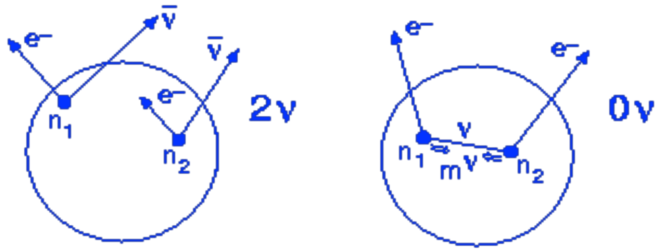
K. Zuber, TU Dresden

INT, 3.6. 2015

Double beta decay experiments

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

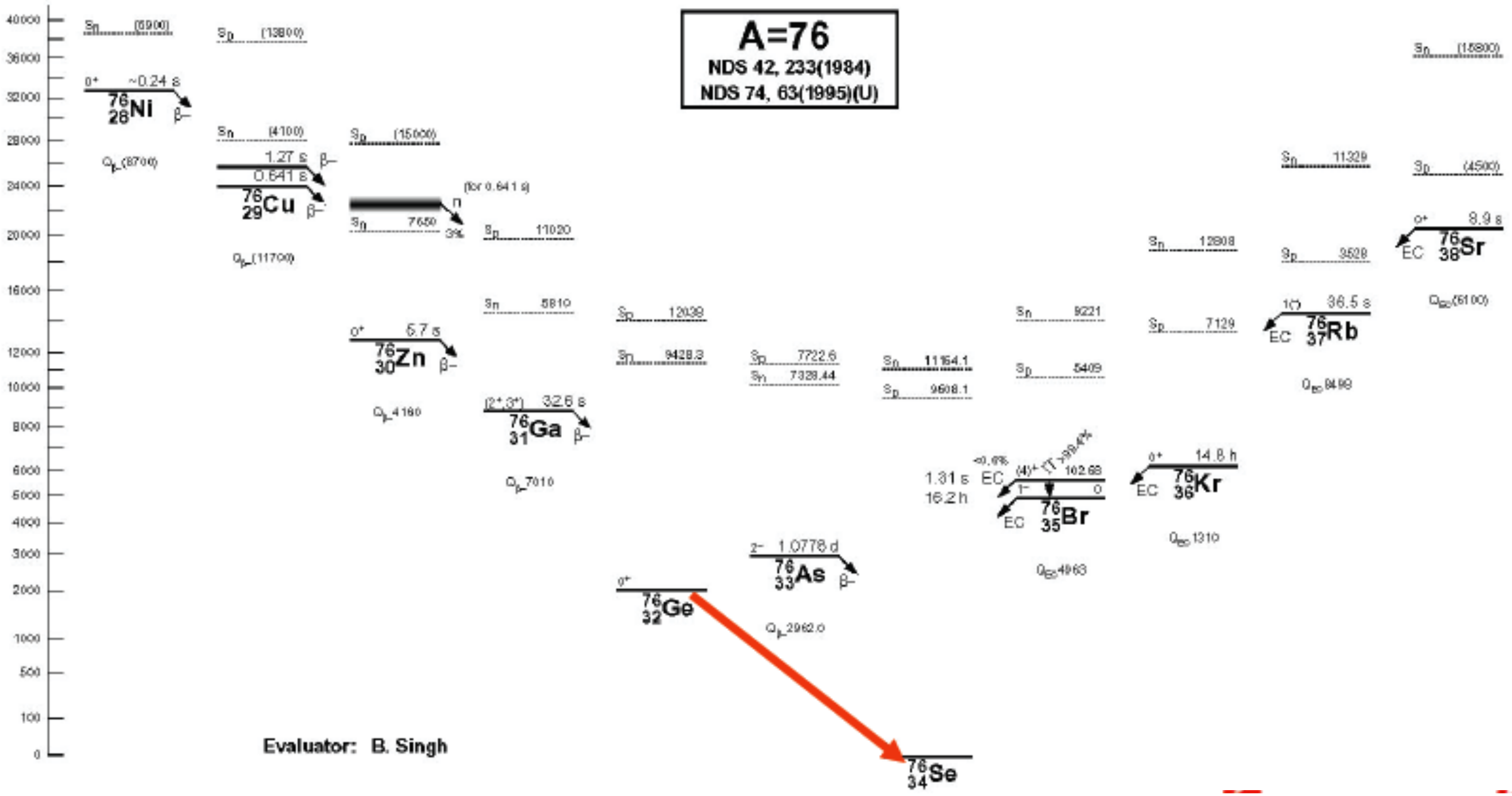
The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

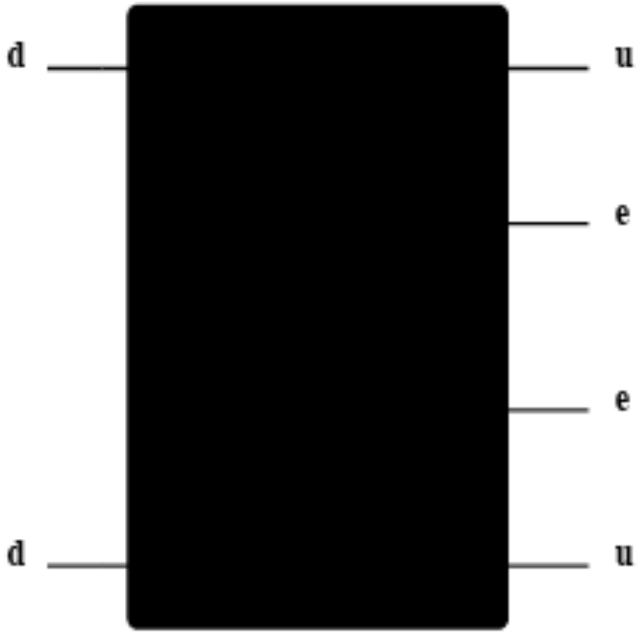
Requires half-life measurements well beyond 10^{20} yrs!!!!

Only 35 isotopes in nature are able to do that!

K. Zuber


A=76
NDS 42, 233(1984)
NDS 74, 63(1995)(U)
Evaluator: B. Singh
76 28 Ni
76 29 Cu
76 30 Zn
76 31 Ga
76 32 Ge
76 33 As
76 34 Se
76 35 Br
76 36 Kr
76 37 Rb
76 38 Sr
~0.24 s
1.27 s
0.641 s
5.7 s
32.6 s
1.0778 d
1.31 s
16.2 h
14.8 h
36.5 s
8.9 s
EC
β−
(for 0.641 s)
40000
36000
32000
28000
24000
20000
16000
12000
10000
8000
6000
5000
4000
3000
2000
1000
500
100
0

Any ΔL=2 process can contribute to 0νββ



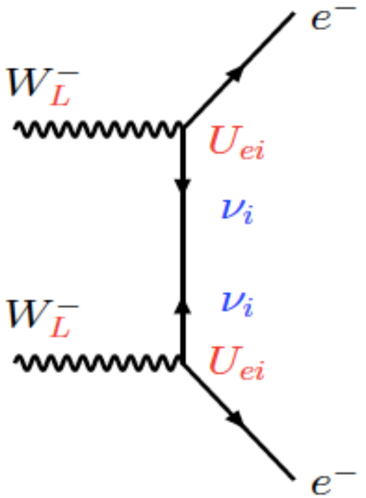
R_p violating SUSY
V+A interactions
Extra dimensions (KK- states)
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
...

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

K. Zuber

Nice interplay with LHC

Light Majorana neutrinos

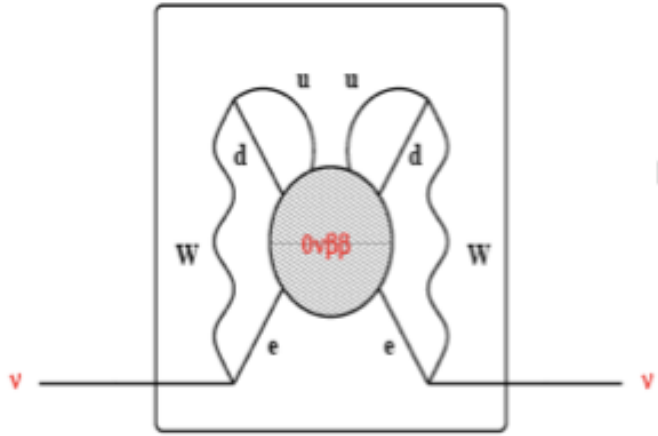


$$\varepsilon \equiv \langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

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

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

K. Zuber

3 Flavour mixing (PMNS)

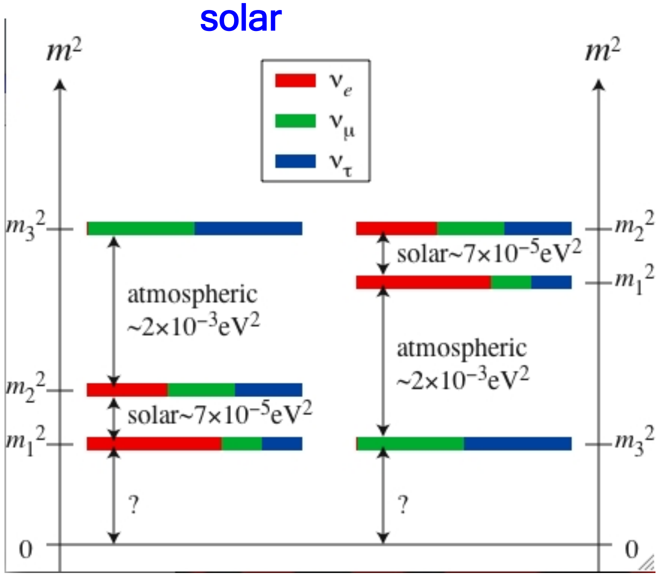
TECHNISCHE UNIVERSITÄT DRESDEN

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

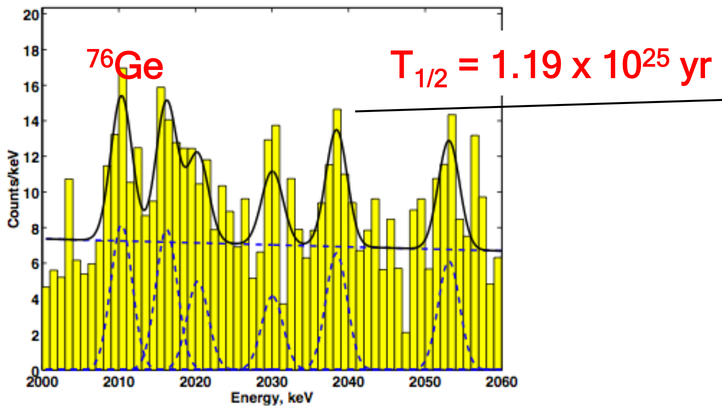
$\sin^2 2\theta_{23} > 0.9$ (90%CL), best fit $\theta_{23} = 45°$

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

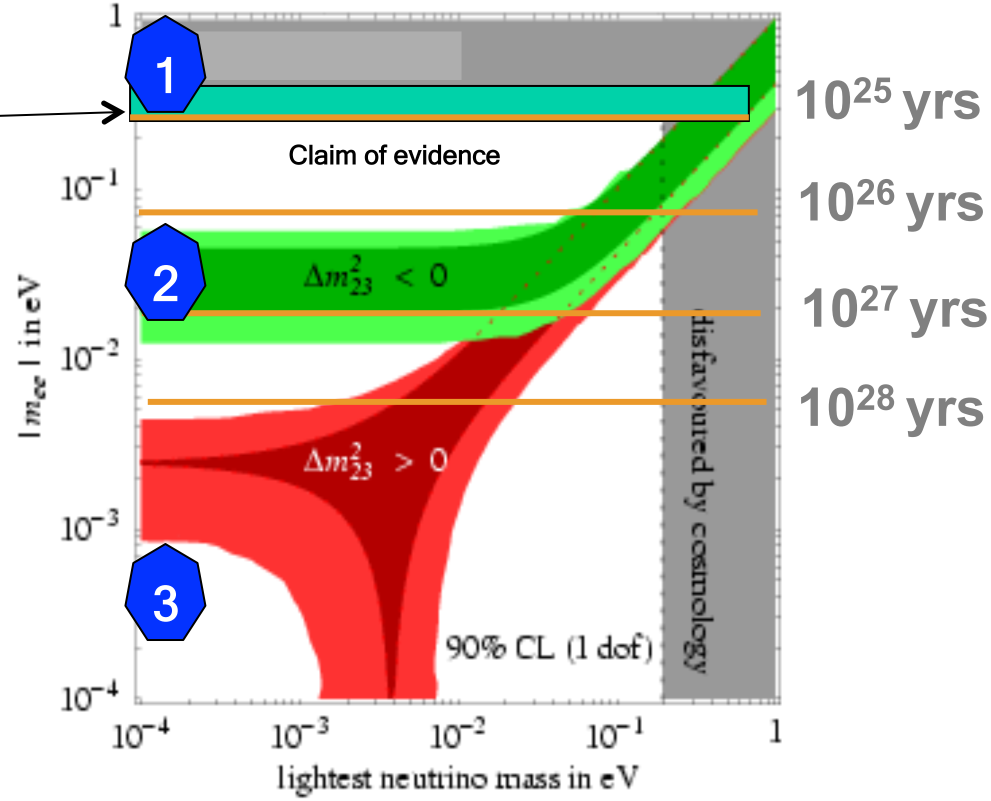
$\sin^2\theta_{12} = 0.32, \theta_{12} = 34^\circ.06^{+1.16}_{-0.84}$

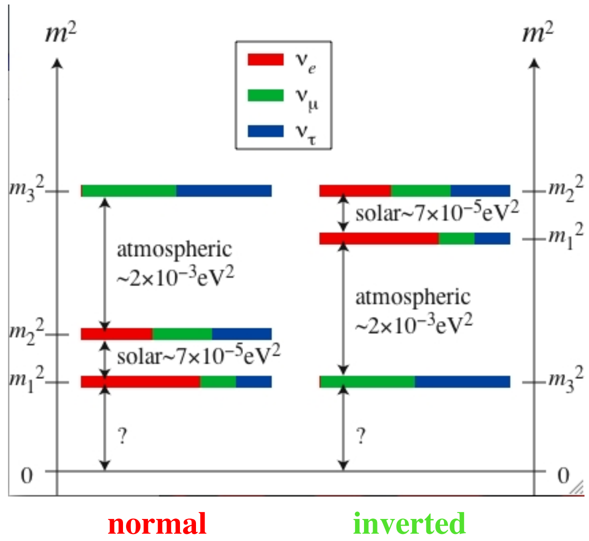
K. Zuber

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

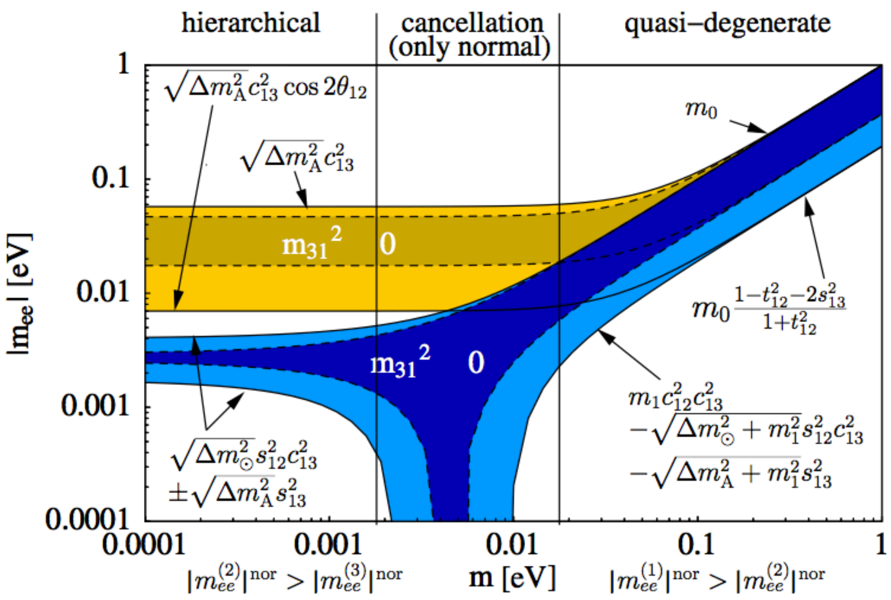
2.) Can we probe the inverted hierarchy?

3.) What about the normal hierarchy?

Mass hierarchies and DBD

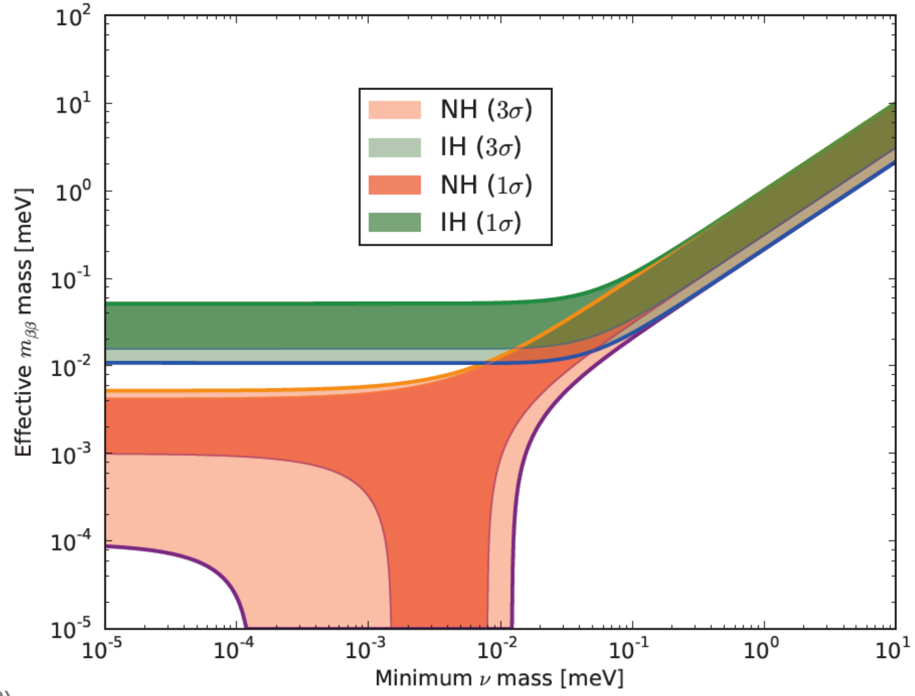
With the known oscillation results everything is fixed

General dependence



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

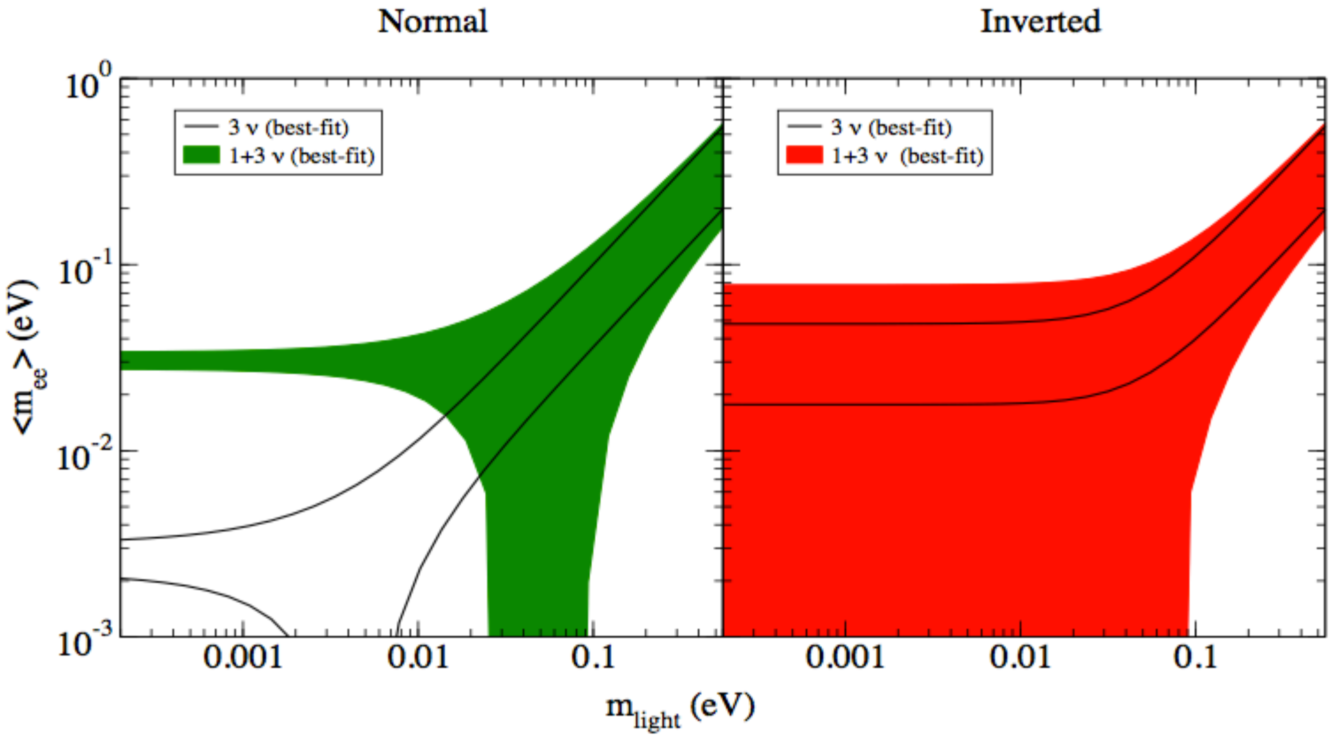
Current data



K. Zuber

Mass hierarchies – Adding a sterile

Plot get's turned around ....



Barry, Rodejohann, Zhang (2011), Giradi, Meroni, Petcov (2013), Giunti, Zavanin, arXiv:1505.00978

Other mass determinations

Beta decay:

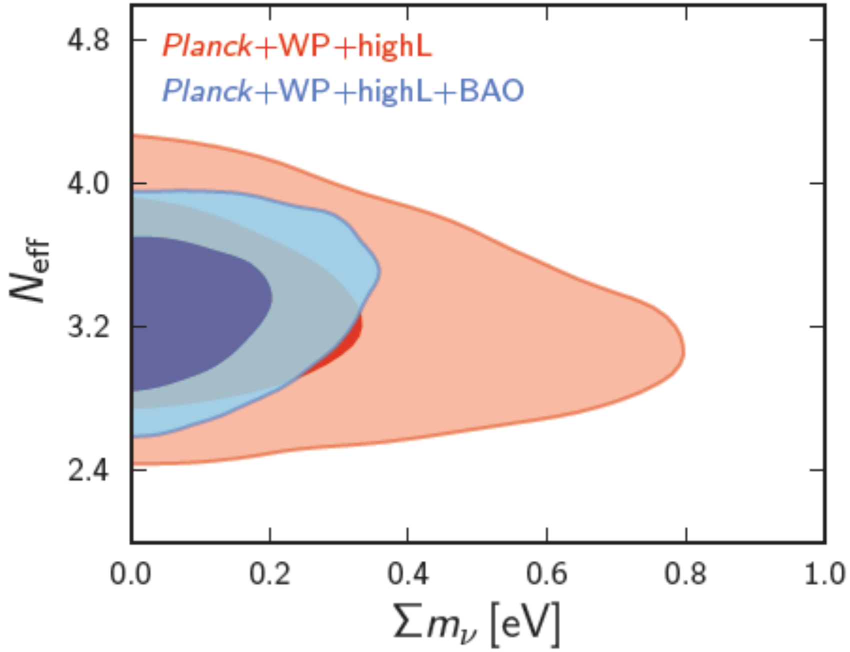
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

http://www.katrin.kit.edu

KATRIN -Sensitivity about 0.2 eV

Cosmology:

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

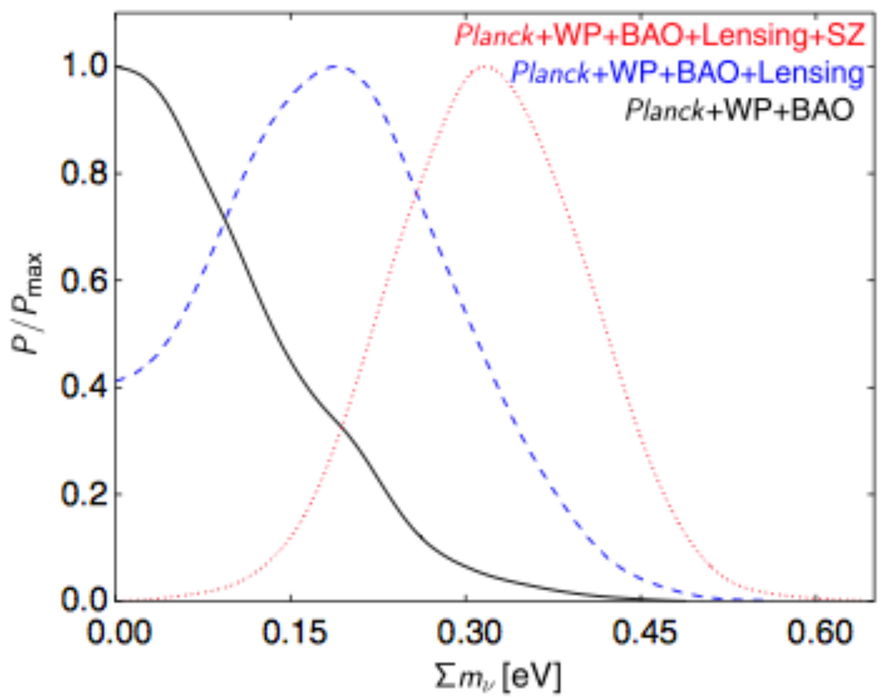


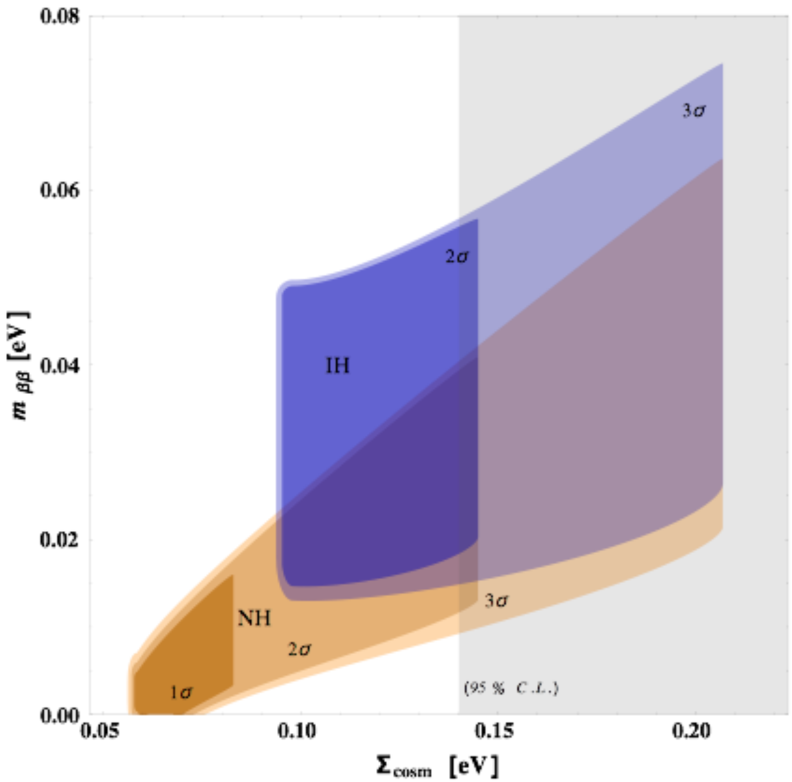
$$\sum m_\nu < 0.23 eV (95\% CL)$$

+ oscillation parameters

K. Zuber

Cosmology – Hint for NH?





$$\sum m_\nu = 0.320 \pm 0.081 eV$$

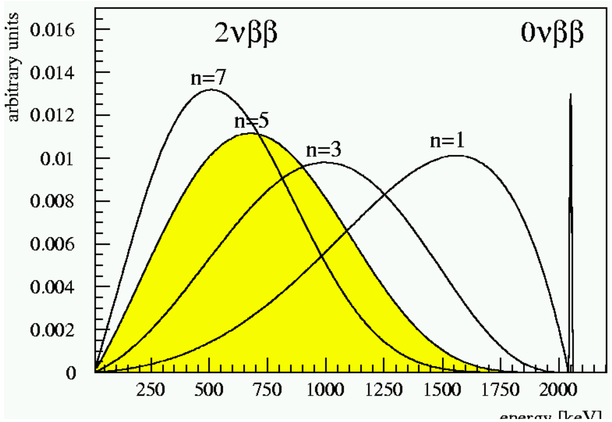
On 1 sigma level IH excluded

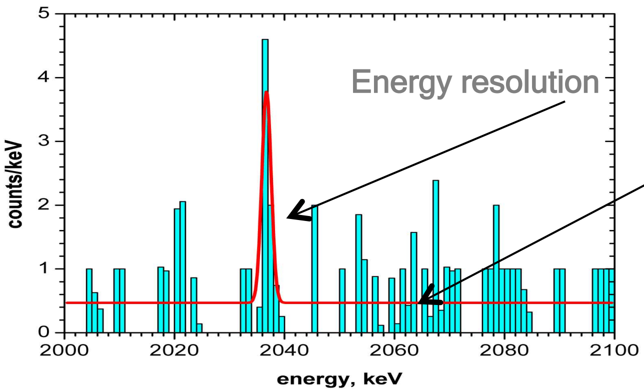
R. Battye, A. Moss, PRL 112, 051303 (2014)

Dell'Oro et al., arXiv:1505.02722,
N. Palanque-Delabrouille et al. JCAP 1502,045 (2015)

$0\nu\beta\beta$: 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 $m_\nu \propto \sqrt[4]{\frac{\Delta EB}{Mt}}$

K. Zuber

TECHNISCHE UNIVERSITÄT DRESDEN

Perfect world experiment

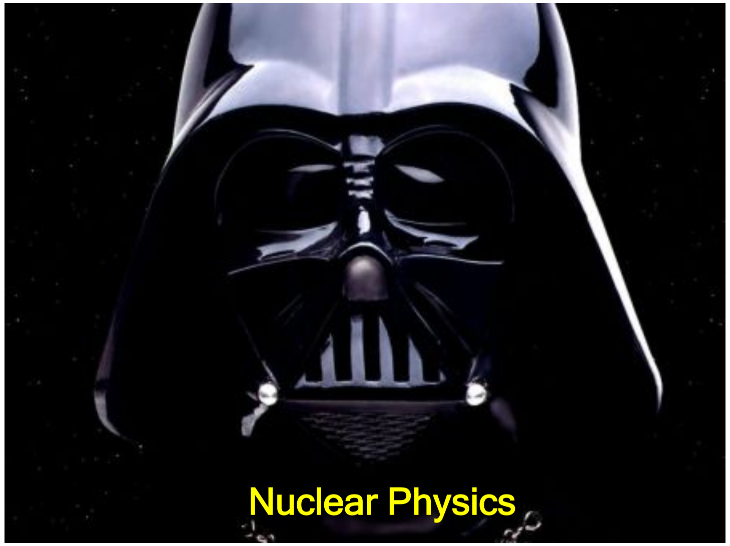
- No background
- δ function as peak
- 100 % abundance
- 100% detection efficiency
- Infinite measuring time
- Infinite mass

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

Life is easy, the rest is just details

Master equation

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



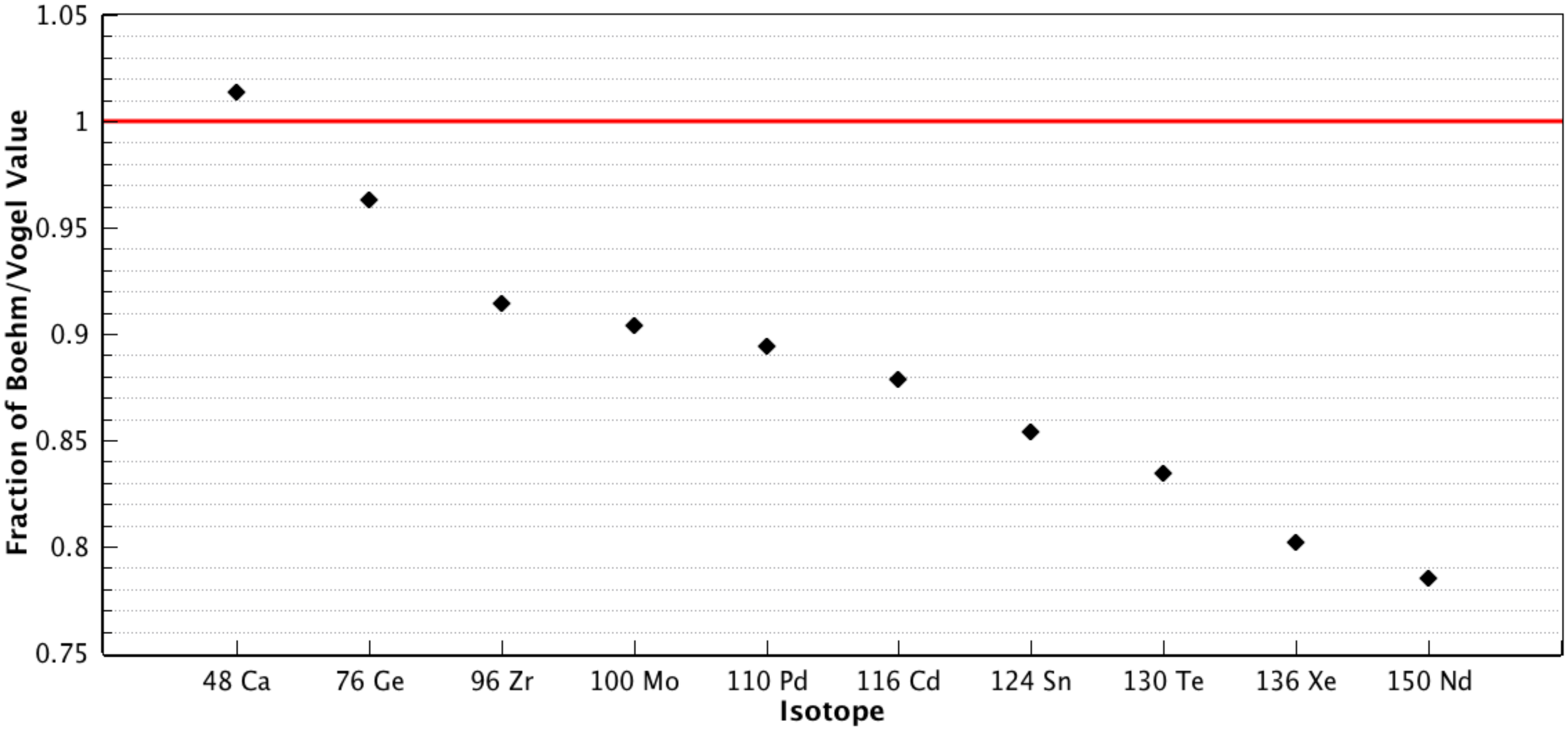
Measurement

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

Complex calculations → **Severe nuclear structure issue** (K. Zuber)

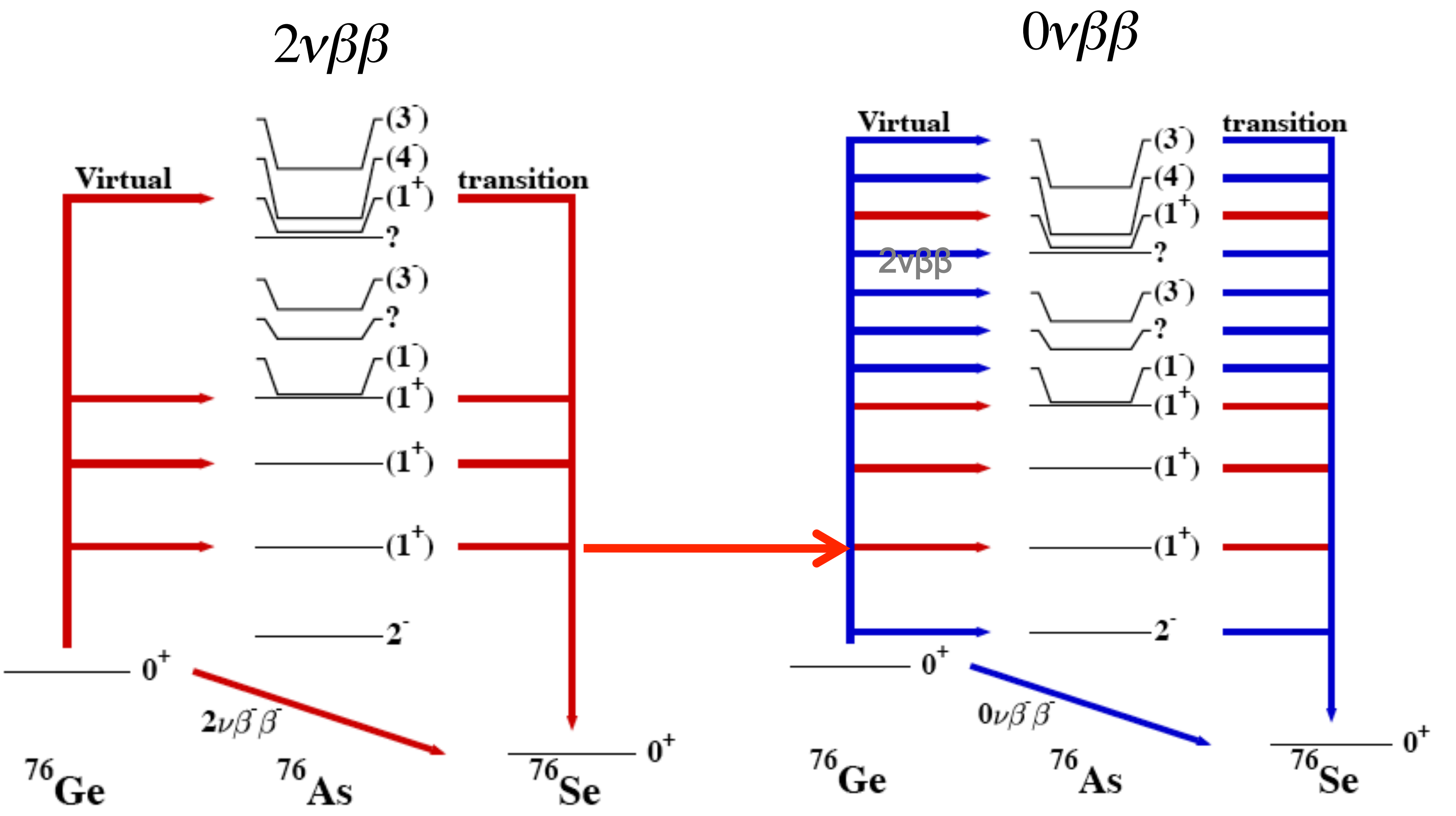
Quantity of interest

Phase space factors (new vs. old)



Kotila, Iachello, PRC 85,034316 (2012), Stoica, Mirea, arXiv:1307.0290

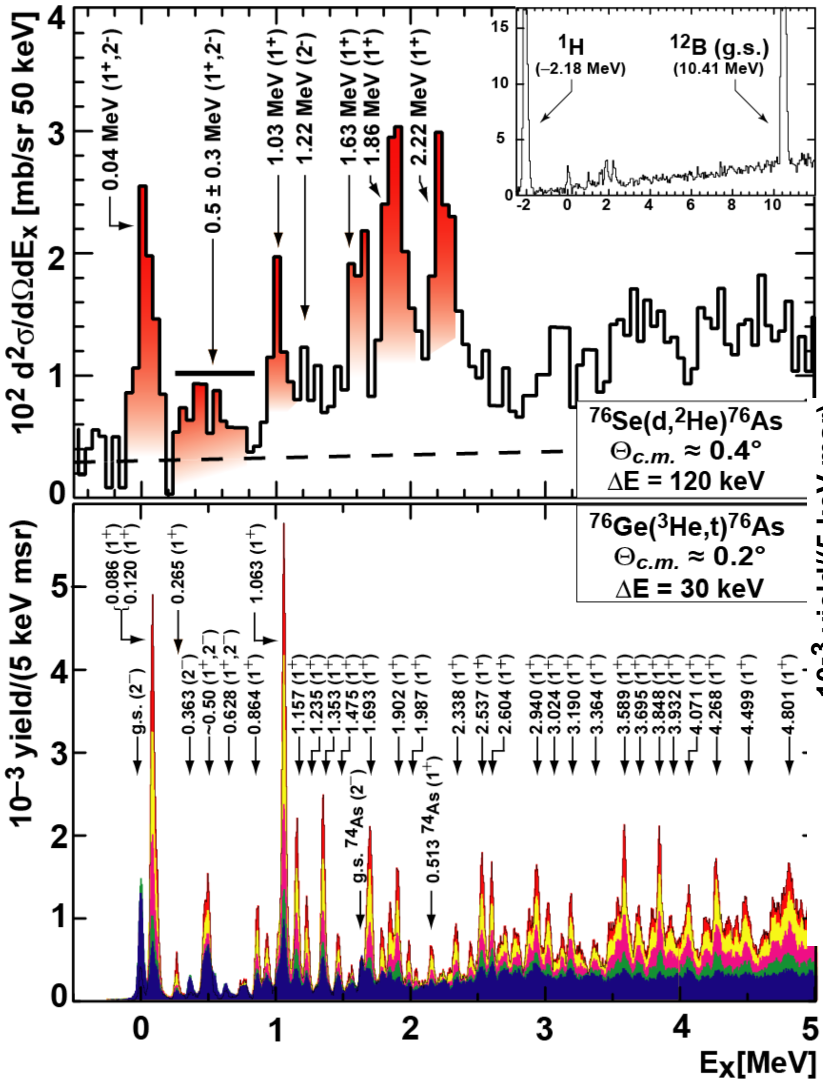
NME – Intermediate states



K. Zuber

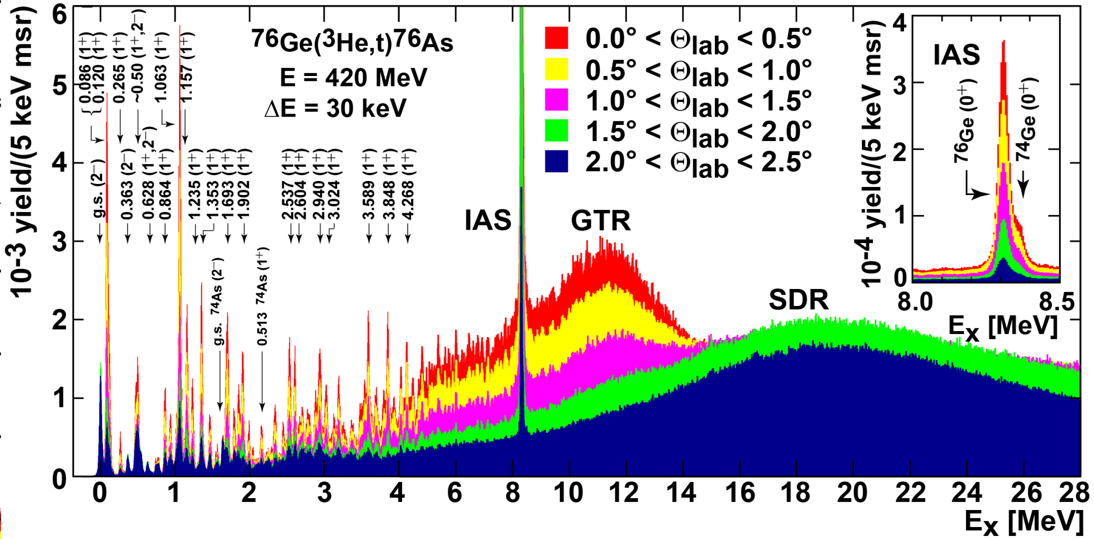
TECHNISCHE UNIVERSITÄT DRESDEN

NME – Intermediate states



Differential cross section in forward direction directly linked to Gamow-Teller strength

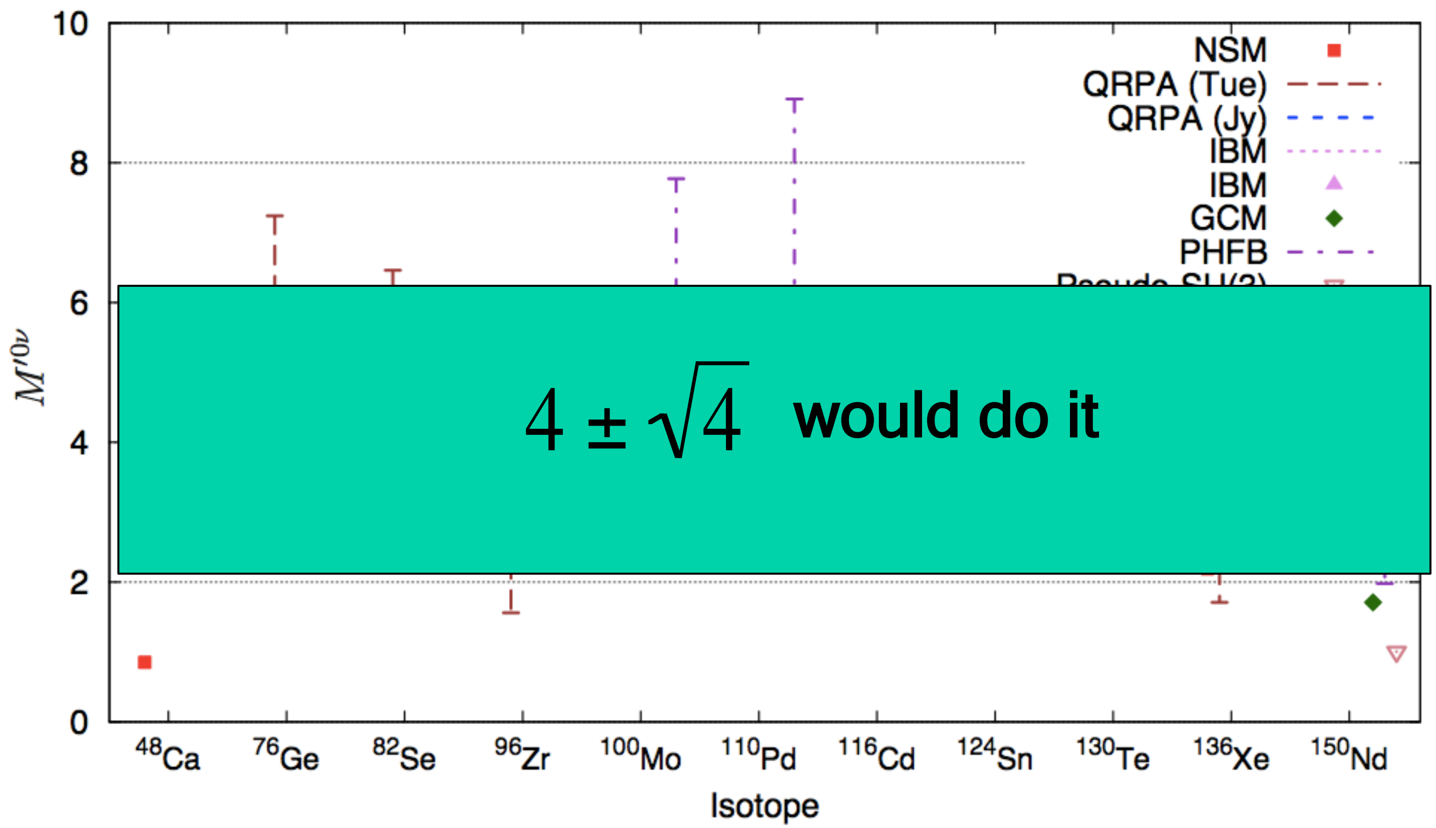
Charge exchange measurements at KVI and RCNP



K. Zuber

Matrix element

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

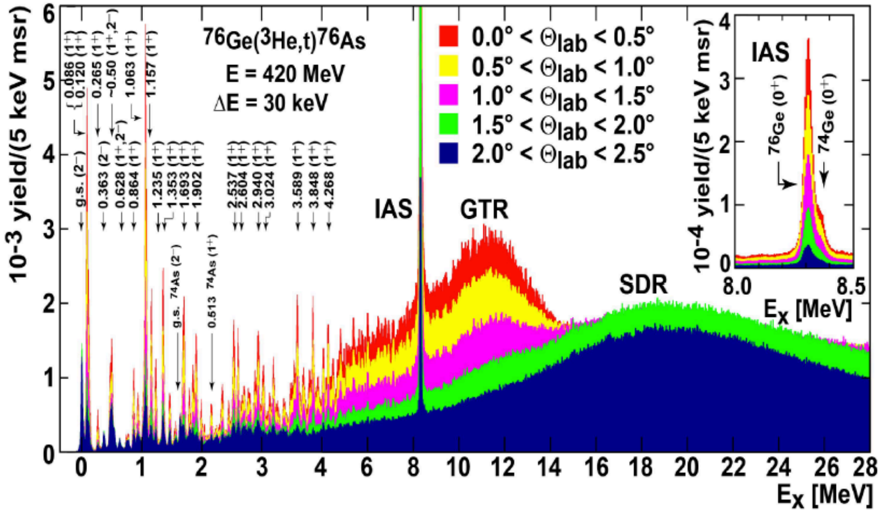


A. Dueck, W. Rodejohann, K. Zuber, arXiv:1103.4152, PRD 83, 113010 (2011)

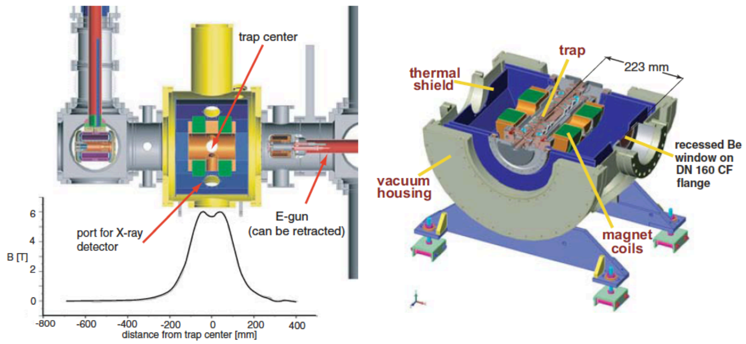
Several new techniques applied in last years

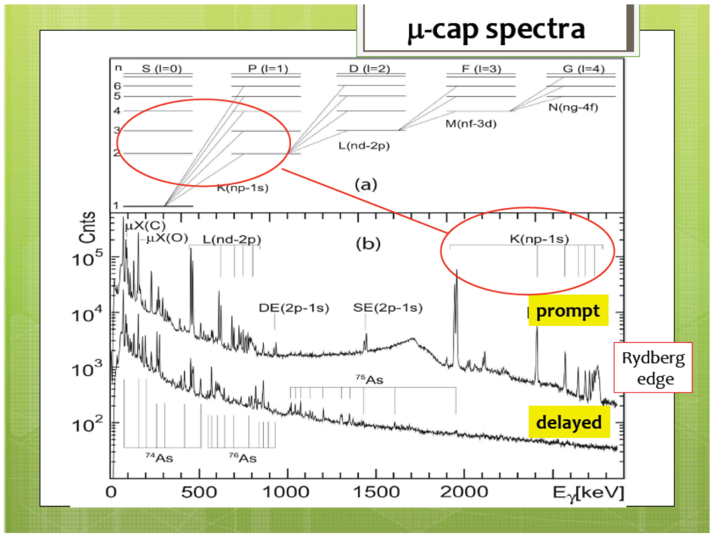
Items studied (examples)

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

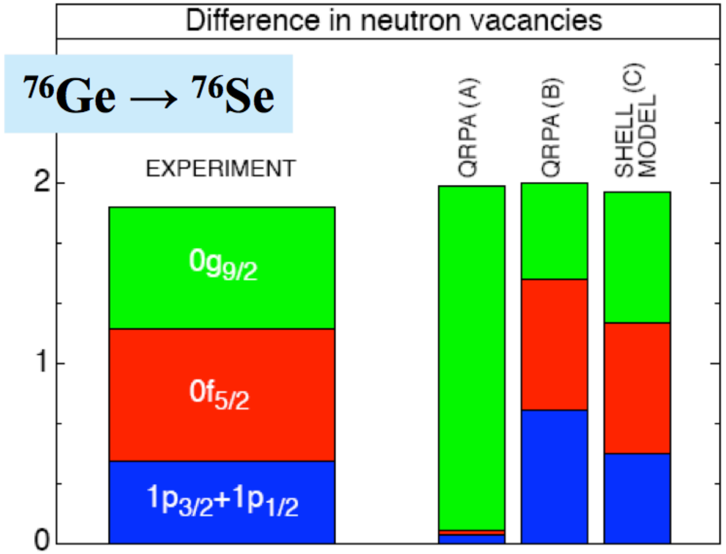


TITAN-EC at TRIUMF





D. Zinatulina, MEDEX 2013



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

Back of an envelope

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

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

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, ...

Experimental approaches

0νββ decay rate scales with Q^5 → only those with Q>2000 keV

11 isotopes of interest

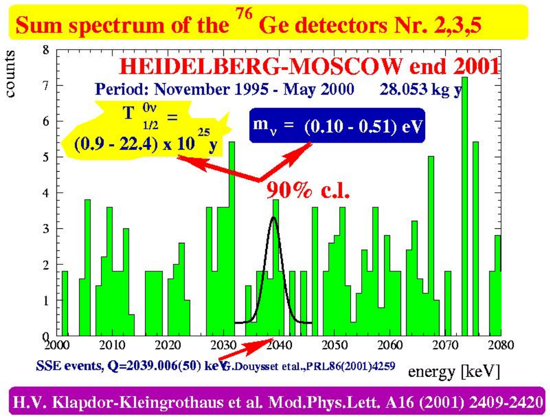
Isotope	Nat. abund. (%)	Q-values 2012	
Ca-48	0.187	4262.96 ± 0.84	Candles
Ge-76	7.44	2039.006 ± 0.050	GERDA, Majorana
Se-82	8.73	2997.9 ± 0.3	SuperNEMO, LUCIFER
Zr-96	2.80	3347.7 ± 2.2	
Mo-100	9.63	3034.40 ± 0.17	MOON, AMore
Pd-110	11.72	2017.85± 0.64	
Cd-116	7.49	2813.50 ± 0.13	COBRA
Sn-124	5.79	2292.64 ± 0.39	TinTin
Te-130	33.80	2527.518± 0.013	CUORE, SNO+
Xe-136	8.9	2457.83± 0.37	EXO, KamLAND-Zen, NEXT, XMASS
Nd-150	5.64	3371.38 ± 0.20	MCT, SuperNEMO(?)

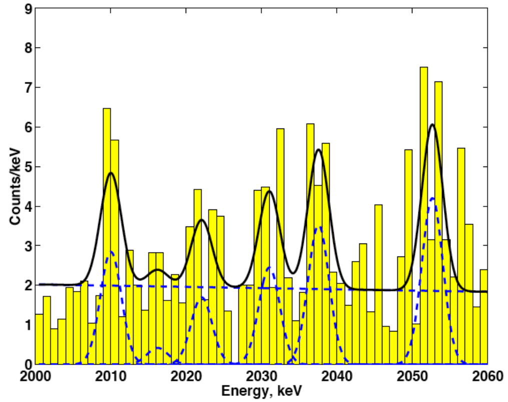
There is no super-isotope

K. Zuber

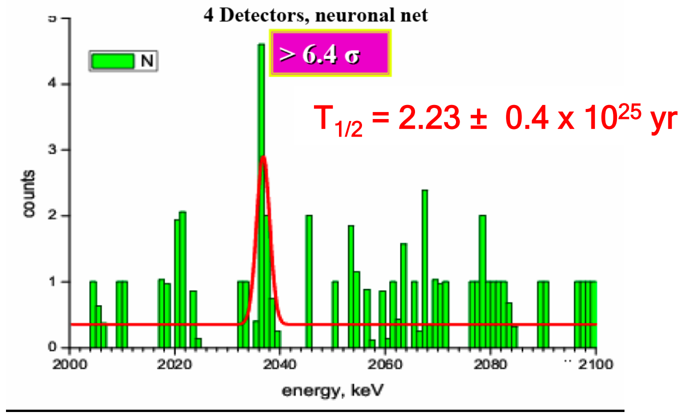
Evidence ?

2001	2004	2006

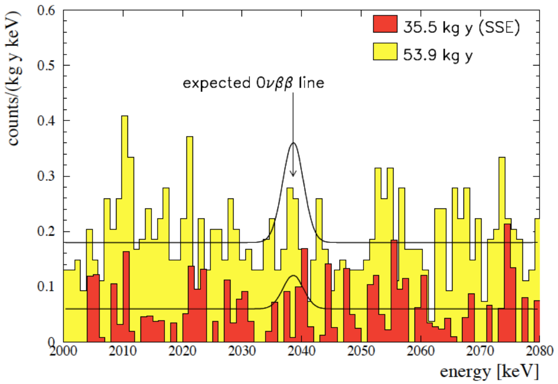




H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586, 198 (2004)

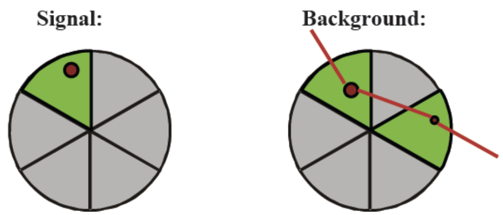


Mod.Phys.Lett.A21:1547-1566 (2006)



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

Background reduction by pulse shape analysis

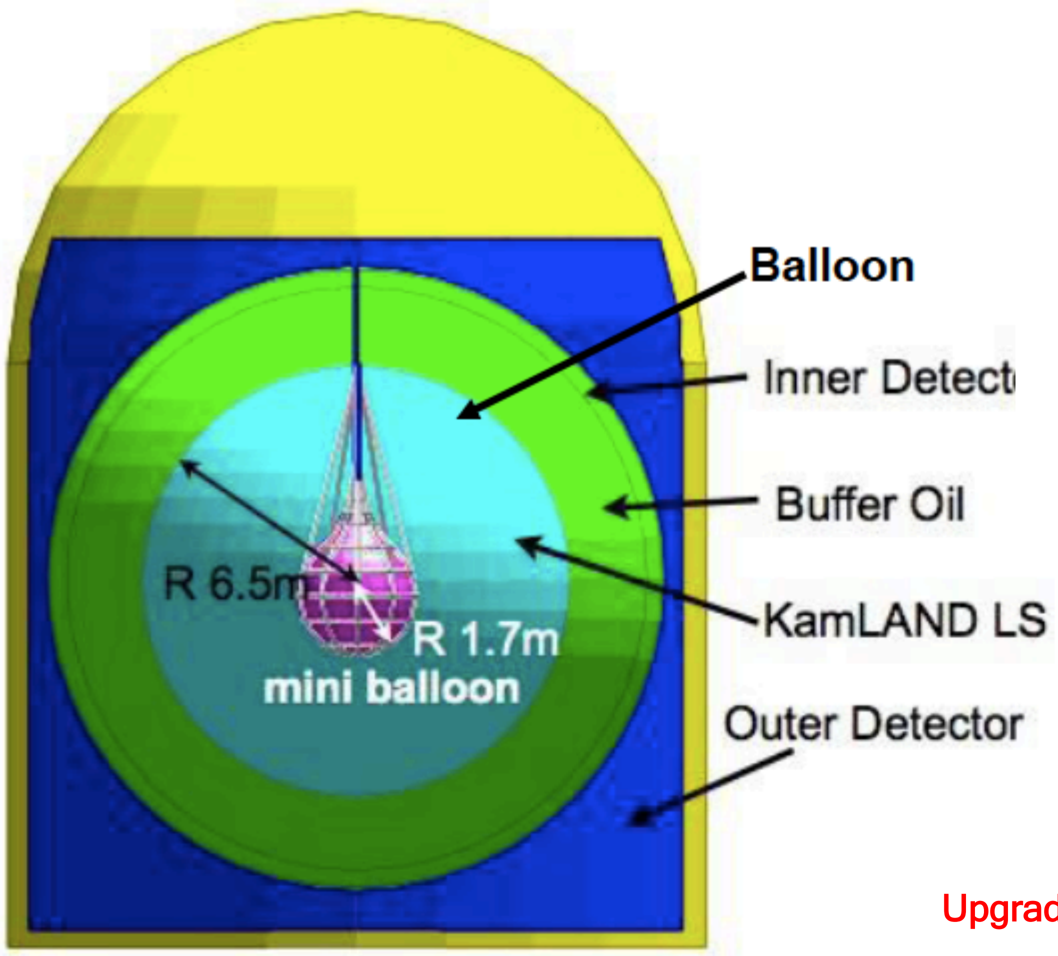


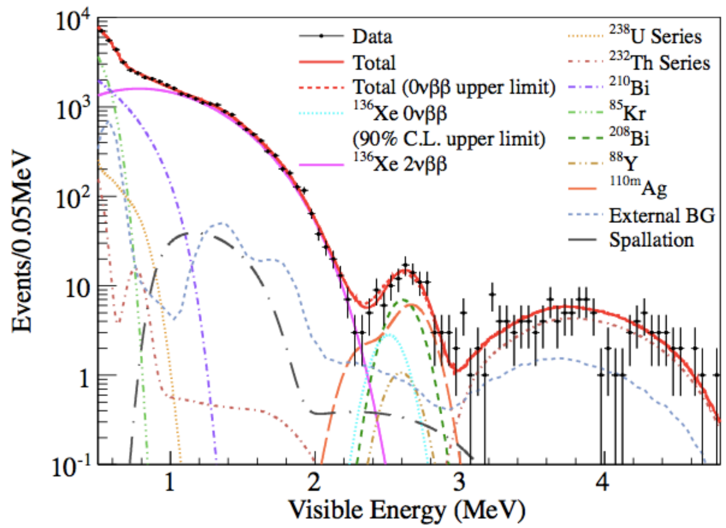
Very controversial discussion in the community

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

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)

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

A. Gando, arXiv:1211.3863

Upgrade to 1 ton enriched Xe planned soon

K. Zuber

EXO-200

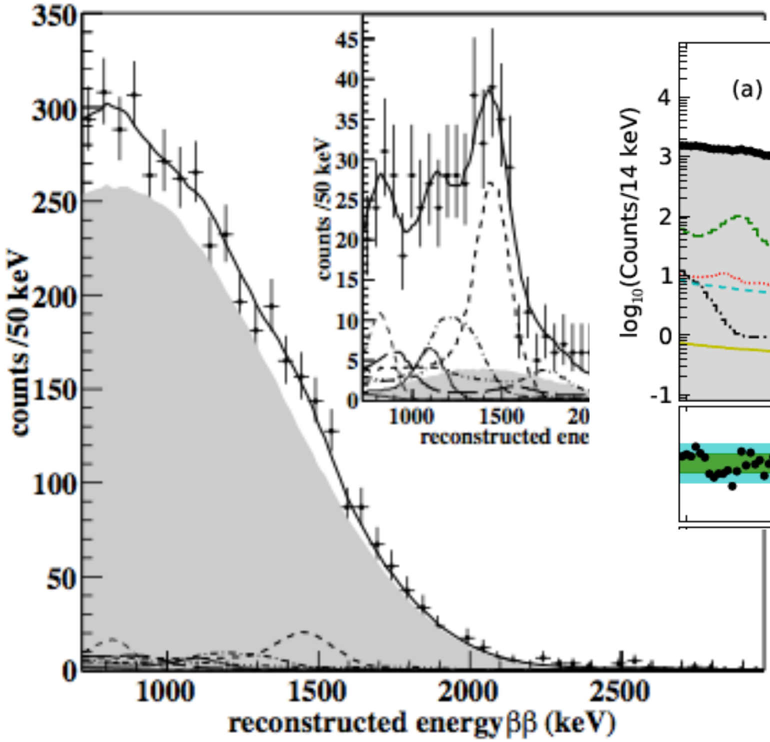
TECHNISCHE UNIVERSITÄT DRESDEN

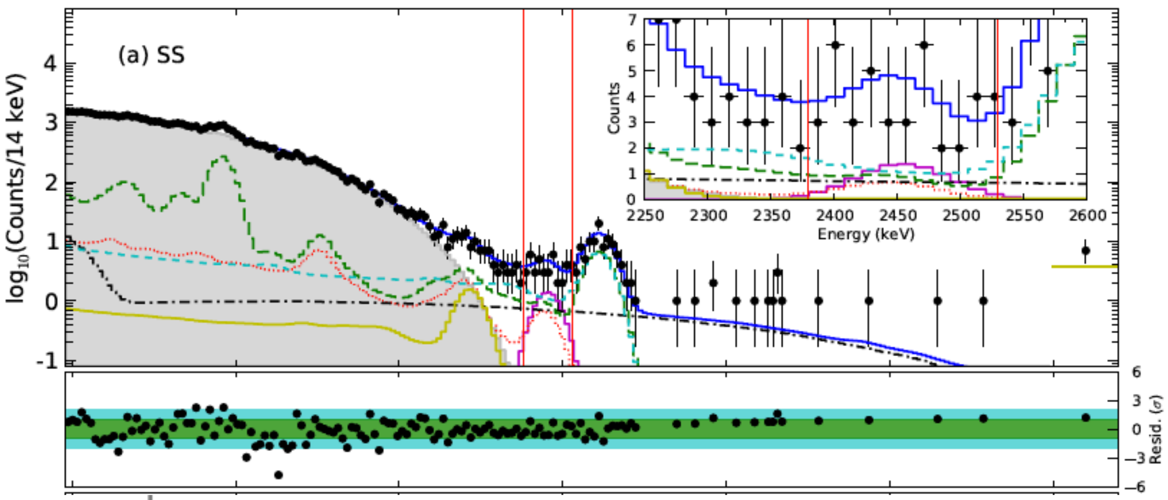
Enriched Xenon Observatory – EXO – for double beta decay

iktp

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

Current half-life limit on 0nu decay :
$T_{1/2} > 1.1 \times 10^{25}$ years (90%CL)
J. B. Albert et al., doi:10.1038/nature13432 (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)

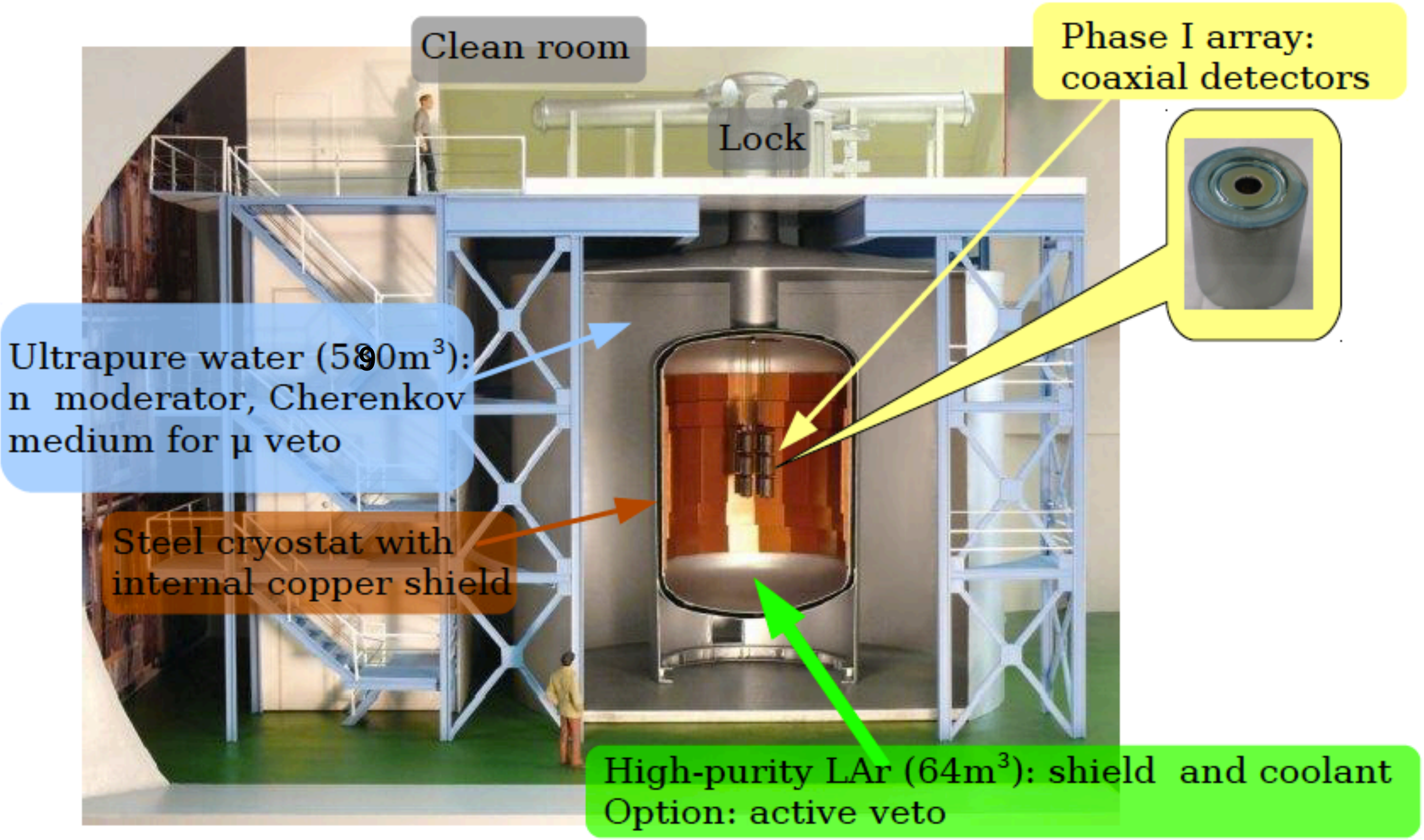
Future option: Barium tagging

DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

TECHNISCHE UNIVERSITÄT DRESDEN

GERDA-Principal Setup

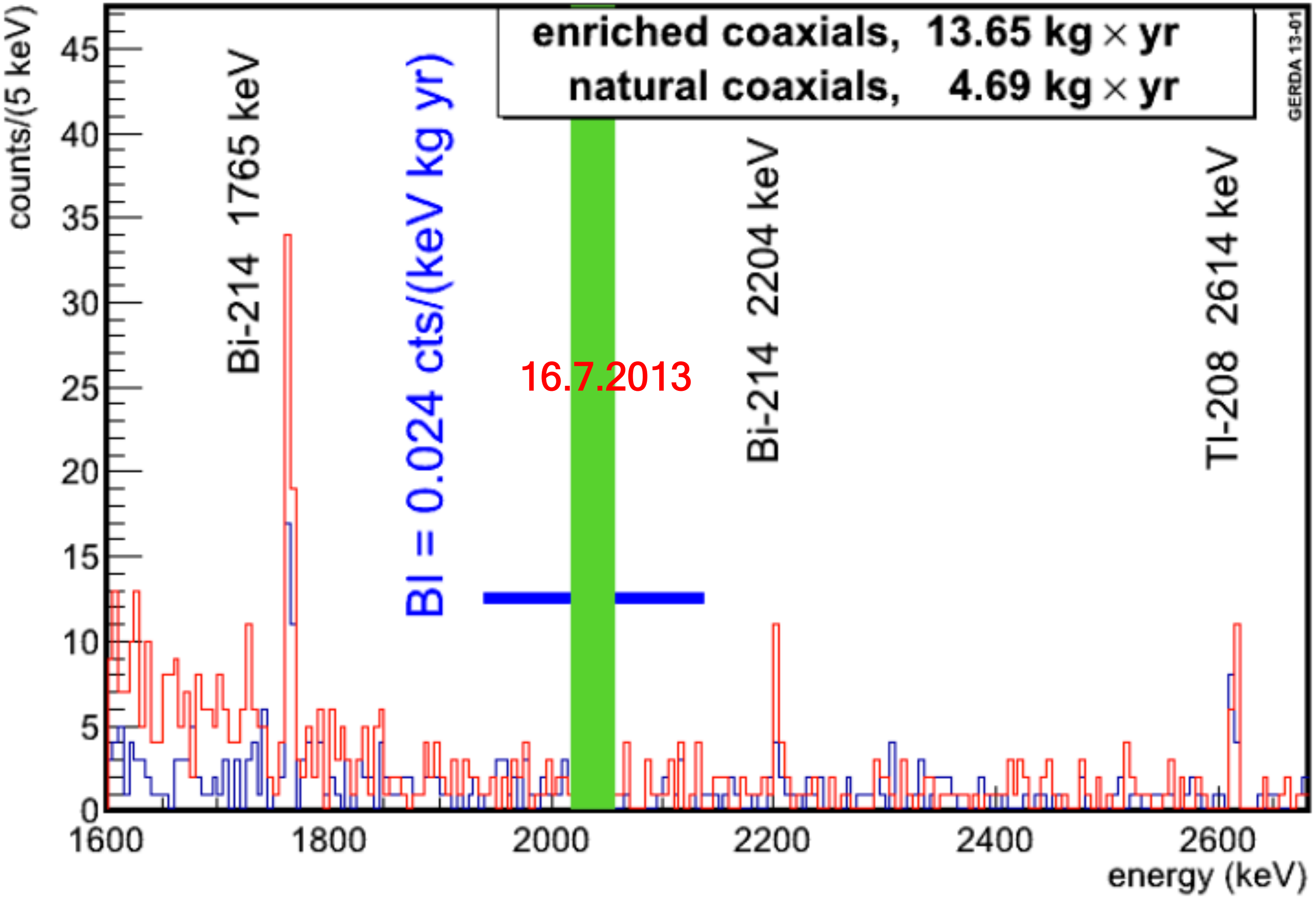
Idea : Running bare Ge crystals in LAr



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

K. Zuber

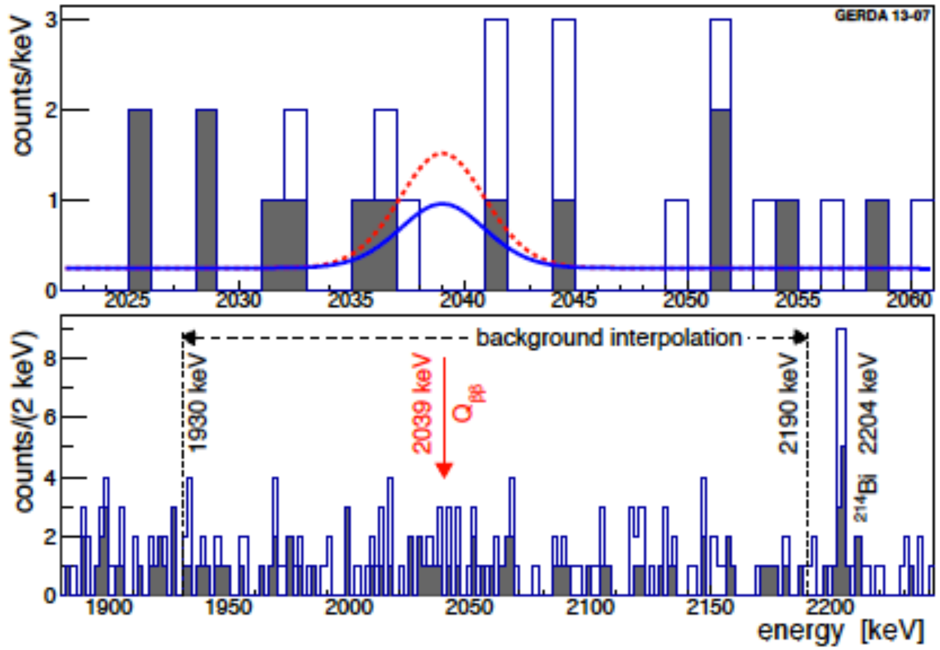
Phase I data taking

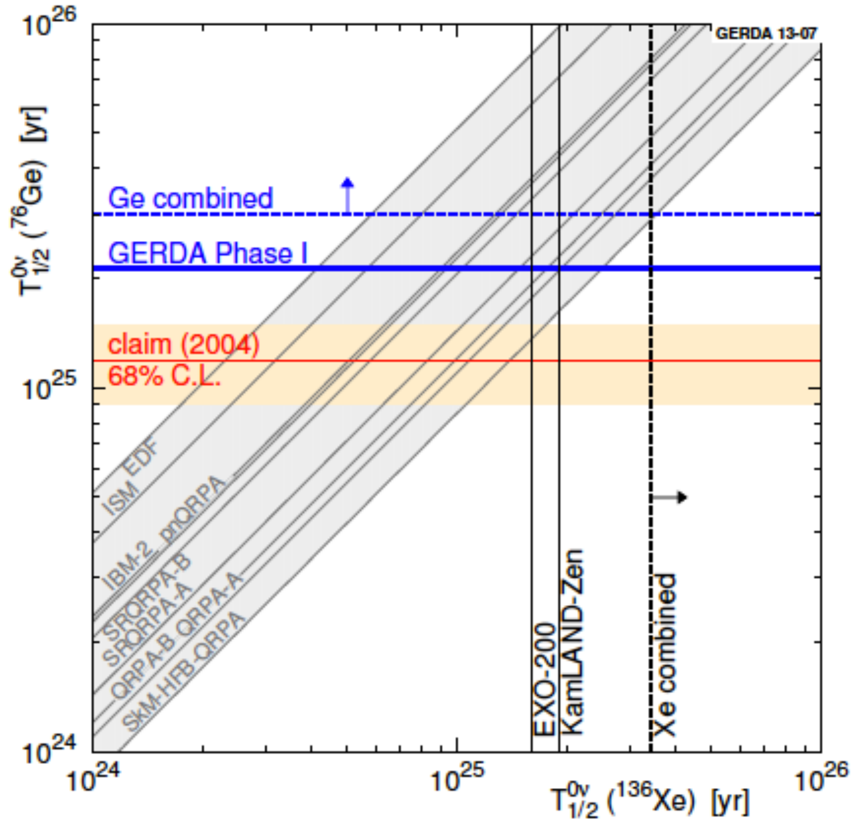


Phase I results

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)



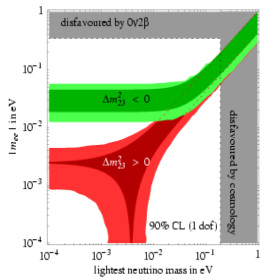


2 Tackling 50 meV (IH)

Inverse hierarchy:

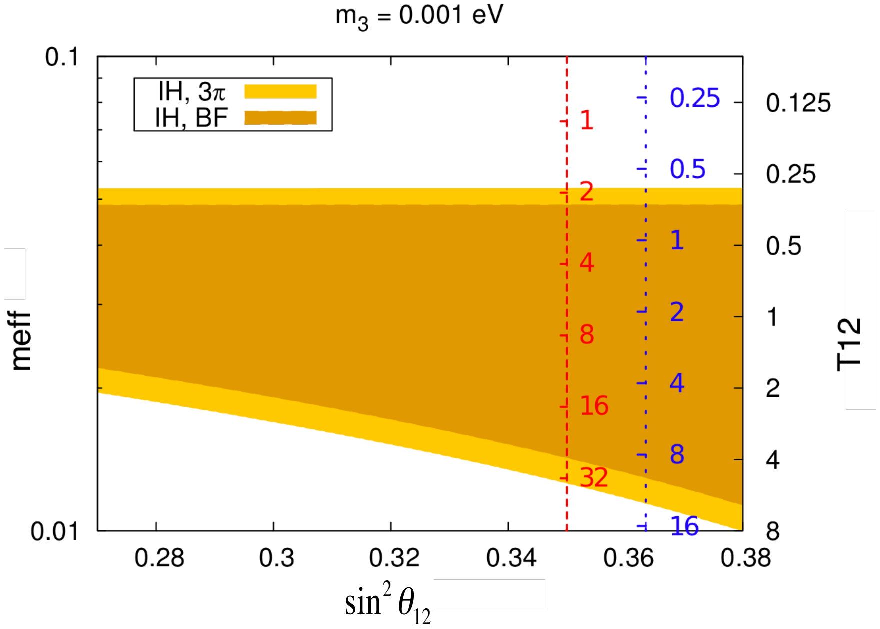
$$\begin{aligned}\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\ &\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 \\ &\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m^2_{Atm}} \\ &\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \text{eV} \ \simeq 19\ \text{meV}\end{aligned}$$

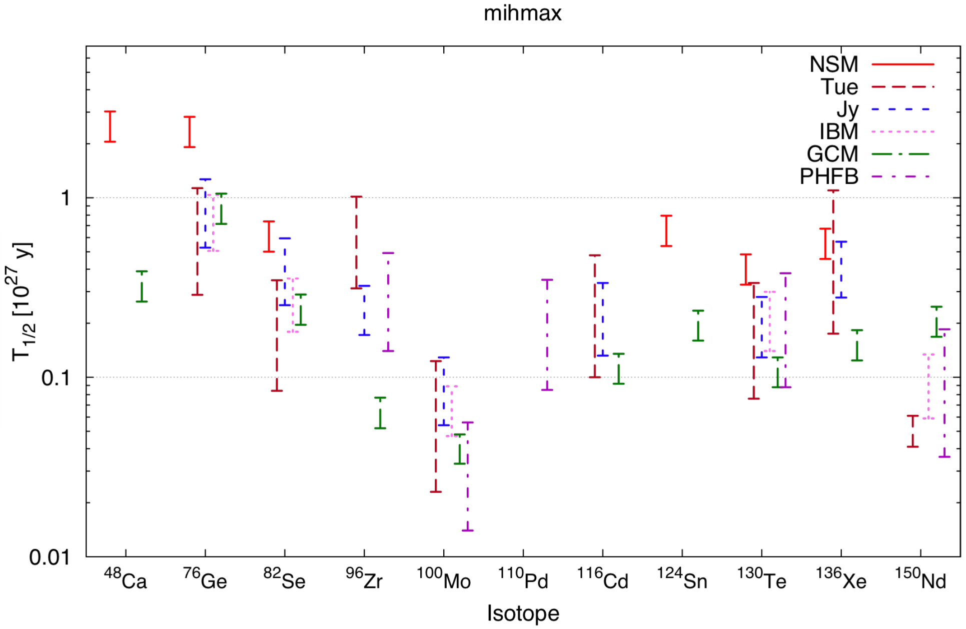
→



Just to touch the IH
^{100}Mo and ^{150}Nd seems most promising

Dependence on solar mixing angle

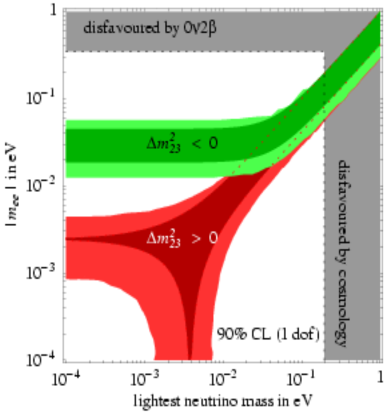




A. Dueck, W. Rodejohann, K. Zuber, PRD 83, 113010 (2011)

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

3 Tackling the normal hierarchy



No real proposal yet

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

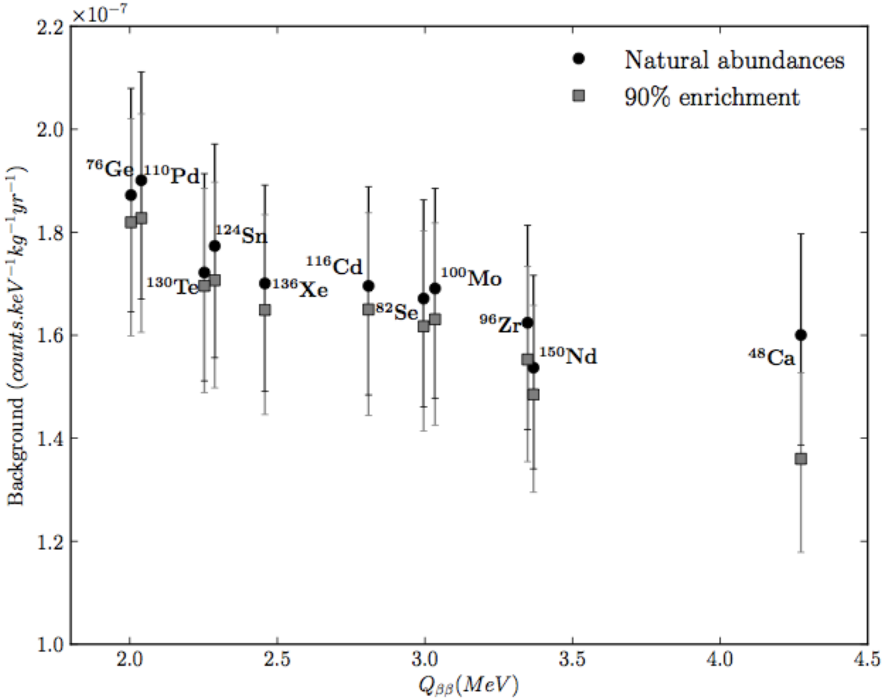
- New background components (f.e. solar neutrino-electron elastic scattering)

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

- More accurate matrix elements

HOW???

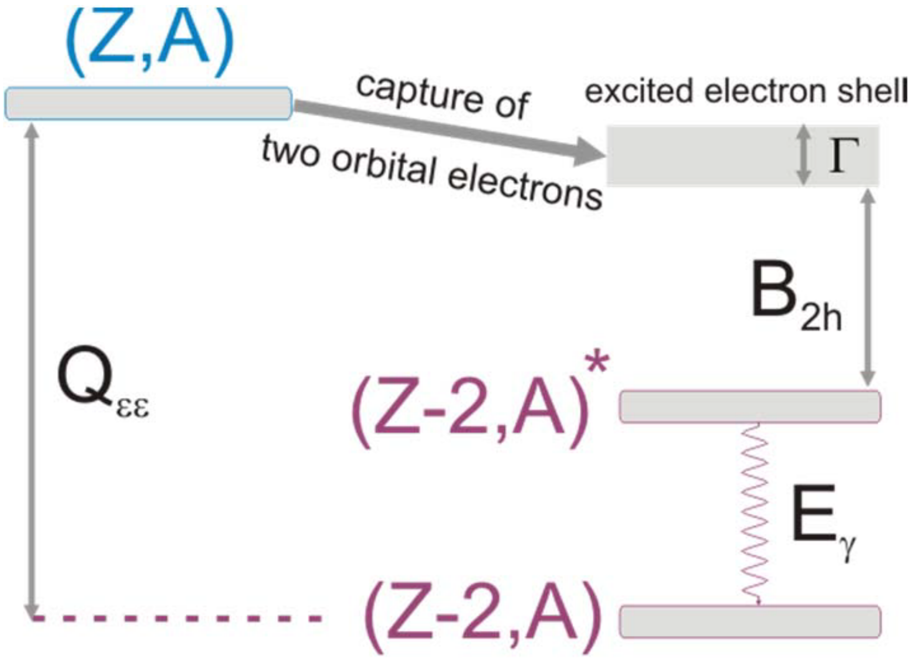
Experiments which work for IH might not work for NH



K. Zuber

Resonant double EC

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



K. Zuber

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

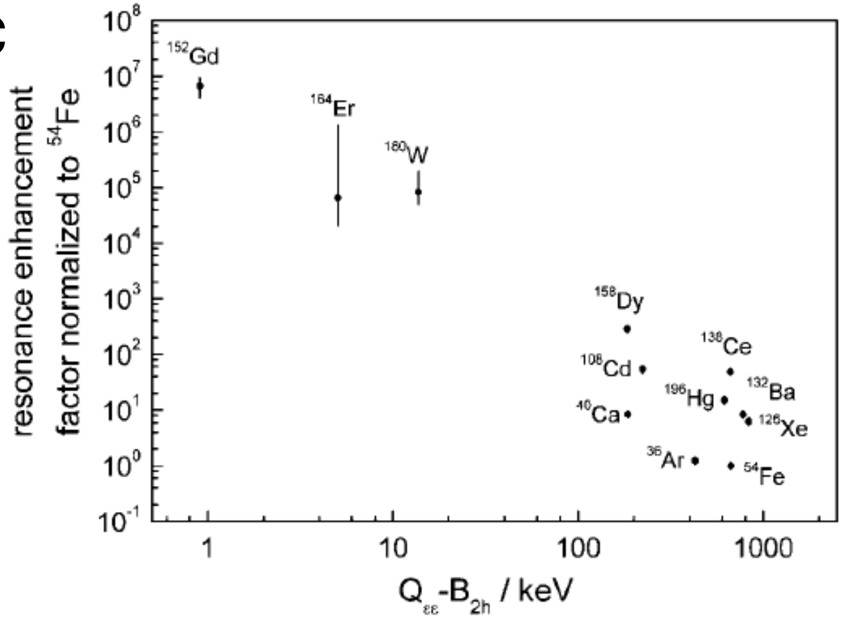
Enhanced if V+A is at work

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)

Conclusion

- **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!!!**