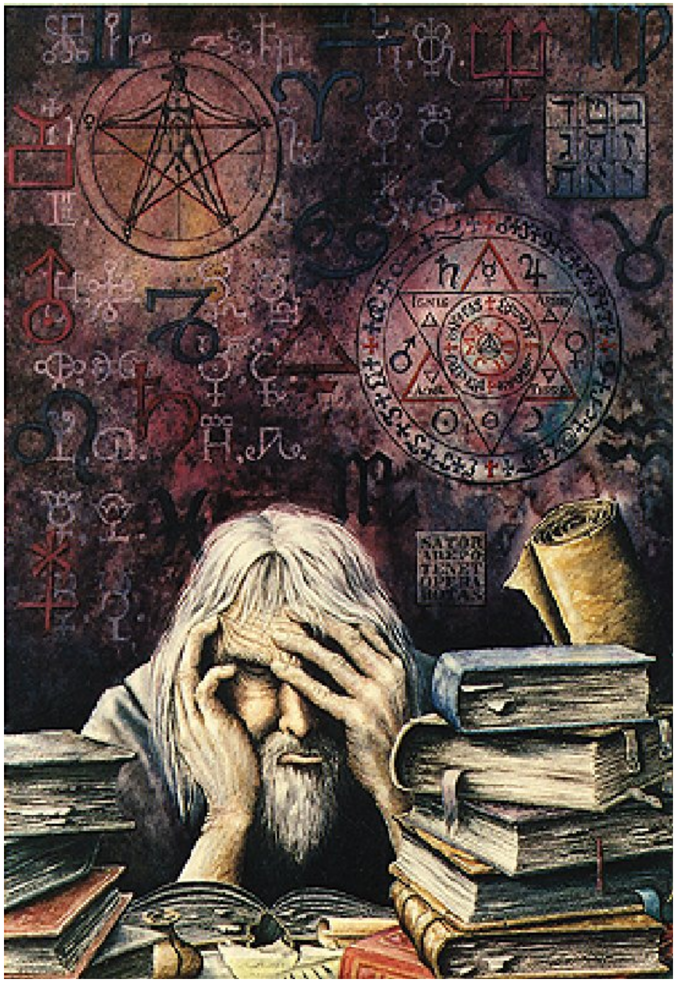
K. Zuber, Techn. Univ. Dresden
NUMEN 2015, Catania 2.12. 2015

Status and perspective of double beta decay experiments

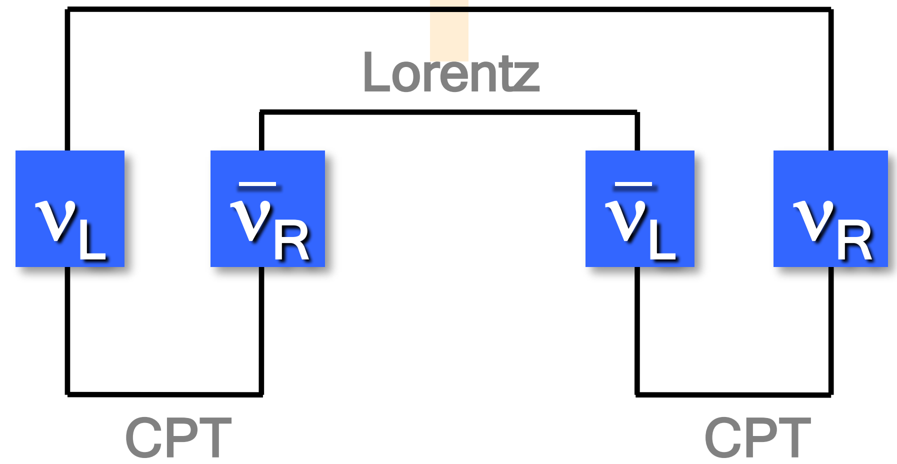
Contents



- Why double beta decay?
- The physics
- General issues
- Experimental issues
- Status of measurements
- Summary

Are neutrinos (very) special?

intrinsic **particle-antiparticle symmetry** of neutrinos?



Dirac neutrino

ν^D

4 ν states

lepton number conservation $\Delta L = 0$

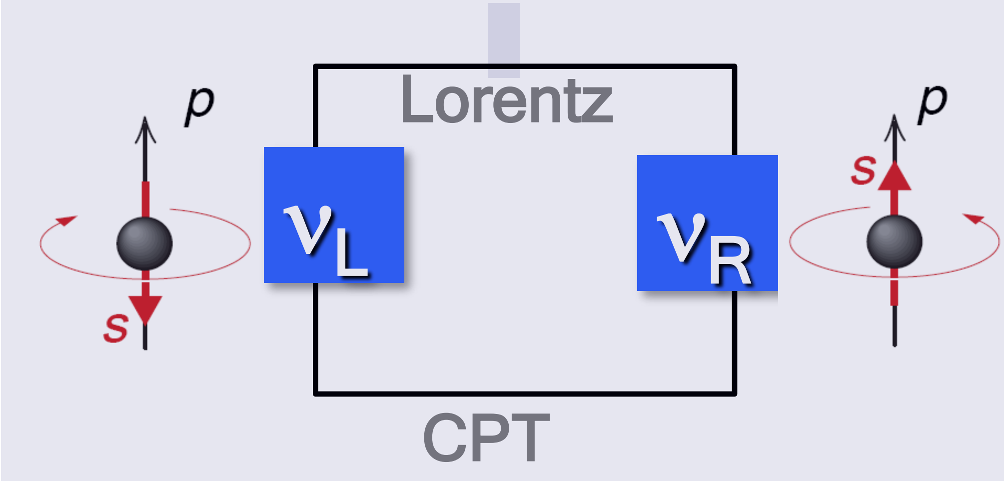
neutrino ≠ antineutrino

Majorana neutrino

ν^M

2 ν states

lepton number violation $\Delta L = 2$



ν^D and ν^M only distinguishable if $m_\nu \neq 0$

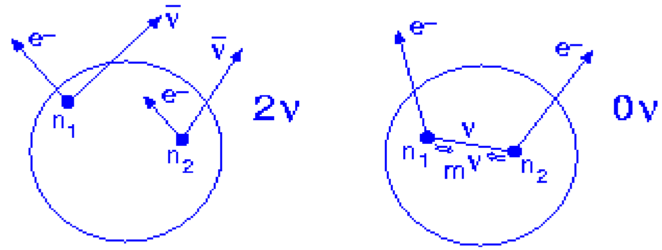
Therefore the subcommittee strongly recommends that R&D efforts aimed at solving specific technical issues relevant to the downselect decision be supported.

The additional R&D required for each technology was presented to the subcommittee and discussed with the collaborations. For several methods, it is clear that a few well-defined issues need attention, and a 2-3 year R&D program offers good prospects for resolution. For the most part, the cases identified in this report will be straightforward to address through further review. Other technical issues have more open-ended R&D requirements to address. In these cases the allocation of resources will be more difficult to assess. In any case, the longer term future of NLDBD will require continued R&D effort. **The subcommittee strongly urges continuation of longer term R&D necessary for the future development of the subject in addition to the support of shorter term R&D aimed at a near future downselect.**

It was noted by the subcommittee that there are several common R&D topics that would benefit several different techniques. It seems in these cases that a coordinated approach could be a more efficient use of resources. **The subcommittee suggests that the funding agencies consider an approach that would encourage several groups to work together on these common goals.**

There is clearly substantial, and growing, international interest in NLDBD. The decision by the US community on its strategy for the next generation experiment will necessarily involve consideration of the international context. Coordination with the international community will clearly be a necessary component in future decisions on technology selection.

- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ 2νββ
- $(A,Z) \rightarrow (A,Z+2) + 2e^-$ 0νββ



Unique process to measure character of neutrino

The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

Requires half-life measurements well beyond 10^{20} yrs!!!!

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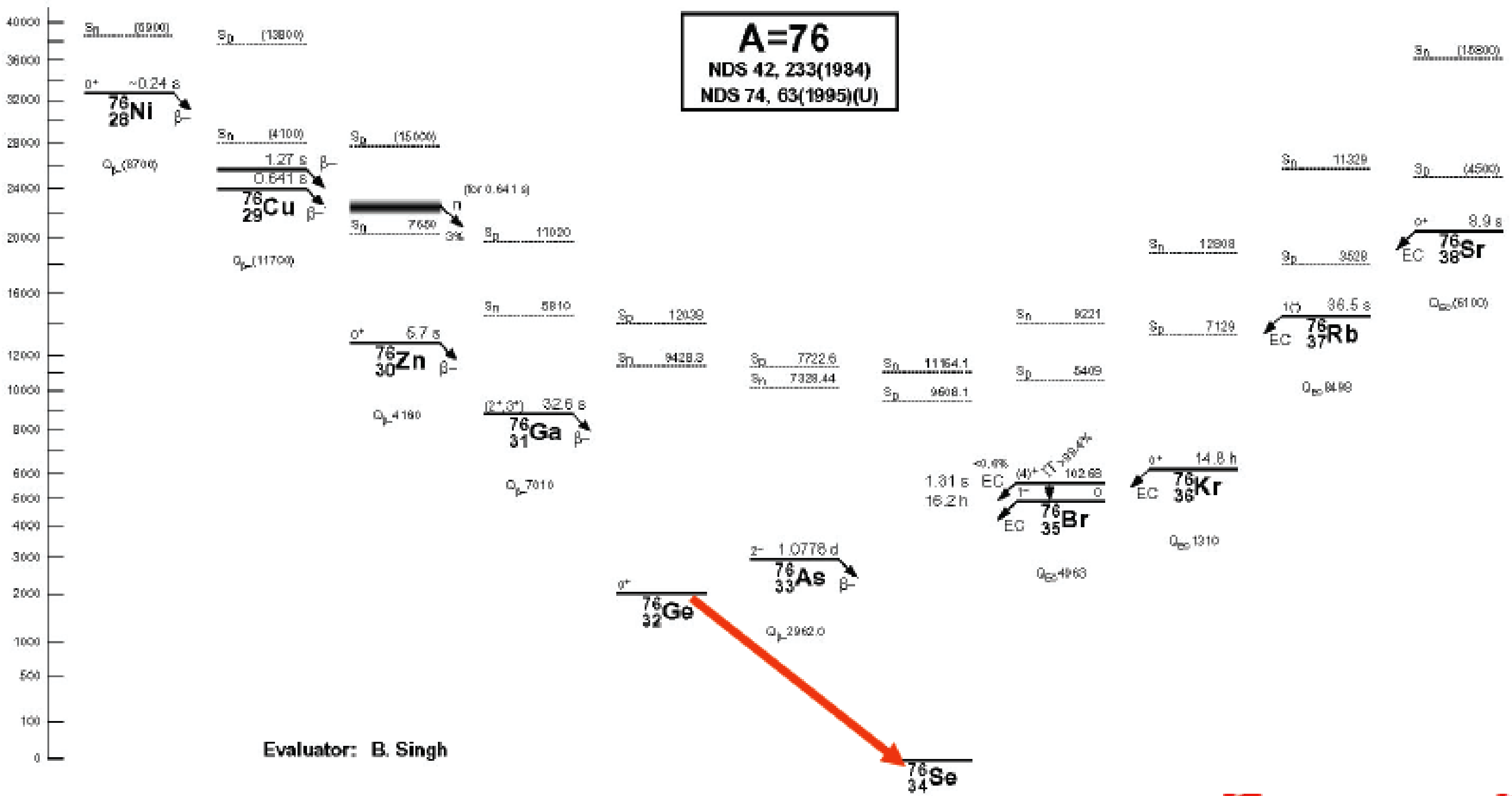

Only 35 isotopes in nature are able to do that!

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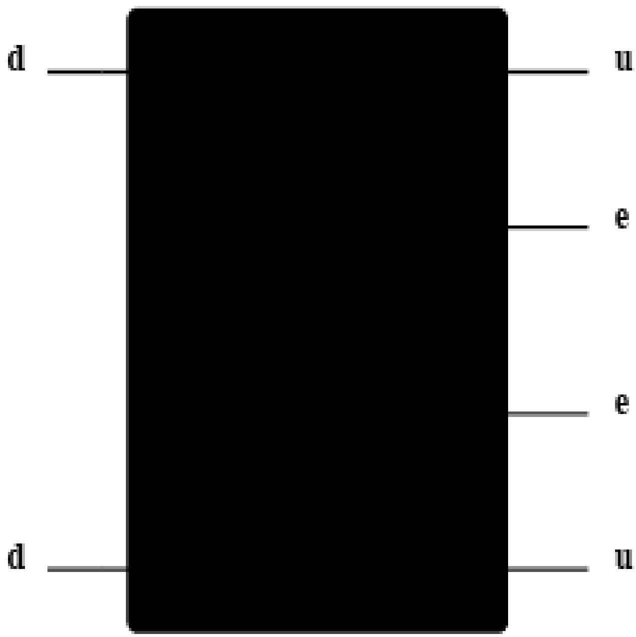
Any $\Delta L=2$ process can contribute to $0\nu\beta\beta$



- R_p violating SUSY
- V+A interactions
- Extra dimensions (KK- states)
- Leptoquarks
- Double charged Higgs bosons
- Compositeness
- Heavy Majorana neutrino exchange
- Light Majorana neutrino exchange
- …

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

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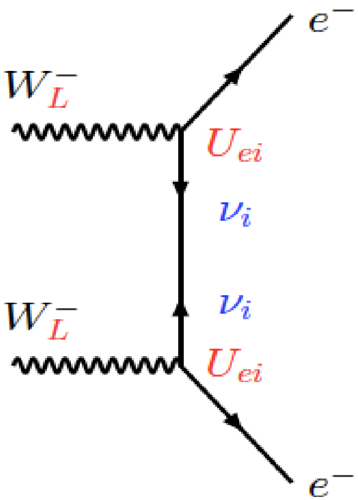
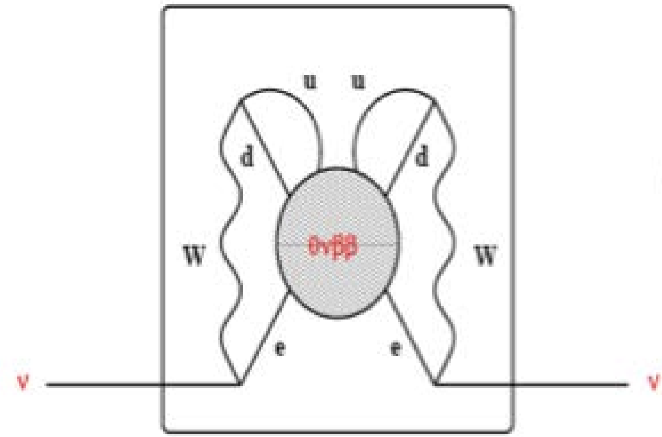
Nice interplay with LHC

Light Majorana neutrinos



$$\varepsilon \equiv \langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

$$1 / T_{1/2} = PS * NME^2 * (\langle m_\nu \rangle / m_e)^2$$



Schechter and Valle 1982:

Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!

Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

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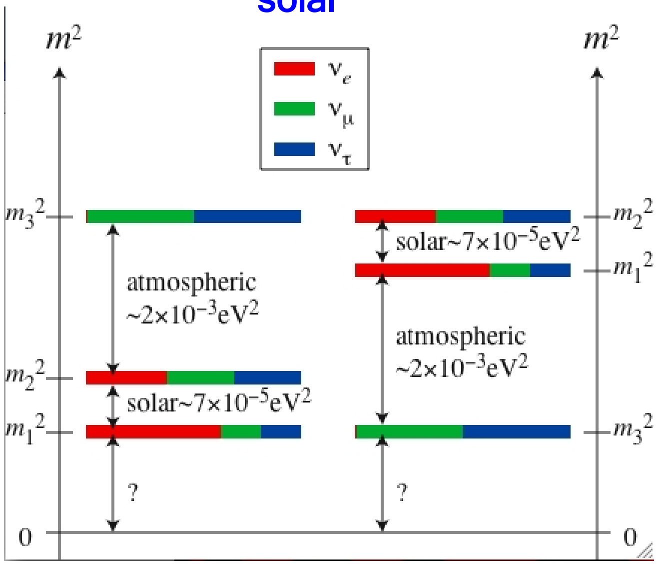
3 Flavour mixing (PMNS)

Neutrinos mix as oscillation experiments have shown, hence

Leptonic mixing (PMNS) matrix (including Majorana character)

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

solar | reactor | atmospheric



normal **inverted**

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i2\alpha_1} m_2 + s_{13}^2 e^{i2(\alpha_2-\delta)} m_3 \right|$$

From oscillation experiments

$\sin^2 2\theta_{23} > 0.9$ (90%CL), best fit $\theta_{23} = 45°$

$\sin^2 2\theta_{13} = 0.09$ (90%CL), $\theta_{13} = 9°$

$\sin^2\theta_{12} = 0.32, \theta_{12} = 34^\circ.06^{+1.16}_{-0.84}$

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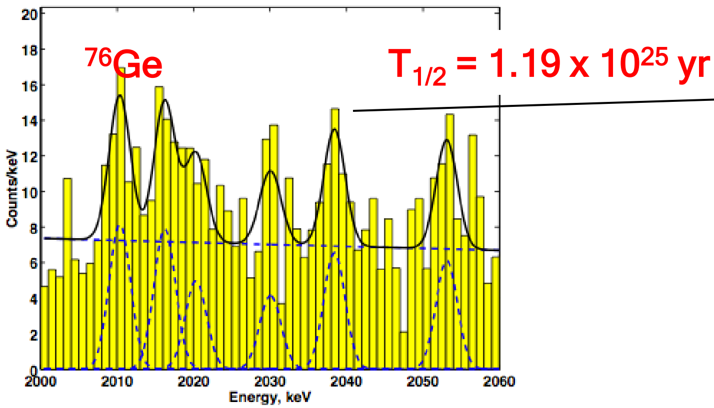
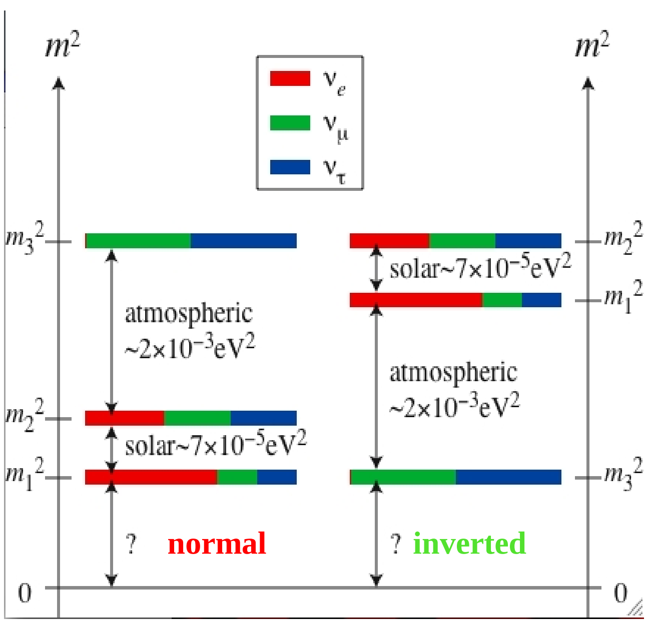
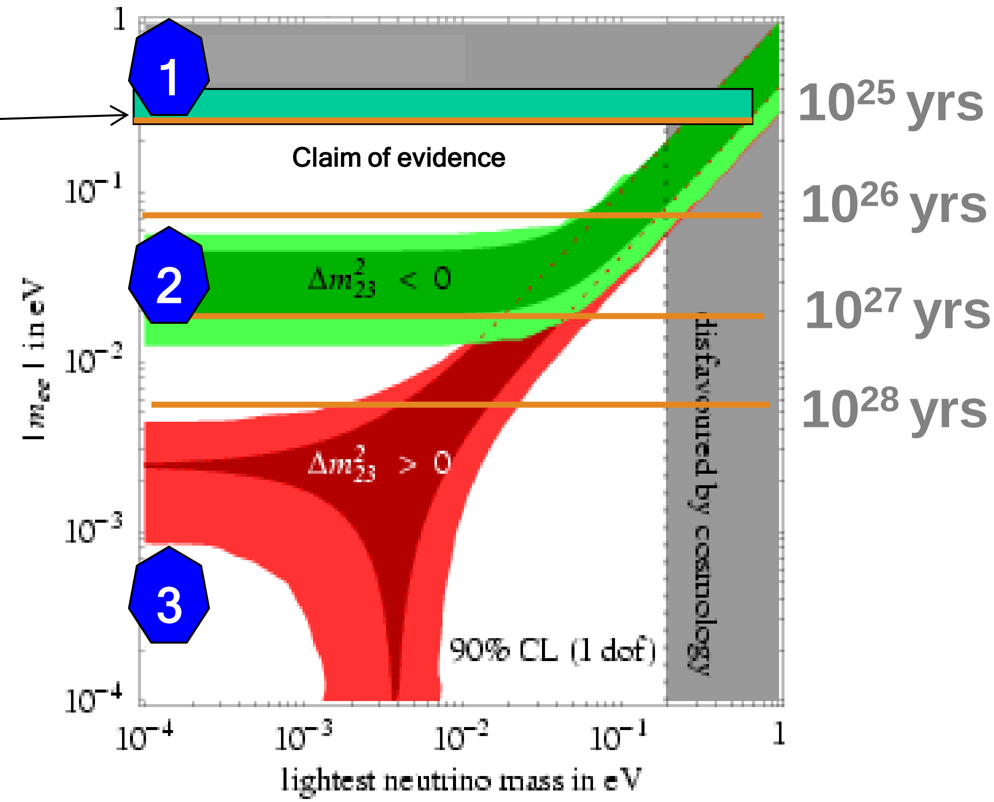
Mass hierarchies and DBD



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





1.) Is the claimed evidence correct?
GERDA phase I, Xe-experiments

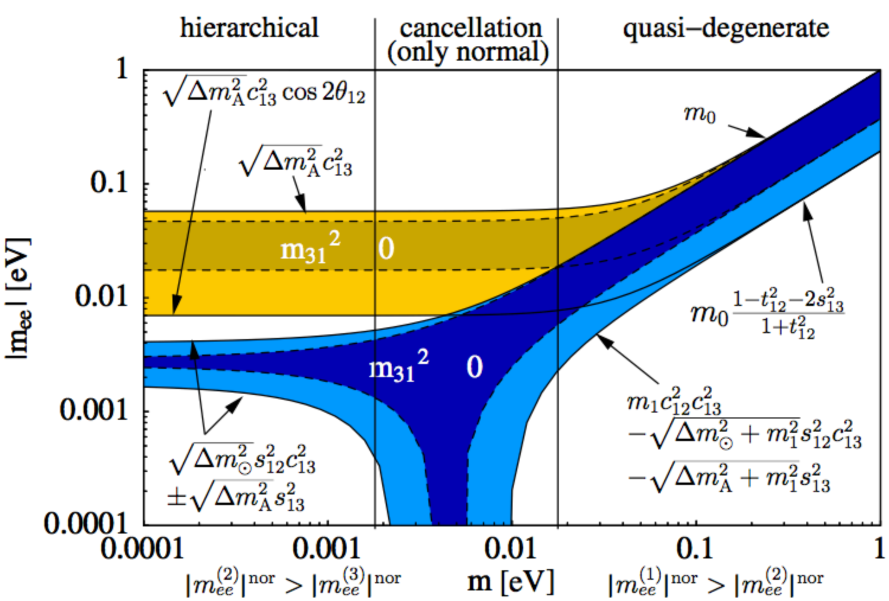
2.) Can we probe the inverted hierarchy?

3.) What about the normal hierarchy?

Mass hierarchies and DBD

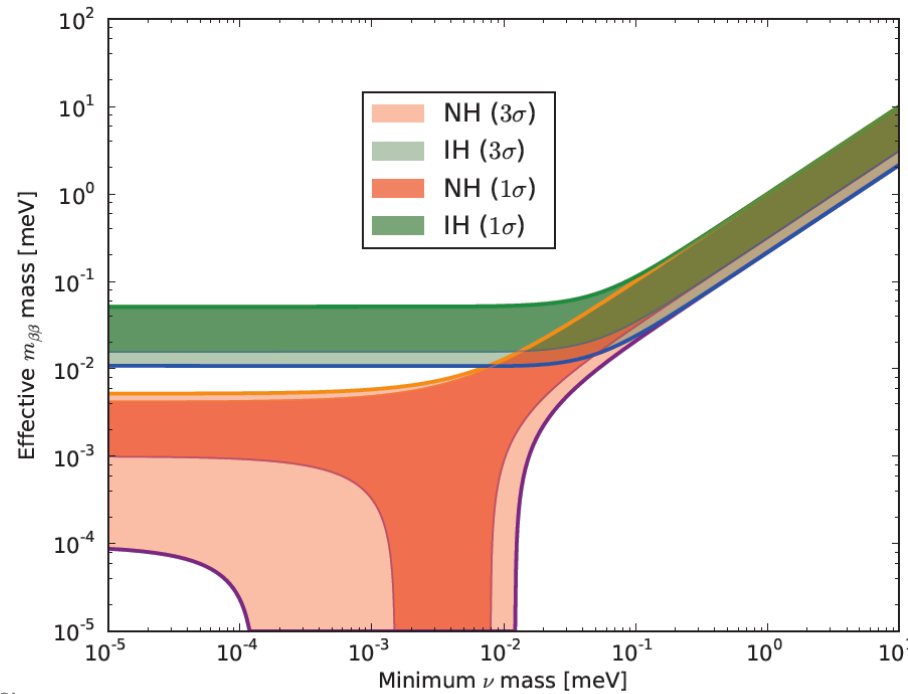
With the known oscillation results everything is fixed

General dependence



M. Lindner, A.. Merle, W. Rodejohann, Phys. Rev. D 73, 053005 (2006)

Current data



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Other mass determinations

Beta decay:

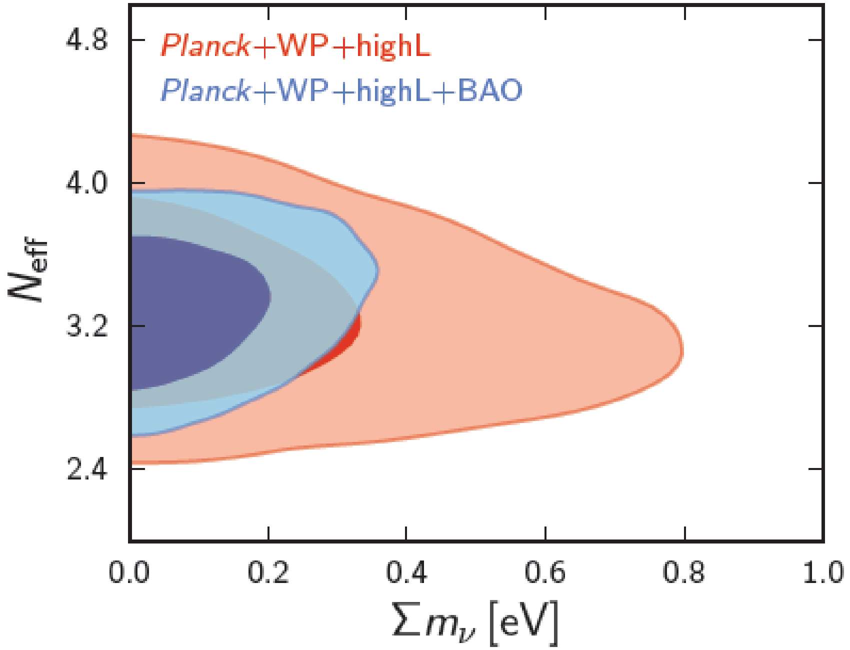
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

http://www.katrin.kit.edu

KATRIN -Sensitivity about 0.2 eV

Cosmology:

$$\Omega_\nu h^2 \Rightarrow \Sigma = m_1 + m_2 + m_3$$



$$\sum m_\nu < 0.23 eV (95\% CL)$$

+ oscillation parameters

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or

Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t \,/\, N_{\beta\beta} \quad (\tau \gg T) \quad \text{(Background free)}$$

For half-life measurements of $10^{26\text{-}27}$ yrs

1 event/yr you need $10^{26\text{-}27}$ source atoms

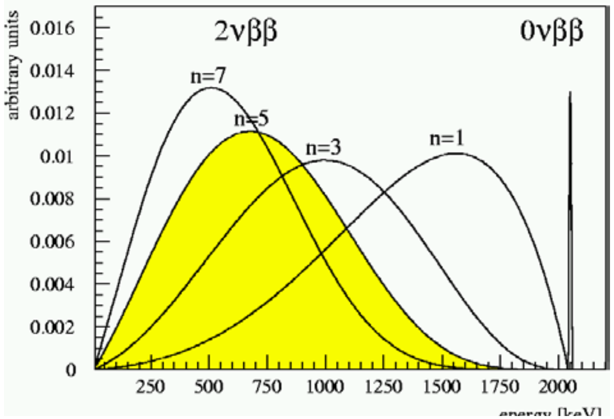
This is about 1000 moles of isotope, implying about 100 kg

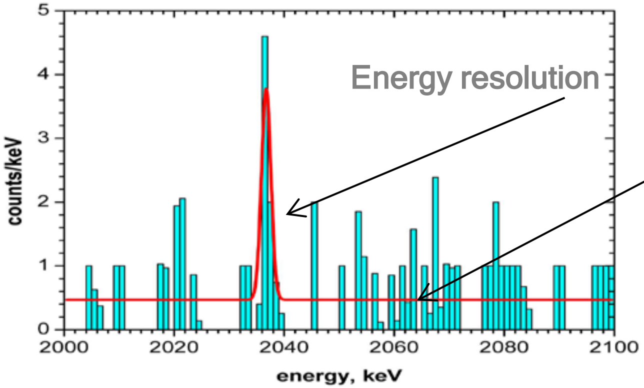
Now you only can loose: nat. abundance, efficiency, background, ...

Going underground

0νββ: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons





Measured quantity: Half-life

$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$

Experimental sensitivity depends on

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta EB}}$$ (BG limited)

$$T_{1/2}^{-1} \propto a\varepsilon Mt$$ (BG free)

If background limited $$m_\nu \propto \sqrt[4]{\frac{\Delta EB}{Mt}}$$

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Perfect world experiment

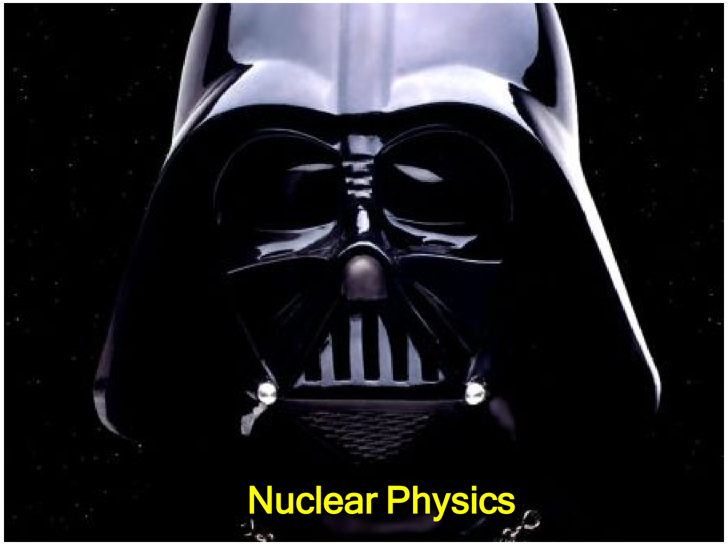
- No background
- δ function as peak
- 100 % abundance
- 100% detection efficiency
- Infinite measuring time
- Infinite mass

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta EB}}$$

Life is easy, the rest is just details

Master equation

$$1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$$



Measurement

Exact calculation

Complex calculations

Quantity of interest

J. Kotila, F. Iachello, PRC 034316 (2012)
S. Stoica, M. Mirea, arXiv:1307.0290

Severe nuclear structure issue

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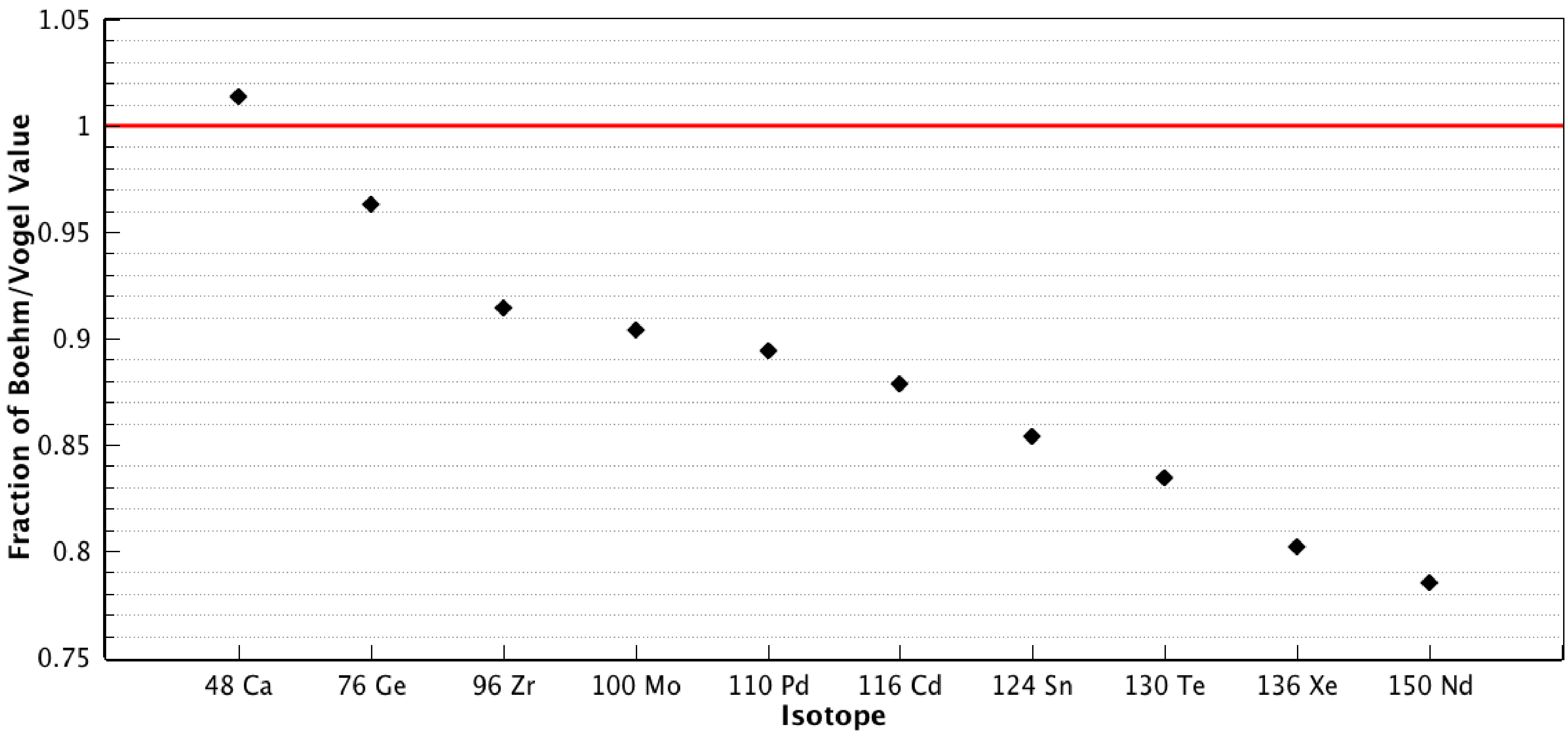
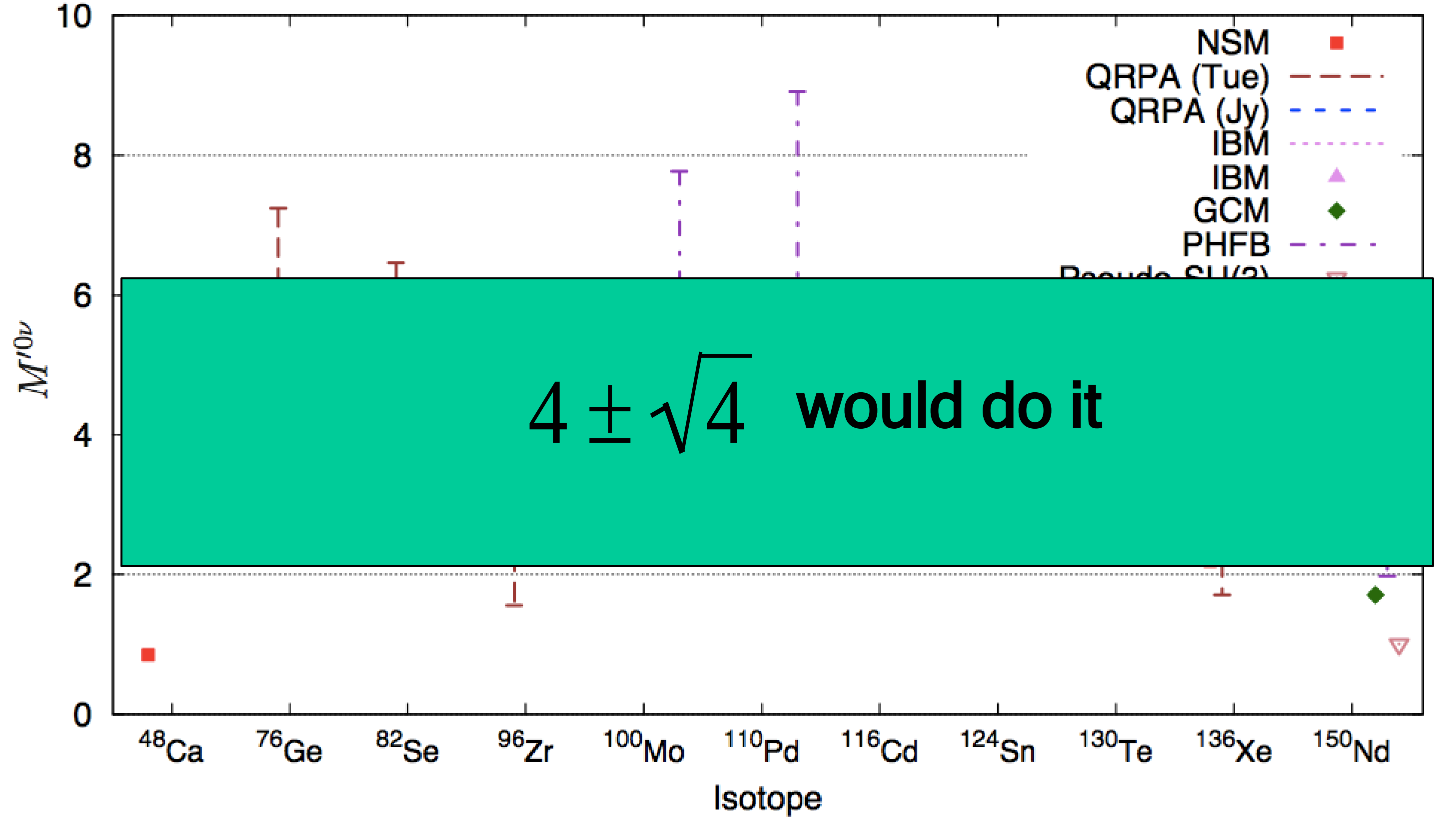
Phase space factors (new vs. old)



Matrix element

Rescaled as people use different g_A (1-1.25) and R_0 (1.0-1.3 fm)

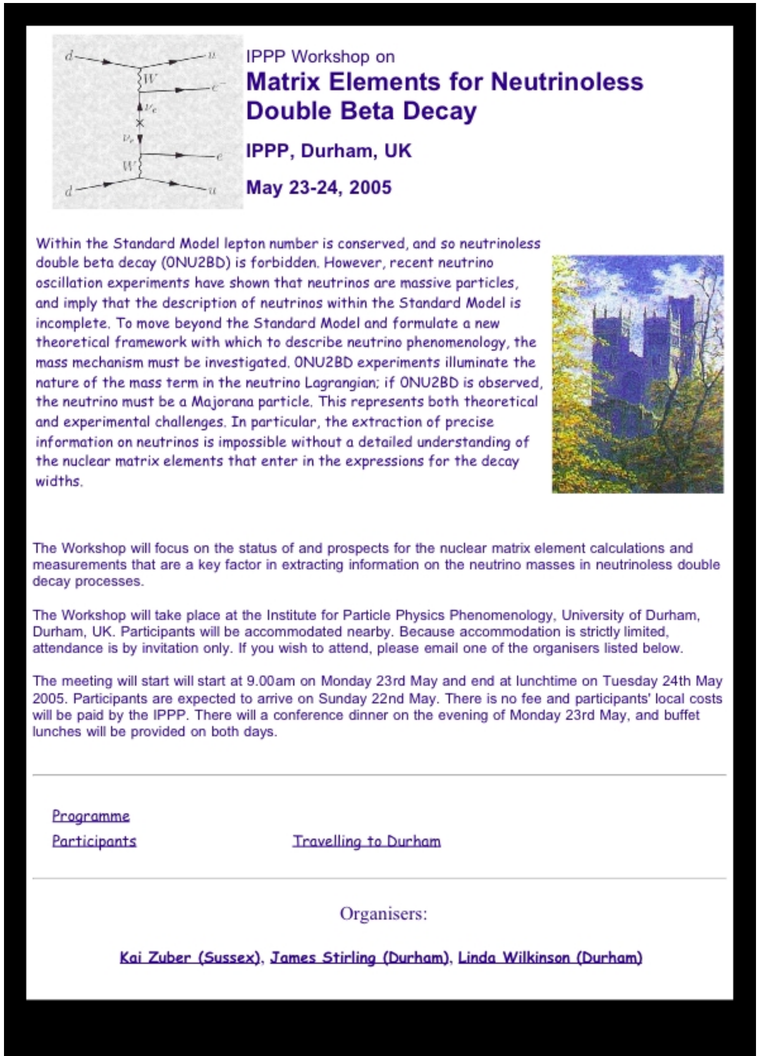


$4 \pm \sqrt{4}$ would do it

A. Dueck, W. Rodejohann, K. Zuber, arXiv:1103.4152, PRD 83, 113010 (2011)

Several new techniques applied in last years

NME + Experiments



IPPP Workshop on

Matrix Elements for Neutrinoless Double Beta Decay

IPPP, Durham, UK

May 23-24, 2005

Within the Standard Model lepton number is conserved, and so neutrinoless double beta decay (0NU2BD) is forbidden. However, recent neutrino oscillation experiments have shown that neutrinos are massive particles, and imply that the description of neutrinos within the Standard Model is incomplete. To move beyond the Standard Model and formulate a new theoretical framework with which to describe neutrino phenomenology, the mass mechanism must be investigated. 0NU2BD experiments illuminate the nature of the mass term in the neutrino Lagrangian; if 0NU2BD is observed, the neutrino must be a Majorana particle. This represents both theoretical and experimental challenges. In particular, the extraction of precise information on neutrinos is impossible without a detailed understanding of the nuclear matrix elements that enter in the expressions for the decay widths.

The Workshop will focus on the status of and prospects for the nuclear matrix element calculations and measurements that are a key factor in extracting information on the neutrino masses in neutrinoless double decay processes.

The Workshop will take place at the Institute for Particle Physics Phenomenology, University of Durham, Durham, UK. Participants will be accommodated nearby. Because accommodation is strictly limited, attendance is by invitation only. If you wish to attend, please email one of the organisers listed below.

The meeting will start will start at 9.00am on Monday 23rd May and end at lunchtime on Tuesday 24th May 2005. Participants are expected to arrive on Sunday 22nd May. There is no fee and participants' local costs will be paid by the IPPP. There will a conference dinner on the evening of Monday 23rd May, and buffet lunches will be provided on both days.

Programme

Participants

Travelling to Durham

Organisers:

Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)

Consensus report: K. Zuber, nucl-ex/0511009

Focus section in JPG 39 (2012)

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iktp

Experimental approaches

$0\nu\beta\beta$ decay rate scales with Q^5 → only those with Q>2000 keV

11 isotopes of interest

Isotope	Nat. abund. (%)	Q-values 2012
Ca-48	0.187	4262.96 ± 0.84
Ge-76	7.44	2039.006 ± 0.050
Se-82	8.73	2997.9 ± 0.3
Zr-96	2.80	3347.7 ± 2.2
Mo-100	9.63	3034.40 ± 0.17
Pd-110	11.72	2017.85 ± 0.64
Cd-116	7.49	2813.50 ± 0.13
Sn-124	5.79	2292.64 ± 0.39
Te-130	33.80	2527.518 ± 0.013
Xe-136	8.9	2457.83 ± 0.37
Nd-150	5.64	3371.38 ± 0.20

Candles

GERDA, Majorana

SuperNEMO, LUCIFER

MOON, AMore

COBRA

Tin.Tin

CUORE, SNO+

nEXO, KamLAND-Zen, NEXT, XMASS

MCT, SuperNEMO(?)

There is no super-isotope!

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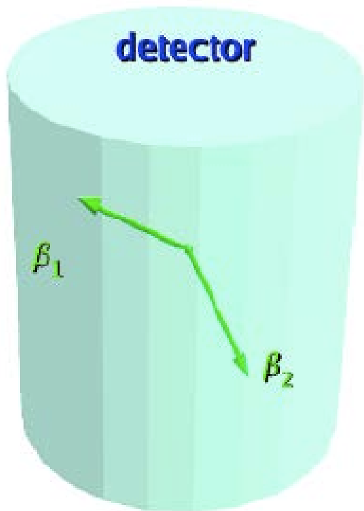
Osvaldo found COBRA at MEDEX 2011

Signatures and approaches

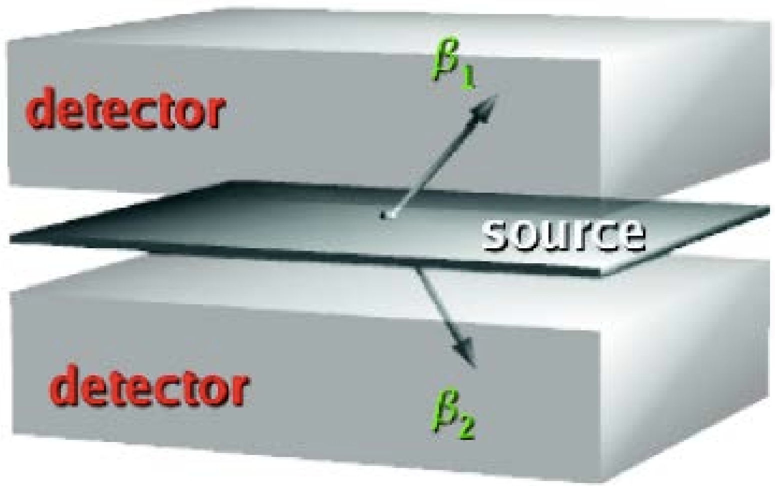
- Sum energy of both electrons
- Single electron spectra and opening angle
- Detection of daughter ion

Source = detector



- Semiconductors
- Cryogenic bolometers
- Scintillators
- Liquid Noble gases

Source ≠ detector



- TPCs (foils)
- Scintillators (foils)

All low background

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The fantastic 4

Because they‘ve started

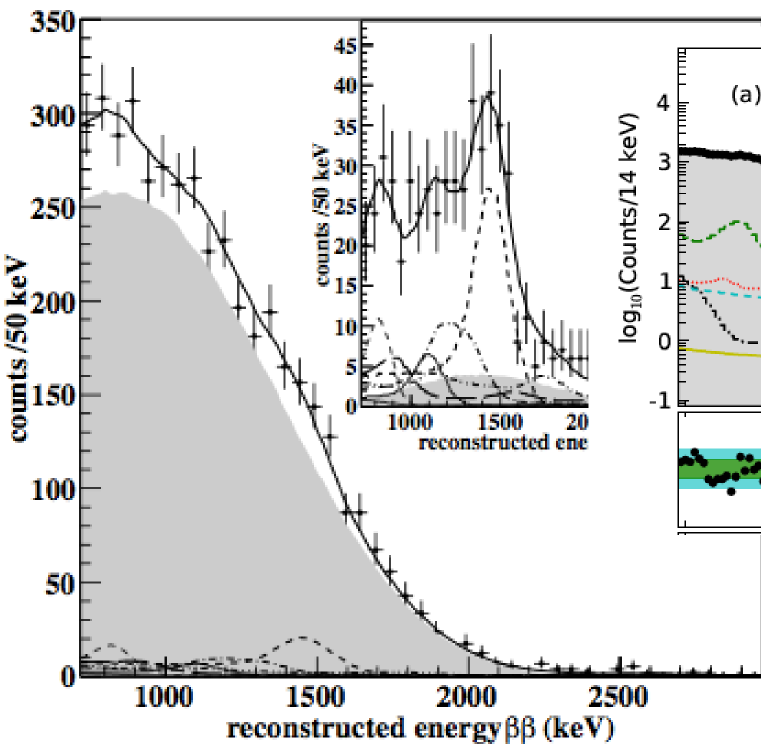
GERDA

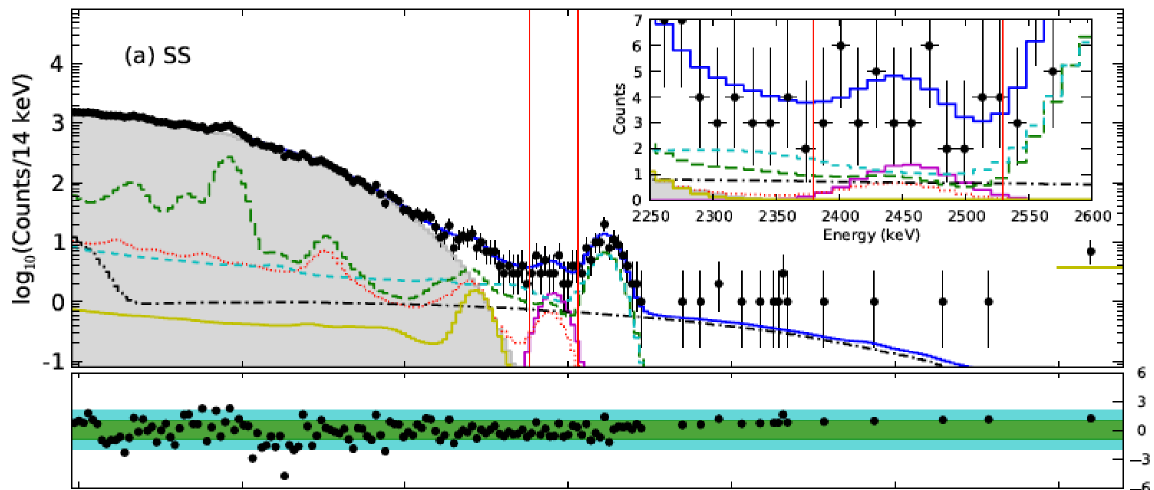
Enriched Xenon Observatory
EXO
for double beta decay

EXO-200

200 kg of enriched (80%) Xe-136 at hand

Current half-life limit on 0nu decay :
$T_{1/2}$ > 1.1 x 10^{25} years (90%CL)
J. B. Albert et al., Nature 510,229 (2014)





In conflict with positive claim for almost all matrix element calculations

Uncertainties due to conversion

First observation of 2nu decay of Xe-136,
N. Ackerman et al., PRL 107, 212501 (2011)

Future option: Barium tagging

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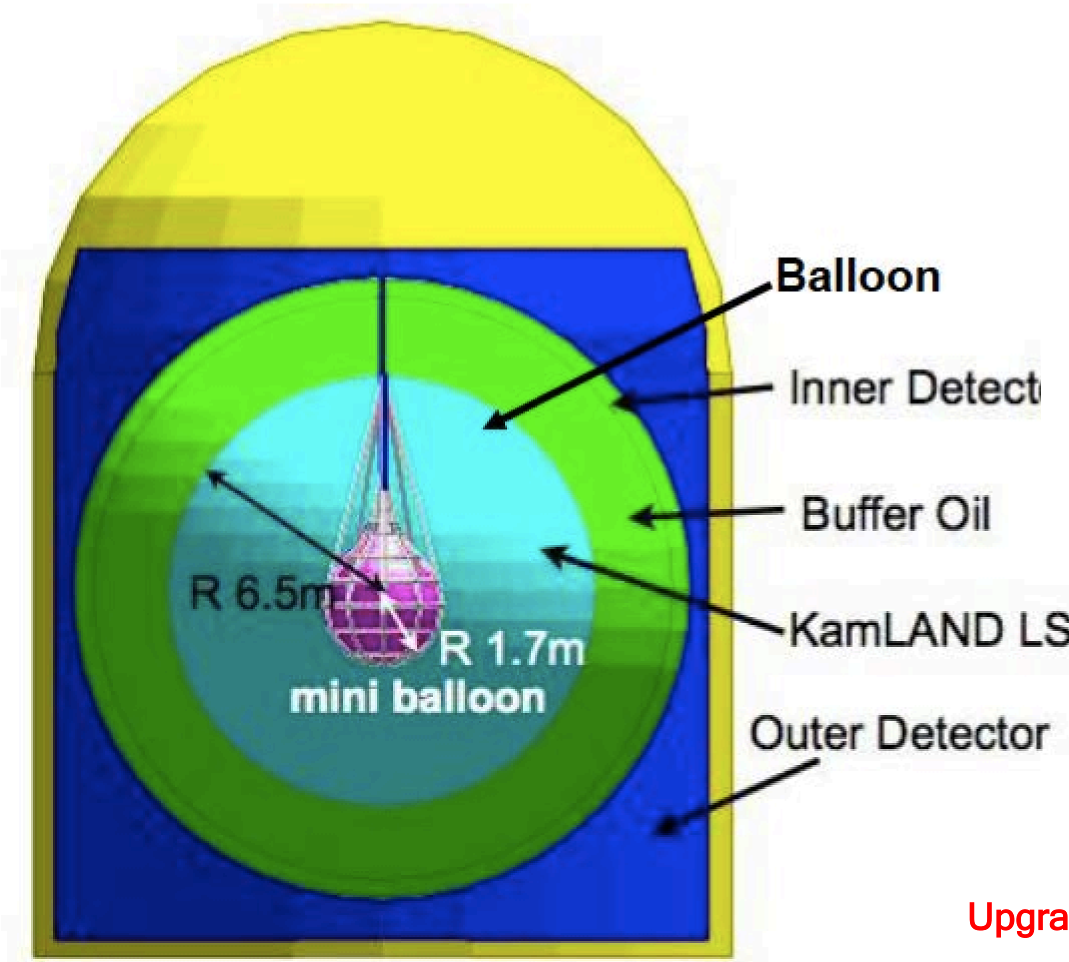
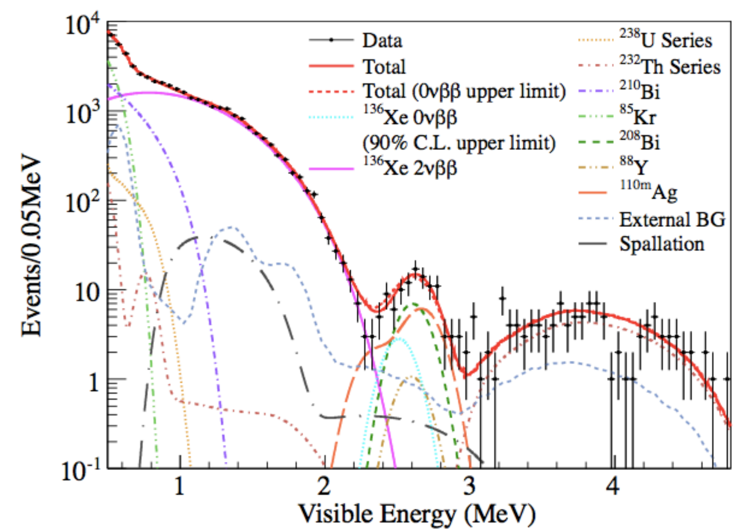
KamLAND - Zen

Using 400 kg of Xe (91.7% enriched in Xe-136)





$$T^{0\nu}_{1/2} > 5.7 \times 10^{24}\ \text{yr (90\% C.L.)}$$

A Gando et al., PRC 85,045504 (2012)

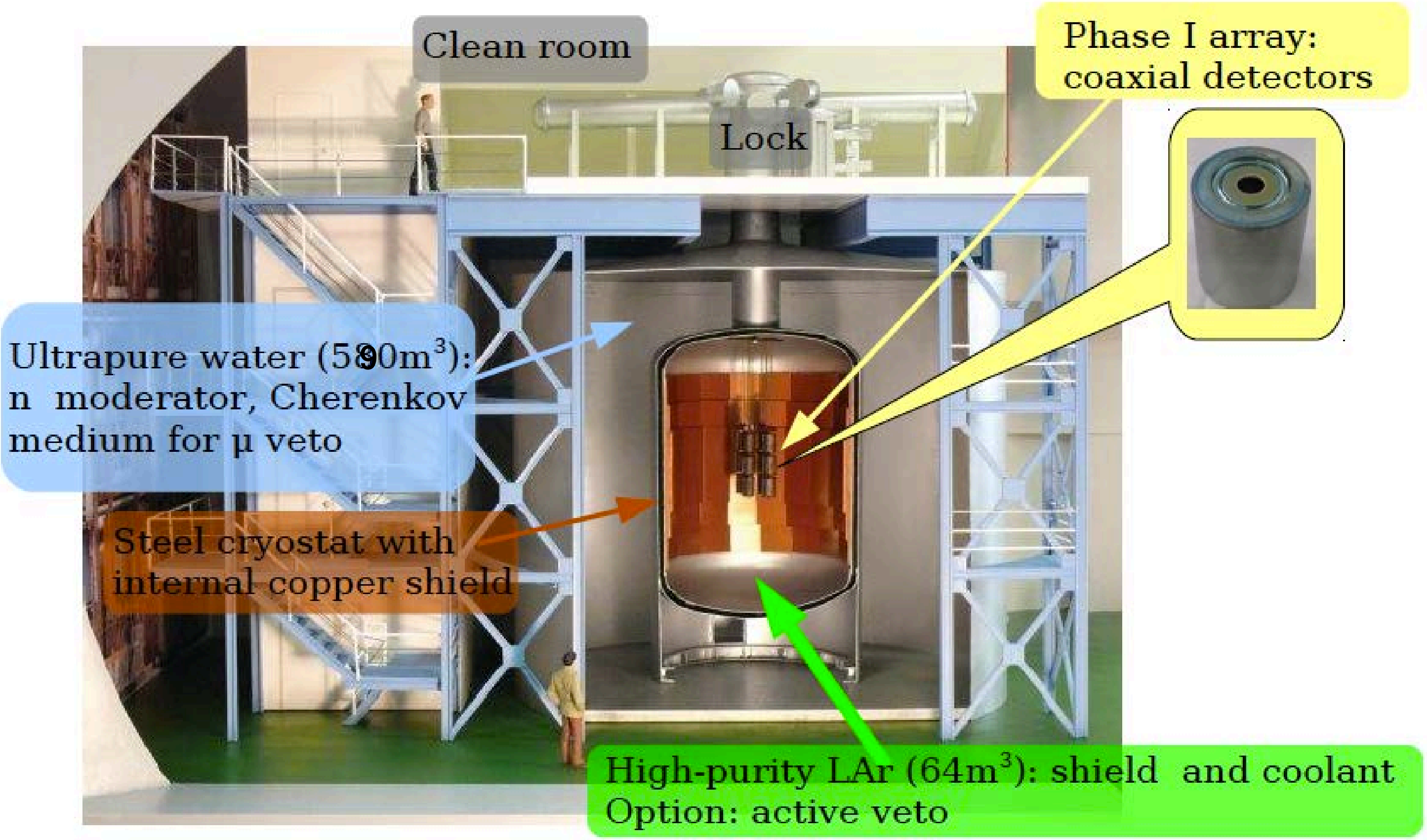
$T_{1/2} > 1.9 \times 10^{25}$ years (90%CL)

A. Gando, PRL 110, 062502 (2013)

Upgrade to 1 ton enriched Xe planned soon

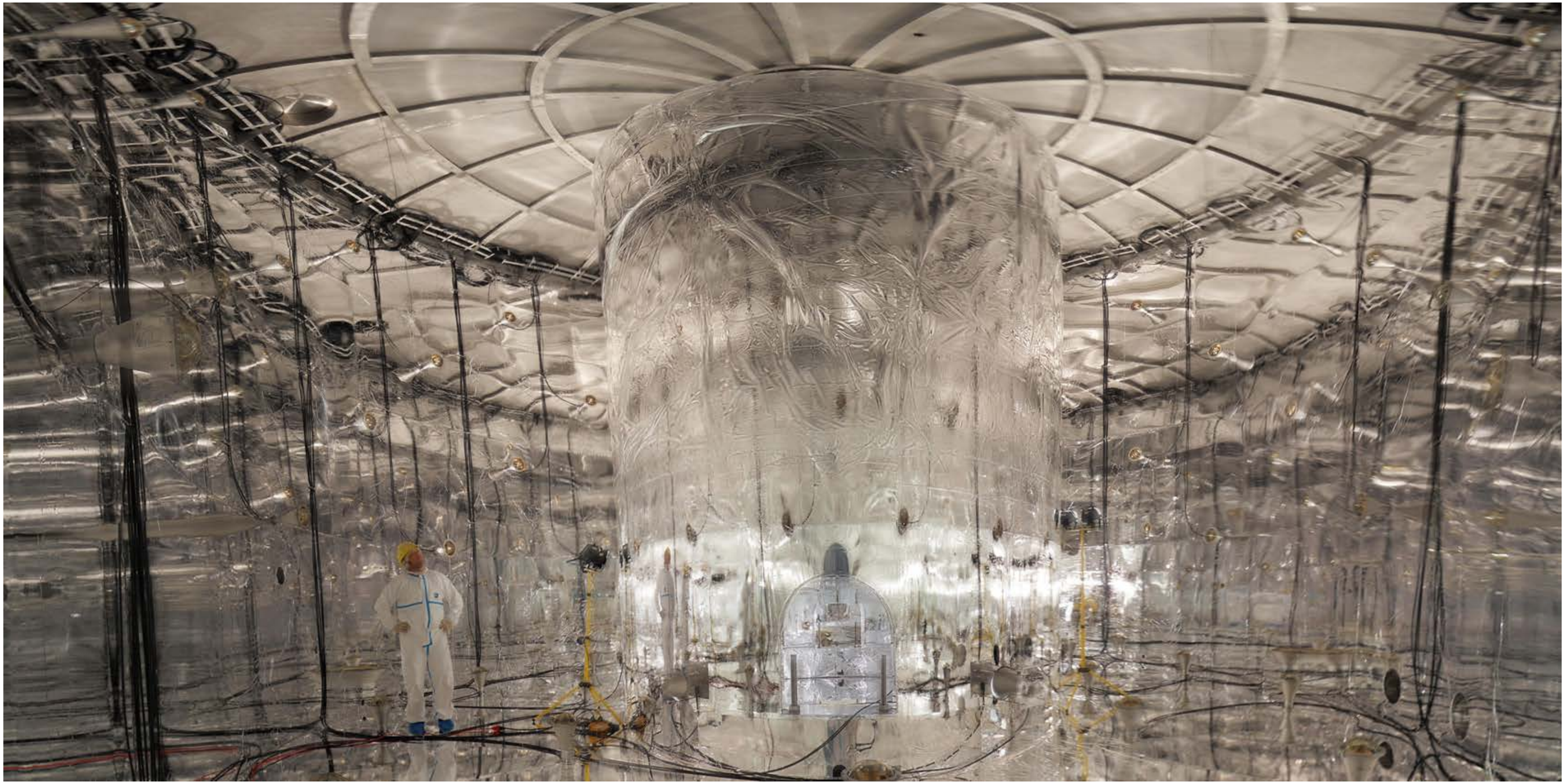
GERDA-Principal Setup

Idea : Running bare Ge crystals in LAr

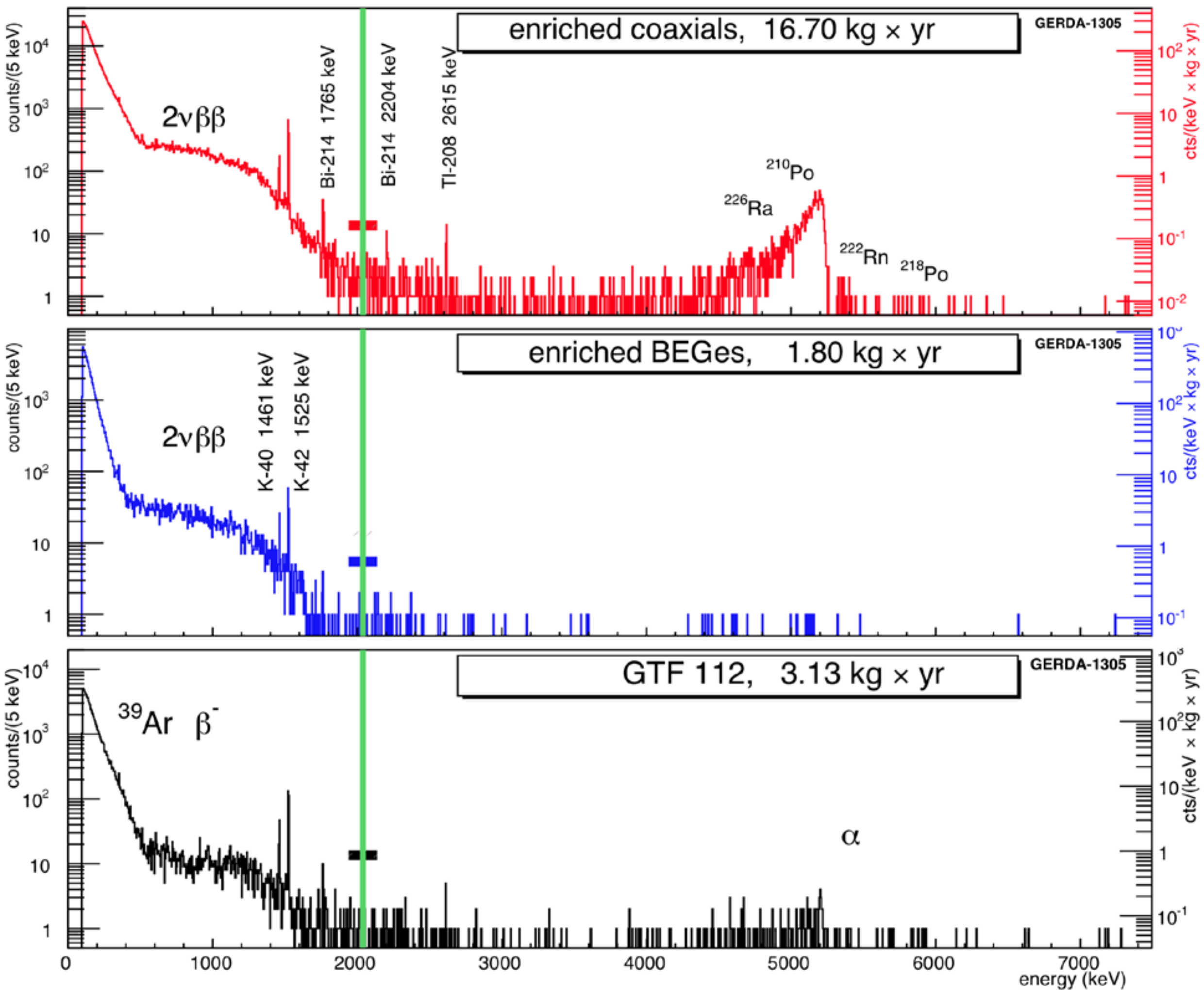


The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge

Eur. Phys. J. C (2013) 73:2330



Phase I data taking



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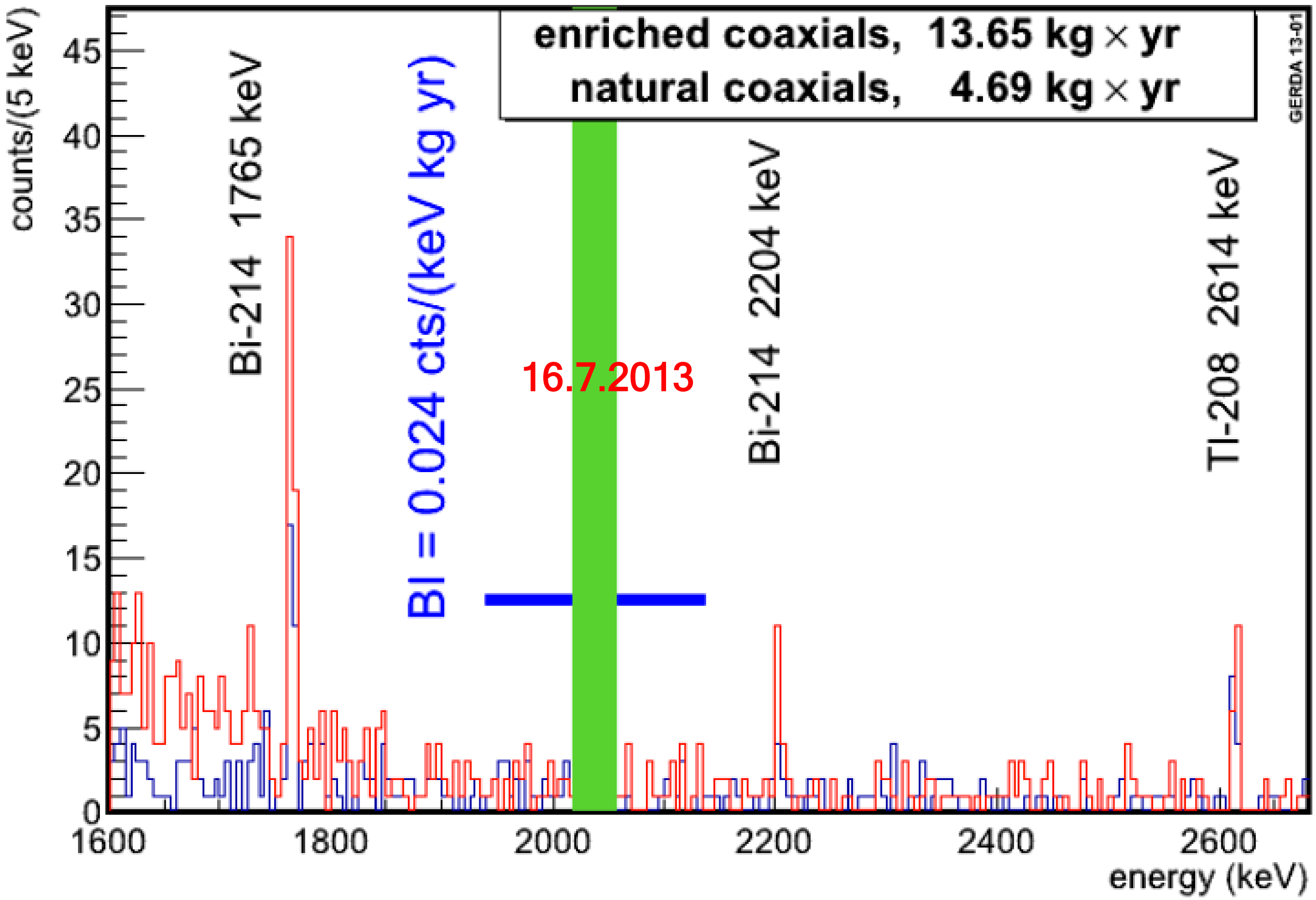
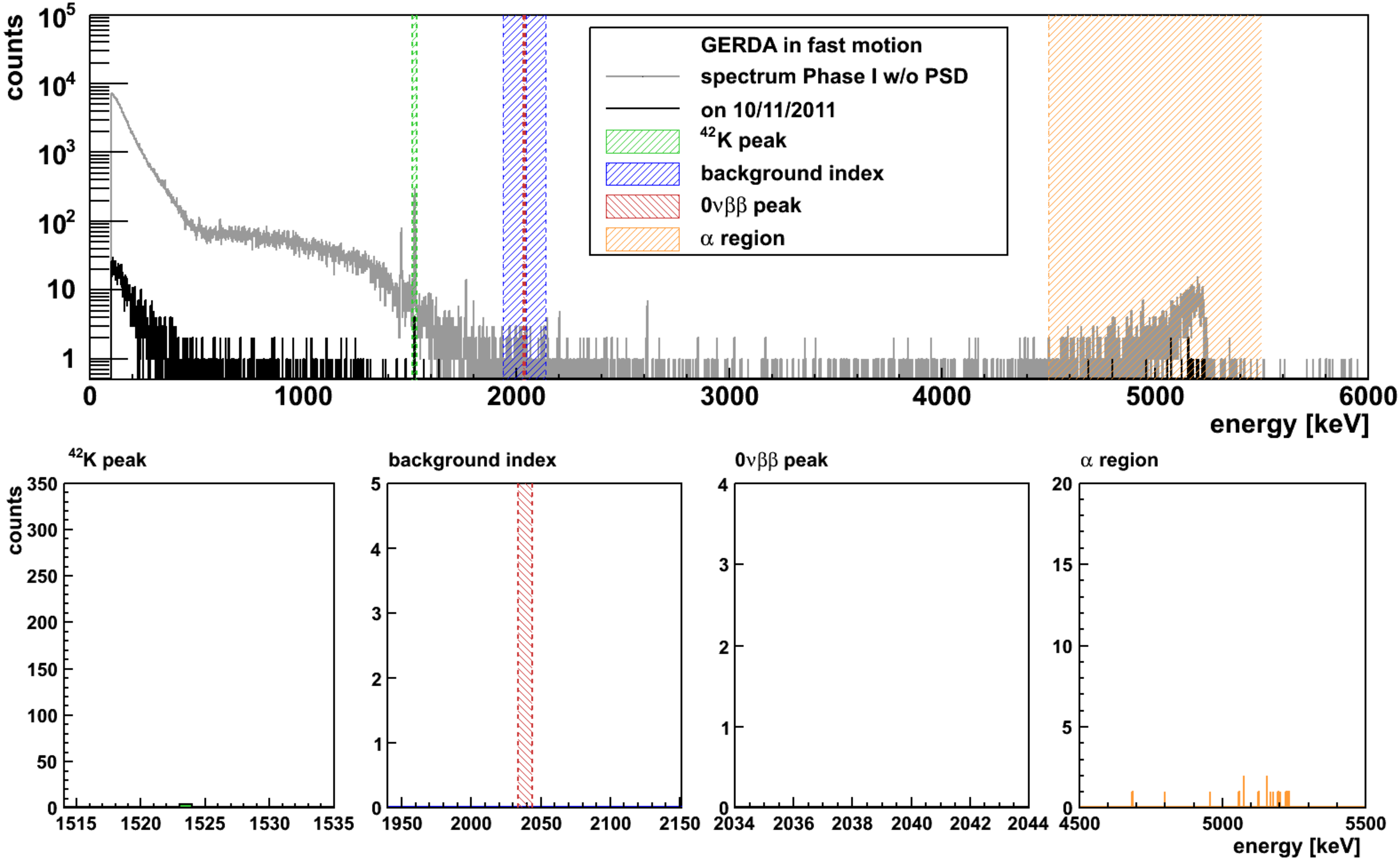
Phase I data taking



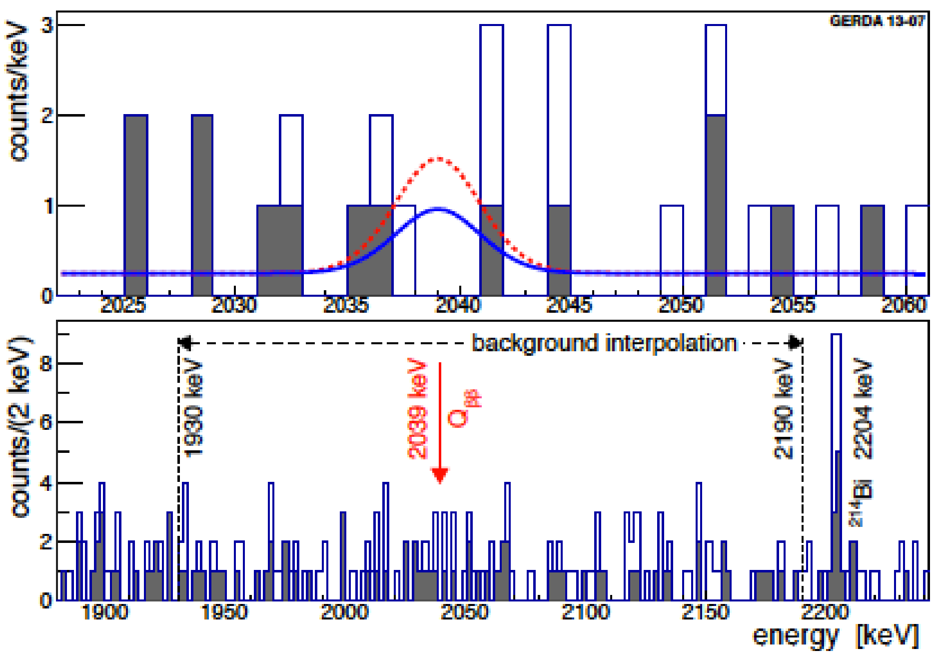


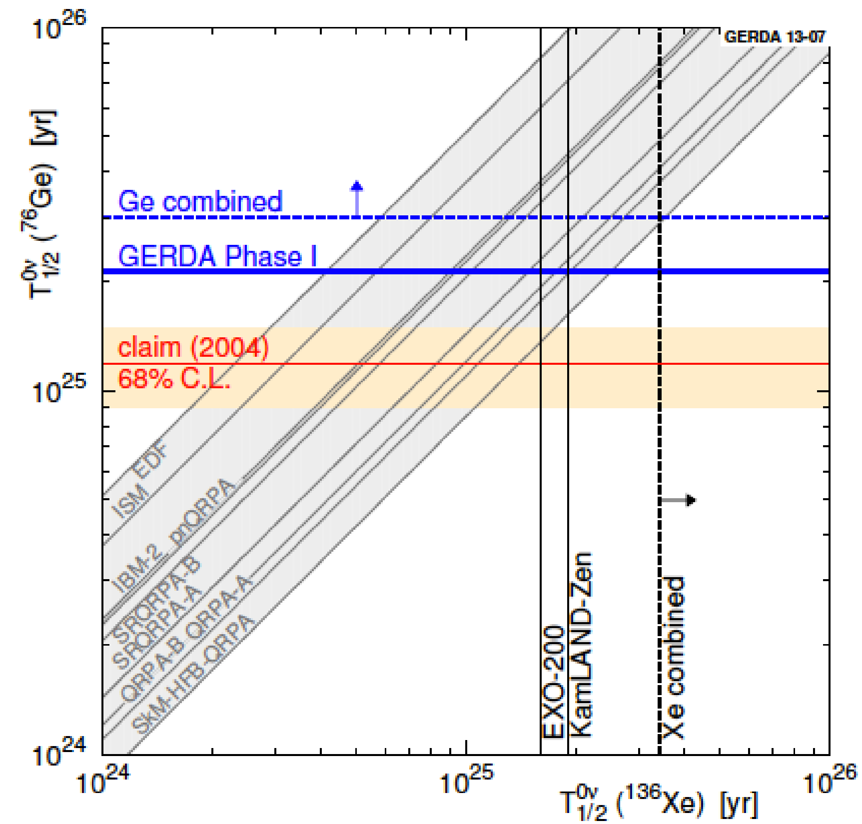
counts
energy [keV]
GERDA in fast motion
spectrum Phase I w/o PSD
on 10/11/2011
42K peak
background index
0νββ peak
α region
42K peak
background index
0νββ peak
α region
counts
energy [keV]

Phase I results

Pulse shape discrimination: M. Agostini et al. Eur. Phys. J. C 71,2583 (2013)

Result Phase 1: M. Agostini et al., PRL 111, 122503 (2013)

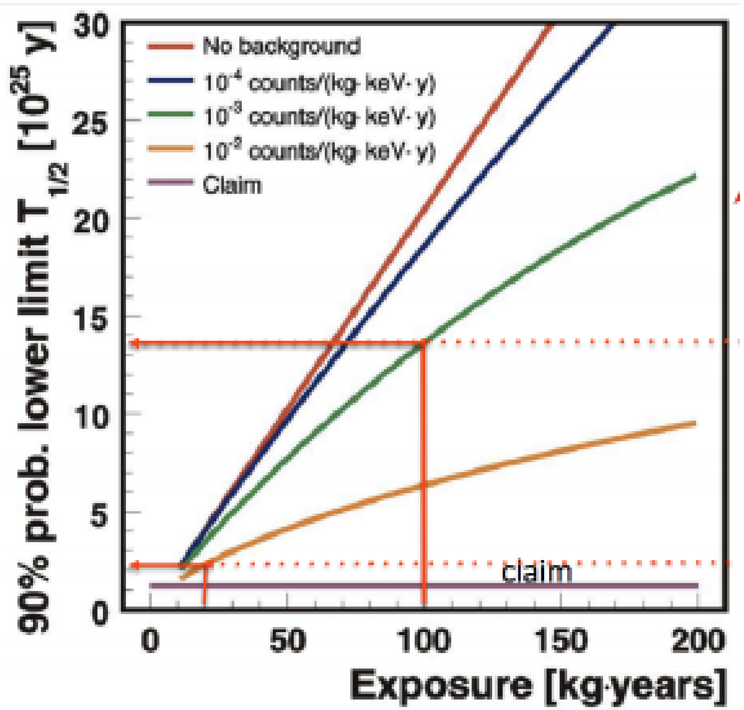




Towards phase 2

Increase mass : Another 30 enriched BEGe detectors (additional 20 kg)

Reduce background by a factor 10 with respect to phase 1 by
- Pulse shape analysis
- LAr instrumentation



10^{-3} counts/keV/kg/yr

10^{-2} counts/keV/kg/yr

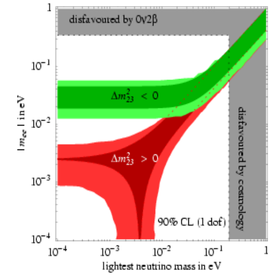
Near term future

- KamLAND-Zen just finished a long data taking run (Xe-136)
- MAJORANA Demonstrator is running (Ge-76)
- GERDA Phase 2 will start this month (Ge-76)
- CANDLES about to start in January 2016 (Ca-48)
- CUORE setup finished, data taking will start about sommer 2016 (Te-130)

Tackling 50 meV (IH)

Inverse hierarchy:

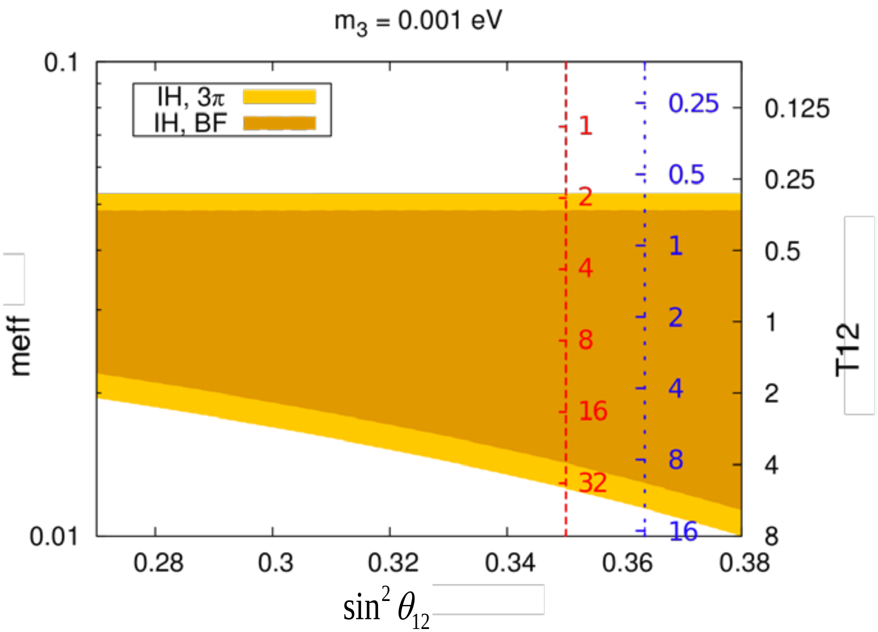
$$\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j$$
$$\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2$$
$$\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}}$$
$$\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \simeq 19\ \mathrm{meV}$$

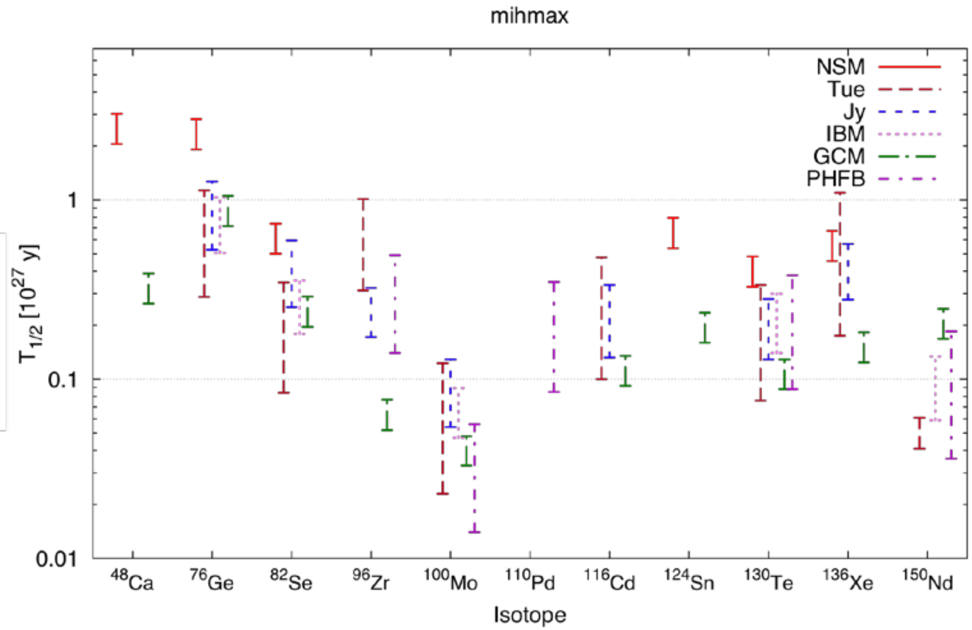


Just to touch the IH

^{100}Mo and ^{150}Nd seems most promising

Dependence on solar mixing angle

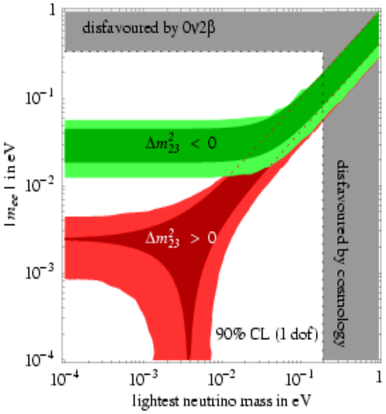




Reminder: Factor 2 in mass implies factor 16 in experimental parameters ➔ better solar measurement ➔SNO+??? Reactors (JUNO , RENO-50)???

A. Dueck, W. Rodejohann, K. Zuber, PRD 83, 113010 (2011)

3 Tackling the normal hierarchy

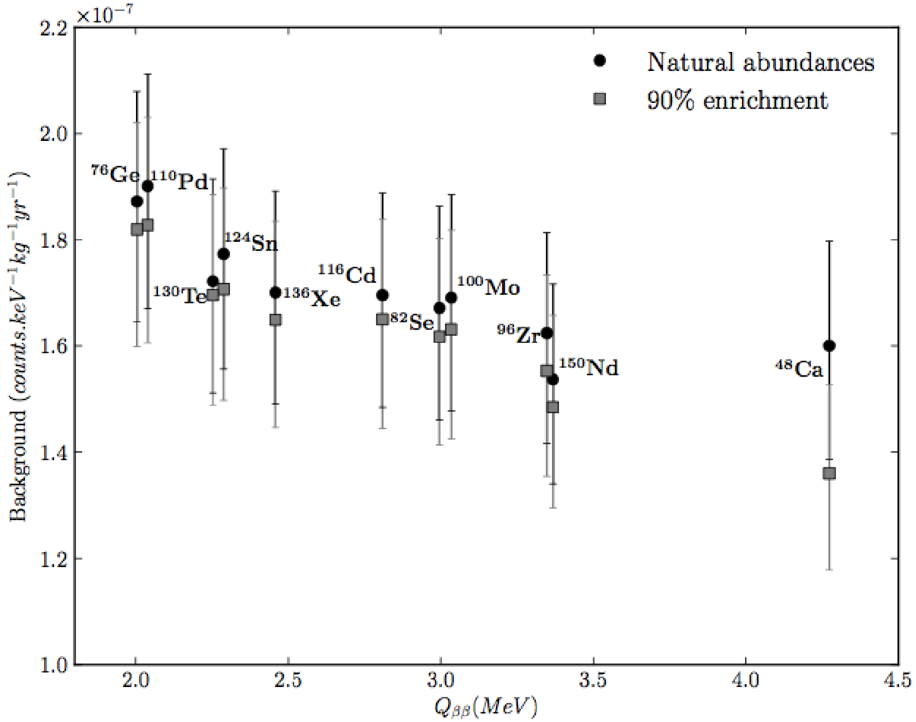


No real proposal yet

- Will be tough and expensive
  > tonne scale detectors
- Needs more precise data from oscillations

- New background components (f.e. solar neutrino-electron elastic scattering)

N. deBarros, K. Zuber, arXiv:1103.5757, JPG 38, 105201 (2011)
H. Ejiri, K. Zuber, submitted



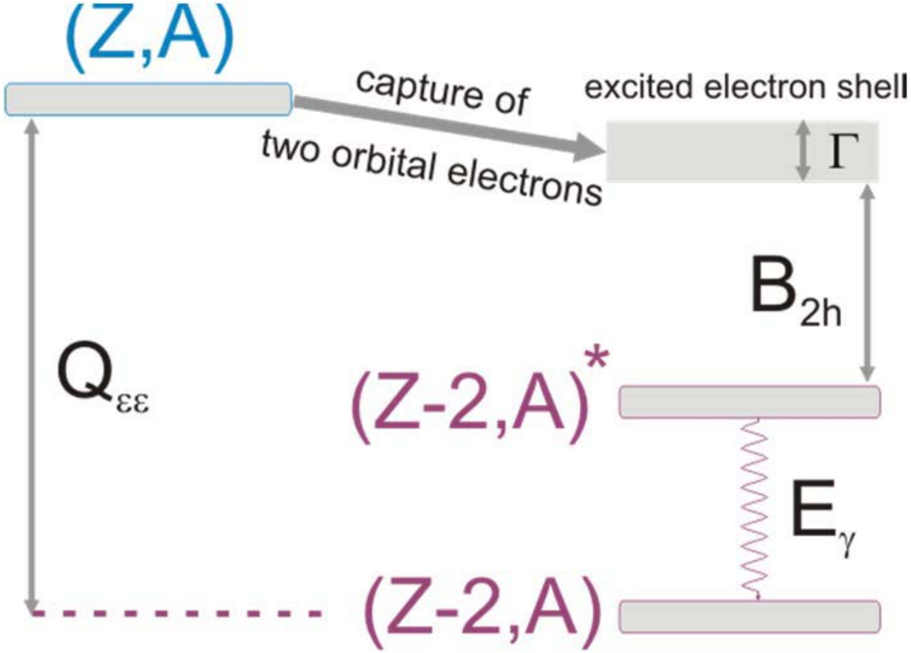
- More accurate matrix elements

HOW???

Experiments which work for IH might not work for NH

Resonant double EC

$$\frac{1}{T_{1/2}} = C \times m_\nu^2 \times |M|^2 \times |\Psi_{1e}|^2 \times |\Psi_{2e}|^2 \times \frac{\Gamma}{(Q - B_{2h} - E_\gamma)^2 + \frac{1}{4}\Gamma^2}$$



Alternative modes

- $(A,Z) \rightarrow (A,Z-2) + 2\,e^+ \; (+2\nu_e)$ $\beta+\beta+$ $Q-4m_ec^2$
- $e^- + (A,Z) \rightarrow (A,Z-2) + e^+ \; (+2\nu_e)$ $\beta+/EC$ $Q-2m_ec^2$
- $2\,e^- + (A,Z) \rightarrow (A,Z-2) \; (+2\nu_e)$ EC/EC Q

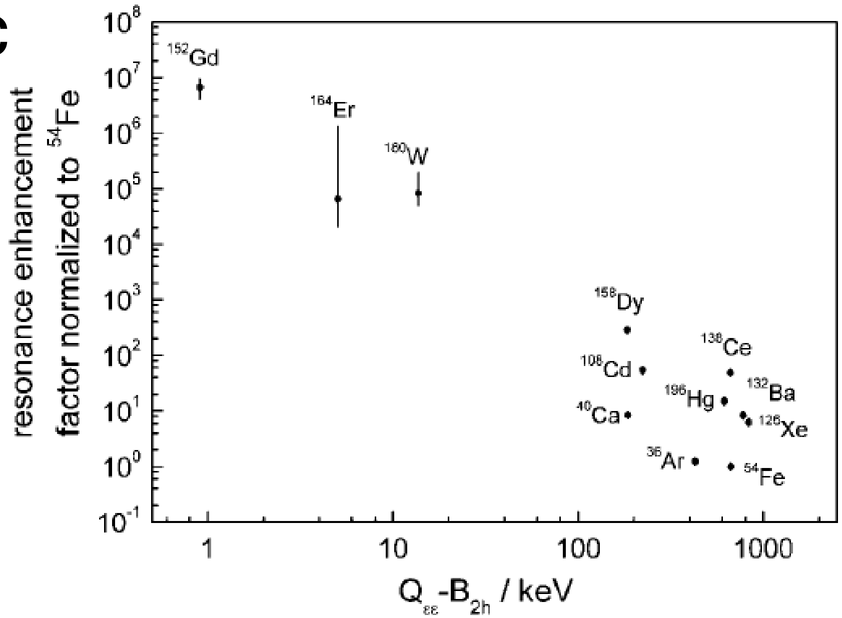
Enhanced if V+A is at work

M. Hirsch et al, Z. Phys. A 347,151 (1994)

Best candidate : 152Gd
measured with SHIPTRAP at GSI

Resonant enhancement (*10^6) of 0nu ECEC if excited state in daughter is degenerate (within 200 eV) with initial ground state (-> Q-values)

J. Bernabeu, A. deRujula, C. Jarlskog, Nucl. Phys. B 221,15 (1983)
S. Zujkoswski, S. Wycech, PRC 70, 052501 (2004)



S. Eliseev et al., Phys. Rev. Lett. 106,052504 (2011)

"I hope you leave here and walk out and say, 'What did he say?'"
—George W. Bush

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Conclusion

iktp

•Double beta decay is of central importance for neutrino physics. Gold plated channel to probe fundamental character of neutrinos

•Interesting times as both LHC and double beta probe TeV scale

•Several next generation experiments started recently (Candles, GERDA, KamLAND-Zen, EXO)
First exciting results from Xe-experiments and GERDA

•Further experiments are in the building up phase, several interesting experimental ideas are investigated

•To go below 50 meV requires hundreds of kilograms of enriched material, lot of ideas...to cover uncertainties at least 3-4 isotopes should be measured

•To support matrix element calculations as much experimental input as possible on nuclear structure is desired! We are only talking about 11 isotope pairs!!!

The future...

or