# Nuclear ßß Decay
# *and*
# Beyond Standard Model Particle Physics

**H.V. Klapdor-Kleingrothaus**

**Heidelberg, GERMANY**

**BEYOND 2010,**

**Cape Town, SA, 2 February 2010**

# DOUBLE-BETA Experiments yield contributions to New Physics in many fields

- *LEPTON NUMBER VIOLATION* ?
- Nature of $\nu_s'$ *(Dirac - Majorana)*
- Light ν Masses and Mixings
- Heavy ν Masses
- Compositeness
- Leptoquarks
- SUSY
  - → R - Parity Violation
  - → R - Parity Conserving Sneutrino Masses
- Superstrings (Lorentz Invariance, Equivalence Principle)

By Search for *Cold Dark Matter*

— SUSY — Neutralino Masses and Structure

*Sensitivity:*

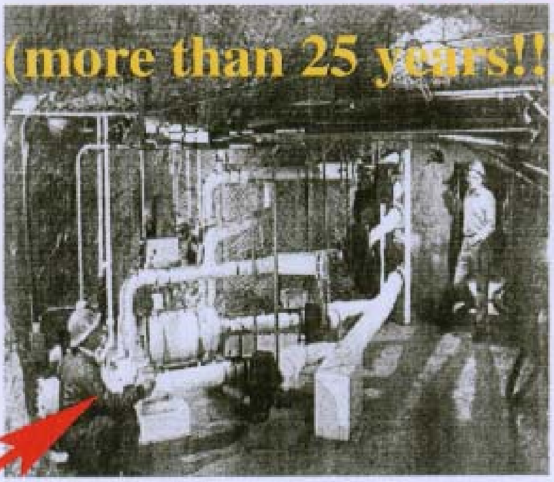
Unique, Better than High-Energy Colliders now:

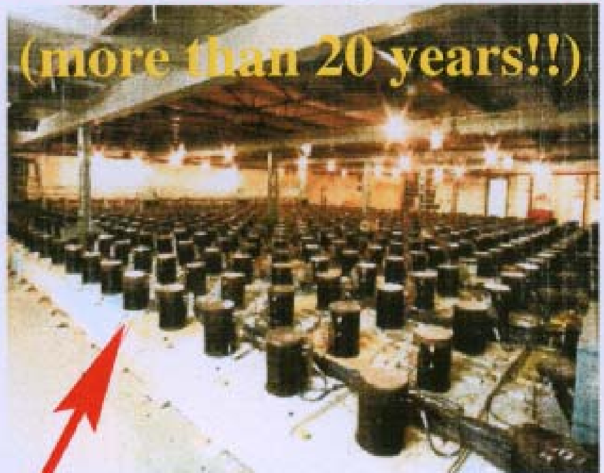
LEP II
HERA B
TEVATRON
NLC

*Future* (GENIUS):

LHC
NLC

# Long Running Underground Experiments:



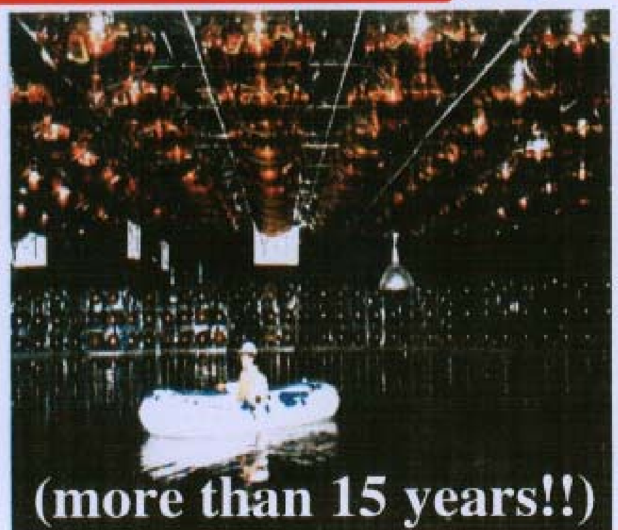


Chlor-Argon Experiment Prof. R. Davis

Baksan Underground Scintillation Telescope

Double Beta HEIDELBERG-MOSCOW Experiment in Gran-Sasso


SAGE, Baksan
GALLEX, Gran Sasso




KAMIOKANDE and SuperK


DAMA, Gran Sasso

## *Development of sensitivity in double beta decay experiments in last 20 years*

- **1987** discovery of $2\nu\beta\beta$ (for $^{82}Se$) with detectors (non-geochemical)

  $(1.1 {}^{+0.8}_{-0.3}) \times 10^{20}$ y
  ( 35 events )

  (68% c.l. 2.2 σ )

  M. Moe et al., PRL 59 (1987) 989

- **2003** $2\nu\beta\beta$ decay (for $^{76}Ge$)

  $(1.74 {}^{+0.18}_{-0.16}) \times 10^{21}$ y
  ( 160 000 events )

  Mod. Phys. Lett. A 21 (2006) 1547

  **> 6 σ from PSA**

***First observation of*** $0\nu\beta\beta$ ( $^{76}Ge$)

$(1.19 {}^{+0.37}_{-0.23}) \times 10^{25}$ y

(99.997% c.l. 4.2 σ )

H.V. Klapdor-Kleingrothaus et al., PLB 586 (2004) 198-212

*Heidelberg, 27.04.2004*

# *First ( third ?)*

**Indication for BEYOND SM physics**

***NEUTRINOLESS DOUBLE BETA DECAY***

**Violation of *TOTAL* *lepton number***

## SU(5)

$$\bar{5} = \begin{bmatrix} d_g^c \\ d_r^c \\ d_b^c \\ e^- \\ -\nu \end{bmatrix}_L \qquad 10 = \begin{bmatrix} 0 & -u_b^c & u_r^c & u_g & d_g \\ & 0 & -u_g^c & u_r & d_r \\ & & 0 & u_b & d_b \\ \text{anti-} & & & 0 & e^+ \\ \text{symmetric} & & & & 0 \end{bmatrix}$$

1090-85 MPI H

$m_\nu = 0$

B, L not conserved
B − L conserved
⇒ p-Zerfall möglich

## SO(10)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $\nu_L$ | $d_g^c$ | $d_r^c$ | $d_b^c$ | $u_b$ | $u_r$ | $u_g$ | $e^+$ |
| $e^-$ | $u_g^c$ | $u_r^c$ | $u_b^c$ | $d_b$ | $d_r$ | $d_g$ | $\nu_R^c$ |

$$16_{SO(10)} = 10_{SU(5)} + \bar{5}_{SU(5)} + 1_{SU(5)}$$

↖ $\nu_R$

$m_\nu^D \approx m_u \approx 0$ (MeV)

B − L ev. not conserved
⇒ 0νββ möglich

Min. SU(5):

1. ∃ no $\nu_r$ (not to be confused with $(\nu_L)^c = \bar{\nu}$) $\longrightarrow m_\nu^D = 0$

2. SU5 invariant Majorana couplings not possible with the Higgs content

$$\longrightarrow m_\nu^{Maj.} = 0$$

However: CP violation

Extensions of standard model:

$\longrightarrow$ finite $\nu$ masses natural

e.g. SU(5) with enlarged particle content (e.g. Zee model)

or

SO(10):

Elementary fermions of one family in 16-dim. spinor representation

$\nu$ mass prop. to u quark mass (Dirac)

Small $\nu$ by interplay between large Dirac mass term and Majorana mass term ??

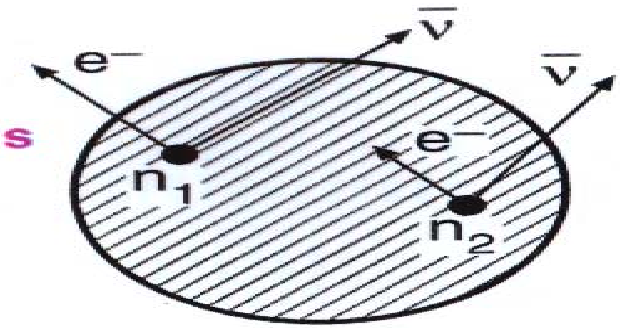
# CONSEQUENCES:

- *Lepton Number not Conserved*
- *Neutrino is Majorana Particle*
- **Neutrino Mass Models:**
  **Degenerate**
- *Neutrino Mass*
- *Cosmology (Dark Matter)*
- *Other Beyond Standard Model Physics*

# DOUBLE BETA DECAY

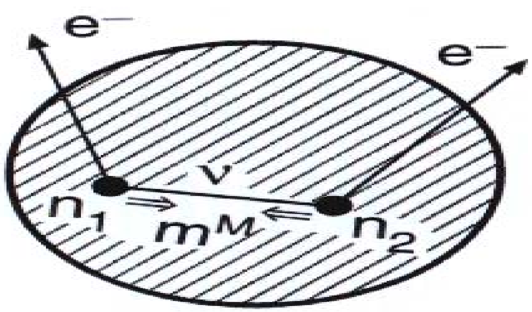
$$ {}^{A}_{Z}X_{N} \longrightarrow {}^{A}_{Z+2}X_{N-2} + 2e^{-} (+2\bar{\nu}) $$

35 potential $\beta^{-}\beta^{-}$ emitters




**2ν:**
allowed
9 cases observed
($^{82}$Se, $^{100}$Mo, $^{76}$Ge,...)

$\Delta L = 0$




**0ν:**
only allowed if
a) V+A
or
b) $m^{M} > 0$

not observed

$\Delta L = 2$

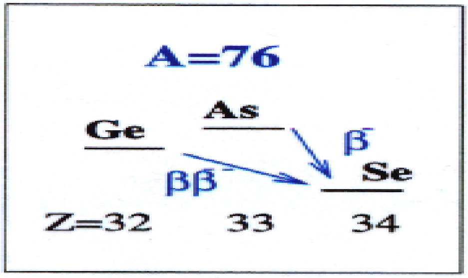
$W_{0\nu} \sim |M_{0\nu}|^2 \; <m_\nu>^2$

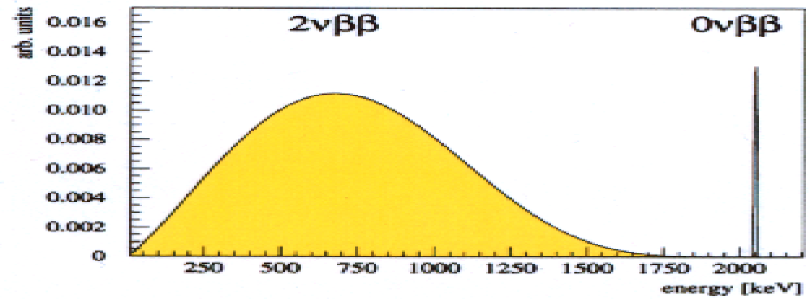
$0\nu\beta\beta$ beyond standard model !

( B–L ) not conserved !

$$ <m_\nu> = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 + |U_{e3}|^2 e^{i2\beta} m_3 $$

# What is double beta decay?




$2\nu\beta\beta$ : ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^- + 2\overline{\nu}_e$

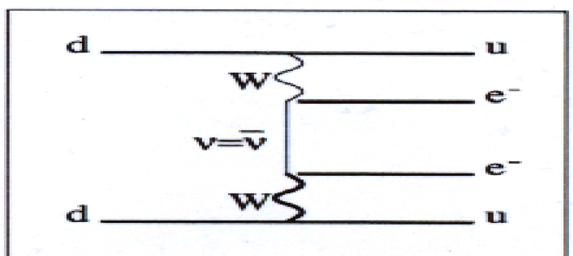
- SM allowed: $T^{2\nu}_{1/2} \simeq 10^{19} - 10^{24}$y
- observed for 10 isotopes

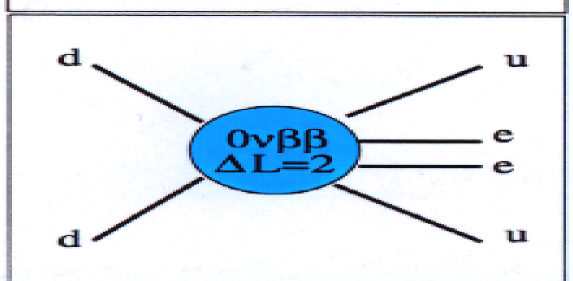
$0\nu\beta\beta$ : ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^-$

- Physics beyond SM ($L$ violation)

$\Delta L = 2$ ;

B − L not conserved



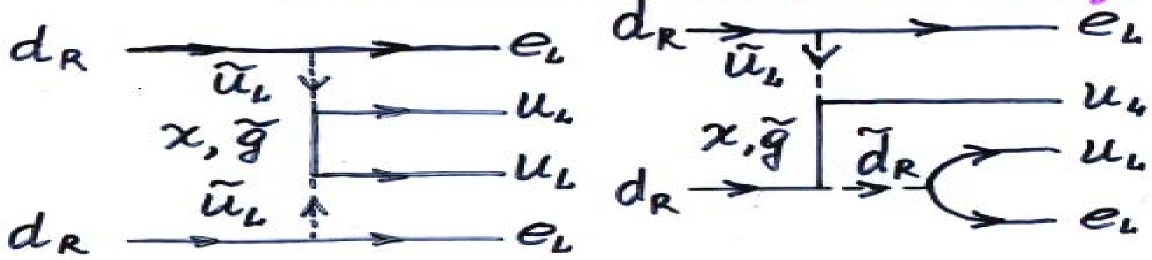

Sensitive on:

- effective Neutrino–Majorana mass: $\langle m_\nu \rangle = \Sigma' U^2_{ej} m_j$

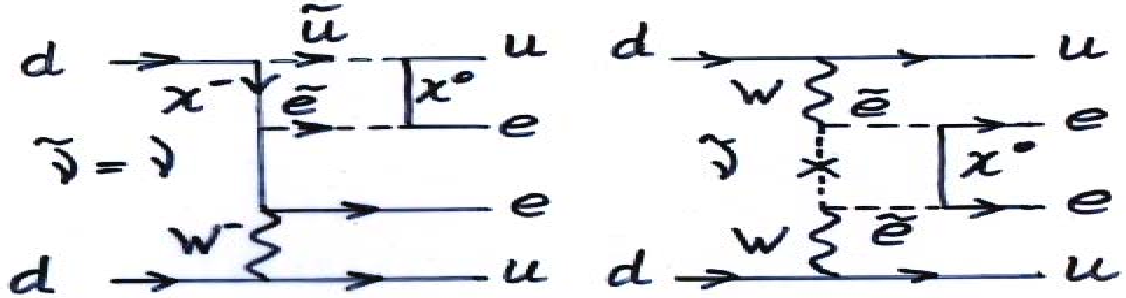
$\omega_{0\nu} \sim |M_{0\nu}|^2 < m_\nu >^2$

- $L$–violating parameters (SUSY, Leptoquarks, $W_R$,...)

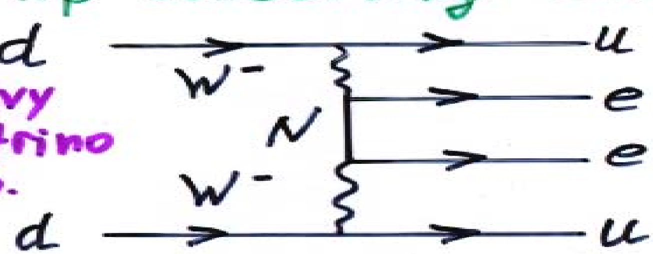
(see: H.V. K-K.: Int. J. of Mod. Phys. A13 (1998) 3953



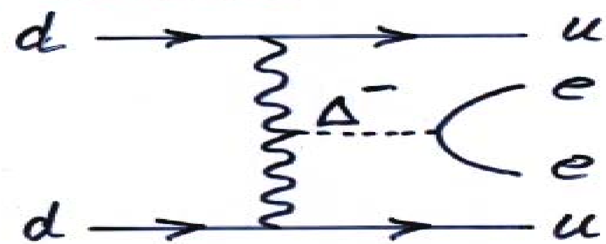

for $0\nu\beta\beta$ decay within R-parity viol. supersym. m.



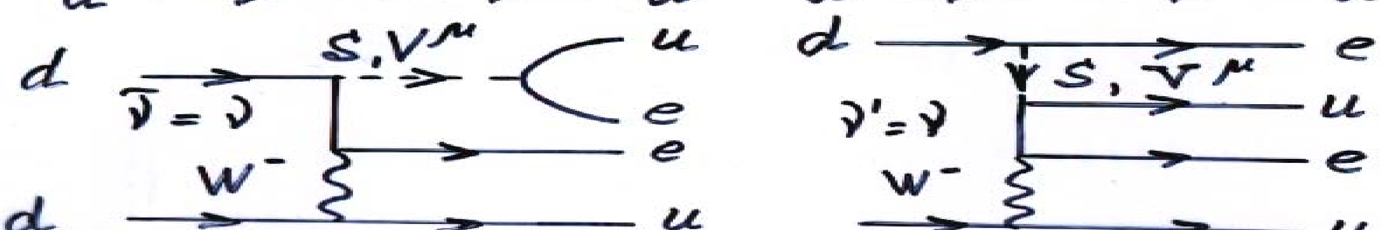

$R_P$ conserving SUSY contributions to $0\nu\beta\beta$-decay




Heavy neutrino exch.

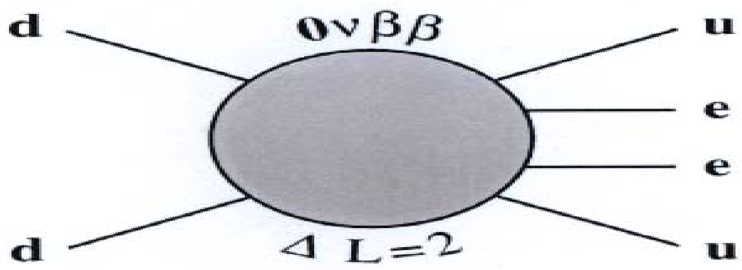



virtual exch. of a double-charged Higgs boson




within LQ models. S and $V^\mu$ - scalar and vector LQs

# Double Beta Decay - more general:




$0\nu\beta\beta$ =

- $\nu = \nu^C$
- $W_R, N_R$
- Leptoquarks
- SUSY-particles
- Compositeness

**Important theorem ( Schechter & Valle 1981):**

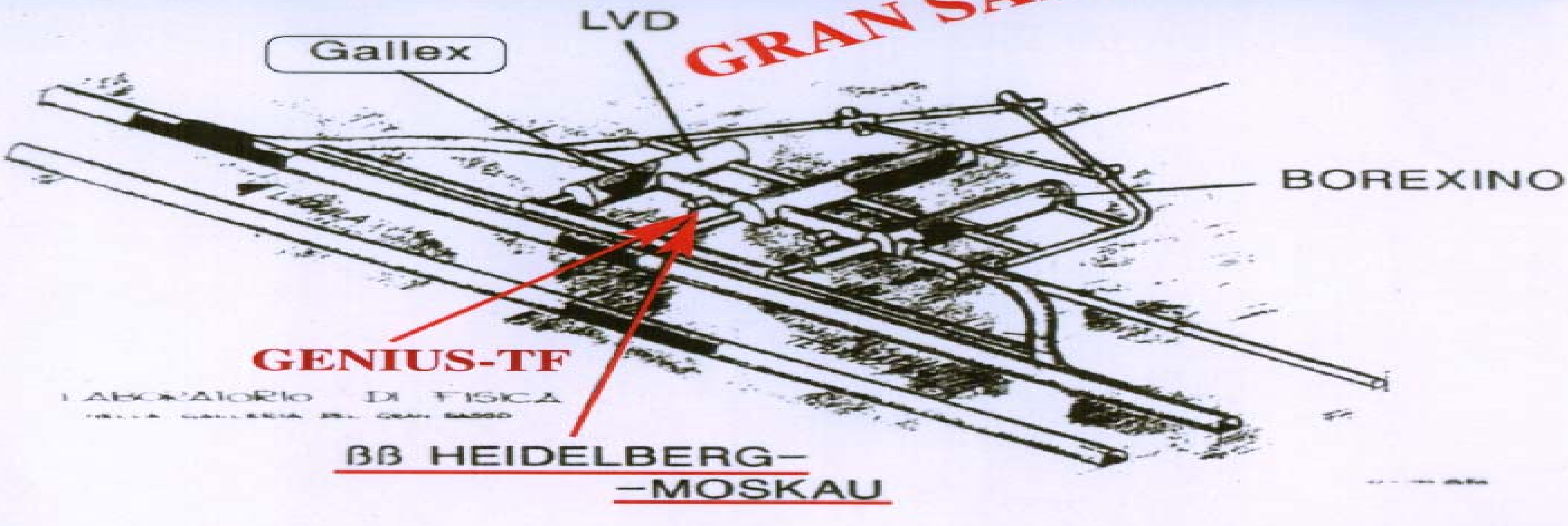
$0\nu\beta\beta$ amplitude $\neq 0 \iff m_\nu^{(M)} \neq 0$

( valid for any gauge model with spontaneously broken symmetry at weak scale)

**Extension to SUSY (Hirsch, K.-K., Kovalenko 1997):**

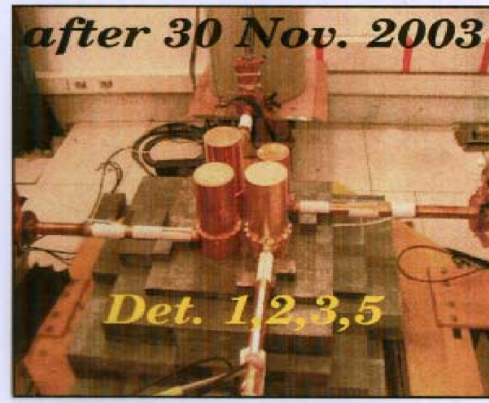
$0\nu\beta\beta$ amplitude $\neq 0 \iff m_\nu^{(M)} \neq 0 \iff \tilde{m}_\nu^M \neq 0$


HEIDELBERG-MOSCOW Experiment
USCITA EMERGENZA
EMERGENCY EXIT
GENIUS-TF
25 April, 2004


GRAN SASSO
LVD
Gallex
BOREXINO
GENIUS-TF
LABORATORIO DI FISICA
ßß HEIDELBERG-
-MOSKAU

# History of HEIDELBERG-MOSCOW




Det. 4


# HEIDELBERG - MOSCOW Experiment

$$T_{1/2} \sim a \sqrt{\frac{M\,t}{B\,\Delta E}}$$

**1990 - 2003** 11.5 kg of Enriched $^{76}$Ge (86%) in 5 High-Purity Ge Detectors in GRAN-SASSO

Runs Since 1990*), in Final Form Since 1996, Reaches with 'a few kg Experiment' the Sensitivity of a 'order of ton' Experiment.
( 10 kg ~= 1.2 ton Natural Ge )

1. *Largest Source Strength in Operation* ~ 11.0 kg
2. *Lowest Background in Operation* ~0.11 c/kgykeV
3. *Highest Efficiency for Detection of a ββ events* ~ 100 %
4. *Highest Energy Resolution* ~ 3.5 keV
5. *Highest 'Duty Cycle'* ~ 80 %
6. *Highest Collected Statistics* ~ 71.7 kg y

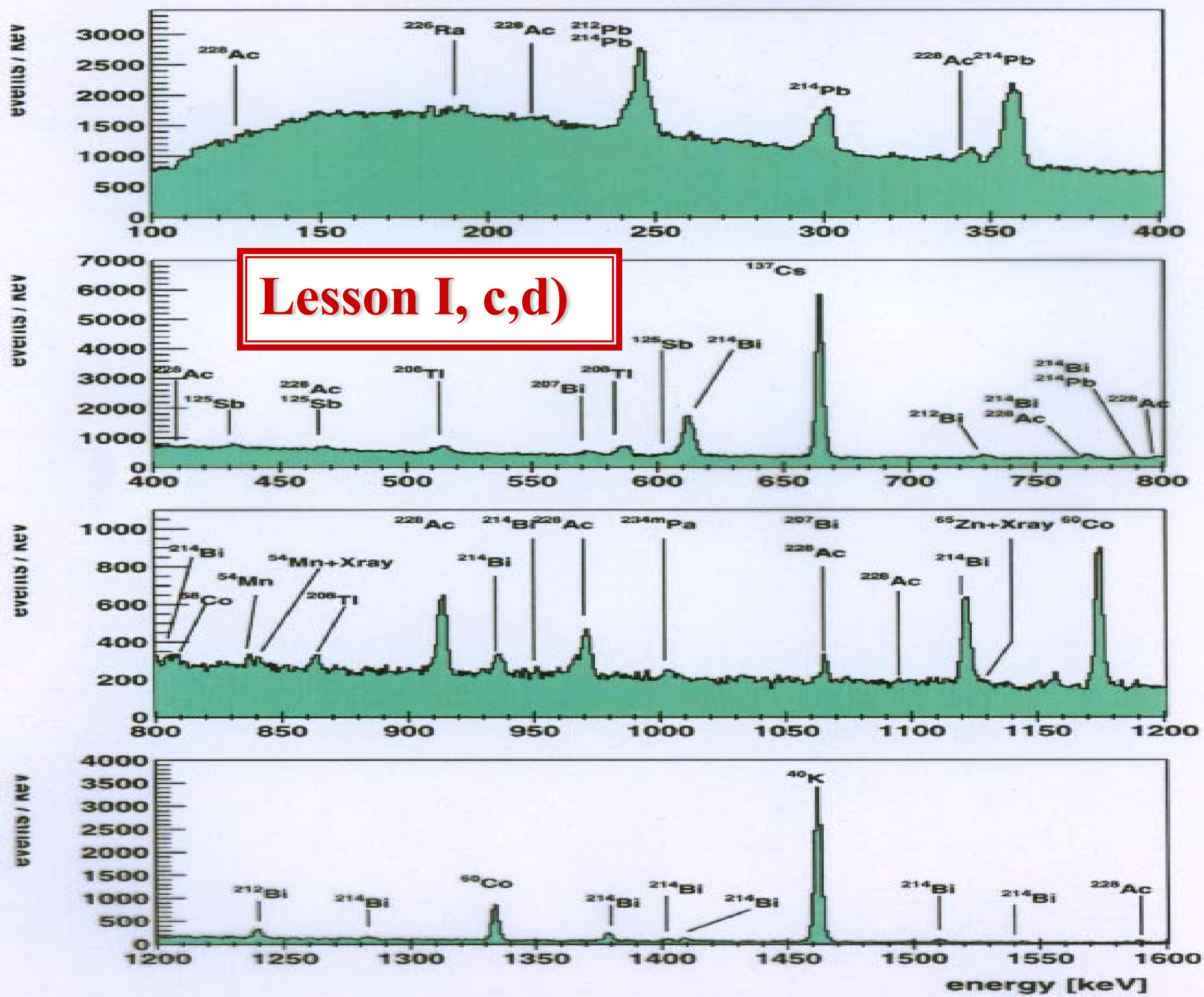
**>~ 10 Years** *ahead of all running ββ experiments*

*) *Since 1992/93 Worldwide Best Value on* $m_\nu$

*(before that since ~ 1985 D. Caldwell and I. Kirpichnikov)*

# 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. A 522 p. 371-406



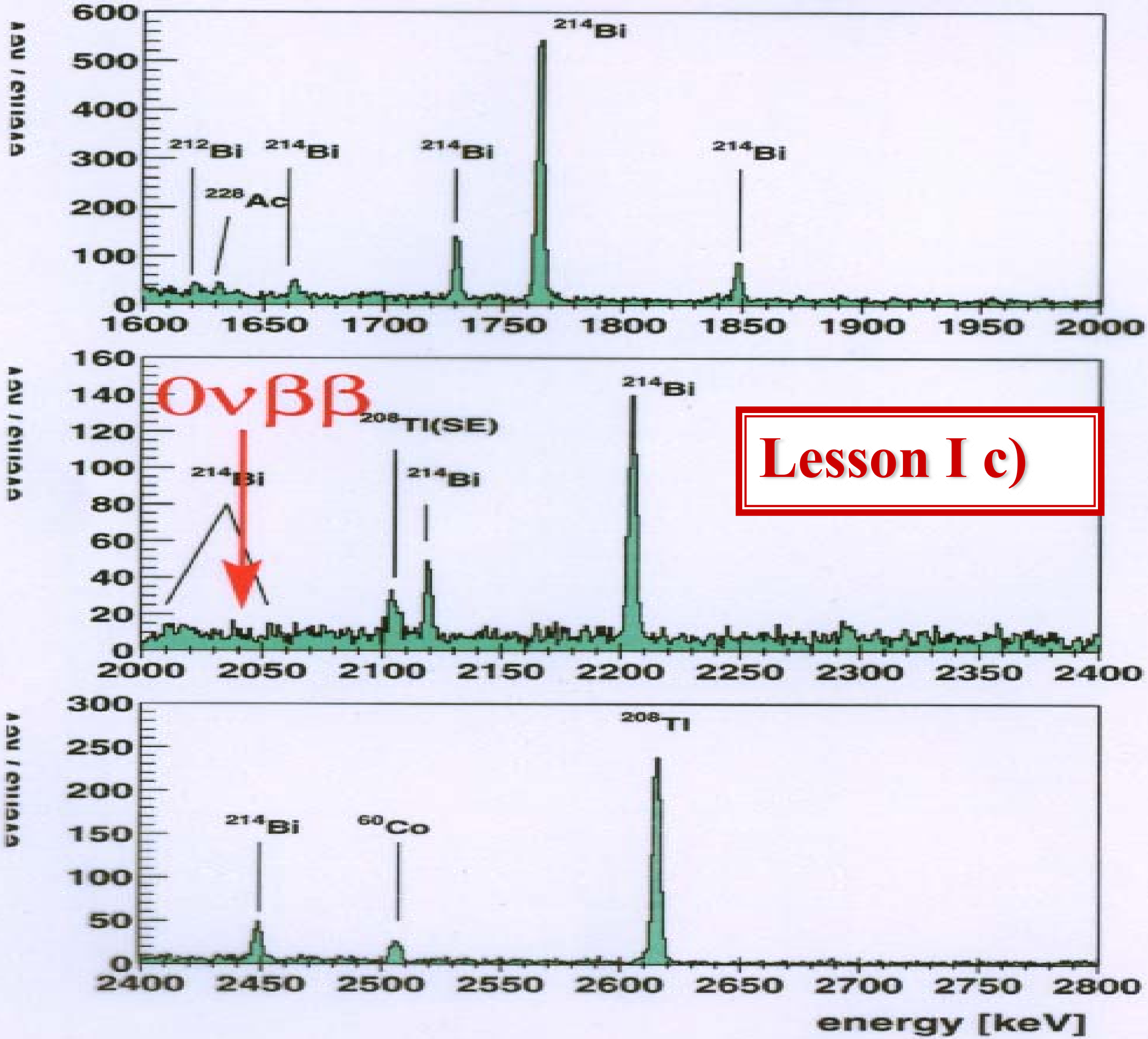
# HEIDELBERG-MOSCOW EXPERIMENT

## Total Spectrum (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**

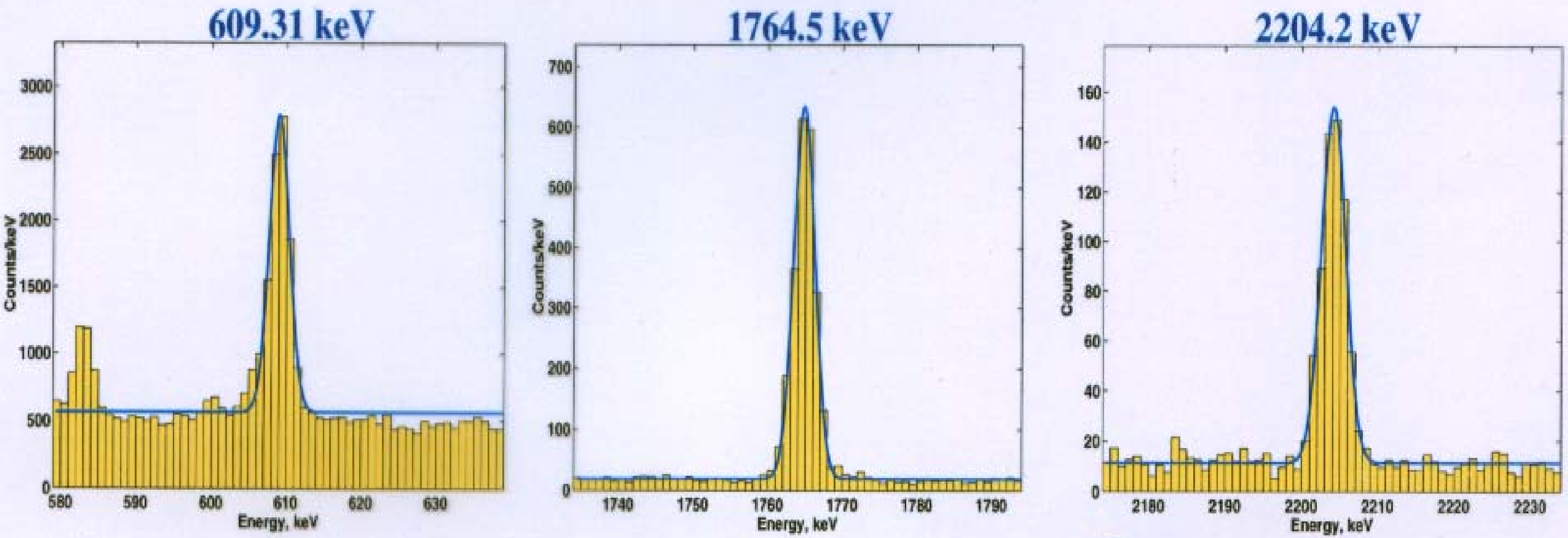



**Lesson I c)**

# HEIDELBERG-MOSCOW Data
# Period: August 1995 - May 2003
## *Reliability of Data Acquisition and Data*

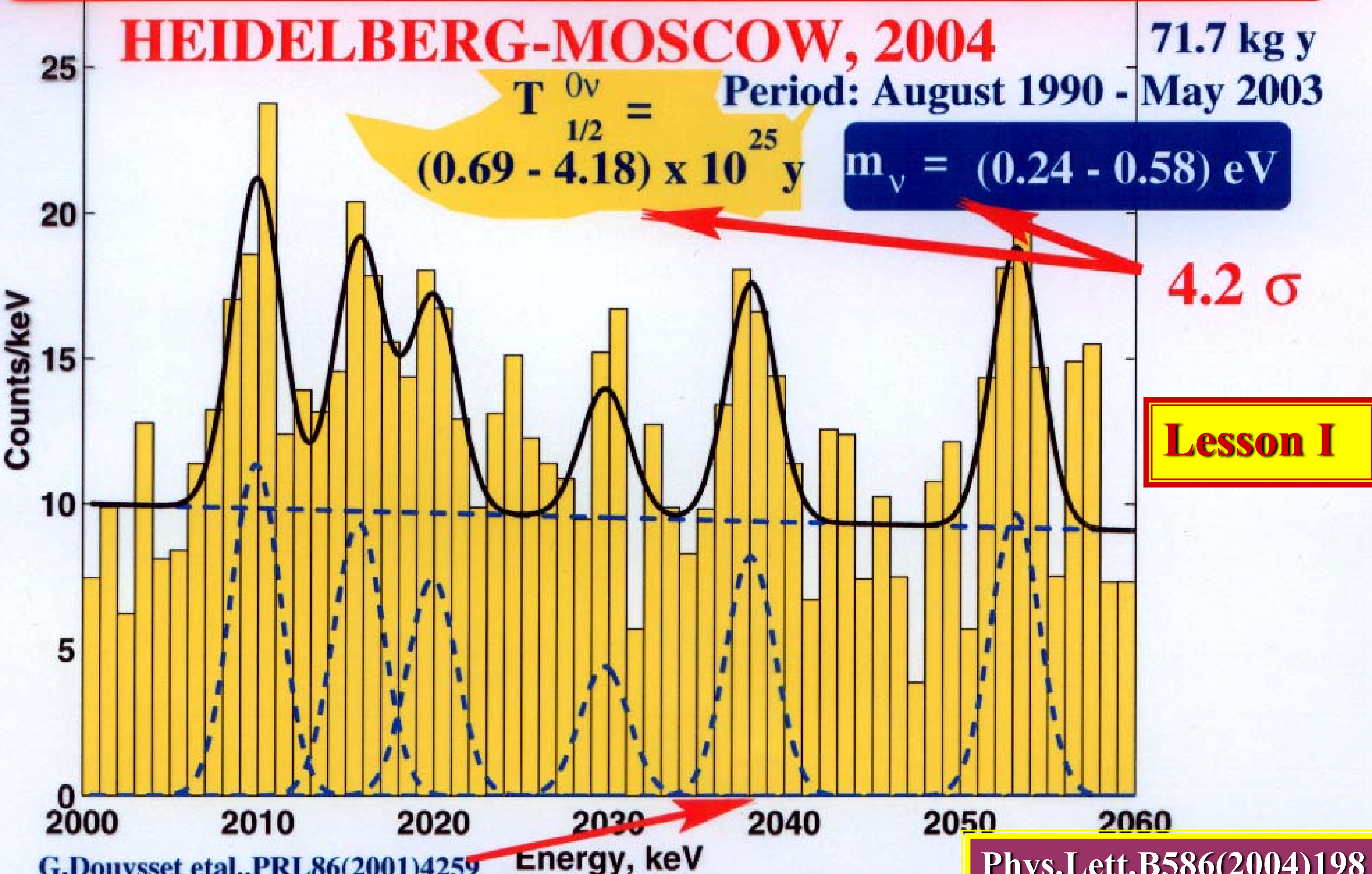
**Lesson I a)**

The strong Bi lines at 609.31 (left), 1764.5 and 2204.2 keV (right)




*H.V. Klapdor-Kleingrothaus et al., NIM A* 522 *(2004),* ~~*in Press*~~ 371-406 pp.

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




G.Douysset etal.,PRL86(2001)4259

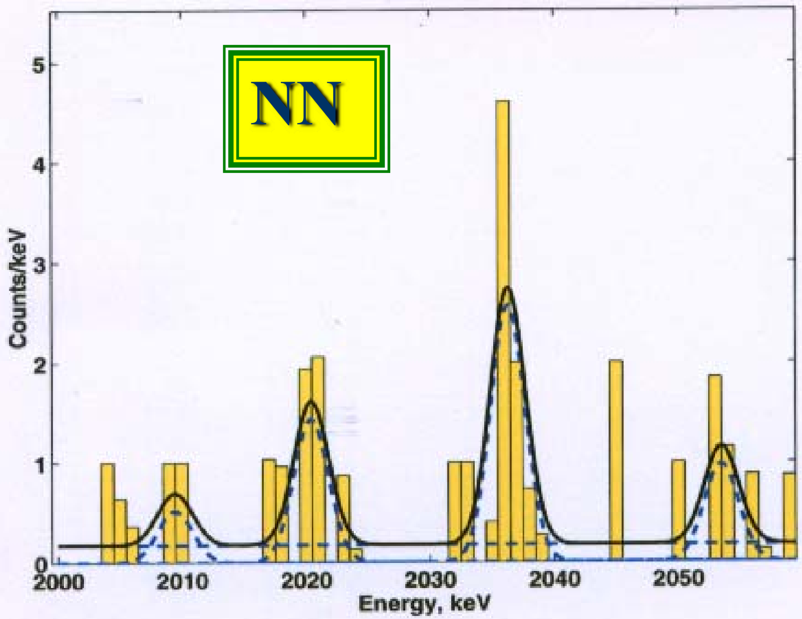
Q=2039.006(50) keV

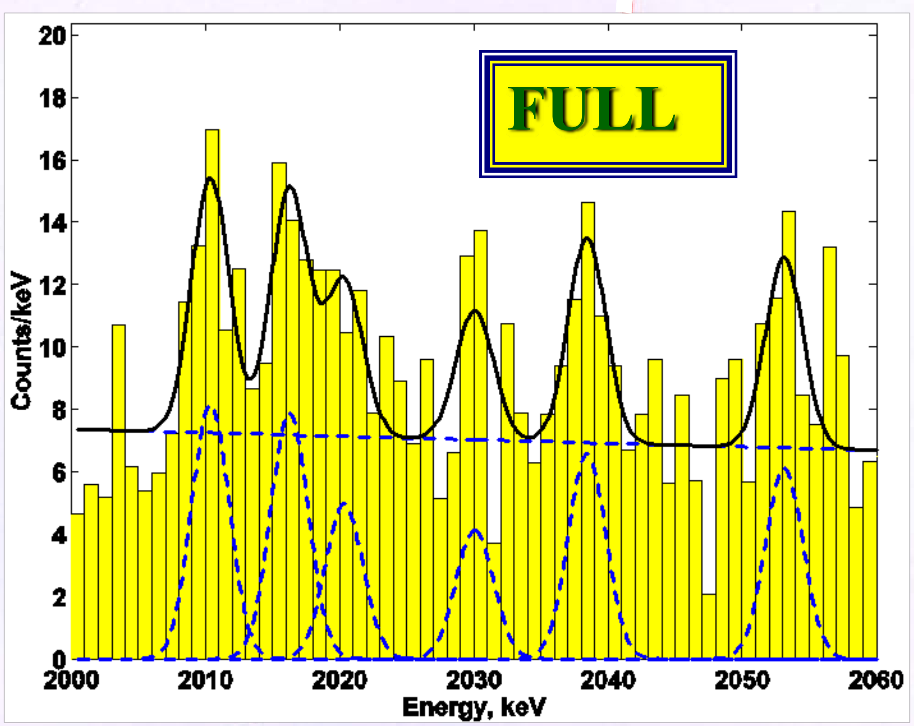
H.V. Klapdor-Kleingrothaus et al.

Phys.Lett.B586(2004)198

NIM A 522 (2004) 371

# HEIDELBERG-MOSCOW, 2004



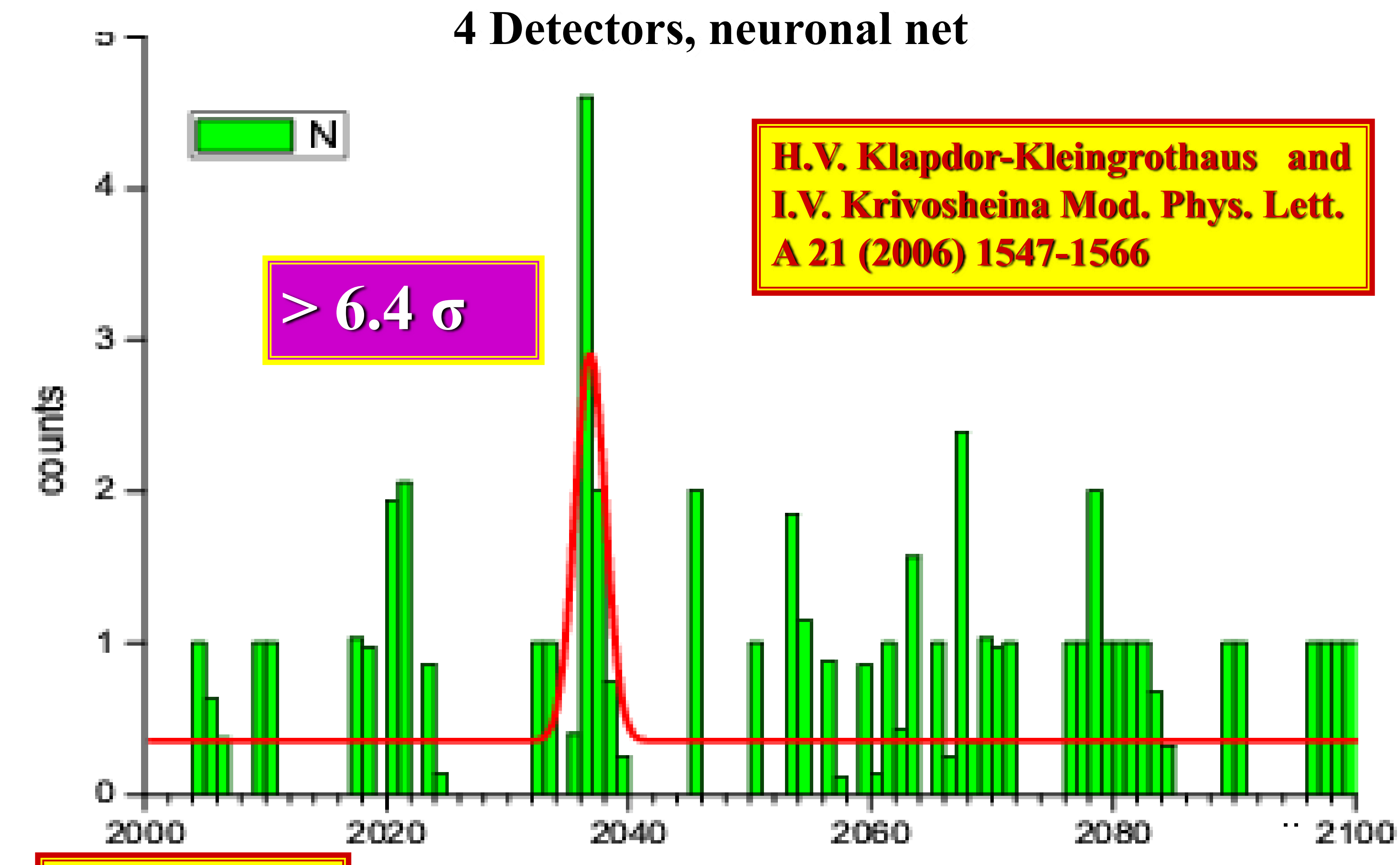

**Lesson I**

H.V. Klapdor-Kleingrothaus et al.

Phys. Lett. B 586 (2004) 198-212

Nucl. Instr. Meth. A 522 (2004) 371 - 406

# Heidelberg – Moscow experiment 1995 – 2003



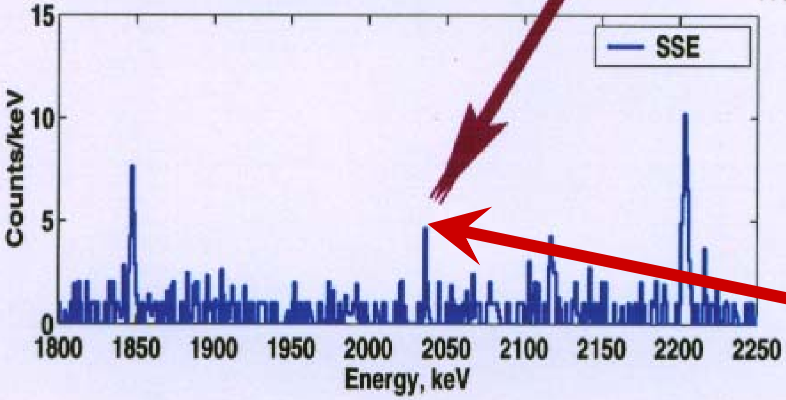

Lessons I and II

## The Single Site Selected Spectrum of the $^{76}$Ge detectors Nr. 2,3,4,5

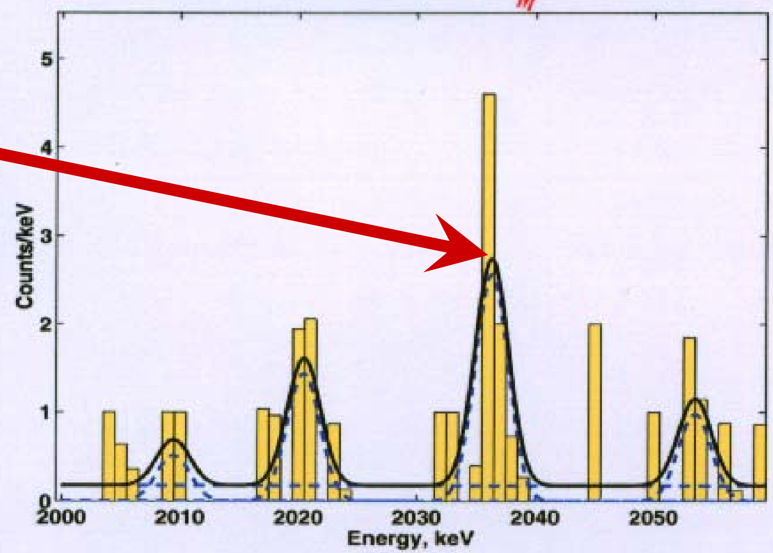
# HEIDELBERG-MOSCOW, 2004

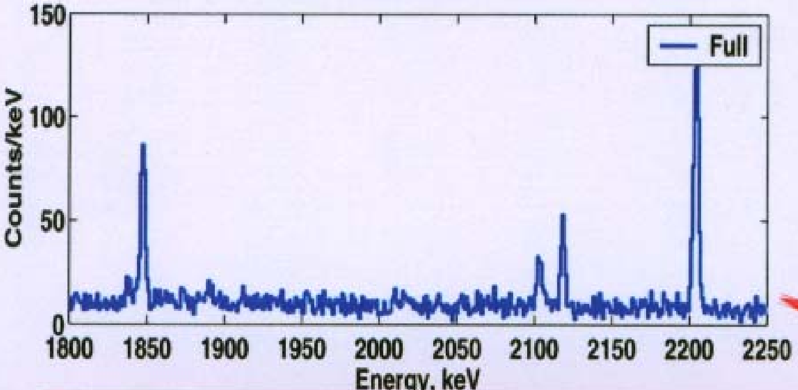
**Period:**
**1995 - May 2003**

**Around $Q_{\beta\beta}$ (1800-2250)keV γ`s reduced by factor > 10, while line near $Q_{\beta\beta}$ starts out clearly (6.6 – 7.2 σ).**




**Energy Range 2000 - 2060 keV**




PLB 586 (2004) 198-212

## The Full Spectrum of the $^{76}$Ge detectors Nr. 2,3,4,5

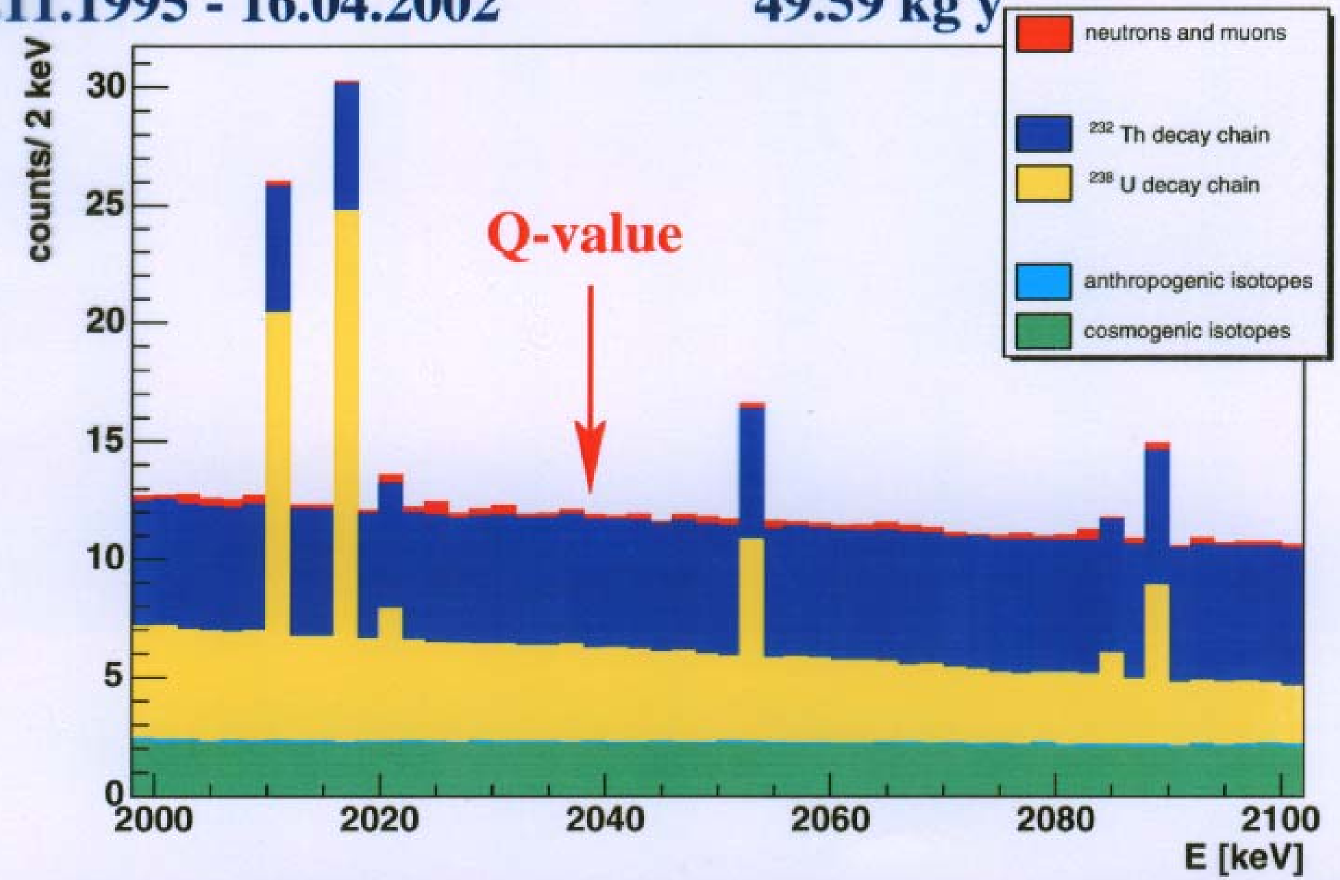
NIM A 522 p.p. 371-406

H.V. Klapdor-Kleingrothaus et al. to be publ. 2004

# Simulated background components of the $^{76}$Ge detectors Nr. 1,2,3,4,5

## HEIDELBERG-MOSCOW, 2004

**20.11.1995 - 16.04.2002** **49.59 kg y**




A bin width of 2 keV was chosen. The simulated spectrum is not folded with the energy resolution of the detectors.

**This is what we EXPECT !!!**

**Lesson I c,d**

H.V. Klapdor-Kleingrothaus et al., NIM A 2004, ~~in Press~~ A 522 pp. 371-406

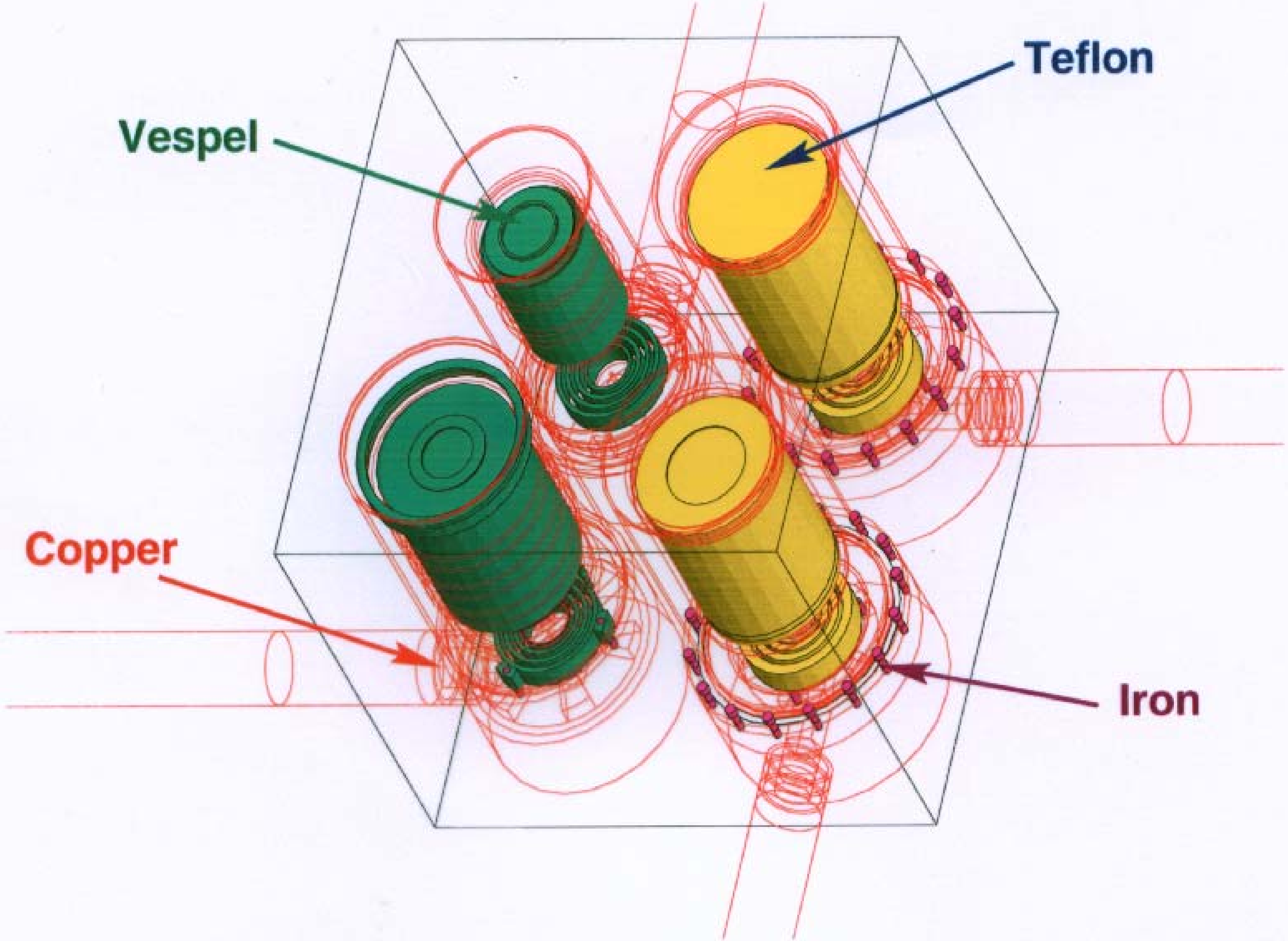
# Background components

- Natural decay-chain of $^{232}$Th and $^{238}$U
- Natural radioactivity of $^{40}$K
- Anthropogenic radionuclides
  $^{125}$Sb, $^{134}$Cs, $^{137}$Cs, $^{207}$Bi
- Cosmogenic produced radionuclides
  $^{54}$Mn, $^{57}$Co , $^{58}$Co, $^{60}$Co, $^{65}$Zn
- Bremsstrahlung of $\beta$-electrons from $^{210}$Bi-decay
- Myons
- Neutrons

Building the background-model:

→determine the activity of the components
→determine the localisation of the components

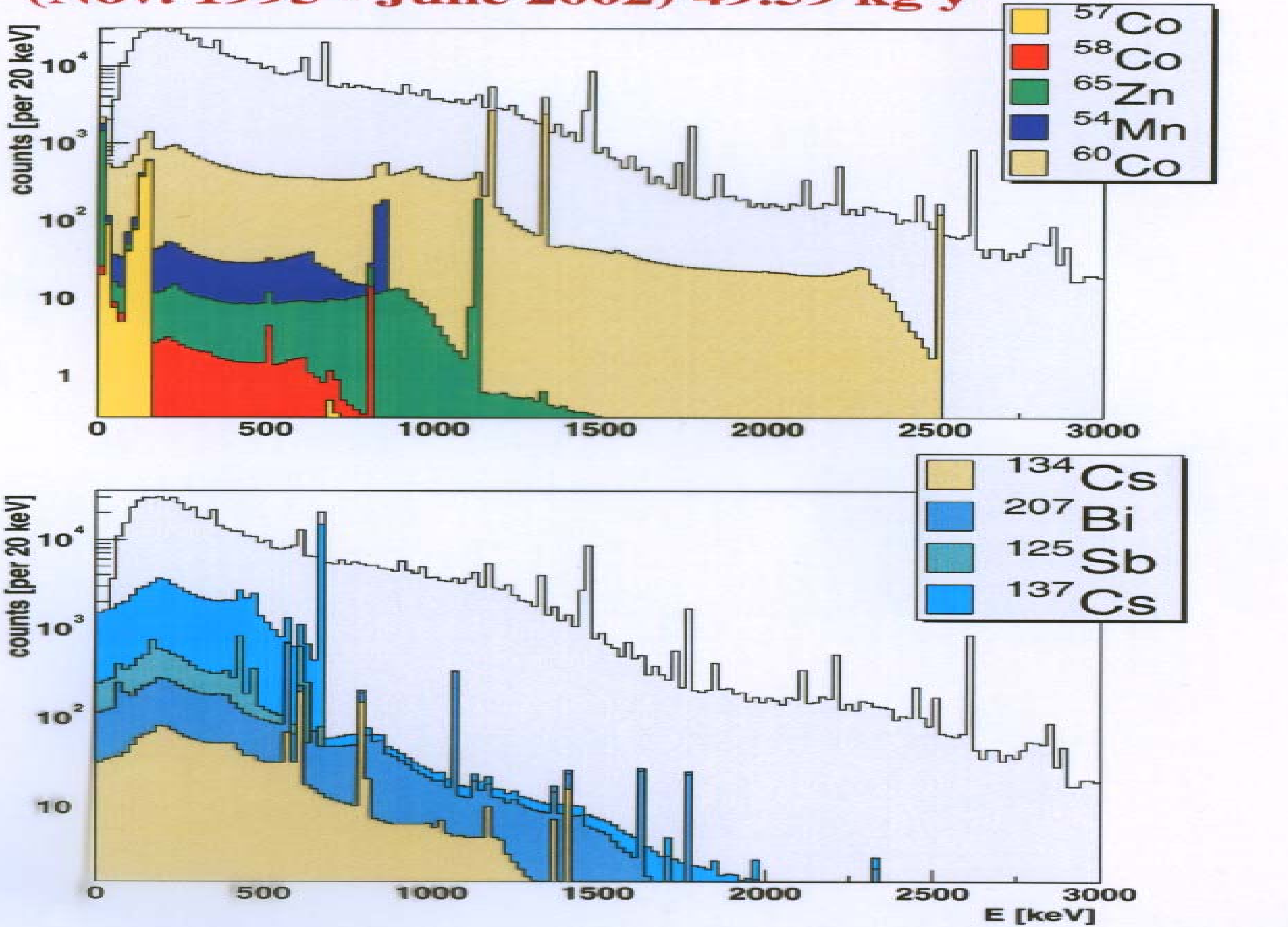
→Simulate the background components in their localisation




Simulated geometry of the detector chamber inside the lead shield in setup.
The colours indicate different materials: green = vespel, yellow = teflon, magenta = iron, red (transparent) = copper

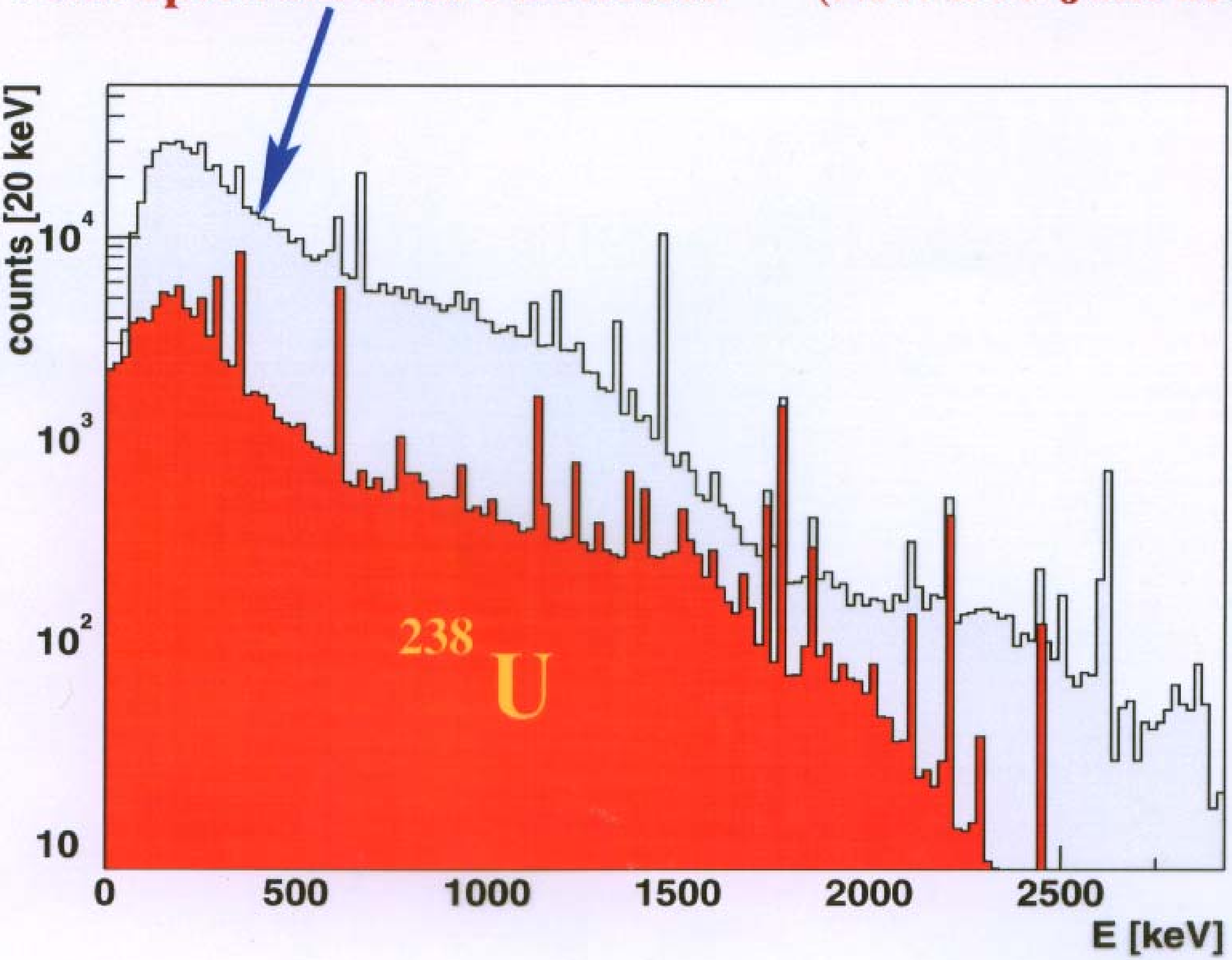
*(see Ch. Doerr and H.V. Klapdor-Kleingrothaus, NIM A 513 (2003) 596-621)*

# HEIDELBERG-MOSCOW EXPERIMENT
# Total Spectrum of all 5 Detectors
# (Nov. 1995 - June 2002) 49.59 kg y

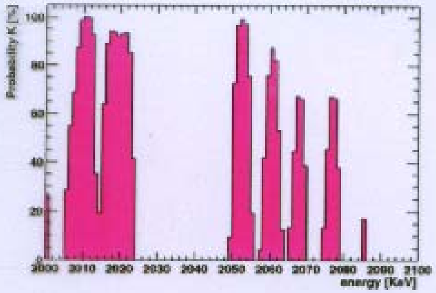


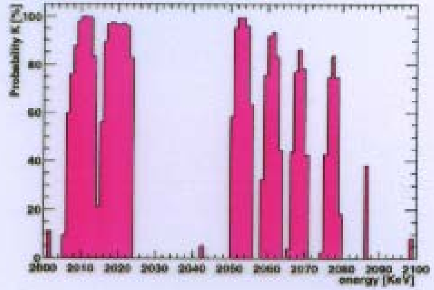
# HEIDELBERG-MOSCOW EXPERIMENT

**Total Spectrum of all 5 Detectors (Nov. 1995-June 2002) 49.59 kgy**



## natural Germanium detectors

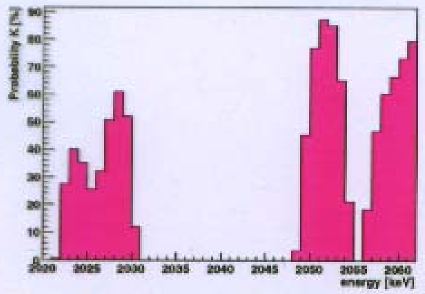


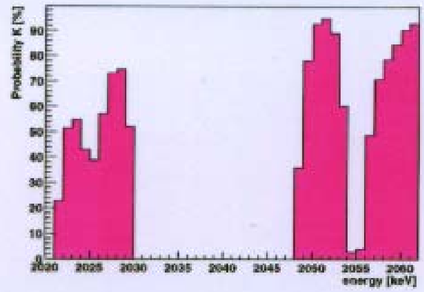




**UCBS/LBL,**

**D. Caldwell etal, J. Phys. G 17 (1991) S137-S144**

## High-purity Germanium detectors



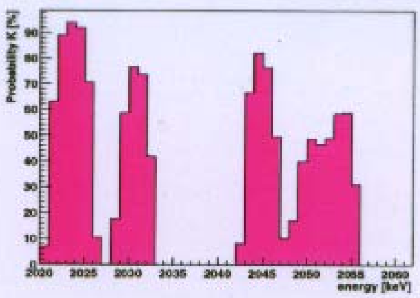



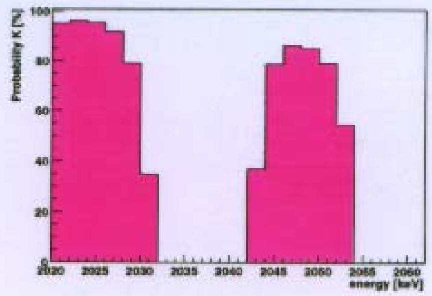

**ITEP/YePI spectrum,**

**A.A. Vasenko etal, Mod.Phys.Lett A 5 (1990) 1299,**

**I. Kirpichnikov, Preprint ITEP (1991)**

## Maximum Likelihood Method    Bayes method




**IGEX,**

**C.E. Aalseth etal, Yad. Fiz. 63 (2000) 1299**

**H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. *Krivosheina*, Tomei**
**NIM A 510 (2003) 281 - 289**

$\beta\beta$ events should be **SINGLE SITE EVENTS,**

i.e. located to a small area in the detector

(emitted electrons run less than one mm).

in contrast to, e.g., **MULTIPLE SITE EVENTS,** corresponding to multiple Compton-scattered $\gamma$ rays.

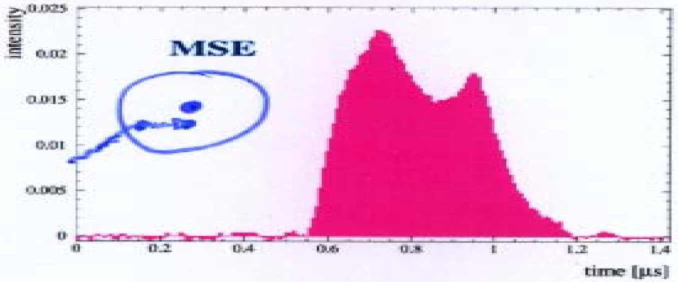
We have developed methods for pulse shape discrimination between these different types of signals:

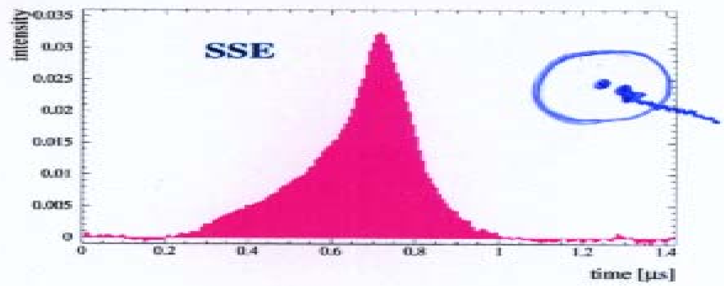
J.Hellmig, F.Petry and H.V.Klapdor-Kleingrothaus, Patent DE19721323A

J. Hellmig and H.V. Klapdor-Kleingrothaus, NIM A 455 (2000) 638-644

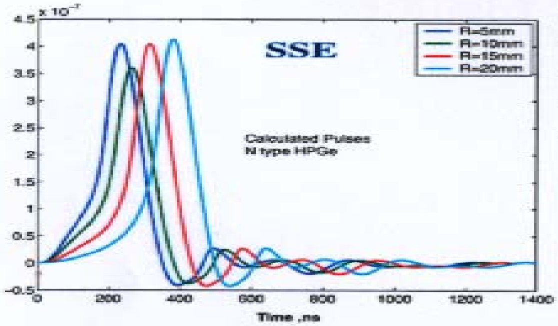
B.Majorovits and H.V.Klapdor-Kleingrothaus, Eur.Phys. J. A6(1999) 463
(based on neuronal nets)

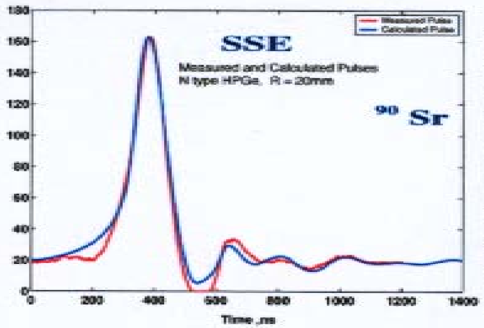
# Shapes of candidates for $0\nu\beta\beta$ decay
## HEIDELBERG-MOSCOW 1990-2003

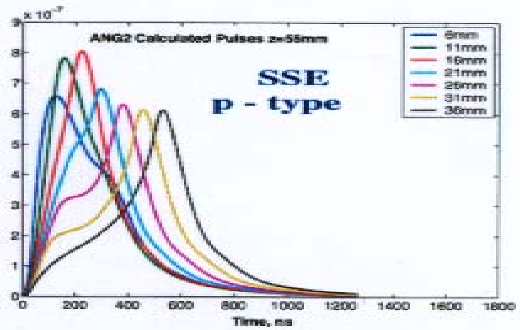


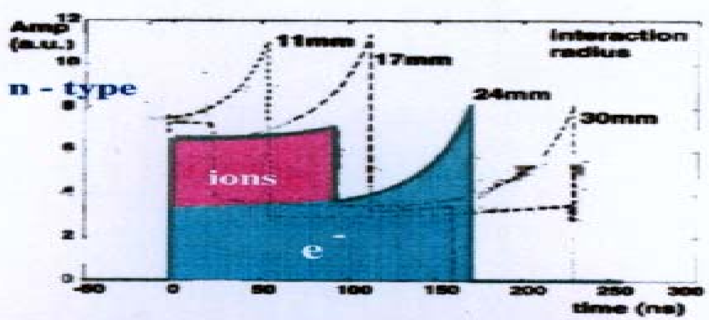




## Dependence on R

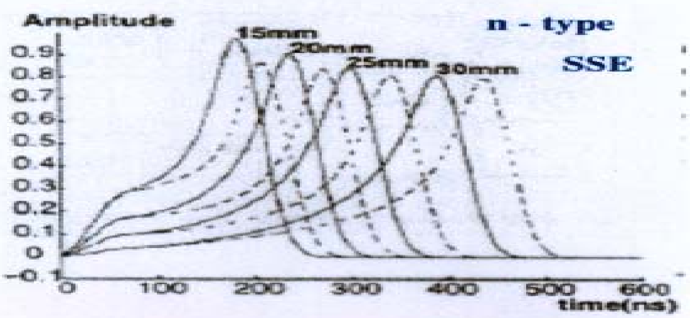



Bazzacco et al., 2003




L. Mihailescu et al.

NIM A447 (2000) 350

H.V. Klapdor-Kleingrothaus
MPI, Heidelberg, GERMANY
27.04.2004

## Pulse Shape analysis:

*two approaches:*

1. Neuronal Net -
   use DE of 2614 keV line from $^{228}Th$,
   to 'calibrate' shapes of $0\nu\beta\beta$ pulses

B. Majorovits and H.V. Klapdor-Kleingrothaus, Eur. Phys. A 6 (1999) 463

2. Calculation of electrical field in Ge detectors
   and of pulse shapes of $0\nu\beta\beta$ pulses, as
   function of location (R,Z) in detector

H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 632 (2006) 623-631

Phys. Rev. D 73 (2006) 013010

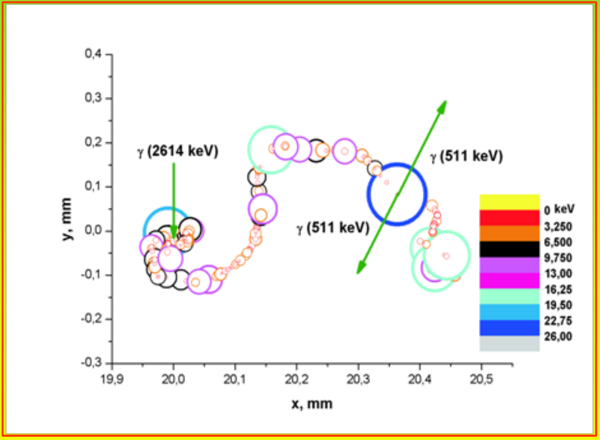
Phys. Lett. B 636 (2006) 235-247

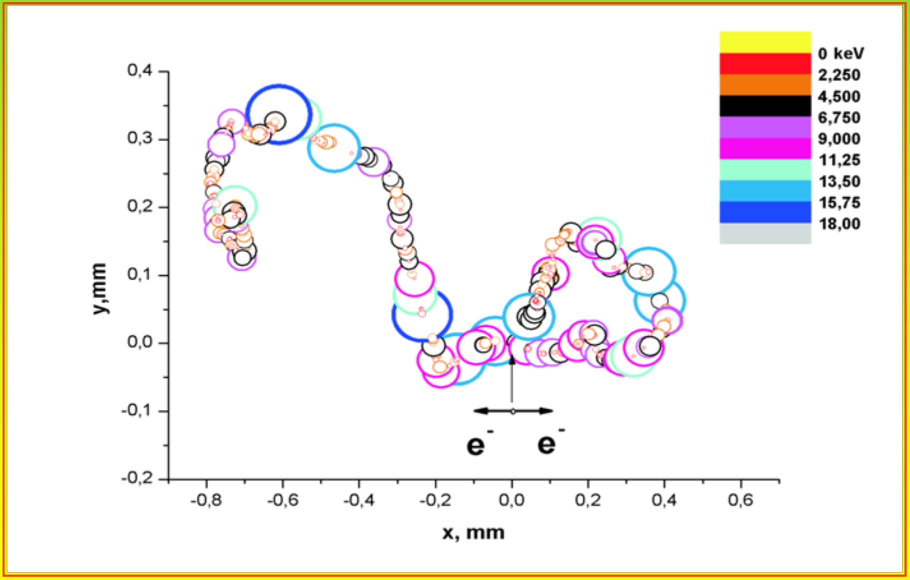
Int. J. of Mod. Phys. A. 21 (2006) 1159-1188,

Modern Phys. Lett. A 16 (2006) 1257-1278

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova,
Phys. Lett. B 632 (2006) 623-631 and Phys. Rev. D 73 (2006) 013010;
Int. J. Mod. Phys. A 21(2006) 1159-1188

# Investigations of Dependence of Beta-Beta Tracks on Particle and Nuclear Physics Parameters

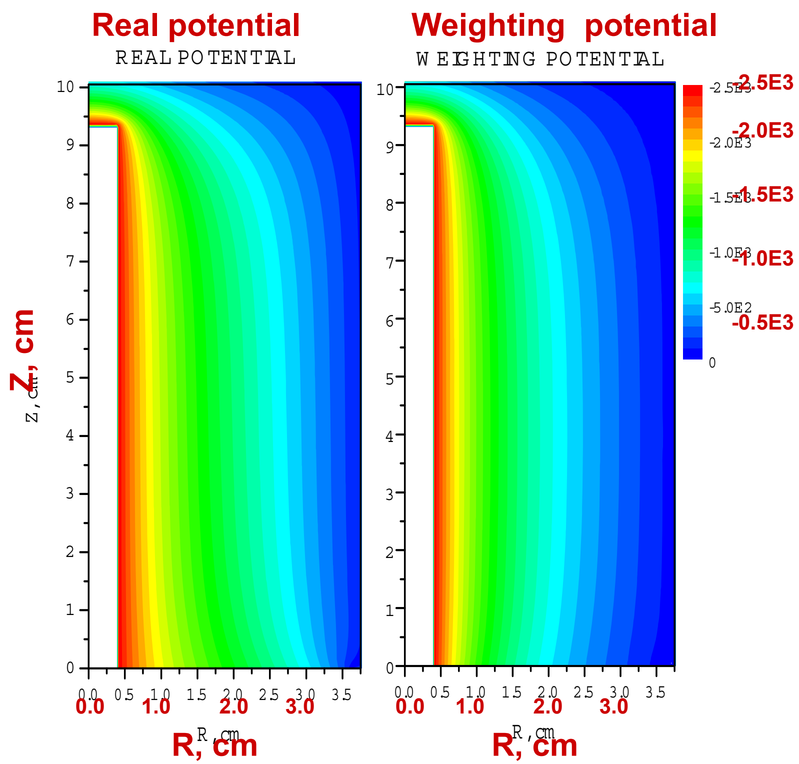


H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, V. Mironov, I.V. Titkova, PLB 636 (2006) 235
H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova, Mod. Phys. Lett. A 21 (2006) 1257-1278

# First 'Microscopic' Calculations of Pulse Shapes corresponding to Monte Carlo calculated ββ events (tracks) *for the big high-purity Ge detectors* of HEIDELBERG-MOSCOW double-β experiment.

Electric field as calculated by the Poisson Superfish code for the detector ANG5 of the HEIDELBERG-MOSCOW experiment in Gran Sasso. The chosen ionized impurity density is 1.37 x 10**9 cm**(-3), (included in the left, but set to zero in the right part). Operation voltage is 2500 V.

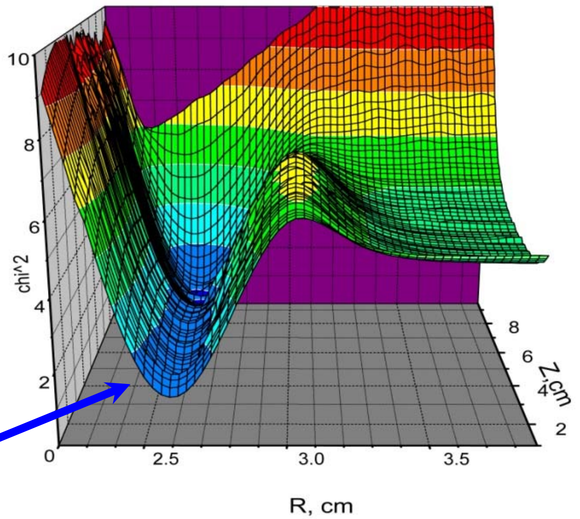



Main measured parameters of the semi-coaxial p-type detectors of HEIDELBERG-MOSCOW Experiment

| Detector | ANG2 | ANG3 | ANG4 | ANG5 |
|---|---|---|---|---|
| Active mass,kg | 2.758 | 2.324 | 2.295 | 2.666 |
| Depletion volt., V | 3000 | 3200 | 2900 | 1200 |
| Operation volt., V | 4000 | 4000 | 3500 | 2500 |
| 76Ge content, % | 86.6 | 88.3 | 86.3 | 85.6 |
| Impurity density, cm**3 | 1. 10**-9 | 1.4 10**-9 | 4.12-9.76 10**-9 | 1.37 10**-9 |
| Crystal diam., mm | 80 | 78.5 | 75 | 78.8 |
| Crystal length, mm | 108 | 93.5 | 100.5 | 105.7 |
| Bore dia-meter, mm | 8 | 9 | 8 | 8 |
| Bore length, mm | 94 | 81.5 | 88.9 | 93.5 |

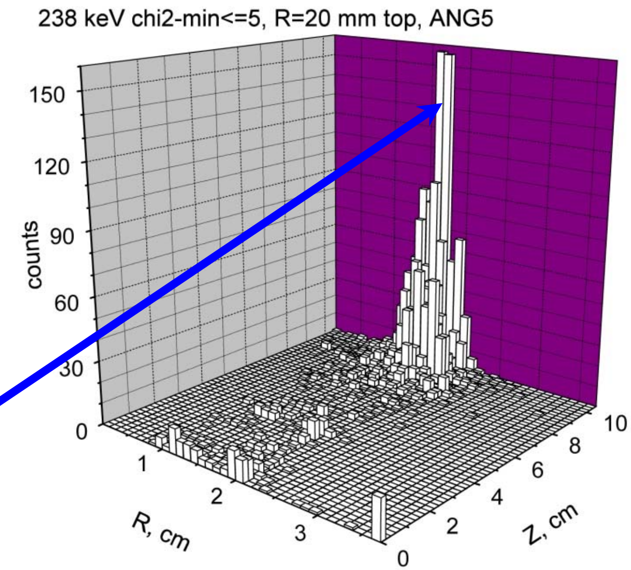
# Examples R-dependence – from upper R-part (det. 5)

**PLBII (2006)**



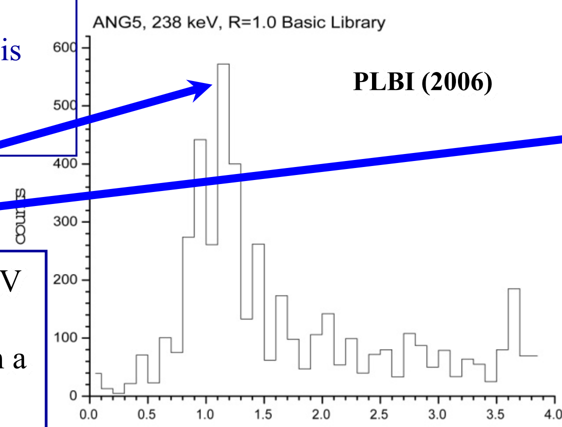

Fit of the location for an event from the HEIDELBERG-MOSCOW ββ measurement seen in the Det. 5, (event Nr. 41 from the Run 1067, energy - 2036.3 keV) from the measured pulse shape by the zero range approximation. The weakness in the localisation in the Z-direction is obvious and known for Ge detectors (see also (Vetter00-c,Kroell01).

**MPLIII (2006)**



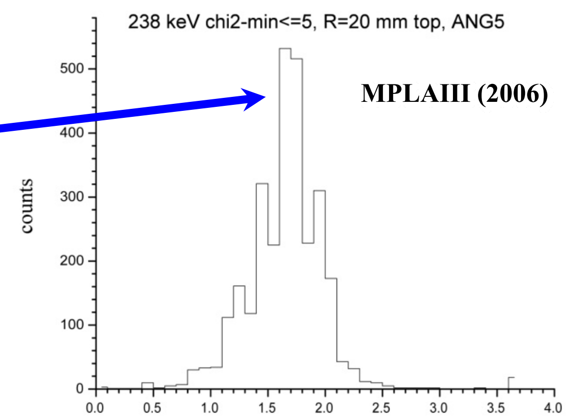

ThreThree-dimensional localization of the 238keV line from the data of calibration of detector 5 of the HM experiment for location of the radiactive source at R=20 mm (right part), by the zero range library calculated with ($\chi^2$<5).

**PLBI (2006)**




**R, cm**

**MPLAIII (2006)**

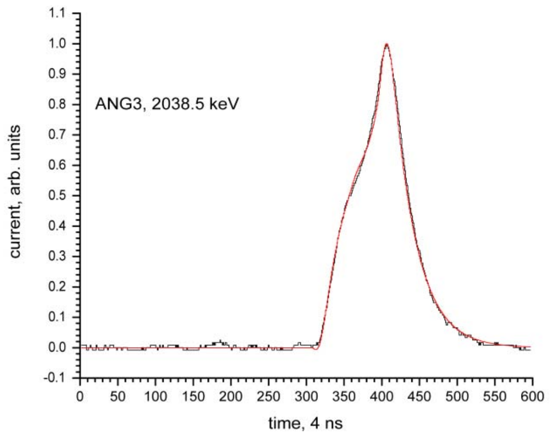


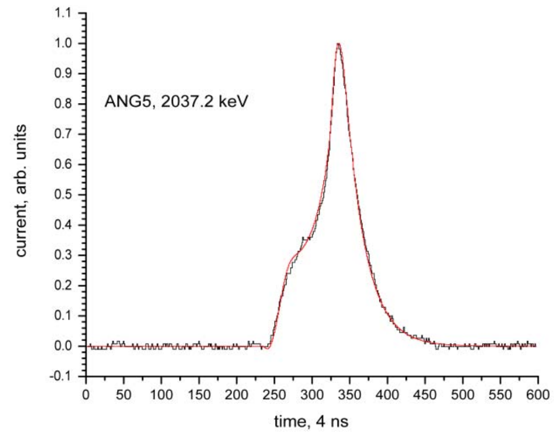

**R, cm**

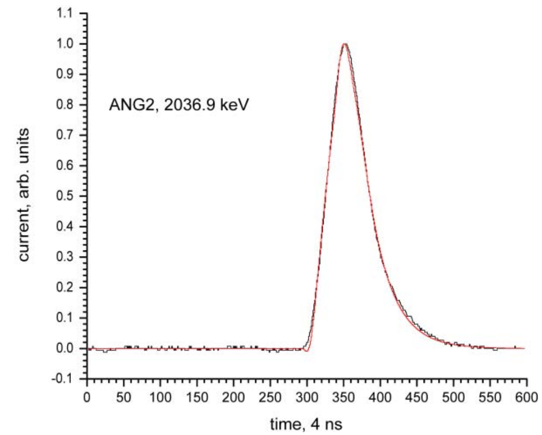
Radial localization, of the events of the 238 keV line determined by pulse shape analysis using the zero range library, from measurement with a collimated 228Th source, at R=10mm, and 20 mm (see top).

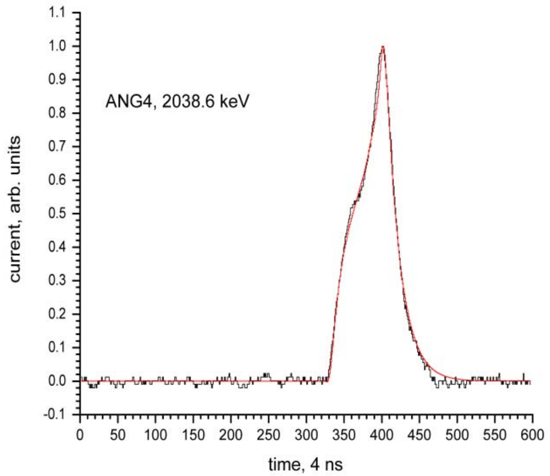
**H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, V. Mironov, I.V. Titkova, PLB 636 (2006) 235**
**H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova, Mod. Phys. Lett. A 21 (2006) 1257-1278**

**Time structure of some events (black lines) measured in the HEIDELBERG-MOSCOW experiment in The energy region 2036-2042 keV by the four enriched 76 Ge detectors (Det.2, 3, 4, 5), which were running with pulse shape analysis.**




**All 4 events were identified by neuronal net method**

**as single site events !!**

**The red lines show fits of the events by the zero range pulse shape approximation library. The determined deviation for the events are less 0.5.**

**All events understood as SSE by Neuronal Net and also by electrical field approach.**

**H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, V. Mironov, I.V. Titkova, PLB 636 (2006) 235**
**H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova, Mod. Phys. Lett. A 21 (2006) 1257-1278**

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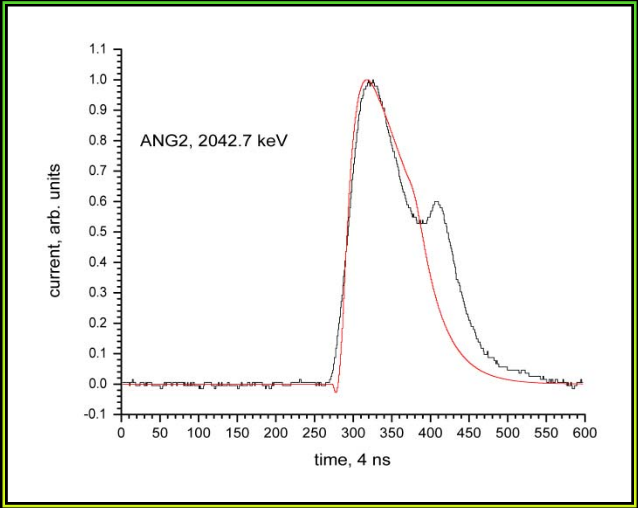


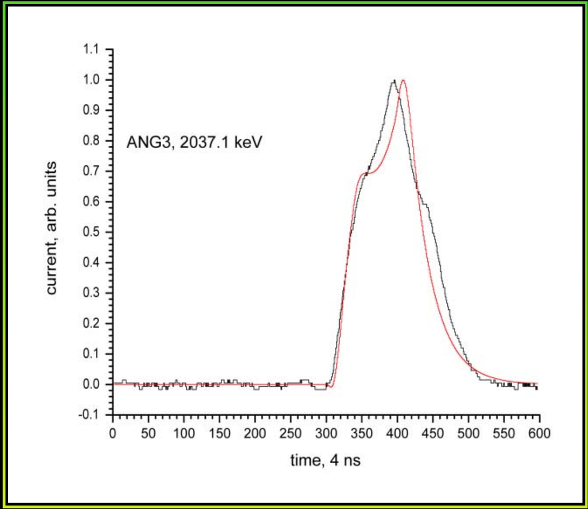


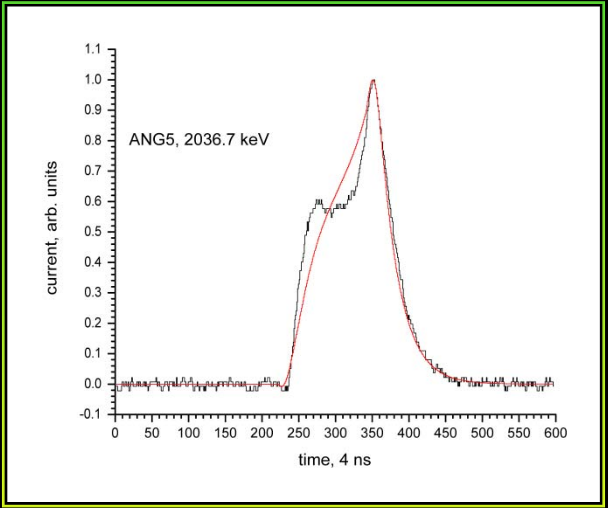


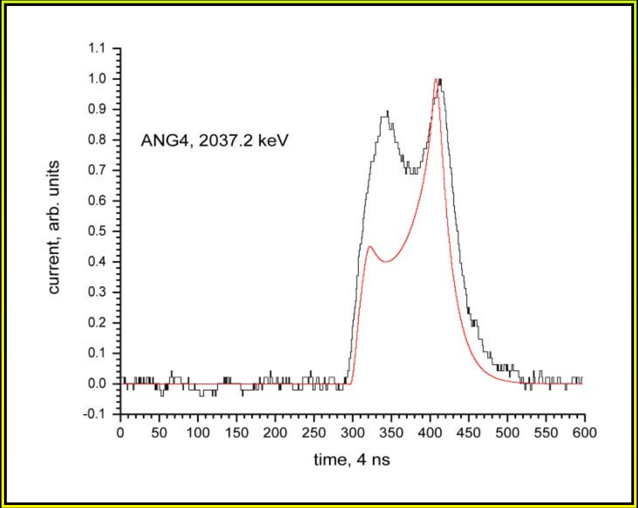


**All 4 events were identified *by neuronal net* method <u>as multiple site</u> events!!**

**The *<u>red lines</u>* show fits of the events *<u>by the zero range</u>* pulse shape approximation library. The determined deviation for the events are large (21.71, 9.33, 6.3, 50.03).**

# Conclusions:

2001 – first signal from *full* spectrum (3.1σ, see also analysis of 2004)

HVKK et al., Mod. Phys. Lett. A 16 (2001) 2409, Found. Phys. 31 (2002) 1181

**2004 – signal (*full* spectrum) of 4.2σ**

- signal (PSA neuronal net subclass) of 6.4σ

HVKK et al., Phys. Lett. B 586 (2004) 198, Nucl. Instr. Meth. A 522 (2004) 371,

Mod. Phys. Lett. A 21 (2006) 1547

2006 – that signal is not known γ-line, confirmed by

Gromov et al., J. Part. Nucl. Lett. 3 (2006) 30

2006 – signal of 4 – 6 σ from PSA with SSE library (subclass) from field calculation.

– signal of 5 – 7 σ from sum of both PSA approaches.

Σ – 11±1.8 events (consistent with 12.4±3.7 events from global N in NIM2004)

$\rightarrow T_{1/2} = (2.23^{+0.44}_{-0.31}) \times 10^{25}$ y

<m> < (0.32 ± 0.03) eV

With normalized matrix element: → < (0.22 ± 0.02) eV

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# *Matrix element:*

**Prediction given by**

A. Staudt, K. Muto, H.V. Klapdor, Eur. Phys. Lett., 13 (1), pp. 31-36 (1990)
K. Muto, E. Bender, H.V. Klapdor, Z. Phys. A 334 (1989) 177

(basing on fit of $g_{pp}$ in QRPA by experimental $\beta^+$ decays)

**for** $2\nu\beta\beta$: $T_{1/2} = 2.99 \times 10^{21}$ y

- ***Later*** **experiment gave**

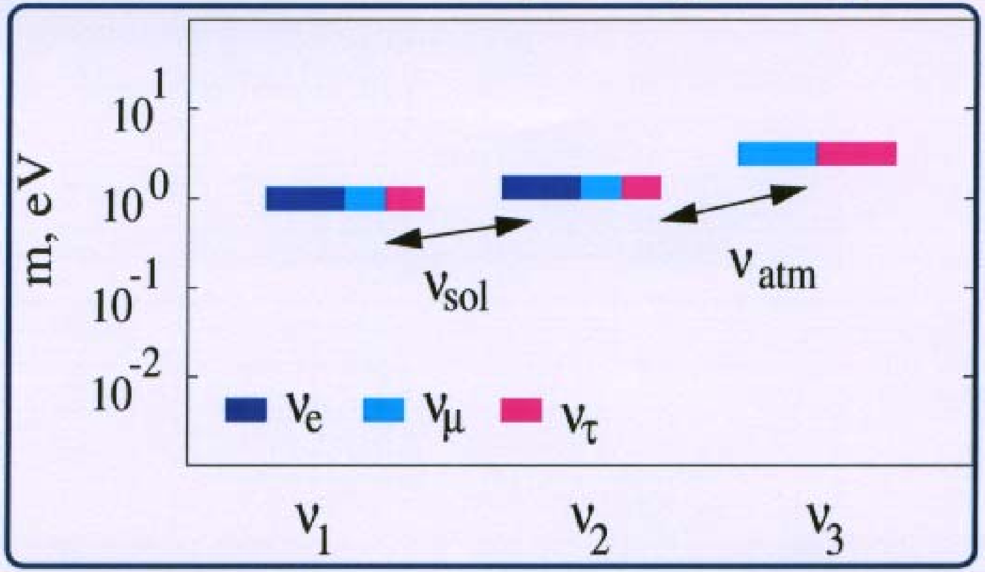
  HEIDELBERG-MOSCOW Coll., Phys. Rev. D 55 (1997) 54
  Ch. Doerr, H.V. Klapdor-Kleingrothaus, Nucl. Instr. Meth. 513 A (2003) 596-621

  $T_{1/2} = 1.74 \times 10^{21}$ y

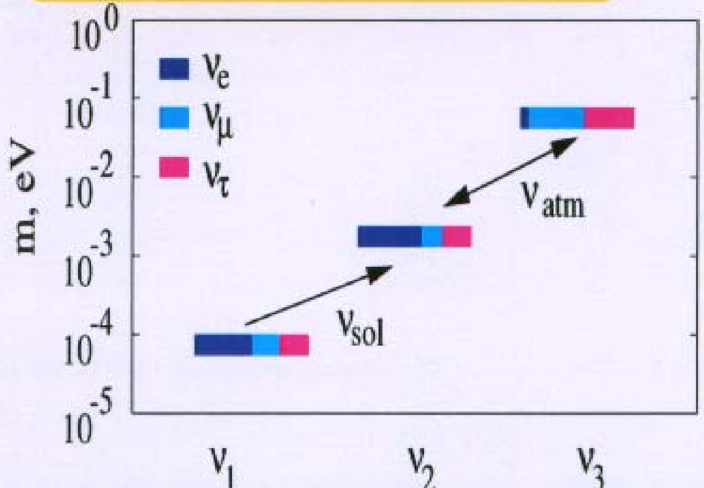
*only* ⇒ **calculation** ***underestimates*** $2\nu$ **matrix element by 29% and thus overestimates** <m> **by** $\lesssim$ 29%

*Heidelberg, 27.04.2004*

## Degenerate case: $m_1 \sim m_2 \sim m_3 \gtrsim 0.1$ eV

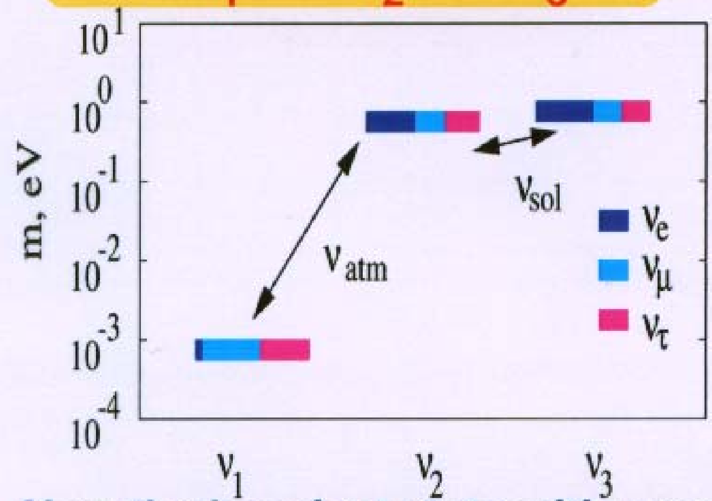



## Hierarchical case: $m_1 << m_2 << m_3$

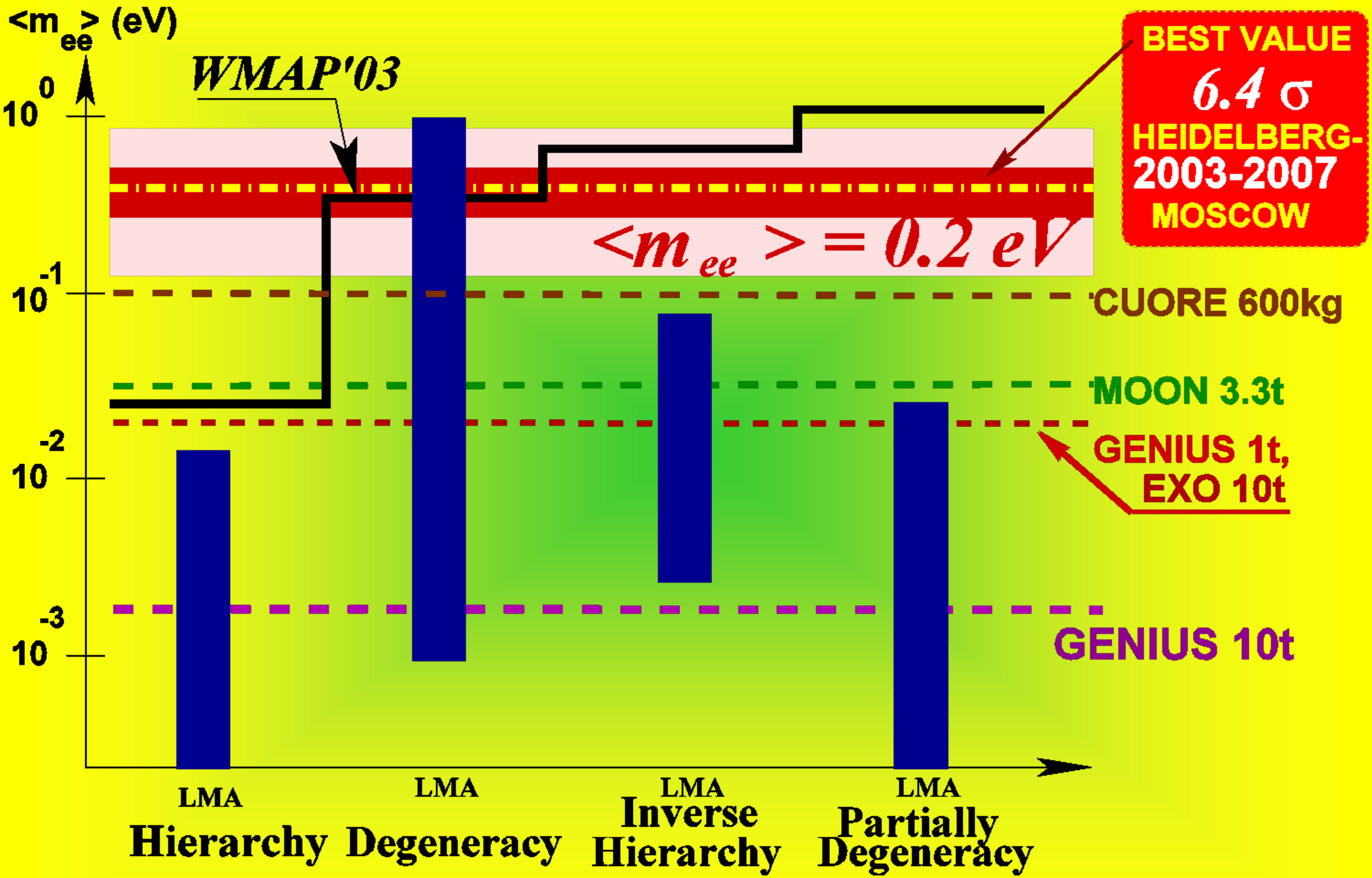



Motivated by analoqies with quark sector and simplest see-saw models.

## Inverse Hierarhy: $m_1 \sim m_2 >> m_3$




Now the heaviest state with mass $m_3$ is mainly electron neutrino.



$<m_{ee}>$ (eV)
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
WMAP'03
$<m_{ee}> = 0.2$ eV
BEST VALUE
6.4 σ
HEIDELBERG-
2003-2007
MOSCOW
CUORE 600kg
MOON 3.3t
GENIUS 1t,
EXO 10t
GENIUS 10t
LMA
Hierarchy
LMA
Degeneracy
LMA
Inverse
Hierarchy
LMA
Partially
Degeneracy

## Double Beta Observable:
$<m> = |\sum U_{ei}^2 m_i|$

$U_{ei}$ elements of neutrino mixing matrix

*For three - neutrino case*

$$<m> = |m_{ee}^{(1)}| + e^{i\Phi_2}|m_{ee}^{(2)}| + e^{i\Phi_3}|m_{ee}^{(3)}|$$

where $m_{ee}^{(i)} = |m_{ee}^{(i)}|e^{i\Phi_i}$ are the contributions to $<m>$ from the individual mass eigenstates, with $\Phi_i$ relative Majorana phases. In terms of oscillation parameters

$$\left.\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2} \end{aligned}\right\} *)$$

Some of the parameters in (*) can be fixed or restricted from oscillation data:

**Normal hierarchy:** $\Delta m_{21}^2$, $|U_{e1}|^2 = \cos^2\Theta_s$ and $|U_{e2}|^2 = \sin^2\Theta_s$ fixed by solar neutrino (LMA or LOW solution); $\Delta m_{32}^2$ fixed by atmospheric neutrinos (Large Mixing) $|U_{e3}|^2$ restricted by experiments looking for $\nu_e$ disappearance

**Inverse hierarchy:** exchange $\nu_1 \longleftrightarrow \nu_3$ in equations (*)

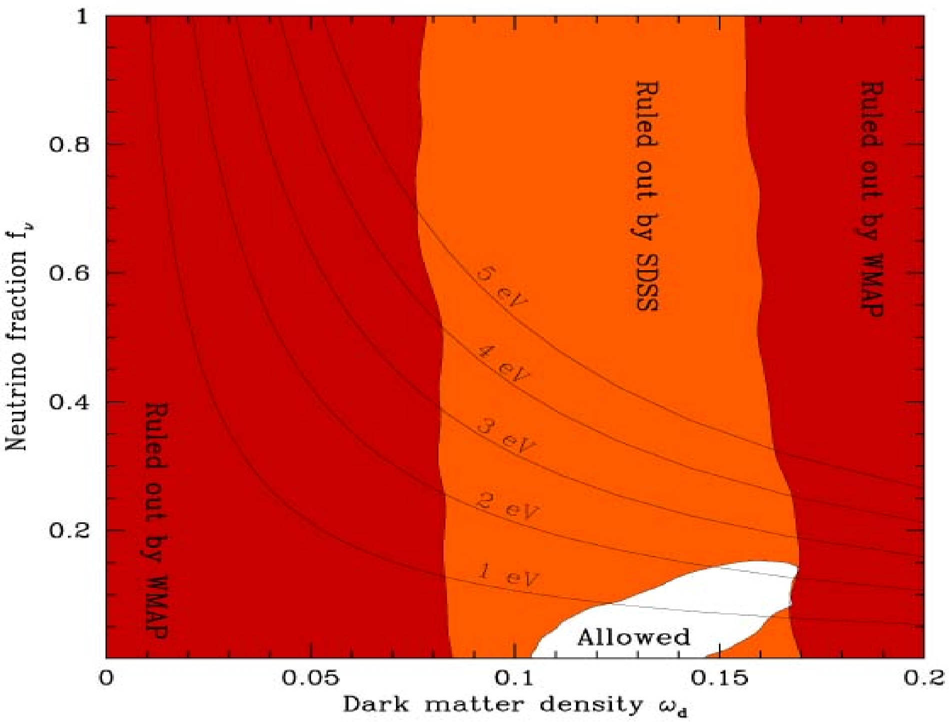
$m_1$ free parameter, phases $\Phi_i$ - connected with CP violation

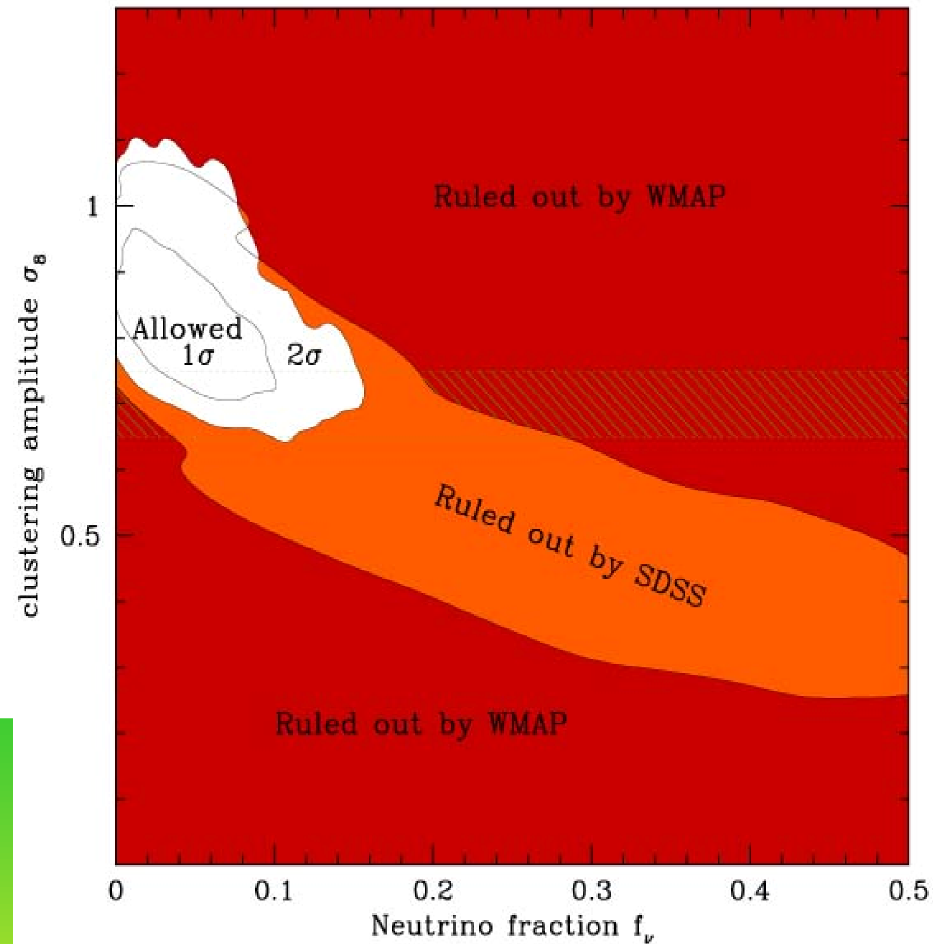
$0\nu\ \beta\beta$ yields information on neutrino mass spectrum and absolute mass scale

Increase of $m_1$ level of degeneracy increases → *distinguish two extreme case*

Hierarchical Spectrum: $m_1^2 << \Delta m_{21}^2 << \Delta m_{31}^2$

Degenerate Spectrum: $\Delta m_{21}^2 << \Delta m_{31}^2 << m_1^2$




**95% constraints in the (w_d,f_ν) plane. Shaded dark red region is ruled out by WMAP alone when neutrino mass is added to the 6 ``vanilla'' models. The shaded light red region is ruled out when adding SDSS information. The five curves correspon to M_ν, the sum of the neutrino masses, equaling 1, 2, 3, 4 and 5 eV, respectively -- barring sterile neutrinos, no neutrino can have a mass exceeding ~M_ν/3. (<~0.6 eV (95%)). Right: Constraints in the (f_ν, σ_8) plane. Shaded dark red region is ruled out by WMAP alone (95%) when neutrino mass is added to the 6 ``vanilla'' models. The shaded light red region is ruled out when adding SDSS information. The recent claim that f_ν>0 [All03**-III] hinges on assuming that galaxy clusters require low σ_8-values (shaded horizontal band) and dissolves when using more reasonable uncertainties in the cluster constraints (see http://space.mit.edu/home/tegmark/).**

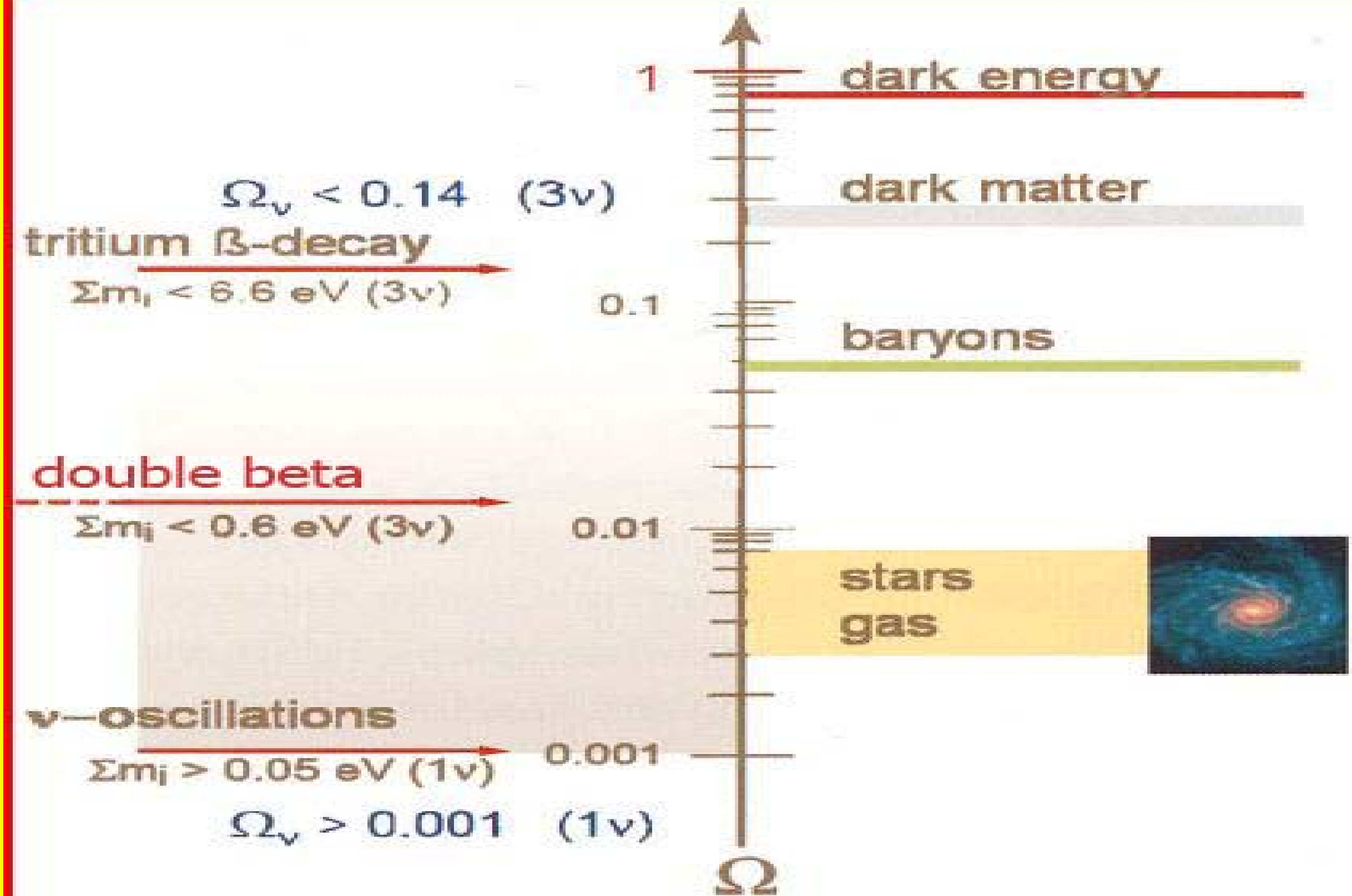
**After** *we published these results in December 2001*
(see NEW RESULTS in H.V. Klapdor-Kleingrothaus et al., NIM A 2004)

$0\nu\beta\beta$ **0.2** eV < **m** < **0.5 eV**

many informations came in **2002-2003** which **supported** our result

| | | | |
|---|---|---|---|
| $\nu$ - Oscillations | | $m > 0.04$ eV | (SuperKamiokande) |
| - CMB | $\Sigma\ m_j < 2.2$ eV | | (J.E. Ruhl, et al., astro-ph/0212229) |
| - Tritium | $\Sigma\ m_j < (2.2 - 2.8)$ eV | | (C.Weinheimer, Appec, Karlsrhue, Sept. 2003) |
| - SDSS+WMAP | | $m_{com} < 0.57$ eV | M. Tegmark et al., astro-ph/0310723 |
| | $\Sigma\ m_j < 0.69$ eV | $m_{com} < 0.23$ eV | (D.N. Spergel et al., astro-ph/0302209) |
| - MAP | $\Sigma\ m_j < 1.0$ eV | $m_{com} < 0.33$ eV | (H. Hannestad, astro-ph/0303076) |
| | $\Sigma\ m_j < 1.38$ eV | $m_{com} < 0.45$ eV | (forth neutrino with very small mass) |
| - CMB<br>- 'prefered value' | $\Sigma\ m_j = 0.66$ eV | $m_{com} \approx 0.22$ eV | (S.W.Allen et al. astro-ph/0309130) |
| - Z-burst | | (0.01 - 1.3) eV | (Z.Fodor, S.D.Katz, A.Ringwald) (JHEP 0206:046,2002, hep-ph/0203198) |
| | | 0.4 eV | (D.Fargion, DARK2000, Heidelberg) (Springer, eds.HVKK, 2001, 455-468) |
| - g-2 | | $m_{com} > 0.2$ eV | (E.Ma, M.Raidal, Phys.Rev.Lett.87(2001)011802) |
| - Theory | | $m_{com} > 0.2$ eV | (K.S.Babu,E.Ma,J.W.F.Valle, hep-ph/0206292) A4-symmetry |
| | | $m_{com} > 0.1$ eV | (R.N. Mohapatra et al., hep-ph/0301234) identical quark and neutrino mixing at GUT scale |

Status: March 2004

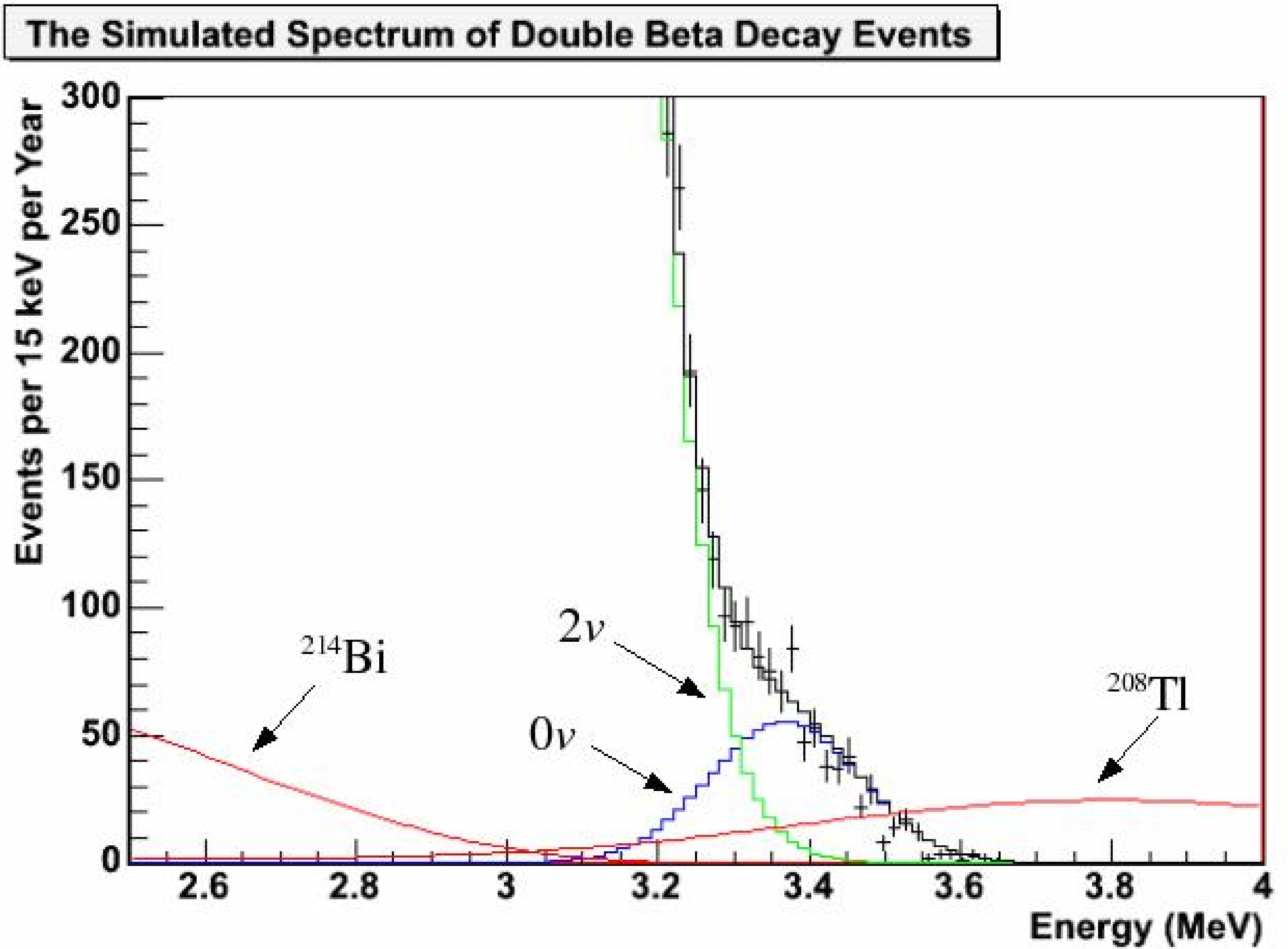



$$\Omega_\nu h^2 = \Sigma m_\nu / 92 \text{ eV}$$

336 relic ν/cm³

# SNO ++


Sudbury Neutrino Observatory
Support Structure for 9500 PMTs, 60% coverage
12 m Diameter Acrylic Vessel
1700 tonnes Inner Shielding $H_2O$
5300 tonnes Outer Shield $H_2O$
Urylon Liner and Radon Seal
1000 tonnes $D_2O$ ($300 M)


The Simulated Spectrum of Double Beta Decay Events
Events per 15 keV per Year
Energy (MeV)
300
250
200
150
100
50
0
2.6
2.8
3
3.2
3.4
3.6
3.8
4
$^{214}$Bi
$2\nu$
$0\nu$
$^{208}$Tl

# LESSON II: Future !!!

## 0νββ

**HEIDELBERG-MOSCOW**

**2001-2006 y**

-Present and future 'confirmation' experiments (CUORICINO, NEMO, EXO, …) *NOT sensitive enough*

- Much worse:

- If *could* confirm → *no new information*
- In general: additional $\beta^-\beta^-$ experiment (e.g. $^{136}Xe$) together with Ge $^{76}$ (HEIDELBERG- MOSCOW) → *no new information (see Z. Phys. A 347 (1994) 151).* Cannot decide contribution of $m_\nu$, η, λ to ββ decay rate ⇨ *Cannot determine effective neutrino mass !!!!*

- **Only way** to get information about

$m_\nu$, η, λ is:

To combine $\beta^-\beta^-$ - *result* (HEIDELBERG- MOS-COW) with very high sensitivity (level of $10^{27}$ y) mixed mode $\beta^+$EC - experiment (e.g. Xe $^{124}$).

H.V. Klapdor-Kleingrothaus et al., PRD 73 (2006) 013010

# The half-life for the neutrinoless decay mode is:

$$\left[T_{1/2}^{0\nu}\left(0_i^+ \rightarrow 0_f^+\right)\right]^{-1}$$

$$= C_{mm}\frac{\langle m\rangle^2}{m_e^2} + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2$$

$$+ C_{m\eta}\langle\eta\rangle\frac{\langle m\rangle}{m_e} + C_{m\lambda}\langle\lambda\rangle\frac{\langle m\rangle}{m_e} + C_{\eta\lambda}\langle\eta\rangle\langle\lambda\rangle$$

$$\langle m\rangle = \left|m_{ee}^{(1)}\right| + e^{i\varphi\varphi}\left|m_{ee}^{(2)}\right| + e^{i\varphi\varphi}\left|m_{ee}^{(3)}\right|$$

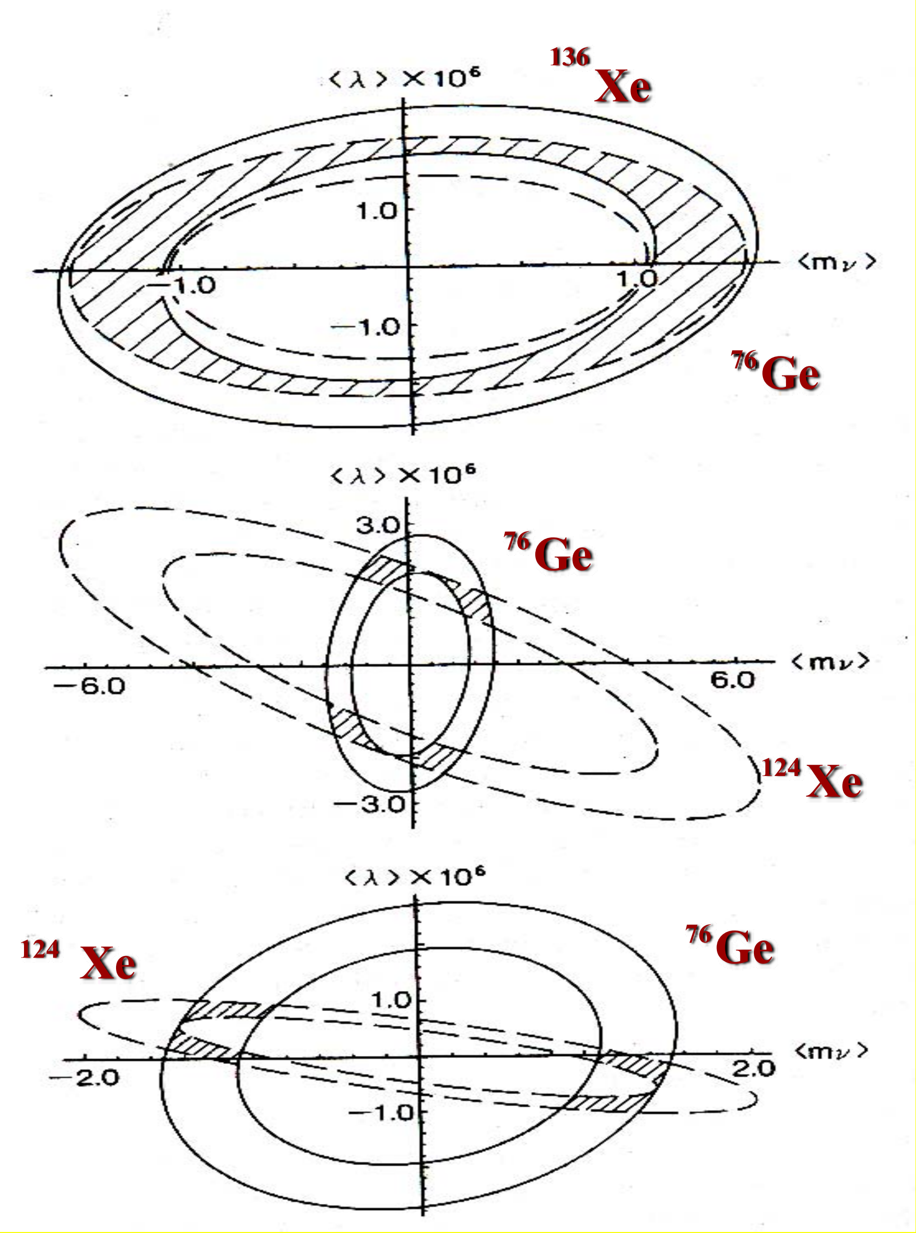
where $m_{ee}^i \equiv \left|m_{ee}^i\right|\exp(i\phi_i)$ (i=1,2,3) are the contributions to the effective mass $\langle m\rangle$ from individual mass eigenstates, with $\phi_i$ denoting relativ Majorana phases connected with CP violation, and $C_{mm}, C_{\eta\eta},\ldots$ denote nuclear matrix elements squared.

**M. Hirsch, K. Muto, T. Oda, H.V. Klapdor-Kleingrothaus, Z. Phys. A 347 (1994) 151-160**

Two $\beta^-\beta^-$ experiments

One $\beta^-\beta^-$ and one $\beta^+$/EC experiment

One $\beta^-\beta^-$ and one $\beta^+$/EC experiment



So far for light neutrinos.

Now some other Beyond Standard Model Physics

## Half-life for SUSY $0\nu\beta\beta$ decay

From the SUSY Feynman graphs one finds:

Rp breaking

$$\left[T_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)\right]^{-1} \sim G_{01}\left\{\frac{\lambda'^2_{111}}{m^4_{\tilde{q},\tilde{e}}\, m_{\tilde{g},\chi}}\mathcal{M}\right\}^2$$

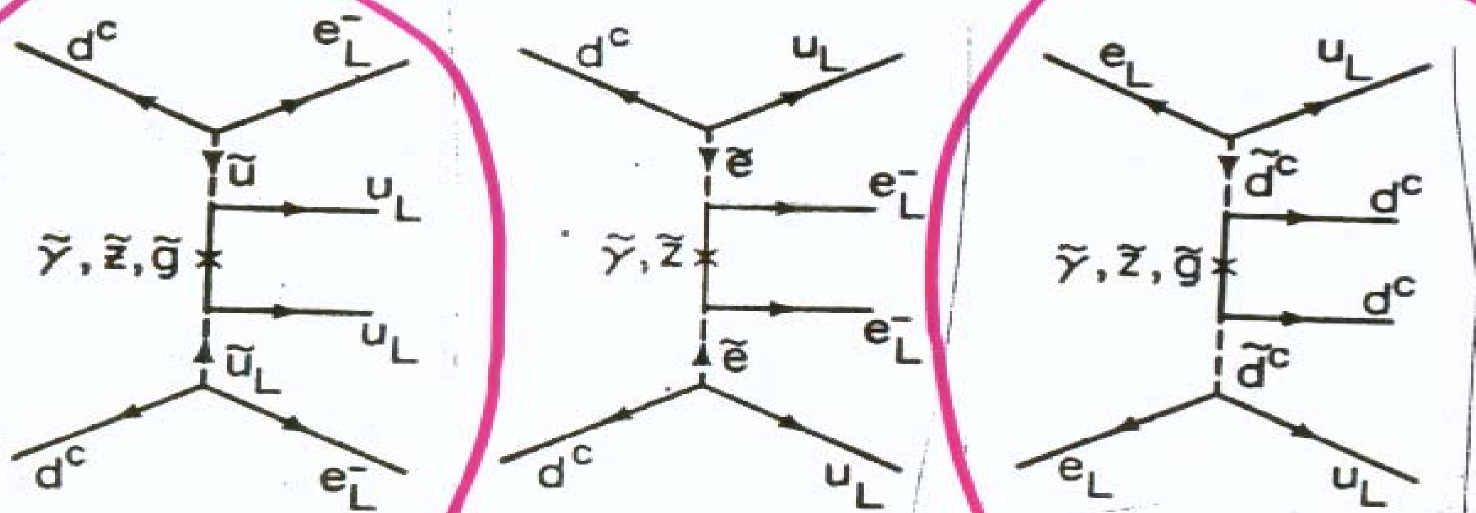



**Abbildung 5.6:** $\beta\beta$-Zerfallsamplituden aufgrund des Austausches supersymmetrischer Teilchen.

# Superpotential

The superpotential can be written as:

$$W = W_{R_p} + W_{\not{R}_p}$$

SUSY analog to SM

The R-parity violating part has the form:

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

$\lambda_{ijk}, \lambda'_{ijk}$ - lepton number violating terms

$\lambda''_{ijk}$ - baryon number violating terms

$L, Q$ - lepton and quark *doublet* superfields

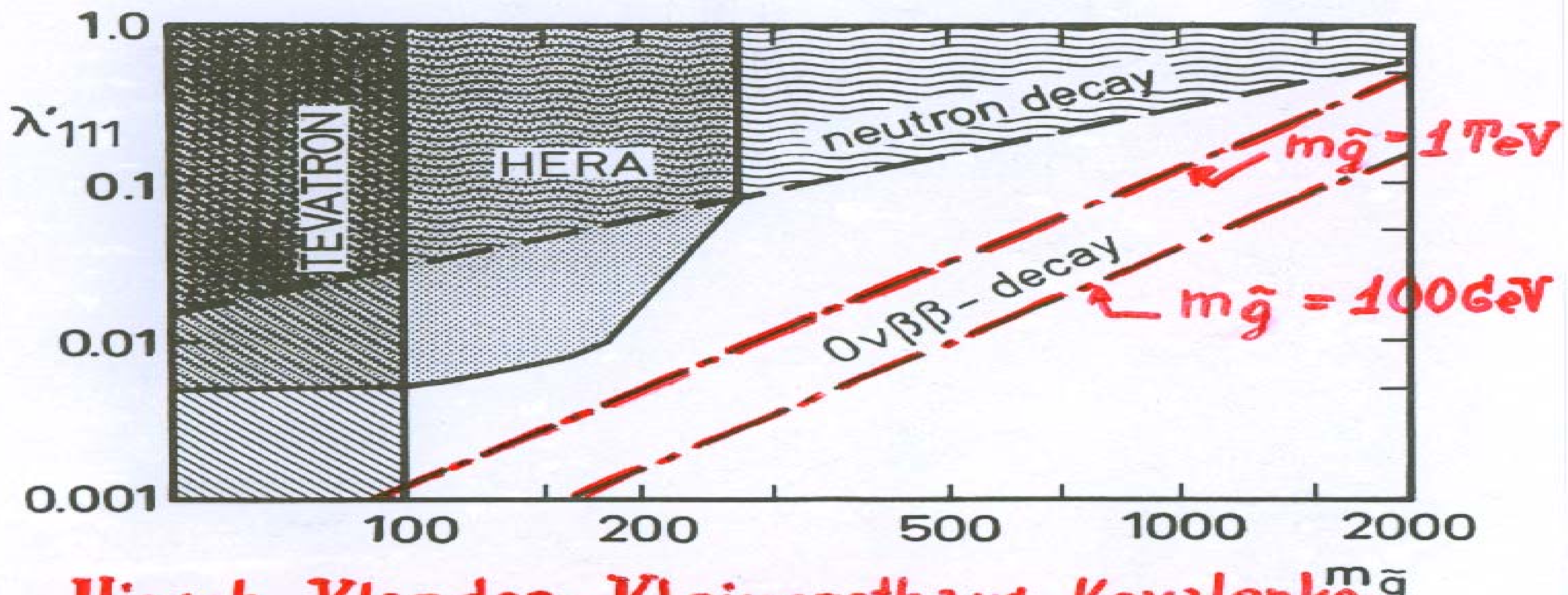
$\bar{L}, \bar{U}, \bar{D}$ - lepton and up, down quark *singlet* superfields

$i, j, k$ : generation indices (1,2,3)

$\lambda'_{ijk}$ : no symmetry

$\lambda_{ijk}$ : antisymmetric in $(i \leftrightarrow j)$

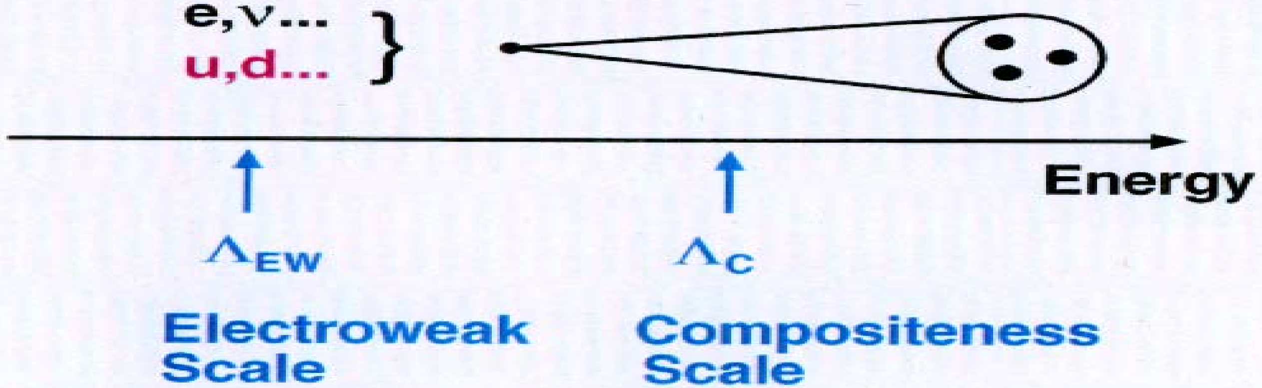
$\lambda''_{ijk}$ : " in $(j \leftrightarrow k)$

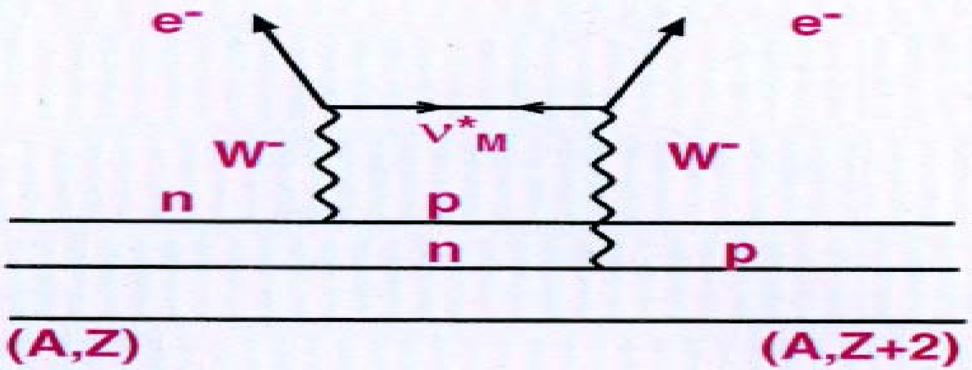



Hirsch, Klapdor-Kleingrothaus, Kovalenko
Phys. Rev. D53 (1996) 1329

1. Low energy constraint: Charged-current universality Neutron decay (V. Barger et al., Phys. Rev D 40 (1989) 2987)
2. Tevatron dilepton data (D. P. Roi, Phys. Let. B 283(1992) 270)
3. Possible limits from HERA, assuming 200 $pb^{-1}$ of data ≈ 1 year (J. Butterworth and H. Dreiner, Nucl. Phys. B 397 (1993) 3
4. Absence of 0νββ decay - $^{76}Ge$ limit from HEIDELBERG-MOSCOW assuming $m_g$ = 100 GeV, 1 TeV (M. Hirsch et al. Phys. Rev. D 53(1996) 1329)

# Compositeness and 0νββ




Heidelberg-Moscow → $m_{\nu^*_M} > 3\, m_W \approx$ 240 GeV

(coupling Λ=1)

Panella et al. hep-ph / 9701251
Takasugi et al. hep-ph / 9706240

$$^{\beta\beta}T_{1/2}^{-1} \underset{\text{Fig. 3}}{=} \left(\frac{f}{\Lambda_c}\right)^4 \frac{m_A^8}{M_N^2} |\mu_{FI}|^2 \frac{G_{01}}{m_e^2}$$

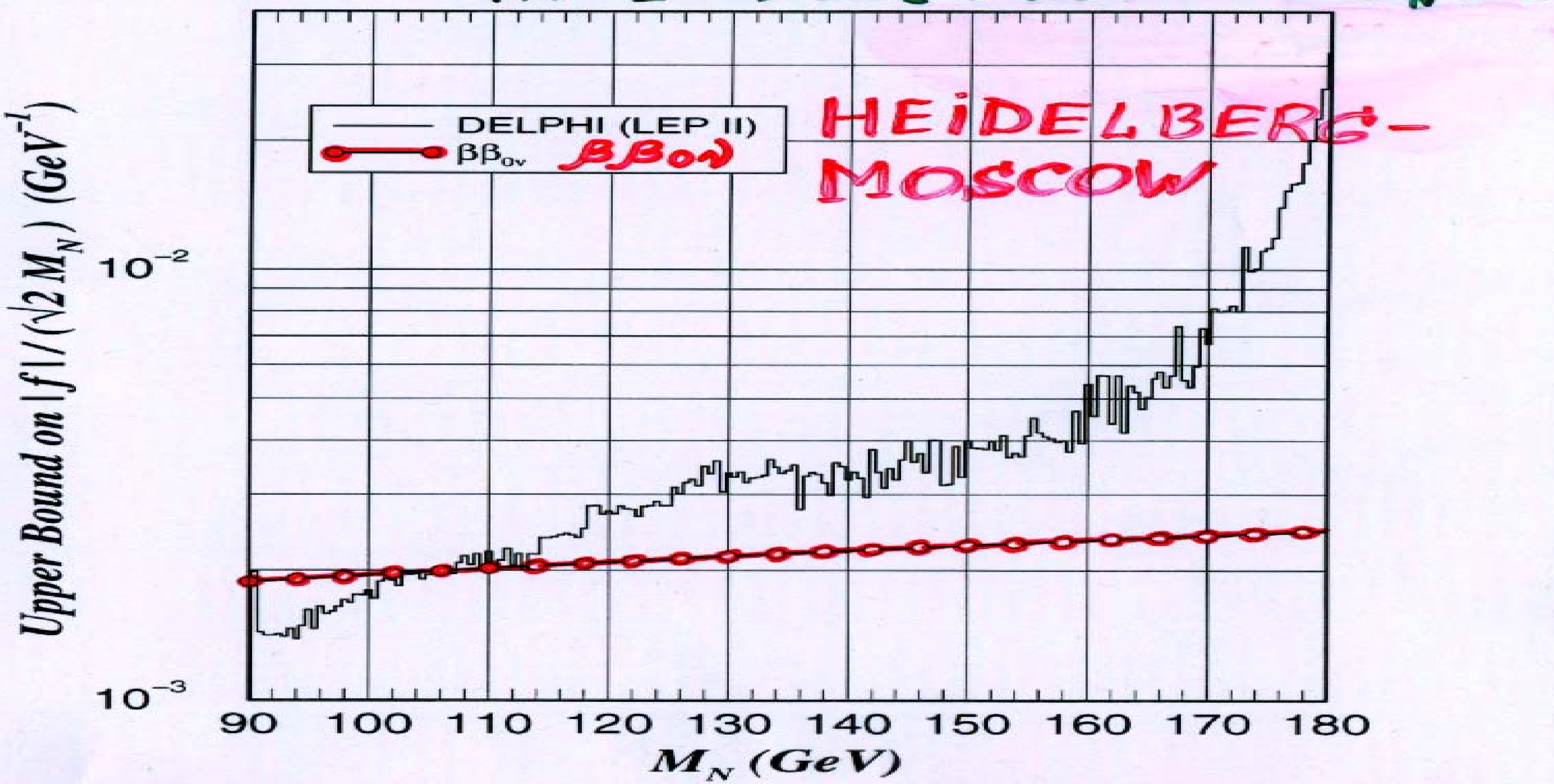
$\Lambda_c$ - Compositeness Scale

$M_N$ - Composite neutrino (Majorana) mass

$0\nu\beta\beta$: $|f| \leq 8 \frac{\Lambda_c}{1\,TeV} \left(\frac{M_N}{1\,TeV}\right)^{1/2}$

$\Lambda_C = M_N$

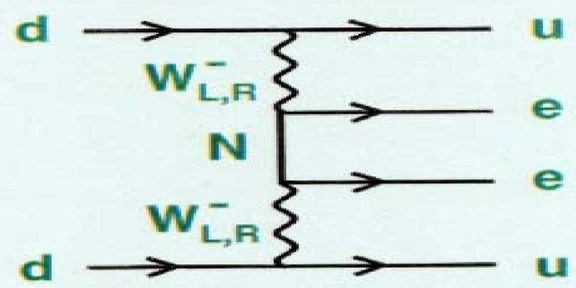
$|f| = 1 \Rightarrow \Lambda_c \geq 0.12\,TeV$ at $M_N = 1\,TeV$

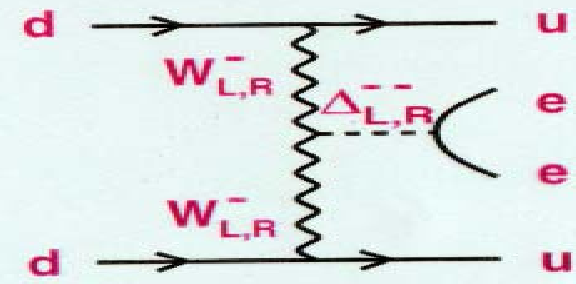



O. Panella et. al hep-ph/9903253 v2

4 Mar. 1999

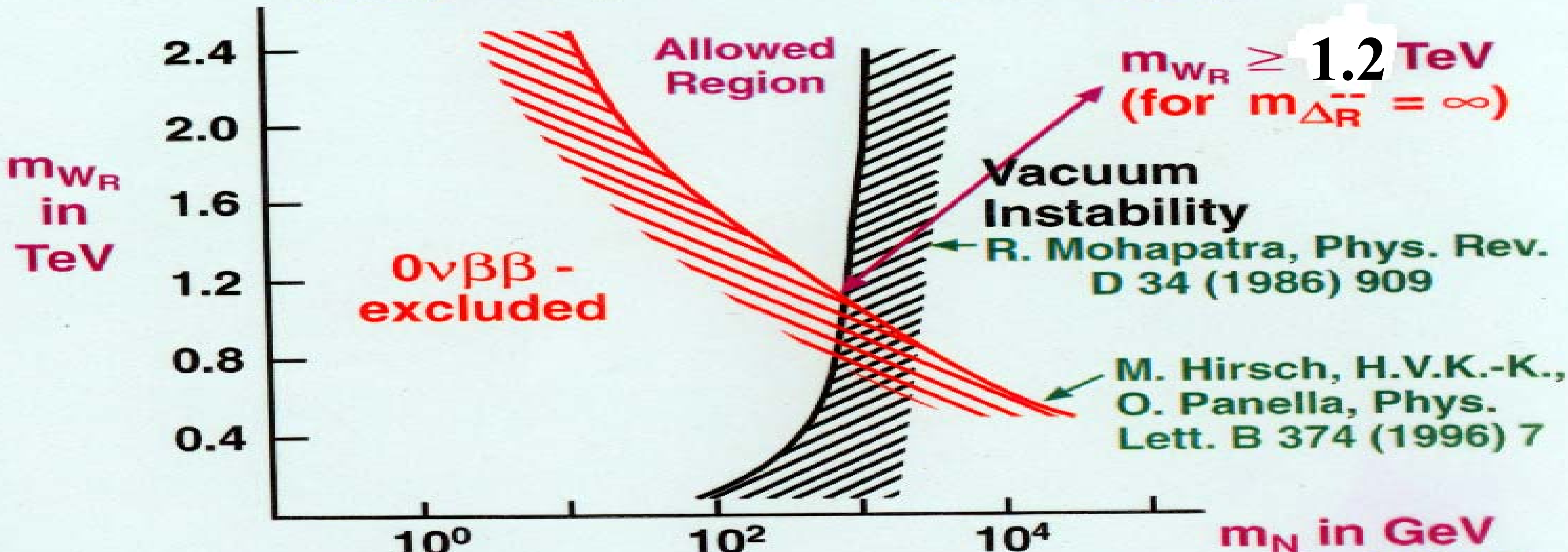
# Heavy right-handed ν and $W_R$ mass




$$A_{RR} \sim \left(\frac{m_{W_L}}{m_{W_R}}\right)^4 \left(\frac{1}{m_N} + \frac{m_N}{m^2_{\Delta^{--}_R}}\right)$$

HEIDELBERG – MOSCOW




GENIUS (1 ton) : $m_{W_R}$ > 8 TeV

LHC : > 5-6 TeV

# Superheavy neutrinos

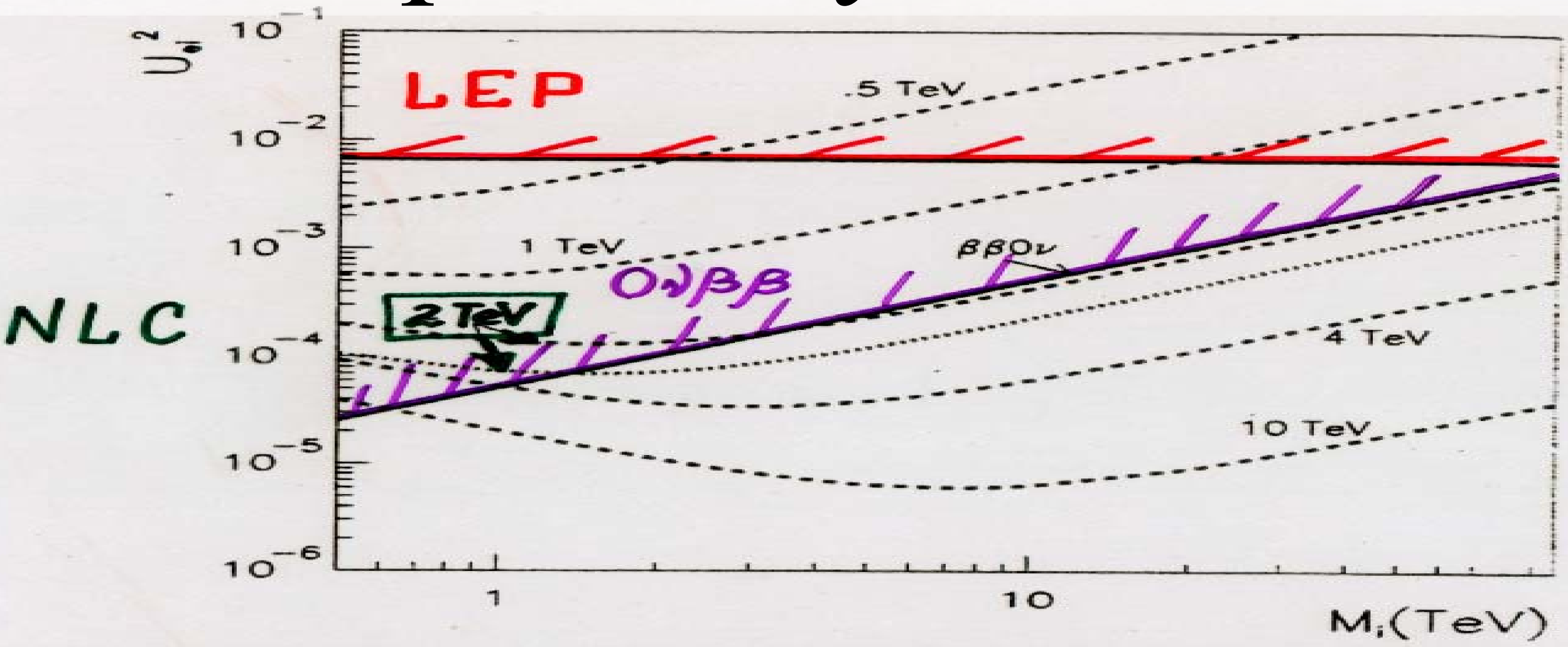



FIG. 2. Discovery limit for $e^-e^- \to W^-W^-$ at the NLC as a function of $M_i$ and $(U_{ei})^2$ for $\sqrt{s} = 500$ GeV, 1 TeV, 2 TeV, 4 TeV, and 10 TeV (dashed lines). We assume unpolarized $e^-$ beams and a luminosity of $80[\sqrt{s}/(1\ \text{TeV})]^2\ \text{fb}^{-1}$. For $\sqrt{s} = 2$ TeV, the limit assuming polarized $e^-$ beams is also shown (dotted line). In all cases, the parameter space above the line corresponds to observable events. We also superimpose the experimental limit from $\beta\beta_{0\nu}$ (diagonal solid line), as well as the limit on $(U_{ei})^2$ (horizontal solid line). Here, the parameter space above the line is ruled out.

Belanger et al., Phys. Rev. D 53 (1996) 6292

## Sneutrino mass, and 0νββ in R_p - conserving SUSY

*Hirsch, HVKK, Kovalenko, PRD 57 (1997) 1947*
***Sneutrino oscillations and 0νββ decay PLB 403 (1997) 291***

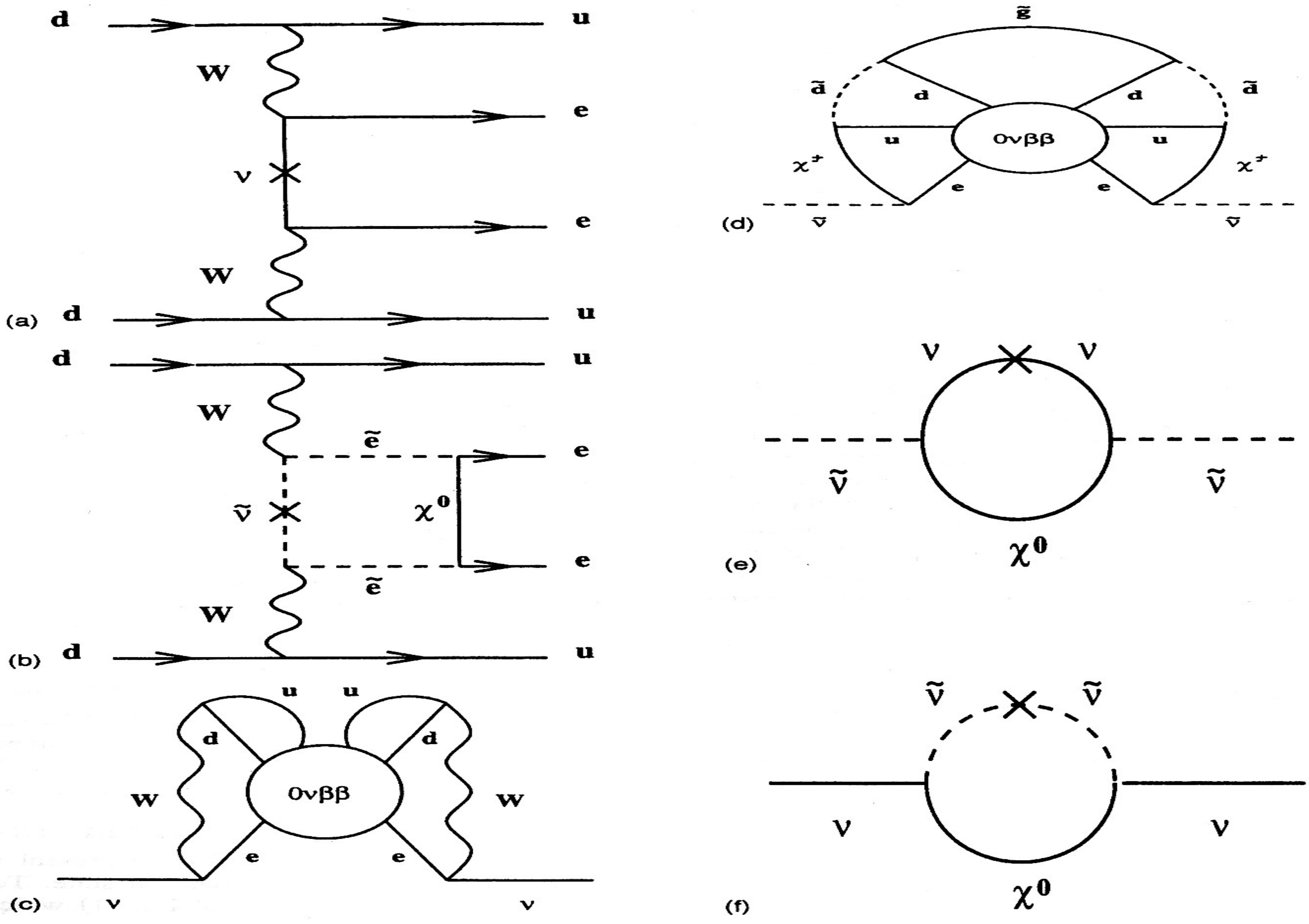
**Hirsch – KK - Kovalenko theorem**
(extension of Schechter - Valle theorem to SUSY):

' The **ν**-mass, the (B_L) violating mass of the sneutrino ( $\tilde{\nu}$ ),
and the **0νββ** amplitude are intimately related,
such that if one of them is non-zero, the other two vanish as well.

**Splitting of the sneutrino mass spectrum into two states separated by $2|\tilde{m}^2_M|$.**

**0νββ Decay Determines $\tilde{m}_M$ !!!**

# R-Parity Conserving SUSY and Sneutrino Mass



## Self - consistent form of neutrino and sneutrino mass terms:

$$\mathcal{L}^{\nu\tilde{\nu}}_{mass} = -\frac{1}{2}(m^{\nu}_{M}\,\bar{\nu}_{C}\,\nu + h.c.) - \frac{1}{2}(\tilde{m}^{2}_{M}\,\tilde{\nu}_{L}\,\tilde{\nu}_{L} + h.c.) - \tilde{m}^{2}_{D}\,\tilde{\nu}_{L}{}^{*}\tilde{\nu}_{L}$$

where $\nu = \nu^{C}$ Majorana field.

First term: Majorana mass term of neutrino.

Second term: 'Majorana' - like mass of sneutrino.

Third term: 'Dirac' - like sneutrino mass term.

The first two terms violate (B-L) symmetry, the third respects it.

$0\nu\beta\beta$ amplitude within MSSM:

$$R_{0\nu\beta\beta} \sim \; m^{\nu}_{M} = M^{(1)} + \; \tilde{m}^{2}_{M}\, M^{(2)}$$

$M^{(i)}$ matrix elements. 14 dominant diagrams prop. to $\tilde{m}^{2}_{M}$ (see Fig.4)

## Half - life due to sneutrino exchange:

$$[\, T^{0\nu\beta\beta}_{1/2}(0^{+} \longrightarrow 0^{+})]^{-1} = G_{01}\;\frac{4m_{p}^{2}}{G_{F}^{4}}\left|\frac{\eta^{SUSY}}{m^{5}_{SUSY}}\,M^{SUSY}\right|^{2}$$

HEIDELBERG - MOSCOW exp. $\Rightarrow$

$$\eta_{SUSY} < 1.0 \times 10^{-8}\left(\frac{m_{SUSY}}{100GeV}\right)^{5}$$

($m_{SUSY}$ = effective SUSY breaking scale)

$\Rightarrow$

$$\tilde{m}_{M(e)} \leq 2 \;\left(\frac{m_{SUSY}}{100GeV}\right)^{3/2} GeV \;,\; \chi \sim \tilde{B}$$

$$\leq 11 \;\left(\frac{m_{SUSY}}{100GeV}\right)^{7/2} GeV \;,\; \chi \sim \tilde{H}$$

actual value of $\tilde{m}_{M}$ between these limiting cases for composition of lightest neutralino $\chi$.

Hirsch, K.-K., Kovalenko PL403 (1997) 291

$$\eta^{SUSY} = (\eta_{\tilde{g}\tilde{d}} + \eta_{\tilde{g}\tilde{u}}) + g^2\Big(\frac{m_{SUSY}}{M_W}\Big)^4(\eta^{(1)}_{WW} + \eta^{(2)}_{WW} + \eta^{(3)}_{WW}). \tag{44}$$

$$\eta_{\tilde{g}\tilde{d}} = \frac{g_s^2 g^4}{72}\Big(\frac{\tilde{m}_M}{m_{SUSY}}\Big)^2 \sum_{i,j} U_{i1}V_{i1}U_{j1}V_{j1}\Big(\frac{m_{\chi_j^\pm}}{m_{SUSY}}\Big)\Big(\frac{m_{\chi_i^\pm}}{m_{SUSY}}\Big) \times \tag{31}$$

$$\times \Big(\frac{m_{\tilde{g}}}{m_{SUSY}}\Big)\mathcal{G}(m_{\tilde{g}}, m_{\chi_j^\pm}, m_{\chi_i^\pm}),$$

$$\eta_{\tilde{g}\tilde{u}} = \frac{g_s^2 g^4}{72}\Big(\frac{\tilde{m}_M}{m_{SUSY}}\Big)^2 \sum_{i,j} V_{i1}^2 V_{j1}^2\Big(\frac{m_{\tilde{g}}}{m_{SUSY}}\Big)\mathcal{F}(m_{\tilde{g}}, m_{\chi_j^\pm}, m_{\chi_i^\pm}), \tag{32}$$

$$\eta^{(1)}_{WW} = \frac{g^4}{4}\Big(\frac{\tilde{m}_M}{m_{SUSY}}\Big)^2 \sum_{i,j,k} V_{k1}V_{j1} \times \tag{33}$$

$$\times \Big[\mathcal{O}^L_{ik}\mathcal{O}^L_{ij}\Big(\frac{m_{\chi_i}}{m_{SUSY}}\Big)\mathcal{J}(m_{\chi_i}, m_{\chi_j^\pm}, m_{\chi_k^\pm})$$

$$+ \mathcal{O}^R_{ik}\mathcal{O}^L_{ij}\Big(\frac{m_{\chi_k^\pm}}{m_{SUSY}}\Big)\mathcal{J}(m_{\chi_i}, m_{\chi_j^\pm}, m_{\chi_k^\pm})$$

$$+ \mathcal{O}^R_{ik}\mathcal{O}^R_{ij}\Big(\frac{m_{\chi_j^\pm}}{m_{SUSY}}\Big)\Big(\frac{m_{\chi_k^\pm}}{m_{SUSY}}\Big)\Big(\frac{m_{\chi_i}}{m_{SUSY}}\Big)\mathcal{I}(m_{\chi_i}, m_{\chi_j^\pm}, m_{\chi_k^\pm})\Big],$$

$$\eta^{(2)}_{WW} = \frac{g^4}{4}\Big(\frac{\tilde{m}_M}{m_{SUSY}}\Big)^2 \sum_{i,j} \mathcal{J}(m_{\tilde{e}}, m_{\chi_i}, m_{\chi_j^\pm})\epsilon_{L_i}(e)V_{j1} \times \tag{34}$$

$$\times \Big[\mathcal{O}^R_{ij}\Big(\frac{m_{\chi_j^\pm}}{m_{SUSY}}\Big) + \mathcal{O}^L_{ij}\Big(\frac{m_{\chi_i}}{m_{SUSY}}\Big)\Big],$$

$$\eta^{(3)}_{WW} = \frac{g^4}{4}\Big(\frac{\tilde{m}_M}{m_{SUSY}}\Big)^2 \sum_{i} \mathcal{J}(m_{\chi_i}, m_{\tilde{e}}, m_{\tilde{e}})\epsilon^2_{L_i}(e)\Big(\frac{m_{\chi_i}}{m_{SUSY}}\Big) \tag{35}$$

## $\tilde{m}_M$ and future accelerators:

$\tilde{m}_M$ describes a splitting in the sneutrino mass spectrum:

$$\mathcal{L}^{\tilde{\nu}}_{mass} = -\frac{1}{2}(\tilde{m}^2_M \, \tilde{\nu}_L \, \tilde{\nu}_L + \text{h.c.}) - \tilde{m}^2 \, \tilde{\nu}_L{}^* \nu_L$$

$$= -\frac{1}{2}\tilde{m}_1^2 \, \tilde{\nu}_1^2 - \frac{1}{2} \, \tilde{m}\,{}_2^2 \tilde{\nu}_2^2 \qquad \text{mit } \tilde{m}^2_{1/2} = \tilde{m}^2_D \pm |\, \tilde{m}_M \,|^2$$

Complex sneutrino field split into two real fields separated in mass by $\tilde{m}_1^2 - \tilde{m}_2^2 = 2\,|\tilde{m}^2_M\,|$

⇛ mixing in $\tilde{\nu} - \tilde{\nu}^C$ system and $\tilde{\nu} - \tilde{\nu}^C$ oscillations.

⇛ new processes at future colliders — if neutrino Majorana particle.

Hirsch, K.-K., Kovalenko PLB 403 (1997) 191

(Only visible — if neutrino masses not degenerate and in eV range)

**Examples:**

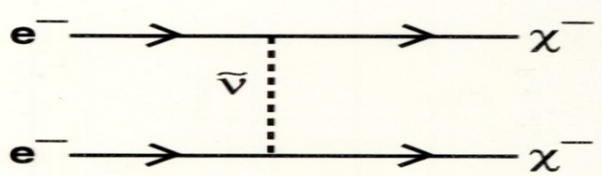
① For Majorana sneutrinos , L-violating processes should occur:

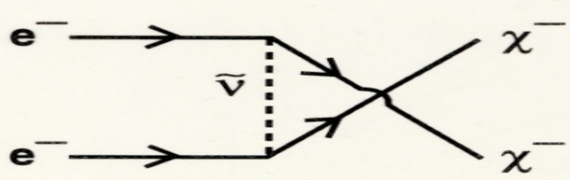
$e^-e^- \rightarrow \chi^-\chi^-$ or

$\mu^-\mu^- \rightarrow \chi^-\chi^-$

└ chargino

( SUSY analog to inverse neutrinoless $\beta\beta$ decay)



## What can we learn in FUTURE from more sensitive experiments (if any):

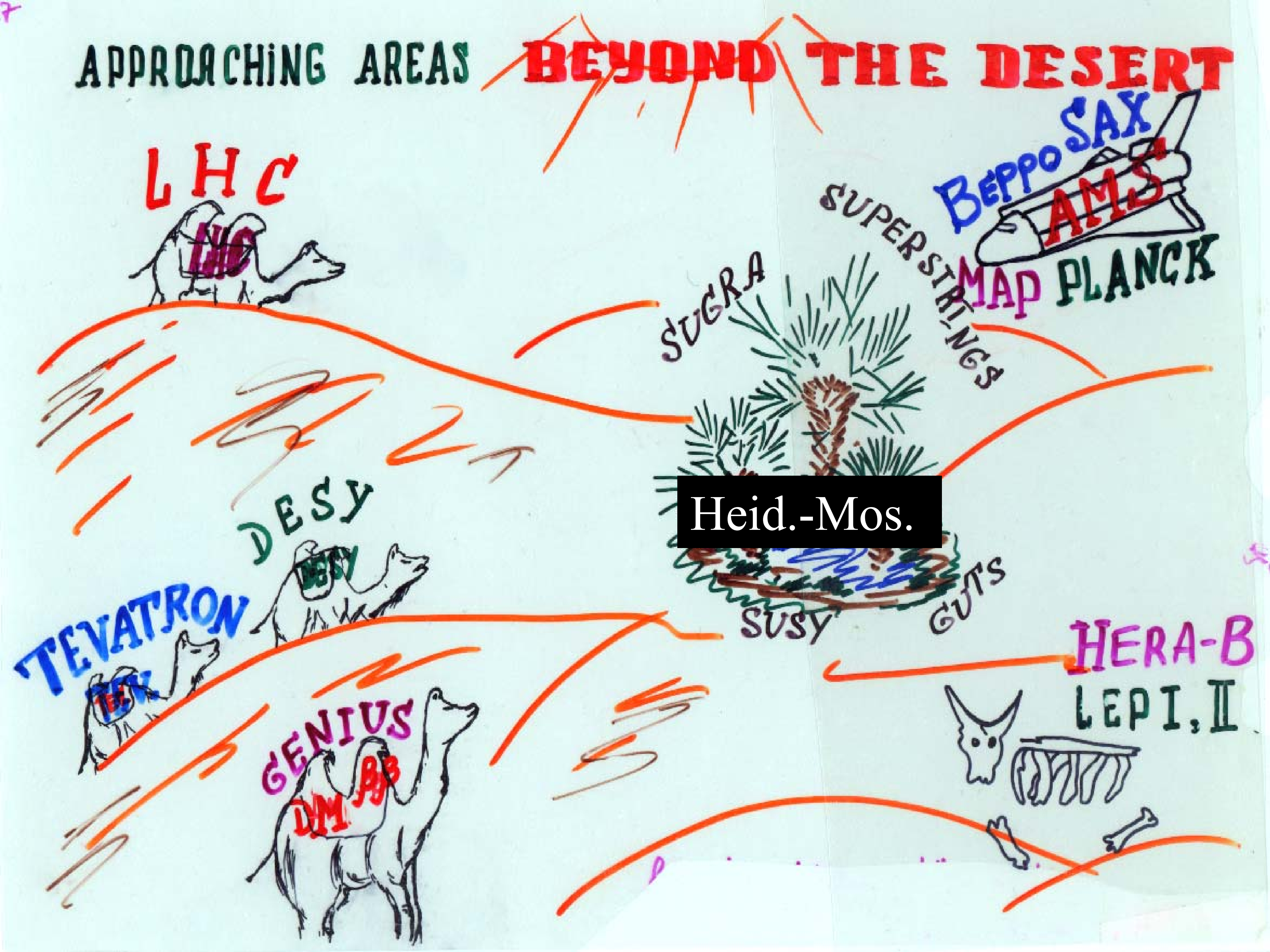
- *independent* ***confirmation*** *of HEIDELBERG result*

**BUT:**

- ***NO MORE*** ***about neutrino properties (mass, ...)***
  ***(because of Matrix Elements)***

- ***NO MORE*** ***about Other Beyond Standard Model Physics: from Half-Life***

- ***Only with HUGE Experiments, out of reach - like GENIUS - 10 tons, or NEMO - like observing tracks (not EXO) -***
  ***possibly***
  ***information about SUSY contribution to*** $0\nu\beta\beta$
  ***(from branchings and angular correlation)***


APPROACHING AREAS BEYOND THE DESERT
LHC
BeppoSAX
AMS
SUPERSTRINGS
SUGRA
MAP PLANCK
DESY
Heid.-Mos.
TEVATRON
SUSY
GUTS
HERA-B
LEP I, II
GENIUS

For other

*Beyond SM Physics from* $0\nu\beta\beta$

I refer to our recent PAPERS and our BOOK

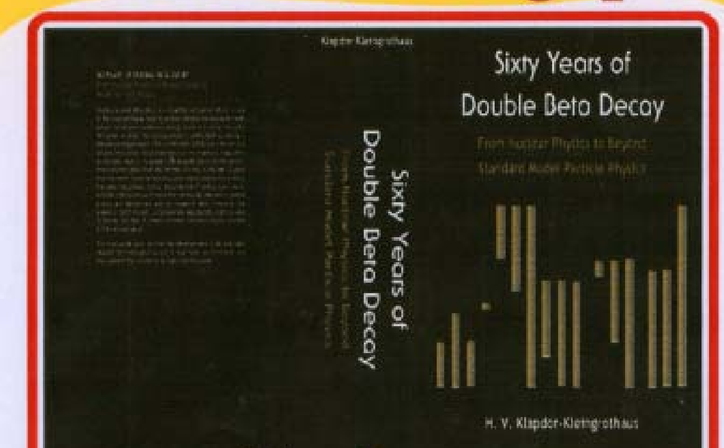
**60 Years of Double Beta Decay**

**- From Nuclear Physics to**

**Beyond Standard Model Particle Physics -**

**H.V. Klapdor-Kleingrothaus**

**World Scientific, Singapore, 2001**



# What did we learn from $^{76}$Ge 0νββ in Gran Sasso 1990-2003

**-(total) Lepton Number is violated**

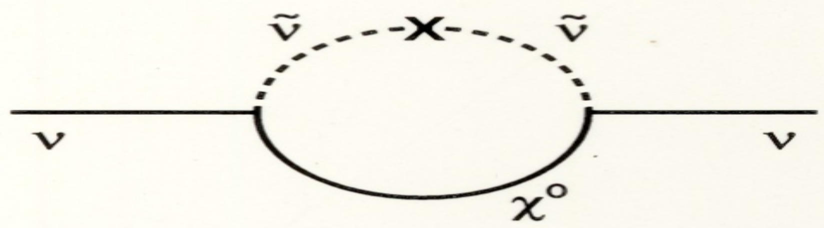
**-Neutrino is Majorana Particle**

**-Neutrinos are degenerate**

**-Other Beyond SM Physics**

**Reached essentially, what we wanted to learn from our large GENIUS project, proposed in 1997, namely observation of 0νββ decay**

Another limit on $\tilde{m}_M$ from exp. $\nu$ mass limits
(since sneutrino contributes to Majorana neutrino mass $m_M^\nu$ at the one-loop level prop. to $\tilde{m}_M^2$ )




Taking into account all four neutralino states ( numerical scan of SUSY parameter space ) $\Rightarrow$ under some assumptions ( e.g. $\tilde{m}_D = m_{SUSY}$ etc.)

$$\tilde{m}_{M(i)} \leq 60\,(125) \left(\frac{m^{exp.}_{\nu(i)}}{1\ \mathrm{eV}}\right)^{1/2} \mathrm{MeV}$$

60: average; (125): upper bound

Hirsch, Klapdor-Kleingrothaus, Kovalenko, Phys.Rev. D57 (1998) 1947
Hirsch, Klapdor-Kleingrothaus, Kolb, Kovalenko, Phys.Rev. D57 (1998) 2020

From $\beta\beta$ decay (0.5 eV) $\Rightarrow$ $\tilde{m}_{M(e)} \lesssim 22$ MeV

From $\nu_\mu$ and $\nu_\tau$ mass limits $\Rightarrow$

$\tilde{m}_{M(\mu)} \sim 0$ (10 GeV)
$\tilde{m}_{M(\tau)} \sim 0$ (200 GeV)

The (less sharp) constraint directly from $\beta\beta$ decay independent on assumptions about neutralino masses and mixings.

M. Hirsch, H.V. K.-K., S. Kovalenko, Phys.Rev. D57 (1998) 1947

# Conclusion at this point:

assuming, that NO
unknown gamma - line

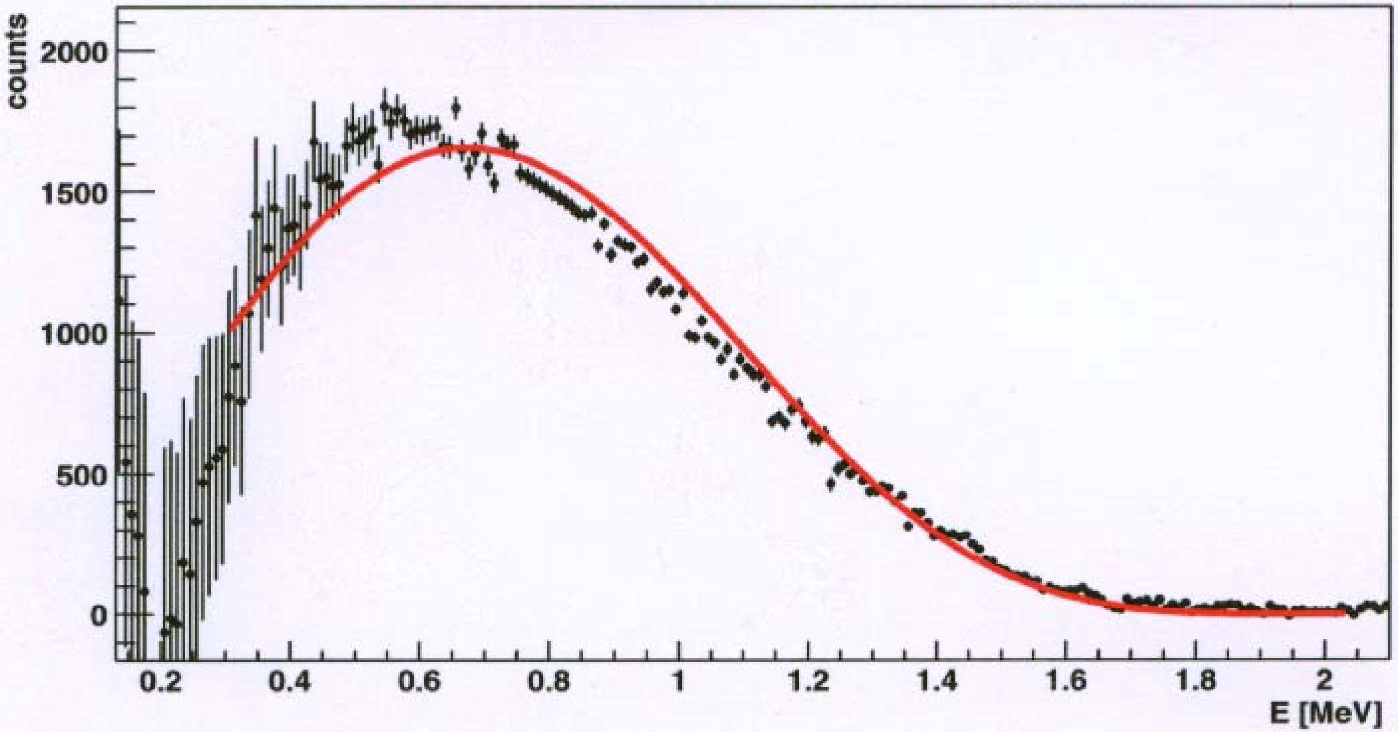
(As confirmed by K.Ya. Gromov et al. Part. Nucl. Lett 3 (2006) 30)

we have a 4.2σ ββ- signal

**And more than 6σ from the SSE data analysis**

*(see Ch. Doerr and H.V. Klapdor-Kleingrothaus, NIM A 513 (2003) 596-621)*

## *Sum Detectors ANG 1,2,3, and 5*

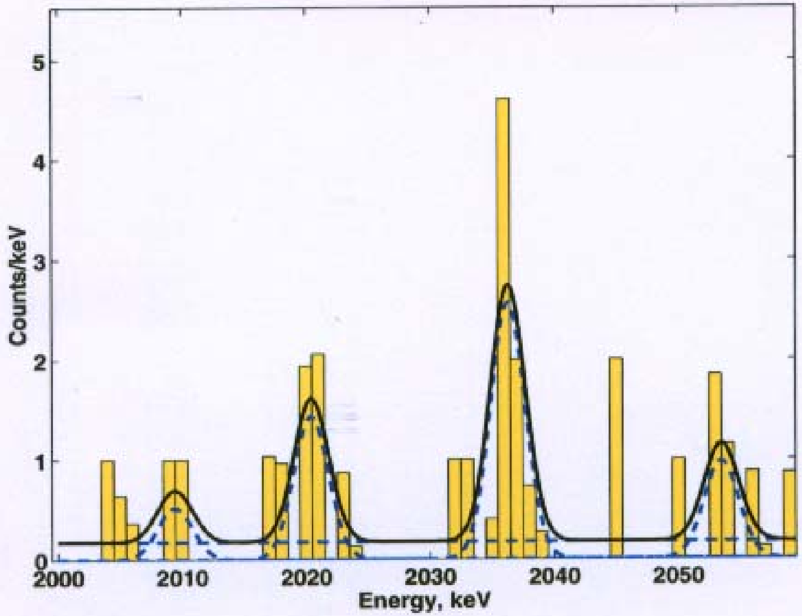


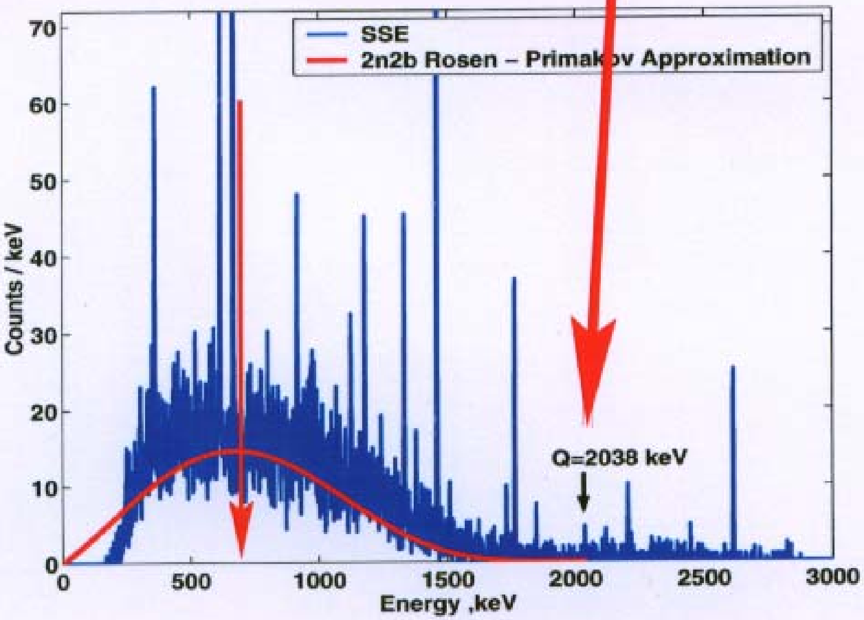

$$T^{2\nu}_{1/2} = (1.74 \pm 0.01(\text{stat}) \pm^{0.04}_{0.04} (\text{norm}) \pm^{0.14}_{0.12} (\text{syst.})) \times 10^{21}\ \text{y}$$

$$= (1.74 \pm^{0.18}_{0.16}) \times 10^{21}\ \text{y}$$

## The Single Site Selected Spectrum of the $^{76}$Ge detectors Nr. 2,3,4,5

# HEIDELBERG-MOSCOW, 2004




**Lesson I**

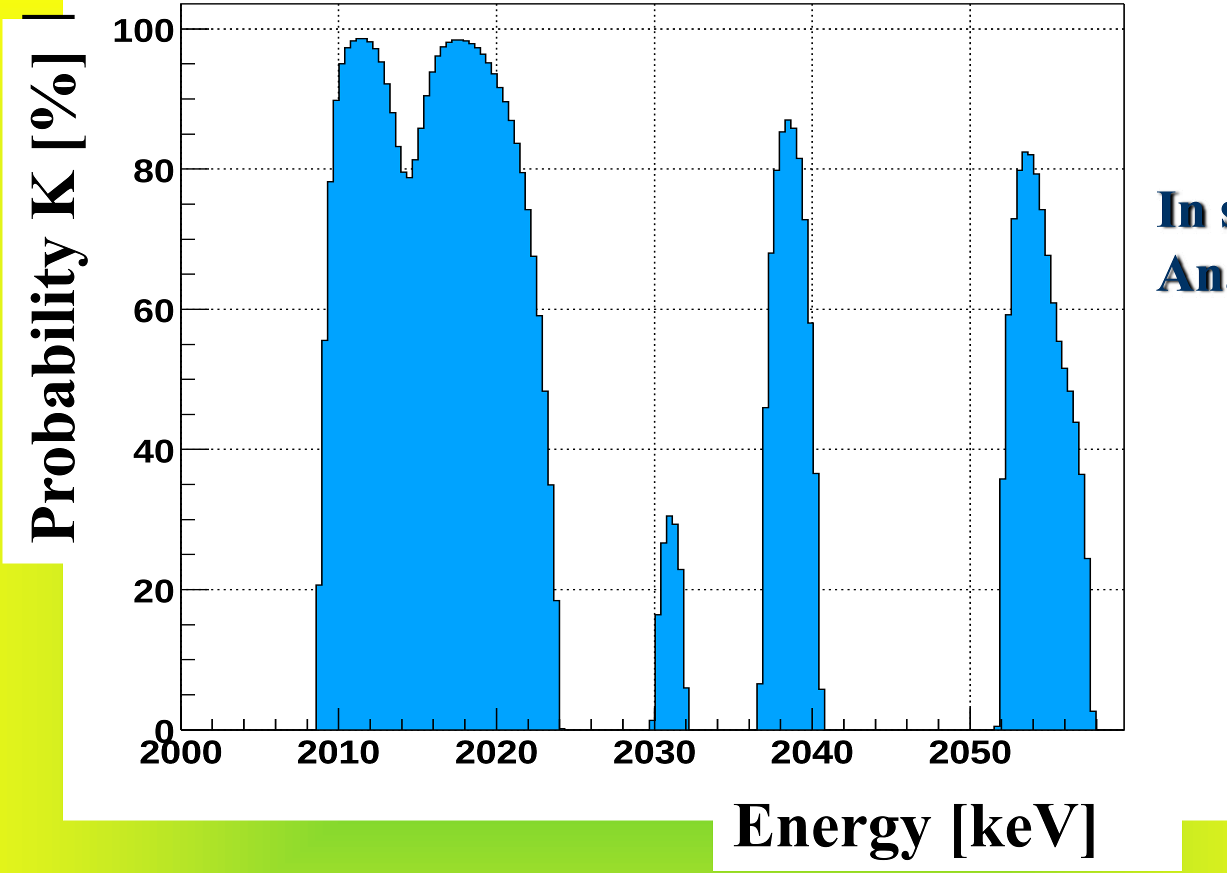
**Energy Range 100 - 3000 keV**

H.V. Klapdor-Kleingrothaus et al.

Phys. Lett. B 586 (2004) 198-212

Nucl. Instr. Meth. A 522 (2004) 371 - 406

**The Bi lines at 2010.7, 2016.7, 2021.8 and 2052.9 keV are clearly seen !**




**In same type of Analysis in our case**

**Scan for lines** in the full spectrum taken from **1995 to 2003 with detectors Nr. 1,2,3,4,5** with Max. L. M method. **The Bi lines at 2010.7, 2016.7, 2021.8 and 2052.9 keV are clearly seen,** and in addition a signal at ~2039 keV. ( See HVKK et al., NIM A 522 (2004) 371-406)

Meeting of Royal Astron. Soc. Friday 1935, "Observatory", 1935, v.58, p.37-38

**Dr. Chandrasekhar: "...An important result of the work is** that the life of a star of small mass must be essentially different from that of a star of large mass. ..."

Sir Arthur Eddington: " ... Dr. Chandrasekhar has been referring **to degeneracy. ...** the point of my paper is that therte is no such thing as relativistig degeneracy! ... I left driven to the conclusion that this was almost a reductio ad absurdum of the relativistic degen. formula. Various accidents may intervene to save the star, but ***I want more protection than that. I think there should be a Law of nature to prevent a star from behaving in this absurd way!"***

---

"EDDINGTON" (The most distinquished astrophysicist of his time)

S. Chandrasekhar (University of Chicago) Cambridge Univ. Press., p.50-53

"... But he (A.Eddington) was unwilling to accept a conclusion that he *so presciently drew;* and he CONVINCED HIMSELF that 'there should be a law of nature to prevent a star from behaving in this absurd way!"

"..For my part I shall only say that I find it hard to understand why Eddington..... ..should found the conclusions that black holes could form during the natural course of the evolution of the stars, *so unacceptable. ...*"

# Alexander Newski said:

Не в силе Бог - а в правде.

Nicht in Kraft ist Gott – sondern in der Wahrheit.

Not in force is God – but in truth.

The probability that the four Bi lines, and the line at $Q_{\beta\beta}$, are produced by fluctuations, is $< 10^{-20}$

## *Independent analysis of our spectra by nuclear spectroscopists from Russia:*

**K.Ya. Gromov et al., J. Part. Nucl. Lett. 3 (2006) 30**

- *decay of nuclides from the families $^{238}$U (4n +2) or $^{232}$Th (4n)*
- *decay of antropogenic nuclei*
- *decay of nuclei, which were produced in reactions (n, γ ) and ($\mu^-$ , γ )*
- *direct production in reactions (n, γ ) and ($\mu^-$ , γ )*

**1** ***570 keV and 1064 keV*** could come from $^{214}$Pb (T =26.8 min) and $^{214}$Bi (19.7 min)

Not from decay of $^{207}$Bi (from $^{211}$At, if $^{209}$Bi (α , 2n) $^{211}$At(α ) $^{207}$Bi, if E ~ 20 MeV)

Most probably decay of $^{206}$Pb (n, γ ) $^{207}$Pb (in Pb shield).

**2** ***Intensities of lines γ - 609.3 keV - $^{214}$Bi and γ - 911.2 keV from $^{228}$Ac***

$^{214}$Bi Was done estimation of lines 2010 keV, 2021 keV, 2053 kev and 2029 keV

Result: γ - lines 2010 keV, 2021 keV and 2053 keV from $^{214}$Bi( $\beta^-$ ) $^{214}$Po ( γ) !!

Transition 2021 and 2053 keV from decay of $^{214}$Bi - transition to g.s. of $^{214}$Po

Observation of 2017 keV - summing impulses from γ - 1408.0 kev and 609.3 keV from the levels $0^+$, 2017.3 keV $^{214}$Po.

Gamma - 2017.3 keV does not exist (E0-transition).

Gamma - 2029 keV is decay of $^{228}$Ac (small intensity expected).

2028.2 keV m.b. $^{28}$Si (n, γ) $^{28}$Si , has level 2028.2 keV ($5/2^+$ )

**Lesson I d)**

**3** ***2039 keV:***

$^{234}$Pa, observed γ -transition with $E_\gamma$ = 2041.2 keV and I = 1.1. $10^{-6}$ decays

On the basis of intensities of γ -line 1001 keV --> no influence to 2039 keV peak!!

**4** ***γ– 2066:*** 2065.6 keV $^{57}$Fe (n, γ) $^{58}$Fe, then in $^{58}$Fe 2065.6 keV --> from 2876 keV ($2^+$ ) to 810 keV ($2^+$ )

**5** ***γ– 2073:***

2071.6 keV $^{86}$Kr (n, γ) $^{87}$Kr. Decay: $^{87}$Br --> $^{87}$Kr 2071.6 keV ($1/2^+$ )

2071.1 keV $^{73}$Ge (n, γ) $^{74}$Ge. Transition 2074.1 keV exists in decay of $^{74}$Ga ---> $^{74}$Ge

| Significance (kg y) | Detectors | $T^{0\nu}_{1/2}$ y (1σ error) | < m > eV (1σ error) | Conf. level σ |
|---|---|---|---|---|
| *Period 1990 - 2003* | | | | |
| 71.7 | 1, 2, 3, 4, 5 | $(1.19 ^{+0.37}_{-0.23}) \times 10^{25}$ | $0.44 ^{+0.05}_{-0.06}$ | 4.2 |
| *Period 1990 - 2000* | | | | |
| 50.57 | 1, 2, 3, 4, 5 | $(1.24 ^{+0.59}_{-0.30}) \times 10^{25}$ | $0.43 ^{+0.07}_{-0.08}$ | 3.1 |
| *Period 1995 - 2003* | | | | |
| 56.66 | 1, 2, 3, 4, 5 | $(1.17 ^{+0.38}_{-0.23}) \times 10^{25}$ | $0.45 ^{+0.06}_{-0.06}$ | 4.1 |
| 51.39 | 2, 3, 4, 5 | $(1.25 ^{+0.48}_{-0.27}) \times 10^{25}$ | $0.43 ^{+0.06}_{-0.07}$ | 3.6 |
| 42.69 | 2, 3, 5 | $(1.49 ^{+0.79}_{-0.38}) \times 10^{25}$ | $0.40 ^{+0.06}_{-0.08}$ | 2.9 |
| 51.39 | 2, 3, 5 SSE | $(1.98 ^{+0.85}_{-0.46}) \times 10^{25}$ | $0.34 ^{+0.05}_{-0.06}$ | 3.3 |
| 28.21 | 1, 2, 4 | $(1.22 ^{+0.84}_{-0.35}) \times 10^{25}$ | $0.44 ^{+0.08}_{-0.10}$ | 2.5 |
| 28.35 | 3, 5 | $(1.03 ^{+0.63}_{-0.28}) \times 10^{25}$ | $0.48 ^{+0.08}_{-0.10}$ | 2.6 |
| *Period 1995 - 09.1999* | | | | |
| 26.59 | 1, 2, 3, 4, 5 | $(0.84 ^{+0.38}_{-0.2}) \times 10^{25}$ | $0.53 ^{+0.08}_{-0.09}$ | 3.2 |
| *Period 09.1999 - 05.2003* | | | | |
| 30.0 | 1, 2, 3, 4, 5 | $(1.12 ^{+0.45}_{-0.27}) \times 10^{25}$ | $0.46 ^{+0.06}_{-0.07}$ | 3.5 |

**see H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198-212**

***Half-Life for the Neutrinoless Decay Mode and deduced effective Neutrino Mass from the HEIDELBERG-MOSCOW experiment.***

# Often Discussed ‘Confirmation Experiments’:

- **NEMO III (ionisation chamber)**

**Present limits (NEUTRINO 2004):**

$T^{0\nu}_{1/2} > 1.0 \cdot 10^{23}$ years, (90% c.l.) for $^{82}Se$ (1.00 kg y measurement)

$T^{0\nu}_{1/2} > 4.6 \cdot 10^{23}$ years, (90% c.l.) for $^{100}Mo$ (7.47 kg y measurement)

***i.e 1.5 σ level !!!!***

Phys. Rev Lett. 95 (2005) 182302

(389 days)

**Sensitivities required for check of HEIDELBERG-MOSCOW result:**

**FACTOR 20 more**

(Matrix element of Staudt, Muto, Klapdor, Eur.Phys. Lett. 13(1990)31)

$T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}$ years, (90% c.l.) for $^{82}Se$

$T^{0\nu}_{1/2} > 8.1 \cdot 10^{24}$ years, (90% c.l.) for $^{100}Mo$

***Factor 400 longer measuring times required, i.e. > 400 years of PERMANENT data taking.***

# CUORICINO/CUORE (bolometer)

**Principle problem:** **Cannot distinguish β from γ events**

**Problem of background:** **Cannot see even 2νββ decay known half-life of only $(2.7 \pm 0.1) \cdot 10^{21}$ years,**

(Measurement of T. Bernatowics et al., PRC 47 (1993) 806)

***Present limit :*** **$T^{0\nu}_{1/2} > 1.8 \cdot 10^{24}$ years, *(90% c.l., i.e 1.5 σ)* for $^{130}Te$ 10.8 kg y** (Neutrino Telescopes Int. Conf. Febr. 2005)

**Required: $2.5 \cdot 10^{24}$ years Can be reached in 5 months continuous running … realistically > 1 y on 90% c.l.**

If matrix element overestimated by (only) factor 2: →

Required: **Sensitivity of $1 \cdot 10^{25}$ year** →

→ **Factor 16 longer measurement (~ 30 years)**

***to get statement on 90 % c.l.***

## Conclusion:

**CUORICINO can - with <u>*good luck*</u> confirm HEIDELBERG-MOSCOW *within a few years* - but <u>never</u> disprove it !!!**

**CUORE: → 16 times larger mass**

**Required: ~ 1y of continuous measurement for 90 % c.l. (1.5 σ ) statement.**

***MANY years for statement on 4-5 σ level.***

# •EXO (liquid Xenon)

Have 200 kg of enriched $^{136}Xe$

**Problems:**

- **no tracks visible**, i.e. ***not*** differentiation **between** $\beta$ **and** $\gamma$

- **Resolution ≈ 100 keV**

- **background - plan first experiment with background on level of HEIDELBERG-MOSCOW**

- **Laser – identification of daughter nucleus not (yet) working**

- **GERDA** (‘copied’ **GENIUS** proposal 1997 by H.V. Klapdor-Kleingrothaus)

## Germanium in Liquid Nitrogen

**In principle,** *according to Monte Carlo simulations, sensitivity could go down to effective neutrino mass of several meV*

(HV.K-K, Int. J. Mod. Phys.A13(1998)3953, HVK-K et al., J. Phys.G24 (1998) 483)

**No other complete MC simulation since then.**

**Problems:** - ***No own long-term*** **experience with naked detectors in liquid nitrogen**

- **Start on level of few tens kilograms similar to HM (→ similar measuring times, ~ 10 y)**

With the HEIDELBERG-MOSCOW experiment,

*the era of the small smart* ***experiments is over.***

New approaches and considerably enlarged experiments

will be required in future to fix the

$0\nu\beta\beta$ half life of $^{76}Ge$ with higher accuracy.

**This will, however, because**

**of the uncertainties in the nuclear matrix elements,**

**which probably hardly**

***can be reduced to less than 50 %,***

**only marginally reduce the precision of the deduced neutrino mass.**

**(See H.V. Klapdor-Kleingrothaus et al., Gran Sasso Reports 2003)**
**hep-ph/0404062**

# Conclusions:

1. There is now a > 6 σ signal of $0\nu\beta\beta$ decay.

2. Presently running or planned experiments are not sensitive enough to check the HEIDELBERG-MOSCOW result.

3. New $\beta^-\beta^-$ experiments in principle will not give more precision in deduced particle physics parameters ($m_\nu$, η, λ …) – only in half-life (error from matrix element always will dominate)

4. Present and presently planned $\beta^-\beta^-$ experiments give ***no information on*** effective ***neutrino mass*** (***only*** under assumptions on right-handed currents, SUSY etc.)

5. ***Only*** visible way to solve this, is ***additional*** experiment with $^{124}Xe$ $\beta^+$ EC decay on $10^{27}$ y sensitivity level.

See H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, I.V. Titkova,

Phys. Lett. B 632 (2006) 623-631; Phys. Rev. D 73 (2006) 013010

# Alexander Newski said:

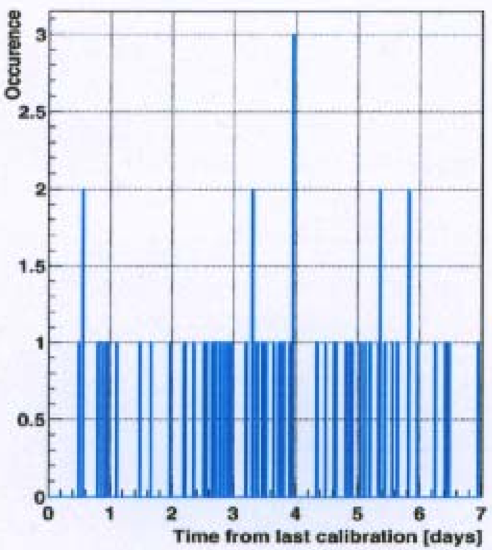
Не в силе Бог – а в правде.

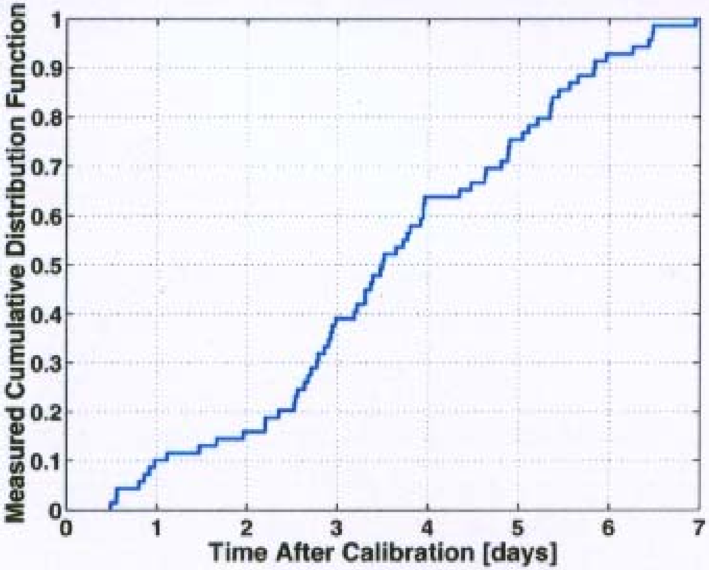
Nicht in Kraft ist Gott – sondern in der Wahrheit.

Not in force is God – but in truth.

# HEIDELBERG-MOSCOW Data
# Period: August 1995 - May 2003

*H.V. Klapdor-Kleingrothaus et al., NIM A (2004),*
~~in Press~~ NIM A 522 (2004) 371-406



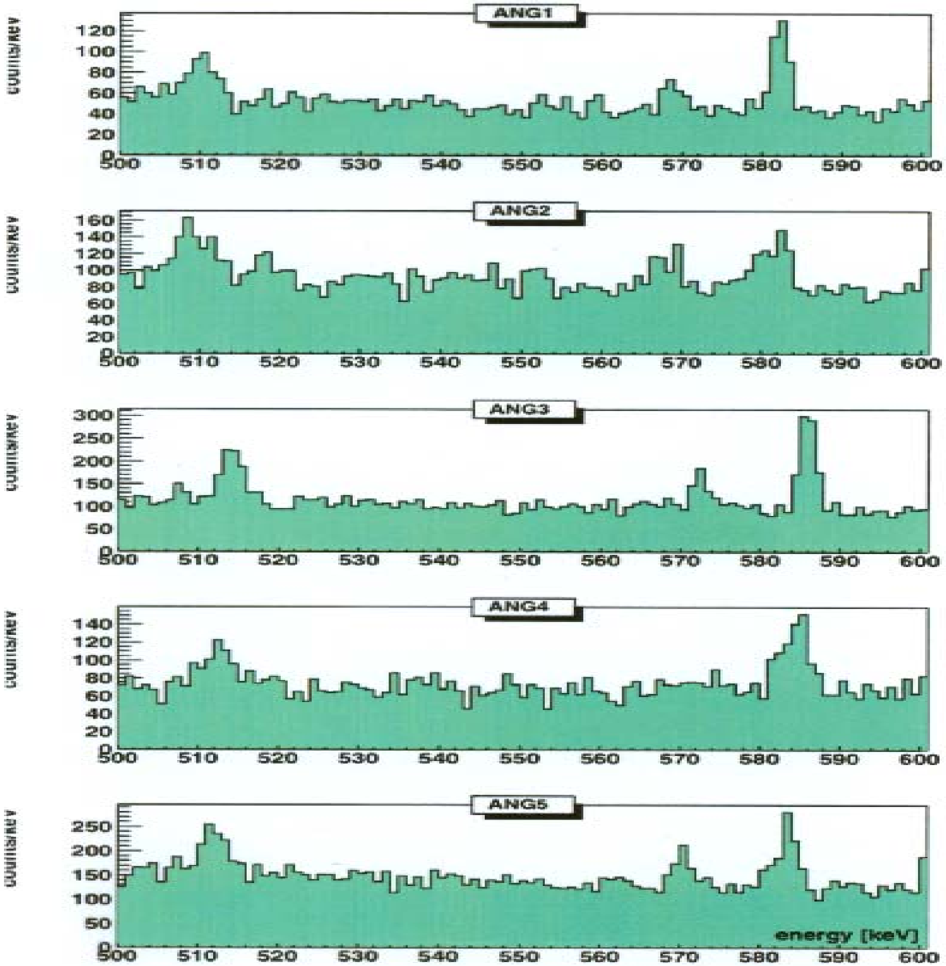



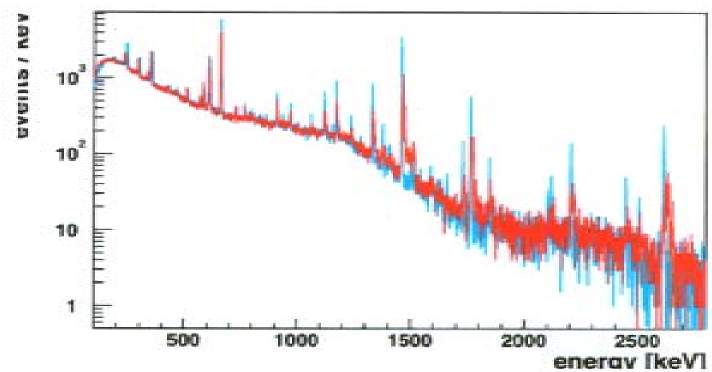

**Left: arrival time for all events the interval 2035.5 - 2042.5 keV as function of time after the calibrations for the period 1995 - 2003.**

**Right: the corresponding cumulative distribution analyzed by the Kolmogorov-Smirnov test.**

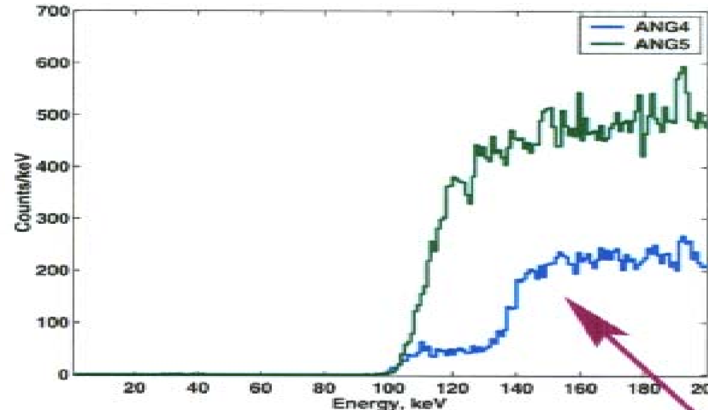
# HEIDELBERG-MOSCOW Data
# Period: August 1995 - May 2003
## *Reliability of Data Acquisition and Data*

**Spectra for all five detectors in energy intervall 500 - 600\,keV.**




**Low- and High-energy measurements of the full spectrum.**




**Threshold ranges for detectors 4 and 5**

*H.V. Klapdor-Kleingrothaus et al., NIM A (2004),* ~~in Press~~ A 522 (2004) 371-406

- Kurchatov group made for *first time* an analysis of data, until 2001 (hep-ex/0309016)

- They reproduce *global* structure of spectrum - thus get the correct half-life for $2\nu$ decay (1.7 x $10^{21}$ years),

- They "see" socalled 'subthreshold events', and artificial lines e.g. at ~ 550 keV.

- In our analysis these effects are not present.

***Conclusion:***

- ***Included corrupted data into the analysis.***

## Most important block of data of the HEIDELBERG-MOSCOW experiment, 56.67 kg y 1995 - 2003

**In 1995:**

- installation of detectors 4,5
- neutron shield (boron-polyethylene, 10 cm)
- active anticoincidence shield against muons
- completely new electronics - 250MHz flash ADC's for digital measurement of pulse shapes for 4 largest detectors (8 bit)
  - energy signals by 13 bit ADC's

Data acquisition on VME basis

Setup not opened between 1995 and 30. November 2003

↓

**4.1 $\sigma$ signal (56.67 kg y)**

Table 1

## Technical parameters

of the five enriched $^{76}Ge$ detectors.

| Detector Number | Total Mass [kg] | Active Mass [kg] | Enrichment in $^{76}Ge$ [%] | PSA |
|---|---|---|---|---|
| No. 1 | 0.980 | 0.920 | $85.9 \pm 1.3$ | no |
| No. 2 | 2.906 | 2.758 | $86.6 \pm 2.5$ | yes |
| No. 3 | 2.446 | 2.324 | $88.3 \pm 2.6$ | yes |
| No. 4 | 2.400 | 2.295 | $86.3 \pm 1.3$ | yes |
| No. 5 | 2.781 | 2.666 | $85.6 \pm 1.3$ | yes |

**Lesson I a, b)**

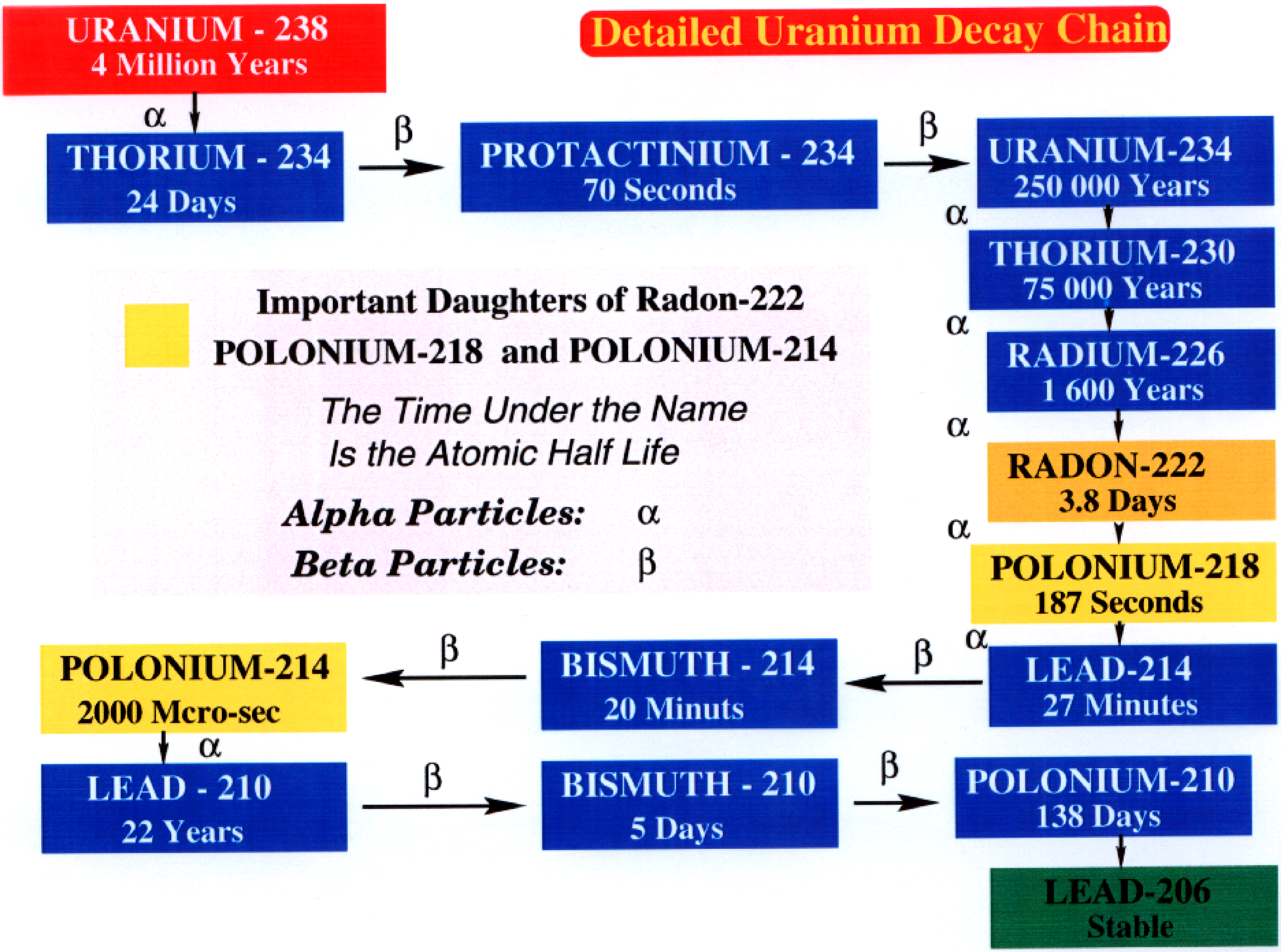
Table 2

## The data acquisition of the HEIDELBERG-MOSCOW experiment during 1995 - 2003.

*) events show up partly in $\mu$ *and* Ge-Ge coincidence, therefore *in total* 25 470 events.

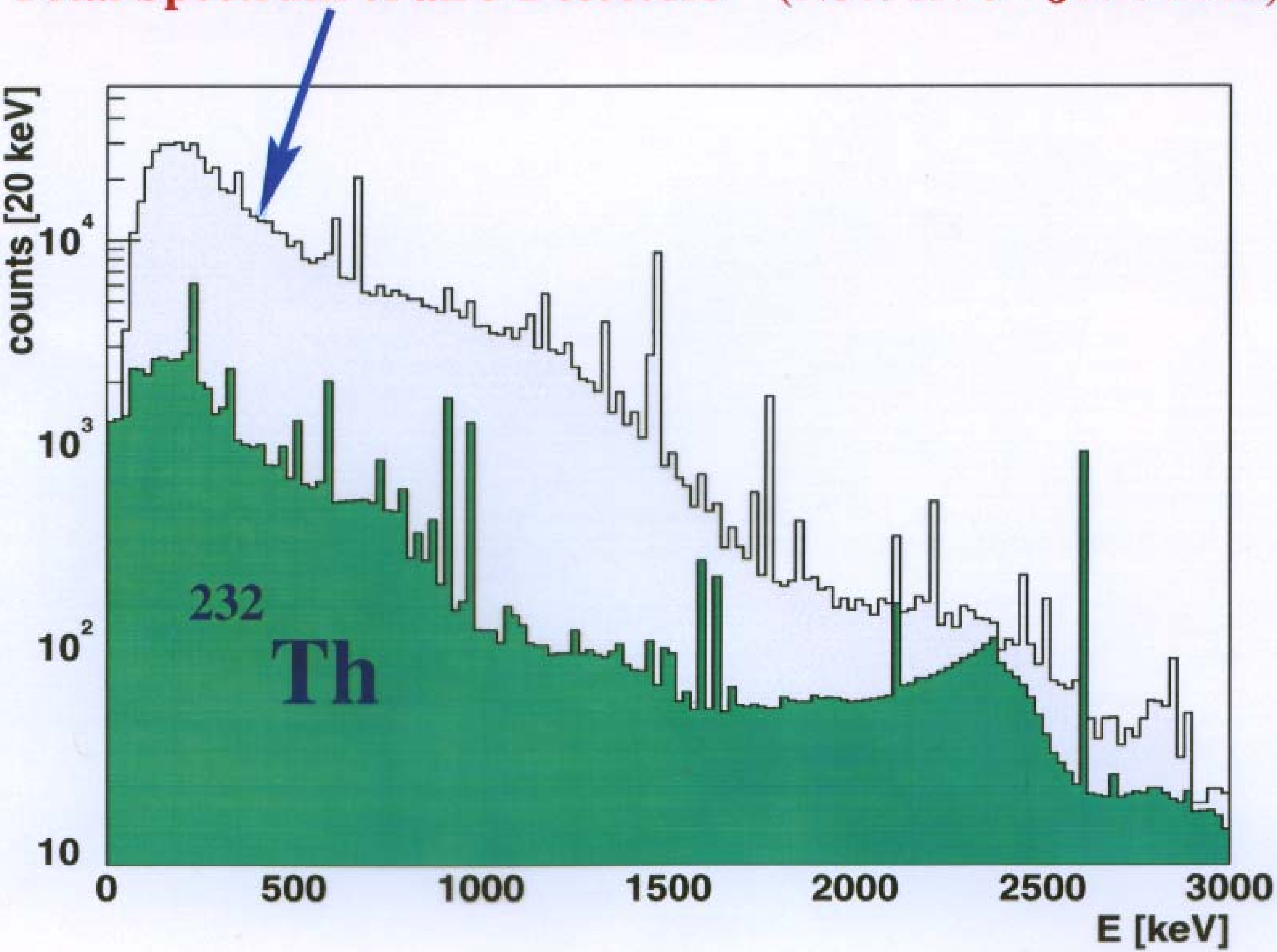
| | Data Sets | Events |
|---|---|---|
| Full measurement | 10 513 | 951 044 |
| Corrupted data sets | 792 | 92 553 |
| Rate > $\pm 5\sigma$ | 151 | 32 922 |
| Muon coincidence * | | 3 672 |
| Ge - Ge coincidence * | | 23 563 |
| EoI selection | | 13 158 |
| Data used | 9 570 | 786 941 |

~562 counts in range 2000–2060 keV


Detailed Uranium Decay Chain
URANIUM - 238
4 Million Years
α
THORIUM - 234
24 Days
β
PROTACTINIUM - 234
70 Seconds
β
URANIUM-234
250 000 Years
α
THORIUM-230
75 000 Years
α
RADIUM-226
1 600 Years
α
RADON-222
3.8 Days
α
POLONIUM-218
187 Seconds
α
LEAD-214
27 Minutes
β
BISMUTH - 214
20 Minuts
β
POLONIUM-214
2000 Mcro-sec
α
LEAD - 210
22 Years
β
BISMUTH - 210
5 Days
β
POLONIUM-210
138 Days
LEAD-206
Stable
Important Daughters of Radon-222
POLONIUM-218 and POLONIUM-214
The Time Under the Name
Is the Atomic Half Life
Alpha Particles: α
Beta Particles: β

# HEIDELBERG-MOSCOW EXPERIMENT

**Total Spectrum of all 5 Detectors (Nov. 1995 - June 2002) 49.59 kgy**



# Neutron capture:

$^{76}Ge\,(n, \gamma)\,^{76}Ge \longrightarrow \beta^- \longrightarrow \gamma$

**Simulation yields, for neutron background in Gran Sasso, 0.15 counts in the range 1990-2110 keV.**

→ **2037.8 keV transition not visible**

**If large neutron flux assumed,**

**then important check (see Table of Isotopes):**

| | | |
|---|---|---|
| relative intensities of | 2037.8 | 0.061 |
| relative intensities of | 2000.1 | 0.56 |

**So 2000.1 keV line is factor 10 stronger than 2037.8 keV.**

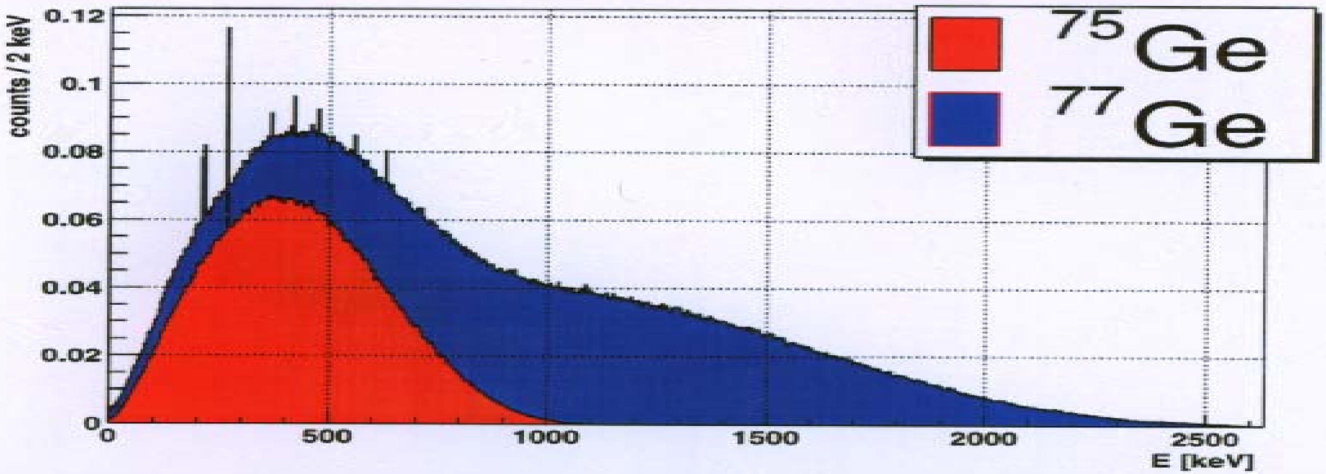
***But: no 2000.1 keV line in spectrum !***

→ **excluded**

**Others:** $^{74}Ga$ ($\mu$ - capture)

| | |
|---|---|
| 2036.2 keV | 0.17 |
| 1999.3 keV | 0.4 |
| 2353.5 keV | 45% |

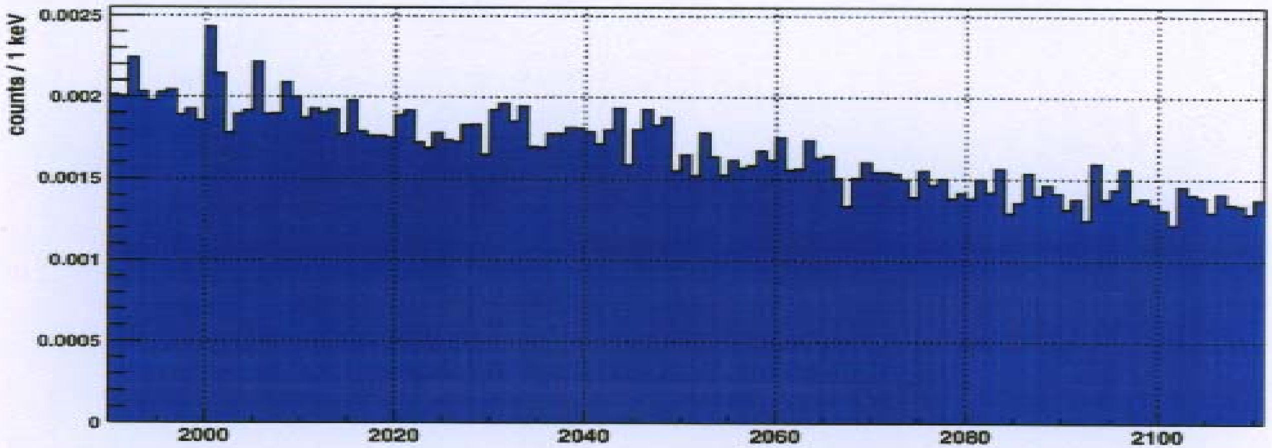
*(see Ch. Doerr and H.V. Klapdor-Kleingrothaus, NIM A 513 (2003) 596-621)*




**Simulated contribution to the measured spectrum of the radioactive decays of the isotopes $^{75}$Ge and $^{77}$Ge produced via neutron capture in the detectors.**

The most prominent line in the simulated spectrum results from the emission with 264.7 keV $^{75}$Ge, intensity 11%) and 264.4 keV ( $^{77}$Ge, 54%).

Further lines in the simulation are located at 211.0 (30.8%), 215.5 (28.6%) and 416.3 (21.8%) keV, they all come from $^{77}$Ge.




**Simulated contribution to the measured spectrumof the radioactive decay of the isotope $^{77}$Ge in the energy range between 1990 and 2110 keV.**

**The line at 2000.4 keV results from $\gamma$ -emission with an intensity of 0.561%**

The $\gamma$ emission at 2037.8 keV with an intensity of 0.061 keV is hidden in the Compton continuum.

**Energy position of this SSE line: 2037.5 keV ± 0.5(stat) ± 1.2(syst) keV**

**$Q_{\beta\beta}$ from various experiments (*not* ββ):**

**$Q_{\beta\beta}$ = 2039.006 ± 0.050 [40] Douysset et al., PRL 86 (2001)**

**$Q_{\beta\beta}$ = 2040.71 ± 0.52 [37] Ellis et al., NPA 435 (1985)**

**$Q_{\beta\beta}$ = 2038.56 ± 0.32 [38] Hykawy et al., PRL 67 (1991)**

**$Q_{\beta\beta}$ = 2038.668 ± 2.142 [39] Audi et al., NPA 595 (1995)**

Note: Effect of ballistic deficit shifts down systematically the energy of a ββ events in a Ge detector (by order of ~ 1 keV) (since events mainly 'outside').

## Conclusion up to this point:

- **in *full* spectrum we had 4.2σ signal**
- **with PSA by neuronal net we obtain a 6-7σ signal near Q**

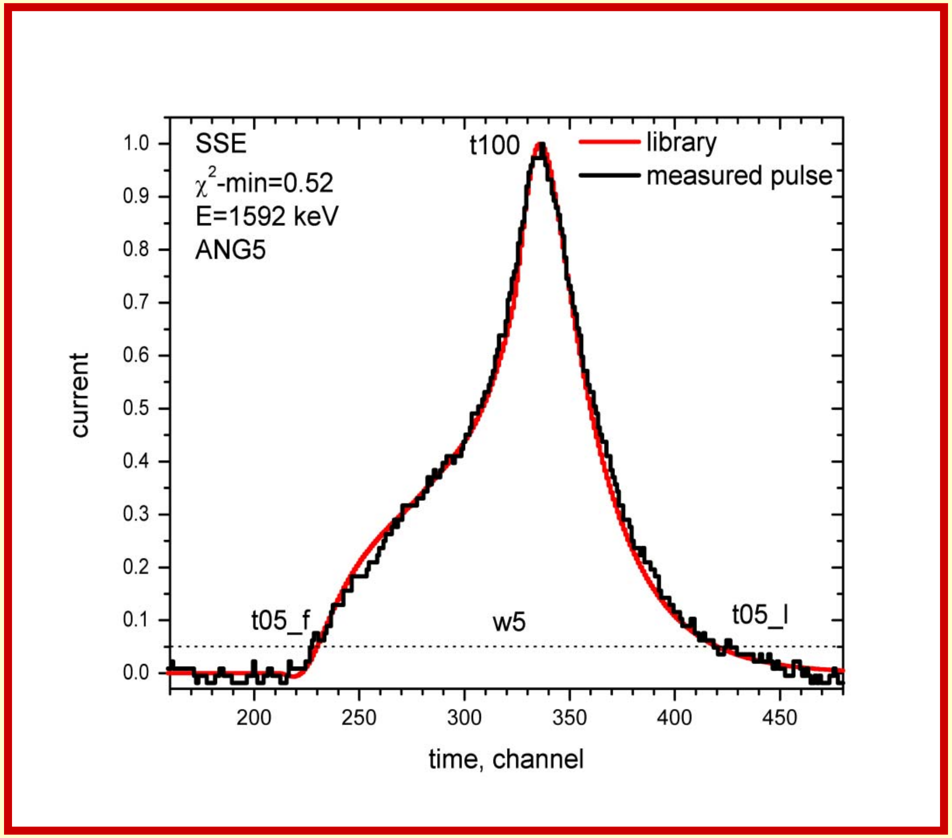
**All published until 2004 (partly extended in 2006)**

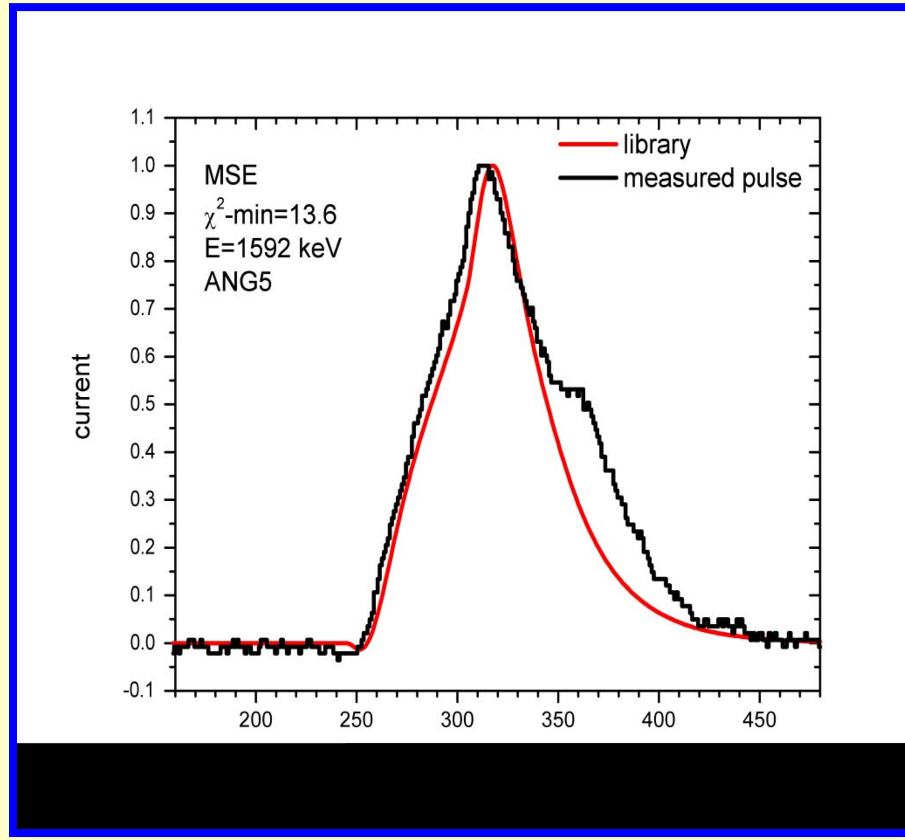
**PLB586(2004)198,**
**NIMA522(2004)371**

**Mod.Phys.Lett.A21(2006)1547**

H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, V. Mironov, I.V. Titkova, in Press

**Result of *fiting* experimental pulse shapes (black) with the library shapes (red lines), for events of the 1592 keV double escape line of the 2614 keV transition from 228 Th.**




**Left: Single Site event (SSE)**

**Right: *Multiple Site* event (MSE)**

UMD-PP-03-038; NEHU-PHY-MP-02-03; IMSc/2003/01/02

# High Scale Mixing Unification and Large Neutrino Mixing Angles

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(Dated: January 27, 2003)

Starting with the hypothesis that quark and lepton mixings are identical at or near the GUT scale, we show that the large solar and atmospheric neutrino mixing angles together with the small reactor angle $U_{e3}$ can be understood purely as a result of renormalization group evolution. The only requirements are that the three neutrinos must be quasi degenerate in mass and have same CP parity. It predicts that the common Majorana mass for the neutrinos must be larger than 0.1 eV making the idea testable in the currently planned or ongoing experiments searching for neutrinoless-double-beta decay.

PACS numbers: 14.60.Pq, 11.30.Hv, 12.15.Lk



The idea that disparate physical parameters describing forces and matter at low energies may unify at very short distances (or high mass scales) has been a very helpful tool in seeking a unified understanding of apparently unrelated phenomena [1]. In the context of supersymmetric grand unifed theories, such an approach explains the weak mixing angle $\sin^2\theta_W$ and thereby the different strengths of the weak, electromagnetic and strong forces. One of the key ingredients of the grand unified theories is the unification between quarks and leptons. One may, therefore, hope that in a quark-lepton unified theory, the weak interaction properties of quarks and leptons parameterized by means of the flavor mixing matrices will become identical at high energies.

On the experimental side, recent measurements on atmospheric and solar neutrino fluxes and those at K2K and KamLAND which are a manifestation of the phenomena of neutrino oscillations suggest that two of the neutrino mixings i.e. the mixings between $\nu_e - \nu_\mu$ and $\nu_\mu - \nu_\tau$ (to be denoted by $\theta_{12}$ and $\theta_{23}$, respectively) are large [2, 3, 4, 5, 6] while the third mixing between the $\nu_e - \nu_\tau$ is bounded to be very small by the CHOOZ-Palo Verde reactor experiments i.e. $\sin^2 2\theta_{13} < 0.15$ [7]. On the other hand, it is now quite well established that all observed quark mixing angles are very small. One may therefore ask whether there is any trace of quark lepton unification in the mixing angles as we move to higher scales.

The first question in this connection is whether high scales have anything to do with neutrino masses or it is purely a weak scale phenomenon. One of the simplest ways to understand small neutrino masses is via the seesaw mechanism [8] according to which the neutrino mixing is indeed a high scale phenomenon, the new high scale being that of the right handed neutrino masses ($M_R$) in an appropriate extension of the standard model. Present data put the seesaw scale $M_R$ very close to the conventional GUT scales. It is therefore tempting to speculate whether quark and lepton mixing angles are indeed unified at the GUT-seesaw scale. This would of course imply that all neutrino mixing angles at the high scale $M_R$ are very small whereas at the weak scale two of them are known to be large. In this letter we show that simple radiative correction effects embodied in the renormalization group evolution of parameters from seesaw scale to the weak scale can indeed provide a complete understanding of all neutrino mixings at the weak scale, starting with very small mixings at the GUT-seesaw scale.

The fact that renormalization group evolution from the seesaw scale to the weak scale [9, 10] can lead to drastic changes in the magnitudes of the mixing angles was pointed out in several papers [9, 11, 12, 13, 14, 15]. In particular, it was shown in [11] that this dependence on renormalization group evolution can be exploited in simple seesaw extensions of the minimal supersymmetric standard model (MSSM) to explain the large value of the atmospheric mixing angle starting with a small mixing at the seesaw scale, provided two conditions are satisfied: (i) the two neutrino-mass eigen states have same CP and (ii) they are very nearly degenerate in mass. In general, in gauge models that attempt to explain the large neutrino mixings [16], one needs to make many assumptions to constrain the parameters. In contrast, in this class of "radiative magnification" models [11], there is no need to invoke special constraints on the parameters at high scales beyond those needed to guarantee the

Typeset by REVTEX

UCRHEP-T341
OSU-HEP-02-07
IFIC/02-26
June 2002



# Underlying $A_4$ Symmetry for the Neutrino Mass Matrix and the Quark Mixing Matrix

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**Abstract**

The discrete non-Abelian symmetry $A_4$, valid at some high-energy scale, naturally leads to degenerate neutrino masses, without spoiling the hierarchy of charged-lepton masses. Realistic neutrino mass splittings and mixing angles (one of which is necessarily maximal and the other large) are then induced radiatively in the context of softly broken supersymmetry. The quark mixing matrix is also calculable in a similar way. The mixing parameter $U_{e3}$ is predicted to be imaginary, leading to maximal CP violation in neutrino oscillations. Neutrinoless double beta decay and $\tau \to \mu\gamma$ should be in the experimentally accessible range.

# Introduction

Particle Physics Research by Accelerators
has provided most of the discoveries of the past 45 years.
Extreme demands on future accelerators push
the interest of the particle physics community to

**NON - ACCELERATOR EXPERIMENTS**

(Proton decay, double beta decay, dark matter search,...)
They have - as propagator physics - no energy
restrictions and are powerful tools to look for

**BEYOND STANDARD MODEL PHYSICS**

Examples: Present beyond SM hints
from neutrino oscillations and dark matter.

( See e.g. Proc. "BEYOND THE DESERT 1997
- Accelerator and Non- Accelerator Approaches"
IOP, Bristol, Philadelphia 1998
eds. H.V. Klapdor-Kleingrothaus, H. Päs)

New Century will be the Century
of NON-ACCELERATOR Physics

# Data Acquisition:

CAMAC system, and CETIA processor in event-by-event mode.

- 250 MHz flash ADC's of type Analog Devices 9038JE (in DL515 modules) allow digital measurement of pulse shapes for the four largest detectors.
- Data acquisition on VME basis.
- Resolution of FADC's was 8 bit.

*Therefore:*

- Energy spectra recorded with 13 bit ADC's developped at MPI.
- The signal from the preamplifier (proportional to collected charge) was differentiated by Timing Filter Amplifiers (TFA), and
- every 4 nsec the voltage read at the TFA's was recorded, for later off-line analysis of the pulse shapes.

In the event-by-event mode also *other* parameters are recorded:

- *time of events*
- *voltage at detectors*
- *temperature at 3 measuring points*
- *information from muon shield*
- *other parameters of electronics crates*

*As additional check of each pulse,* EoI - value was calculated:

EoI = Energy over Integral

$$= \frac{\text{energy deposition in ADC}}{\text{area of pulse in timing channel (PSA measurements)}}$$

# *Electronics*

## 1 *4 8 bit-Flash ADC's*

250 MHz, for pulse shapes developed by Phys. Inst. Univ. HD,
produced by Firma Struck (originally for JADE and OPAL)
yields all 4 nsec voltage value --> memory --> VME-Bus --> ...

## 2 *10 13 bit - ADC's (produced at MPI)*

up to 38 kHz in SINGLE mode, low count rate in EVENT-BY-EVENT mode (or LIST MODE)
SINGLE data --> MPI-memory accumulated to spectra
LIST data --> to buffer, until read by online computer
(CETIA Power PC 601, and 90 MHz Pentium Server
(both connected by EHTERNET))

## 3 *CETIA PC 601:*

32 MByte RAM dynamic memory, 2 G Byte disc
Lynx real time; Pentium Linux PC 1.2.4

## 4 *Data acquisition system:*

in Summer 1995 installed in accelerator hall of MPI (Hellmig)
in November 1995 installed in Gran Sasso

## *Analysis:*

**Fitted simultaneously full range 2000 - 2060 keV.**

**Program determines position of peaks and intensities, and background (assumed to be linear, or constant).**

# Different methods:

- **Non-linear least squares method, using Levenberg Marquardt algoritm**

  **(most developed and tested minimization algorithm, finding fits most directly and efficiently).**

  **applicable under any statistics under following conditions:**

  **1. relative errors asymptotic to zero**

  **2. ratio of signal to function of the data.**

  ***Error estimate:*** **MATLAB statistical toolbox provides functions for confidence interval estimation for all parameters (uses residual of fit and Jacobian matrix around the solution).**

  **Confidence levels tested by numerical simulations:**

  **Simulated 100 000 spectra with Poisson - distributed background and Gaussian- shaped (Poisson-distributed) line of given intensity and look, in how may cases the known intensities lie inside the given confidence range (see Table).**

- **Maximum Likelihood Method - used root package from CERN, which exploits MINUIT for error calculation.**

  **Program had to be extended for application to non-integer numbers.**

  **Confidence levels tested as above.**

- **Feldman Cousins Method**

- ...

Table 5

## Result of simulation of 100 000 (in each entry spectra ) with Poisson-distributed background

## and a Gaussian-shaped line of given intensity

## for different background - B, and peak area - S,

## by the least squares method,

## using the Levenberg-Marquardt algorithm [42,43].

**Given is the number of spectra where the true number of counts in the line is found in the calculated confidence area.**

| B | S = 10 | | | | S = 20 | | | | S = 30 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $1\sigma$ | $2\sigma$ | $3\sigma$ | $4\sigma$ | $1\sigma$ | $2\sigma$ | $3\sigma$ | $4\sigma$ | $1\sigma$ | $2\sigma$ | $3\sigma$ | $4\sigma$ |
| **2** | 66505 | 93781 | 99183 | 99932 | 63967 | 93176 | 99219 | 99952 | 62094 | 92191 | 99121 | 99932 |
| **7** | 66879 | 91683 | 98476 | 99900 | 67618 | 94733 | 99498 | 99961 | 66332 | 94443 | 99539 | 99967 |
| **10** | 64962 | 90029 | 98380 | 99918 | 68210 | 94921 | 99455 | 99933 | 67352 | 94784 | 99554 | 99979 |
| **Expected:** | | | | | | | | | | | | |
| | 68269 | 95449 | 99730 | 99994 | 68269 | 95449 | 99730 | 99994 | 68269 | 95449 | 99730 | 99994 |

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**The GEANT4 program was modified for the simulation of radioactive decays, elastic and inelastic neutron reactions and interactions of cosmic muons with both setups of the Heid,-Mos. Exp.**

**Further developped: For the simulation of radioactive decays a method to reconstruct decay schemes from ENSDF data in order to generate random primary decay particles for the simul. For every decay an alpha, beta or EC transition is generated, including the subsequent $\gamma$-emission, and the possible emission of conversion electrons or X-rays is considered.**
**If the multipolarities and angular momenta of every involved state in a two $\gamma$ cascade are given in the ENSDF data files, then also the angular correlation between the two $\gamma$ emissions is calculated and used for the simulation.**

**This makes it possible to simulate the radioactive decay of each known isotope in any location of the setup and therefore to identify the location of radioactive impurities in different materials. Test: a simulation of the weekly calibration with a 228Th-source.**

**The main problem: not known where the radioactive impurity is located inside the setup.**
Assumed that all materials of same type contain the same amount of radioactive impurities.
**The simulation of each identified radioactive background component is then performed in each material of the setup individually.**
**By comparing the relative intensities of strong $\gamma$ lines in the measured spectrum to the relative intensities obtained from the simulation in different materials of the setup it is then possible to localize the corresponding radioactive impurities and to calculate the most probable start activities of these impurities in the materials of the setup.**
**This method exploits the different degrees of attenuation for $\gamma$ -ray emissions of different energies from different materials and different locations in the setup.**

***(See also B. Maier 92-95, Heid.-Mos. Collab., PR D55 (1997) 54)***

The most important continuous contribution to the background spectrum comes from the contamination extreme low-activity LC2-lead-inner 10cm contributes mainly in range 100-600 keV.
Activity of 210Pb was measured, (0.36+0.03)Bq/kg
**a factor of 100 smaller than in usual low-activity lead.**

**The most important background contribution - from the via characteristic $\gamma$-emissions can be attributed to the natural decay chains of 238U, 232Th to the primordial isotope 40K located in the inner lead shielding and in the copper cryostates of the detectors.**
***)It was assumed that this decay chains are in secular equilibrium, the radioactive isotopes in the respective materials are uniformly distributed.**

**A contamination of the Ge crystals with 238U or 232Th excluded due to the absence of the corresponding alpha-emission peaks in the spectra. The only identified alpha-activity identified from a small 212Pb contamination on the surface of the detector crystals.**

**!) 40K can not be located in the crystals either, as in this case the strong gamma-line at** 1461 keV would be shifted to higher energies due to the additional emission of X-rays immediately after the 40K EC-decay inside the detector.

**Anthropogenic backgr.: 125Sb, 134Cs, 137Cs, 207Bi (nuclear weapon tests, reactor accidents). Their contribution to the background was determined comparing the ratios of strong gamma lines in the experimental spectrum to the ratios obtained from the simulation of decays using the maximum likelihood method.)**

**Background components located inside the germanium detectors-cosmogenic activation!!**
**The short-lived isotopes are 57Co (271.8 d), 58Co (T=70.d) and 65Zn (T=243.9d).**
***are not visible any more in the actual spectrum from 1995 to 2003***

***In Cu cryostat!!!***

***The isotopes 54Mn (T=312.1d) and 60Co (T=1925.3d) still show strong peaks in the spectra of all detectors.***

Identified background components (primordial, cosmogenic, anthropogenic), their estimated activities and most probable locations in the full setup of the HEIDELBERG-MOSCOW experiment (average for all 5 detectors).

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| Isotope | | Info | Localization | Activity (μ Bq/kg) |
|---|---|---|---|---|
| $^{238}$U | | nat.decay chains(#) | Cu cryostat | 116.0 |
| $^{238}$U | | nat.decay chains(#) | Pb shield | 26.6 |
| $^{232}$Th | | nat.decay chains(#) | Cu cryostat | 58.1 |
| $^{232}$Th | | nat.decay chains(#) | Pb shield | 12.3 |
| $^{40}$K | | primordial isot. !) | Cu cryostat | 614.1 |
| $^{40}$K | | primordial isot. !) | LC2 - Pb | 310 |
| $^{210}$Pb | | | LC2 - Pb | $3.6 \times 10^5$ |
| $^{54}$Mn | cosmogenic isotopes | Ge crystal | Ge crystal | 4.2 |
| $^{57}$Co | cosmogenic isotopes | 271.8 d (*) | Ge crystal | 2.6 (*) |
| $^{58}$Co | cosmogenic isotopes | 70.8 d (*) | Ge crystal | 3.4 (N3 and 5)(*) |
| $^{65}$Zn | cosmogenic isotopes | 234.9 d (*) | Ge crystal | 20.2 (N2-4)(*) |
| $^{54}$Mn | cosmogenic isotopes | 312.1 d (**) | Cu cryostat | 6.8(N4 and 5) |
| $^{57}$Co | cosmogenic isotopes | 271.8 d (*) | Cu cryostat | 32.4(*) |
| $^{58}$Co | cosmogenic isotopes | 70.8 d (*) | Cu cryostat | 23.4(only N3-5)(*) |
| $^{60}$Co | cosmogenic isotopes | 1925.3 d (**) | Cu cryostat | 55.6 |
| $^{125}$Sb | anthropogenic isotopes | 2.77 y (%) | Cu cryostat | 29.1 |
| $^{134}$Cs | anthropogenic isotopes | 2.06 y (%) | Cu cryostat | 5.1(*) |
| $^{137}$Cs | anthropogenic isotopes | 30.17 y (%) | Cu cryostat | 141.2(N5: 526.8) |
| $^{207}$Bi | anthropogenic isotopes | 33.4 y (%) | Cu cryostat | 6.7 |

(*) do not show visible peaks in the current spectra due to short half lives. For these isotopes activities determined during an earlier stage of the experiment when these peaks were still verifiable in the measured spectrum (B.Maier93-95, Heid.-Mos.C., PRD55(1997)54) are used for the background model in this analysis.

(**) - still show strong peaks in the spectra of all detectors.

(%) - anthropogenic isotopes, were produced and released to nature during nuclear weapon tests and reactor accidents. (Their contribution to the background was determined comparing the ratios of strong gamma lines in the experimental spectrum to the ratios obtained from the simulation of decays using the maximum likelihood method) Cosmogenic isotopes produced by spallation by cosmic radiation during production of detectors and transport.

(#)It was assumed that this decay chains are in secular equilibrium, the radioactive isotopes in the respective materials are uniformly distributed.
A significant contamination of the Ge crystals with 238U or 232Th excluded. Only in det.4,5 weak alpha-emission peaks in the spectra.

!) 40K can not be located in the crystals either, as in this case the strong gamma-line at 1461 keV would be shifted to higher energies due to the additional emission of X-rays immediately after the 40K EC-decay inside the detector.    Extreme low-activity LC2-lead-inner 10cm. Activity of 210Pb was measured, (0.36+0.03)Bq/kg a factor of 100 smaller than in usual low-activity lead.

## Summary from the simulation of neutrons hitting the experiment.

| Setup | Energy intervall | Expected total numb. of neutrons during measurement ($10^6$) (in one of the setups during $T_{measur.}$) | No. of neutrons sim., GEANT4 ($\times 10^6$) | Counts per detec. induced in range 100-3000keV per $10^6$ neutrons sim. (averaged per detector for setup 1) |
|---|---|---|---|---|
| 1 | (0-50) meV | 11.7 | 50 | 0 |
| 1 | 50meV-1keV | 19.9 | 100 | 0.15 |
| 1 | 1keV-1MeV | 2.3 | 100 | 8.1 |
| 1 | 1MeV-10MeV | 6.0 | 1000 | 275.0 |
| 2 | 0-50meV | 9.1 | 50 | 0 |
| 2 | 50meV-1keV | 15.6 | 50 | 192.2 |
| 2 | 1keV-1MeV | 1.8 | 50 | 27.3 |
| 2 | 1MeV-10MeV | 4.7 | 200 | 464.3 |

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**Neutrons with higher energies (used for the simulations):**

**Neutrons (of >1keV) - pass the shielding material --> reach the inner parts of the setup.**
neutrons can be captured by the copper cryostates, plastic parts, and the detectors themselves.

***A comparison of the simulation for the two different setups shows:***
**the boron--polyethylene shielding reduces the number of hits for setup 1 significantly**
*Reason: the higher neutron capture cross section compared to the lead/copper shield*

**Energy range from 50meV to 1keV:** setup 1 - reduced by a factor of thousand by the neutron shielding
**Energy higher than 1 MeV: inelastic capture processes are less likely to occur.**

**Energies > 10MeV: the total contribution of these neutrons can be neglected (small neutron fluxes).**

**Energies > 25MeV (25-400 MeV) produced by high-energy muons (LVD) -->**
$E_n \sim 10^{-11}$ **neutrons** $s^{-1} cm^{-2}$**:**

**Neutrons with energies above 10 MeV do not contribute significantly to the measured spectrum.**

number of simulated events ( > $10^9$ neutron hits) ---> simulated contribution - 746 counts in the scaled spectrum!

Number of radioactive isotopes produced in the setup by inelastic neutron reactions, neutron capture is recorded.
**The simulation shows: this effect is completely negligible !!!** **G4NeutronIsotopeProduction package**

(This package calculates isotope production based on evaluated neutron scattering data and runs in a parasitic mode in GEANT4 , i.e. new isotopes produced by G4NIP will not be passed to GEANT4 tracking to simulate their subsequent radioactive decays.

**The expected neutron flux energy range (>10 MeV) in the Gran Sasso is extremely small,**
**--> the number of new isotopes produced in the HM is expected to be very small !! (see extra Fig.)**

Number of simulated events (30 x $10^6$ neutron hits)

# Muons:

**The hadronic component of cosmic showers is completely absorbed in the overlying rock.**

**But still there is a small contribution to the measured spectrum by muons that pass the experiment and deposit energy in one or more of the detectors.**

**The cosmic muon flux in the Gran Sasso tunnel is reduced by a factor of about $10^6$ compared to the surface, but still there is a muon flux of**

$$F = (1.16 \pm 0.09)\ \mu\ h^{-1} m^{-2} \quad \text{(GALLEX-1999)}$$

**Using muon flux formula (see MACRO, 1999) ---> the total number of direct muon hits:**

**$7 \times 10^5$ muon hits on setup 1 (1760 days of measurement) with four detectors;**

**$5 \times 10^5$ hits on setup 2 (1271 days of measurement) with detector ANG4.**

**Was done some modification of the programm. GEANT4 was modified to include muon interactions and also spallation processes. For both setups $4 \times 10^6$ muon events were simulated.**

***Energy interval: 100 MeV to 1 TeV.***

***A flat energy spectrum. Only the 511 keV peak of electron-positron annihilation.***

**If shower inside setup, the secondary particles (pions, kaons, protons, neutrons, electrons) produced *are quickly absorbed* by the shielding material of the setup and do not give rise to inelastic hadronic reactions in the detectors.**

**This simulation includes electromagnetic and hadronic shower production induced by high-energy muons, but the simulation shows that it is very unlikely that such an event happens inside the small setup !!**

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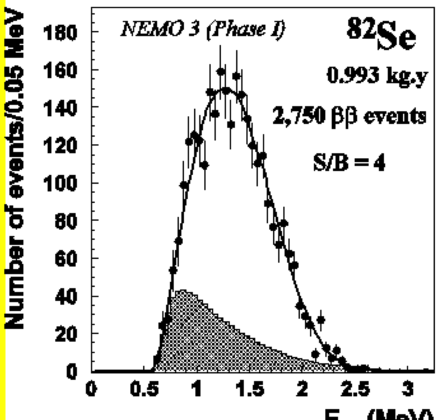
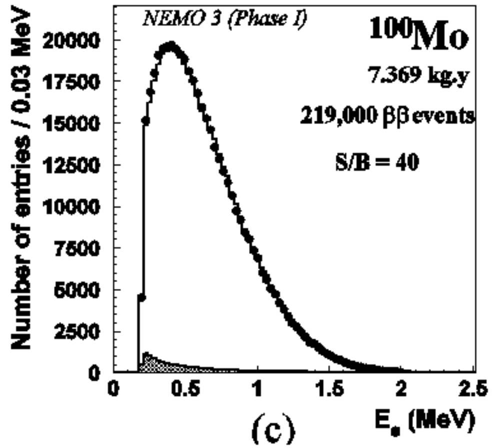
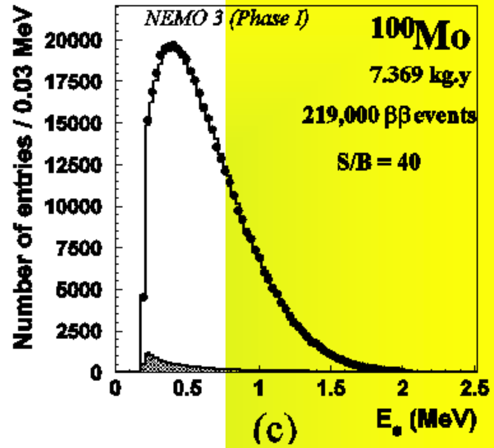
NEMO Collabor. 2005, Phys. Rev. Lett. 95 (2005) 182302



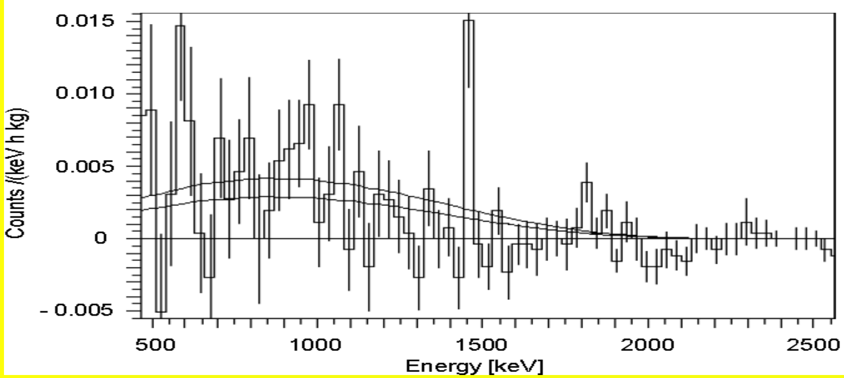



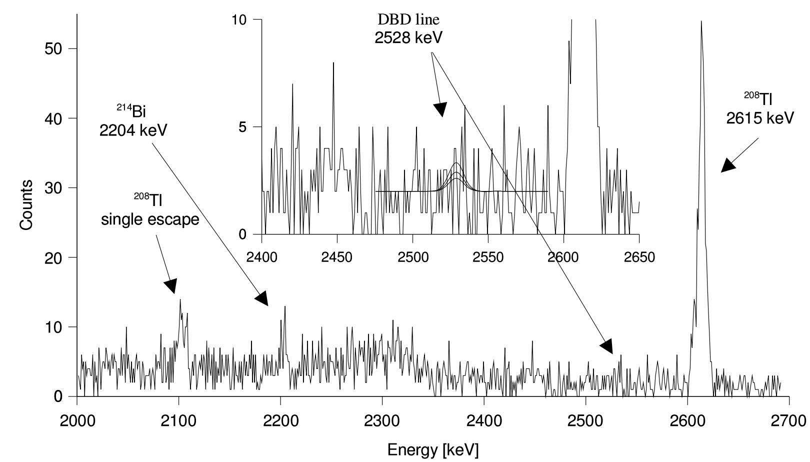

Energy sum spectrum of the two electrons after background substraction from $^{82}$Se and $^{100}$ Mo. 389 effective days of data collection.

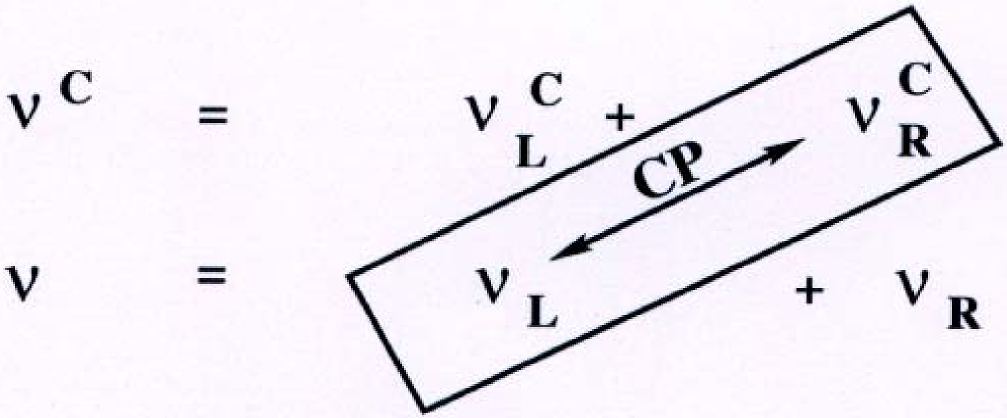
CUORICINO Collabor., Phys. Lett. B 557 (2002) 167

Total difference spectrum between Te and Te detectors. The solid curves represent the best fit (lowest curve) and the 90% C.L. excludede signal.

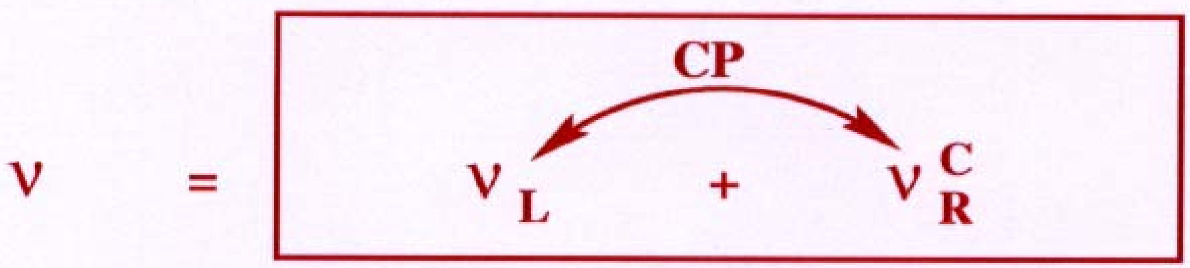
Total spectrum (in anticoincidence) in the region of neutrinoless DBD obtained with the 20 crystal.






**Dirac Neutrino**




**Majorana Neutrino**

**Possible assignment of the experimentally known (in boxes) neutrino states (of one family) in the theoretical description for Dirac and Majorana fields.**

# History of ßß Decay Experiments

1948-52 First experiments – sensitivity 10**18 years

1949-50 First geochemical experiment, 130Te – 130Xe,
first observation of 2vßß decay $T_{1/2}$ = 1.4 x 10**21 years
(later, 1967, confirmed within factor 2

1987 First result for 2vßß in ‚direct‘ experiment, 82Se - ??,
(30 events, 2.2 σ), $T_{1/2}$ = 1.1 x 10**20 years

1966 First ‚active source‘ experiment, Ca2F2

1990 -2003 **NEW ERA** of ßß Experiments USING ENRICHED HIGH-PURITY GERMANIUM , 11 kg, in active source exp.
(Heidelberg-Moscow experiment)

HUGE STEP in SENSITIVITY!

Factor more than 50000, compared to 1987

Most sensitive since 1992.

**Result:** $T_{1/2}$ = 2.2 x 10**25 years for 0vßß decay
$m_\nu$ = 0.22 eV