JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

# RARE WEAK DECAYS AND NEUTRINO MASS

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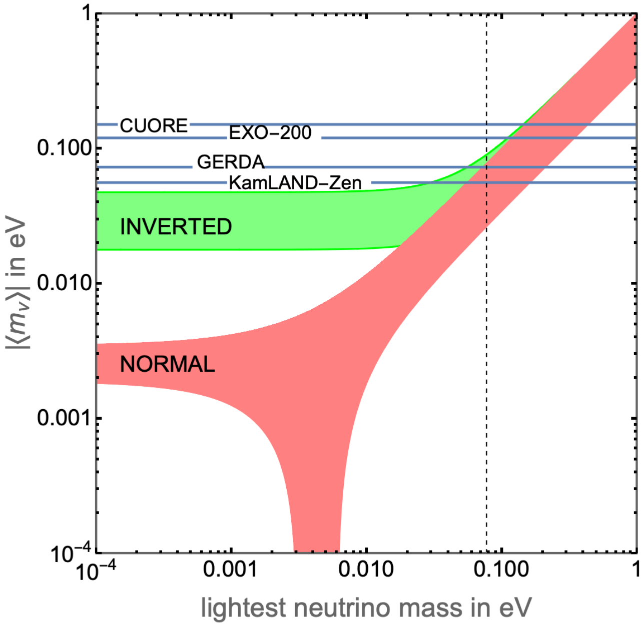
JYU. Since 1863.

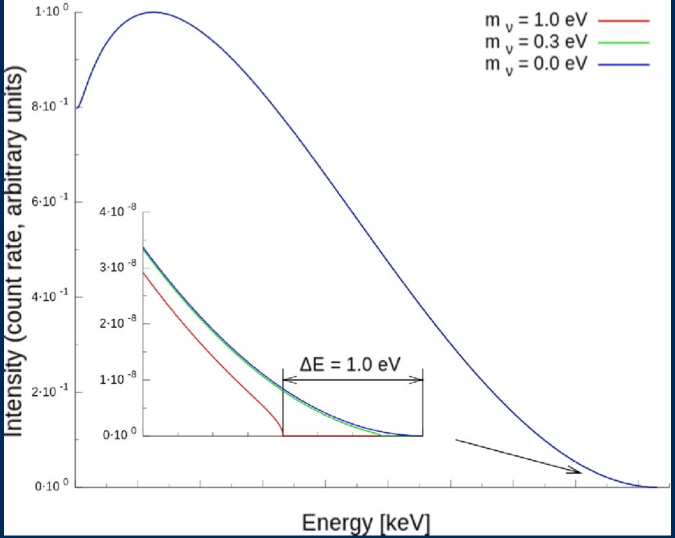
Spring Seminar on Nuclear Physics 2022, Ischia 15-20 May, 2022

# OUTLINE

- Part 1: Neutrino nature and mass scale from double beta decay

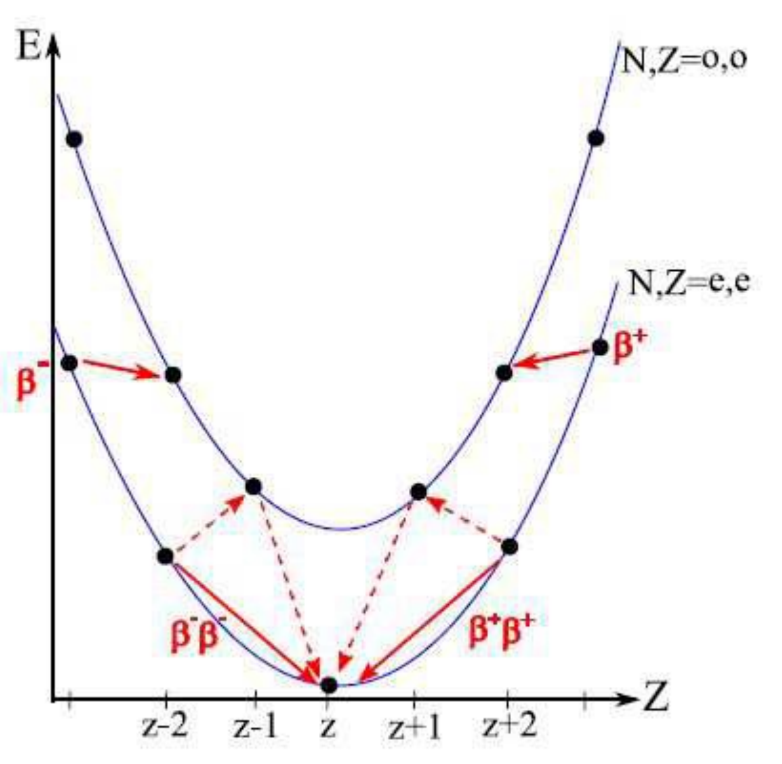
- Part 2: Neutrino mass from single beta decay





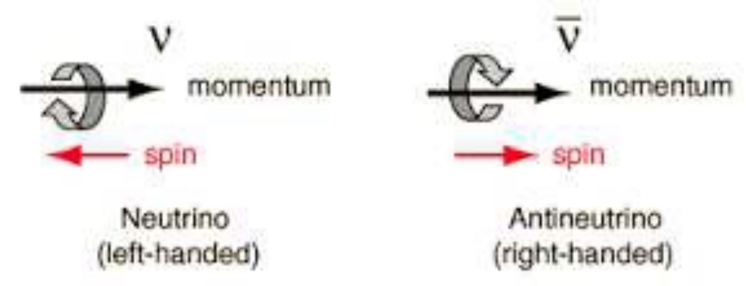
# $\beta\beta$-decay: History

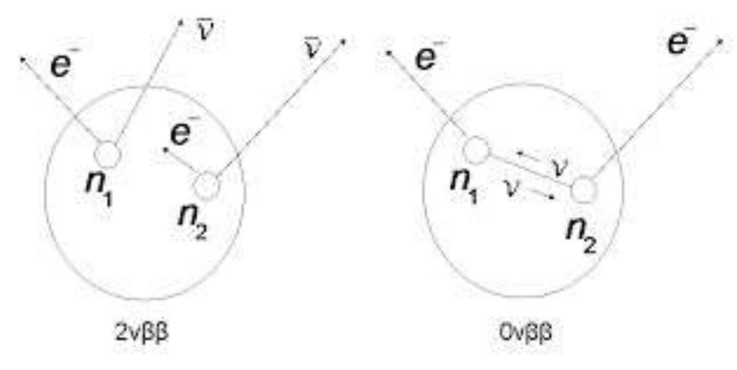
- 1930's: The idea of double beta decay was suggested by Eugene Paul Wigner as a second-order weak transition between isobars differing by two units in atomic number
- 1935: Assuming the emission of two electrons and two neutrinos Maria Goeppert-Mayer made the first theoretical estimate of the extremely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



# $\beta\beta$-decay: **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 were of the order of $10^{15–16}$ years, and $0\nu\beta\beta$ was thought to be more likely to occur than $2\nu\beta\beta$





# $\beta\beta$-decay: **History**

- 1948: Edward L. Fireman made an attempt to measure the $\beta\beta$-decay half-life of $^{124}$Sn with Geiger counter, without success ($\tau_{1/2}^{2\nu\beta\beta} > 3 \times 10^{15}$yr).
- 1950: $\beta\beta$-decay half-life of $1.4 \times 10^{21}$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: $\tau_{1/2}^{2\nu\beta\beta}(^{82}\mathrm{Se}) = 1.1^{+0.8}_{-0.3} \times 10^{20}$yr.
- Since then $2\nu\beta\beta$-decay has been observed in laboratory in 12 different nuclei 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.

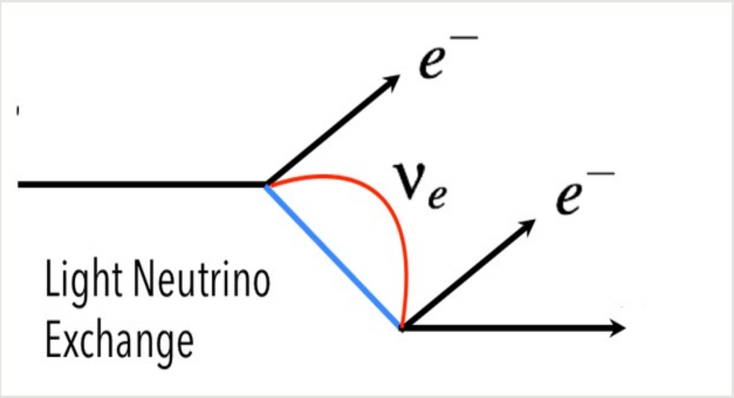
# And now…

- $0\nu\beta\beta$-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 $10^{25\text{-}26}$yr

# Mass mechanism

- After the discovery of neutrino oscillations, attention has been mostly focused on the mass mechanism of $0\nu\beta\beta$-decay, wherein the three species of neutrinos have masses $m_i$ and couplings to the electron neutrino $U_{ei}$. In this case, the inverse decay rate is given by

$$\left[\tau_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$



- **G** is the phase space factor
- **M** is the nuclear matrix element
- **f($m_i$,$U_{ei}$)=** $\frac{\langle m_\nu \rangle}{m_e}$ contains the physics beyond standard model

# Calculation of 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
- Two phase space factors to be calculated: $G^{(0)}$ and $G^{(1)}$
  - From these one obtains half-life: $$\left[\tau^{0\nu}_{1/2}(0^+ \to 0^+)\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$
  - Single electron spectrum: $$\frac{dW_{0\nu}}{d\epsilon_1} = \mathcal{N}_{0\nu}\frac{dG^{(0)}_{0\nu}}{d\epsilon_1}$$
  - Angular correlation: $$\alpha(\epsilon_1) = \frac{f^{(1)}_{11}(\epsilon_1)}{f^{(0)}_{11}(\epsilon_1)} = \frac{dG^{(1)}_{0\nu}/d\epsilon_1}{dG^{(0)}_{0\nu}/d\epsilon_1}$$

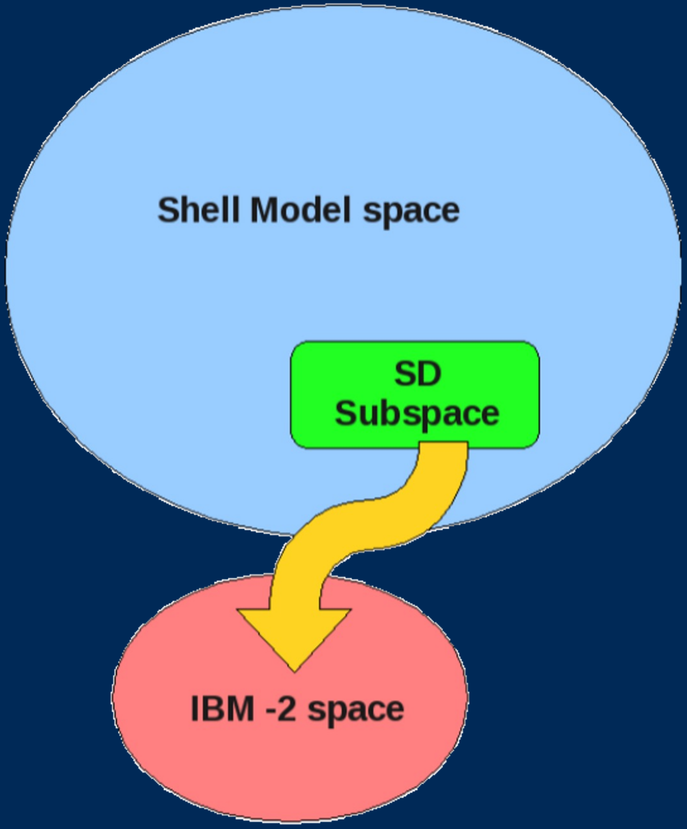
Can be compared with experimental data!

# Calculation of nuclear matrix element M

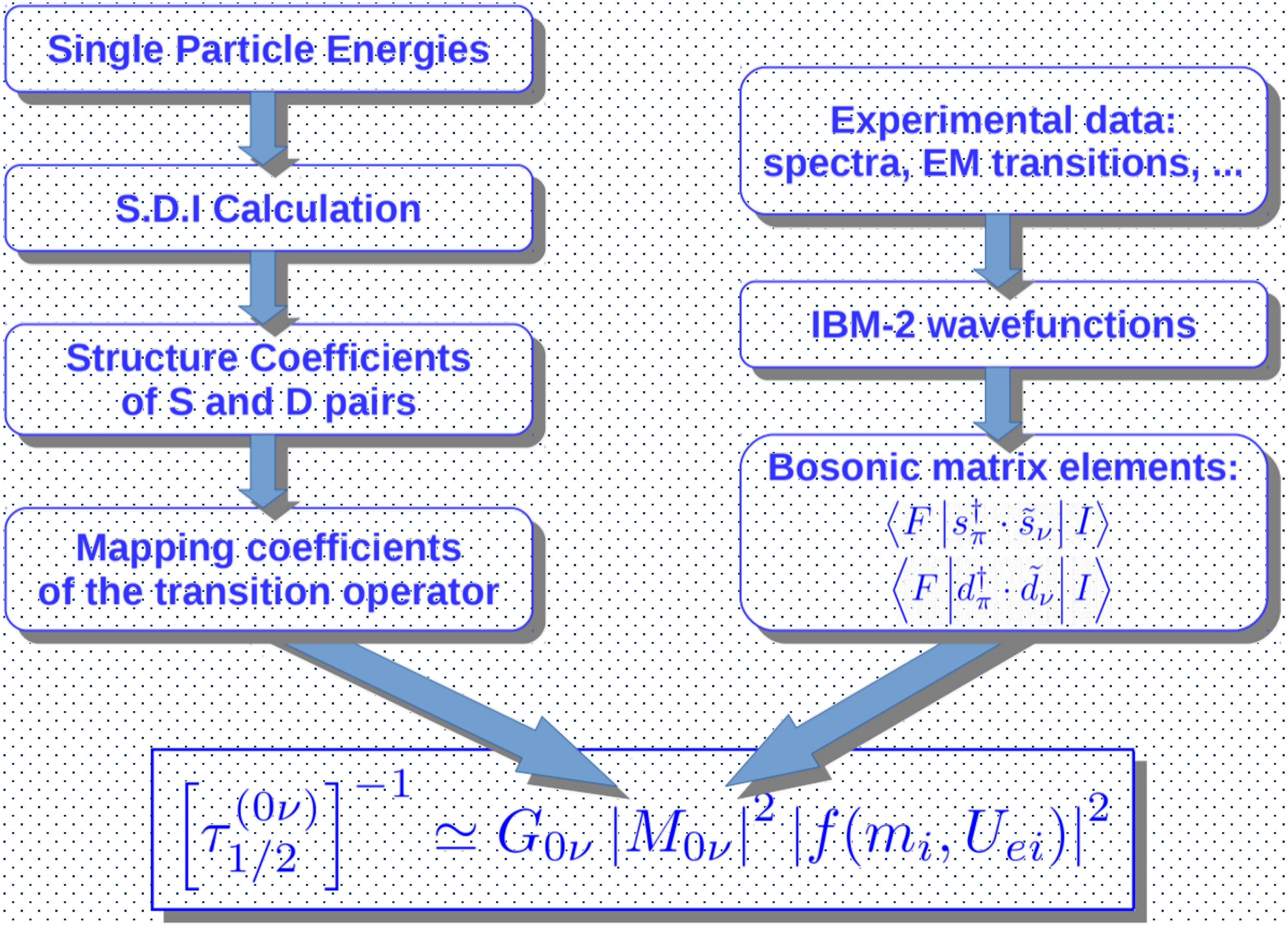
- NMEs are calculated in nuclear models, such as the quasiparticle random phase approximation, **QRPA**, the nuclear shell model, **NSM**, energy density functional theory, **EDF** and the microscopic interacting boson model, **IBM-2**
  - IBM-2: Can be used in any nucleus and thus all nuclei of interest can be calculated within the same model making it easier to recognize model dependent uncertainties
- Recent ab initio calculations: multi-reference version of the similarity renormalization group **IMSRG** and coupled-cluster **CC** theory
- 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 wavefunctions, and eventually $M^{(0\nu)}$, has to be then tested using other available relevant data

# Nuclear model: IBM-2

- In IBM-2 the very large shell model space is truncated to states built from pairs of nucleons with J = 0  and 2
- These pairs are then assumed to be collective and are taken as bosons
- The Hamiltonian is constructed phenomenologically and two- and four valence-nucleon states are generated by a schematic interaction
- The fermion operators are mapped onto a boson space and the matrix elements of the mapped operators are then evaluated with realistic wavefunctions



# Nuclear model: IBM-2



Single Particle Energies

S.D.I Calculation

Structure Coefficients of S and D pairs

Mapping coefficients of the transition operator

Experimental data: spectra, EM transitions, ...

IBM-2 wavefunctions

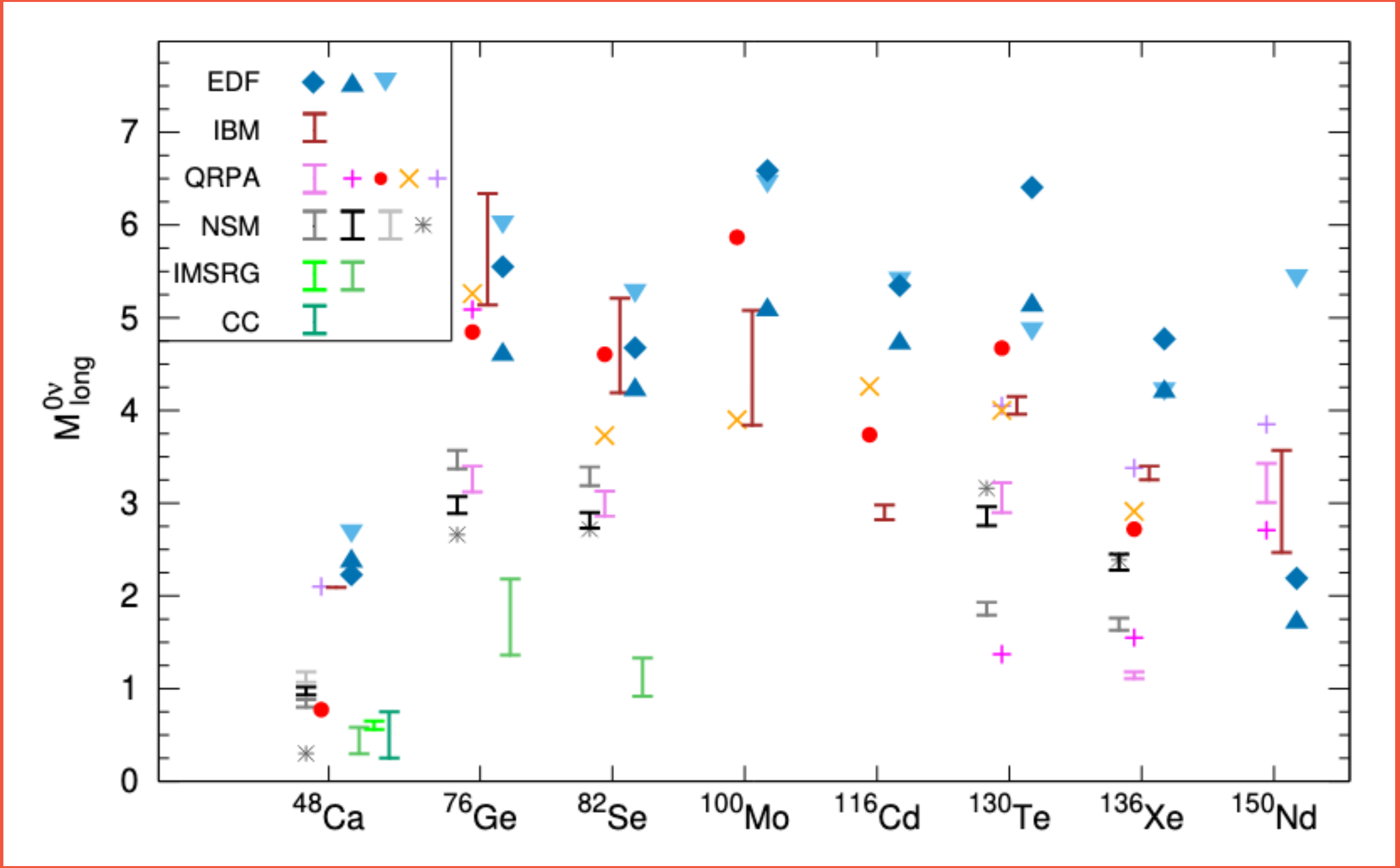
Bosonic matrix elements:

$$\left\langle F \middle| s^\dagger_\pi \cdot \tilde{s}_\nu \middle| I \right\rangle$$

$$\left\langle F \middle| d^\dagger_\pi \cdot \tilde{d}_\nu \middle| I \right\rangle$$

$$\left[\tau^{(0\nu)}_{1/2}\right]^{-1} \simeq G_{0\nu} \left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2$$

# Calculation of NME: Mass mechanism



Summary of current situation:
M. Agostini,
G. Benato,
J. A. Detwiler,
J. Menéndez,
F. Vissani
arXiv:2202.01787
(2022)

- **IMSRG and CC smaller than NSM NMEs, EDF theory the largest, and IBM and QRPA somewhere in between**
- **Still large differences between the different models but some of them can be explained by model dependent quenching of $g_A$**
- **NME + PSFs: can be compared with experimental half-life limits**

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

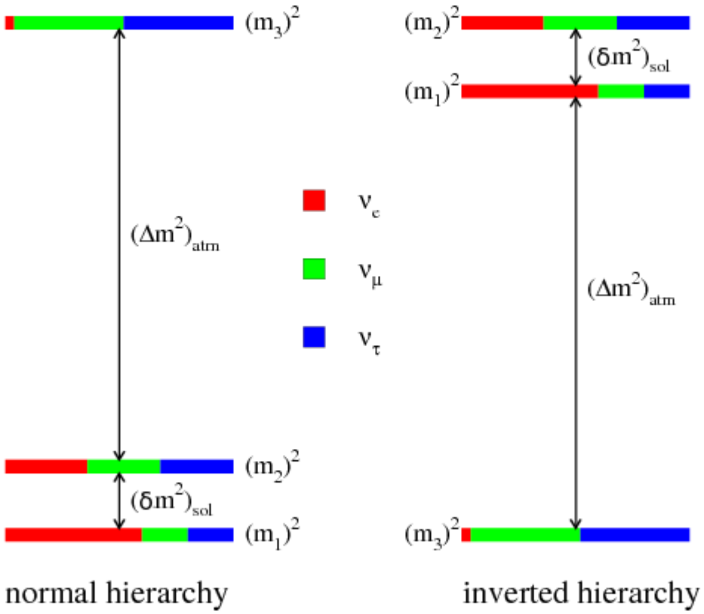
Current lower half-life limits coming from different experiments:

| Experiment | nucleus | $\tau_{1/2}$ | $\langle m_\nu \rangle$ |
|---|---|---|---|
| Majorana | $^{76}$Ge | $> 2.7 \times 10^{25}$yr | $< 0.21$ eV |
| GERDA | $^{76}$Ge | $> 1.8 \times 10^{26}$yr | $< 0.079$ eV |
| NEMO-3 | $^{100}$Mo | $> 1.1 \times 10^{24}$yr | $< 0.44$ eV |
| CUORE | $^{130}$Te | $> 2.2 \times 10^{25}$yr | $< 0.14$ eV |
| EXO-200 | $^{136}$Xe | $> 5.0 \times 10^{25}$yr | $< 0.12$ eV |
| Kamland-Zen | $^{136}$Xe | $> 2.3 \times 10^{26}$yr | $< 0.052$ eV |

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

Majorana: S. I. Alvis et al., PRC 100, 025501 (2019), GERDA: M. Agostini et al. PRL 125 252502 (2020), NEMO-3: R. Arnold, et al., PRD 92, 072011 (2015), CUORE: D.Q Adams et al. Nature 604 53–58 (2022), EXO: G. Anton et al., PRL 123 161802 (2019) , KamLAND-Zen: S. Abe et al., arXiv:2203.02139 (2022)

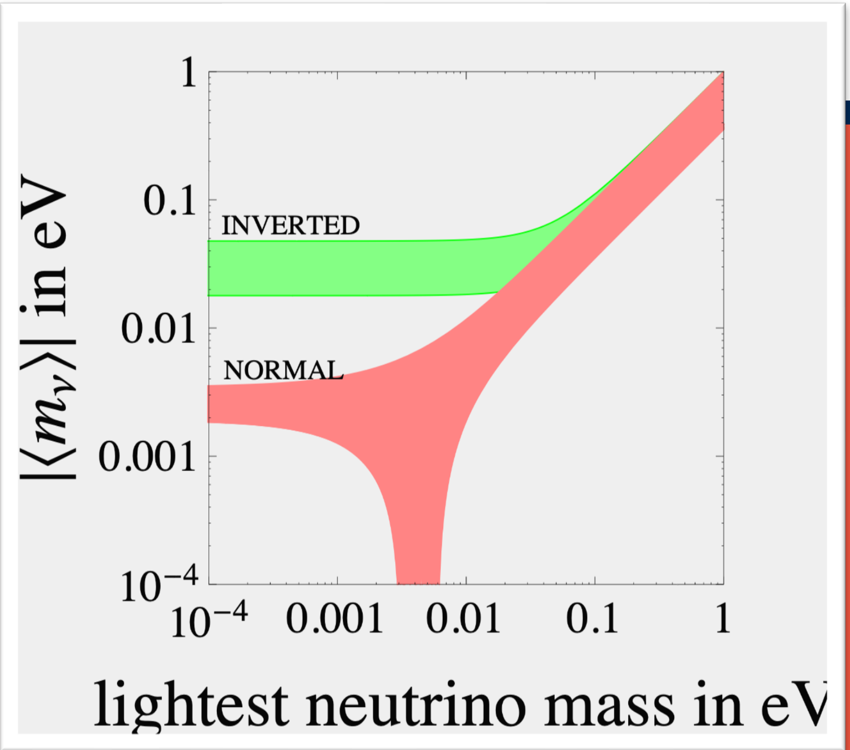
# Neutrino oscillations



Light neutrinos:

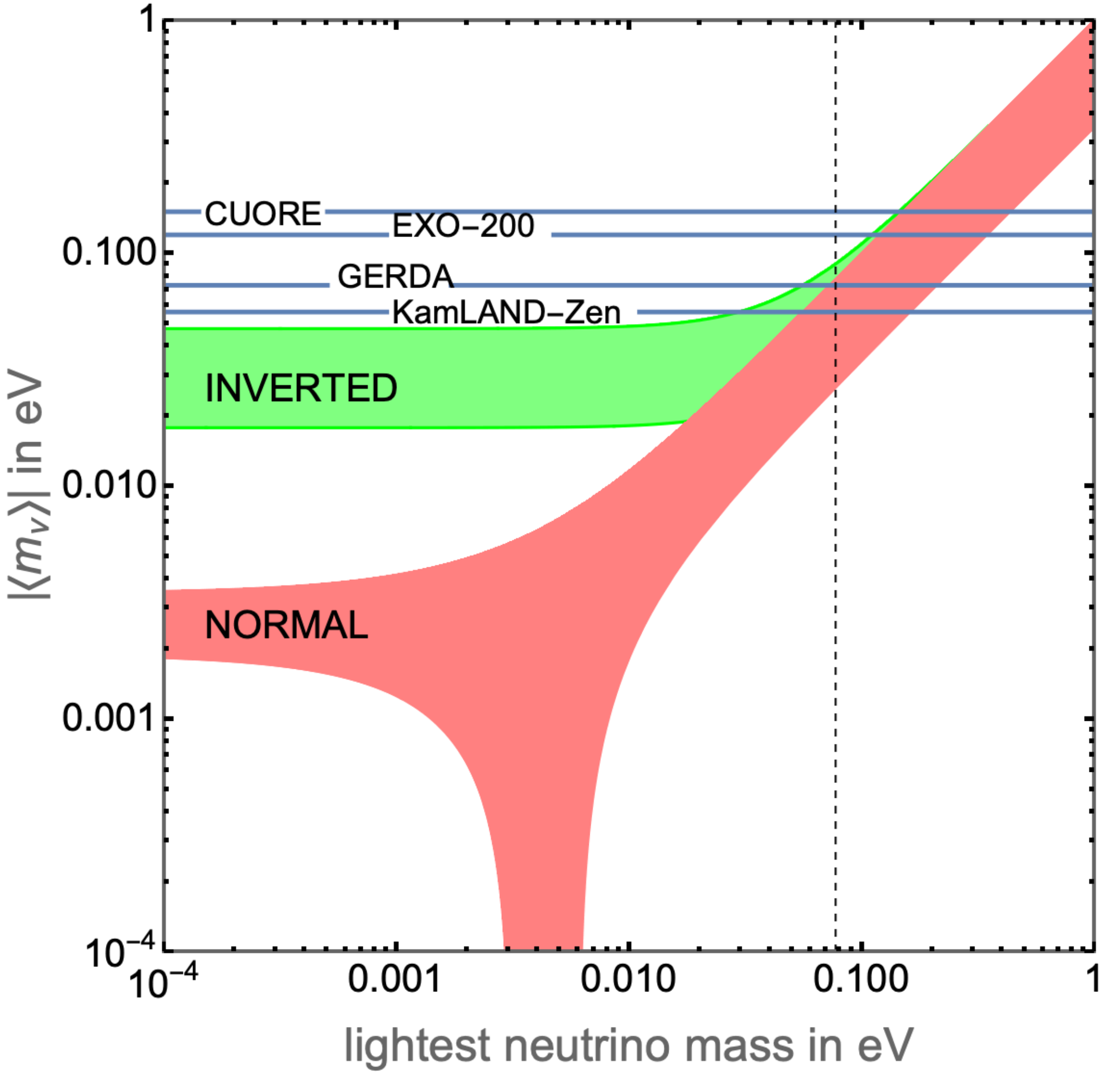
$$f(m_i,U_{ei})=\frac{\langle m_\nu\rangle}{m_e}=\frac{1}{m_e}\sum_{k=light}(U_{ek})^2 m_k$$

- 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 $\langle m_\nu \rangle$



CUORE: D.Q Adams et al. Nature 604 53–58 (2022), GERDA: M. Agostini et al. PRL 125 252502 (2020),
EXO: G. Anton et al., PRL 123 161802 (2019) , KamLAND-Zen: S. Abe et al., arXiv:2203.02139 (2022).

# 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 omission of non-nucleonic degrees of freedom, $q_\Delta$
  - The limited model space in which the calculations done, $q_{Nex}$
- The former effect is not expected to be present in 0vββ decay
  - the average neutrino momentum is ~100 MeV, while in 2vββ decay is of the order of 1–2 MeV
- The latter effect instead appears both in 0vββ and 2vββ decays
- $2\nu\beta\beta$ may be used to get an idea of the model dependent quenching
  - In $2\nu\beta\beta$ only the 1+ (GT) multipole contributes. In 0vββ all multipoles 1+ , 2– ,...; 0+ , 1– ,... contribute. Some of which could be even unquenched
- This is a critical issue, since the fact that $g_A$ enters the equations to the power of 4
- Effective value of $g_A$ is a work in progress!

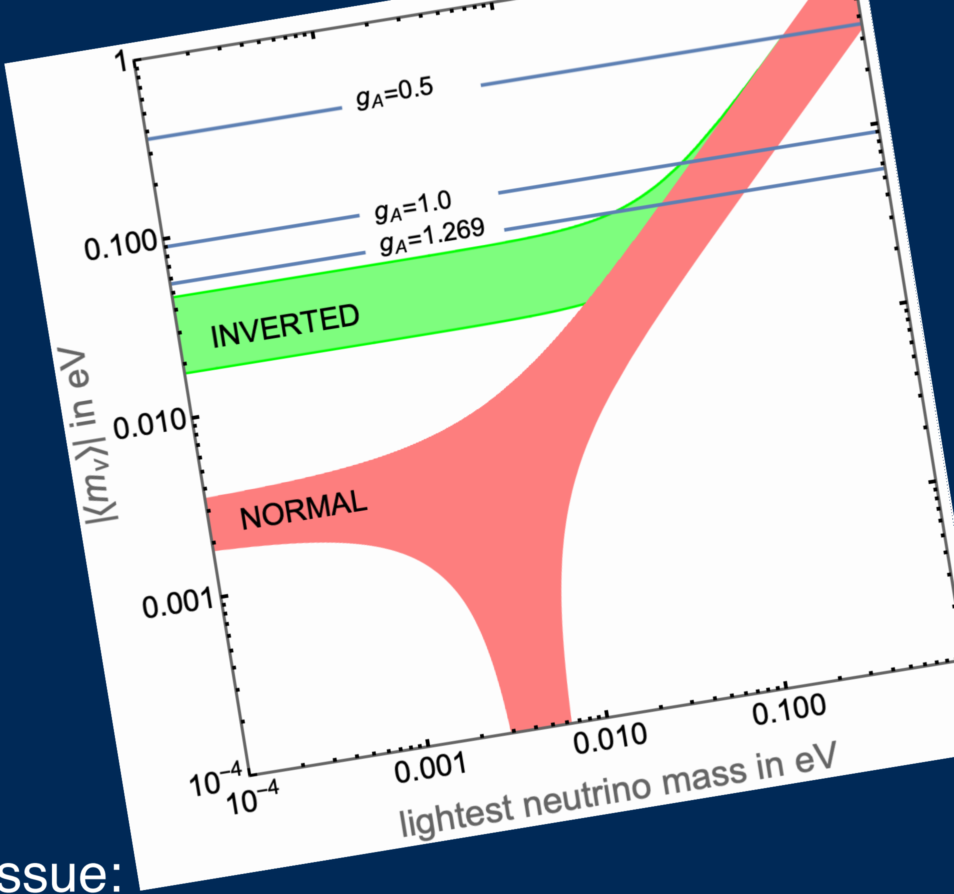
# Quenching of $g_A$

- Three suggested scenarios are:

- Free value: 1.269

- Quark value: 1

- Even stronger quenching: $g_{A,\mathrm{eff}} < 1$



- 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 studies employing single and double charge exchange reactions.

# Other scenarios: Sterile neutrinos

- Neutrinos with no standard model interaction
- Several types of sterile neutrinos have been suggested
  - Light sterile neutrinos: $m_N \sim 1\text{eV}$ or at keV mass range
    - $m_N \sim 1\text{eV}$ neutrinos could account for the reactor anomaly in oscillation experiments and for the gallium anomaly
  - Heavy sterile neutrinos: $m_N \gg 1\text{eV}$
  - If there are sterile neutrinos, the equation for half-life is different…

Known neutrinos

Unknown light sterile $\nu$

eV

keV

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

PRD 92 (2015) 093001
+ update in progress

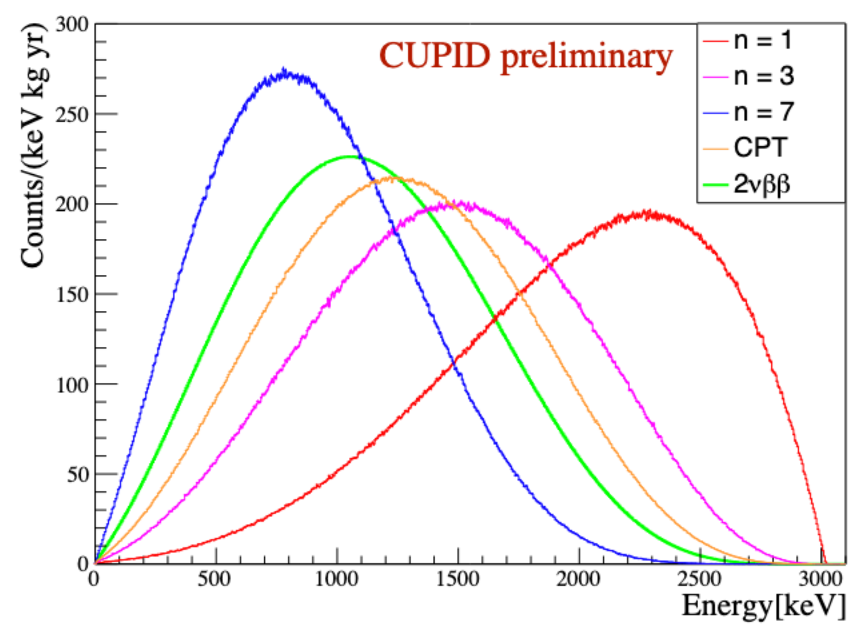
Unknown heavy sterile $\nu$

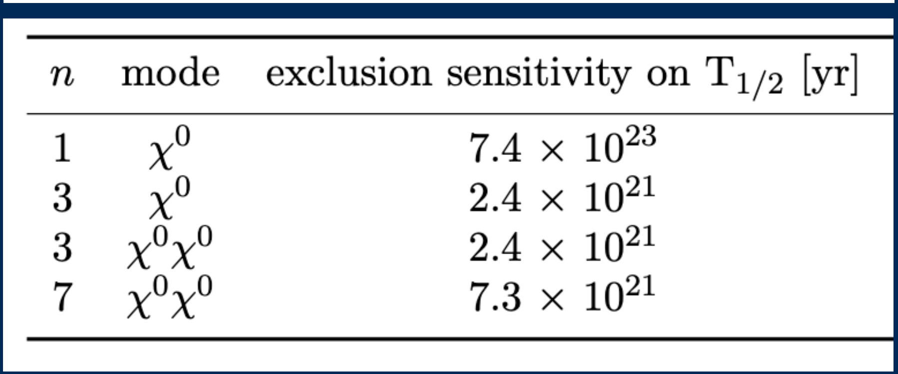
Unknown heavy neutrinos

# Other scenarios: Majoron emitting $0\nu\beta\beta$

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

$$\left[\tau_{1/2}^{0\nu M}\right]^{-1} = G_{m\chi_0 n}^{(0)} \left|\langle g_{\chi_{ee}^M}\rangle\right|^{2m} \left|M_{0\nu M}^{(m,n)}\right|^2$$





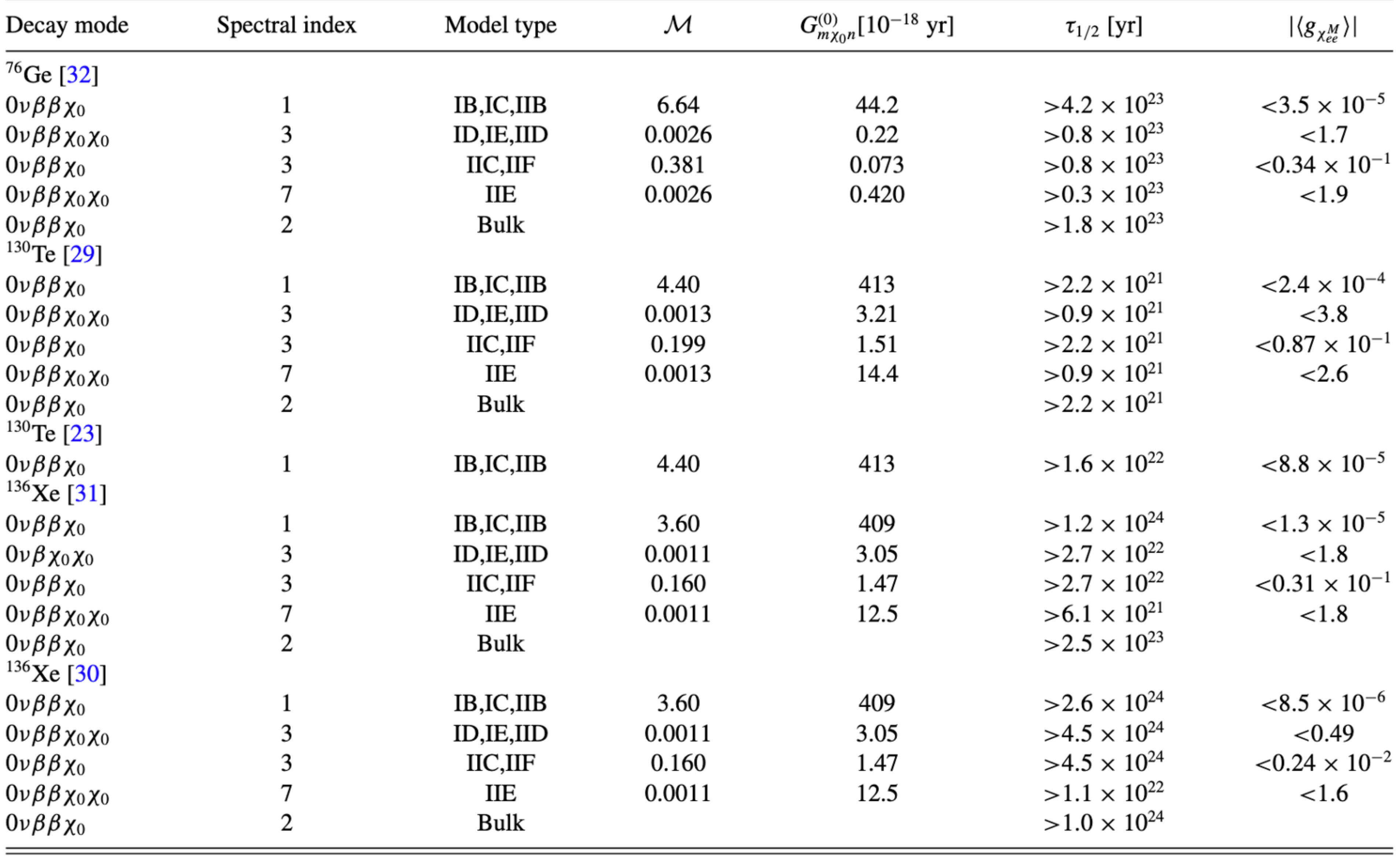
| $n$ | mode | exclusion sensitivity on $T_{1/2}$ [yr] |
|---|---|---|
| 1 | $\chi^0$ | $7.4 \times 10^{23}$ |
| 3 | $\chi^0$ | $2.4 \times 10^{21}$ |
| 3 | $\chi^0\chi^0$ | $2.4 \times 10^{21}$ |
| 7 | $\chi^0\chi^0$ | $7.3 \times 10^{21}$ |

Journal of Physics: Conference Series 2156 (2022) 012233

# Majoron emitting $0\nu\beta\beta$

- Limits on majoron-neutrino coupling constant for different models

*PRC 103 (2021)* 044302

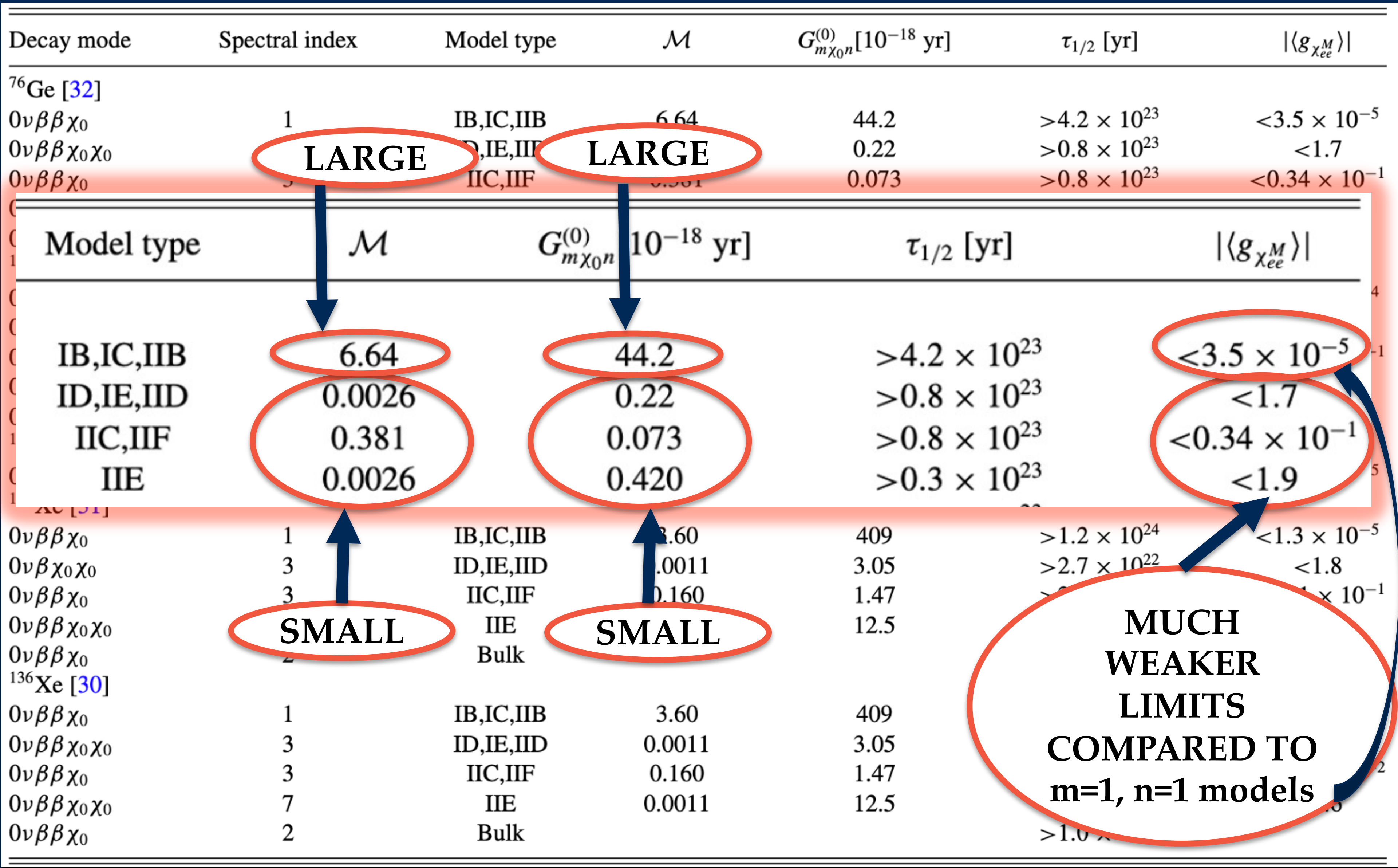


| Decay mode | Spectral index | Model type | $\mathcal{M}$ | $G^{(0)}_{m\chi_0 n}[10^{-18}\text{ yr}]$ | $\tau_{1/2}$ [yr] | $\lvert\langle g_{\chi^M_{ee}}\rangle\rvert$ |
|---|---|---|---|---|---|---|
| $^{76}$Ge [32] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 6.64 | 44.2 | $>4.2\times10^{23}$ | $<3.5\times10^{-5}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 3 | ID,IE,IID | 0.0026 | 0.22 | $>0.8\times10^{23}$ | $<1.7$ |
| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | 0.381 | 0.073 | $>0.8\times10^{23}$ | $<0.34\times10^{-1}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 7 | IIE | 0.0026 | 0.420 | $>0.3\times10^{23}$ | $<1.9$ |
| $0\nu\beta\beta\chi_0$ | 2 | Bulk | | | $>1.8\times10^{23}$ | |
| $^{130}$Te [29] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 4.40 | 413 | $>2.2\times10^{21}$ | $<2.4\times10^{-4}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 3 | ID,IE,IID | 0.0013 | 3.21 | $>0.9\times10^{21}$ | $<3.8$ |
| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | 0.199 | 1.51 | $>2.2\times10^{21}$ | $<0.87\times10^{-1}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 7 | IIE | 0.0013 | 14.4 | $>0.9\times10^{21}$ | $<2.6$ |
| $0\nu\beta\beta\chi_0$ | 2 | Bulk | | | $>2.2\times10^{21}$ | |
| $^{130}$Te [23] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 4.40 | 413 | $>1.6\times10^{22}$ | $<8.8\times10^{-5}$ |
| $^{136}$Xe [31] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 3.60 | 409 | $>1.2\times10^{24}$ | $<1.3\times10^{-5}$ |
| $0\nu\beta\chi_0\chi_0$ | 3 | ID,IE,IID | 0.0011 | 3.05 | $>2.7\times10^{22}$ | $<1.8$ |
| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | 0.160 | 1.47 | $>2.7\times10^{22}$ | $<0.31\times10^{-1}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 7 | IIE | 0.0011 | 12.5 | $>6.1\times10^{21}$ | $<1.8$ |
| $0\nu\beta\beta\chi_0$ | 2 | Bulk | | | $>2.5\times10^{23}$ | |
| $^{136}$Xe [30] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 3.60 | 409 | $>2.6\times10^{24}$ | $<8.5\times10^{-6}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 3 | ID,IE,IID | 0.0011 | 3.05 | $>4.5\times10^{24}$ | $<0.49$ |
| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | 0.160 | 1.47 | $>4.5\times10^{24}$ | $<0.24\times10^{-2}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | 7 | IIE | 0.0011 | 12.5 | $>1.1\times10^{22}$ | $<1.6$ |
| $0\nu\beta\beta\chi_0$ | 2 | Bulk | | | $>1.0\times10^{24}$ | |

# Majoron emitting $0\nu\beta\beta$

- Limits on majoron-neutrino coupling constant for different models

*PRC 103 (2021) 044302*



| Decay mode | Spectral index | Model type | $\mathcal{M}$ | $G^{(0)}_{m\chi_0 n}[10^{-18}\ \text{yr}]$ | $\tau_{1/2}$ [yr] | $\lvert\langle g_{\chi^M_{ee}}\rangle\rvert$ |
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| $0\nu\beta\beta\chi_0\chi_0$ | | D,IE,III | | 0.22 | $>0.8 \times 10^{23}$ | $<1.7$ |
| $0\nu\beta\beta\chi_0$ | | IIC,IIF | | 0.073 | $>0.8 \times 10^{23}$ | $<0.34 \times 10^{-1}$ |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | .60 | 409 | $>1.2 \times 10^{24}$ | $<1.3 \times 10^{-5}$ |
| $0\nu\beta\chi_0\chi_0$ | 3 | ID,IE,IID | .0011 | 3.05 | $>2.7 \times 10^{22}$ | $<1.8$ |
| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | .160 | 1.47 | | $\times 10^{-1}$ |
| $0\nu\beta\beta\chi_0\chi_0$ | | IIE | | 12.5 | | |
| $0\nu\beta\beta\chi_0$ | | Bulk | | | | |
| $^{136}$Xe [30] | | | | | | |
| $0\nu\beta\beta\chi_0$ | 1 | IB,IC,IIB | 3.60 | 409 | | |
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| $0\nu\beta\beta\chi_0$ | 3 | IIC,IIF | 0.160 | 1.47 | | |
| $0\nu\beta\beta\chi_0\chi_0$ | 7 | IIE | 0.0011 | 12.5 | | |
| $0\nu\beta\beta\chi_0$ | 2 | Bulk | | | $>1.0 \times$ | |

| Model type | $\mathcal{M}$ | $G^{(0)}_{m\chi_0 n}[10^{-18}\ \text{yr}]$ | $\tau_{1/2}$ [yr] | $\lvert\langle g_{\chi^M_{ee}}\rangle\rvert$ |
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LARGE

LARGE

SMALL

SMALL

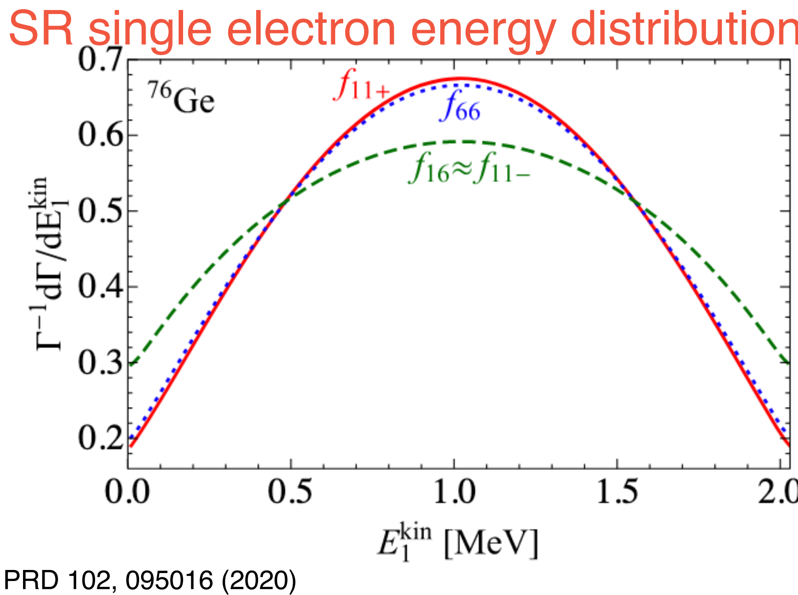
MUCH
WEAKER
LIMITS
COMPARED TO
m=1, n=1 models

# Other scenarios:Non standard mechanisms

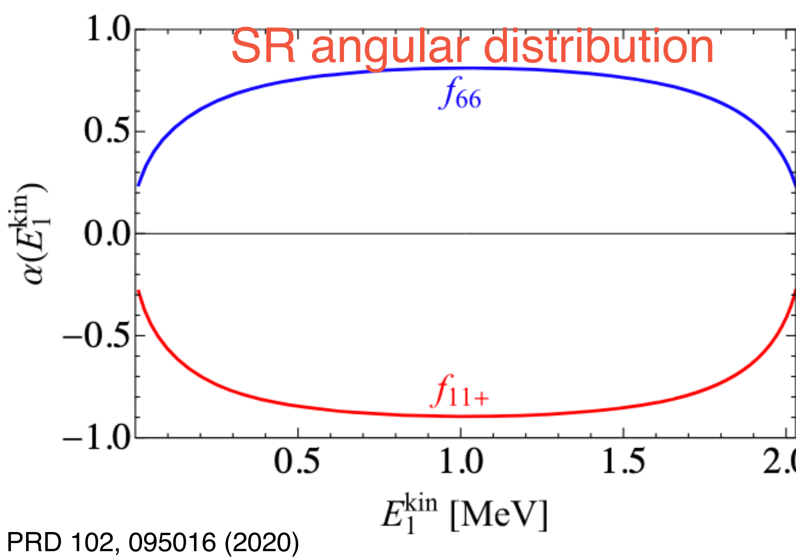
- General Lagrangian can be written in terms of effective couplings $\varepsilon$ corresponding to the point like vertices at the Fermi scale: $\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{\mathrm{LR}} + \mathcal{L}_{\mathrm{SR}}$
- In general description experimental half-life limits give information about the constraints on effective couplings $\varepsilon$:

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

- Example: the single electron energy and angular correlation distributions for the exotic short-range 0νββ decay mechanisms
  - single energy spectrum is not expected to help distinguish between the standard mass mechanism and any of the short-range mechanisms.
  - The angular correlation can distinguish between different mechanisms

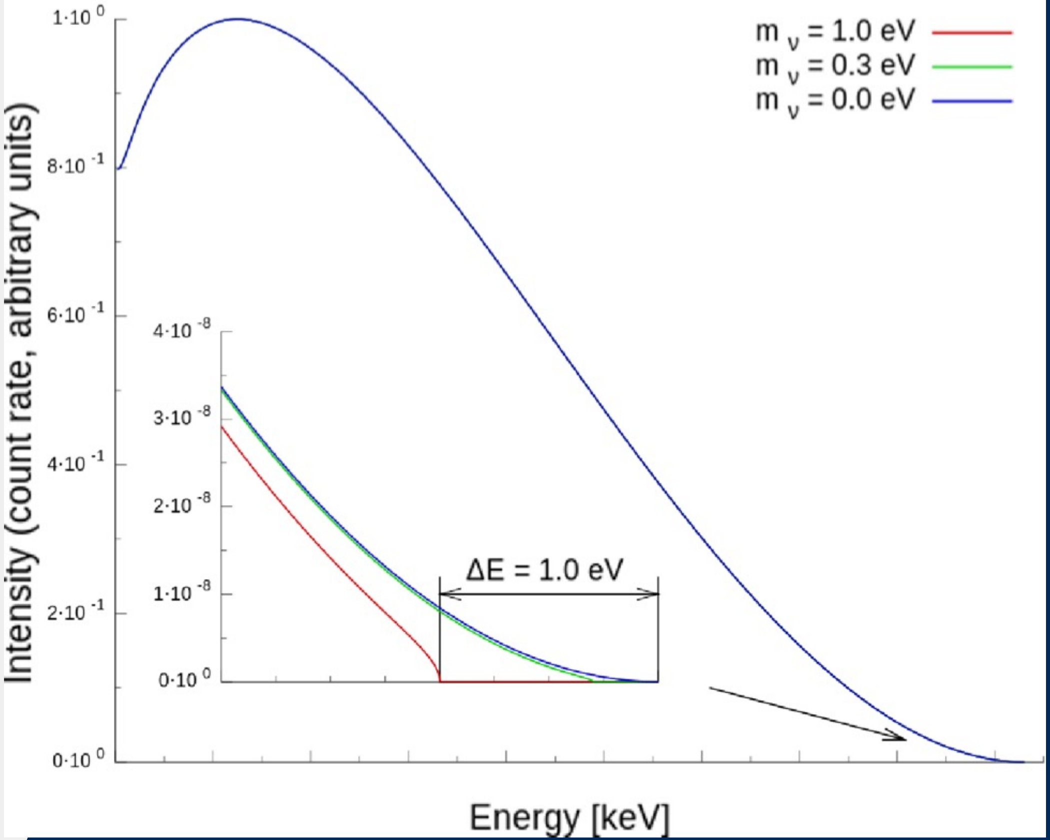

SR single electron energy distribution

PRD 102, 095016 (2020)


SR angular distribution

PRD 102, 095016 (2020)

# Part 2: Single beta decay



# Classification of β-transitions

| **Type of transition** | **Order of forbiddenness** | **$\Delta J$** | **$\pi_i\pi_f$** |
|---|---|---|---|
| Allowed | | 0,+1 | +1 |
| Forbidden unique | 1 | $\mp 2$ | -1 |
| | 2 | $\mp 3$ | +1 |
| | 3 | $\mp 4$ | -1 |
| | 4 | $\mp 5$ | +1 |
| | . | . | . |
| Forbidden non-unique | 1 | 0, $\mp 1$ | -1 |
| | 2 | $\mp 2$ | +1 |
| | 3 | $\mp 3$ | -1 |
| | 4 | $\mp 4$ | +1 |
| | . | . | . |

- The order of forbiddeness is given by the angular momentum carried by the electron (positron) and neutrino.

# Characteristics of β-transitions

- ALLOWED transitions are well known and much studied
  - The energy dependence of the nuclear matrix elements can be factored out
- FORBIDDEN UNIQUE involve maximum possible angular momentum difference

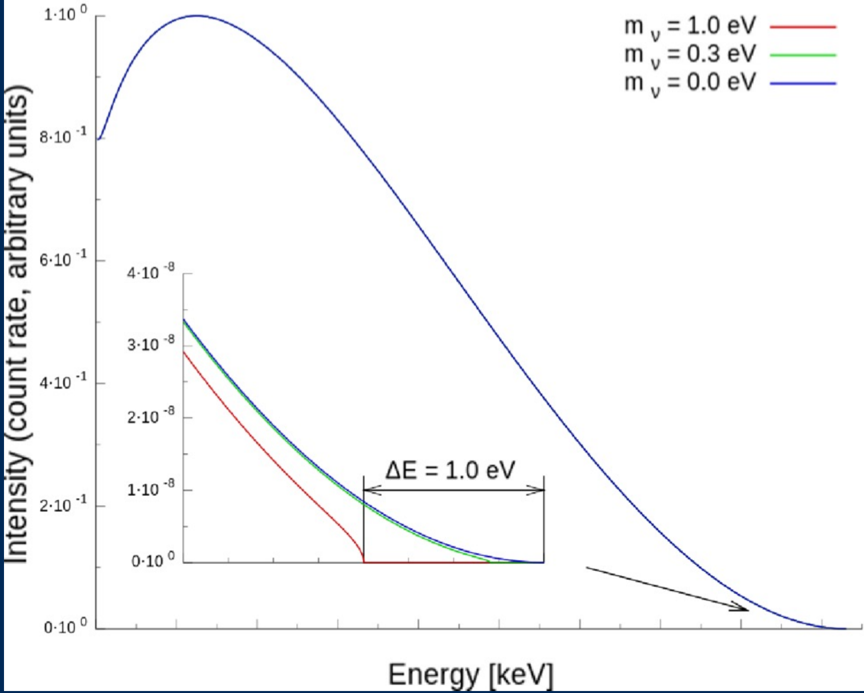
  => only one matrix element involved

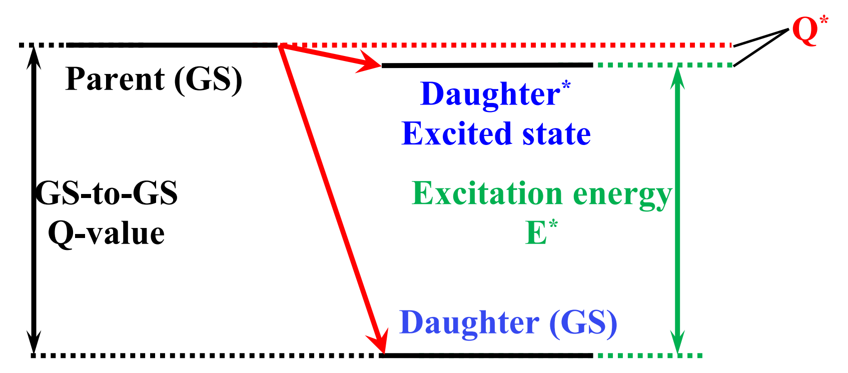
  => the factorization with NME and PSF is clear
- FORBIDDEN NON-UNIQUE β-decays feature shape functions that are complicated combinations of different NMEs and PSFs
  - They depend in a very nontrivial way on the values of the weak coupling constants, $g_V$ for the vector part and $g_A$ for the axial-vector part
  - Application: spectrum shape method which offers complementary information on the magnitude of effective $g_A$ : IBFM-2, NSM, MQPM yield a consistent result, $g_A \approx 0.92$ for the decay of $^{113}$Cd for which β-spectrum data are available [PRC 95 (2017) 024327]

Ingredients needed: Precise measurement for Q-value, spectrum shape data and calculations for phase space factor & nuclear matrix element!

# Very low Q-value cases

- In kinematical approaches, the neutrino mass is determined via precise measurement of the spectral shape distortion close to the endpoint of the spectrum
- Only a very small fraction of the events land near the endpoint and thus it is desirable to study a decay with as small *Q*-value as possible
- Some decays to excited states potentially have very small decay energy
- To determine the $Q^*$, the GS-to-GS Q-value and the excitation energy $E^*$ are needed.
- The excitation energies are usually well known ($E^* < 100$ eV)
- Campaign of new high precision GS-to-GS Q-value measurements in Jyväskylä





# Some already studied low Q candidates

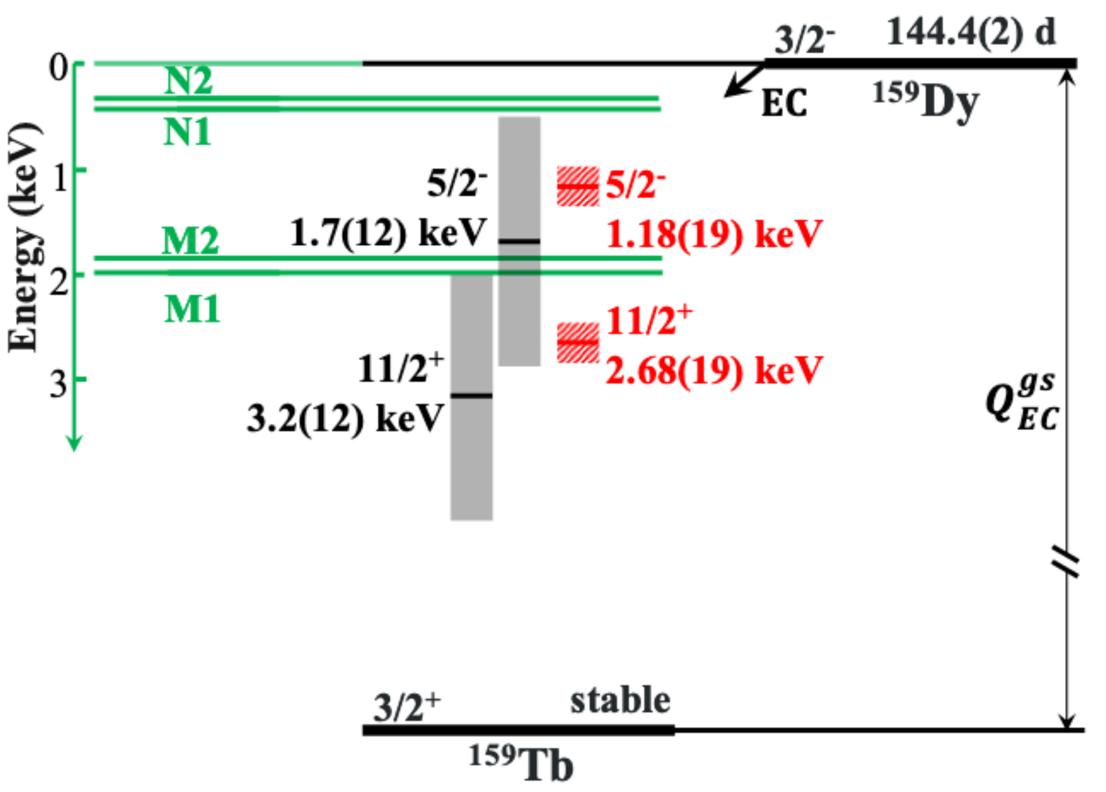
| Parent | Daughter | E* (keV) ENSDF | decay type | Q*（keV）AME2020 | Q*（keV）NEW | decay |
|---|---|---|---|---|---|---|
| 111In(9/2+) | 111Cd(3/2+) | 866.60(6) | 2nd FU | −6.4(34) | -8.97(18) | EC |
| | 111Cd(3/2+) | 864.8(3) | 2nd FU | −4.6(35) | -7.17(35) | EC |
| | 111Cd(3/2+) | 855.6(10) | 2nd FU | 4.6(36) | 2.0(10) | EC |
| | 111Cd(7/2+) | 853.94(7) | Allowed | 6.3(34) | 3.69(19) | EC |
| 131I(7/2+) | 131Xe(9/2+) | 971.22(13) | Allowed | −0.42(61) | 1.03(23) | β- |
| | 131Xe(7/2+) | 973.11(14) | Allowed | −2.31(62) | -0.86(24) | β- |
| 159Dy(3/2−) | 159Tb(5/2−) | 363.5449(14) | Allowed | 1.7(12) | 1.18(19) | EC |
| | 159Tb(11/2+) | 362.050(40) | 3rd FU | 3.2(12) | 2.68(19) | EC |
| … | … | … | … | … | … | … |

arXiv:2201.12573 (2022),PLB 830 (2022) 137135, PRL 127 (2021) 272301

- Some cases require also more precise excitation energy measurement

# Example: $^{159}\mathrm{Dy}(3/2^-) \xrightarrow{\mathrm{EC}} {}^{159}\mathrm{Tb}(5/2^-)$

PRL 127 272301 (2021)



- Allowed decay to 5/2- state, new Q-value 1.18(19) keV: Excellent candidate!
    - IBFM-2 prediction consistent with measured half-life $2.08 \times 10^5$ y
- 3rd forbidden unique transition to 11/2+ state, excluded due to predicted half-life of $10^{25}$ y

# Conclusions

- Big open questions in physics: The nature and absolute mass scale of neutrino
- Even though many milestones in the research of double beta decay has been achieved, $0\nu\beta\beta$ remains yet to be observed and fully understood.
- Observation of $0\nu\beta\beta$ would clarify many fundamental aspects of neutrino physics
  - lepton number non-conservation
  - neutrino nature: whether the neutrino is a Dirac or a Majorana particle
  - absolute neutrino mass scale
  - the type of neutrino mass ordering (normal or inverted)
  - CP violation in the lepton sector
- 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.
- Single β-decay can be used as complimentary approach to pinpoint the mass of the neutrino, as well as, to study effective value of $g_A$

Joint effort of theory and experiments (i) to interpret the data, as well as, (ii) to identify new good candidates to study

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# THANK YOU!

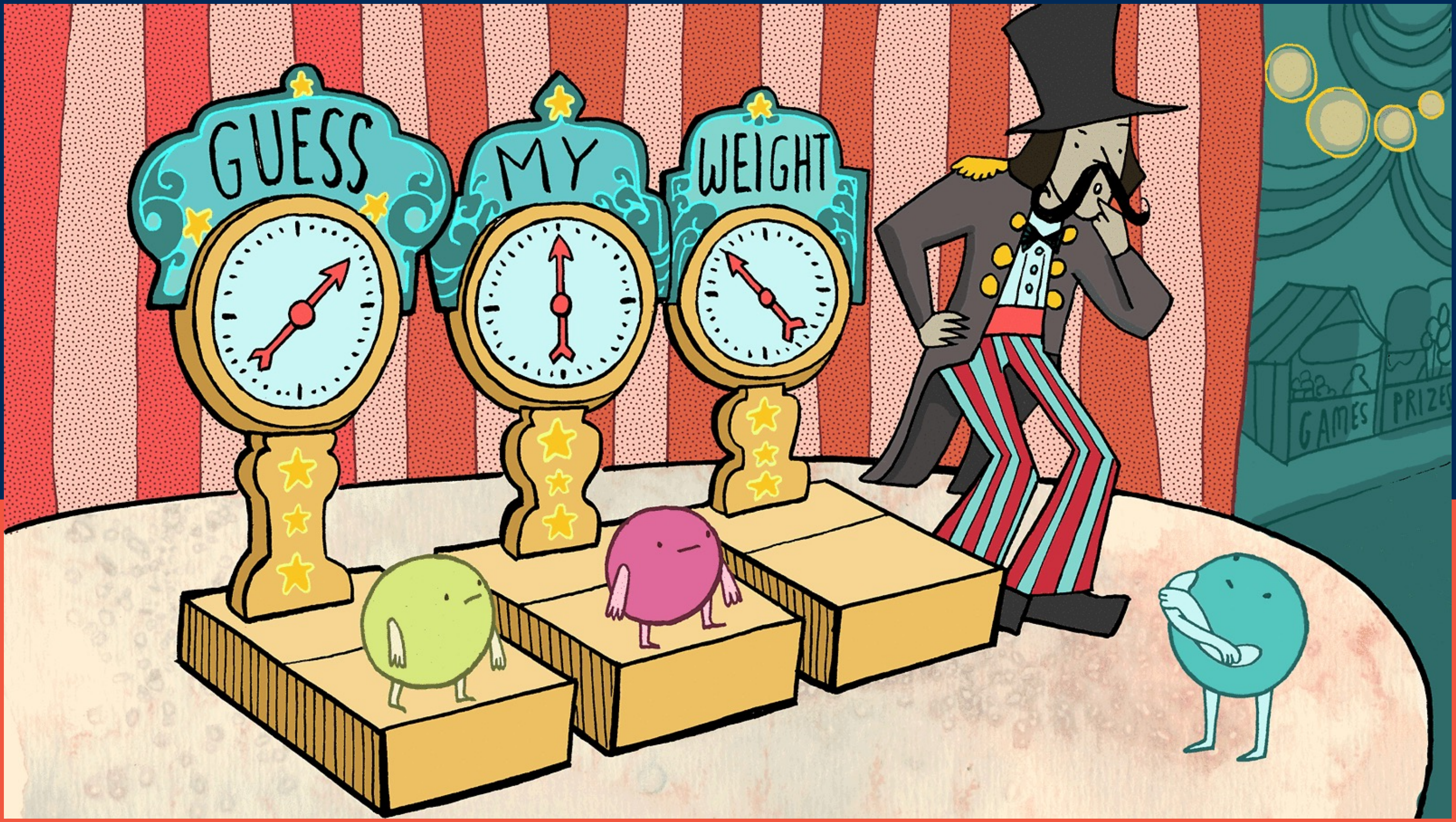

Illustration by Sandbox Studio, Chicago with Corinne Mucha