Neutrinoless Double Beta Decay

Petr Vogel, Caltech

Lecture # 2

TASI-06, Boulder, June 13

i) Overview of the experimental status of the search for $\beta\beta$ decay.

ββ History

- ββ(2ν) rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? Background

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

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

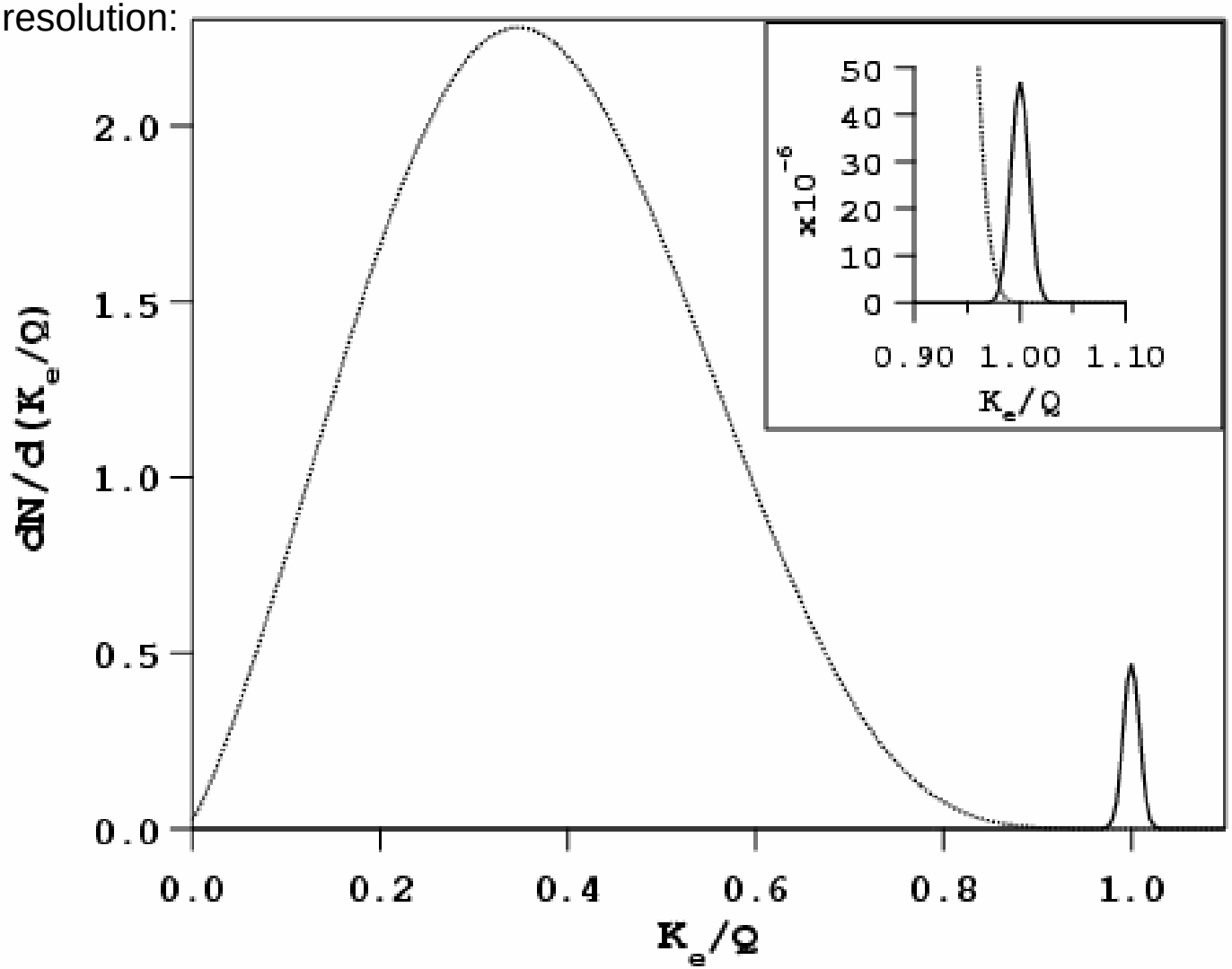
- But next we want to look for a process with:

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

Slide by S. Elliott

Separating the two modes: Finite resolution and unequal rates.
Ultimately we would like to observe the $0\nu\beta\beta$ transition with a rate that is $>10^6$ smaller than the $2\nu\beta\beta$ one

With 2% resolution:



ratio $1:10^6$

ratio 1:100

from S. Elliott

Candidate Nuclei for Double Beta Decay

	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow ^{48}Ti$	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

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

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

$^{(1)}$deduced from the geochemically determined half-life ratio ^{128}Te/^{130}Te
$^{(2)}$geochemical result includes all decay modes; other geochemical determinations only marginally agree
$^{(3)}$radiochemical result, again for all decay modes

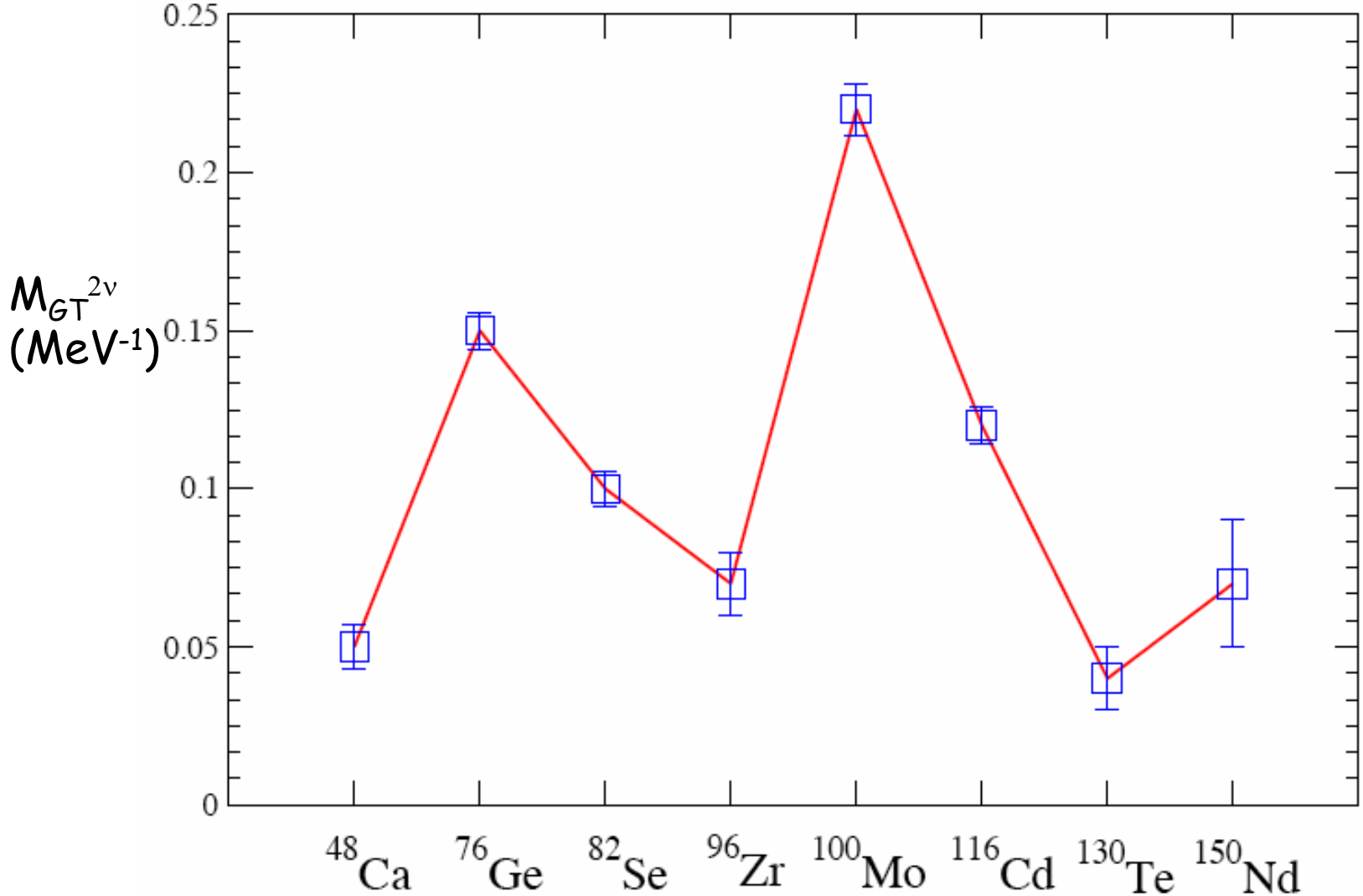
$$1/T_{1/2} = G(E,Z)\,(M_{GT}^{2\nu})^2$$

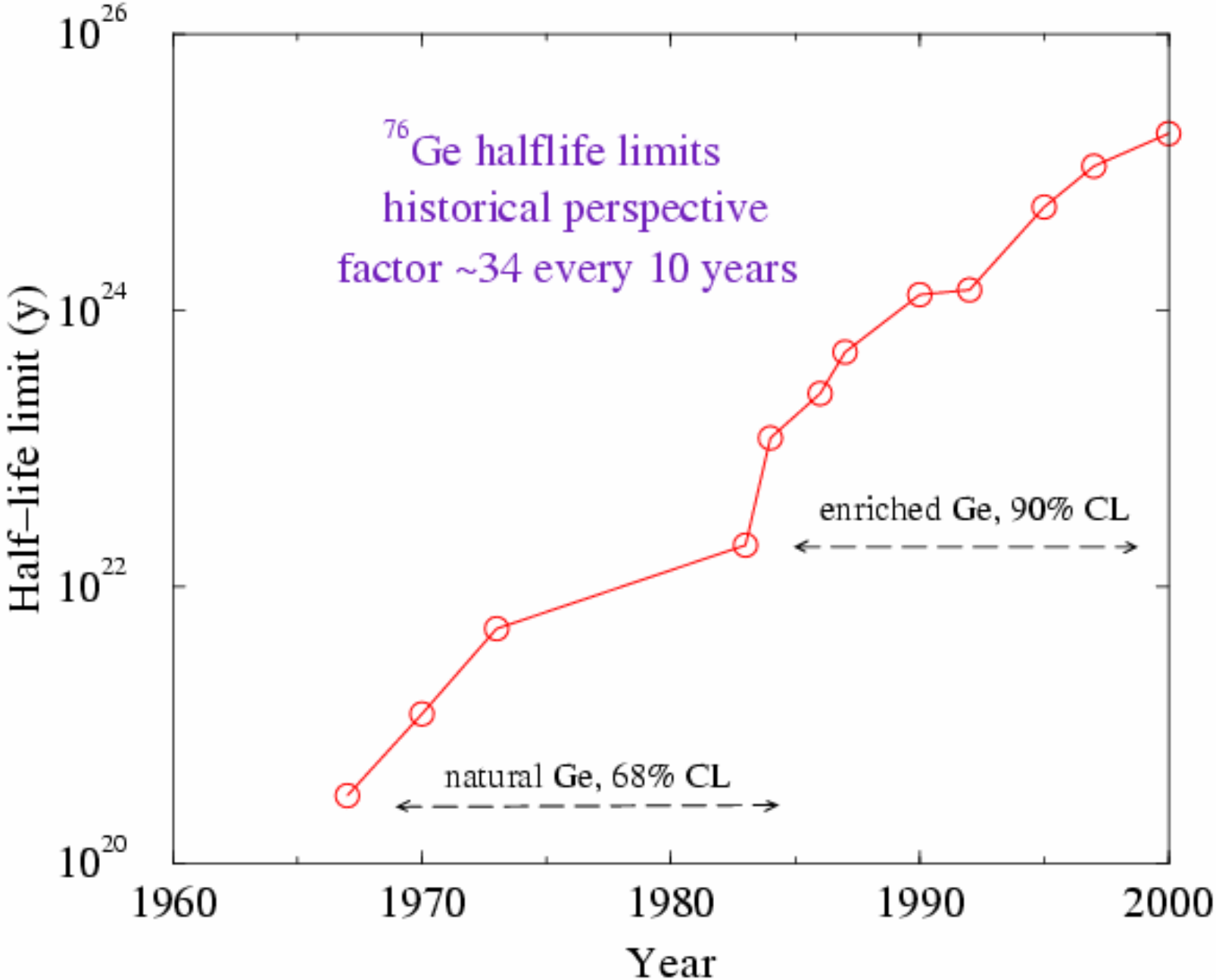
$$M^{2\nu}_{GT} = \Sigma_m \frac{\langle f|\vec{\sigma}\tau^+|m\rangle \cdot \langle m|\vec{\sigma}\tau^+|i\rangle}{E_m - (M_i + M_f)/2}$$

Nuclear matrix elements for the 2ν decay deduced from measured halflives.
Note the pronounced shell dependence.

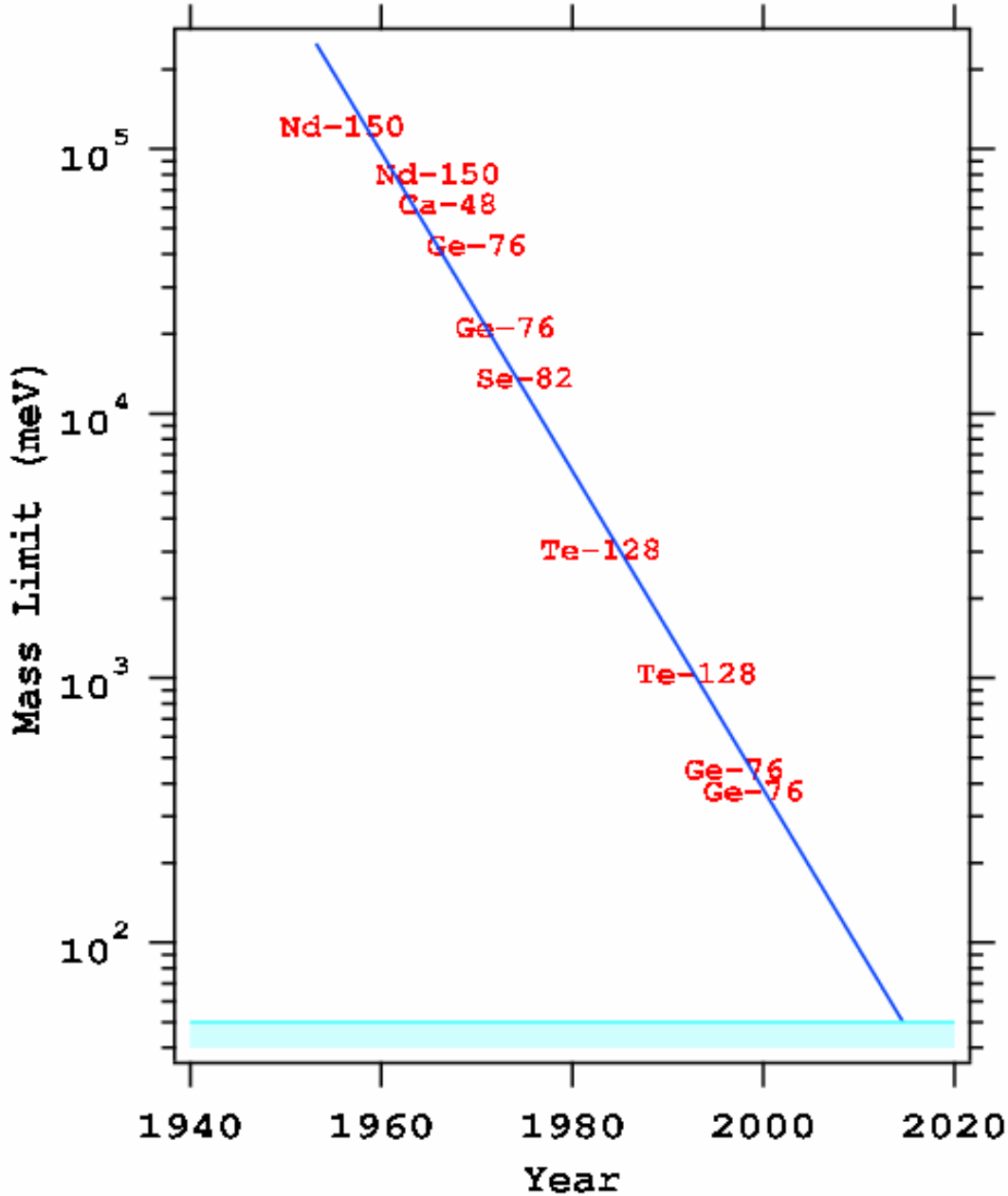
$1/T_{1/2} = G(E,Z)\,(M_{GT}^{2\nu})^2$

easily calculable phase space factor




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

Moore's law in $0\nu\beta\beta$ decay (progress in the last ~50 years)

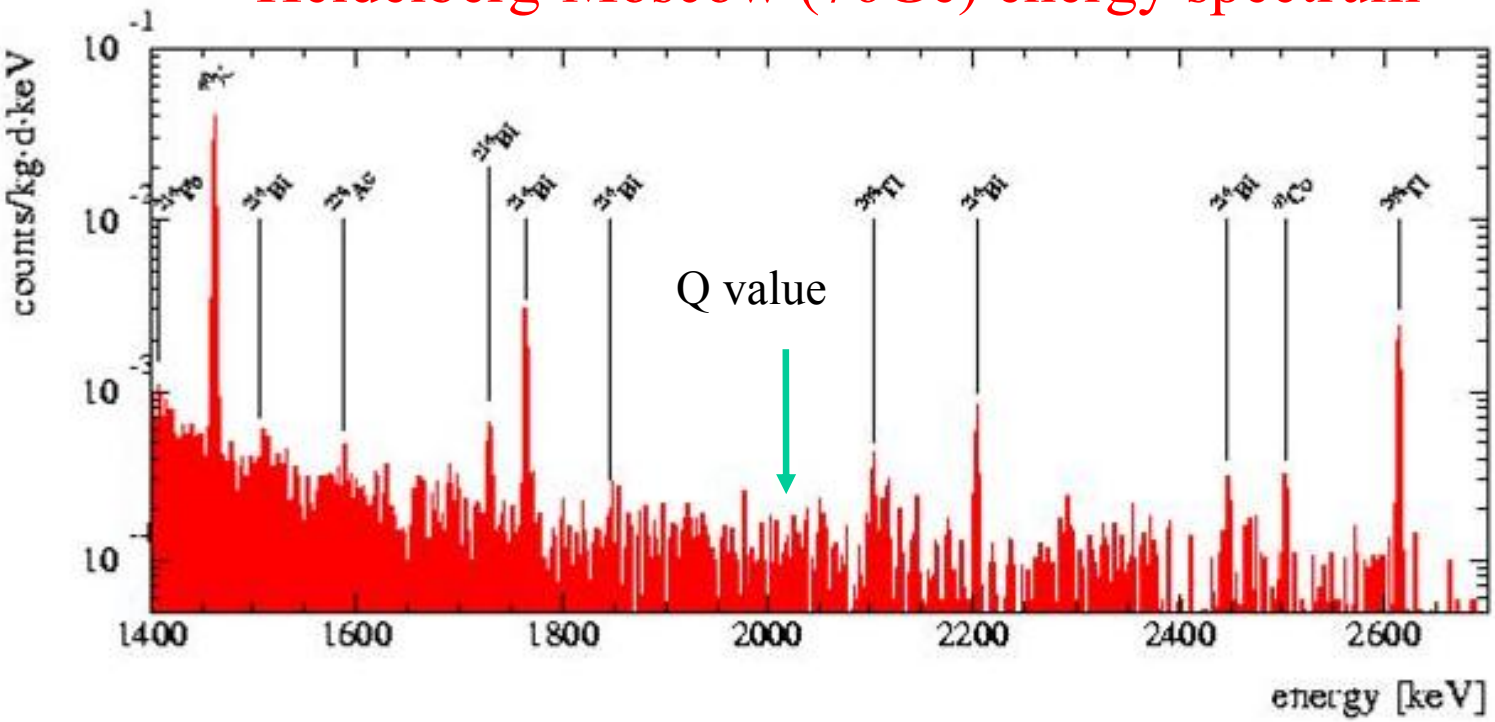


$\langle m_{\beta\beta} \rangle < 1/[M^{0\nu}(G_{0\nu}T_{1/2})^{1/2}]$,
and use the $T_{1/2}$ limits

from S. Elliott

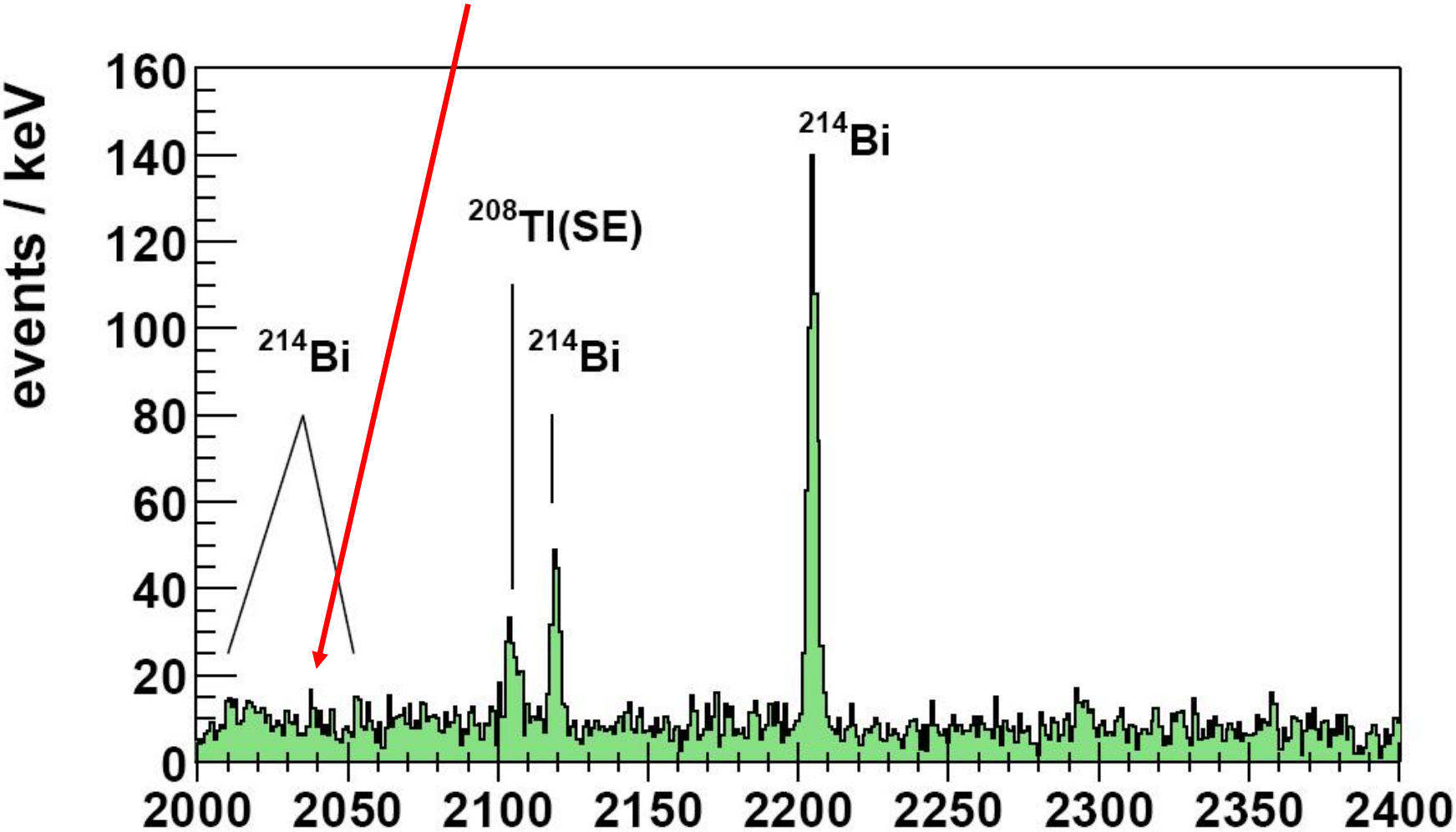
The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum



Half-life limit: 1.9 x 10^{25} years (H-M and IGEX)
Majorana neutrinos ruled out for masses greater than ~0.35-1.0 eV

ββ0ν discovery claim



HV. Klapdor-Kleingrothaus, et. al,
Nuclear Instruments and Methods A **553** (2004) 371-406

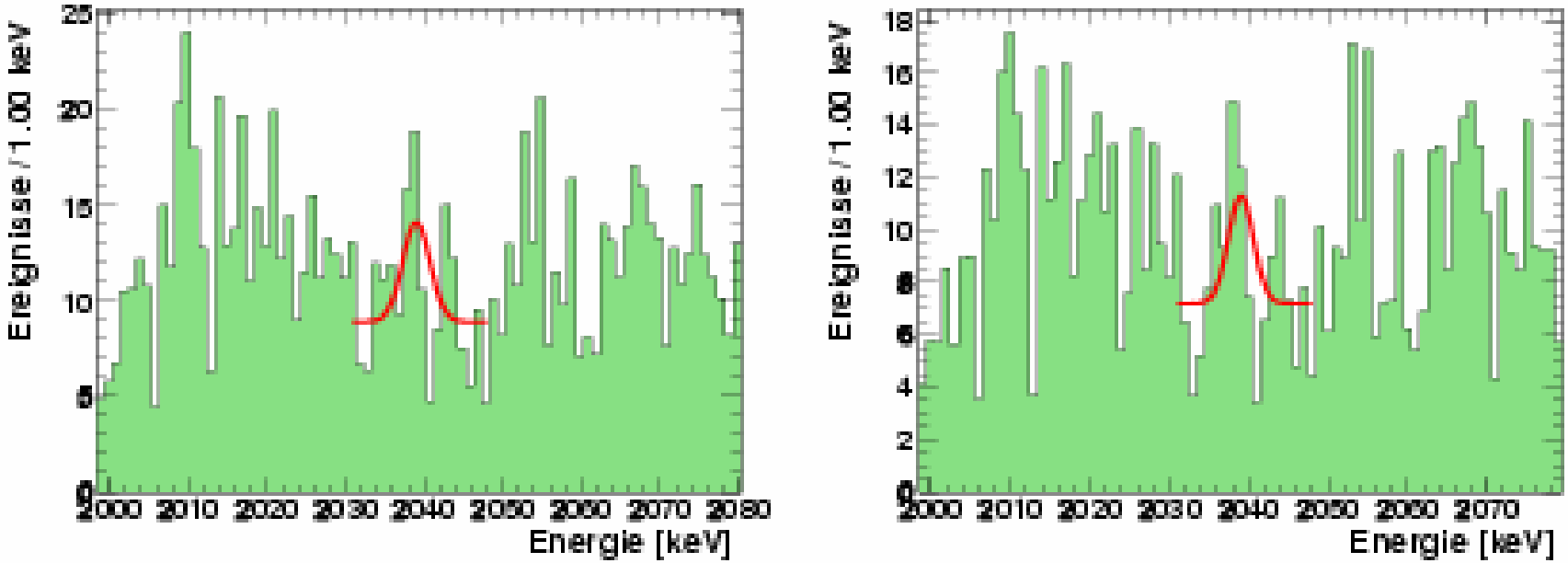


Abbildung 6.13: Darstellung des Summenspektrums mit den Daten von August 1990 bis November 2002 für alle fünf Detektoren (links, 70.62 kg y) und ohne Detektor ANG4 (rechts, 55.57 kg y). Die eingezeichnete Linie ist ein Fit an eine Gaußlinie bei einer Energie von 2039.006 keV im Bereich von 2031 bis 2048 keV.

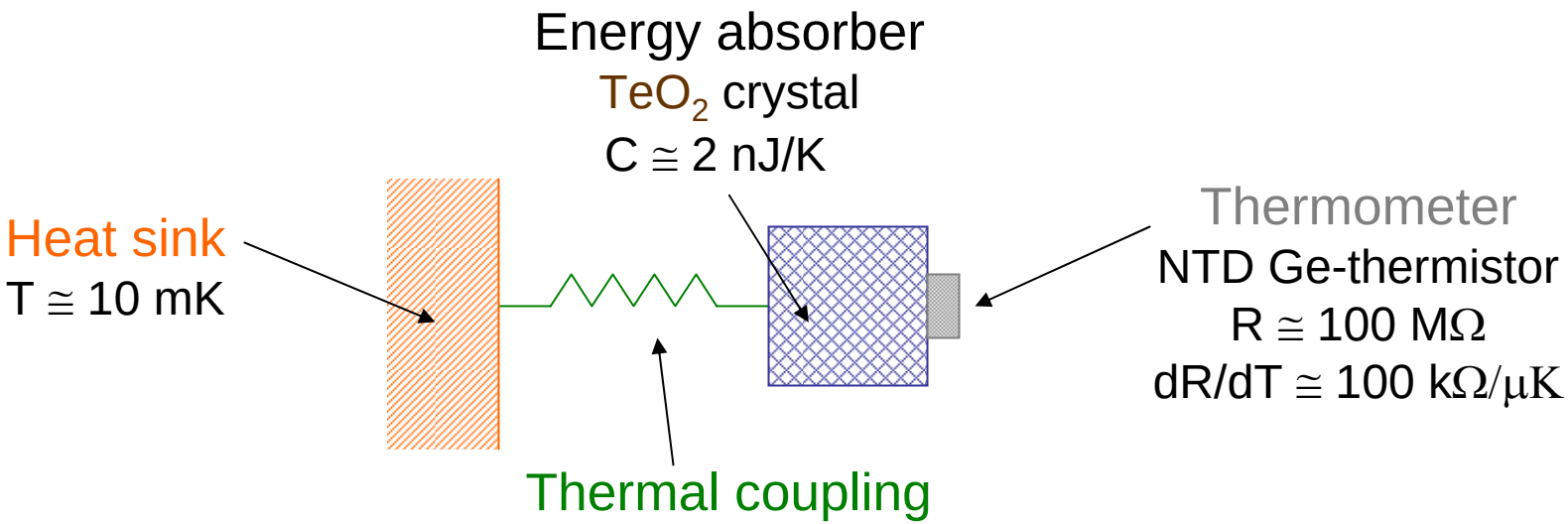
Halflife deduced: $1.50^{+7.55}_{-0.71} \times 10^{25}$ y at 95%C.L.

Brief review of competing next generation proposals CUORE, EXO, GERDA,MAJORANA

designed to explore the `degenerate' mass region $\langle m_{\beta\beta} \rangle > 0.1$ eV with ~100 kg sources of decaying nuclei. All of these, if their background projections are confirmed, can be scaled to ~ton size sources capable of exploring most of the `degenerate' neutrino mass region.

CUORE

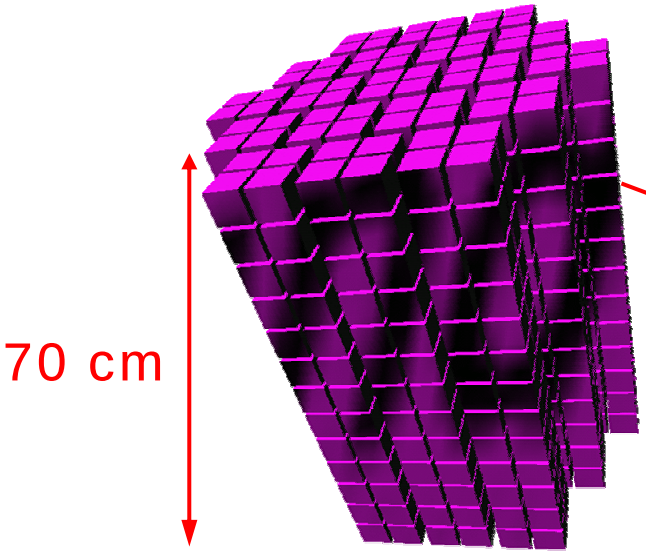
Cryogenic Underground Observatory for Rare Events

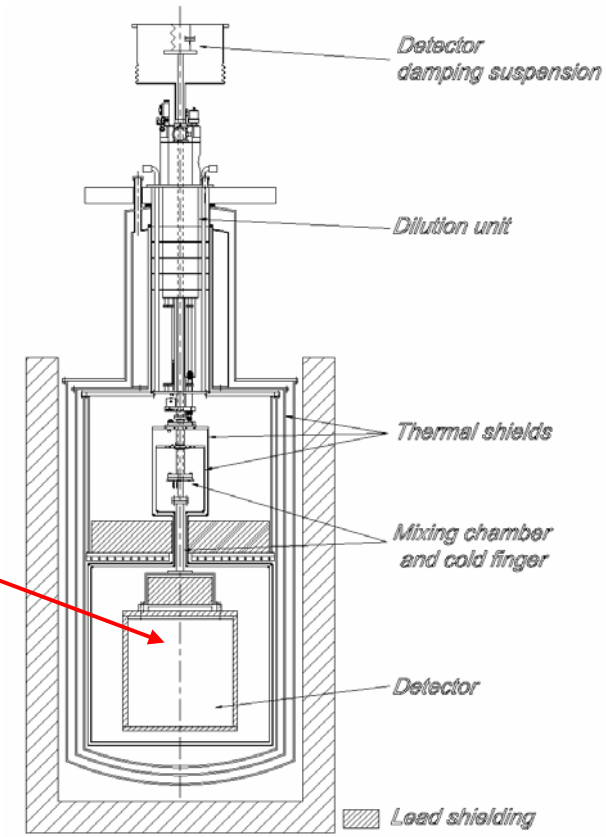


- Temperature signal: $\Delta T = E/C \cong 0.1$ mK for $E = 1$ MeV
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V = 1$ mV for $E = 1$ MeV
- Signal recovery time: $\tau = C/G \cong 0.5$ s

Energy resolution (FWHM): $\cong 5$ keV at 2500 keV

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





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

CUORE Sensitivity

5 year sensitivity

Pessimistic

b = 0.01 – Γ = 5 keV

$F^{0\nu}$ = 2.1 x10^{26} y

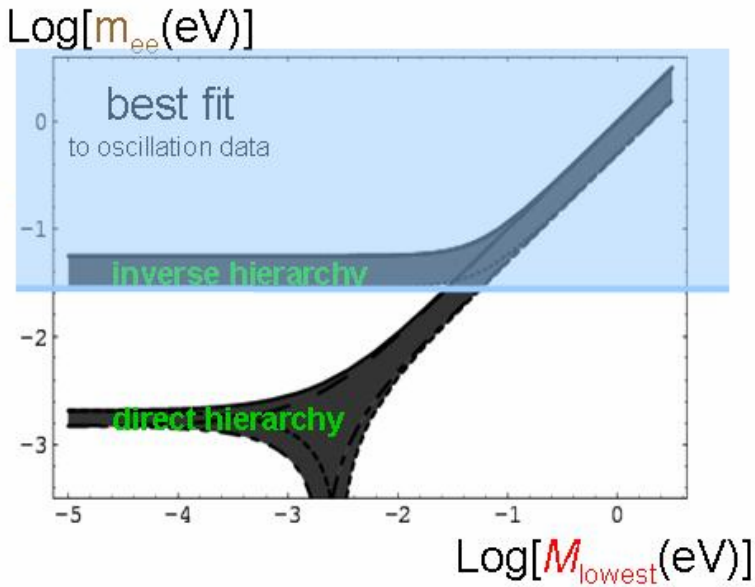
m_{ee} < **20 – 103** meV

Optimistic

b = 0.001 - Γ = 5 keV

$F^{0\nu}$ = 6.5 × 10^{26} y

m_{ee} < **10 - 55** meV



Running prototype CUORICINO:

exposure = 10.85 kg y

$\tau^{0\nu}_{1/2}$ > 1.8 x 10^{24} y at 90% C.L.

Enriched Xenon Observatory

EXO

for double beta decay

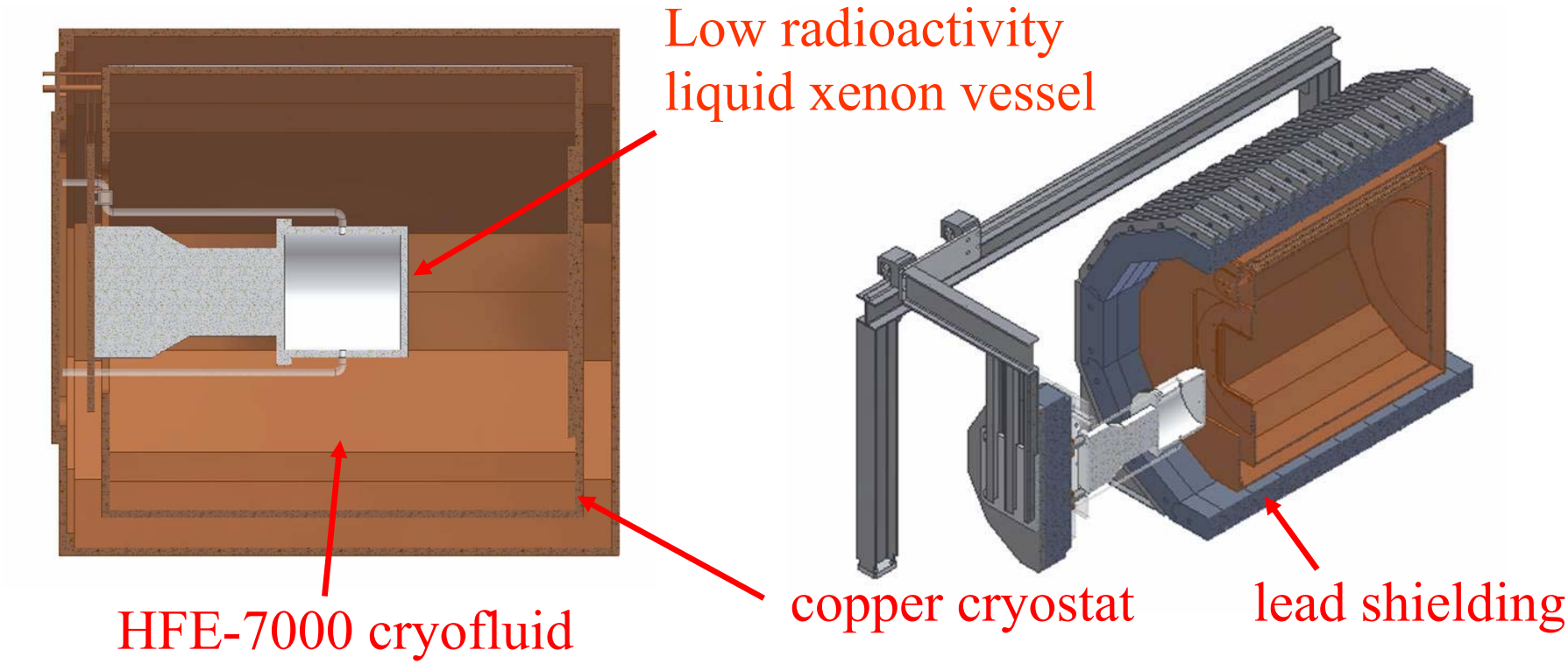
A liquid xenon TPC as a $\beta\beta0\nu$ detector

The crown jewels of EXO

200 kg of xenon enriched to 80% in ^{136}Xe:
the most isotope in possession by any ββ0ν collaboration.

11 times larger than previous experiments.

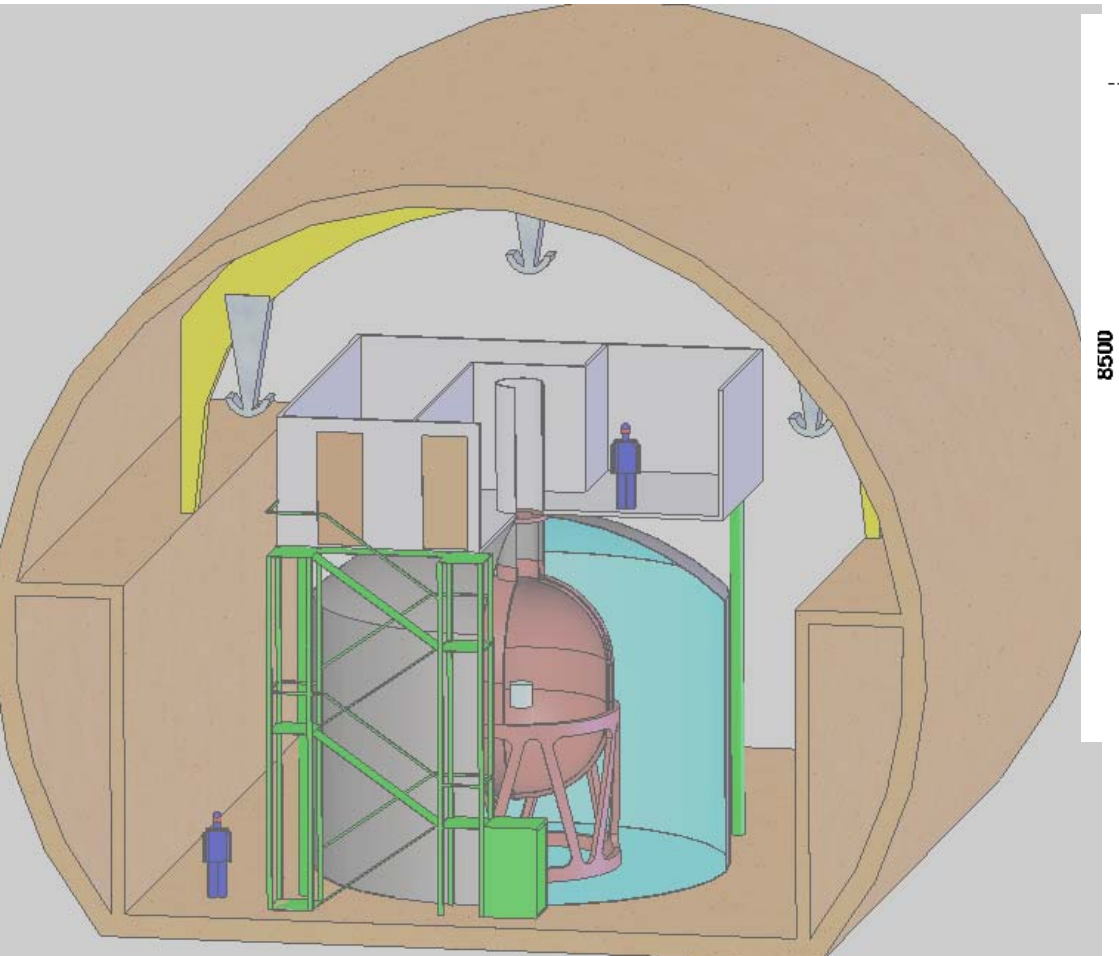
EXO-200: the first 200 kg 0νββ experiment

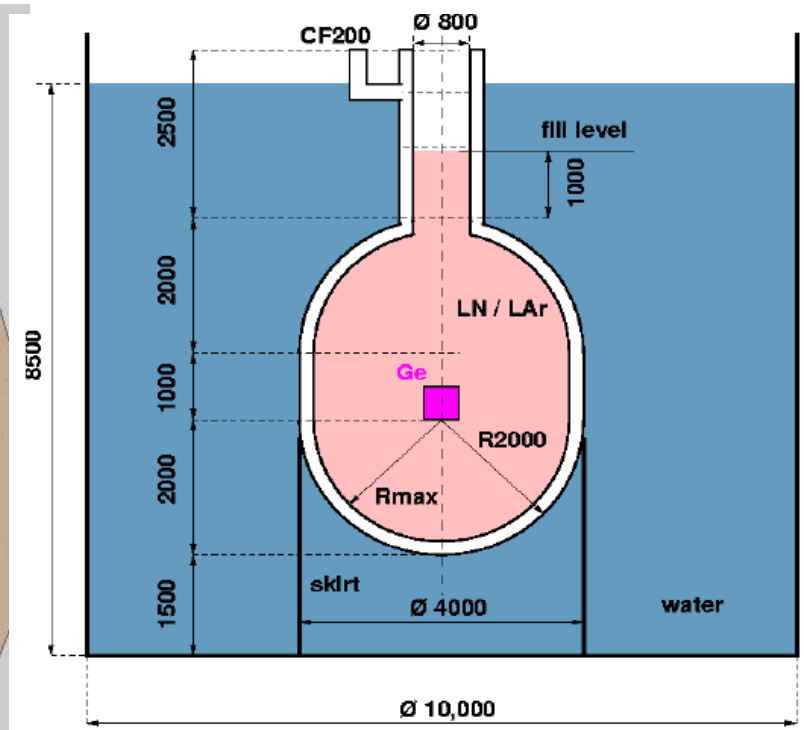


200 kg of Liquid Xenon to be contained in low background vessel, surrounded by 50 cm of ultra pure cryofluid inside a copper cryostat and shielded by 25 cm of lead.

Projected sensitivity of EXO-200: $T_{1/2} > 6.4 \times 10^{25}$ y in 2 years of running. Data taking to begin in 2007. TPC is being assembled and tested at Stanford right now

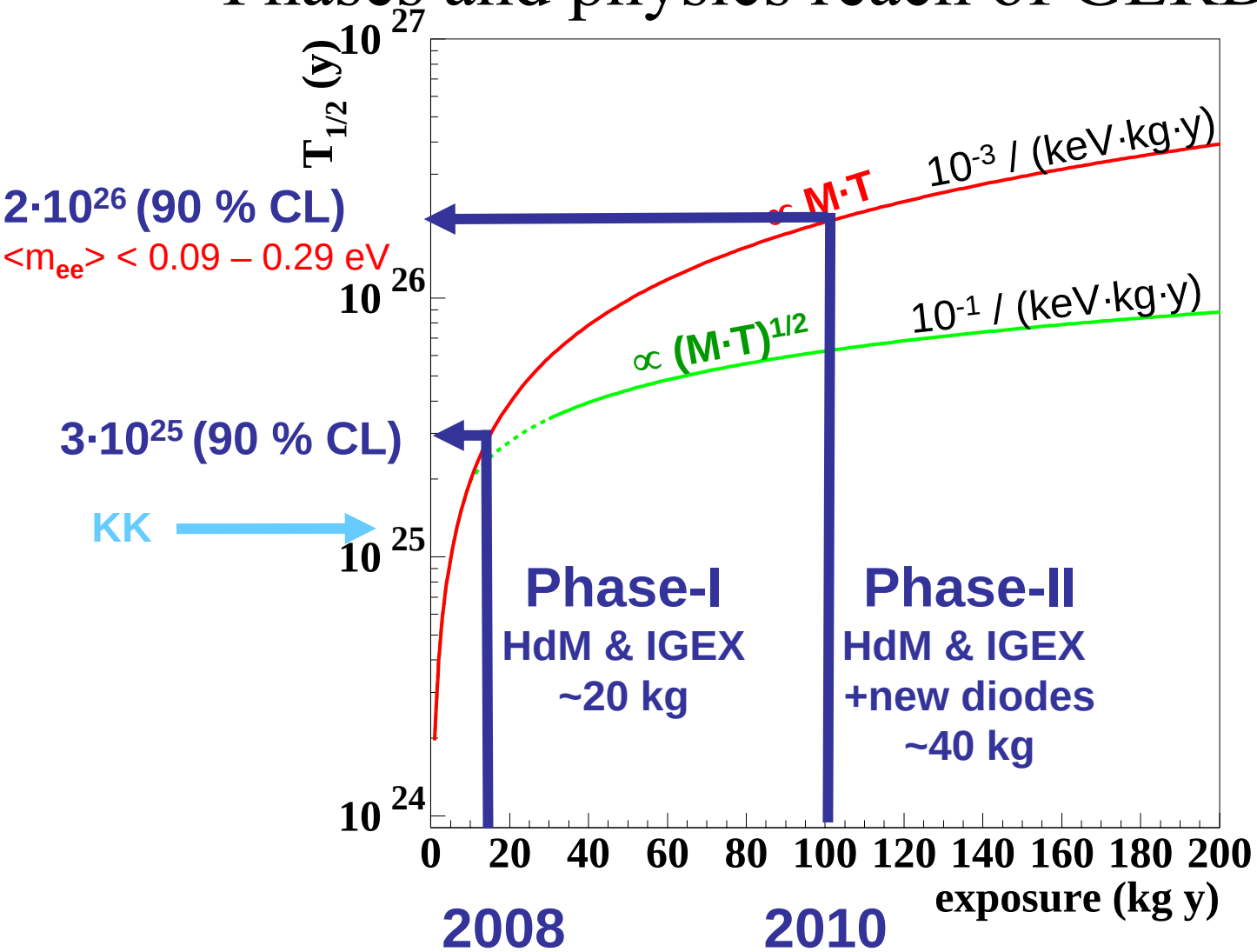
The Germanium Detector Array for the search of neutrinoless decays of ^{76}Ge at LNGS (GERDA)



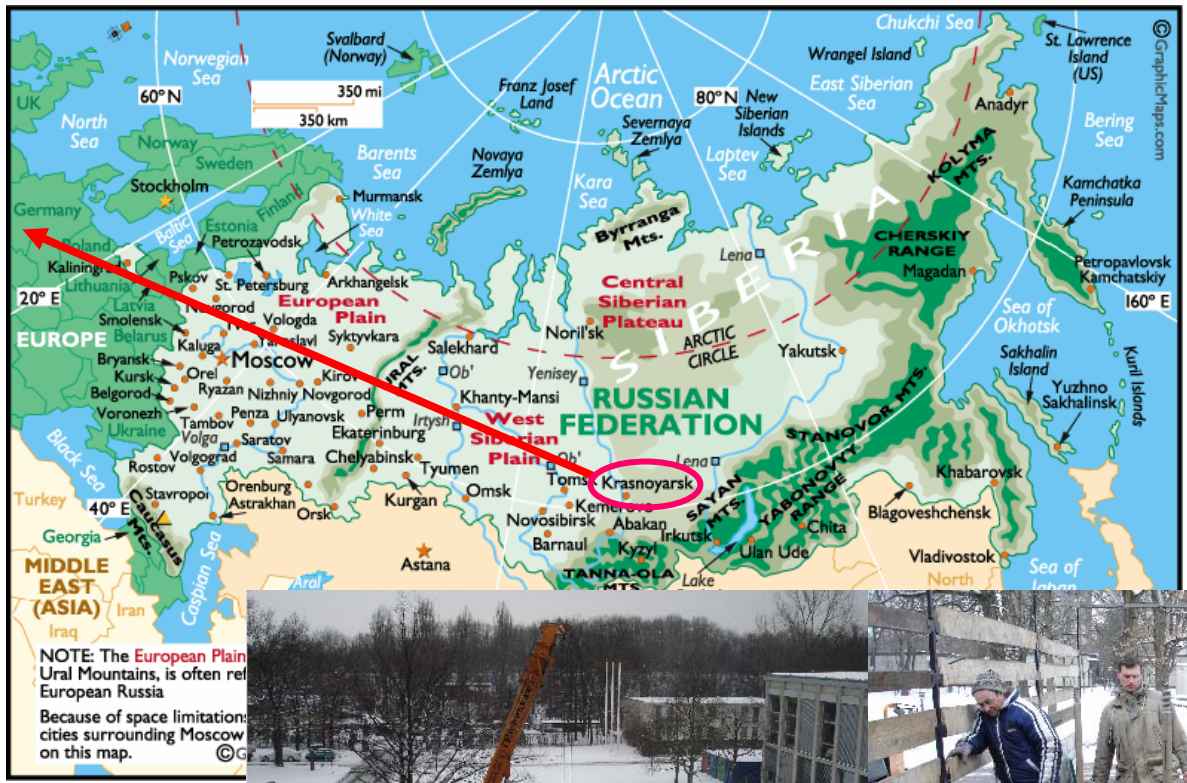


`Naked' Ge detectors in a large LN/LAr container.

Phases and physics reach of GERDA



New detectors for Phase II: Procurement of enriched Ge



1) procurement of 15 kg of natural Ge ('test run')
2) enrichment of 37.5 kg of Ge-76 completed !

Specially designed protective steel container reduces activation by cosmic rays by factor 20

^{nat}Ge sample received March 7, 2005

The Majorana 180 kg Experiment Overview

Majorana is scalable, allowing expansion to 1000 kg.

The 180 kg Experiment (M180)

- Reference Design
  - 171 segmented, n-type, 86% enriched ^{76}Ge crystals.
  - 3 independent, ultra-clean, electroformed Cu cryostat modules.
  - Enclosed in a low-background passive shield and active veto.
  - Located deep underground (6000 mwe).
- Background Specification in the $0\nu\beta\beta$ peak ROI

  1 count/t-y
- Expected Sensitivity to $0\nu\beta\beta$
  (for 3 years, or 0.46 t-y of ^{76}Ge exposure)

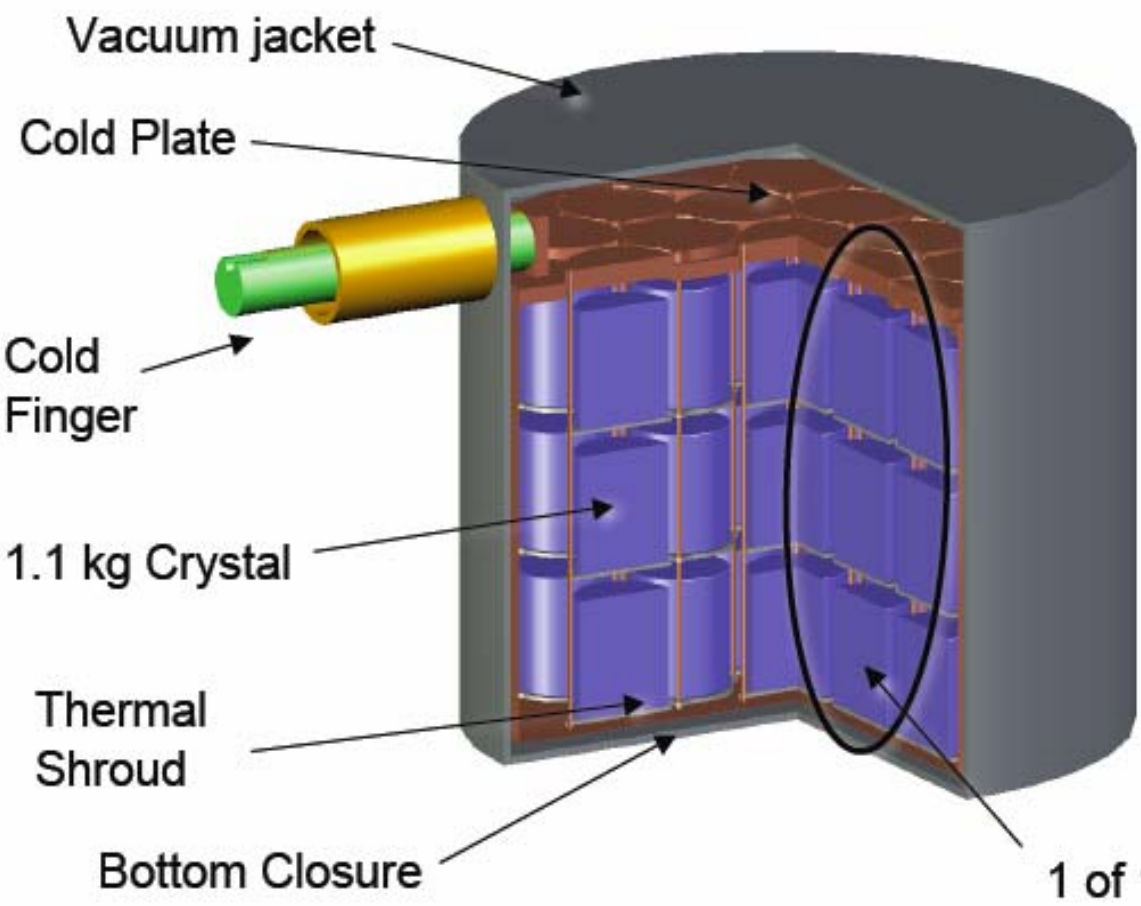
  $T_{1/2} >= 5.5 \times 10^{26}$ y (90% CL)

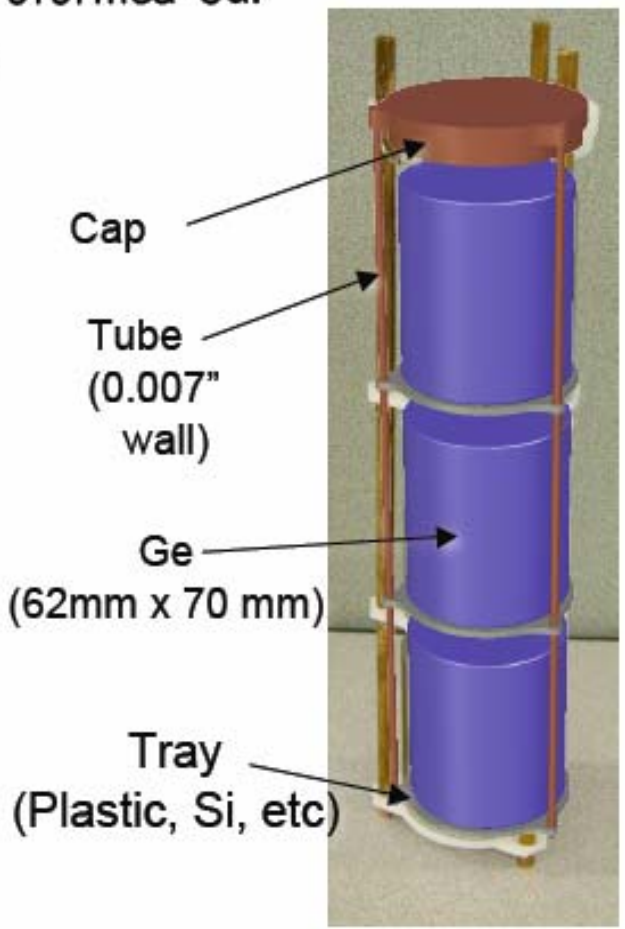
  $<m_\nu> < 100$ meV (90% CL) ([Rod05] RQRPA matrix elements)

  or a 10% measurement assuming a 400 meV value.

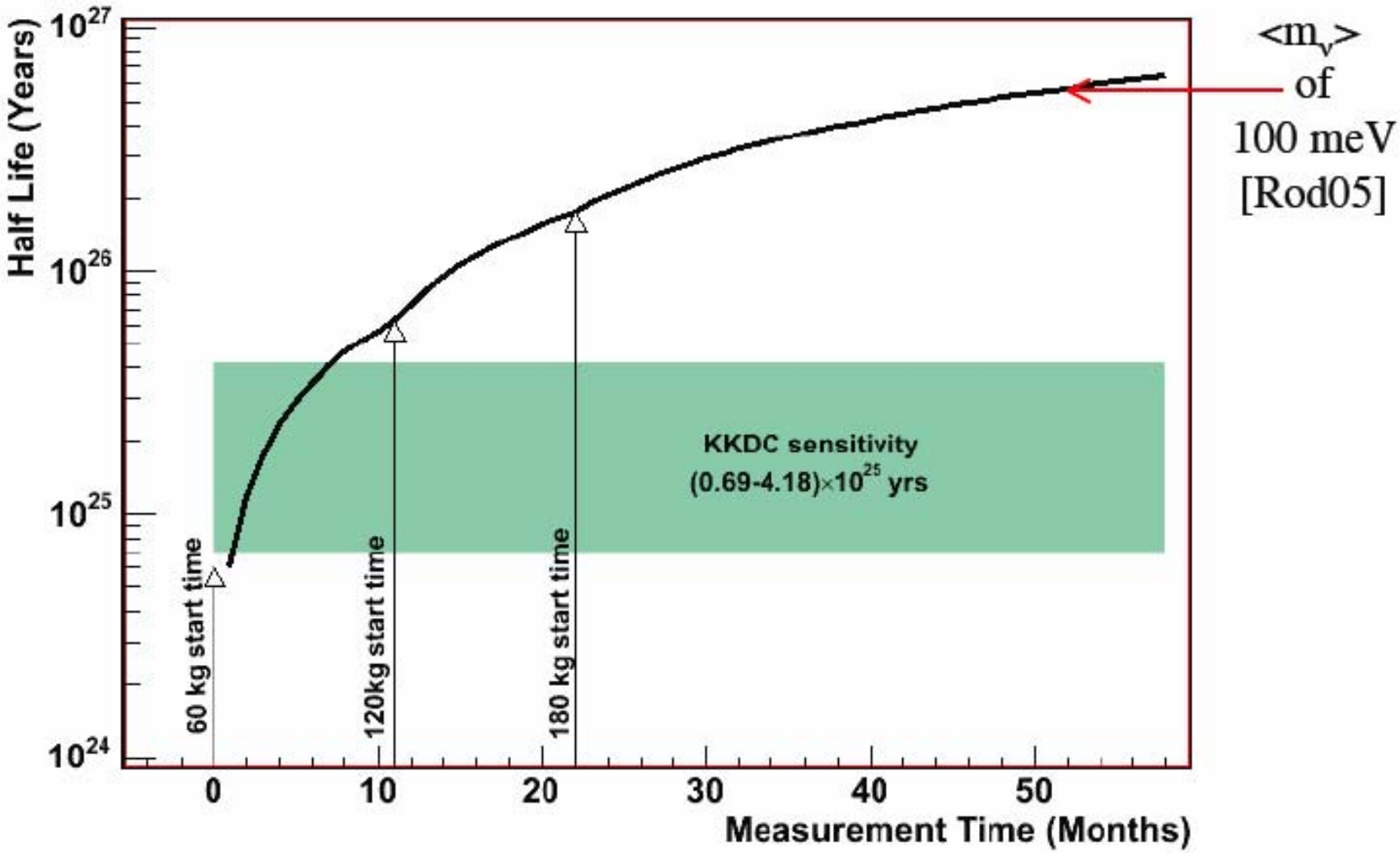
The Majorana Modular Approach

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





Majorana Sensitivity: Realistic runtime



Nuclear matrix elements, continued

In order to relate decay rate to the effective mass $\langle m_{\beta\beta} \rangle$ we have to know the corresponding nuclear matrix elements. Any error in them is directly reflected as a like size error in $\langle m_{\beta\beta} \rangle$.

The operator, including the Fourier transform of the neutrino propagator, is $\Sigma\, h(r_{ij})[\vec{\sigma}_i \cdot \vec{\sigma}_j - (g_V/g_A)^2]\tau_+\tau_+$ where the sum is over all nucleon pairs, and r_{ij} is the distance between the nucleons. h(r) is the `neutrino potential', the Fourier transform of the neutrino propagator $h(r) \sim e^{-1.5Er}/r$. Tests show that it is OK to treat this two-body operator in closure.

For evaluation of the matrix element it is important to consider:

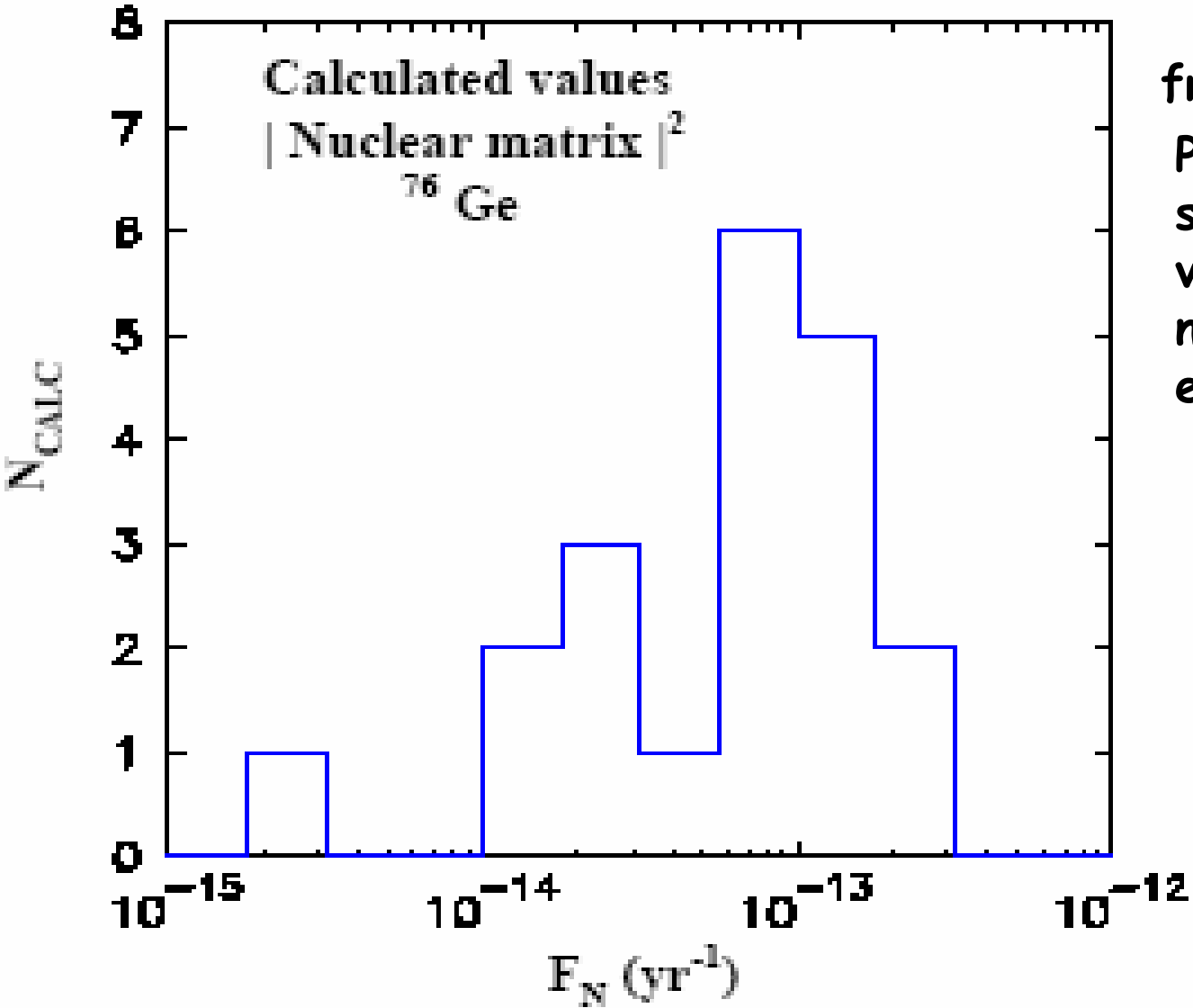
1) How many single particle states near the Fermi level are included
2) How complicated configurations of the valence nucleons are included

There are two basic methods:

1) Nuclear shell model (SM) treats complicated configurations,
   but only few single-particle states (one shell or less).
2) Quasiparticle Random Phase Approximation (QRPA) can treat many single-particle states, but only simple particle-hole configurations.

Most existing calculations are QRPA, only very few are SM. The spread of calculated values is often used as a measure of uncertainty. Often, however, it merely reflects a spread in various assumptions and different choices of adjustable parameters in QRPA.

A provocative question: Do we know at all how large the matrix elements really are? Or, in other words, why there is so much variation among the published calculated matrix elements?



from Bahcall et al., Phys.Rev.D70,033012 spread of published values of squared nuclear matrix element for ^{76}Ge

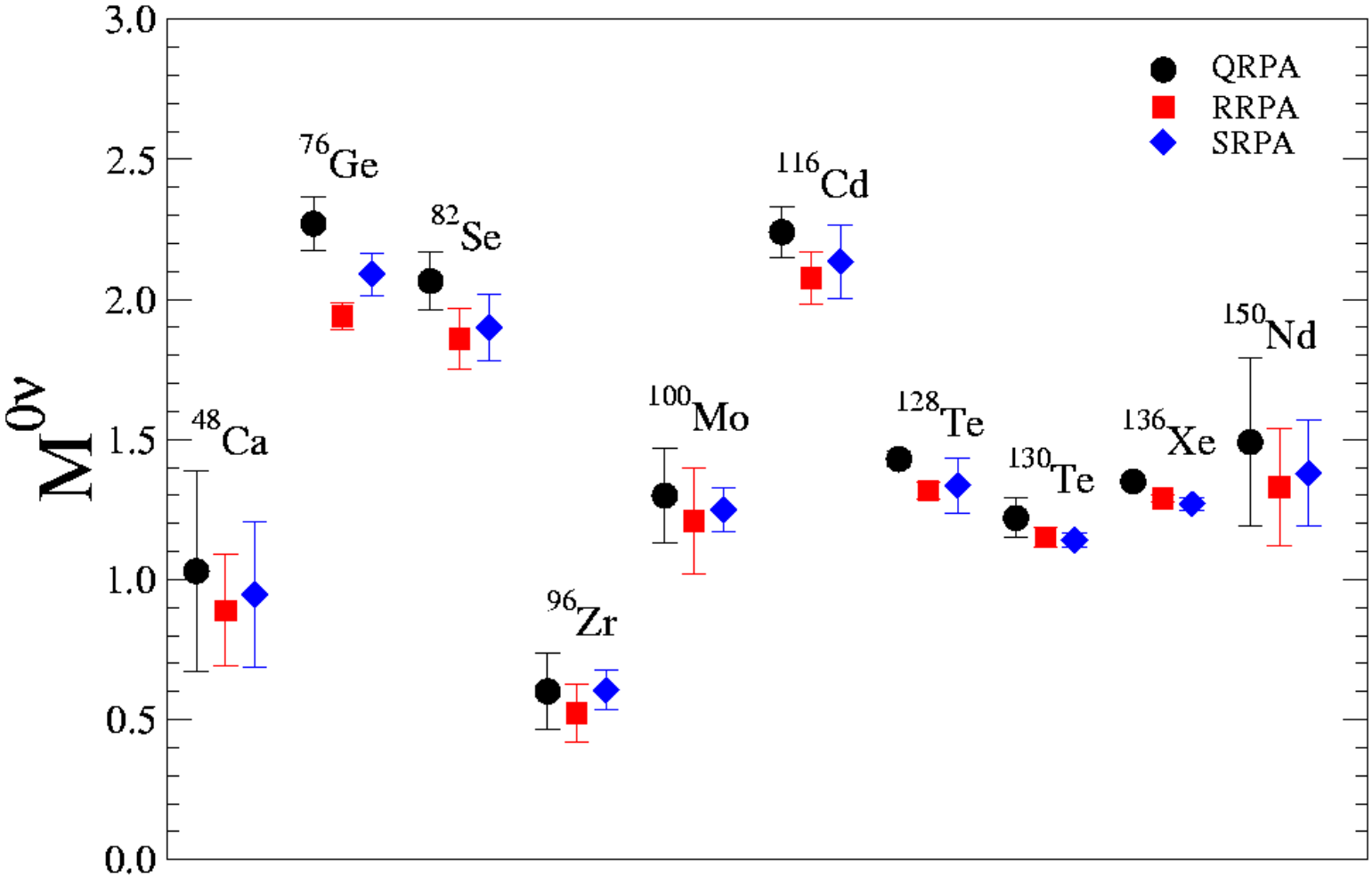
This suggests an uncertainty of as much as a factor of 5. <u>Is it really so bad?</u>

In contrast, Rodin et al, Nucl. Phys. A766, 107 (2006) suggest that the uncertainty is much less, perhaps only ~ 30% (within QRPA and its generalizations, naturally). So, who is right?

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Slowly and smoothly decreasing (except ^{96}Zr) with *A*

SRQRPA results

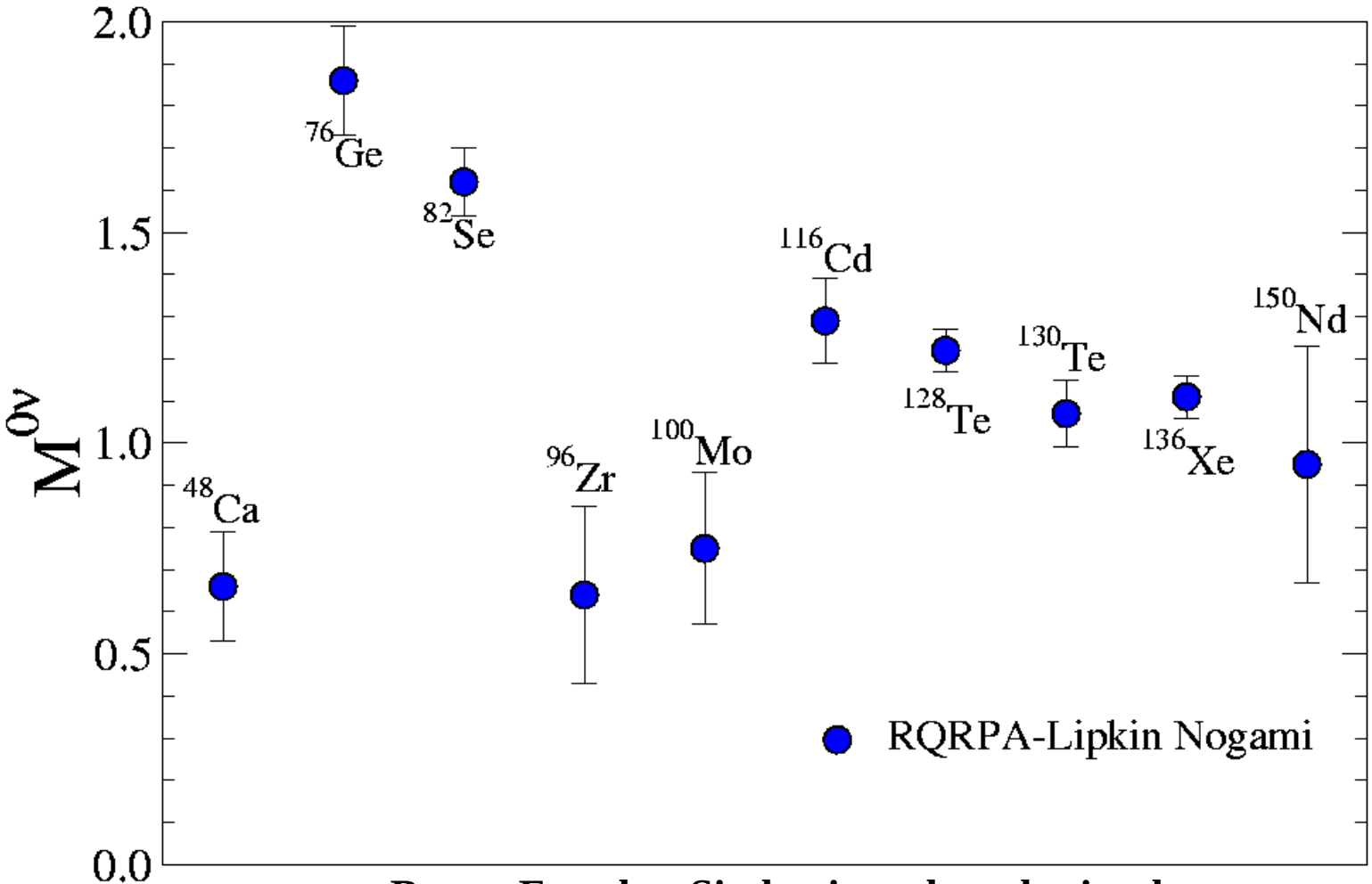


This moves the left outlier of Bahcall et al. right in the middle

Benes, Faessler, Simkovic, to be submitted, June 2006

- **Pairing fixed to exp. pairing gaps (constant pairing considered)**
- **BCS overlap factor taken into account**
- **uncertainties of 2νββ-decay half-lives not considered**

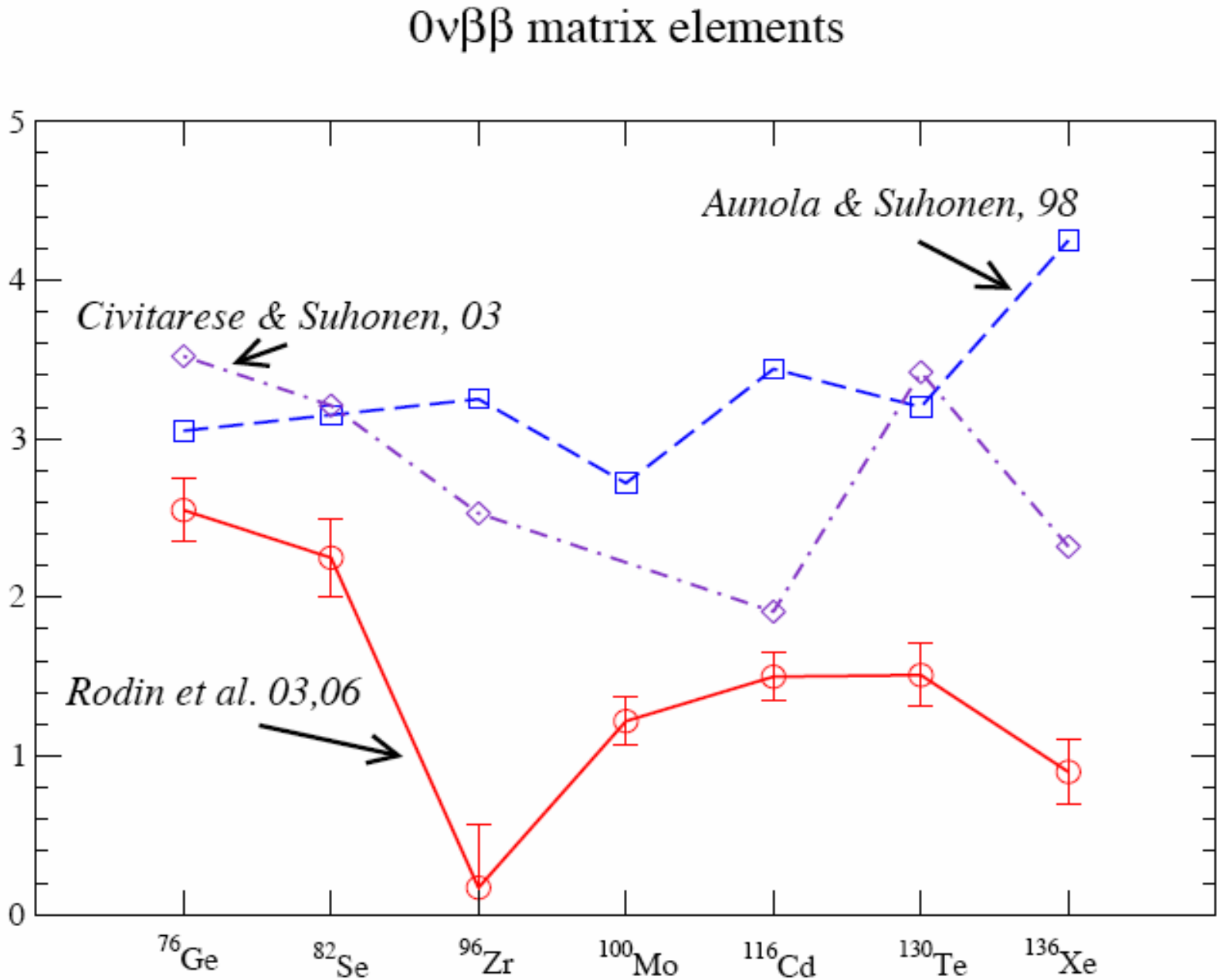
Lipkin-Nogami BCS ground state



Benes, Faessler, Simkovic, to be submitted

Closed shell nuclei: ^{48}Ca, ^{116}Sn, ^{136}Xe, deformed ^{150}Nd

Results of Suhonen et al. are larger (about 2x) than those of Rodin, but again only mildly varying from one nucleus to the next.



Where are the differences of these two examples coming from?

The bulk of the differences is understood, but there is no consensus which approach is correct (or at least more correct).

The main effect (by a factor of ~2) comes from **taking into account** (for Rodin et al.) and **not taking into account** (Civitarese and Suhonen) the short-range nucleon repulsion *O -> fOf* .

Another effect comes (by ~30%) from including (or not) the induced pseudoscalar coupling.

Why the effect of short range correlation is so large could be understood (as well as other things) if one separates the contribution of `Cooper pairs' (pairs with $0^+$) and of the `broken pairs' or `higher seniority states'.

The 0^+ pairs are highly correlated, the s.r.c. affects them by ~30%. At the same time, their contribution is not affected by n-p force characterized by the coupling constant g_{pp} ~1.

The `broken pairs' are less affected by s.r.c., but strongly depend on g_{pp}. They have a tendency to cancel the contribution of 0^+ pairs.

The sum of these two contributions is much smaller than either of them, depends sensitively on g_{pp} and is strongly reduced by s.r.c.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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

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

The only case of a large difference

Except for ^{100}Mo the agreement between these very different calculations is reasonably good.
Note that the SM calculations include the reduction caused by the s.r.c. and induced currents.

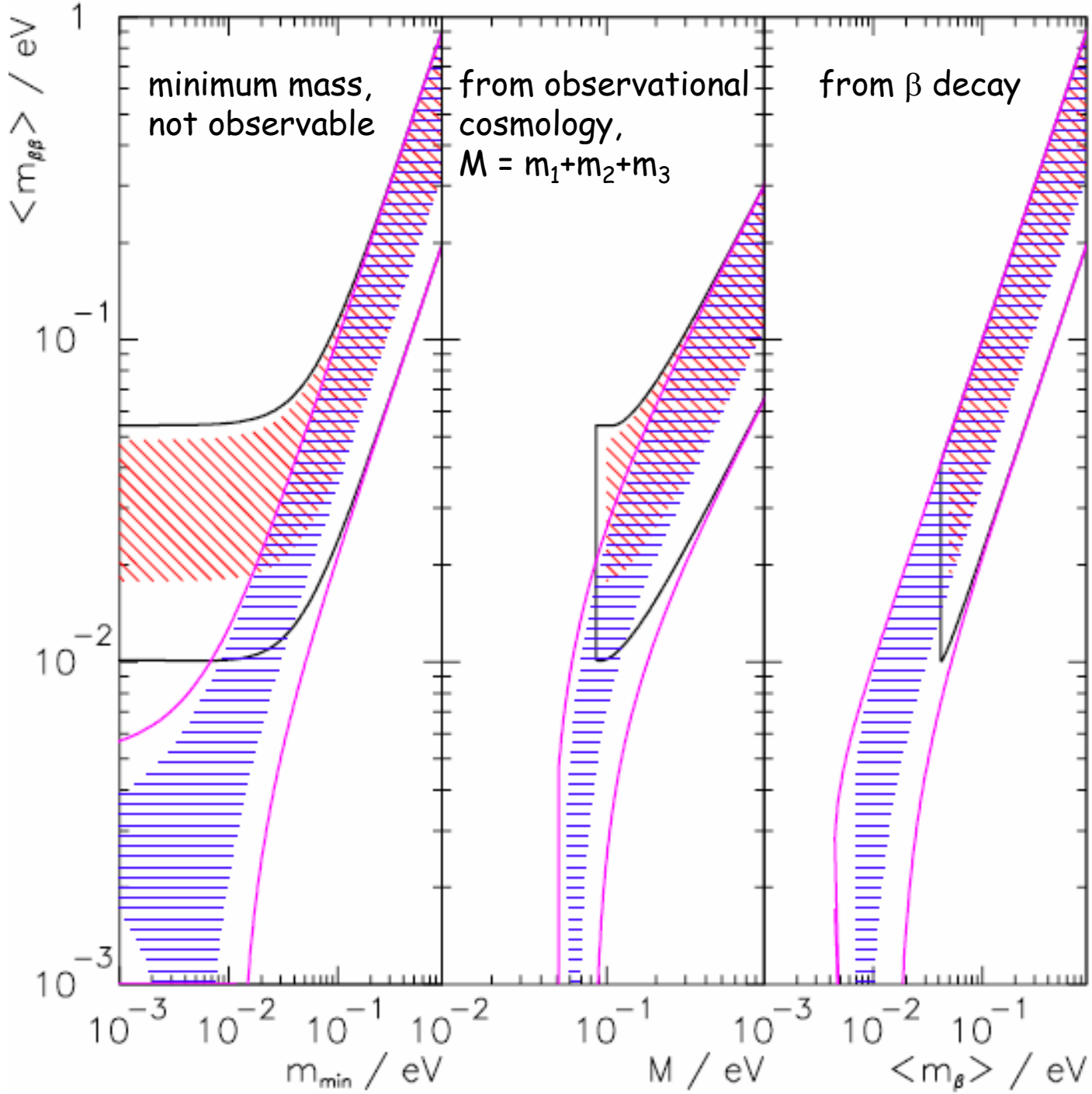
$0\nu\beta\beta$ half-lives for $\langle m_{\beta\beta}\rangle$ = 50 meV based on the matrix elements of Rodin et al.

^{76}Ge	$(2.1 - 2.6) \times 10^{27}$ y
^{82}Se	$(6.0 - 8.7) \times 10^{26}$ y
^{100}Mo	$(1.1 - 1.7) \times 10^{27}$ y
^{130}Te	$(0.7 - 1.7) \times 10^{27}$ y
^{136}Xe	$(1.5 - 5.6) \times 10^{27}$ y (no 2ν observed yet)

Note: Calculated matrix elements decrease with increasing A, but the phase-space factors usually increase, particularly the Coulomb factor, hence relatively little variation of $T_{1/2}$ with A.

Note: The sensitivity to $\langle m_{\beta\beta}\rangle$ scales as $1/(T_{1/2})^{1/2}$. 50 meV is near the top of the `inverted hierarchy' mass region, its bottom is ~20 meV so sensitivity to ~10^{28} years would be needed

$\langle m_{\beta\beta} \rangle$ vs. the absolute mass scale



blue shading:
normal hierarchy,
$\Delta m^2_{31} > 0$.
red shading:
inverted hierarchy
$\Delta m^2_{31} < 0$

shading:best fit parameters, lines 95% CL errors.

Thanks to A. Piepke

iii) Neutrino magnetic moment and the distinction between the Dirac and Majorana neutrinos.

Neutrino mass and magnetic moment are intimately related. In the orthodox SM with massless neutrinos magnetic moments vanish. However, in the minimally extended SM

containing gauge-singlet right-handed neutrinos, one finds that μ_ν is nonvanishing, but unobservably small: $\mu_\nu \approx 3 \times 10^{-19} \mu_B [m_\nu / 1 \text{ eV}]$ [1].

$$\mu_\nu = 3eG_F/(2^{1/2}\, \pi^2\, 8)\, m_\nu$$

Typically, magnetic moment could be observed in ν-e scattering. A nonvanishing μ_ν will be recognizable only if the corresponding electromagnetic cross section is comparable in magnitude with the well-understood weak interaction cross section. The magnitude of μ_ν which can be probed in this way is then given by

$$\frac{|\mu_\nu^{\exp}|}{\mu_B} \simeq \frac{G_F m_e}{\sqrt{2}\pi\alpha}\sqrt{m_e T} \sim 10^{-10}\sqrt{\frac{T}{m_e}}. \qquad (1)$$

Considering realistic values of T, it would be difficult to reach sensitivities below $\sim 10^{-11}\mu_B$. The limits derived

$\sigma_{elm} = \pi\alpha^2\mu^2/m_e^2\,(1-T/E_\nu)/T$

characteristic T dependence

Limits on μ_ν can also be derived from bounds on unobserved energy loss in astrophysical objects. For sufficiently large μ_ν, the rate for plasmon decay into $\nu\bar{\nu}$ pairs would conflict with such bounds. Since plasmons can also decay weakly into $\nu\bar{\nu}$ pairs, the sensitivity of this probe is again limited by size of the weak rate, leading to [4]

$$\frac{|\mu_\nu^{\text{astro}}|}{\mu_B} \simeq \frac{G_F m_e}{\sqrt{2}\pi\alpha}(\hbar\omega_p), \tag{2}$$

where ω_p is the plasma frequency. Since $(\hbar\omega_p)^2 \ll m_e T$, this bound is stronger than the limit in Eq. (1). Given the

The interest in μ_ν and its relation to m_ν dates from ~1990 when it was suggested that there is an anticorrelation between the neutrino flux observed in the Cl (Davis) experiment, and the solar activity (number of sunspots that follows a 11 year cycle).

A possible explanation of this was proposed by Voloshin, Vysotskij and Okun, with $\mu_\nu \sim 10^{-11}\,\mu_B$ and its precession in solar magnetic field. Even though the effect does not exist, the possibility of a large μ_ν and small mass was widely discussed.

I like to describe a model independent constraint on the μ_ν that depends on the magnitude of m_ν and moreover depends on the charge conjugation properties of neutrinos, i.e. makes it possible, at least in principle, to decide between Dirac and Majorana nature of neutrinos.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

$$m_\nu \sim \Lambda^2/2m_e\, \mu_\nu/\mu_B \sim \mu_\nu/10^{-18}\, \mu_B\, [\Lambda(\mathrm{TeV})]^2\, \mathrm{eV}$$

It is difficult to reconcile small m_ν with large μ_ν

To overcome this difficulty Voloshin (88) proposed existence of a $SU(2)_\nu$ symmetry in which ν_L and $(\nu_R)^c$ form a doublet. Under this symmetry m_ν is forbidden but μ_ν is allowed.

For Dirac neutrinos such symmetry is broken by weak interactions, but for Majorana neutrinos it is broken only by the Yukawa couplings.

Note that Majorana neutrinos can have only transition in flavor magnetic moments.

Also note, that in flavor basis the mass term for Majorana neutrinos is symmetric but the magnetic moments are antisymmetric.

In the following I show that the existence of nonvanishing μ_ν leads through loop effects to an addition to the neutrino mass δm_ν that, naturally cannot exceed the magnitude of m_ν .
(See Bell et al, PRL**95,**151802, Davidson et al. Phys.Lett. B**626**, 151, and Bell et al., in preparation)

Consider first the Dirac case:

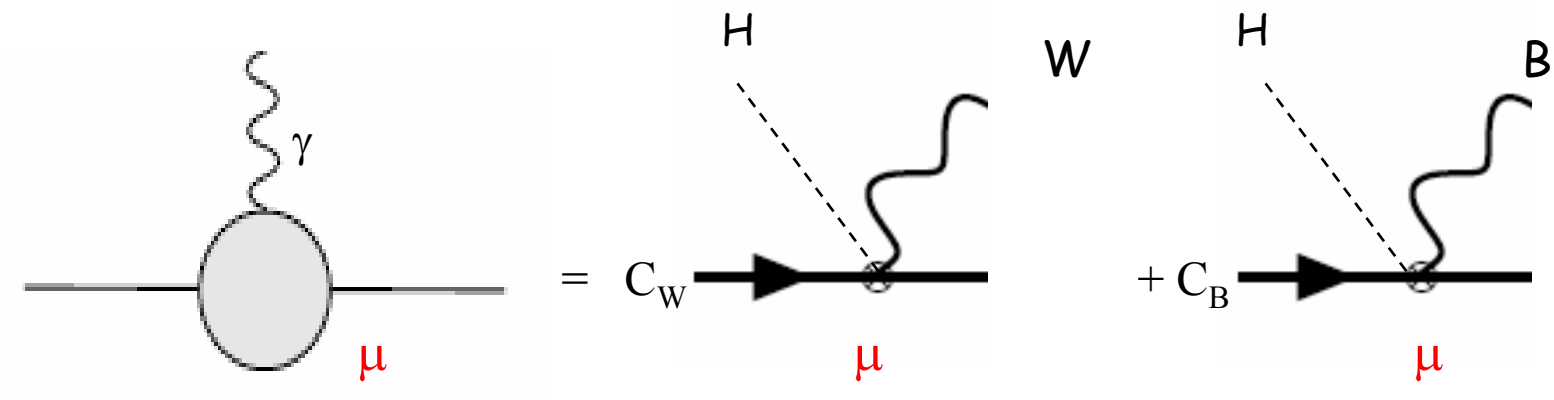
Assuming that μ_ν is generated by some physics beyond the SM at a scale Λ, its leading contribution to the neutrino mass, δm_ν, scales with Λ as

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

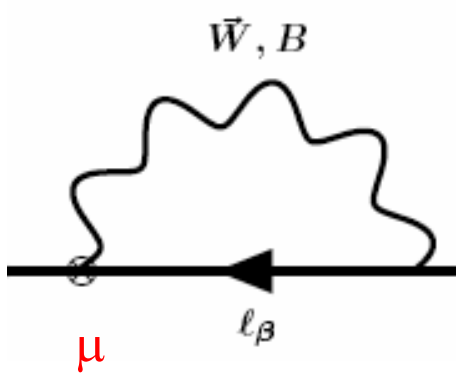
where δm_ν is the contribution to a generic entry in the 3×3 neutrino mass matrix arising from radiative corrections at one-loop order. The dependence on Λ^2 arises from the quadratic divergence appearing in the renormalization of the dimension four neutrino mass operator. Although the

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

The usual graph for μ_ν can be expressed in a gauge invariant form:



One can now close the loop and obtain a quadratically divergent contribution to the Dirac mass



$$m_\nu \sim \frac{\alpha}{16\pi}\frac{\Lambda^2}{m_e}\frac{\mu_\nu}{\mu_B}$$

When Λ is not substantially larger than v, the contribution to δm_ν from higher dimension operators can be important

A neutrino magnetic moment coupling would be generated by gauge-invariant, dimension six operators that couple the matter fields to the $SU(2)_L$ and $U(1)_Y$ gauge fields W^a_μ and B_μ, respectively.

$$\mathcal{O}_1^{(6)} = g_1 \bar{L}\,\tilde{\phi}\,\sigma^{\mu\nu}\nu_R B_{\mu\nu},$$

$$\mathcal{O}_2^{(6)} = g_2 \bar{L}\tau^a\tilde{\phi}\sigma^{\mu\nu}\nu_R W^a_{\mu\nu}, \qquad \mathcal{O}_3^{(6)} = \bar{L}\,\tilde{\phi}\,\nu_R(\phi^\dagger\phi),$$

Consider an effective $\mathcal{L}_{\rm eff} = \sum_{n,j} \frac{C_j^n(\mu)}{\Lambda^{n-4}} \mathcal{O}_j^{(n)}(\mu) + \text{H.c.},$

After SSB $\frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)[C_1^6(v) + C_2^6(v)]. \quad \delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2}.$

Thus $\delta m_\nu = \frac{v^2}{16 m_e}\frac{C_3^6(v)}{C_+(v)}\frac{\mu_\nu}{\mu_B}, \quad C_+(\mu) \equiv C_1^6(\mu) + C_2^6(\mu)$

This leads to a similar bound on μ_ν as from the dim-4 operator. Thus, the μ_ν for a Dirac neutrino is essentially unobservable at present time.

Now consider the Majorana case:

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

The lowest order contribution to μ_ν arises at dim-7

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

After SSB

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

In the case that

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

and thus as in Dirac case

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

However for the case of arbitrary C_{W^+} we obtain constraints from either O_W or O_B by inserting of two Yukawa couplings to achieve the required symmetry.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

The above is also valid if C_{W^-} is replaced by C_B.
The most general bound on Majorana magnetic moment is

$$\mu_{\alpha\beta} \leq 4 \times 10^{-9} \mu_B \left(\frac{[m_\nu]_{\alpha\beta}}{1 \text{ eV}} \right) \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2 \left| \frac{m_\tau^2}{m_\alpha^2 - m_\beta^2} \right|,$$

Thus if a neutrino magnetic moment is observed near its present experimental limit we would conclude that **<u>neutrinos are Majorana</u>**, and that the corresponding new scale $\Lambda < 100$ TeV.

If we, further, could assume that all elements of the matrix $\mu_{\alpha\beta}$ are of similar magnitude, than a discovery Of μ_ν at, say $10^{-11}\mu_B$ would imply $\Lambda < 10$ TeV with a possible implication for the mechanism of $0\nu\beta\beta$ decay.

Hence search for μ_ν is in some sense complementary to the search for $0\nu\beta\beta$ decay. But, unlike the $0\nu\beta\beta$ decay, we have just an upper bound, and not a clear map where to look.

The distinction between Dirac and Majorana **does not** require processes that violate lepton number, just amplitudes. For example the neutrino γ decay:

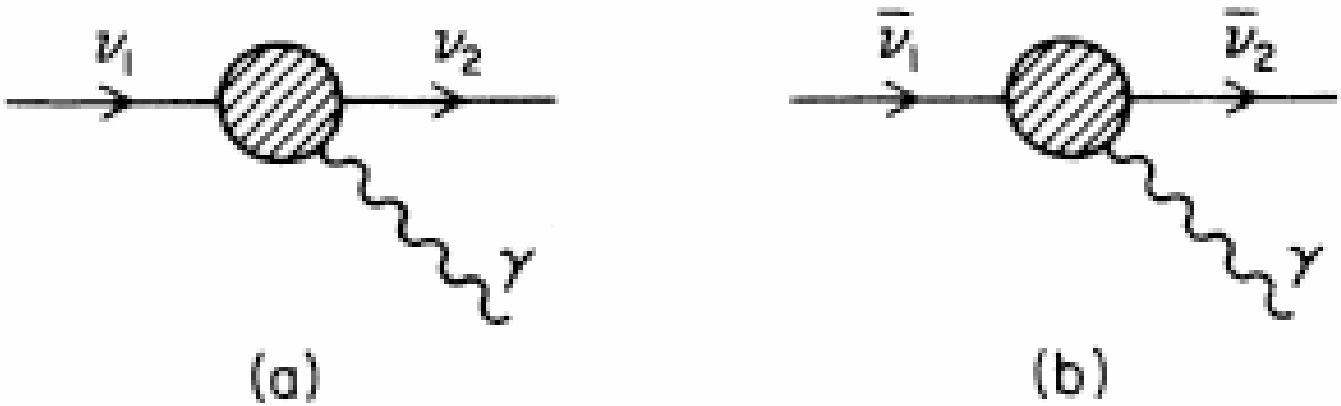


FIG. 1. Processes which interfere for Majorana, but not for Dirac, neutrinos.

Angular distribution of photons in the lab system with respect to the neutrino beam direction is

$$dN = \frac{1}{2}(1 + a\cos\theta)d\cos\theta \ ,$$

where a = 0 for Majorana and a=-1 for Dirac and left handed couplings

Summary and/or Conclusions

Study of $0\nu\beta\beta$ decay entered a new era. No longer is the aim just to push blindly the sensitivity higher and the background lower, but to explore specific regions of the $\langle m_{\beta\beta} \rangle$ values.

The `phased' program means that first we will explore the `degenerate' region (0.1-1 eV), with ~100 kg sources, and prepare for the `inverted hierarchy' (0.01-0.1eV) region with ~ ton sources that should follow later.

It is also important to keep in mind the questions that I discussed:

a) Relation of $\langle m_{\beta\beta} \rangle$ and the absolute mass (rather clear already, becoming less uncertain with better oscillation results).

b) Mechanism of the decay (exploring LFV, models of LNV, running of LHC to explore the ~TeV mass particles).

c) Nuclear matrix elements (exploring better, and agreeing on, the reasons for the spread of calculated values, and deciding on the optimum way of performing the calculations, while pursuing vigorously also the application of the shell model).

d) Other processes sensitive to Majorana vs. Dirac (neutrino magnetic moments etc.)