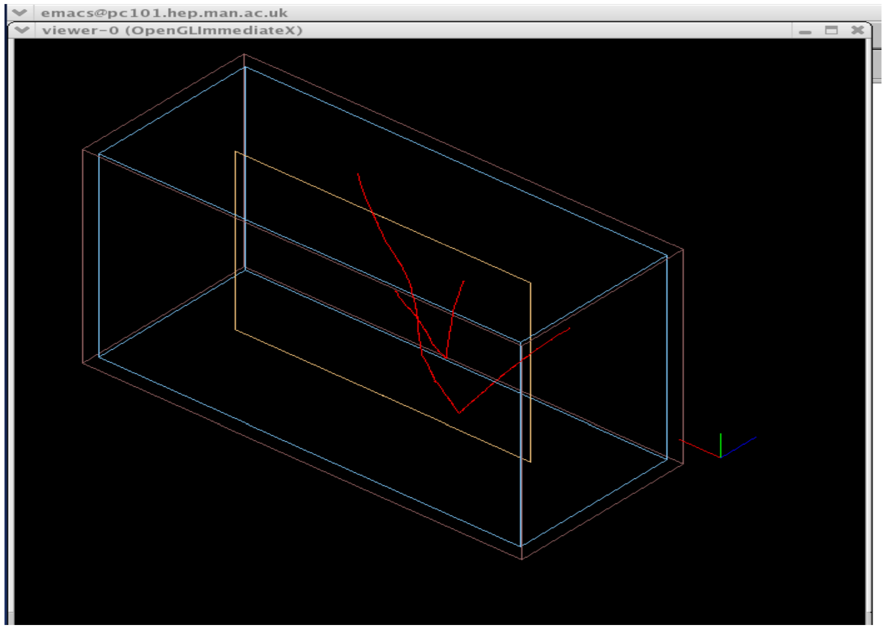
2003 : Demonstrations on MENPHIS
204 kg @ 2.5% 235U

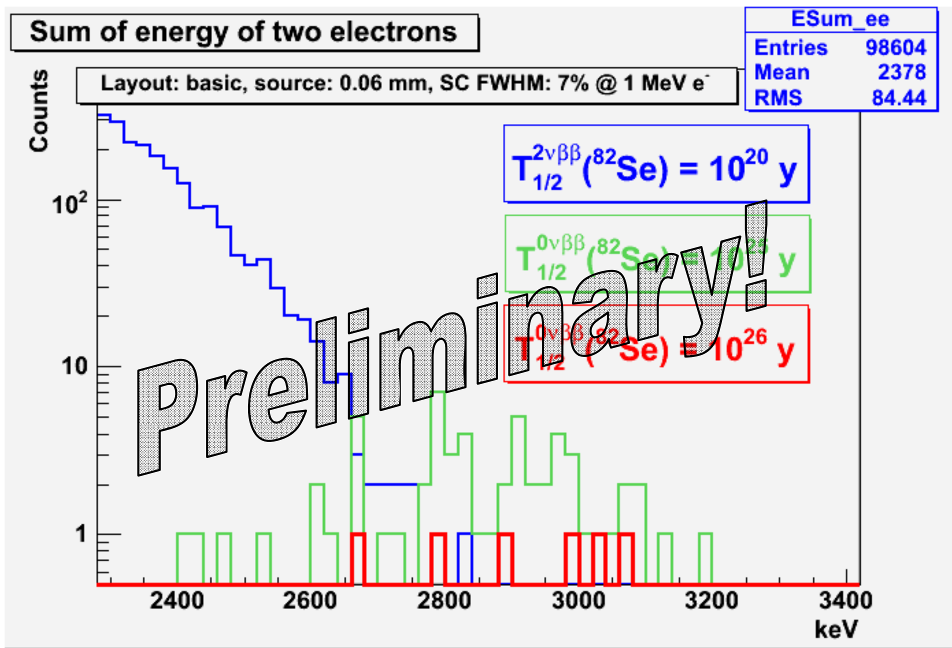
Current status: mothbolled
^{150}Nd is possible, but:
- Cost?
- Enrichement?
- Purity?



R&D: physics simulations

- Full MC simulation under development
  - GEANT4 for low energy physics simulation
  - Use NEMO-3 & prototype data for accurate tracking chamber simulation
  - Simulate light transmission for accurate calorimeter simulation
  - DECAY-4 library for decay kinematics (ββ and all radioactive backgrounds)
  - Cellular automate + Kalman filter for track fit
- Will be used to provide input for TDR





neutrino mass limits comparison

Experiment	Isotope	$T_{1/2}$	QRPA [1], eV	QRPA [2], eV	QRPA [3] , eV	Shell model [4], eV	SU(3) [5], eV
NEMO 3	Mo-100	>5.8 10^{23} y	<1.06	<0.58-0.92	<1.01-1.20		
NEMO 3	Se-82	>2.1 10^{23} y	<1.96	<1.20-2.56	<1.70-2.04	<3.38	
COURICINO	Te-130	>2.2 10^{24} y	<0.42	<0.31-0.60	<0.42-0.53	<1.38	
KDHK claim	Ge-76	~1.2 10^{25} y	~0.56	~0.41-1.06	~0.42-0.48	~1.21	
SuperNEMO	Se-82	2.0 10^{26} y	63 meV	39-82 meV	55-66 meV	110 meV	
SuperNEMO	Nd-150	2.0 10^{26} y			16-21 meV*		44-52 meV

* Deformation of ^{150}Nd nucleus is not taken into account

<u>NME calculatios from the following works:</u>

[1] O. Civatarese and J. Suhonen, Nucl. Phys. A 729 (2003) 867 (Table 4)
[2] S. Stoica and H. Klapdor-Kleingrothaus, Nucl. Phys. A 694 (2001) 269
[3] V.A. Rodin et al., Nucl. Phys. A 766 (2006) 107 (nucl-th/0503063) + ***erratum (Table 1)***
[4] E. Caurier, F. Nowacki, A. Poves and J. Retamosa, Nucl. Phys. A654 (1999) 973c (Shell model calculation)
[5] H.G. Hirsch, O. Castanos, P.O. Hess, Nucl. Phys A582 (1995) 124