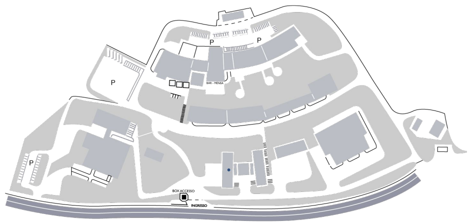
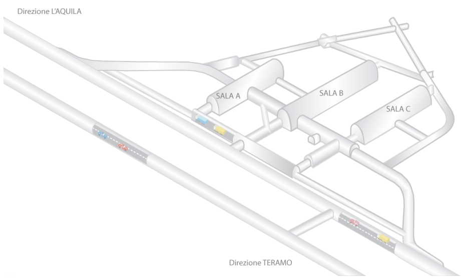
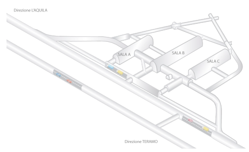




Double Beta Decay

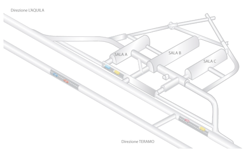
Ezio Previtali - LNGS

Outline



- Some aspects connected with neutrino physics
- Description of nuclear double beta decay
- 2 neutrinos and neutrinoless double beta decay
- Neutrinoless double beta decay mechanisms
- Nuclear matrix elements
- Experimental approaches and sensitivities
- Present experimental status and future perspective

What we know about neutrinos



What we know:

- neutrinos are massive fermions
- there are 3 active neutrino flavors (ν_α)
- neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator | Reactor / Accelerator | Solar / Reactor

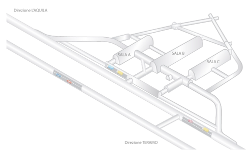
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Precision measurements of neutrino parameters: available and ongoing

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	[illegible]	[illegible]	[illegible]	[illegible]
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	$34.03^{+0.81}_{-0.77}$	$31.78 \to 36.56$
$\sin^2\theta_{23}$	$0.437^{+0.061}_{-0.031}$	$0.357 \to 0.654$	$0.436^{+0.047}_{-0.032}$	$0.356 \to 0.653$
$\theta_{23}/^\circ$	$41.4^{+3.5}_{-1.8}$	$36.7 \to 54.0$	$41.3^{+2.7}_{-1.8}$	$36.6 \to 53.9$
$\sin^2\theta_{13}$	$0.0231^{+0.0023}_{-0.0022}$	$0.0161 \to 0.0299$	$0.0252^{+0.0022}_{-0.0023}$	$0.0181 \to 0.0320$
$\theta_{13}/^\circ$	$8.75^{+0.42}_{-0.44}$	$7.29 \to 9.96$	$9.13^{+0.40}_{-0.42}$	$7.73 \to 10.31$
$\delta_{CP}/^\circ$	341^{+58}_{-46}	$0 \to 360$	345^{+77}_{-46}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.08$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.421^{+0.022}_{-0.023}$	$+2.248 \to +2.612$	$+2.429^{+0.029}_{-0.027}$	$+2.256 \to +2.635$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.063}$	$-2.603 \to -2.226$	$-2.422^{+0.061}_{-0.063}$	$-2.618 \to -2.239$

This is an interesting picture but still uncomplete

Questions on Neutrinos



- What is the absolute neutrino mass scale?
  Is the lightest ν massless?
  Hierarchical or degenerate?

- What is the neutrino mass ordering?
  Normal ($m_1 < m_2 \ll m_3$) or inverted ($m_3 \ll m_1 < m_2$)?

- Are neutrinos **Dirac or Majorana particles**?
  Lepton number violation, **neutrinoless double beta decays**,…..

- What is the origin of neutrino masses and flavor mixing?
  See saw mechanisms, flavor symmetries, ...

- Is there CP violation in the lepton sector?
  What is the value of the Dirac CP-violating phase δ?

This is a **crucial question** not only to neutrino properties but also on our knowledge on the **Standard Model of Particles Physics** and the **description of the Universe**

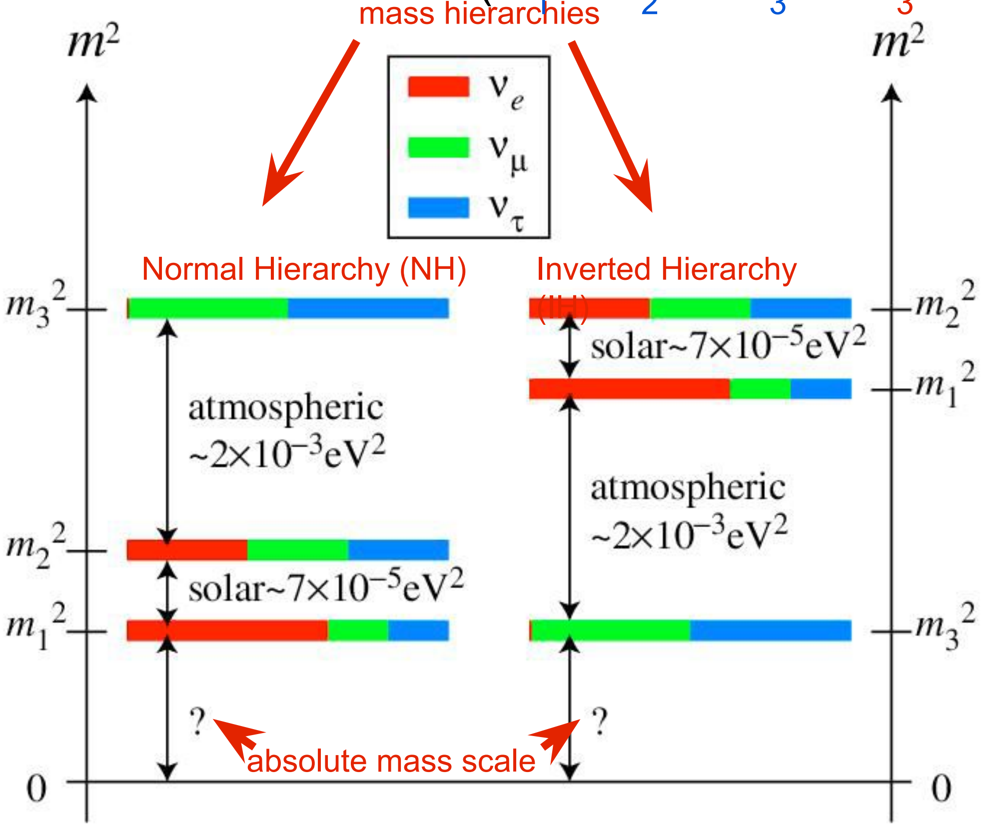
Neutrino Physics is an important test of the Standard Model of Particles Physics

Neutrino masses are strictly linked (directly or indirectly) to all the above questions

What we know on neutrino masses

Two main questions are directly related to neutrino masses:

- absolute mass scale: i.e. mass of the lightest ν
- degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses ($m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$)

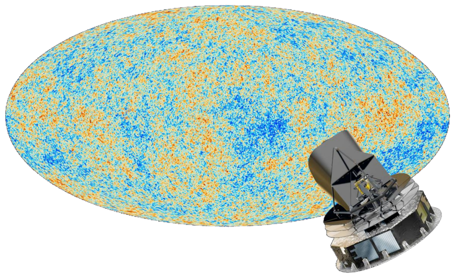


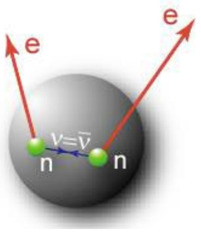
Neutrino oscillation experiments are blind to the first but can solve the second

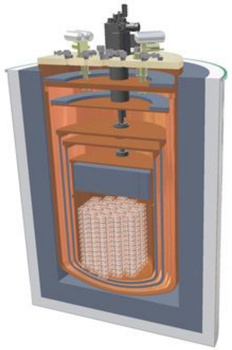
How we measure neutrino masses

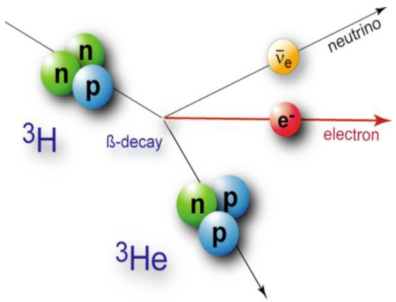
Three complementary approaches

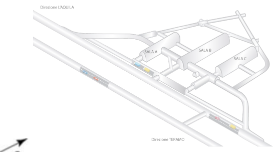
- Different sensitivities
- Related to different models
- Complementary pro and cons





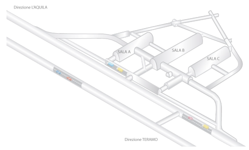






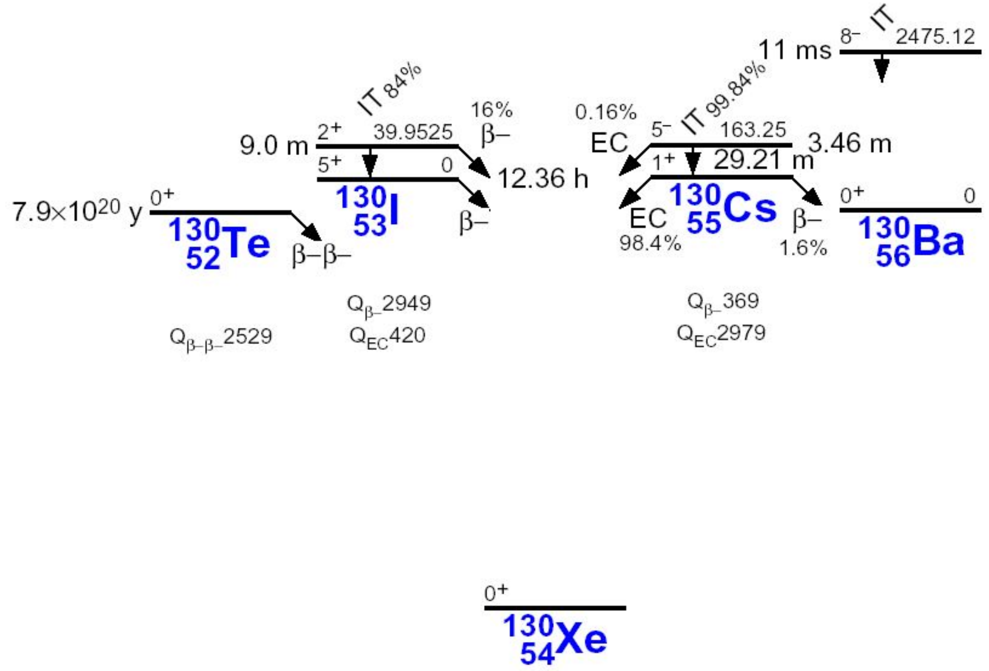
	Cosmology (CMB+LSS+...)	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu k}$	$m_{\beta\beta}=\|\Sigma_k m_{\nu k} U_{ek}^2\|$	$m_\beta=(\Sigma_k m_{\nu k}^2 \|U_{ek}\|^2)^{1/2}$
present sensitivity	≈ 0.1 eV	≈ 0.1 eV	0.7 eV
future sensitivity	0.01 eV	0.01 eV	0.2 eV
model dependency	↓ yes	↓ yes	↑ no
systematics	↓ large	yes	↓ large

Nuclear Double Beta Decay (DBD)

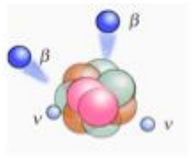


Very rare nuclear decay that occurs in **even-even nuclei**

$$(A,Z) \rightarrow (A,Z+2) + 2e^- \ (+X)$$



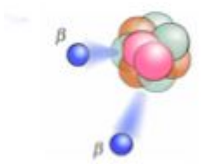
2νββ decay: X=2ν



- allowed within Standard model,
  - 2nd order process in Fermi theory
- observed for 12 isotopes:
  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128,130}Te, ^{136}Xe, ^{150}Nd and ^{238}U
- First double beta plus decay: ^{130}Ba

- $T^{2\nu\beta\beta} \sim 10^{(19-25)}$ y

0νββ decay (neutrinoless DBD): X=ø



→ violates lepton number by 2 units

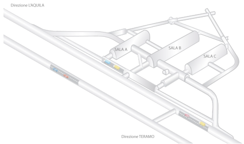
→ Current bounds:

- $T^{0\nu\beta\beta}_{1/2} > \sim 10^{25}$ y
- $m_\nu \leq O(\mathbf{0.1 - 0.5})$ eV

→ Observation implies Physics beyond the Standard Model

→ Favorite mechanism: virtual neutrino exchange

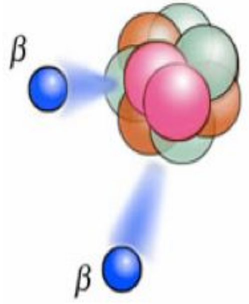
Neutrinoless DBD



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

Have very strong implications

- **Lepton Number** non conservation
- Beyond the Standard model of Particle Physics



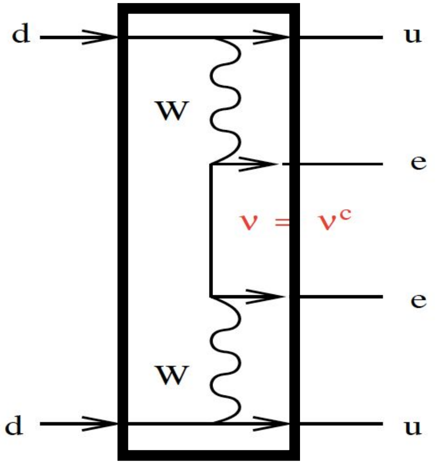
It can be considered as a black box diagram with only few constraints.
In principle any theory satisfying the constraints must be taken into account to fill the box.

It was originally proposed in the framework of the weak interactions (Furry 1939) as a possible mode of the nuclear double beta decay proceeding through the exchange of a virtual neutrino. Since then, it is considered as a unique tool to check

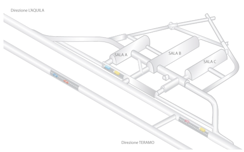
- **Majorana nature of the neutrino**

and can provide relevant information on

- Absolute ν **mass scale**
- Neutrino **mass hierarchy**
- **CP** violation in the leptonic sector



Such a mission has become particularly compelling after the evidence of neutrino oscillations.

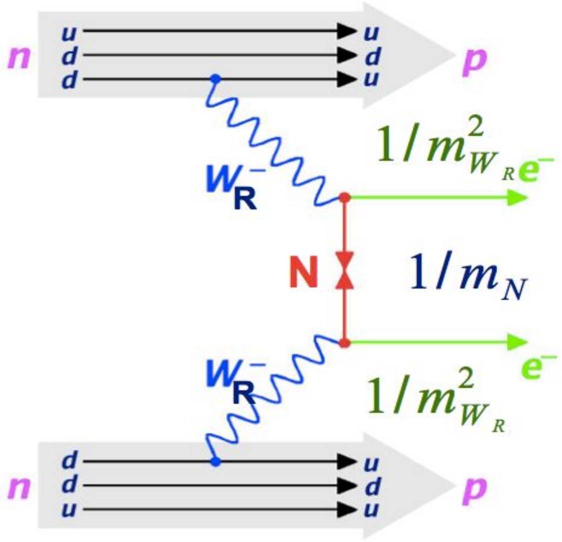


Neutrinoless DBD models??

- Many models beyond SM with lepton number violation can contribute!
- Constraints on the model parameters
  - Left-right symmetric models
  - R-parity violating ...
  - R-parity conserving supersymmetric models
  - [...]
  - Light neutrinos
- Nonstandard contributions when:
- Exchange of a massive neutrino
- Constraints on the model parameters:

One example: left-right symmetric model

$$M_{W_R} > 1.4\left(\frac{m_N}{[1TeV]}\right)^{-1/4} TeV$$

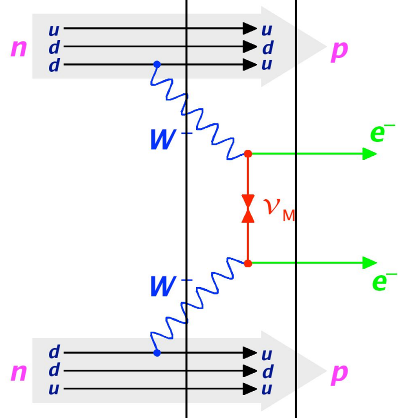


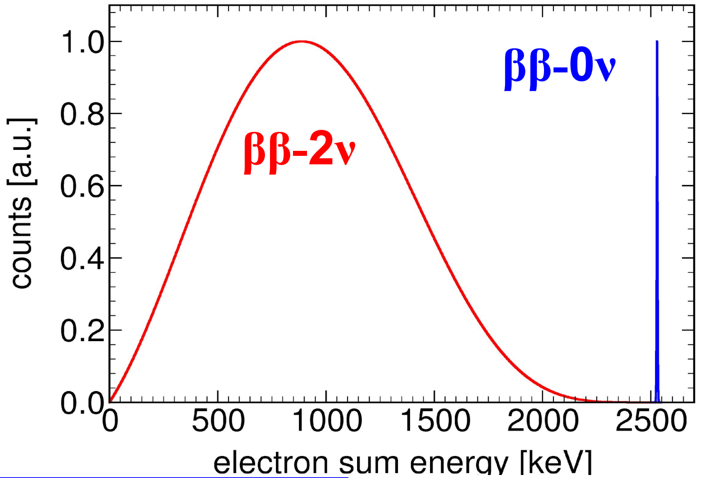
Neutrinoless DBD mass mechanism

Exchange of a light Majorana neutrino

RH antineutrino (L=1) is emitted at one vertex
LH neutrino (L=-1) is absorbed at the other vertex

- **Majorana particle**
- **Helicity flip (neutrino mass dependence)**





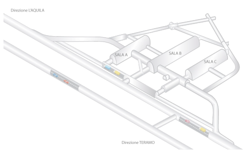
Phase space factor **Nuclear Matrix Element**

$$\tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_{ee}\rangle|^2 = F_N \cdot \frac{|\langle m_{ee}\rangle|^2}{m_e^2}$$

Effective Neutrino Mass **Nuclear Factor of Merit**

- Amplitude proportional to coherent sum ("effective mass"):
- Majorana phases imply that cancellations are possible

$$|m_{ee}| \equiv |\sum U_{ei}^2 m_i| = ||U_{e1}|^2 m_1| + ||U_{e2}|^2 m_2|e^{2i\alpha} + ||U_{e3}|^2 m_3|e^{2i\beta}$$



Phase Space Factor

- $G^{0\nu}$ accurate calculation for all ββ nuclei, it contains kinematics and atomic physics

$$G^{0\nu} \sim \int F(Z,E_{e1})F(Z,E_{e2})p_{e1}p_{e2}E_{e1}E_{e2}\,\delta(E_0-E_{e1}-E_{e2})dE_{e1}dE_{e2}$$

Primakoff Rosen
$$F(Z,E) = \frac{E}{p}\,\frac{2\pi Z\alpha}{1-e^{-2\pi Z\alpha}}$$

$$G^{0\nu}_{PR} \sim \left(\frac{E_0^5}{30} - \frac{2E_0^2}{3} + E_0 - \frac{2}{5}\right)$$

PHYSICAL REVIEW C **85**, 034316 (2012)

Phase-space factors for double-β decay

J. Kotila* and F. Iachello†
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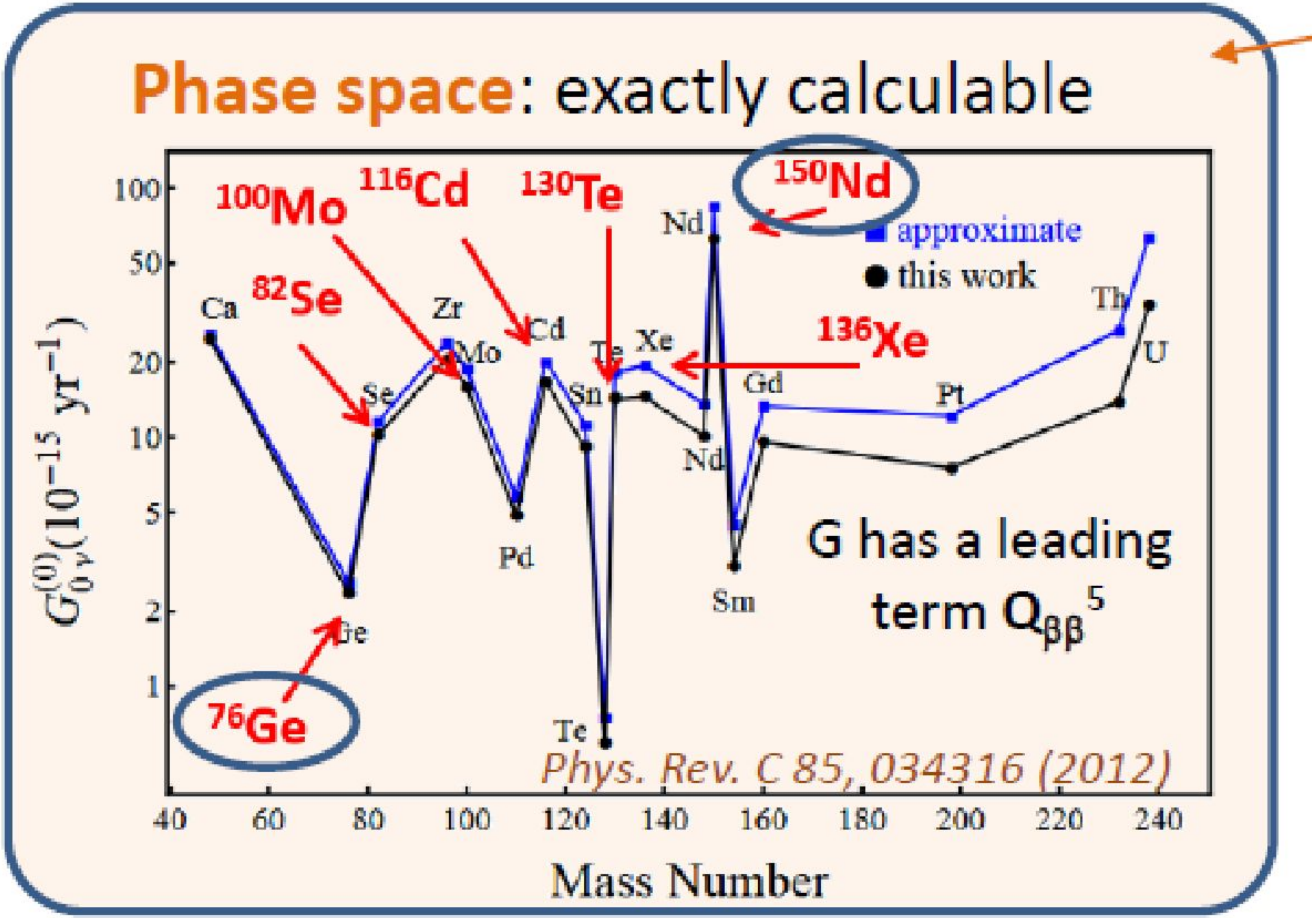
(Received 9 November 2011; revised manuscript received 24 February 2012; published 19 March 2012)

A complete and improved calculation of phase-space factors for $2\nu\beta\beta$ and $0\nu\beta\beta$ decay is presented. The calculation makes use of exact Dirac wave functions with finite nuclear size and electron screening and includes lifetimes, single and summed electron spectra, and angular electron correlations.

DOI: 10.1103/PhysRevC.85.034316 PACS number(s): 23.40.Hc, 23.40.Bw, 14.60.Pq, 14.60.St

Phase Space Factor



The Phase Space Factors were completed calculated for all the DBD nuclei

Differences between various authors impact in a negligible amount on the decay amplitude

Higher transition DBD energy will be translated in a favorable Phase Space and consequently in a high Phase Space Factor

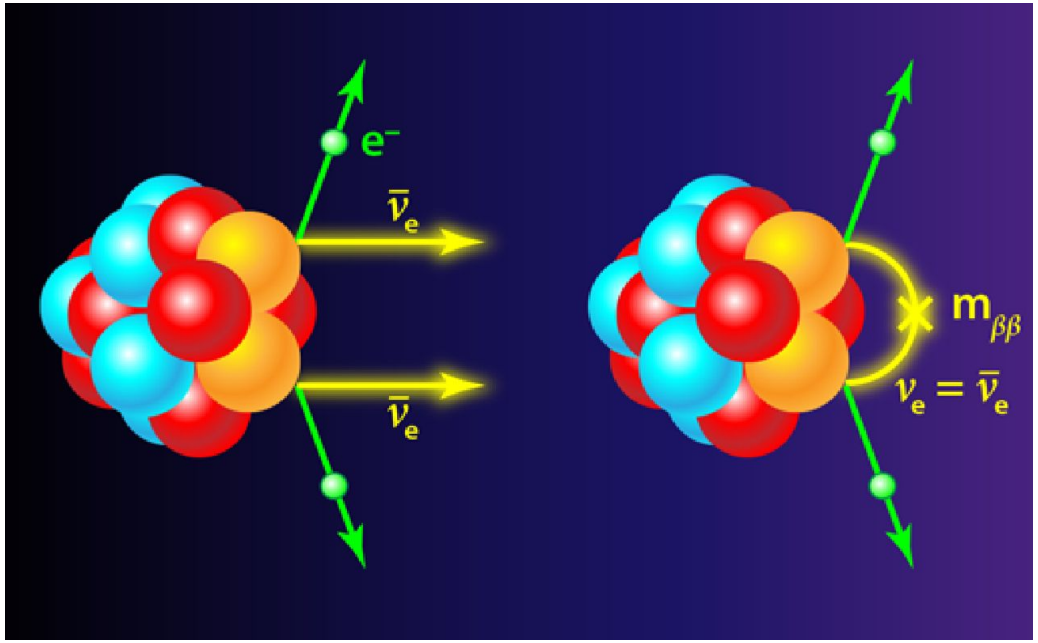
Nuclear Matrix Elements

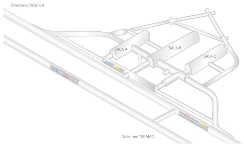
Nuclear matrix elements needed in low-energy new physics searches

$$\langle \text{Final} \,|\mathcal{L}_{\text{leptons}-\text{nucleons}}|\, \text{Initial} \rangle = \langle \text{Final} \,|\int dx\, j^{\mu}(x) J_{\mu}(x) \,|\, \text{Initial} \rangle$$

- Nuclear structure calculation of the initial and final states: Shell model, QRPA, IBM, Energy-density functional Ab initio many-body theory GFMC, Coupled-cluster, IMSRG...

- Lepton-nucleus interaction: Hadronic current in nucleus: phenomenological, effective theory of QCD





Nuclear Matrix Element Models

Density Functional Theory & Related Techniques: Mean-field-like theory plus relatively simple (e.g. RPA or GCM) corrections in very large single-particle space with phenomenological interaction.

Shell Model: Partly phenomenological interaction in a small valence single-particle space — a few orbitals near nuclear Fermi surface — but with arbitrarily complex correlations.

Interacting Boson Model: Truncation of shell model to collective pairs followed by replacement of pairs by bosons, with phenomenological boson interaction.

Ab Initio Calculations: Start from a well justified two-nucleon + three-nucleon Hamiltonian, then solve full many-body Schr¨odinger equation to good accuracy in space large enough to include all important correlations. At present, works pretty well in with A up to about 50.

Nuclear Matrix Element Calculations

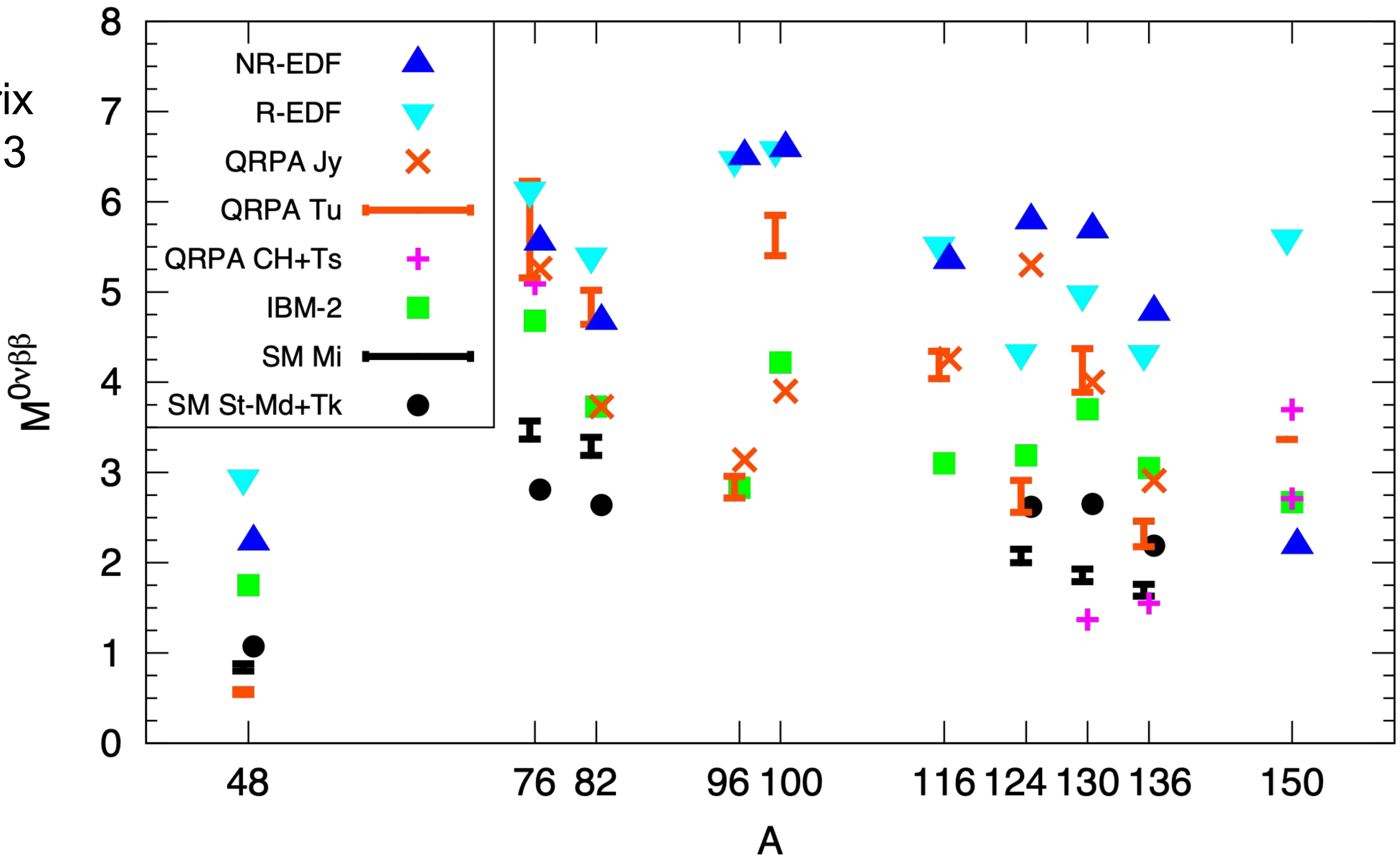
Large difference in nuclear matrix element calculations: factor 2 - 3

EDF: large NMEs

QRPA: wider range

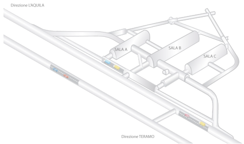
NSM: small NMEs

IMSRG ab initio
48Ca NME: quite small



Jonathan Engel and Javier Menéndez 2017 *Rep. Prog. Phys.* **80** 046301

Axial vector coupling constant



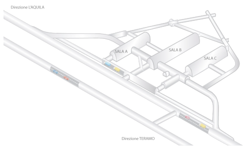
$$\tau^{-1} = G_{0\nu} \cdot (g_a{}^4 \cdot |M_{GT}{}^{0\nu}|^2 - g_v{}^4 \cdot |M_F{}^{0\nu}|^2) \cdot |\langle m_{ee}\rangle|^2$$

After discussing the level of (relative) agreement between the different nuclear matrix elements, one should consider their (absolute) agreement with experiments. This is the realm of **the renormalization of the axial vector coupling constant g_A in nuclei.** (g_A = 1.269 for free nucleon)

Theory deficiencies in M_{GT} fixed adjusting gA ("queching")

- A well-known problem for single β decay where $g_{A,eff} \sim 0.7\ g_A$
- A crucial problem for extraction of the neutrino mass.
- g_A appears to the fourth power in the half-life!

g_A renormalization



Origin of the renormalization:

- Limited model space (limiting factor is the size of the matrices (>109))
- Missing hadronic degrees of freedom, Δ,… (incomplete knowledge of the decay process)

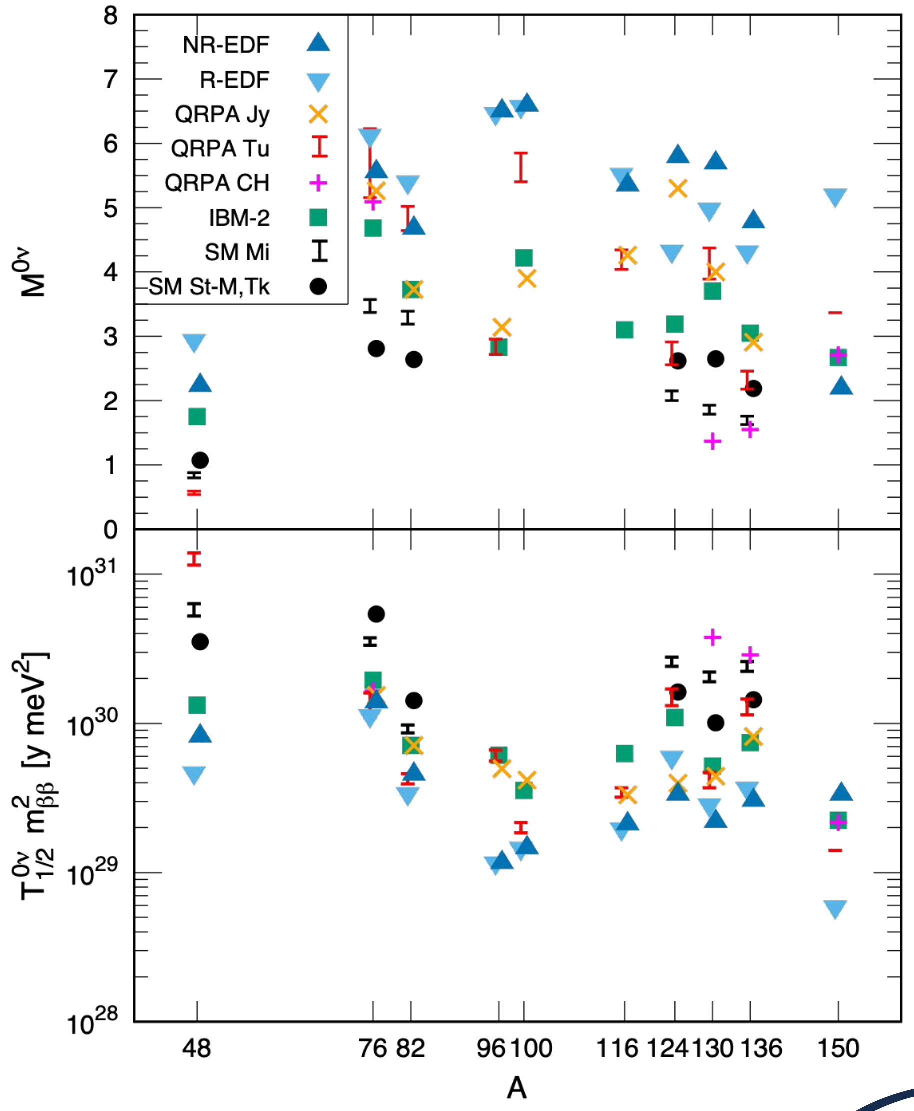
It appears in different nuclear processes

- Beta-
- Beta+
- EC
- but specially 2νββ
  depending on the NME
    - IBM-2 0.6-0.5
    - QRPA 0.7-0.6
    - NSM 0.8-0.7

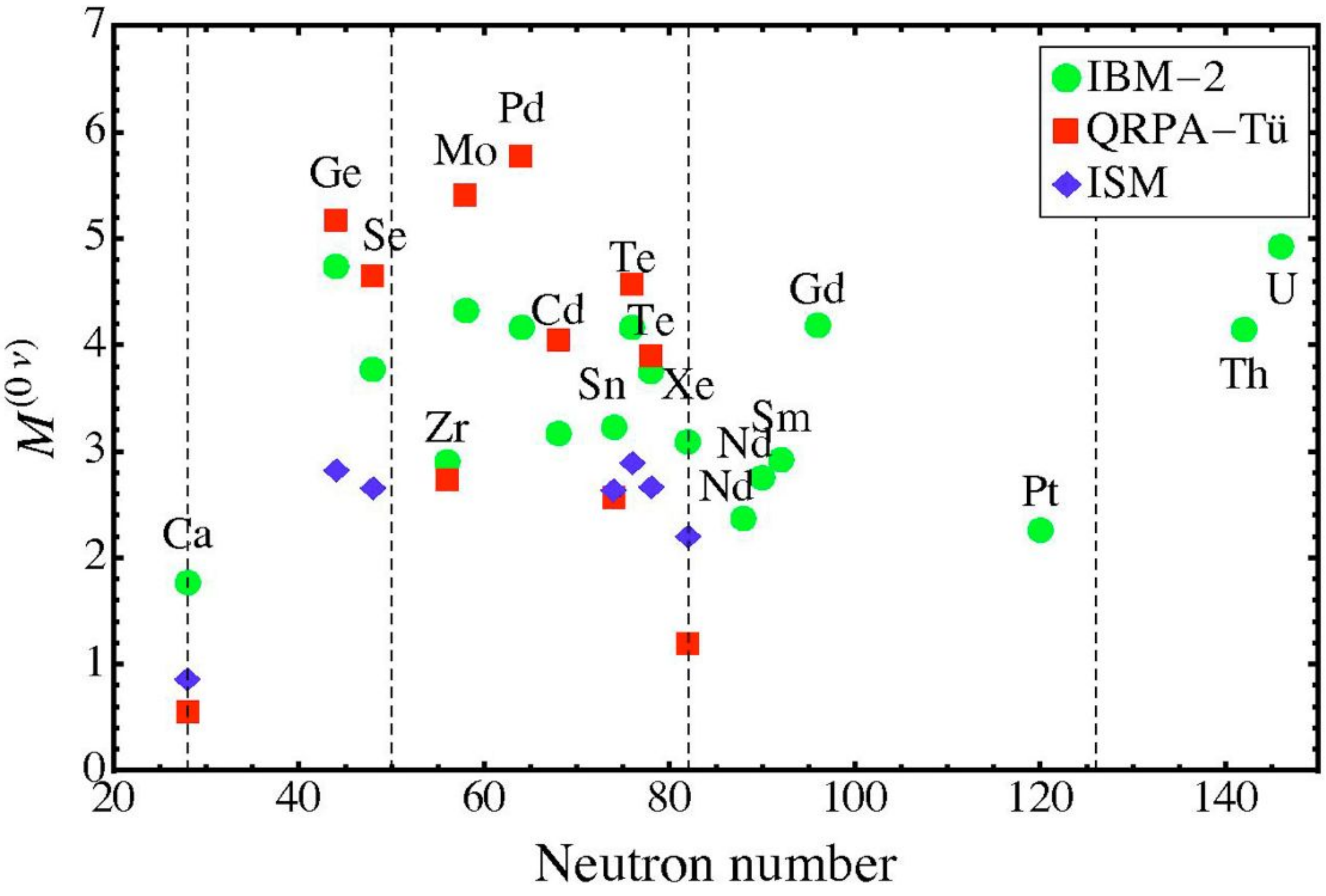
The question is: will this be also the case for 0νββ???

Nuclear Matrix Element Calculations

- Nuclear matrix elements ($M^{0\nu}$) for $0\nu\beta\beta$ decay candidates as a function of mass number A.
- All the plotted results are obtained with the assumption that the axial coupling constant g_A (~1.27) is unquenched and are from different nuclear models.
- QRPA error bars result from the use of two realistic nuclear interactions, while shell model error bars result from the use of several different treatments of short-range correlations



Nuclear Matrix Element Summary



IBM-2*: J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 91, 034304 (2015).

QRPA-Tu *: F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C 87, 045501 (2013).

ISM: J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009).

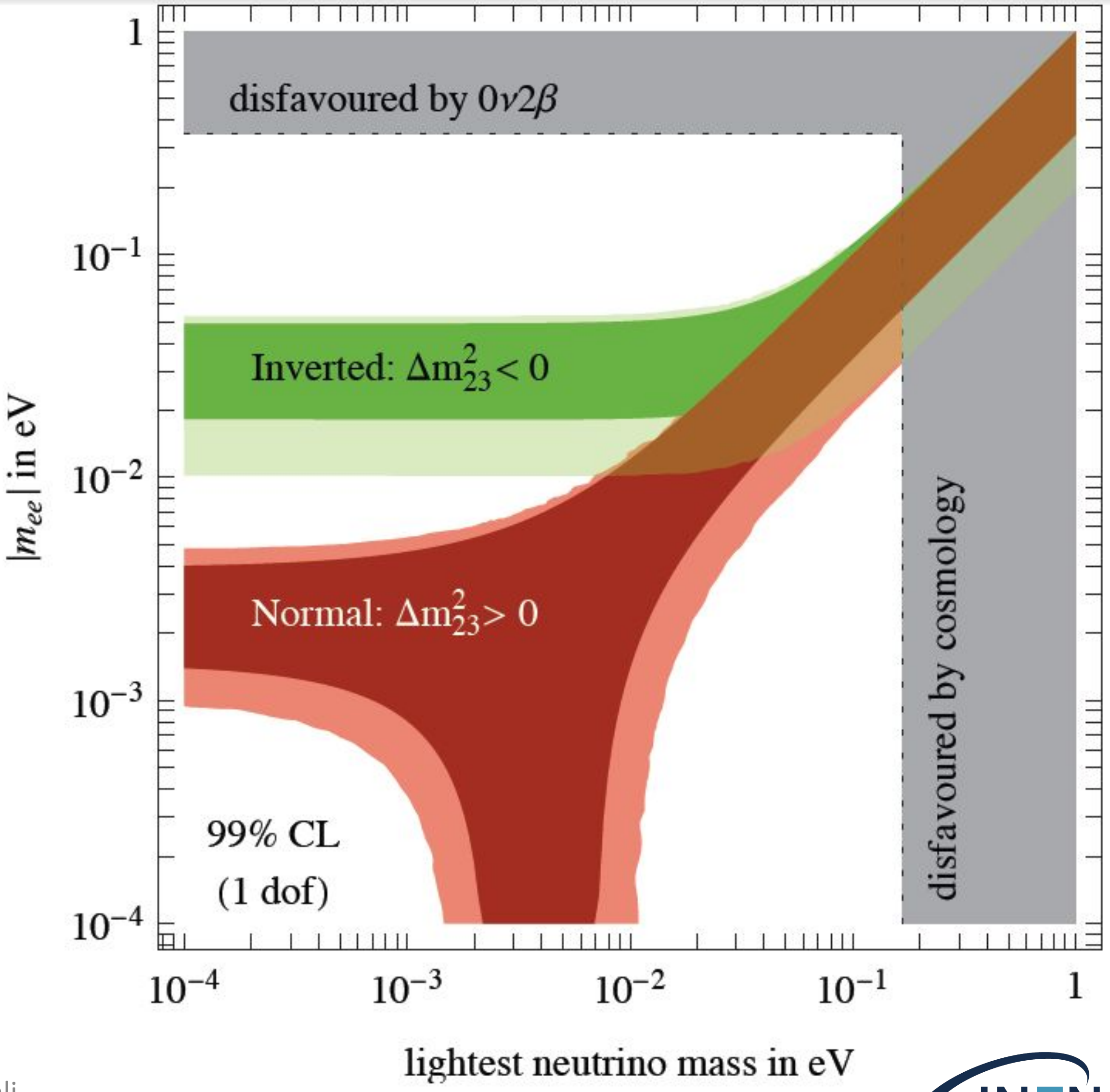
NL-DBD and neutrino oscillations

Thanks to the information from oscillations m_{ee} can be expressed in terms of three unknown quantities:

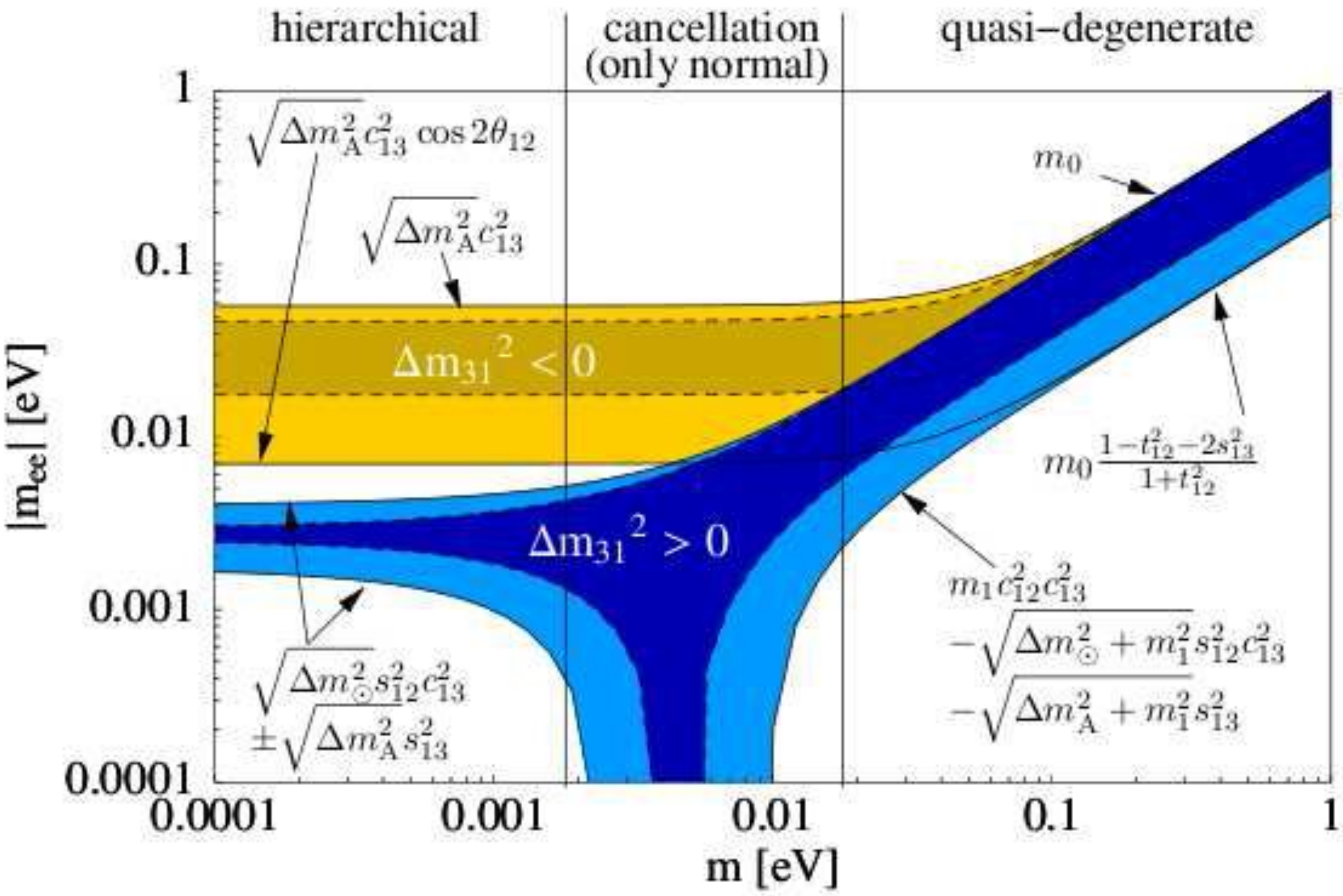
- the mass scale, represented by the mass of the lightest neutrino $\mathbf{m_{min}}$
- the two Majorana phases.

It is then common to distinguish three mass patterns:

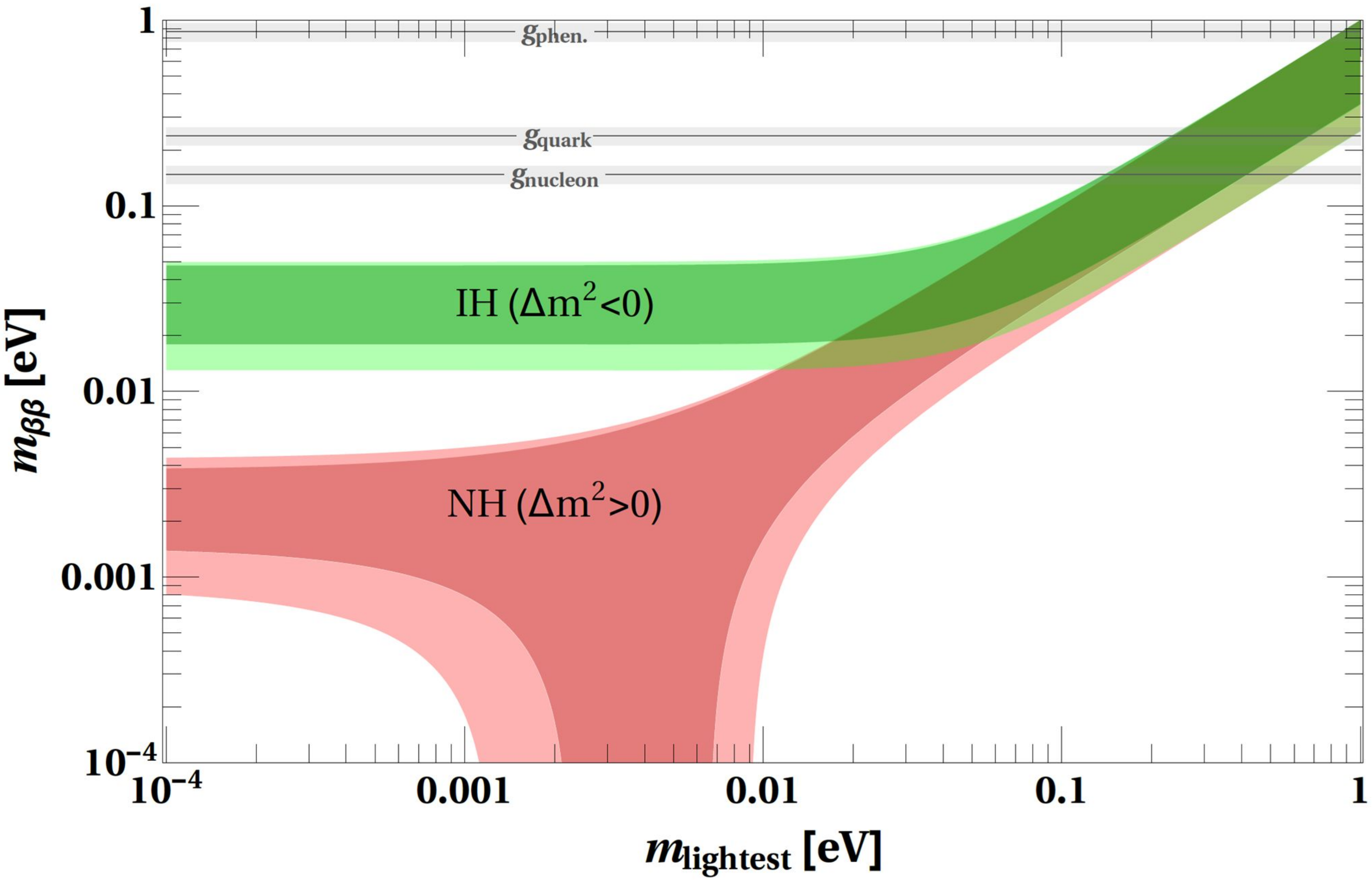
- **normal hierarchy (NH)**, where $\mathbf{m_1 < m_2 < m_3}$
- **inverted hierarchy (IH)** where $\mathbf{m_3 < m_1 < m_2}$
- **quasi-degenerate pattern (QD)**, where the differences between the masses are small with respect to their absolute values



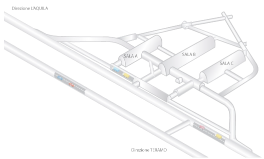
NL-DBD and neutrino oscillations



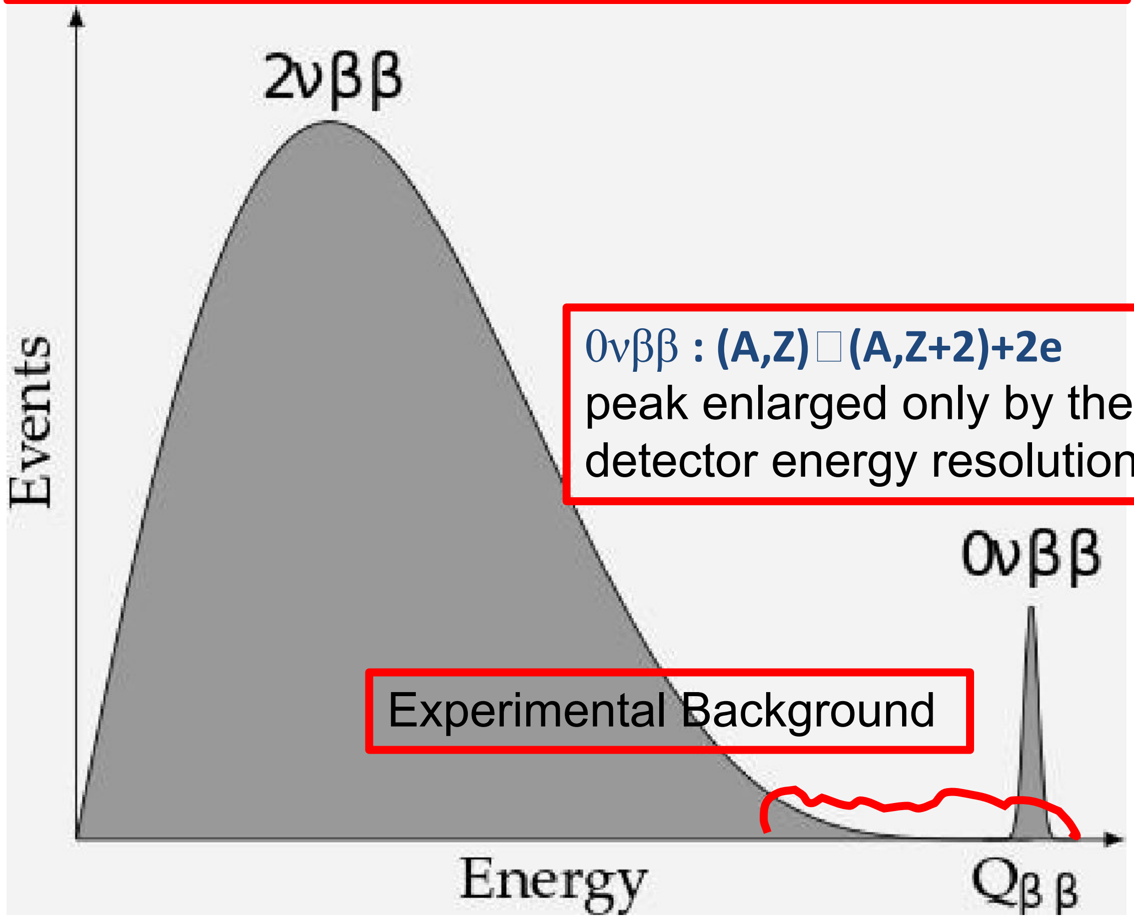
NL-DBD and g_A renormalization



Neutrinoless DBD Experimental Signature



2νββ : **(A,Z)□(A,Z+2)+2e+2ν**
continuum spectrum with maximum at about 1/3 Q



0νββ : **(A,Z)□(A,Z+2)+2e**
peak enlarged only by the detector energy resolution

Experimentally a peak will be produced by the sum of **the energy acquired by two electrons** in the decay

Two neutrinos decay and experimental background could **interfere** with the peak identification

Additional signatures:

- Single electron energy spectrum
- Angular correlation between the two electrons
- Daughter nuclear species
- Track and event topology
- Time Of Flight

Moreover, to study NME systematics:

- measure as many as possible different isotopes

INFN LNGS

Experimental Sensitivity

with no ββ-0ν decay observed

$N_{\beta\beta} \leq (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{1/2}$ at 1σ

$\tau_{1/2}^{0\nu}$ sensitivity

$$S(\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M\, t_{meas}}{\Delta E \cdot bkg}}$$

measuring time [y]

detector mass [kg]

detector efficiency

isotopic abundance
atomic number

energy resolution [keV]

background [c/keV/y/kg]

We need very massive detectors (1 ton scale)

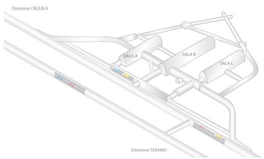
We need high isotopic abundaces

We need very low radioactive background

We need high energy resolution detectors (critical also for background)

If bkg = 0 □ $S_{1/2}^{0\nu} \propto \epsilon \frac{i.a.}{A} M \cdot t_{meas}$

DBD Nuclei



$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
^{46}Ca→^{46}Ti	987 ±4	0.0035	8.71E21	7.16E26
^{48}Ca→^{48}Ti^a	4271 ±4	0.187	2.52E16	4.10E24
^{70}Zn→^{70}Ge	1001 ±3	0.62	3.17E21	4.27E26
^{76}Ge→^{76}Se	2039.6±0.9	7.8	7.66E18	4.09E25
^{80}Se→^{80}Kr	130 ±9	49.8	8.20E27	2.34E28
^{82}Se→^{82}Kr	2995 ±6	9.2	2.30E17	9.27E24
^{86}Kr→^{86}Sr	1256 ±5	17.3	3.00E20	1.57E26
^{94}Zr→^{94}Mo	1145.3±2.5	17.4	4.34E20	1.57E26
^{96}Zr→^{96}Mo^a	3350 ±3	2.8	5.19E16	4.46E24
^{98}Mo→^{98}Ru	112 ±7	24.1	1.03E28	1.49E28
^{100}Mo→^{100}Ru	3034 ±6	9.6	1.06E17	5.70E24
^{104}Ru→^{104}Pd	1299 ±2	18.7	1.09E20	8.32E25
^{110}Pd→^{110}Cd	2013 ±19	11.8	2.51E18	1.86E25
^{114}Cd→^{114}Sn	534 ±4	28.7	6.93E22	6.10E26
^{116}Cd→^{116}Sn	2802 ±4	7.5	1.25E17	5.28E24
^{122}Sn→^{122}Te	364 ±4	4.56	9.55E23	1.16E27
^{124}Sn→^{124}Te	2288.1±1.6	5.64	5.93E17	9.48E24
^{128}Te→^{128}Xe	868 ±4	31.7	1.18E21	1.43E26
^{130}Te→^{130}Xe	2533 ±4	34.5	2.08E17	5.89E24
^{134}Xe→^{134}Ba	847 ±10	10.4	1.16E21	1.30E26
^{136}Xe→^{136}Ba	2479 ±8	8.9	2.07E17	5.52E24
^{142}Ce→^{142}Nd	1417.6±2.5	11.1	1.38E19	2.31E25
^{146}Nd→^{146}Sm^b	56 ±5	17.2	2.06E29	7.05E27
^{148}Nd→^{148}Sm^b	1928.3±1.9	5.7	9.35E17	7.84E24
^{150}Nd→^{150}Sm	3367.1±2.2	5.6	8.41E15	1.25E24
^{154}Sm→^{154}Gd	1251.9±1.5	22.6	2.44E19	2.38E25
^{160}Gd→^{160}Dy	1729.5±1.4	21.8	1.51E18	7.99E24
^{170}Er→^{170}Yb	653.9±1.6	14.9	1.82E21	6.92E25

$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
^{176}Yb→^{176}Hf	1078.8±2.7	12.6	3.26E19	1.75E25
^{186}W→^{186}Os^b	490.3±2.2	28.6	7.68E21	6.95E25
^{192}Os→^{192}Pt	417 ±4	41.0	1.98E22	7.70E25
^{198}Pt→^{198}Hg	1048 ±4	7.2	1.63E19	8.74E24
^{204}Hg→^{204}Pb	416.5±1.1	6.9	1.23E22	5.06E25
^{232}Th→^{232}U^b	858.2±6	100	1.68E19	3.97E24
^{238}U→^{238}Pu^b	1145.8±1.7	99.27	1.47E18	1.68E24
$\beta^+\beta^+$ candidates	**T_0 (keV)**	**Abundance (%)**	**$(G^{2\nu})^{-1}$ (y)**	**$(G^{0\nu})^{-1}$ (y)**
^{78}Kr→^{78}Se	838	0.35	2.56E24	1.8E29
^{96}Ru→^{96}Mo	676	5.5	3.34E25	8.8E29
^{106}Cd→^{106}Pd	738	1.25	1.69E25	7.4E29
^{124}Xe→^{124}Te	822	0.10	7.57E24	5.9E29
^{130}Ba→^{130}Xe	534	0.11	6.92E26	6.4E30
^{136}Ce→^{136}Ba	362	0.19	5.15E28	6.1E31

EX signifies 10^x

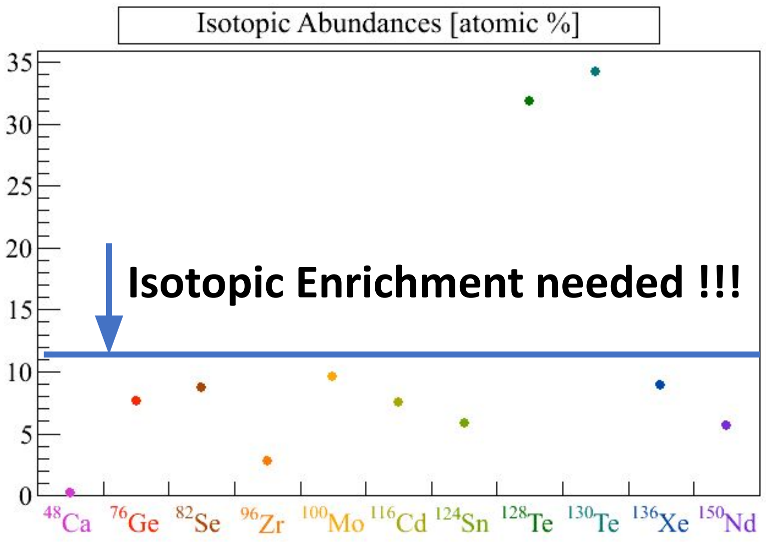
^{a} The single beta decay is kinematically allowed.

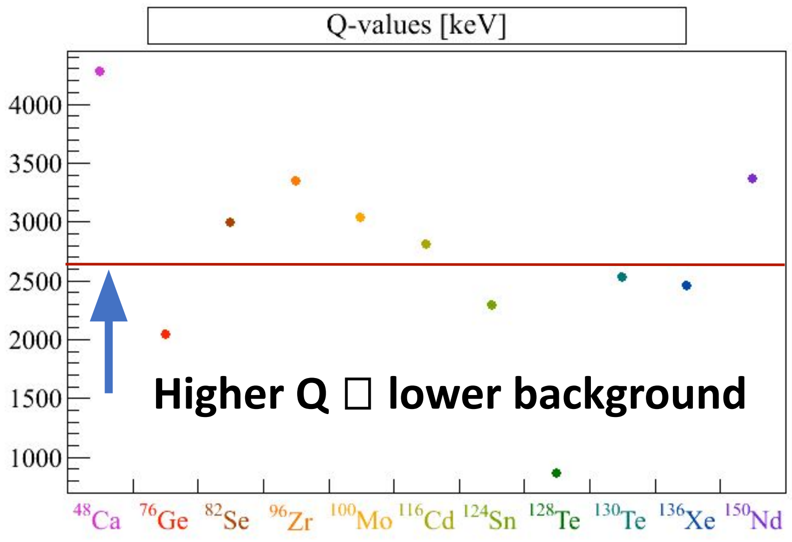
^{b} The daughter nucleus is unstable against alpha decay.

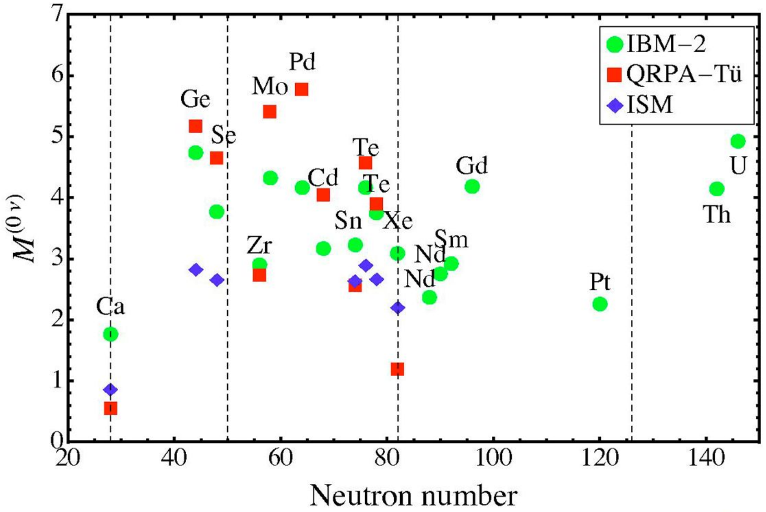
Many DBD Nuclei
We must select some
What are the best ones?

Some experimental aspects must be considered

DBD Nuclei selection



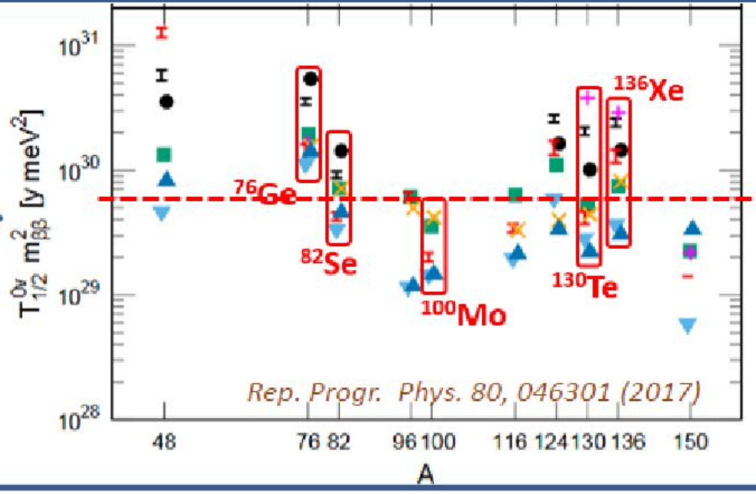




0νββ rate

The 0νββ community still assumes $g_A \approx 1.27$ (no quenching) with «traditional models» for M_{nucl}

This point should be revised in the future, after an expected maturation of ab initio calculations



$$T_{1/2}^{0\nu} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \mathrm{y}$$

Working formula for general experiment design