V International Pontecorvo Neutrino Physics School

Neutrino-less double beta decay experiments

Part I

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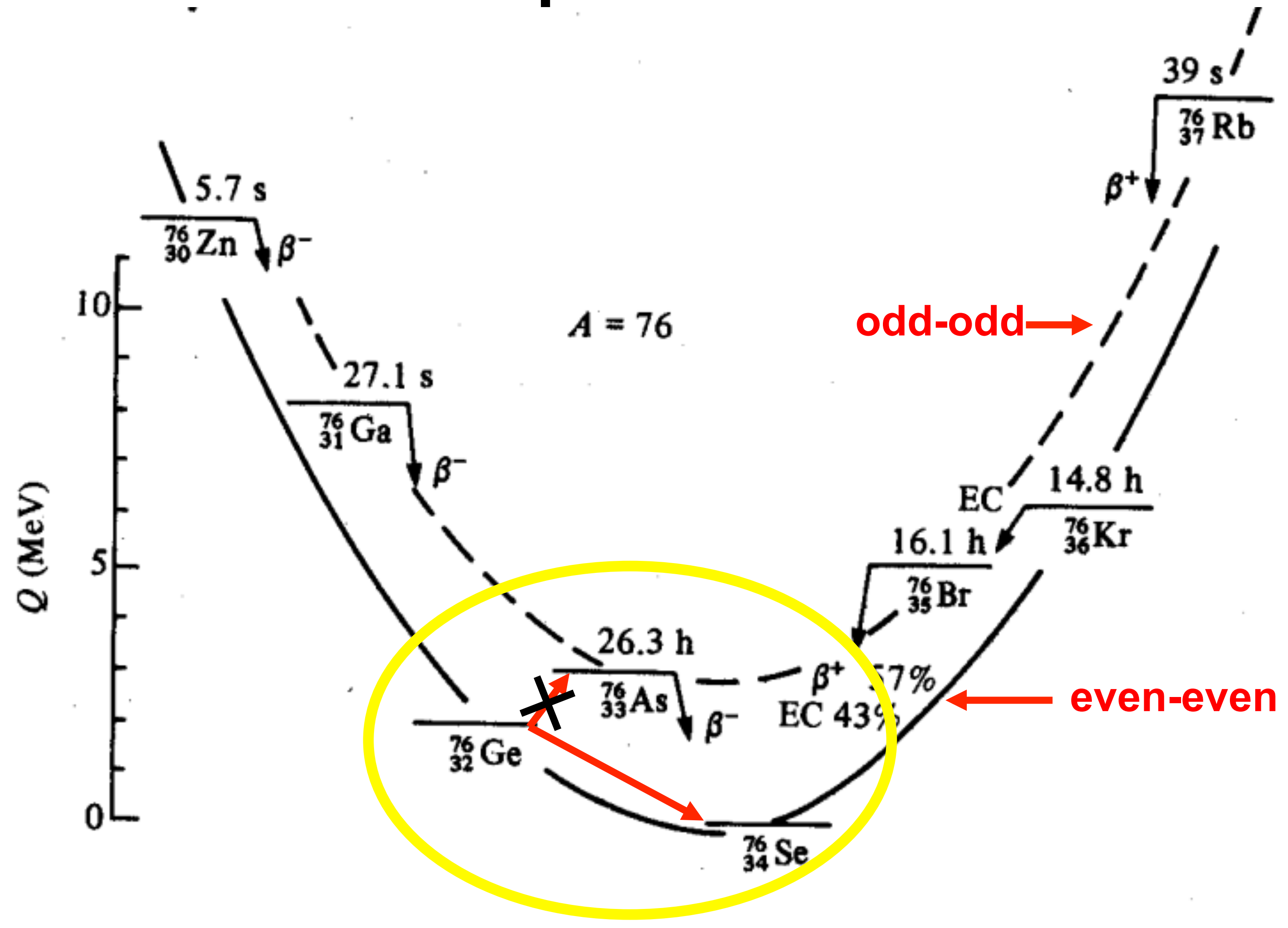
Outline for today's lecture

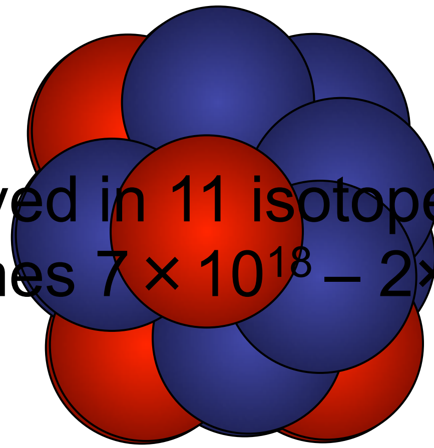
- Intro: basics about double beta decay
- Predictions on <m> from oscillation experiments
- Sensitivity vs. exposure and background
- Remarks about backgrounds
- The claim & experimental status until early 2012

Mass parabolas



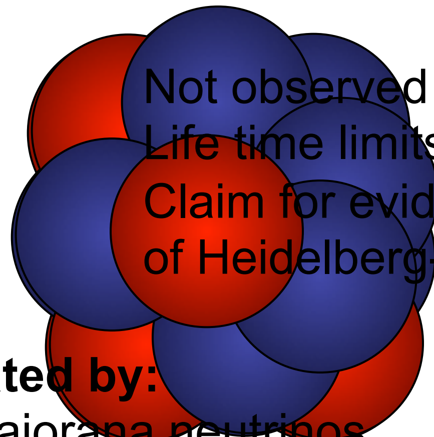
Ground states of even-even nuclei: 0^+

2ν-ββ Decay



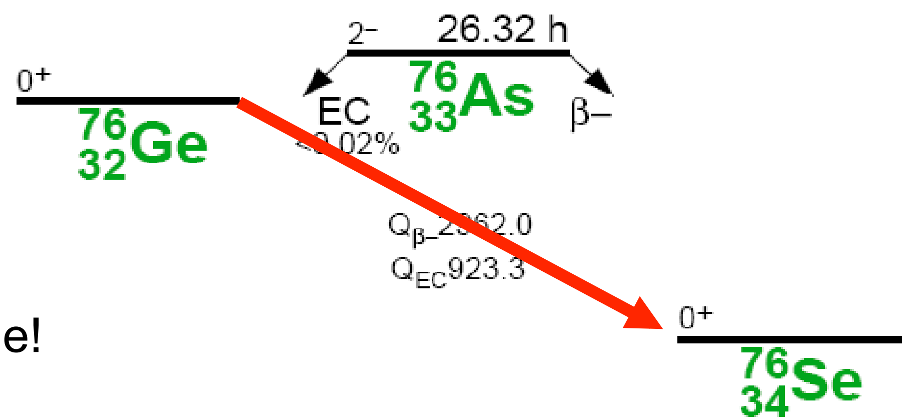
Observed in 11 isotopes
Life times $7 \times 10^{18} - 2 \times 10^{22}$ years

0ν-ββ Decay



Not observed yet;
Life time limits > $10^{24} – 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

0νββ can be generated by:
- exchange of light Majorana neutrinos
- SUSY
- LR
- …..



Schechter & Valle:
if 0νββ observed ⇒ ν is Majorana particle!

Why is it interesting?

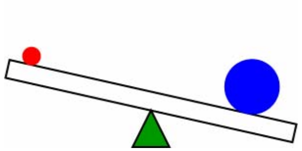
1) Violation of lepton number conservation ($\Delta L=2$)

Dirac vs. Majorana particle: (i.e. its own anti-particle)?

$0\nu\beta\beta \Rightarrow$ Majorana nature

Majorana $\Rightarrow$ See-Saw mechanism

$$m_\nu = \frac{m_D^2}{M_R} << m_D$$



For $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$ ➔ $M_R \sim 10^{15}$ GeV

2) Absolute mass scale:

(effective) neutrino mass

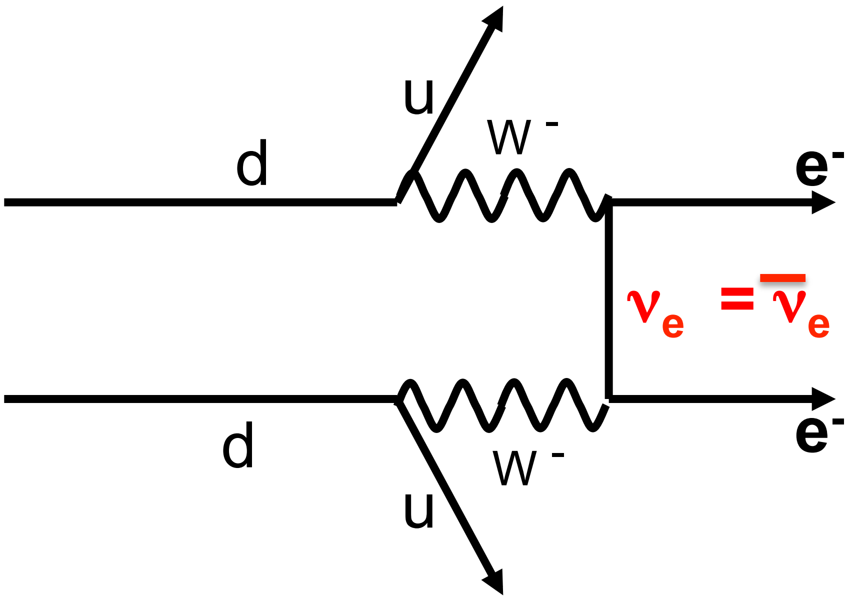
Hierarchy: degenerate, inverted or normal

sensitive to Majorana CP phases

0ν-$\beta\beta$ Decay

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

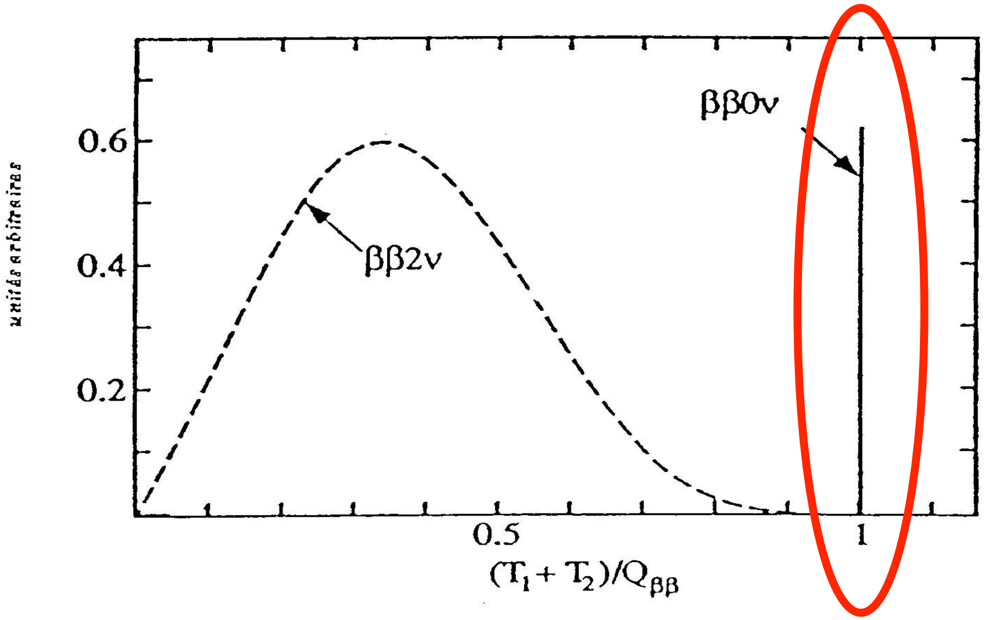
$\Delta L=2$



Assume leading term is exchange of light Majorana neutrinos

Main 0νββ experimental observables:

- Sum energy of 2 electrons equal to Q-value



- 2 electrons from one vertex
  - ➔ point-like in high density detectors
  - ➔ Two tracks from single vertex in tracking detector

Life time and effective Majorana mass

$$1 / t_{1/2}(0\nu) = G\, M^2\, m^2_{ee}$$

Effective neutrino mass

Phase space

Nuclear matrix element

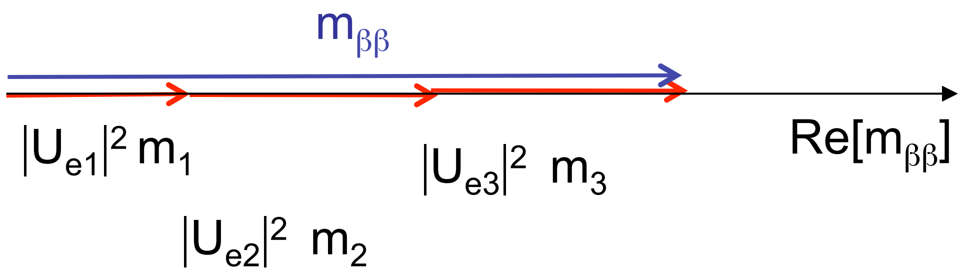
$$m_{ee} = |\sum_i U_{ei}^{\,2}\, m_i|$$

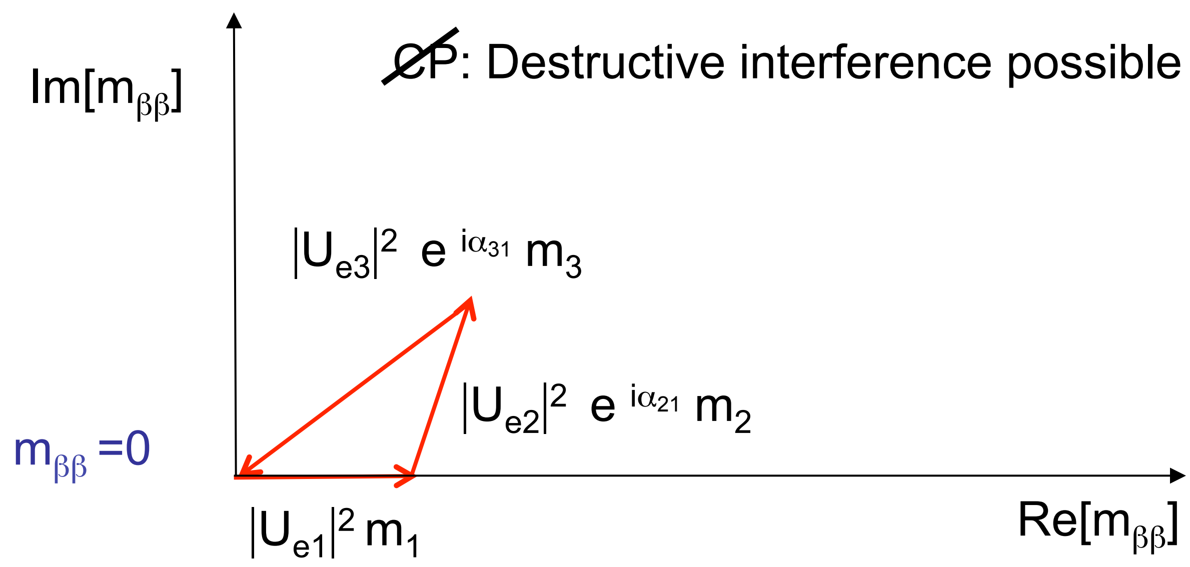
U_{ei} complex:

⇒ sensitive to CP violating phases (optimist☺)

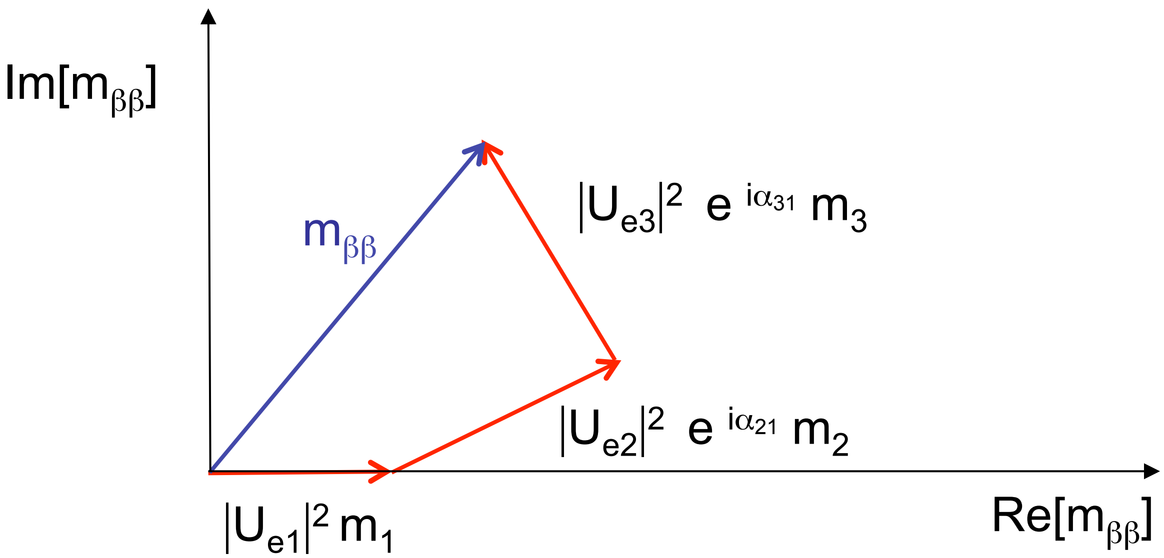
⇒ cancellation possible (pessimist)

If all CP phases = 0:





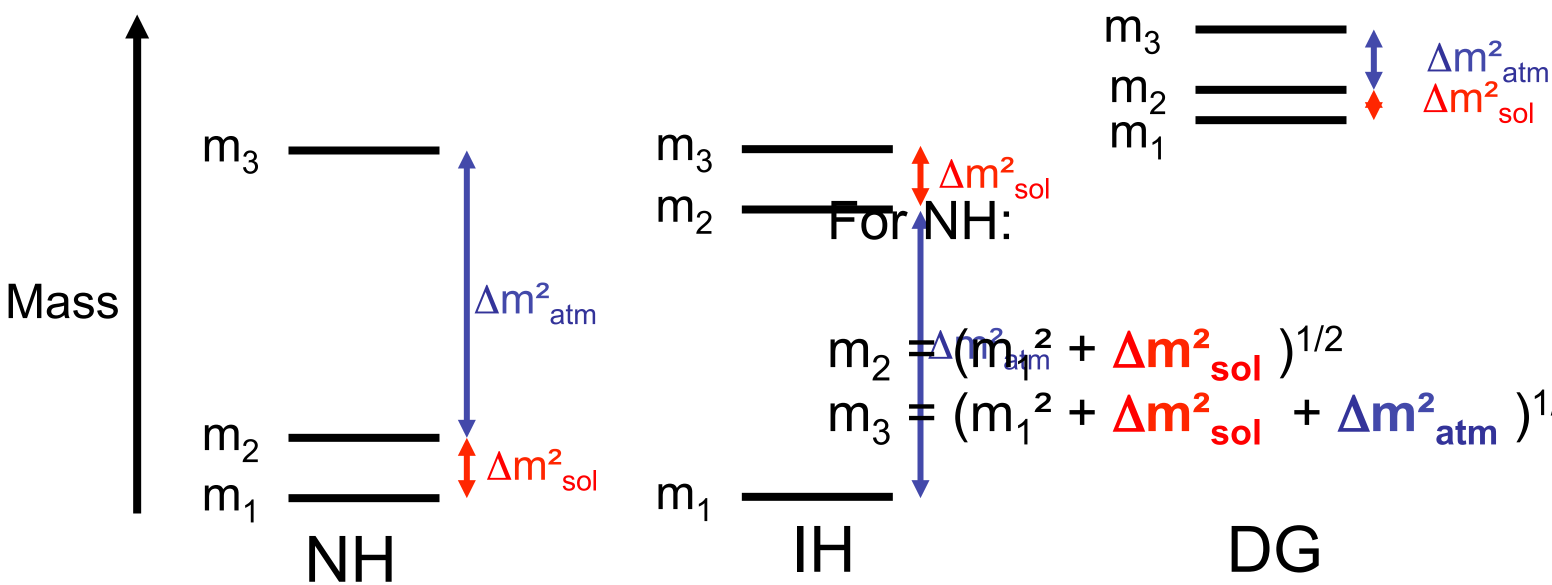
$\not{CP}$: Destructive interference possible
$Im[m_{\beta\beta}]$
$|U_{e3}|^2 \ e^{i\alpha_{31}} \ m_3$
$|U_{e2}|^2 \ e^{i\alpha_{21}} \ m_2$
$m_{\beta\beta} = 0$
$|U_{e1}|^2 \ m_1$
$Re[m_{\beta\beta}]$


$Im[m_{\beta\beta}]$
$m_{\beta\beta}$
$|U_{e3}|^2\ e^{i\alpha_{31}}\ m_3$
$|U_{e2}|^2\ e^{i\alpha_{21}}\ m_2$
$|U_{e1}|^2\ m_1$
$Re[m_{\beta\beta}]$

Predictions on <m> from oscillation experiments

Input for m_{ee} from ν-oscillations

Solar/Reactor -ν: θ_{12}, Δm^2_{sol} **Atmosph.-ν: Δm^2_{atm}** **Reaktor-ν: θ_{13}**



For NH:

$m_2 = (m_1^2 + \Delta m^2_{sol})^{1/2}$

$m_3 = (m_1^2 + \Delta m^2_{sol} + \Delta m^2_{atm})^{1/2}$

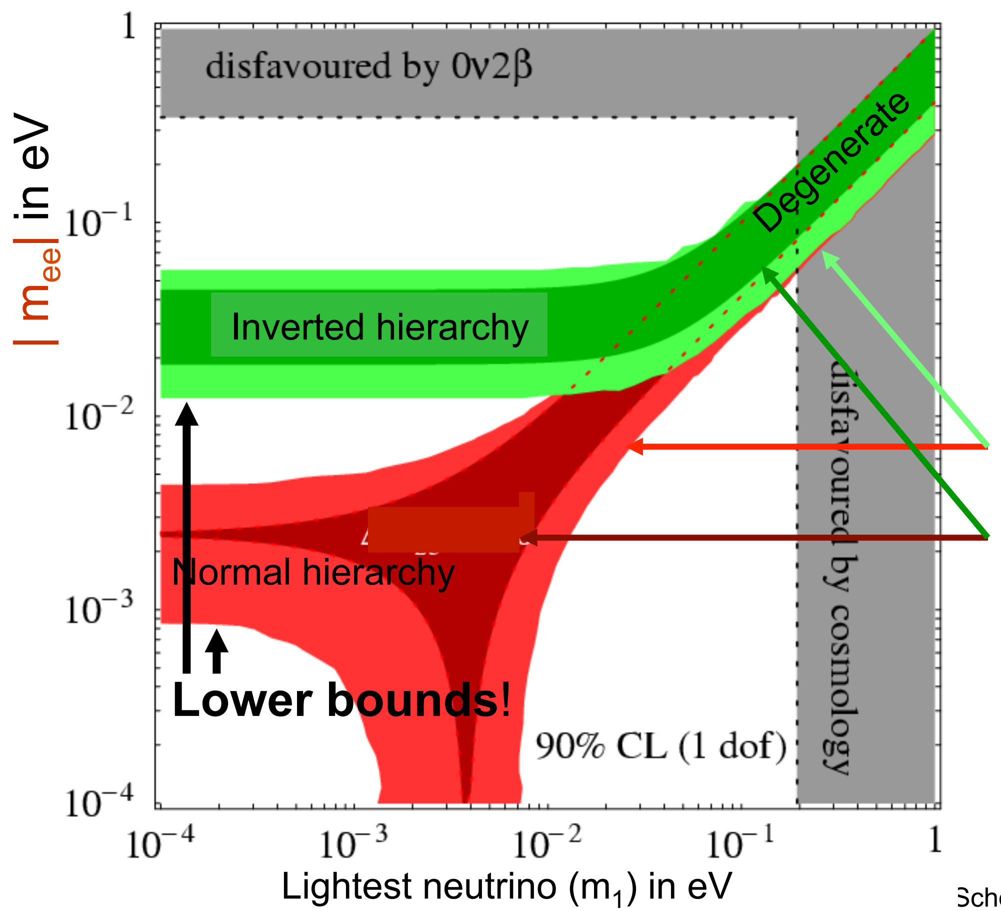
$$m_{ee} = \left| \cos^2\theta_{13} \, (m_1 \cos^2\theta_{12} + m_2 \, e^{2i\alpha} \sin^2\theta_{12}) + m_3 \, e^{2i\beta} \sin^2\theta_{13} \right|$$

$$\Rightarrow m_{ee} = \mathbf{f}(m_1, \Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha, \beta)$$

0νββ: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$



F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

90% CL

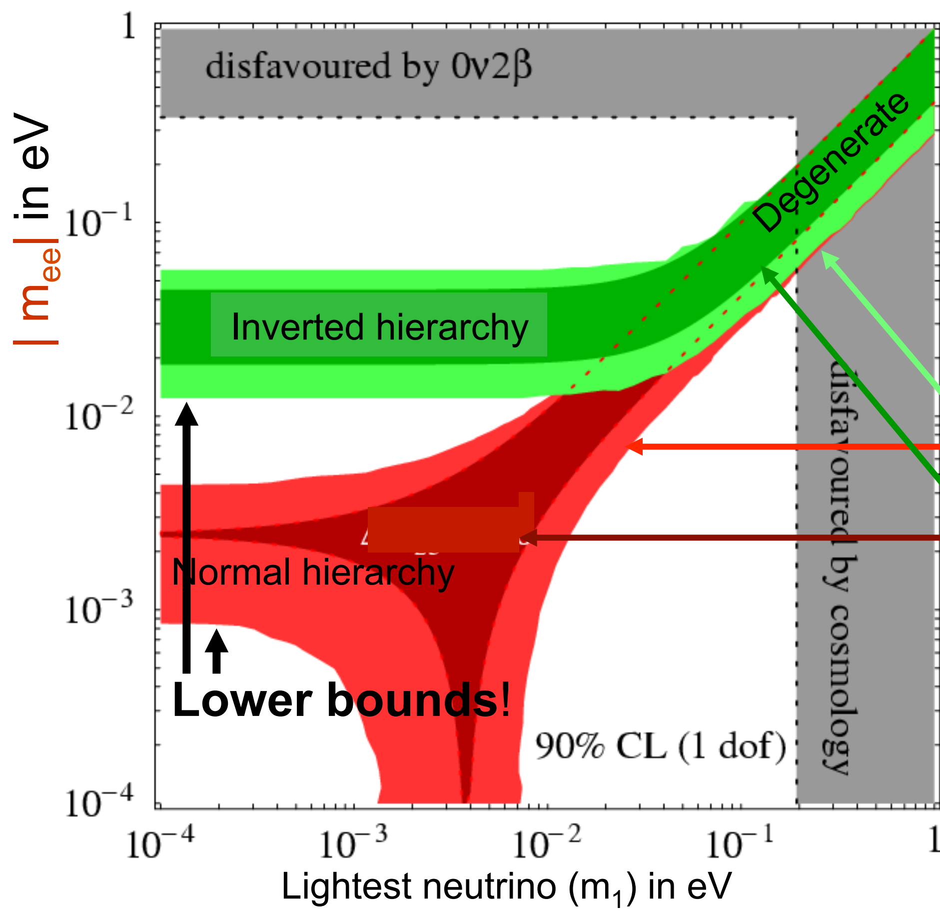
Negligible errors from oscillations; width due to CP phases

$0\nu\beta\beta$: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

KDKC claim:
0.44 eV

Goal of next generation experiments:
~10 meV



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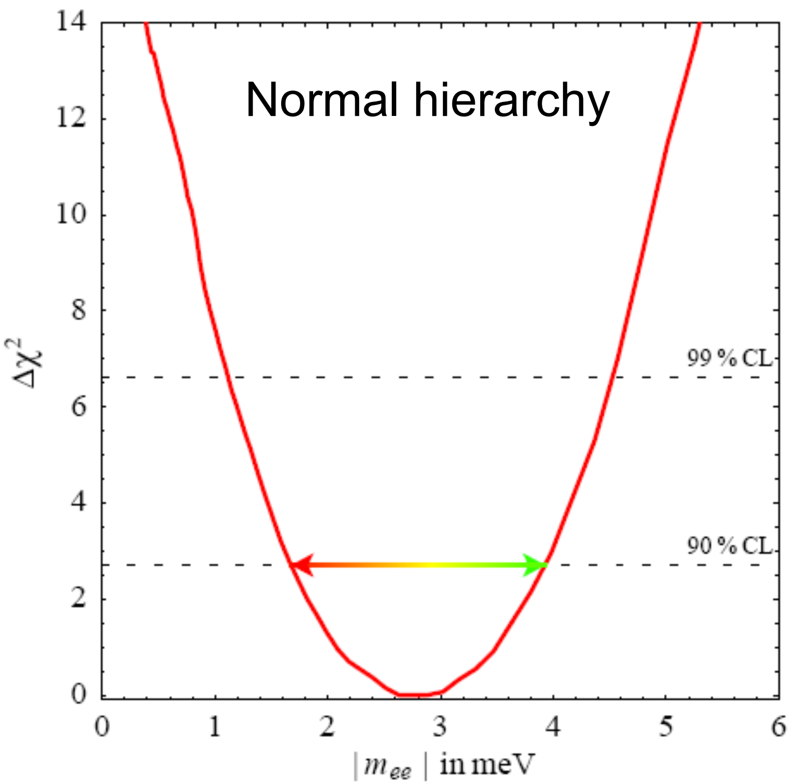
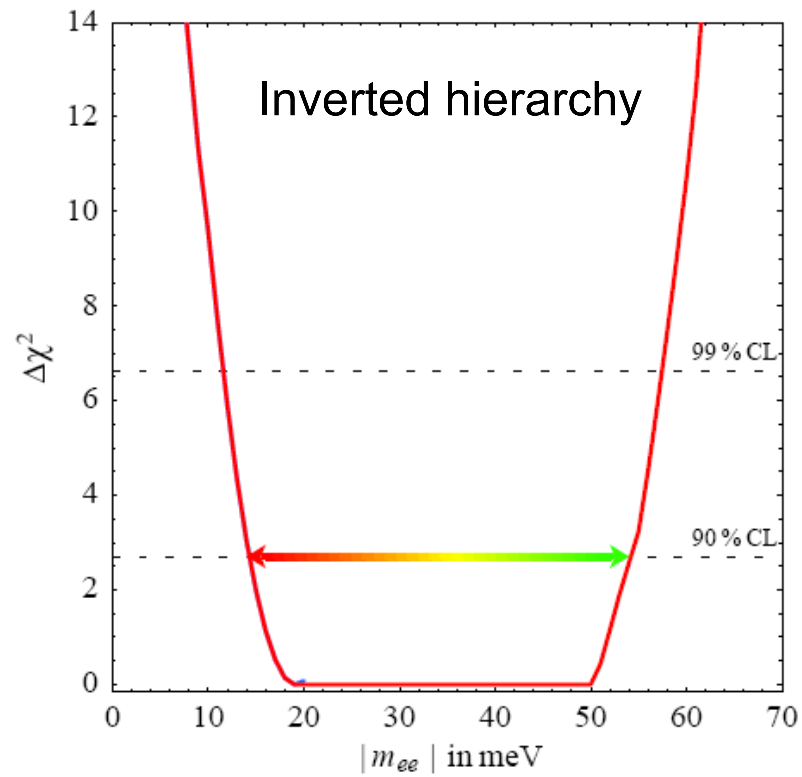
90% CL

Negligible errors from oscillations; width due to CP phases

Predictions from oscillation experiments (with 3 active neutrinos)

(Analysis prior to θ_{13} measurement by Double Chooz, Daya Bay and Reno, however only small changes with updated oscillations parameter)





$|m_{ee}|$ = 1.1 – 4.5 meV (99% CL)

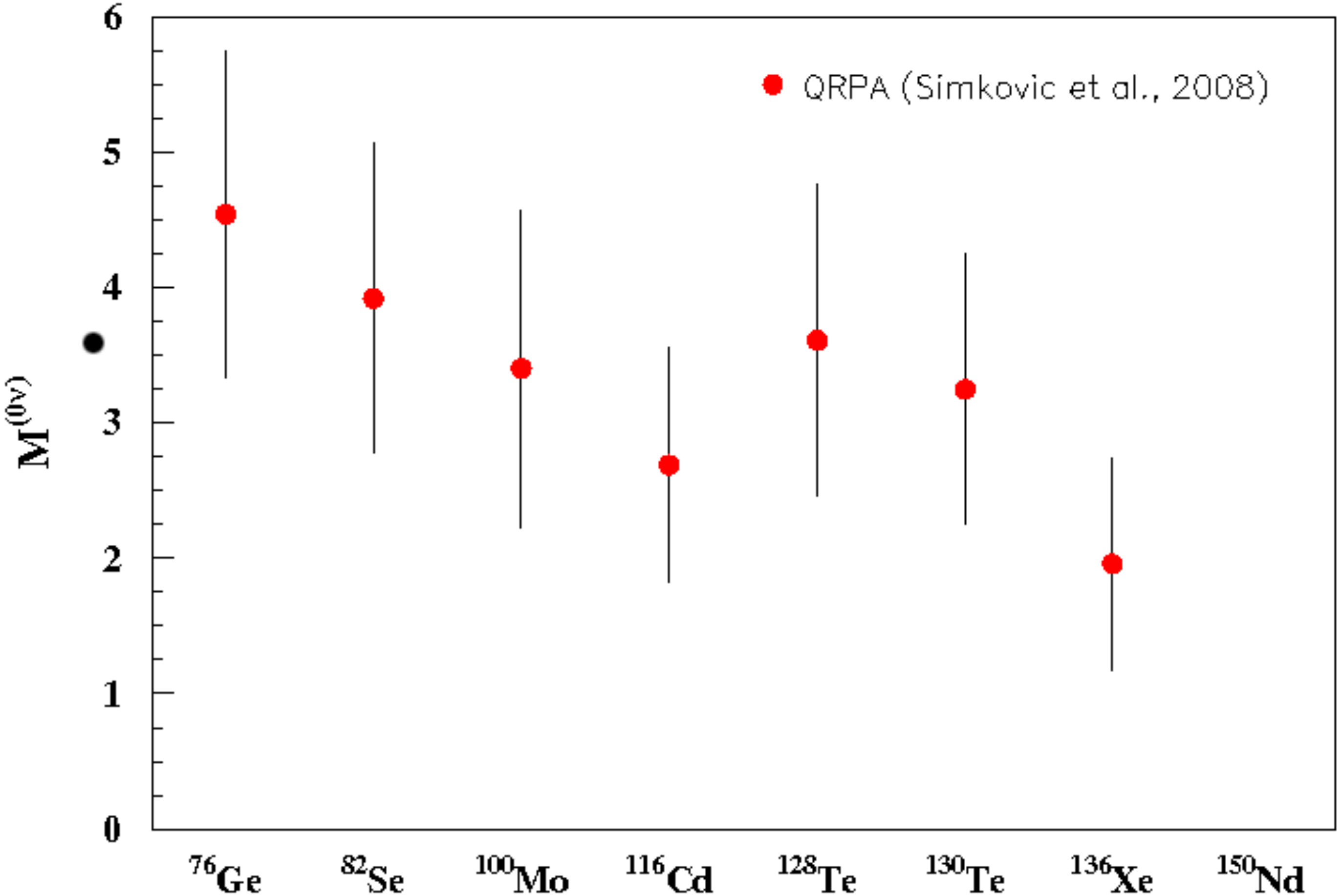
$|m_{ee}|$ = 12 - 57 meV (99% CL)

Strumia & Vissani hep-ph/0503246

Double beta Isotopes

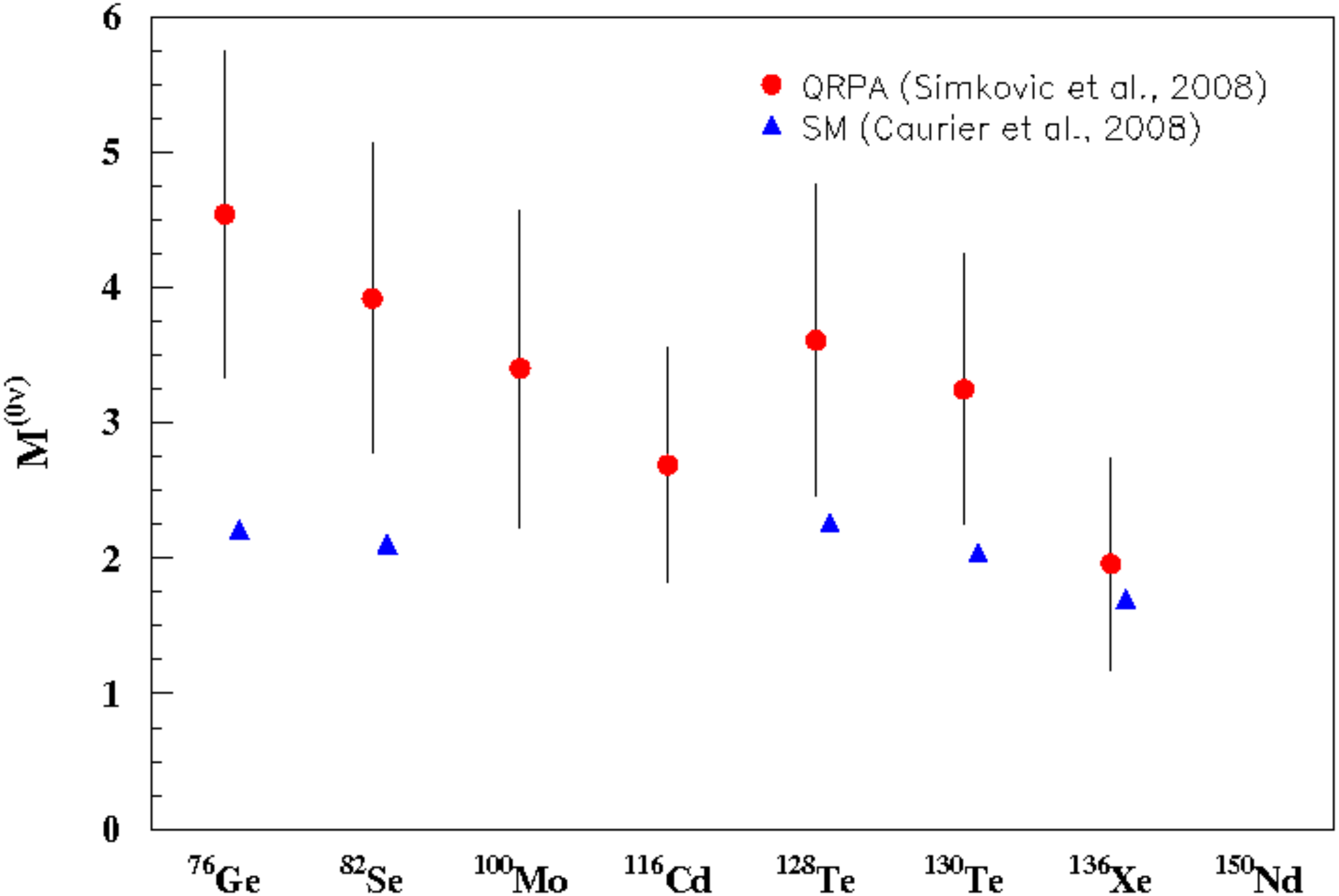
	Q (MeV)	abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$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

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



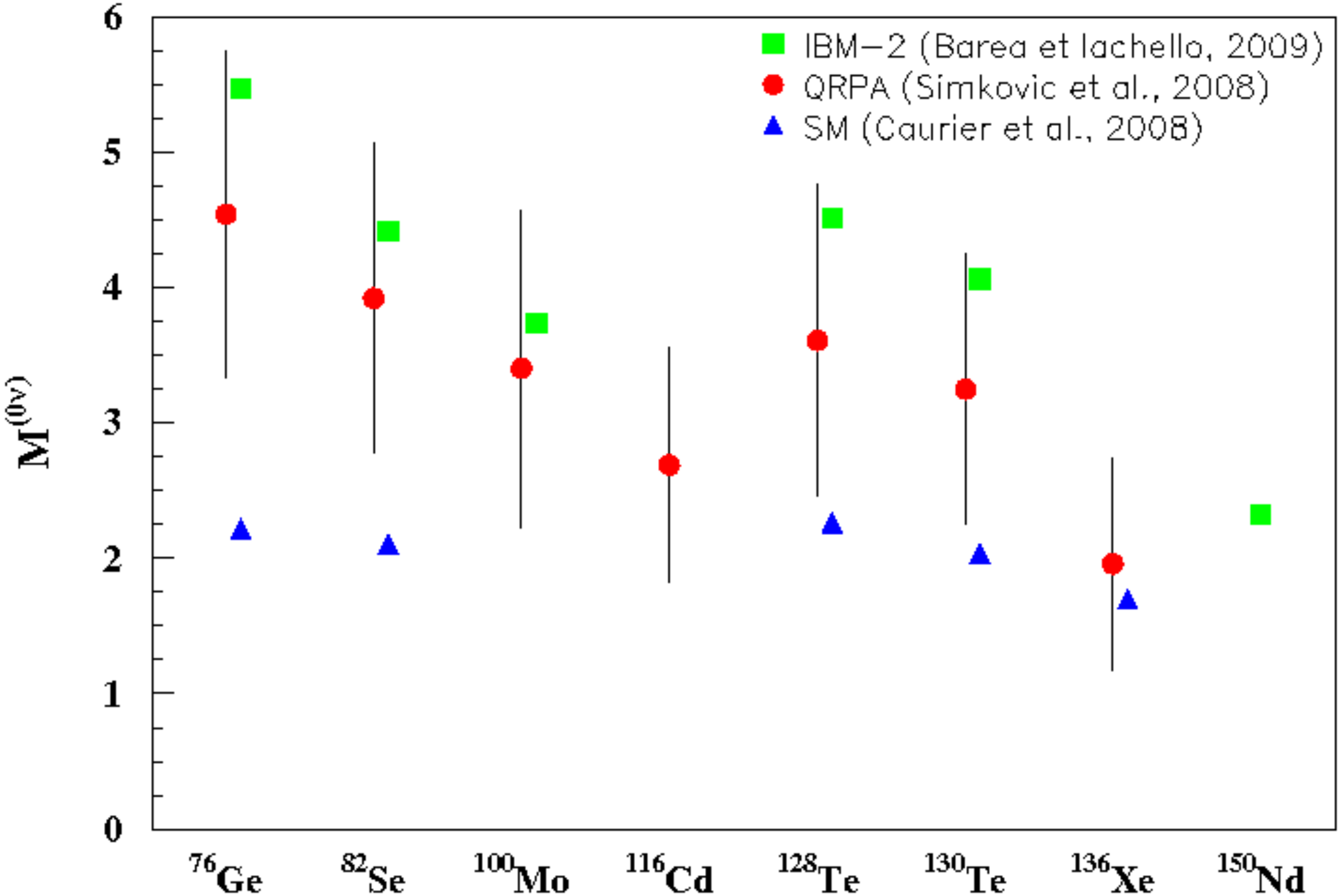
QRPA calculations from other groups give similar results

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



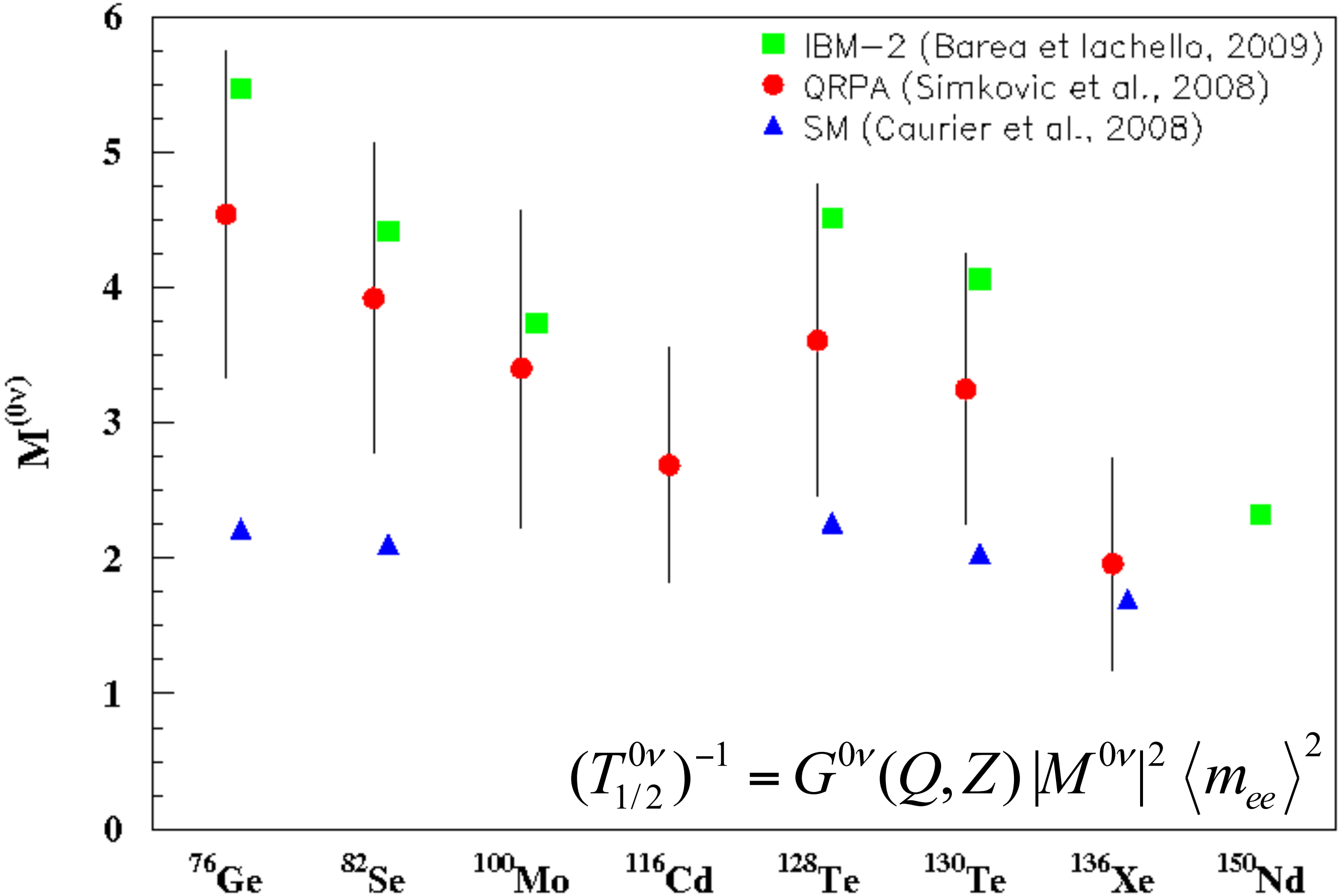
But shell model and QRPA calculations still disagree up to a factor 2 for lighter nuclei

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



IBM-2 calculations agree (coincide?) with QRPA values!
(IBM-2 includes deformations for ^{150}Nd)

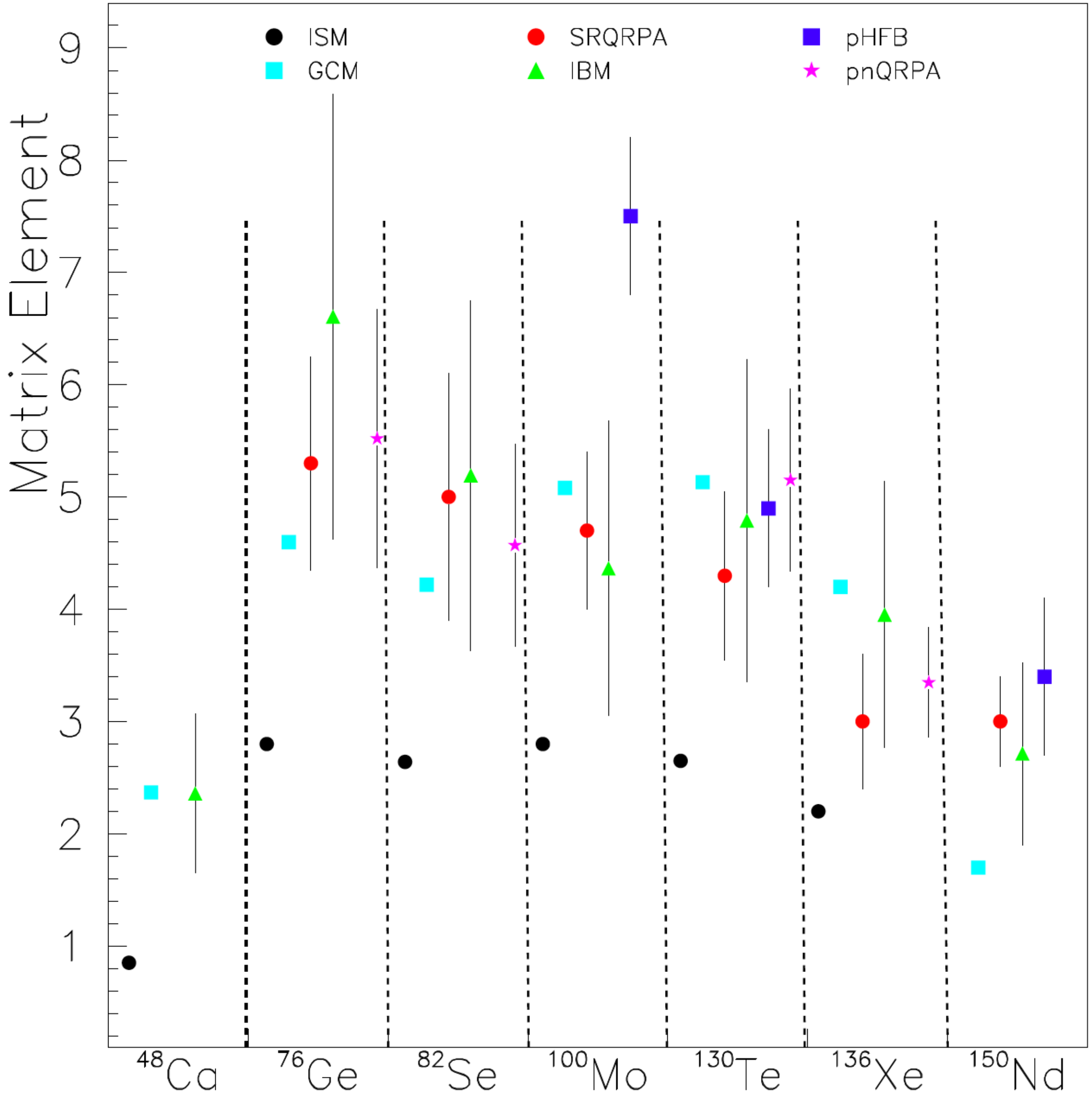
Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



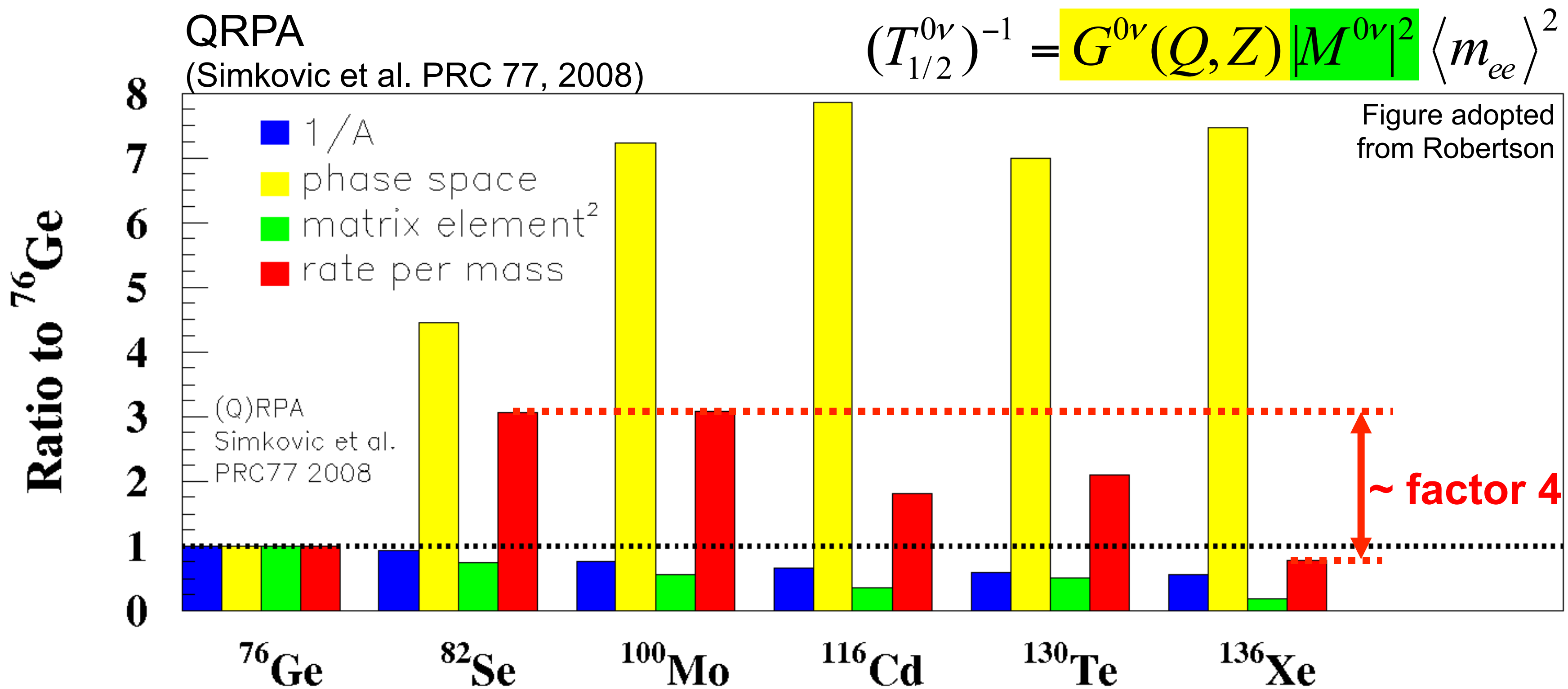
Is M decreasing with $A^{-2/3}$ (IBM-2, QRPA) or constant with A (SM) ?

Compilation of most recent NME calculations

(from Schwingenheuer,Annalen der Physik, 2012)

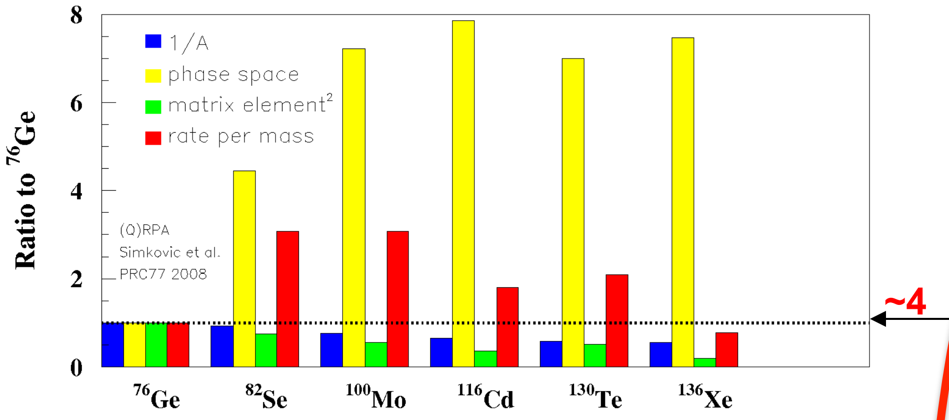


Comparison of isotopes: Is there a *super-DBD-isotope* ?



Expected 0νββ **rates per mass** vary within a factor ~ 4 !

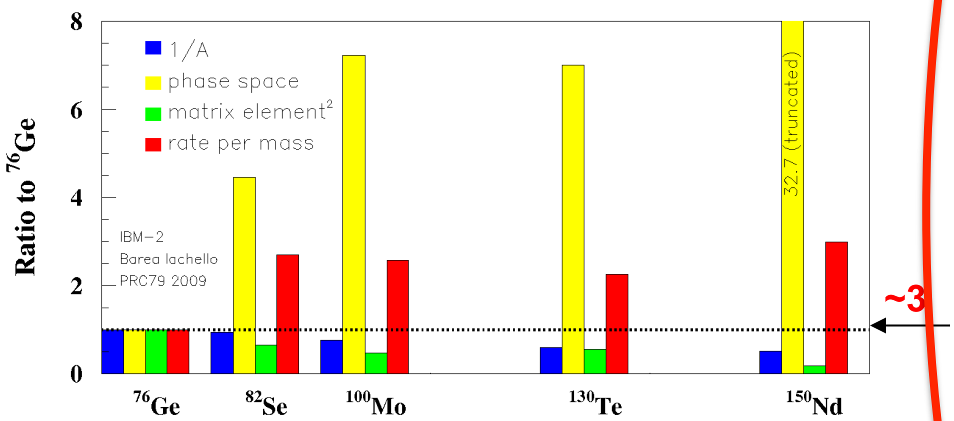
QRPA
(Simkovic et al. PRC 77, 2008)



for $\langle m \rangle = 50$ meV :

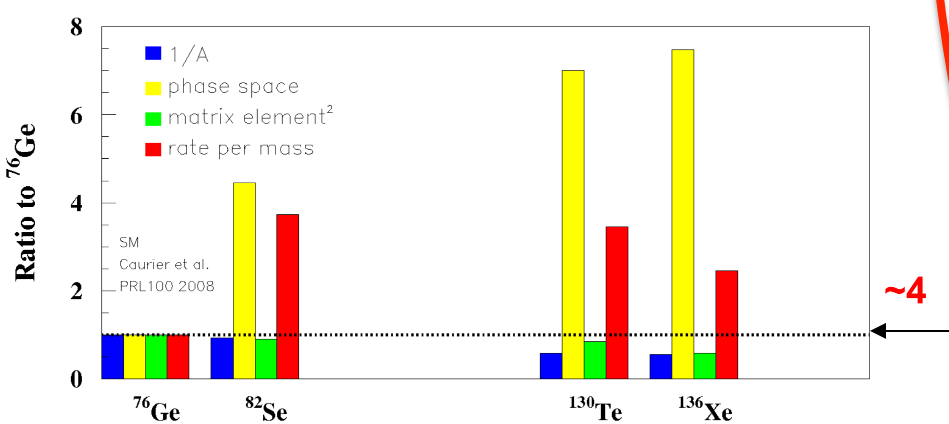
9.1 cts/(ton year)

IBM2
(Barea and Iachello, PRC 79, 2009)



13.2 cts/(ton year)

SM
(Caurier et al., PRL 100, 2008)



2.2 cts/(ton year)

Sensitivity versus exposure and background

Sensitivity: w/o background

Experimental life time

number of nuclides under control ∝ M

Time of measurement

$$\tau = \frac{N_N \; T}{N_S}$$

number of detected decays

Background free limit:
0 cnts in the analysis energy window ⇒ Poisson upper limit: N_P

Remember: $1/t_{1/2}(0\nu) = G\,M^2\,m^2_{ee}$

$$\tau \geq \frac{N_N \; T}{N_P} \propto \mathbf{M \cdot T} \quad \Rightarrow \quad \langle m \rangle < \frac{const}{(M\,T)^{1/2}}$$

Sensitivity: with background

If no decay is observed in presence of N_B background events in an energy window ΔE:

detector energy resolution

$$N_S < (N_B)^{1/2} \quad \Rightarrow \quad \tau > \frac{N_N\, T}{(N_B)^{1/2}}$$

$$N_B = b\, M\, T\, \Delta E$$

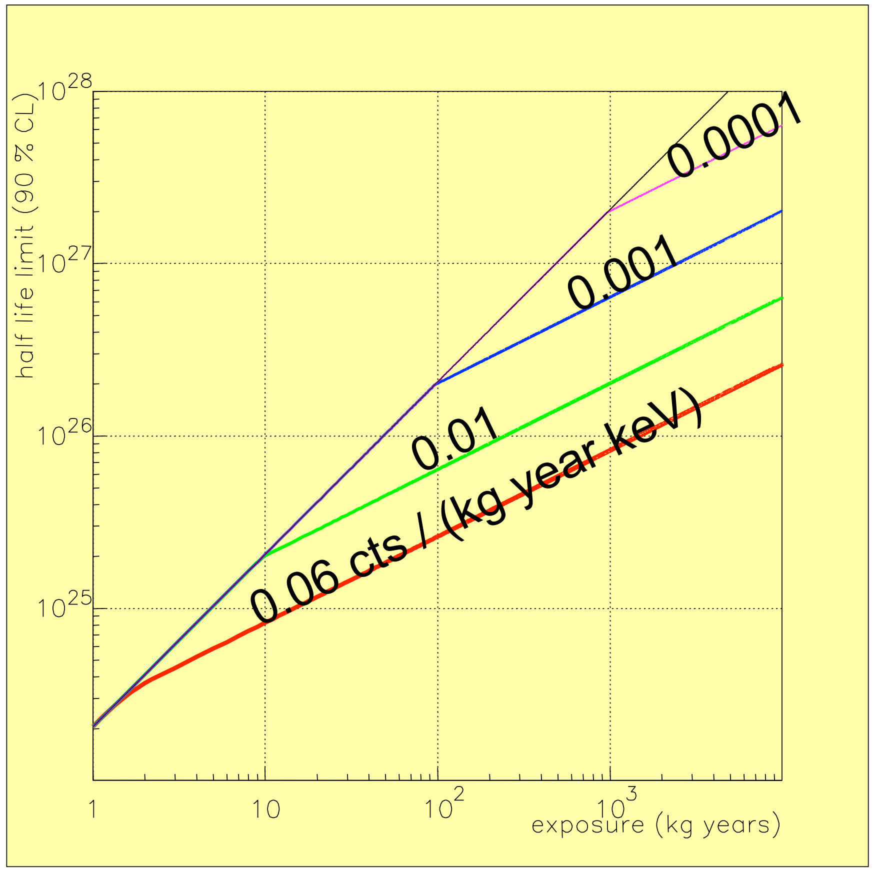
b: background index [1/(kg · year · keV)]

$$\Rightarrow \quad \tau > \frac{N_N\, T}{(b\, M\, T\, \Delta E)^{1/2}} \propto \left(\frac{M\, T}{b\, \Delta E}\right)^{1/2}$$

$$\Rightarrow \quad \langle m \rangle < \text{const.} \cdot \left(\frac{b\, \Delta E}{M\, T}\right)^{1/4}$$

Sketch of sensitivity for a Ge-experiment with and w/o background

10^{27}years



Sensitivity w/o background: $m_{ee} \propto (1 / M\ T)^{1/2}$

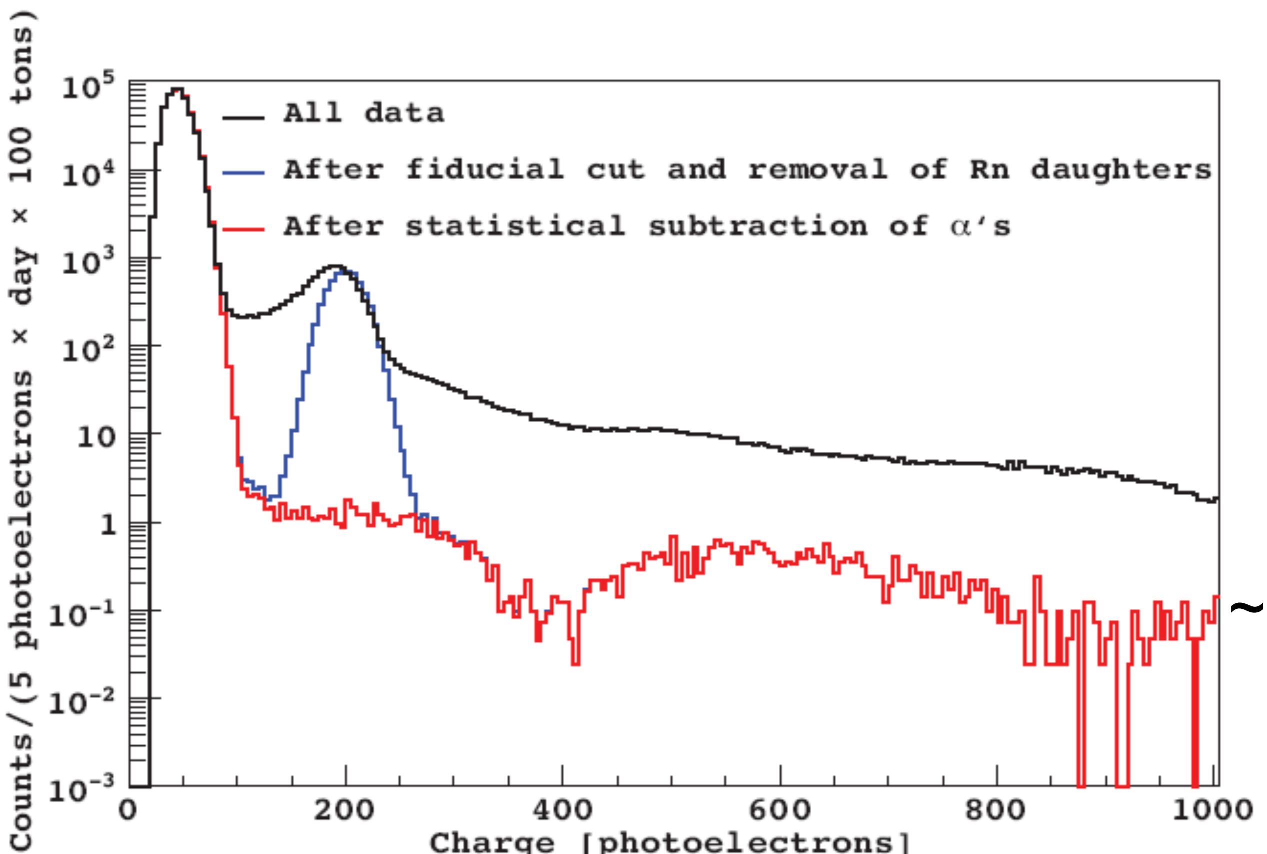
with background: $m_{ee} \propto (b\ \Delta E / M\ T)^{1/4}$

Remarks on sensitivity

- Exposure (= M T) essential
- Enrichment as high as possible: $b \propto M$
- Background reduction even more important then exposure: operate 'background free' within designed exposure
- Energy resolution:
  - w/o bgd : ΔE less critical $\Rightarrow$ limit !
  - with bgd: ΔE essential !
  - essential for discovery

Backgrounds

Borexino: lowest backgrounds ever achieved in counting experiment!



~2E-5 cts/(keV kg y)

(but energy resolution σ≈5%/√E(MeV))

2 MeV

$0\nu\beta\beta$ sginature vs. bgd

- $0\nu\beta\beta$:
  - Energy sum of electrons $E_{sum}=Q_{\beta\beta}$
  - point-like (in calorimeter)
  - two electron tracks (in tracko-cal, gas/solid TPC)
  - daughter isotope (no discrimination w/r to $2\nu\beta\beta$)
- background:
  - primary energy $\geq Q_{\beta\beta}$
  - residual energy is deposited somewhere else
  - different event topology (e.g. γ: MSE or escape)
  - different track topology
  - no daughter isotope

$Q_{\beta\beta}$ and background components

Natural radioactivity (^{40}K, ^{60}Co, ^{234m}Pa, external ^{214}Bi and ^{208}Tl…)

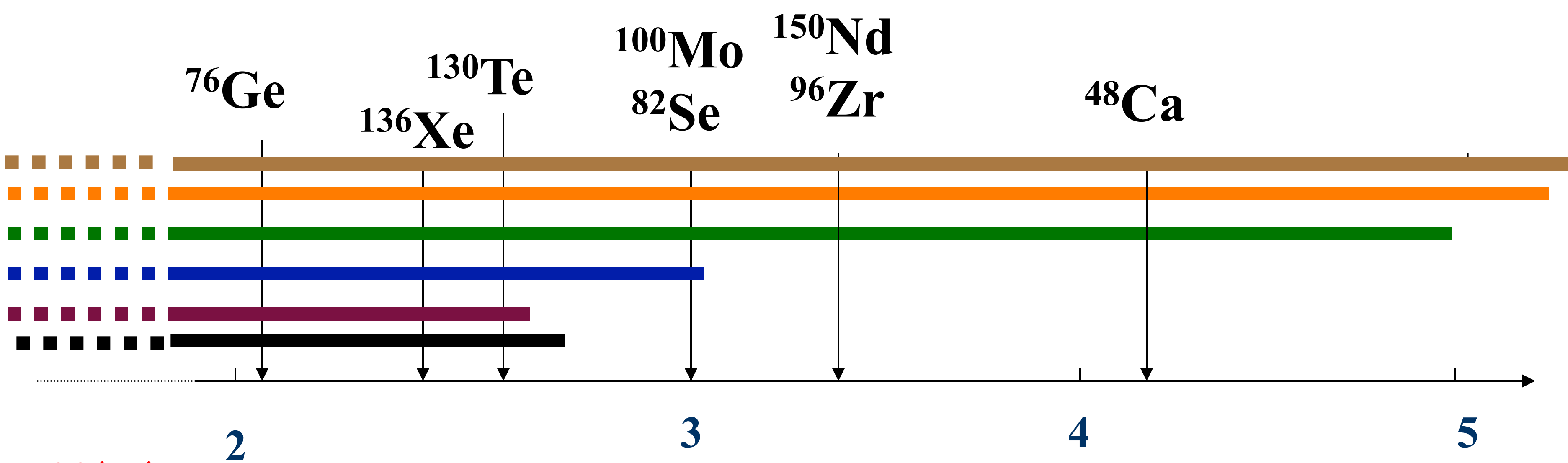
^{214}Bi and Radon

^{208}Tl (2.6 MeV γ line) and Thoron

γ from (n,γ) reaction and muon bremstrahlung

Surface or bulk contamination in α emitters

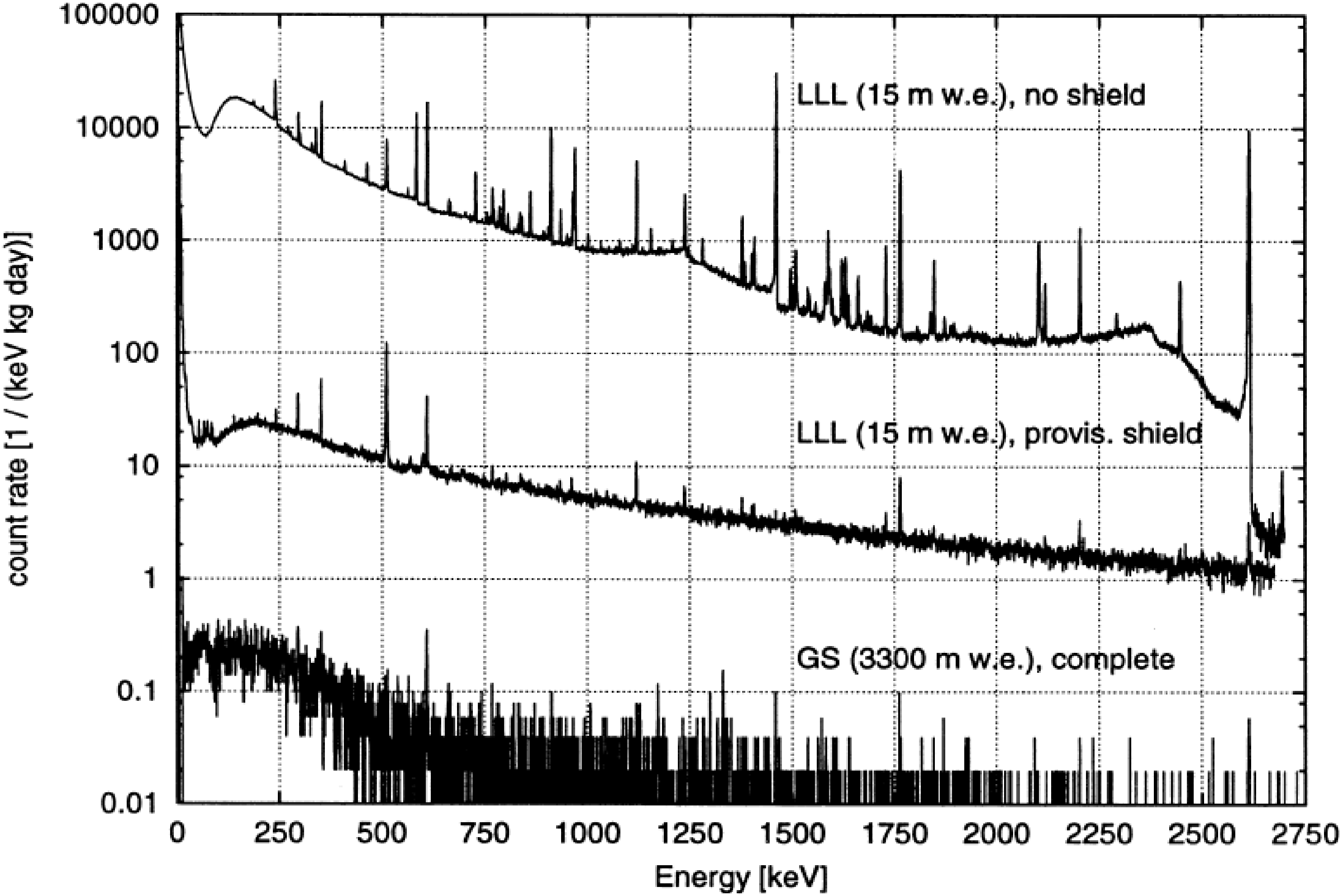
cosmogenic production



+ ββ(2ν) for tracko-calo or calorimeter with modest energy resolution

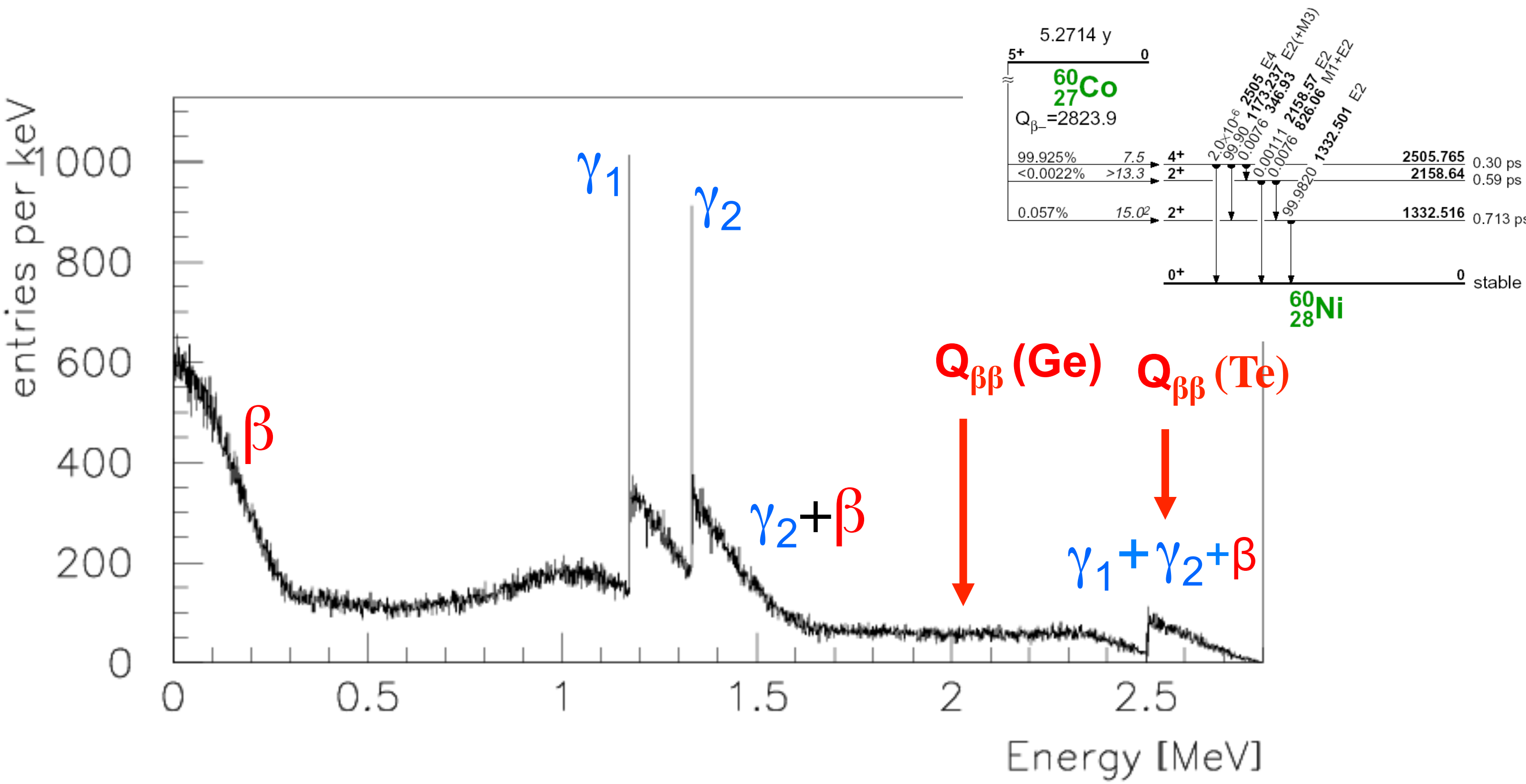
From F. Piquemal Taup 07

Underground location, high purity shielding and material selection:

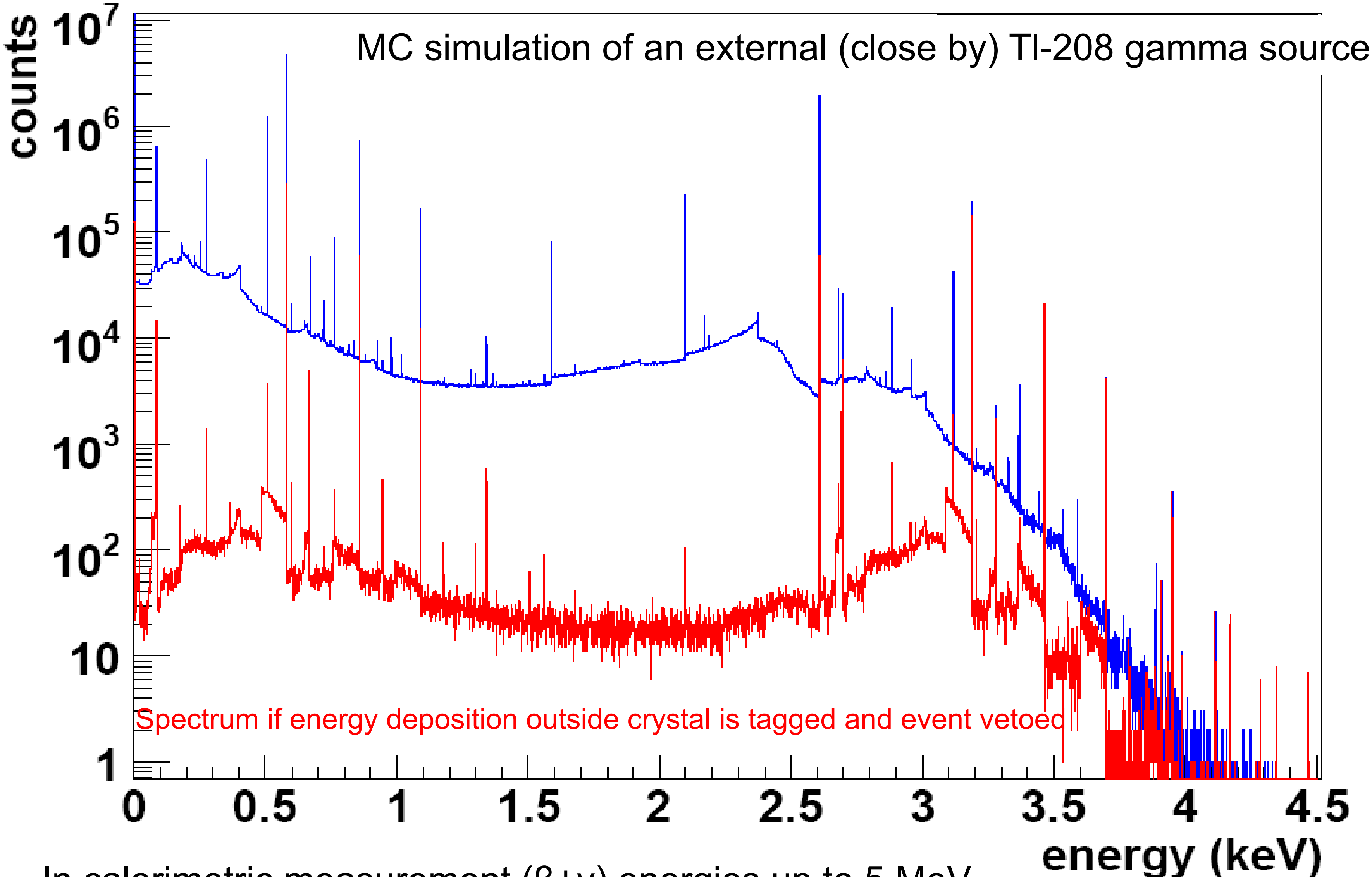


Background examples:

cosmogenic Co-60 inside Ge (similar in TeO2)

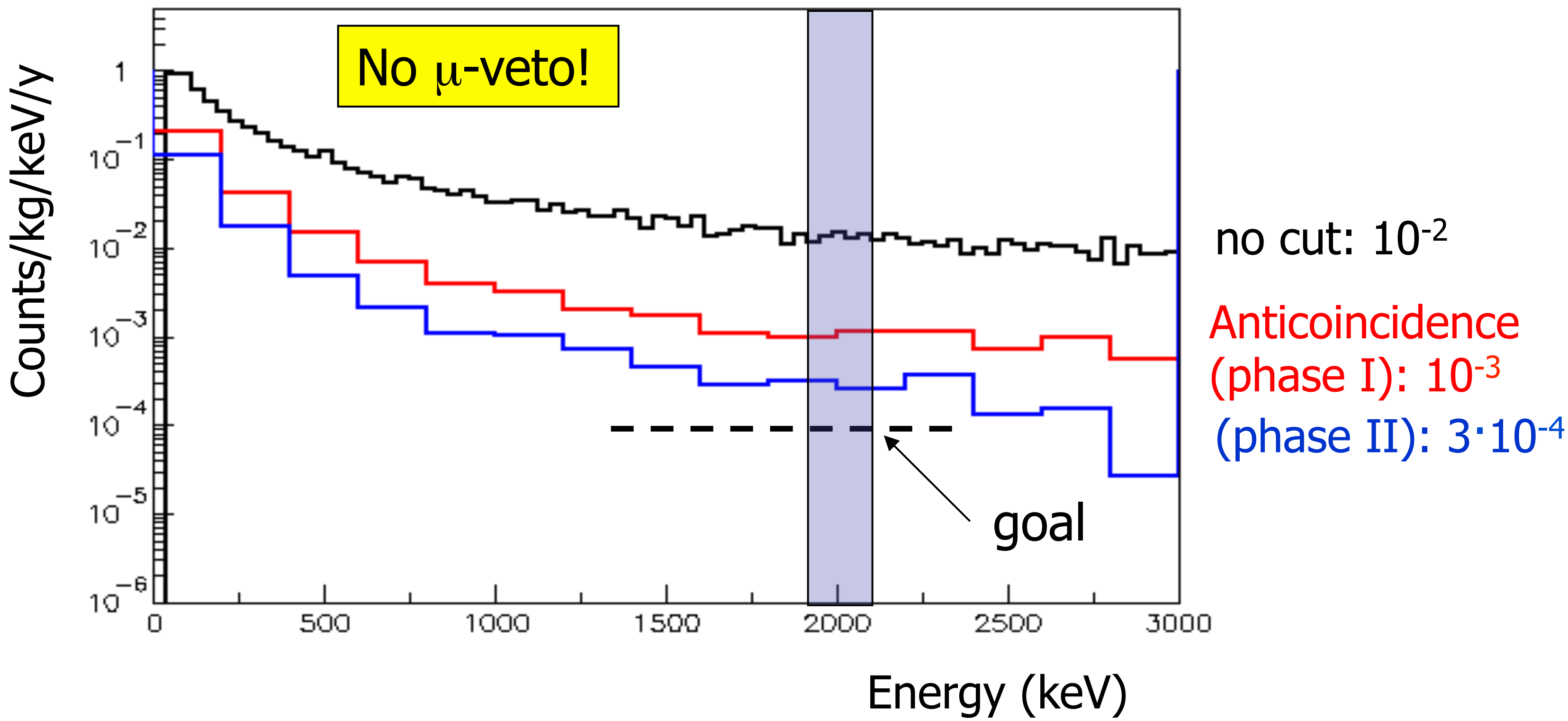


Background example: ^{232}Th (^{208}Tl) γ's



In calorimetric measurement (β+γ) energies up to 5 MeV

Background examples: Muon-induced prompt background in GERDA



Dominant contribution: secondary particles of EM shower induced by muons deep underground

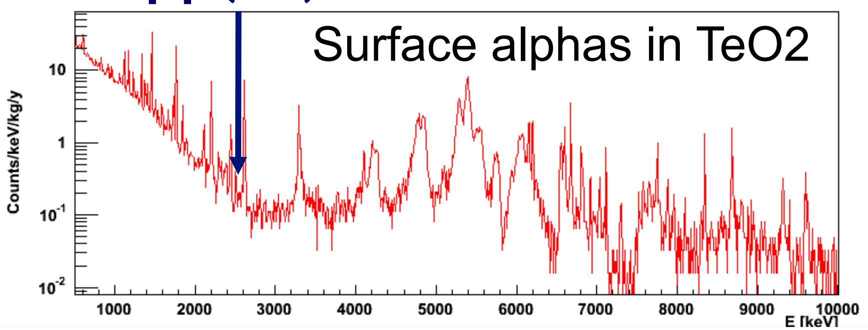
➔Efficient muon-veto required even for deep underground location

Examples for α, 2ν & Rn backgrounds

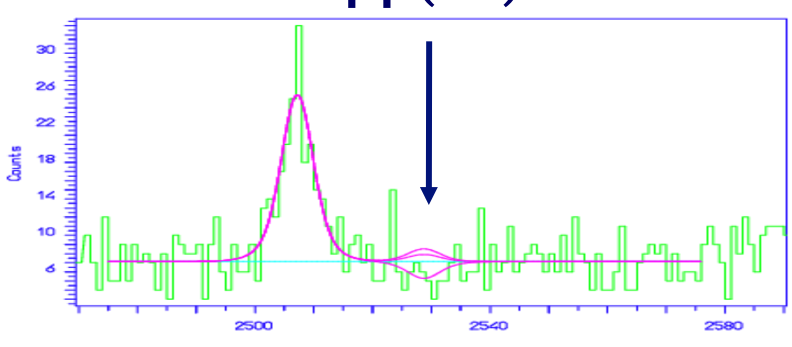
Calorimeter

High energy resolution
modest background rejection
(different in future experiments)

ββ(0ν)



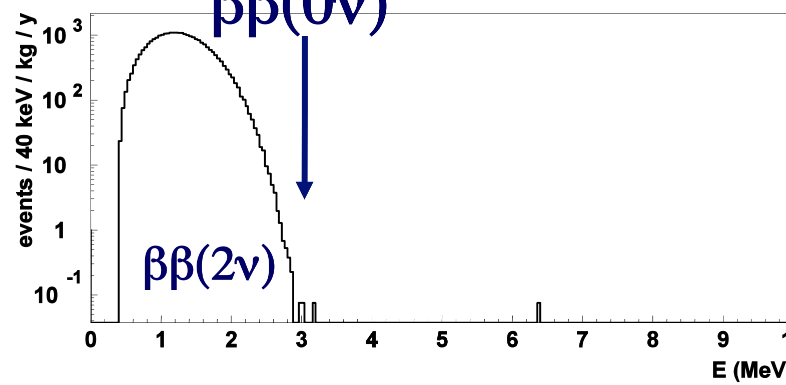
ββ(0ν)

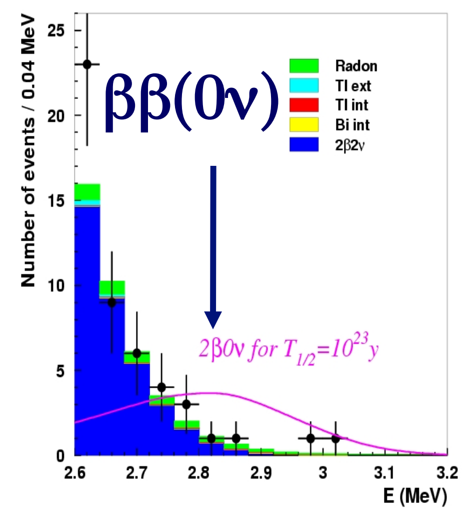


Tracko-calo

High background rejection
Modest energy resolution

ββ(0ν)





Results from Ge-76 experiments and & KK's claim

Heidelberg-Moscow Experiment @ LNGS

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 ± 1.3	No
No. 2	2.906	2.758	86.6 ± 2.5	Yes
No. 3	2.446	2.324	88.3 ± 2.6	Yes
No. 4	2.400	2.295	86.3 ± 1.3	Yes
No. 5	2.781	2.666	85.6 ± 1.3	Yes

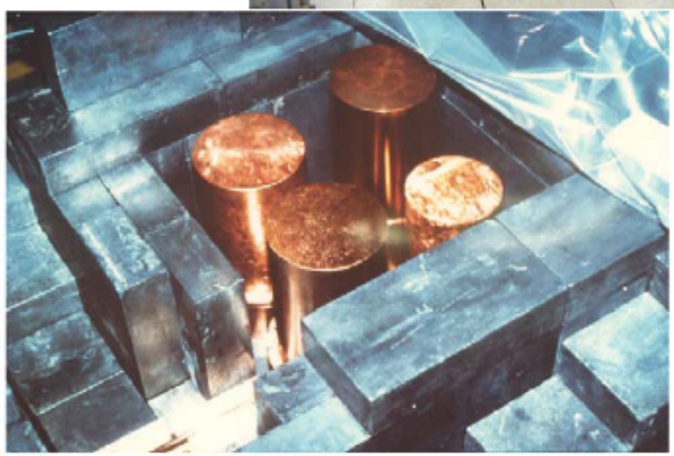


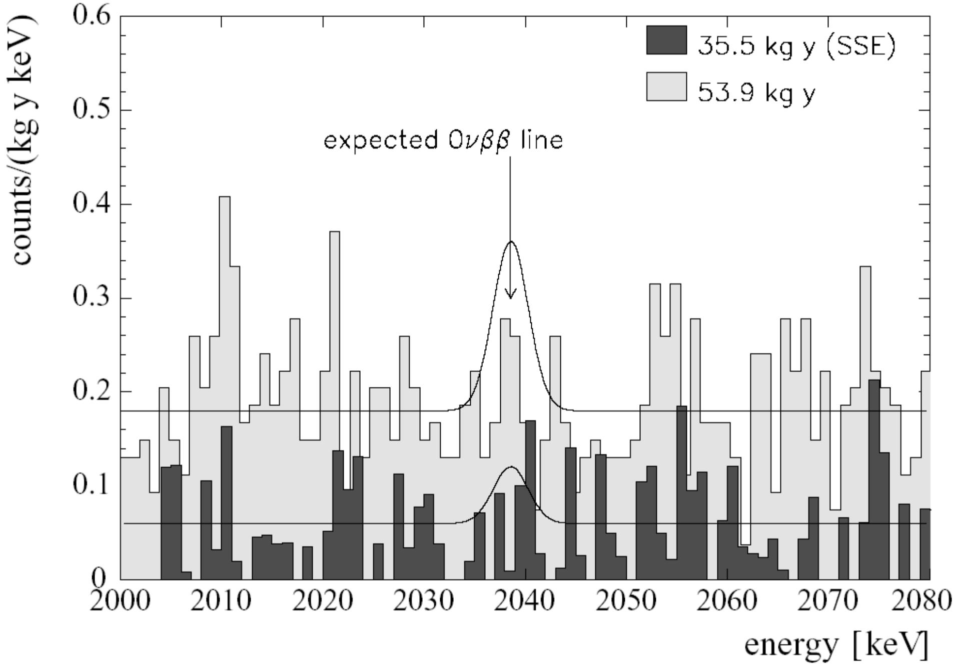
Fig. 1. The HEIDELBERG–MOSCOW ββ-experiment in the Gran Sasso (top), and four of the enriched detectors during installation (bottom left). The fifth detector was installed in an extra shielding using electrolytic copper as inner shield (bottom right).

Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

H.V. Klapdor-Kleingrothaus*[,1], A. Dietz, I.V. Krivosheina[2], O. Chkvorets

NIM A 522 (2004)

Heidelberg-Moscow



- Q(^{76}Ge) = 2.039 MeV
- 5 detectors operating @ LNGS
- 10.96 kg active mass (86% enriched)
- 125.5 mol of ^{76}Ge

$t_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y
$m_{ee} < 0.35$ eV (90% c.l.)

H.V. Klapdor-Kleingrothaus, A. Dietz, L. Baudis, G. Heusser, I.V. Krivosheina, S. Kolb, B. Majorovits, H. Paes, H. Strecker, V. Alexeev, A. Balysh, A.Bakalyarov, S.T. Belyaev, V.I. Lebedev, and S. Zhukov
Eur. Phys. J. A 12 (2001) 147

Experiment completed Nov. 2003

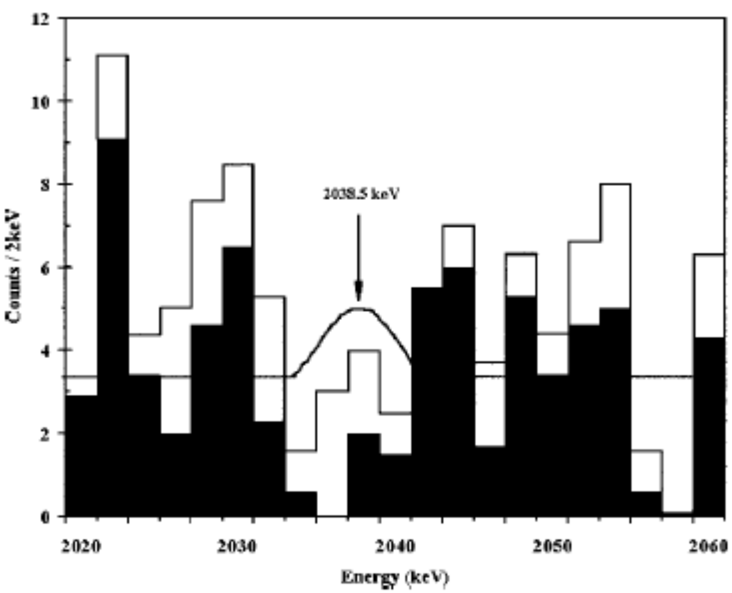
IGEX

PHYSICAL REVIEW D, VOLUME 65, 092007

IGEX ^{76}Ge neutrinoless double-beta decay experiment: Prospects for next generation experiments

C. E. Aalseth,[1,*] F. T. Avignone III,[1] R. L. Brodzinski,[2] S. Cebrian,[3] E. Garcia,[3] D. Gonzalez,[3] W. K. Hensley,[2] I. G. Irastorza,[3] I. V. Kirpichnikov,[4] A. A. Klimenko,[5] H. S. Miley,[2] A. Morales,[3] J. Morales,[3] A. Ortiz de Solorzano,[3] S. B. Osetrov,[5,†] V. S. Pogosov,[6] J. Puimedon,[3] J. H. Reeves,[2] M. L. Sarsa,[3] A. A. Smolnikov,[5] A. S. Starostin,[4] A. G. Tamanyan,[6] A. A. Vasenko,[4] S. I. Vasiliev,[5] and J. A. Villar[3]

(IGEX Collaboration)



Solid: all data; black: after PSD

117 mol year of Ge-76 (~ 10 kg y)
90% CL: < 3.1 events above bgd

$t_{1/2}^{0\nu} > 1.6 \times 10^{25}$ y
$m_{ee} < 0.33$ - 1.5eV (90% c.l.)

Claim for ββ(0ν) detection

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Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

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Abstract

Data acquisition in a long-running underground experiment has its specific experimental challenges, concerning data acquisition, stability of the experiment and background reduction. These problems are addressed here for the HEIDELBERG–MOSCOW experiment, which collected data in the period August 1990–May 2003. The measurement and the analysis of the data are presented. The duty cycle of the experiment was ~80%, and the collected statistics is 71.7 kg year. The background achieved in the energy region of the Q value for double beta decay is 0.11 events/kg year keV. The two-neutrino accompanied half-life is determined on the basis of more than 100 000 events. The confidence level for the neutrinoless signal has been improved to a 4σ level.

PACS: 14.60.Pq; 23.40.−s; 29.40.−n; 95.55.Vj

Keywords: Neutrino mass and mixing; Beta decay; Double beta decay; HEIDELBERG – MOSCOW experiment; High purity; Ge-detectors; Majorana neutrino

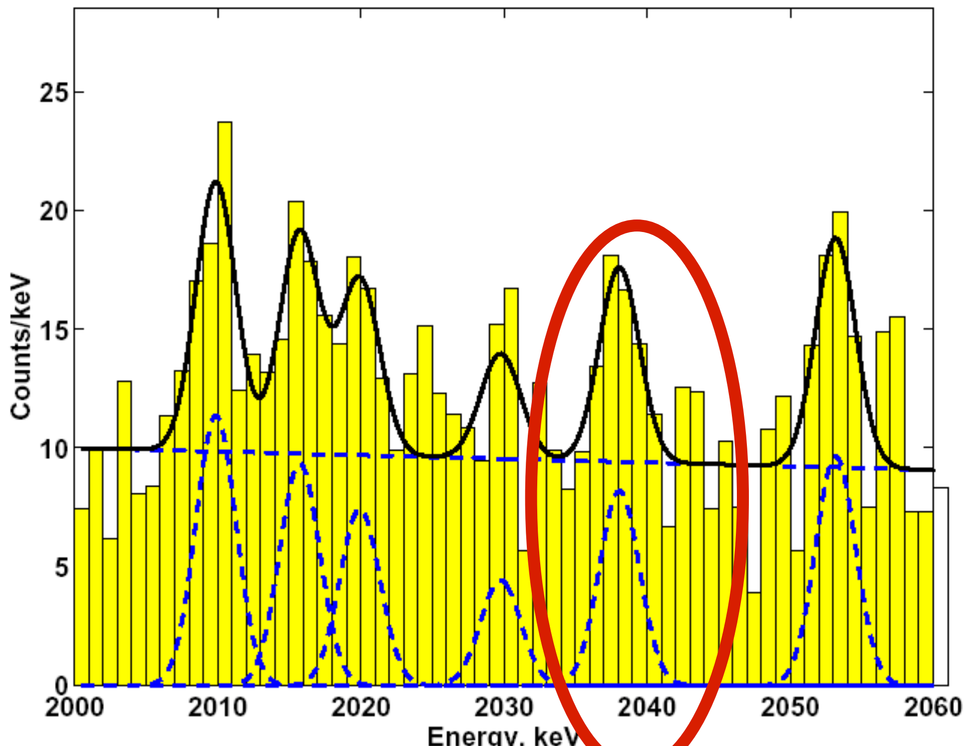


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

- Nov 1990- May 2003
- 71.7 kg year
- Bgd 0.11 / kg y keV
- 28.75 ± 6.87 events (bgd:~60)
- 4.2 sigma evidence for $0\nu\beta\beta$

- (0.69–4.18) $\times 10^{25}$ y (3 sigma)
- Best fit 1.19 $\times 10^{25}$ y

- m_{ee} = (0.24–0.58) eV
- best fit 0.44 eV

NB. Statistical significance depends on background model!

Criticisms

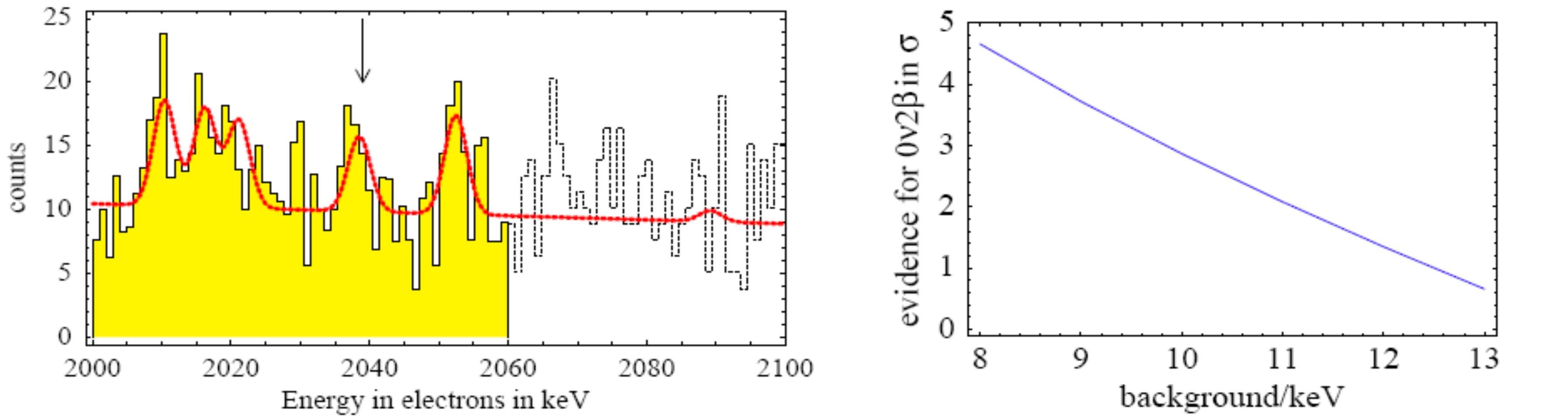
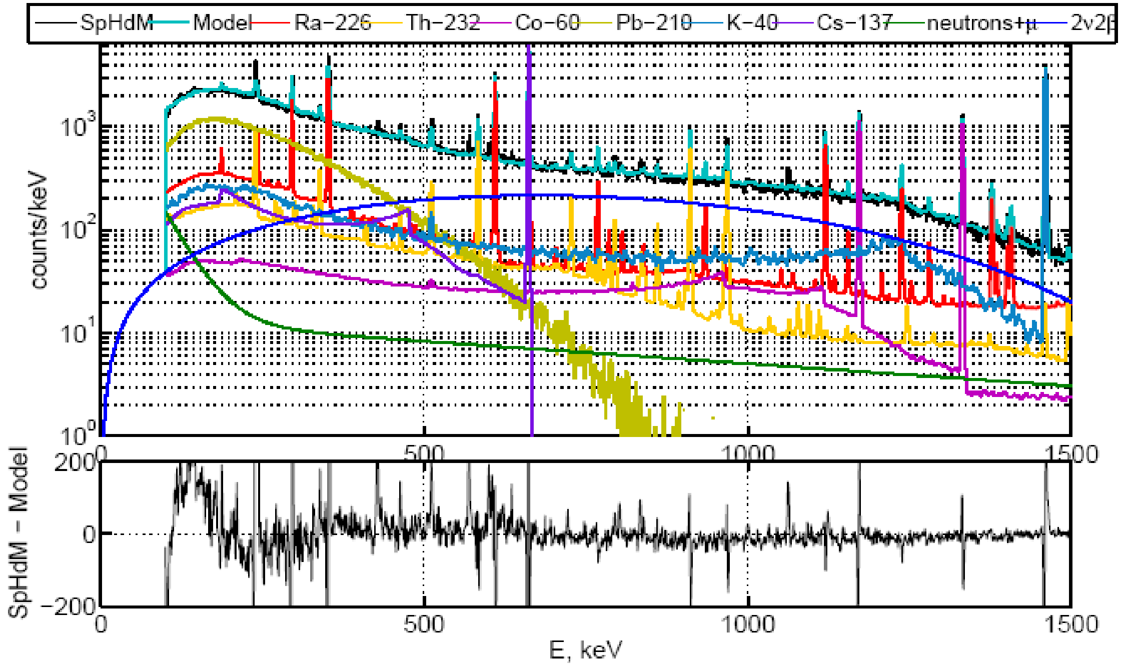
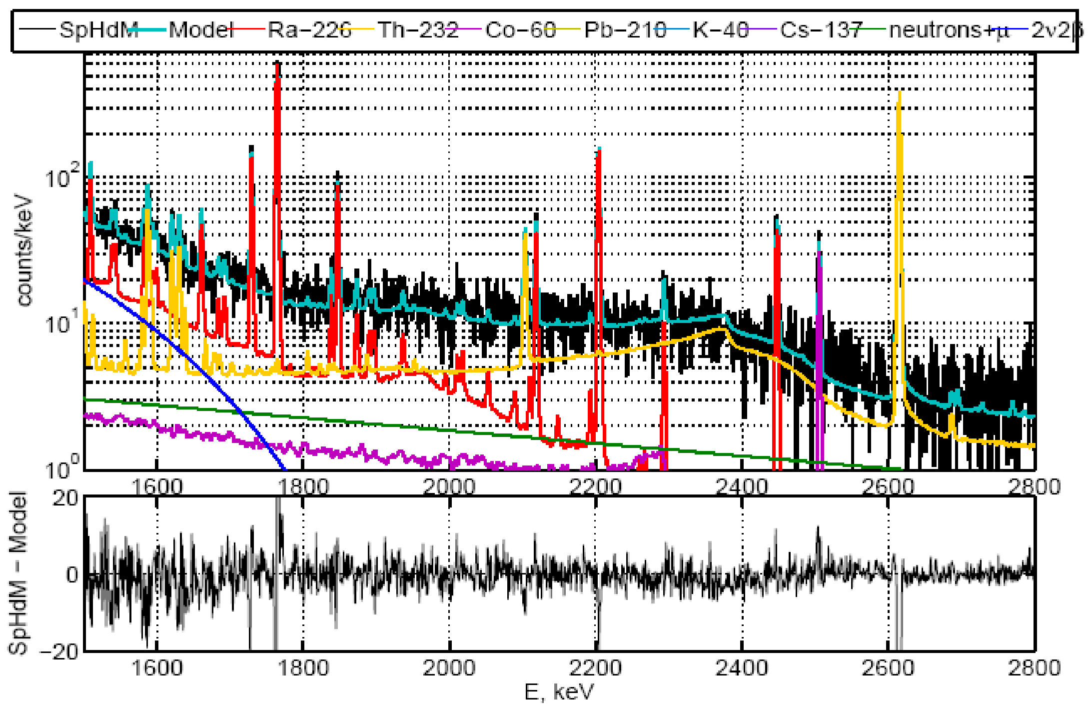


Figure 8: *Fig. 8a: the latest HM data [13]* (71.7kg · yr) *used to claim a* 4.2σ *evidence for* $0\nu2\beta$. *Fig. 8b: the statistical significance of the* $0\nu2\beta$ *signal, as function of the assumed flat component of the background.*

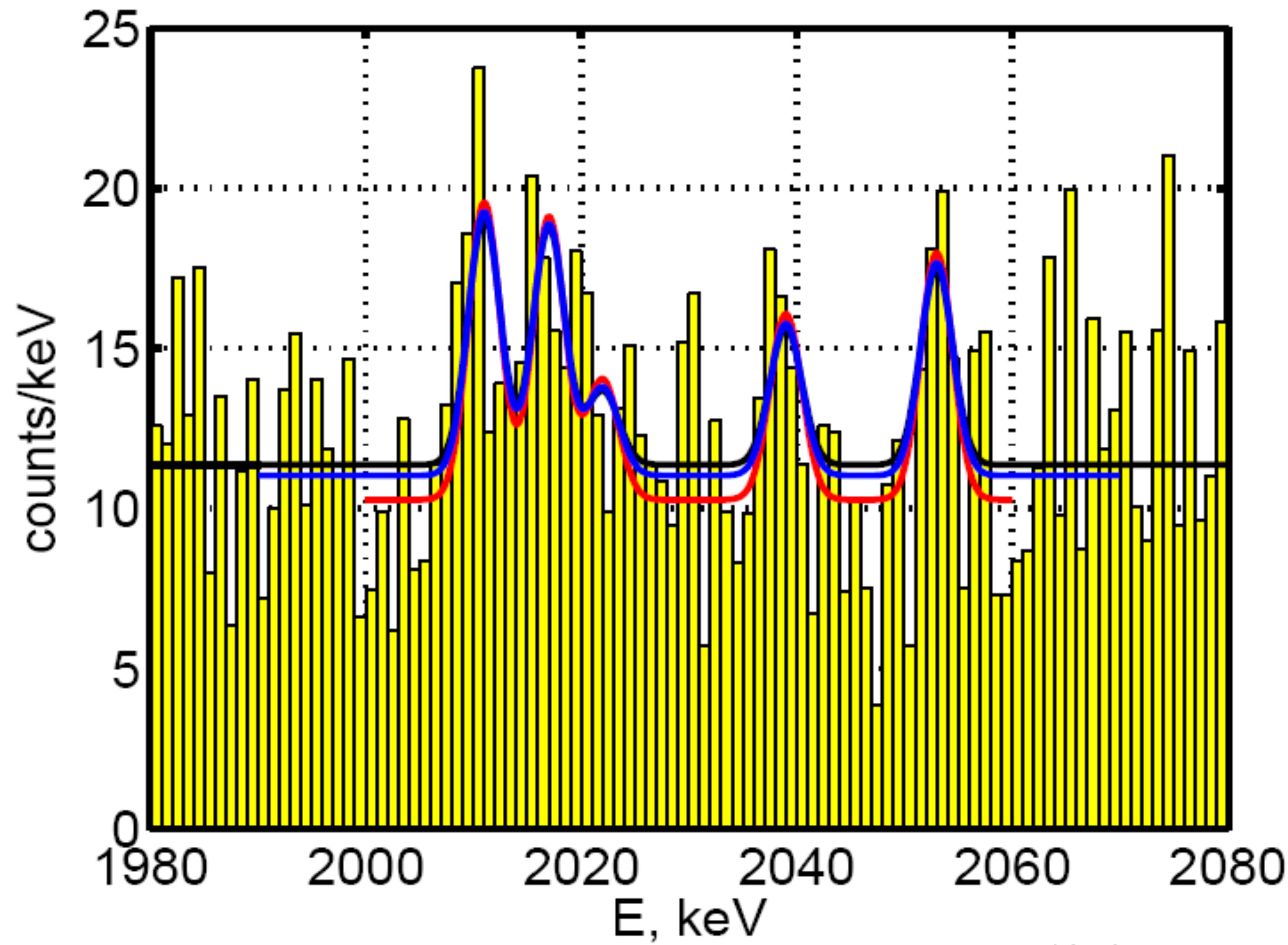
A. Strumia, F. Vissani





New background model for HdM data

(O.Chkvorets, Dissertation Univ. Heidelberg 2008)



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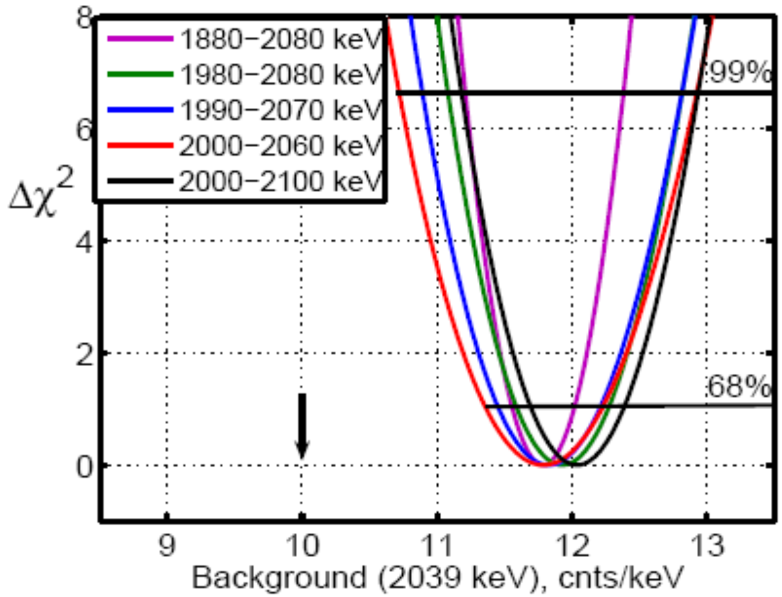


Figure 4.8: χ^2 as a function of the scaled model background for the five energy windows (Eq. 4.3). The arrow shows the background value obtained with an unconstrained fit (Fig. 3.13) in the 2000-2060 keV energy interval.

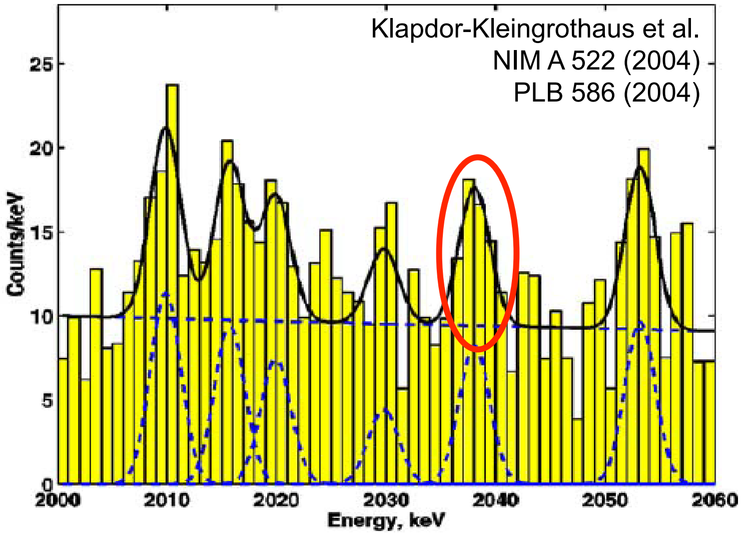
(O.Chkvorets, Dissertation Univ. Heidelberg 2008)

Method	E_{peak} [keV]	Peak area [counts]
$S_{Feldman-Cousins}$	2039.0	15±12
S_{Fit}	2038.1±1.3	13.0±8.5

Significance: ~1.3-1.5 σ !

Table 4.7: The 2039 keV peak intensity determined with Feldman-Cousins and LSQ methods using background 11.9±0.5 counts/keV.

As of early 2012: limits & claim



Significance and $T_{1/2}$ depend on bgd discription:
•Strumia & Vissani Nucl.Phys. B726 (2005)
•Chkvorets, PhD dissertation Univ. HD, (2008):
using realistic background model
$\Rightarrow$ peak significance: 1.3σ,
$\Rightarrow T_{1/2}$ = 2.2x10^{25} y

- •71.7 kg year - Bgd 0.11 / (kg y keV)
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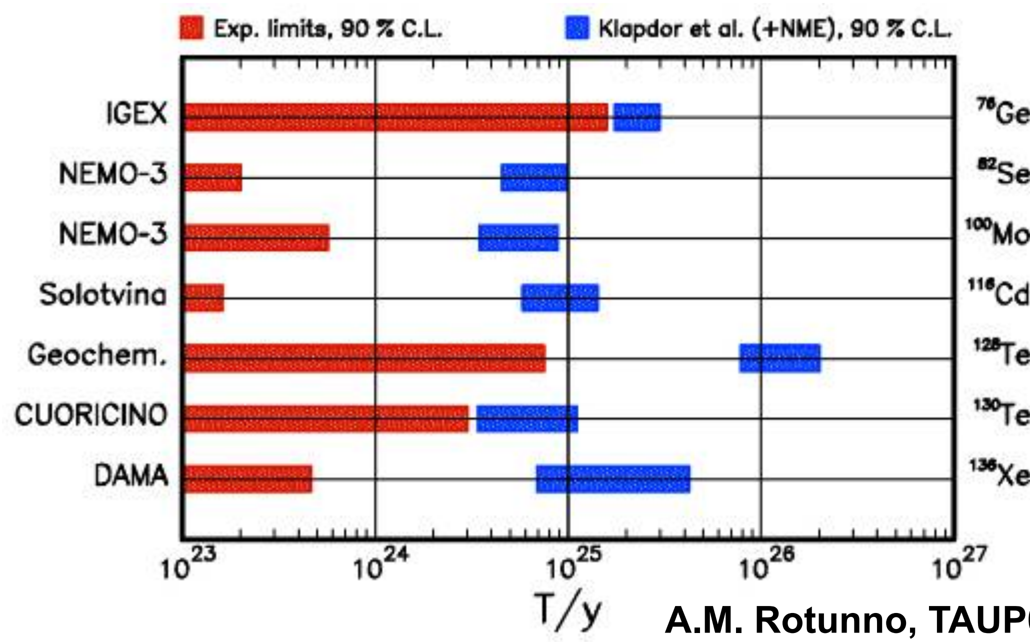
- Claim:4.2σ evidence for $0\nu\beta\beta$
- (0.69–4.18) x10^{25} y (3σ)
- Best fit: 1.19 x10^{25} y (NIMA 522/PLB 586)
- PSA analysis (Mod. Phys. Lett. A21): (2.23 + 0.44 – 0.31)x10^{25} y (6σ) (but analysis & results flawed….)
- Tuebingen/Bari group (PRD79): m_{ee} /eV = 0.28 [0.17-0.45] 90%CL



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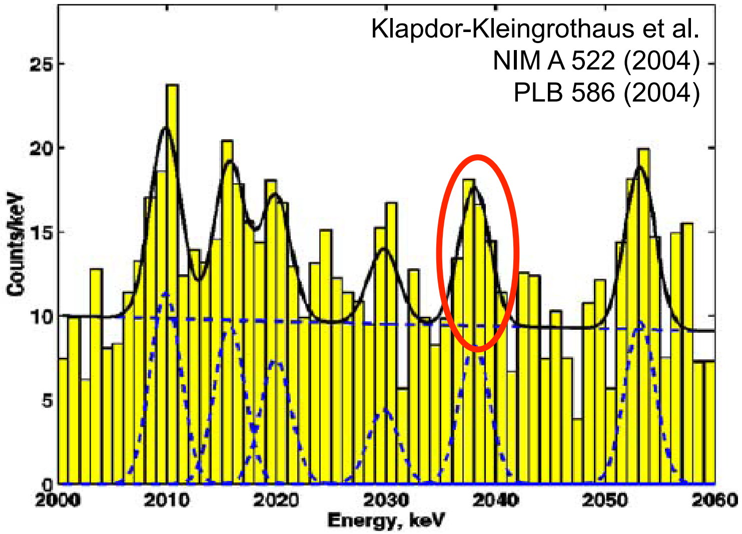
As of early 2012: limits & claim



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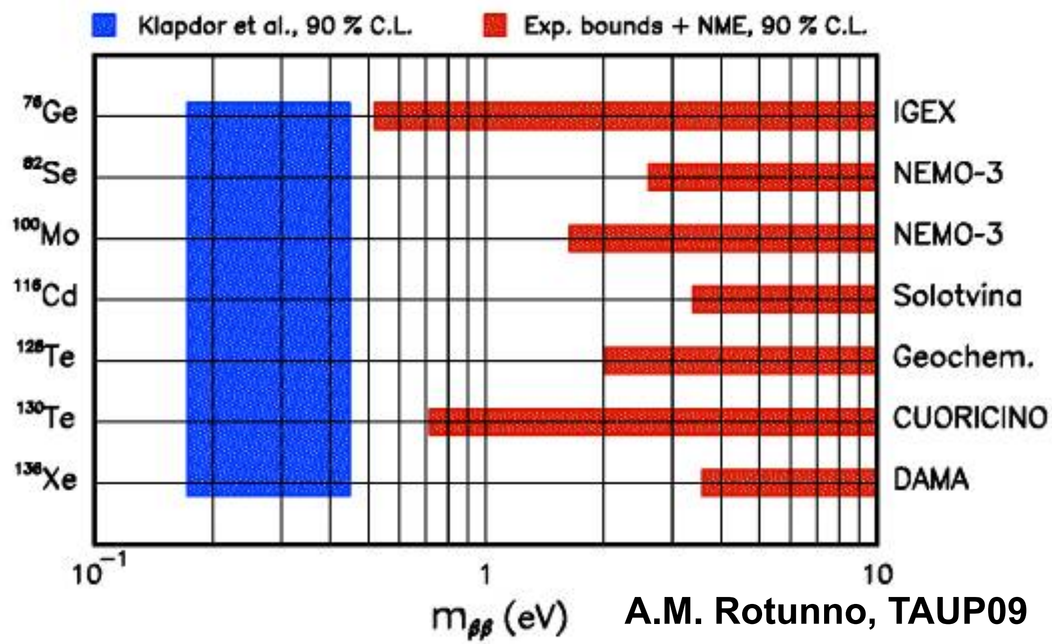
- Chkvorets, PhD dissertation Univ. HD, (2008): using realistic background model
  $\Rightarrow$ peak significance reduced to 1.3σ,
  $\Rightarrow T_{1/2}$ = 2.2$\times 10^{25}$ y



A.M. Rotunno, TAUP09

$\Rightarrow$ Claim must be scrutinized with ^{76}Ge AND other isotopes