NEMO-3 and SuperNEMO
Double Beta Decay Experiments

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on behalf of the NEMO Collaboration

OUTLINE

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II. NEMO-3 and main results

III. SuperNEMO

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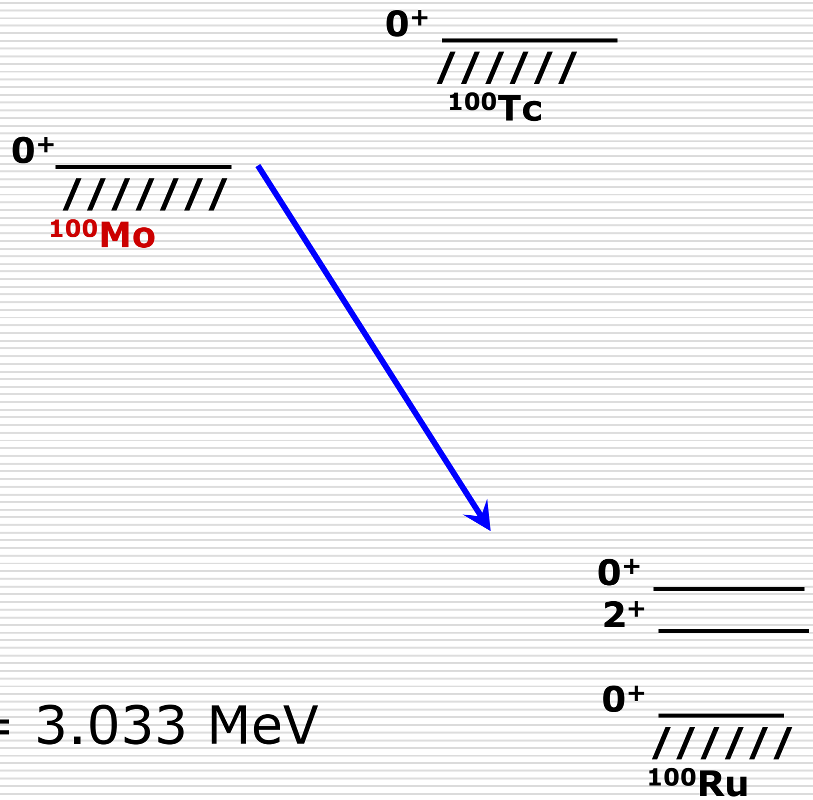
I. Introduction



$^{100}Mo \Rightarrow$ $^{100}Ru + 2e^-$

$^{100}Mo \Rightarrow$ $^{100}Ru + 2e^- + \chi^0$ $(+\chi^0)$

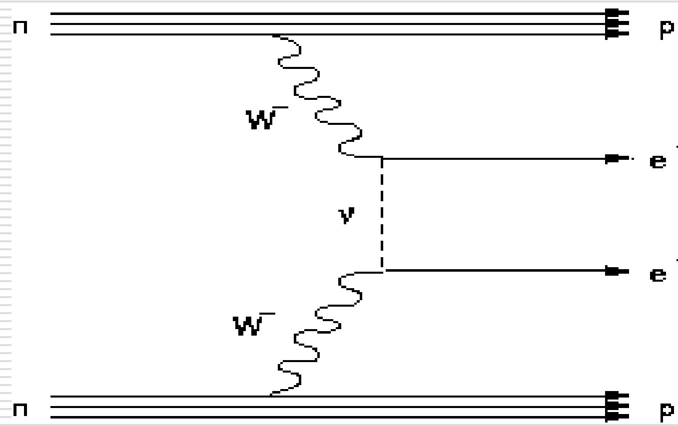
$^{100}Mo \Rightarrow$ $^{100}Ru + 2e^- + 2v$

$Q_{\beta\beta} = 3.033$ MeV

NEUTRINOLESS DOUBLE BETA DECAY

Experimental signature:

2 electrons
$E_{\beta 1} + E_{\beta 2} = Q_{\beta\beta}$



Neutrinoless double beta decay is being actively searched, because it is closely related to many fundamental concepts of nuclear and particle physics:

- **- the lepton number nonconservation ($\Delta L = 2$);**
- **- the existence of neutrino mass and its origin**
- **(Dirac or Majorana?);**
- - the presence of right-handed currents in electroweak interactions;
- - the existence of Majoron (spontaneous breaking of a global **B-L** symmetry);
- - the structure of Higg's sector;
- - the supersymmetry;
- - the heavy sterile neutrino;
- - the existence of leptoquarks.

What one can extract from 2β-decay experiments? ⇒

- **L** violation
- Nature of neutrino mass (**Dirac or Majorana?**).
- Absolute mass scale (value or limit on $\mathbf{m_1}$).
- Type of hierarchy (normal, inverted, quasi-degenerated).
- **CP** violation in the lepton sector.

Two neutrino double beta decay

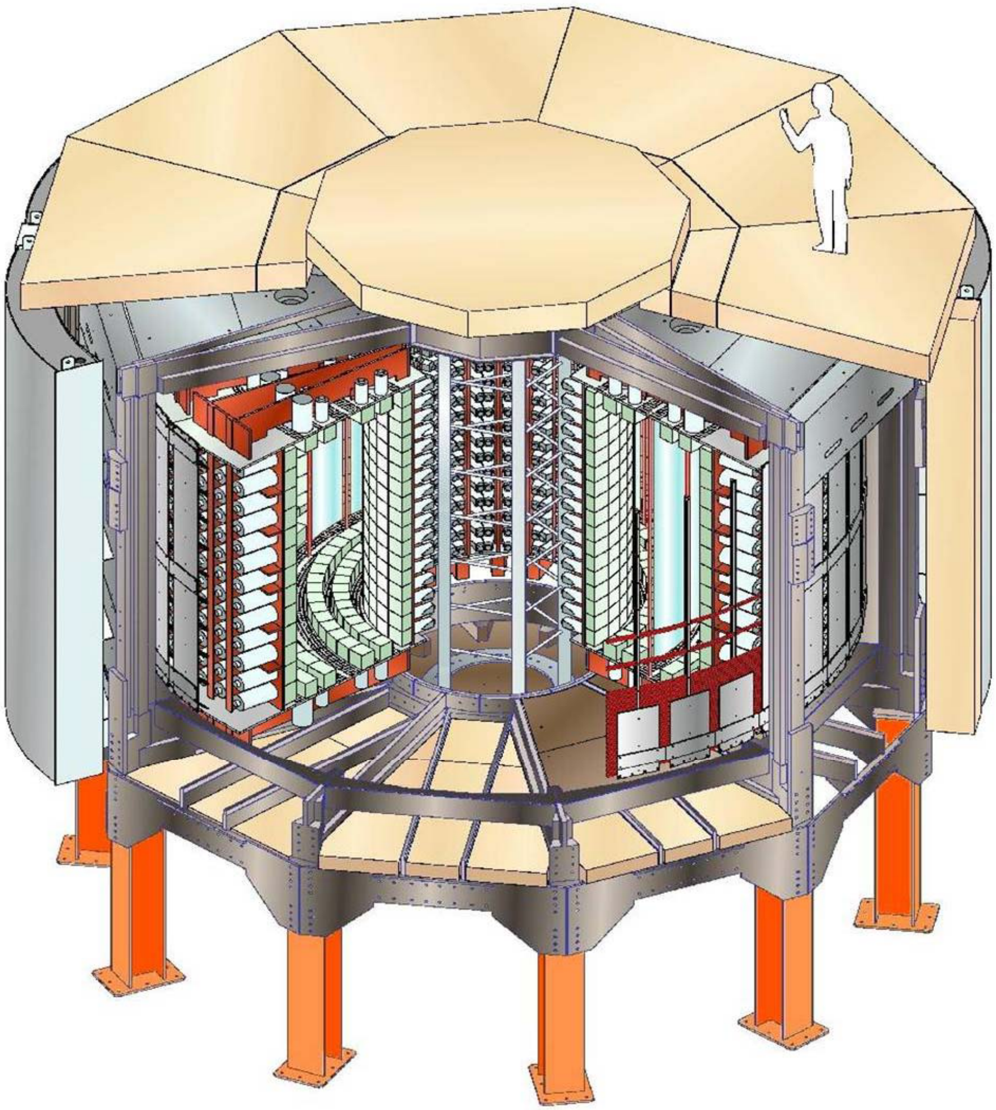
- Second order of weak interaction
- Direct measurement of NME values! $\Rightarrow$
  - The only possibility to check the quality of NME calculations!!!
  - g_{pp} (QRPA parameter $\Rightarrow$ NME(0ν))!

$$\Downarrow$$

- This is why it is very important to measure this type of decay for many nuclei, for different processes (**$2\beta^-$, $2\beta^+$, $K\beta^+$, 2K, excited states**) and with high accuracy.

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



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

Tracking detector:
drift wire chamber operating
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 (~30 cm) + **Wood (Top/Bottom/Gapes between water tanks)**

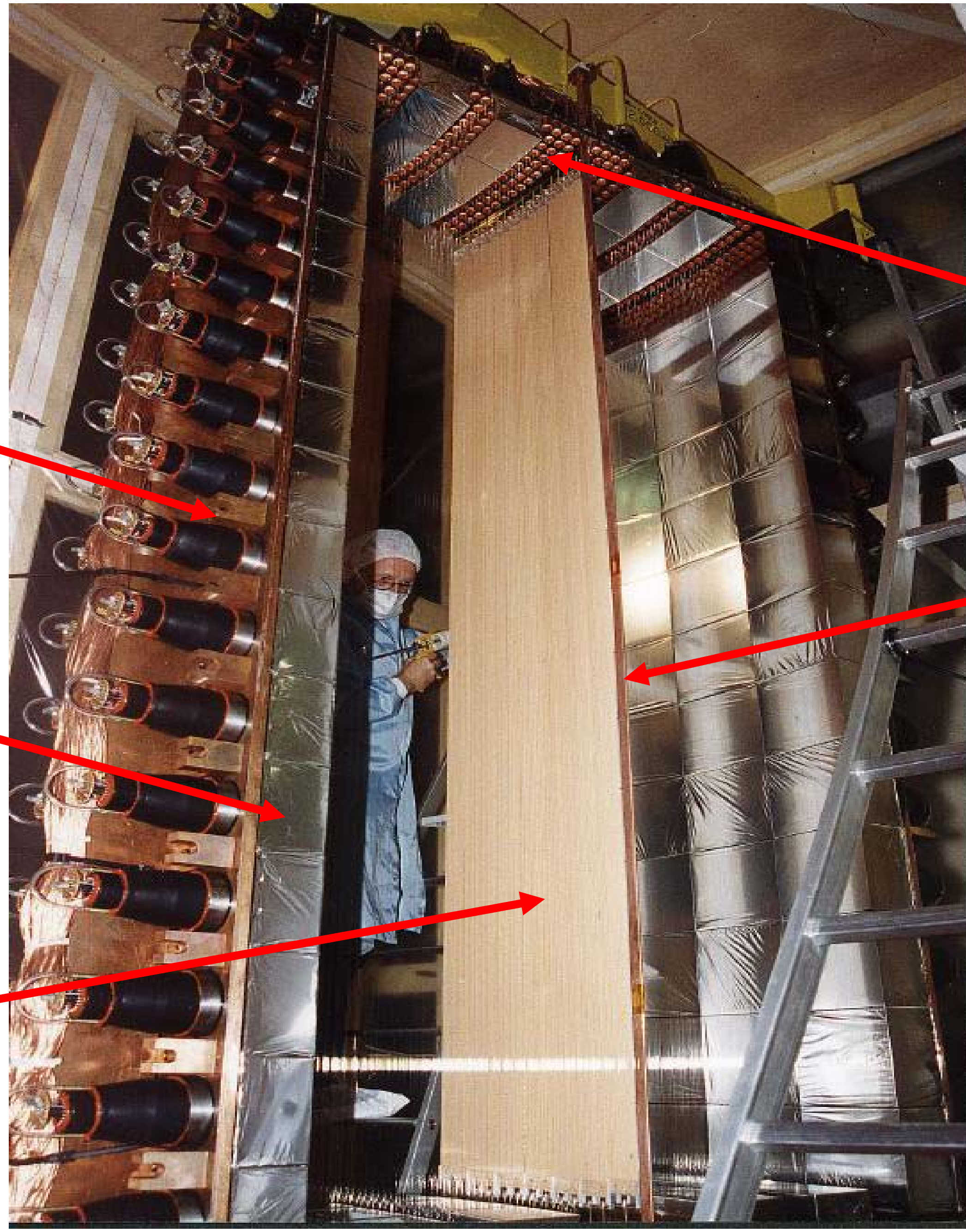
Able to identify e$^-$, e$^+$, γ and α

Sector interior view

PMT

scintillators

$\beta\beta$ isotope foils



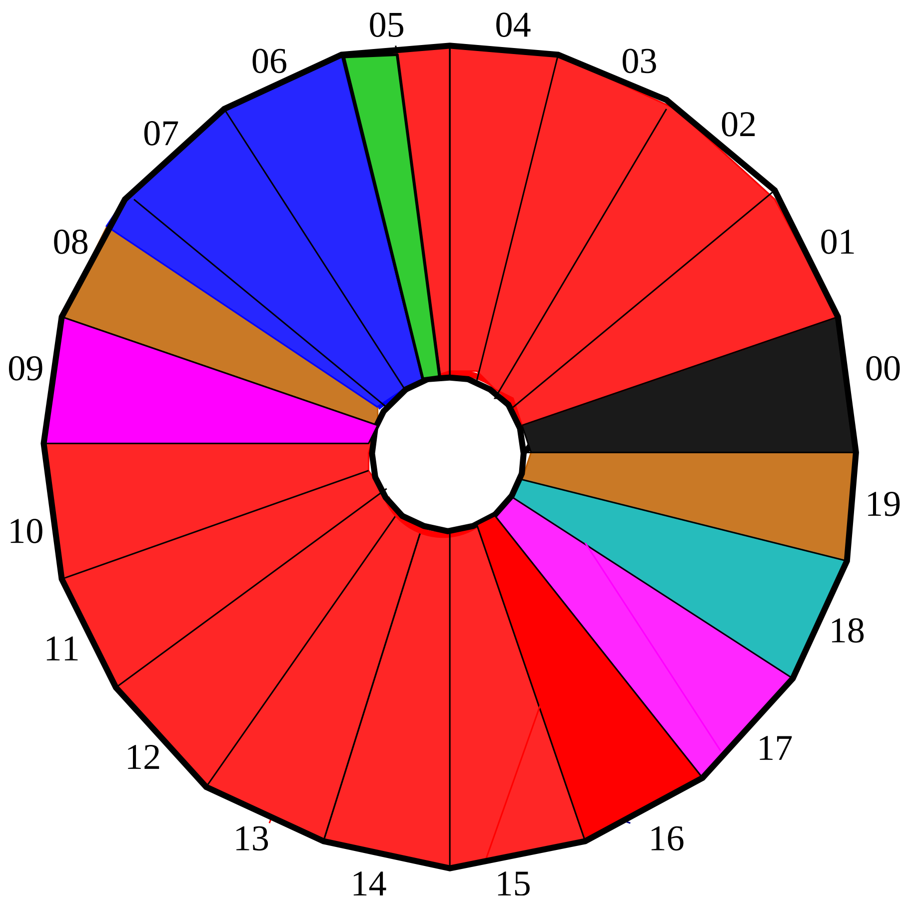
cathode rings
wire chamber

calibration tube

Calibration source

^{207}Bi
2e– (IC) lines
~0.5 ,~1 MeV
^{90}Sr
^{60}Co

$\beta\beta$ decay isotopes in NEMO-3 detector



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

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

$\beta\beta0\nu$ search

$\beta\beta2\nu$ 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 491 g

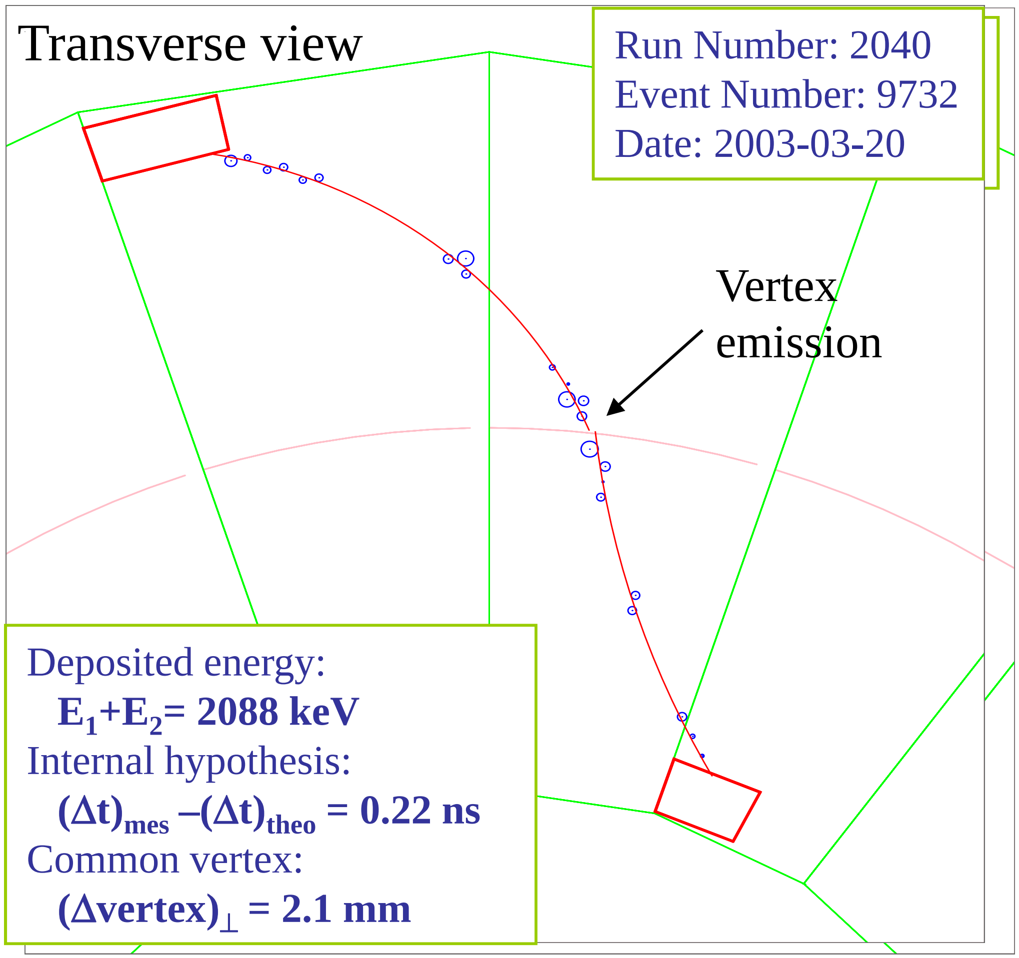
Cu 621 g

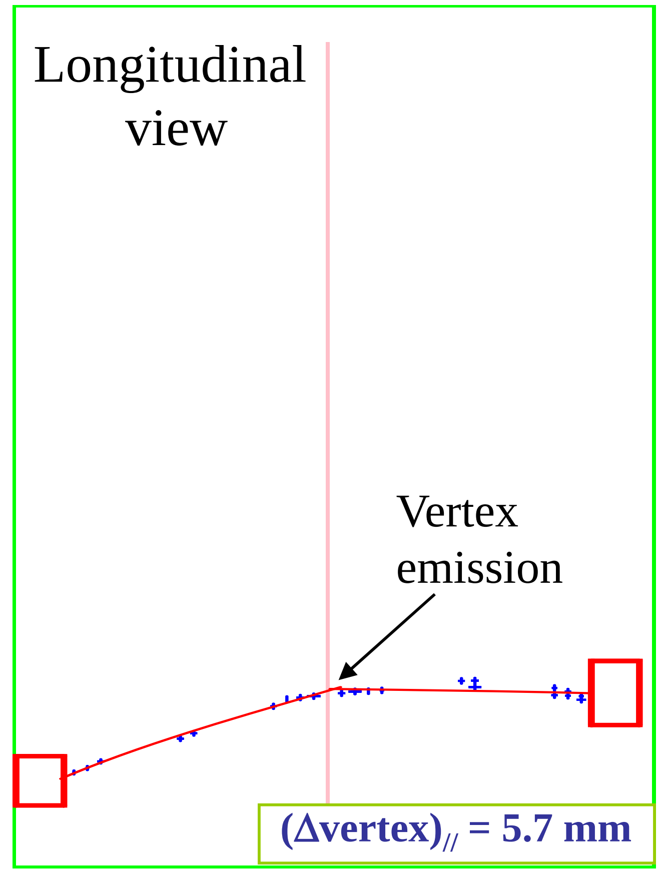
External bkg measurement

(All enriched isotopes produced in Russia)

ββ events selection in NEMO-3

Typical ββ2ν event observed from ^{100}Mo





Trigger: at least 1 PMT > 150 keV

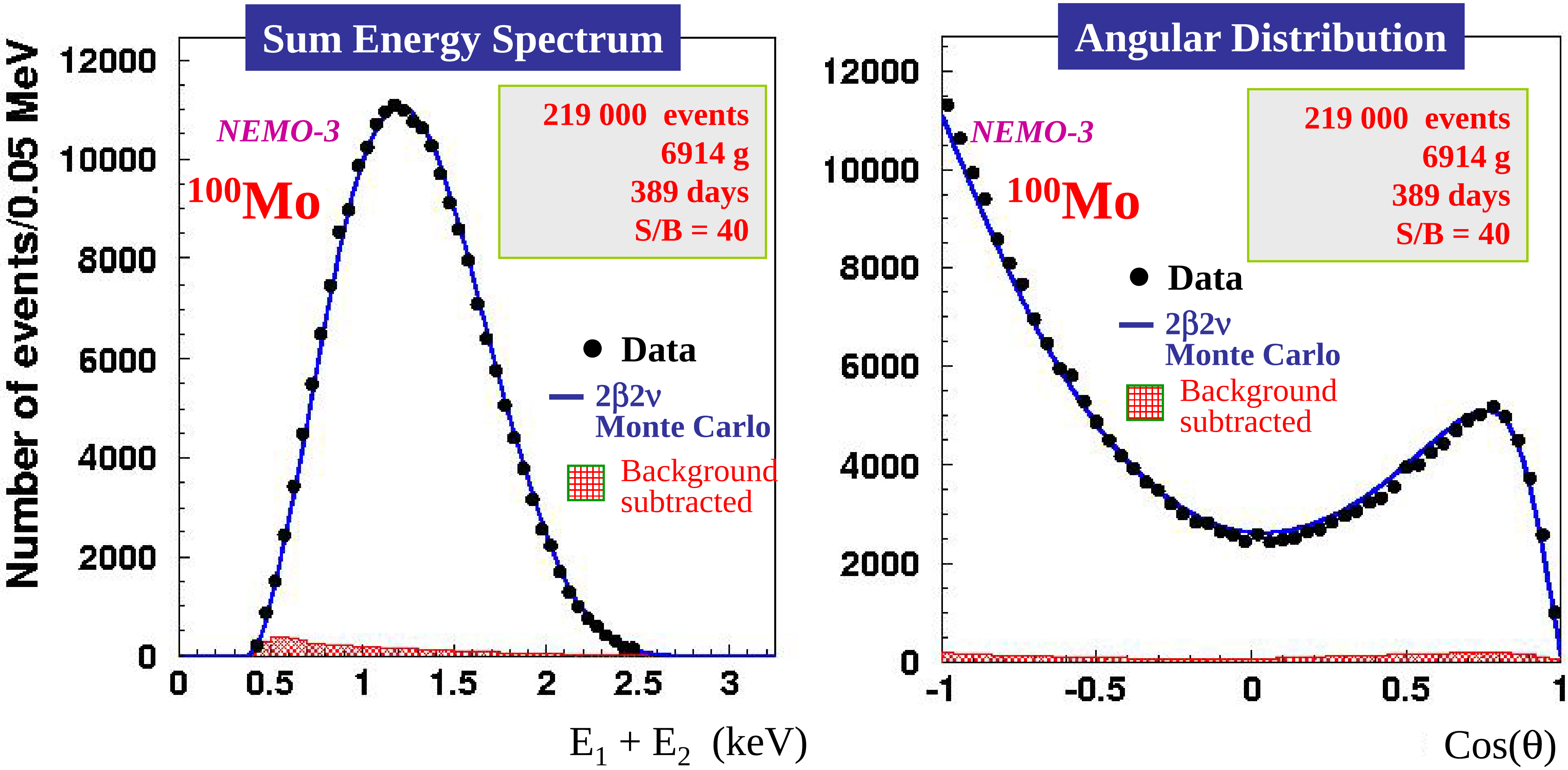
≥ 3 Geiger hits (2 neighbour layers + 1)

Trigger rate = 7 Hz

ββ events: 1 event every 2.5 minutes

^{100}Mo 2β2ν result

(Phase I: Feb. 2003 – Dec. 2004)



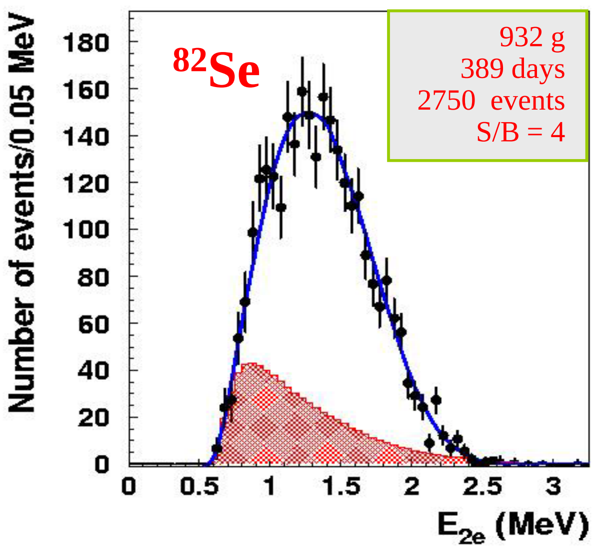
7.37 kg.y

$$T_{1/2} = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ y}$$

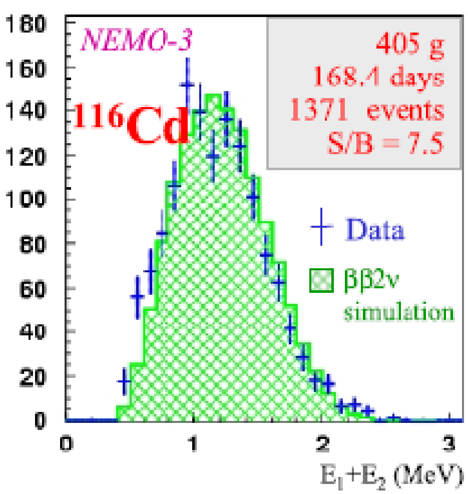
Phys. Rev. Lett. 95 (2005) 182302

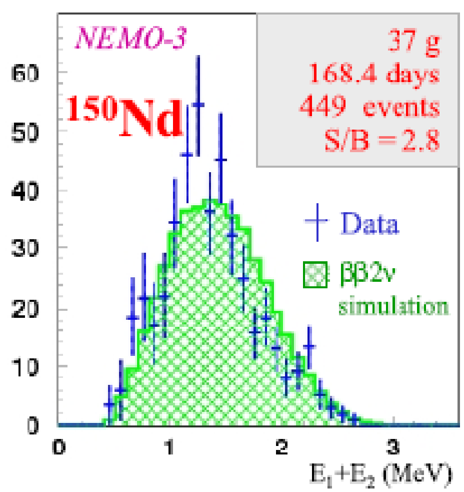
ββ2ν results with other nuclei

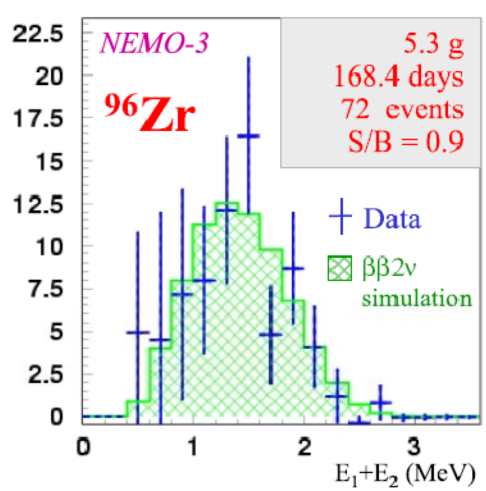
Background subtracted

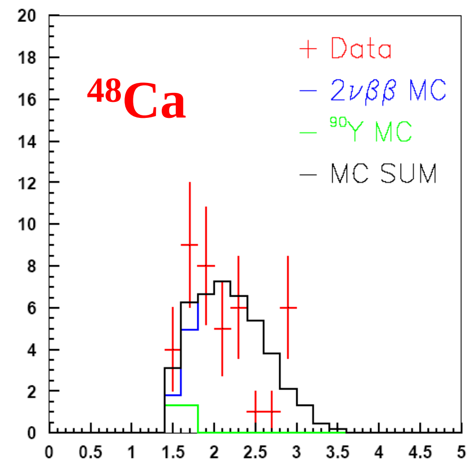


^{82}Se	$T_{1/2} = 9.6 \pm 0.3\,(stat) \pm 1.0\,(syst) \times 10^{19}$ y
^{116}Cd	$T_{1/2} = 2.8 \pm 0.1\,(stat) \pm 0.3\,(syst) \times 10^{19}$ y
^{150}Nd	$T_{1/2} = 9.7 \pm 0.7\,(stat) \pm 1.0\,(syst) \times 10^{18}$ y
^{96}Zr	$T_{1/2} = 2.0 \pm 0.3\,(stat) \pm 0.2\,(syst) \times 10^{19}$ y
^{48}Ca	$T_{1/2} = 3.9 \pm 0.7\,(stat) \pm 0.6\,(syst) \times 10^{19}$ y
^{130}Te	$T_{1/2} = 7.6 \pm 1.5\,(stat) \pm 0.8\,(syst) \times 10^{20}$ y (new!)
^{100}Mo-	
^{100}Ru(0^+_1)	$T_{1/2} = 5.7^{+1.3}_{-0.9}\,(stat) \pm 0.8\,(syst) \times 10^{20}$ y









NEMO-3 is 2β(2ν)-decay factory!!!

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

- Geochemical experiments:
  (26 ± 2.8) x 10^{20} years (Kirsten 83)
  (27 ± 1) x 10^{20} years (Bernatowicz 93)

  (7.9 ± 1) x 10^{20} years (Takaoka 96)
  ~8 x 10^{20} years (Manuel 91)

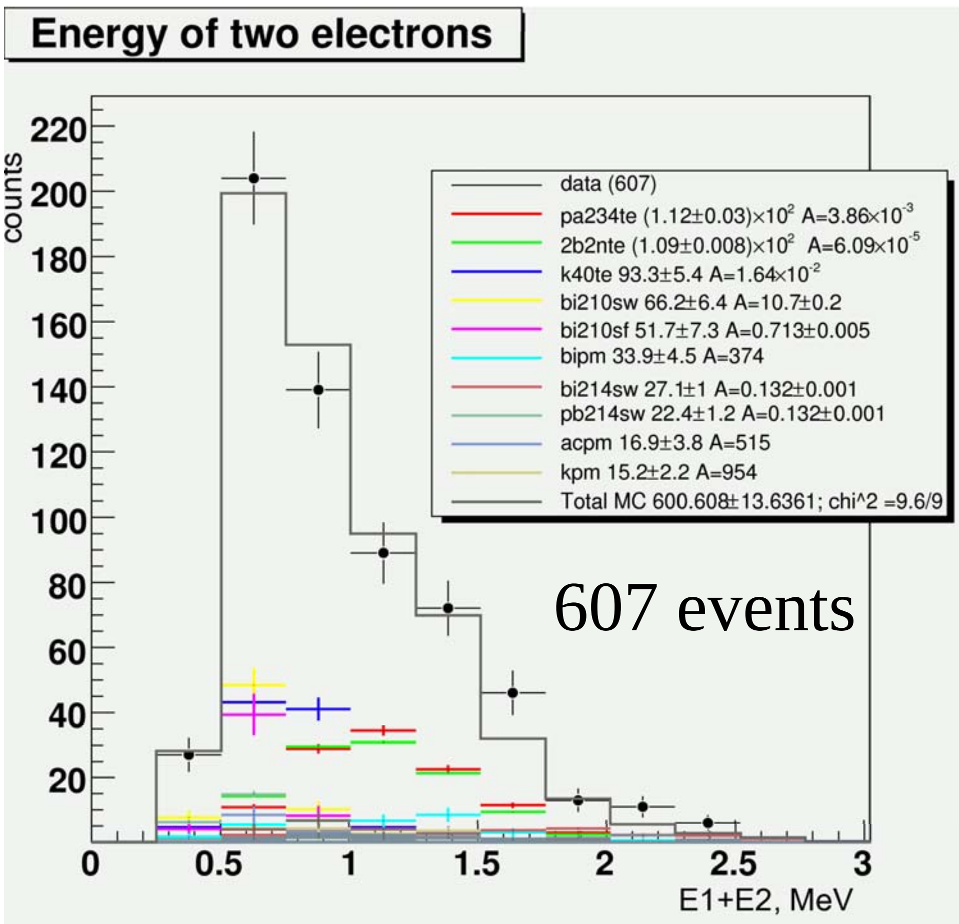
- Difference between 'old' and 'young' ores due to time dependence of constants..? [A.S.B. JETP Lett. 68 (1998) 1]

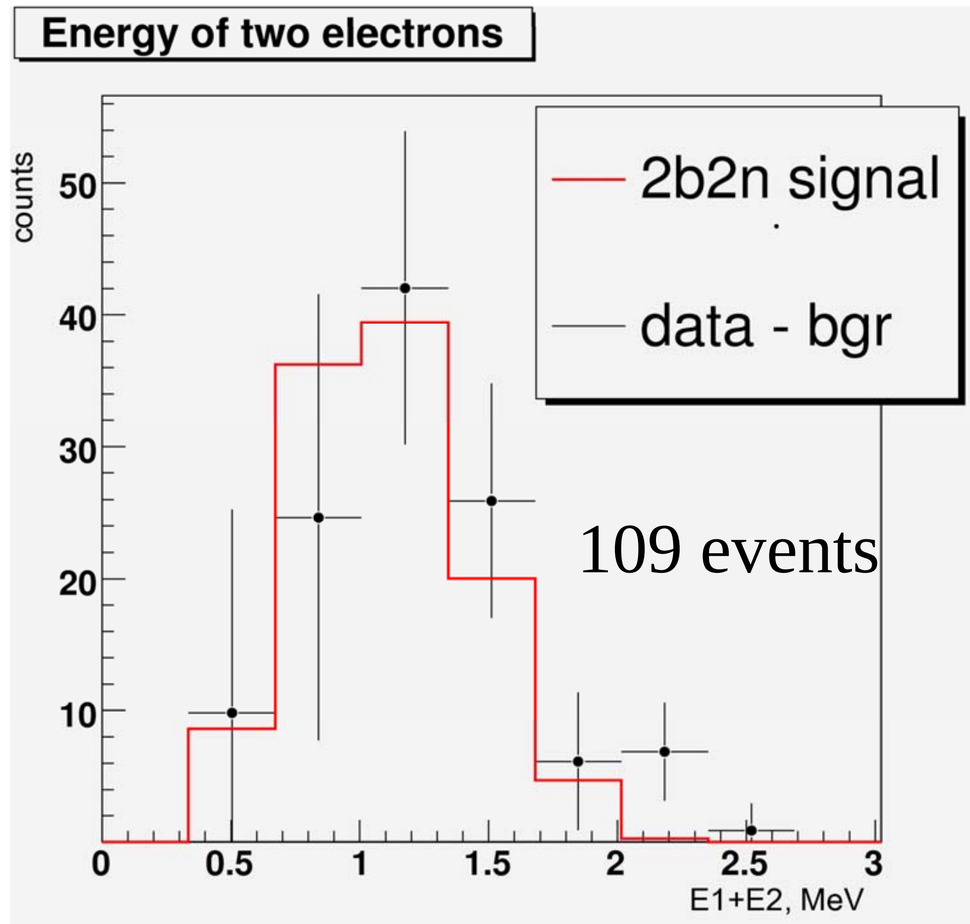
- Using geochemical ratio of ^{82}Se/^{130}Te and present half-life value for ^{82}Se from direct experiments:
  (9 ± 1) x 10^{20} years (recommended value, A.S.B. 2001)

- Direct measurement:
  [6.1 ± 1.4 (stat)$^{+2.9}_{-3.4}$ (syst)] x 10^{20} years (Arnaboldi 2003)

^{130}Te (preliminary)

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





534 days, 454 g of ^{130}Te

background subtracted

Other interesting results using information obtained with 2ν-decay of ^{100}Mo

- **SSD** mechanism is confirmed for 2ν decay of ^{100}Mo [Phys.At.Nucl. 69(2006) 2090]
- **"Bosonic"** properties of neutrino[1)] is checked:

  - pure "bosonic" neutrinos are excluded;
  - conservative upper limit $\sin^2\chi$ <0.6 is obtained

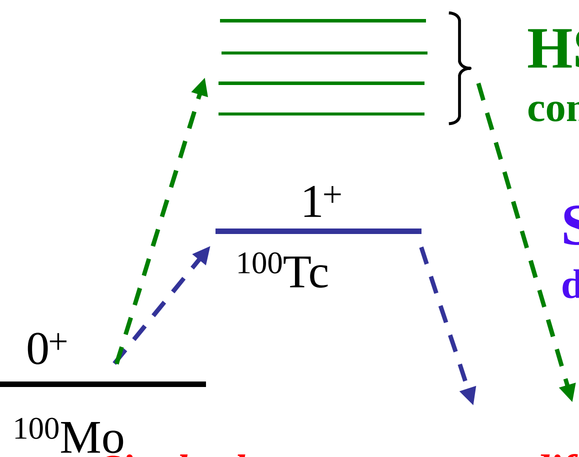
[A.S. Barabash, A.D. Dolgov, R. Dvornicky, F. Simkovic and A.Yu. Smirnov, Nucl.Phys. B 782 (2007) 90.]

1) A. Dolgov and A. Smirnov, PL B621 (2005) 1

Single electron spectrum 2νββ (^{100}Mo)

$T_{1/2} = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ y
Phys. Rev. Lett. 95 (2005) 182302

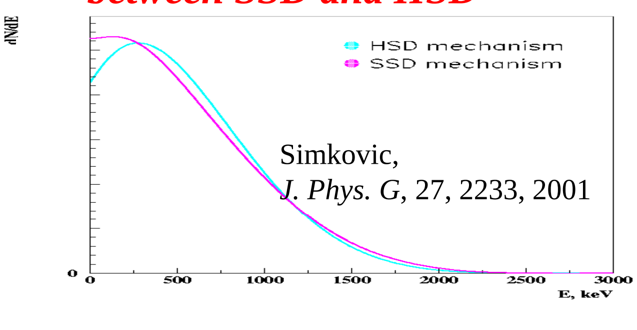
SSD model confirmed



HSD, higher levels contribute to the decay

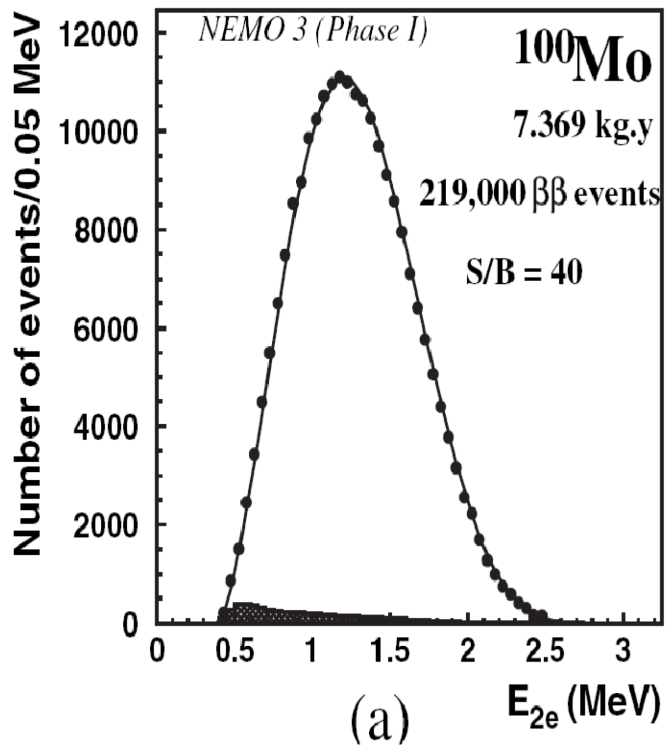
SSD, 1+ level dominates in the decay
(Abad et al., 1984, *Ann. Fis.* A 80, 9)

Single electron spectrum different between SSD and HSD

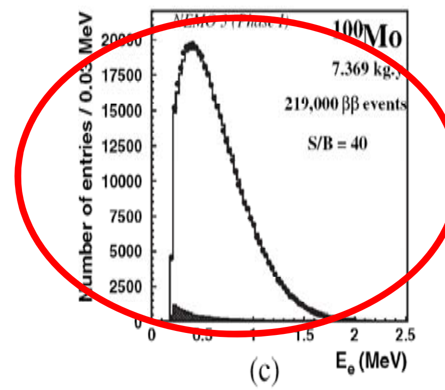


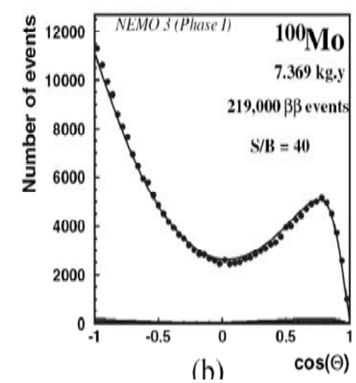
Simkovic, *J. Phys. G*, 27, 2233, 2001

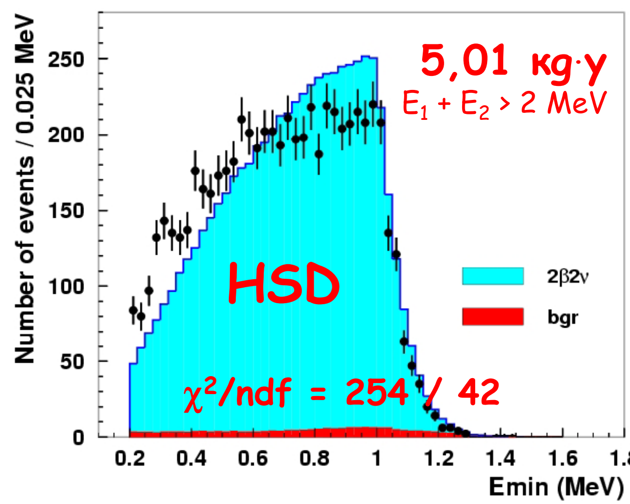
E_{single} (keV)

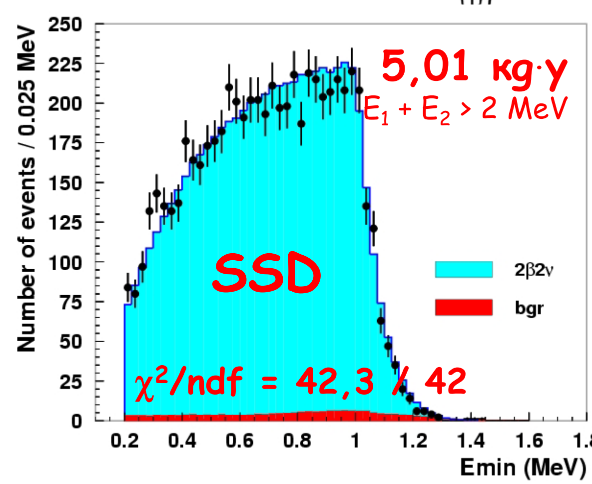


SSD simulation



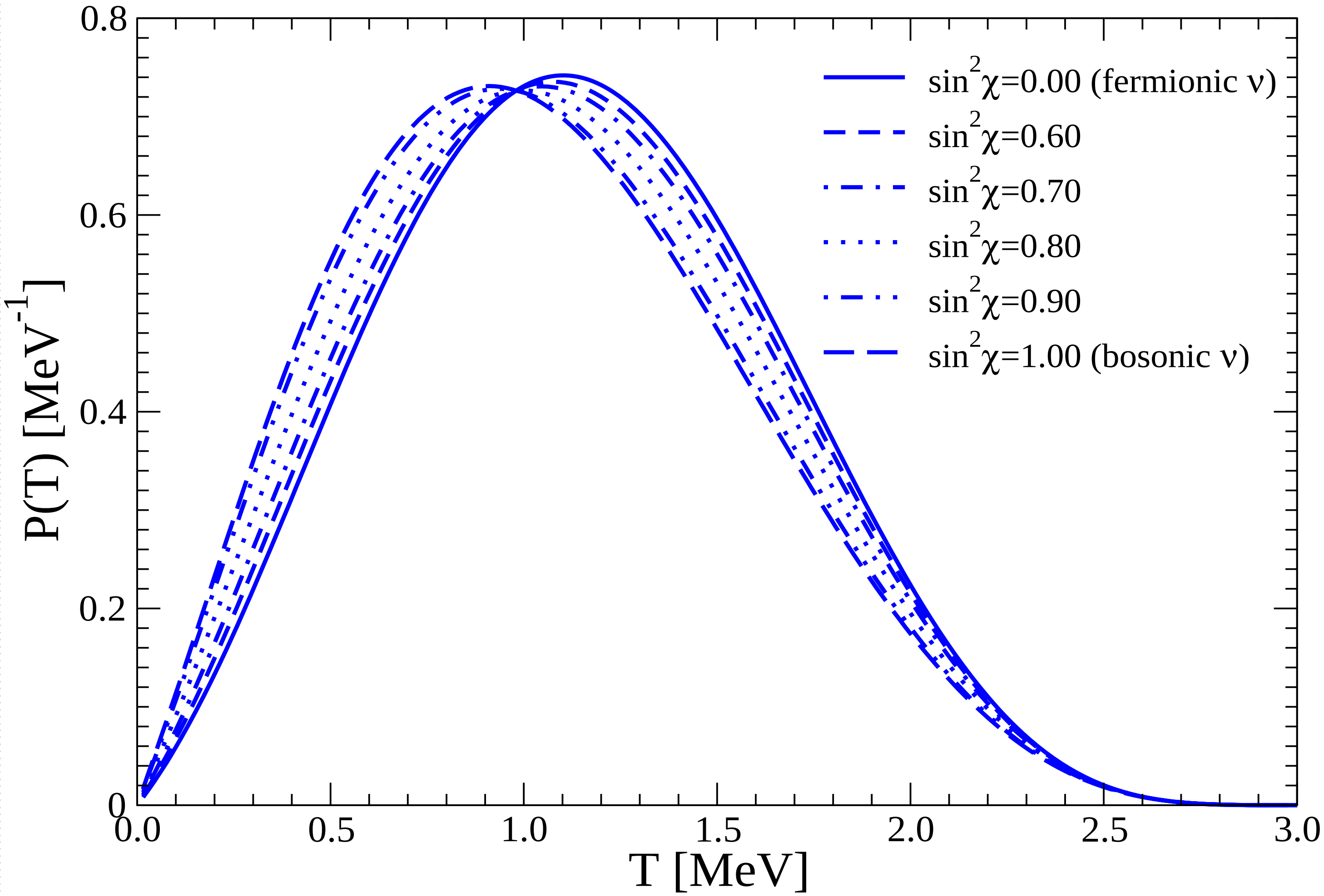






The normalized distribution of the total energy of two electrons

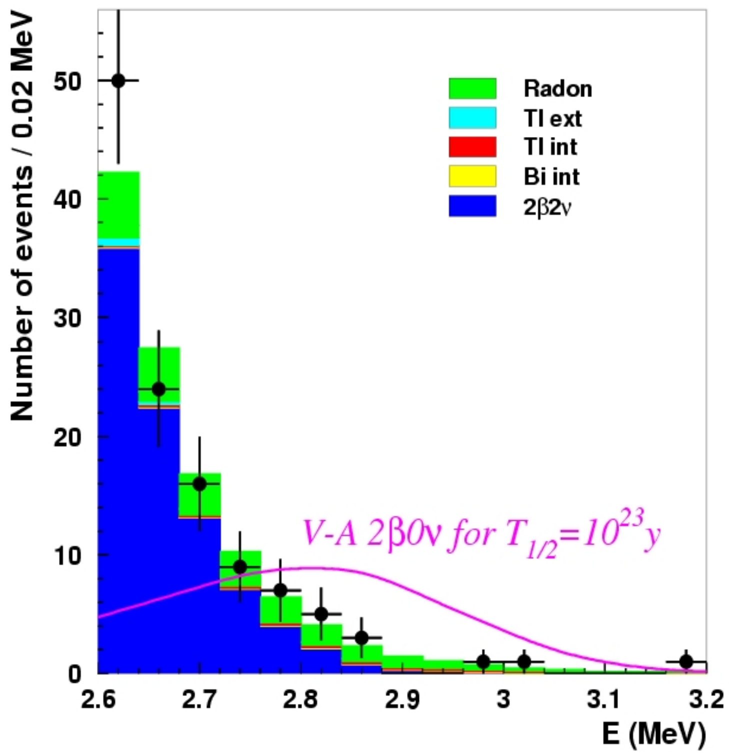
$^{100}Mo(0^+_{g.s.}) \to {}^{100}Ru(0^+_{g.s.})$ [A.S. Barabash, A.D. Dolgov, R. Dvornicky, F. Simkovic and A.Yu. Smirnov, Nucl.Phys. B 782 (2007) 90.]



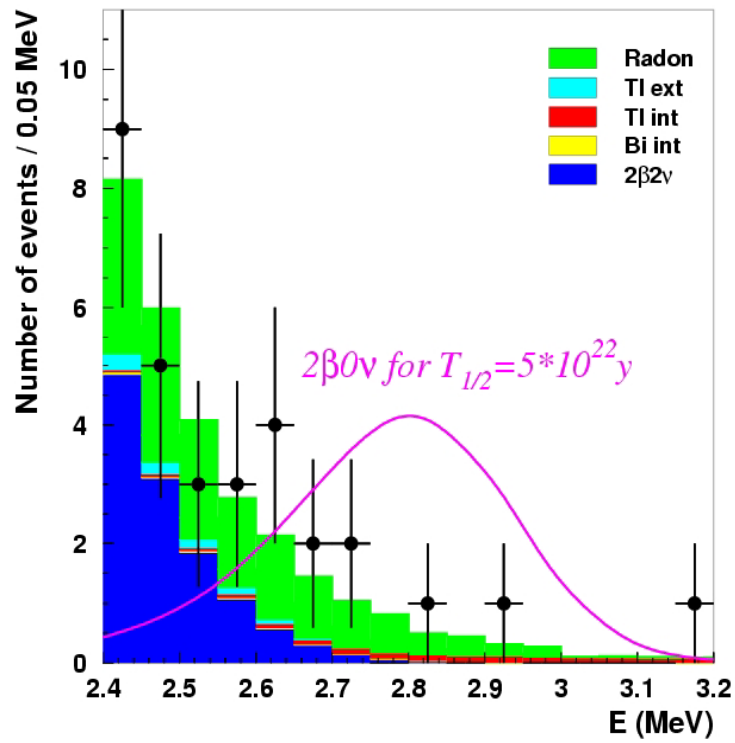
Large admixture of bosonic ν is excluded: $\sin^2\chi < 0.6$

ββ0ν search (ΔL = 2)

^{100}Mo, Phase I + II, 693 days



^{82}Se ,Phase I + II, 693 days



$T_{1/2}^{\beta\beta0\nu} > 5.8 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 0.8 – 1.3$ eV

$T_{1/2}^{\beta\beta0\nu} > 2.1 \times 10^{23}$ (90 % CL)
$\langle m_\nu \rangle < 1.4\text{-}2.2$ eV

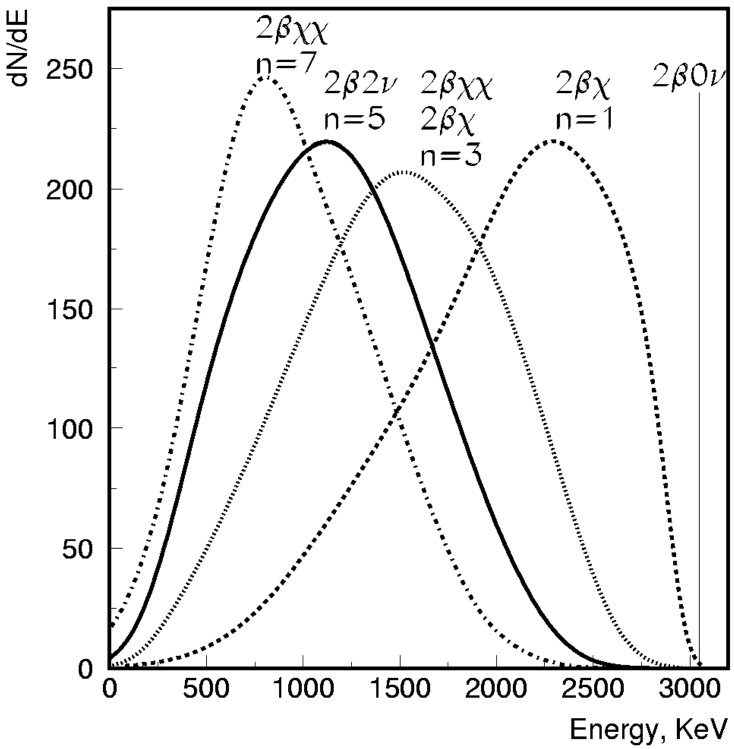
expected in 2009: $T_{1/2}^{\beta\beta0\nu} > 2 \times 10^{24}$ (90 % CL)
$\langle m_\nu \rangle < 0.4 – 0.7$ eV

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

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

Majorons and V+A currents

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



best limits

	V+A *	n=1 **	n=2 **	n=3 **	n=7 **
Mo	**$>3.2\cdot10^{23}$** $\lambda<1.8\cdot10^{-6}$	**$>2.7\cdot10^{22}$** $g_{ee}<(0.4-1.8)\cdot10^{-4}$	**$>1.7\cdot10^{22}$**	**$>1.0\cdot10^{22}$**	**$>7\cdot10^{19}$**
Se	**$>1.2\cdot10^{23}$** $\lambda<2.8\cdot10^{-6}$	**$>1.5\cdot10^{22}$** $g_{ee}<(0.7-1.9)\cdot10^{-4}$	**$>6\cdot10^{21}$**	**$>3.1\cdot10^{21}$**	**$>5\cdot10^{20}$**

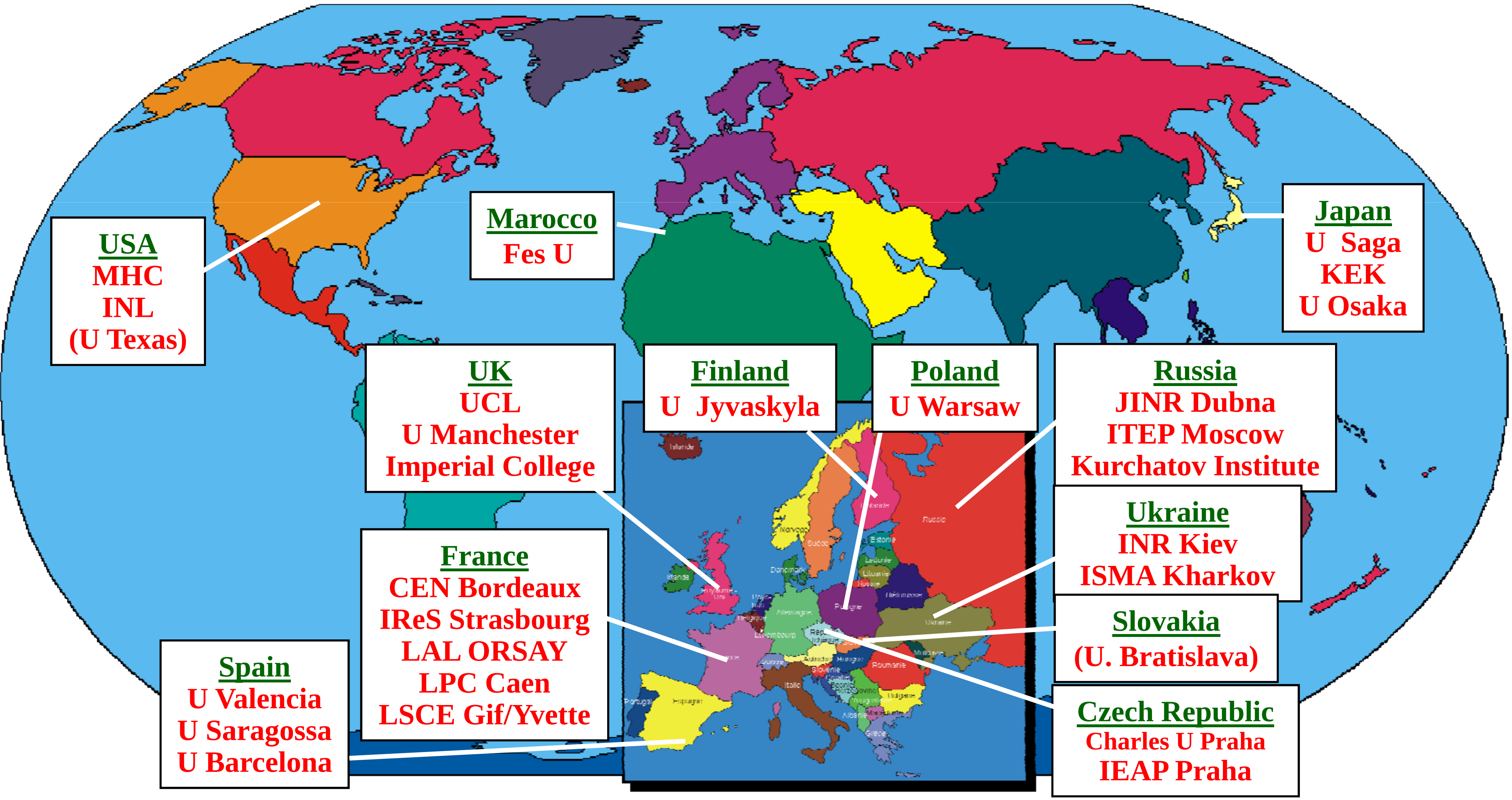
n: spectral index, limits on half-life in years

* PI+PII data

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

SuperNEMO Collaboration

~ 60 physicists, 12 countries, 27 laboratories



SuperNEMO preliminary design

Planar geometry

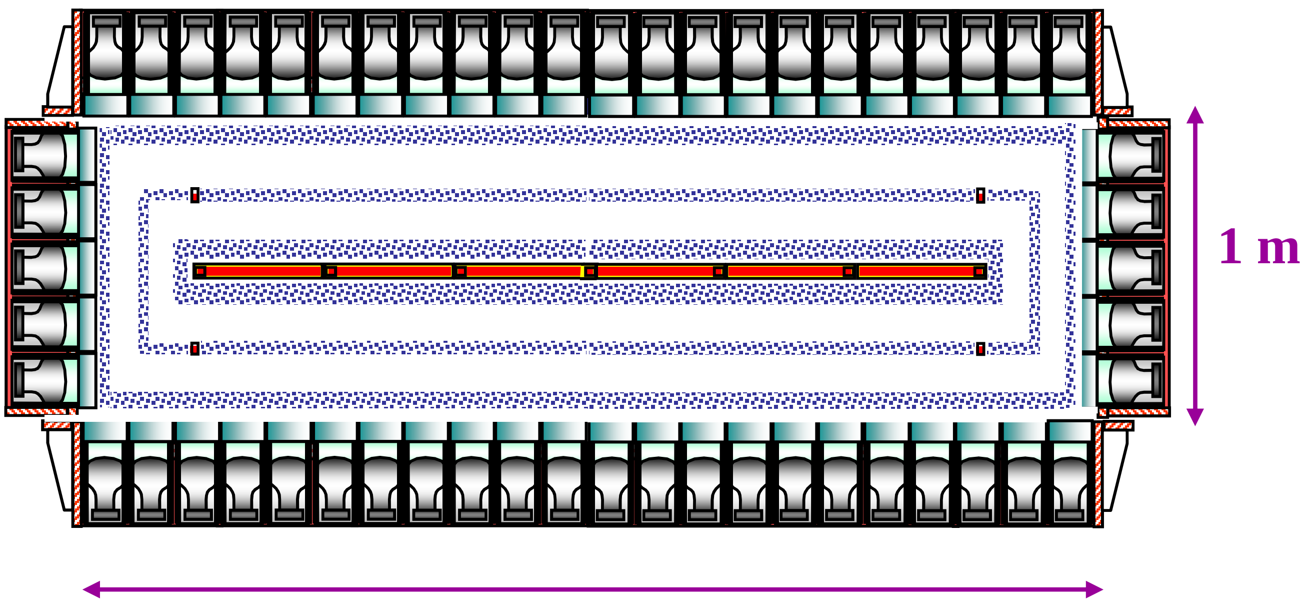
Source (40 mg/cm^2) 12m^2 , tracking volume (~3000 channels) and calorimeter (~1000 PMT)

Modular (~5 kg of enriched isotope/module)

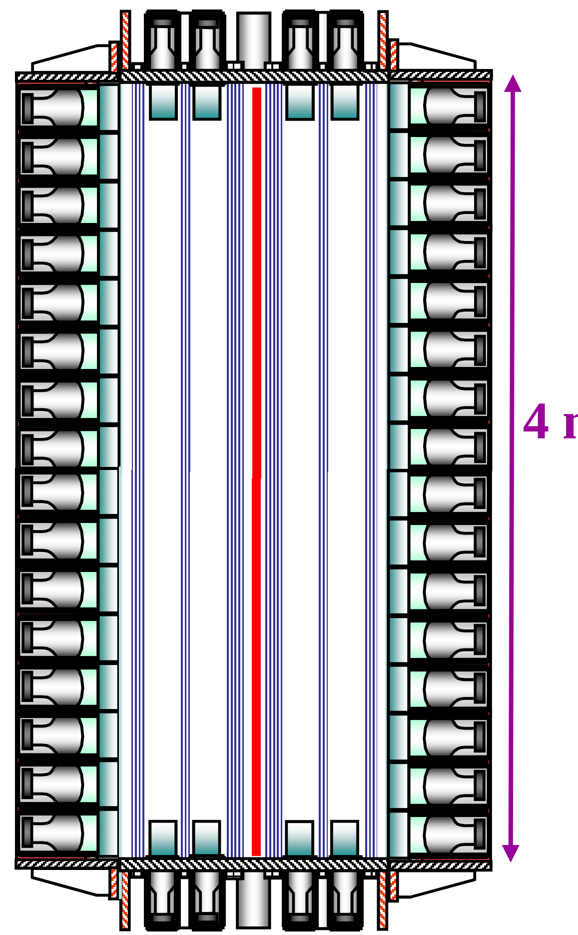
100 kg: 20 modules

~ 60 000 channels for drift chamber

~ 20 000 PMT (2 000 if scintillator bars)

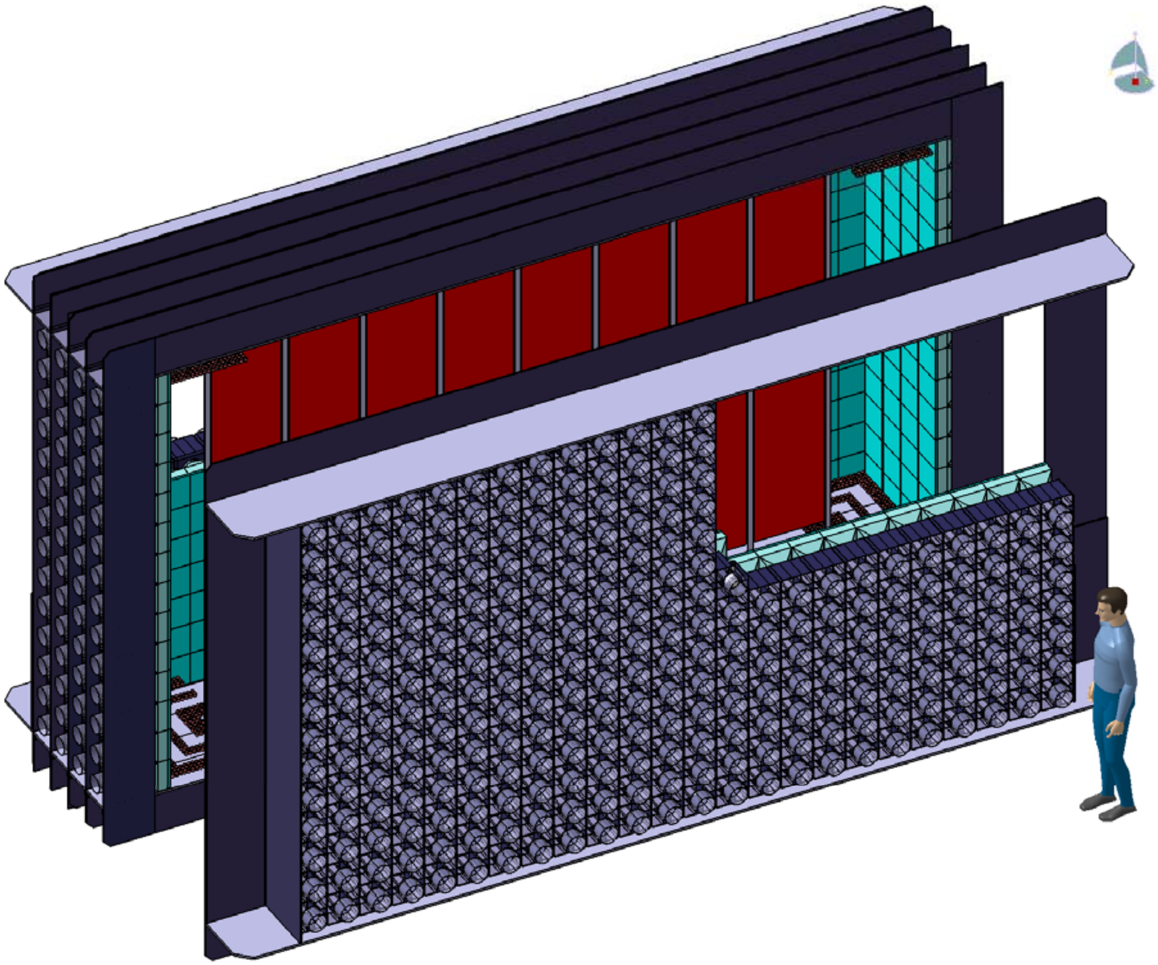


Top view

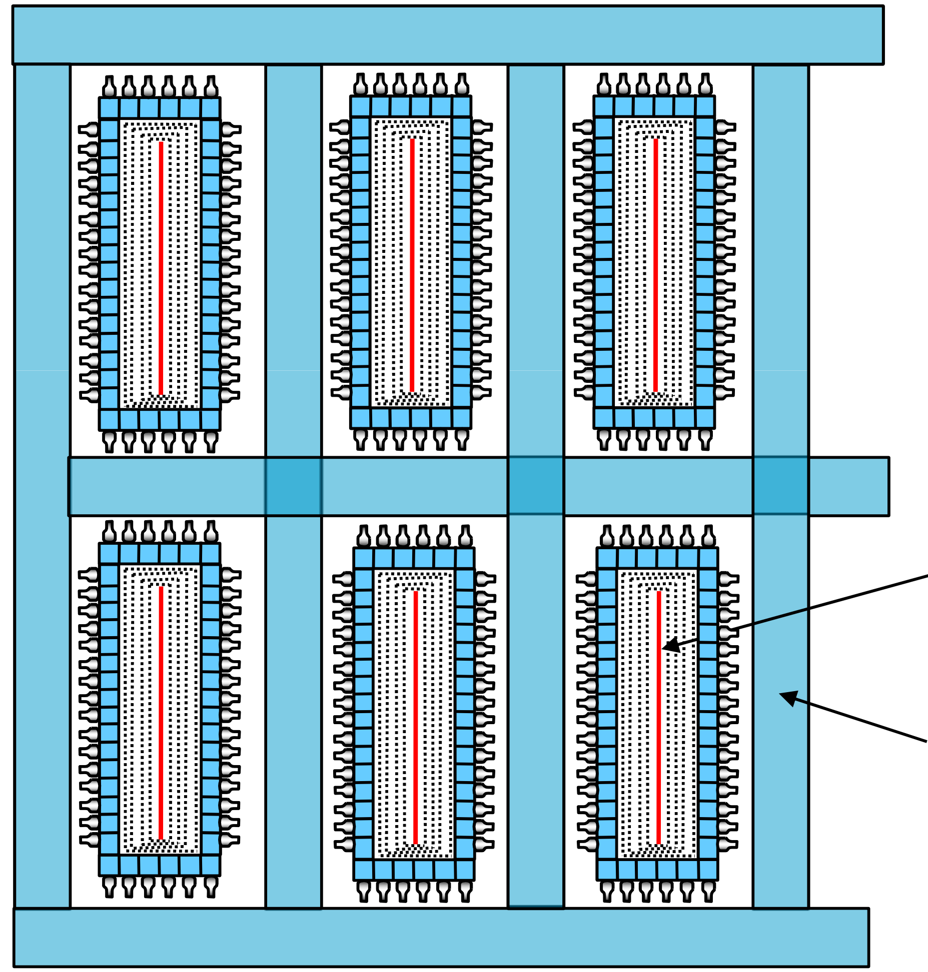


Side view

Very preliminary design



Single sub-module
with ~7 kg of isotope



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

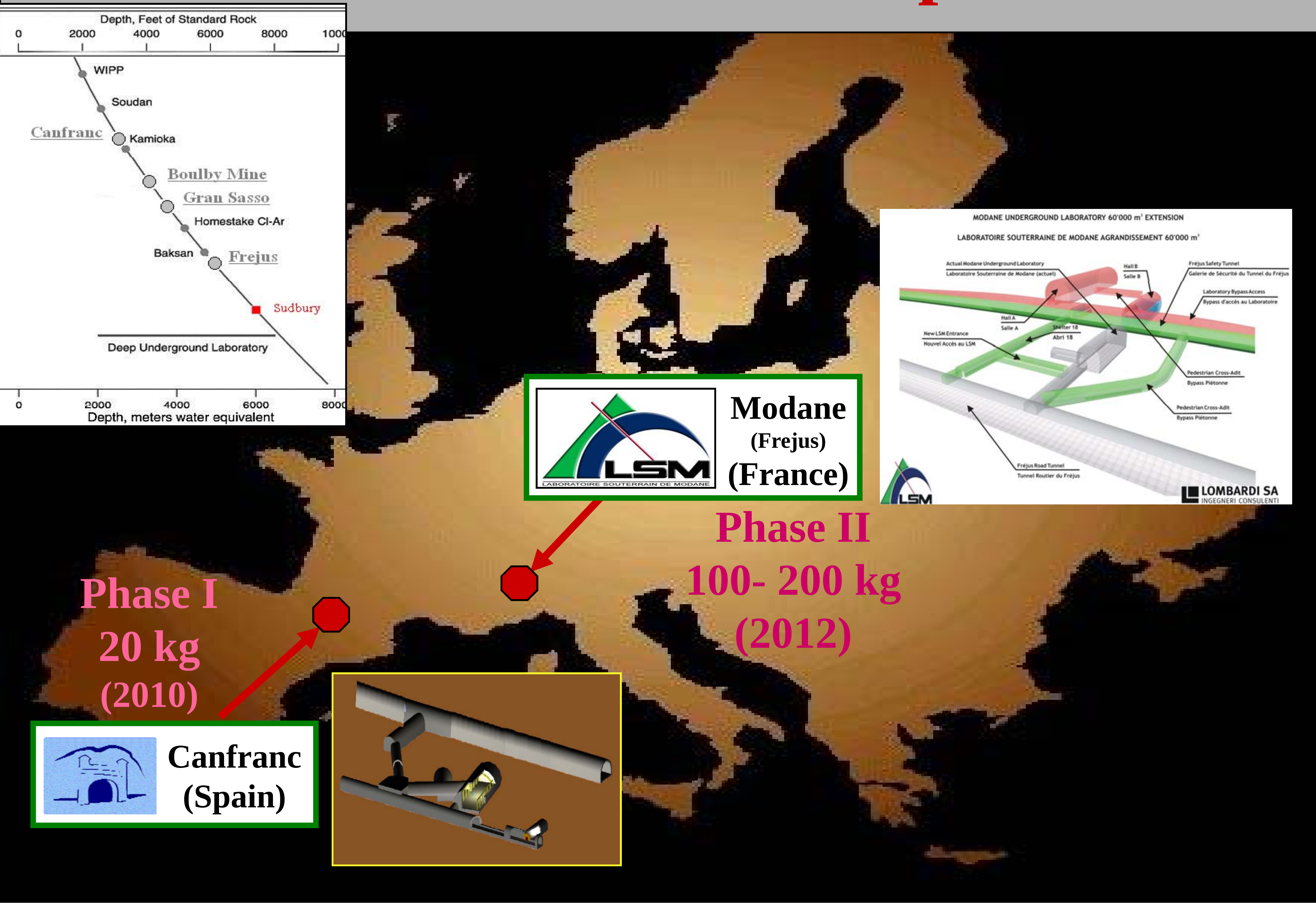
From NEMO-3 to SuperNEMO

NEMO-3		SuperNEMO
^{100}Mo	Choice of isotope	^{82}Se or ^{150}Nd
7 kg	Isotope mass M	100-200 kg
8% @3MeV	Energy resolution FWHM (calorimeter)	4% @ 3MeV
8 %	Efficiency $\varepsilon(\beta\beta0\nu)$	~ 30 %
^{208}Tl < 20 μBq/kg ^{214}Bi < 300 μBq/kg	*Internal radiopurity* *^{208}Tl and ^{214}Bi* *in the $\beta\beta$ foils*	^{208}Tl < 2 μBq/kg (*If ^{82}Se*: ^{214}Bi < 10 μBq/kg)
$T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y $\langle m_\nu \rangle < 0.3 – 1.3$ eV	SENSITIVITY	$T_{1/2}(\beta\beta0\nu) > (1\text{-}2)\cdot 10^{26}$ y $\langle m_\nu \rangle \sim 40\text{-}140$ meV

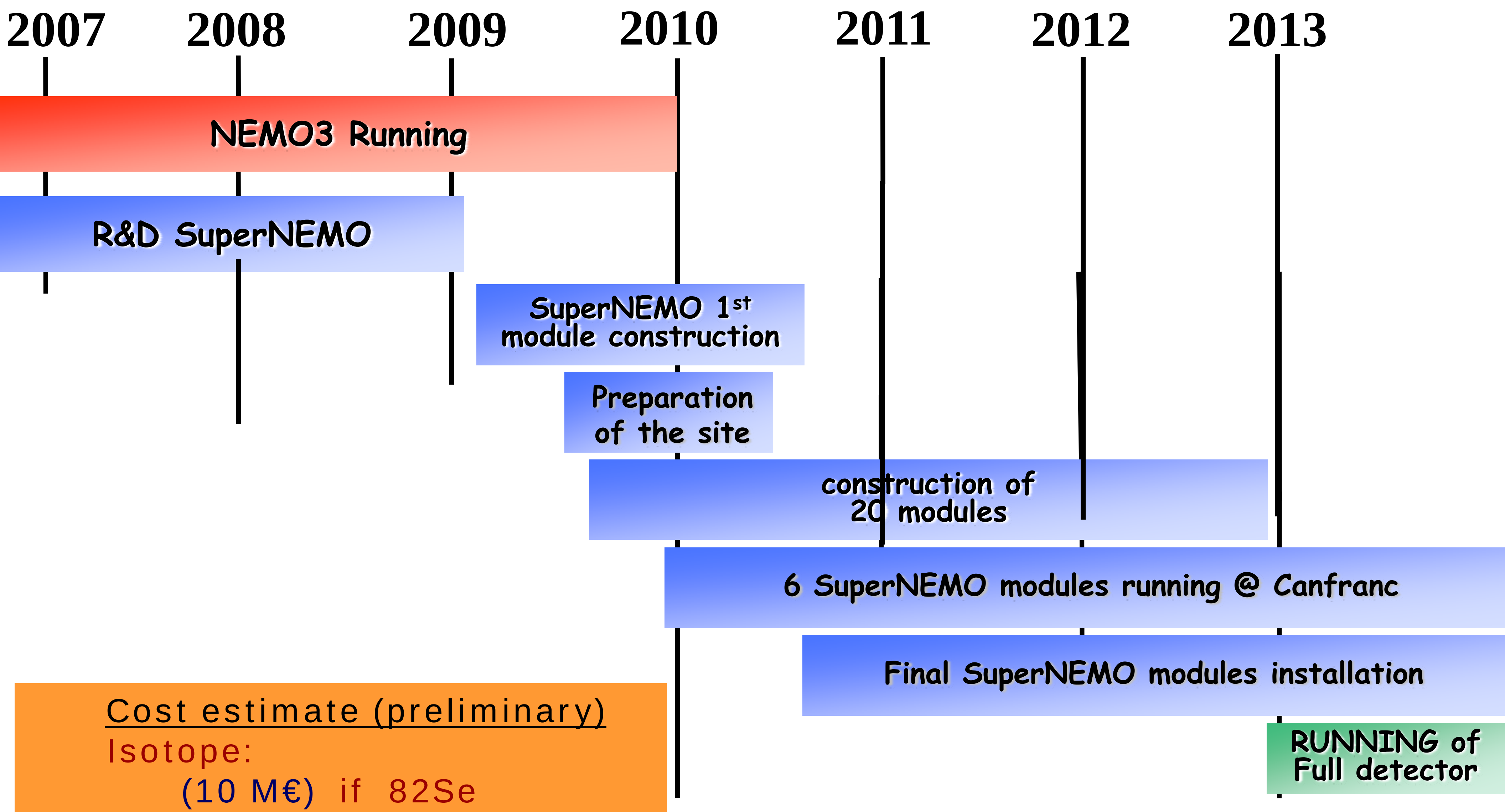
Main R&D tasks:

1) ββ source production
2) Energy resolution
3) Radiopurity
4) Tracking

Possible location for SuperNEMO



Schedule / cost



Cost estimate (preliminary)

Isotope:

(10 M€) if 82Se

20 M€ if 150Nd (AVLIS)

Detector:

20 M€

Grand Total: 40 - 50 M€

CONCLUSION

- **NEMO-3:**

  - strong limits on **0ν**-decay (**^{100}Mo** and **^{82}Se**, **$5.8\cdot10^{23}$** and **$2.1\cdot10^{23}$** y respectively) have been obtained

  - strong limits on **0ν**-decay with **Majoron** emission (**^{100}Mo** and **^{82}Se**) have been obtained

  - **2ν**-decay for **^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te** and **^{150}Nd** have been investigated

  - is taking data and all results will be improved in the future

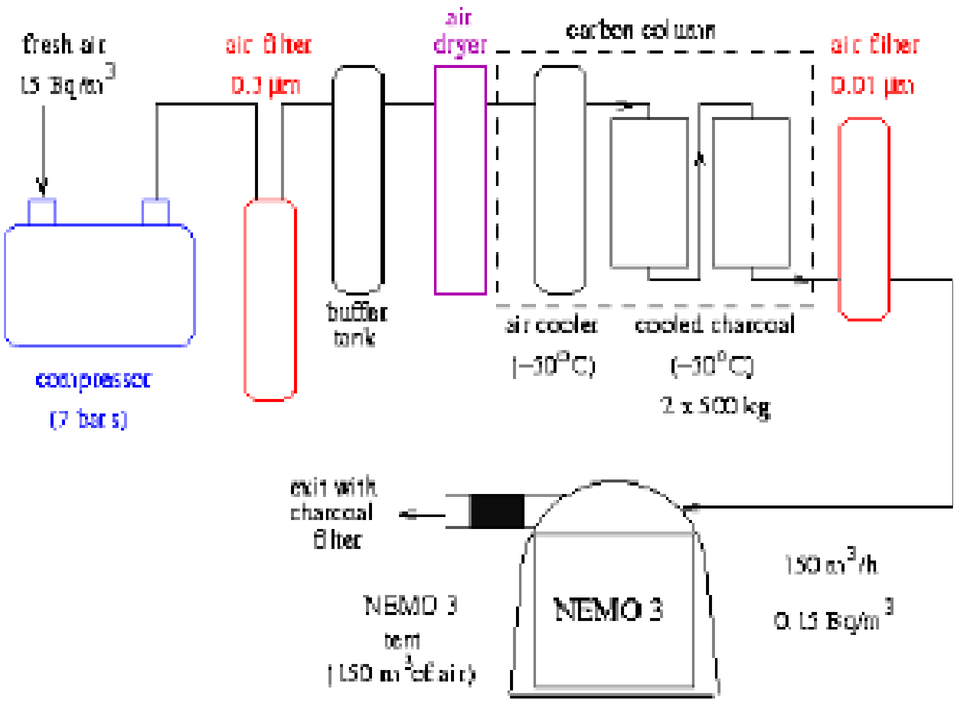
- **SuperNEMO:**

  - is on **R&D** stage

  - beginning of running in ~ **2010** (a few modules) and ~**2012-2013** (full detector)

BACKUP SLIDES

Radon purification facility



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

1 ton charcoal @ -50^{o}C, 7 bars

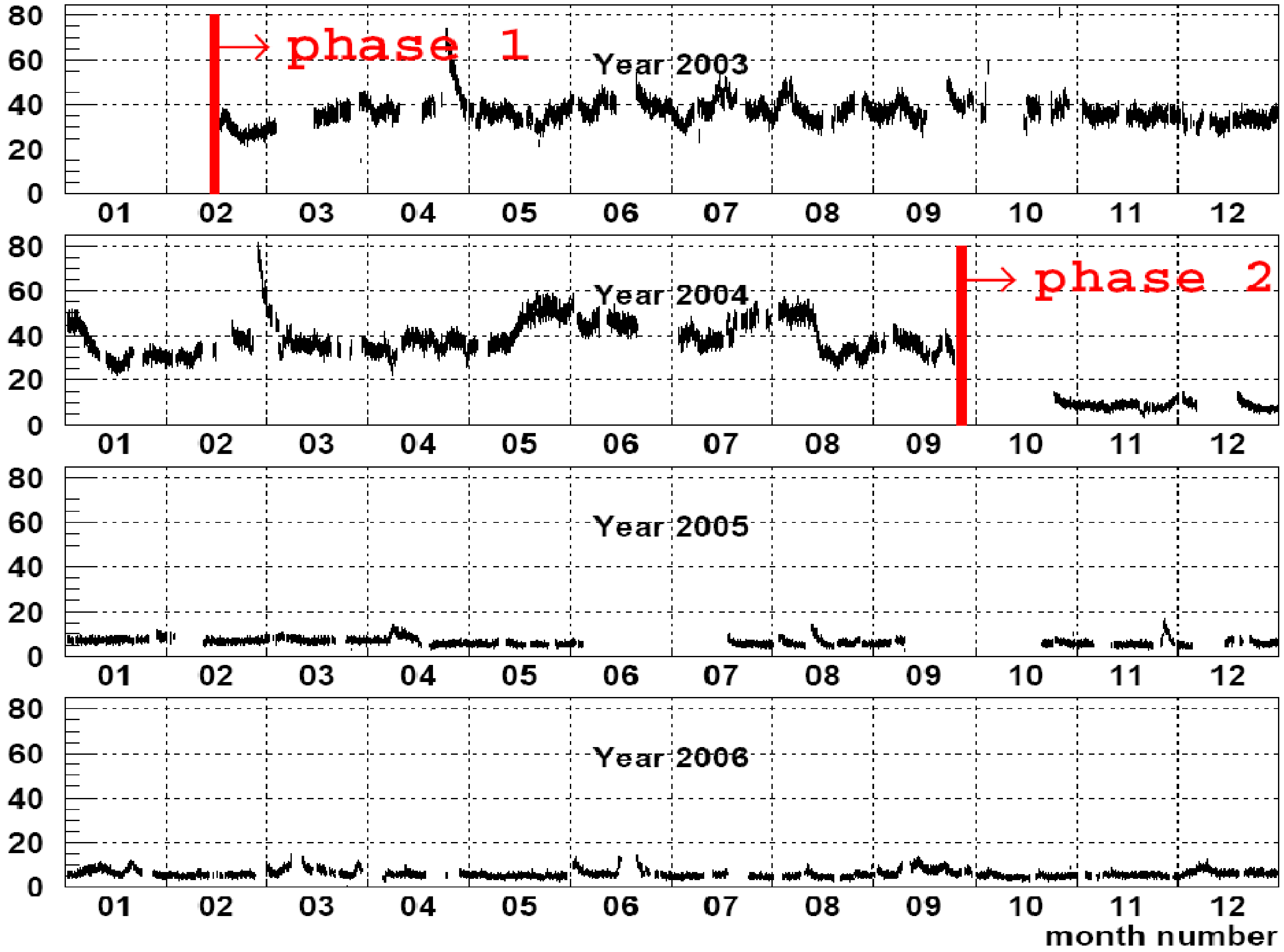
Flux: 150 m^3/h

Activity of ^{222}Rn :

Before Facility = 15 Bq/m^3

After Facility < 15 mBq/m^3

Radon purification facility, effect inside NEMO3



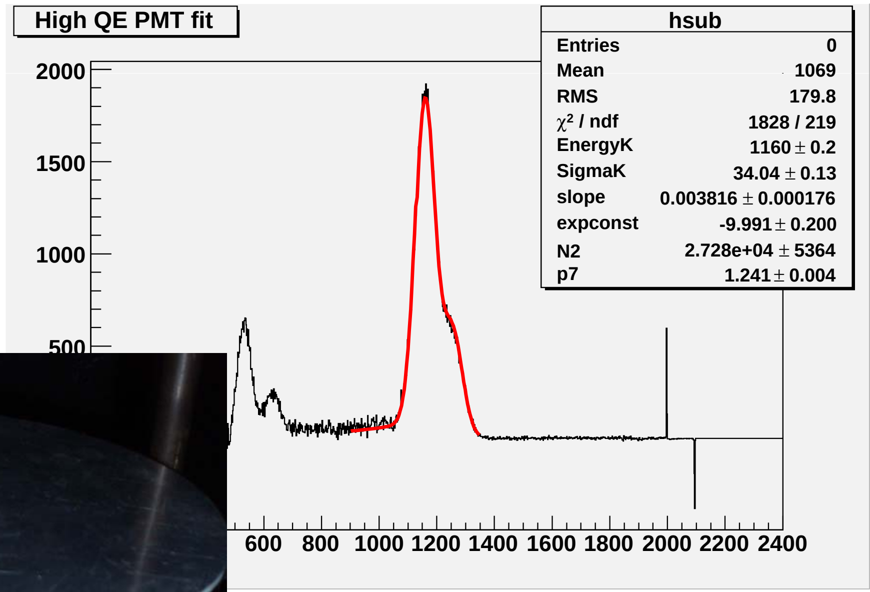
Best present limits on $<m_\nu>$

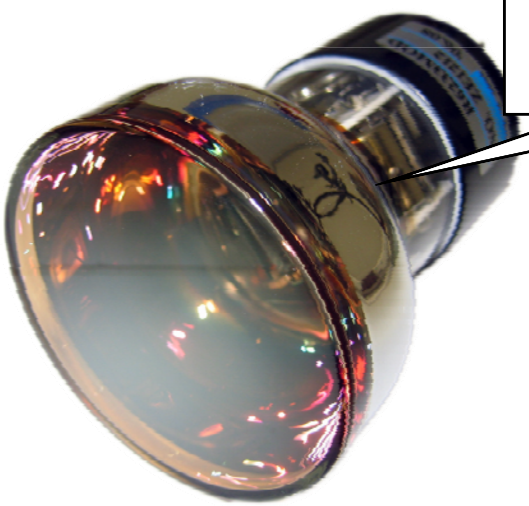
Nuclei	$T_{1/2}$, y	$<m_\nu>$, eV QRPA [MEDEX07]	$<m_\nu>$, eV [SM]	Experiment
^{76}Ge	$>1.9\cdot10^{25}$ $\approx1.2\cdot10^{25}$(?) $\approx2.2\cdot10^{25}$(?) $>1.6\cdot10^{25}$	< 0.22-0.41 ≈ 0.28-0.52(?) ≈ 0.21-0.38(?) <0.24-0.44	< 0.69 ≈ 0.87(?) ≈ 0.64(?) <0.75	HM Part of HM'04 Part of HM'06 IGEX
^{130}Te	$>3.0\cdot10^{24}$	< 0.34-0.57	< 1.08	CUORICINO
^{100}Mo	$>5.8\cdot10^{23}$	< 0.81-1.28	-	NEMO
^{136}Xe	$>4.5\cdot10^{23}$	< 1.41-2.67	< 3.02	DAMA
^{82}Se	$>2.1\cdot10^{23}$	< 1.40-2.17	< 4.47	NEMO
^{116}Cd	$>1.7\cdot10^{23}$	< 1.45-2.76	< 3.76	SOLOTVINO

SM: E. Caurier, F. Nowacki, A. Poves, Int.J.Mod.Phys. E16 (2007) 552

Calorimeter R&D

- Goal: FWHM ≈ $7\%/\sqrt{E} \Rightarrow 4\%$ at 3 MeV (Currently 14-16%/$\sqrt{E}$ in NEMO3)
- A combination of energy losses in the foil and calorimeter resolution
- Studies
  - Organic (plastic and liquid)
  - Shape, size, coating
  - PMTs (Photonics, Hamamatsu, ETL)
  - Light guides, optical contact
  - Chemistry





High QE Hamamatsu tube

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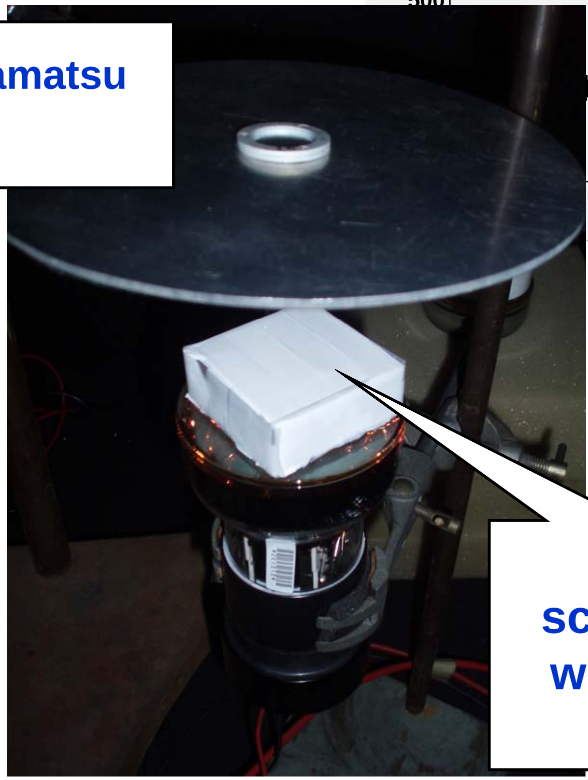

BC404 scintillator wraped in teflon

=

$\Delta E/E = 6.5\%$ at 1 MeV
$\Downarrow$
3.8% at 3 MeV if $1/\sqrt{E}$