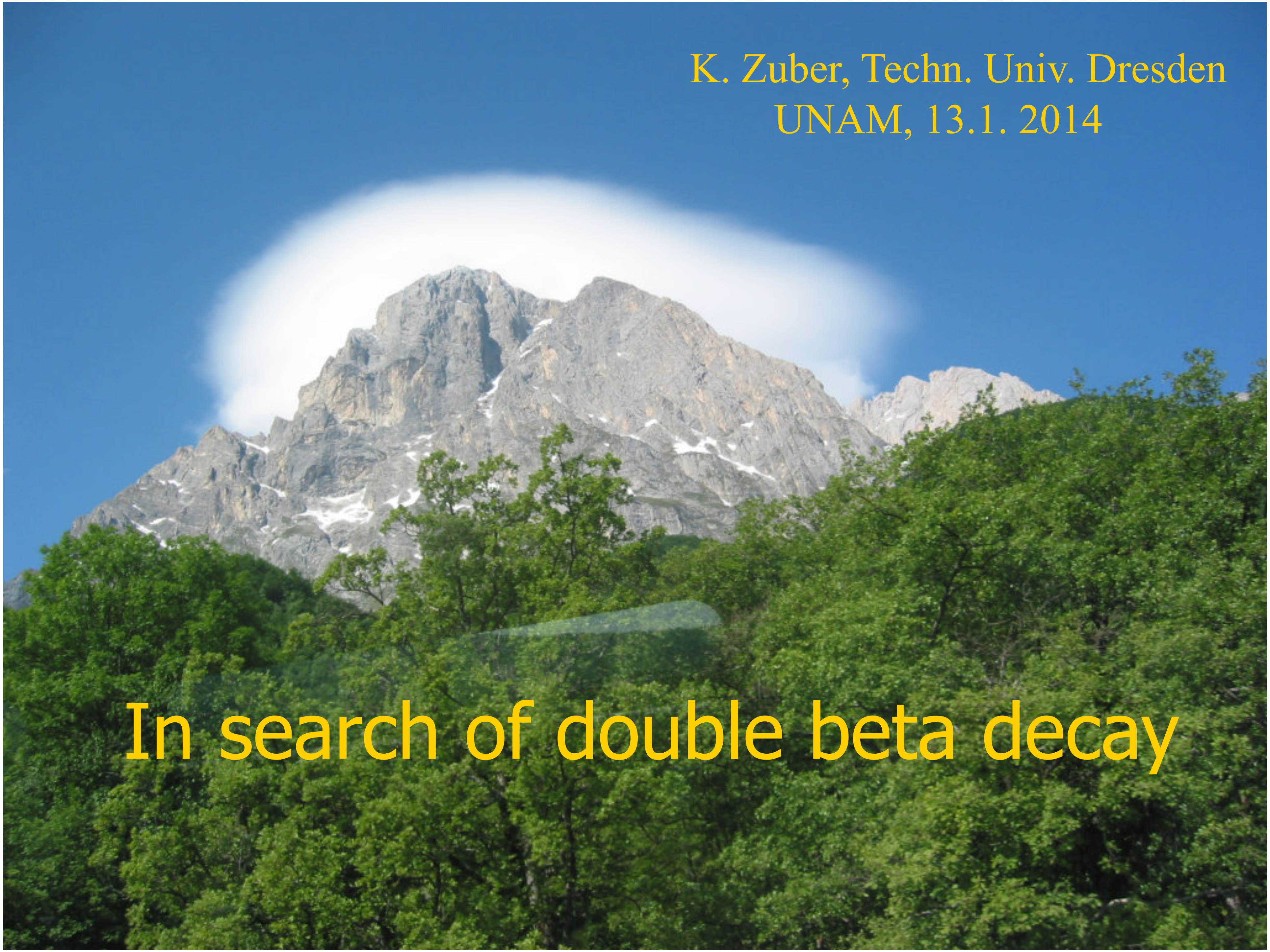
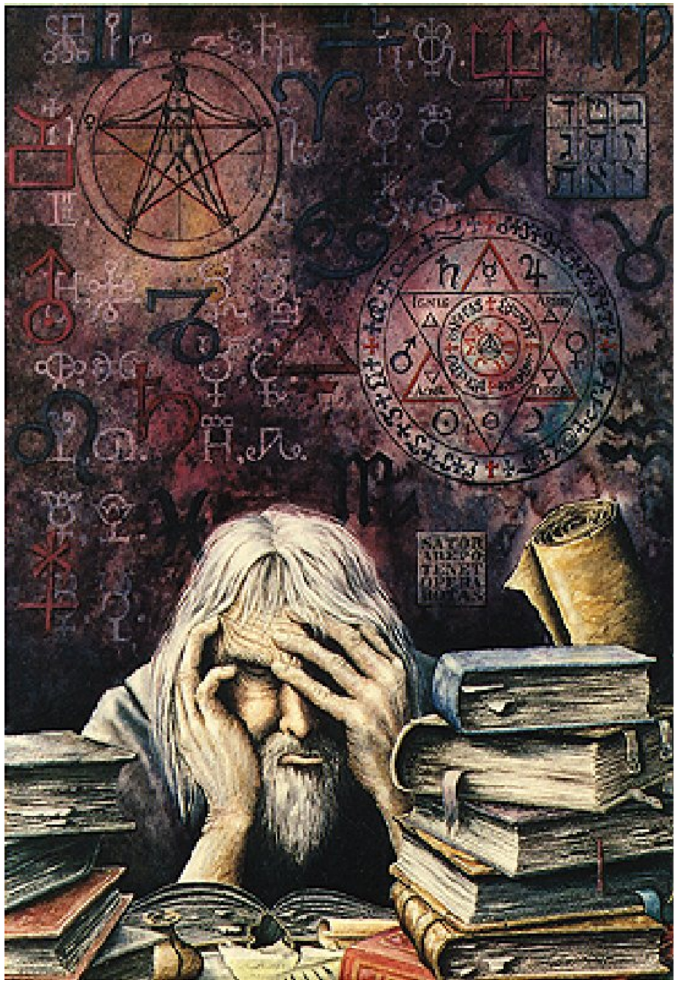


K. Zuber, Techn. Univ. Dresden
UNAM, 13.1. 2014

In search of double beta decay

How to explain everything about double beta in 45 mins

Contents



- Why double beta decay?
- The physics
- General issues
- Some experiments (GERDA, Xe)
- New results
- Alternative modes
- Summary

K. Zuber

Are neutrinos (very) special?

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

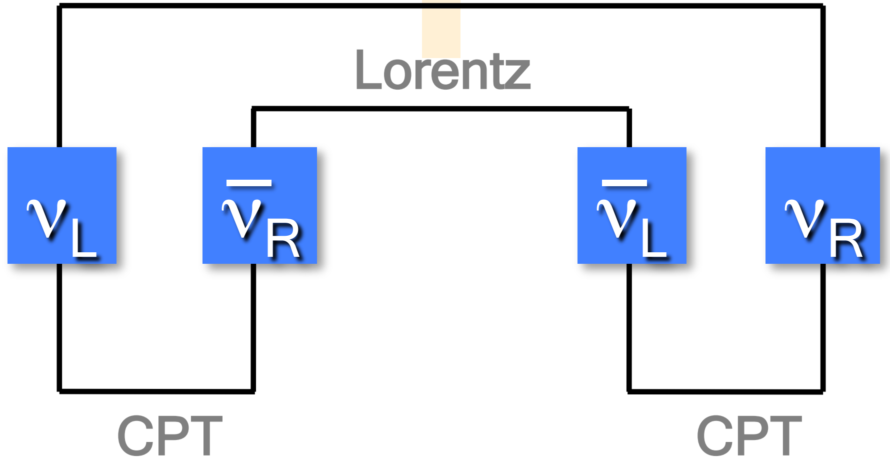
Dirac neutrino

ν^D

4 ν states

lepton number conservation $\Delta L = 0$

neutrino ≠ antineutrino



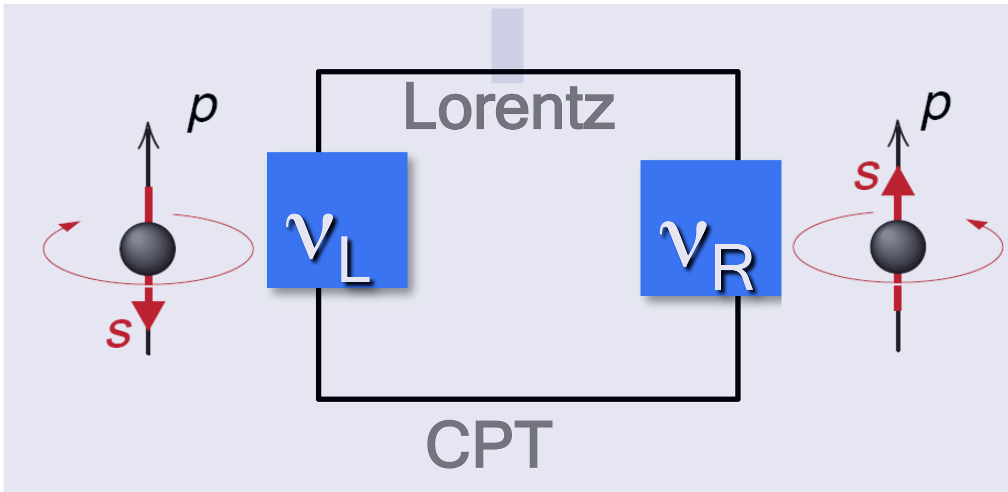
Majorana neutrino

ν^M

2 ν states

lepton number violation $\Delta L = 2$

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



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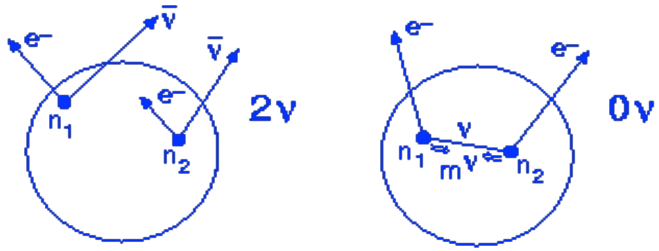
Double beta decay

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

Only 35 isotopes in nature are able to do that!

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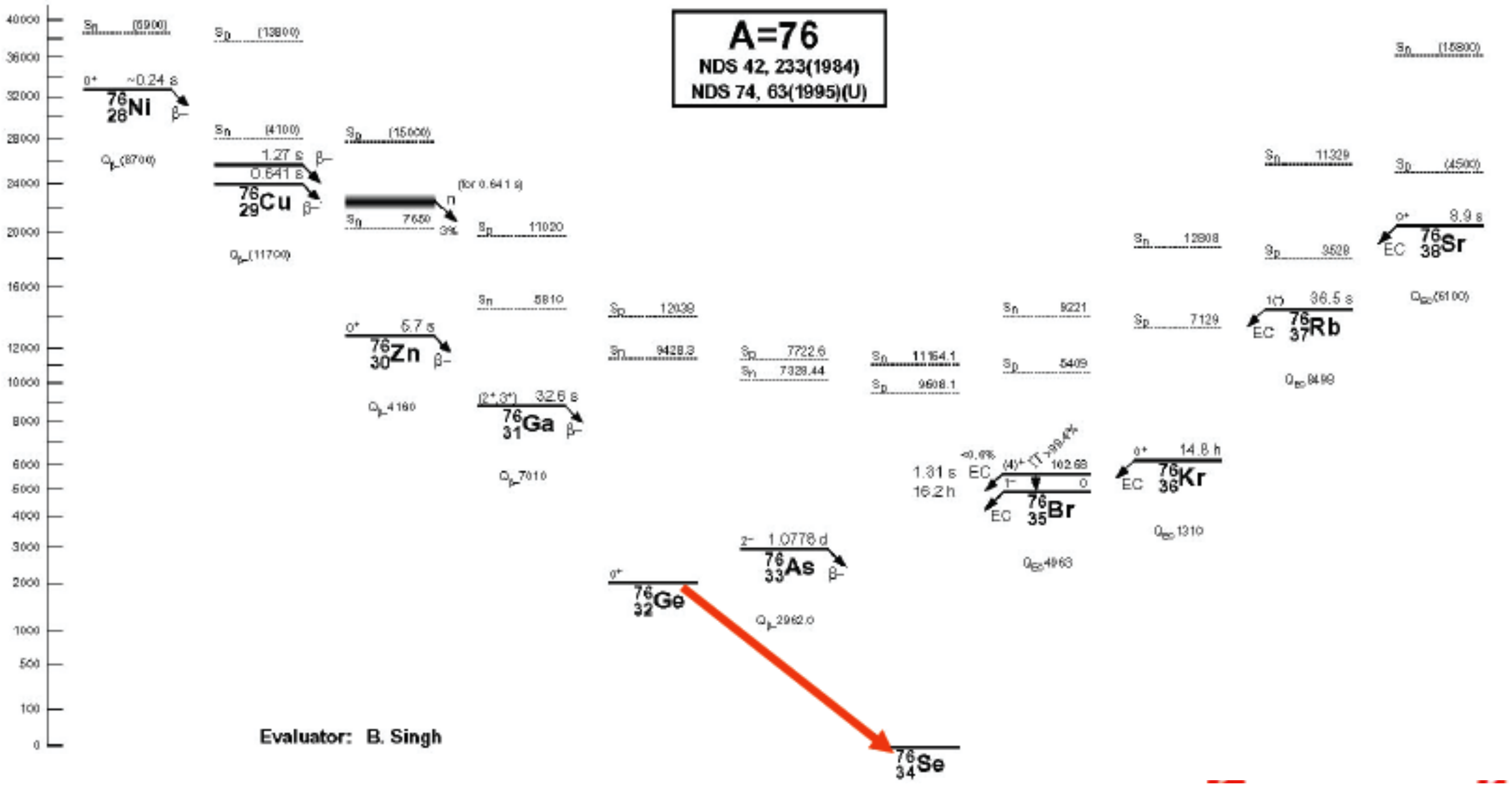
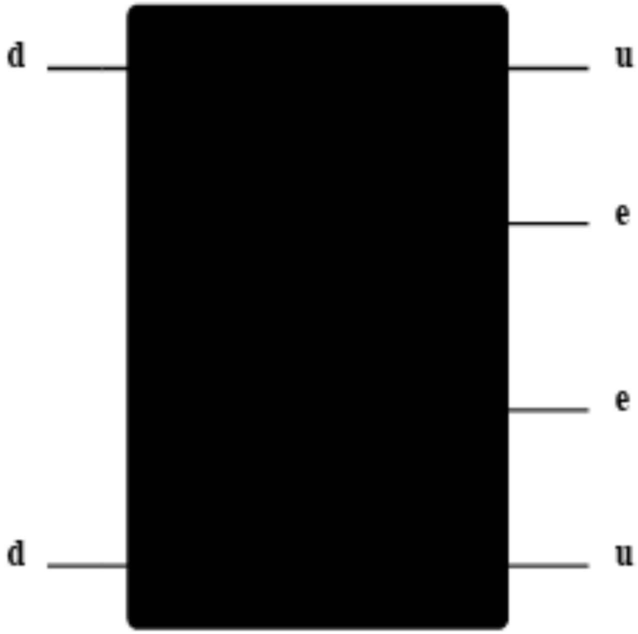


There are only 35 candidates K. Zuber

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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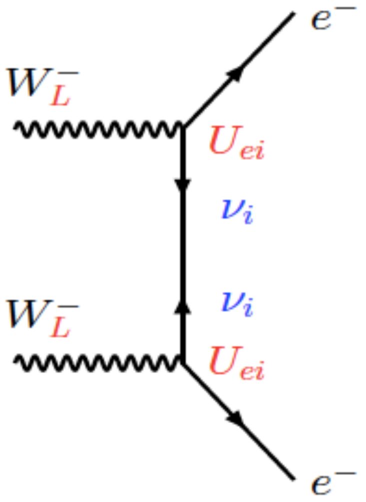
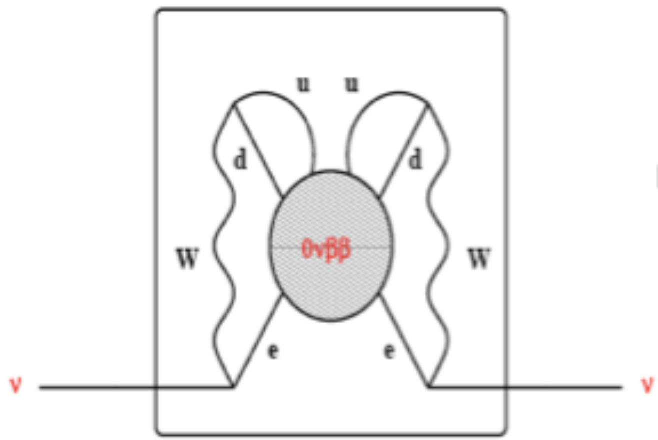
Nice interplay with LHC

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 $0\nu\beta\beta$ aecay

$\equiv$

Neutrinos are Majorana particles

3 Flavour mixing (PMNS)

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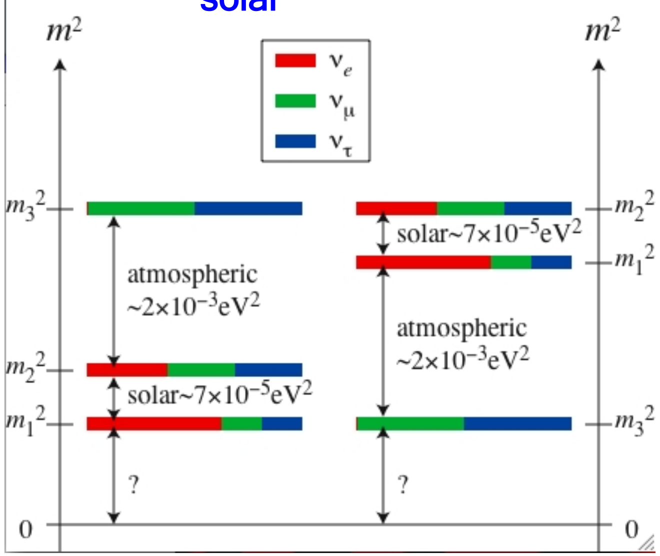
Neutrinos mix as oscillation experiments have shown, hence

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**

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

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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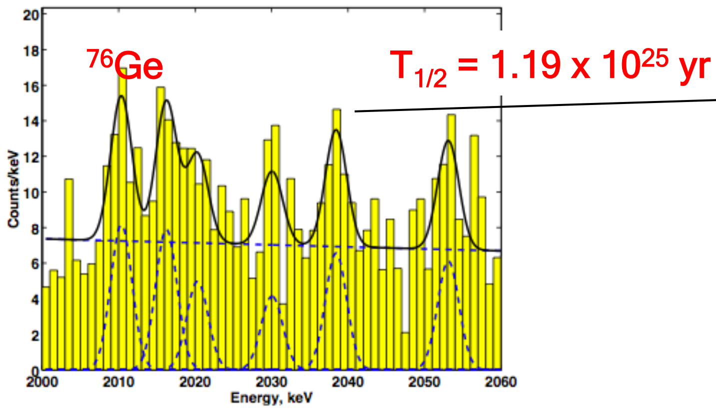
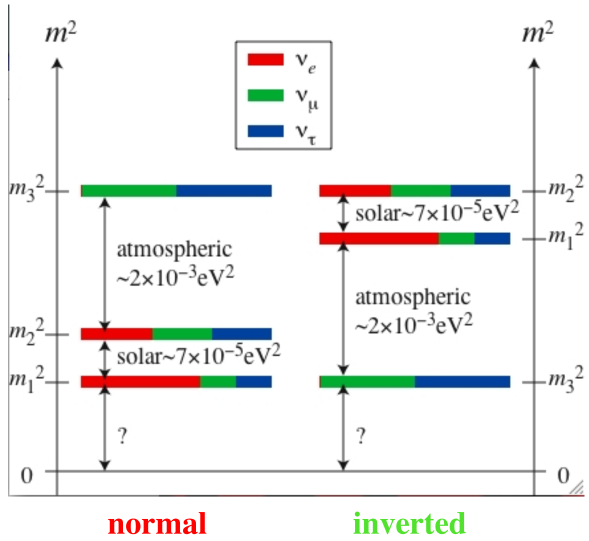
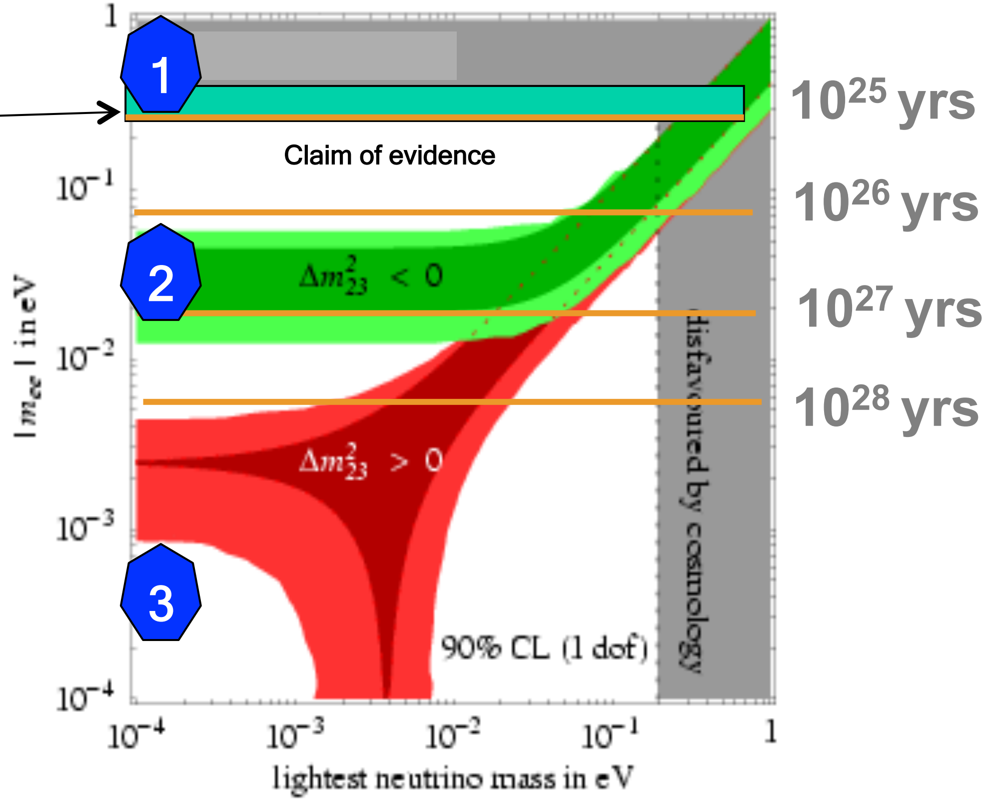
Mass hierarchies and DBD



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





1.) Is the claimed evidence correct?
GERDA phase I

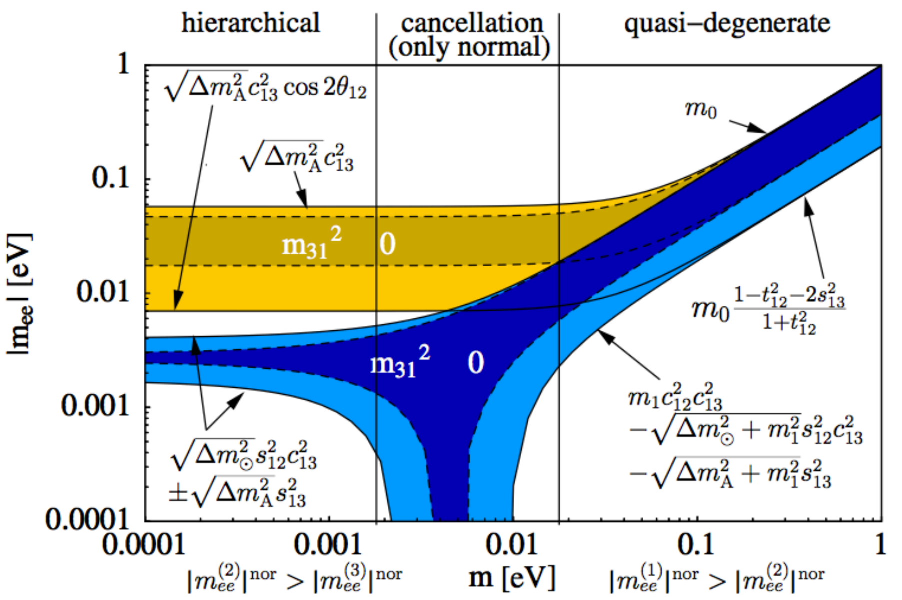
2.) Can we probe the inverted hierarchy?

3.) What about the normal hierarchy?

Mass hierarchies and DBD

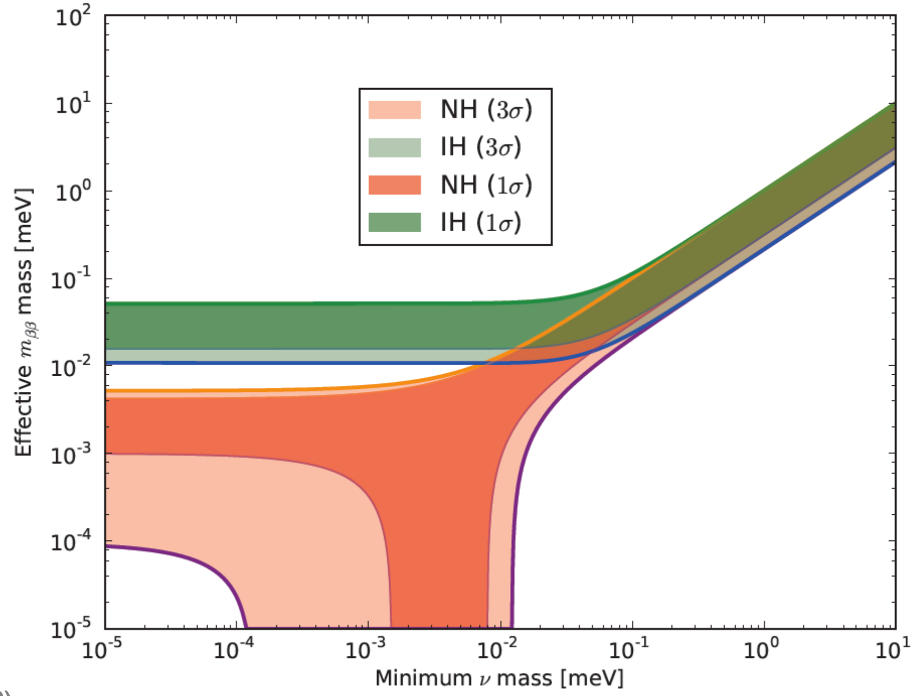
With the known oscillation results everything is fixed

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:

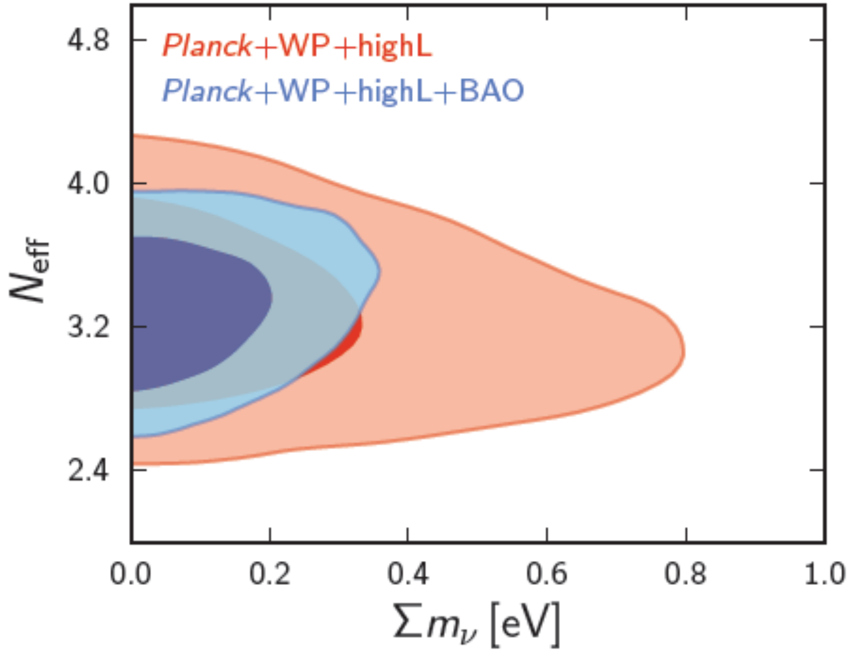
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

http://www.katrin.kit.edu

KATRIN -Sensitivity about 0.2 eV

Cosmology:

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



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

+ oscillation parameters

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or

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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, ...

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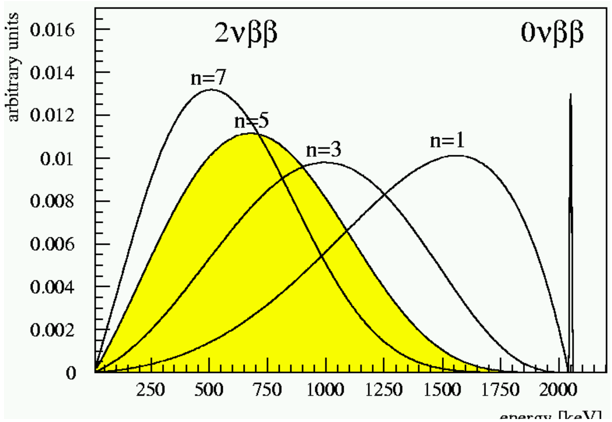
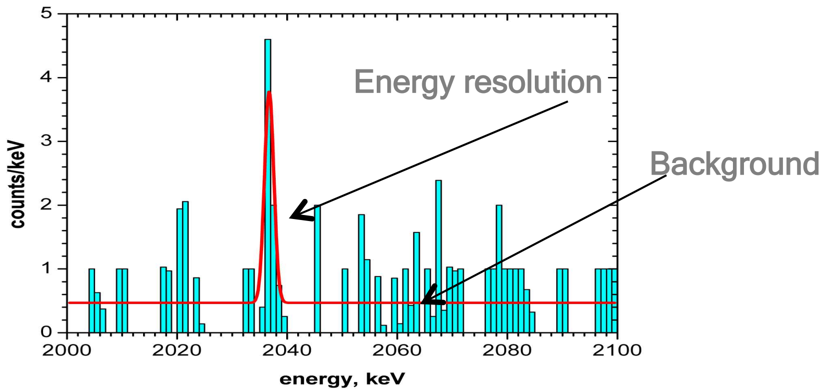
Going underground

Spectral shapes

0νββ: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons





Measured quantity: Half-life

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

Experimental sensitivity depends on

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

$$T_{1/2}^{-1} \propto a\varepsilon M t \quad \text{(BG free)}$$

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

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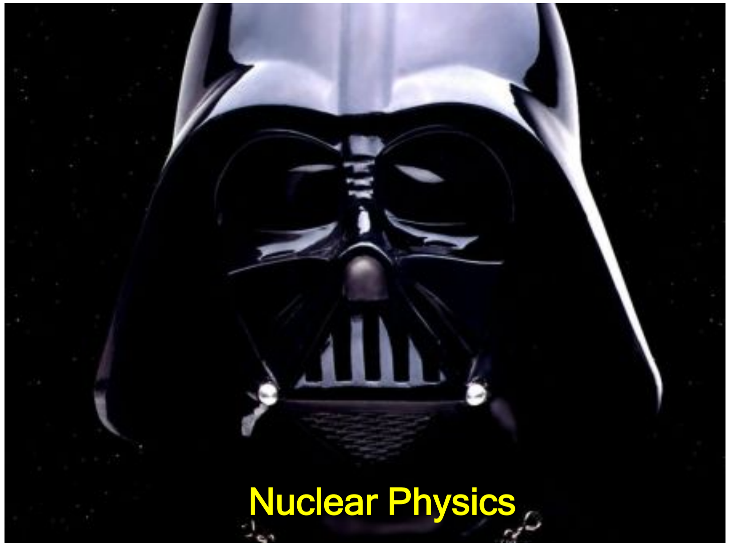
Master equation

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



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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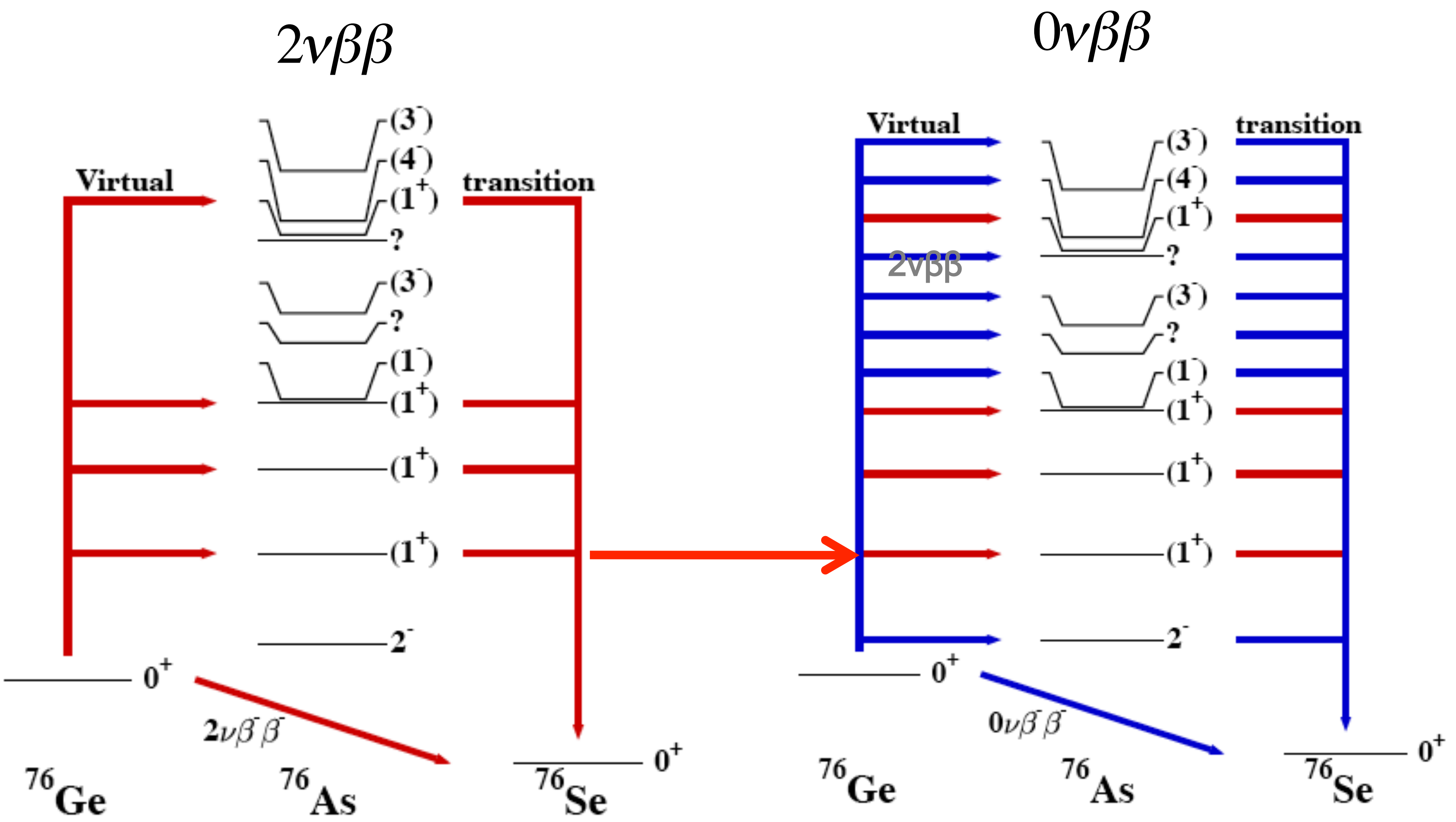
NME – Intermediate states



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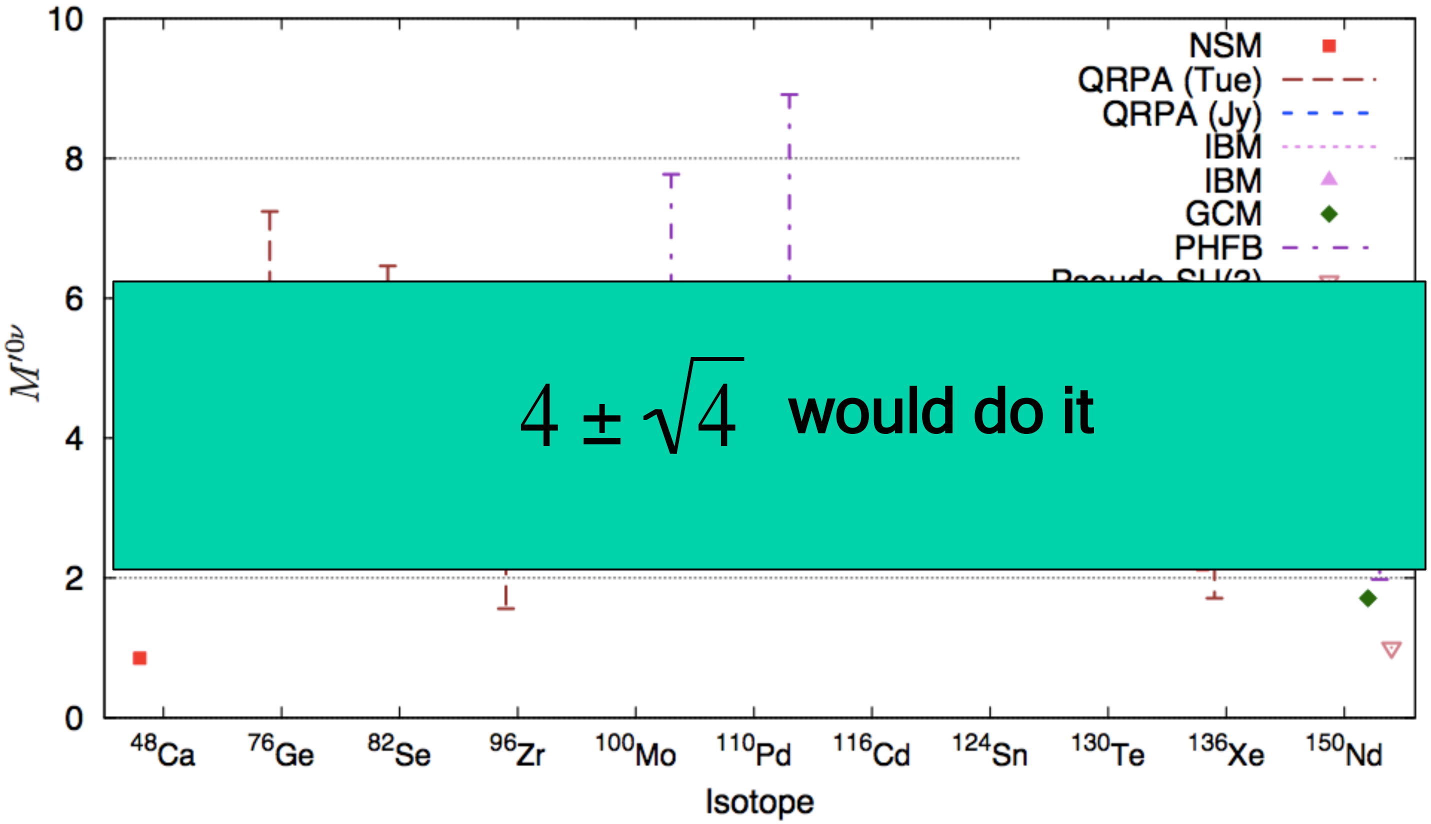
Matrix element

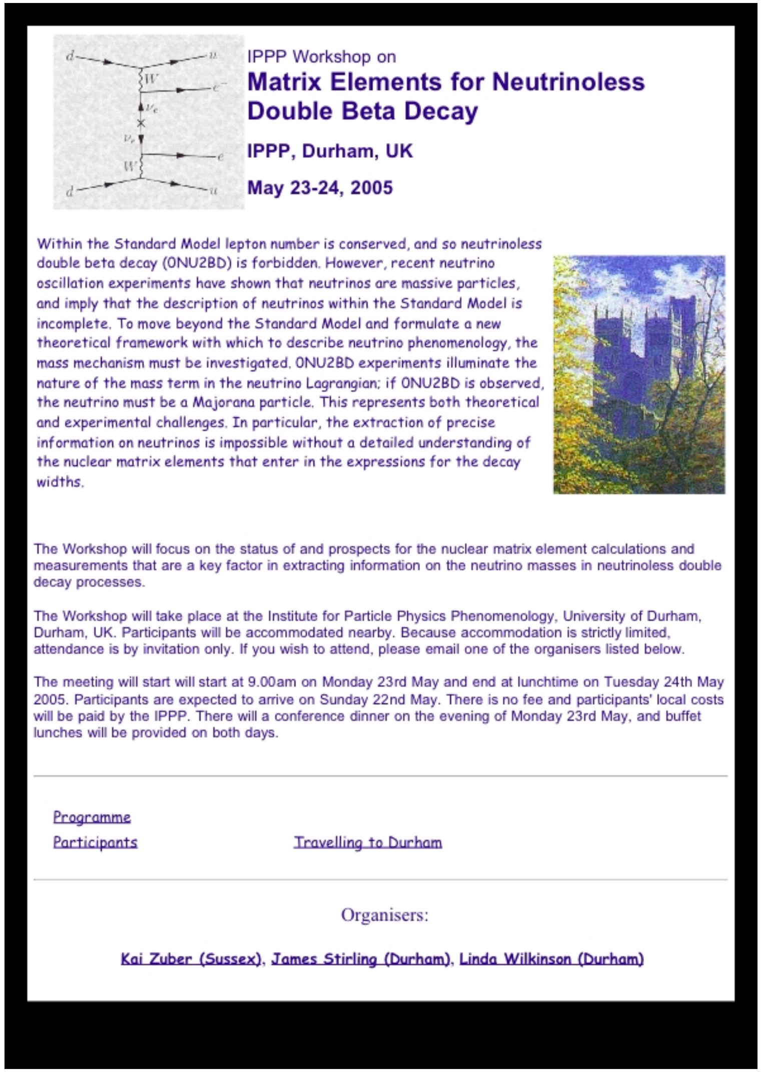
Rescaled as people use different g_A (1-1.25) and R_0 (1.0-1.3 fm)



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:

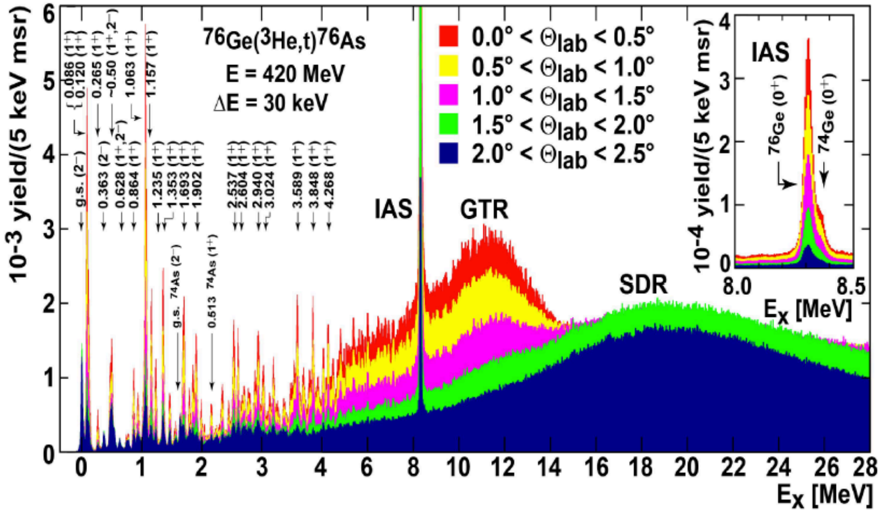
Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)

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

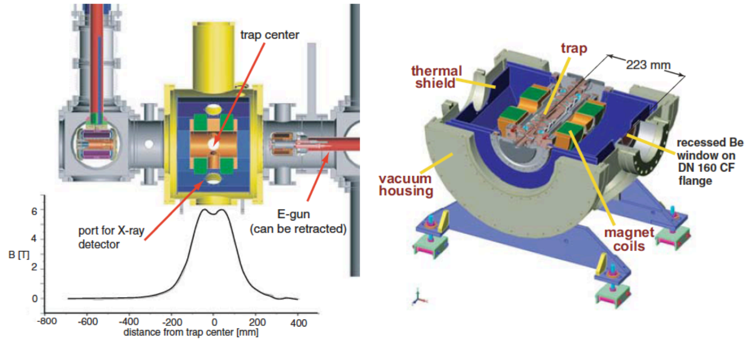
Focus section in JPG 39 (2012)

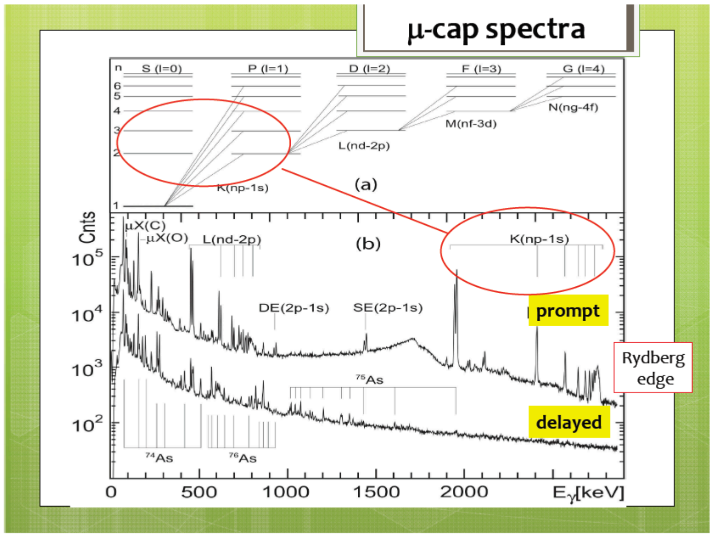
Items studied (examples)

D. Frekers, H. Ejiri et al., RCNP Osaka

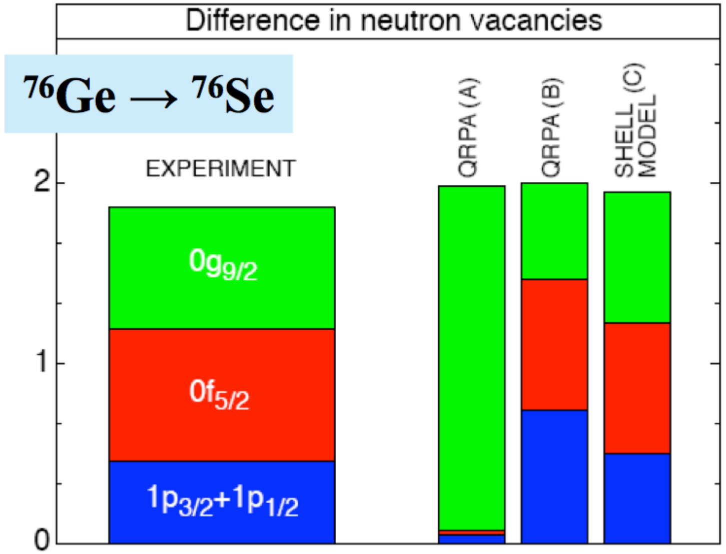


TITAN-EC at TRIUMF





D. Zinatulina, MEDEX 2013



J. Schiffer et al., Phys. Rev. Lett. 100, 112501 (2008)

Experimental approaches

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

11 isotopes of interest

Isotope	AME 2003	Q-values 2012
Ca-48	4272 ± 4	4262.96 ± 0.84
Ge-76	2039.006 ±0.050	2039.006 ± 0.050
Se-82	2995.5 ± 1.9	2997.9 ± 0.3
Zr-96	3347.7 ±2.2	3347.7 ± 2.2
Mo-100	3035 ±6	3034.40 ± 0.17
Pd-110	2004 ±11	2017.85± 0.64
Cd-116	2809 ± 4	2813.50 ± 0.13
Sn-124	2287.8±1.5	2292.64 ± 0.39
Te-130	2530.3 ±2.0	2527.518± 0.013
Xe-136	2462 ±7	2457.83± 0.37
Nd-150	3367.7 ±2.2	3371.38 ± 0.20

Candles

GERDA, Majorana

SuperNEMO, LUCIFER

MOON, AMore

COBRA

India

CUORE, SNO+

EXO, KamLAND-Zen, NEXT, XMASS

MCT, SuperNEMO(?)

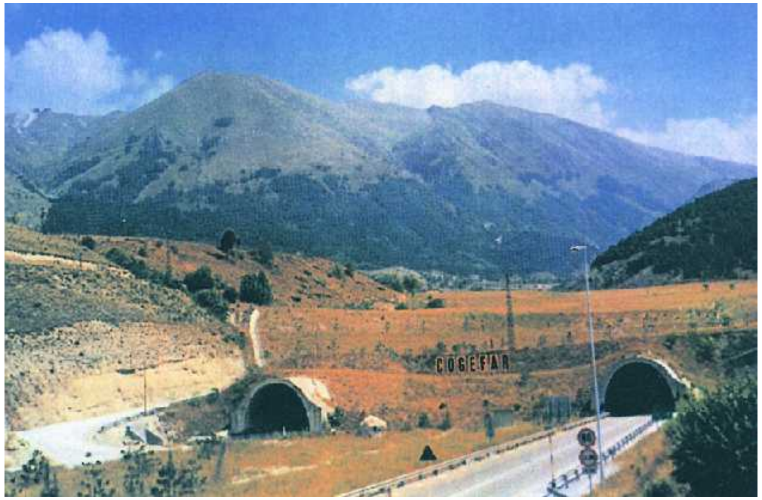
Heidelberg – Moscow Experiment

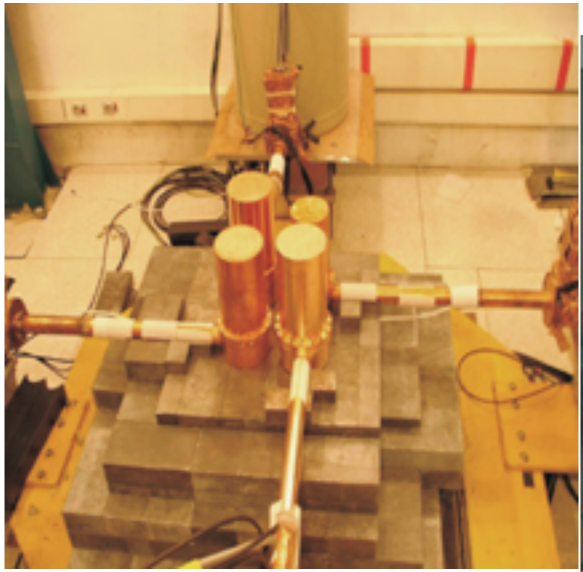
Isotope of interest: 76Ge

- **The detectors are decaying!!**
- **5 isotopical enriched Ge-detectors**
- **Sum energy -> Peak at 2039 keV**

Still only 1 decay per year per 10 kg Ge

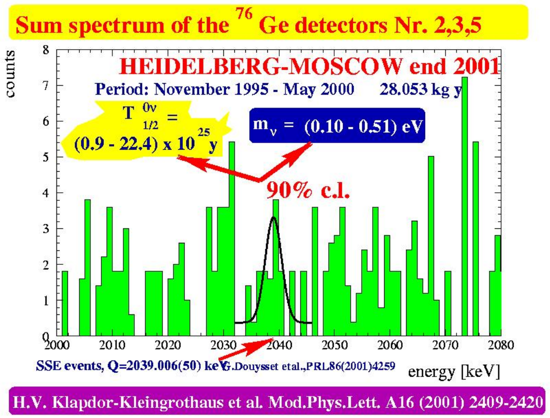
Background obtained 0.1 count/keV/kg/yr



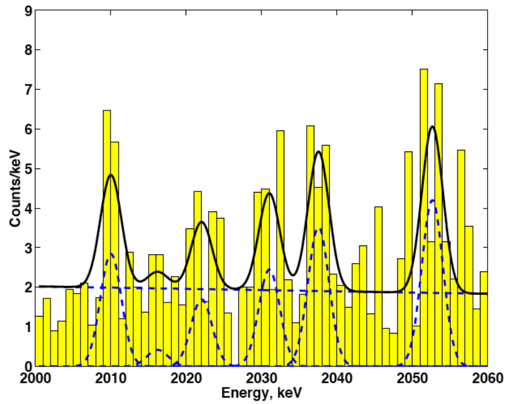


Evidence ?

2001

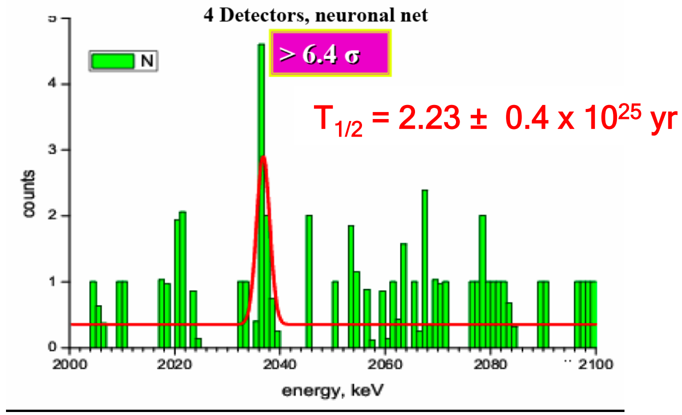


2004

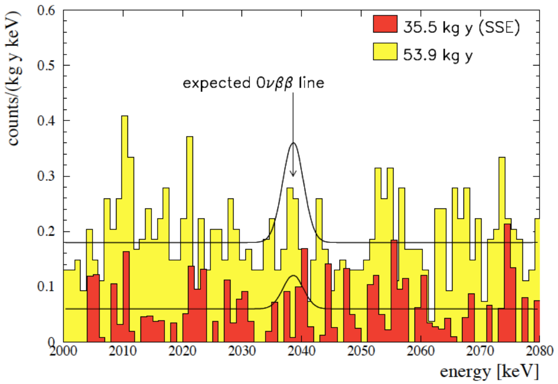


H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586, 198 (2004)

2006

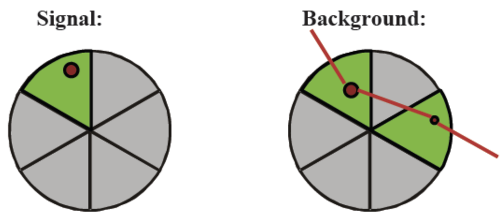


Mod.Phys.Lett.A21:1547-1566 (2006)



H.V. Klapdor-Kleingrothaus et al., Eur.Phys.J. A12 (2001) 147-154

Background reduction by pulse shape analysis



Very controversial discussion in the community

If right, neutrino mass is around 0.3 eV and masses are almost degenerate

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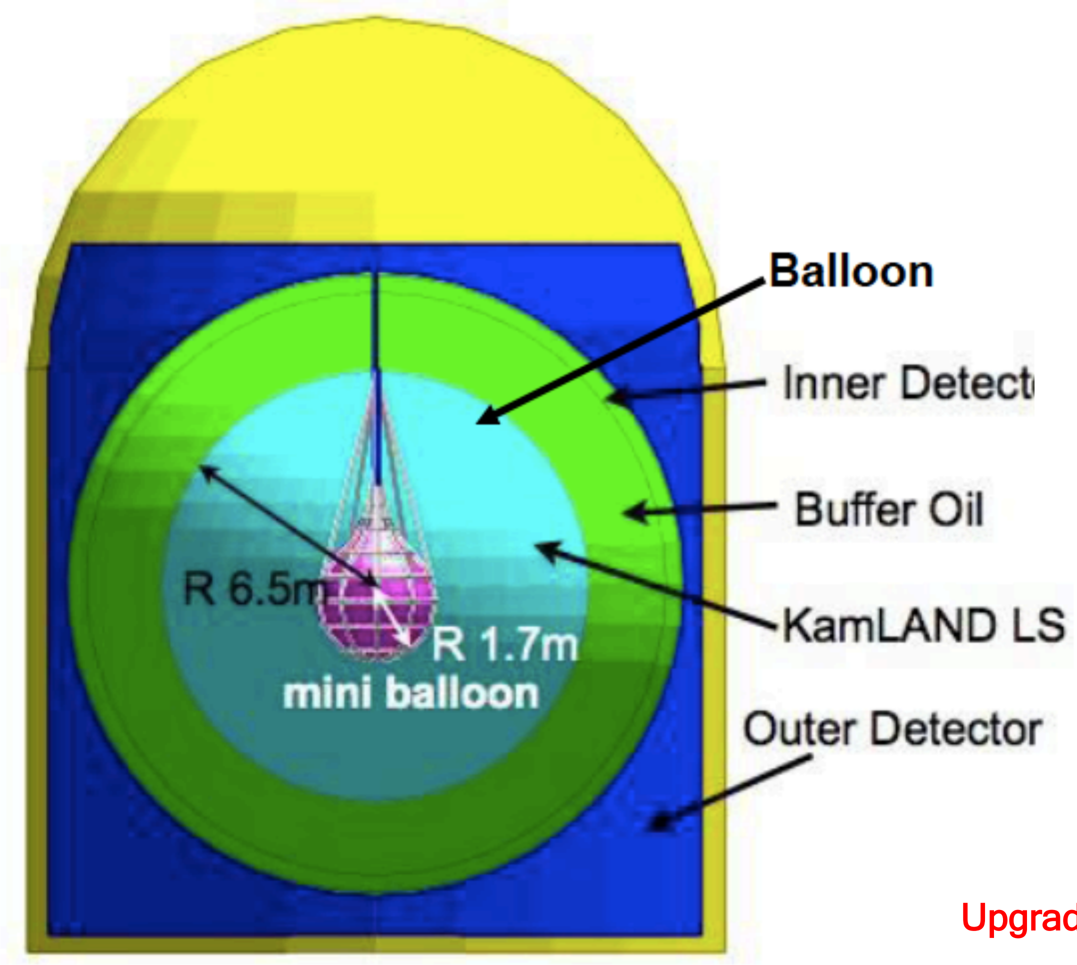
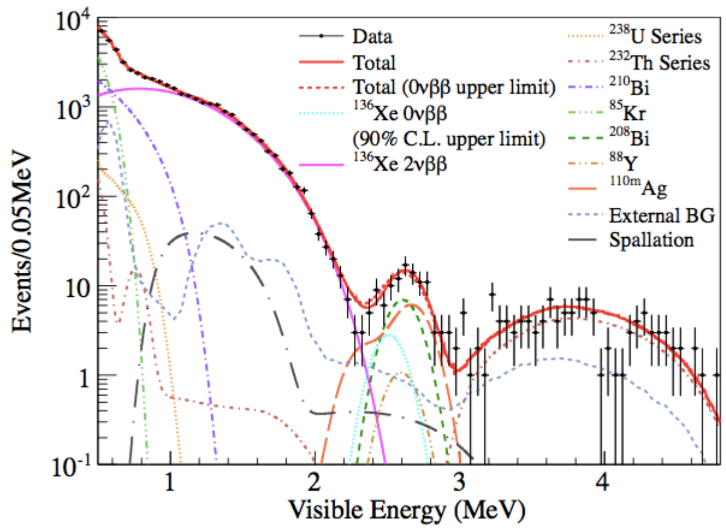
The fantastic 4

Because they‘ve started

KamLAND - Zen

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





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

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

$T_{1/2}$ > 1.9 x 10^{25} years (90%CL)
A. Gando, arXiv:1211.3863

Upgrade to 1 ton enriched Xe planned in 2014

EXO-200

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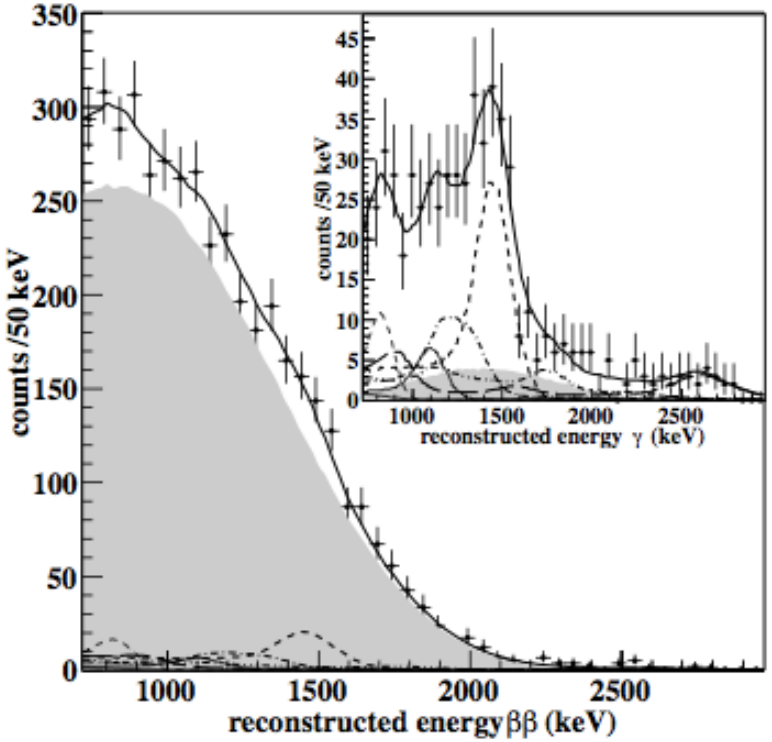
Enriched Xenon Observatory EXO for double beta decay

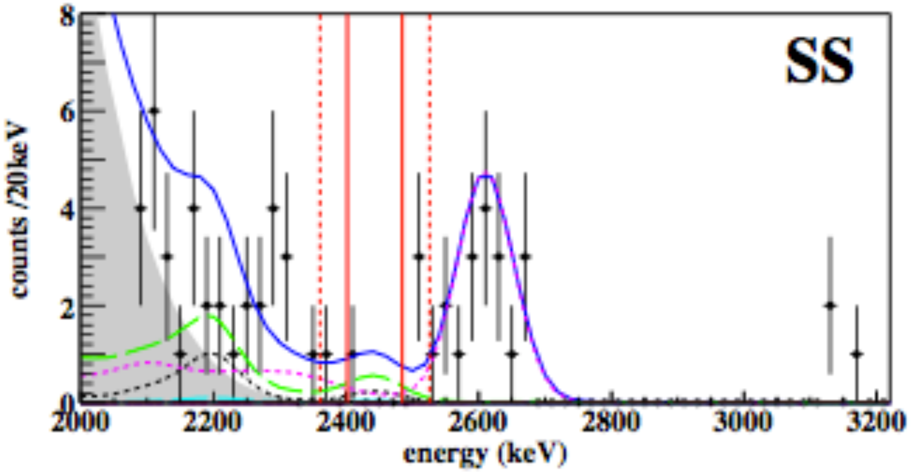
iktp

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



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

First half-life limit on 0nu decay :
$T_{1/2}$ > 1.6 x 10^{25} years (90%CL)
M. Auger et al., PRL 109,032505 (2012)



In conflict with positive claim for almost all matrix element calculations

Uncertainties due to conversion

Future option: Barium tagging

GERDA-Principal Setup

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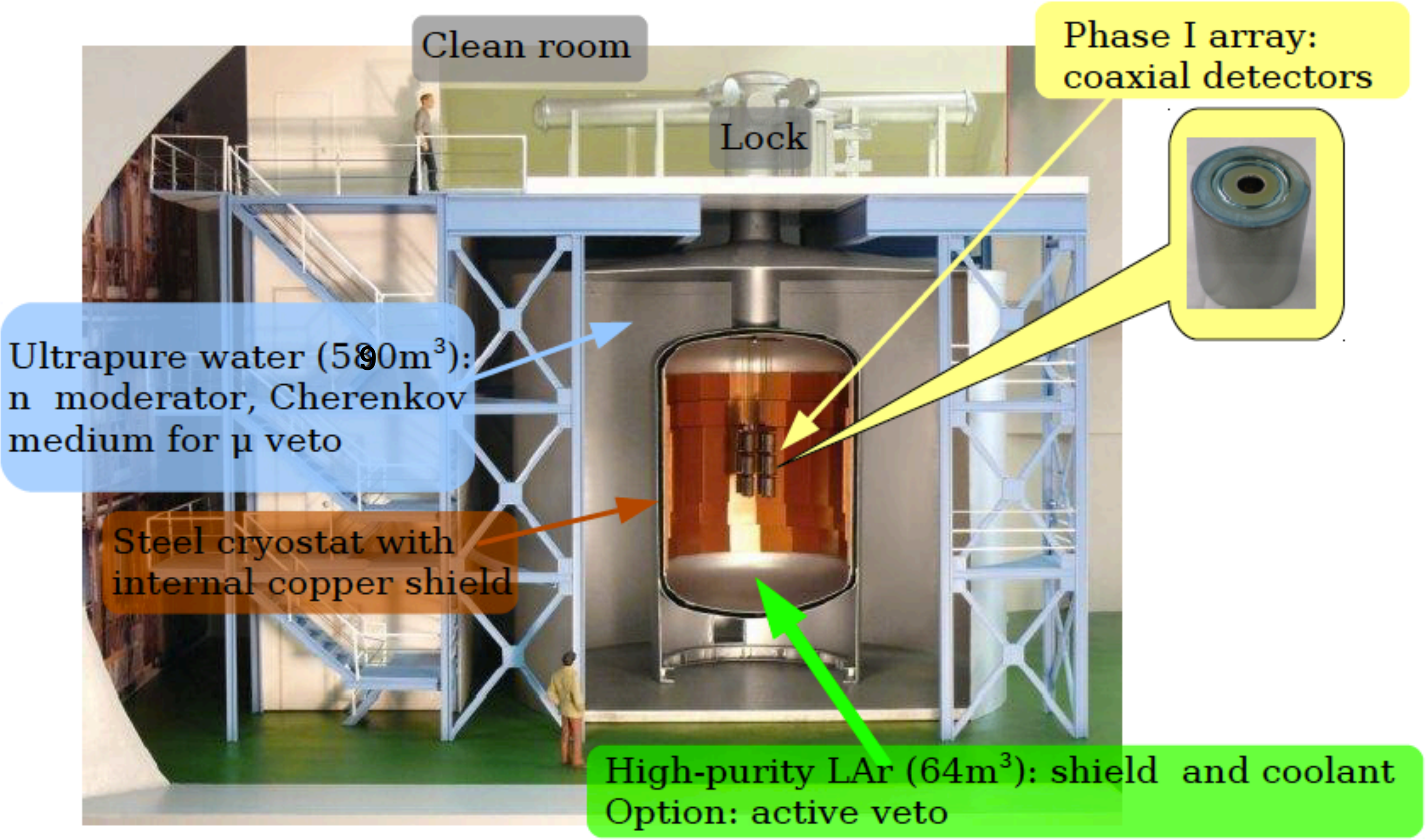
GERDA

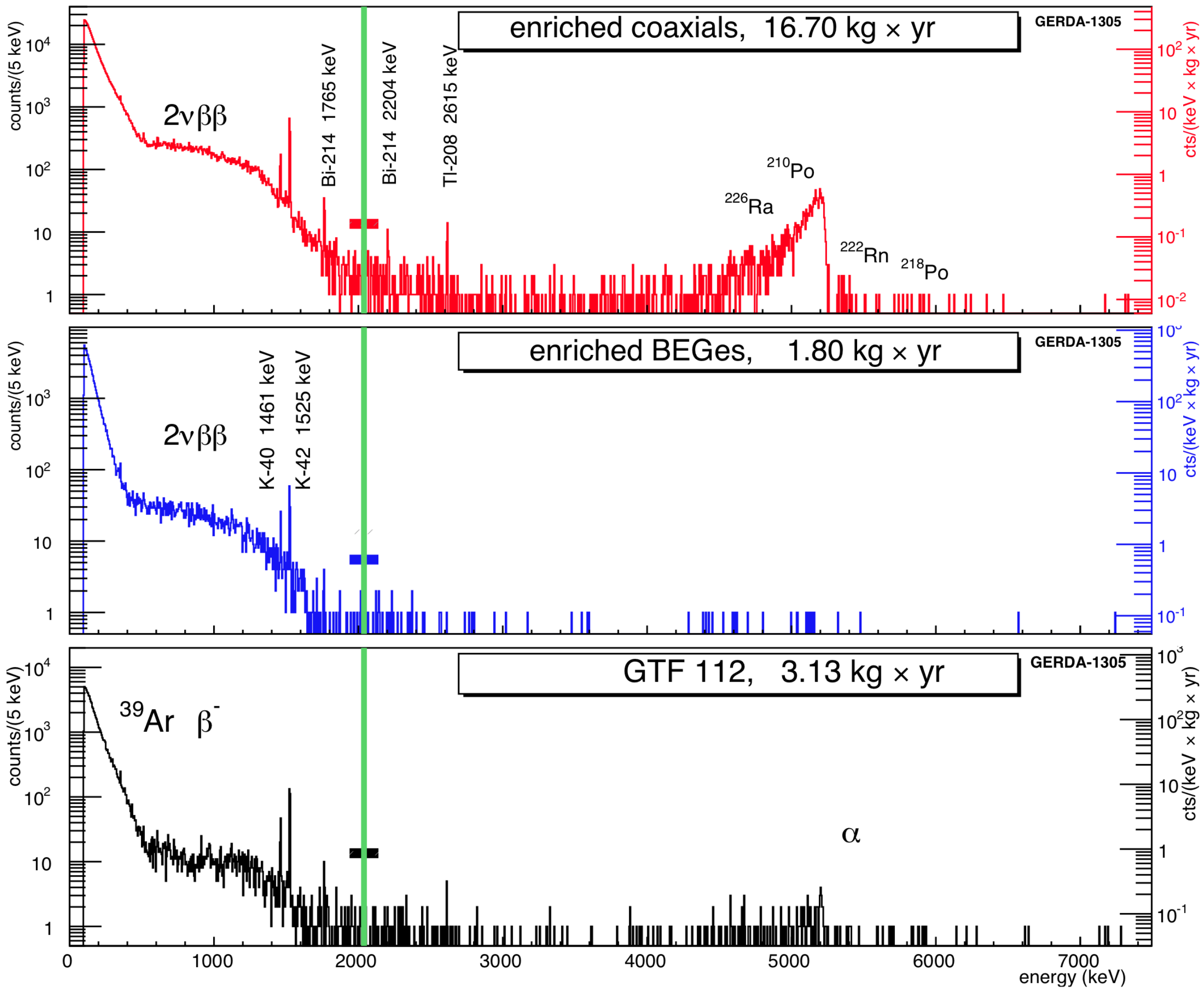
Idea : Running bare Ge crystals in LAr



The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge
Eur. Phys. J. C (2013) 73:2330

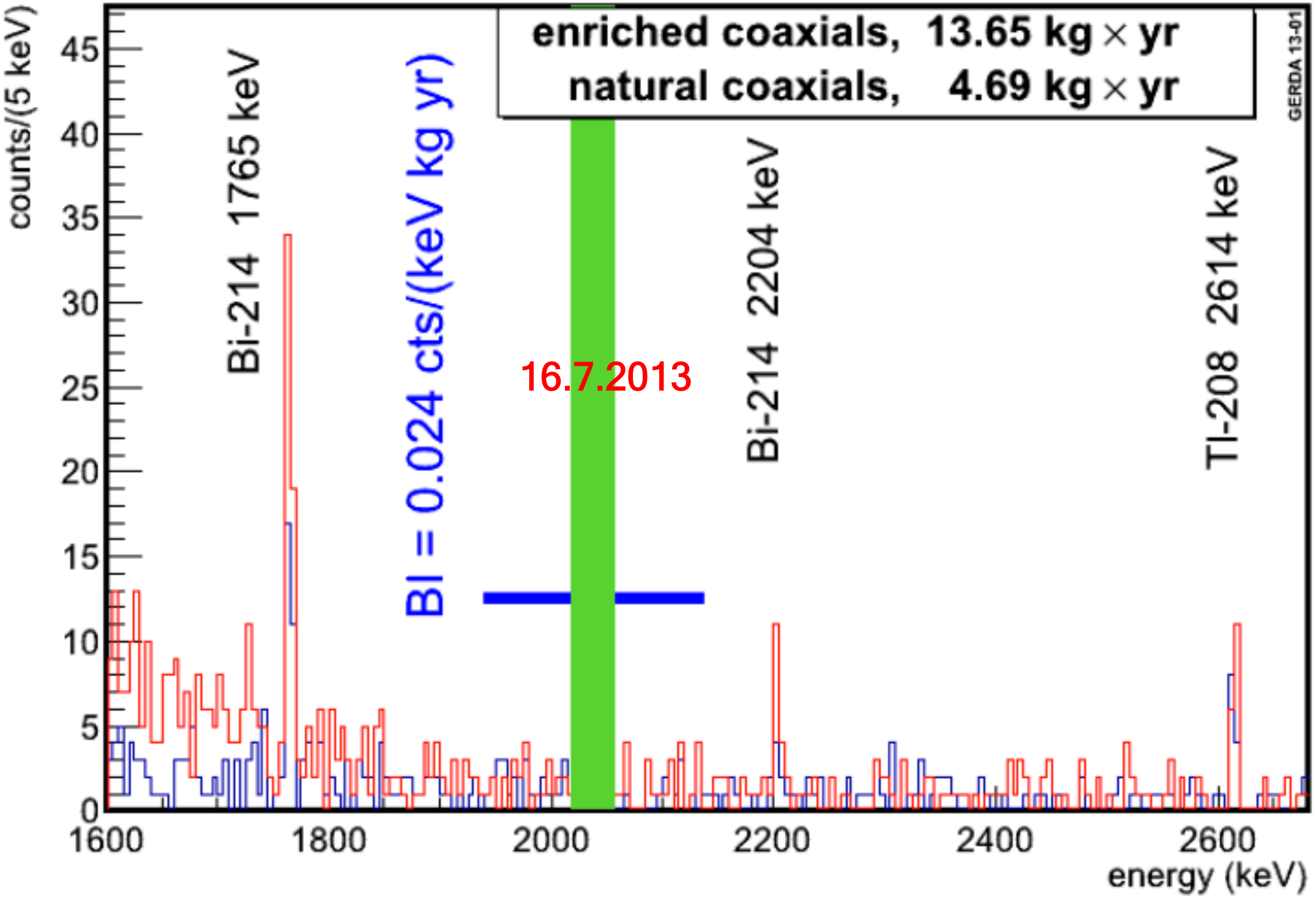
K. Zuber

Phase I data taking



K. Zuber

Phase I data taking



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)

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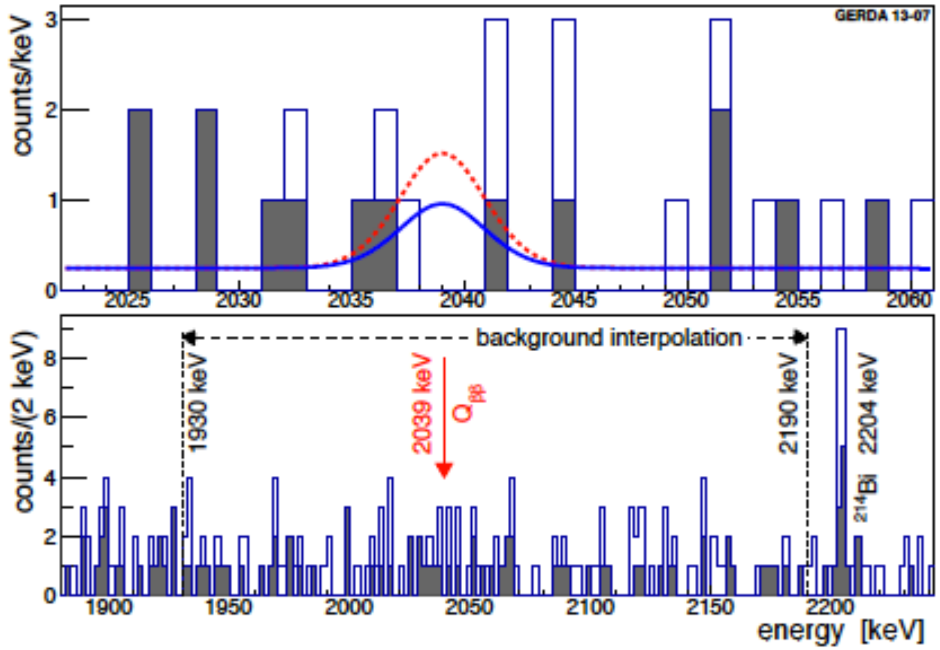

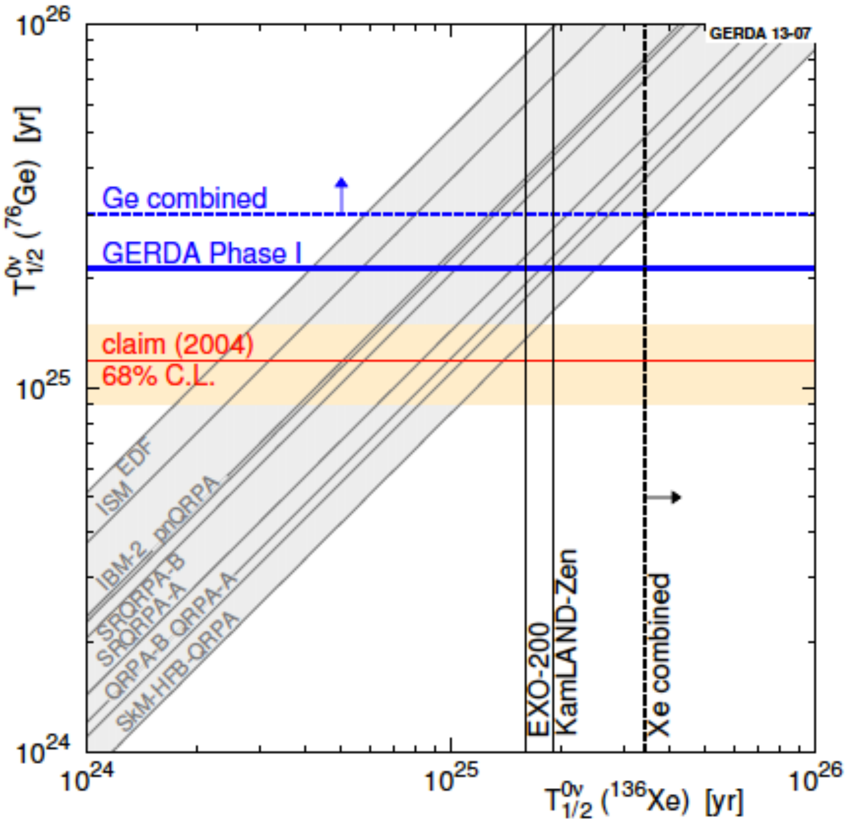

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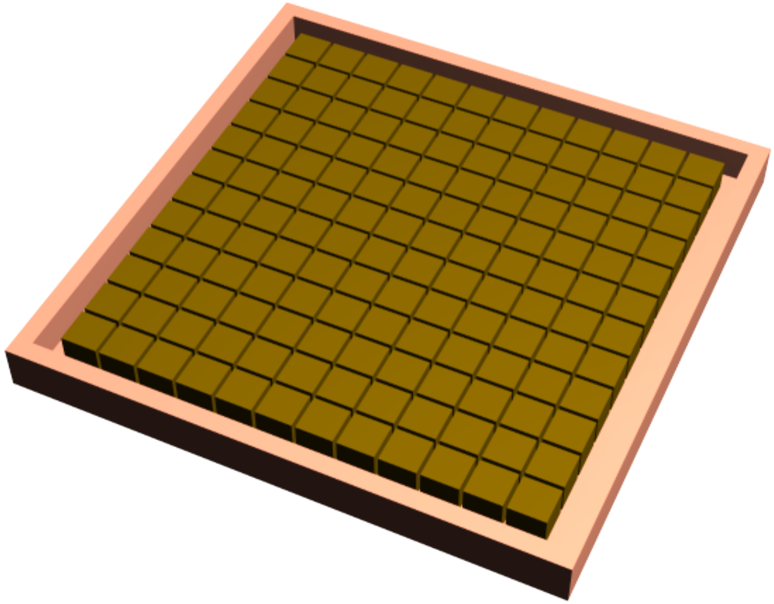
The magnificent 7

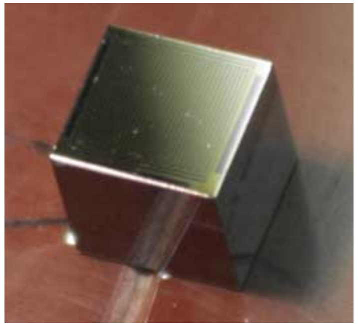
Because they should be online 2014

K. Zuber

Use large amount of CdZnTe Semiconductor Detectors

K. Zuber, Phys. Lett. B 519,1 (2001)



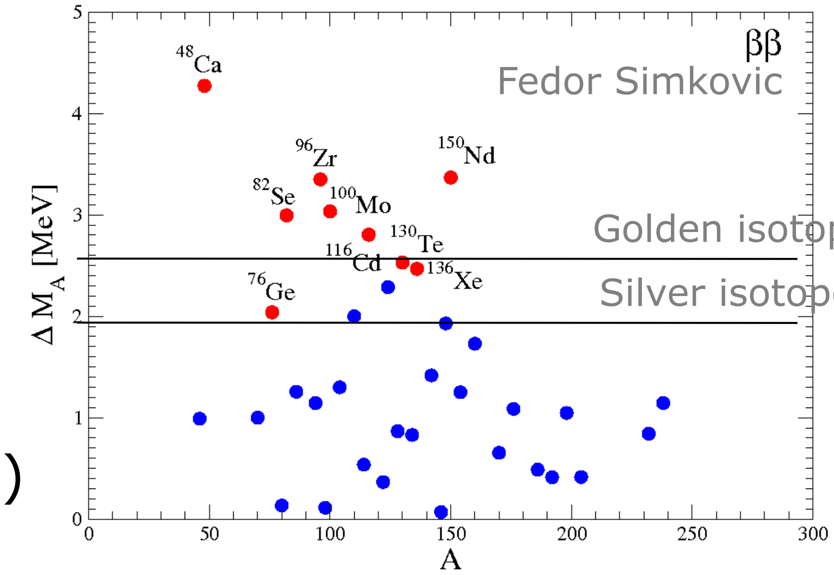


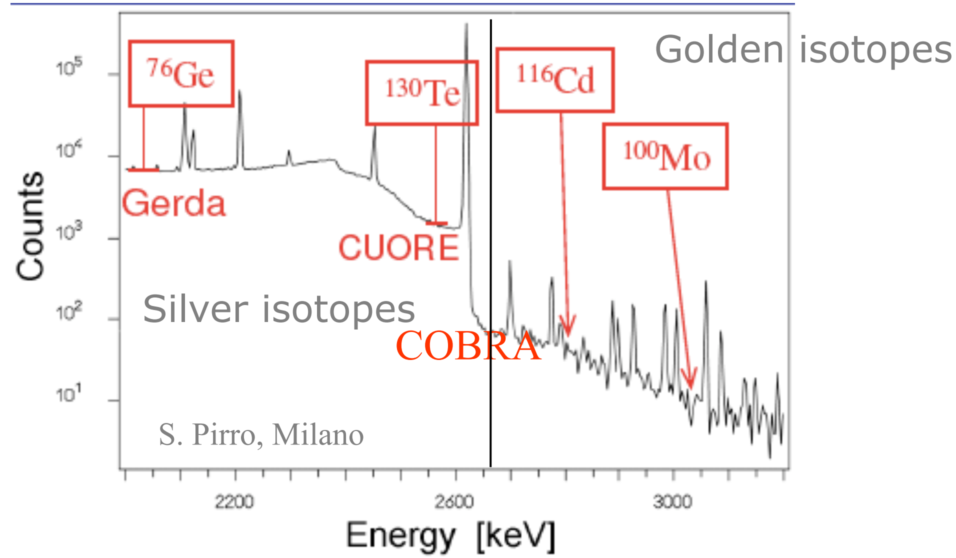
64 detectors running at LNGS

Focus on ^{116}Cd

Advantages

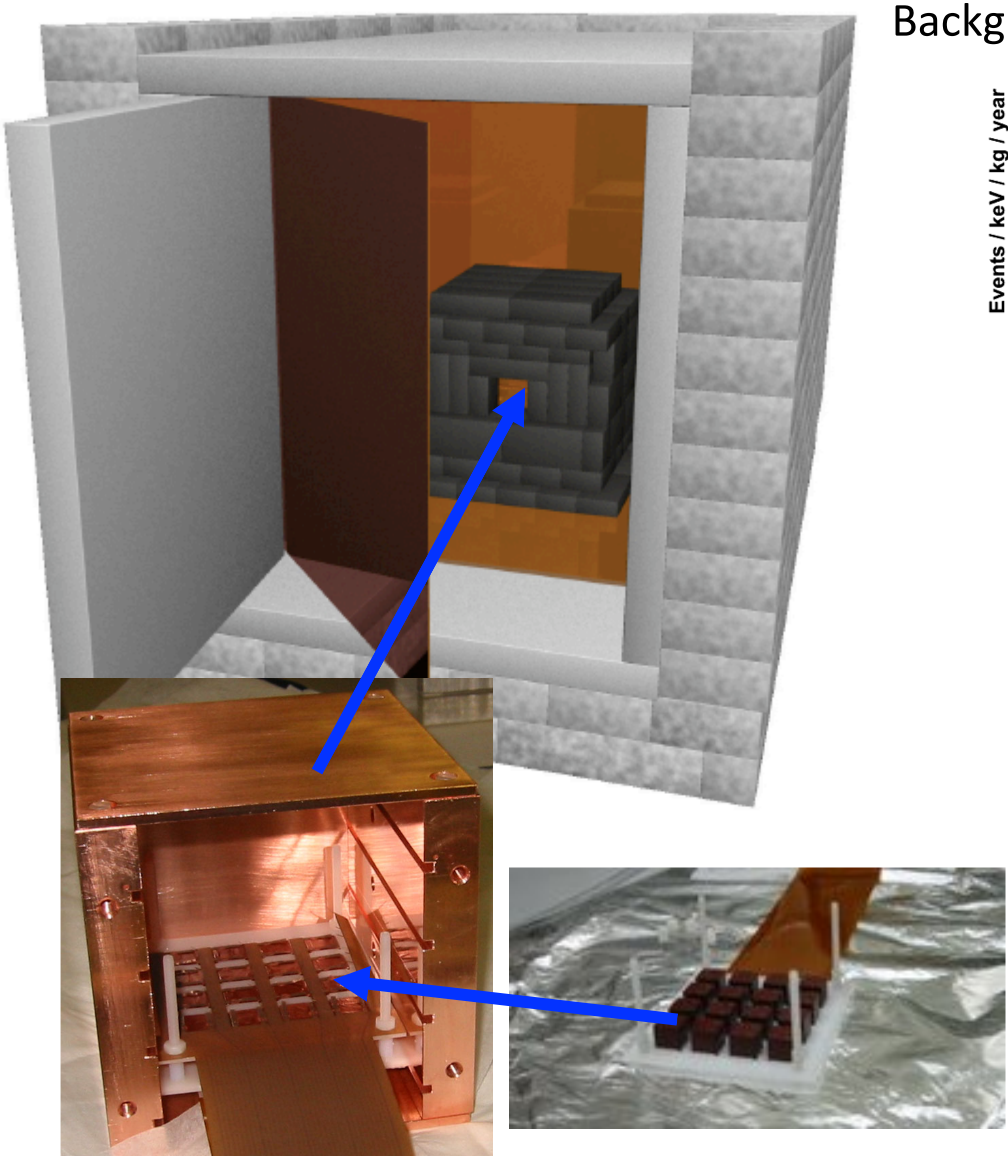
- Source = detector
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Industrial development of CdTe detectors
- ^{116}Cd above 2.614 MeV
- Tracking („Solid state TPC")





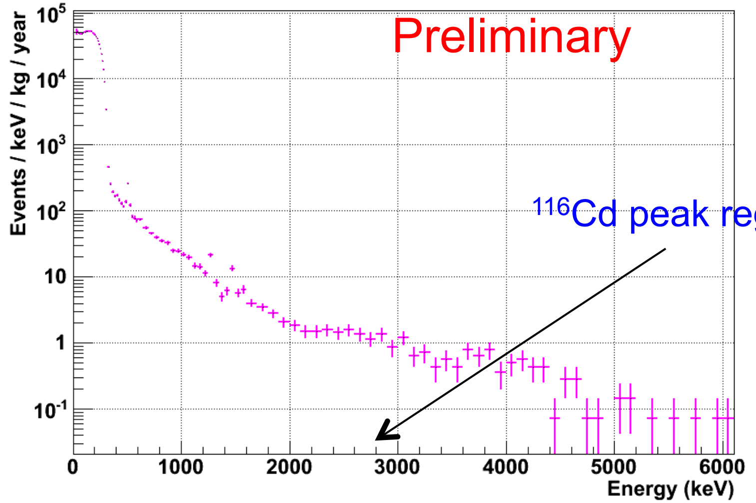
Setup at Gran Sasso Lab

64 CZT detectors

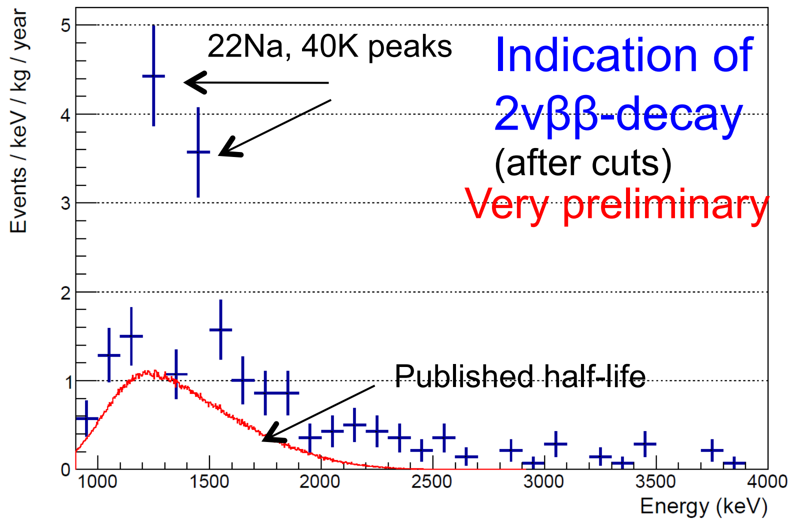


spectrum (32 detectors), 51.1 kg*days

Background at 2813 keV about 1 ct/keV/kg/yr

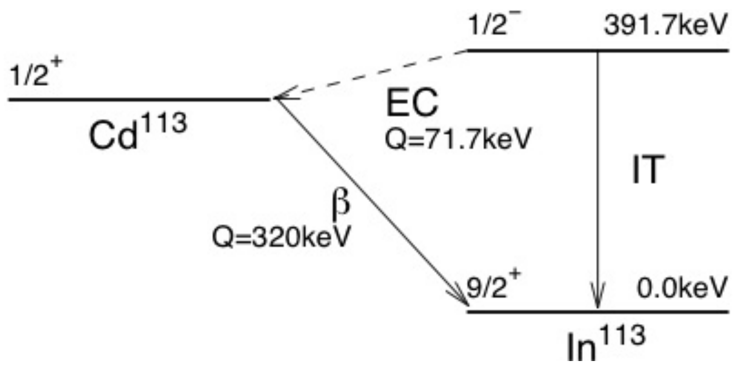


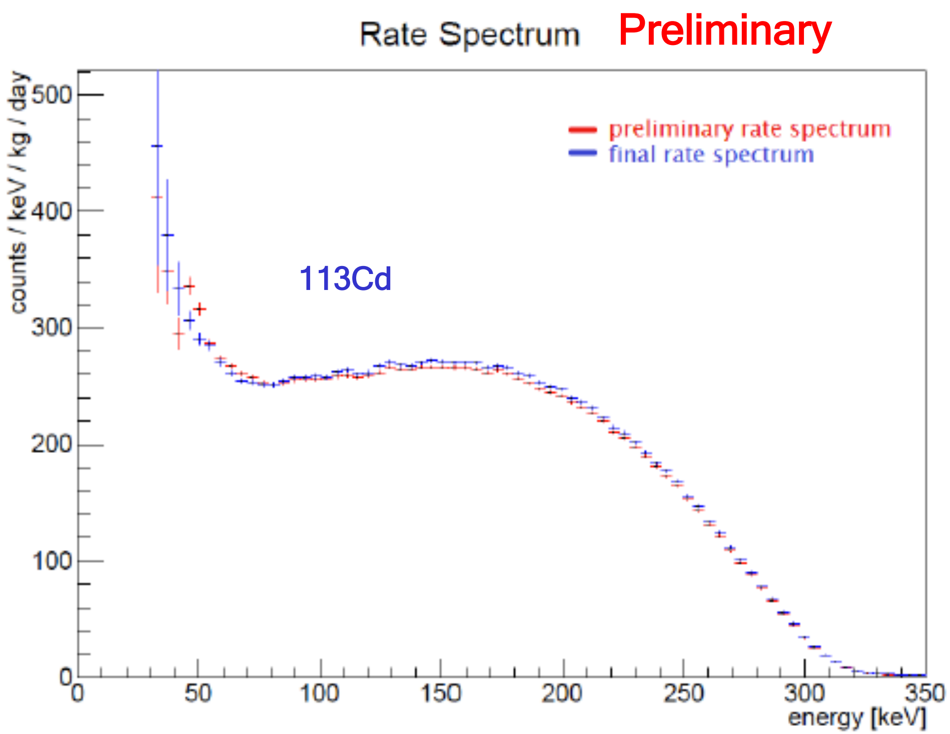
LNGS CPG array, 51.1 kg×days



COBRA – ^{113}Cd

4-fold non-unique beta decay ($1/2^+ \rightarrow 9/2^+$)





Half-life:

$$T_{1/2} = 8.00 \pm 0.11(stat.) \pm 0.24(sys.) \times 10^{15} \text{ years}$$

48 independent measurements of the half-live!

Q-value:

$$322 \pm 0.3(stat.) \pm 0.9(sys.) \text{ keV}$$

J. V. Dawson et al., Nucl. Phys. A 818,264 (2009)

Fits extremely well to AME 2012

Next: Spectral shape

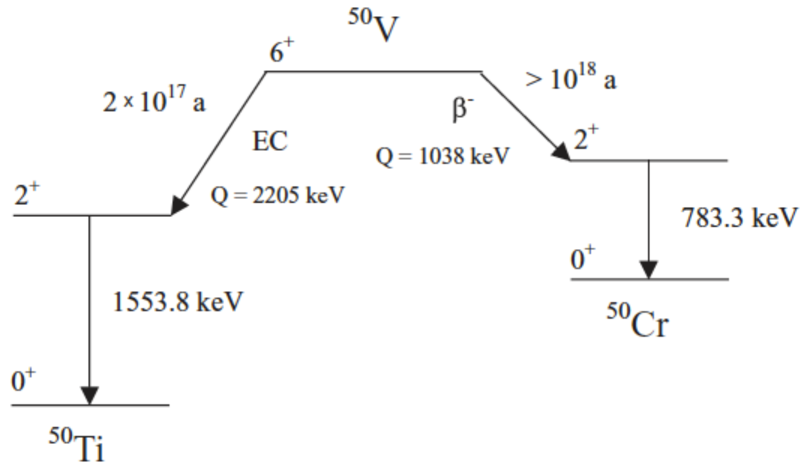
Microscopic calculation:

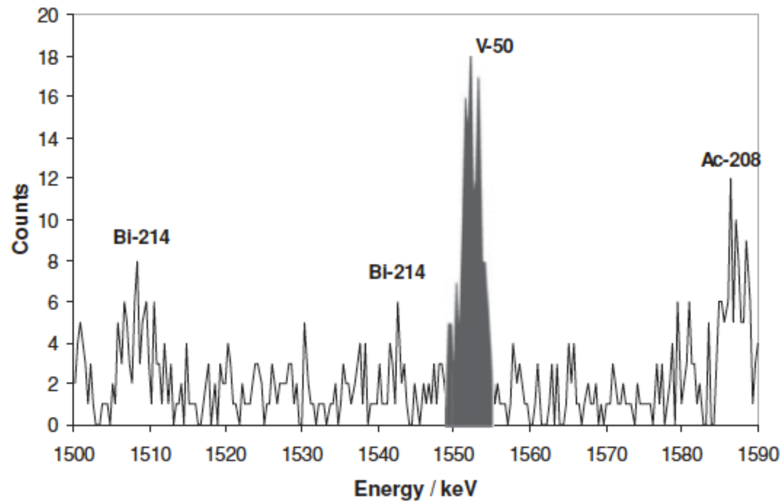
M. T. Mustonen, M. Aunola, J. Suhonen , PRC 73,054301 (2006)
M. T. Mustonen, J. Suhonen,, PLB 657,38 (2007)

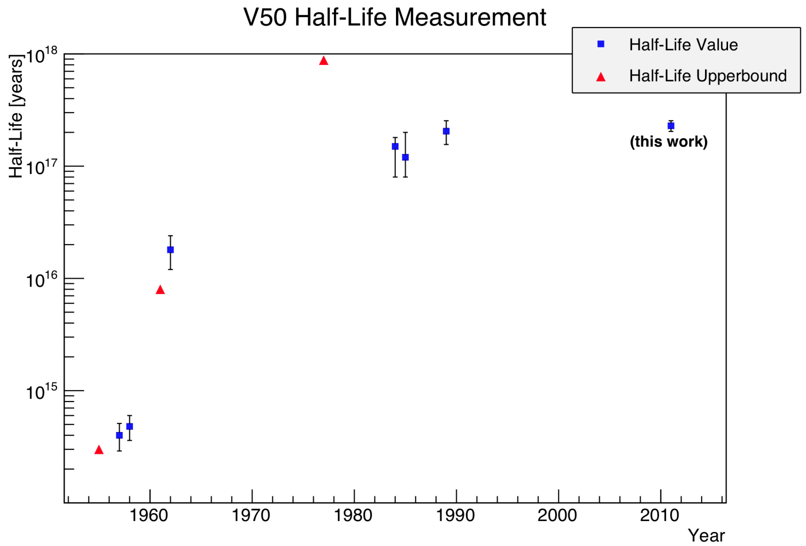
4-fold forbidden beta decays – ^{50}V

Two more: ^{115}In (well measured) , ^{50}V

H. Dombrowski, S. Neumaier, K. Zuber, PRC 83, 054322 (2011)







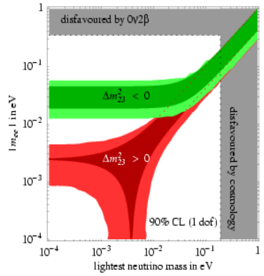
Only limit on beta branch

Higher forbidden beta decays (48Ca, 96Zr)
-> DBD is more likely!

2 Tackling 50 meV (IH)

Inverse hierarchy:

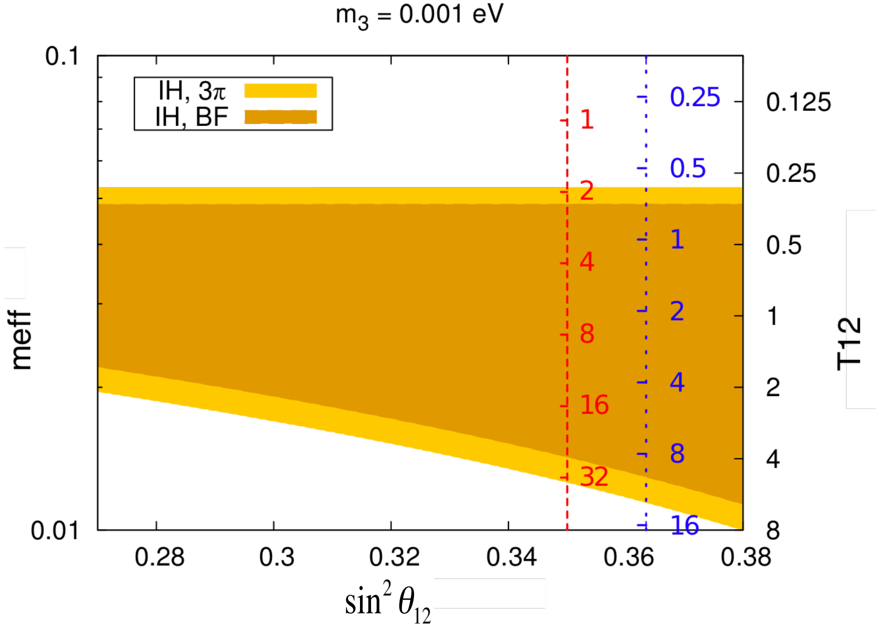
$$\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j$$
$$\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2$$
$$\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}}$$
$$\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \ \simeq 19\ \mathrm{meV}$$



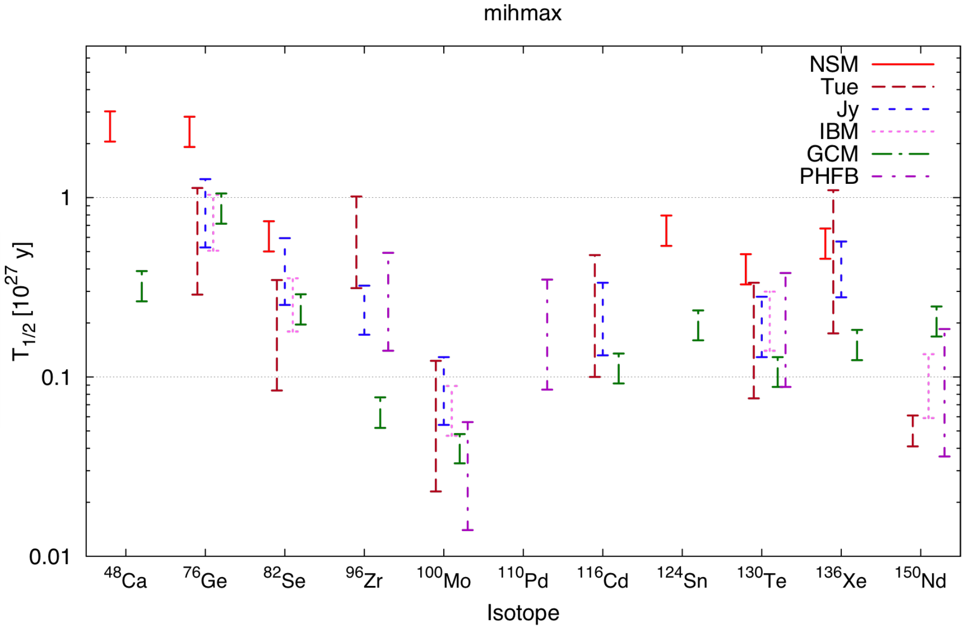
Just to touch the IH

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

Dependence on solar mixing angle

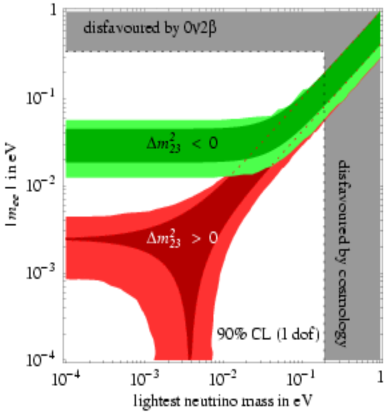


Reminder: Factor 2 in mass implies factor 16 in experimental parameters ➔ better solar measurement ➔SNO+??? Reactors (JUNO , RENO-50)???



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

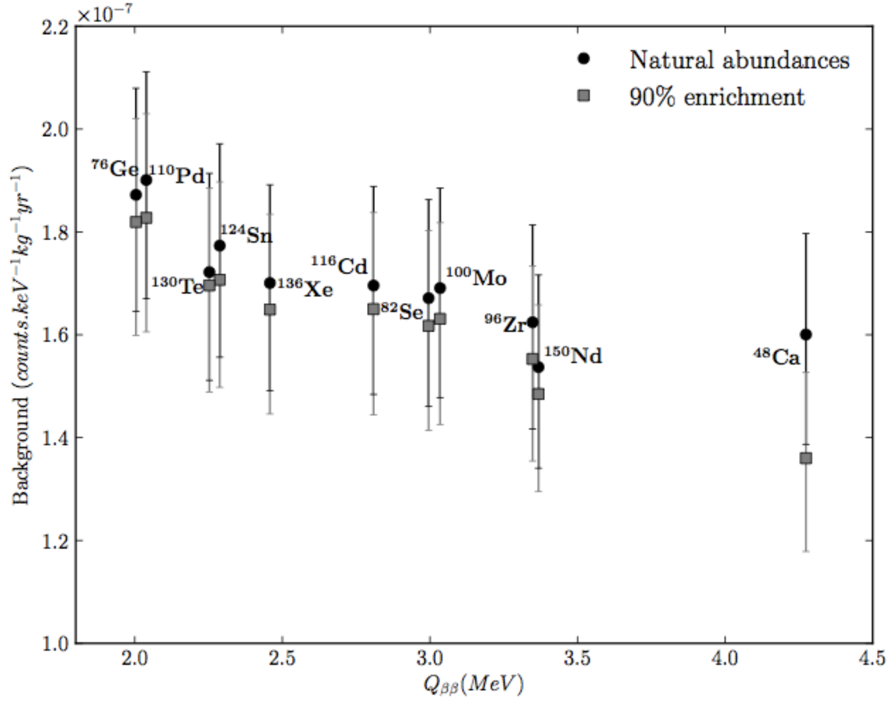
- New background components (f.e. solar neutrino-electron elastic scattering)

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

- More accurate matrix elements

HOW???

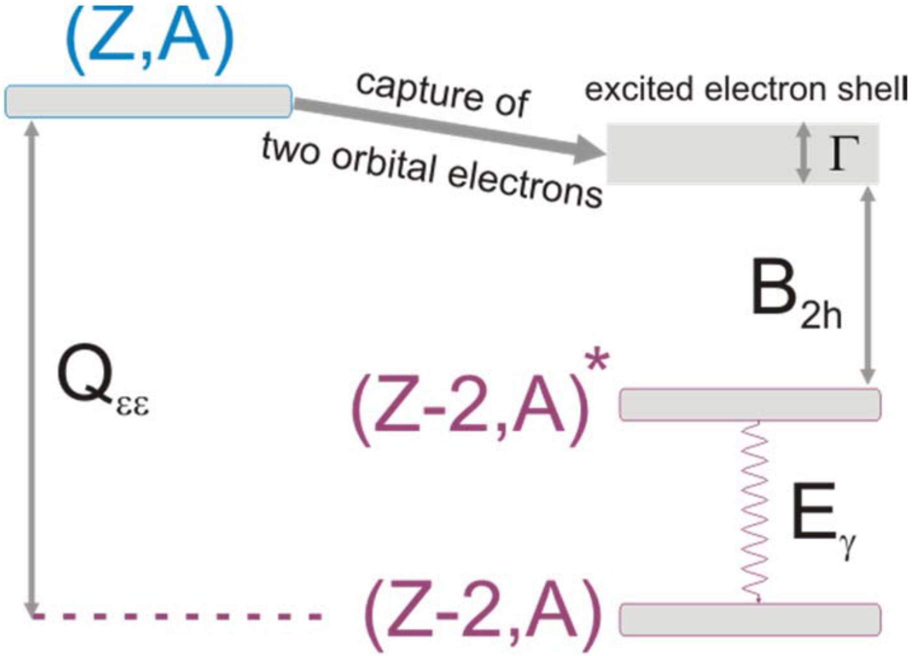
Experiments which work for IH and claim might not work for NH



K. Zuber

Resonant double EC

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



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Alternative modes

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

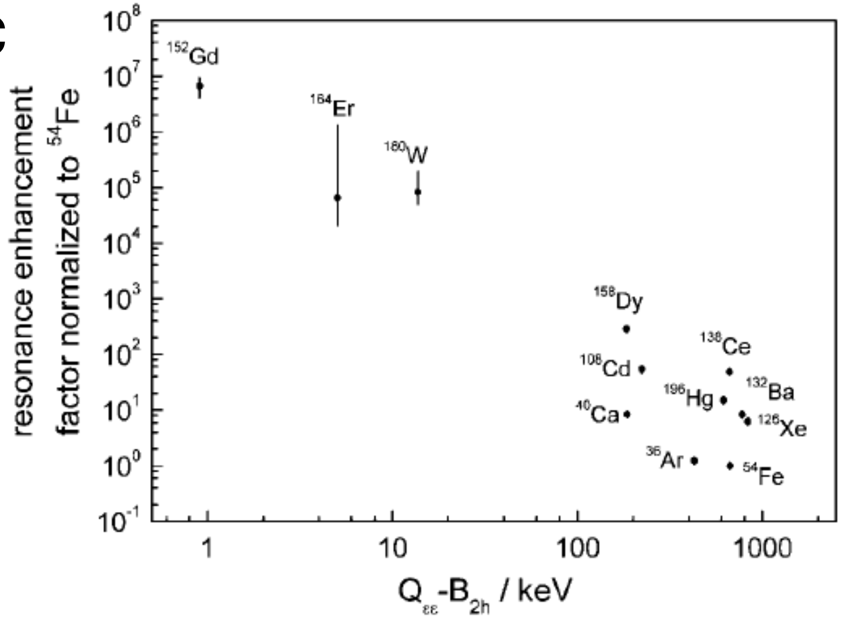
Enhanced if V+A is at work

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 last (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