# Are Neutrinos Majorana Particles ?

## Super-NEMO - a possible experiment to test it!

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Uniwersytet Warszawski, Wydzial Fizyki, Hoza 69, Warszawa
Pazdziernik 28, 2005

# Disclaimer/clarification/ acknowledgements

- I have no expertise in this field
- I have many questions myself
- Lot's of borrowed slides
    - C. Augier, X. Sarazin, F. Piquemal, R. Arnold… (NEMO-3)
    - P. Vogel, B. Kayser, S. Elliot….
- I have exploited the patience of
    - Alexei Smirnov and Duane Dicus
- This talk has too many slides… (will skip or skim over many)

# *Outline*

- *Neutrino Physics ("political") landscape*
- *Physics motivations for* 0νββ
- *NEMO-3*
- *Super-NEMO*
- *Competition (or complementary experiments)*
- *Any US future for Super-NEMO?*

# Motivation

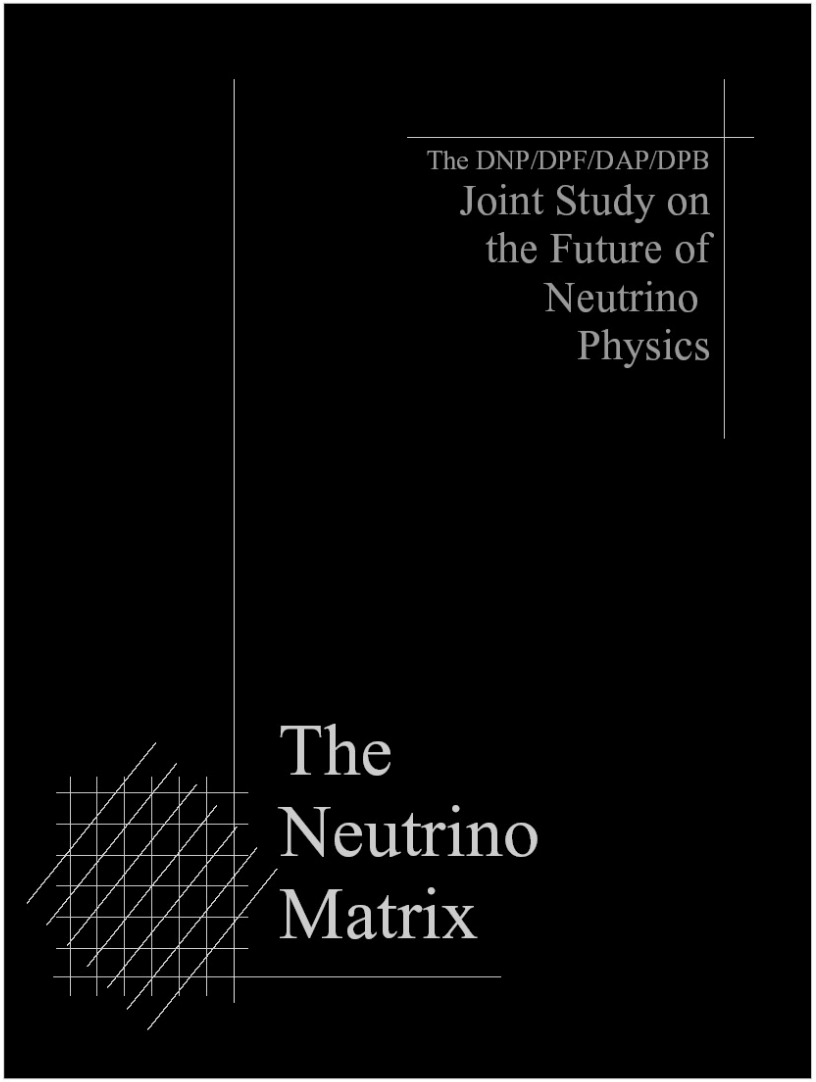
- **Determine fundamental property of an elementary particle**

  **(A. Smirnov:… “presently, one of two main questions about neutrinos”…)**
- **It will likely have far-reaching consequences in particle physics and cosmology**

- **Inherently, a particle physics problem…**
- **… but most experiments are very much un-particle physics-like (at least in a traditional accelerator sense) with little expertise in hep/np communities**

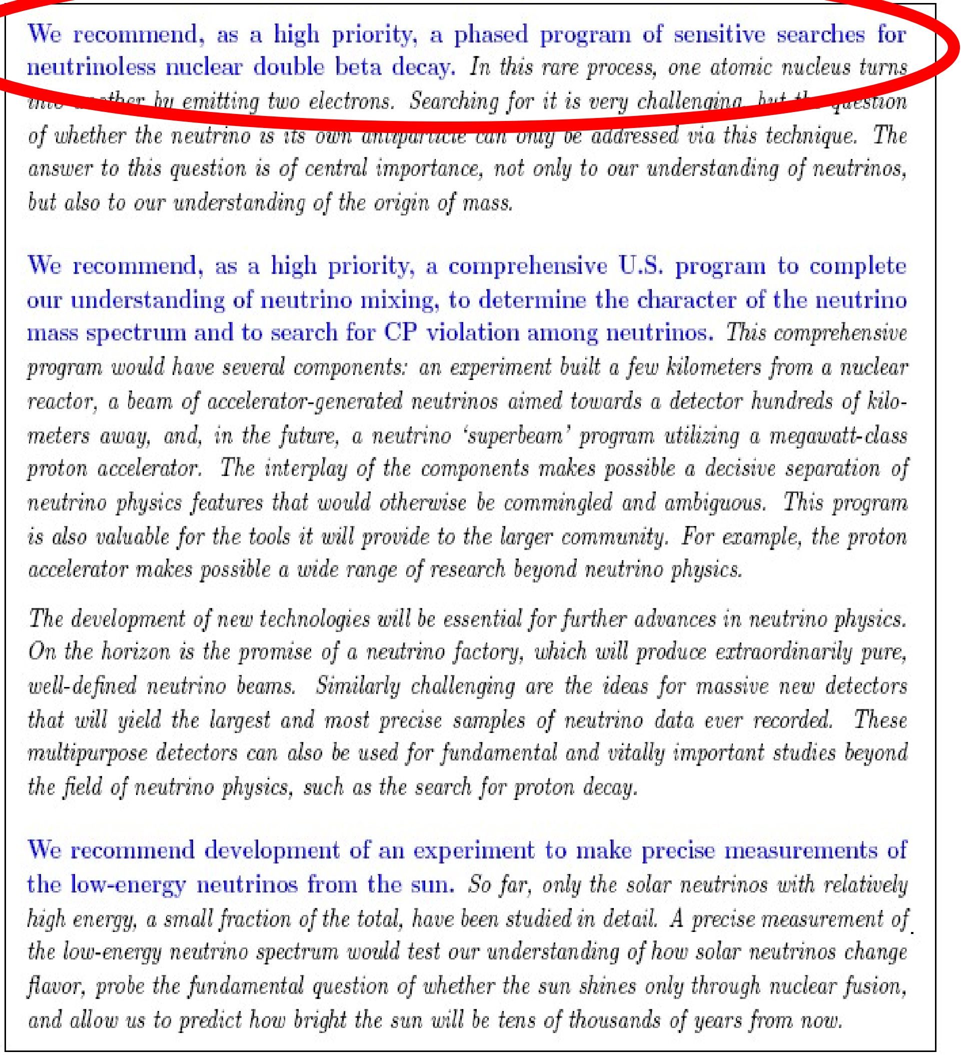
- **NEMO and Super-NEMO use hep/np techniques (at ~1MeV scale) !**
- **A <u>compelling</u> argument for an hep experimentalist.**

# *The Neutrino Matrix*



The DNP/DPF/DAP/DPB
Joint Study on
the Future of
Neutrino
Physics

The
Neutrino
Matrix



**We recommend, as a high priority, a phased program of sensitive searches for neutrinoless nuclear double beta decay.** *In this rare process, one atomic nucleus turns into another by emitting two electrons. Searching for it is very challenging, but the question of whether the neutrino is its own antiparticle can only be addressed via this technique. The answer to this question is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.*

**We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum and to search for CP violation among neutrinos.** *This comprehensive program would have several components: an experiment built a few kilometers from a nuclear reactor, a beam of accelerator-generated neutrinos aimed towards a detector hundreds of kilometers away, and, in the future, a neutrino 'superbeam' program utilizing a megawatt-class proton accelerator. The interplay of the components makes possible a decisive separation of neutrino physics features that would otherwise be commingled and ambiguous. This program is also valuable for the tools it will provide to the larger community. For example, the proton accelerator makes possible a wide range of research beyond neutrino physics.*

*The development of new technologies will be essential for further advances in neutrino physics. On the horizon is the promise of a neutrino factory, which will produce extraordinarily pure, well-defined neutrino beams. Similarly challenging are the ideas for massive new detectors that will yield the largest and most precise samples of neutrino data ever recorded. These multipurpose detectors can also be used for fundamental and vitally important studies beyond the field of neutrino physics, such as the search for proton decay.*

**We recommend development of an experiment to make precise measurements of the low-energy neutrinos from the sun.** *So far, only the solar neutrinos with relatively high energy, a small fraction of the total, have been studied in detail. A precise measurement of the low-energy neutrino spectrum would test our understanding of how solar neutrinos change flavor, probe the fundamental question of whether the sun shines only through nuclear fusion, and allow us to predict how bright the sun will be tens of thousands of years from now.*

# Fundamental 'Matrix' questions

Experimental Questions

- Are neutrinos their own anti-particles?
- What are the masses of the neutrinos?
- Do neutrinos violate the CP symmetry?
- Are there sterile neutrinos?
- Do neutrinos have exotic properties?

Theoretical / phenomelogical Question

- What do neutrinos tell us about the new models of physics and the evolution of the universe?
- What is the role of neutrinos in shaping the universe?
- Are neutrinos the key to the understanding of the matter-antimatter asymmetry of th Universe?
- What can neutrinos teach us about astrophysical objects

  and Ultra High Energy Cosmic Rays?

- *Are neutrinos their own anti-particles?*
  - *Neutrino-less double beta decay expts.*

    *IGEX, Heidelberg-Moscow, CUORicino, NEMO,...*

- *What are the masses/mixings of the neutrinos?*
  - *Long baseline experiments*

    *SuperK, SNO, K2K, KamLAND, MINOS, NEXTEX, KATRIN, reactor expts*

- *Do neutrinos violate the CP symmetry?*
  - *Future offaxis experiments:*

    *NOvA, T2K, …*

- *Are there sterile neutrinos?*
  - *Long and short baseline experiments: SuperK, MINOS, MiniBooNE,…*

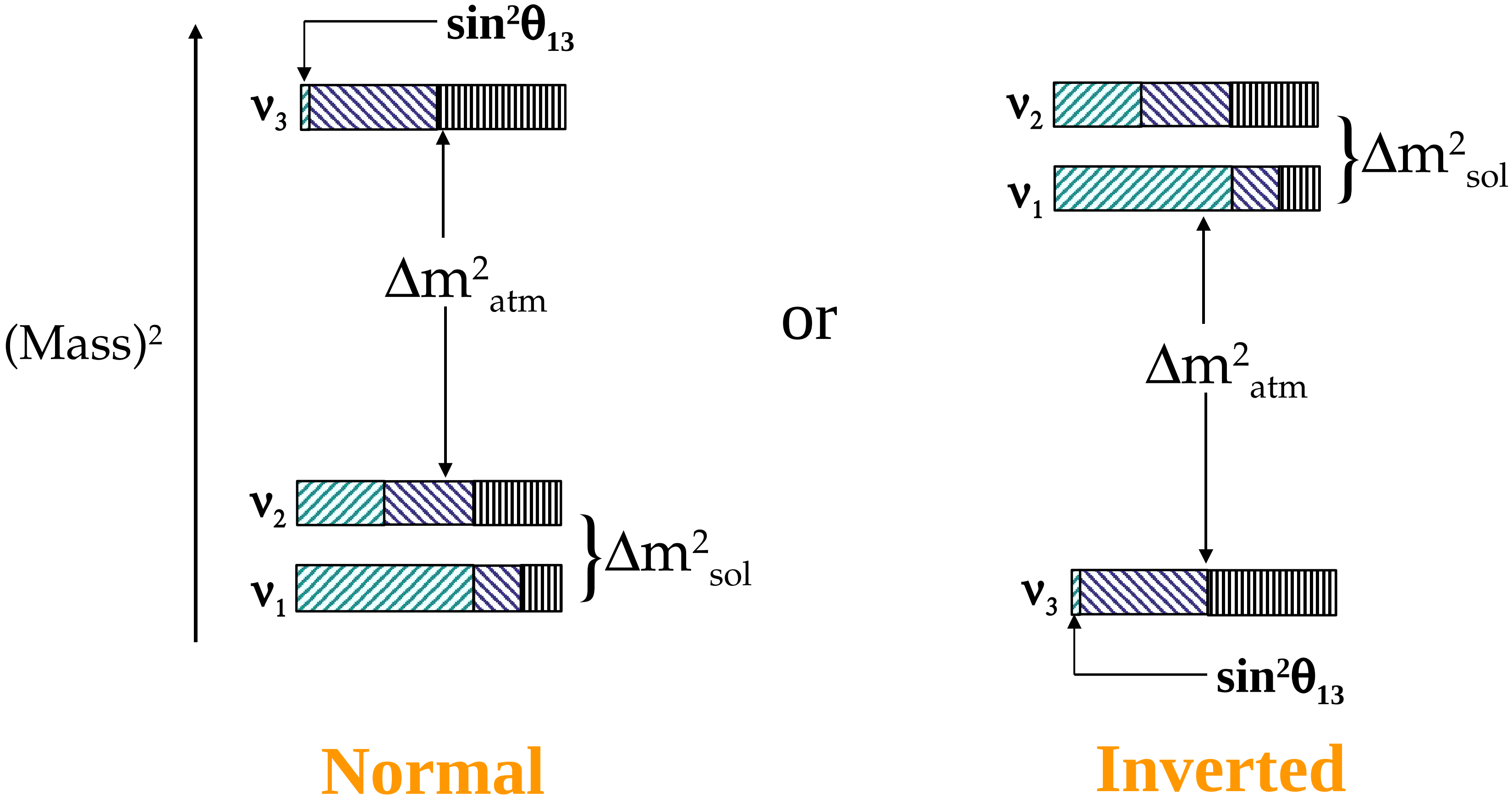
- *Do neutrinos have exotic properties?*
  - *All experiments try to shed some light*

## *Several categories of experiments*

*And now there is also NuSAG (Neutrino Scientific Assessment Group) to recommend the specific projects… (more later or if asked…)*

**(from B. Kayser)**

# *Neutrino (Mass)$^2$ spectrum*

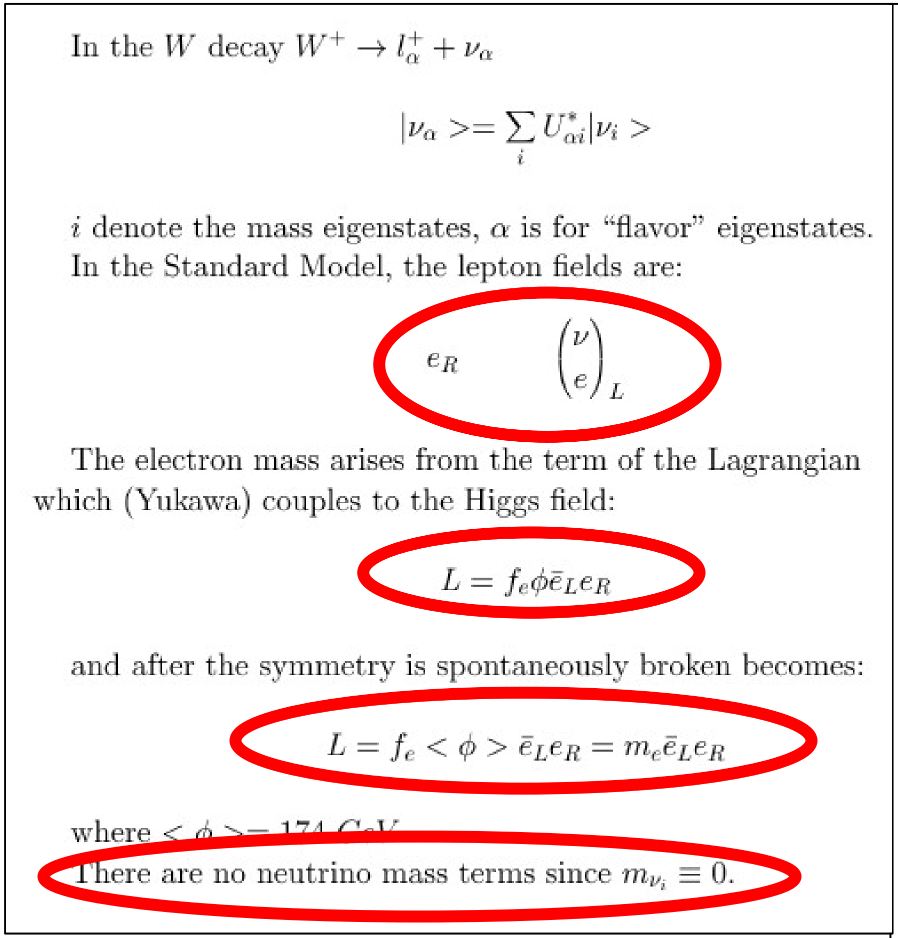


$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ \mathrm{eV}^2, \qquad \Delta m^2_{atm} \cong 2.5 \times 10^{-3}\ \mathrm{eV}^2$

Are there *more* mass eigenstates, as LSND suggests?

▨ $\nu_e$ [ $|U_{ei}|^2$ ]  ▧ $\nu_\mu$[ $|U_{\mu i}|^2$ ]  ▥ $\nu_\tau$[ $|U_{\tau i}|^2$ ]

# *Dirac and Majorana mass terms*



In the $W$ decay $W^+ \to l_\alpha^+ + \nu_\alpha$

$$|\nu_\alpha >= \sum_i U^*_{\alpha i} |\nu_i >$$

$i$ denote the mass eigenstates, $\alpha$ is for "flavor" eigenstates. In the Standard Model, the lepton fields are:

$$e_R \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

The electron mass arises from the term of the Lagrangian which (Yukawa) couples to the Higgs field:

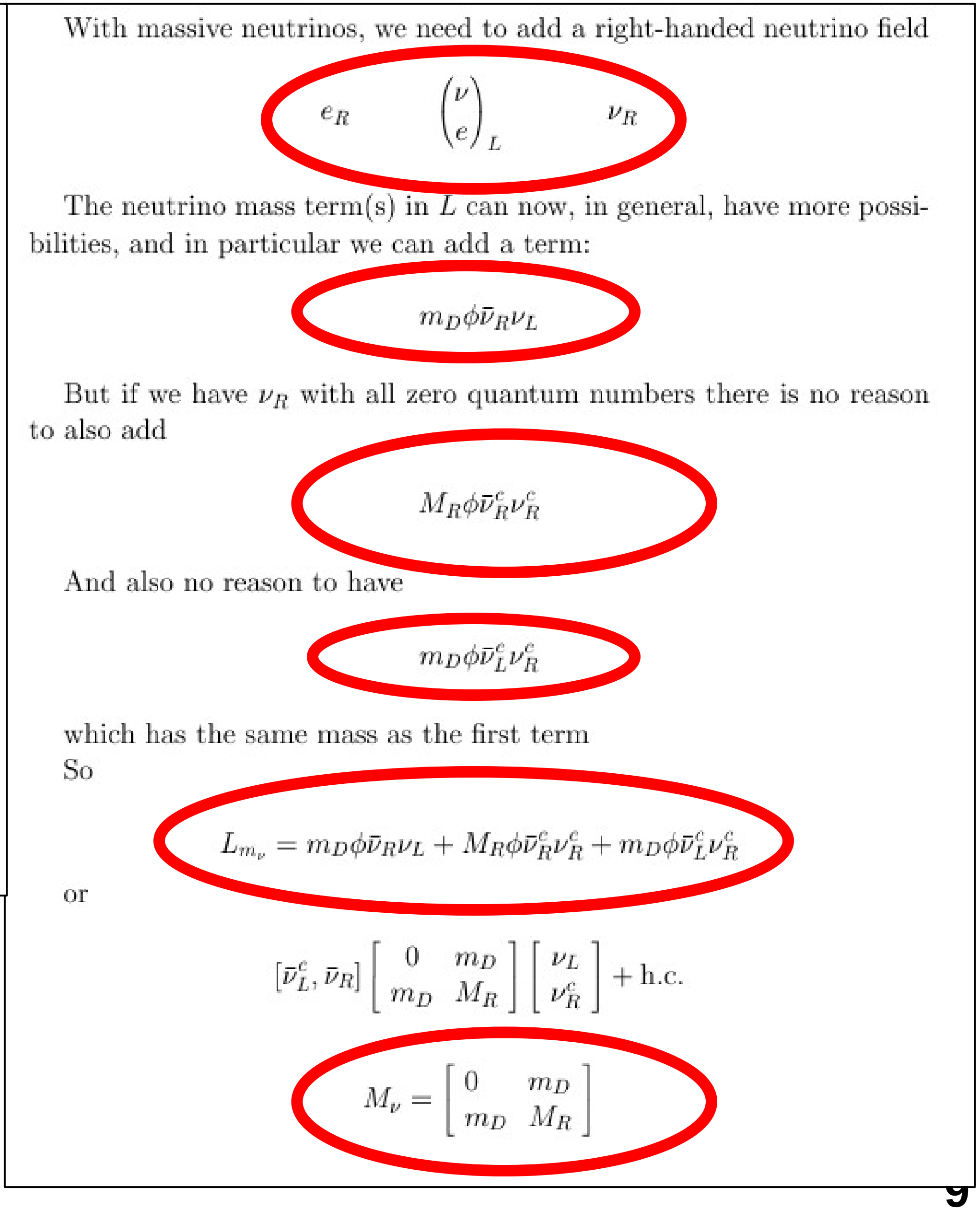
$$L = f_e \phi \bar{e}_L e_R$$

and after the symmetry is spontaneously broken becomes:

$$L = f_e < \phi > \bar{e}_L e_R = m_e \bar{e}_L e_R$$

where $< \phi >= 174$ GeV

There are no neutrino mass terms since $m_{\nu_i} \equiv 0$.



With massive neutrinos, we need to add a right-handed neutrino field

$$e_R \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \nu_R$$

The neutrino mass term(s) in $L$ can now, in general, have more possibilities, and in particular we can add a term:

$$m_D \phi \bar{\nu}_R \nu_L$$

But if we have $\nu_R$ with all zero quantum numbers there is no reason to also add

$$M_R \phi \bar{\nu}^c_R \nu^c_R$$

And also no reason to have

$$m_D \phi \bar{\nu}^c_L \nu^c_R$$

which has the same mass as the first term

So

$$L_{m_\nu} = m_D \phi \bar{\nu}_R \nu_L + M_R \phi \bar{\nu}^c_R \nu^c_R + m_D \phi \bar{\nu}^c_L \nu^c_R$$

or

$$[\bar{\nu}^c_L, \bar{\nu}_R] \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu^c_R \end{bmatrix} + \text{h.c.}$$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix}$$

# The see-saw mechanism

$$L_{m_\nu} = m_D \phi \bar{\nu}_R \nu_L + M_R \phi \bar{\nu}_R^c \nu_R^c + m_D \phi \bar{\nu}_L^c \nu_R^c$$

$$[\bar{\nu}_L^c, \bar{\nu}_R] \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R^c \end{bmatrix} + \text{h.c.}$$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & M_R \end{bmatrix}$$

can be diagonalized

$$Z^T M_\nu Z = D_\nu$$

where

$$D_\nu = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$$

$$Z = \begin{bmatrix} 1-\rho^2 & \rho \\ -\rho & 1 \end{bmatrix} \begin{bmatrix} i & 0 \\ 0 & 1-\rho^2 \end{bmatrix}$$

and the $D_\nu$ becomes:

$$D_\nu = \begin{bmatrix} \frac{m_D^2}{M_R} & 0 \\ 0 & M_R \end{bmatrix}$$

where

$$m_1 \simeq \frac{m_D^2}{M_R} \quad \text{and} \quad m_2 \simeq M_R$$

Thus, $L_{m_\nu}$ equals to:

$$L_{m_\nu} = m_1 \bar{\nu}_1 \nu_1 + M_R \bar{\nu}_2 \nu_2$$

where

$$\nu_1 = -i(1 - \frac{1}{2}\rho^2)(\nu_L - \nu_L^c) + i\rho(\nu_R^c - \nu_R)$$

$$\nu_2 = \rho(\nu_L + -\nu_L^c) + (1 - \frac{1}{2}\rho^2)(\nu_R + \nu_R^c)$$

with

$$\nu_1^c = C\gamma^0 \nu_1^* = \nu_1$$
$$\nu_2^c = C\gamma^0 \nu_2^* = \nu_2$$

# Ettore Majorana

(Catania, Sicily, 1906 -
Tirrenian Sea (supposedly), 1938)

- Published 9 papers in his lifetime, (including his 1932 relativistic theory of particles with arbitrary spin)
- His final paper in 1937 was "A Symmetrical Theory of the Electron and the Positron" (introduced the revolutionary concept of what's now known as a "Majorana particle"
- Archived papers in the Domus Galileana in Pisa show that he had already formulated these ideas in 1933

(CERN Courier, 2005)

**Fermi:**

**There are many categories of scientists, people of second and third rank, who do their best, but do not go very far. There are also people of first class, who make great discoveries, fundamental for the development of science. But then there are the geniuses, like Galilei and Newton.**

**Well, Ettore Majorana was one of them...**

# *Various and Complementary ways to measure* $m_\nu$

**Cosmology**

$$\Sigma = m_1 + m_2 + m_3$$

**Oscillation**

$$\delta m_{ij}^2 = m_j^2 - m_i^2$$

**Beta decay**

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

**ββ**

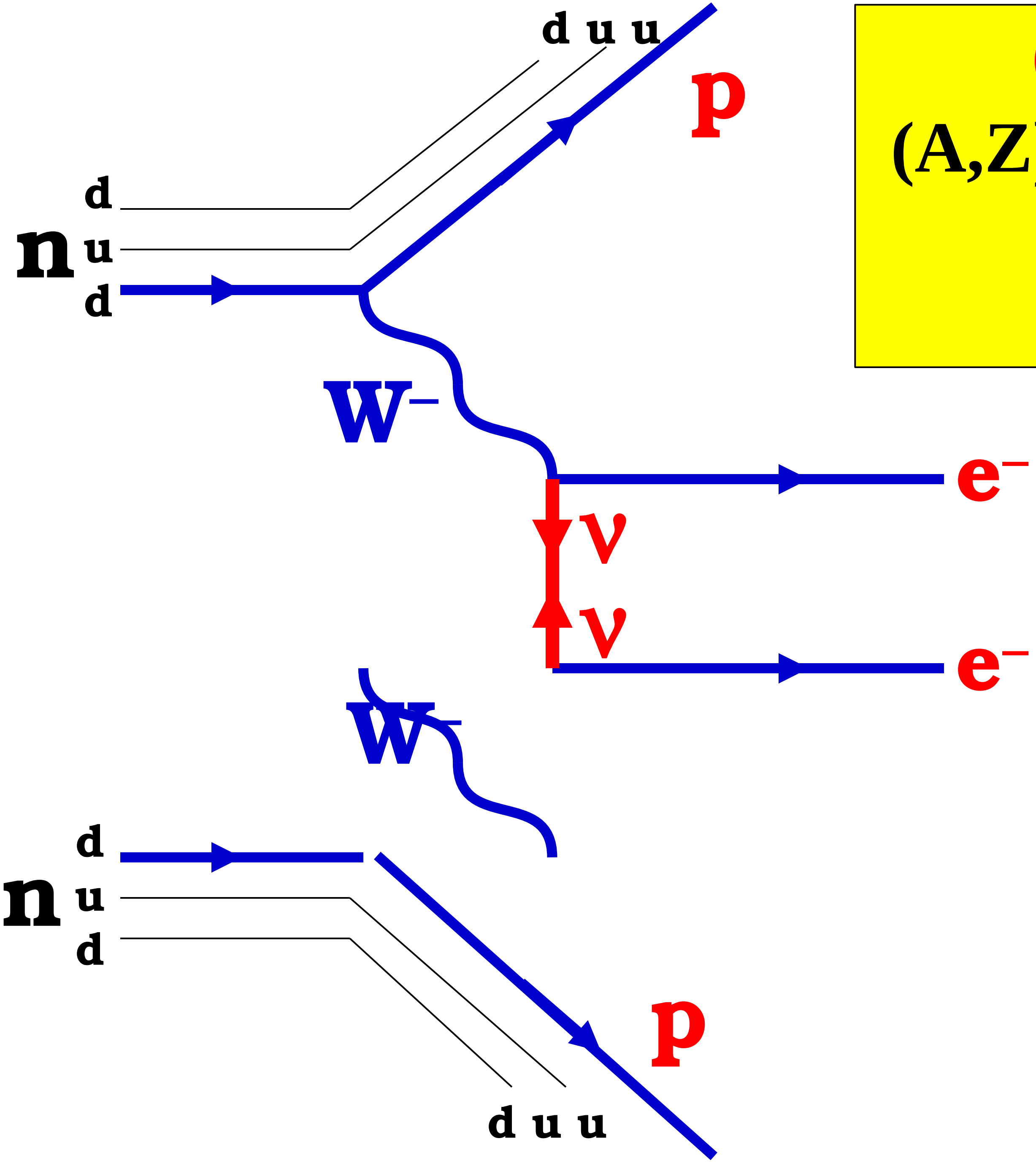
$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i$$

*Partial Slide from S. Elliott*

## 0νββ decay:

$(A,Z) \quad (A, Z+2) + 2e^-$

$\Delta L = 2$



$\nu = \bar{\nu}$

and

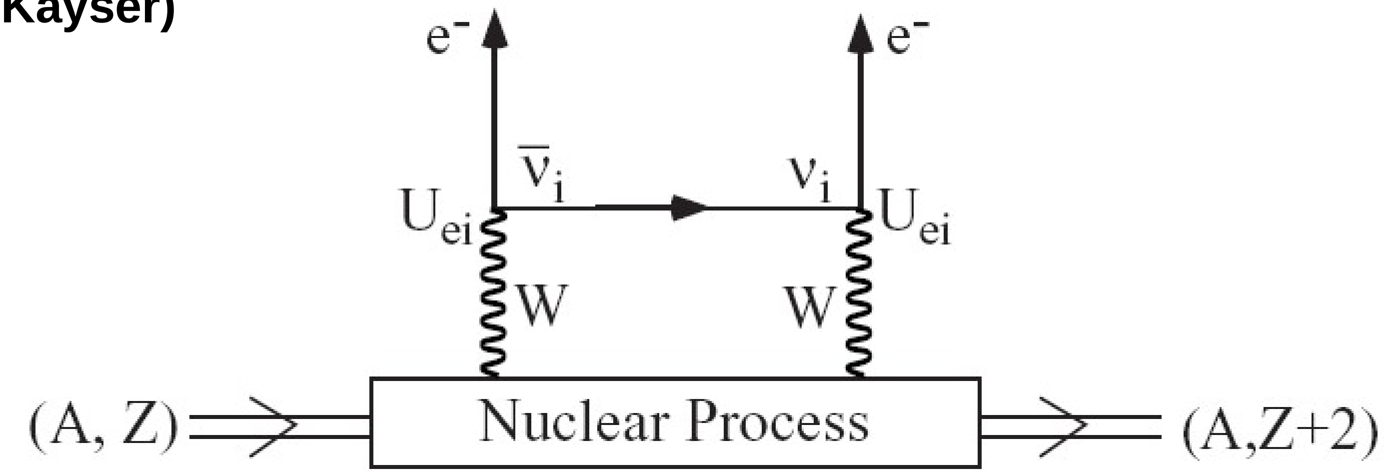
$m_\nu \neq 0$

(helicity has to flip)

*The lepton number is not conserved*

# Neutrinoless double beta decays

**(after B. Kayser)**



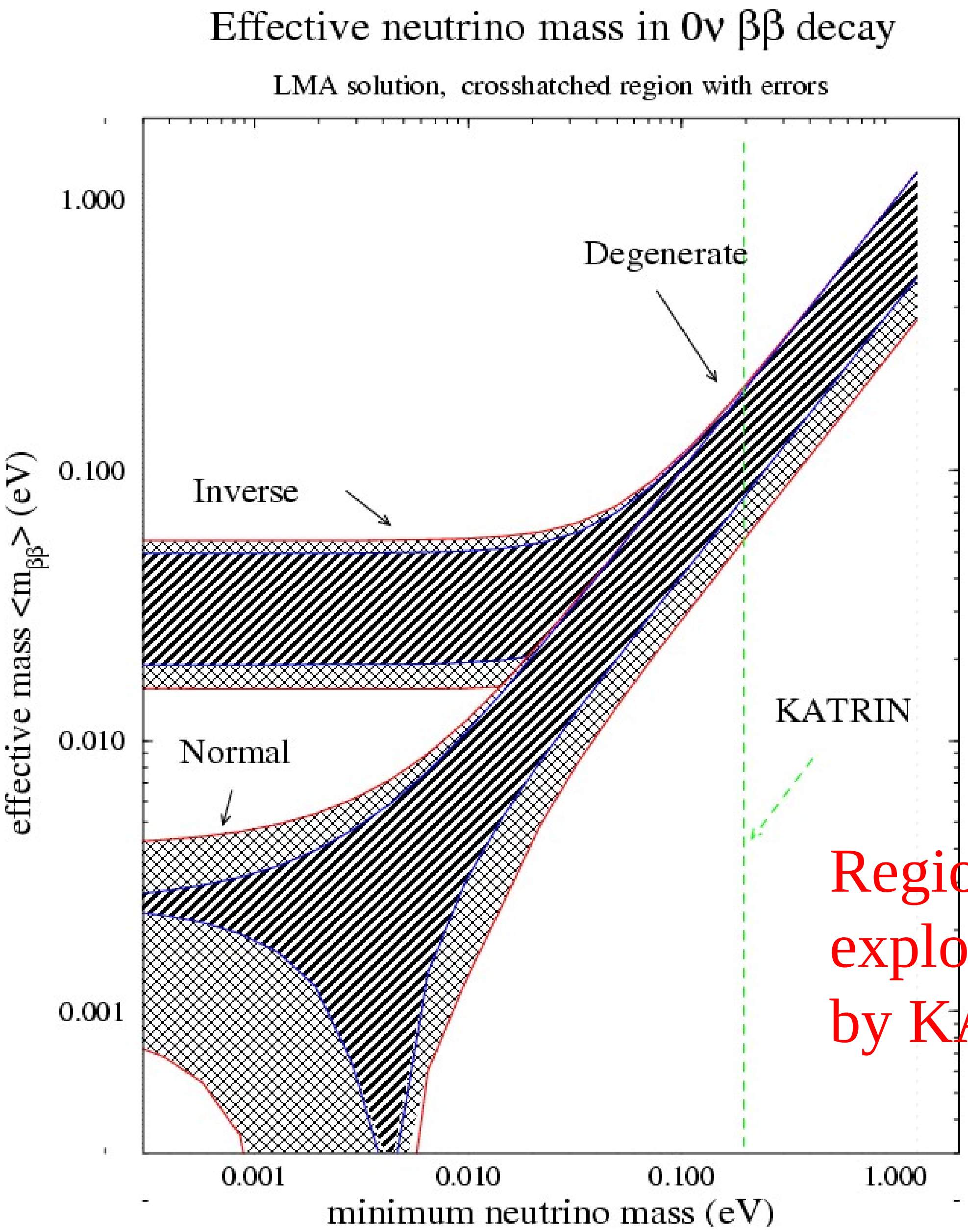
$$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G^{0\nu}(E_0, Z) \left| M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_\nu \rangle^2$$

$$|\langle m_\nu \rangle| \equiv ||U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2 \mathrm{e}^{\mathrm{i}\phi_2} + |U^L_{e3}|^2 m_3 \mathrm{e}^{\mathrm{i}\phi_3}|$$

$$|\langle m_\nu \rangle| = |(0.70 \pm 0.03) m_1 + (0.30 \pm 0.03) \mathrm{e}^{\mathrm{i}\phi_2} m_2 + (< 0.05) \mathrm{e}^{\mathrm{i}\phi_3} m_3|$$

$$\left| \sum_i m_i U_{ei}^2 \right| \equiv | < m_{\beta\beta} > |$$

$$| < m_{\beta\beta} > | \simeq m_0 \sqrt{1 - \sin^2 2\theta_\odot \sin^2 \left( \frac{\Delta\alpha}{2} \right)}$$



***Blue lines: LMA I (best fit only)***
***Red lines: errors in oscillation parameters included*.**

Region to be
explored
by KATRIN

# $\Delta L = 2$ processes

**$K^+$ $\pi^-\mu^+\mu^+$**

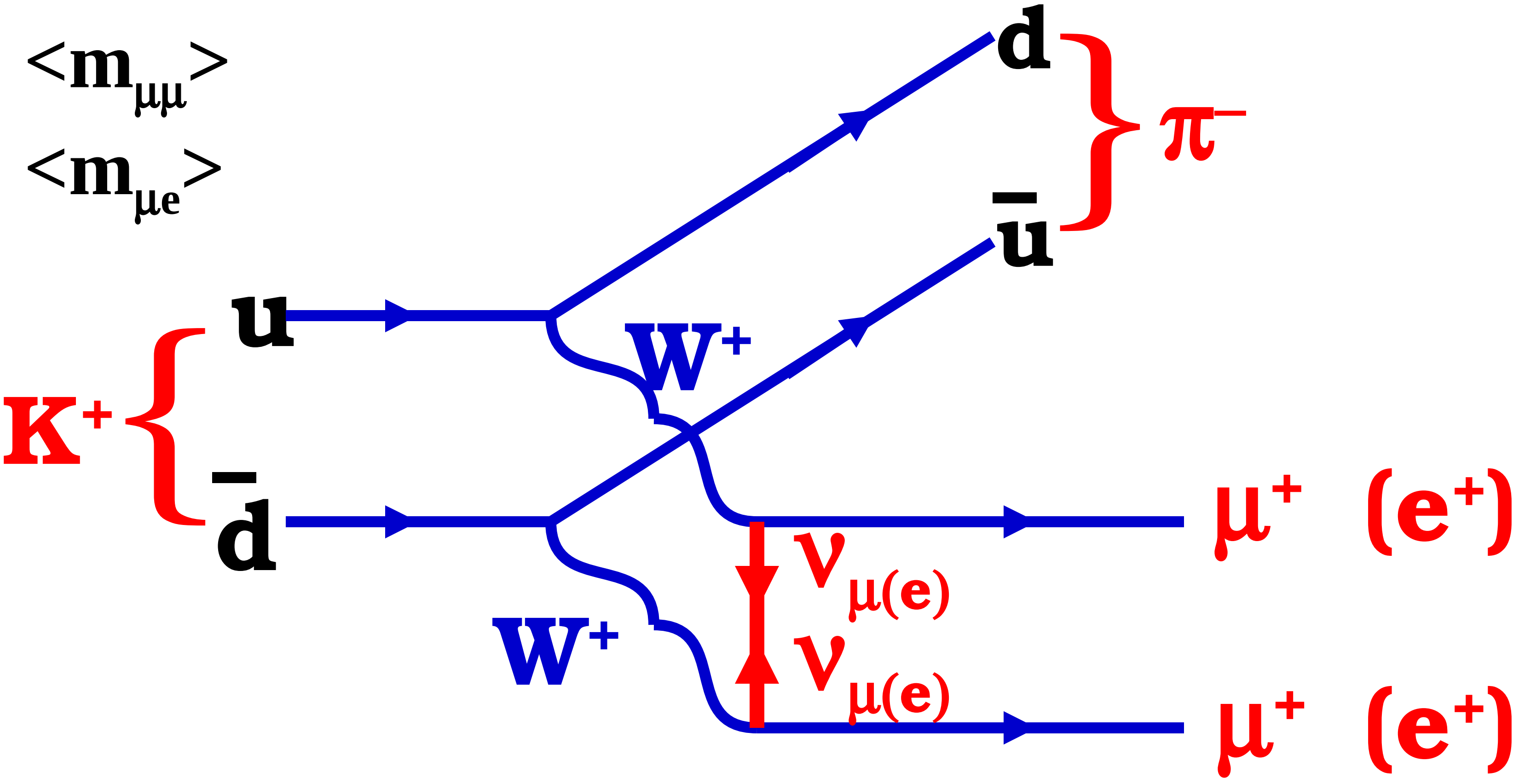
**$K^+$ $\pi^-e^+e^+$**

**$K^+$ $\pi^-\mu^+e^+$**

$\langle m_{ee} \rangle$

$\langle m_{\mu\mu} \rangle$

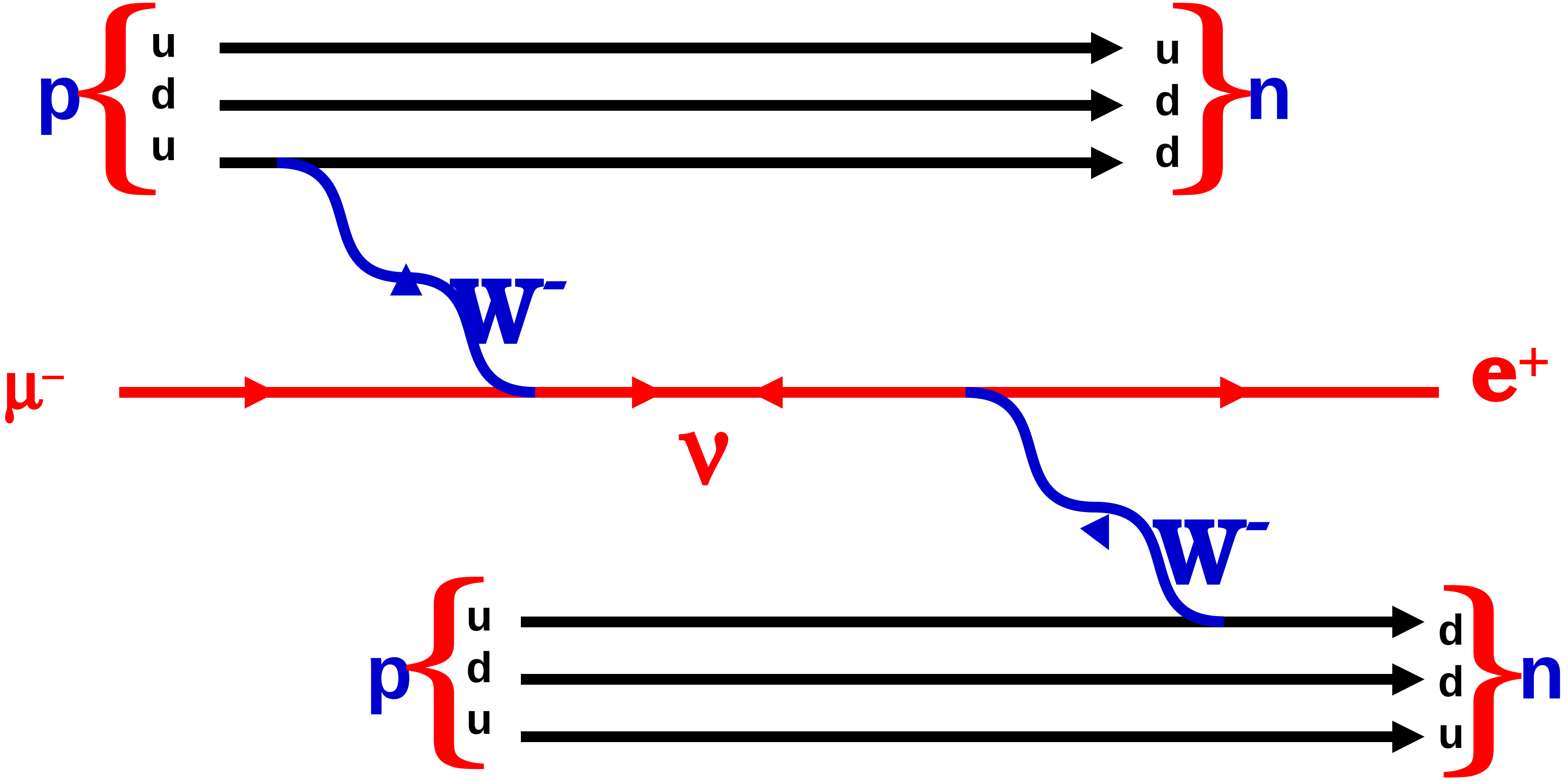
$\langle m_{\mu e} \rangle$



## $\mu^-$ to e+ conversion

$$\mu^- + (A,Z) \qquad (A, Z\text{-}2) + e^+$$

$$\Delta L = 2$$



$$BR(K^+ \to \pi^- \mu^+ \mu^+) \sim 10^{-(13\pm2)} r_{\mu\mu} \left| \sum_j U_{\mu j}^2 f(m_{\nu_j}/(100\ \mathrm{MeV}) \right|^2$$

$$|U_{\mu j}|^2 \left( \frac{m_{\nu_j}}{100\ \mathrm{MeV}} \right) < 4 \times 10^2 \left[ \frac{BR(K^+ \to \pi^- \mu^+ \mu^+)}{3 \times 10^{-9}} \right]^{1/2}$$

**$<m_{\mu\mu}>$ < 5000 GeV**

$$\Gamma = \frac{\Gamma(\mu^- + \mathrm{Ti} \to \mu^+ + \mathrm{Ca})}{\Gamma(\mu^- + \mathrm{Ti} \to \nu_\mu + \mathrm{Sc})} \simeq 5 \cdot 10^{-24} \left( \frac{\langle m_{\mu\mu} \rangle}{250 keV} \right)^2$$

**$<m_{\mu\mu}>$ < 150 GeV**

*L. Littenberg & R. Shrock, 2000*
*K. Zuber, 2000*
*S. Vogel & Vogel, 2002*

# ββ *History*

ββ(2ν) *rate first calculated by Maria Goeppert-Mayer in 1935*.

*First observed directly in 1987*.

*Why so long? Background*

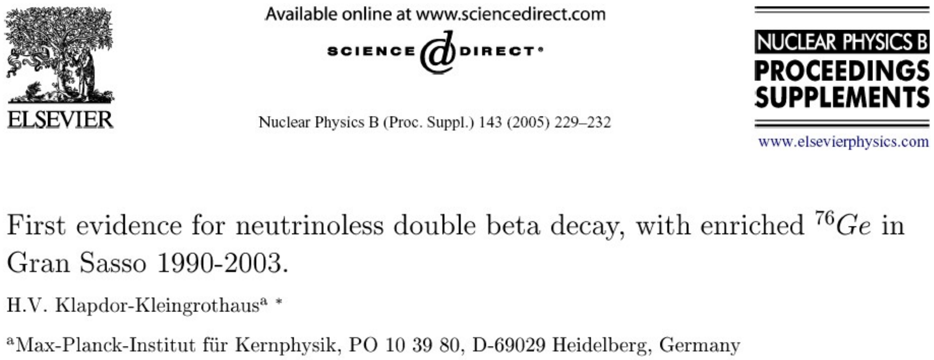
$\tau_{1/2}(\mathrm{U, Th}) \sim 10^{10}$ years

$\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{20}$ years

*But next we want to look for a process with:*

$\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{25\text{-}27}$ years

***2004 claim:***



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Nuclear Physics B (Proc. Suppl.) 143 (2005) 229–232

First evidence for neutrinoless double beta decay, with enriched $^{76}Ge$ in Gran Sasso 1990-2003.

H.V. Klapdor-Kleingrothaus[a] *

[a]Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany

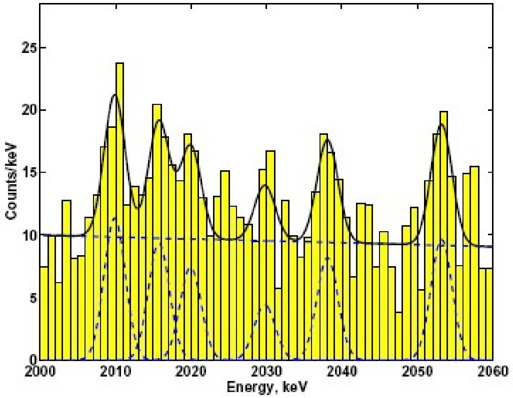
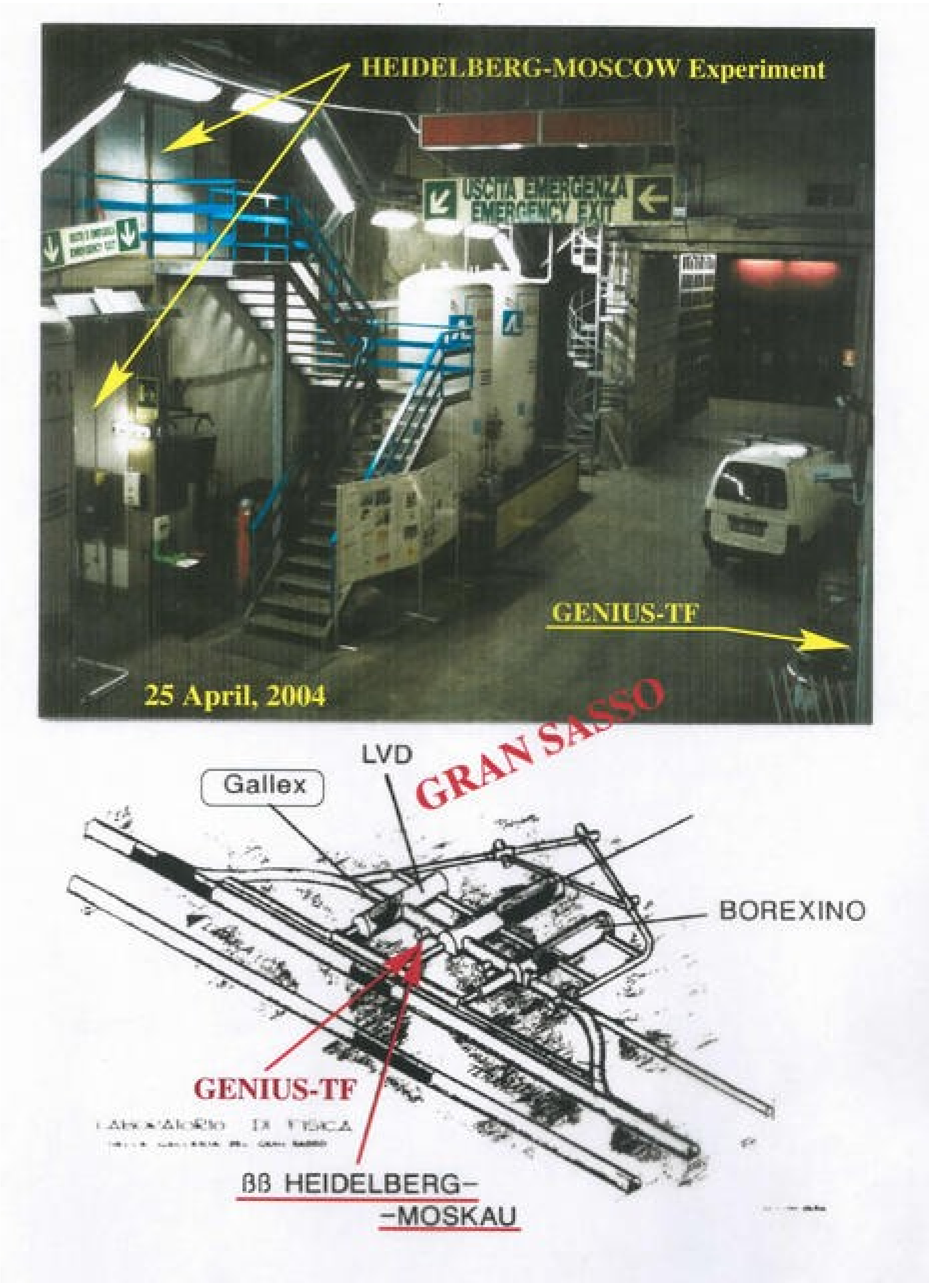
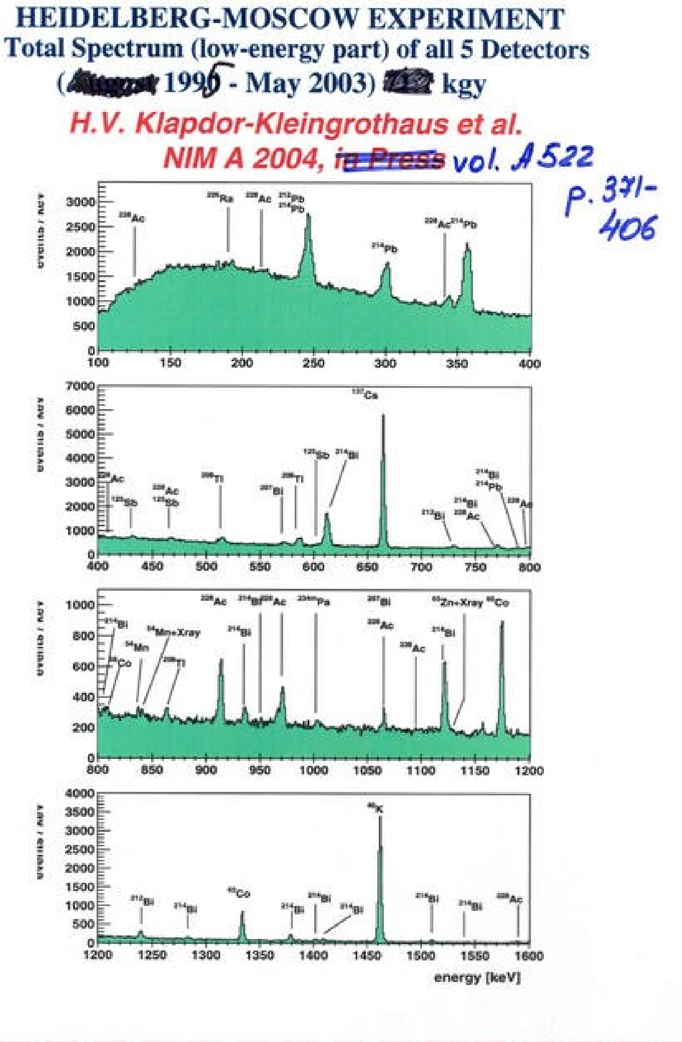


Figure 1. The total sum spectrum of all five detectors (in total 10.96 kg enriched in $^{76}Ge$), in the range 2000 - 2060 keV and its fit, for the period: August 1990 to May 2003 (71.7 kg y) (see [3]).


HEIDELBERG-MOSCOW Experiment
USCITA EMERGENZA
EMERGENCY EXIT
GENIUS-TF
25 April, 2004
GRAN SASSO
LVD
Gallex
BOREXINO
GENIUS-TF
LABORATORIO DI FISICA
ββ HEIDELBERG-
-MOSKAU

# *The 4.2 σ claim*



**HEIDELBERG-MOSCOW EXPERIMENT**

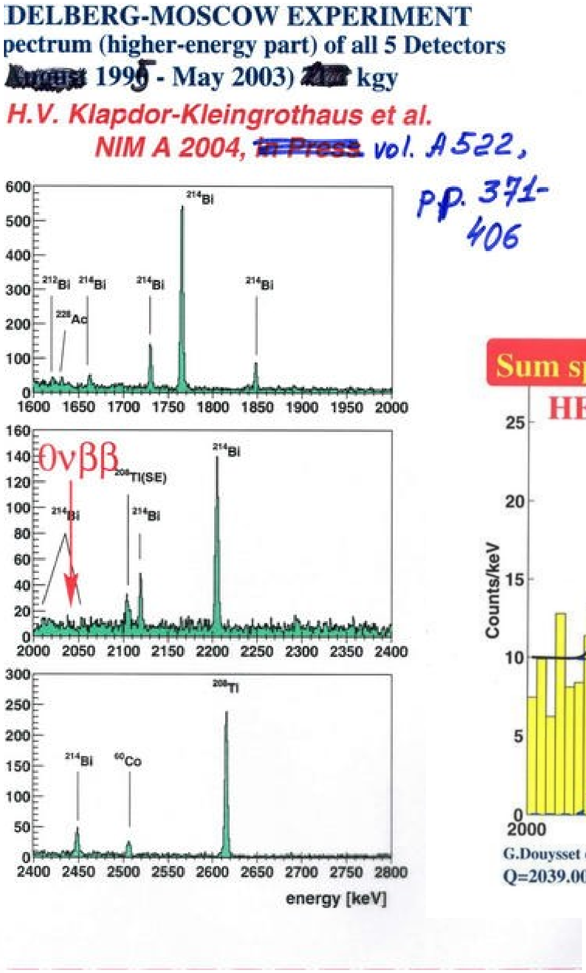
**Total Spectrum (low-energy part) of all 5 Detectors**

**([redacted] 1995 - May 2003) [redacted] kgy**

*H.V. Klapdor-Kleingrothaus et al.*

*NIM A 2004, ~~in Press~~ vol. A522*

p. 371-406



**DELBERG-MOSCOW EXPERIMENT**

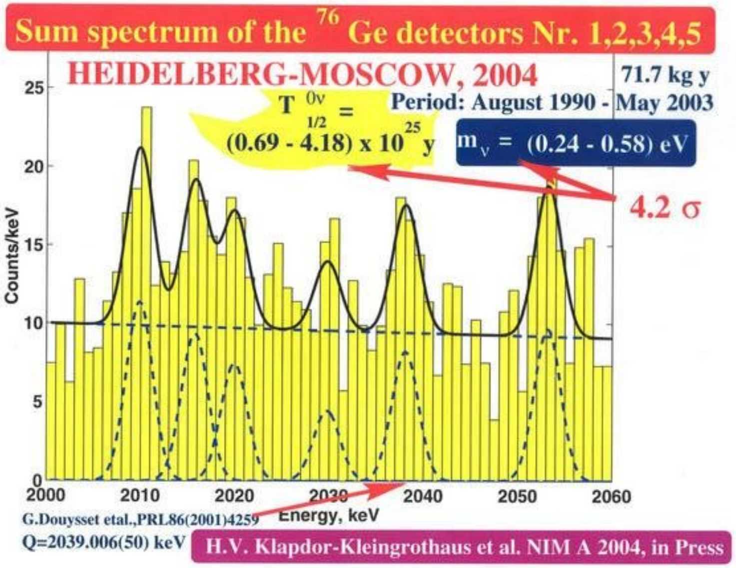
**pectrum (higher-energy part) of all 5 Detectors**

**[redacted] 1995 - May 2003) [redacted] kgy**

*H.V. Klapdor-Kleingrothaus et al.*

*NIM A 2004, ~~in Press~~ vol. A522,*

pp. 371-406



**Sum spectrum of the $^{76}$Ge detectors Nr. 1,2,3,4,5**

**HEIDELBERG-MOSCOW, 2004**

71.7 kg y

Period: August 1990 - May 2003

$T^{0\nu}_{1/2} = (0.69 - 4.18) \times 10^{25}$ y

$m_\nu = (0.24 - 0.58)$ eV

4.2 σ

G.Douysset etal.,PRL86(2001)4259

Q=2039.006(50) keV

H.V. Klapdor-Kleingrothaus et al. NIM A 2004, in Press

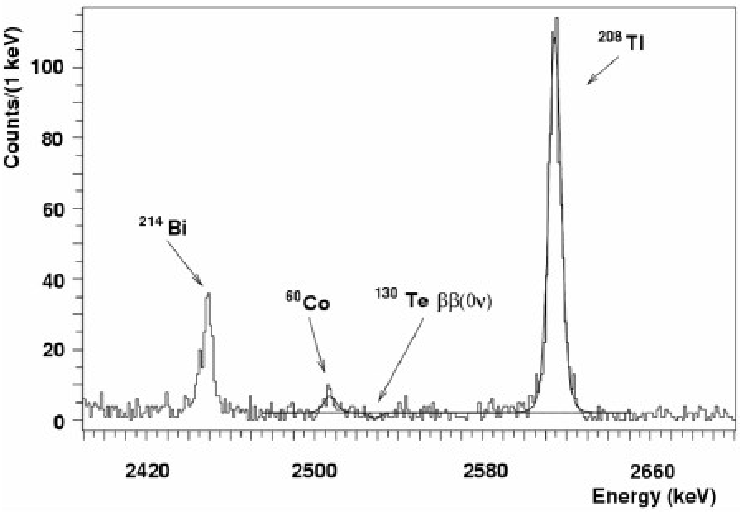
# *Main challenges in searching for* $0\nu\beta\beta$

**Decay rate is:** $1/T_{1/2} = G(E_{tot},Z)\, M^2 <m_{\beta\beta}>^2$

**G(E,Z)** *is a calculable phase space*
*M is a nuclear matrix element, calculable with difficulties*
$<m_{\beta\beta}>$ *is the effective neutrino Majorana mass*

*Have to suppress backgrounds due to natural radioactivity*
*omnipresent:*

$^{214}Bi$
$^{208}Tl$



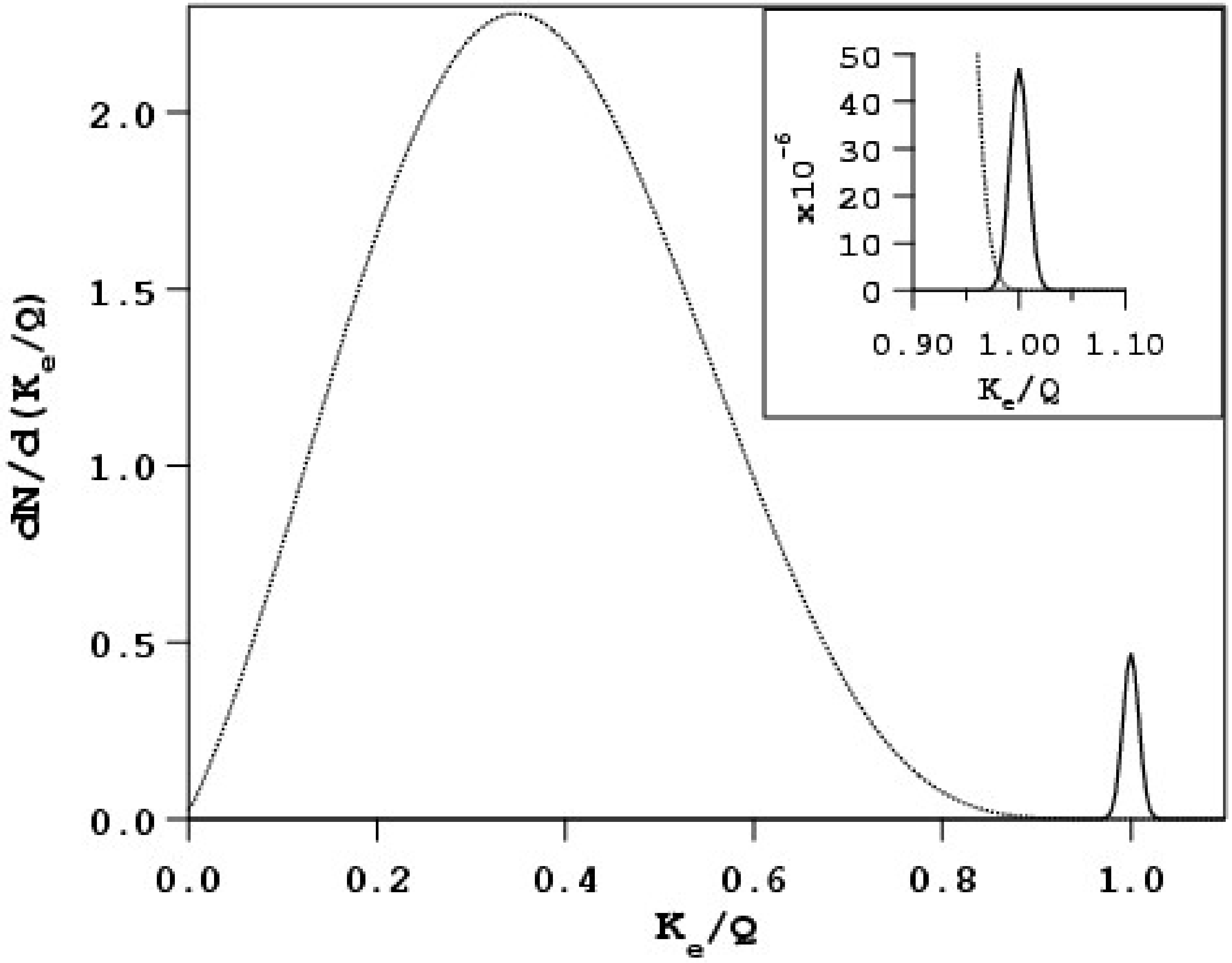
*Have to positively identify the final state (in most experiments just through an excellent energy resolution)*

# Candidate Nuclei for Double Beta Decay

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

# *The $2\nu$ decay is an unavoidable background*

With 2% resolution:

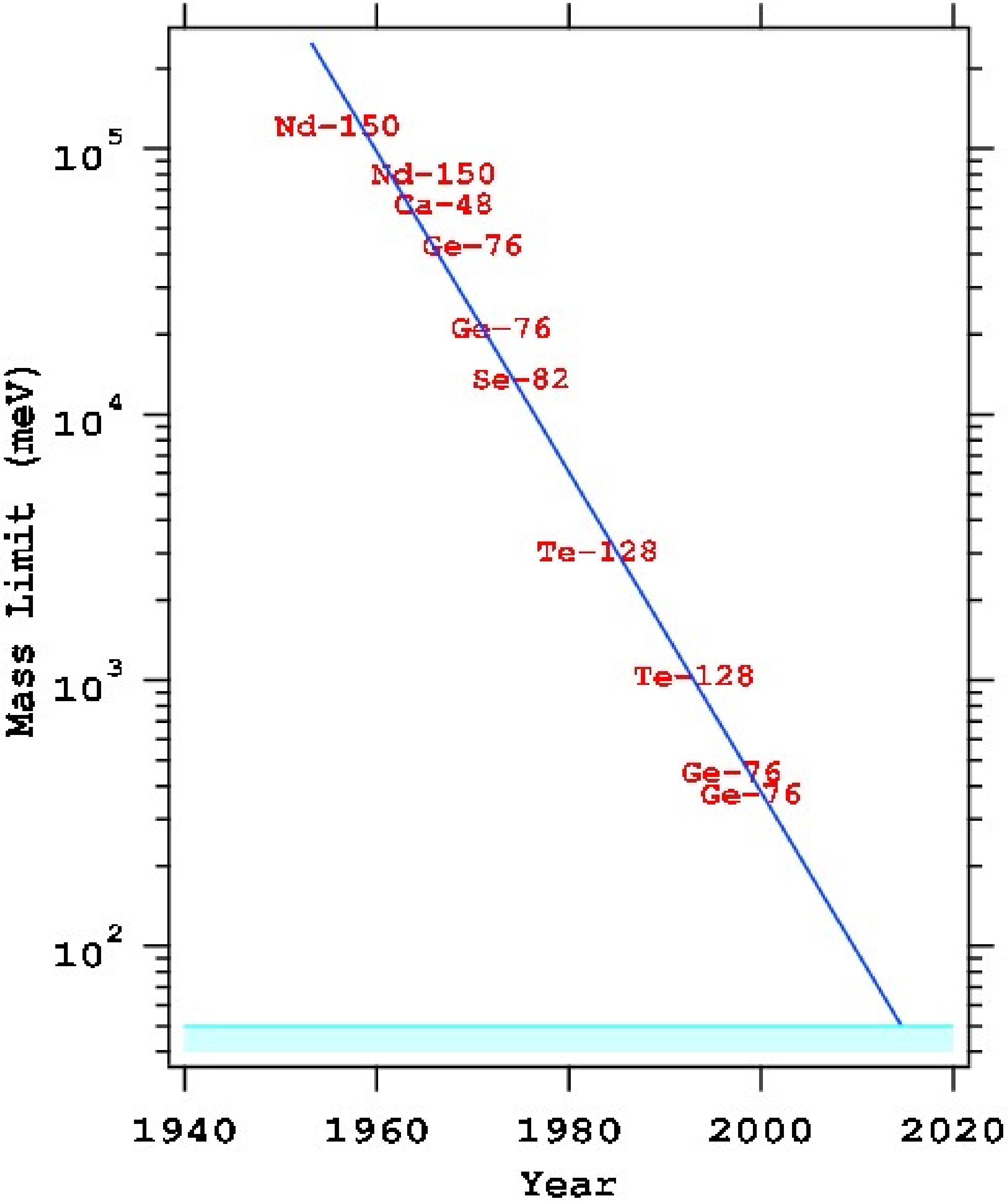


ratio
1:$10^6$

ratio
1:100

from S. Elliott

# Moore’s law in 0νββ decay *(progress in the last ~50 years)*



from S. Elliott

# Nuclear matrix elements

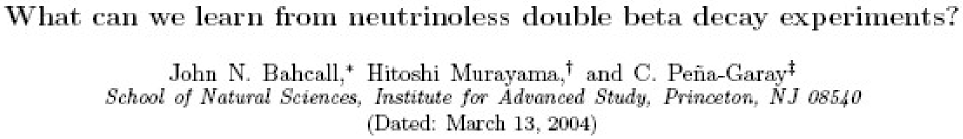
In order to relate decay rate to the effective mass $<m_{\beta\beta}>$ we have to know the corresponding nuclear matrix elements.

Any error in them is directly reflected as a like size error in $<m_{\beta\beta}>$.

Two main theoretical approaches:

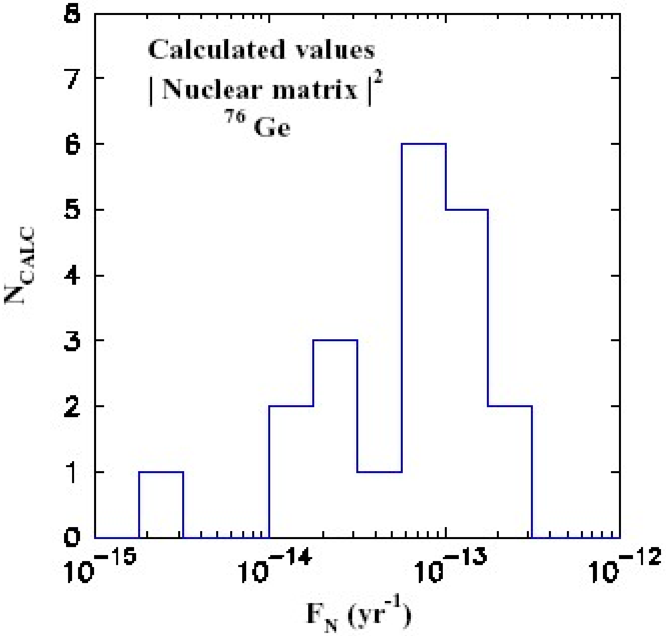
Shell Model **(SM)**

Quasi Random Phase Approximation **(QRPA)**

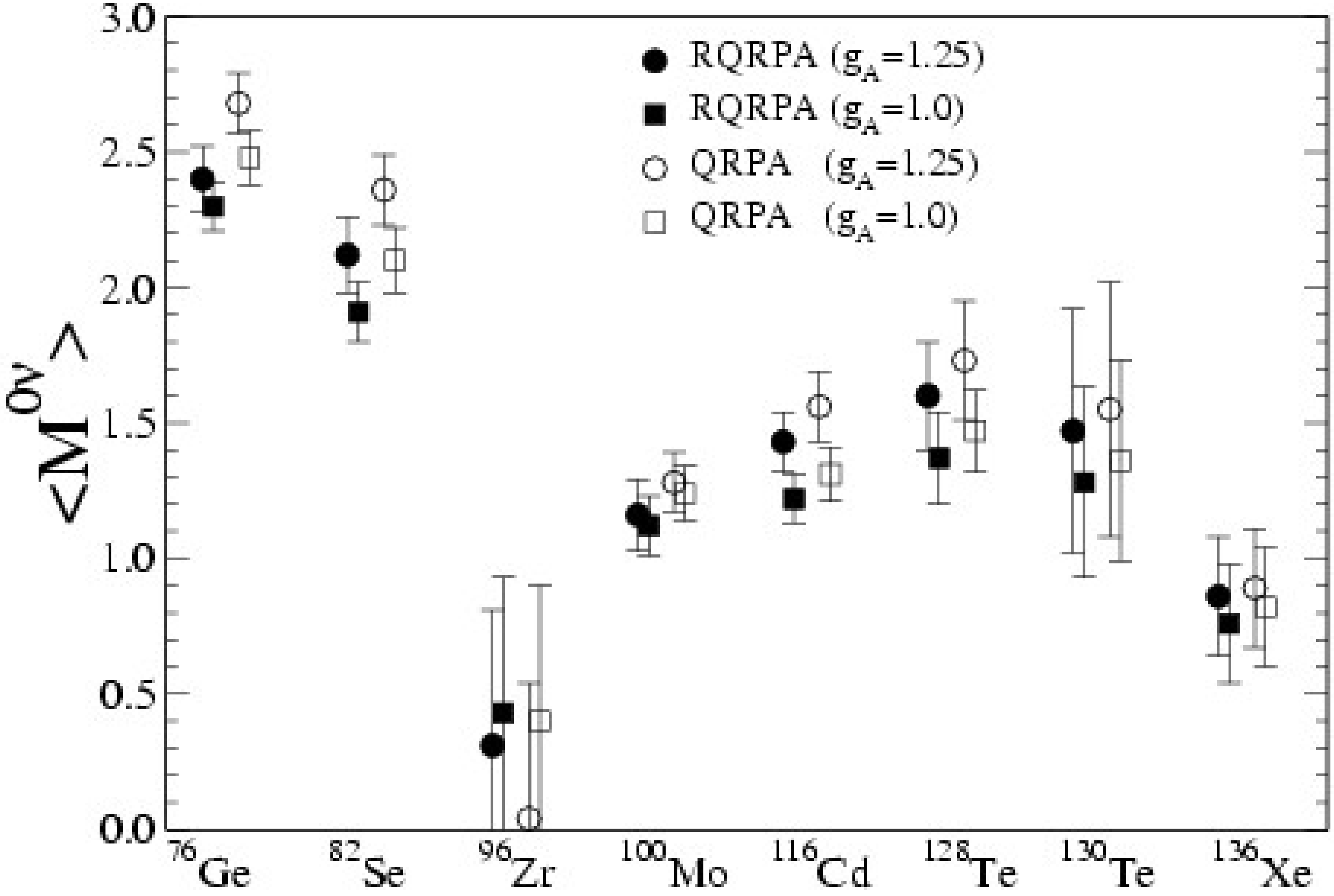


What can we learn from neutrinoless double beta decay experiments?

John N. Bahcall,* Hitoshi Murayama,† and C. Peña-Garay‡
*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540*
(Dated: March 13, 2004)



*From Rodin et al. nucl-th/0503063.*



# NEMO

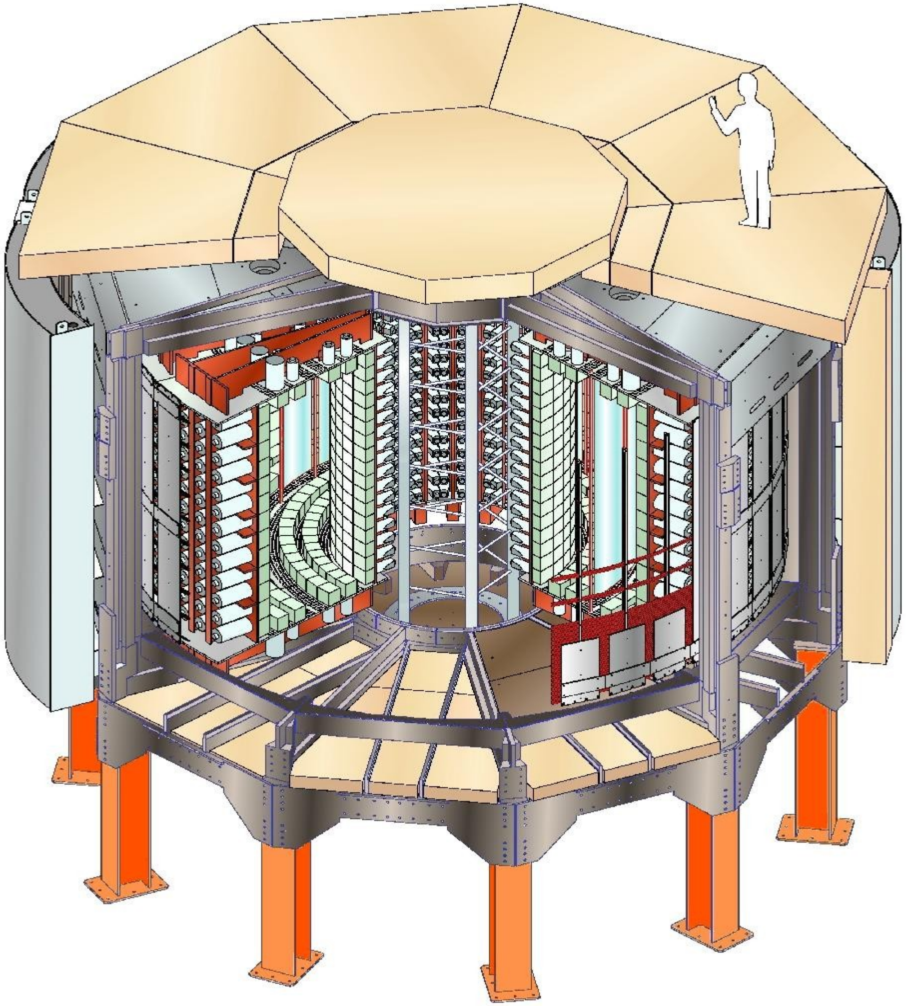
# **N**eutrino **E**ttore **M**ajorana **O**bservatory

## *NEMO collaboration*

**CENBG**, IN2P3-CNRS et Université de Bordeaux, **France**
**IReS**, IN2P3-CNRS et Université de Strasbourg, **France**
**LAL**, IN2P3-CNRS et Université Paris-Sud, **France**
**LPC**, IN2P3-CNRS et Université de Caen, **France**
**LSCE,** CNRS Gif sur Yvette, **France**
**Fes** University, **Marocco**
**FNSPE**, Prague University, **Czech Republic**
**INL,** Idaho Falls**, USA**
**ITEP**, Moscou, **Russia**
**JINR**, Dubna, **Russia**
**JYVASKYLA** University, **Finland**
**KURCHATOV** Institute**, Russia**
**Manchester** University, **UK**
**MHC,** Massachusets **, USA**
**Saga** University**, Japan**
**Texas** University**, USA**
**UCL** London**, UK**

# 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**
**+ Wood**

**Background:** natural radioactivity, mainly $^{214}$Bi et $^{208}$Tl (~ 2.6 MeV)

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

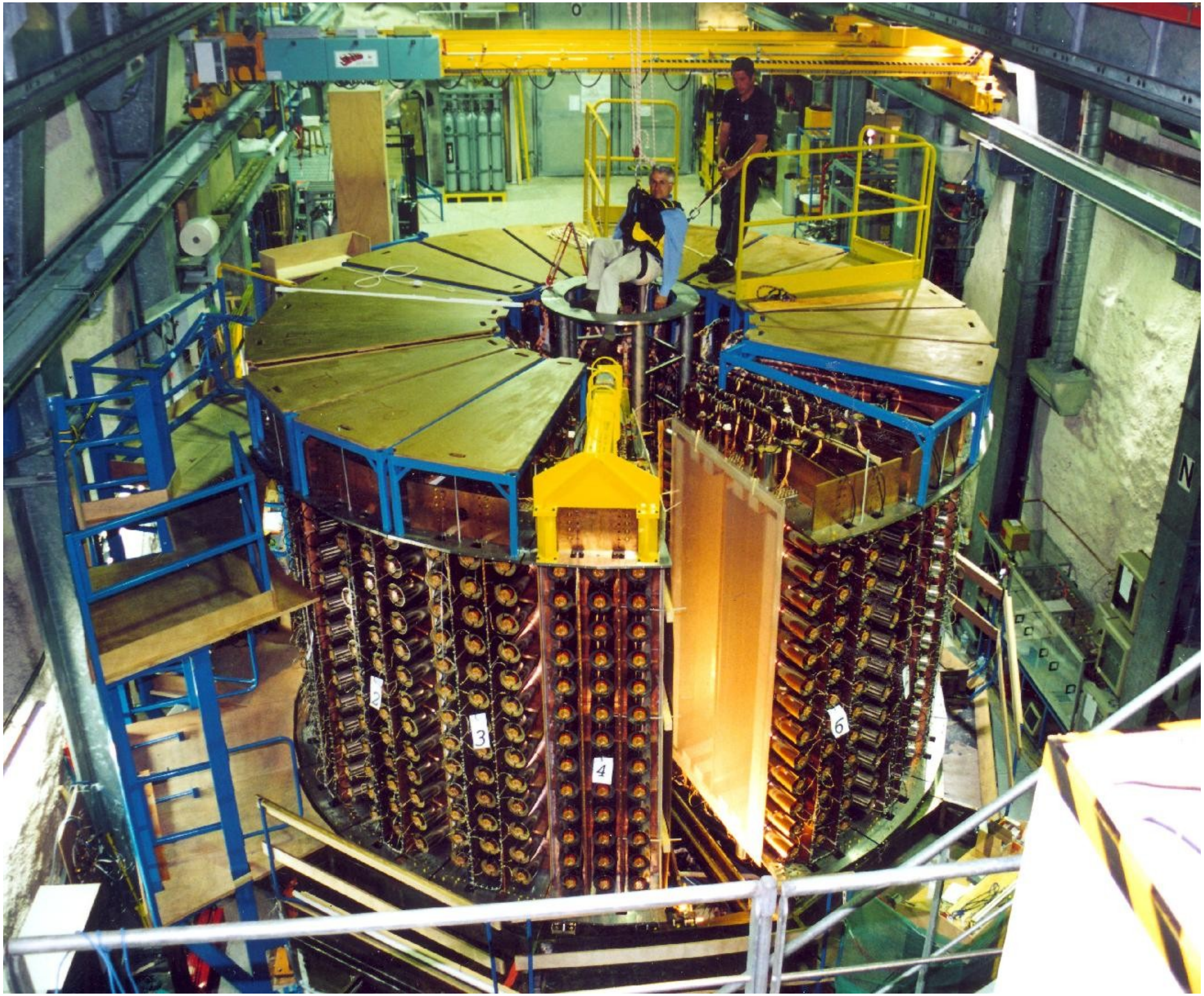
Cathodic rings
Wire chamber

PMTs

Calibration tube

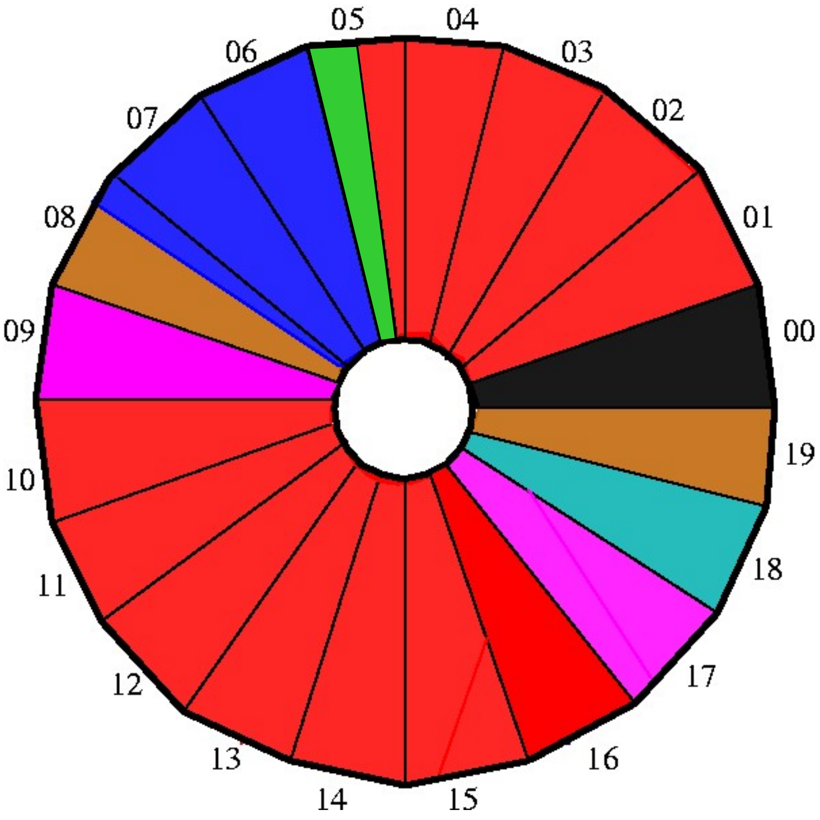
scintillators

ββ isotope foils



During installation AUGUST 2001

# ββ 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

**ββ0ν search**

**~ 5 kg $^{100}$Mo purified in INL (USA)**

**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 491 g**

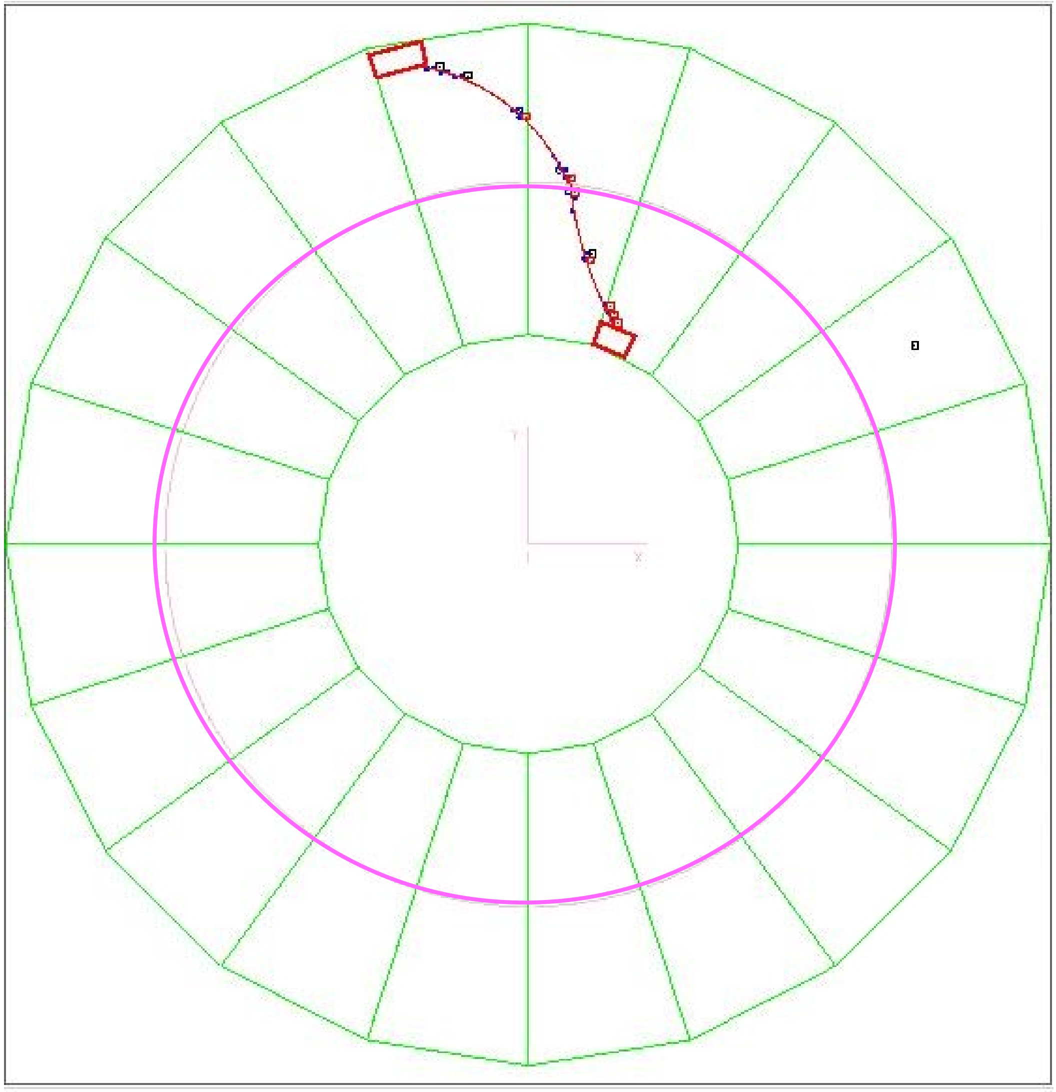
**Cu 621 g**

**External bkg measurement**

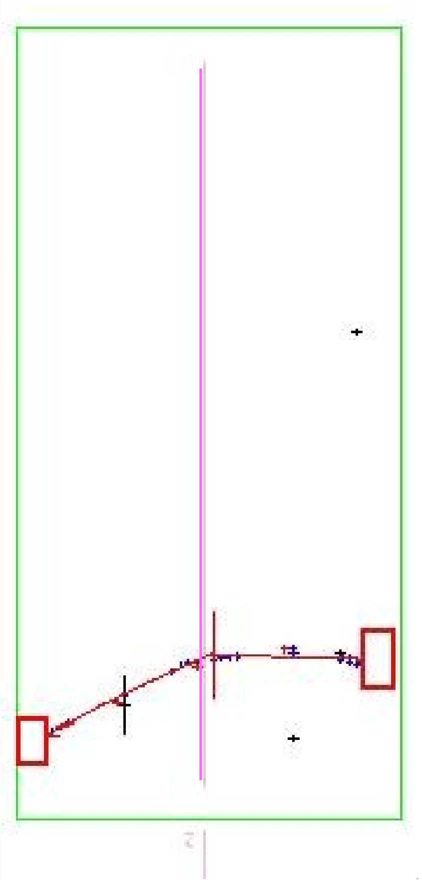
*(All enriched isotopes produced in Russia)*

# ββ events selection in NEMO-3

## Typical ββ2ν event observed from $^{100}$Mo



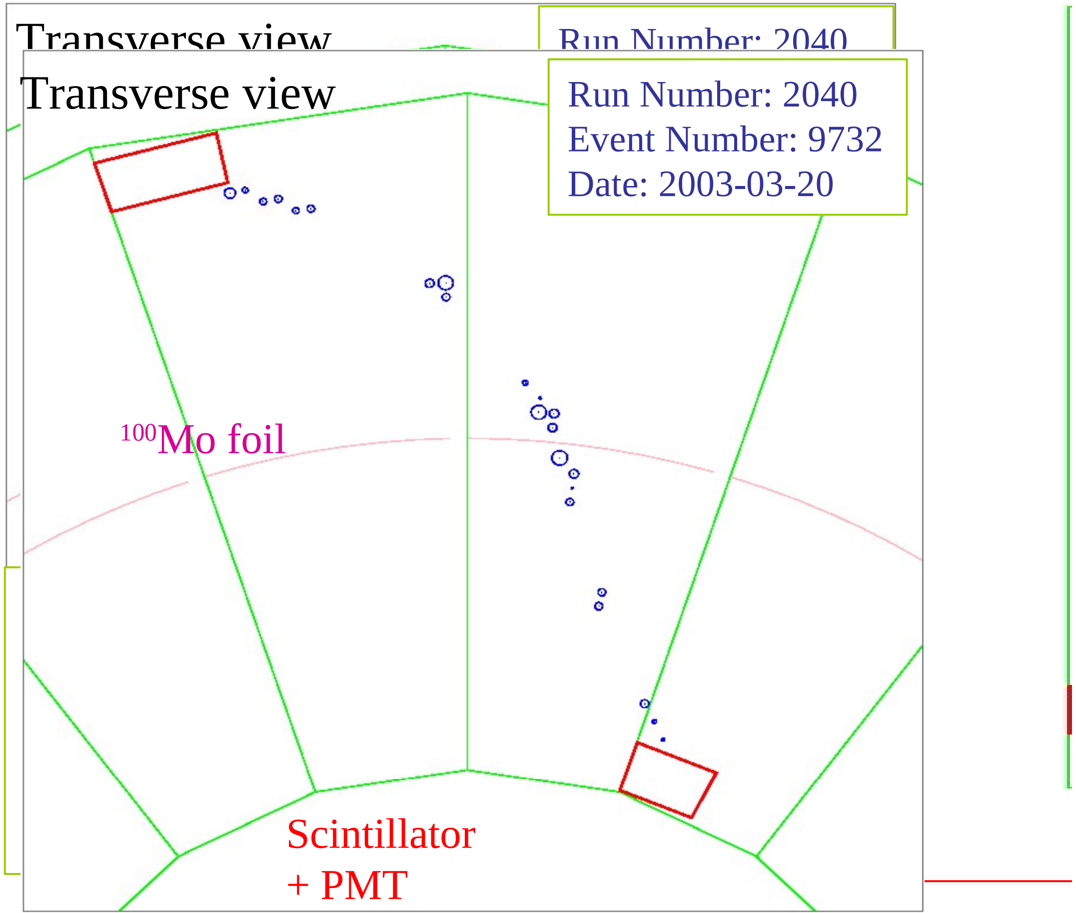
Top view

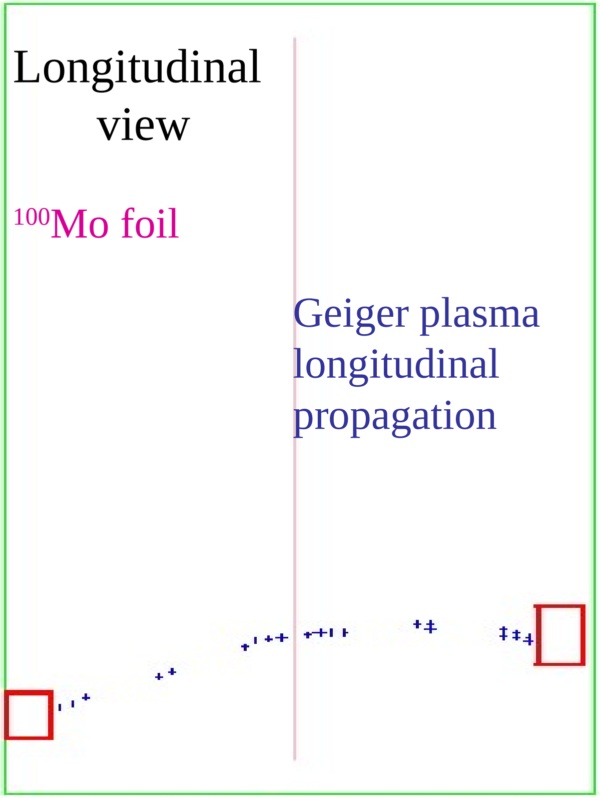


Side view

# ββ events selection in NEMO-3

## Typical ββ2ν event observed from $^{100}$Mo



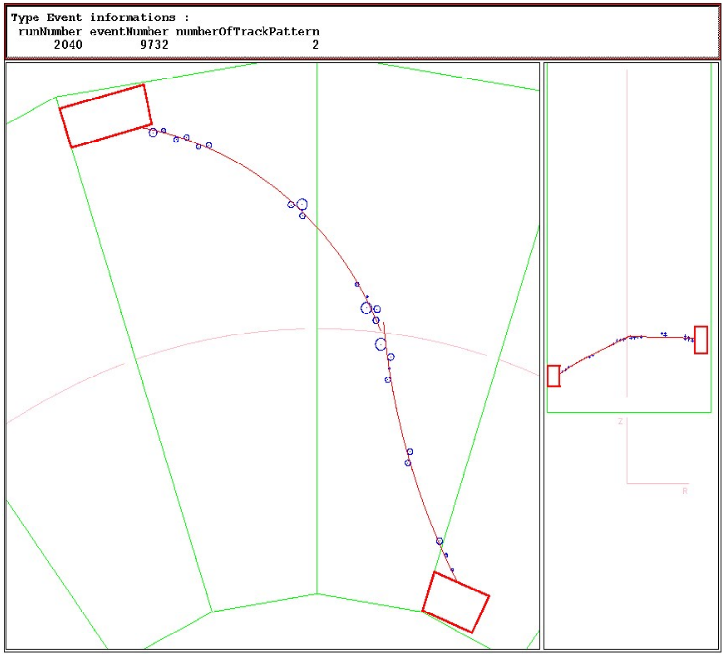


**Trigger:** at least 1 PMT > 150 keV

≥ 3 Geiger hits (2 neighbou

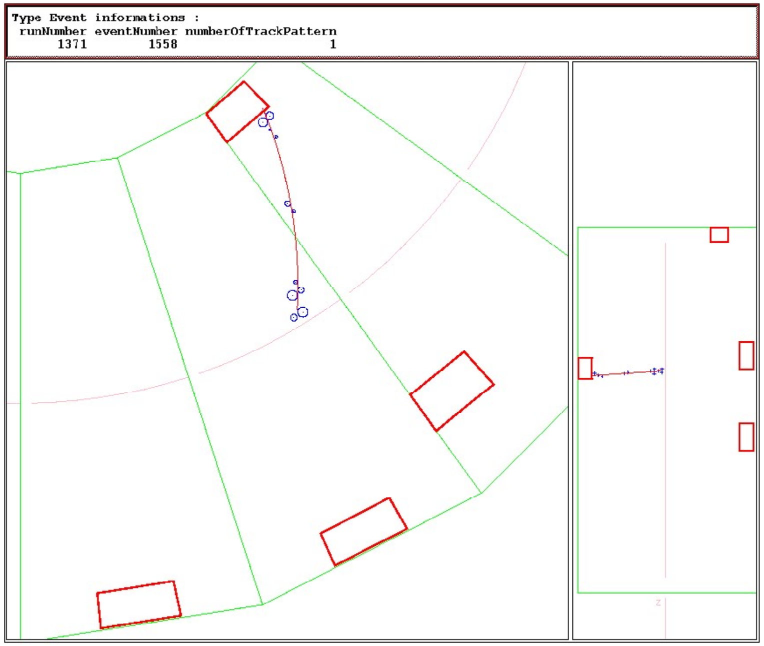
Trigger rate = 5.8 Hz

ββ events: 1 event every 2.5 minutes



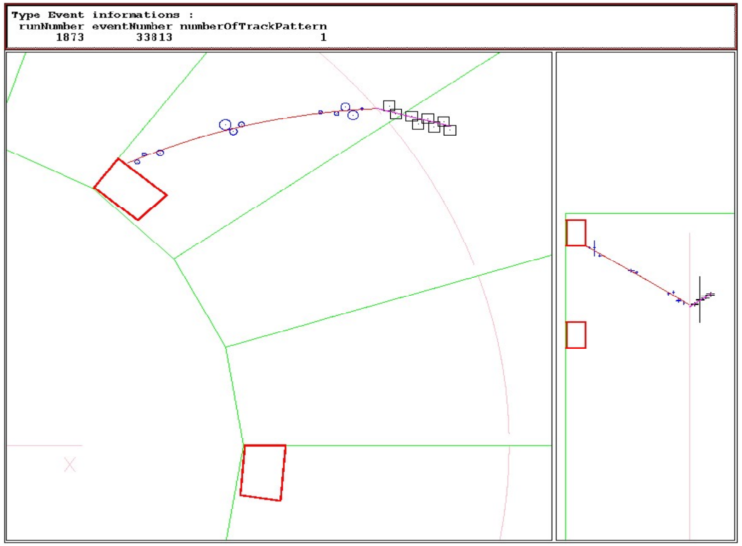
```
Type Event informations :
 runNumber eventNumber numberOfTrackPattern
      2040        9732                    2
```

$2e^-$ event



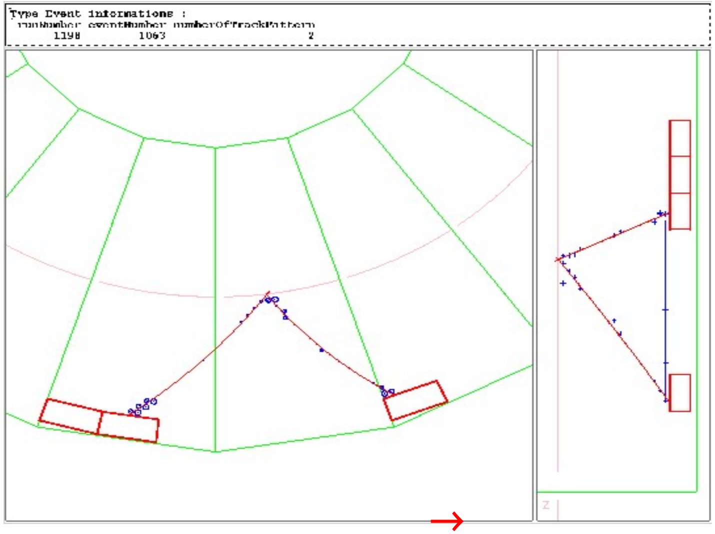
```
Type Event informations :
 runNumber eventNumber numberOfTrackPattern
      1371        1558                    1
```

$e^-N\gamma$ event to measure $^{208}Tl$



```
Type Event informations :
 runNumber eventNumber numberOfTrackPattern
      1873       33813                    1
```

$\beta$ - $\alpha$ (delay track) event $^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$

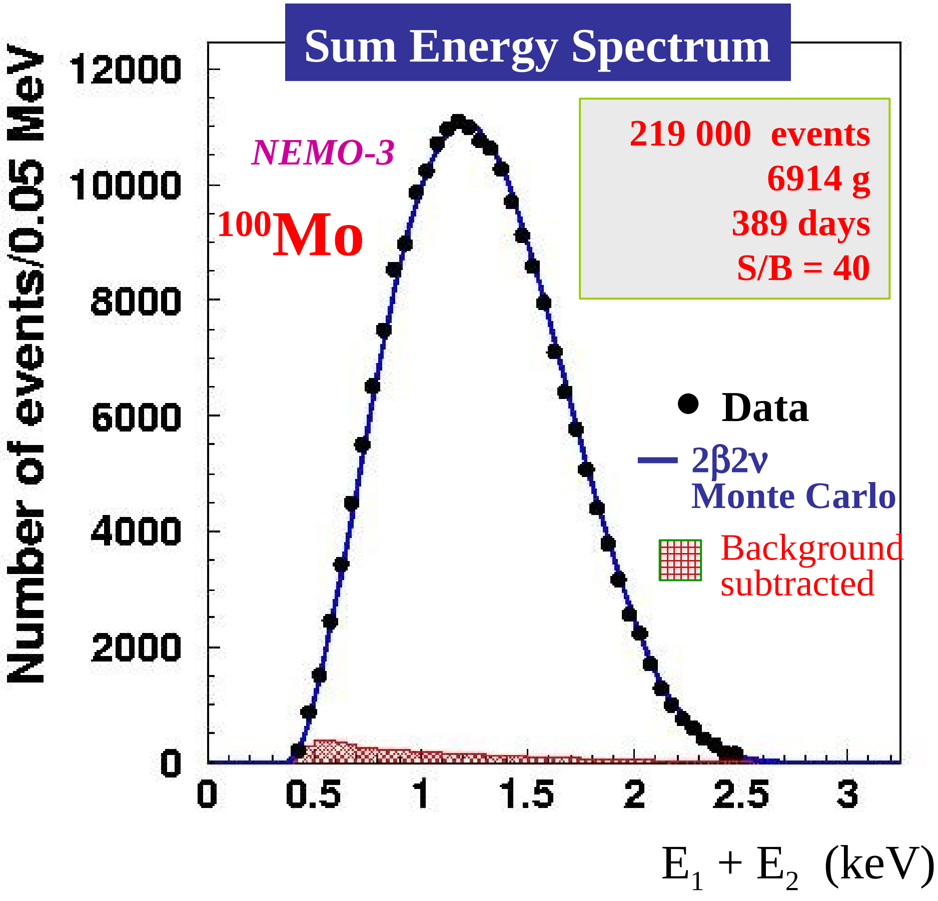


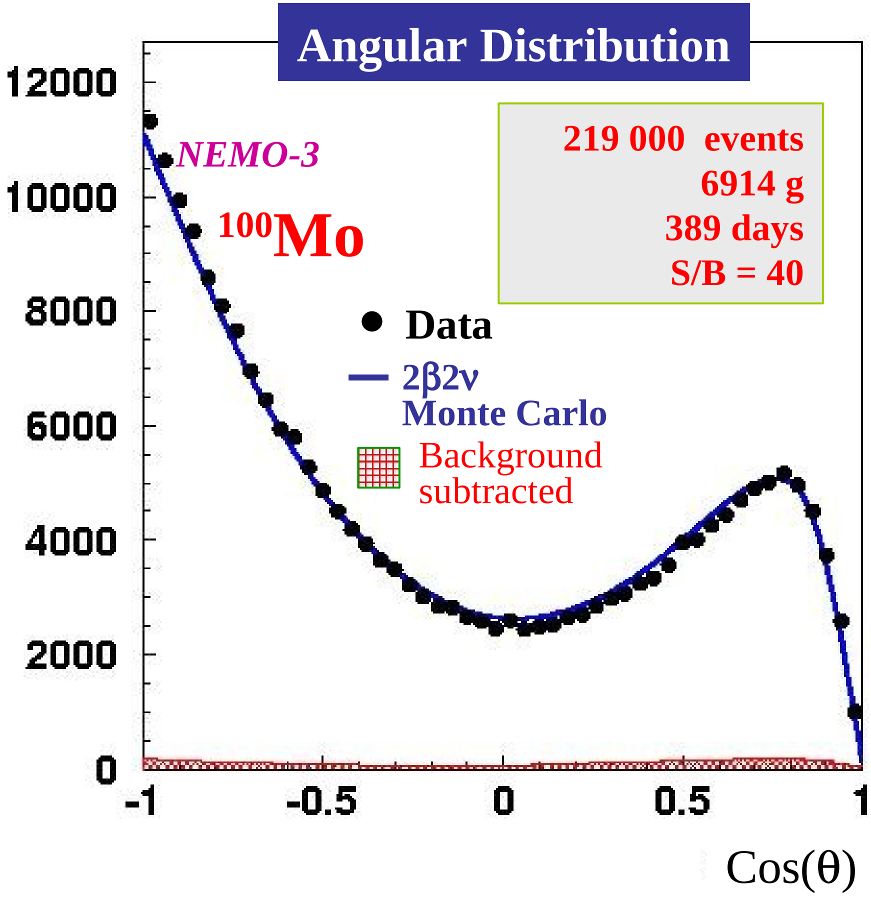
```
Type Event informations :
 runNumber eventNumber numberOfTrackPattern
      1198        1063                    2
```

$e^+ - e^-$ pair event $\vec{B}$ rejection

# $^{100}$Mo 2β2ν preliminary results

(Data Feb. 2003 – Dec. 2004)





**7.37 kg.y**

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

# Limit on the effective mass of the Majorana neutrino

## Phase 1 (Feb. 2003 – Sept. 2004: 1.08 y of data) with radon bkg

## (limits @ 90% CL)

**$^{100}$Mo** (6.914 kg)

**$T_{1/2}(\beta\beta0\nu) > 4.6\ 10^{23}$ y**

**$\langle m_\nu \rangle < 0.66 – 2.81$ eV**

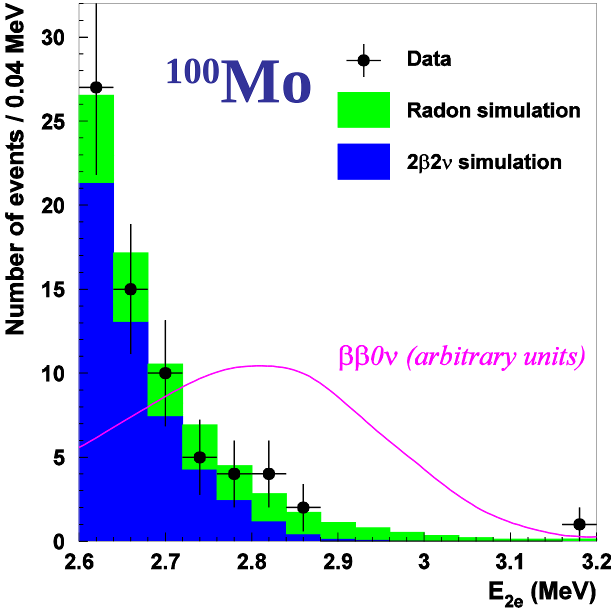
**$^{82}$Se** (0.932 kg)

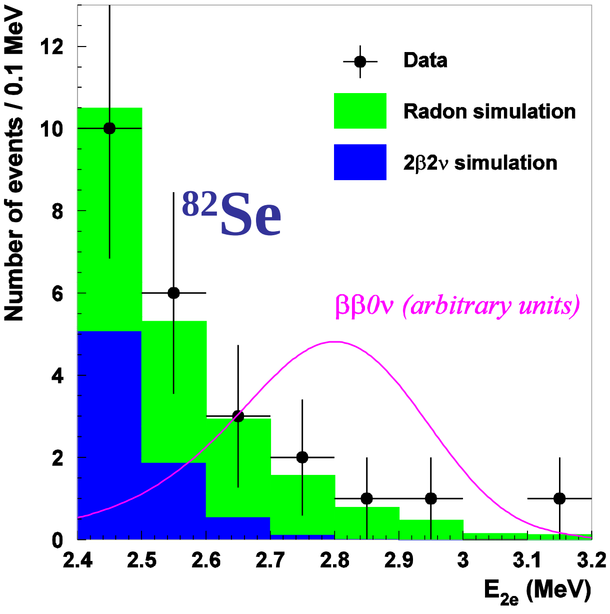
**$T_{1/2}(\beta\beta0\nu) > 1.0\ 10^{23}$ y**

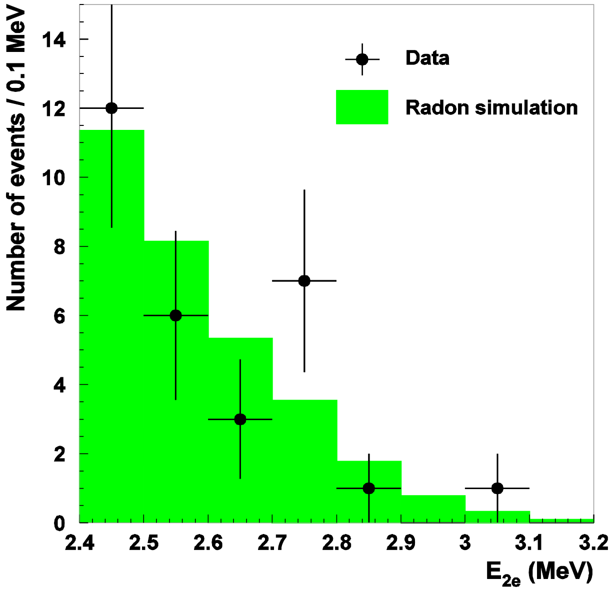
**$\langle m_\nu \rangle < 1.75 – 4.86$ eV**

**Cu+$^{nat}$Te+$^{130}$Te**

**In agreement with only Radon bkg expected**







[2.8-3.2] MeV: $\varepsilon(\beta\beta0\nu) = 8$ %
Expected bkg = 8.1 ± 1.3
$N_{observed}$ = 7 events

[2.7-3.2] MeV: $\varepsilon(\beta\beta0\nu) = 13$ %
Expected bkg = 3.1 ± 0.6
$N_{observed}$ = 5 events

Previous limits: $T_{1/2}(\beta\beta0\nu) > 5.5\ 10^{22}$ y
Ejiri et al. (2001)

Previous limits: $T_{1/2}(\beta\beta0\nu) > 9.5\ 10^{21}$ y
Arnold et al. (1992)

Nuclear Matrice Elements Ref: Simkovic (1999), Stoica (2001), Suhonen (1998,2003), Rodin (2005), Caurier (1996)

# Limit on Majoron and on V+A (limits @ 90% CL)

## Limit on Majoron

$^{100}$**Mo:** $T_{1/2}(\beta\beta 0\nu M) > 1.8\ 10^{22}$ y

$g_M < (5.3 - 8.5)\ 10^{-5}$ **(best limit)**

Simkovic (1999), Stoica (1999)

$^{82}$**Se:** $T_{1/2}(\beta\beta 0\nu M) > 1.5\ 10^{22}$ y

$g_M < (0.7 - 1.6)\ 10^{-4}$

Simkovic (1999), Stoica (2001)

## Limit on V+A

$^{100}$**Mo:** $T_{1/2}(\beta\beta 0\nu\ V{+}A) > 2.3\ 10^{23}$ y

$\lambda < (1.5 - 2.0)\ 10^{-6}$

Tomoda (1991), Suhonen (1994)

$^{82}$**Se:** $T_{1/2}(\beta\beta 0\nu\ V{+}A) > 1.0\ 10^{23}$ y

$\lambda < 3.2\ 10^{-6}$

Tomoda (1991)

# NEMO-3 Expected sensitivity

## Background

External Background: negligible

Internal Background: $^{208}$Tl : 60 μBq/kg for $^{100}$Mo
300 μBq/kg for $^{82}$Se
$^{214}$Bi : < 300 μBq/kg
~ 0.1 count $kg^{-1}$ $y^{-1}$ with $2.8<E_1+E_2<3.2$ MeV

ββ2ν $^{100}$Mo $T_{1/2} = 7.14\ 10^{18}$ y
~ 0.3 count $kg^{-1}$ $y^{-1}$ with $2.8<E_1+E_2<3.2$ MeV

in 2009 after 5 years of data

6914 g of $^{100}$Mo $T_{1/2}(\beta\beta0\nu) > 2\ 10^{24}$ y (90% C.L.)
$<m_\nu> < 0.3 – 1.3$ eV

932 g of $^{82}$Se $T_{1/2}(\beta\beta0\nu) > 8\ .10^{23}$ y (90% C.L.)
$<m_\nu> < 0.6 – 1.7$ eV

Nuclear Matrice Elements Ref: Simkovic (1999), Stoica (2001), Suhonen (1998,2003), Rodin (2005), Caurier (1996)


NEMO
S

# From NEMO-3 to SuperNEMO

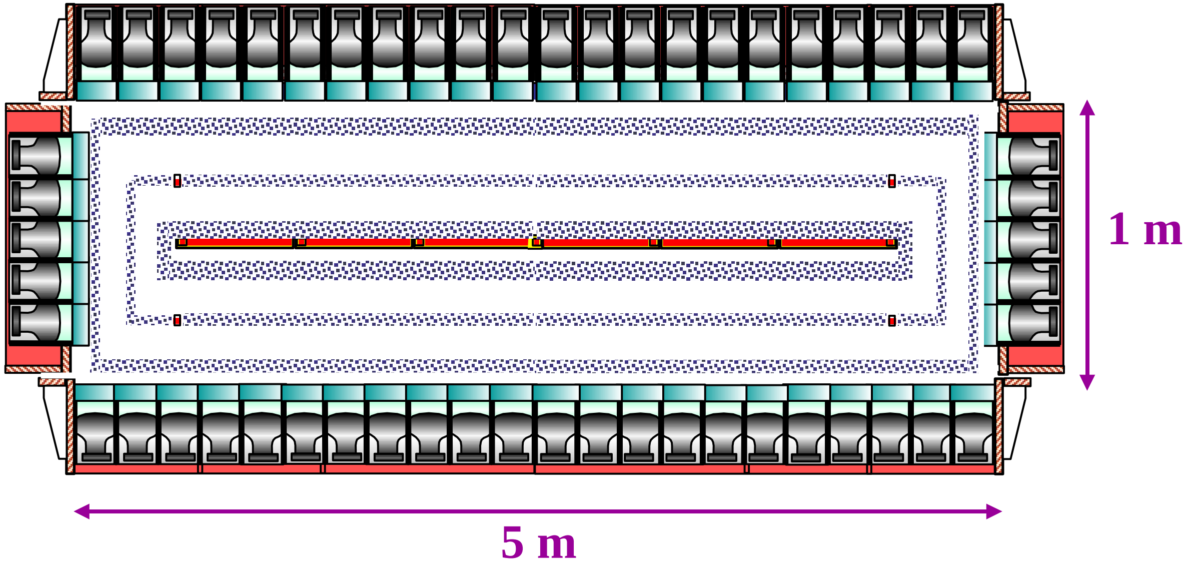
| NEMO-3 | | SuperNEMO |
|---|---|---|
| 7 kg $^{100}$Mo<br>$T_{1/2}(\beta\beta2\nu) = 7.\ 10^{18}$ y | **Mass of isotope** | 100 kg $^{82}$Se<br>$T_{1/2}(\beta\beta2\nu) = 10^{20}$ y |
| $T_{1/2}(\beta\beta0\nu) > 2.\ 10^{24}$ y<br>$<m_\nu> < 0.3 – 1.3$ eV | **Sensitivity** | $T_{1/2}(\beta\beta0\nu) > 2.\ 10^{26}$ y<br>$<m_\nu> < 40 – 110$ meV |
| FWHM ~ 12% at 3 MeV<br>(dominated by calorimeter ~ 8%) | **Energy resolution**<br>**(FWHM of the ββ0ν ray)** | FWHM ~ 6% at 3 MeV<br>(dominated by source foil) |
| $\varepsilon(\beta\beta0\nu) = 8$ %<br>poor energy resolution<br>$e^-$ backscattering on scintillator | **Efficiency** | $\varepsilon(\beta\beta0\nu) \sim 40$ % |
| $^{214}$Bi < 300 μBq/kg<br>$^{208}$Tl < 20 μBq/kg | **Internal contaminations**<br>**in the source foils in $^{208}$Tl and $^{214}$Bi** | $^{214}$Bi < 10 μBq/kg<br>$^{208}$Tl < 2 μBq/kg |
| ββ2ν ~ 2 cts / 7 kg / y<br>($^{208}$Tl, $^{214}$Bi) ~ 0.5 cts/ 7 kg /y | **Background** | ββ2ν + ($^{208}$Tl,$^{214}$Bi)<br>≤ 1 cts/ 100 kg /y |

# SuperNEMO preliminary design

Plane and Modular Geometry (~5 kg of enriched isotope/module)

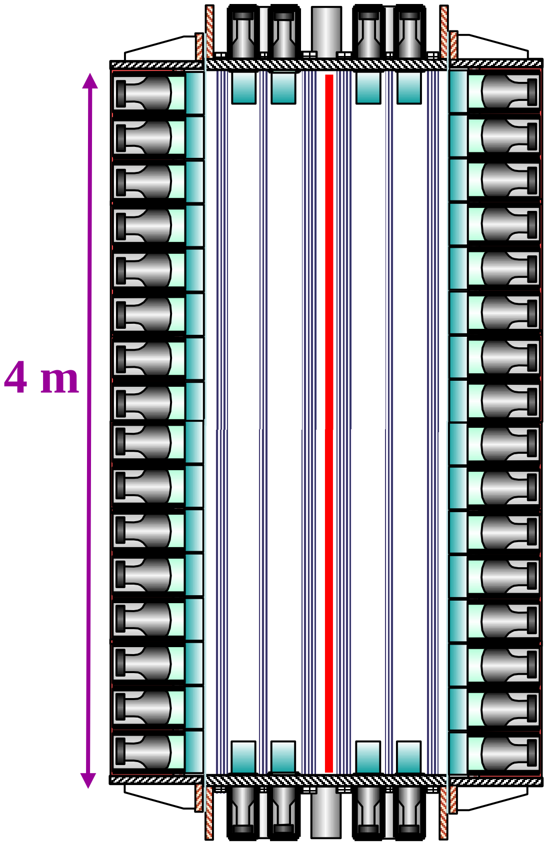
1 Module: Source (40 mg/cm2) 4 x 3 m2
Tracking volume: drift wire chamber in Geiger mode, ~ 3000 cells
Calorimeter: scintillators + PMTs (~1000 PMTs)

20 modules: 100 kg of enriched isotope
- ~ 60 000 channels for drift chamber
- ~ 20 000 PMT if scint. block
- ~ 2 000 PMT if scint. bars

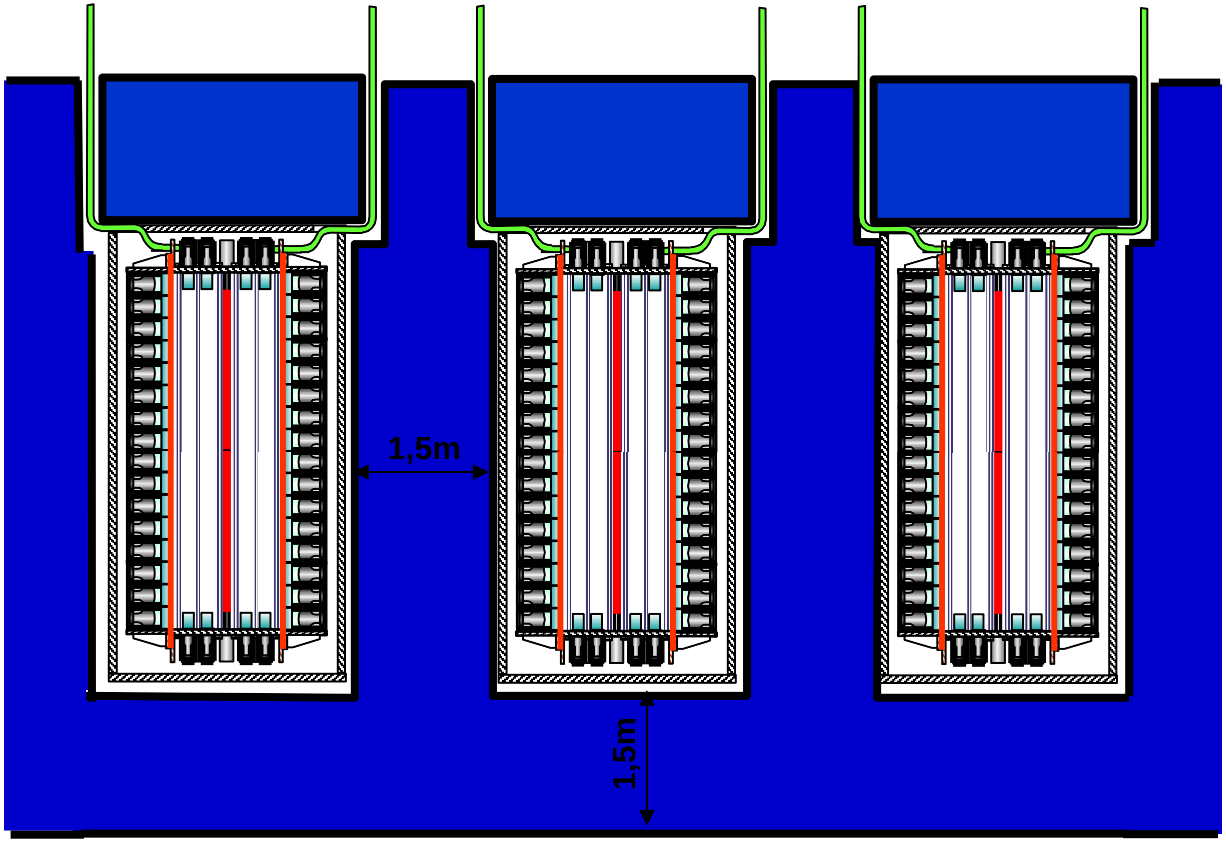


Top view

Side view

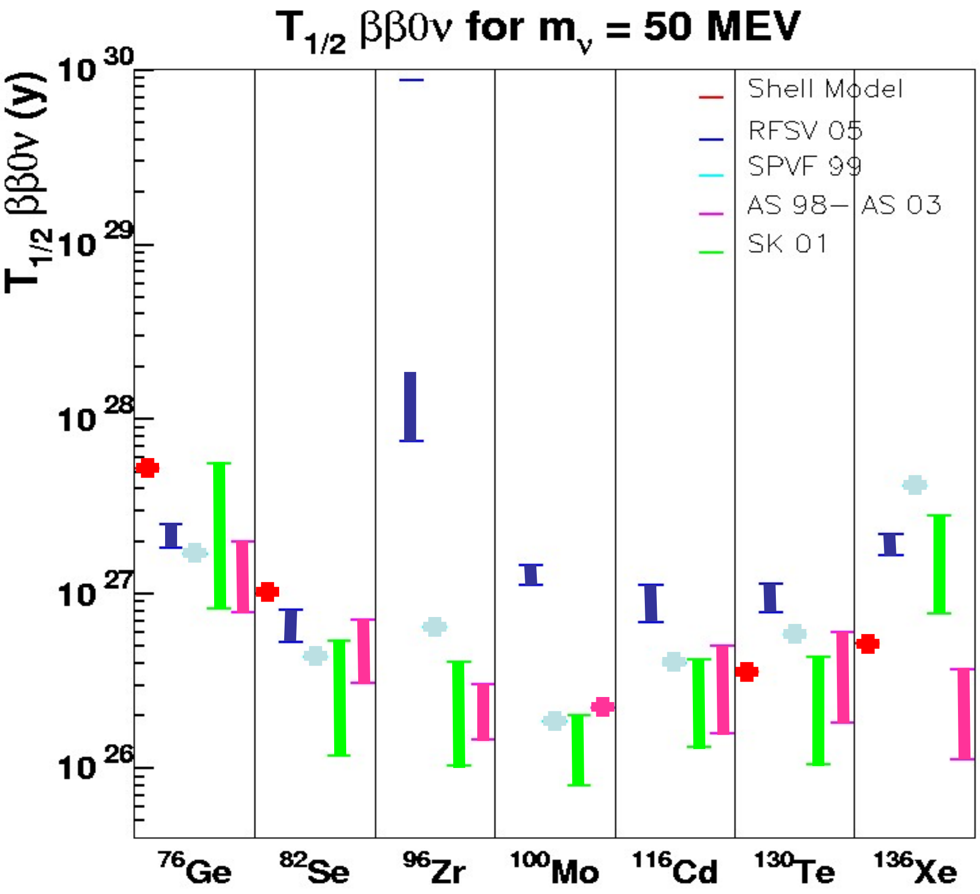


# Water shield



Need of cavity of ~ 60m x 15m x15m
Possible in Gran Sasso or in Modane if a new cavity

# Choice of the nucleus



## Nuclear matrice elements
## Theoretical calculations

Recent calculation done systematically on several experimental interesting nuclei

- ✚ Shell Model: Caurier et al. 2004) private com.
- ✚ QRPA Simkovic et al. (1999)
- ✚ Stoica et al. (2001)
- ✚ Suhonen et al. (1998 and 2003)
- ✚ Rodin, Simkovic (2005)

No strong theoritical criteria. Nucleus choice depends on:

- enrichment possibilities
- experimental technics
- $Q_{\beta\beta}$ value (phase space factor, background)
- $\beta\beta(2\nu)$ life-time

→

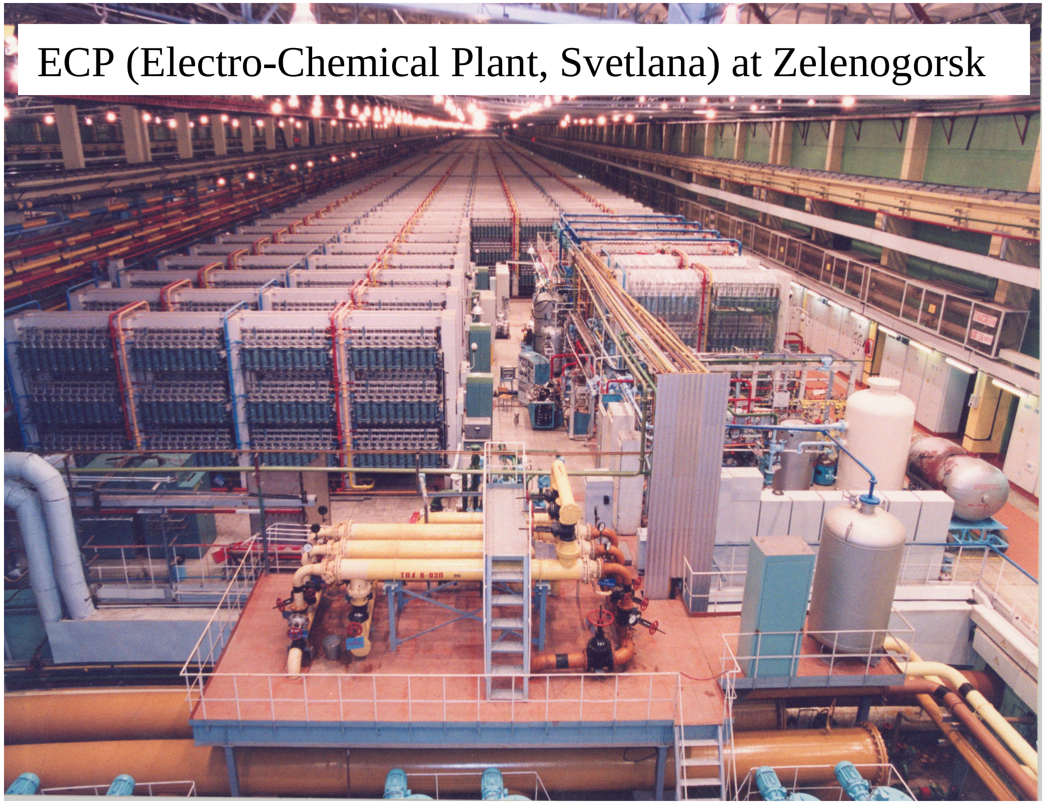
**$^{82}$Se**

$Q_{\beta\beta}$= 2 995 keV

Nat. abund. = 9.2%

# Enrichment of $^{82}$Se

**Goal:** To be able to produce 100 kg of $^{82}$Se



ECP (Electro-Chemical Plant, Svetlana) at Zelenogorsk

5 kg of $^{82}$Se funded by ILIAS (Europe)

Enrichment:

- 1 kg of $^{82}$Se in 2005
- 2 kg of $^{82}$Se in 2006
- 5 kg of $^{82}$Se in 2007

Enrichment of 100 kg of $^{82}$Se is possible in 3 years at ECP

Cost today ~ 40 k$ / kg

*Participants:* *LAL (France)*
*ITEP, Kurchatov, JINR (Russia)*

# Purification of $^{82}$Se

**Goal:** internal contaminations $^{208}$Tl < 2 μBq/kg and $^{214}$Bi < 10 μBq/kg
(NEMO-3: $^{208}$Tl < 2 μBq/kg and $^{214}$Bi < 10 μBq/kg

Chemical purification (INL, USA)

- 2x100 g $^{nat}$Se already processed at INL
- We must purify 5 kg of $^{82}$Se at INL

USA R&D

Source foils production

~250 m$^2$ with 40 mg/cm$^2$ thickness

ΔE/E ~ 4% (FWHM) at 3 MeV

Best solution: purify and prepare foils in the same lab in INL (USA)

*Participants: CENBG, LAL, LSCE (France)*
*INL, MHC (USA)*

# Planning

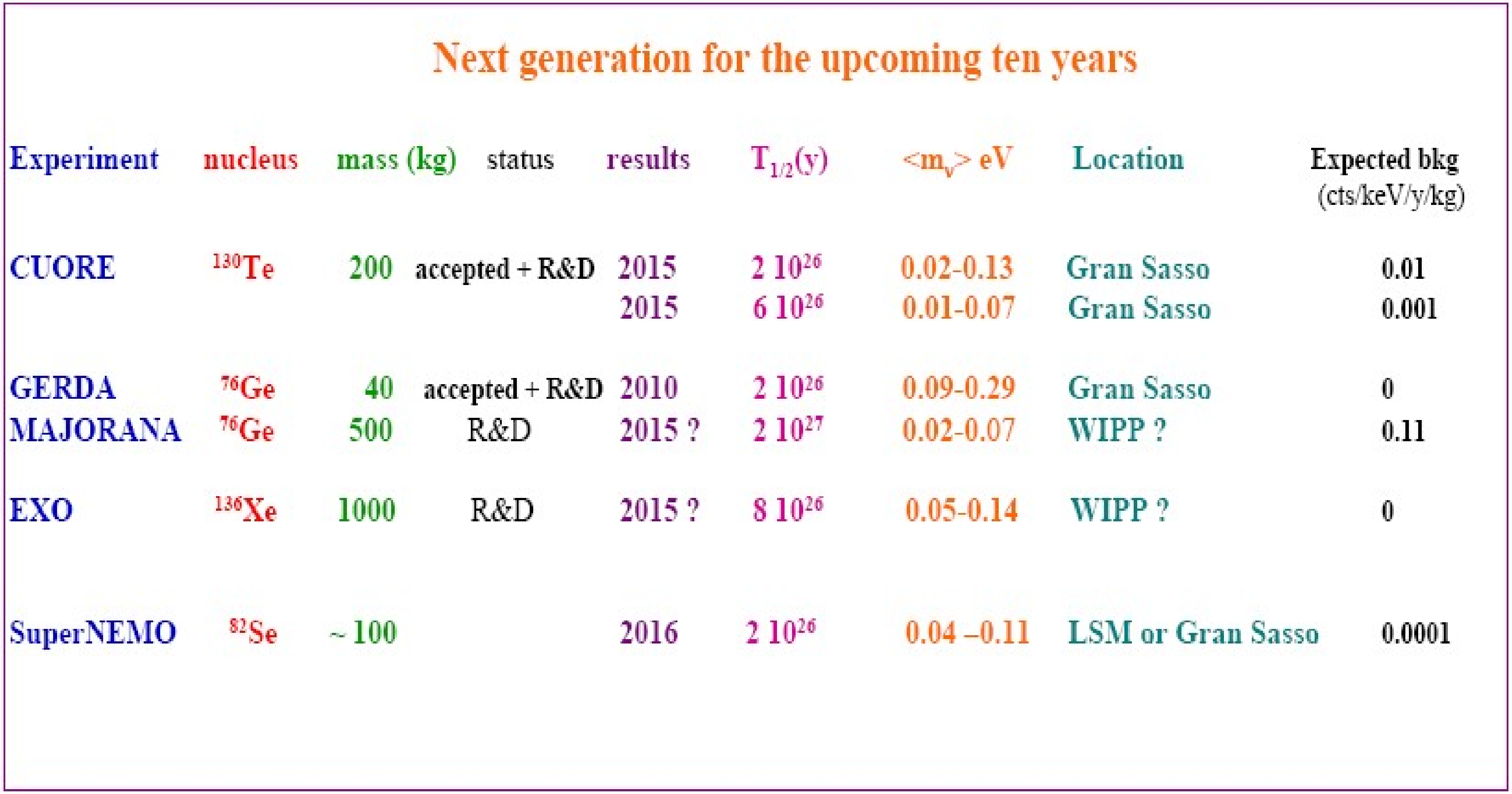
2005 – 2007 : R&D program

2008: construction of the first SuperNEMO module with 5 kg $^{82}$Se

2009-2011: construction and installation of the 20 modules ⇒ 100 kg of $^{82}$Se
start tacking data with delivered modules

2012: full SuperNEMO running with 100 kg of $^{82}$Se

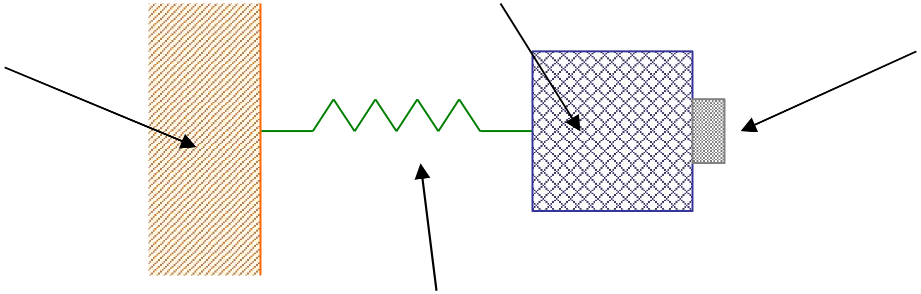
# Competition/complementary experiments



Next generation for the upcoming ten years

| Experiment | nucleus | mass (kg) | status | results | $T_{1/2}(y)$ | $<m_\nu>$ eV | Location | Expected bkg (cts/keV/y/kg) |
|---|---|---|---|---|---|---|---|---|
| CUORE | $^{130}Te$ | 200 | accepted + R&D | 2015 | $2\ 10^{26}$ | 0.02-0.13 | Gran Sasso | 0.01 |
| | | | | 2015 | $6\ 10^{26}$ | 0.01-0.07 | Gran Sasso | 0.001 |
| GERDA | $^{76}Ge$ | 40 | accepted + R&D | 2010 | $2\ 10^{26}$ | 0.09-0.29 | Gran Sasso | 0 |
| MAJORANA | $^{76}Ge$ | 500 | R&D | 2015 ? | $2\ 10^{27}$ | 0.02-0.07 | WIPP ? | 0.11 |
| EXO | $^{136}Xe$ | 1000 | R&D | 2015 ? | $8\ 10^{26}$ | 0.05-0.14 | WIPP ? | 0 |
| SuperNEMO | $^{82}Se$ | ~ 100 | | 2016 | $2\ 10^{26}$ | 0.04 –0.11 | LSM or Gran Sasso | 0.0001 |

# CUORE Detector concepts



Energy absorber
$TeO_2$ crystal
C ≅ 2 nJ/K

Heat sink
T ≅ 10 mK

Thermometer
NTD Ge-thermistor
R ≅ 100 MΩ
dR/dT ≅ 100 kΩ/μK

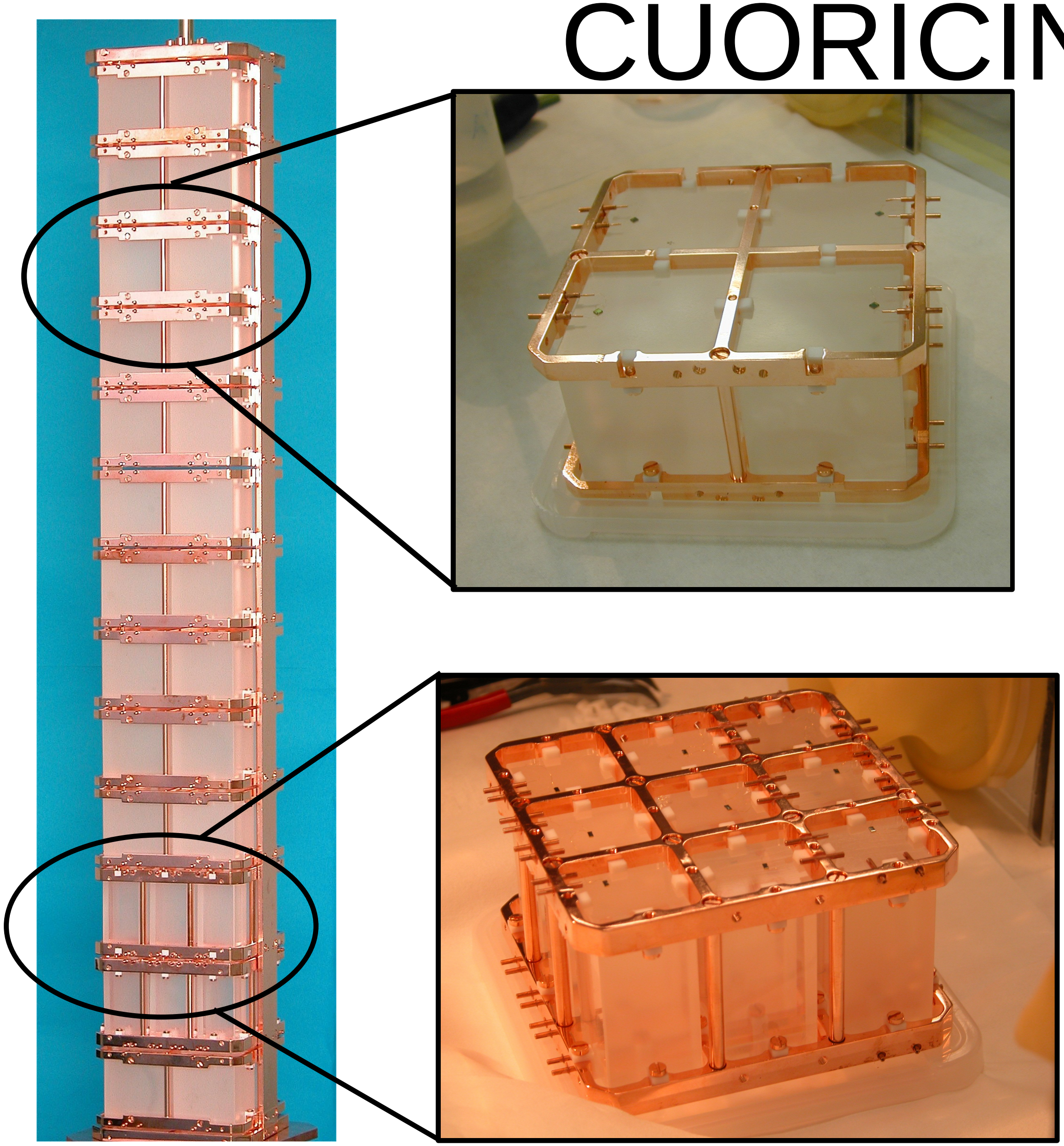
Thermal coupling

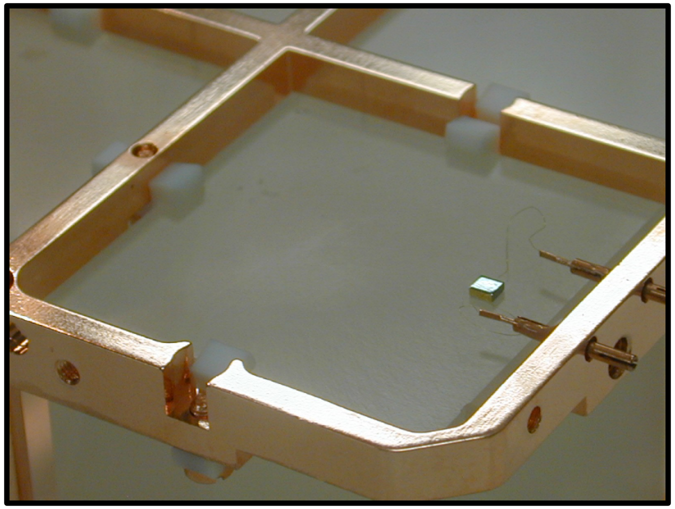
- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for $E = 1$ MeV
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s

Energy resolution (FWHM): ≅ 5 keV at 2500 keV

# CUORICINO

## A prototype for CUORE





**Active mass during first runs:**

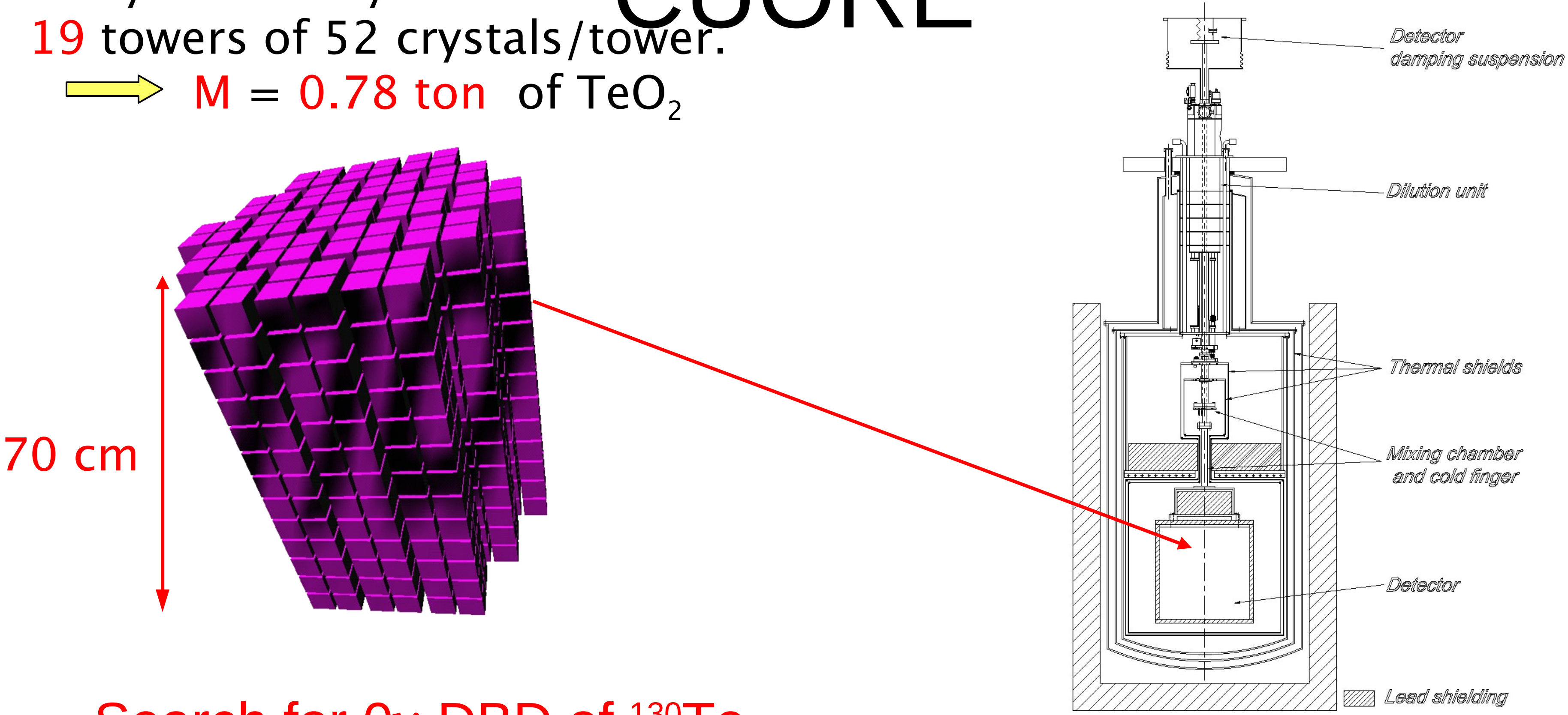
42 x 0.790 kg = 33.2 kg

17 x 0.330 kg = 5.6 kg

→ *~ 11 kg $^{130}$Te*

# CUORE

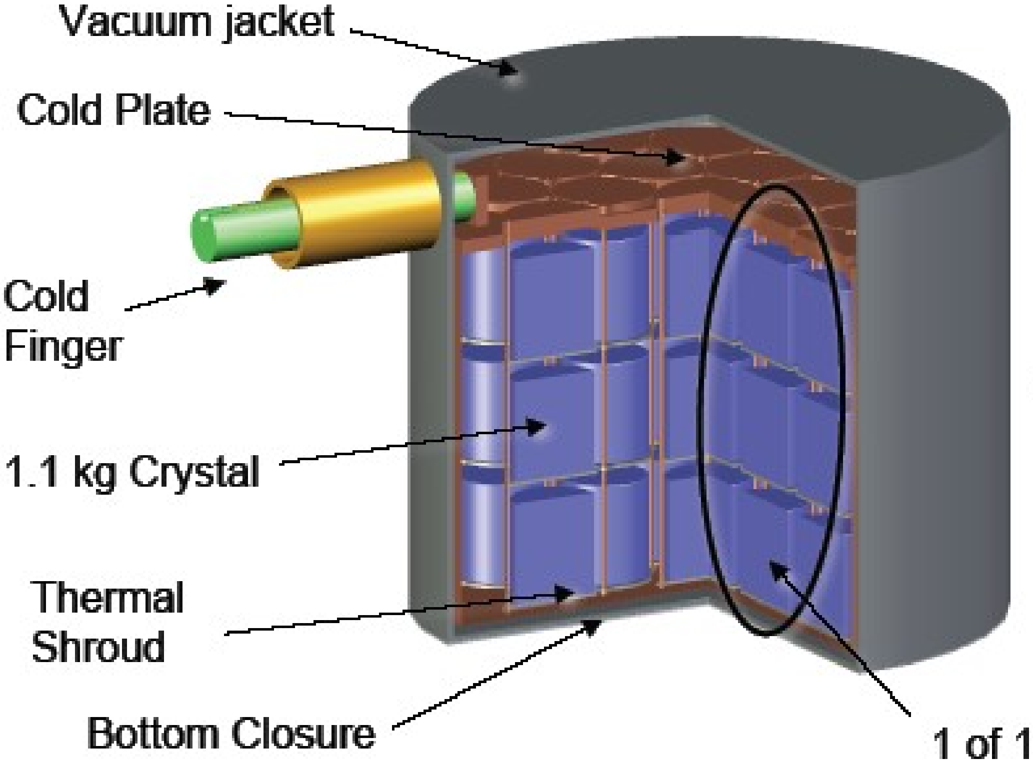
Array of 988 crystals:
19 towers of 52 crystals/tower.
⇨ M = 0.78 ton of $TeO_2$

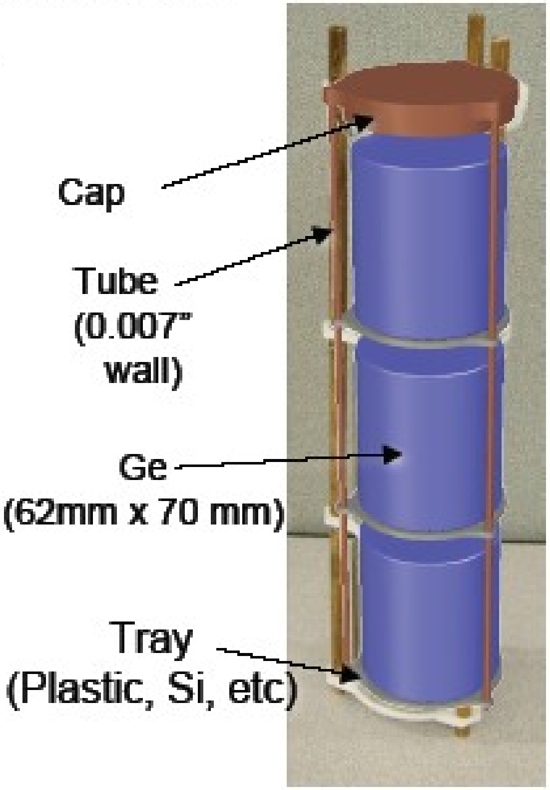


Search for 0ν DBD of $^{130}Te$
$Q_{\beta\beta}$ = 2529 keV
Natural isotopic abundance [$^{130}Te$] = 34.08%
Therefore, isotopic enrichment is unnecessay

# The Majorana Modular Approach

- **57 crystal module**
  - Conventional vacuum cryostat made with electroformed Cu.
  - Three-crystal stack are individually removable.

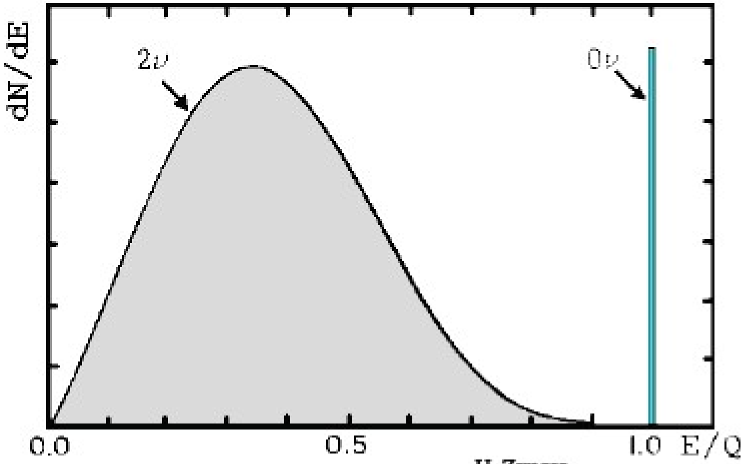




# Experimental Considerations

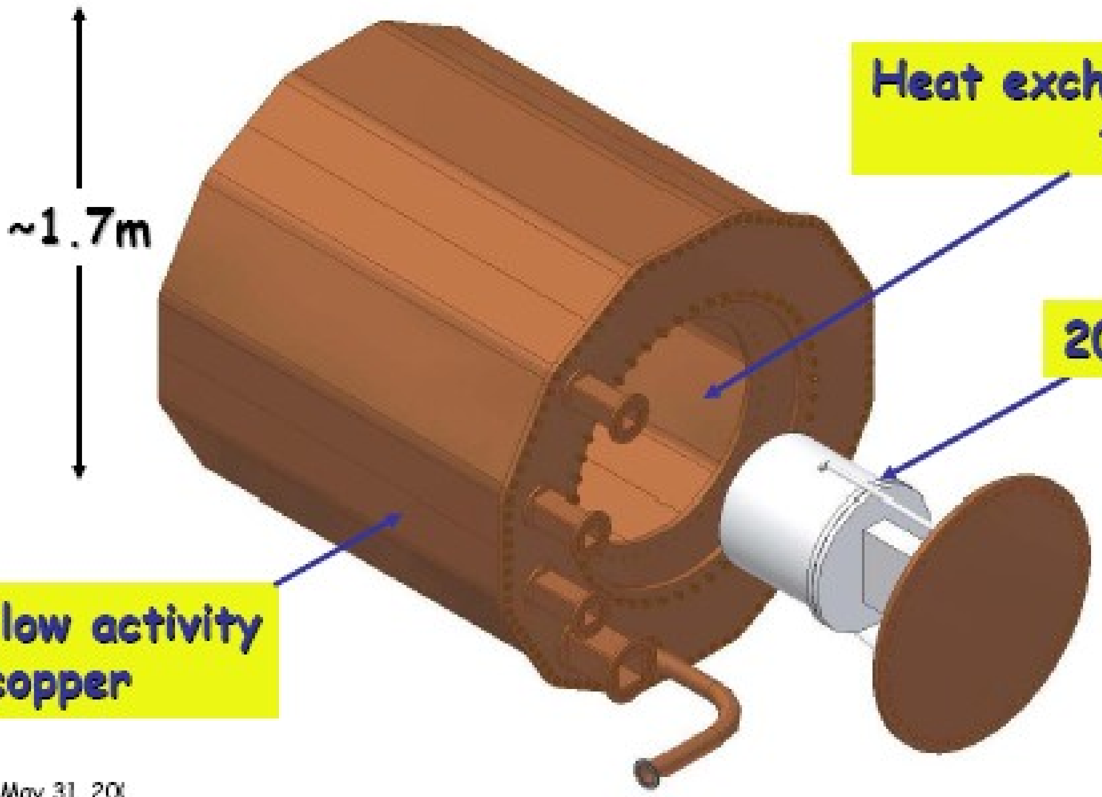
To measure *extremely* rare decay rates ($T_{1/2}$ ~ $10^{26}$ -$10^{27}$ years) Majorana utilizes:

- Large, highly efficient source mass of enriched $^{76}$Ge
- Extremely low (near-zero) backgrounds in the 0νββ peak region-of-interest (ROI) (1 count/t-y)
    - Requires ultra-clean materials & sophisticated discrimination techniques
- Best possible energy resolution (0.16%, 4 keV ROI)
    - Minimize 0νββ peak ROI to maximize S/B
    - Separate 2νββ/0νββ

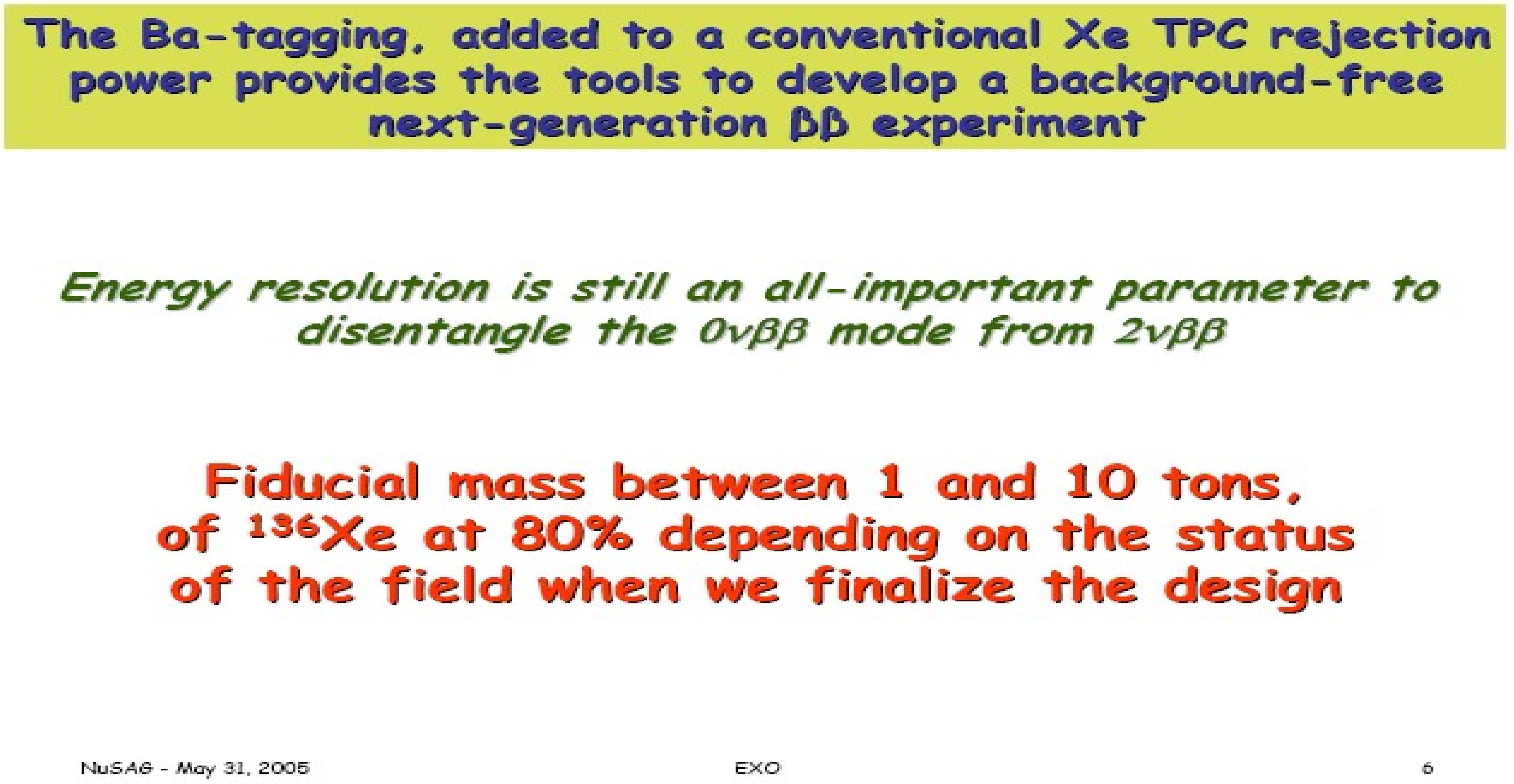


U. Zargosa

# EXO-200: a 200kg LXe TPC with scintillation readout in a ultra-low background cryostat/shielding



# EXO



**The Ba-tagging, added to a conventional Xe TPC rejection power provides the tools to develop a background-free next-generation $\beta\beta$ experiment**

*Energy resolution is still an all-important parameter to disentangle the $0\nu\beta\beta$ mode from $2\nu\beta\beta$*

**Fiducial mass between 1 and 10 tons, of $^{136}$Xe at 80% depending on the status of the field when we finalize the design**

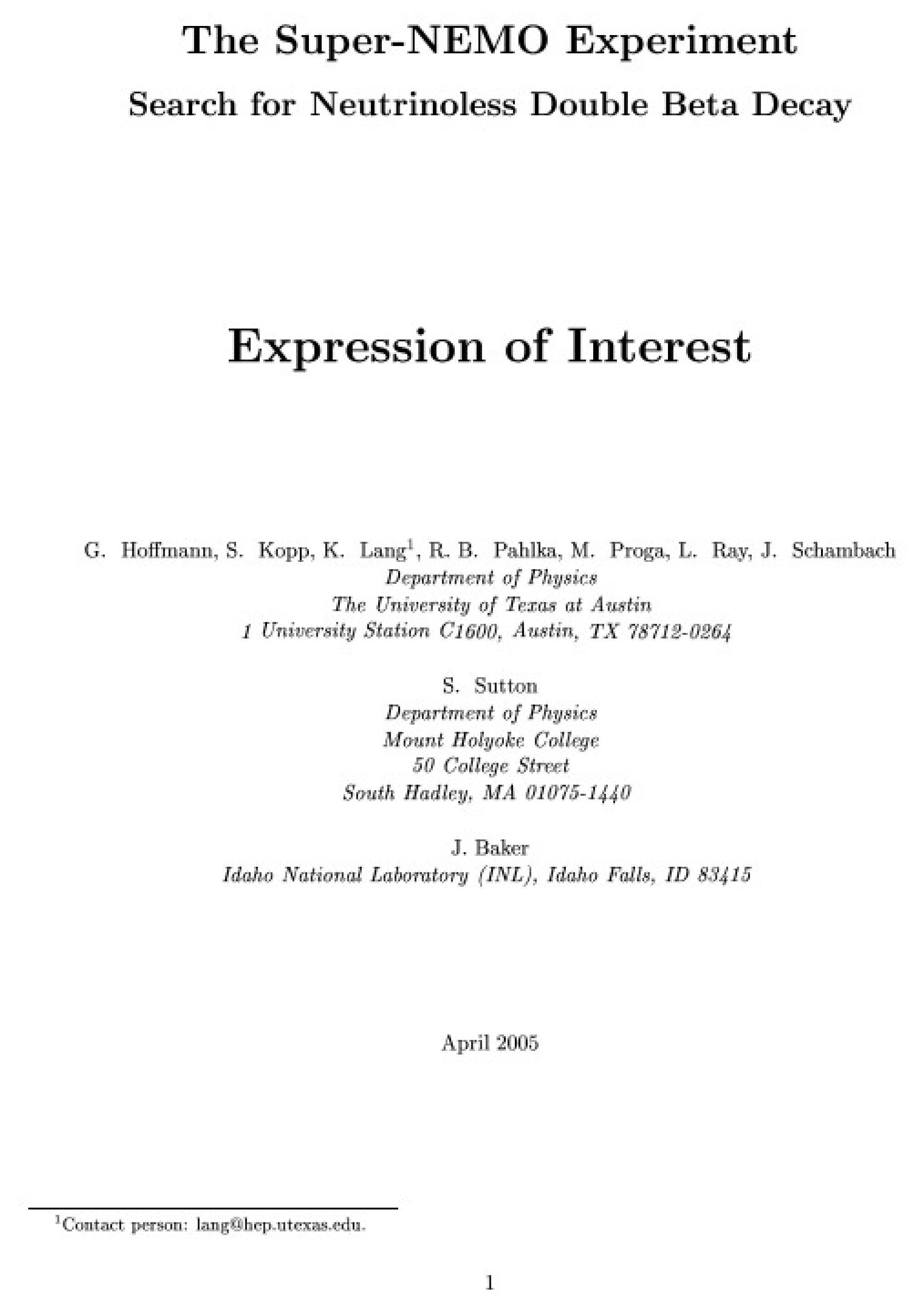
NuSAG - May 31, 2005 EXO 6

# NuSAG

## (tight funding implies more reviews)

- **NuSAG = Neutrino Scientific Assessment Group**
  - joint DOE-NSF committee
    - DOE ONP (Office of Nuclear Physics)
    - DOE OHEP (Office of High Energy Physics)
    - NSF EPP (Elementary Particle Physics)
  - chaired by **Gene Beier** (Penn) and **Peter Meyers** (Princeton)
  - committee to make recommendations for **specific** neutrino experiments
  - **no action** on funding of any (?) neutrino experiment
    - **before** the conclusions of this committee
  - **unclear** relation with **P5**
    - (US **P**article **P**hysics **P**roject **P**rioritization **P**anel- which is being (re)formed now)

- **Three domains of NuSAG**
  - reactor theta13
  - neutrinoless double beta decay
  - long baseline off-axis



# The Super-NEMO Experiment

## Search for Neutrinoless Double Beta Decay

# Expression of Interest

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S. Sutton
*Department of Physics*
*Mount Holyoke College*
*50 College Street*
*South Hadley, MA 01075-1440*

J. Baker
*Idaho National Laboratory (INL), Idaho Falls, ID 83415*

April 2005

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[1] Contact person: lang@hep.utexas.edu.

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# Super-NEMO

- Super-NEMO seeks to expand from NEMO-3
  - New groups:
    - UCL, Manchester U. (UK)
    - Osaka U. (Japan)
    - University of Texas (proposed)
- An estimated cost (crude) - $20-30M
- Main contributing countries
  - France
  - UK
  - Russia (mostly in-kind)
  - USA (proposed, $5-10M)
- Location of the experiment – TBD. Possibilities:
  - New cavern at Frejus (France)
  - Boulby mine (UK)
  - Gran Sasso (Italy)

# Concerns/issues

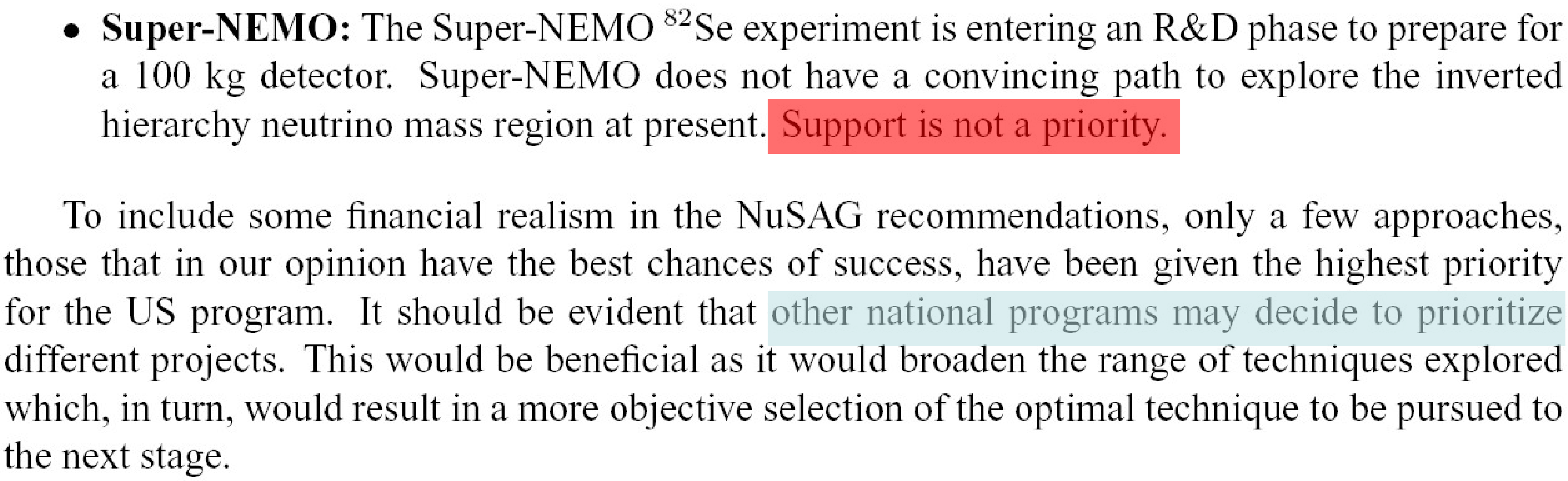
- It is a non-accelerator experiment (funding issues!).
- US will likely be a minority participant.
- The experiment will be in Europe.
- Who would fund the US effort?

- US participation compatible with the APS recommendations.
- Very little risk.

- We seek NuSAG endorsement with which we would approach DOE and/or NSF.
- We would re-evaluate (and possibly propose specific US contribution) in a year.

# *From NuSAG:*

*Super-NEMO – No go.*



- **Super-NEMO:** The Super-NEMO $^{82}$Se experiment is entering an R&D phase to prepare for a 100 kg detector. Super-NEMO does not have a convincing path to explore the inverted hierarchy neutrino mass region at present. Support is not a priority.

To include some financial realism in the NuSAG recommendations, only a few approaches, those that in our opinion have the best chances of success, have been given the highest priority for the US program. It should be evident that other national programs may decide to prioritize different projects. This would be beneficial as it would broaden the range of techniques explored which, in turn, would result in a more objective selection of the optimal technique to be pursued to the next stage.

*US*

*In*

*Super-NEMO ?*

# Summary and outlook

- **$0\nu\beta\beta$ physics is very compelling**
- **Several 100-200 kg experiments which may reach the neutrino mass sensitivity in the "interesting" range**
  - Super-NEMO
  - CUORE
  - Gerda/Majorana
  - EXO
- **Super-NEMO – extremely appealing to particle physicists**

# backup slides

# $\beta\beta0\nu$ Analysis: Background Measurement

NEMO-3 can measure each component of its background !

External Background $^{208}$Tl (PMTs)

Measured with ($e^-$, $\gamma$) external events

~ $10^{-3}$ $\beta\beta0\nu$-like events year$^{-1}$ kg$^{-1}$ with $2.8<E_1+E_2<3.2$ MeV

External Neutrons and High Energy gamma

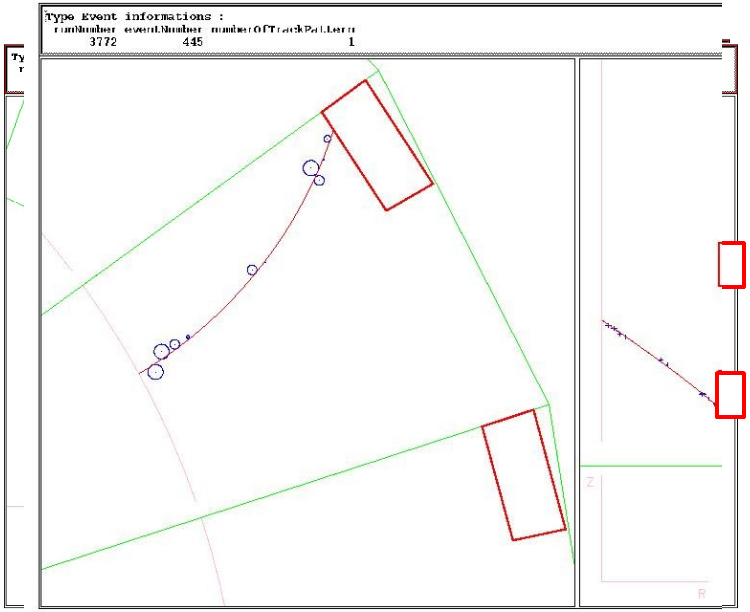
Measured with crossing $e^-$ or $(e^-,e^+)_{int}$ events with $E_1+E_2 > 4$ MeV

< 0.05 $\beta\beta0\nu$-like events year$^{-1}$ kg$^{-1}$ with $2.8<E_1+E_2<3.2$ MeV

$^{208}$Tl impurities inside the foils ~ 60 µBq/kg

Measured with ($e^-$,2$\gamma$), ($e^-$,3$\gamma$) events coming from the foil

~ 0.06 $\beta\beta0\nu$-like events year$^{-1}$ kg$^{-1}$ with $2.8<E_1+E_2<3.2$ MeV



```
Type Event informations :
 runNumber  eventNumber  numberOfTrackPattern
      3772          445                     1
```

~~Radon inside NEMO-3 detector~~

~~Measured with ($e^-$,$\gamma$,$\alpha$) events from the gas or the foil~~

~~~ 1 $\beta\beta0\nu$-like events year$^{-1}$ kg$^{-1}$ with $2.8<E_1+E_2<3.2$ MeV~~

Radon background suppressed by a factor 10 in Dec. 2004 with a radon-free air purification system

$^{100}$Mo $\beta\beta2\nu$ decay    $T_{1/2} = 7.14\ 10^{18}$ y

~ 0.3 $\beta\beta0\nu$-like events year$^{-1}$ kg$^{-1}$ with $2.8<E_1+E_2<3.2$ MeV
~~~

# Possible US contributions to R&D for Super-NEMO

- Enriched isotopic source
  - Large mass ($^{82}$Se ?) purification process
  - Develop source foils
- Modeling and simulation
  - GEANT4-based
  - Optimization of a detector design
- Detector R&D (overlapping with our experience from previous experiments)
  - Scintillator/Photodetectors (calorimetry)
  - Tracking
  - Data acquisition

# US in NEMO-3

- Super-NEMO will grow out of NEMO-3

- Present US participation in NEMO-3
  - Mount Holyoke College (Sean Sutton)
  - Idaho National Laboratory (INL, formerly INEEL) (John D. Baker)
  - Main involvement – purification of isotopic sources (5kg of $^{100}$Mo)
  - Currently working on purifying $^{82}$Se

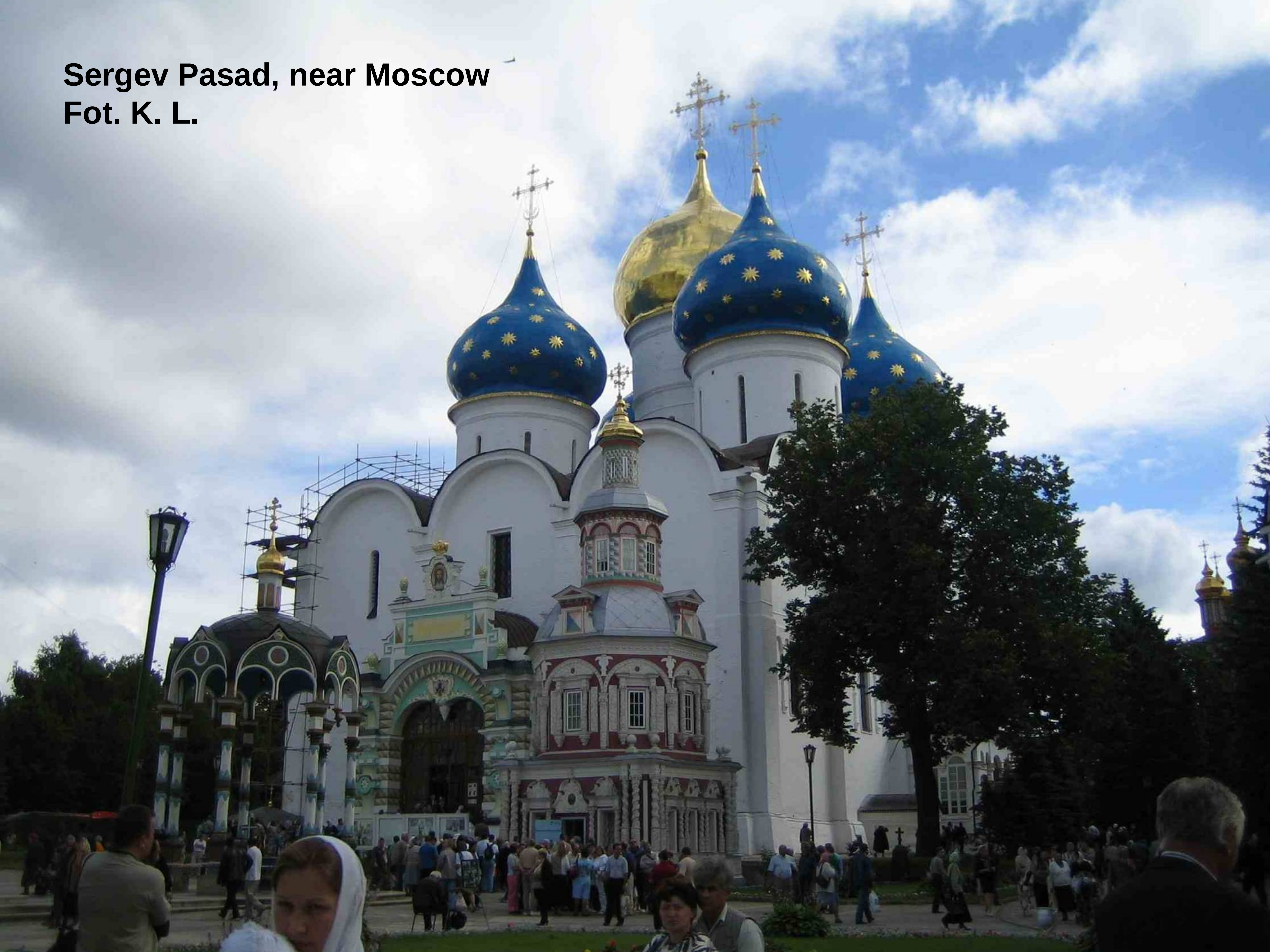
- Small DOE HEP grant for Mount Holyoke College

Repin:Burlaki

Potential for collaboration?

Colorado River (Texas)
Travis Lake, Austin, TX

Fot: K. Lang (2004)

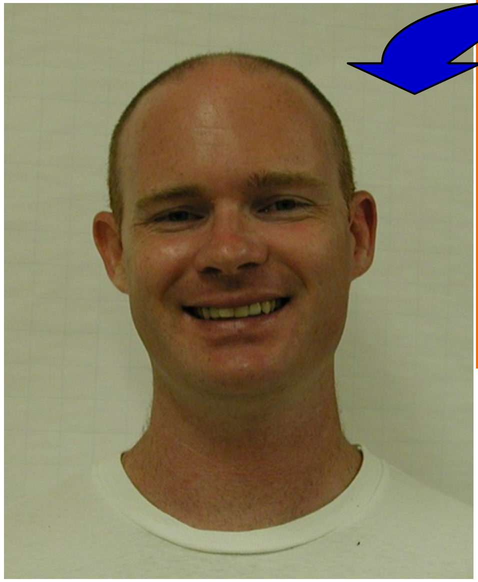


Sergev Pasad, near Moscow
Fot. K. L.

# *Preliminary scintillator studies for SuperNEMO*

*Karol Lang*

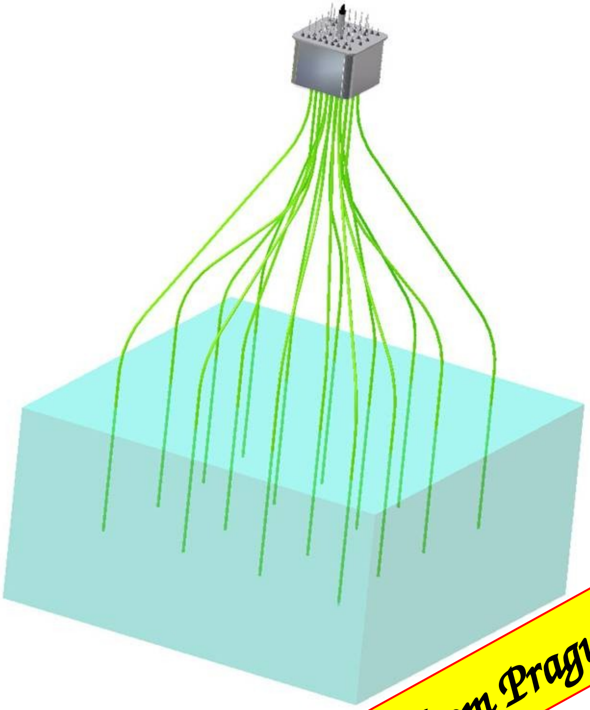
*for*

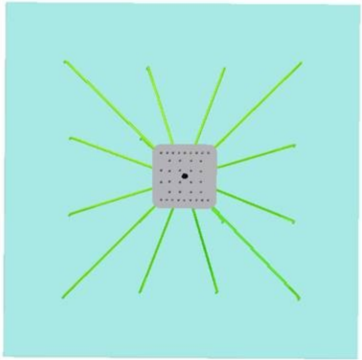


**Benton Pahlka and Ben Loer**

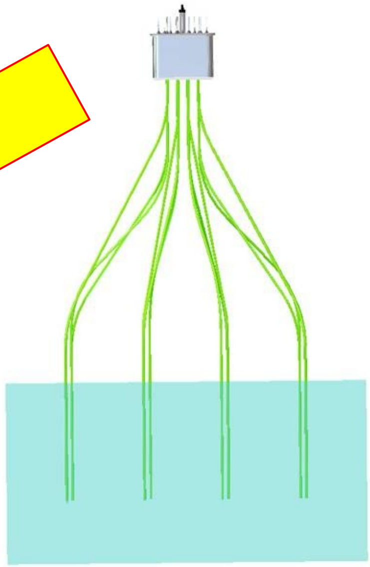
***University of Texas at Austin***

# A very different (i.e., perhaps naïve) idea





Top view

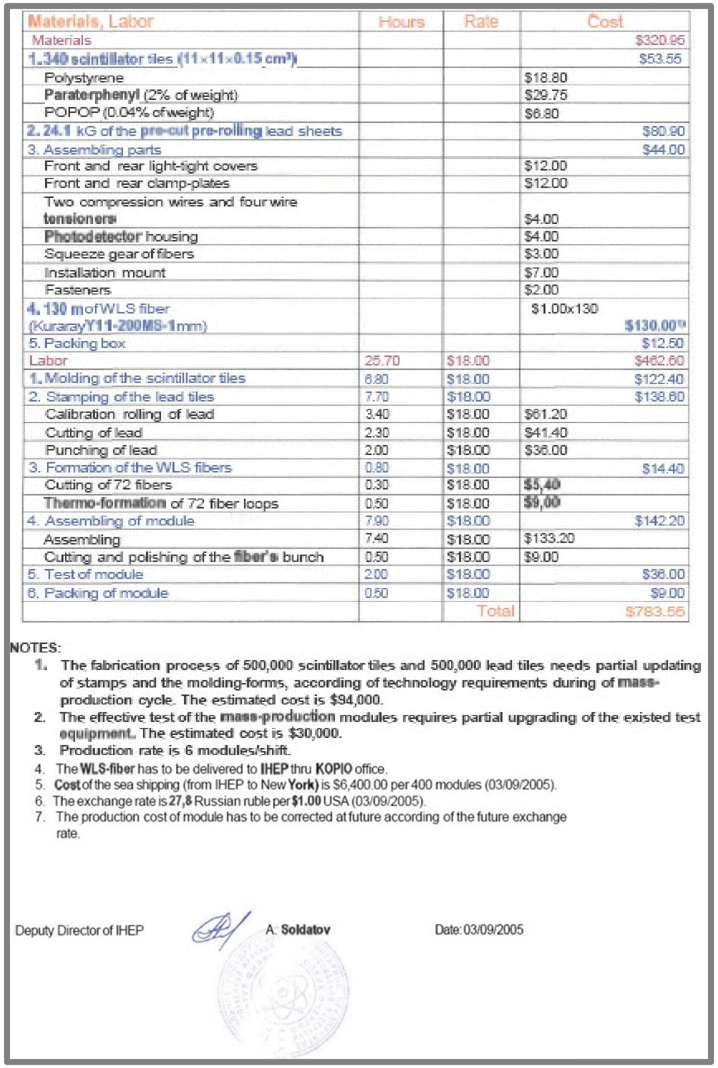


Side view

*A slide from Prague, Nov 2004*

# IHEP quotation for the module production

## A IHEP quoted price of the KOPIO module ( ≥ 1600)



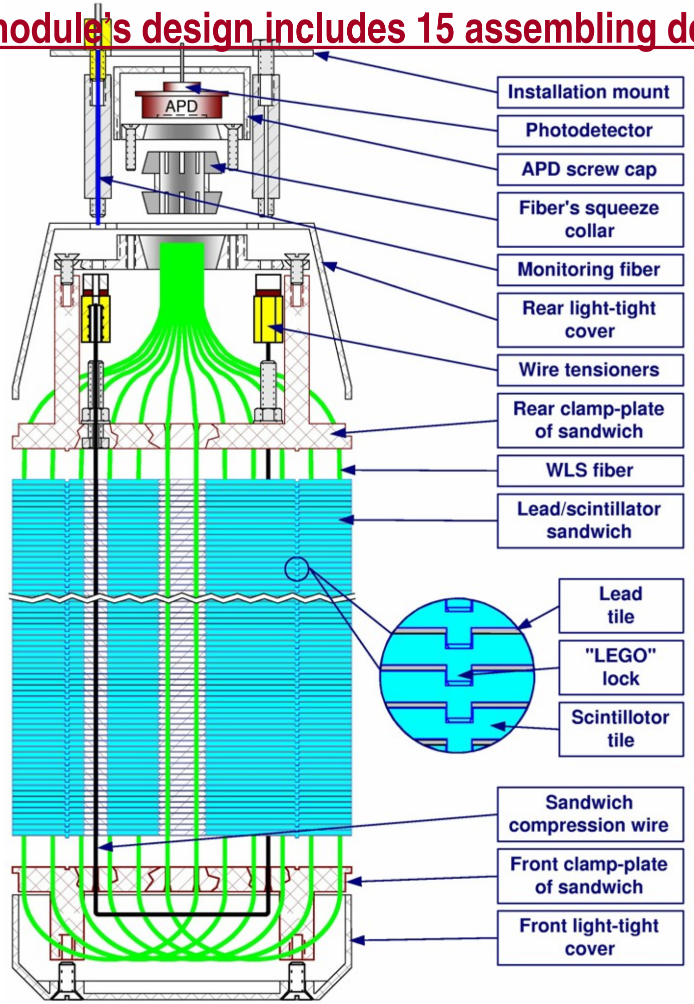
| Materials, Labor | Hours | Rate | Cost | |
|---|---|---|---|---|
| Materials | | | | $320.95 |
| 1. 340 scintillator tiles (11×11×0.15 cm³) | | | | $53.55 |
| Polystyrene | | | $18.80 | |
| **Paraterphenyl** (2% of weight) | | | $29.75 | |
| POPOP (0.04% of weight) | | | $6.80 | |
| 2. 24.1 kG of the pre-cut pre-rolling lead sheets | | | | $80.90 |
| 3. Assembling parts | | | | $44.00 |
| Front and rear light-tight covers | | | $12.00 | |
| Front and rear clamp-plates | | | $12.00 | |
| Two compression wires and four wire **tensioners** | | | $4.00 | |
| **Photodetector** housing | | | $4.00 | |
| Squeeze gear of fibers | | | $3.00 | |
| Installation mount | | | $7.00 | |
| Fasteners | | | $2.00 | |
| 4. 130 m of WLS fiber (Kuraray Y11-200MS-1mm) | | | $1.00x130 | $130.00[4] |
| 5. Packing box | | | | $12.50 |
| Labor | 25.70 | $18.00 | | $462.60 |
| 1. Molding of the scintillator tiles | 6.80 | $18.00 | | $122.40 |
| 2. Stamping of the lead tiles | 7.70 | $18.00 | | $138.60 |
| Calibration rolling of lead | 3.40 | $18.00 | $61.20 | |
| Cutting of lead | 2.30 | $18.00 | $41.40 | |
| Punching of lead | 2.00 | $18.00 | $36.00 | |
| 3. Formation of the WLS fibers | 0.80 | $18.00 | | $14.40 |
| Cutting of 72 fibers | 0.30 | $18.00 | **$5,40** | |
| **Thermo-formation** of 72 fiber loops | 0.50 | $18.00 | **$9,00** | |
| 4. Assembling of module | 7.90 | $18.00 | | $142.20 |
| Assembling | 7.40 | $18.00 | $133.20 | |
| Cutting and polishing of the **fiber's** bunch | 0.50 | $18.00 | $9.00 | |
| 5. Test of module | 2.00 | $18.00 | | $36.00 |
| 6. Packing of module | 0.50 | $18.00 | | $9.00 |
| | | Total | | $783.55 |

NOTES:

1. The fabrication process of 500,000 scintillator tiles and 500,000 lead tiles needs partial updating of stamps and the molding-forms, according of technology requirements during of **mass-production** cycle. The estimated cost is $94,000.
2. The effective test of the **mass-production** modules requires partial upgrading of the existed test **equipment**. The estimated cost is $30,000.
3. Production rate is 6 modules/shift.
4. The **WLS-fiber** has to be delivered to **IHEP** thru **KOPIO** office.
5. **Cost** of the sea shipping (from IHEP to New **York)** is $6,400.00 per 400 modules (03/09/2005).
6. The exchange rate is **27,8** Russian ruble per **$1.00** USA (03/09/2005).
7. The production cost of module has to be corrected at future according of the future exchange rate.

Deputy Director of IHEP A. **Soldatov** Date: 03/09/2005

## The module's design includes 15 assembling details



**Production cost is $784.**
**Production rate is 6 units/shift**

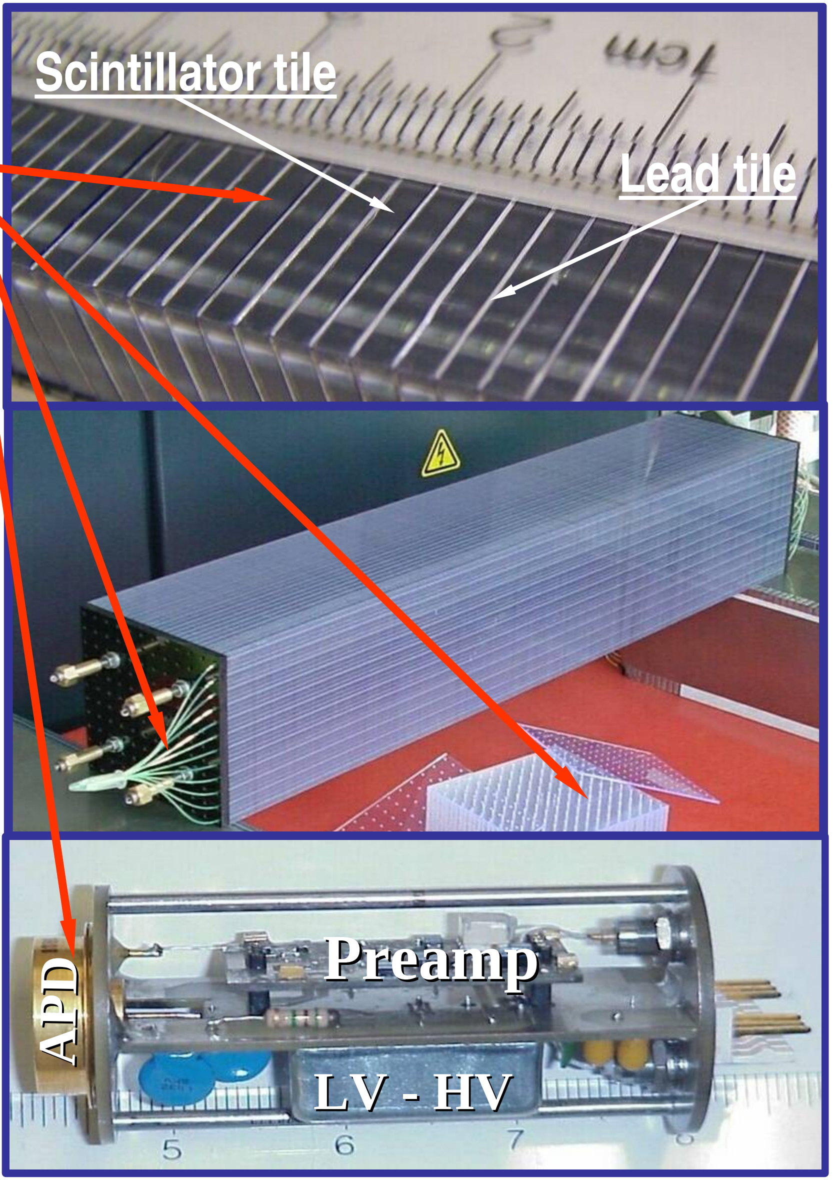
# Shashlyk calorimeter module

**Through simulation (Nucl. Instr. and Meth. A 531, 467, 2004) and prototyping, we have improved the energy & time resolution of Shashlyk modules over the past few years.**

**Four important innovations to reach $\Delta E/E \approx 3\%/\sqrt{E}$(GeV) are:**

- **New mechanical design (sampling term $\leq 2.3\%/\sqrt{E}$ );**
- **New scintillator (light ~ 60 ph/MeV, nonuniformity term $\leq 0.5\%$);**
- **New WLS fiber (longitudinal fluctuation term $\leq 1.1\%/\sqrt{E}$ );**
- **New photodetector (QE≈94%, photo-statistics term $\leq 0.7\%/\sqrt{E}$).**

| | |
|---|---|
| Cross sectional size | 110×110 mm$^2$ |
| Total depth (without Photodetector) | 735 mm |
| Total weight | 22.5 kG |
| Number of layers (Lead+Scintillator) | 340 |
| Scintillator thickness | 1.5 mm |
| Lead absorber thickness | 0.300 mm |
| Gap between scintillator tiles | 0.350 mm |
| Active depth | 19.4 $X_o$ (628 mm) |
| Effective $X_o$ | 32.4 mm |
| Effective $R_M$ | 54.8 mm |
| Type of WLS-fiber and a fiber's diameter | Y11-200MS, 1.0 mm |
| Effective attenuation length of WLS fiber | ≥ 300 cm |
| Fiber spacing | 9.3 × 9.3 mm$^2$ |
| Holes diameter in Scintillator/Lead tiles | 1.3 mm |
| Fiber bundle diameter | 14.0 mm |
| Emission peak of WLS fiber | ~ 500 nm |
| Effective light yield | ~ 60 photons/MeV |
| External wrapping (TYVEK paper) | 150 µ |



# Shashlyk - test beam results

**The best results were achieved for the calorimeter prototype with APD/WFD readout:**

| | |
|---|---|
| Energy resolution | $\approx (2.9\pm0.1)\%/\sqrt{E(\mathrm{GeV})}$. |
| Time resolution | $\approx (90\pm10)\mathrm{psec}/\sqrt{E(\mathrm{GeV})}$. |
| Photon detection inefficiency | $\approx 5\times10^{-5}$ (for $E_\gamma = 250$ MeV and incident beam angle $\geq 5$ mrad). |
| APD gain stability | $\leq 1\%$ (for tested period of 24 hours). |

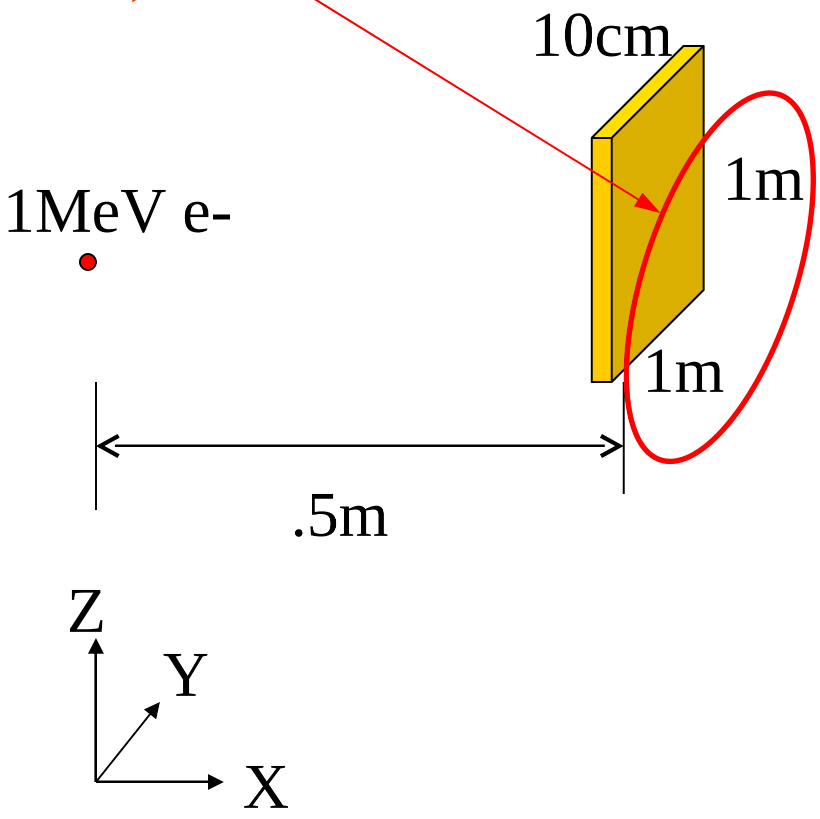
# Simulation Parameters

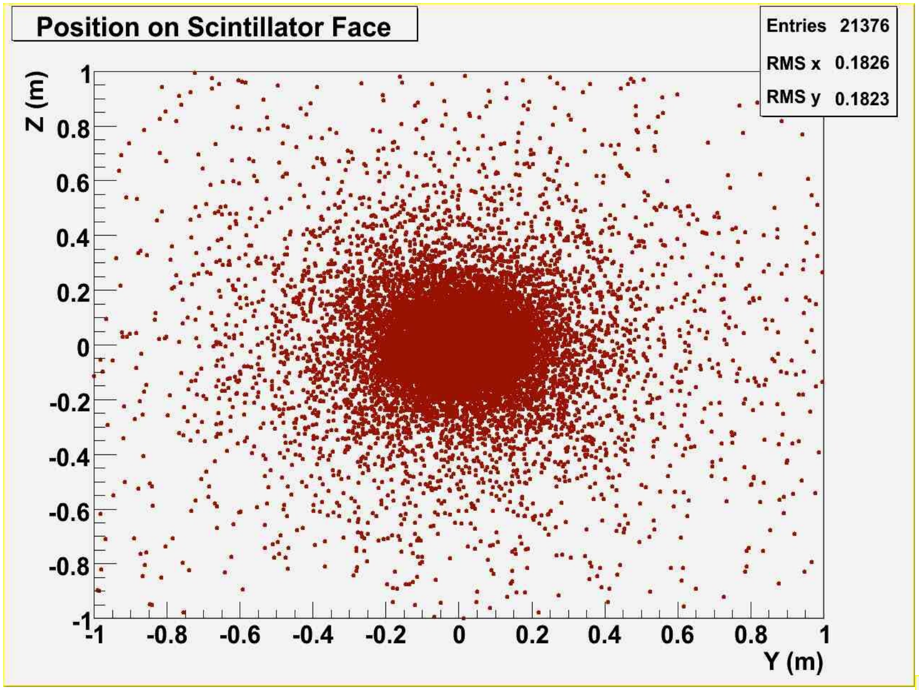
**Large scintillator area was needed to capture most electrons (.7% missed detector in this scheme)**

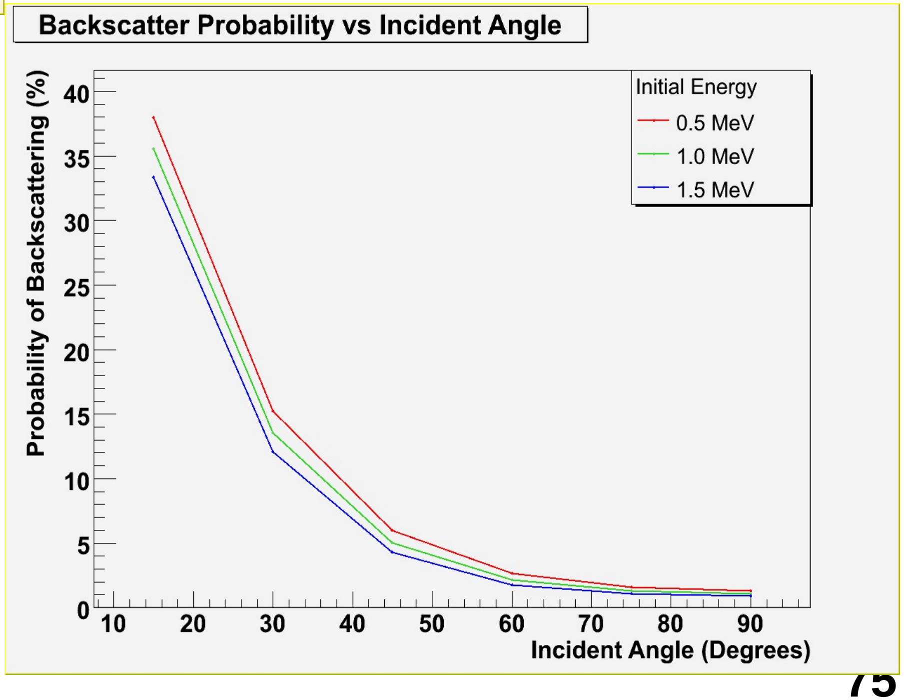
- GEANT4
- 1 MeV electrons (“pencil beam”)
- 0.5m travel through He at STP
- Scintillator:

  1m x 1m x 10cm

  of EJ-204
- 1 million runs

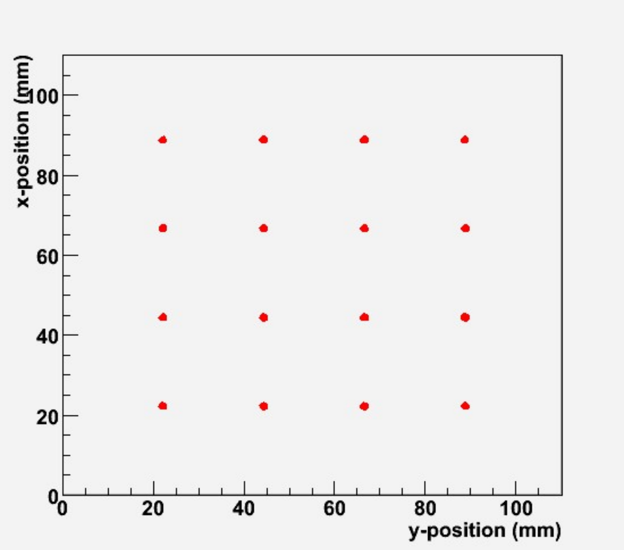



Position on Scintillator Face
Entries 21376
RMS x 0.1826
RMS y 0.1823
Z (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Y (m)

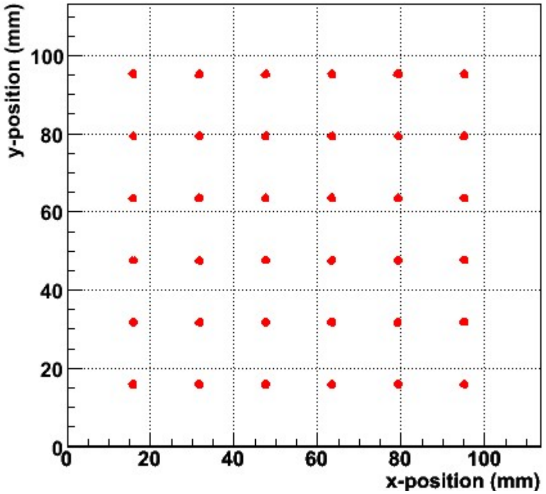

Backscatter Probability vs Incident Angle
Initial Energy
0.5 MeV
1.0 MeV
1.5 MeV
Probability of Backscattering (%)
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
Incident Angle (Degrees)

# 4 Detector configurations

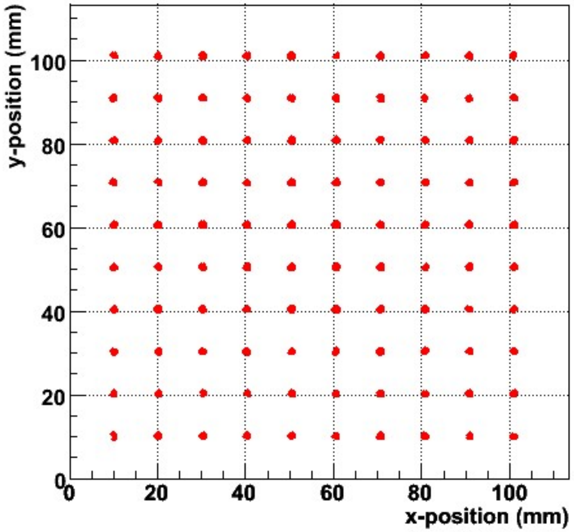
16



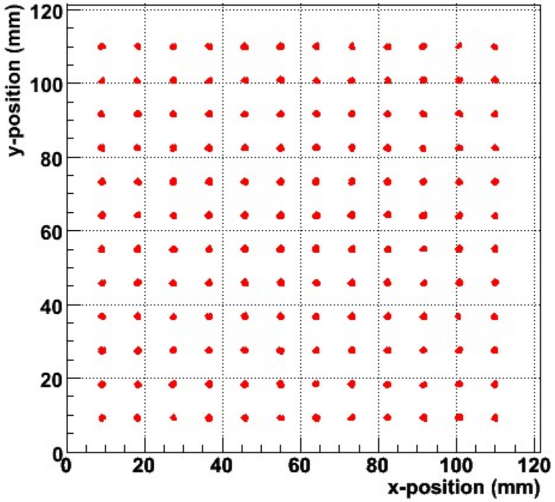
36



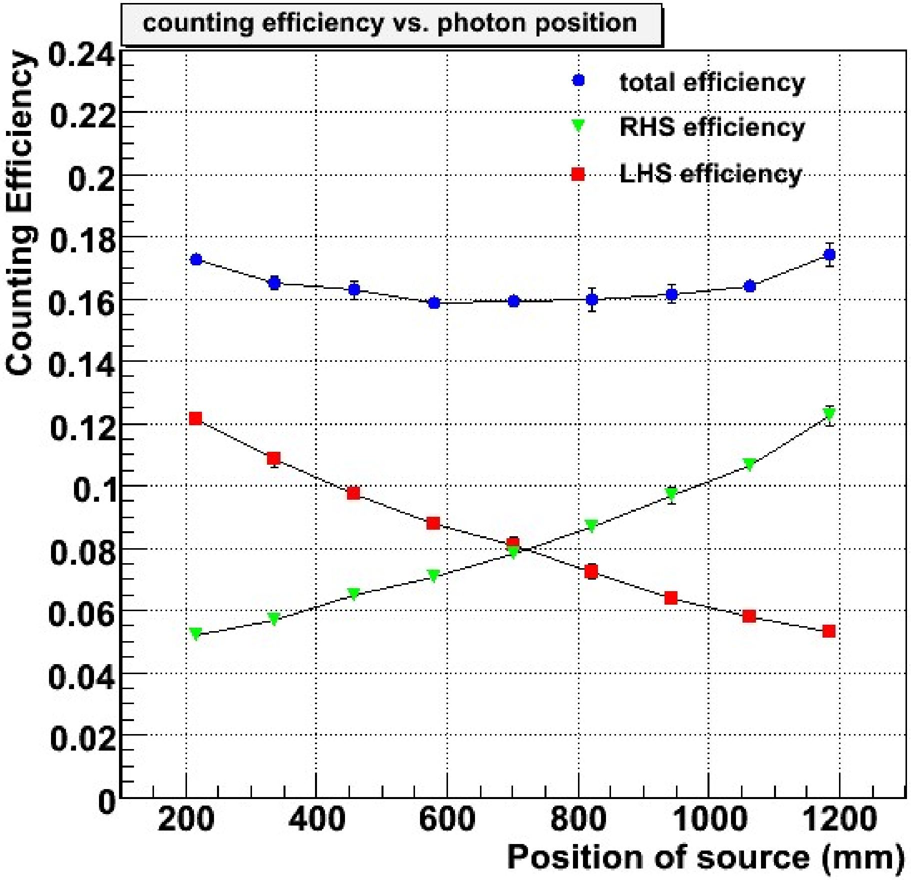
100



144



# Results:
# Position of impact

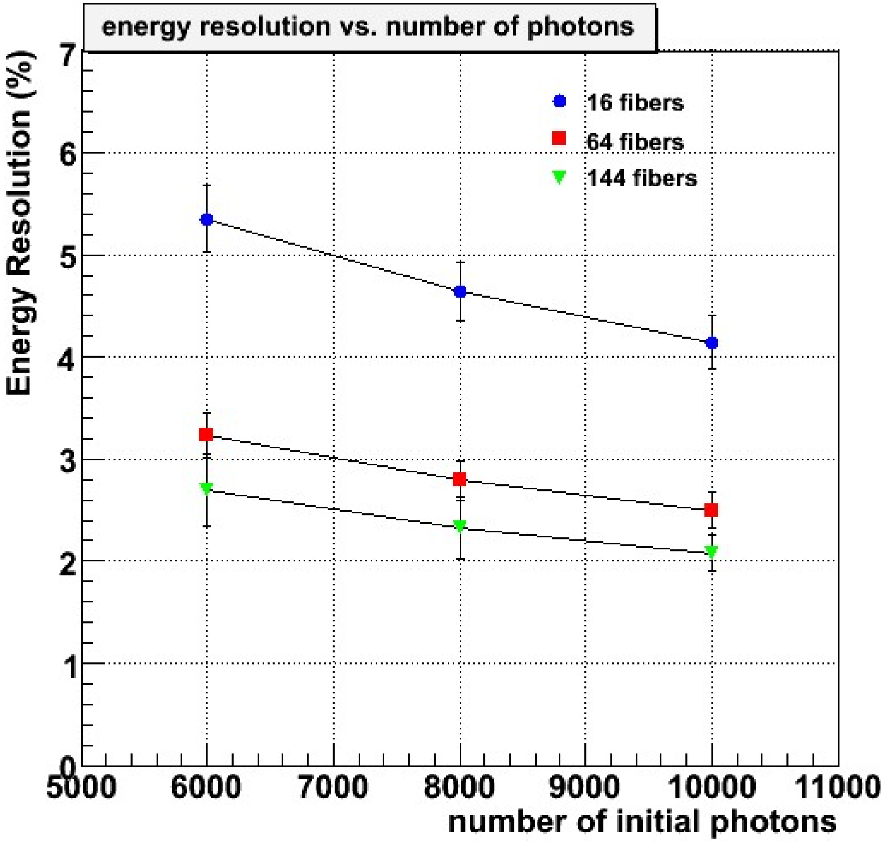


- Simulations are for three trials, 25000 photons each.

- CE decreased from last time due to reflection coefficient decrease (.95 -> .93) and WLS distance decrease to 3 mm. Could not find a reference for this number. Also, couldn't get NIM paper.

- 64 fibers, 1mm diameter, 1.5 mm plate thickness

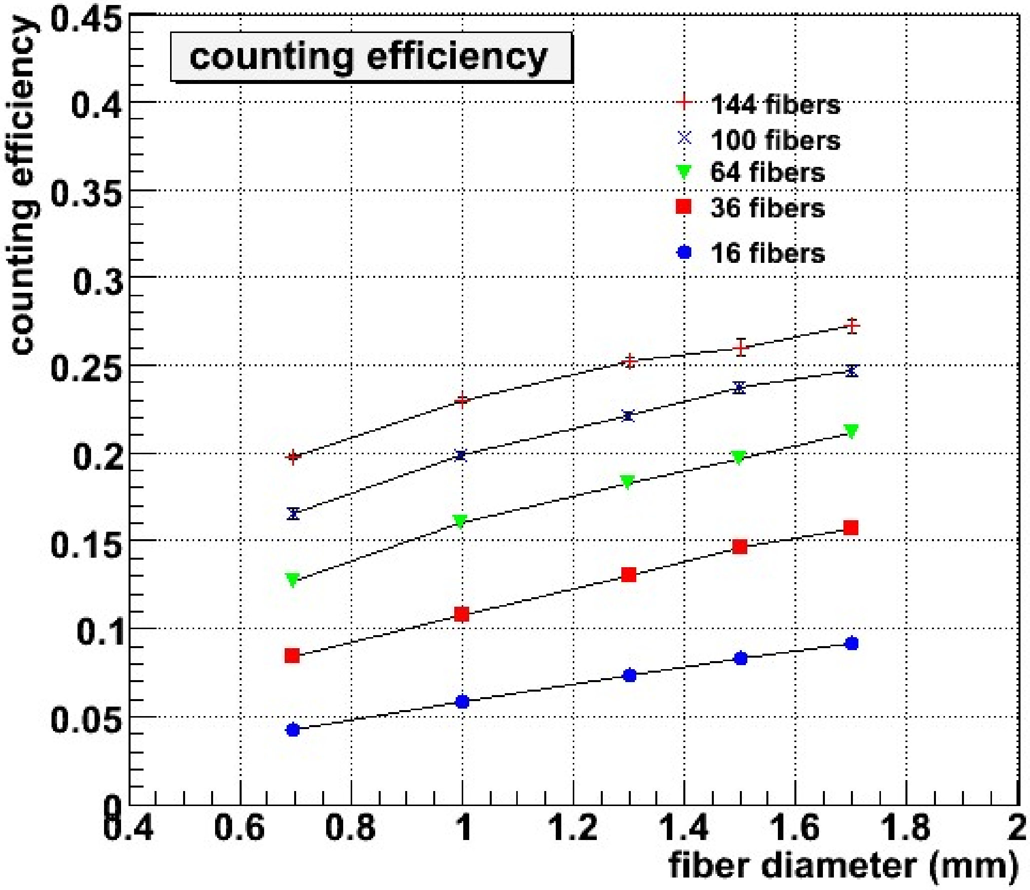
# *Results:*
# *Energy resolution*



*This figure shows the resolution variation with number of initial photons*

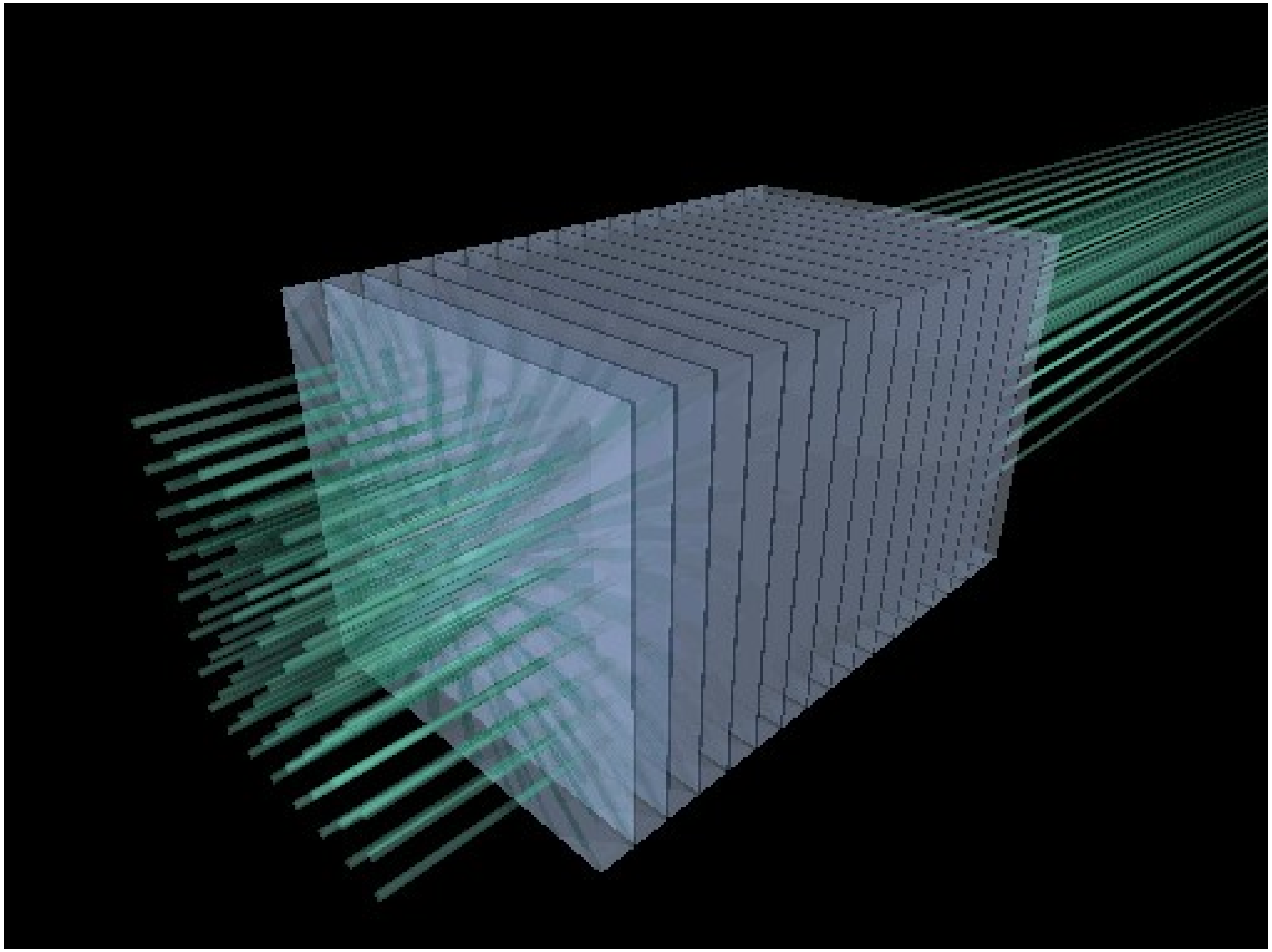
- *1.0 mm fibers*
- *Lots of improvement over 16 fibers*
- *Limited improvement over 64 fibers*

# *Results:*
# *efficiency vs fiber diameter*



- *Error bars are included.*
- *This is for three trials at 25000 photons per trial.*
- *25000 photons was an arbitrary number to optimize error but minimize simulation time.*
- *Resolutions would be calculated using ~6k – 10k photons.*

# Shashlyk Detector Design



*Only the first few scintillator plates!*

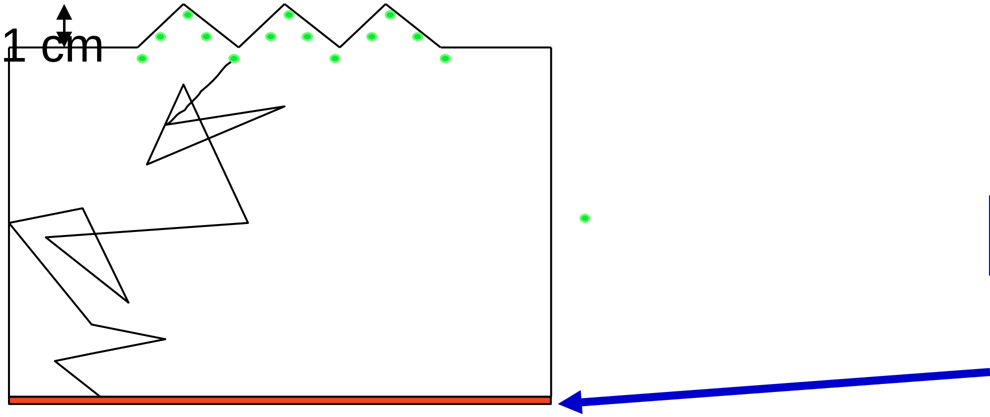
# *Study of a “Grooved” Surface*

*(from Benton)*

*Volume is 1000 $cm^3$*

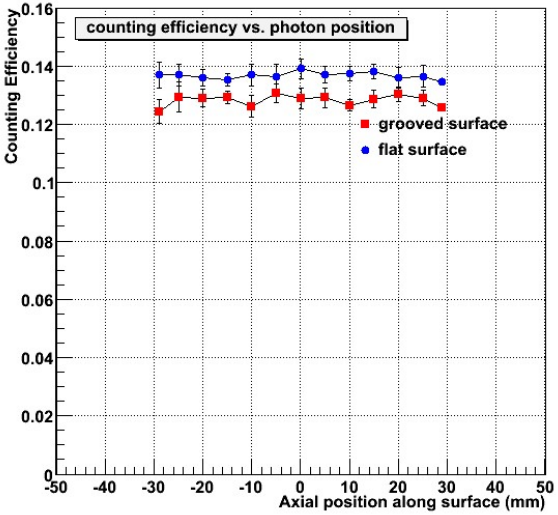
*Studied a flat surface versus a “grooved” surface with three grooves*

*Groove height is 1 cm*



● = *position of photon generation*

***Surface marked for detection***



*(From P. Vogel)*

*If (or when) the 0νββ decay is observed two problems must be resolved:*

*a) What is the mechanism of the decay,*
*i.e., what kind of virtual particle is exchanged ?*

*The* **0νββ** *decay can proceed either by*
*1) the exchange of a virtual light (~ eV mass or less) Majorana neutrino,*

*or*

*2) by the exchange of some other much heavier (~ TeV)*
*and as yet hypothetical particle that will also cause*

*b) How to relate the observed decay rate to the fundamental parameters,*
*i.e., what is the value of the corresponding nuclear matrix element?*

(from P. Vogel)

- In $0\nu\beta\beta$ *decay with the exchange of light Majorana neutrinos,*

$$\langle m_{\beta\beta}\rangle = |\Sigma_i \, |U_{ei}|^2 \, m_i \, e^{i\delta(i)} \,|$$

*where* $\delta(i)$ *are the Majorana CP phases of* $U_{ei}$.

- *These phases are relevant only for Majorana neutrinos; they do not affect flavor oscillations.*
- *The complete neutrino mass matrix is thus characterized by:*
  - *N masses*
  - *N(N-1)/2 mixing angles*
  - *(N-1)(N-2)/2 CP violating phases (Dirac)*
  - *N-1 Majorana CP violating phases*
  - *Thus* $N^2$ *parameters altogether*

For N = 3 we know 4 of them reasonably well (but not the sign of $\Delta m^2_{23}$), for another two, $\Theta_{13}$ and the absolute mass scale, we have upper limits, but we have no idea about the values of the 3 CP phases.

- *Independently of these phases*

$$\mathrm{Max}[2|U_{ei}|^2 m_i] - \Sigma |U_{ei}|^2 \leq \langle m_{\beta\beta}\rangle \leq \Sigma |U_{ei}|^2 m_i$$

*These upper and lower limits depend only on the oscillation parameters and one mass* $m_{min}$.

# Extrapolated panorama for $\beta\beta(0\nu)$ ~ 2008

| Experiment | Detector | Mass (kg) | Isotope | $T_{1/2}$(y) | $<m_\nu>$ (eV) |
|---|---|---|---|---|---|
| **NEMO 3** | **tracko-calo** | **6.9** | **$^{100}$Mo** | **$4\ 10^{24}$** | **0.2 –0.35** |
| **NEMO 3** | | **0.9** | **$^{82}$Se** | **$8\ 10^{23}$** | **0.65 –1.8** |
| **CUORICINO** | **bolometers** | **12** | **$^{130}$Te** | **$4\ 10^{24}$** | **0.2 – 1.2** |
| **EXO** | **TPC** | **200** | **$^{136}$Xe** | **$3\ 10^{25}$** | **0.39 – 1.2** |
| **GERDA** | **Ge diodes** | **20** | **$^{76}$Ge** | **$3.10^{25}$** | **0.28 – 0.9** |

# Other task sharings

## Calibration survey

Goal: To develop a daily calibration check to follow the absolute calibration at a level better than 1% (currently 2% in NEMO 3)

- Extrapolation of the NEMO 3 system based on laser light: *CENBG (France), University of Texas*
- System based on the use of LED light: *CENBG (France), UCL (UK), University of Texas*

## Electronics and slow control

- Trigger: *LPC-Caen (France)*
- Data acquisition: *CENBG, IReS, LPC-Caen (France), Manchester, UCL (UK)*
- Slow control: *IReS, LPC-Caen (France), Manchester, UCL (UK)*

## Simulations

Goal: To design the detector, to determine precisely the required energy resolution, the required level of radiopurity and the ultimate sensitivity of SuperNEMO.

` *CENBG, IReS, LAL, LPC-Caen (France), JINR, ITEP (Russia), Manchester, UCL (UK), Univ. Of Texas (USA)*

## Mechanics

Goal: Design study of the detector

*LAL (France), Manchester (UK)*

## Nuclear matrix element theory

Goal: To improve the nuclear matrix element calculations to predict the best ββ candidate.

- Calculations based on Shell Model: *IReS (France)*
- Calculations based on QRPA: *Jyvaskula (Finland), Prague (Czech Republic)*

# Performance of the detector

## Tracking Detector:

**99.5 % Geiger cells ON**

**Vertex resolution**:

2 $e^-$ channels (482 and 976 keV) using $^{207}$Bi sources at 3 well known positions in each sector

**$\sigma_\perp$ (ΔVertex) = 0.6 cm**

**$\sigma_{//}$ (ΔVertex) = 1.3 cm** (Z=0)

**$e^+/e^-$ separation** with a magnetic field of 25 G

**~ 3% confusion at 1 MeV**

## Calorimeter:

**97% of the PMTs+scintillators are ON**

**Energy Resolution**:

calibration runs (every ~ 40 days) with $^{207}$Bi sources

| | Ext. Wall 5" PMTs | Int. Wall 3" PMTs |
|---|---|---|
| **FWHM (1 MeV)** | **14%** | **17%** |

**Daily Laser Survey** to control gain stability of each PM

**gamma**: efficiency ~ 50 % @ 500 keV, $E_{thr}$ = 30 keV

## Time Of Flight:

**Time Resolution** (ββ channel) ≈ **250 ps at 1 MeV**

**ToF (external crossing $e^-$ ) > 3 ns**

**external crossing $e^-$ totally rejected**

**Expected Performance of the detector has been reached**

# What have we learnt with NEMO 3 detector

to identify and measure all sources of background

to control internal and external backgrounds at the level of 10 kg of enriched isotopes

to build a very low-background detector

to prove the reliability of the chosen techniques

to purify ββ isotopes by removing $^{214}$Bi and $^{208}$Tl contaminants

to remove background due to radon

to develop ultra low background HPGe detectors

to gain expertise in developping radon detectors sensitive to 1 mBq/m$^3$

Technique can be extrapolated for larger mass detector
3 years R&D program (2005-2007) have been approved
in March 2005 by IN2P3 France

# Radon free air purification system

A($^{222}$Rn) in the LSM ~ **20 Bq/m³**

Inside NEMO 3 ~ **20 mBq/m³**

(measured by NEMO 3 itself and radon detectors developed by the collaboration sensitive to 1mBq/m³ )

~ 1 count/kg/y in [2.8-3.2] MeV ββ0ν energy window

**Radon background factor 10 TOO HIGH**

May 2004 : Tent surrounding the detector

October 2004 : Radon-free SuperKamiokande-like Air Factory (2×500 kg charcoal @ -50°C)

December 2004

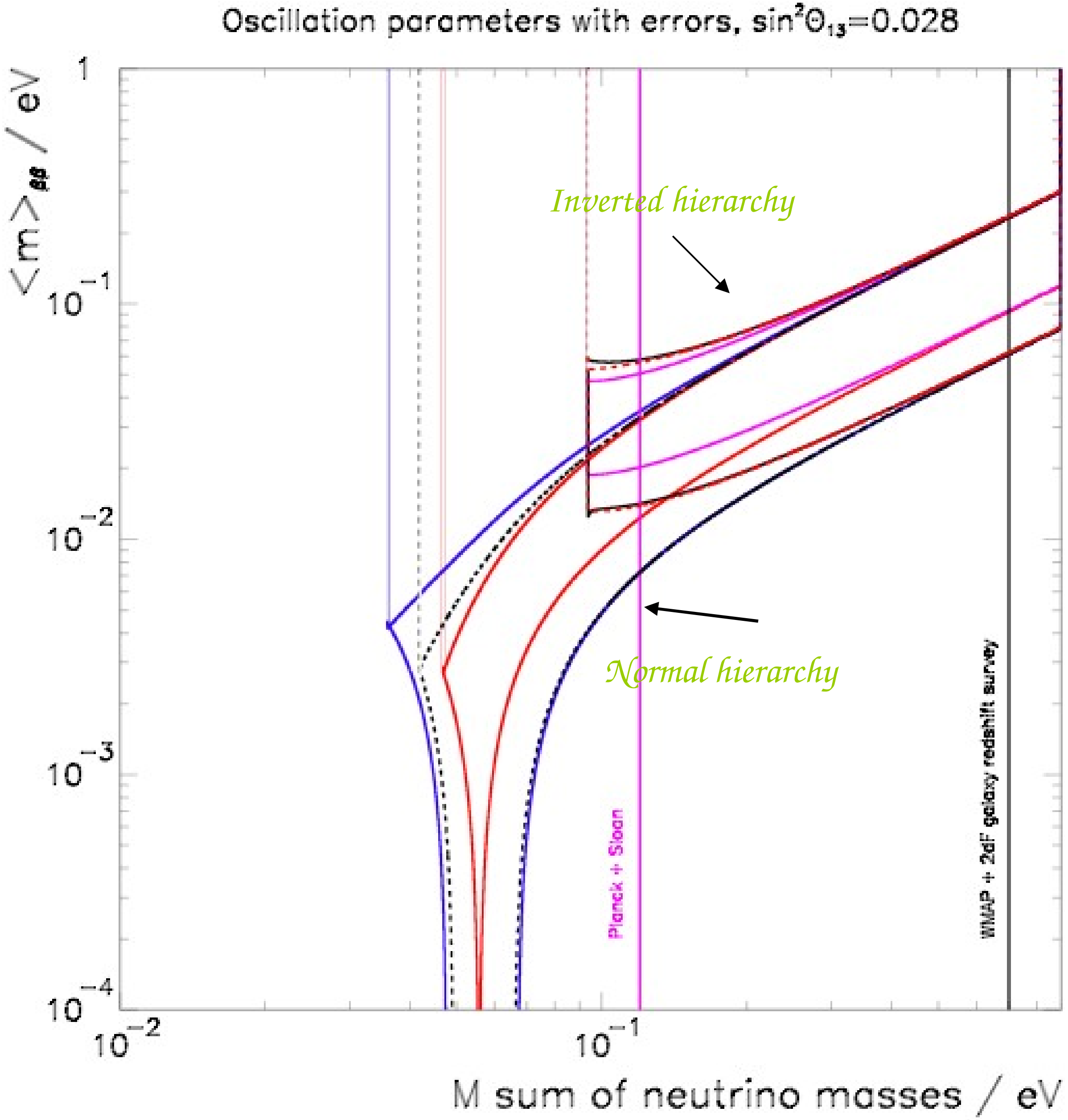
A($^{222}$Rn) ~ **0.1 Bq/m³** in the tent

reduction factor ~200

A(222Rn) inside NEMO 3 **~ 2 mBq/m³**

Reduction factor of Radon Backgound ~ 10

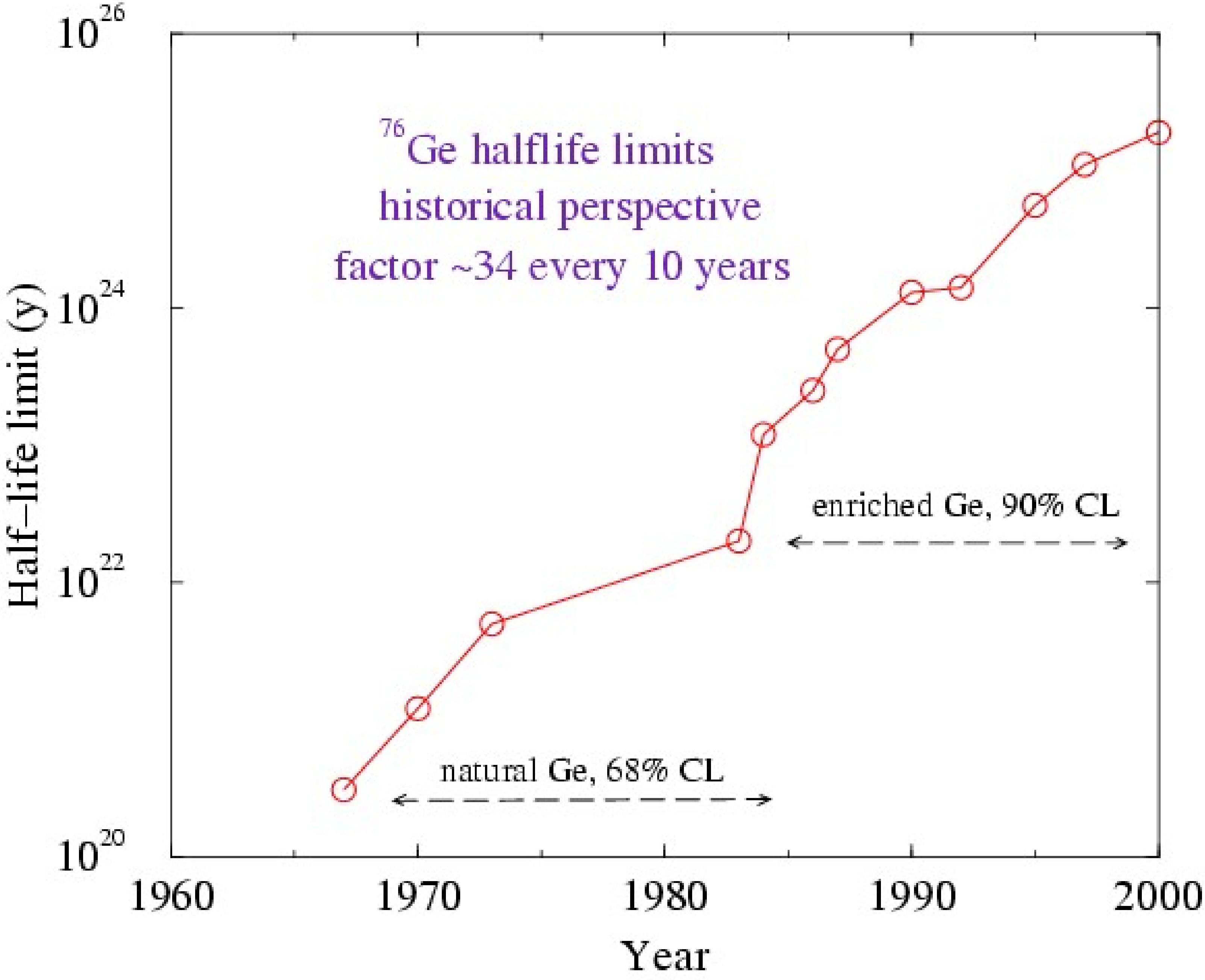
**RADON BACKGROUND IS NEGLIGEABLE TODAY**



*Inverted hierarchy*

*Normal hierarchy*

Slide by A.Piepke


$^{76}$Ge halflife limits
historical perspective
factor ~34 every 10 years
enriched Ge, 90% CL
natural Ge, 68% CL
Half–life limit (y)
$10^{26}$
$10^{24}$
$10^{22}$
$10^{20}$
1960
1970
1980
1990
2000
Year

$$\langle m_\nu \rangle = (2.50 \times 10^{-8}\mathrm{eV}) \left[ \frac{W}{f x \epsilon G^{0\nu} |M_{0\nu}|^2} \right]^{1/2} \left[ \frac{b \Delta E}{MT} \right]^{1/4} \quad \text{background limited}$$

$$\langle m_\nu \rangle = (2.67 \times 10^{-8}\mathrm{eV}) \left[ \frac{W}{f x \epsilon G^{0\nu} |M_{0\nu}|^2} \right]^{1/2} \times \frac{1}{\sqrt{MT}} \quad \text{zero background}$$

***W = molecular weight of the source material***

***f = isotopic abundance***

***x = number of ββ atoms per molecule***

***ε = detector efficiency***

***b = number of bkg counts***

***M = mass of isotope in kg***

***T = the live time***

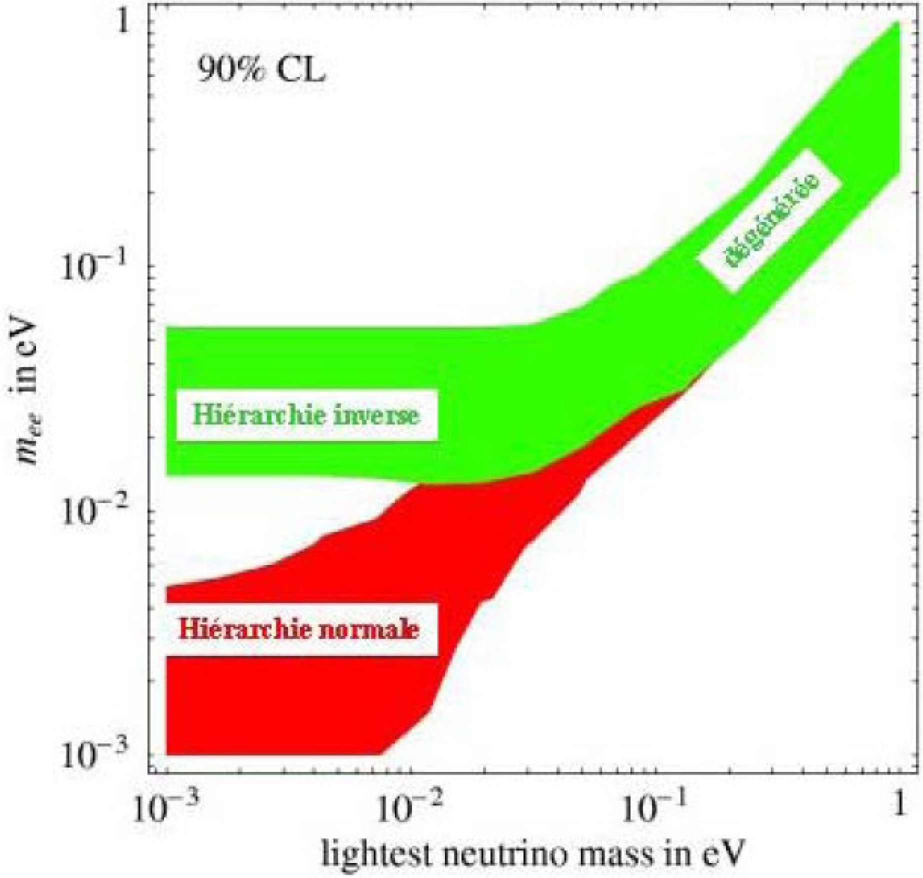
***ΔE = energy window in keV***

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

where :

$\theta_{ij}$ are the mixing angles between i and j eigenstates

$\alpha$ et $\beta$ are Majorana phases



| *Isotope* | $T_{1/2}$ (90% CL) (ans) | $<m_\nu>$ (eV) | Masse (kg.an) | Référence |
|---|---|---|---|---|
| $^{48}Ca$ | $>1.8\ 10^{22}$ | $<6.3$-$39.4$ | 0.005 | [Ume03] |
| $^{76}Ge$ | $>1.9\ 10^{25}$ | $<0.35 – 1.05$ | 35.5 | [Kla01a] |
|  | $>1.57\ 10^{21}$ | $<0.33 – 1.55$ | 8.9 | [Gon03] |
| $^{82}Se$ | $>1.9\ 10^{23}$ | $<1.3$-$3.6$ | 0.55 | [Sar04] |
| $^{100}Mo$ | $>3.5\ 10^{23}$ | $<0.7 – 1.2$ | 4.10 | [Sar04] |
| $^{116}Cd$ | $>1.3\ 10^{23}$ | $<1.7$ | 0.159 | [Biz03] |
| $^{130}Te$ | $>7.3\ 10^{23}$ | $<0.3 – 1.90$ | 3.16 | [Arn04] |
| $^{136}Xe$ | $>4.4\ 10^{23}$ | $<2$-$3$ | 2.27 | [Lue98] |
| $^{150}Nd$ | $>1.2\ 10^{21}$ | $<3$ | 0.009 | [Des97] |

*Table 1: Present limits for different double beta decay isotopes*

$$\frac{\Gamma(\mathrm{Ti}+\mu^- \rightarrow e^+ + \mathrm{Ca}_{\mathrm{gs}})}{\Gamma(\mathrm{Ti}+\mu^- \rightarrow \nu_\mu + \mathrm{Sc})} < 1.7 \times 10^{-12} \ (90\% \ CL)$$

$$\langle m_{\mu e}\rangle \equiv \langle \sum_i U_{ei}U_{\mu i}m_i\rangle < 17(82)\mathrm{MeV}$$

$$\frac{\Gamma(K^+ \rightarrow \pi^-\mu^+\mu^+)}{\Gamma(K^+ \rightarrow \mathrm{all})} < 3.0 \times 10^{-9} \ (90\% \ CL)$$

$$\langle m_{\mu\mu}\rangle \equiv \sum_i U_{\mu i}^2 m_i \ < \ 4 \times 10^4 \ \mathrm{MeV}$$

*S. Elliot & P. Vogel, 2002*

NEMO-3 Opening Day, July 2002

**Start taking data 14 February 2003**

Water tank

wood

coil

Iron shield

# Comparison of $M^{0\nu}$ of Rodin et al. (RQRPA) and Nowacki et al. (SM, private comm., preliminary 2004) and older published (Caurier et al. 1996)

| Nucleus | RQRPA | SM |
|---|---|---|
| $^{76}$Ge | 2.3-2.4 | 1.6 |
| $^{82}$Se | 1.9-2.1 | 1.7 |
| $^{96}$Zr | 0.3-0.4 | 0.4 |
| $^{100}$Mo | 1.1-1.2 | 0.3 |
| $^{116}$Cd | 1.2-1.4 | 1.9 ← |
| $^{130}$Te | 1.3 | 2.0 (1.0) |
| $^{136}$Xe | 0.6-1.0 | 1.6 (0.6) |

*Except for $^{100}$Mo the agreement between these very different calculations is reasonably good.*

# KOPIO Shashlyk Photon Calorimeter

*(a few slides from V. Issakov)*

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V.Semenov, I.Shein, A. Soldatov, N.Tyurin,
V.Vassil'chenko and A.Yanovich

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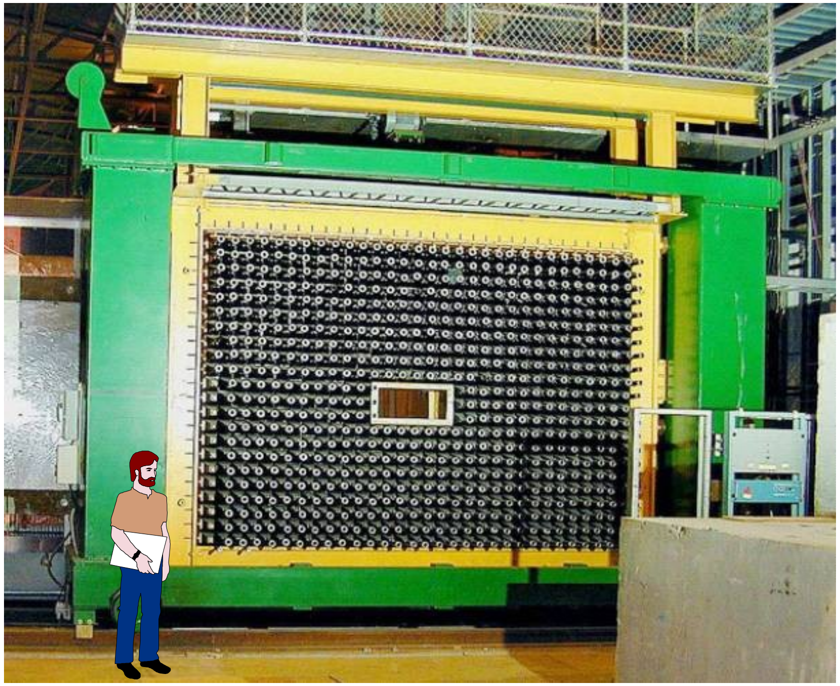
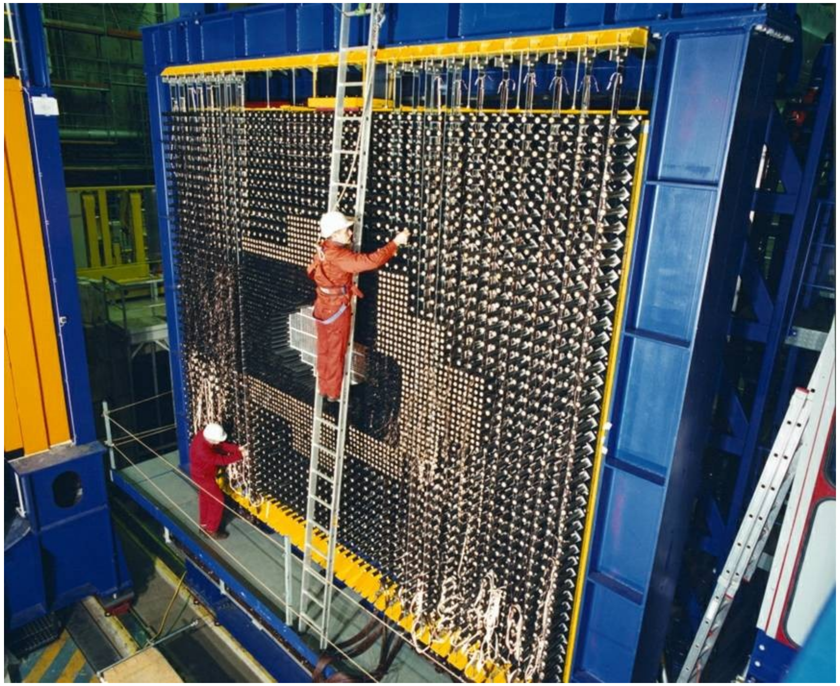
*Protvino, Moscow region, Russia*



Shashlyk Calorimeter of 22×32 modules.
E865 experiment. BNL, 1993.



Shashlyk Calorimeter of 42×56 modules.
HERA-B experiment. DESY, 1998.

# *Monte Carlo Simulations at UT*

**SOFTWARE: DETECT2000 (F. Cayouette *et al*.)**

**Models the behavior of optical systems with emphasis on scinitillation counting**

**Has the capacity to model:**
- **Quantum efficiency**
- **Primary and wavelength shifted photons**
- **Surface coatings (metal, paint, sanded, polished)**
- **Surface reflection coefficients (diffuse and specular reflection)**
- **Fiber optics**
- **Bulk and surface attenuation lengths**

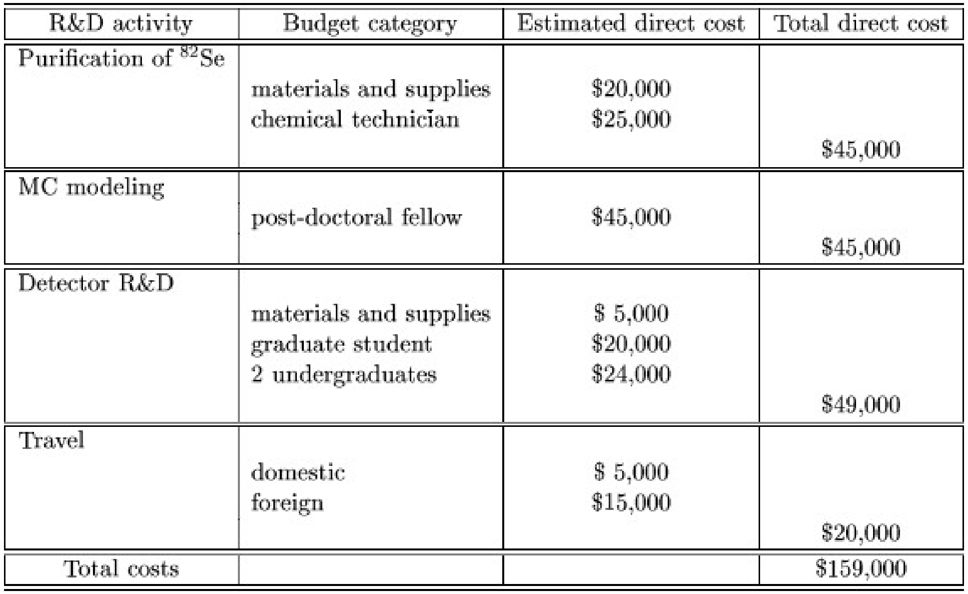
**Has the capacity to score or tally:**
- **counted vs. scattered vs. absorbed photons**
- **photon time of flight**
- **position and component of counted photons**
- **number of surfaces encountered**

**THIS IS A ROBUST SOFTWARE PACKAGE**

# Summary

- Super-NEMO provides for the US program an attractive opportunity to participate in a fore-front experiment in a cost-efficient way.

- With NuSAG endorsement, we plan to ask DOE HEP/NP and/or NSF for funding to help to launch the R&D effort.



| R&D activity | Budget category | Estimated direct cost | Total direct cost |
|---|---|---|---|
| Purification of $^{82}$Se | materials and supplies | $20,000 | $45,000 |
| | chemical technician | $25,000 | |
| MC modeling | post-doctoral fellow | $45,000 | $45,000 |
| Detector R&D | materials and supplies | $ 5,000 | $49,000 |
| | graduate student | $20,000 | |
| | 2 undergraduates | $24,000 | |
| Travel | domestic | $ 5,000 | $20,000 |
| | foreign | $15,000 | |
| Total costs | | | $159,000 |

- If endorsed, we would expand the US collaboration.

# NEMO Tracko-Calo experimental approach for ββ(0ν) search

Detection of the 2 electrons: rejection of unknown nuclear gamma line

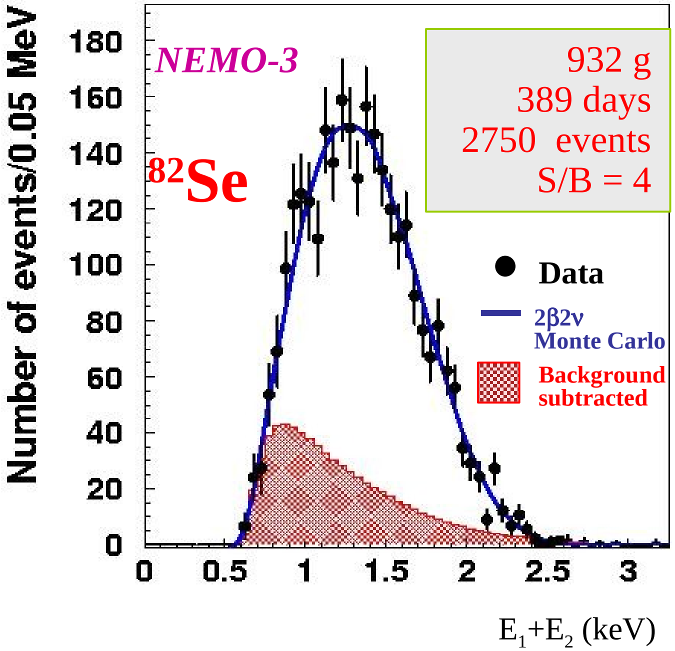
3 observables: single energy spectrum, angular correlation, energy sum
(identification of the ββ(0ν) process)

Sources separated from the detector: allows to measure $T_{1/2}$ for several isotopes

Identification: $e^-$, $e^+$, γ, α particles

If any ββ0ν signal seen in any isotope, it will HAVE to be observed by a tracko-calo detector « a la NEMO » to tag the 2 $e^-$ emitted in ββ0ν

# 2β2ν preliminary results for other nuclei



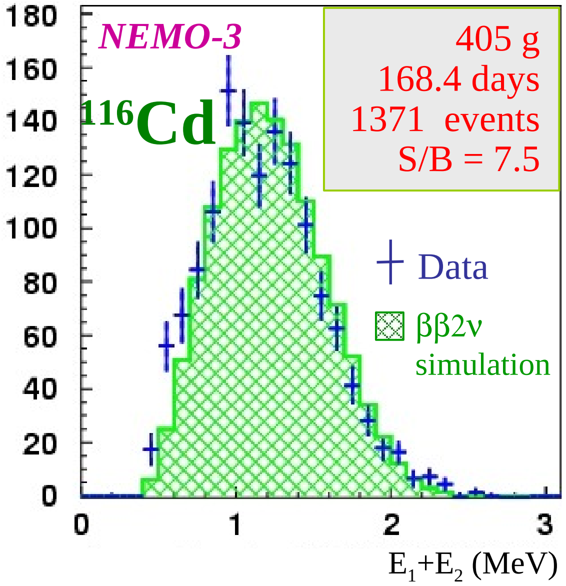
$^{82}$Se  $T_{1/2}$ = 9.6 ± 0.3 (stat) ± 1.0 (syst) × $10^{19}$ y

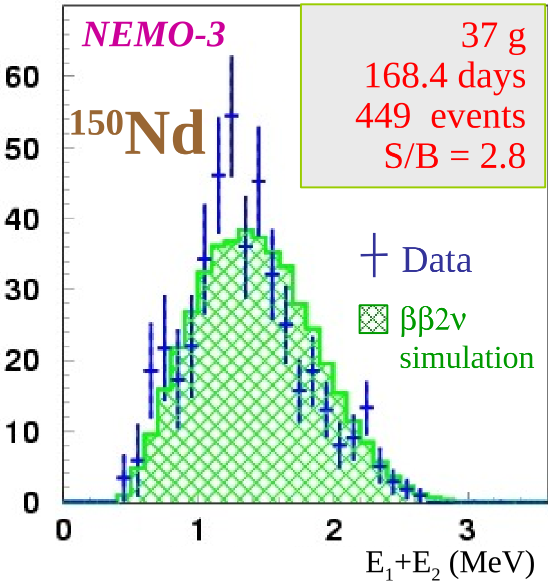
$^{116}$Cd  $T_{1/2}$ = 2.8 ± 0.1 (stat) ± 0.3 (syst) × $10^{19}$ y

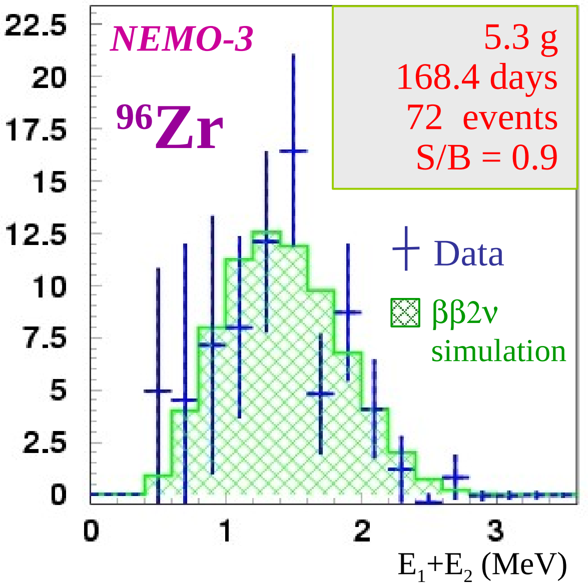
$^{150}$Nd  $T_{1/2}$ = 9.7 ± 0.7 (stat) ± 1.0 (syst) × $10^{18}$ y

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

**Background subtracted**







# R&D for the calorimeter 1/2

**Goal:** To reach 4% (FWHM) at 3 MeV (7% at 1 MeV) with plastic scintillators coupled to PMTs
To reduce number of PMT
To control quality with test mass production of ~100 units
To reduce backscattering in order to improve ββ0ν efficiency

## Plastic scintillators

Light yields, homogeneity of response, design

- Improvement of Polyvinyltoluene in Karkhov and Dubna
- Development of Polyvinylxylene in Kharkov
- Studies for use of liquid scintillator
- Studies of scintillator bars
- Measurements: in France, 2 $e^-$ spectrometers

**2nd R&D test station in USA would be important help**

## Photomultipliers

Resolution and low radioactivity

- In France, agreement with Photonis company
- **In US and UK, tests of Hamamatsu and ETL PMT**

## $e^-$ backscattering

Reduce backscattering in order to improve ββ0ν efficiency
Design study of the entrance surface of scintillator
Measurement of $e^-$ backscattering

# R&D for Low radioactivity measurements

Goal: To develop detectors towards a sensitivity of 2 μBq/kg in $^{208}$Tl and 10 μBq/kg in $^{214}$Bi
To improve HPGe detectors for selection of materials for SuperNEMO
To develop detectors sensitive to 0.1 mBq/m$^3$ of radon

## Ge detectors

Today best NEMO HPGe 400 cm$^3$ sensitive to 60 μBq/kg in $^{208}$Tl and 200 μBq/kg in $^{214}$Bi (1 month, 1 kg)
Development with Canberra-Eurysis: larger volume (1000 cm$^3$), background reduced by a factor 10 and higher mass measurement.
Need of new set of measurements to select very pure materials for both cryostat and shielding.

Planar detector to measure very low energy gamma-rays with 0.5 keV resolution at 40 keV ($^{235}$U and $^{238}$U)

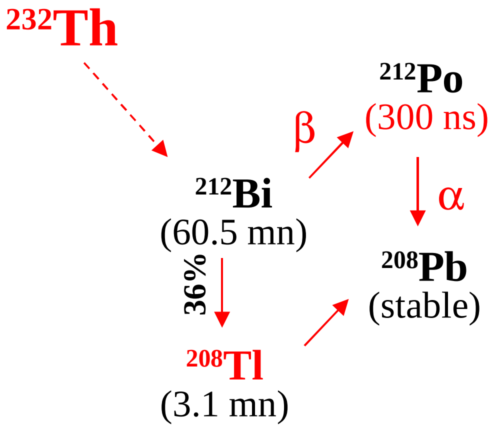
## Radon detectors

Present radon detector sensitive to 1 mBq/m$^3$ (based on Po ions collection in 70 l volume)
Development of 1000 l detectors or new methods like drift chambers or using ~20 l liquid scintillator.

*Participants: CENBG, IReS, LAL (France)*
*Saga (Japan)*
*JINR (Russia)*
*UCL at Boulby (UK)*

# R&D for $^{208}$Tl purity measurement in the source foils

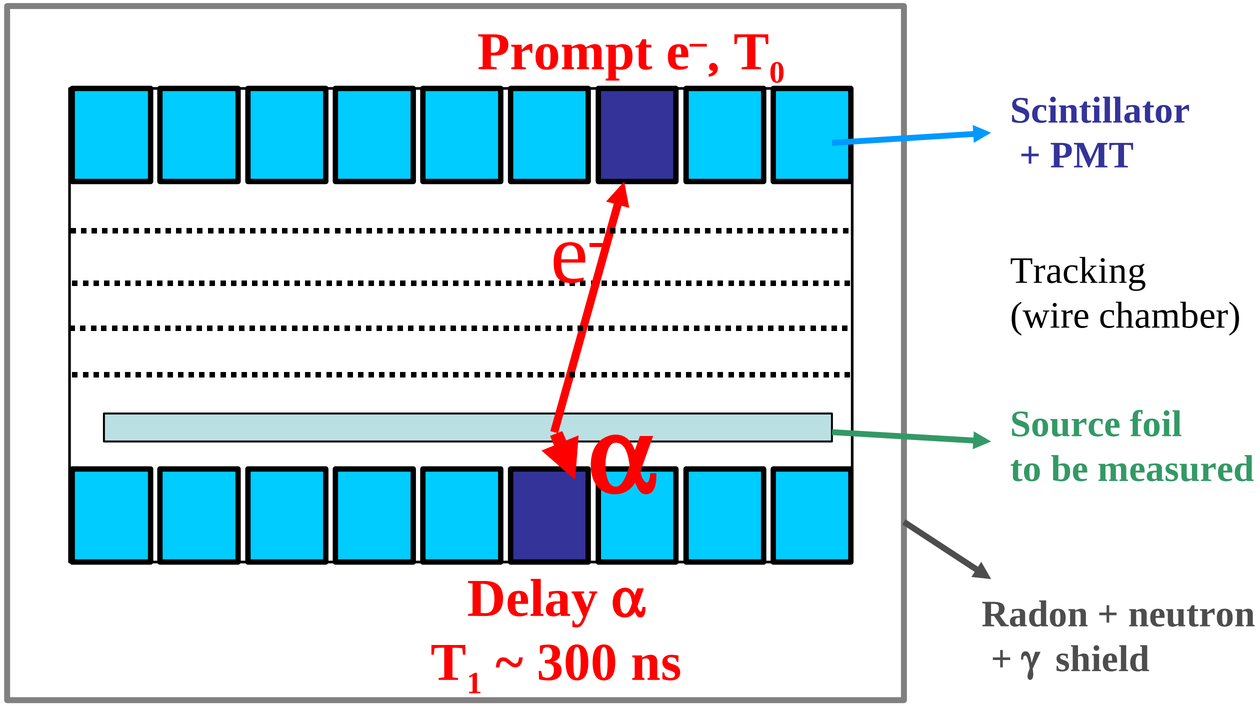
Goal: Detect $^{212}$Bi → $^{212}$Po → $^{208}$Pb (β,delayed α) decays
in order to measure $^{208}$Tl impurities in the source foils
at the level of few μBq/kg



With 4 kg of $^{82}$Se source foil (~ 10 m$^2$, 40 mg/cm$^2$)
and 2 μBq/kg of $^{208}$Tl
~ 37 (e$^-$, delay α) decays / month

Efficiency (e$^-$,delay α) tagging
~ 6 % if bulk contamination

Sensitivity of 2 μBq/kg of $^{208}$Tl
is reachable in 1 month



*Participants:* *LAL (France)*

# R&D for drift chamber

Goal: To propagate signal along 4 m of wires
To improve transparency of tracking volume.

To improve transparency by decreasing diameter of wires from 50 µm to 30 µm

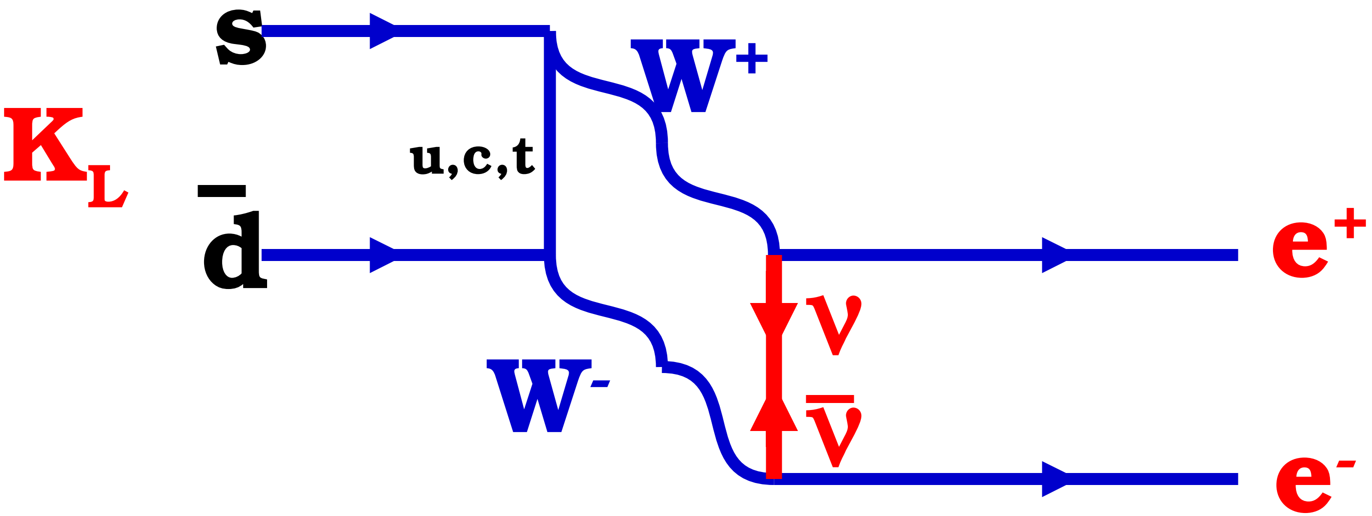
Use of Carbon instead of Stainless steel for cathode wires

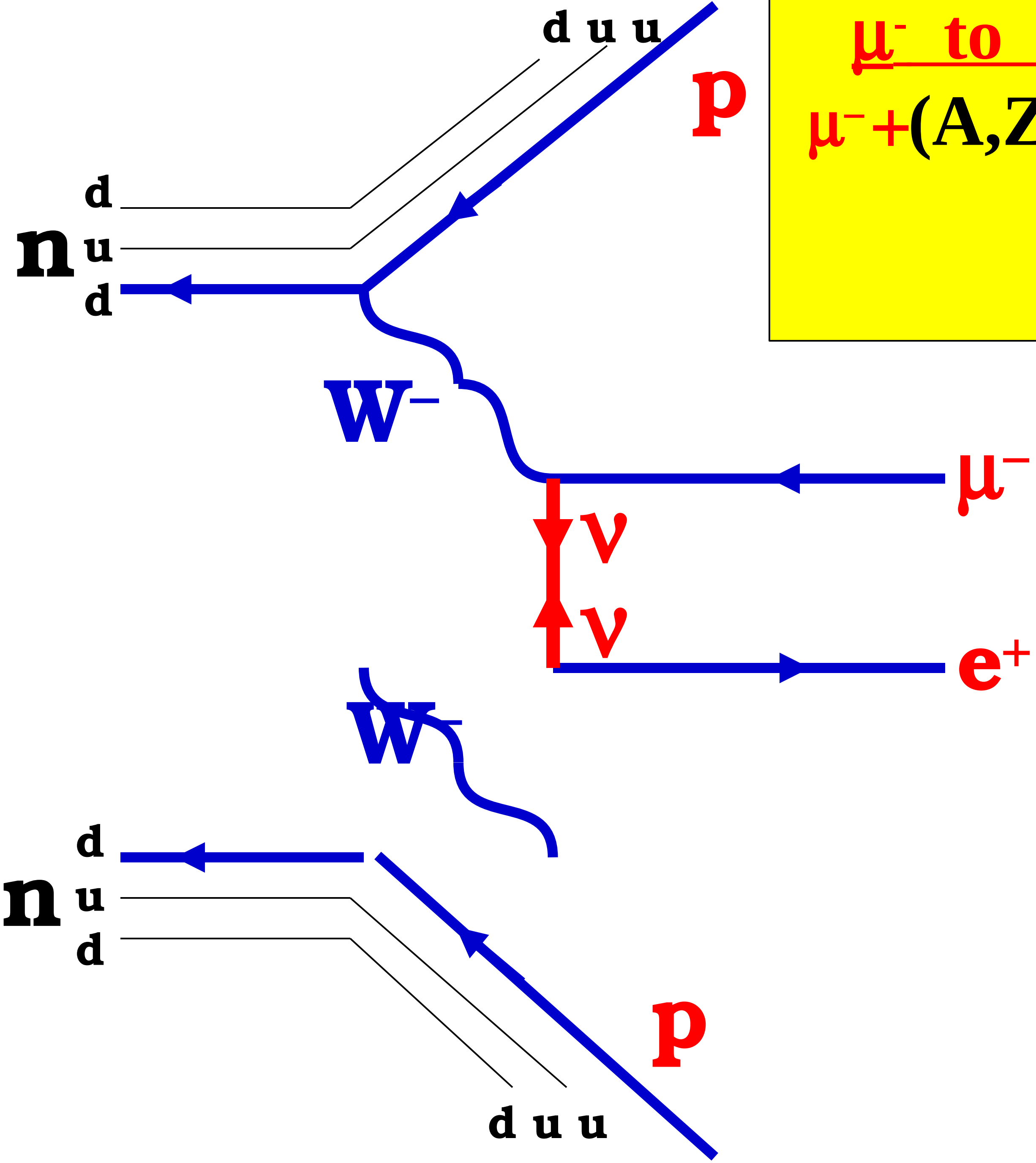
Need of prototypes

Electronics: low background ASIC

*Participants: LAL (France)*
*Manchester (UK)*

**$K_L$ $e^+e^-$**





## μ⁻ to e+ conversion

$\mu^- + (A,Z) \quad (A, Z-2) + e^+$

$\Delta L = 2$

# *Possible Majorana* $\Delta L = 2$ *processes*

$K^+ \quad \pi^-\mu^+\mu^+$

$K^+ \quad \pi^-e^+e^+$

$K^+ \quad \pi^-\mu^+e^+$

**$\mu^-$ to e+ conversion**

$\mu^- + (A,Z) \quad (A, Z-2) + e^+$

**$(\beta\beta)0\nu$ decay:**

$(A,Z) \quad (A, Z+2) + 2e^-$

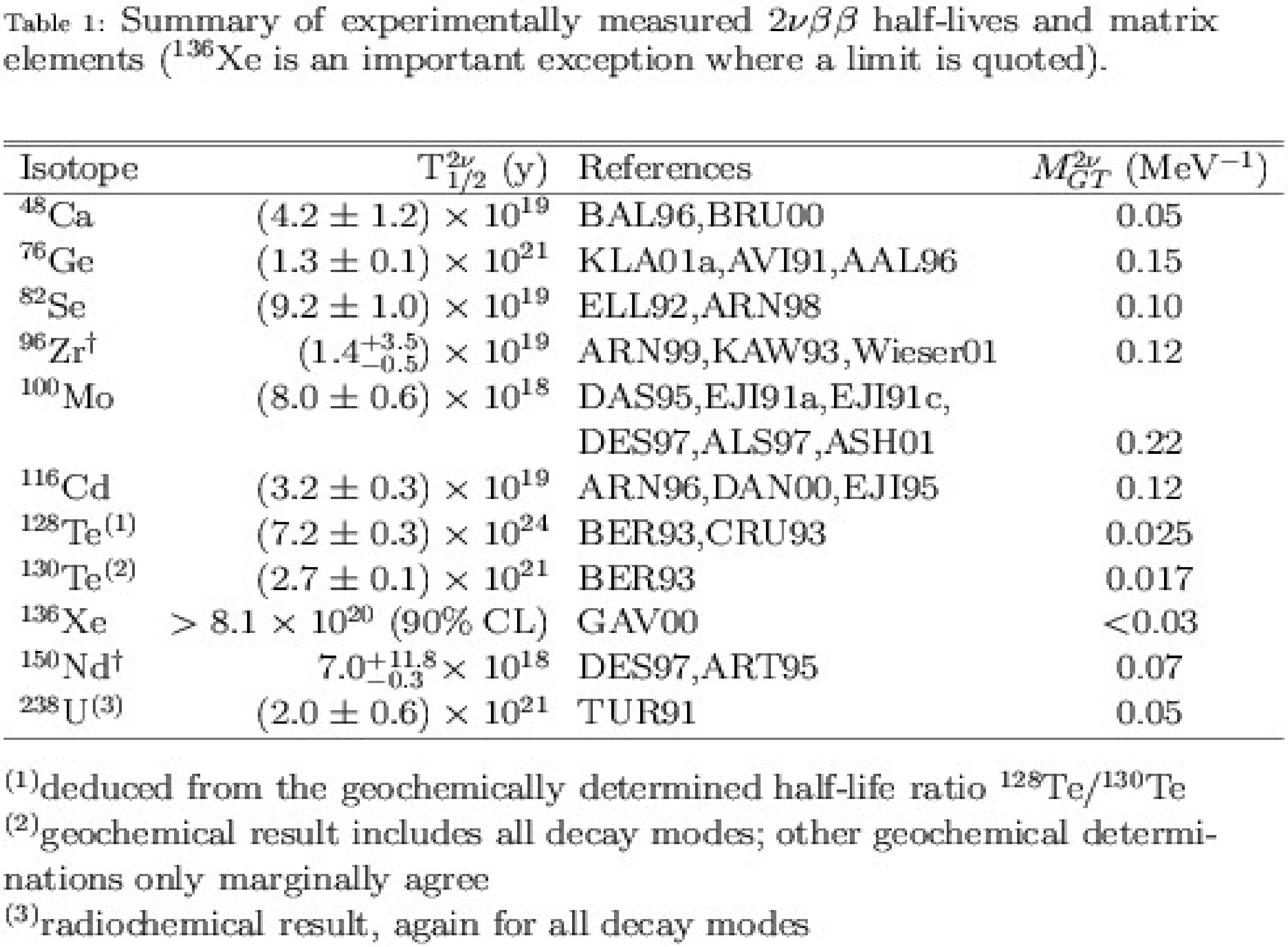


Table 1: Summary of experimentally measured $2\nu\beta\beta$ half-lives and matrix elements ($^{136}$Xe is an important exception where a limit is quoted).

| Isotope | $T^{2\nu}_{1/2}$ (y) | References | $M^{2\nu}_{GT}$ (MeV$^{-1}$) |
|---|---|---|---|
| $^{48}$Ca | $(4.2 \pm 1.2) \times 10^{19}$ | BAL96,BRU00 | 0.05 |
| $^{76}$Ge | $(1.3 \pm 0.1) \times 10^{21}$ | KLA01a,AVI91,AAL96 | 0.15 |
| $^{82}$Se | $(9.2 \pm 1.0) \times 10^{19}$ | ELL92,ARN98 | 0.10 |
| $^{96}$Zr$^{\dagger}$ | $(1.4^{+3.5}_{-0.5}) \times 10^{19}$ | ARN99,KAW93,Wieser01 | 0.12 |
| $^{100}$Mo | $(8.0 \pm 0.6) \times 10^{18}$ | DAS95,EJI91a,EJI91c,<br>DES97,ALS97,ASH01 | 0.22 |
| $^{116}$Cd | $(3.2 \pm 0.3) \times 10^{19}$ | ARN96,DAN00,EJI95 | 0.12 |
| $^{128}$Te$^{(1)}$ | $(7.2 \pm 0.3) \times 10^{24}$ | BER93,CRU93 | 0.025 |
| $^{130}$Te$^{(2)}$ | $(2.7 \pm 0.1) \times 10^{21}$ | BER93 | 0.017 |
| $^{136}$Xe | $> 8.1 \times 10^{20}$ (90% CL) | GAV00 | <0.03 |
| $^{150}$Nd$^{\dagger}$ | $7.0^{+11.8}_{-0.3} \times 10^{18}$ | DES97,ART95 | 0.07 |
| $^{238}$U$^{(3)}$ | $(2.0 \pm 0.6) \times 10^{21}$ | TUR91 | 0.05 |

(1) deduced from the geochemically determined half-life ratio $^{128}$Te/$^{130}$Te

(2) geochemical result includes all decay modes; other geochemical determinations only marginally agree

(3) radiochemical result, again for all decay modes

$$1/T_{1/2} = G(E,Z)\,(M_{GT}^{2\nu})^2$$

$$M^{2\nu}_{GT} = \Sigma_m \frac{\langle f|\vec{\sigma}\tau^+|m\rangle \cdot \langle m|\vec{\sigma}\tau^+|i\rangle}{E_m - (M_i + M_f)/2}$$