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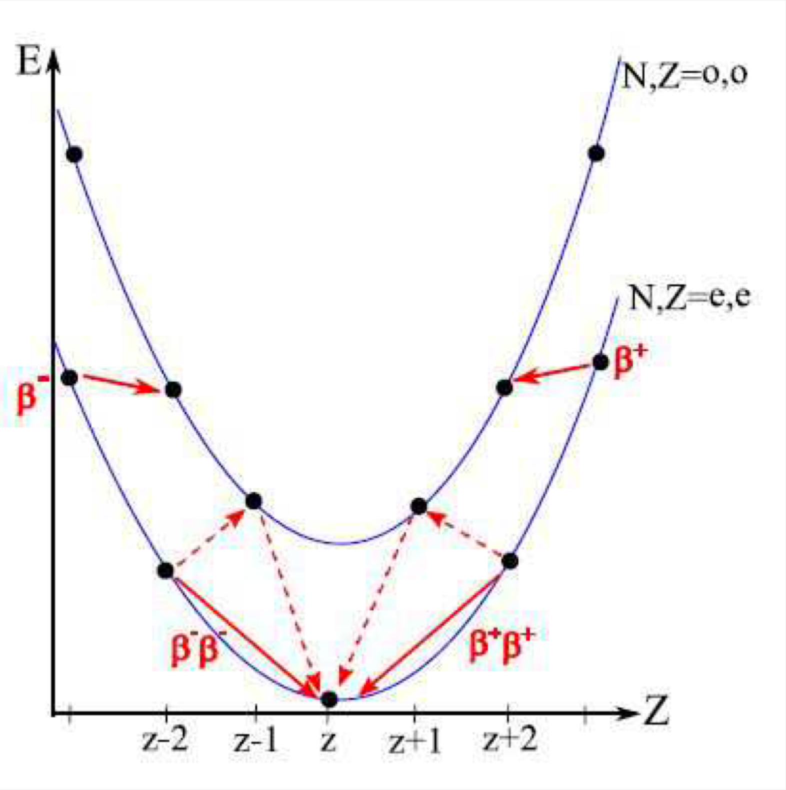
Double beta decay and the quest for Majorana neutrinos

Jenni Kotila

Women in Nuclear and Hadron Theoretical Physics: the last frontier - WTPLF 2018

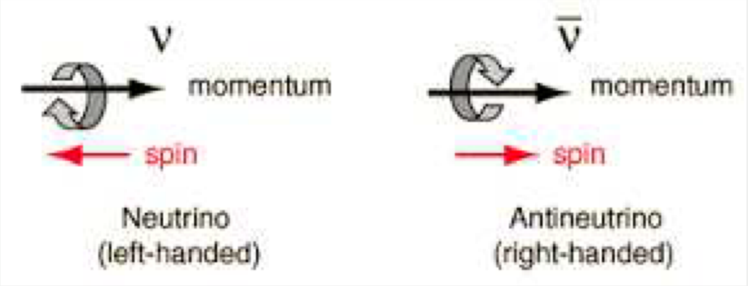
History

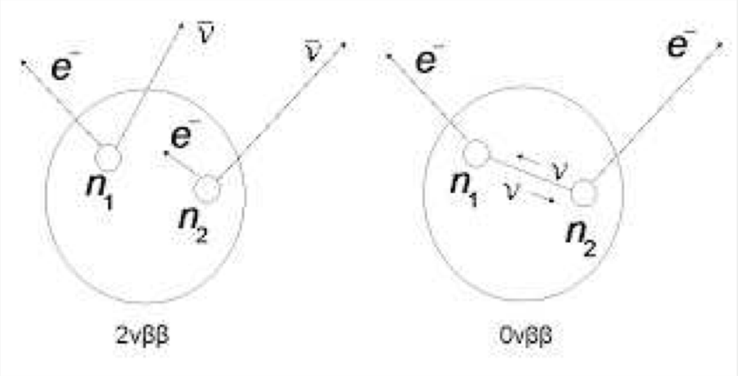
- 1930's: The idea of double beta decay was suggested by Eugene Paul Wigner as a second-order weak transition between isobars differing by two units in atomic number
- 1935: Assuming the emission of two electrons and two neutrinos Maria Goeppert-Mayer made the first theoretical estimate of the extremely low rates for this process $\tau^{1/2} > 10^{20}$yr



History

- 1937: Ettore Majorana demonstrated that all results of beta decay theory remain unchanged if neutrino is its own antiparticle (Majorana particle)
- 1939: Wendell H. Furry proposed that if neutrinos are, indeed, Majorana particles, then double beta decay could proceed without the emission of any neutrinos ($0\nu\beta\beta$)
- In 1940's the predicted half-lives of were of the order of 10^{15-16} years, and $0\nu\beta\beta$ was thought to be more likely to occur than $2\nu\beta\beta$





History

- 1948: Edward L. Fireman made an attempt to measure the $\beta\beta$-decay half-life of ^{124}Sn with Geiger counter, without success ($\tau_{1/2}^{2\nu\beta\beta}$ >3 x 10^{15}yr).
- 1950: $\beta\beta$-decay half-life of 1.4x10^{21}yr for ^{130}Te was measured by geochemical methods.
- 1956: Parity violation in weak interactions was established and it became clear that $2\nu\beta\beta$-decay would be much more likely to occur than $0\nu\beta\beta$-decay.
- 1987: First observation of $2\nu\beta\beta$-decay in laboratory by Elliott, Hahn, and Moe: $\tau_{1/2}^{2\nu\beta\beta}$ (^{82}Se)=$1.1^{+0.8}_{-0.3}$ x 10^{20}yr.
- Since then $2\nu\beta\beta$-decay has been observed in laboratory in 10 different nuclei, and in several different experiments, with half-lives of 10^{18-22}yr.
- 2001: A sub-group of the Heidelberg-Moscow experiment claimed first evidence for $0\nu\beta\beta$-decay. This, however, remains unconfirmed.

And now…

- $0\nu\beta\beta$-decay remains unobserved and continues to intrigue both theorists and experimentalists
- It has unique potential for neutrino physics, beyond Standard Model physics, and the understanding of matter-antimatter asymmetry of the universe.
- It remains the most sensitive probe to test lepton number and to answer the following open questions:
  - What is the absolute neutrino mass scale?
  - Are neutrinos Dirac or Majorana particles?
  - How many neutrino species are there?
- At the moment experiments are reporting lower half-life limits of the order of 10^{25}yr

Theoretical aspects

- From theoretical side it *seems* that there are only few pieces to figure out:

$2\nu\beta\beta$:

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{2\nu} g_A^4 |M^{(2\nu)}|^2$$

$0\nu\beta\beta$:

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 |M^{(0\nu)}|^2 |f(m_i, U_{ei})|^2$$

$0\nu ECEC$|:

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M^{0\nu}\right|^2 |f(m_i, U_{ei})|^2 \frac{(m_e c^2)\Gamma}{\Delta^2 + \Gamma^2/4}$$

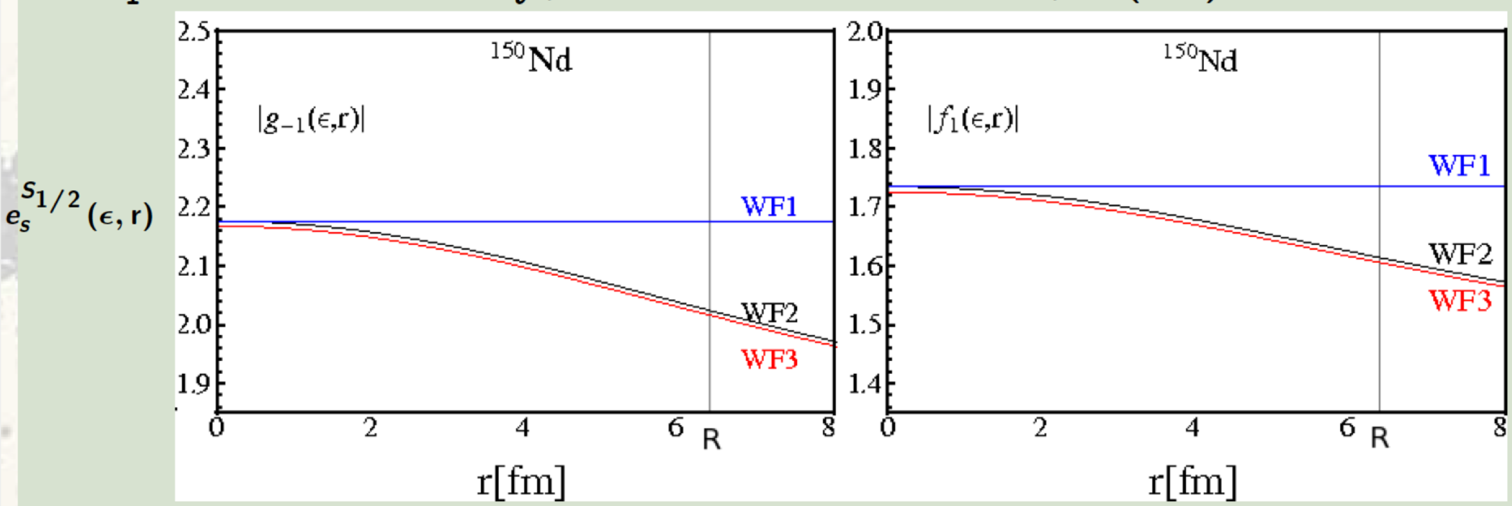
Theoretical aspects

- **G** is the phase space factor which varies depending on the decaying nucleus, Q-value of the decay, as well as the mode, scenario, and mechanism of the decay
- **M** is the nuclear matrix element which is calculated using chosen theoretical model. The model gives the wave functions of the initial and final states, and they are connected by proper transition operator, that varies depending on the mode, scenario, and mechanism of the decay
- $\mathbf{g_A}$ is the axial vector coupling constant, which effective value is essentially model dependent
- $\mathbf{f(m_i,U_{ei})}$ contains the physics beyond standard model and is different for different scenarios and mechanisms: exchange of light or heavy neutrino, emission of Majoron, exchange of sterile neutrino(s)...

Phase space factor G

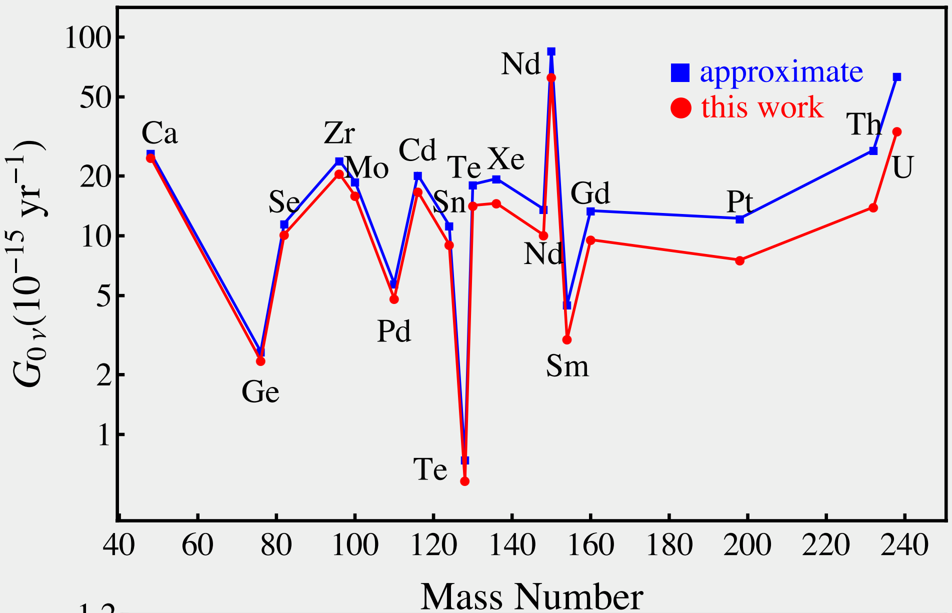
- The key ingredient for the evaluation of phase space factors are the electron wave functions
- To simulate realistic situation, we take radial functions that satisfy Dirac equation and potential that takes into account the finite nuclear size and the electron screening
- Comparison with previous calculations:

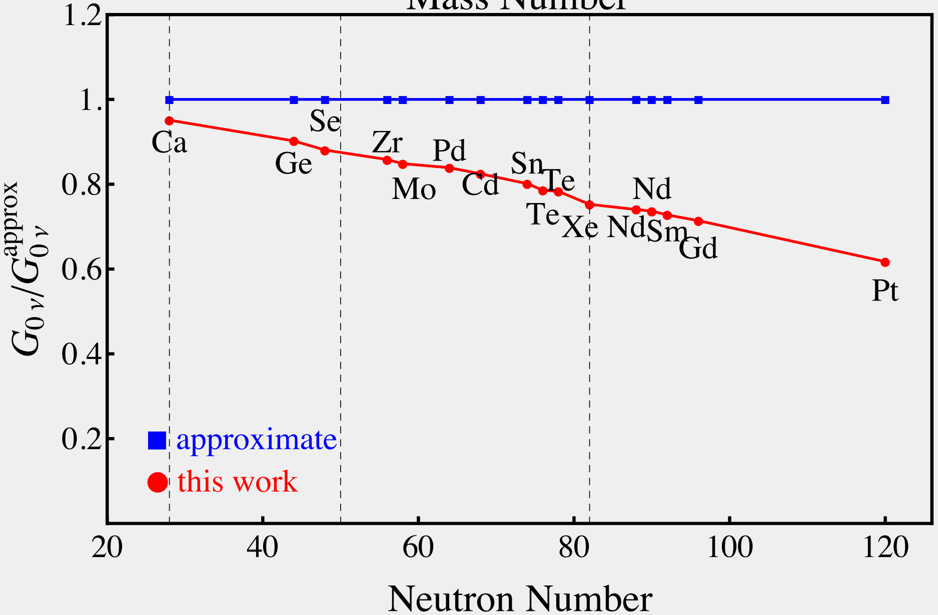
Example: ^{150}Nd decay, $Z_d = 62$ at $\epsilon = 2.0$MeV, $R(150) = 6.38$fm



WF1 = Leading finite size Coulomb (previous studies)
WF2 = Exact finite size Coulomb
WF3 = Exact finite size Coulomb & el. screening

Phase space factor G





- Current $0\nu\beta^-\beta^-$ PSFs (PRC 85, 034316, 2012) (red) compared to previous calculations (blue)
- Our results have been confirmed by independent calculations of Stoica et al. (PRC 88, 037303, 2013)

- Relative difference: $G_{0\nu}/G_{0\nu}^{\mathrm{approx}}$

- Estimate of uncertainties
  - Q-value 3 x $\delta Q/Q$
  - $R = r_0A^{1/3}$ 7%
  - Screening 0.10%

Nuclear matrix element M

- NMEs are calculated in nuclear models, such as the quasiparticle random phase approximation, **QRPA**, the interacting shell model, **ISM**, energy density functional theory, **EDF** and the microscopic interacting boson model, **IBM-2**
  - IBM-2: Can be used in any nucleus and thus all nuclei of interest can be calculated within the same model making it easier to recognize model dependent uncertainties.
- The fact that $0\nu\beta\beta$ -decay is a unique process, and there is no direct probe which connects the initial and final states other than the process itself makes the prediction challenging for theoretical models.
- The reliability of the used wave functions, and eventually $M^{(0\nu)}$, has to be then tested using other available relevant data.

PRL 108, 062502 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

Q Value and Half-Lives for the Double-β-Decay Nuclide ^{110}Pd

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The ^{110}Pd double-β decay Q value was measured with the Penning-trap mass spectrometer ISOLTRAP to be $Q = 2017.85(64)$ keV. This value shifted by 14 keV compared with the literature value and is 17 times more precise, resulting in new phase-space factors for the two-neutrino and neutrinoless decay modes. In addition a new set of the relevant matrix elements has been calculated. The expected half-life of the two-neutrino mode was reevaluated as $1.5(6) \times 10^{20}$ yr. With its high natural abundance, the new results reveal ^{110}Pd to be an excellent candidate for double-β decay studies.

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PRL 111, 172501 (2013) PHYSICAL REVIEW LETTERS week ending 25 OCTOBER 2013

Constraint on $0\nu\beta\beta$ Matrix Elements from a Novel Decay Channel of the Scissors Mode: The Case of ^{154}Gd

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The nucleus ^{154}Gd is located in a region of the nuclear chart where rapid changes of nuclear deformation occur as a function of particle number. It was investigated using a combination of γ-ray scattering experiments and a $\gamma\gamma$-coincidence study following electron capture decay of ^{154}Tb^m. A novel decay channel from the scissors mode to the first excited 0^+ state was observed. Its transition strength was determined to $B(M1; 1^+_{sc} \rightarrow 0^+_2) = 0.031(4)\mu_N^2$. The properties of the scissors mode of ^{154}Gd imply a much larger matrix element than previously thought for the neutrinoless double-β decay to the 0^+_2 state in such a shape-transitional region. Theory indicates an even larger effect for ^{150}Nd.

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PHYSICAL REVIEW C 85, 054309 (2012)

Shape phase transitions in the interacting boson model: Phenomenological versus microscopic descriptions

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We investigate the shape phase transition in even-even $_{64}$Gd and $_{66}$Dy isotopes within the proton-neutron interacting boson model (IBM-2). The parameters of the IBM-2 Hamiltonian are fixed in two different ways: the usual phenomenological fitting calculation and the mapping of the constrained self-consistent mean-field calculation with a Skyrme energy density functional onto the appropriate boson system. Notable differences are found between the energy surfaces for the phenomenological and the mapped IBM-2. Key quantities for the collective structural evolution, including level energies, B(E2) values, quadrupole moments, and the two-neutron separation energies, are analyzed in comparison to the experimental data. We show that the transition in these quantities occurs rapidly with the neutron number in the IBM-2 phenomenology but is somewhat smeared out in the mapped IBM-2. The differences in the measurable quantities are consistent with what is suggested by the energy-surface analysis.

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PHYSICAL REVIEW C 85, 054309 (2012)

Shape phase transitions in the interacting boson model: Phenomenological versus microscopic descriptions

energy-surface analysis.

PHYSICAL REVIEW C 89, 064304 (2014)

Collective features of Cr and Fe isotopes

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The question of the sudden increase of collectivity in neutron-rich nuclei when approaching $N = 40$ has recently interested both experimentalists and theorists. In this paper we study the development of collectivity along the chromium and iron isotopic chains. The calculations are performed within two different perspectives, namely, the proton-neutron interacting boson model (IBM-2) and interacting shell model (ISM) and compared with the available experimental data. The onset of collectivity is studied through nuclear quantities and observables that suggest differences in the nuclear structure of Cr and Fe isotopical chains. Furthermore, a prediction for the shape transition from a spherical vibrator to γ-soft rotor with nucleus ^{58}Cr standing at the critical point is discussed.

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PRL 108, 062502 (2012) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2012

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PHYSICAL REVIEW C 85, 054309 (2012)

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PHYSICAL REVIEW C 89, 064304 (2014)

Collective features of Cr and Fe isotopes

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PHYSICAL REVIEW C 94, 034320 (2016)

Occupation probabilities of single particle levels using the microscopic interacting boson model: Application to some nuclei of interest in neutrinoless double-β decay

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We have developed a new method to calculate the occupancies of single particle levels in atomic nuclei. This method has been developed in the context of the microscopic interacting boson model, in which neutron and proton degrees of freedom are treated explicitly. The energies of the single particle levels constitute a very important input for the calculation of the occupancies in this method. In principle these energies can be considered as input parameters that can be fitted to reproduce the experimental occupancies. Instead of fitting, in this study we have extracted the single particle energies from experimental data on nuclei with a particle more or one particle less than a shell closure. We provide the sets of these single particle energies suitable for several major shells and apply our method to calculate the occupancies of several nuclei of interest in neutrinoless double-β decay using these sets. Our results are compared with other theoretical calculations and experimental occupancies, when available.

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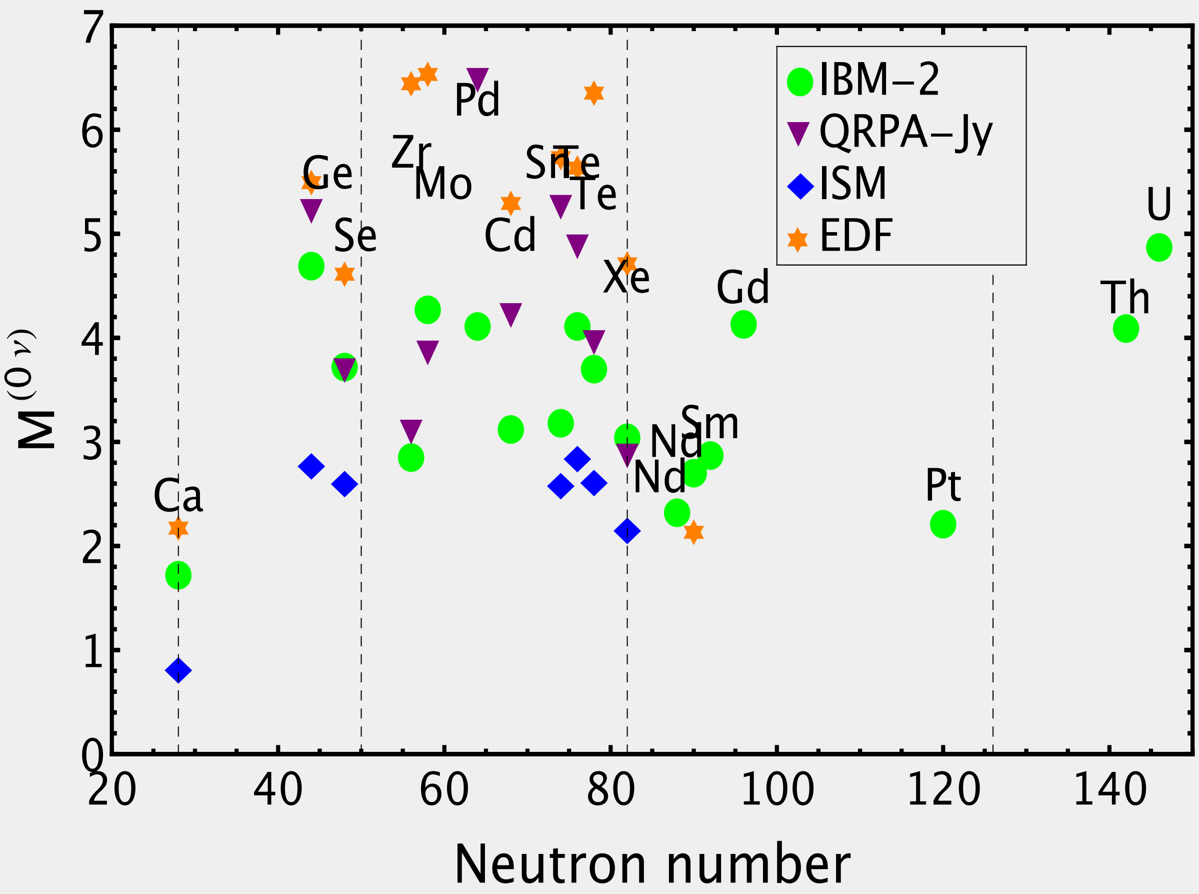
Nuclear matrix element M



IBM-2: J. Barea et al., PRC 91, 034304 (2015),
QRPA-Jy: J. Hyvärinen et al., PRC 91 024613 (2015),
ISM: J. Menendez et al., NPA 818, 139 (2009),
EDF: N.L. Vaquero et al., PRL 111, 142591 (2013)

- Comparison of IBM-2, QRPA, ISM, and EDF $g.s. \to g.s.$ NMEs for light neutrinos
- IBM-2/QRPA/ISM similar trend:
  - Larger values at the middle of the shell than at closed shells
- The ISM is a factor of ~ 2 smaller than both the IBM-2 and QRPA in the lighter nuclei and the difference is smaller for heavier
  - Effective value of g_A?

Experimental aspects: $\tau_{1/2}$

Current lower half-life limits coming from different experiments:

Experiment	nucleus	$\tau_{1/2}$	$\langle m_\nu \rangle$
Majorana	^{76}Ge	$> 1.9 \times 10^{25}$yr	< 0.27eV
GERDA	^{76}Ge	$> 8 \times 10^{25}$yr	< 0.13eV
NEMO-3	^{100}Mo	$> 1.1 \times 10^{24}$yr	< 0.44eV
CUORE	^{130}Te	$> 1.5 \times 10^{25}$yr	< 0.19eV
EXO-200	^{136}Xe	$> 1.8 \times 10^{25}$yr	< 0.21eV
Kamland-Zen	^{136}Xe	$> 1.07 \times 10^{26}$yr	< 0.09eV

$$\tau_{1/2} \Rightarrow \langle m_\nu \rangle < \frac{m_e}{\sqrt{\tau_{1/2}^{exp} G_{0\nu} g_A^2} |M^{(0\nu)}|}$$

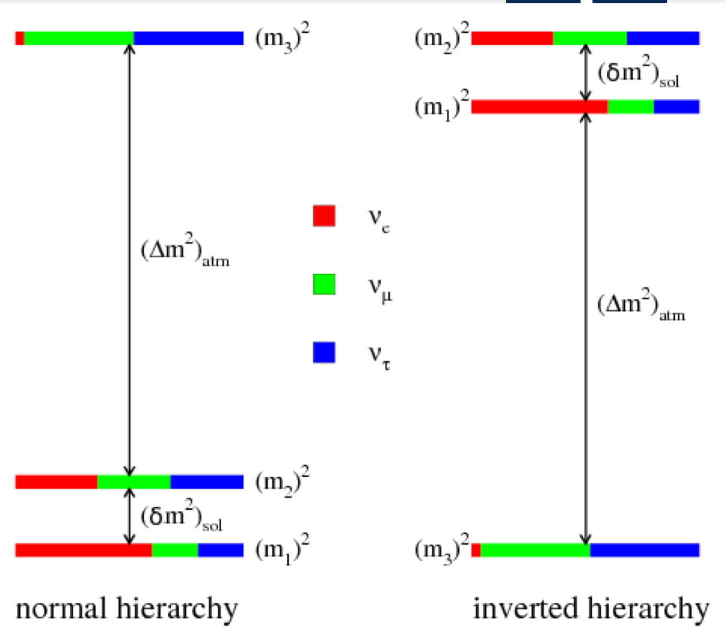
Majorana: C. E. Aalseth et al., PRL 120, 132502 (2018), GERDA: M. Agostini et al. PRL 120 132503 (2018),
NEMO-3: R. Arnold, et al., PRD 92, 072011 (2015),
CUORE: C. Alduino et al., PRL 120, 132501 (2018),
EXO: J.B. Albert et al., PRL 120 072701 (2018) , KamLAND-Zen: A. Gando etal., PRL. 117, 082503 (2016)

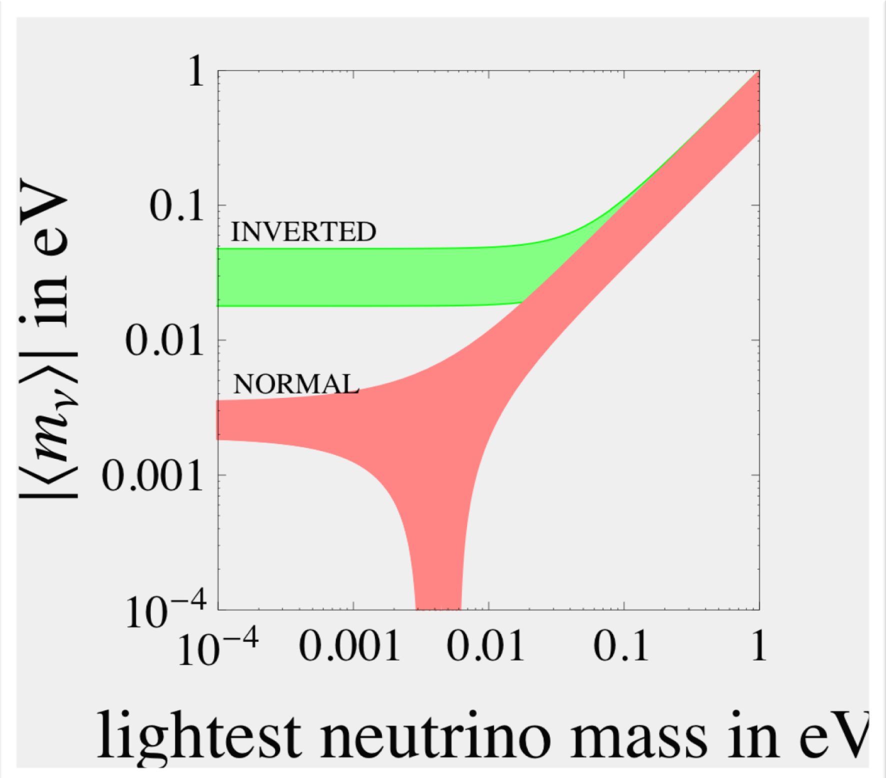
Neutrino oscillations

Light neutrinos:

$$f(m_i,U_{ei})=\frac{\langle m_\nu\rangle}{m_e}=\frac{1}{m_e}\sum_{k=light}(U_{ek})^2 m_k$$

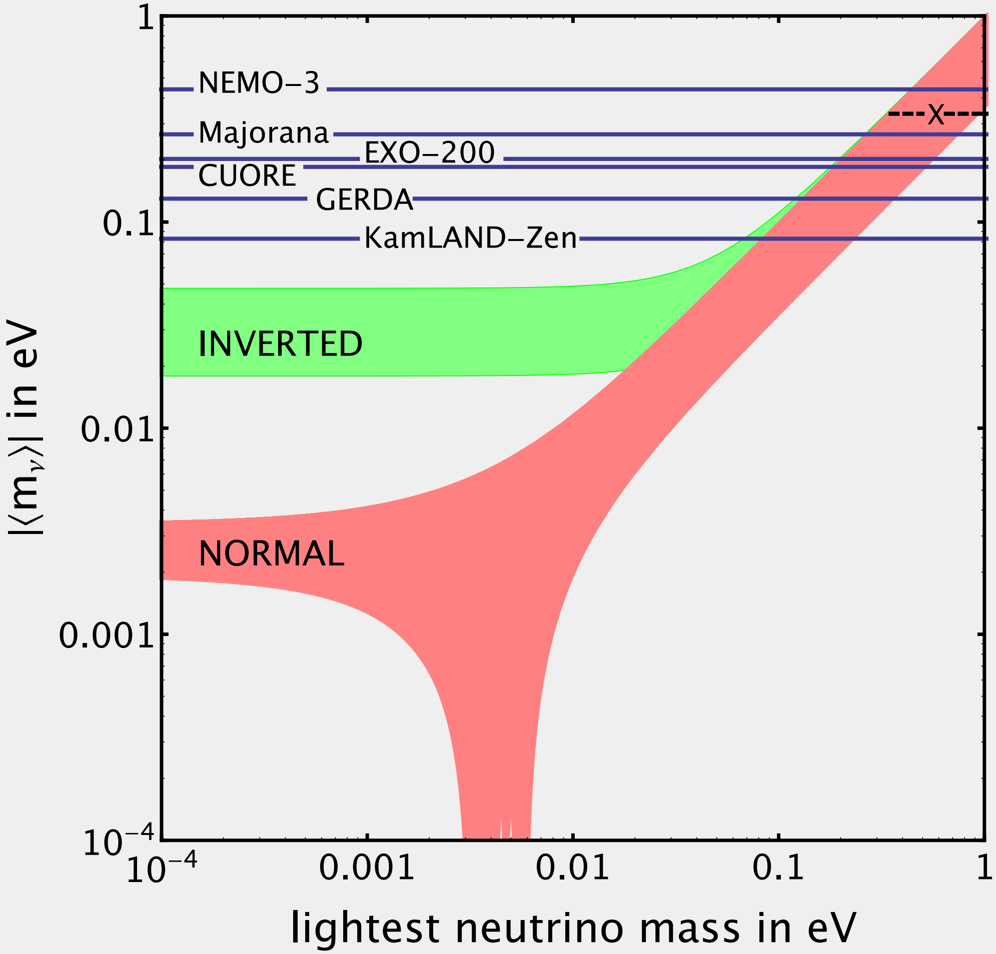
- Obtained information on mass differences and their mixing leaves two possibilities: Normal and inverted hierarchy





- The average light neutrino mass is constrained by atmospheric, solar, reactor and accelerator neutrino oscillation experiments

THEORY+EXPERIMENTS: Limits on $\langle m_\nu \rangle$



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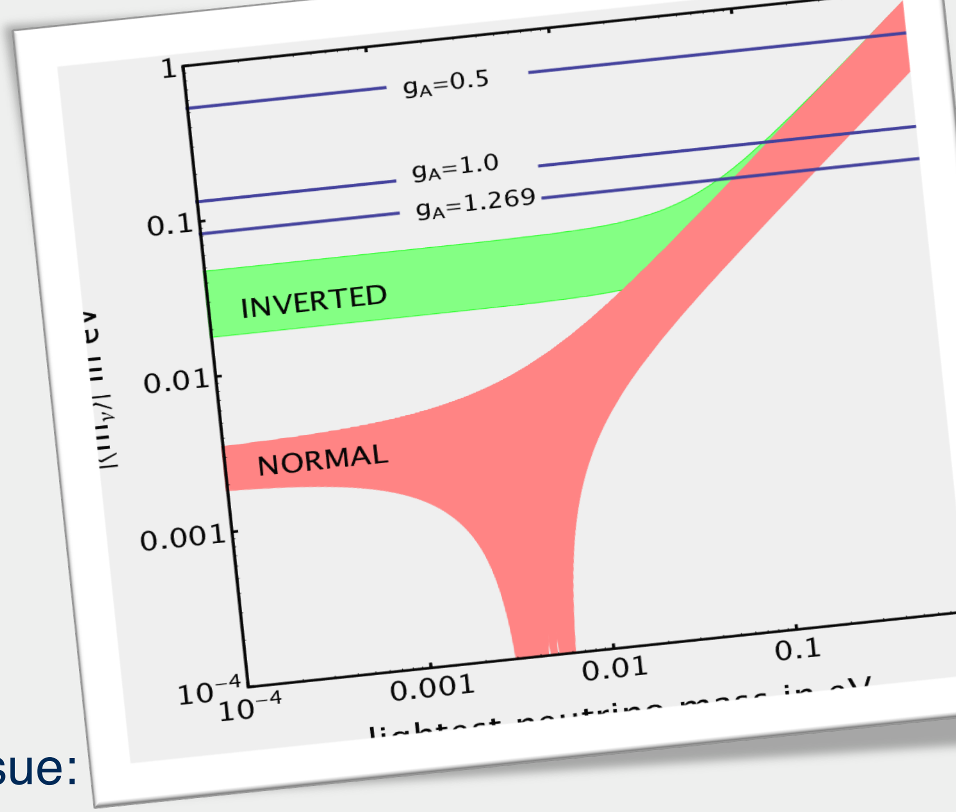
Cause of worry: Quenching of g_A

- It is well known from single beta decay and electron capture that g_A is renormalized in models of nuclei. Two reasons for this are:
  - The limited model space in which the calculations done, q_{Nex}
  - The omission of non-nucleonic degrees of freedom, q_{Δ}
- $2\nu\beta\beta$ may be used to get and idea of the quenching. But effective value of g_A is a work in progress:
  - Is the renormalization of g_A the same in $2\nu\beta\beta$ as in $0\nu\beta\beta$?
    - → In $2\nu\beta\beta$ only the 1+ (GT) multipole contributes. In $0\nu\beta\beta$ all multipoles 1+ , 2− ,...; 0+ , 1− ,... contribute. Some of which could be even unquenched.
    - → The two processes differ by the momentum transferred to leptons. In $2\nu\beta\beta$ this is or the order of few MeV, while in $0\nu\beta\beta$ it is of the order of 100 MeV.
- This is a critical issue, since half-life predictions with maximally quenched g_A are up to 6 times longer due to the fact that g_A enters the equations to the power of 4!

Quenching of g_A

- Three suggested scenarios are:
- Free value: 1.269
- Quark value: 1
- Even stronger quenching: $g_{A,eff} < 1$



- Various studies are addressing this issue:
  - Theoretical studies using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents)
  - Experimental and theoretical studies of single beta decay and single charge exchange reactions involving the intermediate odd-odd nuclei
  - Experimental program (NUMEN) to measure both single and double charge exchange reaction intensities with heavy ions. Useful information on the Fermi and Gamow-Teller matrix elements of interest in $0\nu\beta\beta$ and $2\nu\beta\beta$ decay will also be provided.

Other modes and scenarios than $0\nu\beta^-\beta^-$

- Like in the case of single beta decay, modes where positrons are emitted or electrons are captured are also possible:
  - $\beta^+\beta^+$, $EC\beta^+$:

    Available kinetic energy much smaller $\Longrightarrow$ much smaller phase space $\Longrightarrow$ much longer half-lives
  - ECEC:

    0νECEC available energy larger than $\beta^+\beta^+$, $EC\beta^+$, but since all the energies are fixed, additional requirement that Q-value matches the final state energy $\Longrightarrow$ high precision Q-value measurements $\Longrightarrow$ many candidates ruled out
- It might also be that there are heavy neutrinos, $\langle m_{\nu heavy} \rangle$ >>1GeV:
  - Average inverse heavy neutrino mass is not constrained by experiments, and only model dependent limits of $\langle m_{\nu heavy} \rangle$ can be set
    - → Using a model by Tello et al. (PRL106(2011)151801), stringent experimental half-life limit correspond to $\langle m_{\nu heavy} \rangle$ >610GeV

Other modes and scenarios than $0\nu\beta^-\beta^-$

- Majoron emission
  - Requires the emission of one or two additional massless bosons, Majorons $\Longrightarrow$ similarities with $2\nu\beta\beta$
  - There are many different models, and exp. limits on $\tau_{1/2}$ give information about the majoron-neutrino coupling constant

TABLE I. Different Majoron emitting models of $0\nu\beta\beta$ decay [3–7]. The third, fourth, and fifth columns indicate whether the Majoron is Nambu-Goldstone boson or not, its leptonic charge L, and the model's spectral index n.

Model	Decay Mode	NG boson	L	n
IB	$0\nu\beta\beta\chi_0$	No	0	1
IC	$0\nu\beta\beta\chi_0$	Yes	0	1
ID	$0\nu\beta\beta\chi_0\chi_0$	No	0	3
IE	$0\nu\beta\beta\chi_0\chi_0$	Yes	0	3
IIB	$0\nu\beta\beta\chi_0$	No	-2	1
IIC	$0\nu\beta\beta\chi_0$	Yes	-2	3
IID	$0\nu\beta\beta\chi_0\chi_0$	No	-1	3
IIE	$0\nu\beta\beta\chi_0\chi_0$	Yes	-1	7
IIF	$0\nu\beta\beta\chi_0$	Gauge boson	-2	3
"Bulk"	$0\nu\beta\beta\chi_0$	Bulk field	0	2

Other modes and scenarios than $0\nu\beta^-\beta^-$:
Sterile neutrinos

- Scenario also frequently discussed, is the mixing of additional "sterile" neutrinos (no standard model interactions)
- Several types of sterile neutrinos have been suggested.
  - Light sterile neutrinos
    - → Neutrino masses are $m_N \sim 1eV$ or at keV mass range
    - → $m_N \sim 1eV$ neutrinos could account for the reactor anomaly in oscillation experiments and for the gallium anomaly
  - Heavy sterile neutrinos: $m_N \gg 1eV$
    - → MeV-GeV mass range, TeV mass range

Sterile neutrinos

- If there are sterile neutrinos, the equation for half-life is different…

Known neutrinos

Unknown light sterile ν

eV

keV

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} \left| \left[\frac{1}{m_e} \sum_{k=1}^{3} U_{ek}^2 m_k + \frac{1}{m_e} \sum_i U_{ei}^2 m_i + \frac{1}{m_e} \sum_j U_{ej}^2 \right] M^{(0\nu)} + \left[m_p \sum_N U_{eN}^2 \frac{m_N}{\langle p^2 \rangle + m_N^2} + m_p \sum_{k_h=1}^{3} U_{ek_h}^2 \frac{1}{m_{k_h}} \right] M^{(0\nu_h)} \right|$$

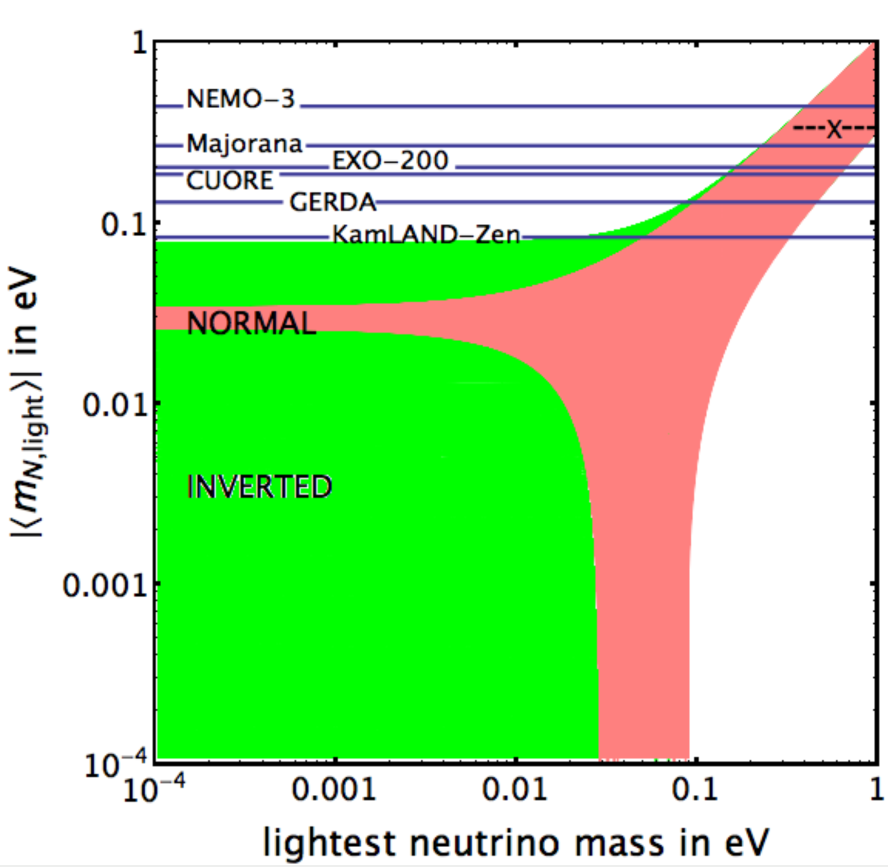
Unknown heavy sterile ν

Unknown heavy neutrinos

Sterile neutrinos

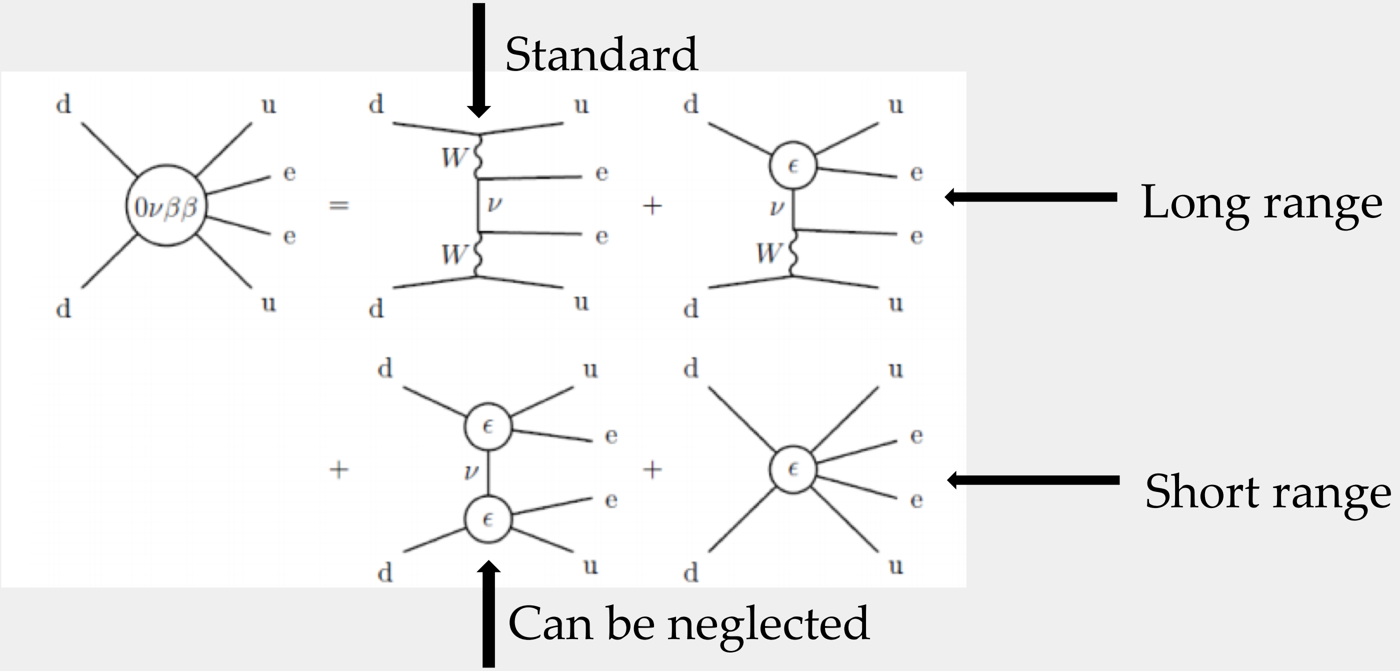
- … as is the picture of limits on $\langle m_\nu \rangle$
  - Example: 4*th* neutrino with mass $m_4 = 1$eV and $|U_{e4}|^2 = 0.03$:

$$\langle m_{N,light} \rangle = \sum_{k=1}^{3} U_{ek}^2 m_k + U_{e4}^2 e^{i\alpha_4} m_4$$



Non standard mechanisms

- On the other hand the underlying interaction does not have to be as simple as the standard neutrino mass mechanism.



- General Lagrangian can be written in terms of effective couplings ε corresponding to the point like vertices at the Fermi scale: $\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{\mathrm{LR}} + \mathcal{L}_{\mathrm{SR}}$

Non standard mechanisms

- In general description experimental half-life limits give information about the constraints on effective couplings ε:

$$[\tau_{1/2}]^{-1} = \left|\varepsilon_{\alpha}^{\beta}\right|^{2} G_i |M_i|^2$$

- A thorough theoretical description of non-standard $0\nu\beta\beta$-decay mechanisms is a work in progress, meaning
  - Complete, consistent and cross-checked description of all contributions
  - Application of IBM-2 to numerical calculation of nuclear matrix elements
  - Numerical computation of relevant phase space factors
  - Interdisciplinary project; collaboration with Francesco Iachello, Frank Deppisch and Lukas Graf

Conclusions

- Even though many milestones in the research of double beta decay has been achieved, it remains yet to be observed and fully understood.
- $0\nu\beta\beta$-decay continues to possess great potential to test lepton number, to determine the nature of neutrino mass, and to probe its values
- We do not yet know what is the mechanisms of $0\nu\beta\beta$-decay. Number of different mechanisms can trigger $0\nu\beta\beta$–decay and several mechanisms may contribute with different relative phases.

- The next generation of experiments is expected to reach at least the inverted mass hierarchy. In case there are sterile neutrinos, the situation might be more complicated.
- The planning and interpretation of these experiments relies on the good understanding of the decay half-life and thus theory.
- With or without sterile neutrinos, the reliability of nuclear matrix elements, as well as the quenching of g_A are becoming more and more important.

THANK YOU!

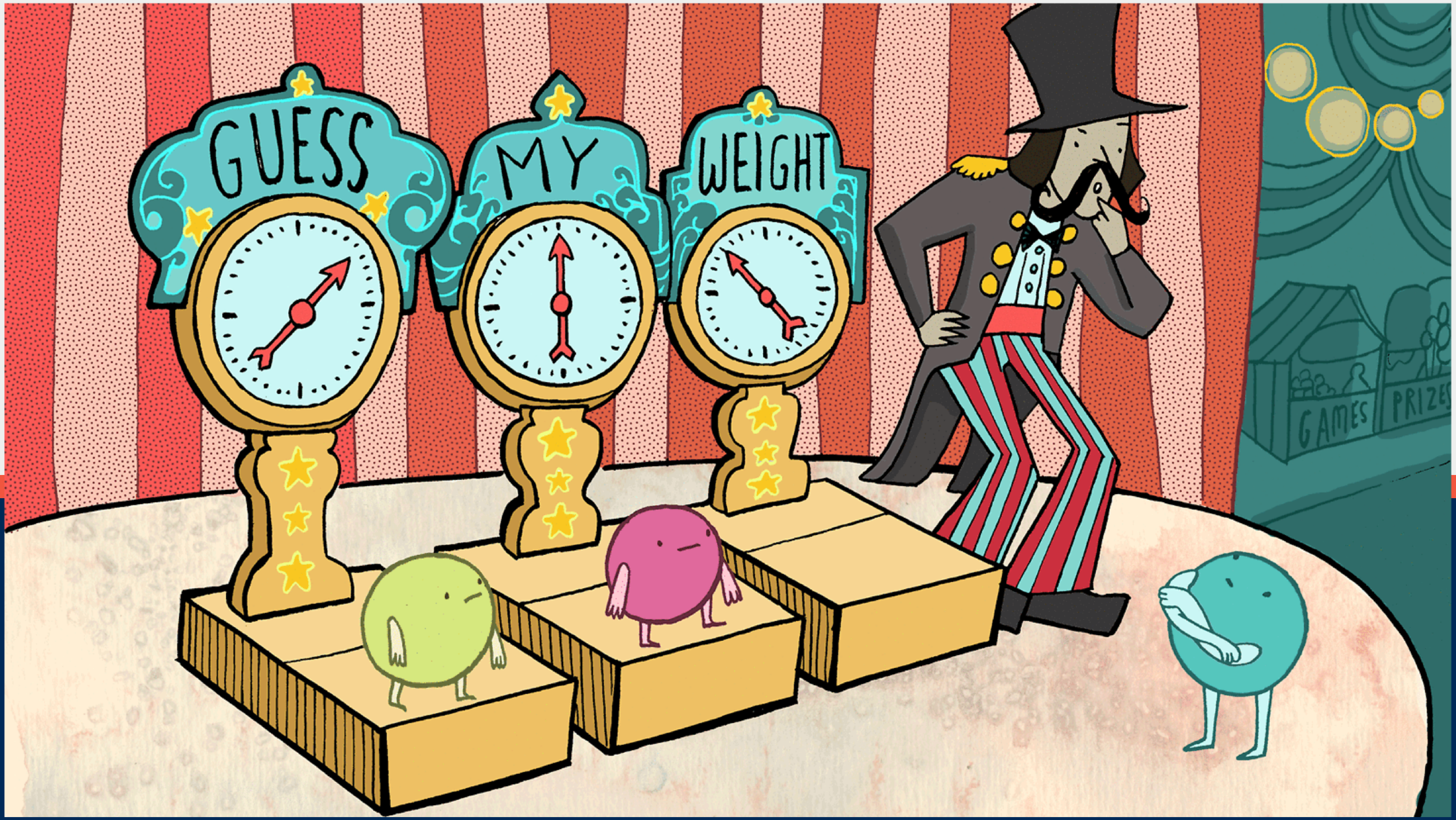


Illustration by Sandbox Studio, Chicago with Corinne Mucha