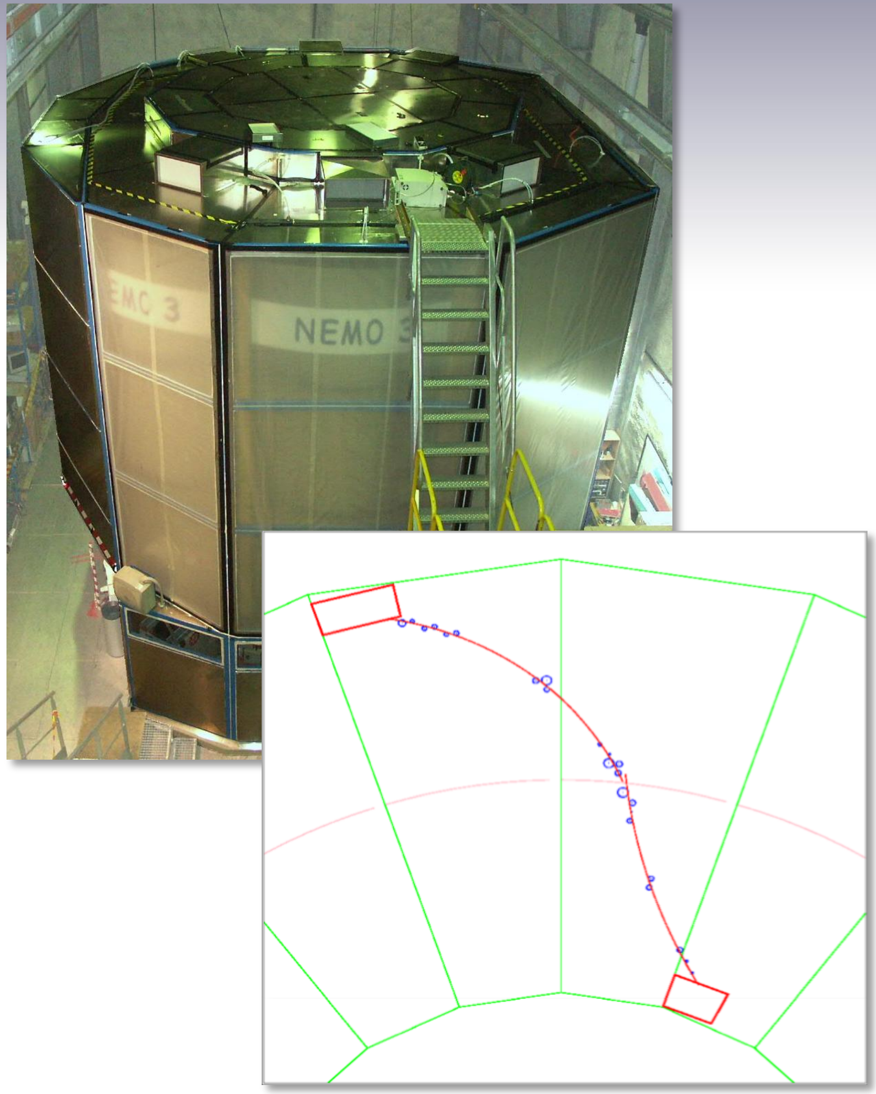
Search for neutrinoless double beta decay with NEMO3 and SuperNEMO



Outline

- Search for ββ decay with a tracko-calo detector
- NEMO3 results
- From NEMO3 to SuperNEMO

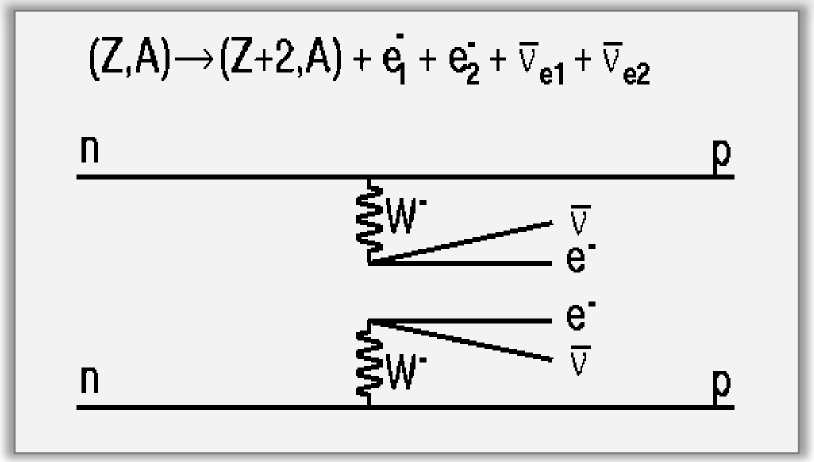
Christine Marquet
CENBG-Bordeaux
For NEMO3 and SuperNEMO collaboration

ICHEP 2010
Paris, 23 July 2010

A tracko-calo detector to search for ββ

Double beta decay

ββ(2ν)



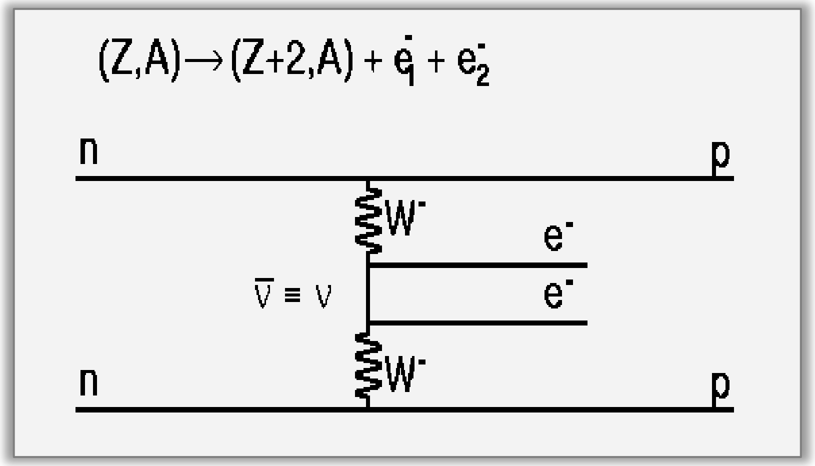
$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \bar{\nu}_{e1} + \bar{\nu}_{e2}$

Allowed SM process $T_{1/2} \sim 10^{19}\text{-}10^{21}$ y

$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

ββ(0ν)

Beyond the SM $T_{1/2} \geq \sim 10^{24}$ y



$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^-$

- Violates lepton number conservation
- Neutrino is Majorana
- Probe New physics mechanisms

  (V+A, SUSY …)

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

η can be due to

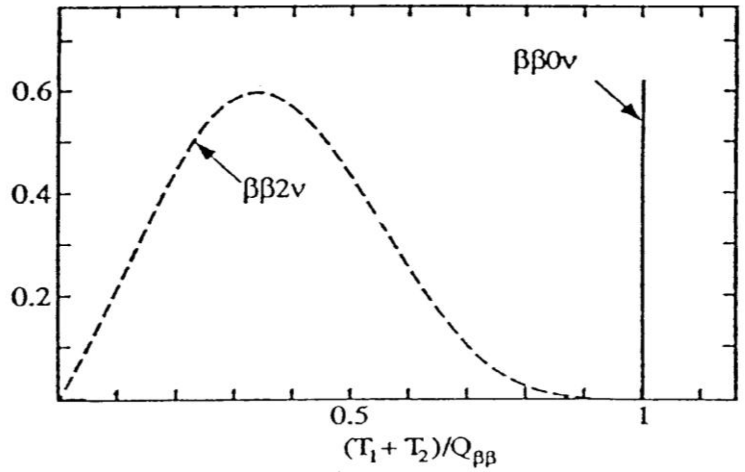
$\langle m_\nu \rangle$,V+A, Majoron,…

NEMO3/SuperNEMO experimental technique

Calorimetry + tracking

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

Calorimeter



☑ Identification of particles : e^-, e^+, γ, α

Kinematics :

☑ Time of flight coincidence

☑ Individual energy of each e^-

Tracker

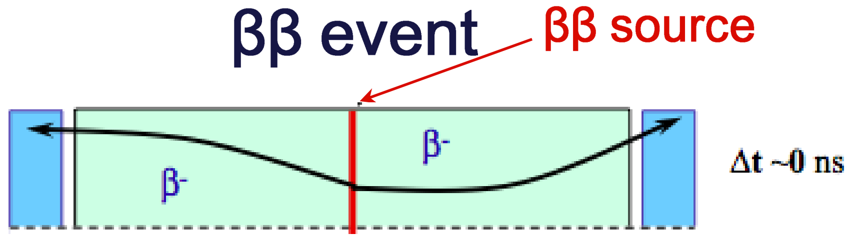
Topology :

☑ Common vertex

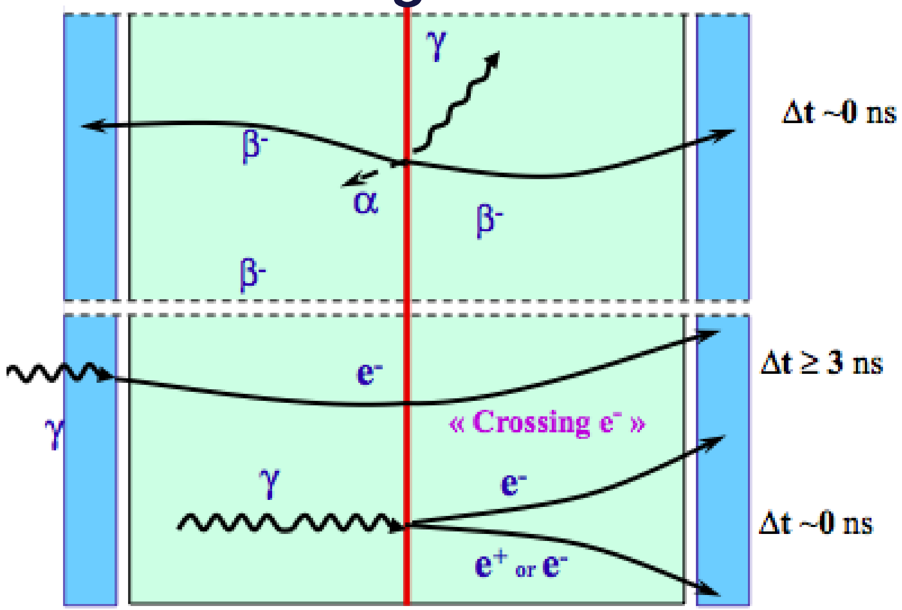
☑ Angular distribution between e^-

☑ Source ≠ detector : several isotopes

ββ event

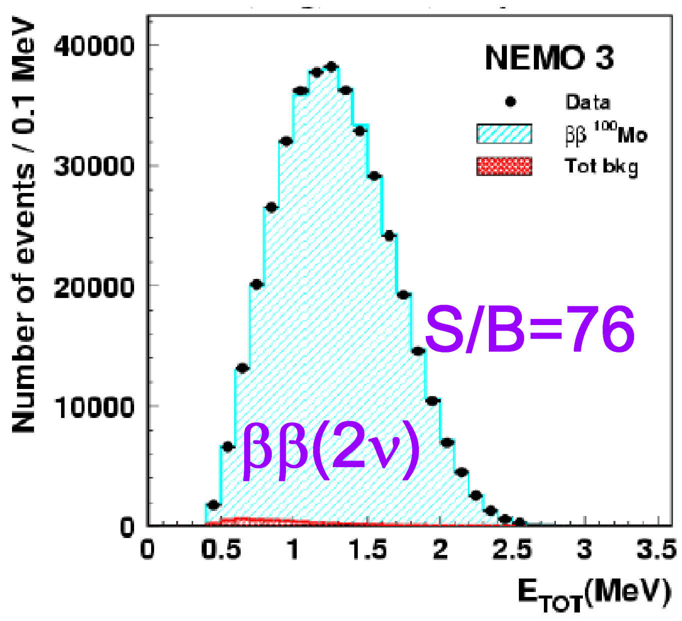


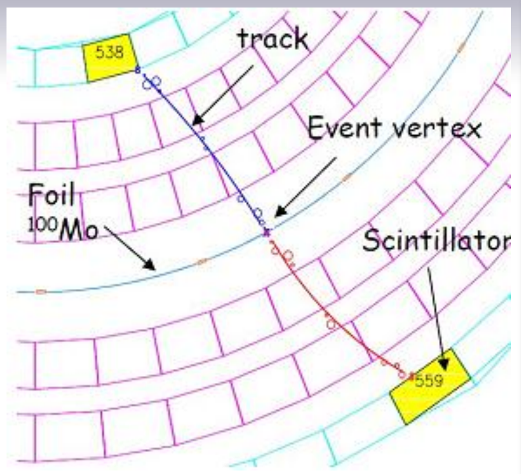
Background



NEMO3/SuperNEMO features

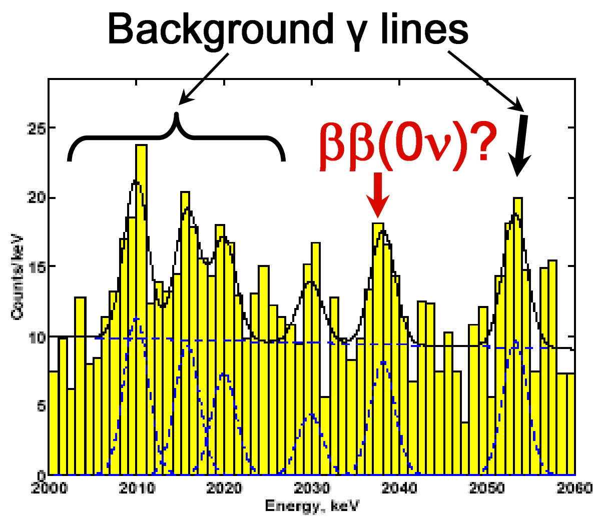
Signature of the signal : 2 e$^-$





Pure calorimeter

Very good energy resolution
High detection efficiency



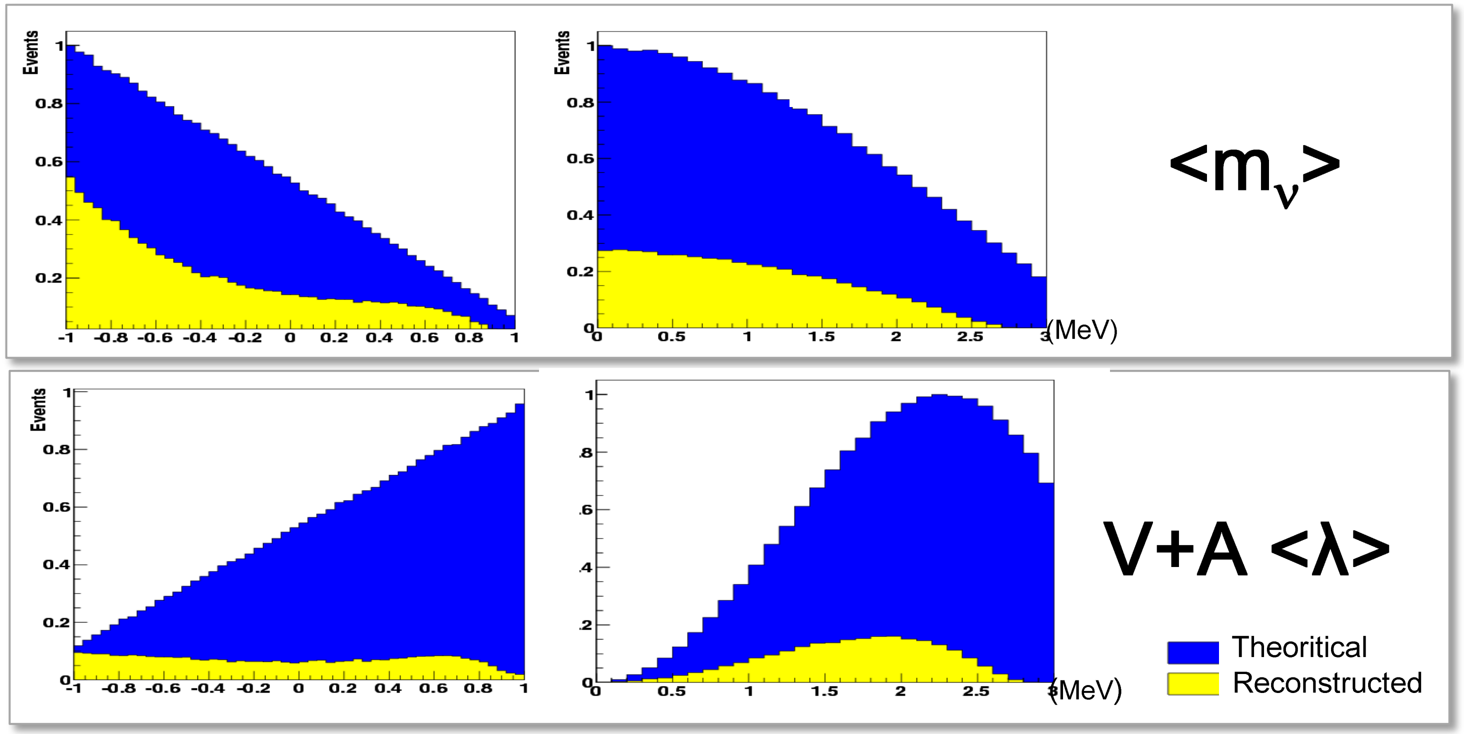
HPGe spectrum (KK claim)

High backgound rejection

Study mechanism of ββ decay

Cosine of angle between e-

Electron energy difference



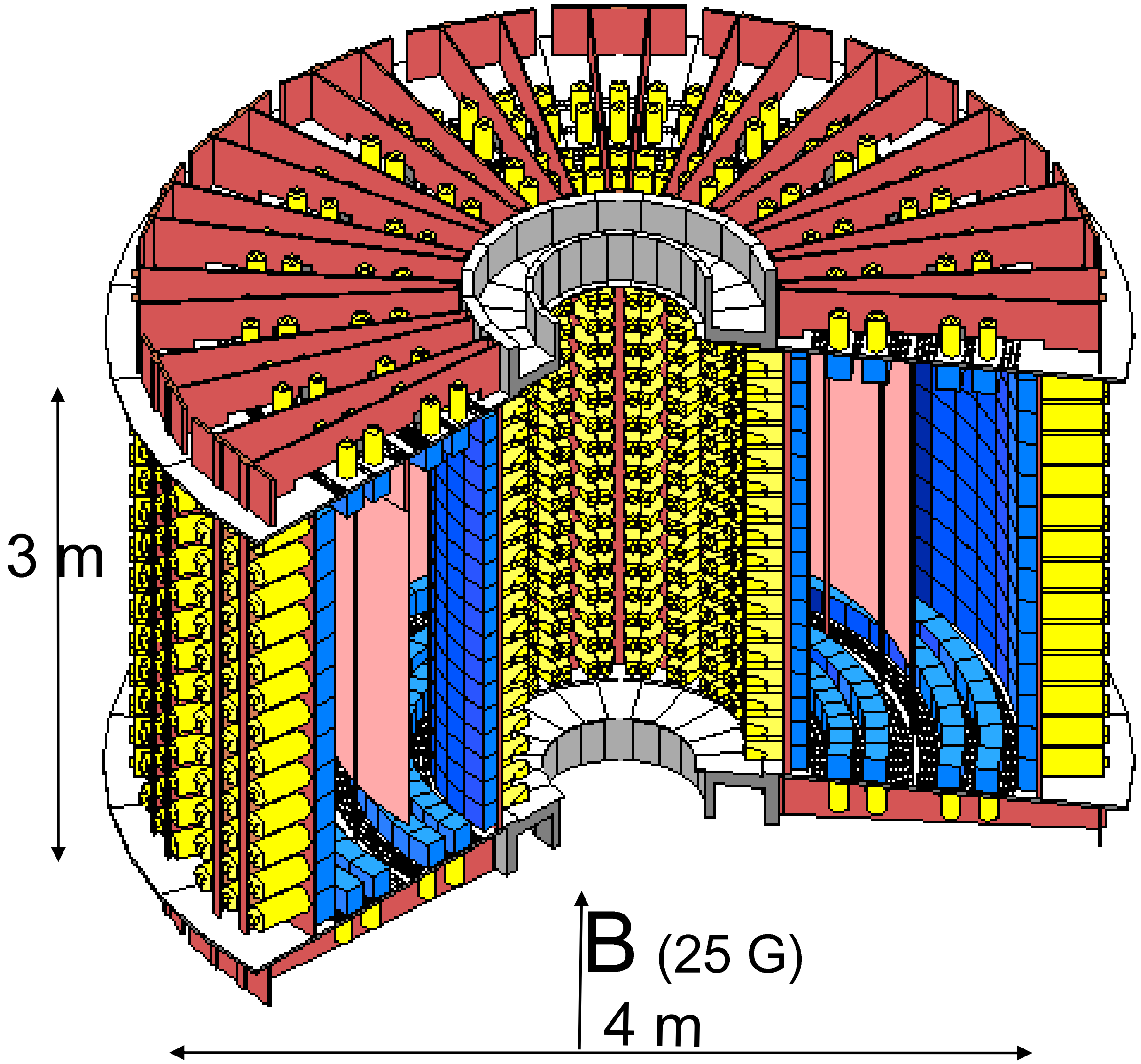
$<m_\nu>$

V+A $<\lambda>$

The NEMO3 detector

Neutrino Ettore Majorana Observatory

20 sectors



Source:

10kg of ββ isotopes: ^{100}Mo (7kg), ^{82}Se (1kg)

+ smaller quantities of ^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd

Tracking detector:

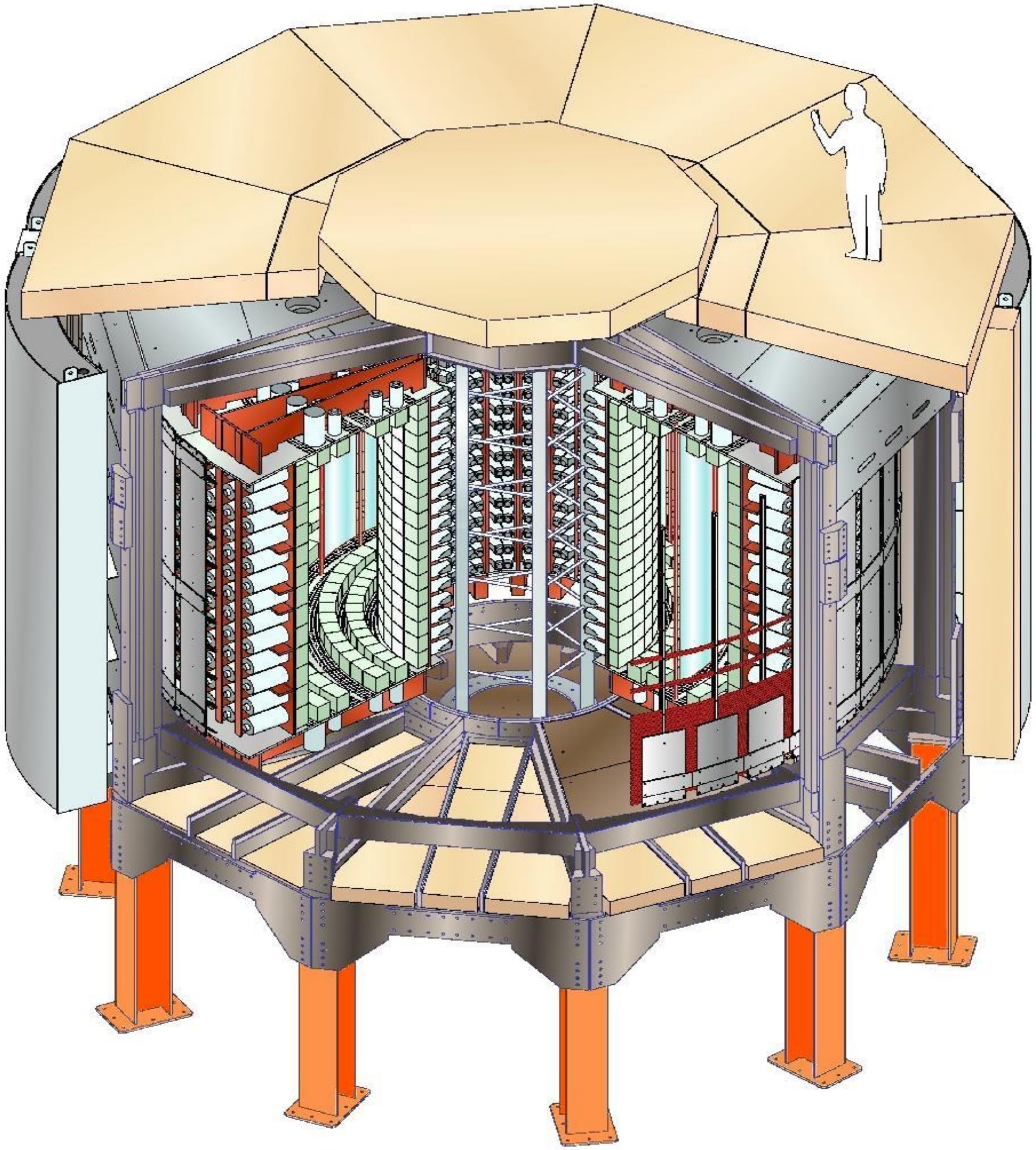
Drift wire chamber in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

The NEMO3 detector



Source:

10kg of ββ isotopes: ^{100}Mo (7kg), ^{82}Se (1kg)
+ smaller quantities of ^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd

Tracking detector:

Drift wire chamber in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: Borated water (30cm, wall)
\+ wood (40 cm, top and bottom)

Modane Underground Laboratory: 4800 m.w.e.

The NEMO3 detector

Modane Underground Laboratory: 4800 m.w.e.

Source:
10kg of ββ isotopes: ^{100}Mo (7kg), ^{82}Se (1kg)
+ smaller quantities of ^{130}Te, ^{116}Cd, ^{48}Ca, ^{96}Zr, ^{150}Nd

Tracking detector:
Drift wire chamber in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:
1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: Borated water (30cm, wall)
+ wood (40 cm, top and bottom)

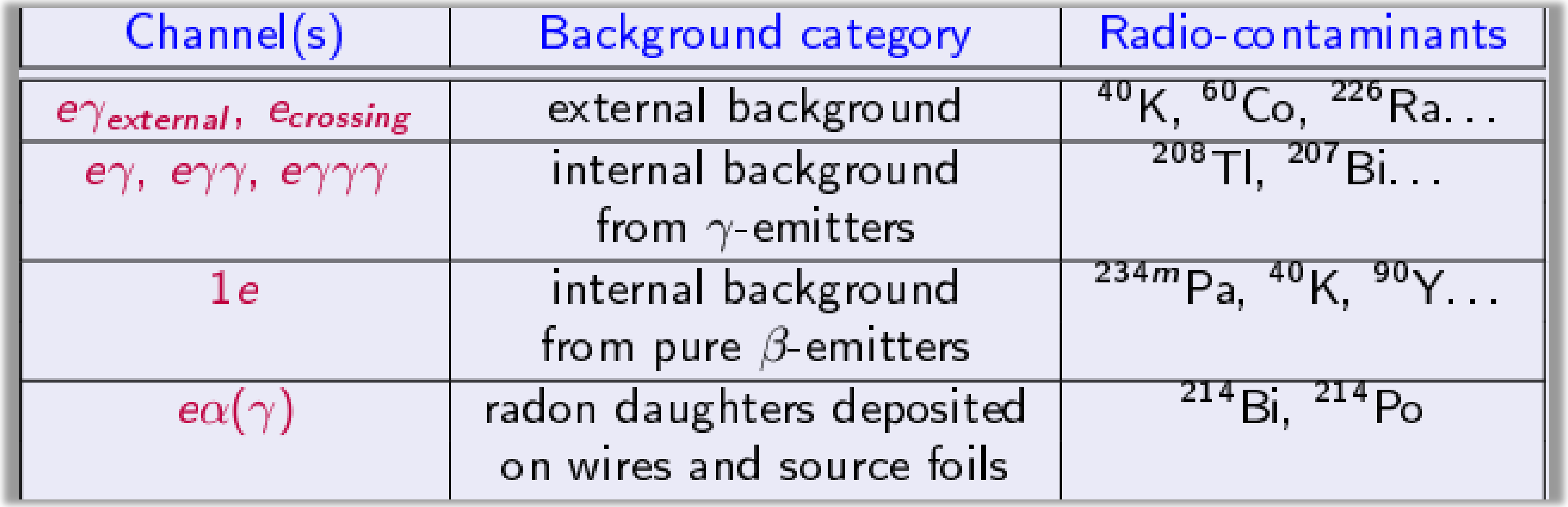
Radon-free air around the detector
- Phase I (Feb 2003 - Oct. 2004): High Radon
- Phase II (Dec 2004 - Now): Low Radon

(Radon cont. reduced by factor 6)

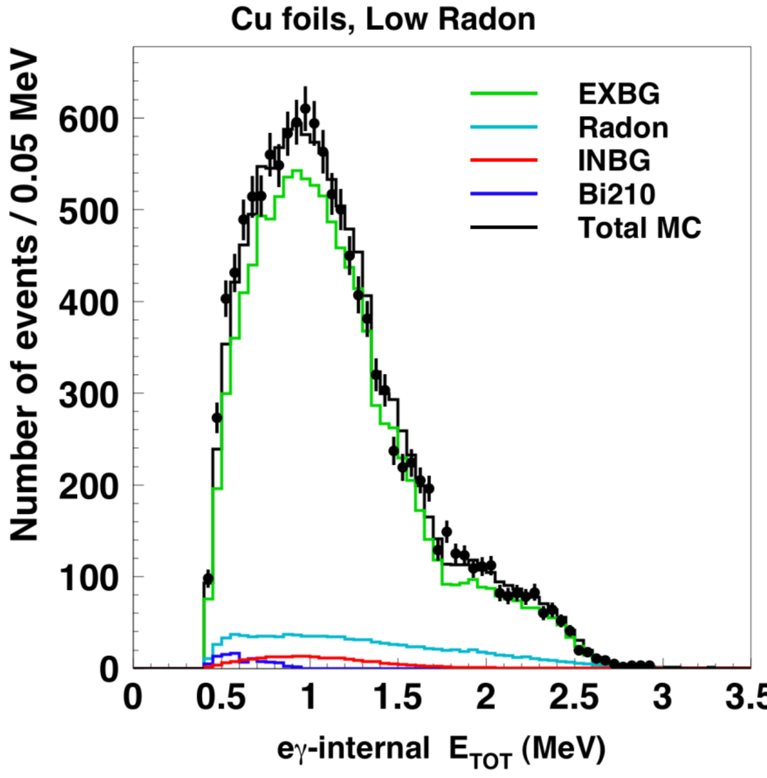
NEMO3 Results

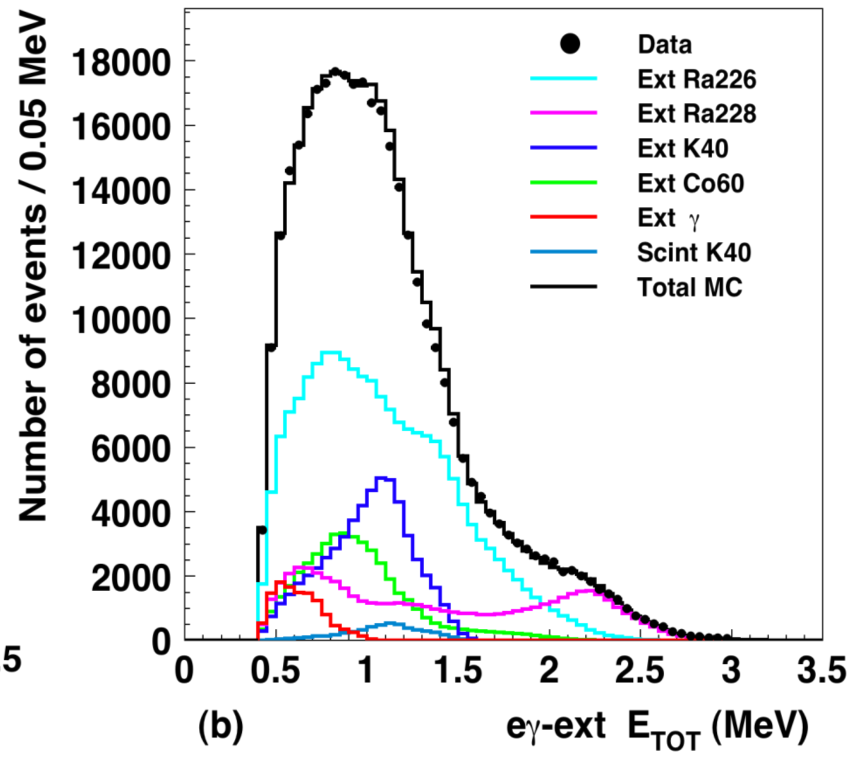
Background mesurements

Measurement of ALL background components in independent channels:



Channel(s)	Background category	Radio-contaminants
$e\gamma_{external}$, $e_{crossing}$	external background	^{40}K, ^{60}Co, ^{226}Ra...
$e\gamma$, $e\gamma\gamma$, $e\gamma\gamma\gamma$	internal background from γ-emitters	^{208}Tl, ^{207}Bi...
1e	internal background from pure β-emitters	^{234m}Pa, ^{40}K, ^{90}Y...
$e\alpha(\gamma)$	radon daughters deposited on wires and source foils	^{214}Bi, ^{214}Po





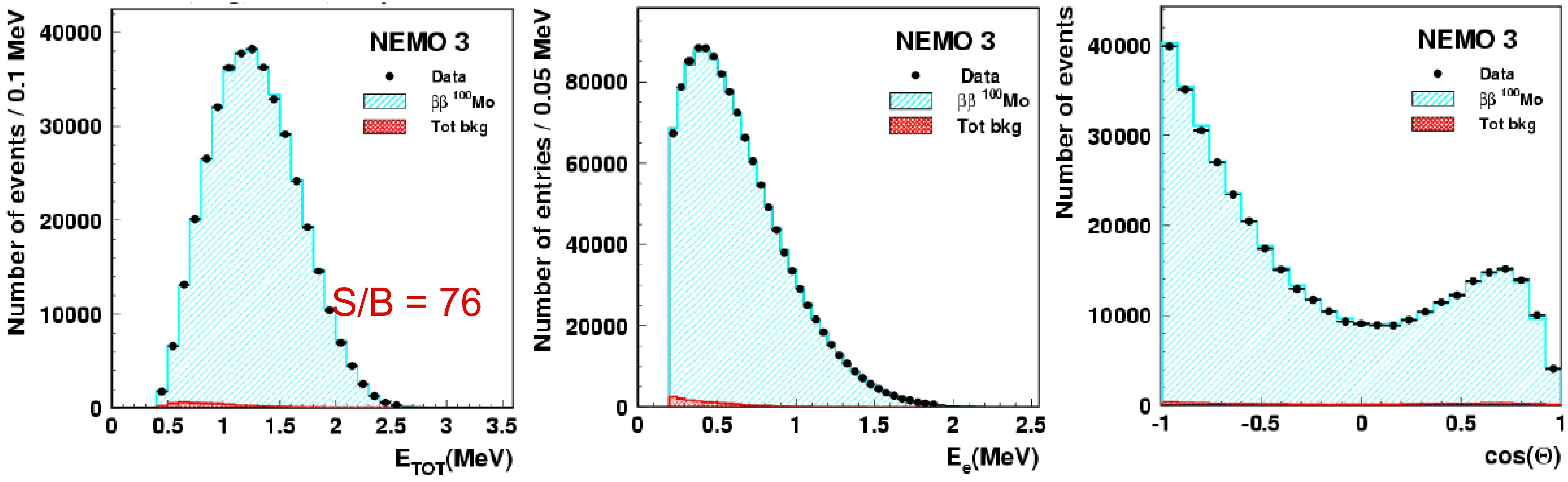
Can measure:

- Internal backgrounds in foils,
- external backgrounds from detector components,
- radon in gas,
- cross check with Cu control foils.

NIM A606 (2009) 449-465

$\beta\beta(2\nu)$ results ^{100}Mo (7kg)

~3.5 yr, Phase II (low Rn),

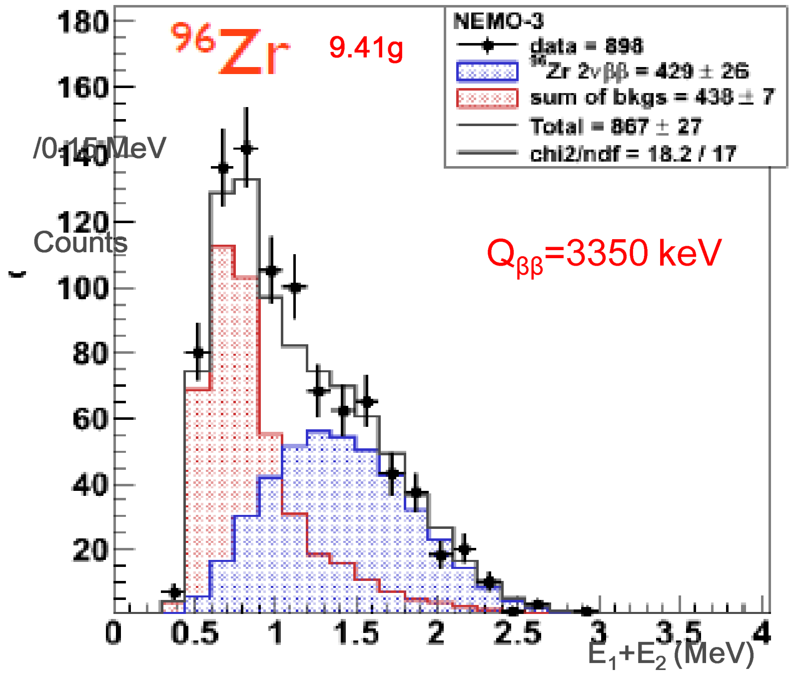


$T_{1/2}(2\nu)$ = [**7.17** ± 0.01(stat) ± 0.54(sys)] × **10^{18} yr**

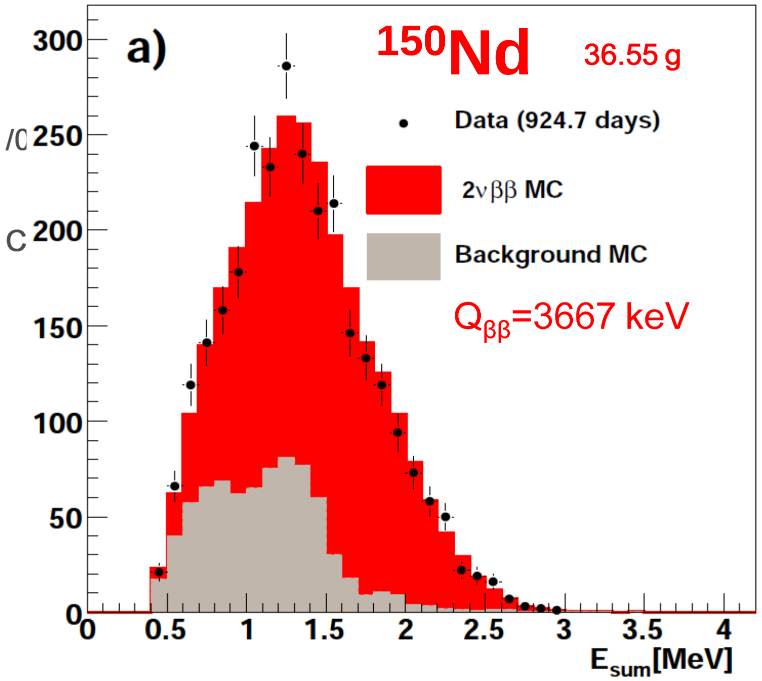
To be compared with earlier published in *PRL 95 (182302) 2005:*

$T_{1/2}(2\nu)$ = [7.11 ± 0.02(stat) ± 0.54(sys)] × 10^{18} yr (~1 yr, Phase I, S/B = 40)

ββ(2ν) results for other isotopes

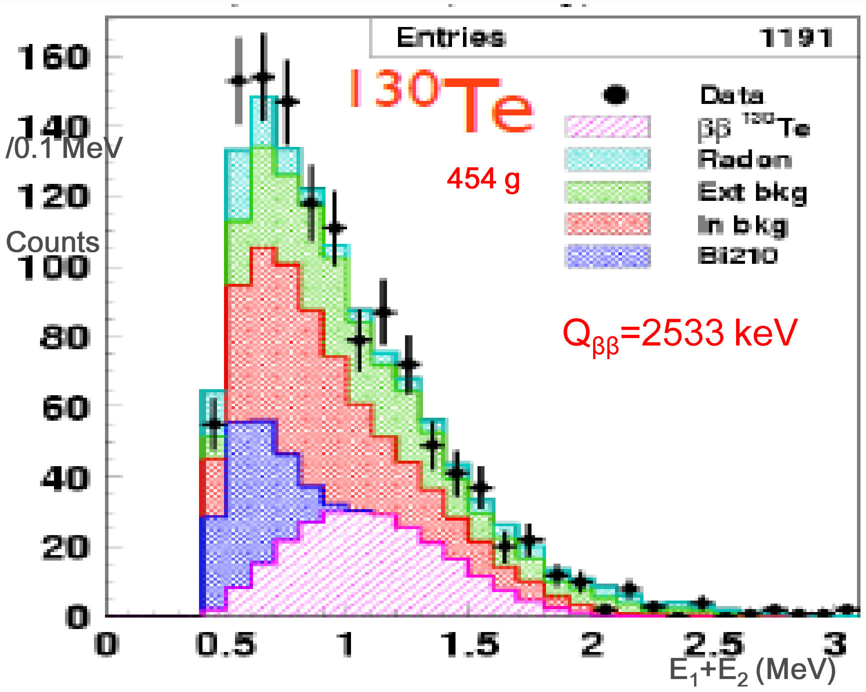


[2.35 ± 0.14(stat) ± 0.16(sys)]10^{19} yr

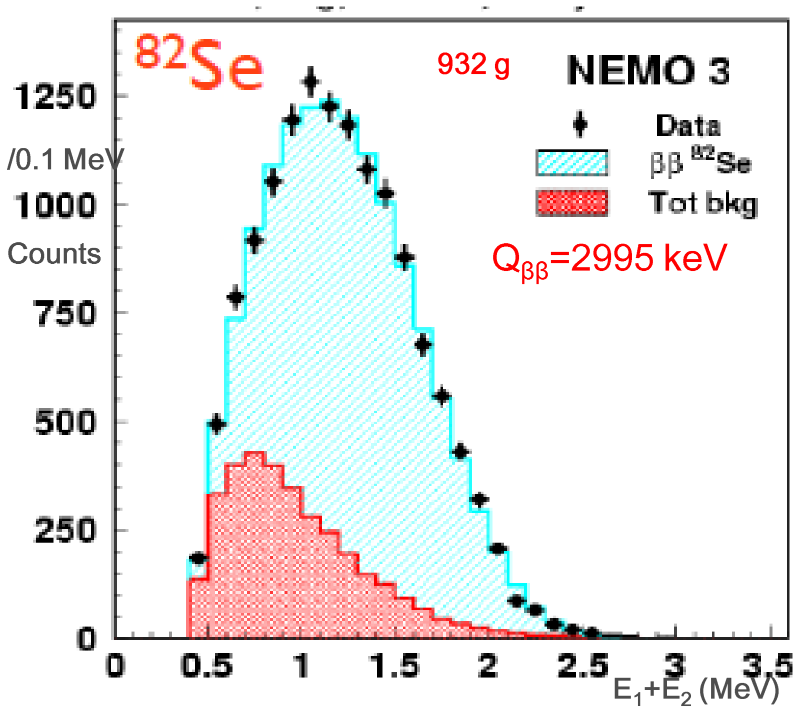


[9.11 $^{+0.25}_{-0.22}$(stat) ± 0.63(sys)]10^{18} yr

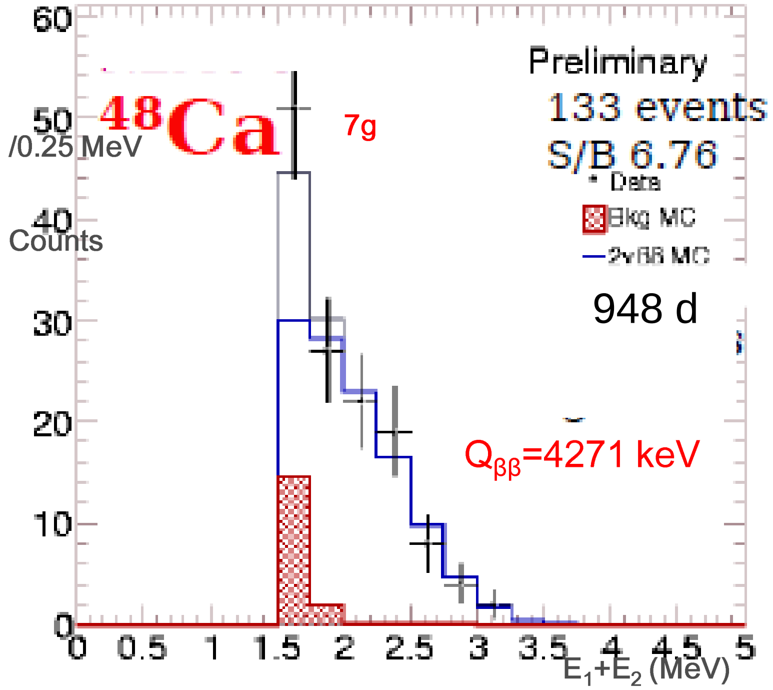
Phys.Rev.C80:032501,2009.



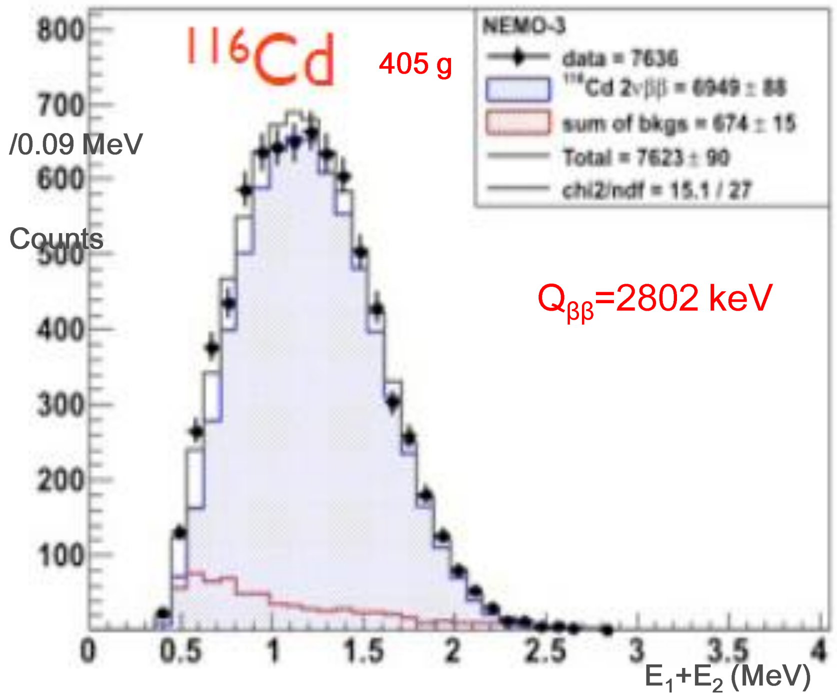
[7.0 $^{+1.0}_{-0.8}$(stat) $^{+1.1}_{-0.9}$(sys)]10^{20} yr



[9.6 ± 0.1(stat) ± 1.0(sys)]10^{19} yr



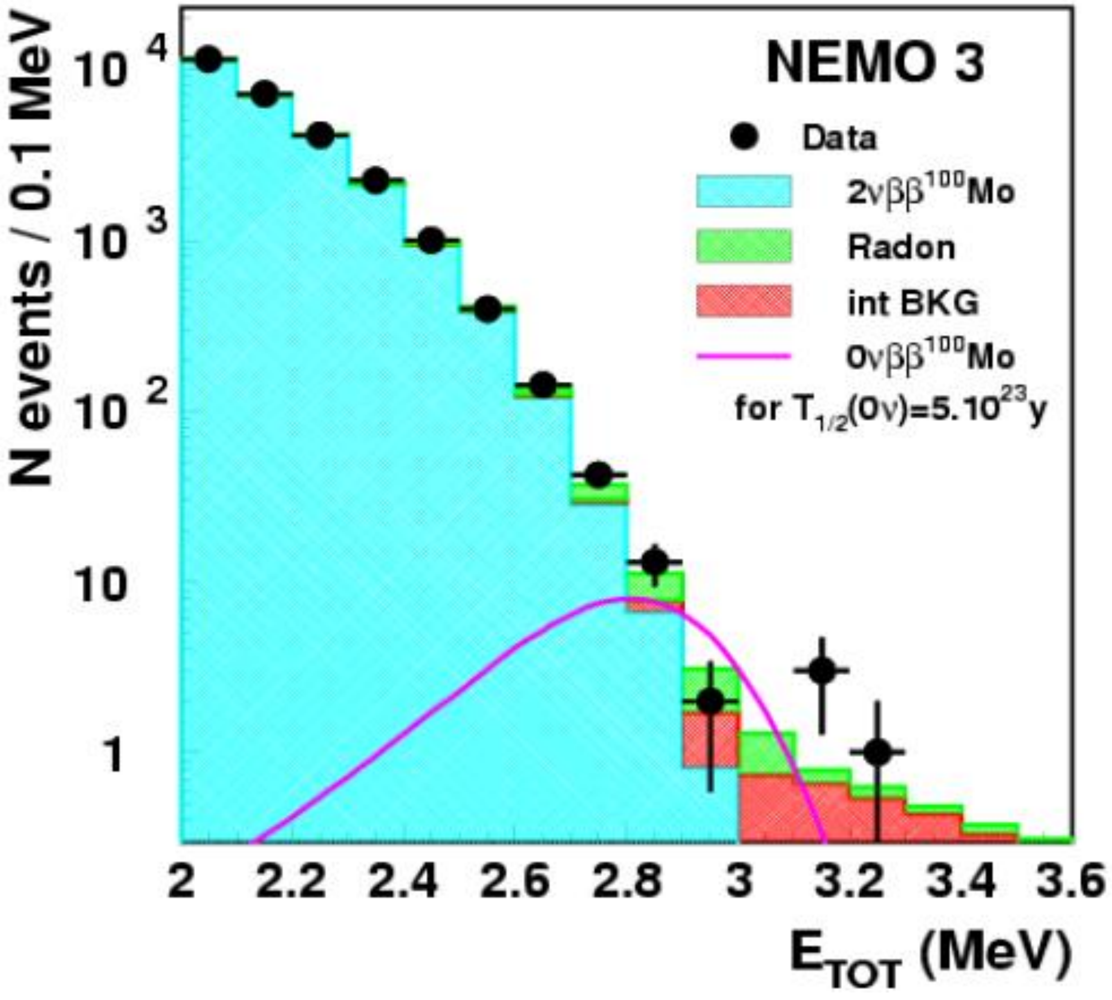
[4.4 $^{+0.5}_{-0.4}$(stat) ± 0.4(sys)]10^{19} yr



[2.88 ± 0.04(stat) ± 0.16(sys)]10^{19} yr

ββ(0ν) results ^{100}Mo (7 kg) and ^{82}Se (1kg)

^{100}Mo   7kg 4,5 y

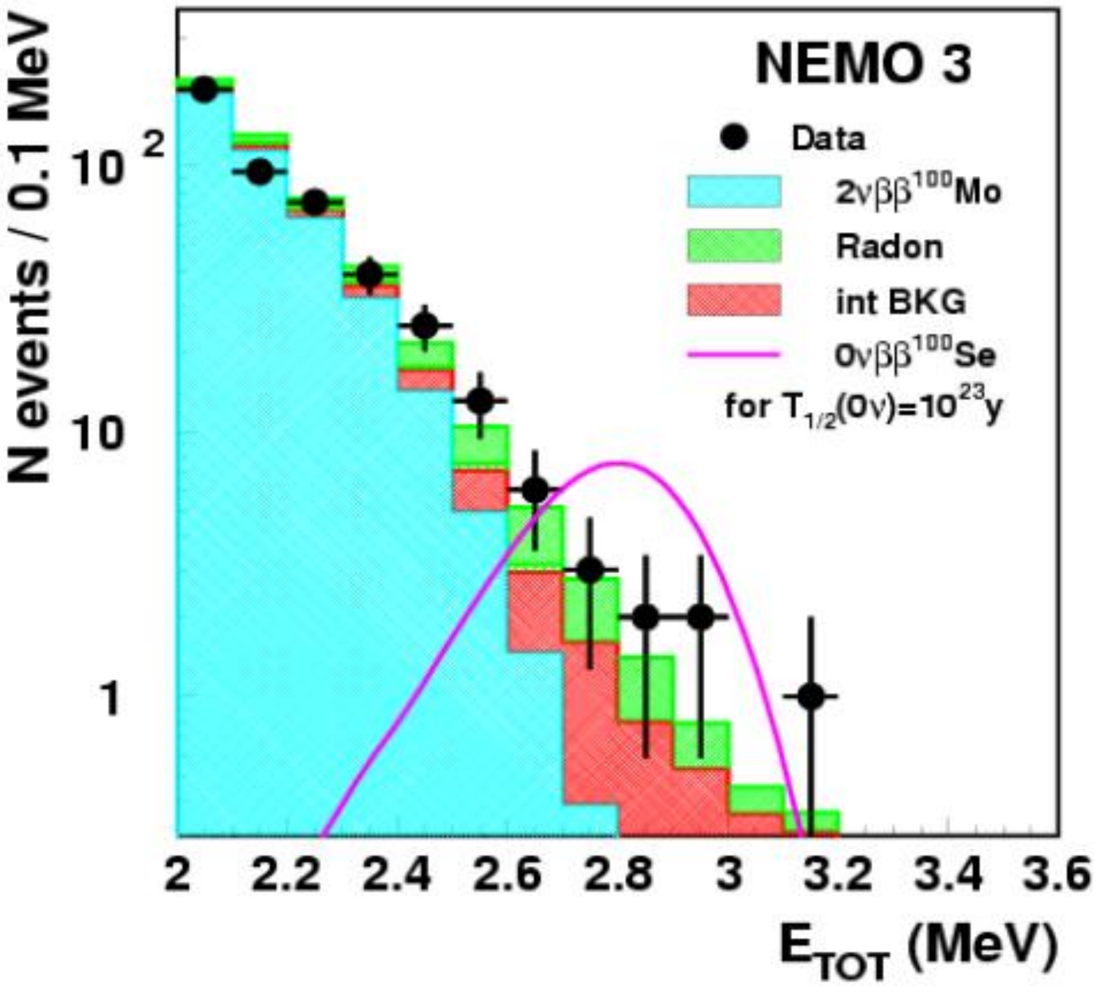


[2.8-3.2] MeV: DATA = 18; MC = 16.4±1.4

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

$\langle m_\nu \rangle < (0.47 - 0.96)$ eV *

^{82}Se   1kg 4,5 y



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

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

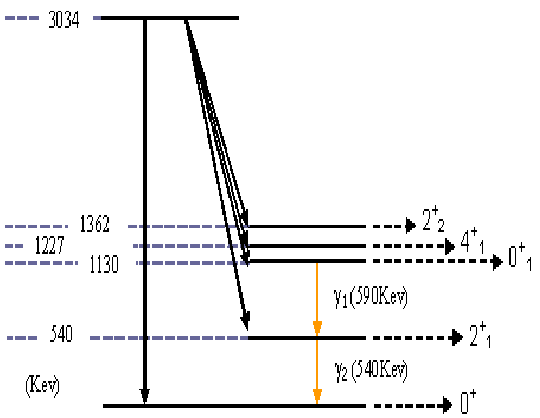
$\langle m_\nu \rangle < (0.94 - 2.5)$ eV *

(*) Using NME from: E. Caurier et al., PRL 100 (2008) 052503
Simkovic et al., PRC 77 (2008) 045503
Suhonnen et al., J. Mod. Phys E 17 (2008) 1)

Other results

Decays to Excited States

^{100}Mo



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

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

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

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

Nucl. Phys. A781 (2007) 209

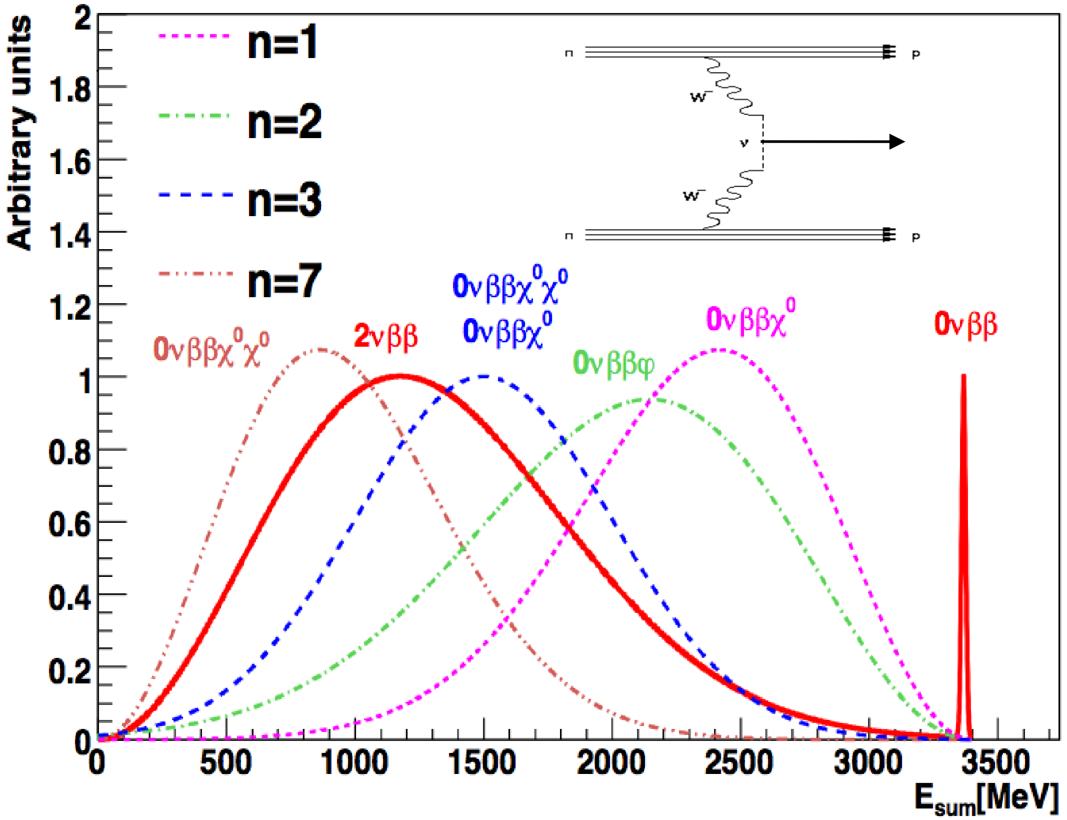
Right Handed Currents

^{100}Mo

V+A: $T_{1/2}(0\nu) > 5.4\times10^{23}$ yr   at 90%CL

$\langle\lambda\rangle < 1.4\times10^{-6}$

Majoron Emission



Spectral index	^{100}Mo	^{82}Se
$n=1$	$> 2.7 \times 10^{22}$	$> 1.5 \times 10^{22}$
$n=2$	$> 1.7 \times 10^{22}$	$> 6.0 \times 10^{21}$
$n=3$	$> 1.0 \times 10^{22}$	$> 3.1 \times 10^{21}$
$n=7$	$> 7 \times 10^{19}$	$> 5.0 \times 10^{20}$

Nucl. Phys. A765 (2006) 483

From NEMO3
to SuperNEMO

From NEMO3 to SuperNEMO

NEMO-3	R&D since 2006 →	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
$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y $<m_\nu> < 0.3 – 0.9$ eV *	Sensitivity	$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y $<m_\nu> < 0.04 - 0.11$ eV*

(*) Using NME from: E. Caurier et al., PRL 100 (2008) 052503
Simkovic et al., PRC 77 (2008) 045503
Suhonnen et al., J. Mod. Phys E 17 (2008) 1)

SuperNEMO

20 modules, each containing :

Source

~40 mg/cm^2 4 x 2.7 m^2

^{82}Se first choice : High $Q_{\beta\beta}$, long $T_{1/2}$(2v), proven enrichment technology

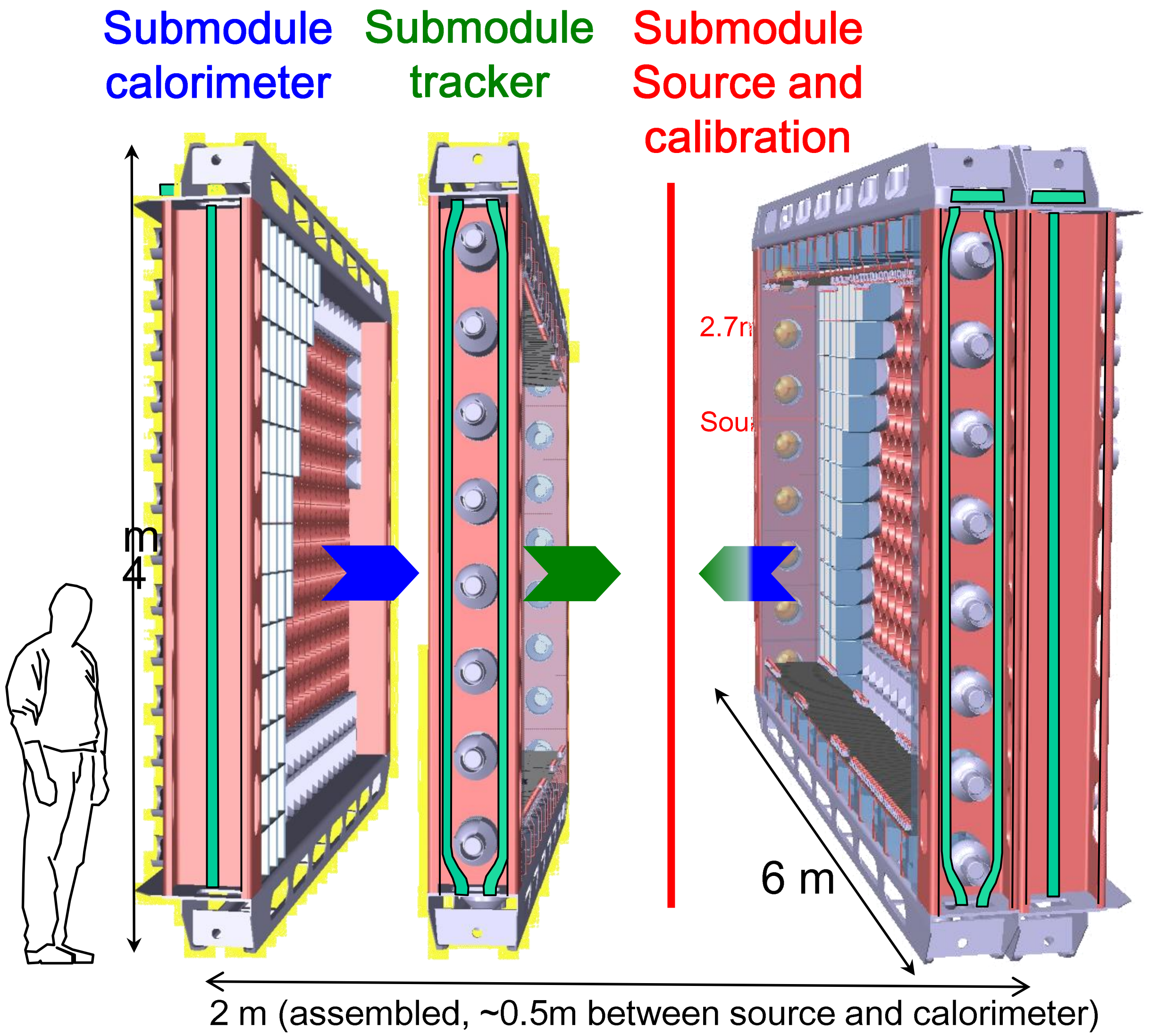
^{150}Nd, ^{48}Ca being looked at

Tracking :

drift chamber ~2000 cells in Geiger mode

Calorimeter:

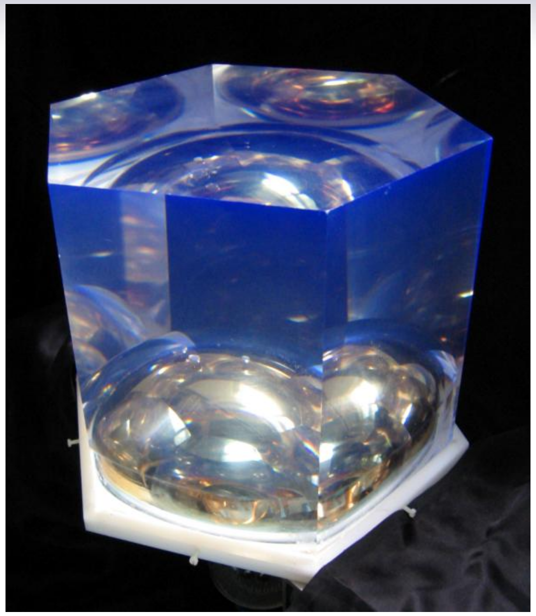
550 plastic scintillators coupled to PMTs



Planar geometry

Modules surrounded by water passive shielding

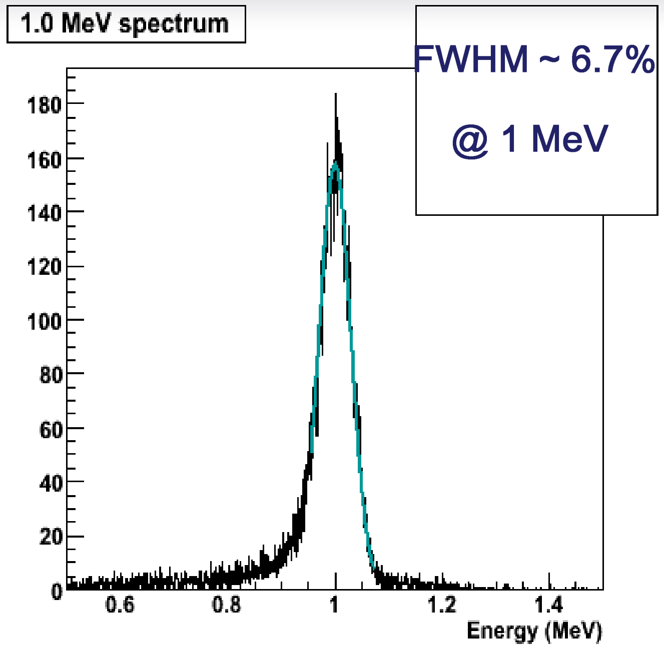
R&D



Calorimeter

Scintillator and PMt R&D :
Required resolution demonstrated
with 28cm Hex block (≥10cm thick) coupled to 8” PMT

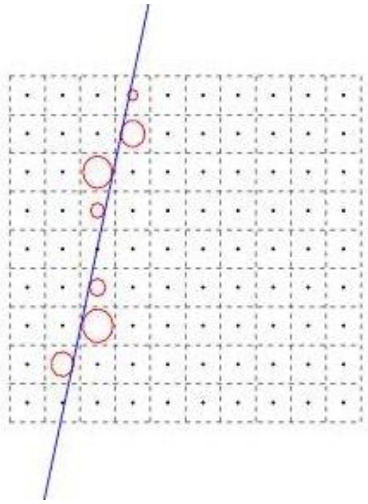
FWHM = 4% @ $Q_{\beta\beta}$ = 3 MeV



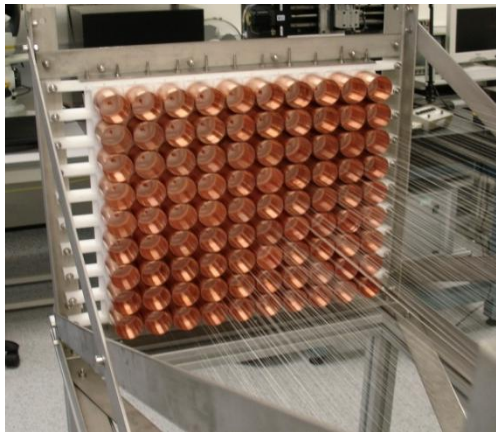
Tracker

Basic cell design developed and verified
Required performances demonstrated
using cosmic muon data.

$\sigma_T \sim 0.7\text{mm}$
$\sigma_L \sim 1\text{cm}$
$\varepsilon > 98\%$

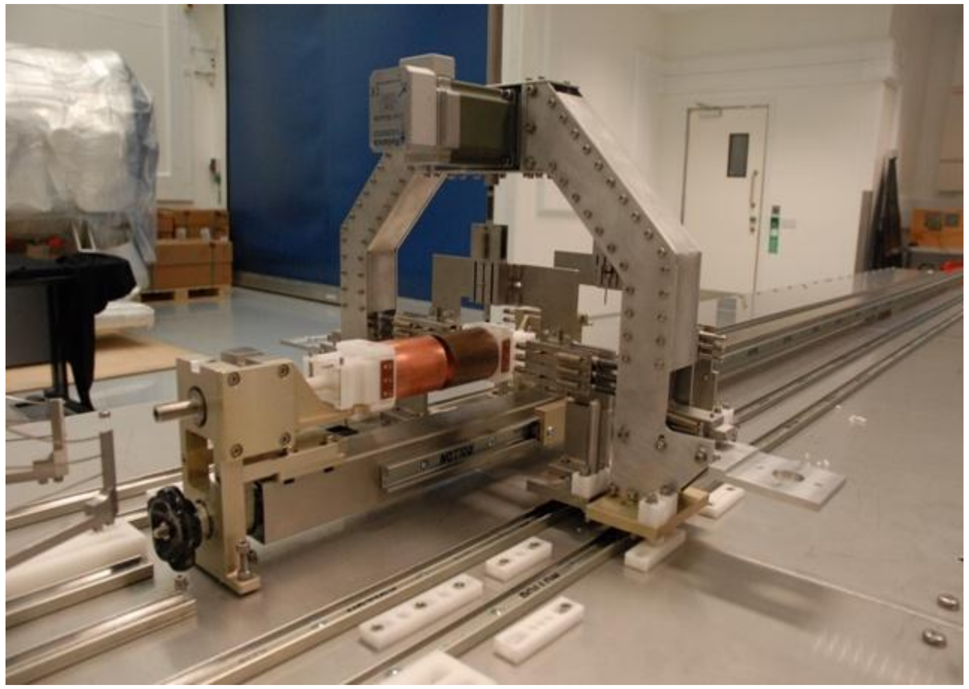


90- Cell prototype



Cells :
Radius: 44 mm
Length: 3.7 m

Robot for automatic wiring



R&D

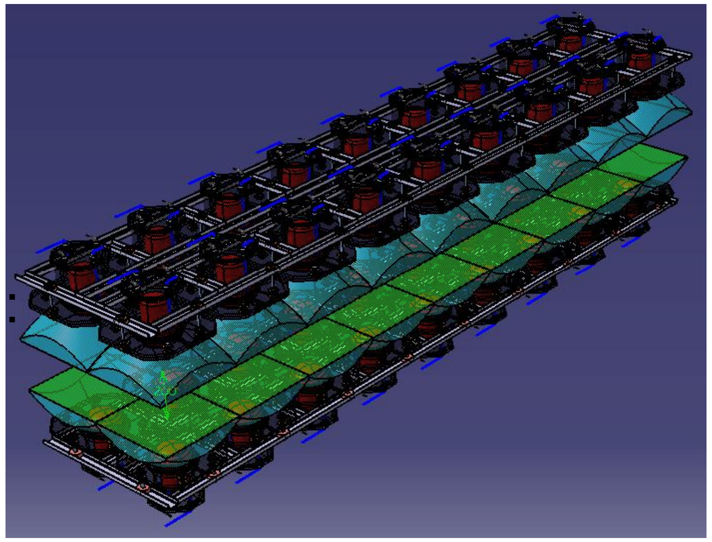
ββ source (^{82}Se)

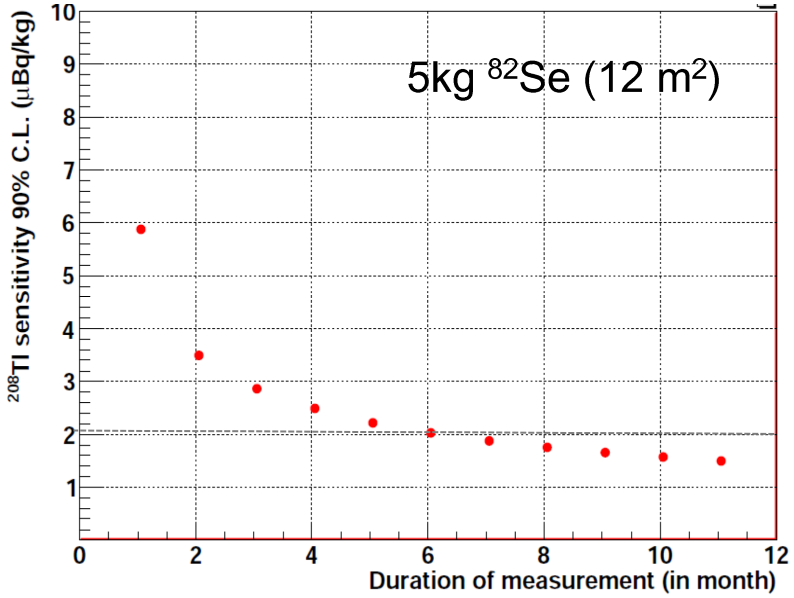
BiPo detector to measure foil radio-purity. *arXiv:1005.0343*

Enrichment:
100 kg by centrifugation is feasible

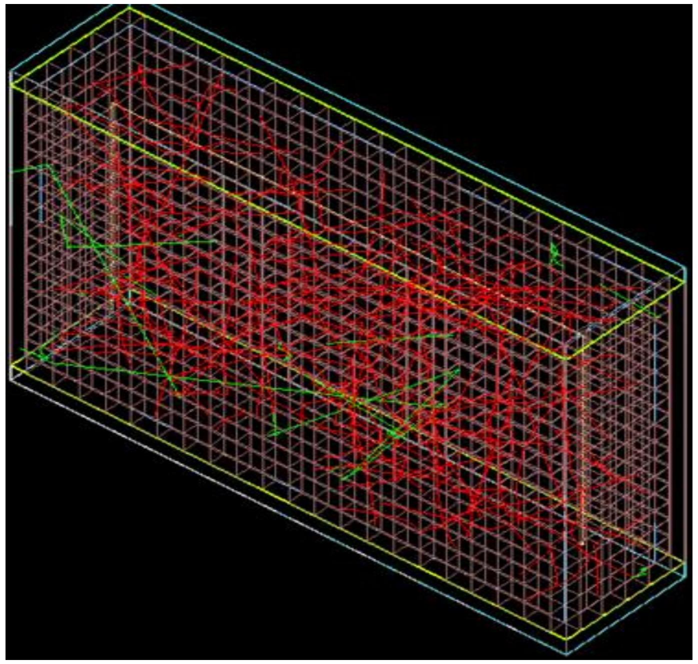
Radio-purity:
Chemical and physical purification tested for :
^{208}Tl < 2 µBq/kg,
^{214}Bi < 10 µBq/kg

Foil production: ~40 mg/cm^2 “composite” foil

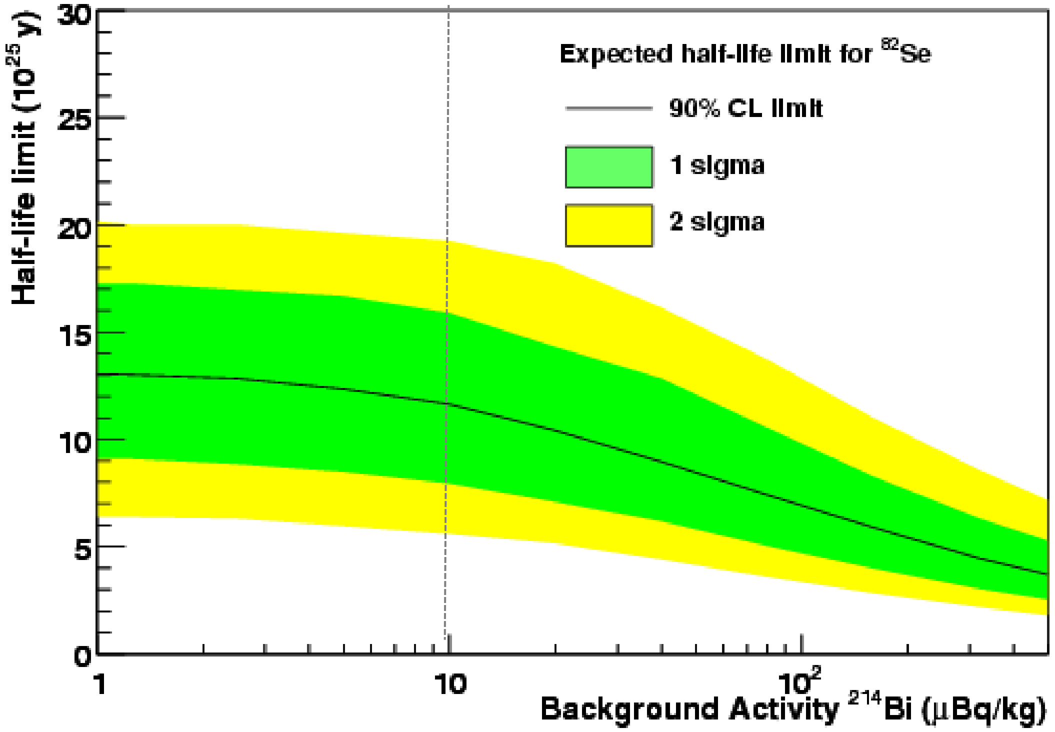




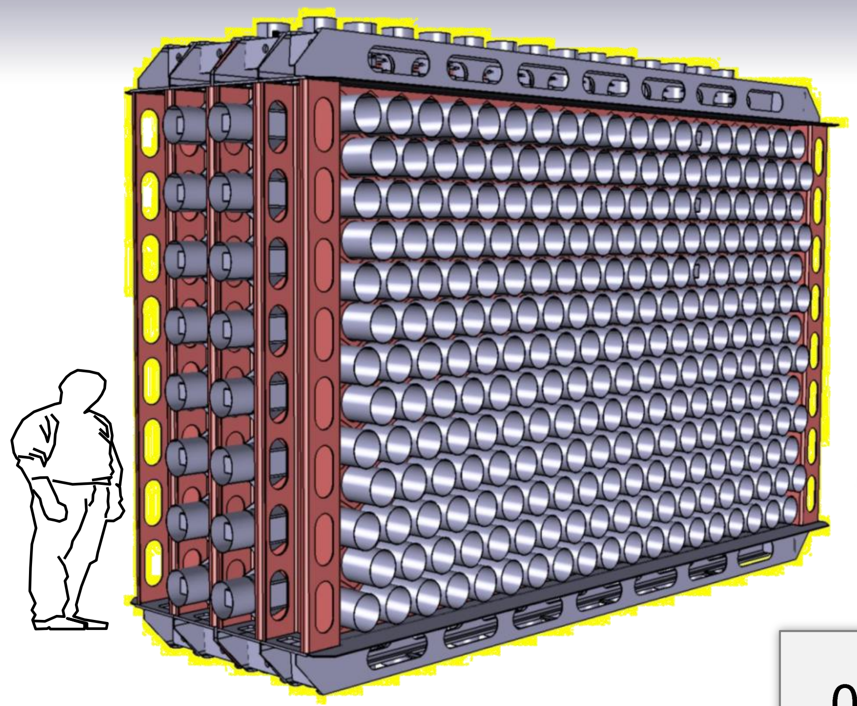
Simulation



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



SuperNEMO demonstrator



1 Super-module to:

- Confirm R&D results on large scale mass production
- Measure backgrounds especially from radon
- Produce a competitive physics measurement

0.3 expected bkg events in 2.8 - 3.2 MeV with 7kg of ^{82}Se in 2 yr

Sensitivity by 2015 : 6.5 10^{24} yr (90% CL)

Equivalent to 3 10^{25} yr for ^{76}Ge (using phase space ratio only)

or ~4 expected “golden events” if KK claim is correct

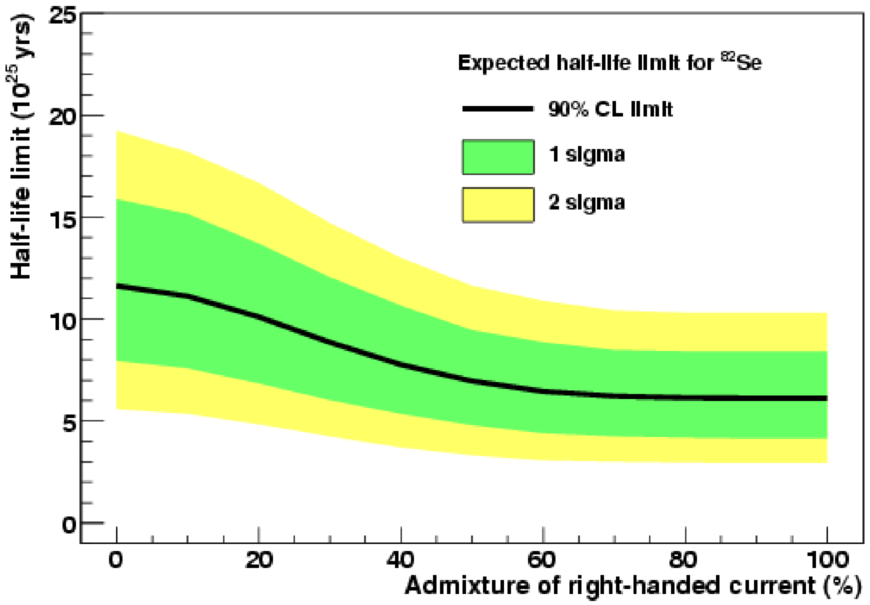
Full SuperNEMO

5 yr with 100kg of ^{82}Se

$T_{1/2} > 10^{26}$ yr, $<m_\nu> < 50$-100 meV at 90%CL

Probing new physics with $\beta\beta(0\nu)$ mechanism studies

arXiv:1005.1241



Schedule

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019

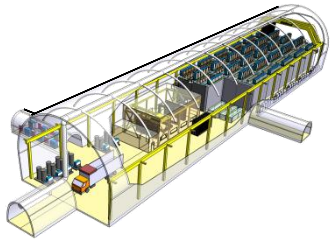
NEMO3 running

NEMO3 dismantled

SuperNEMO demonstrator construction

SuperNEMO demonstrator running:
7 kg ^{82}Se
$T_{1/2} > 6.5 \cdot 10^{24}$ y

Confirm Klapdor claim?



Full SuperNEMO construction:
-Likely to be located in new LSM Hall
Full Sensitivity by 2019
($m_\nu \sim 0.05$ eV)

Conclusions

- NEMO experiments use **tracking+calorimetry** technique
  - Full event reconstruction
  - Clear ββ event signature
  - Excellent background rejection
  - New physics studies using event topology

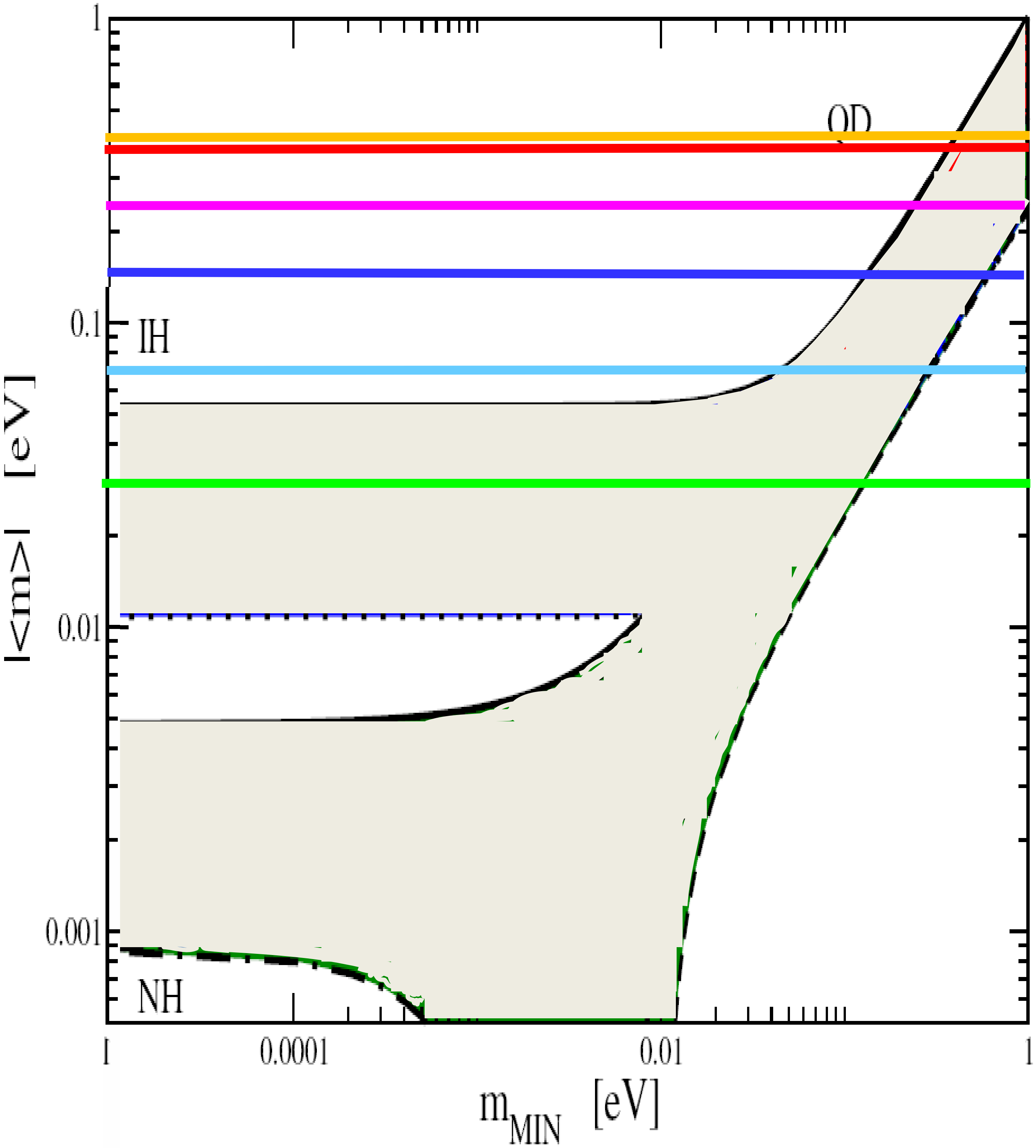
- **NEMO3** is a running 2νββ **factory**
  - $T_{1/2}(2\nu) = [7.17 \pm 0.01(stat) \pm 0.54(sys)] \times 10^{18}$ yr in ^{100}Mo
  - 7 isotopes studied
- NEMO3 provides **competitive 0νββ limits**
  - $T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL ($<m_\nu> < (0.47 - 0.96)$ eV) in ^{100}Mo

- **SuperNEMO** is next generation experiment
  - **R&D** objectives **reached**
  - Demonstrator module sensitive to Klapdor claim by 2015
  - Full detector sensitivity by 2019 : $T_{1/2} > 10^{26}$ yr, $<m_\nu> < 50\text{-}100$ meV at 90%CL
  - Possibility to probe **0νββ mechanism**

BACK-UP

<mν> : state of the art

$$< m_\nu > = \left|\sum_i U_{ei} m_i\right| = \left|\cos^2\theta_{13} \quad m_1 \cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12} \quad + m_3 e^{2i\beta}\sin^2\theta_{13}\right|$$

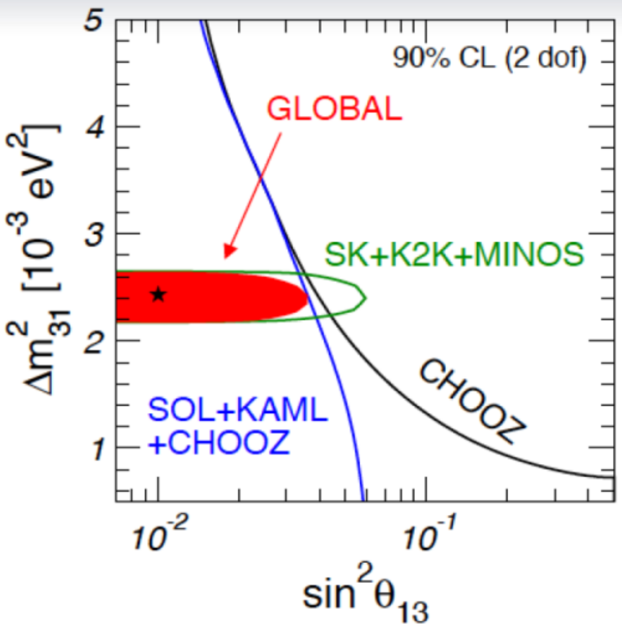


HM CLAIM Ge (2000)
NEMO 3 (running)
CUORICINO bolometersTe (2008)
~ 10 kg

GERDA I Ge (2010) & II
15-40 kg

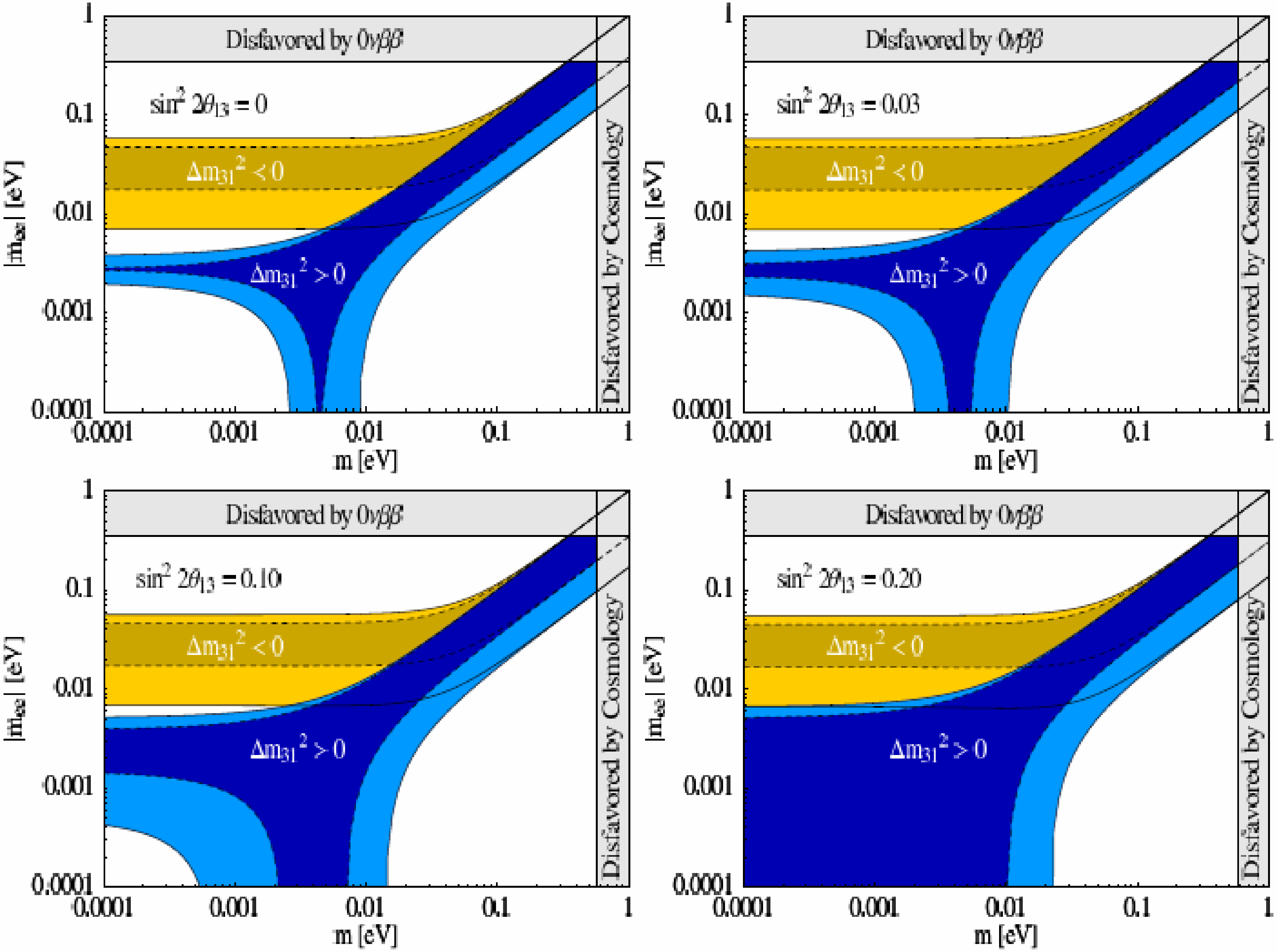
SuperNEMO Se
CUORE Te
EXO Xe
GERDA - MAJORANA Ge
100 kg

$<m_\nu>$ and θ_{13}



$\sin^2 2\theta_{13}$ <~ 0.05

A. Merle, and W. Rodejohann Phys. Rev. D 73, 073012 (2006)



Best fit and 3σ ranges of the oscillation parameters

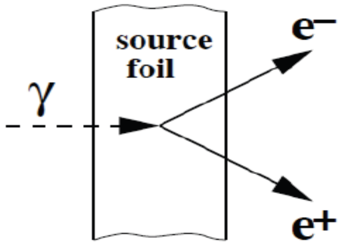
NEMO3 backgrounds for ββ(0ν)

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

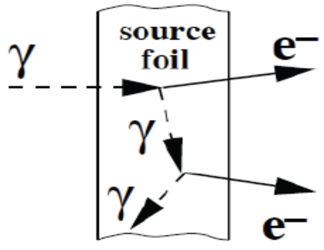
Natural radioactivity of the detector or neutrons

Main bkg for ββ(2ν) but negligeable for ββ(0ν)

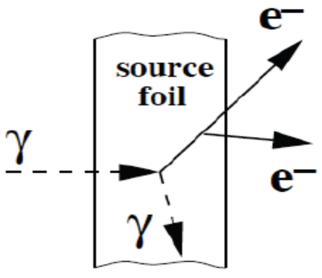
(^{100}Mo and ^{82}Se $Q_{\beta\beta}$~ 3 MeV > Eγ(^{208}Tl) ~ 2.6 MeV)



pair creation



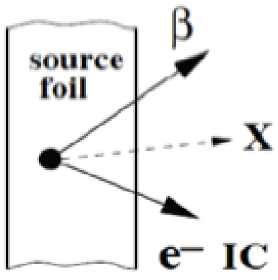
Compton + Compton



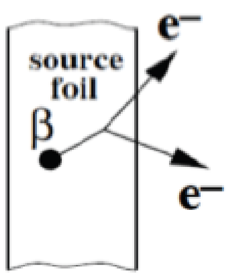
Compton + Möller

- **^{232}Th (^{208}Tl) and ^{238}U (^{214}Bi)**

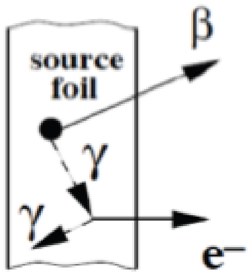
contaminations inside the ββ source foil



beta + IC



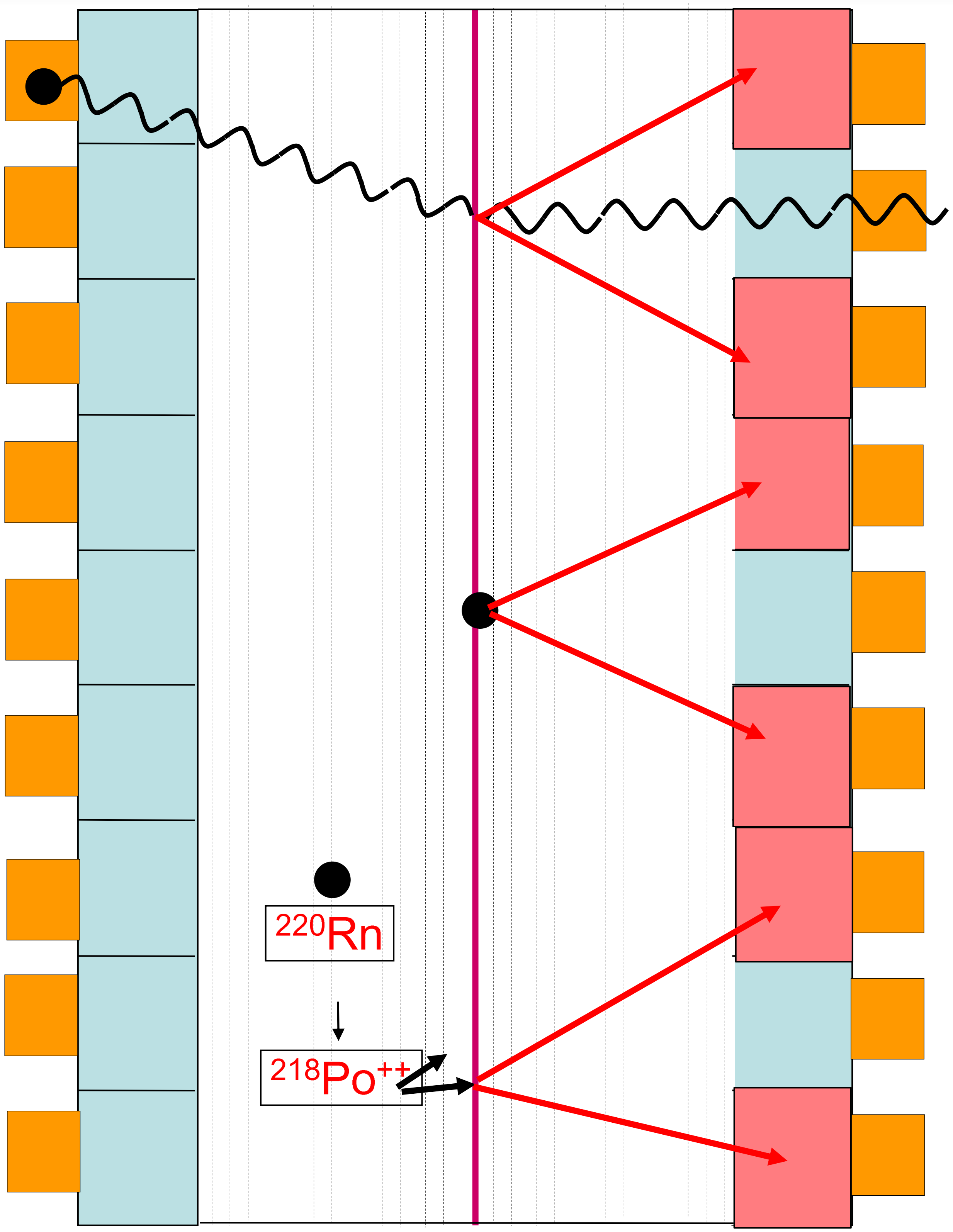
beta + Möller



beta + Compton

- **Radon (^{214}Bi)**

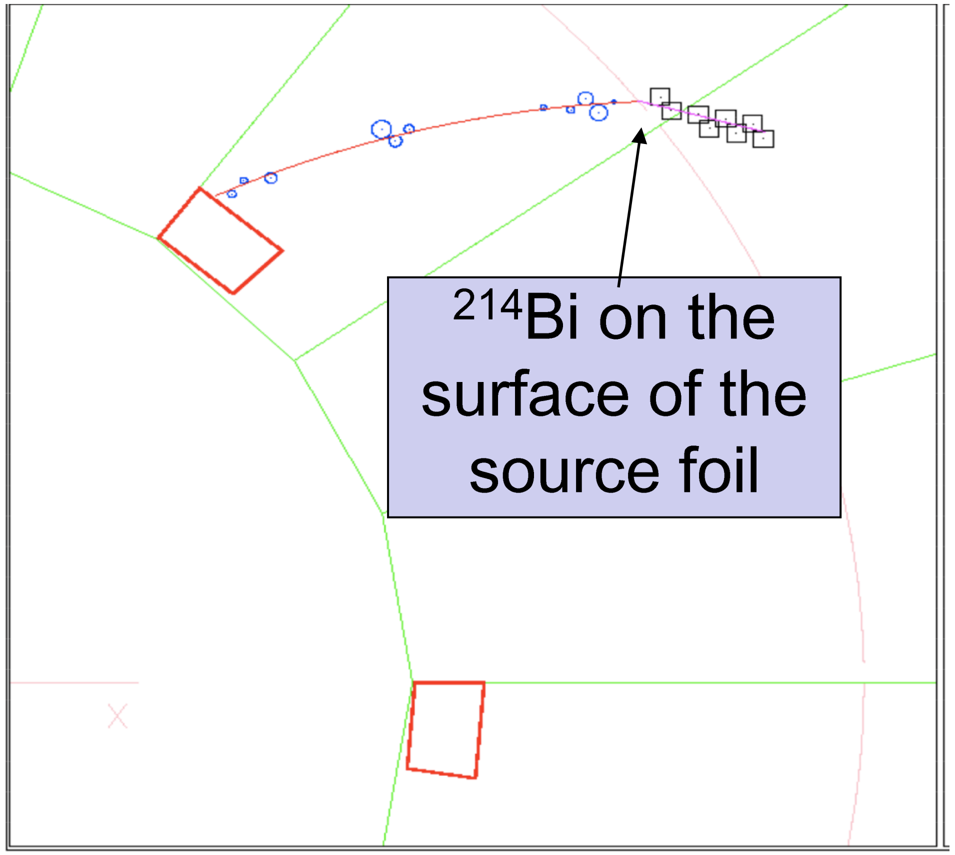
  - deposits on the wire near the ββ foil
  - deposits on the surface of the ββ foil



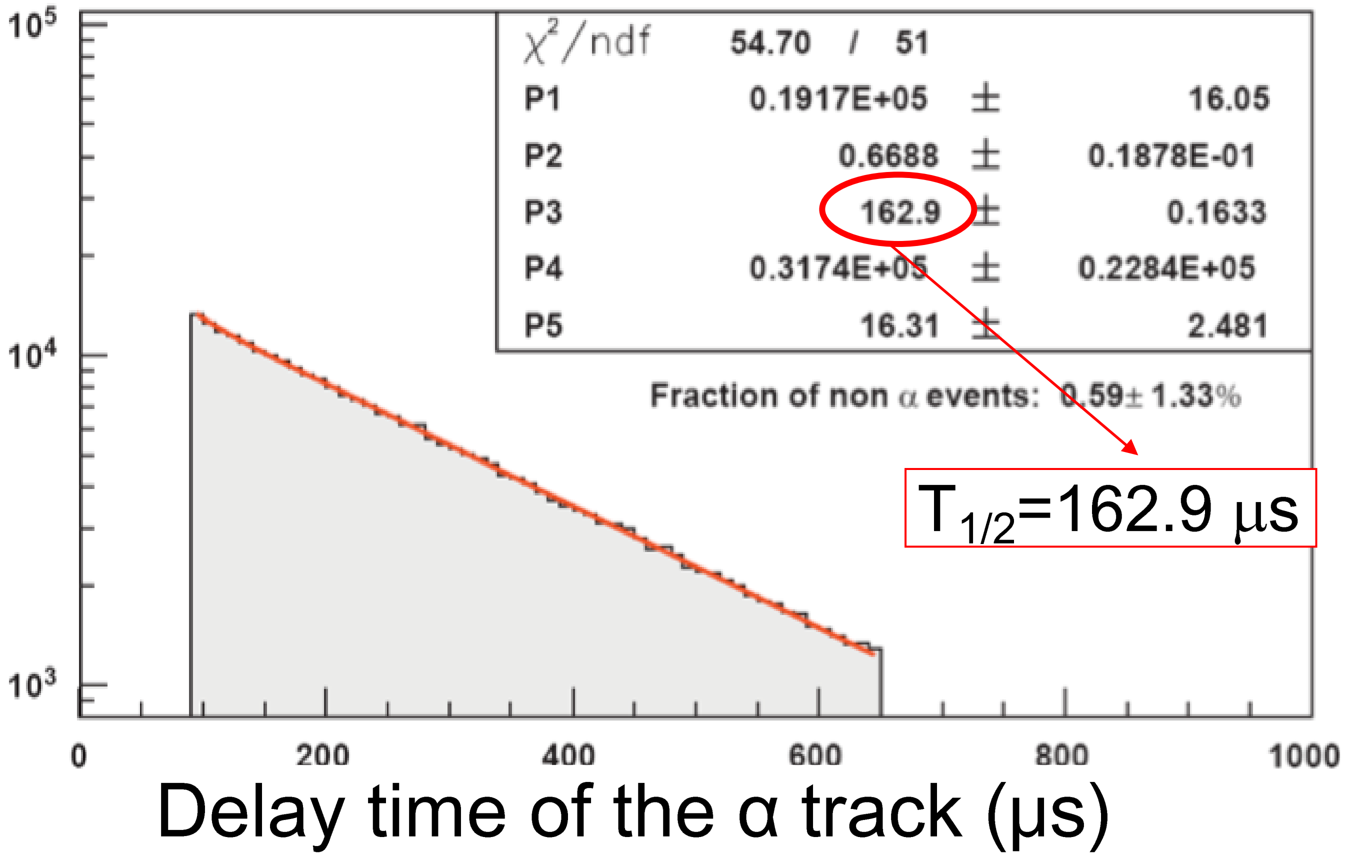
Measurement of the Radon background

$$^{214}\mathrm{Bi} \xrightarrow{\beta} {}^{214}\mathrm{Po} \xrightarrow{\alpha} {}^{210}\mathrm{Pb}$$

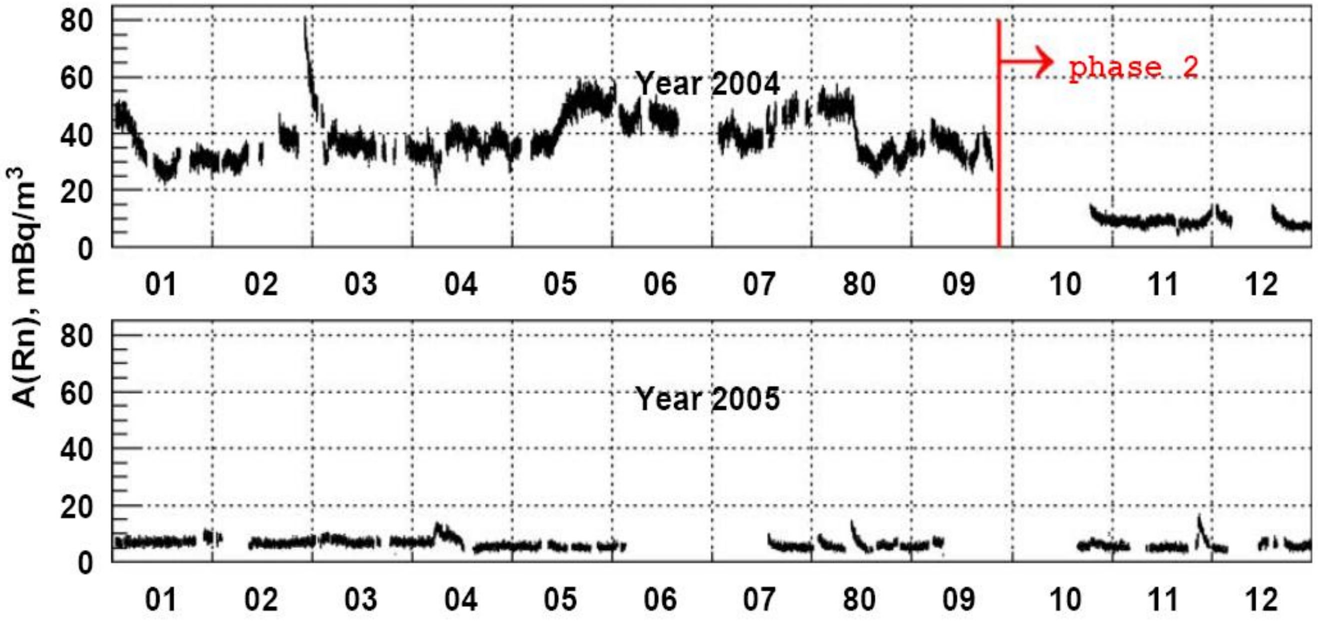
(164 μs)



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

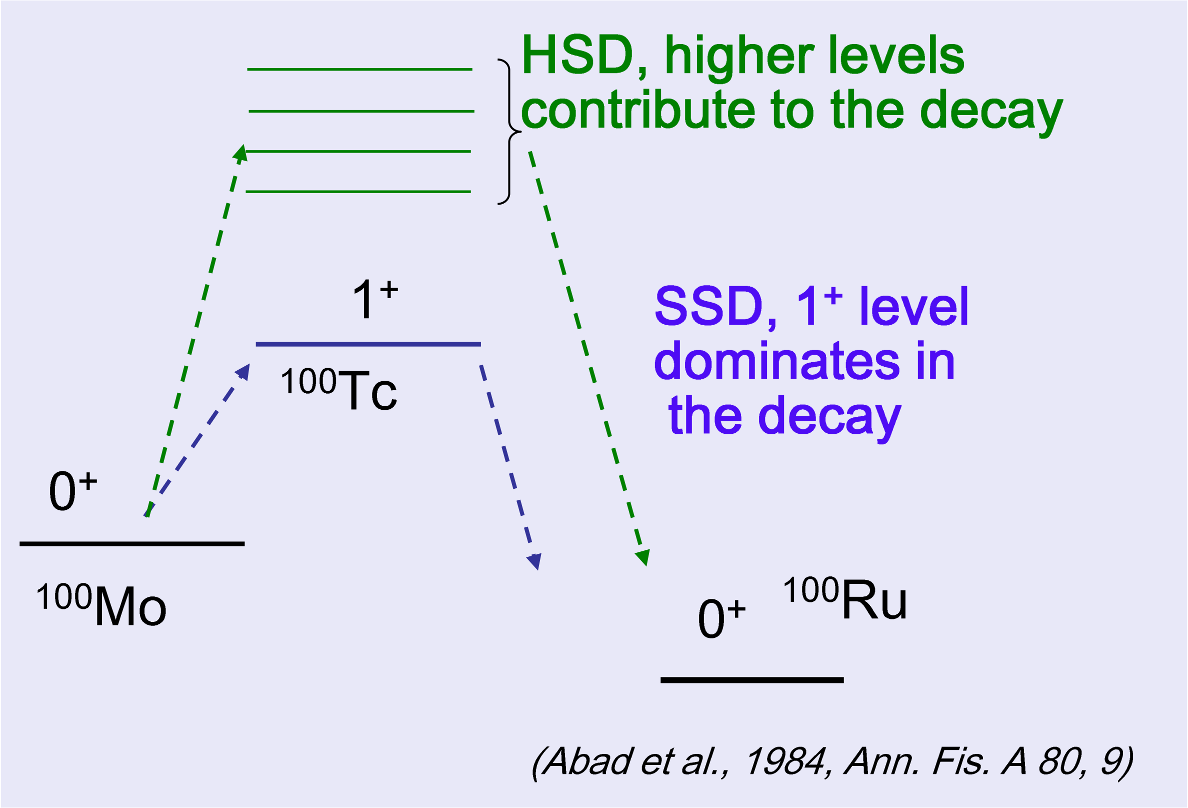


Monitoring of the Radon bkg every day

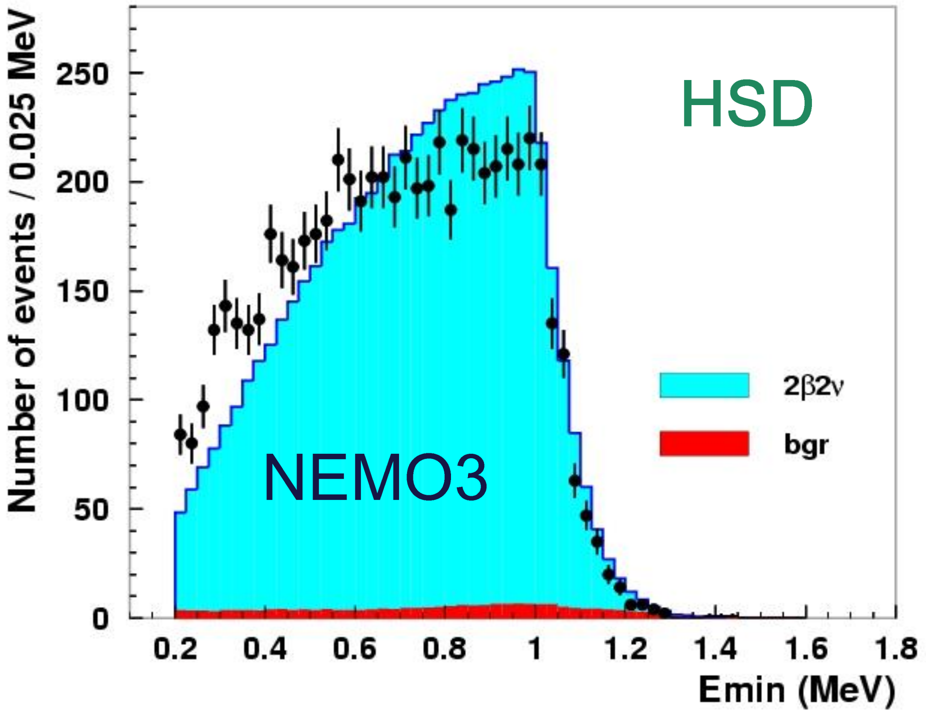


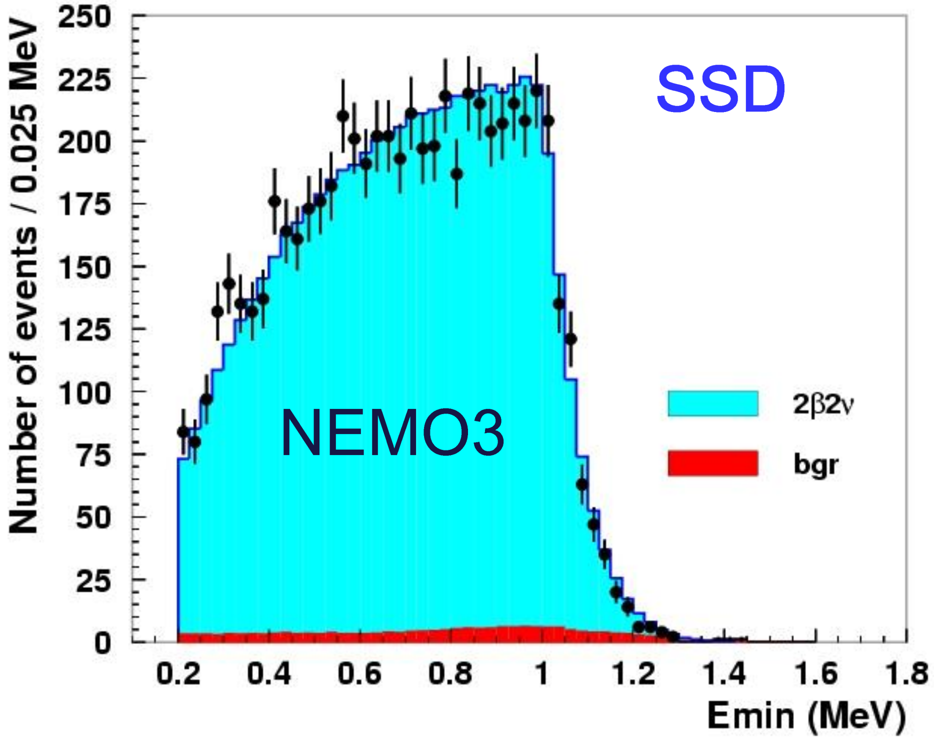
- Phase 1: Feb. 2003 → Sept. 2004
  Radon Contamination
- Phase 2: Dec. 2004 → Today
  A (Radon) ≈ 5 mBq/m^3

ββ(2ν) of ^{100}Mo : SSD or HSD ?



(Abad et al., 1984, Ann. Fis. A 80, 9)

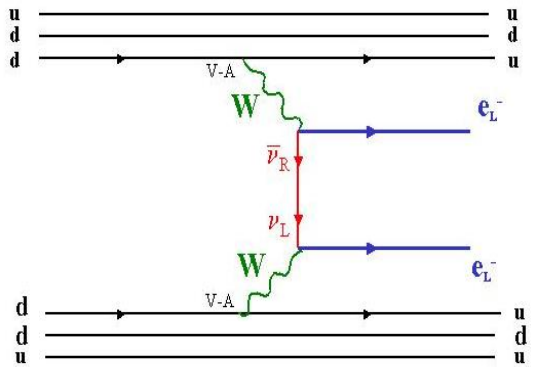




SSD mechanism established from ^{100}Mo single e^- spectra

Some $\beta\beta(0\nu)$ mechanisms

MM



$T_{1/2}^{-1} = F(Q_{bb}^5, Z)\, |M|^2 \langle m_\nu \rangle^2$

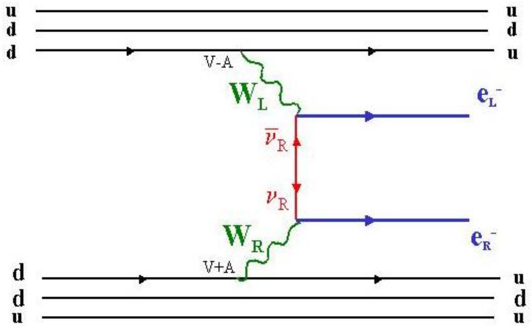
NEMO3 : $\langle m_\nu \rangle < (0.47\text{-}0.96)$ eV

$\langle m_\nu \rangle$

$= m_1|U_{e1}|^2 + m_2|U_{e2}|^2.e^{ia1} + m_3|U_{e3}|^2.e^{ia2}$

Uei|: mixing matrix element
a1 et a2: Majorana phase

RHC



$T^{0\nu}_{1/2}{}^{-1} = C \langle \lambda \rangle^2$

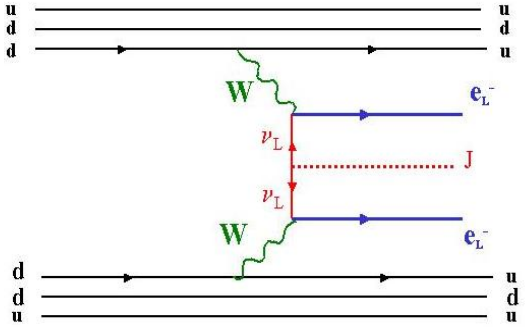
NEMO3 : $\langle \lambda \rangle < 1.4\times10^{-6}$

$\langle \lambda \rangle$

Coupling between right lepton and left quarks

$\langle \lambda \rangle \neq \lambda \approx (M_{WL}/M_{WR})^2 \approx 2\ 10^{-3}$ pour $m_{WR} = 1{,}8$ TeV
Depends on mixing matrix elements of right neutrinos

Majoron



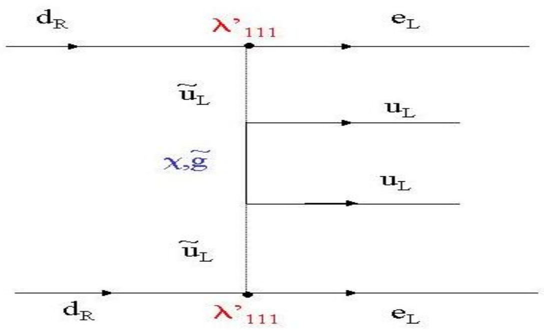
$T_{1/2}^{-1} = C \langle g_M \rangle^2$

NEMO3 : $\langle g_M \rangle < 0.5\times10^{-4}$

$\langle g_M \rangle$

Coupling between Majoron and neutrinos

SUSY



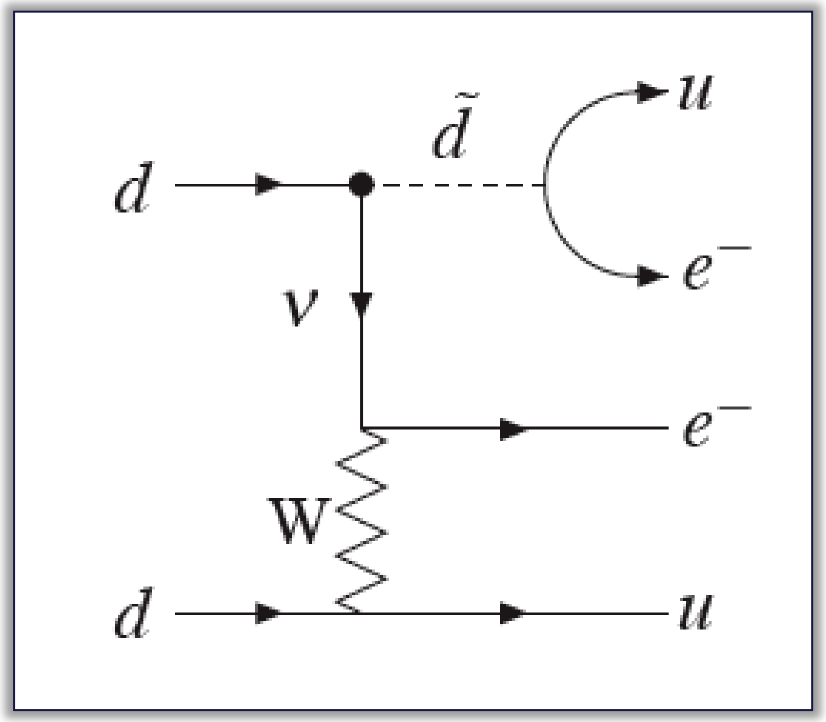
R-parity violation
$T_{1/2}$ depends on λ'_{111}, gluino and squarks mass

$\lambda'_{111}, \lambda'_{113}, \lambda_{131}, \ldots..$

$\beta\beta(0\nu)$ from Rp violating - SUSY

A. Faessler, Th. Gutsche, S. Kovalenko, F. Simkovic, Phys. Rev. D77 (2008) 113012

$$W_{\not{R}_p} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k + \kappa^iL_iH_2$$



$$\boxed{\frac{1}{T_{1/2}} = G_{01}|M_h^{\tilde{q}}|^2|\eta^{11}_{(q)LR}|^2}$$

phase space NME SUSY LNV parameter:

$$\eta^{nj}_{(q)LR} = \sum_k \frac{\boxed{\lambda'_{j1k}\lambda'_{nk1}}}{2\sqrt{2}G_F}\sin 2\theta^d_{(k)}\left(\frac{1}{m^2_{\tilde{d}_1(k)}} - \frac{1}{m^2_{\tilde{d}_2(k)}}\right)$$

Limits on trilinear RPV couplings $\lambda'_{11k}\lambda'_{1k1}$ (k = 1,2,3):

	$T_{1/2}$	$\eta^{11}(q)_{LR}$ **	$\lambda'_{111}\,\lambda'_{111}$ **	$\lambda'_{112}\,\lambda'_{121}$ **	$\lambda'_{113}\,\lambda'_{131}$ **
Mo	$> 10^{24}$	$< 6.4\times10^{-9}$	$< 1.2\times10^{-5}$	$< 6.1\times10^{-7}$	$< 2.5\times10^{-8}$

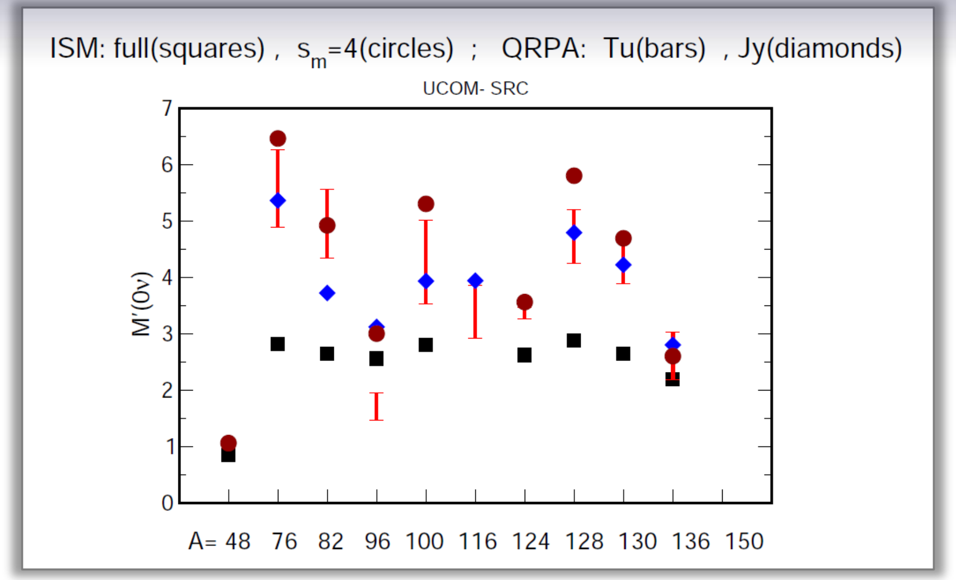
** ***Phys. Rev. D77 (2008) 113012***

^{82}Se, ^{150}Nd or ^{48}Ca ?

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

$$T_{1/2}(90\%CL) > N_A \frac{\varepsilon \ln 2}{A} \frac{M\,T}{Nexclu}$$

(***)arXiv:1006.5631v2



	^{82}Se	^{150}Nd	^{48}Ca	^{76}Ge
Qββ (keV)	2995	3667	4271	2040
$T^{2\nu}_{1/2}/T^{2\nu}_{1/2}$ Se		0.09	0.45	14.6
A/A$_{Se}$		1.82	0.58	0.92

Experimentaly

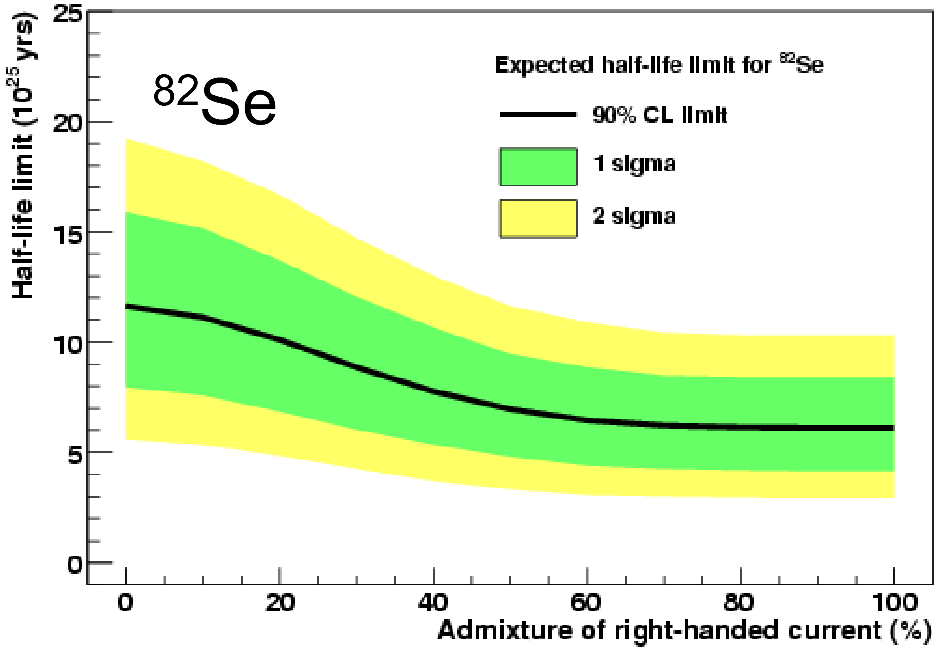
	^{82}Se	^{150}Nd	^{48}Ca	^{76}Ge
$G^{0\nu}/G^{0\nu}_{Se}$		7.41	2.25	0.22
$M^{0\nu}/M^{0\nu}_{Se}$		~ 1.5* ~ 0.55**	~ 0.25***	~ 1.00***
$T^{0\nu}_{1/2}/T^{0\nu}_{1/2}$ Se		~ 0.06* ~ 0.45**	~ 7	~4.5

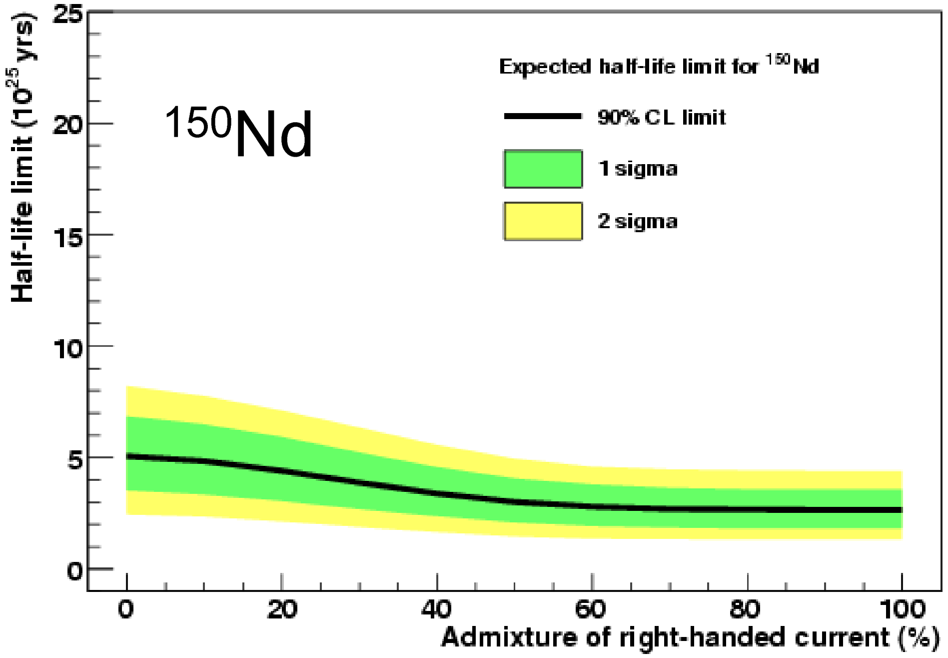
Models

(*) Spherical approach , QRPA, gA=1.25, V. Rodin et al. *Nuclear Physics A 793 (2007) 213–215*

(**)Nuclear deformation, factor 2.7 F. ˇSimkovic, *AIP Conf. Proc. 942, 77 (2007).*

^{82}Se or ^{150}Nd in SuperNEMO ?

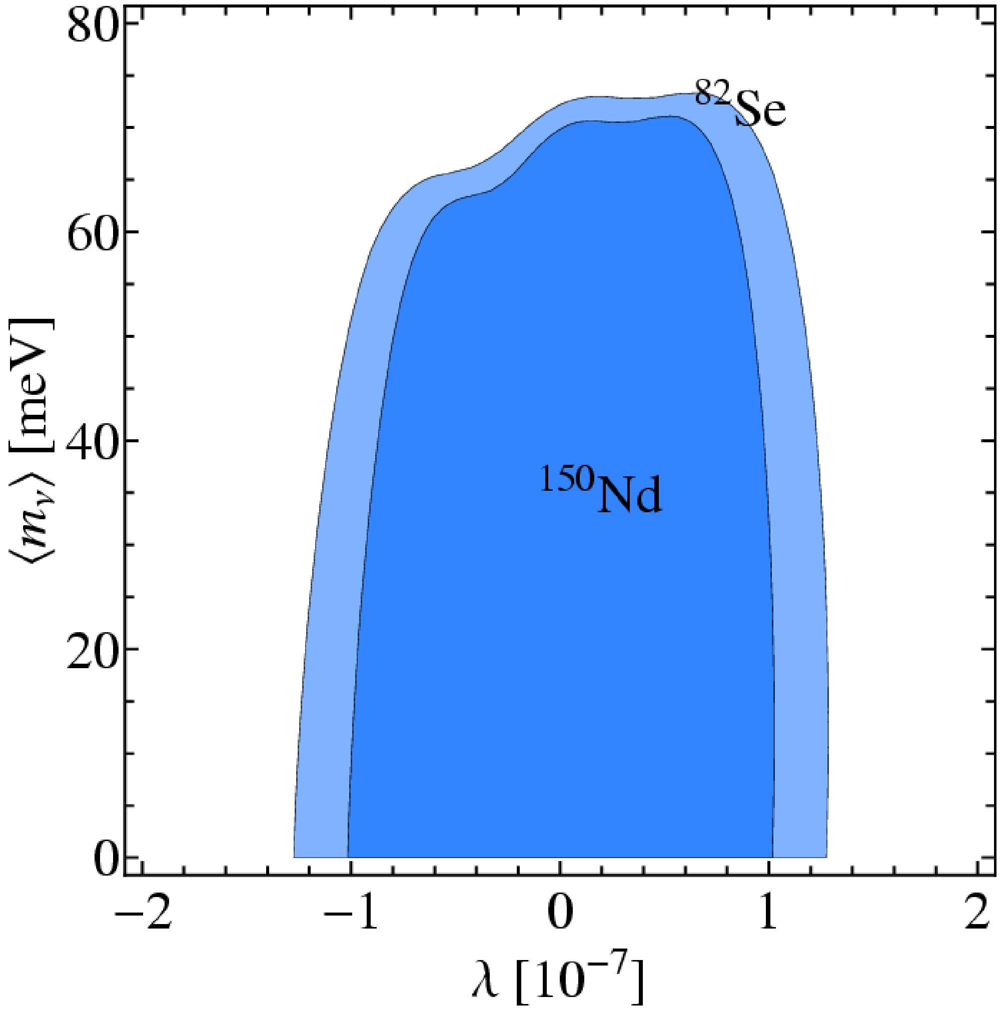




Limit Setting at 90% CL

(500 kg y exposure)

Acceptance effects lead to lower RHC$_\lambda$ half-life limit



Using NME from Muto, Bender, Klapdor (1989) and factor 2.7 suppression in ^{150}Nd NME to account for nuclear deformation.

Probing new physics in SuperNEMO with multi-isotopes

Multi-isotope option in SuperNEMO – 50% ^{82}Se and 50% ^{150}Nd.

Make two measurements and **compare rates**:

$$\mathrm{MM}: \frac{T_{1/2}^{^{82}\mathrm{Se}}}{T_{1/2}^{^{150}\mathrm{Nd}}} = \frac{C_{mm}^{^{150}\mathrm{Nd}}}{(2.7)^2 \cdot C_{mm}^{^{82}\mathrm{Se}}} = 2.45,$$

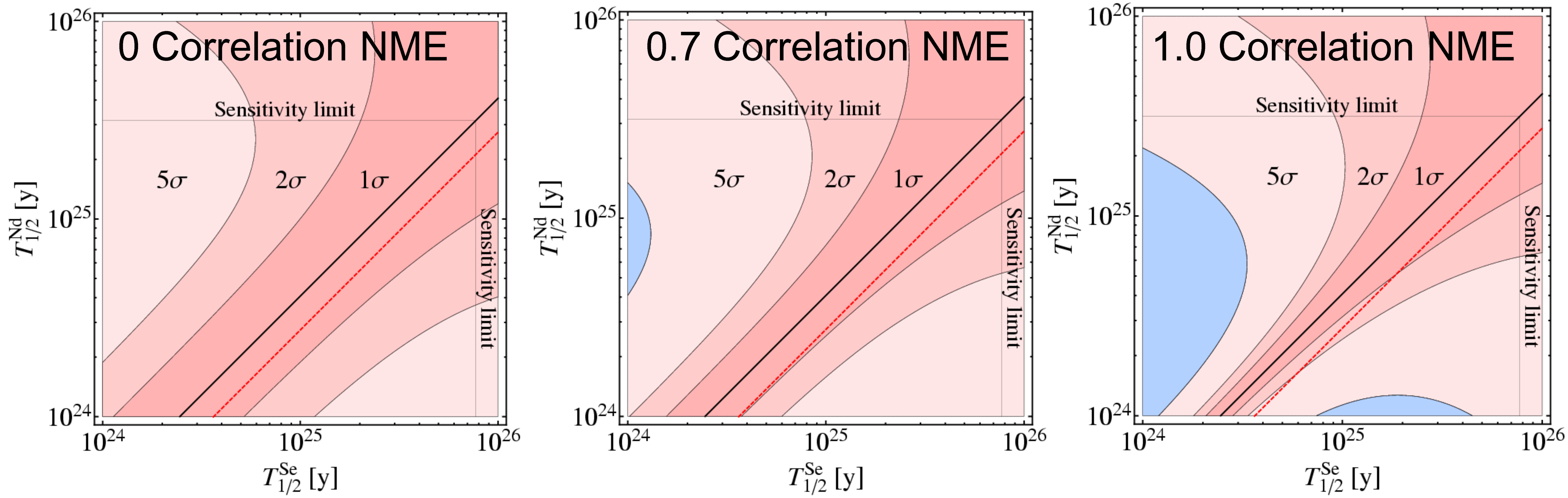
$$\mathrm{RHC}_\lambda: \frac{T_{1/2}^{^{82}\mathrm{Se}}}{T_{1/2}^{^{150}\mathrm{Nd}}} = \frac{C_{\lambda\lambda}^{^{150}\mathrm{Nd}}}{(2.7)^2 \cdot C_{\lambda\lambda}^{^{82}\mathrm{Se}}} = 3.64.$$

Check **consistency of measurements** with model prediction.

If NME errors are correlated can reduce uncertainty on half-lives.

(Faessler, Fogli, Lisi, Rodin, Rotunno, Simkovic (2009))

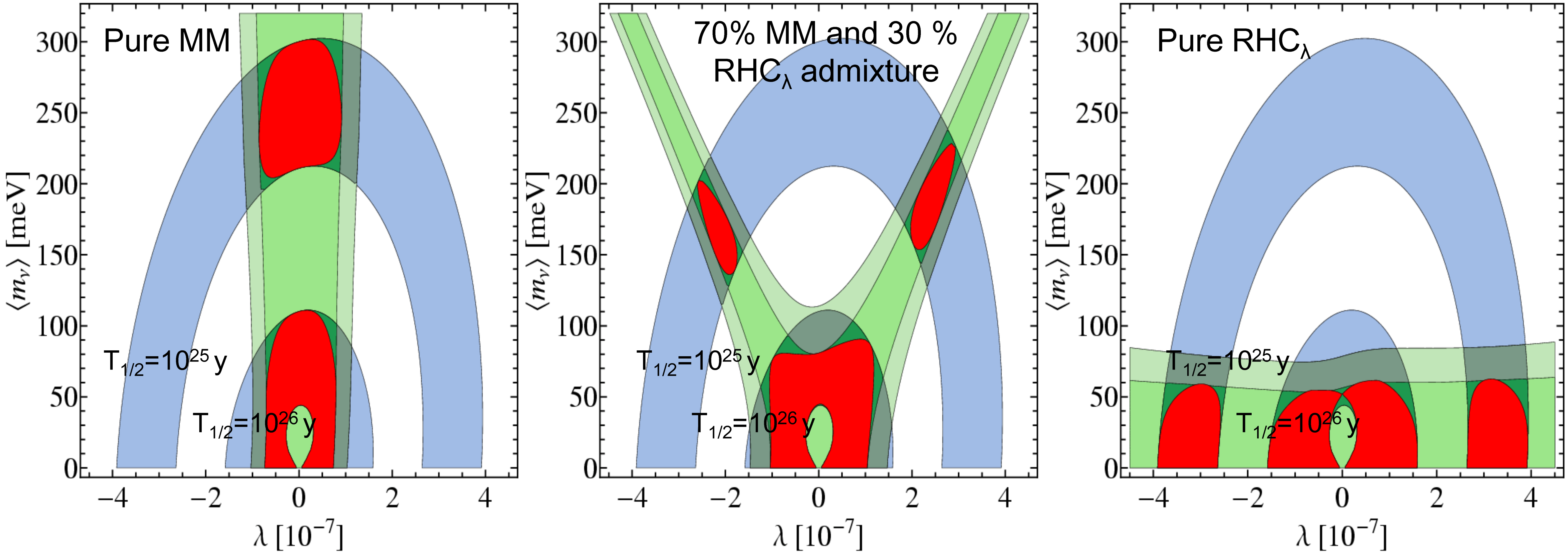
Case of **pure MM** mechanism :



Measurement in blue region leads to MM (black line) exclusion at 5σ.

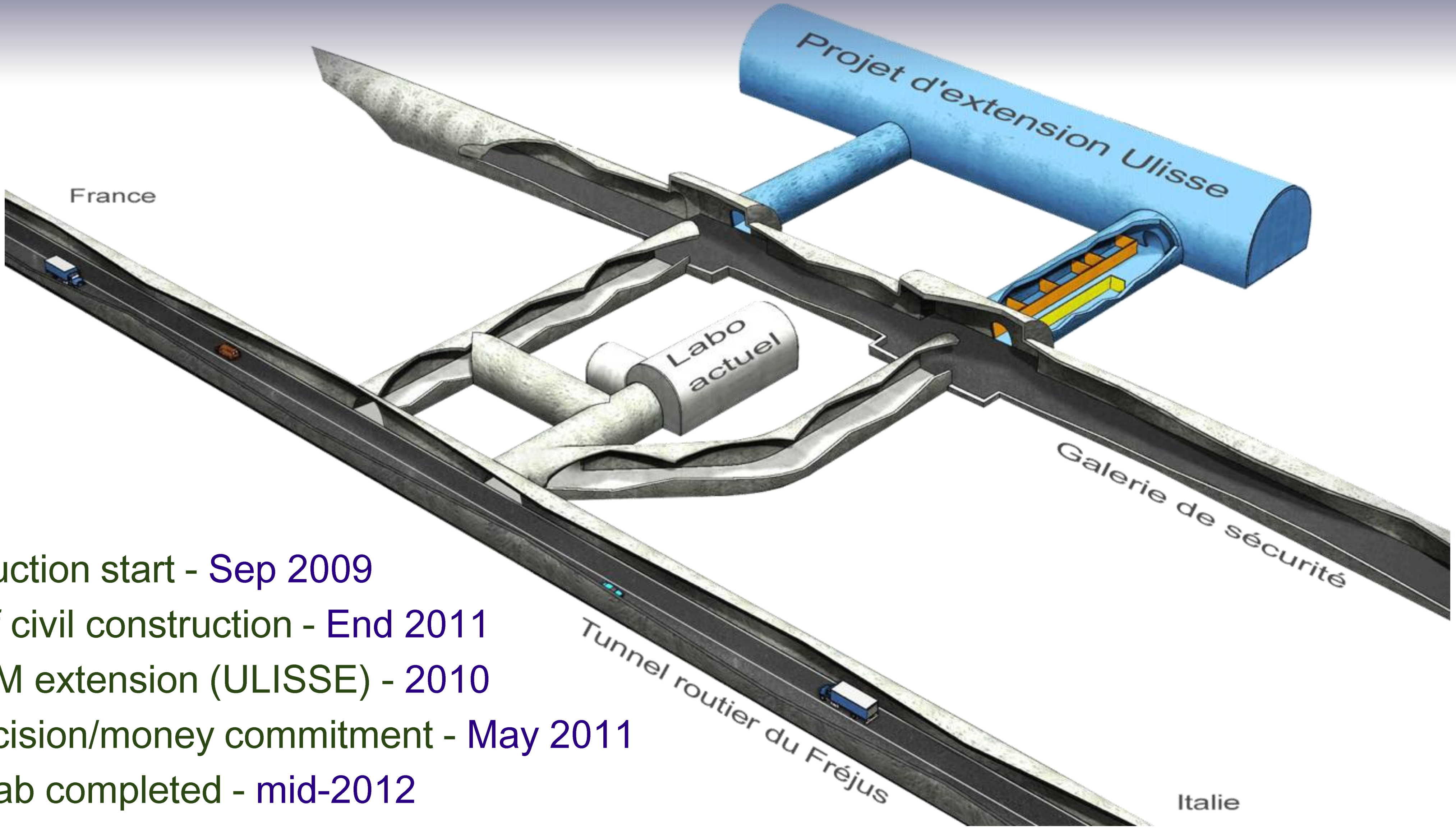
Probing new physics in SuperNEMO with kinematic parameters

In case of **observation** measure energy difference and cosine of separating angle between electrons to identify mechanism of 0νββ.



Combination of **half-life measurement** (blue contour) and **topological parameter reconstruction** (green contours) leads to **parameter space restriction** (red contour) at 1 standard deviation.

LSM extension



Schedule

- Safety tunnel construction start - Sep 2009
- Safety tunnel, end of civil construction - End 2011
- Detailed study of LSM extension (ULISSE) - 2010
- Deadline for final decision/money commitment - May 2011
- Excavation of new Lab completed - mid-2012
- Outfitting completed, Lab ready to host experiments - 2013

Minimal scenario: 45,000m^3 (100m long), 12M€ excavation + 3M€ outfitting

11 LOIs received.

Background levels

NEMO3 (^{100}Mo)

		events/7kg.5yr [2.8-3.2]	events/kg.yr [2.8-3.2]	events/kg.yr.keV
ββ(2ν)	7. 10^{18} yr	8.75	0.25	0.00125
Radon	5mBq/m^3	5.25	0.15	0.00075
^{208}Tl	100µBq/kg	3.5	0.10	0.00050
TOTAL		**17.5**	0.50	0.0025

SuperNEMO (^{82}Se)

		events/100kg.5yr [2.8-3.0]	events/kg.yr [2.8-3.0]	events/kg.yr.keV
ββ(2ν)	9.6. 10^{19} yr	5	0.01	0.000050
^{214}Bi	10µBq/kg	1.6	0.003	0.000015
^{208}Tl	2µBq/kg	1.7	0.003	0.000015
Radon	0.15mBq/m^3	1.6	0.003	0.000015
TOTAL		**10**	0.02	0.000095