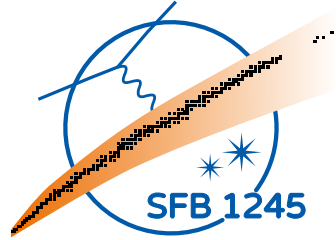




LOEWE

Exzellente Forschung für
Hessens Zukunft



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RARE NUCLEAR DECAYS AND PHYSICS BEYOND THE STANDARD MODEL

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École Joliot Curie – Saint Pierre d'Oléron, France, 2026



OUTLINE

Lecture 1

Introduction to ab initio nuclear theory

Lecture 2

From nuclear forces to nuclear properties

Lecture 3

From weak interactions to nuclear observables

Lecture 4

Nuclear probes of physics beyond the standard model

LECTURE 3

▪ **Introduction**

Selection rules for beta decays. Theory for allowed decays. Beta decay of a neutron.

▪ **Wigner-Eckart theorem**

Wigner-Eckart theorem and its consequences.

▪ **Ab initio theory for weak decays**

Electroweak interaction in the Standard Model. Chiral effective field theory for weak currents. Axial-vector quenching puzzle.

▪ **Examples of other weak interactions in nuclei**

Muon capture on light nuclei.

CHART OF NUCLIDES

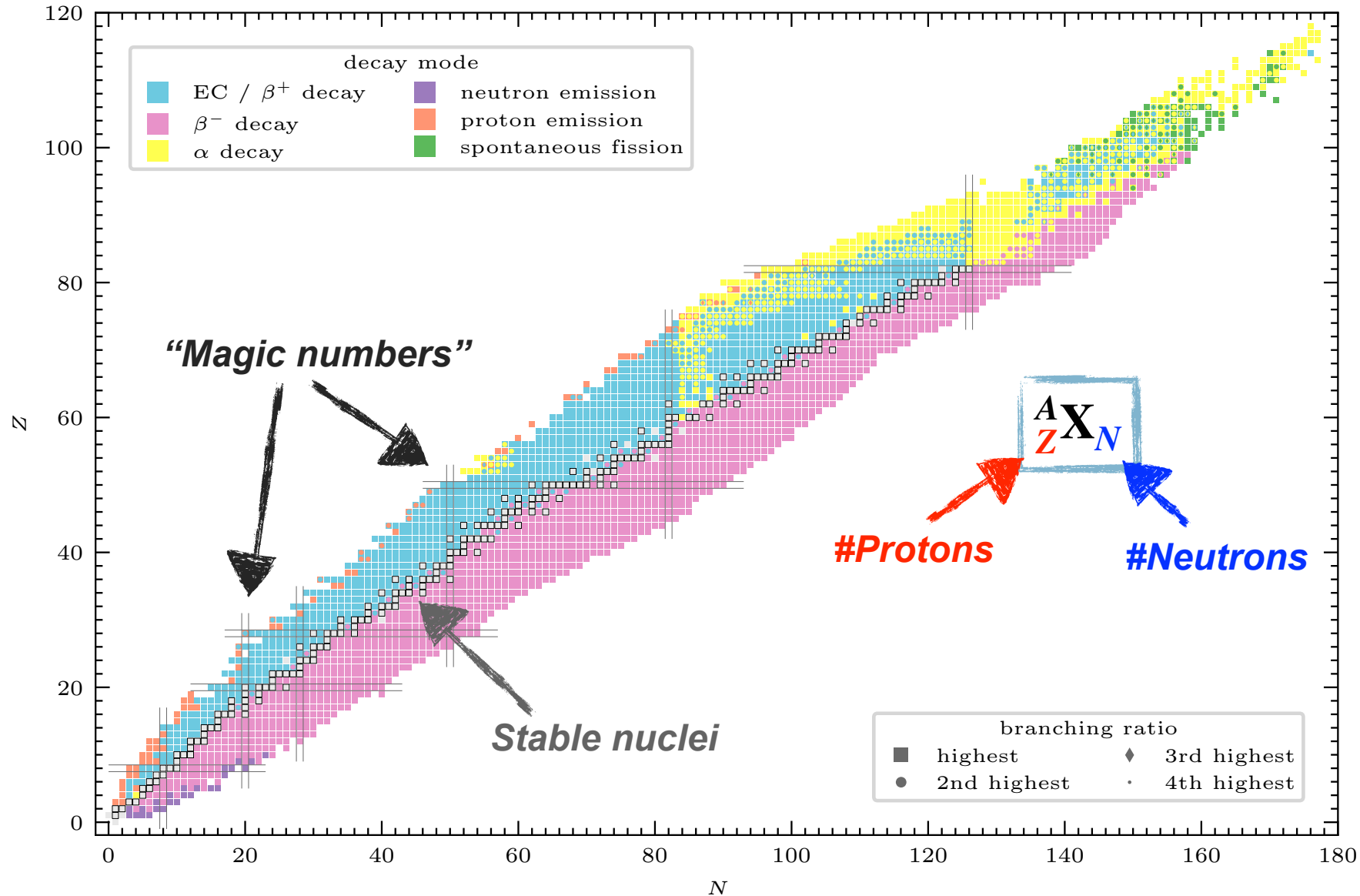


Figure courtesy of Catharina Brase

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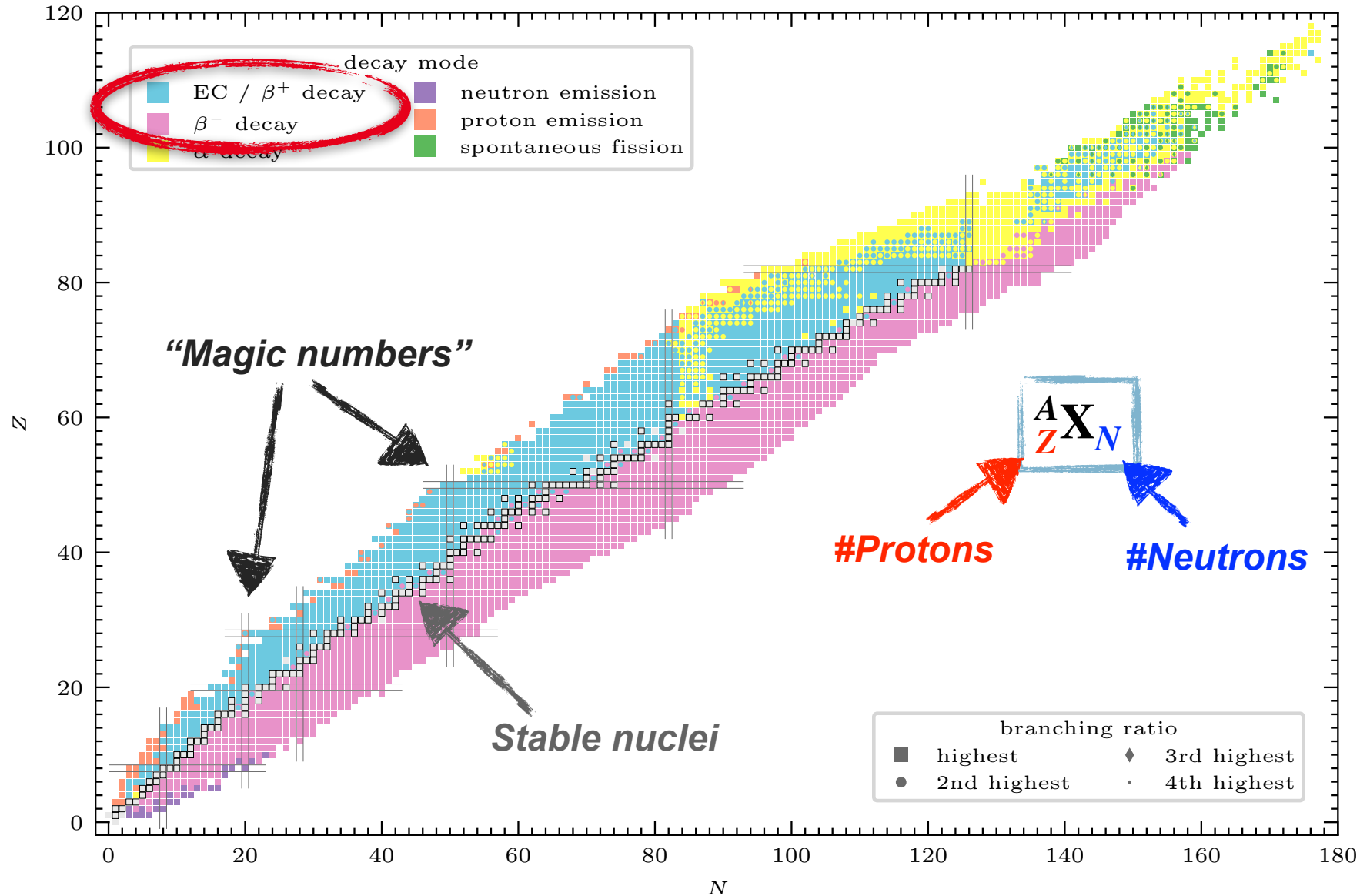


Figure courtesy of Catharina Brase

SELECTION RULES



$${}^A_Z X(J_i^{\pi_i}) \rightarrow {}^A_{Z+1} X'(J_f^{\pi_f}) + e^- + \bar{\nu}_e$$

	Spin change $ J_i - J_f $	Parity change $\pi_i \neq \pi_f?$
Allowed (Fermi or Gamow-Teller)	0, 1	No
First forbidden	0, 1, 2	Yes
Second forbidden	2, 3	No
Third forbidden	3, 4	Yes

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Weak current

$$\mathcal{J}^0 = \tau[g_V(q^2)]$$

$$\mathbf{J} = \tau \left[g_A(q^2) \boldsymbol{\sigma} - g_P(p^2) \frac{\mathbf{q}(\mathbf{q} \cdot \boldsymbol{\sigma})}{q^2 + m_\pi^2} + i g_M \frac{\boldsymbol{\sigma} \times \mathbf{q}}{2m_N} \right]$$

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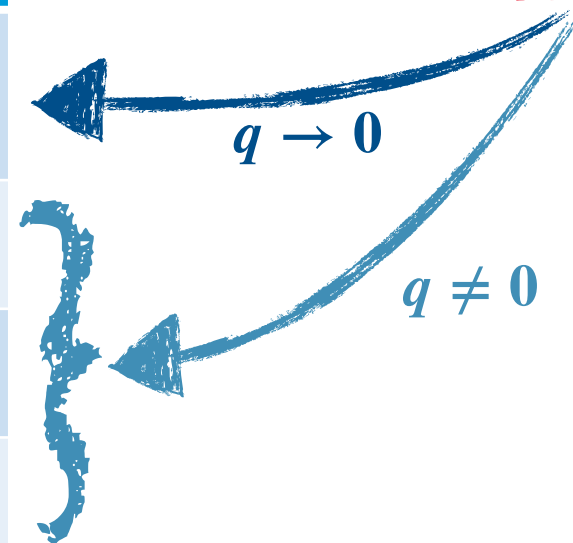
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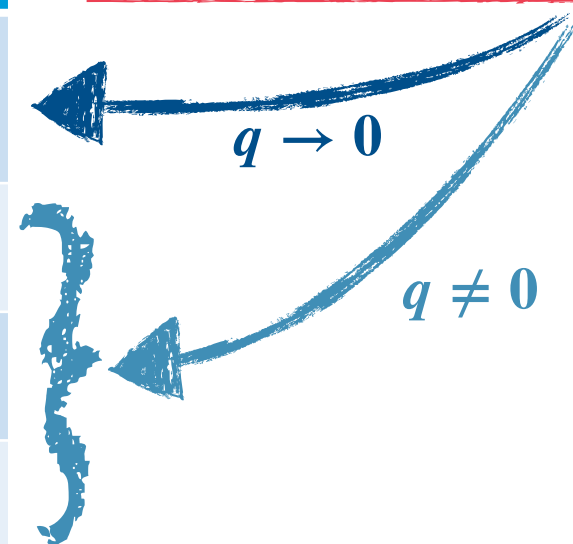
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Can be applied also to other transitions (electron/muon capture on nuclei, ...)

ALLOWED β DECAYS

Suhonen, "From Nucleons to Nucleus: concepts of microscopic nuclear theory" (2007)



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- Half-life of an allowed β decay can be written as

$$\log(ft) = \log(f_0 t_{1/2}) = \log\left(\frac{\kappa}{B_{\text{GT}} + B_{\text{F}}}\right), \quad \kappa = 6144(6) \text{ s}$$

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*Axial-vector coupling constant,
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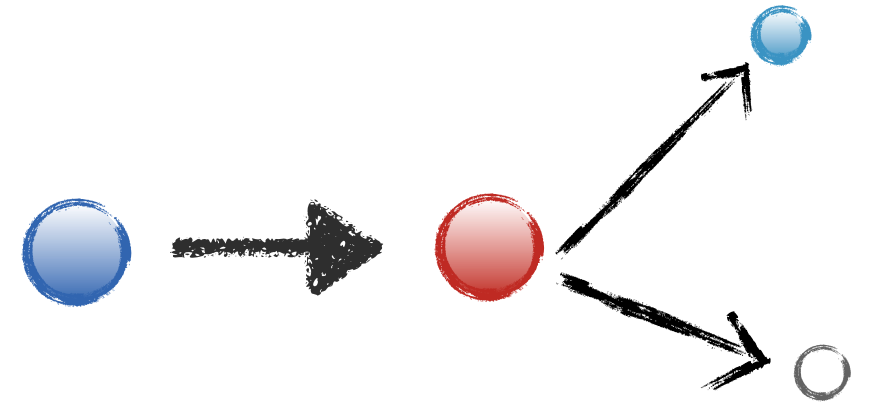
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$g_{\text{V}} = 1$
*(conserved vector-current
hypothesis)*

β DECAY OF A NEUTRON

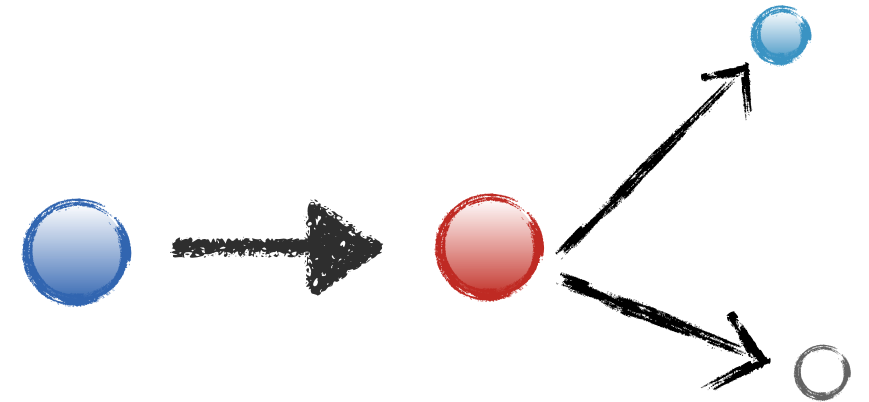
$$n\left(\frac{1}{2}^{+}\right) \rightarrow p\left(\frac{1}{2}^{+}\right) + e^{-} + \bar{\nu}_e$$



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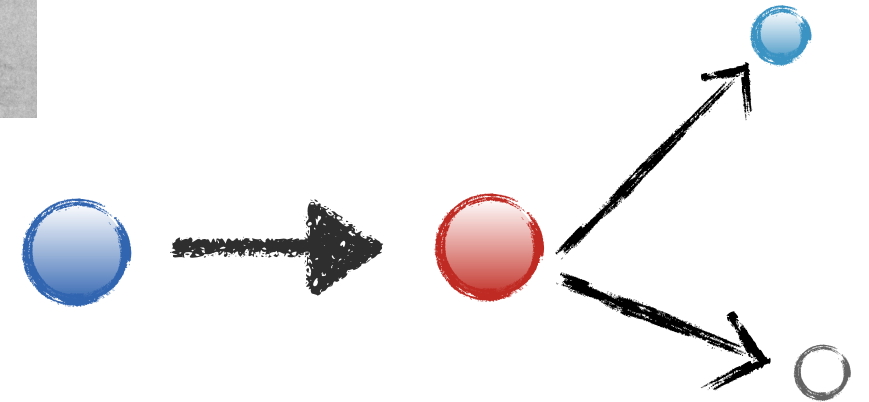
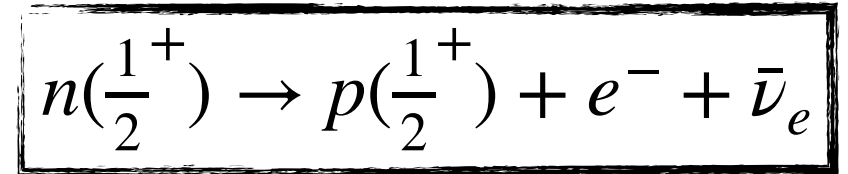
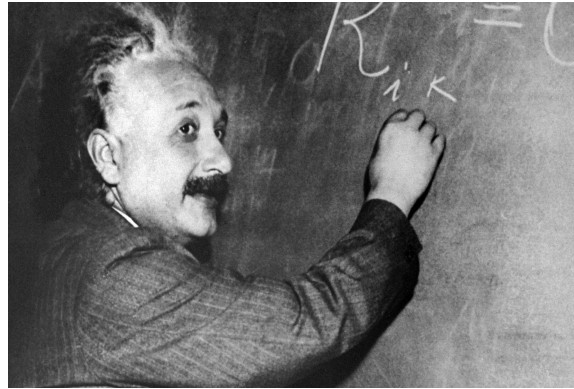
- Free neutron decays into proton via the **weak force** in ~ 15 min:

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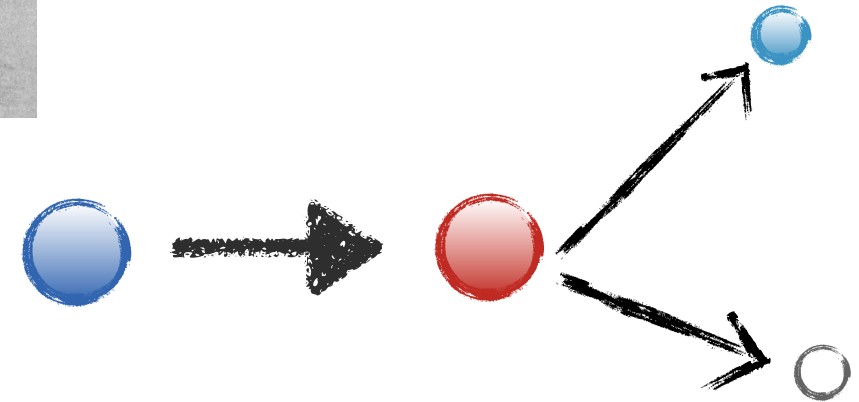
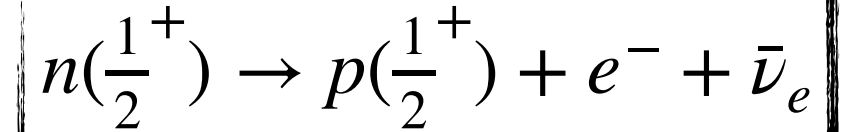
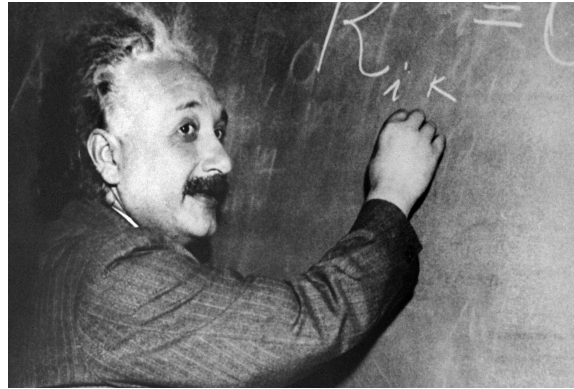
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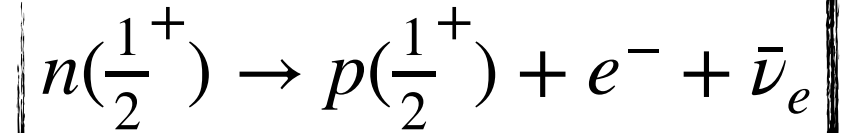
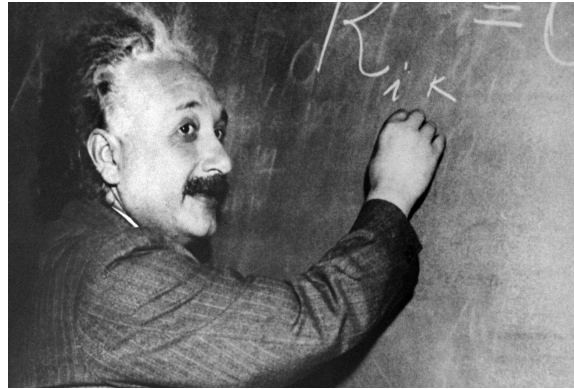
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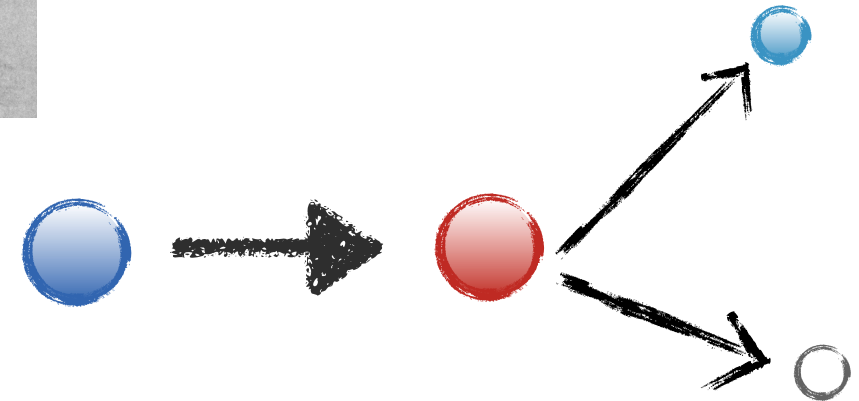


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$$\begin{aligned}\Delta E &= (m_i - m_f)c^2 \\ &= (m_n - m_p - m_{\nu} - m_e)c^2 \\ &\approx (939.565 - 938.272 - 1 \times 10^{-8} - 0.511) \text{ MeV} \\ &= 0.782 \text{ MeV}\end{aligned}$$



β DECAY OF A NEUTRON

Annu. Rev. Part. Sci. 71, 139 (2021)



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β DECAY OF A NEUTRON

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■ Life-time of a neutron

$$\frac{1}{\tau_n} = \frac{G_F^2 (m_n c^2)^5}{2\pi^2 \hbar (\hbar c)^6} V_{ud}^2 \left(1 + 3 \left(\frac{g_A}{g_V} \right)^2 \right) f (1 + \delta'_R) (1 + \Delta_R)$$

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- From recent experimental data

$$\tau_n = 879.4(0.6) \text{ s}$$

$$\rightarrow g_A = 1.2754(11)$$

WIGNER-ECKART'S THEOREM

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Suhonen, "From Nucleons to Nucleus: concepts of microscopic nuclear theory" (2007)



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WIGNER-ECKART'S THEOREM

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▪ Spherical tensor:

An operator T_L with $2L + 1$ components (z -projections) $T_{L,-L}, T_{L,-L+1}, \dots, T_{L,L-1}, T_{LL}$ which transforms under a unitary rotation $U(R)$ as

$$U(R)T_{LM}U^\dagger(R) = \sum_{M'=-L}^L T_{LM'}D_{M'M}^L(R)$$

is called a spherical tensor of rank L . Here $D_{MM'}^L$ are Wigner D matrices.

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- Examples of spherical tensors: $\mathbf{r}, \boldsymbol{\sigma}, \mathbf{J}, Y_L, \dots$

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Let T_{LM} be a spherical tensor of rank L and $|\xi j m\rangle$ quantum states with good angular momentum j and its z projection m . Then

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**Reduced matrix
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Clebsch-Gordan coefficient → (j m L M | j' m') ⟨ξ' j' || T_L || ξ j⟩ ← *Reduced matrix element*

WIGNER-ECKART'S THEOREM FOR COUPLED TENSOR OPERATORS

Suhonen, "From Nucleons to Nucleus: concepts of microscopic nuclear theory" (2007)



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- Let $\mathbf{J}_1$ and $\mathbf{J}_2$ be commuting angular momentum operators and $\{ |j_1 j_2 j m\rangle \}$ the corresponding coupled basis. Let $\mathbf{T}_{L_1}$ and $\mathbf{T}_{L_2}$ be commuting spherical tensors operating in the Hilbert spaces spanned by the basis states $\{ |j_1 m_1\rangle \}$ and $\{ |j_2 m_2\rangle \}$, respectively. Let

$$T_{LM} = [\mathbf{T}_{L_1} \mathbf{T}_{L_2}]_{LM} = \sum_{M_1 M_2} (L_1 M_1 L_2 M_2 | L M) T_{L_1 M_1} T_{L_2 M_2} .$$

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Then, the reduced matrix element is

$$\langle j_1 j_2 j || \mathbf{T}_L || j'_1 j'_2 j' \rangle = \sqrt{2j+1} \sqrt{2L+1} \sqrt{2j'+1} \begin{Bmatrix} j_1 & j_2 & j \\ j'_1 & j'_2 & j' \\ L_1 & L_2 & L \end{Bmatrix} \langle j_1 || \mathbf{T}_{L_1} || j'_1 \rangle \langle j_2 || \mathbf{T}_{L_2} || j'_2 \rangle$$

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Wigner 9j symbol

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EXAMPLE

Suhonen, “From Nucleons to Nucleus: concepts of microscopic nuclear theory” (2007)



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EXAMPLE



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- The reduced matrix element for the spin operator σ can be derived rewriting it as $\sigma = [1\sigma]_1$ and using the Wigner-Eckart theorem for coupled tensor operators

$$\begin{aligned}\langle n_a l_a \tfrac{1}{2}; j_a \| \sigma \| n_b l_b \tfrac{1}{2}; j_b \rangle &= \langle n_a l_a \tfrac{1}{2}; j_a \| [1\sigma]_1 \| n_b l_b \tfrac{1}{2}; j_b \rangle \\ &= \sqrt{2j_a + 1} \sqrt{3} \sqrt{2j_b + 1} \begin{Bmatrix} l_a & \tfrac{1}{2} & j_a \\ l_b & \tfrac{1}{2} & j_b \\ 0 & 1 & 1 \end{Bmatrix} \langle l_a \| \mathbf{1} \| l_b \rangle \langle \tfrac{1}{2} \| \sigma \| \tfrac{1}{2} \rangle \\ &= \sqrt{6} \sqrt{2j_a + 1} \sqrt{2j_b + 1} \delta_{n_a n_b} \delta_{l_a l_b} (-1)^{l_a + j_b + \frac{3}{2}} \begin{Bmatrix} j_a & j_b & l_a \\ \tfrac{1}{2} & \tfrac{1}{2} & 1 \end{Bmatrix}\end{aligned}$$

EXAMPLE



Suhonen, "From Nucleons to Nucleus: concepts of microscopic nuclear theory" (2007)

- The reduced matrix element for the spin operator σ can be derived rewriting it as $\sigma = [1\sigma]_1$ and using the Wigner-Eckart theorem for coupled tensor operators

$$\langle n_a l_a \frac{1}{2}; j_a \| \sigma \| n_b l_b \frac{1}{2}; j_b \rangle = \langle n_a l_a \frac{1}{2}; j_a \| [1\sigma]_1 \| n_b l_b \frac{1}{2}; j_b \rangle$$

$$= \sqrt{2j_a + 1} \sqrt{3} \sqrt{2j_b + 1} \begin{Bmatrix} l_a & \frac{1}{2} & j_a \\ l_b & \frac{1}{2} & j_b \\ 0 & 1 & 1 \end{Bmatrix} \langle l_a \| \mathbf{1} \| l_b \rangle \langle \frac{1}{2} \| \sigma \| \frac{1}{2} \rangle$$

Wigner 6j symbol

$$= \sqrt{6} \sqrt{2j_a + 1} \sqrt{2j_b + 1} \delta_{n_a n_b} \delta_{l_a l_b} (-1)^{l_a + j_b + \frac{3}{2}} \begin{Bmatrix} j_a & j_b & l_a \\ \frac{1}{2} & \frac{1}{2} & 1 \end{Bmatrix}$$

WIGNER-ECKART THEOREM

Suhonen, "From Nucleons to Nucleus: concepts of microscopic nuclear theory" (2007)



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WIGNER-ECKART THEOREM

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- For a **one-body spherical tensor**, one can derive

$$T_{\lambda\mu} = \sum_{\alpha\beta} \langle \alpha | T_{\lambda\mu} | \beta \rangle a_{\alpha}^{\dagger} a_{\beta} = \frac{1}{\sqrt{2\lambda + 1}} \sum_{ab} \langle a || \mathbf{T}_{\lambda} || b \rangle [a_a^{\dagger} \tilde{a}_b]_{\lambda\mu} ,$$

$$\text{where } \tilde{a}_{\alpha} \equiv (-1)^{j_a + m_{\alpha}} a_{-\alpha}, \quad a_{-\alpha} = a_{a, -m_{\alpha}}$$

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*Reduced single-particle
matrix element*

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- Evaluating **electroweak processes** (such as β decay) in nuclei, we need to compute nuclear matrix elements of the type

$$\langle \xi_f J_f M_f | T_{\lambda\mu} | \xi_i J_i M_i \rangle = \sum_{\alpha\beta} \langle \alpha | T_{\lambda\mu} | \beta \rangle \langle \xi_f J_f M_f | a_{\alpha}^{\dagger} a_{\beta} | \xi_i J_i M_i \rangle$$

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- Applying **Wigner-Eckart theorem** to this gives

$$\langle \xi_f J_f || T_{\lambda} || \xi_i J_i \rangle = \frac{1}{\sqrt{2\lambda + 1}} \sum_{ab} \langle a || T_{\lambda} || b \rangle \langle \xi_f J_f || [a_a^{\dagger} \tilde{a}_b]_{\lambda} || \xi_i J_i \rangle$$

GAMOW-TELLER MATRIX ELEMENT

Suhonen, “From Nucleons to Nucleus: concepts of microscopic nuclear theory” (2007)



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GAMOW-TELLER MATRIX ELEMENT



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- We can apply the Wigner-Eckart theorem to derive a useful form for the reduced Gamow-Teller matrix element

$$\langle \xi_f J_f || \sum_a \boldsymbol{\sigma}_a \tau_a^- || \xi_i J_i \rangle = \frac{1}{\sqrt{3}} \sum_{ab} \langle a || \boldsymbol{\sigma} || b \rangle \langle \xi_f J_f || [a_a^\dagger \tilde{a}_b]_1 || \xi_i J_i \rangle \langle t_a t_{z,a} | \tau^- | t_b t_{z,b} \rangle ,$$

GAMOW-TELLER MATRIX ELEMENT



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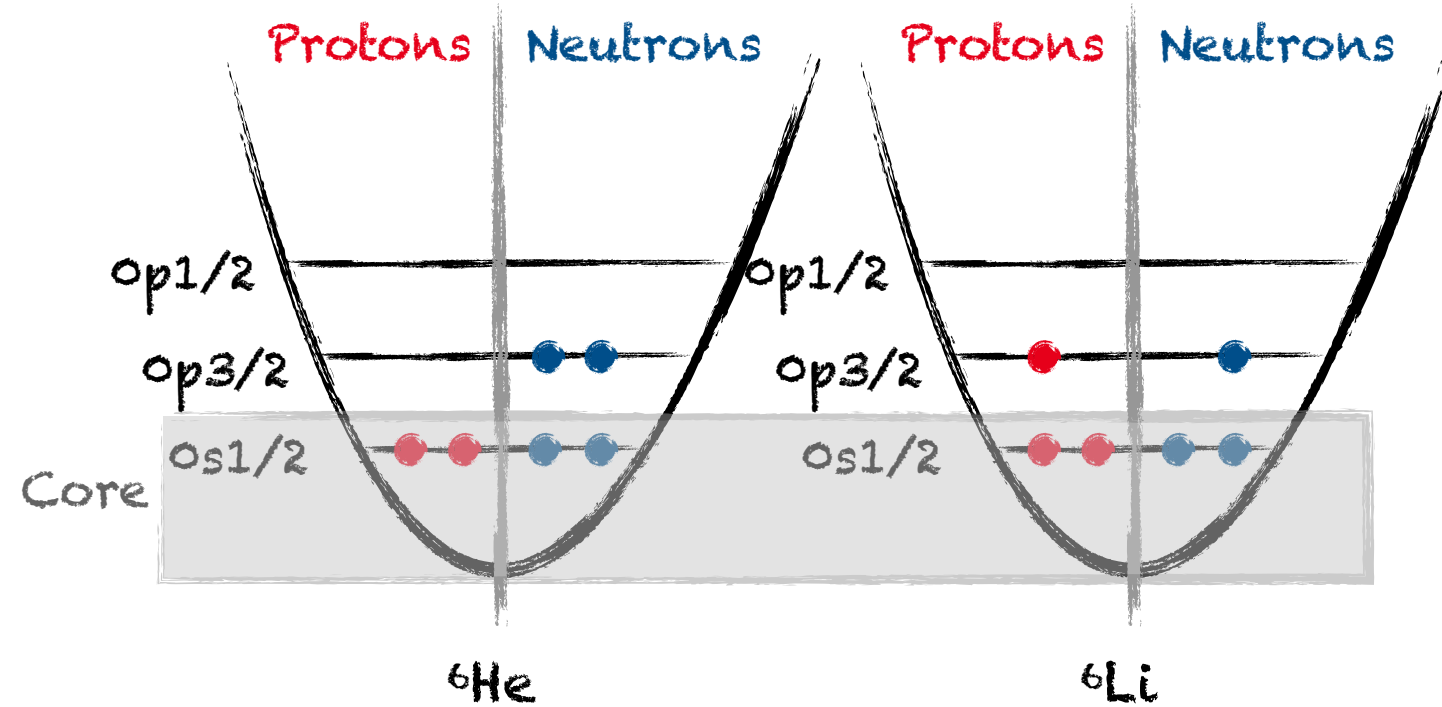
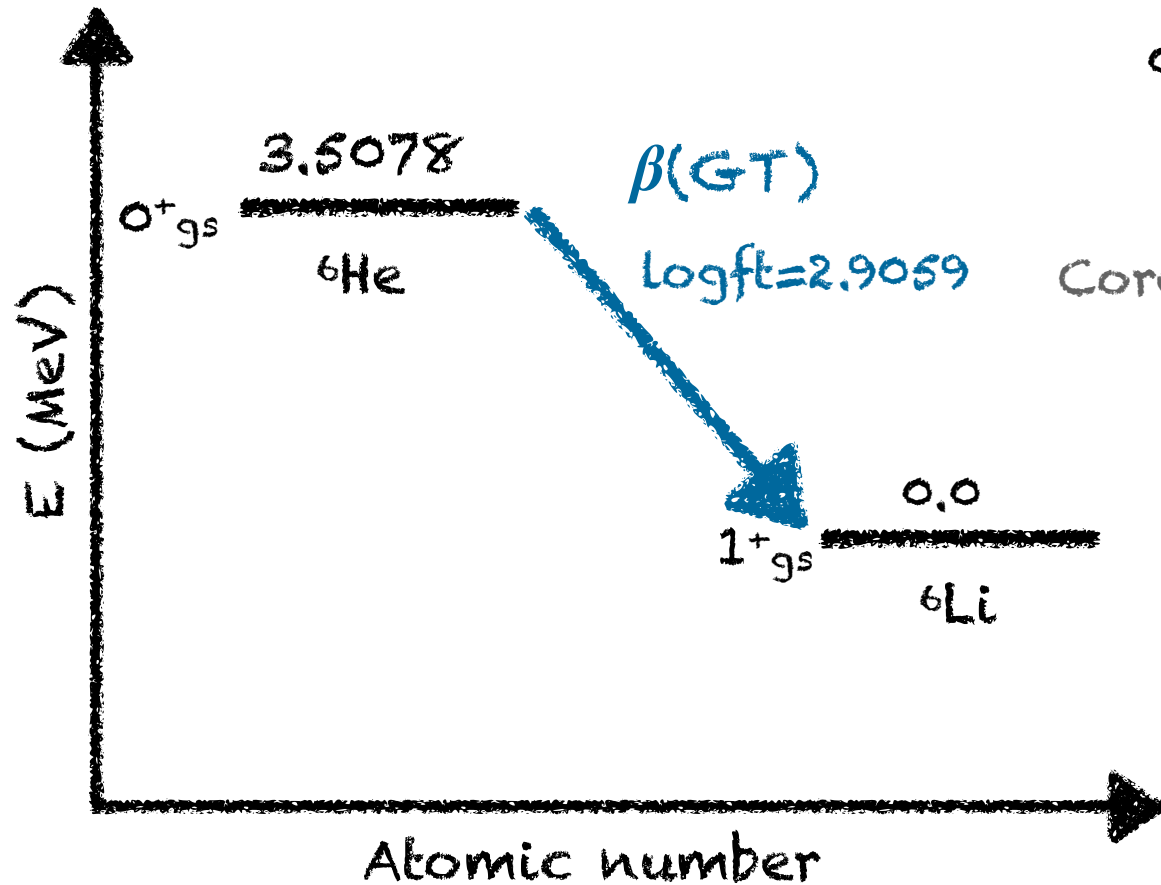
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- Where

$$\langle a || \boldsymbol{\sigma} || b \rangle = \sqrt{6} \sqrt{2j_a + 1} \sqrt{2j_b + 1} \delta_{n_a n_b} \delta_{l_a l_b} (-1)^{l_a + j_b + \frac{3}{2}} \begin{Bmatrix} j_a & j_b & l_a \\ \frac{1}{2} & \frac{1}{2} & 1 \end{Bmatrix}$$

DO IT YOURSELF: β DECAY OF ${}^6\text{He}$

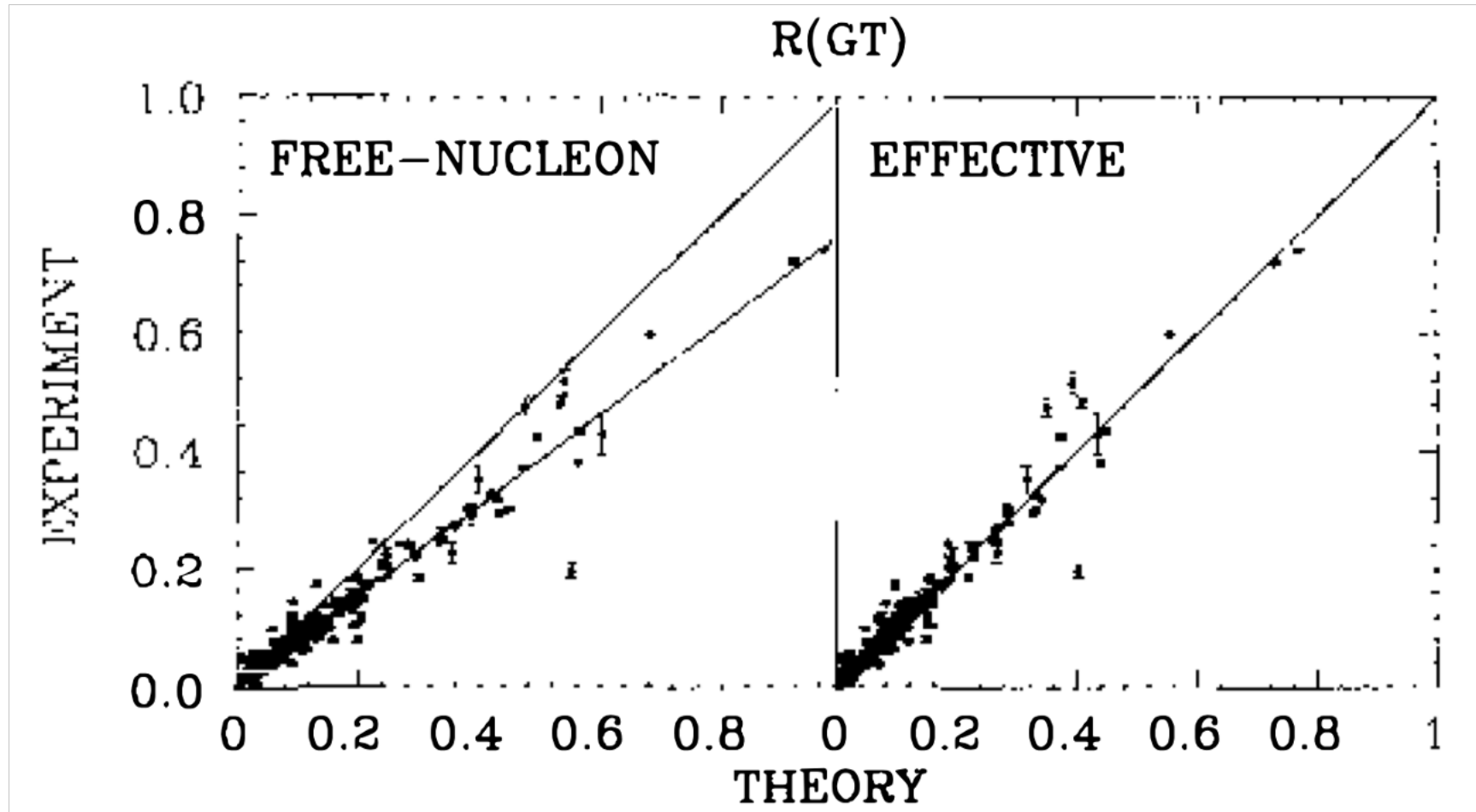


$$|{}^6\text{He}; 0^+\rangle = \frac{1}{\sqrt{2}}[a_{\nu 0 p_{3/2}}^\dagger a_{\nu 0 p_{3/2}}^\dagger]_{0^+} |\Phi\rangle$$

$$|{}^6\text{Li}; 1^+\rangle = [a_{\pi 0 p_{3/2}}^\dagger a_{\nu 0 p_{3/2}}^\dagger]_{1^+} |\Phi\rangle$$

AB INITIO THEORY FOR WEAK INTERACTIONS

AXIAL-VECTOR QUENCHING PUZZLE

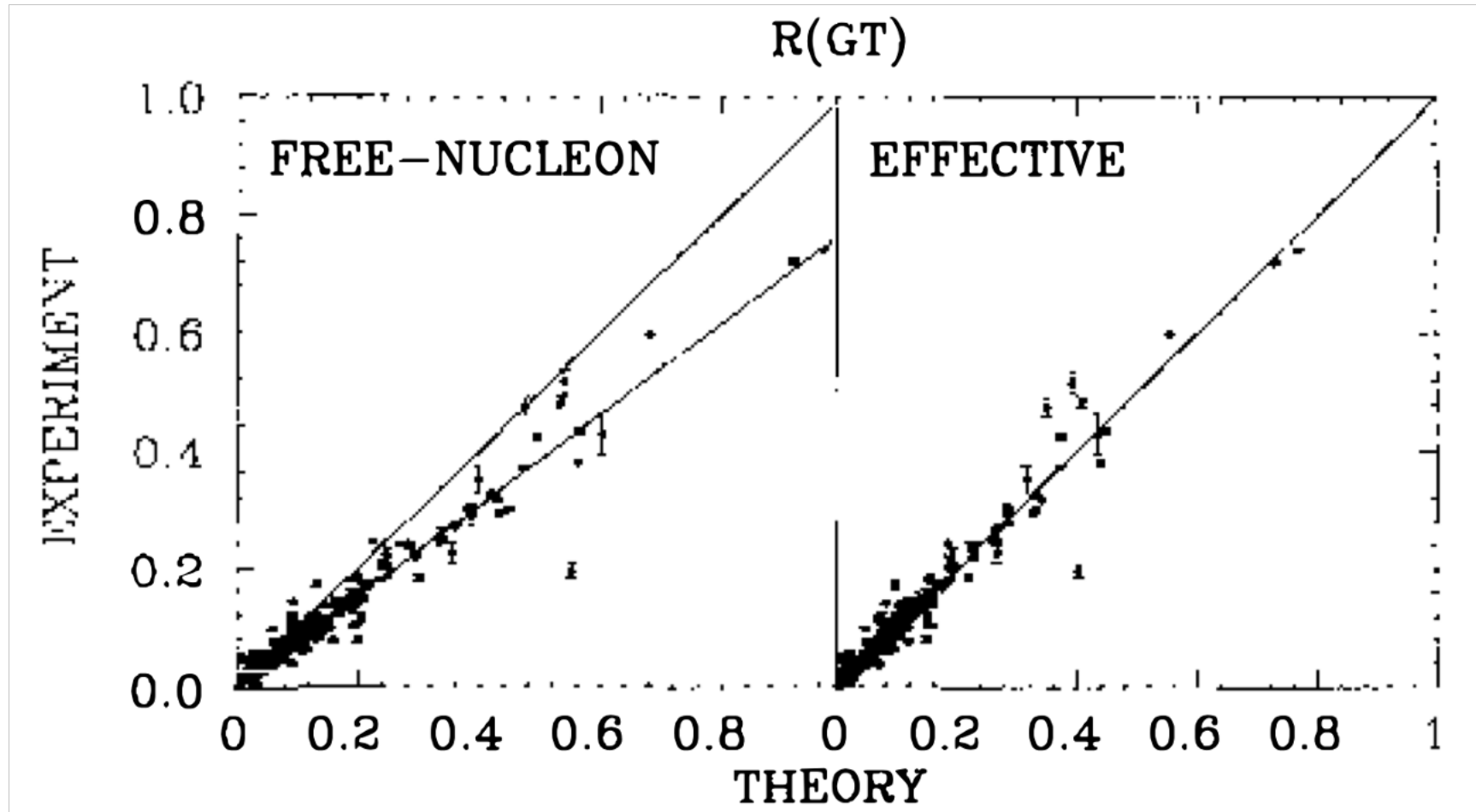


Brown, Wildenthal, Ann. Rev. Nucl. Part. Sci. 38, 29 (1988)

AXIAL-VECTOR QUENCHING PUZZLE



Phenomenological methods overestimate β -decay rates

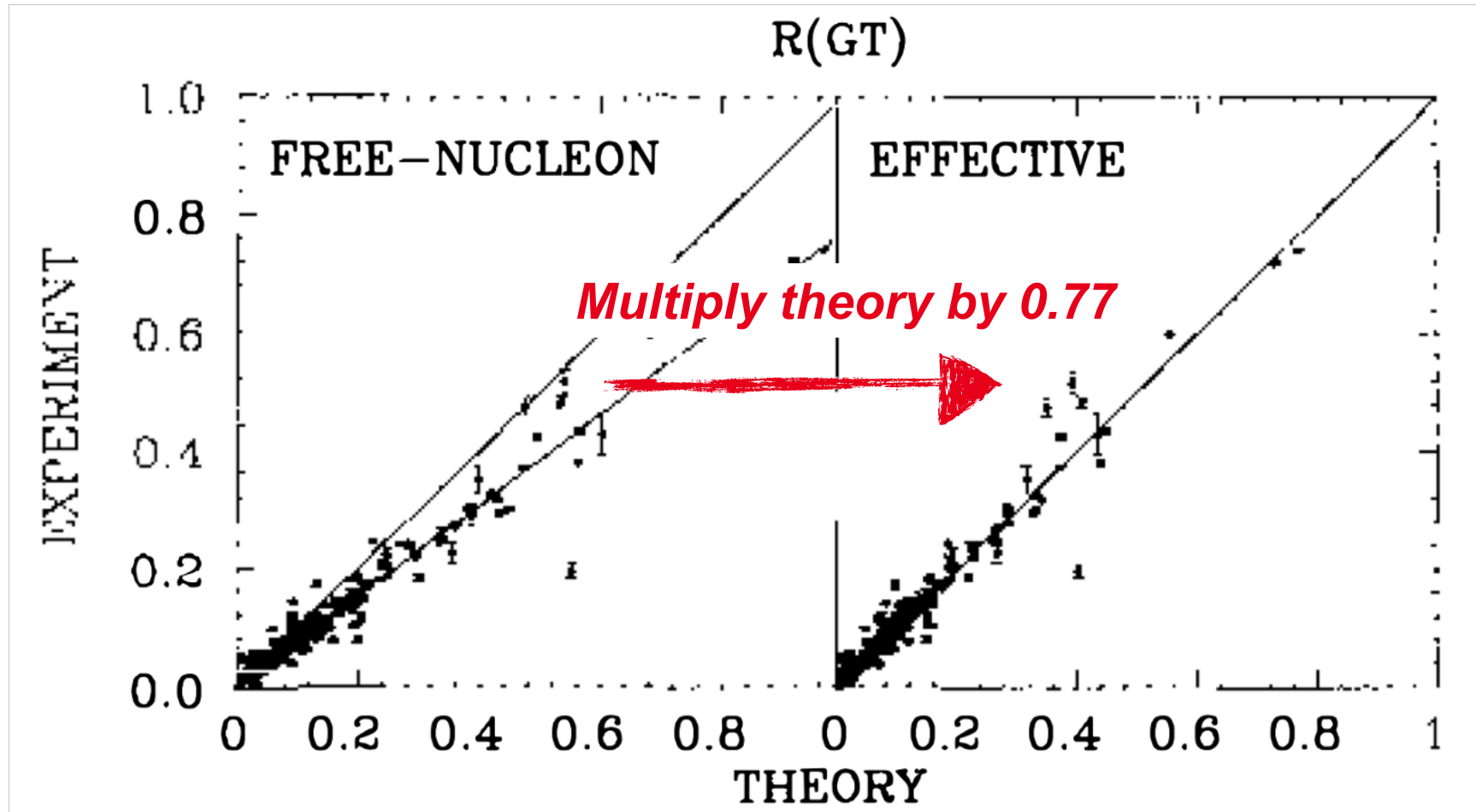


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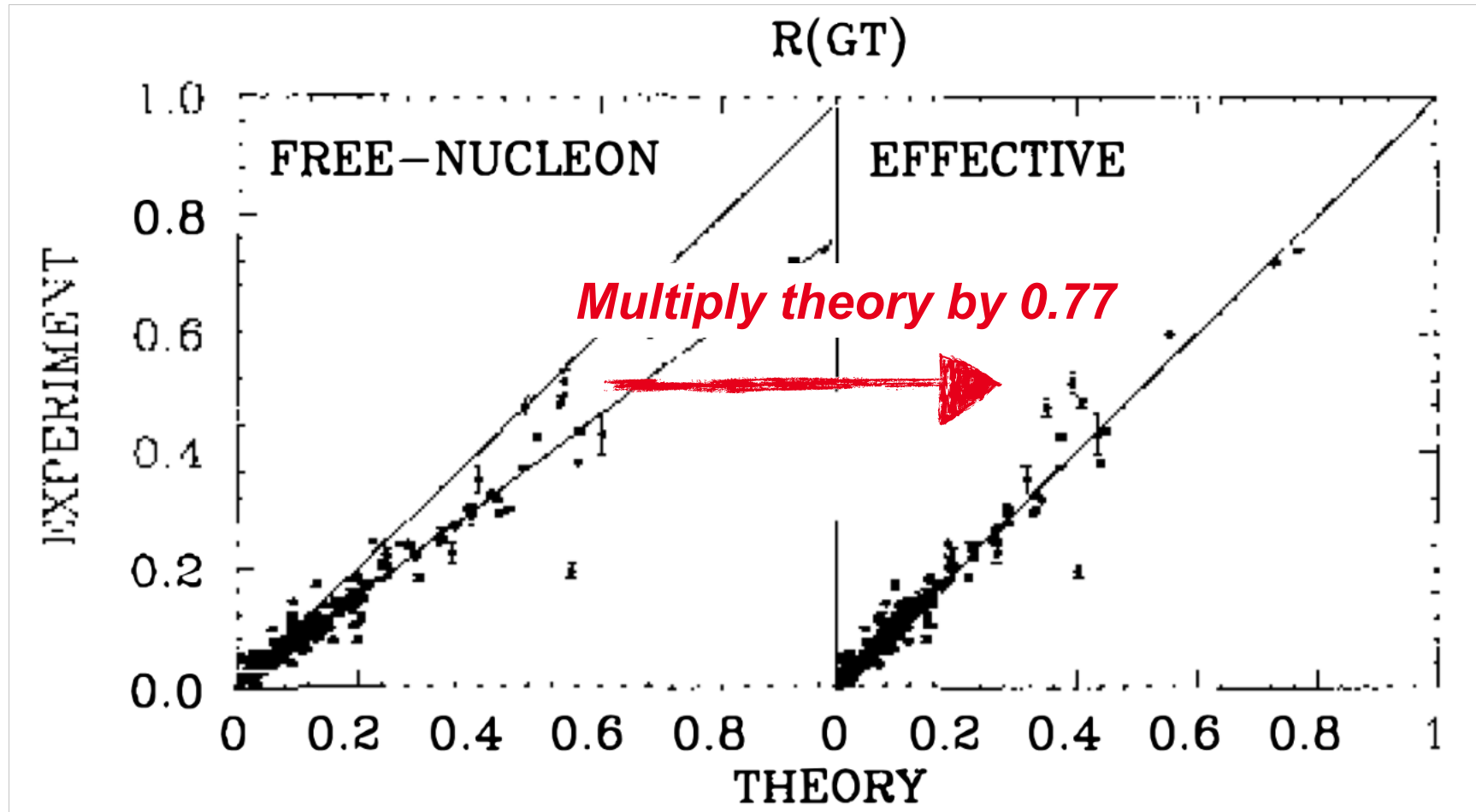
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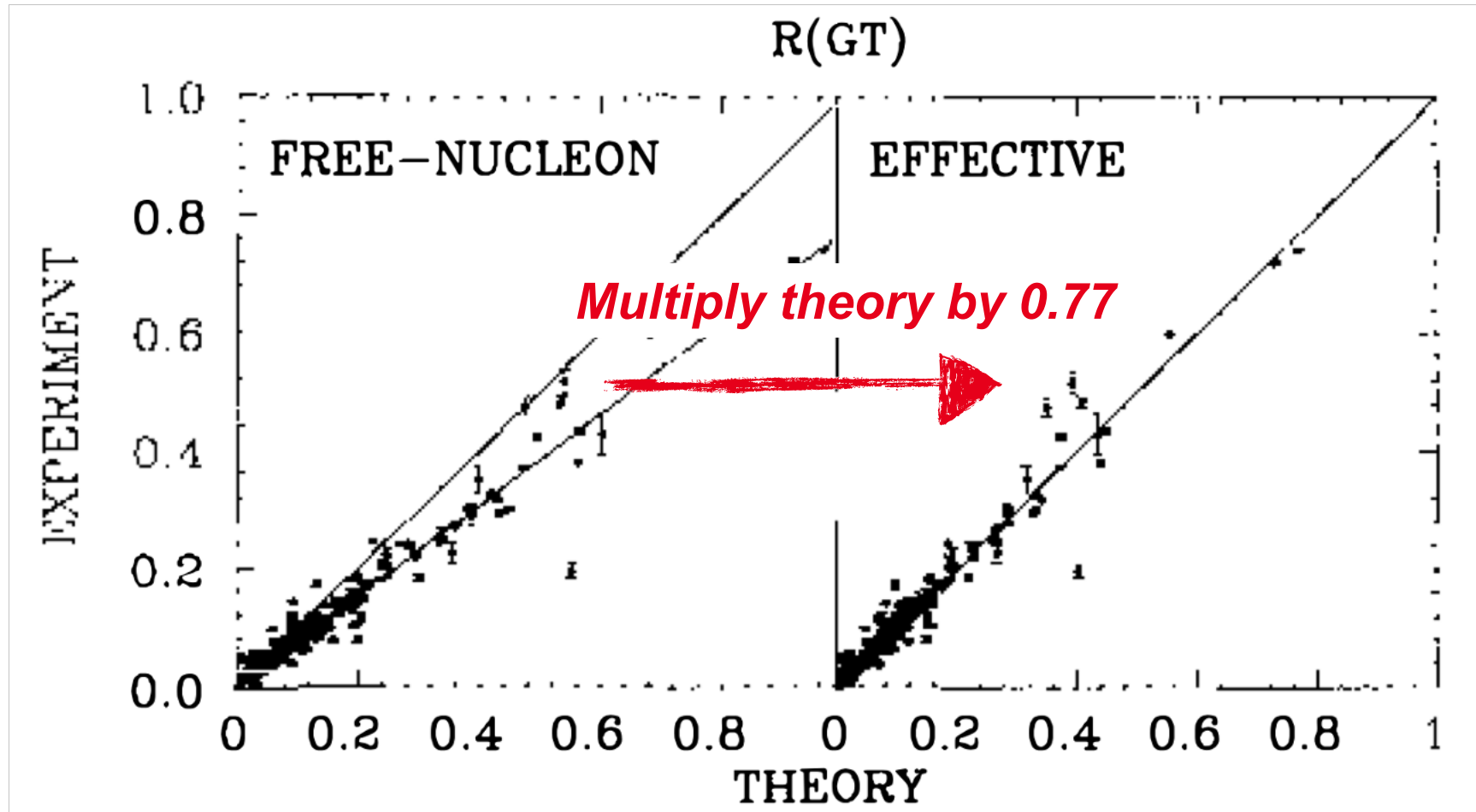
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*In-medium
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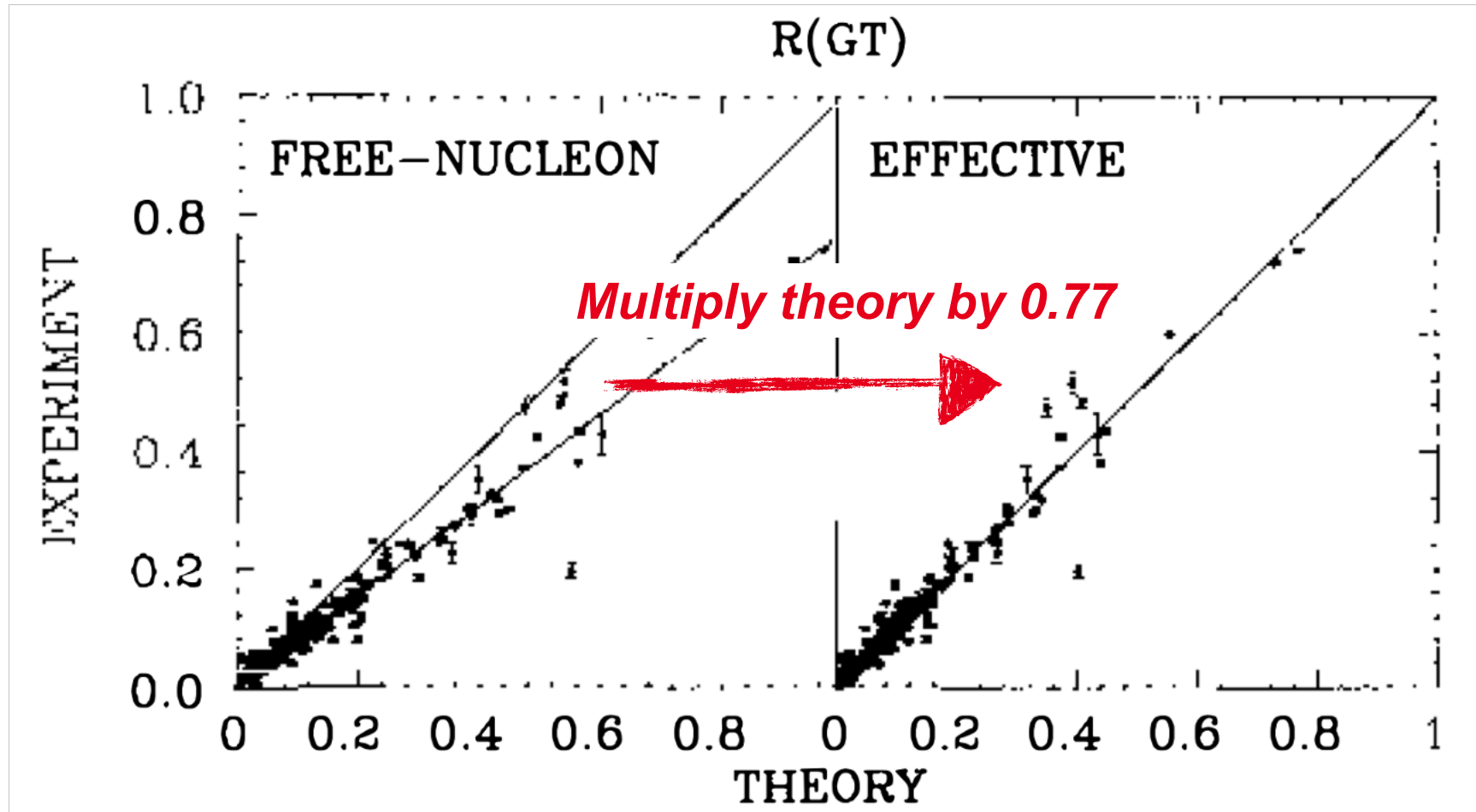
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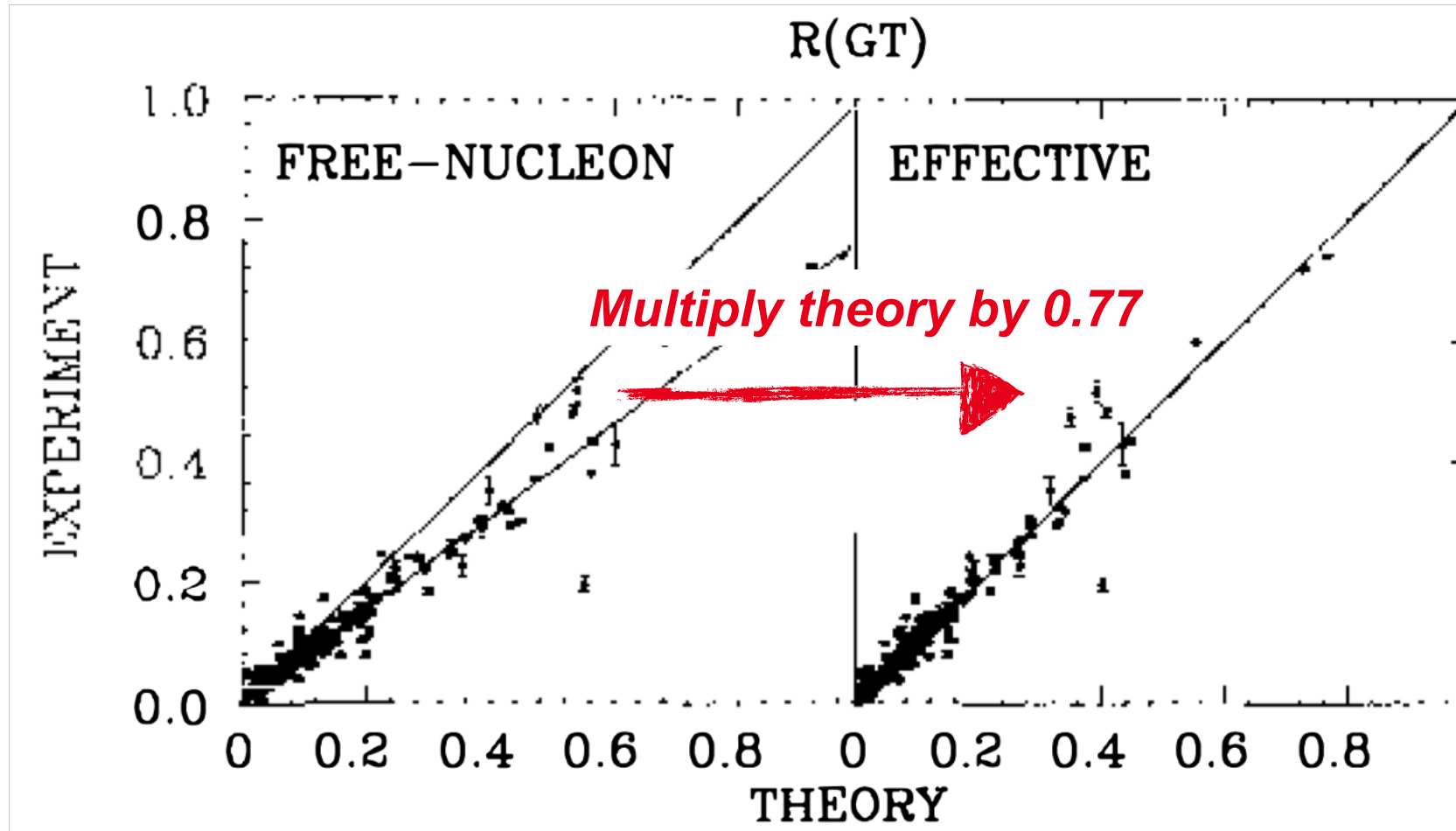
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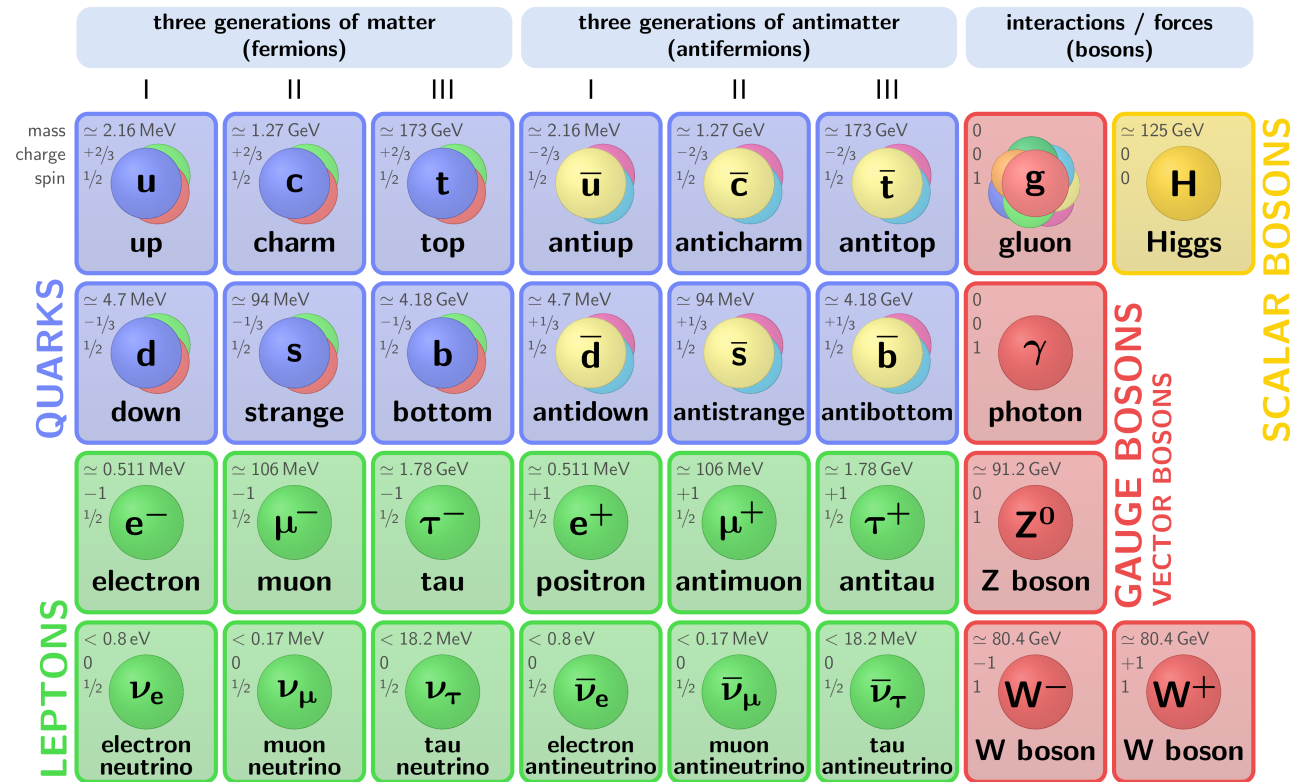
STANDARD-MODEL INTERACTIONS



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Weinberg, *Phys. Rev. Lett.* 19, 1264 (1967);

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STANDARD-MODEL INTERACTIONS

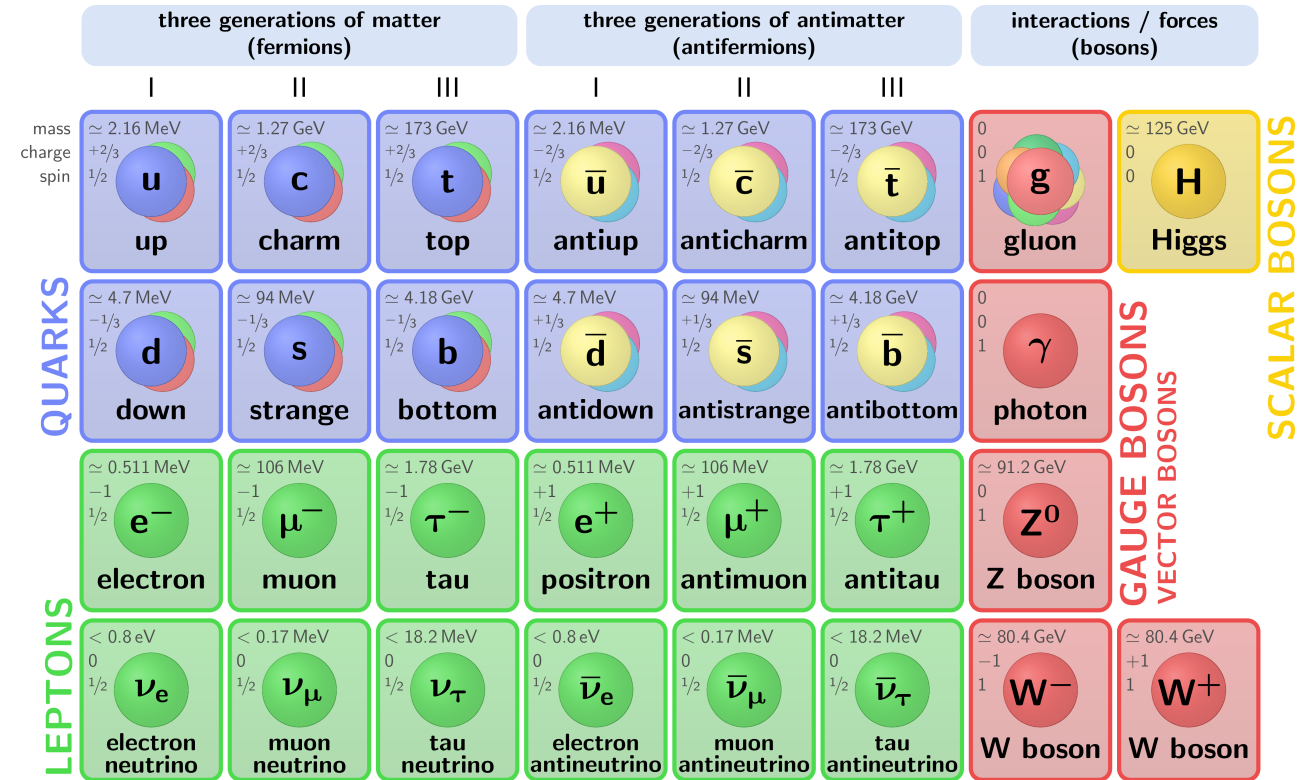


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■ The Standard Model describes



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STANDARD-MODEL INTERACTIONS

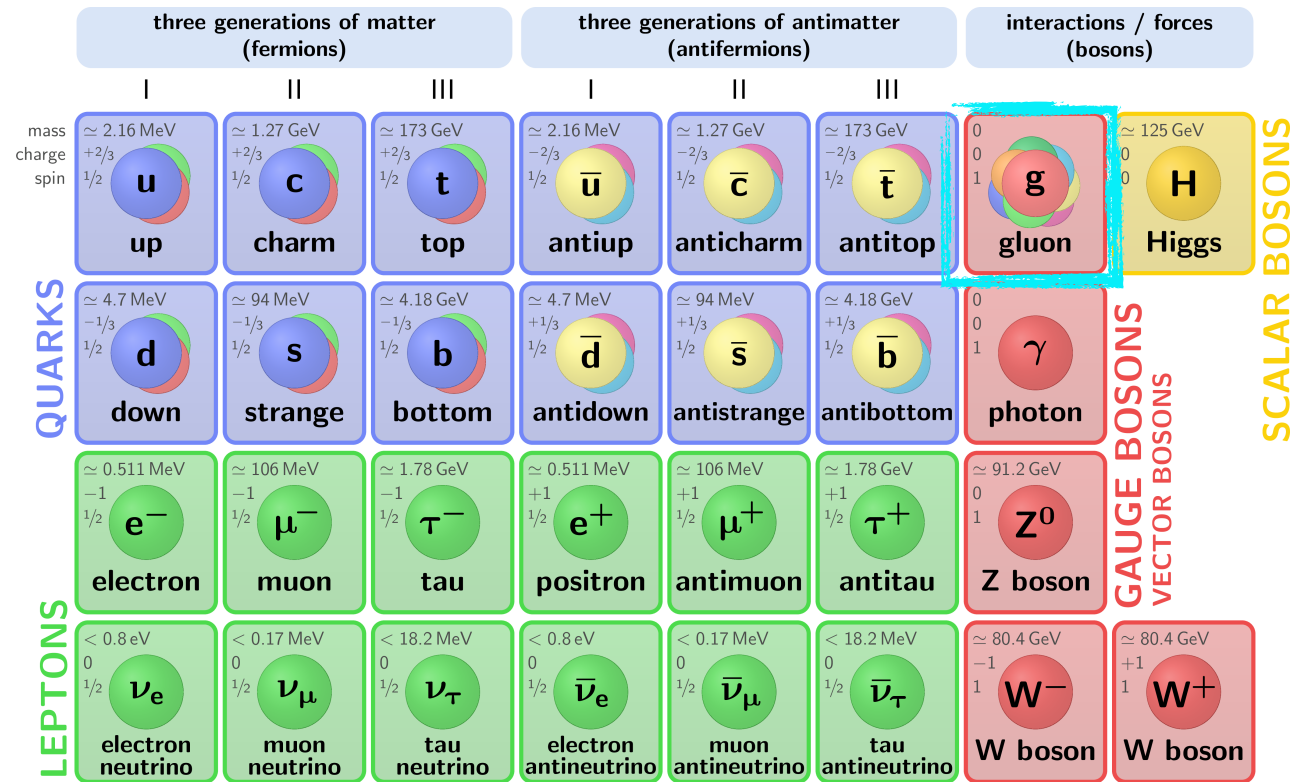


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STANDARD-MODEL INTERACTIONS

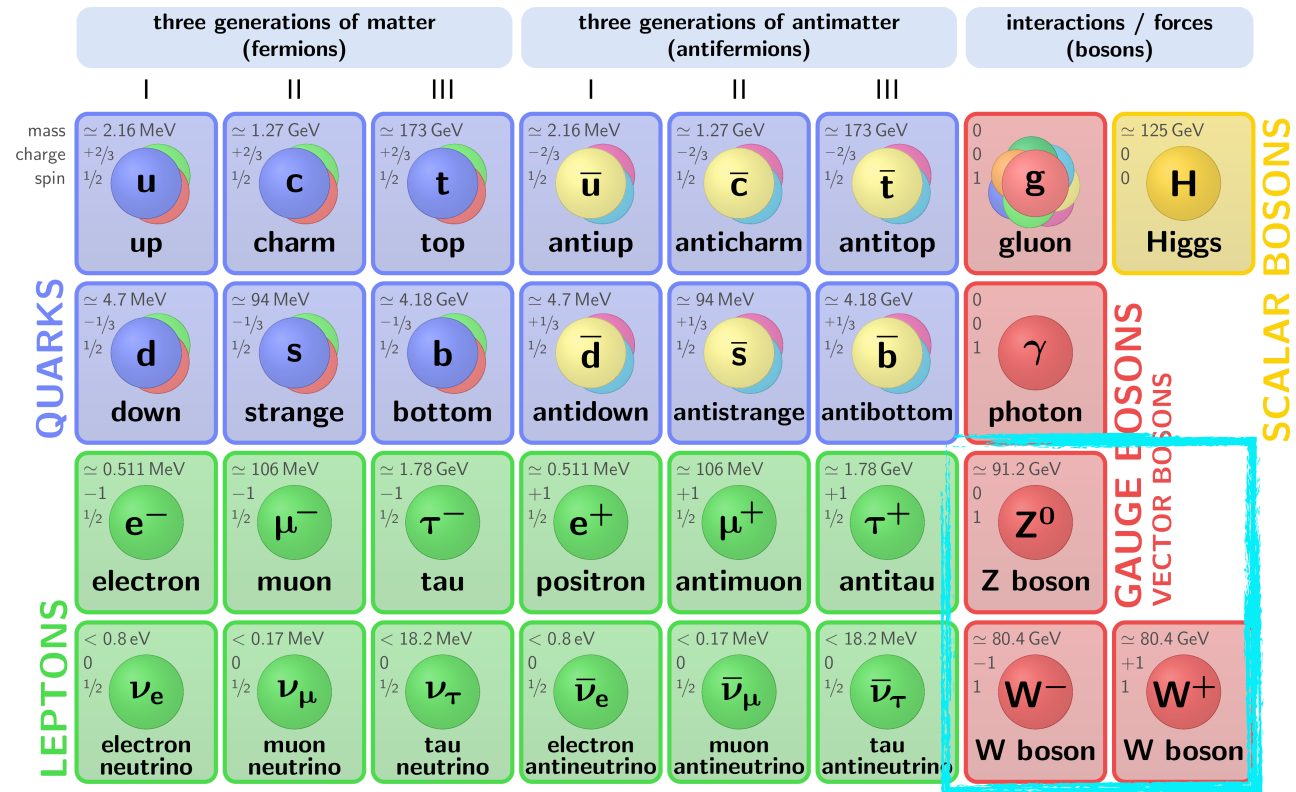


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STANDARD-MODEL INTERACTIONS



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- The Standard Model describes
 - **Strong interaction** between particles via the exchange of **8 massless gluons**,
 - **Weak interaction** via the exchange of **3 massive bosons**, and
 - **Electromagnetic interactions** via the exchange of **1 massless photon**

three generations of matter (fermions)						three generations of antimatter (antifermions)			interactions / forces (bosons)				
I		II		III		I		II		III			
mass charge spin	$\approx 2.16 \text{ MeV}$ $+\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.27 \text{ GeV}$ $+\frac{2}{3}$ $\frac{1}{2}$	$\approx 173 \text{ GeV}$ $+\frac{2}{3}$ $\frac{1}{2}$	$\approx 2.16 \text{ MeV}$ $-\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.27 \text{ GeV}$ $-\frac{2}{3}$ $\frac{1}{2}$	$\approx 173 \text{ GeV}$ $-\frac{2}{3}$ $\frac{1}{2}$				0 0 1	$\approx 125 \text{ GeV}$ 0 0		
	u up	c charm	t top	$\bar{u}$ antiup	$\bar{c}$ anticharm	$\bar{t}$ antitop	g gluon				H Higgs		
	down	strange	bottom	antidown	antistrange	antibottom	photon						
QUARKS	$\approx 4.7 \text{ MeV}$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 94 \text{ MeV}$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.18 \text{ GeV}$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.7 \text{ MeV}$ $+\frac{1}{3}$ $\frac{1}{2}$	$\approx 94 \text{ MeV}$ $+\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.18 \text{ GeV}$ $+\frac{1}{3}$ $\frac{1}{2}$				0 0 1	γ		
	down	strange	bottom	antidown	antistrange	antibottom							
	electron	muon	tau	positron	antimuon	antitau							
LEPTONS	$\approx 0.511 \text{ MeV}$ -1 $\frac{1}{2}$	$\approx 106 \text{ MeV}$ -1 $\frac{1}{2}$	$\approx 1.78 \text{ GeV}$ -1 $\frac{1}{2}$	$\approx 0.511 \text{ MeV}$ $+1$ $\frac{1}{2}$	$\approx 106 \text{ MeV}$ $+1$ $\frac{1}{2}$	$\approx 1.78 \text{ GeV}$ $+1$ $\frac{1}{2}$				Z^0			
	electron	muon	tau	positron	antimuon	antitau				Z boson			
	$< 0.8 \text{ eV}$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}$ 0 $\frac{1}{2}$	$< 0.8 \text{ eV}$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}$ 0 $\frac{1}{2}$				W^-	W^+		
	electron neutrino	muon neutrino	tau neutrino	electron antineutrino	muon antineutrino	tau antineutrino				W boson	W boson		

Neutelings, Standard Model – TikZ.net

STANDARD-MODEL INTERACTIONS

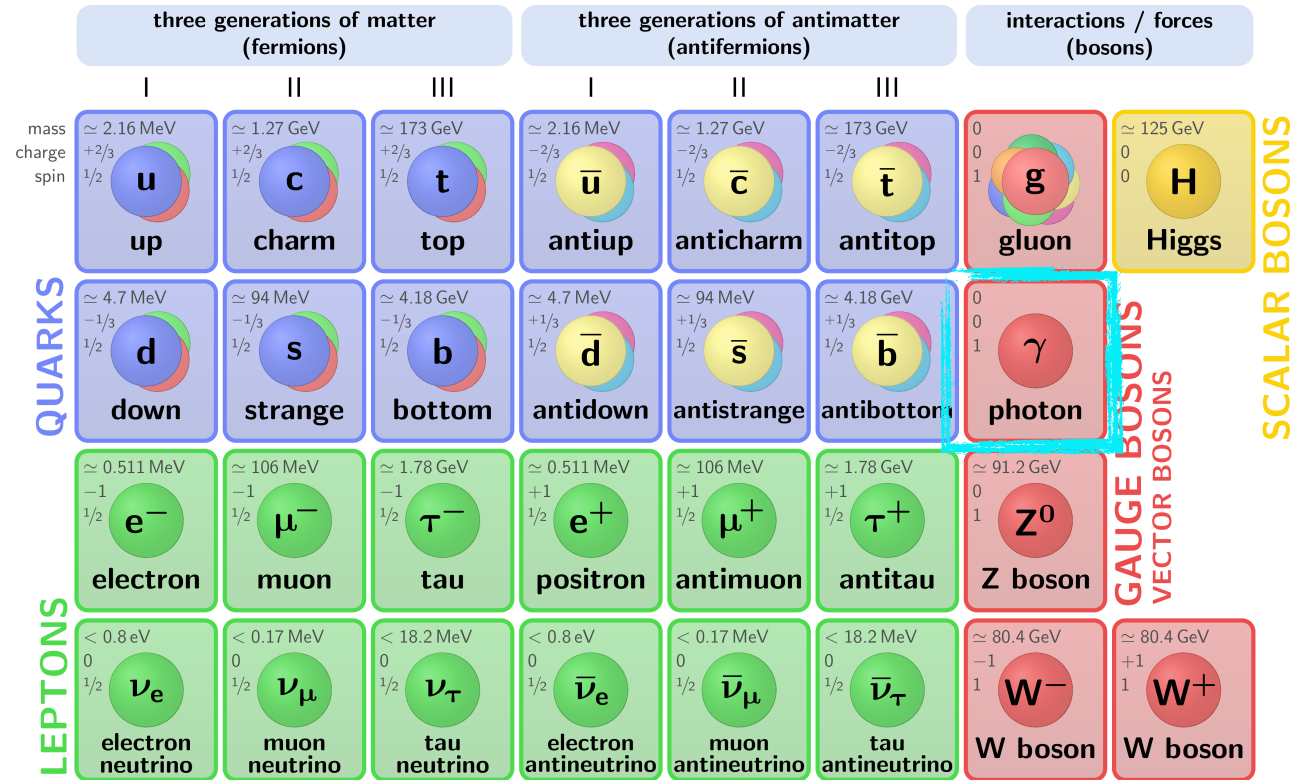


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- Electromagnetic and weak interactions are unified above the electroweak scale $\approx 246 \text{ GeV}$



Neutelings, *Standard Model* – TikZ.net

CHIRAL EFFECTIVE FIELD THEORY FOR WEAK CURRENTS



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Krebs, Epelbaum, Meißner, Annals of Physics 378, 317-395 (2017), Park, Marcucci, Schiavilla et al., Phys. Rev. C 67, 055206 (2003)

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$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\pi}^{(2)} + \mathcal{L}_{\pi}^{(4)} + \mathcal{L}_{\pi N}^{(1)} + \mathcal{L}_{\pi N}^{(2)} + \mathcal{L}_{\pi N}^{(3)} + \mathcal{L}_{NN}^{(0)} + \mathcal{L}_{\pi NN}^{(1)},$$

where the superscripts refer to the #derivatives and/or insertions of the pion mass

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- **Use power counting to organize the resulting diagrams into order of importance**

CHIRAL EXPANSION OF CURRENTS



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Vector
 $V^\mu = (\textcolor{red}{V}^0, \textcolor{blue}{V})$

Axial-vector
 $A^\mu = (\textcolor{red}{A}^0, \textcolor{blue}{A})$

	Single-nucleon	Two-nucleon	Three-nucleon
Q^{-3}			
Q^{-1}			
Q^0			
Q^1		 depend on $d_{8,9,18,21,22}$ parameter-free depend on $C_{2,4,5,7}$ and $L_{1,2}$	 depend on C_T (known) parameter-free depend on C_T (known)

	Single-nucleon	Two-nucleon	Three-nucleon
Q^{-3}			
Q^{-1}			
Q^0			
Q^1		 parameter-free depend on $d_{2,5,6,15,23}$ parameter-free depend on C_T (known) depend on $Z_{1,2,3,4}$	 parameter-free depend on C_T (known)

Systematic expansion of charge (time-like) and current operators

Epelbaum, arXiv:1908.09349

CHIRAL EXPANSION OF CURRENTS



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Axial-vector
 $A^\mu = (\textcolor{red}{A}^0, \textcolor{blue}{A})$

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Q^{-3}		—	—
Q^{-1}			—
Q^0		—	—
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	Single-nucleon	Two-nucleon	Three-nucleon
Q^{-3}		—	—
Q^{-1}			—
Q^0	—		—
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GAMOW-TELLER β DECAYS

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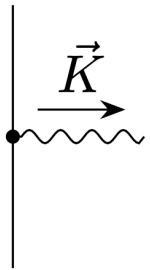
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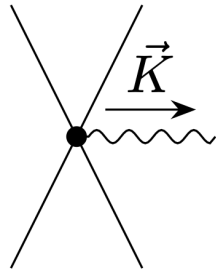


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- At the zero-momentum transfer limit, the relevant axial currents up to $N^2\text{LO}$ are

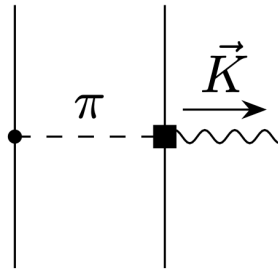


LO, $\sigma\tau$



Heavy meson
exchange

c_D



Pion exchange

c_3, c_4

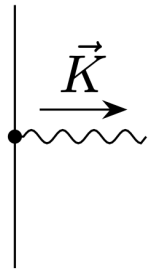
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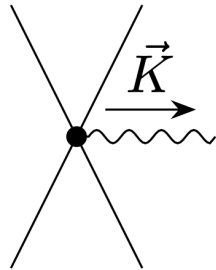


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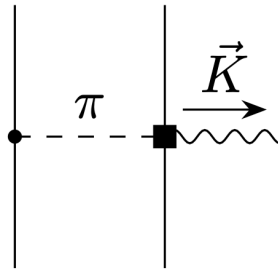
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LO, $\sigma\tau$

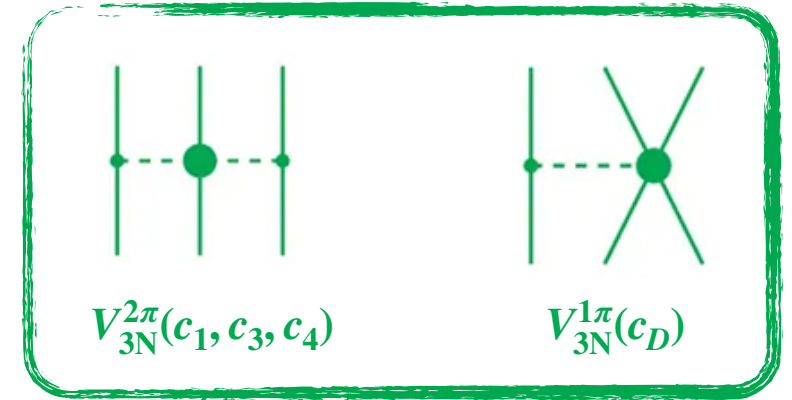


Heavy meson
exchange
 c_D



Pion exchange
 c_3, c_4

Counterparts in the 3N force



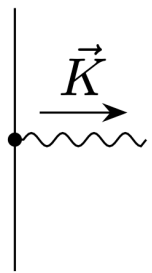
GAMOW-TELLER β DECAYS

Li, Miyagi, Schwenk, Phys. Rev. Lett. 136, 182501 (2026); Gysbers et al., Nature Physics 15, 428 (2019)

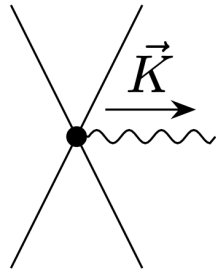


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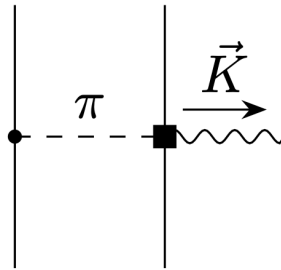


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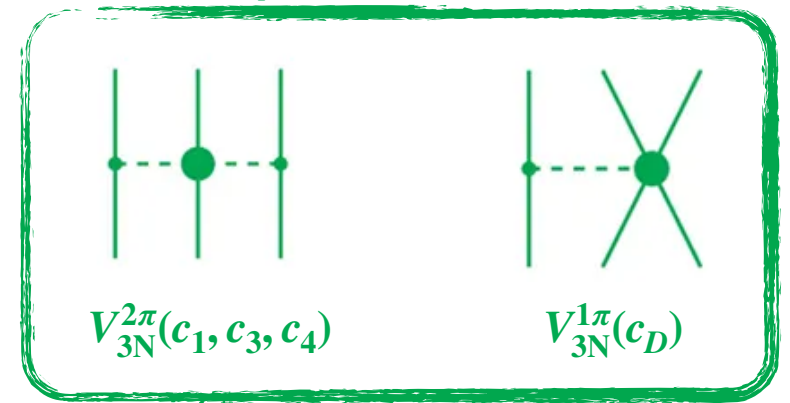
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exchange

c_D



Pion exchange
 c_3, c_4

Counterparts in the 3N force



- The axial current can be written as $\mathbf{J} = \mathbf{J}_{1B} + \mathbf{J}_{2B}^{\text{ct}} + \mathbf{J}_{2B}^{1\pi}$ with

$$\mathbf{J}_{1B,i} = \frac{g_A}{2} \boldsymbol{\sigma}_i \boldsymbol{\tau}_i,$$

$$\mathbf{J}_{2B,12}^{\text{ct}} = -d_1(\boldsymbol{\sigma}_1 \boldsymbol{\tau}_1 + \boldsymbol{\sigma}_2 \boldsymbol{\tau}_2) - d_2(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2),$$

$$\mathbf{J}_{2B,12}^{1\pi} = -\frac{g_A}{2F_\pi^2} \frac{\boldsymbol{\sigma}_2 \cdot \mathbf{k}_2}{\mathbf{k}_2^2 + m_\pi^2} \left[2c_3 \boldsymbol{\tau}_2 \mathbf{k}_2 + \left(c_4 + \frac{1}{4m} \right) \boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2 (\boldsymbol{\sigma}_1 \times \mathbf{k}_2) \right] + (1 \leftrightarrow 2)$$

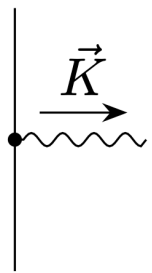
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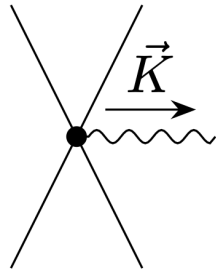


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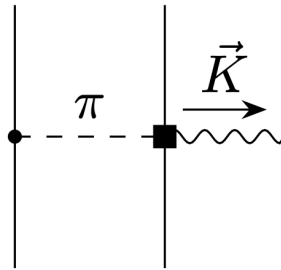


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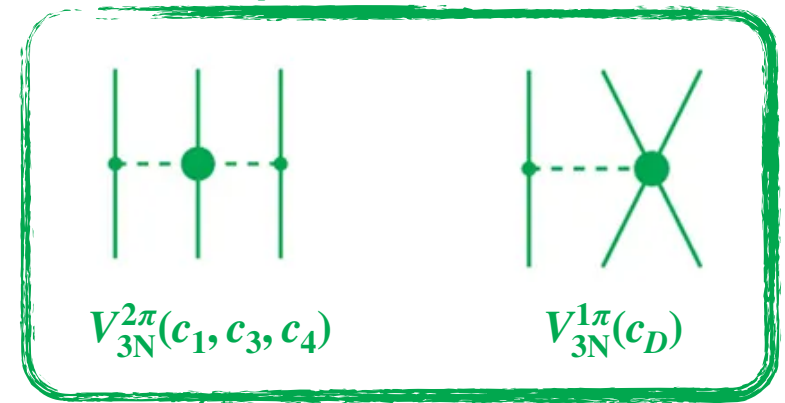
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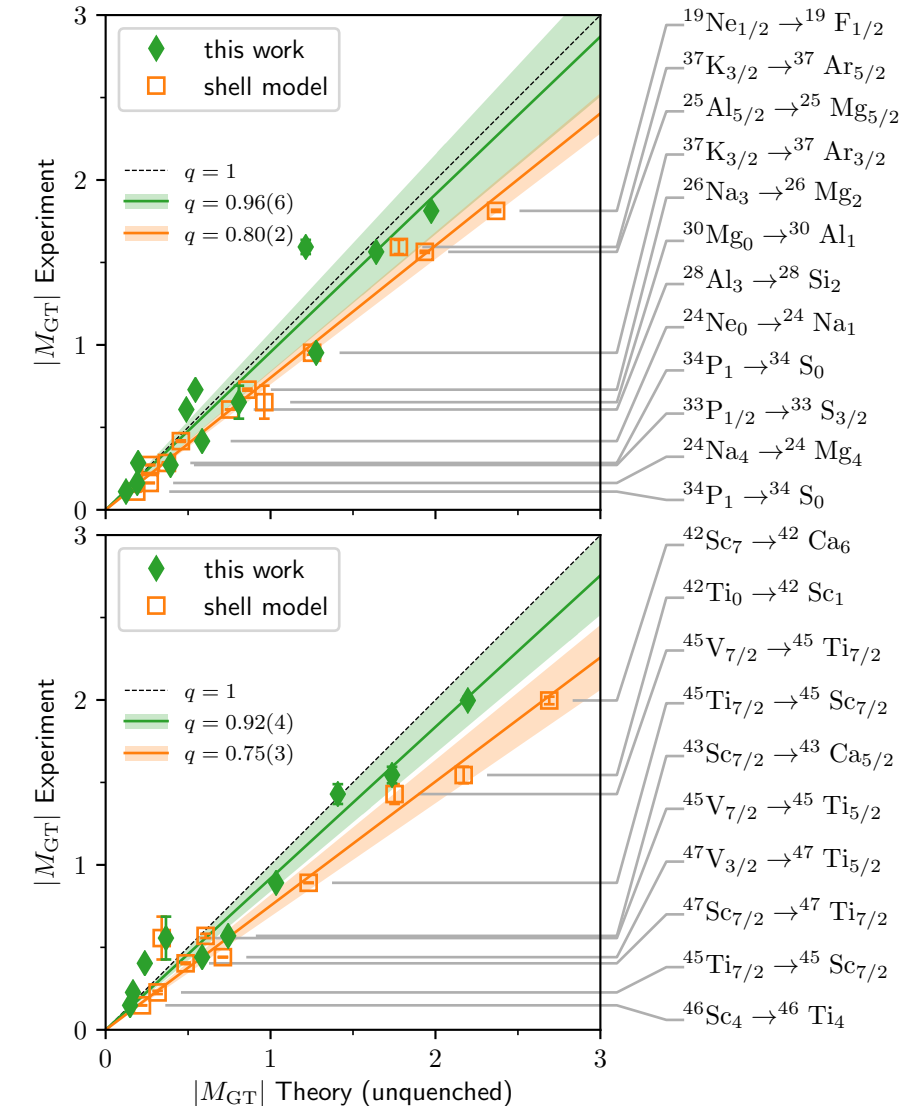
$$c_D = -4(d_1 + 2d_2)F_\pi^2 \Lambda_\chi$$

QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

Gysbers et al., *Nature Physics* 15, 428 (2019)



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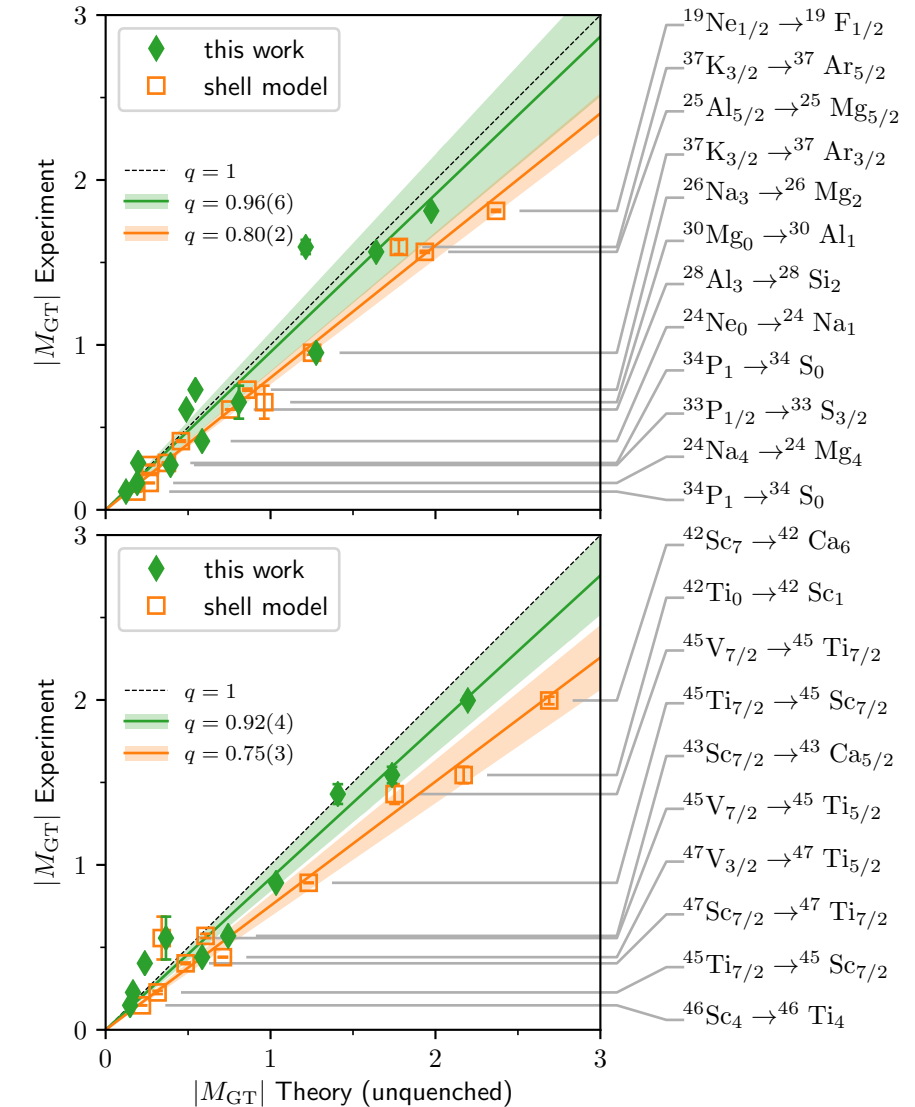
QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

Gysbers et al., *Nature Physics* 15, 428 (2019)



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■ Culprit:



QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

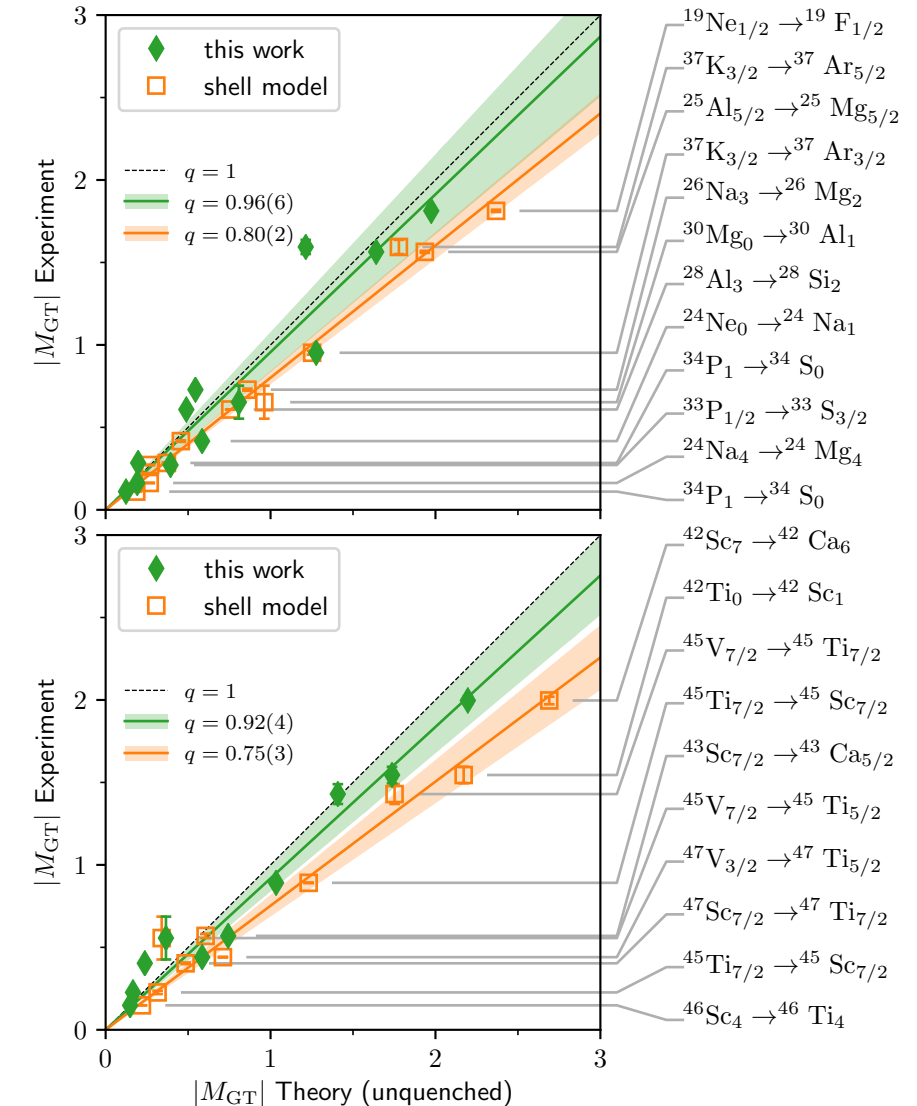
Gysbers et al., *Nature Physics* 15, 428 (2019)



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- **Culprit:**

- **Coupling of the weak force to two nucleons**
(two-body currents)



QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

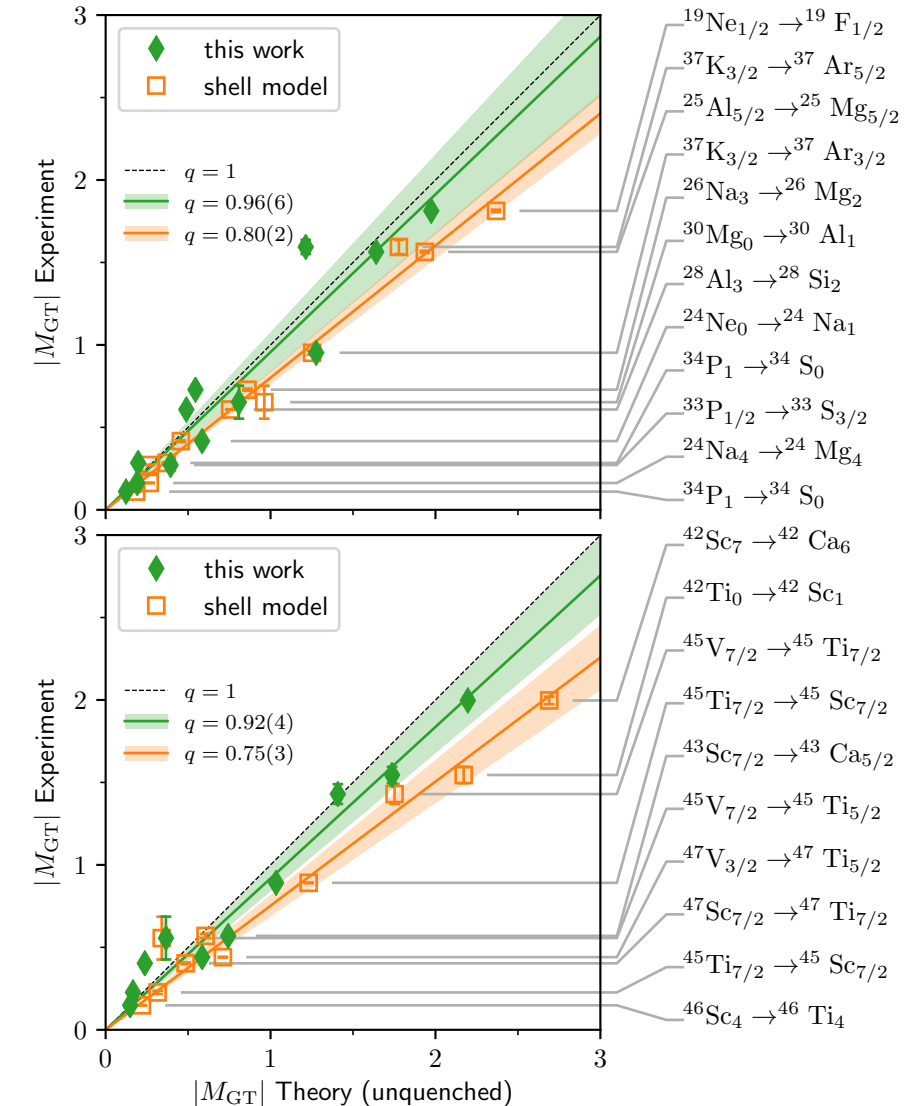
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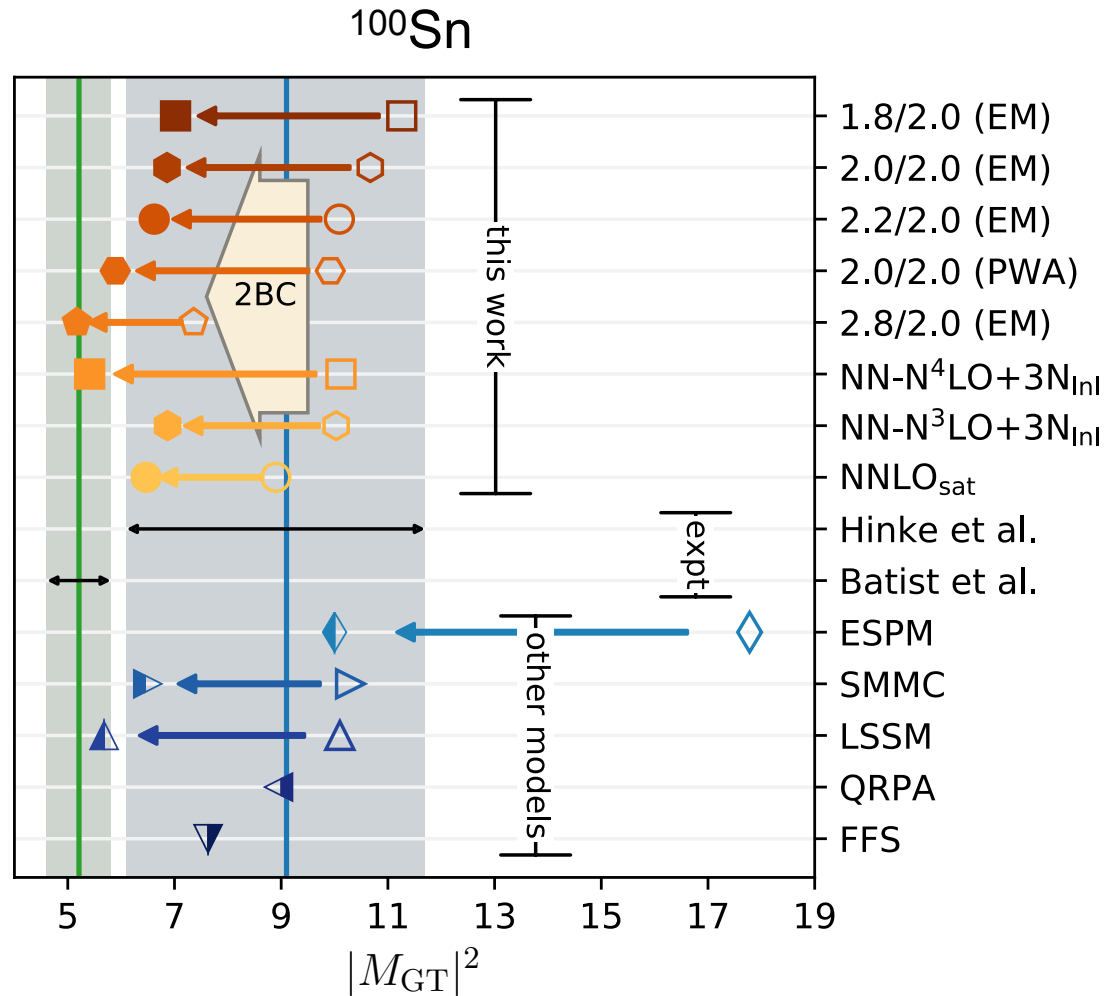
■ Culprit:

- Coupling of the weak force to two nucleons (two-body currents)
- Strong correlations in the nucleus (that are not well described by mean-field approaches)



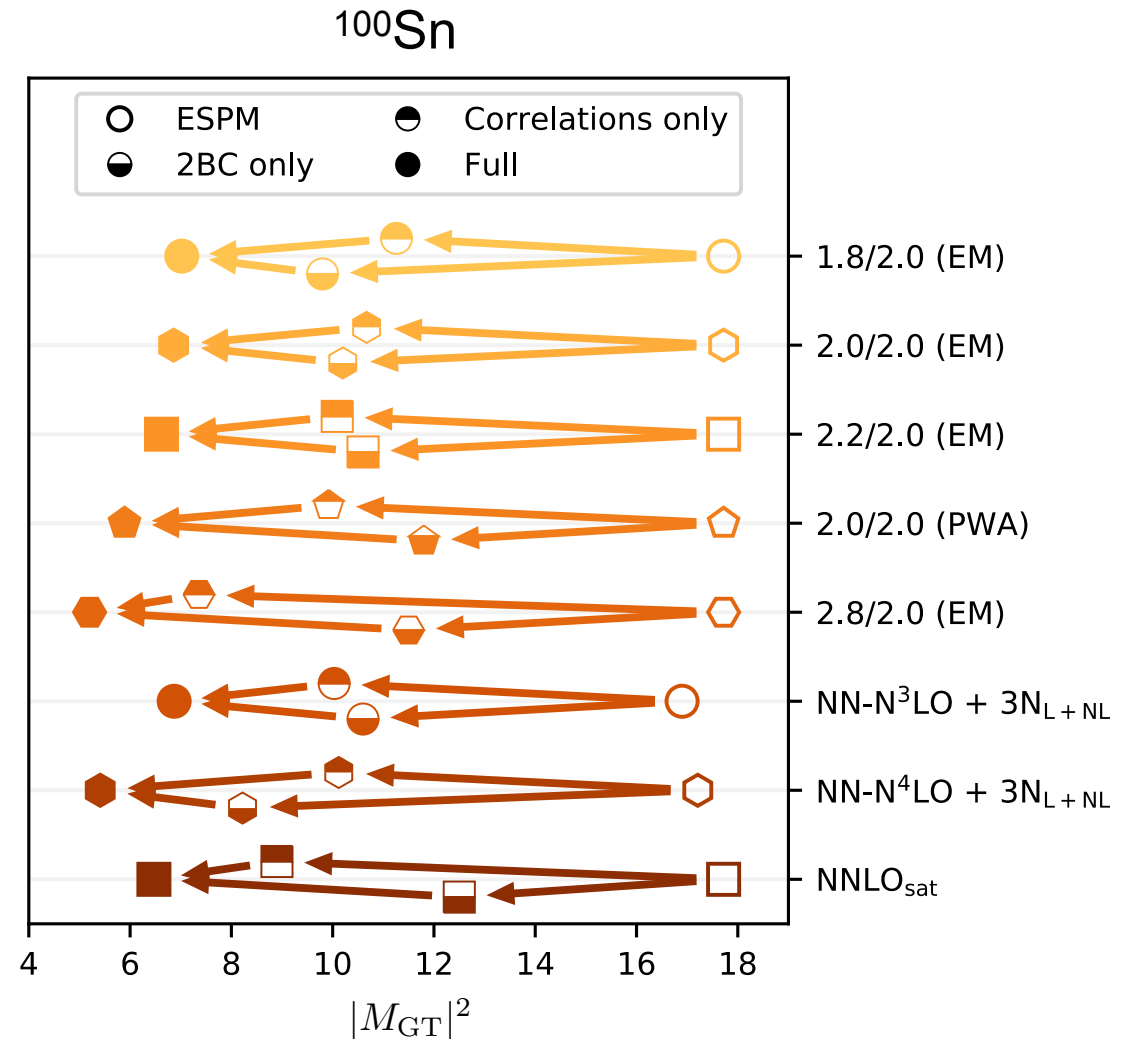
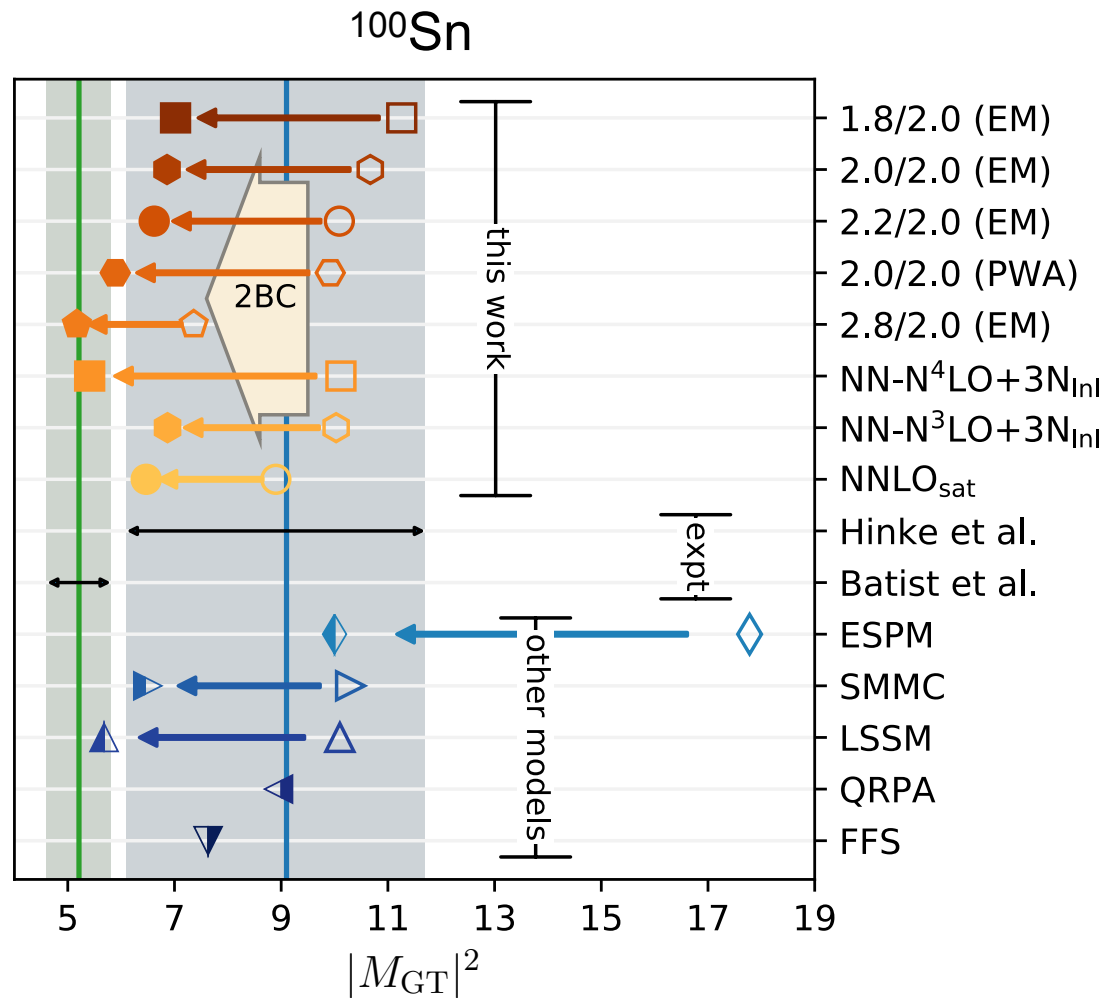
QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

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QUENCHING PUZZLE RESOLVED FROM FIRST PRINCIPLES

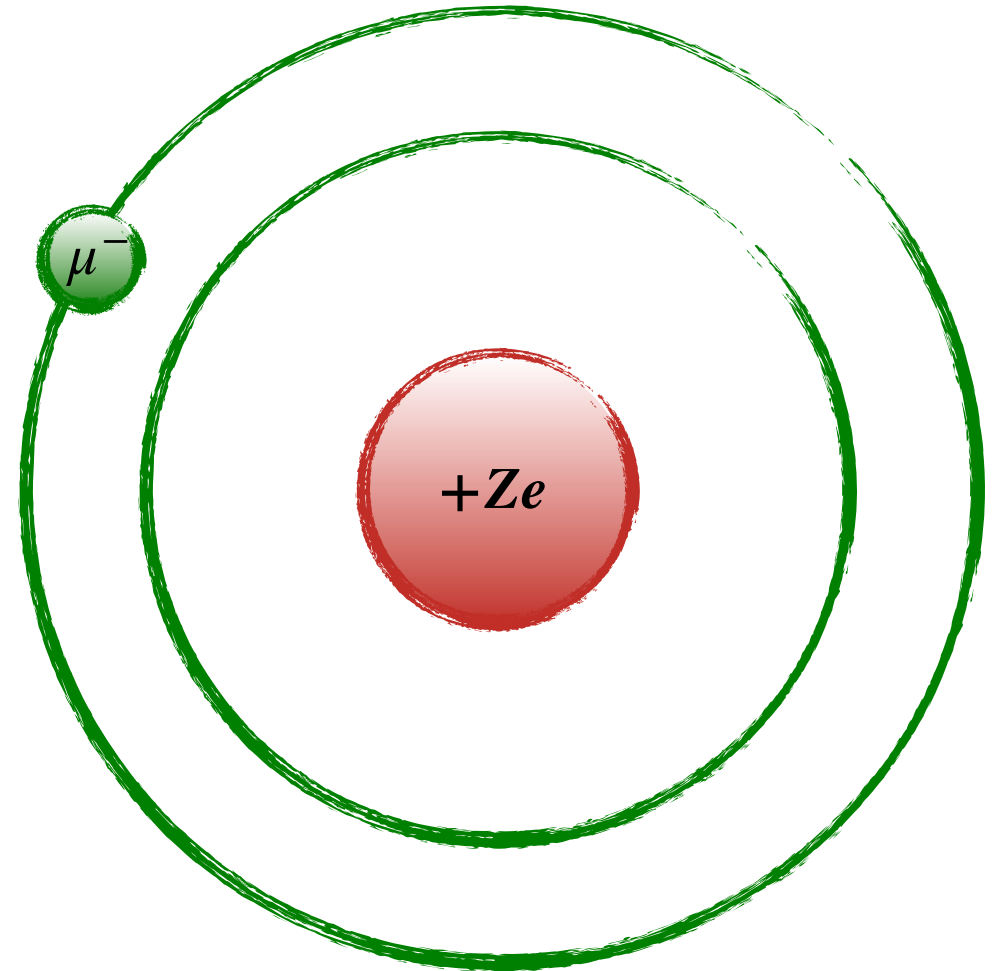
Gysbers et al., *Nature Physics* 15, 428 (2019)





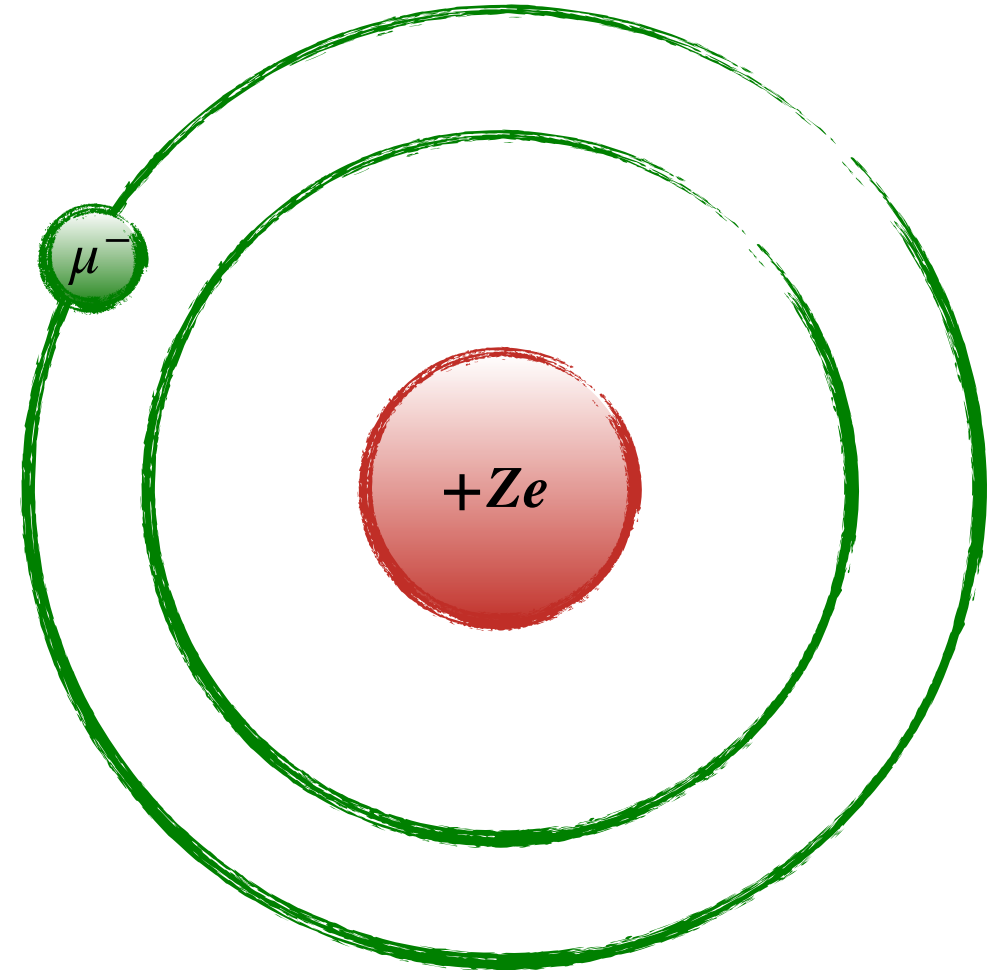
EXAMPLE: MUON CAPTURE ON ${}^6\text{Li}$

ORDINARY MUON CAPTURE



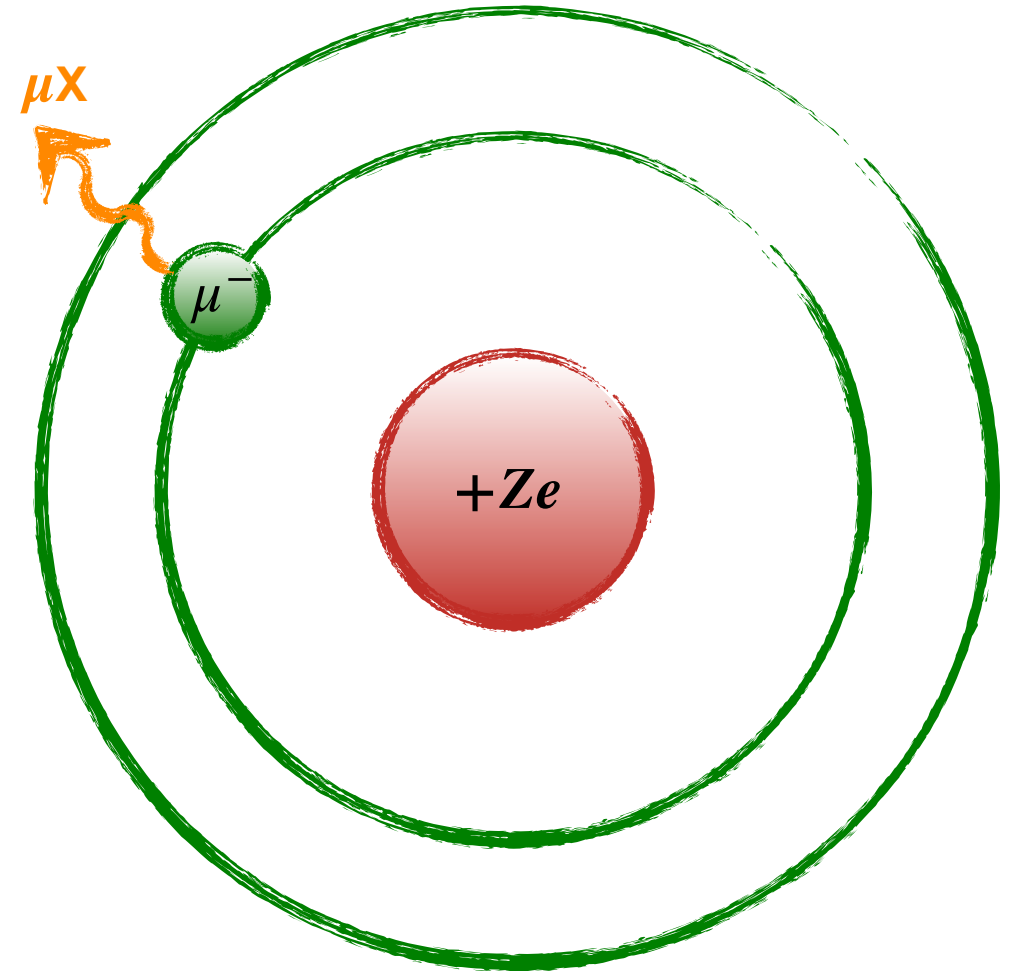
ORDINARY MUON CAPTURE

- Starting point: a muonic atom



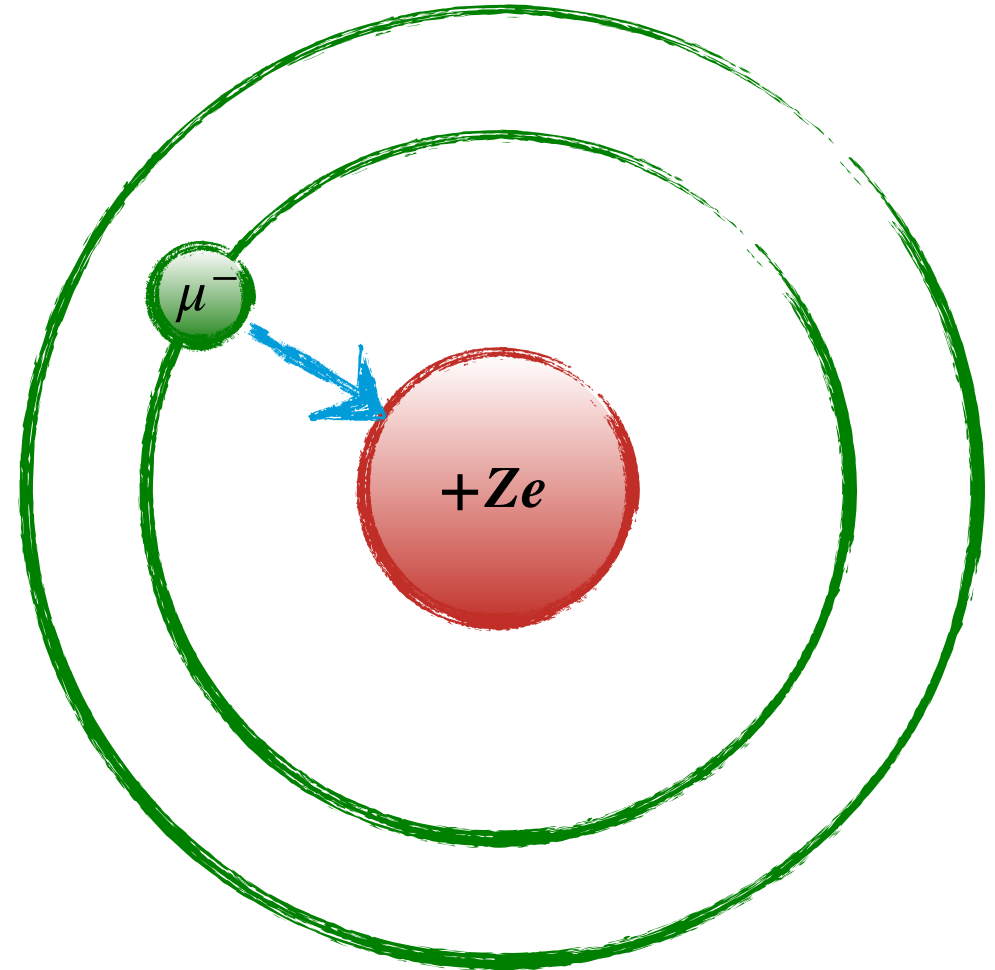
ORDINARY MUON CAPTURE

- Starting point: a **muonic atom**
- The muon quickly transitions to the lowest, **$1s_{1/2}$ orbit**



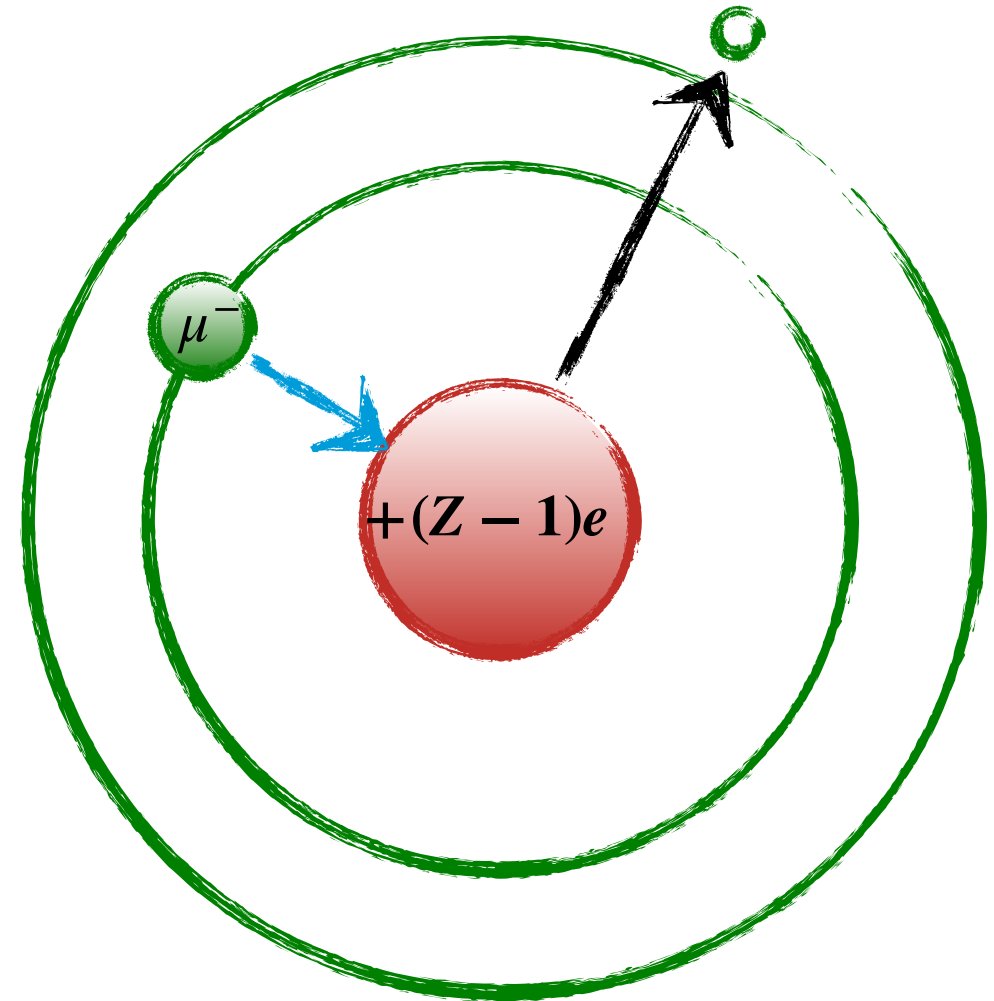
ORDINARY MUON CAPTURE

- Starting point: **a muonic atom**
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- From there, the muon can be **captured by the nucleus**



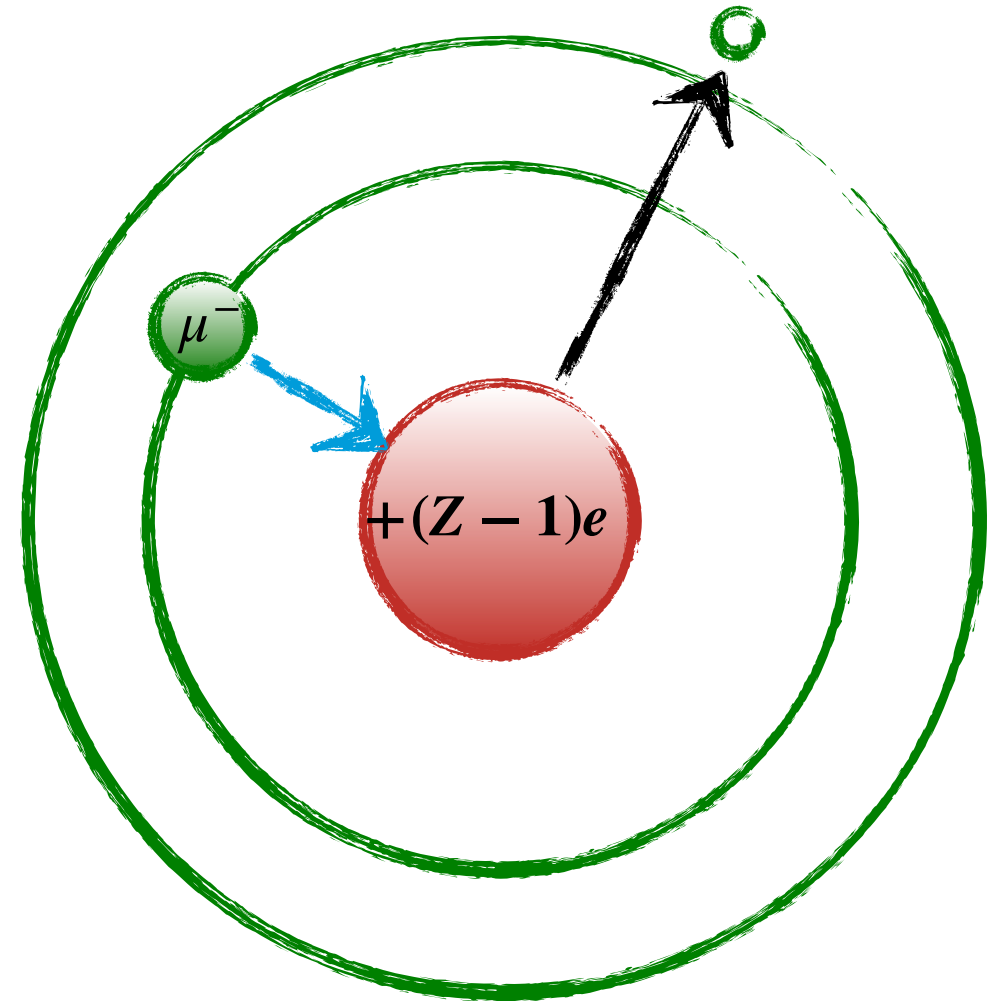
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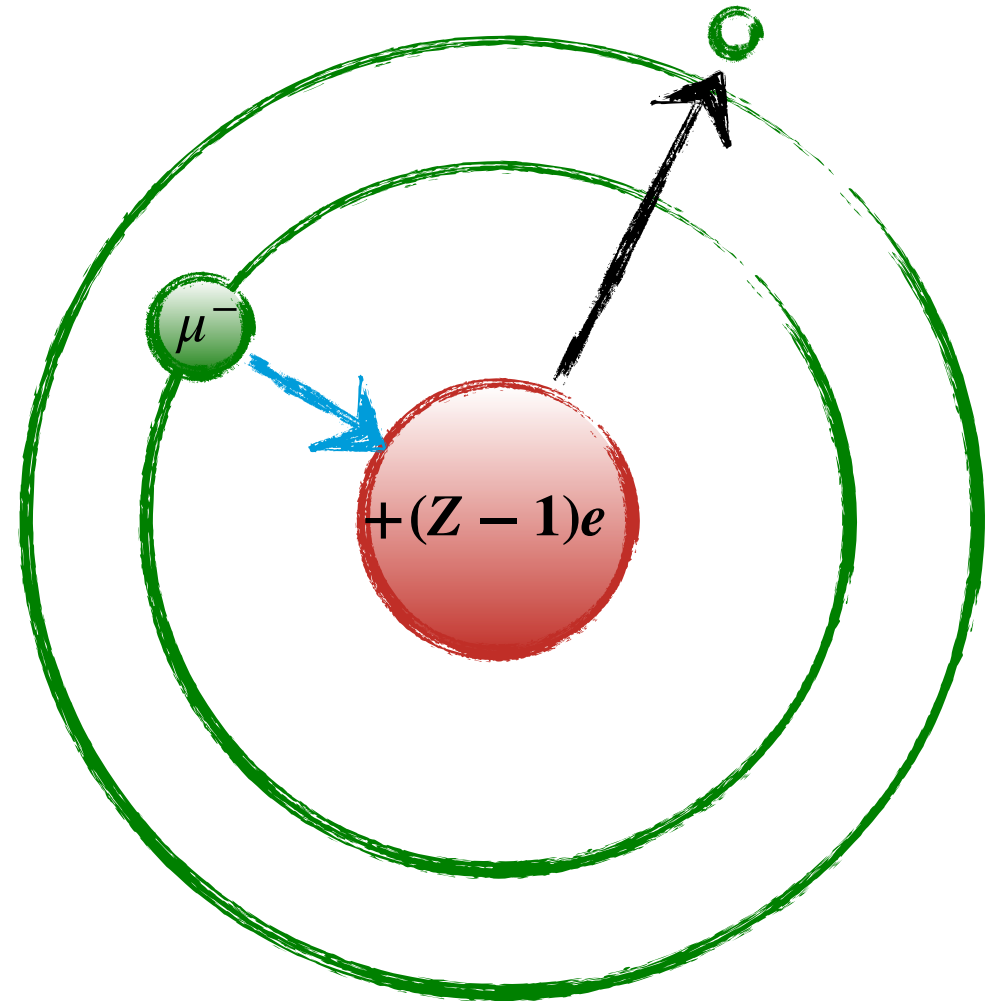
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ORDINARY MUON CAPTURE

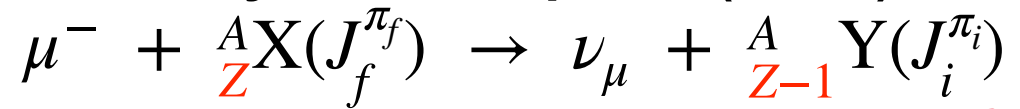
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- **Momentum transfer** $q_{\text{OMC}} \sim 100 \text{ MeV}$



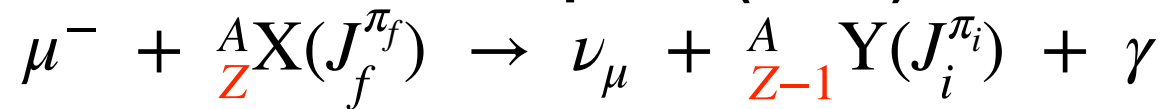
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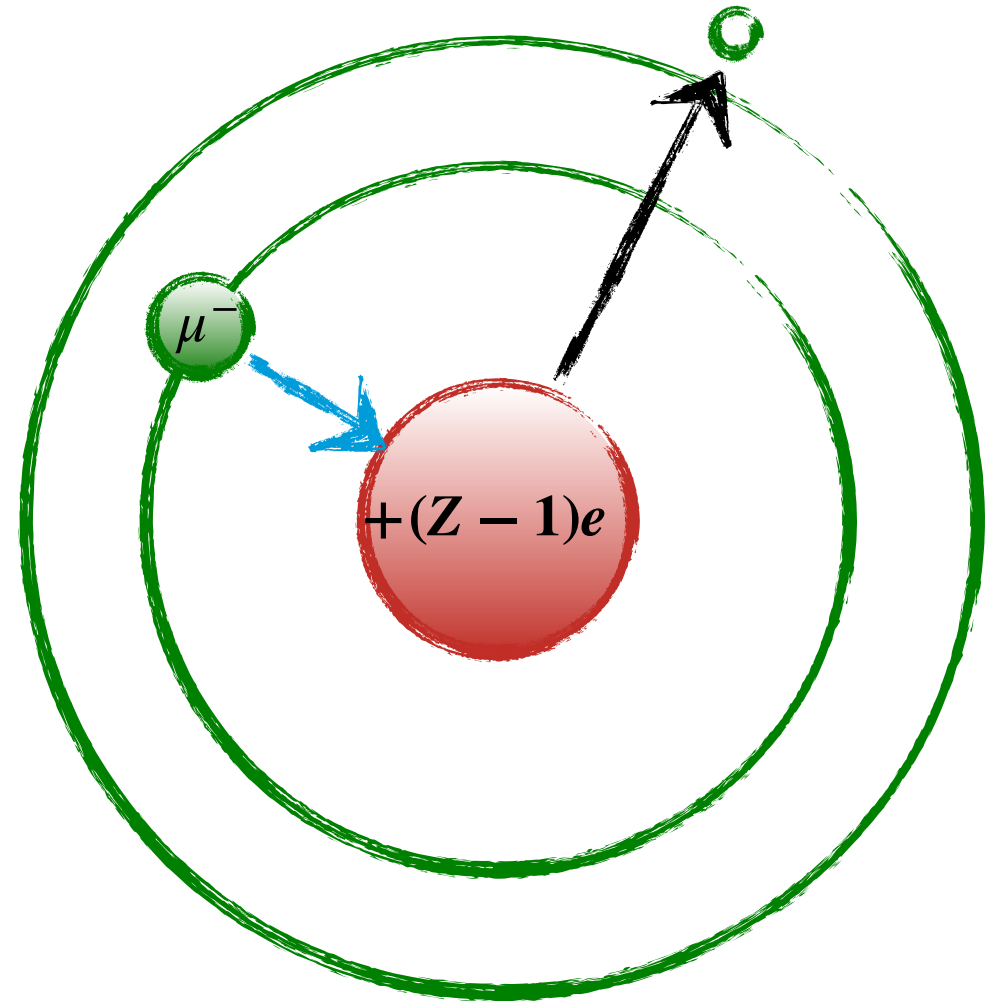
- **Ordinary muon capture (OMC):**



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MUON CAPTURE THEORY



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Partial muon capture rates expressed as:

$$W(J_i \rightarrow J_f) = \frac{1}{2J_i + 1} \left(1 - \frac{q}{m_\mu + AM} \right) q^2 \sum_{\kappa, u} |g_V M_V(\kappa, u) + g_A M_A(\kappa, u) + g_M M_M(\kappa, u) + g_P M_P(\kappa, u)|^2$$

PHYSICAL REVIEW

VOLUME 118, NUMBER 2

APRIL 15, 1960

Theory of Allowed and Forbidden Transitions in Muon Capture Reactions*

MASATO MORITA

Columbia University, New York, New York

AND

AKIHIKO FUJII†

Brookhaven National Laboratory, Upton, Long Island, New York

(Received November 9, 1959)

MUON CAPTURE THEORY



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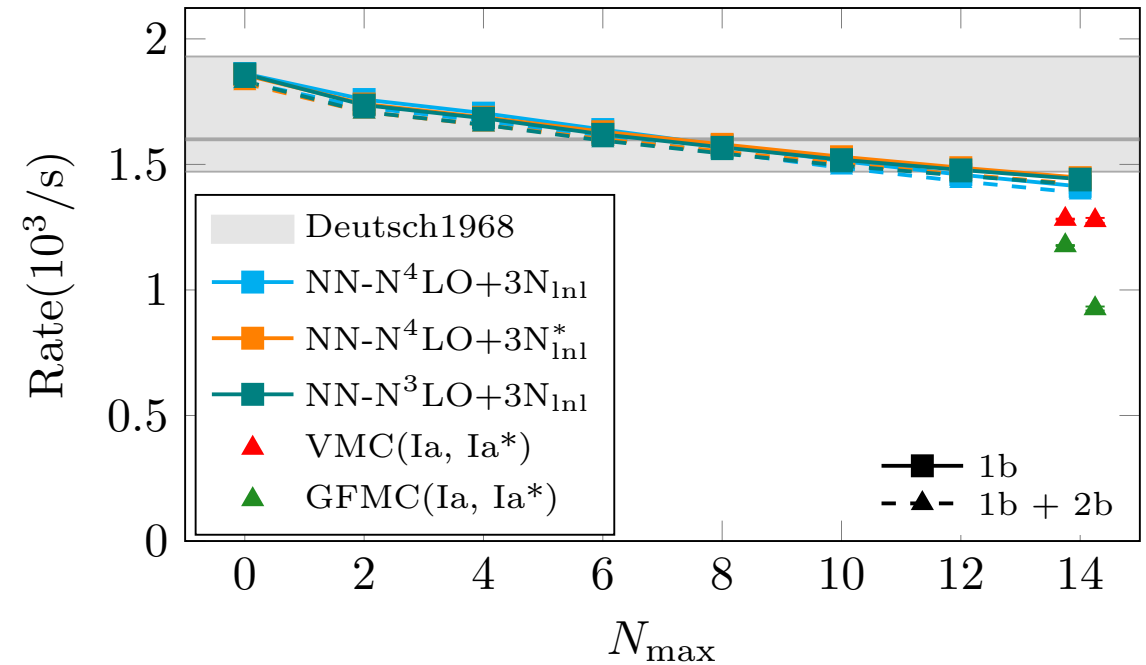
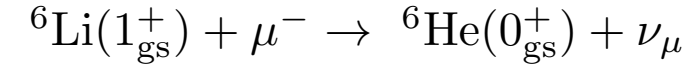
Columbia University, New York, New York

- + Realistic bound-muon wave functions
- + Nuclear wave functions from no-core shell model
- + Approximate two-body currents

MUON CAPTURE TO GROUND STATE OF ${}^6\text{He}$



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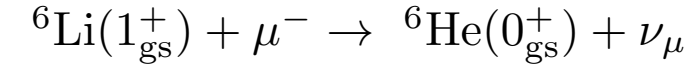


*LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C
109, 065501 (2024)*

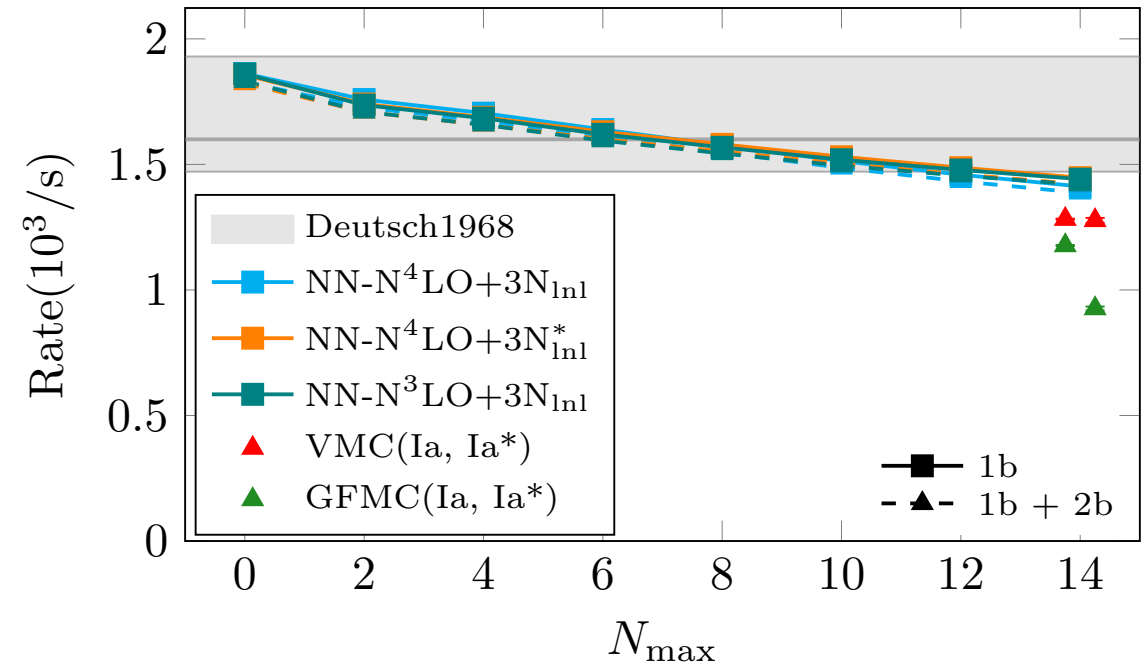
MUON CAPTURE TO GROUND STATE OF ${}^6\text{He}$



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- Practically no interaction dependence

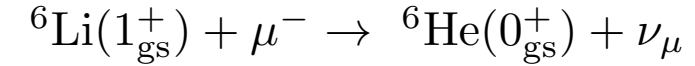


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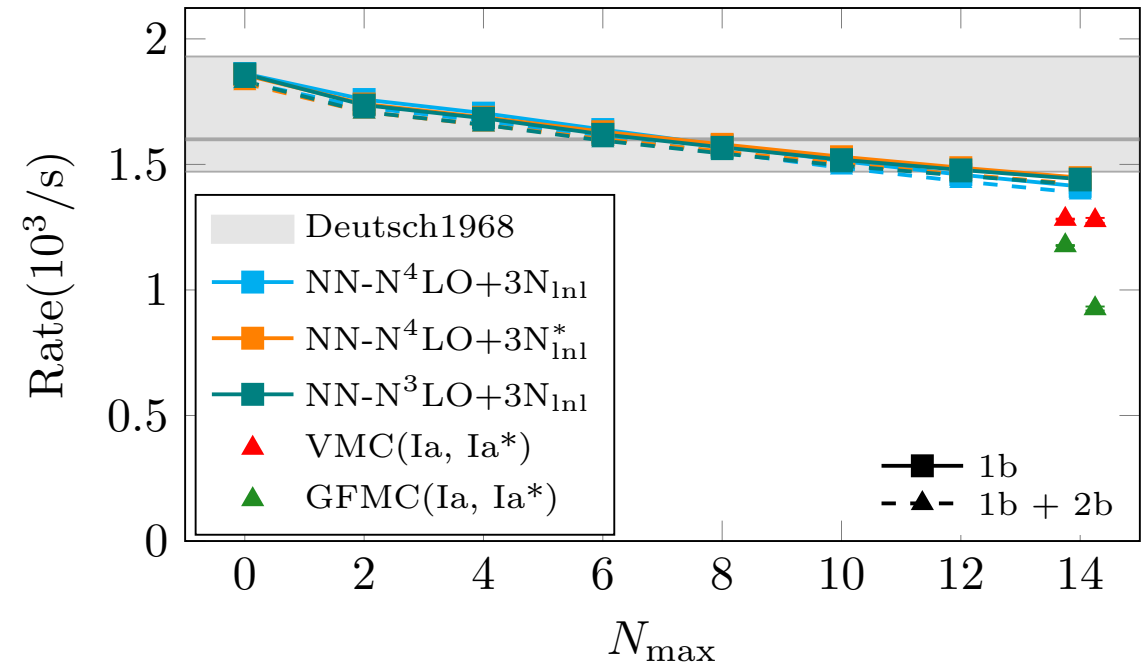
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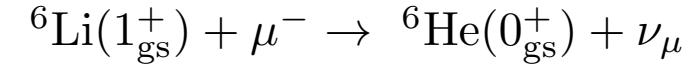


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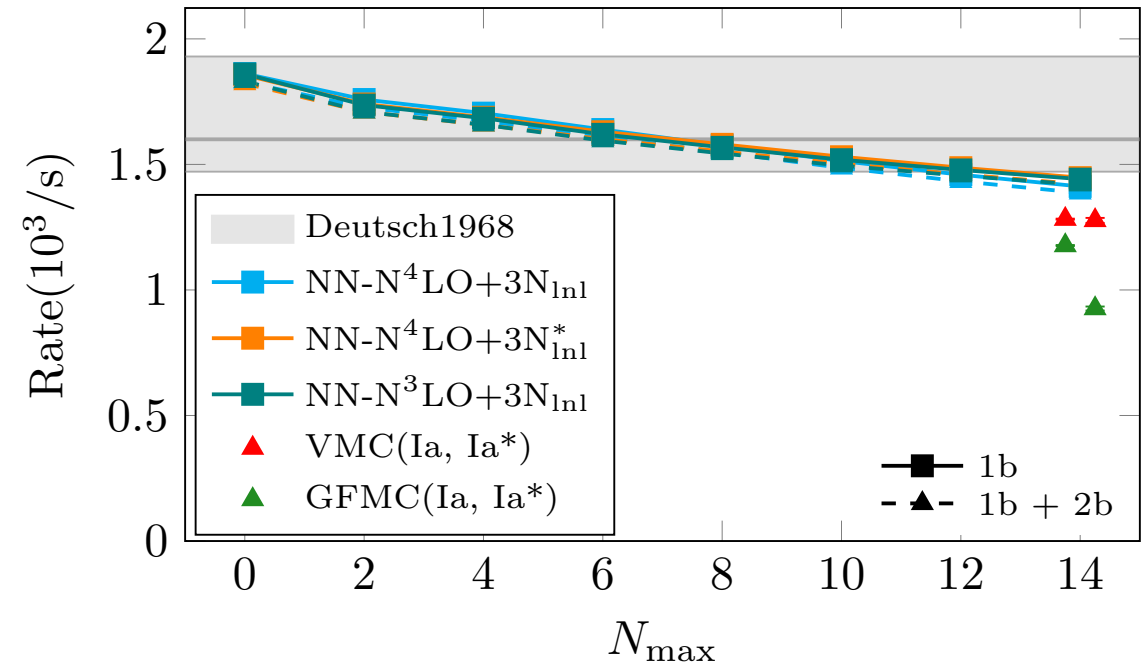
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Variational Monte Carlo (VMC) and
Green's Function Monte Carlo (GFMC)

G. B. King et al., Phys. Rev. C 105, L042501 (2022)

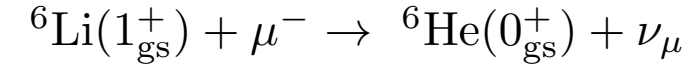


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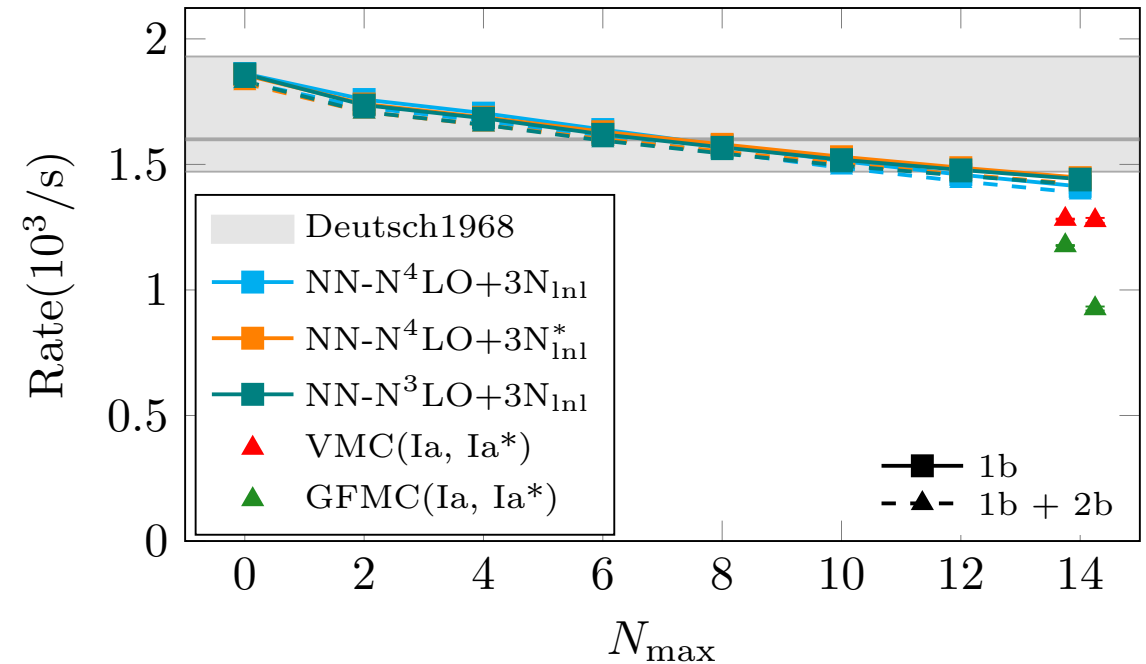
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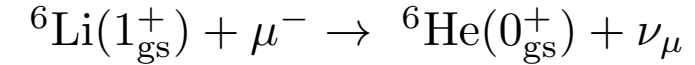


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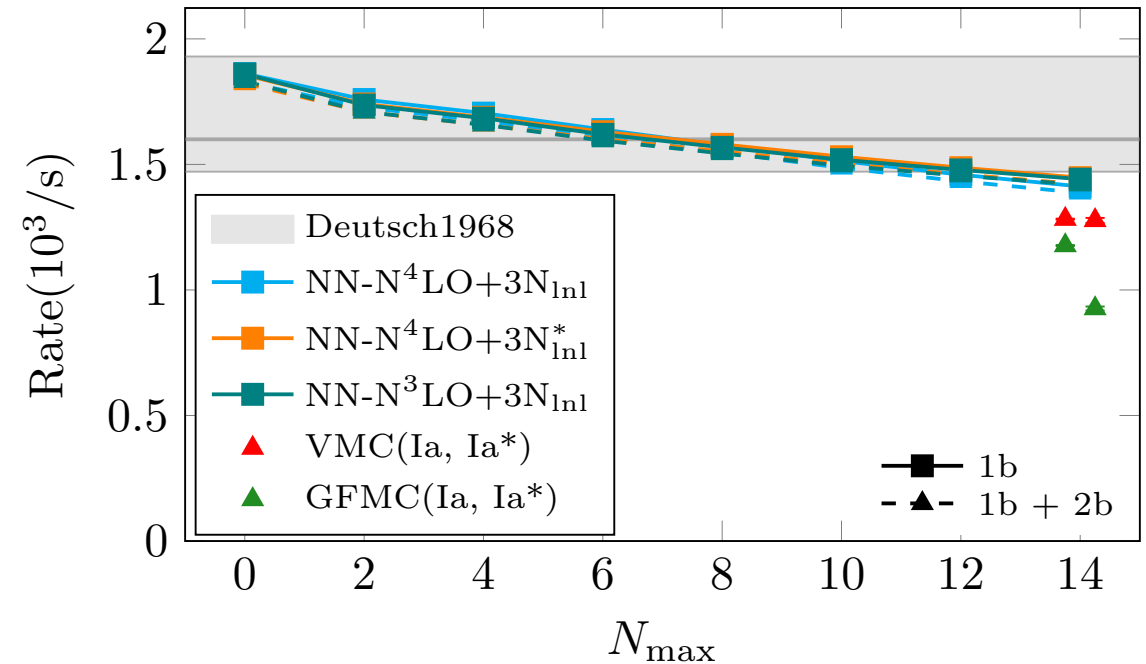
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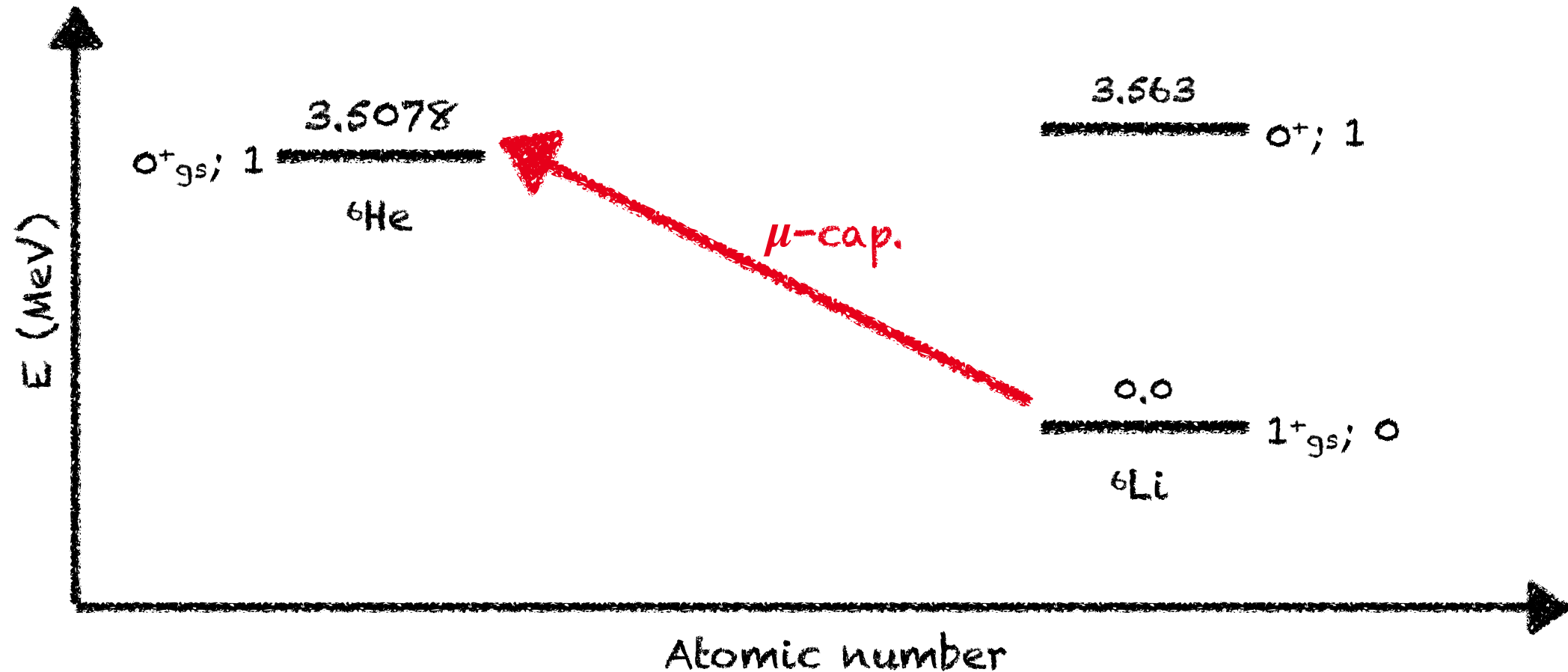


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G. B. King et al., Phys. Rev. C 105, L042501 (2022)
- **Slow convergence due to clustering** not captured by the NCSM?
 - **NCSM with continuum (NCSMC)** might give better results?

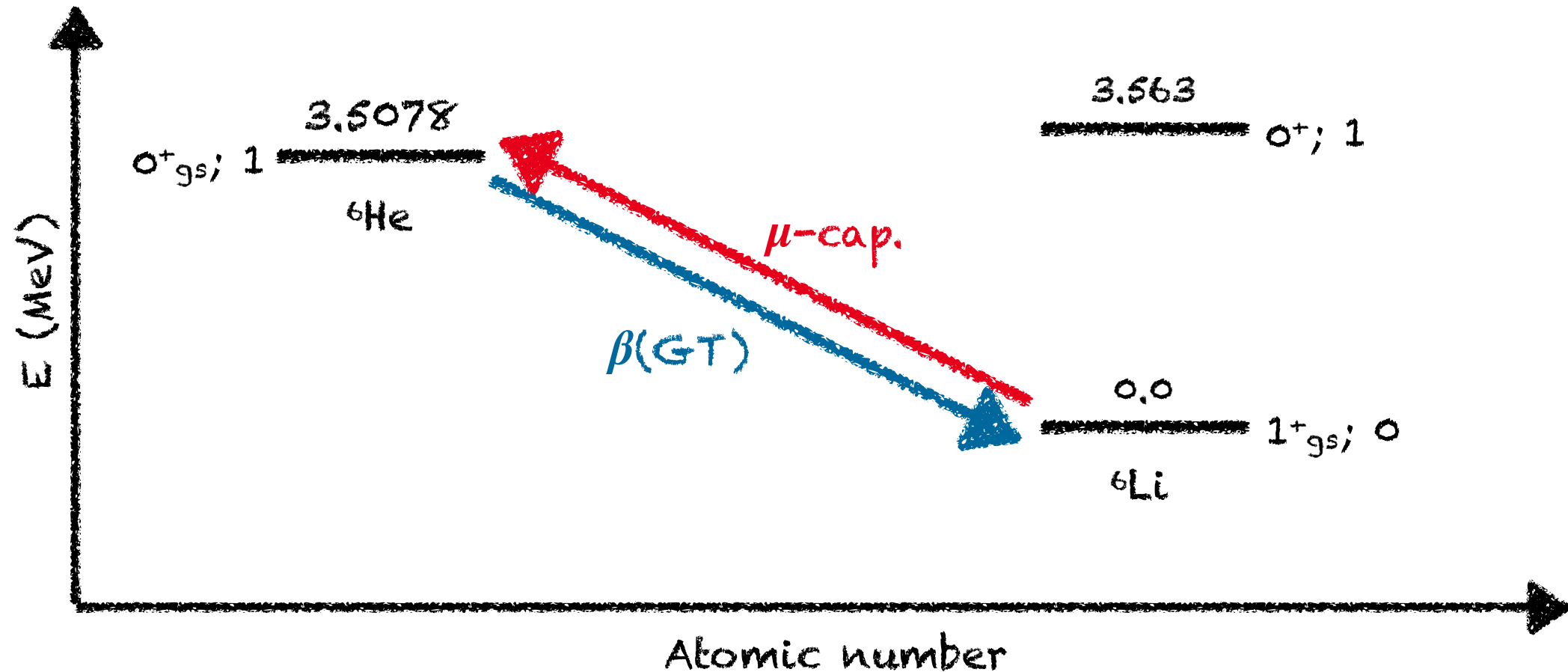


LJ, P. Navrátil, J. Kotila, K. Kravvaris, Phys. Rev. C 109, 065501 (2024)

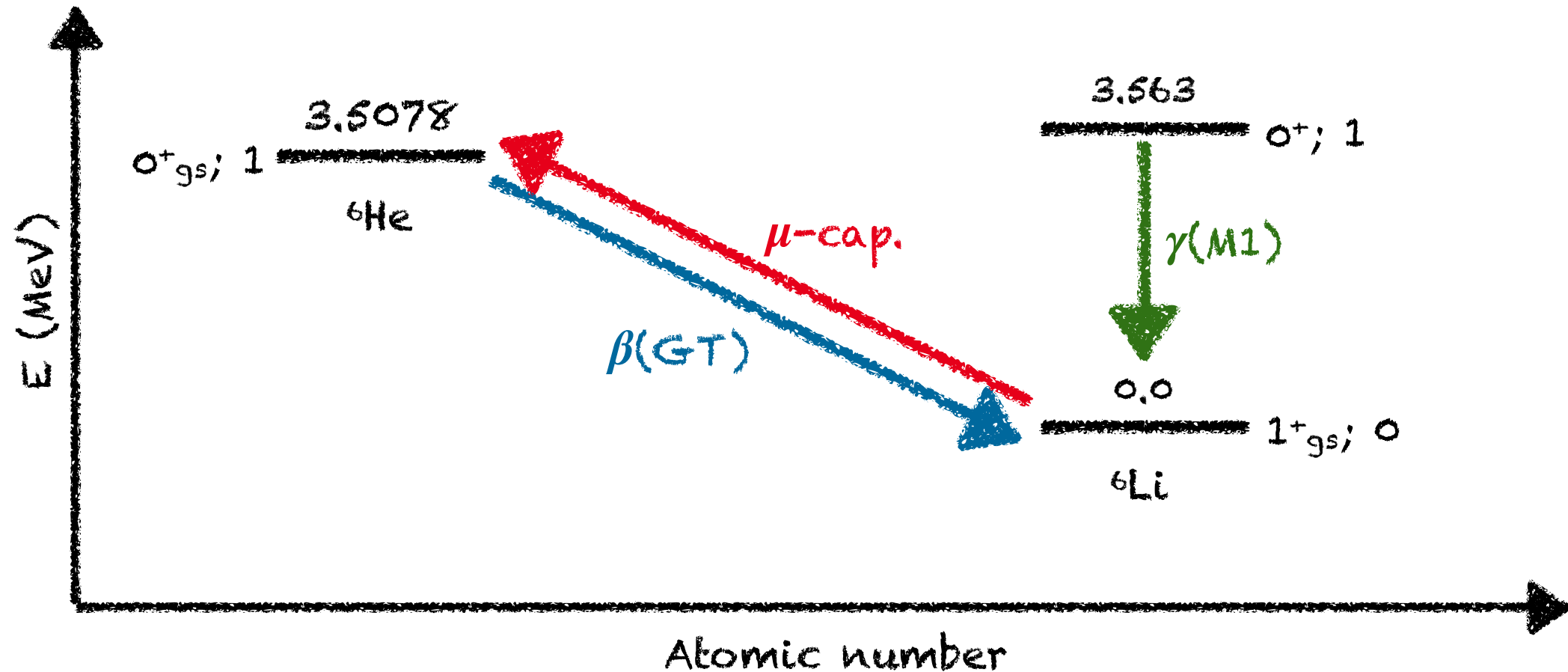
CORRELATIONS WITH OTHER OBSERVABLES



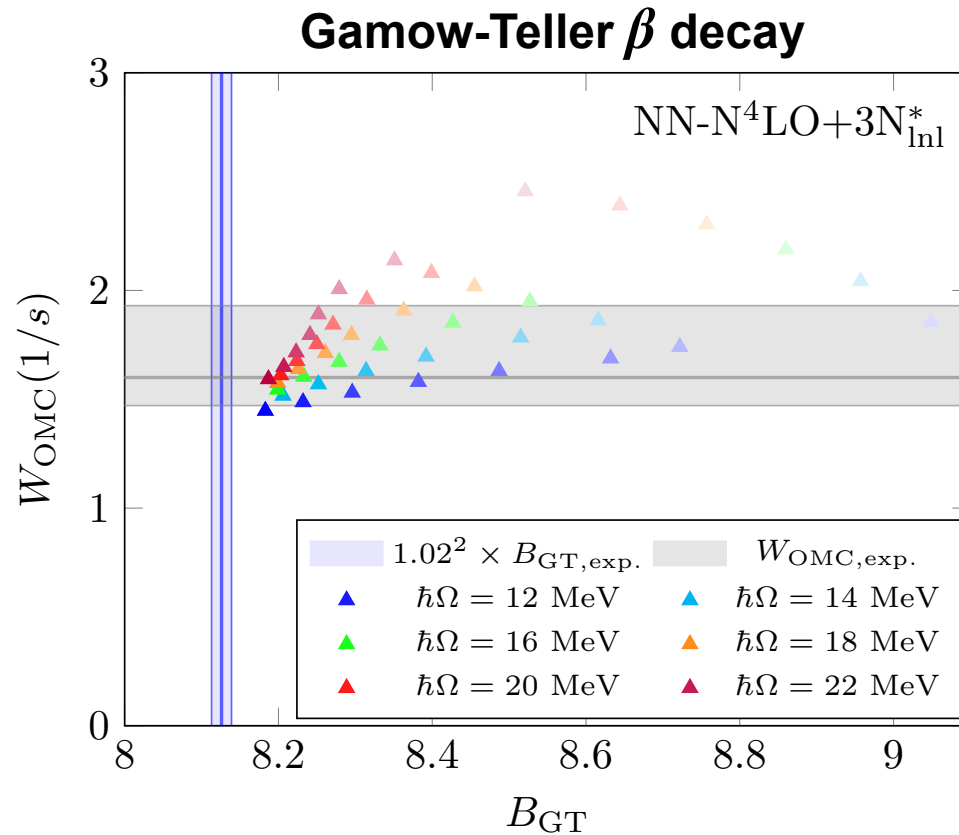
CORRELATIONS WITH OTHER OBSERVABLES



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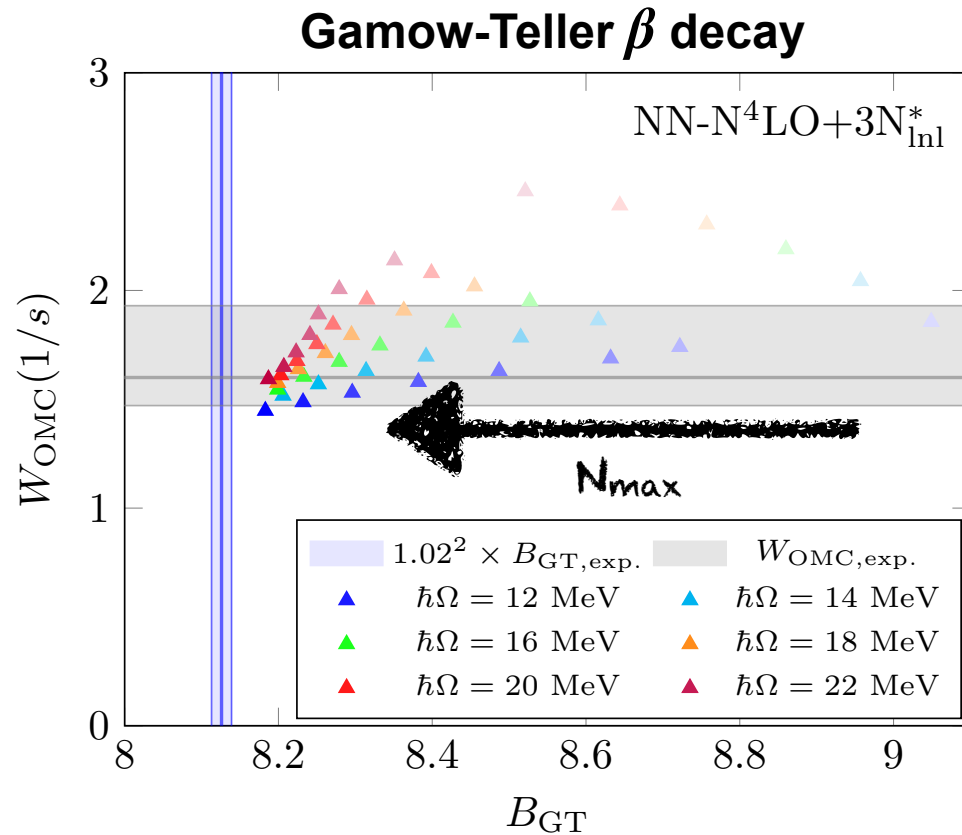


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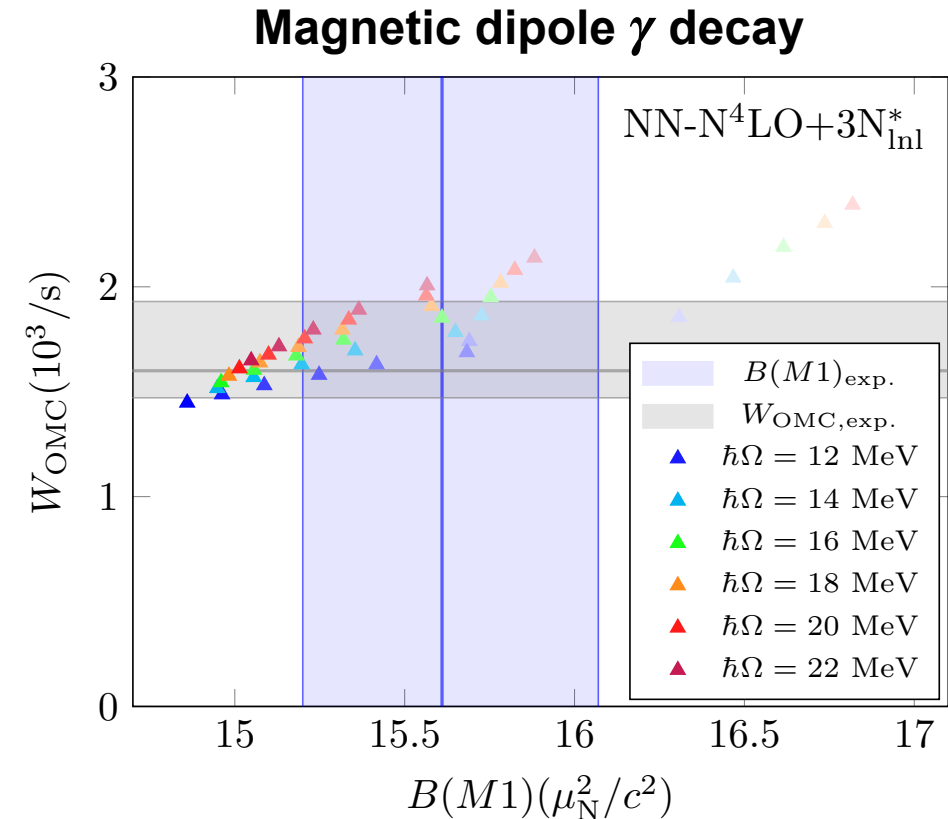
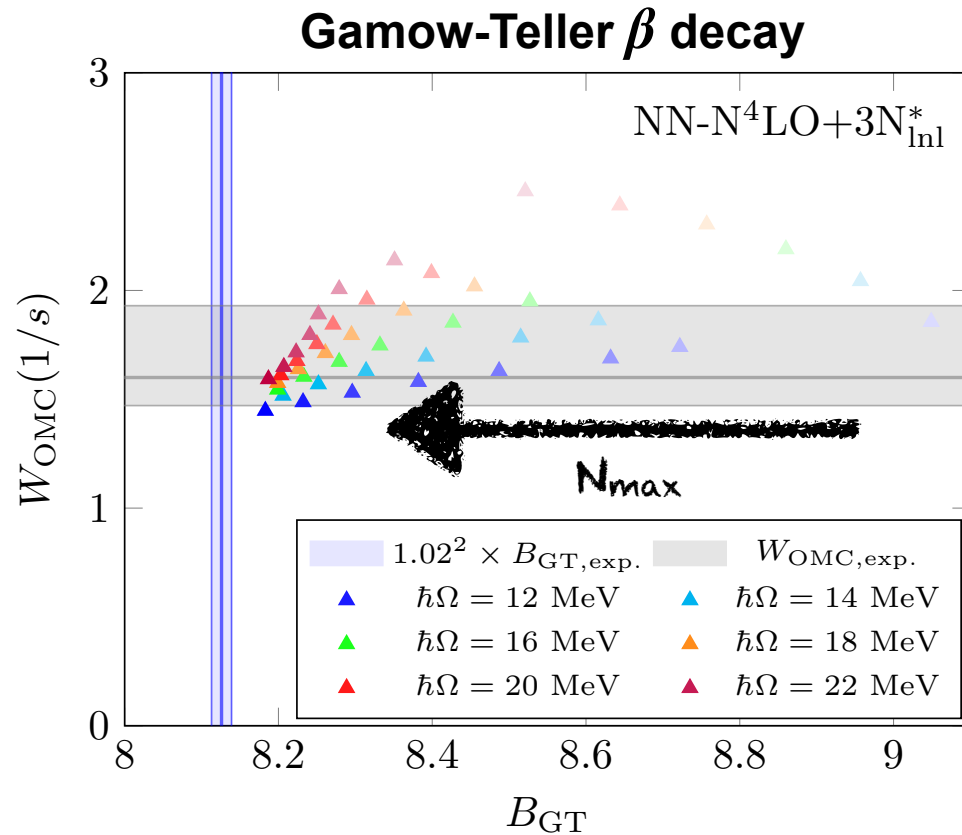
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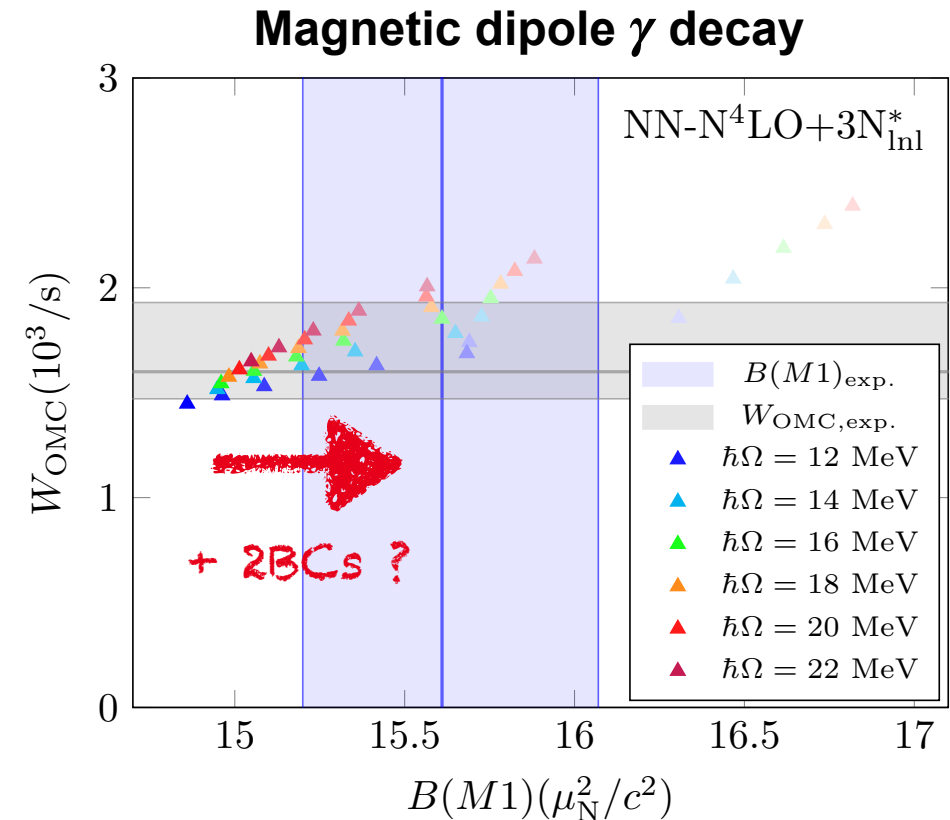
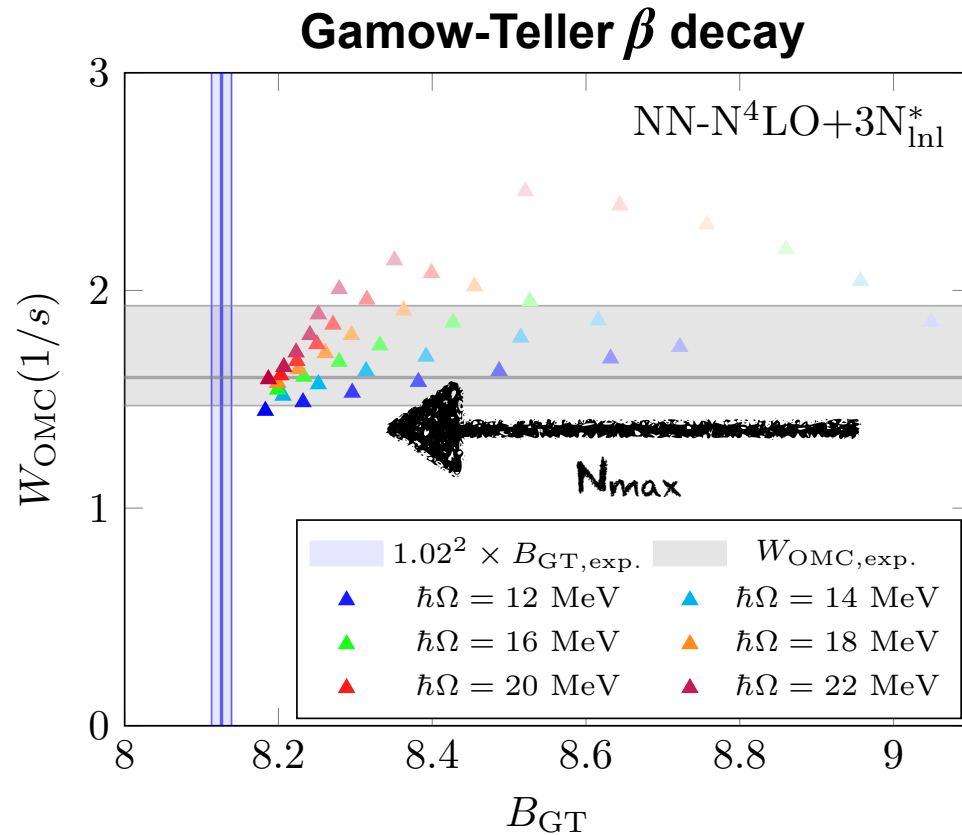
LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

CORRELATIONS WITH OTHER OBSERVABLES



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CORRELATIONS WITH OTHER OBSERVABLES



LJ, P. Navrátil, J. Kotila, K. Kravvaris, *Phys. Rev. C* 109, 065501 (2024)

TAKE-HOME MESSAGES

- Most nuclei in the nuclear chart are radioactive
- Chiral effective field theory allows for consistent derivation of nuclear interactions and electroweak currents
- *Ab initio* calculations suggest a solution to the decades-old axial-vector quenching puzzle:
 - Two-body currents
 - Inclusion of relevant nuclear many-body correlations
- *Ab initio* no-core shell model describes well muon capture on ${}^6\text{Li}$ (and other light nuclei)

UP NEXT

Lecture 4 *Nuclear probes of physics beyond the standard model*

OUTLINE

Lecture 1

Introduction to ab initio nuclear theory

Lecture 2

From nuclear forces to nuclear properties

Lecture 3

From weak interactions to nuclear observables

Lecture 4

Nuclear probes of physics beyond the standard model

LECTURE 4

▪ **Introduction**

Physics in the Standard model and beyond. How atomic nuclei can be used in BSM searches?

▪ **Double-beta decay**

What is double-beta decay? What can we learn from it? How is it searched for?

▪ **Nuclear matrix elements of double-beta decays**

How are they computed? How can they be improved?

▪ **Global neutrino-mass limits from double-beta decays**

How can we obtain global neutrino-mass limits from neutrinoless double-beta-decay searches?

▪ **Precision beta-decay searches**

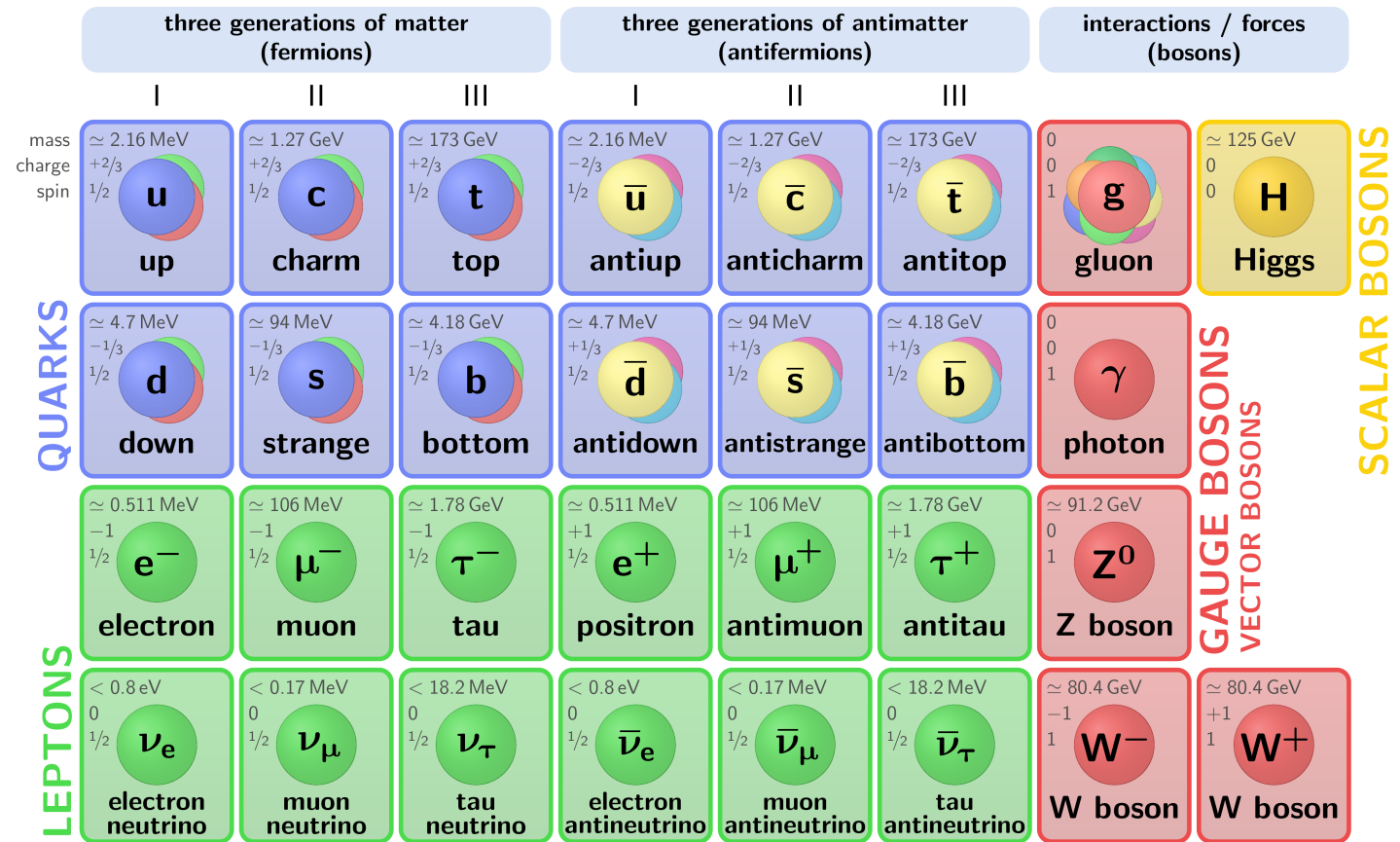
and how we can look for deviations from the standard model.

INTRODUCTION

THE STANDARD MODEL OF PARTICLE PHYSICS



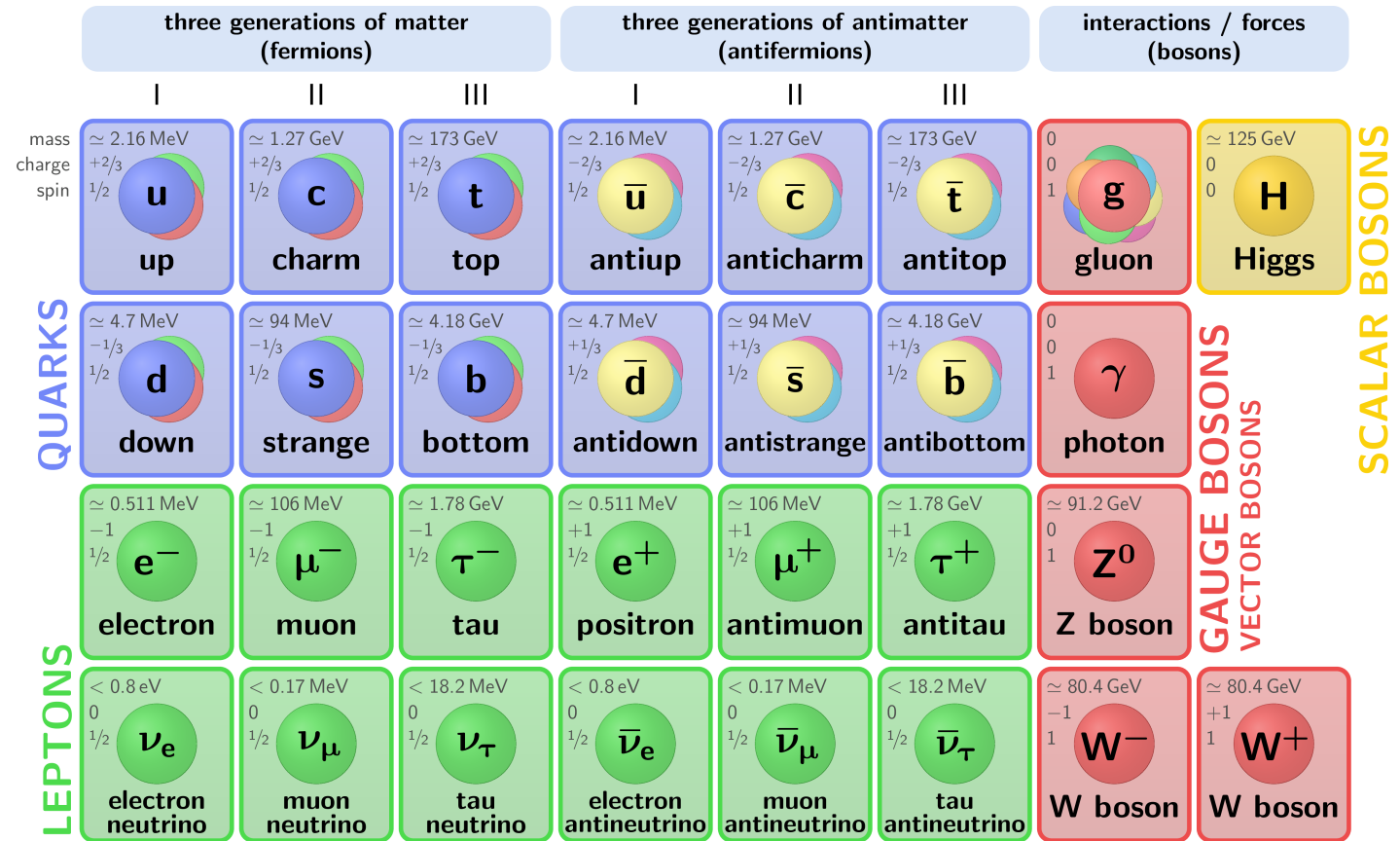
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Neutelings, Standard Model – TikZ.net

THE STANDARD MODEL OF PARTICLE PHYSICS

- Particles have antiparticles

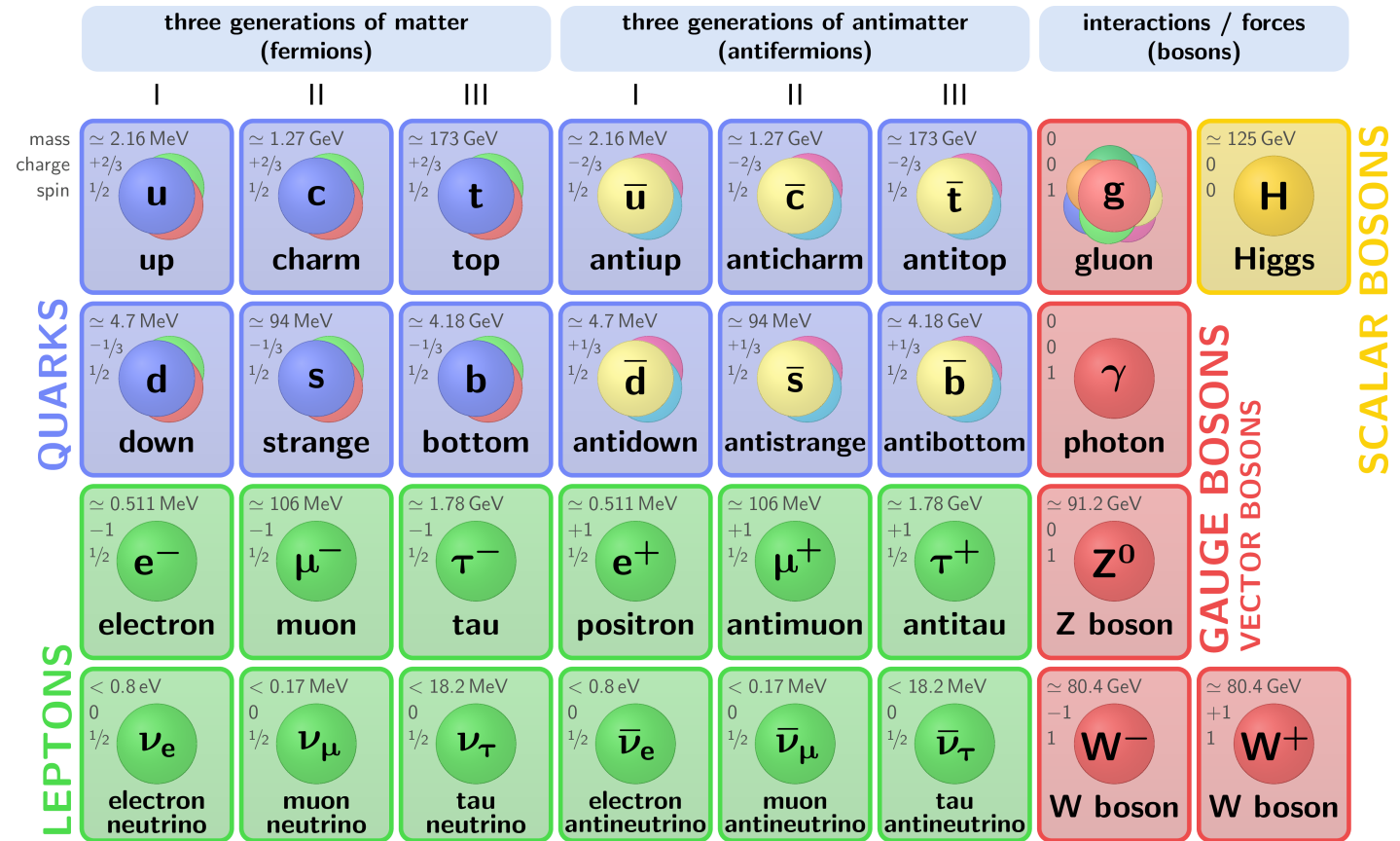


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- E.g. $\bar{e}^- = e^+$



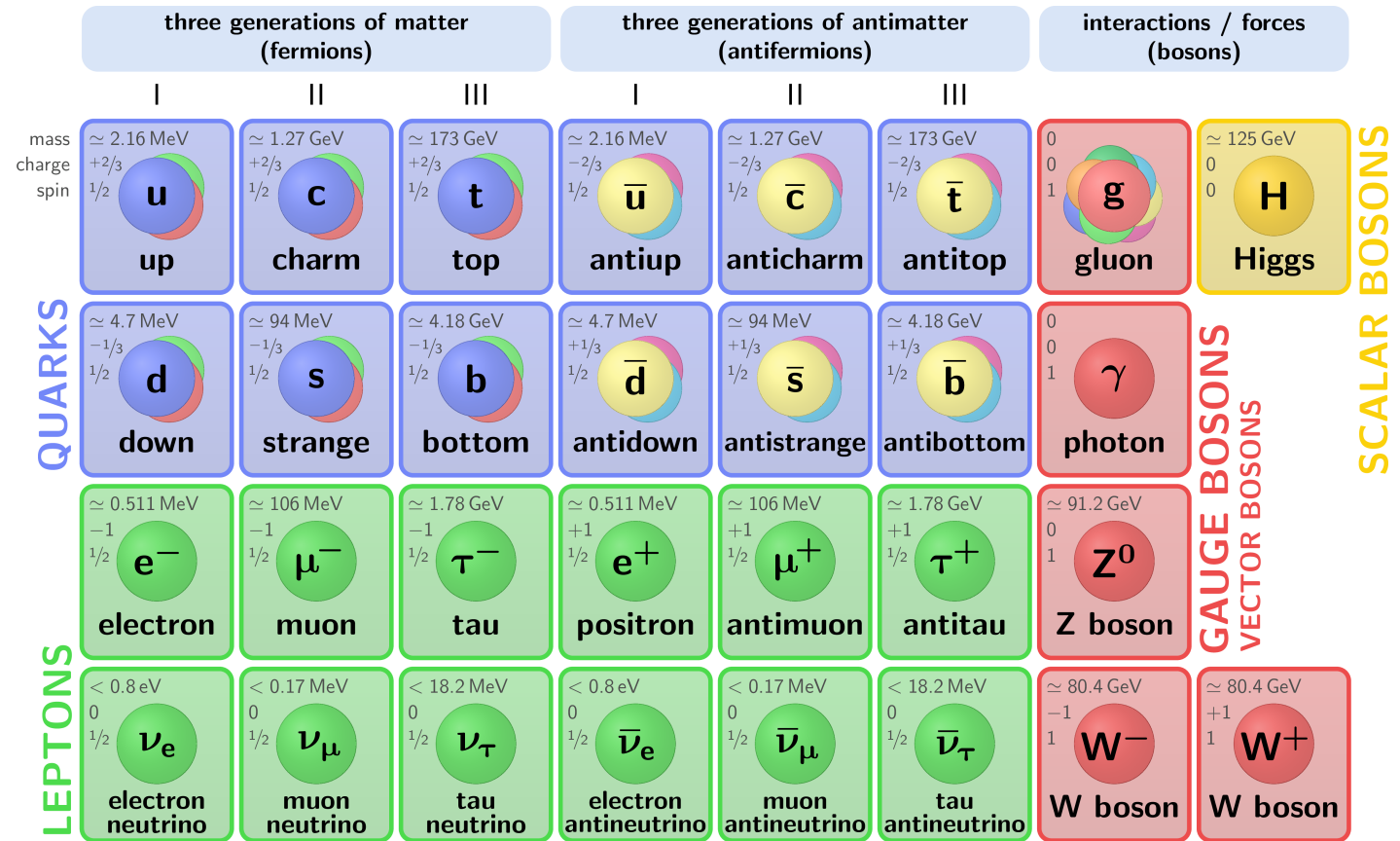
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THE STANDARD MODEL OF PARTICLE PHYSICS



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- Particles have **antiparticles**
 - E.g. $\bar{e}^- = e^+$
- **Matter and antimatter** are created in pairs



Neutelings, Standard Model – TikZ.net

THE STANDARD MODEL OF PARTICLE PHYSICS



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- Particles have antiparticles

- E.g. $\bar{e}^- = e^+$

- Matter and antimatter are created in pairs

- e.g. $n \rightarrow p + e^- + \bar{\nu}_e$

three generations of matter (fermions)			three generations of antimatter (antifermions)			interactions / forces (bosons)	
I	II	III	I	II	III		
mass charge spin							
$\approx 2.16 \text{ MeV}$ $+2/3$ $1/2$	$\approx 1.27 \text{ GeV}$ $+2/3$ $1/2$	$\approx 173 \text{ GeV}$ $+2/3$ $1/2$	$\approx 2.16 \text{ MeV}$ $-2/3$ $1/2$	$\approx 1.27 \text{ GeV}$ $-2/3$ $1/2$	$\approx 173 \text{ GeV}$ $-2/3$ $1/2$	0 0 1	$\approx 125 \text{ GeV}$ 0 0
u up	c charm	t top	ū antiup	c̄ anticharm	t̄ antitop	g gluon	H Higgs
$\approx 4.7 \text{ MeV}$ $-1/3$ $1/2$	$\approx 94 \text{ MeV}$ $-1/3$ $1/2$	$\approx 4.18 \text{ GeV}$ $-1/3$ $1/2$	$\approx 4.7 \text{ MeV}$ $+1/3$ $1/2$	$\approx 94 \text{ MeV}$ $+1/3$ $1/2$	$\approx 4.18 \text{ GeV}$ $+1/3$ $1/2$	0 0 1	
d down	s strange	b bottom	d̄ antidown	s̄ antistrange	b̄ antibottom	γ photon	
$\approx 0.511 \text{ MeV}$ -1 $1/2$	$\approx 106 \text{ MeV}$ -1 $1/2$	$\approx 1.78 \text{ GeV}$ -1 $1/2$	$\approx 0.511 \text{ MeV}$ $+1$ $1/2$	$\approx 106 \text{ MeV}$ $+1$ $1/2$	$\approx 1.78 \text{ GeV}$ $+1$ $1/2$	$\approx 91.2 \text{ GeV}$ 0 1	
e⁻ electron	μ⁻ muon	τ⁻ tau	e⁺ positron	μ⁺ antimuon	τ⁺ antitau	Z⁰ Z boson	
$< 0.8 \text{ eV}$ 0 $1/2$	$< 0.17 \text{ MeV}$ 0 $1/2$	$< 18.2 \text{ MeV}$ 0 $1/2$	$< 0.8 \text{ eV}$ 0 $1/2$	$< 0.17 \text{ MeV}$ 0 $1/2$	$< 18.2 \text{ MeV}$ 0 $1/2$	$\approx 80.4 \text{ GeV}$ -1 1	$\approx 80.4 \text{ GeV}$ $+1$ 1
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	ν̄_e electron antineutrino	ν̄_μ muon antineutrino	ν̄_τ tau antineutrino	W⁻ W boson	W⁺ W boson
LEPTONS						GAUGE BOSONS VECTOR BOSONS	
						SCALAR BOSONS	

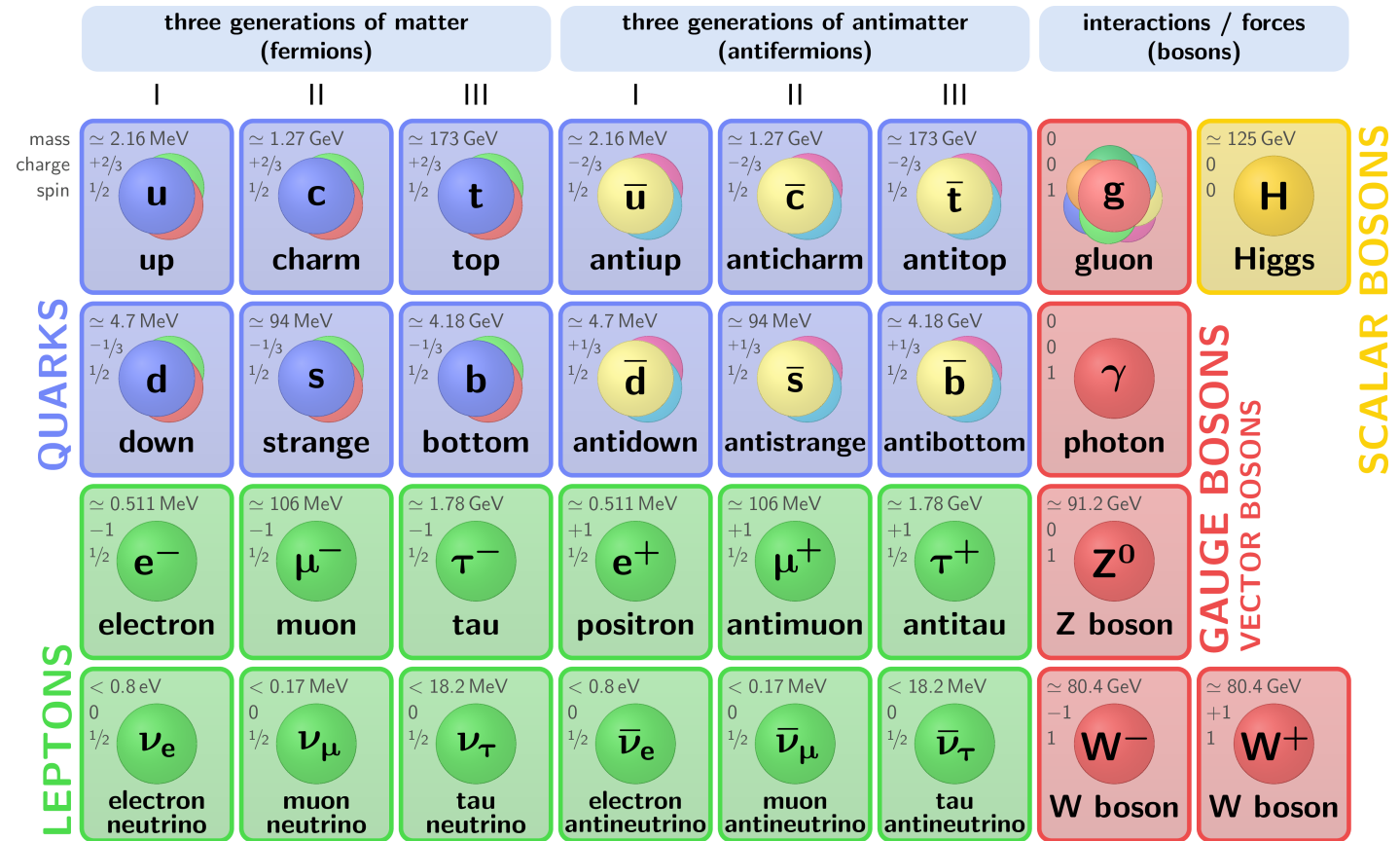
Neutelings, Standard Model – TikZ.net

THE STANDARD MODEL OF PARTICLE PHYSICS



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- Particles have antiparticles
 - E.g. $\bar{e}^- = e^+$
- Matter and antimatter are created in pairs
 - e.g. $n \rightarrow p + e^- + \bar{\nu}_e$
- Separately conserved lepton numbers



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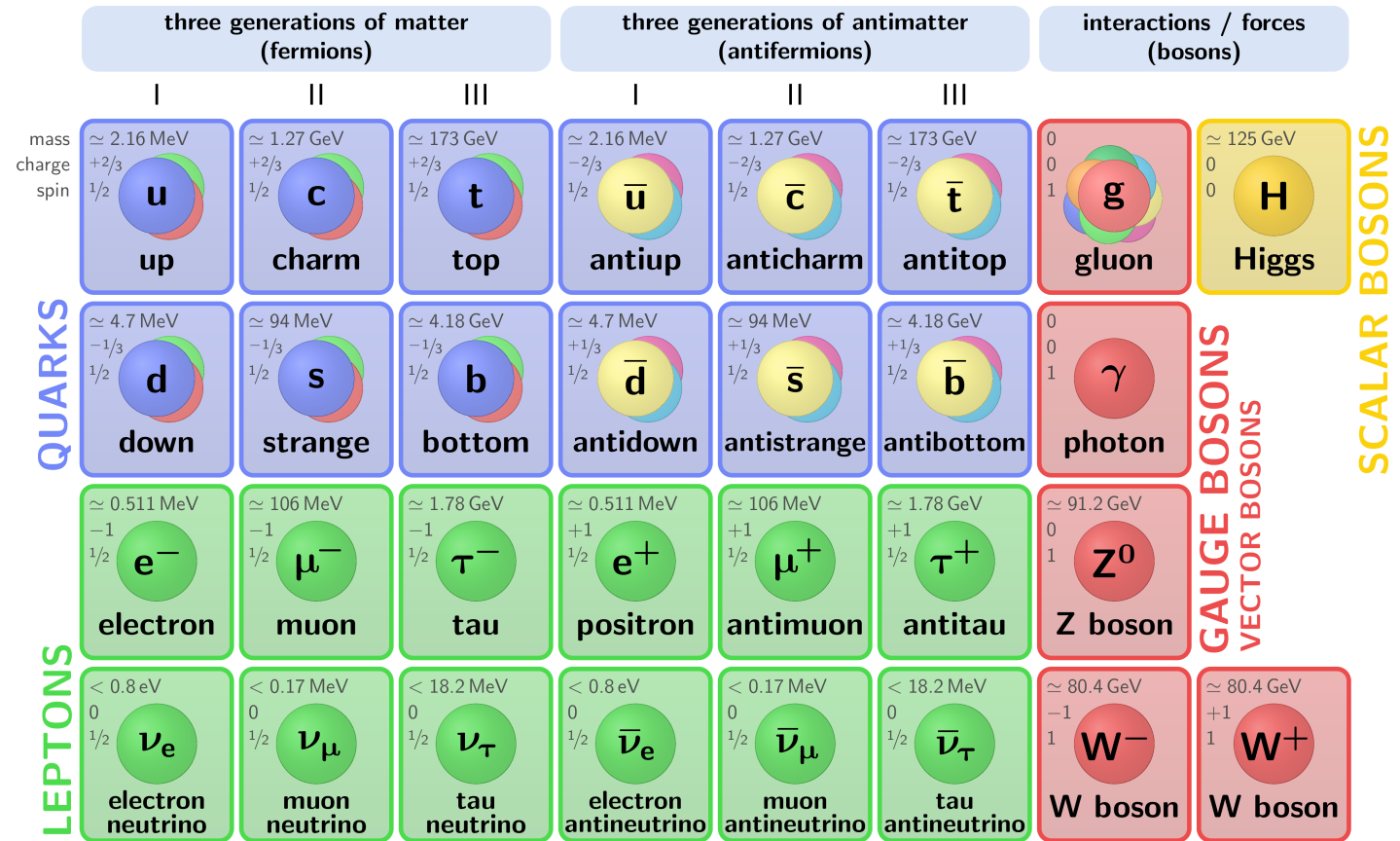
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- Separately conserved lepton numbers

- e.g. $\nu_e + n \rightarrow e^- + p$
but $\nu_\mu + n \nrightarrow e^- + p$



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PHYSICS BEYOND THE STANDARD MODEL



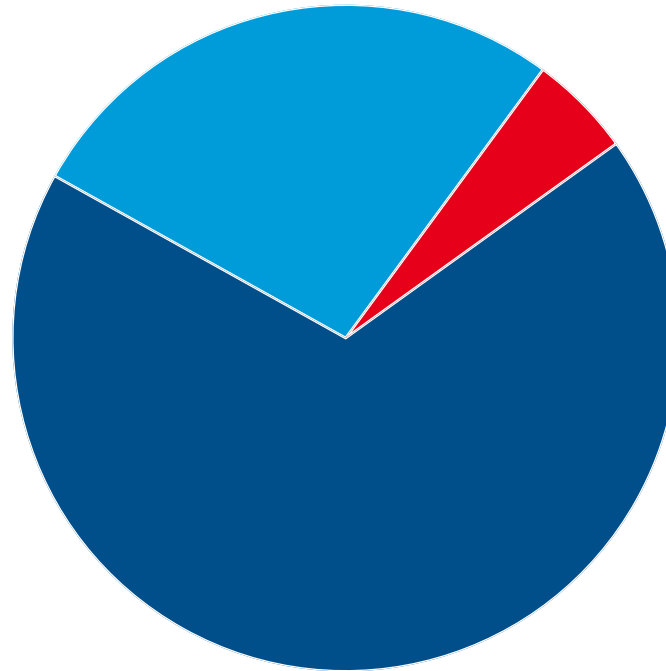
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Dark matter and dark energy

● Ordinary matter

● Dark matter

● Dark energy



*Energy decomposition of the
Universe*

PHYSICS BEYOND THE STANDARD MODEL



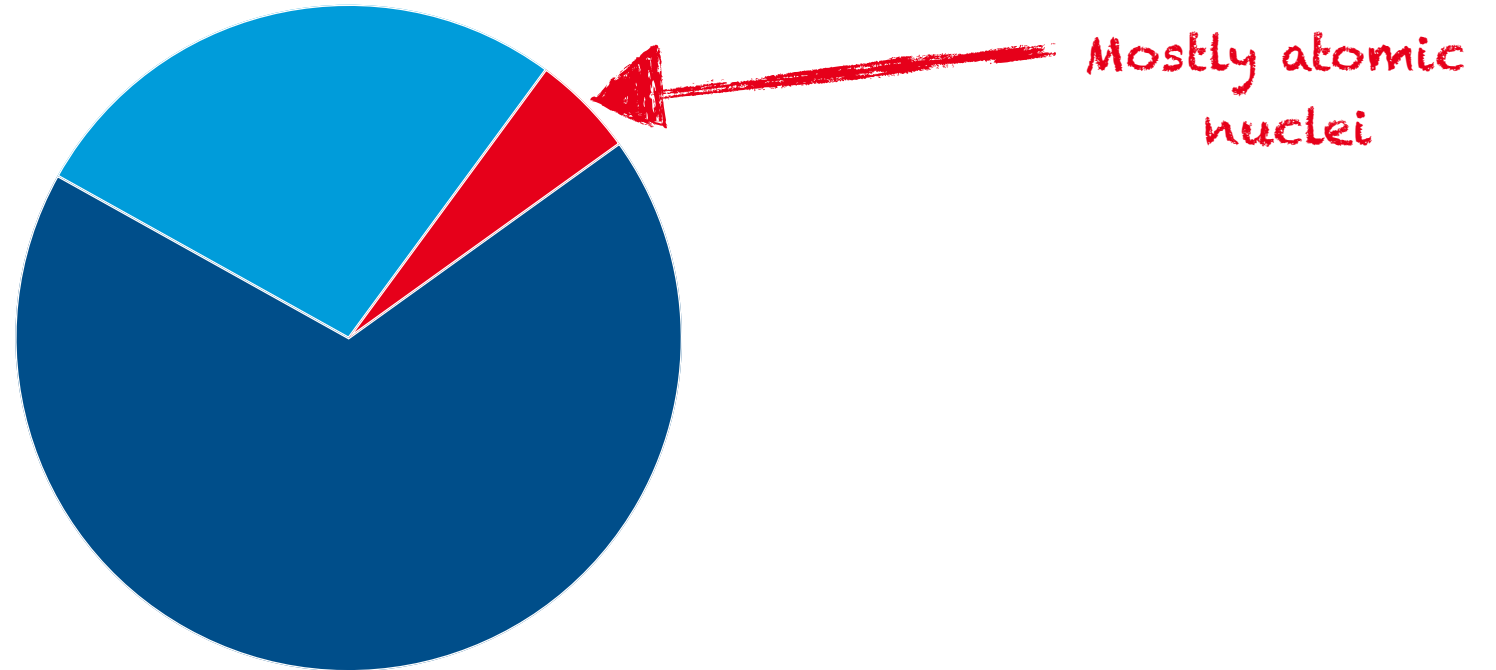
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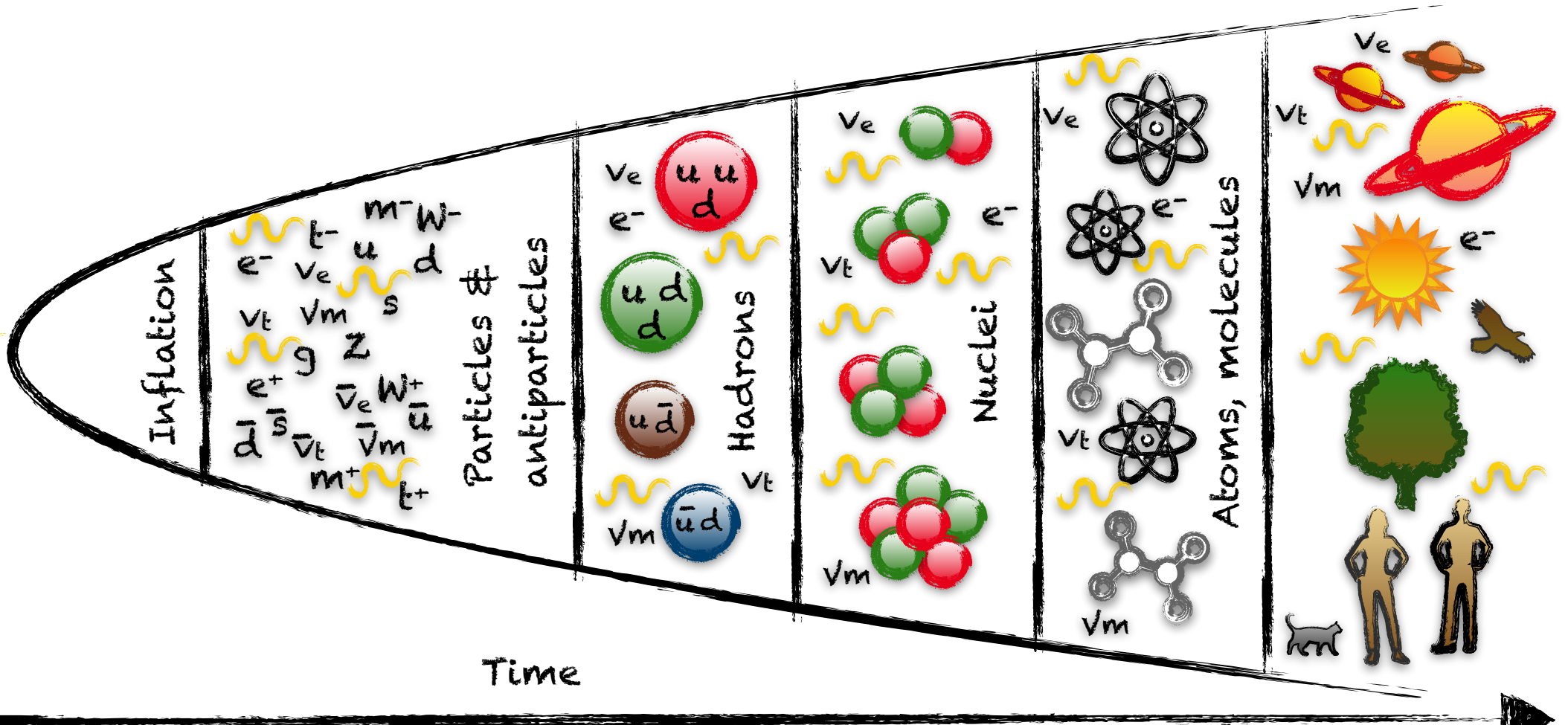
PHYSICS BEYOND THE STANDARD MODEL

Matter-antimatter asymmetry



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Matter

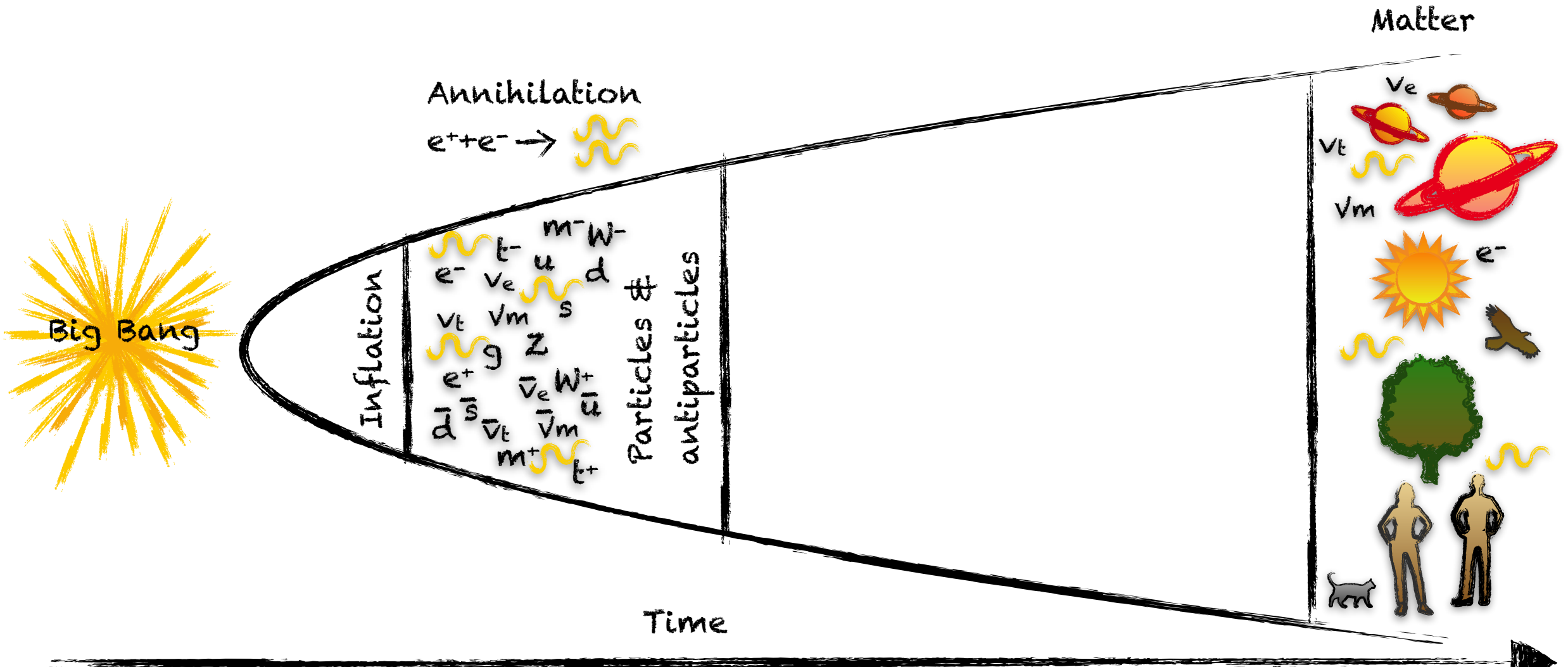


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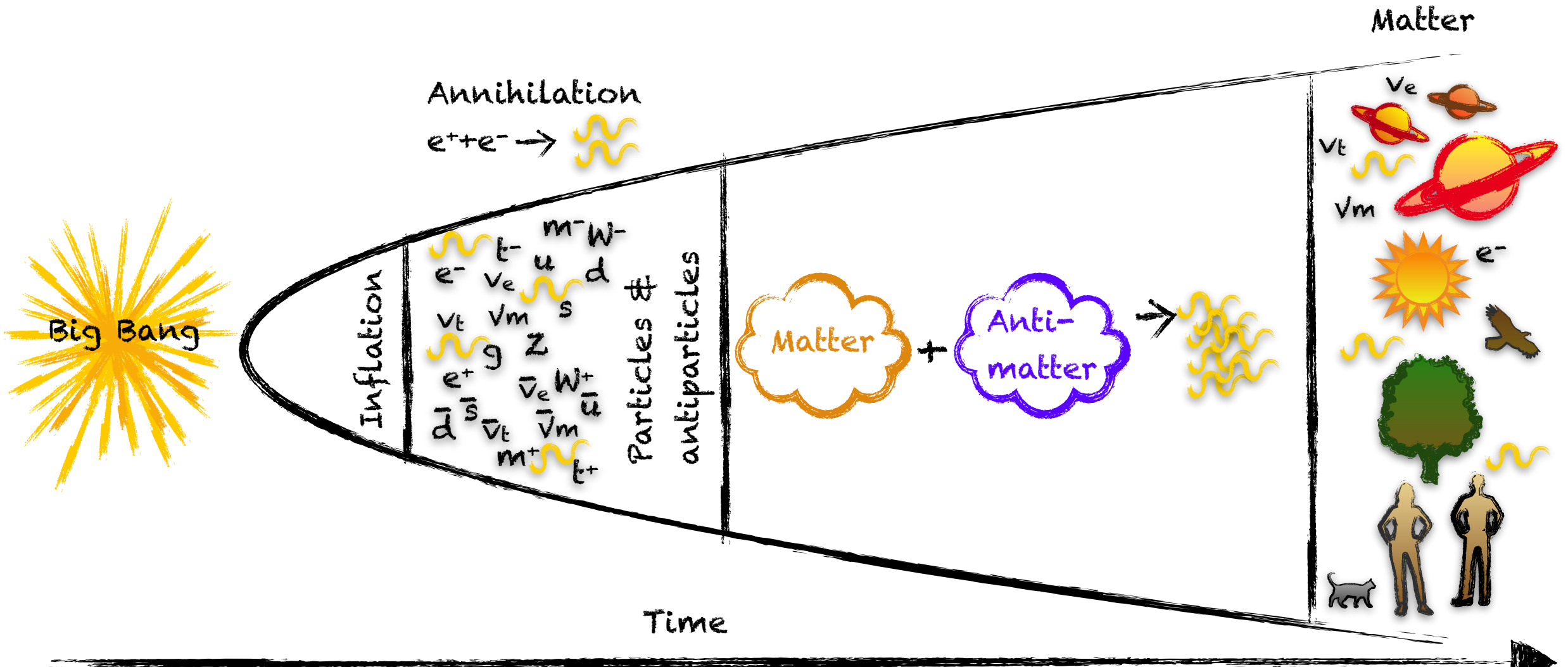


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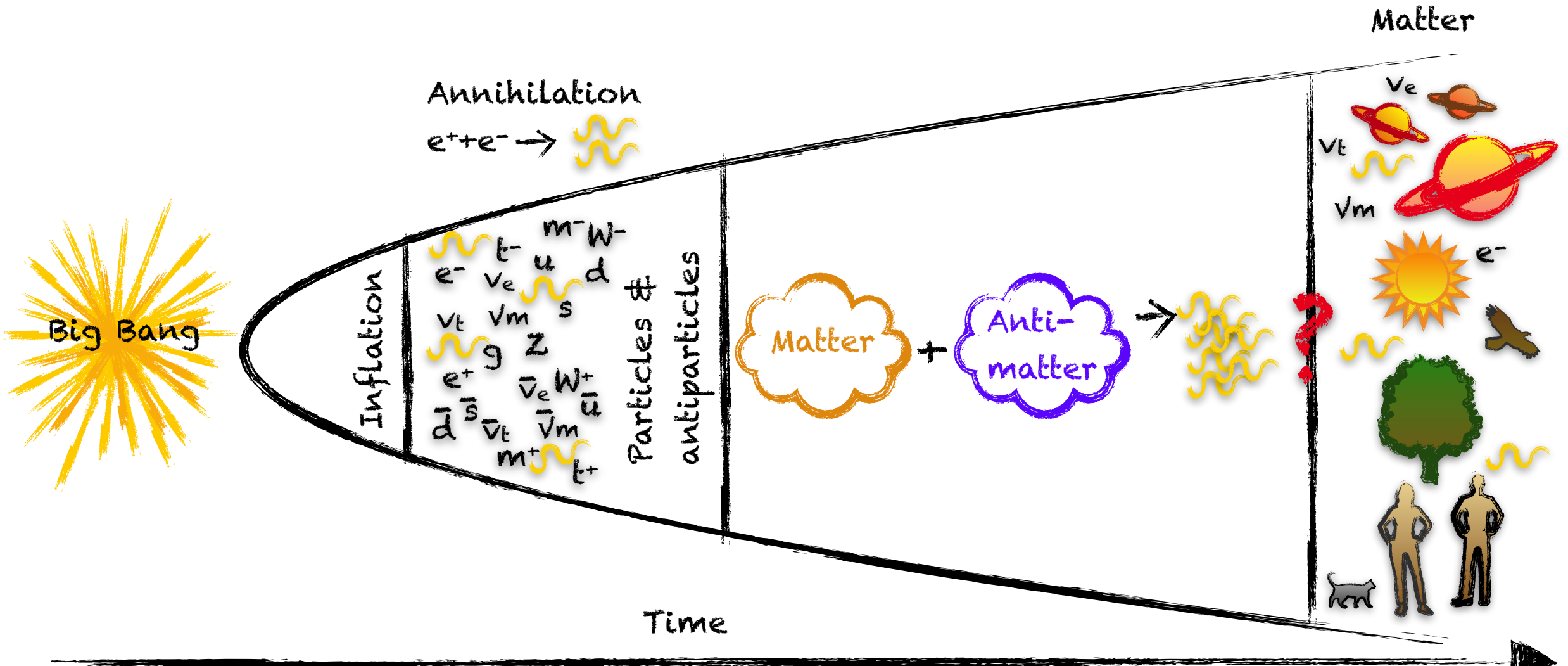


PHYSICS BEYOND THE STANDARD MODEL



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PHYSICS BEYOND THE STANDARD MODEL

Mysterious neutrinos

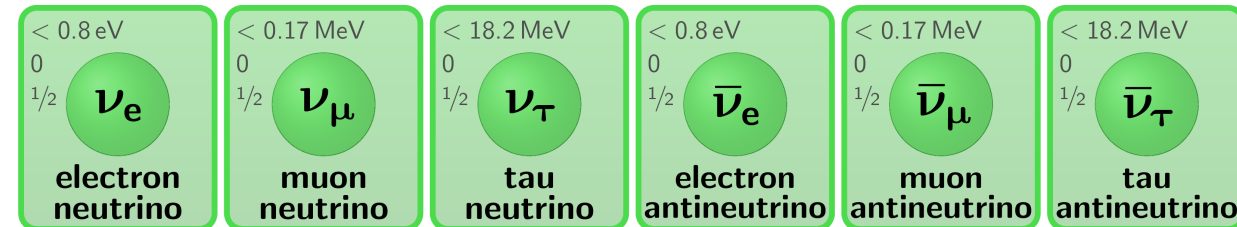


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PHYSICS BEYOND THE STANDARD MODEL

Mysterious neutrinos

- Neutrino: **electrically neutral** and **massless** lepton (SM)



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“I have done a terrible thing. I have postulated a particle that cannot be detected” – W. Pauli, ca. 1930



PHYSICS BEYOND THE STANDARD MODEL



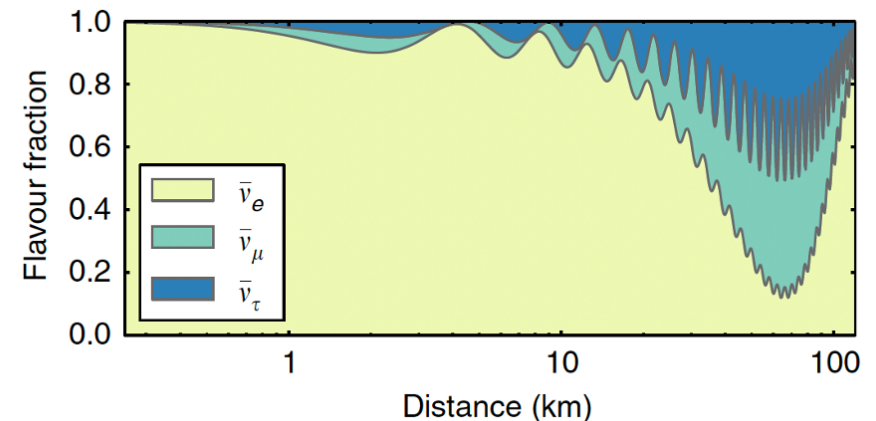
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$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\alpha j}^* U_{\beta j} e^{-i \frac{m_j^2 L}{2E}} \right|^2$$



Vogel, Wen, Zhang, Nature Comm. 6, 6935 (2015)

PHYSICS BEYOND THE STANDARD MODEL

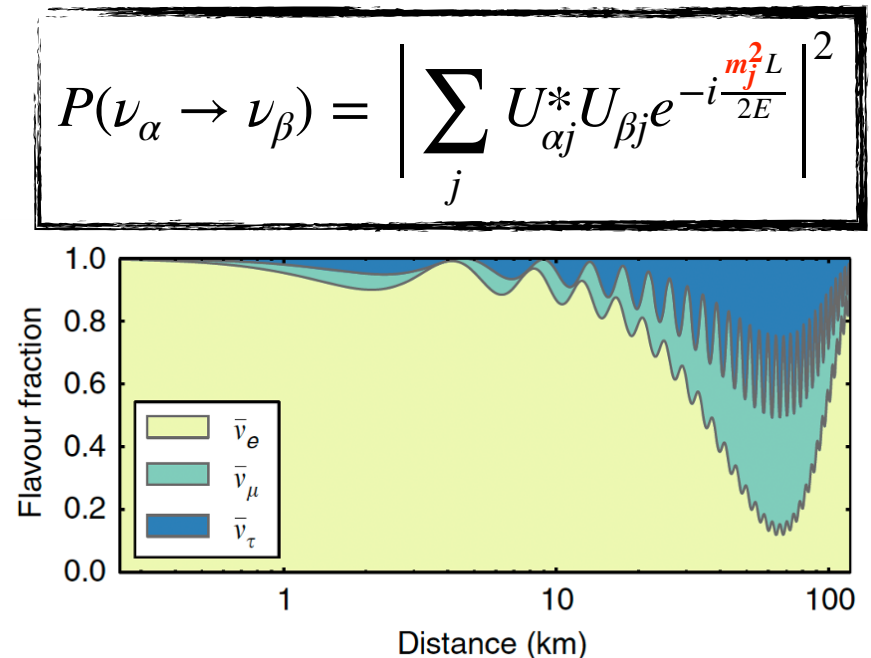


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→ **Neutrinos must be massive**



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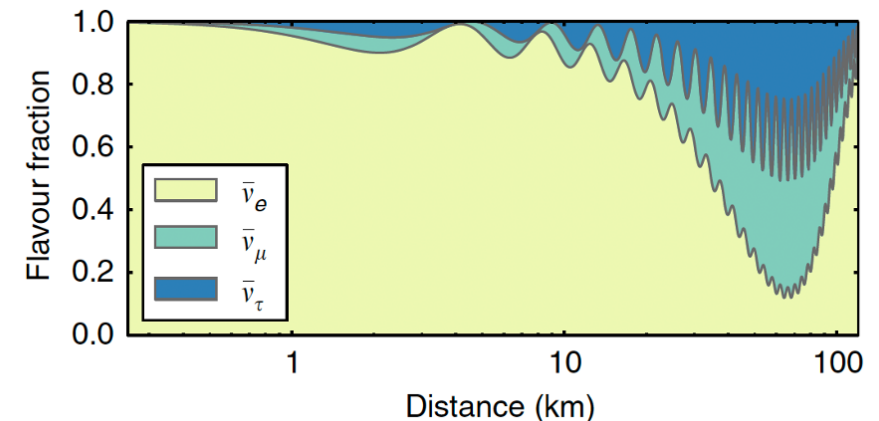
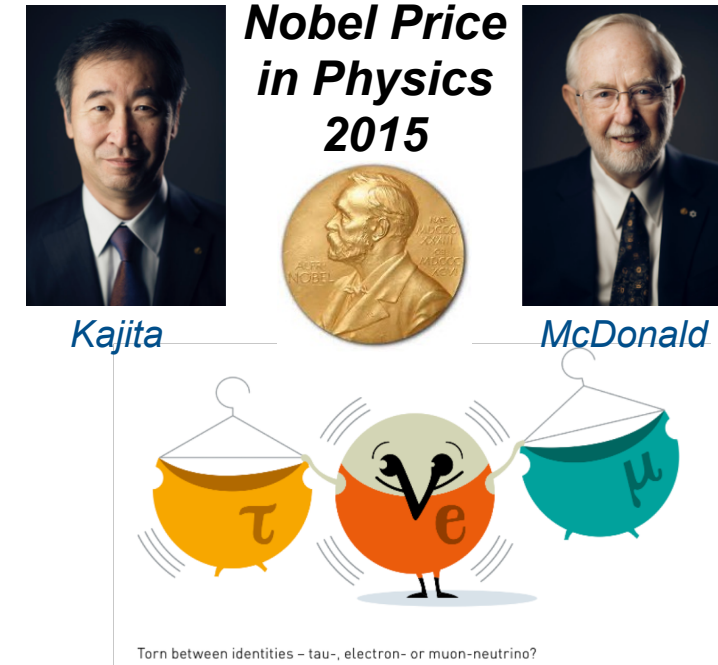
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NEUTRINOS ARE MASSIVE – BUT WHAT ARE THE MASSES?



Neutrino mixing matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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Flavor eigenstates

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Flavor eigenstates *Mass eigenstates*

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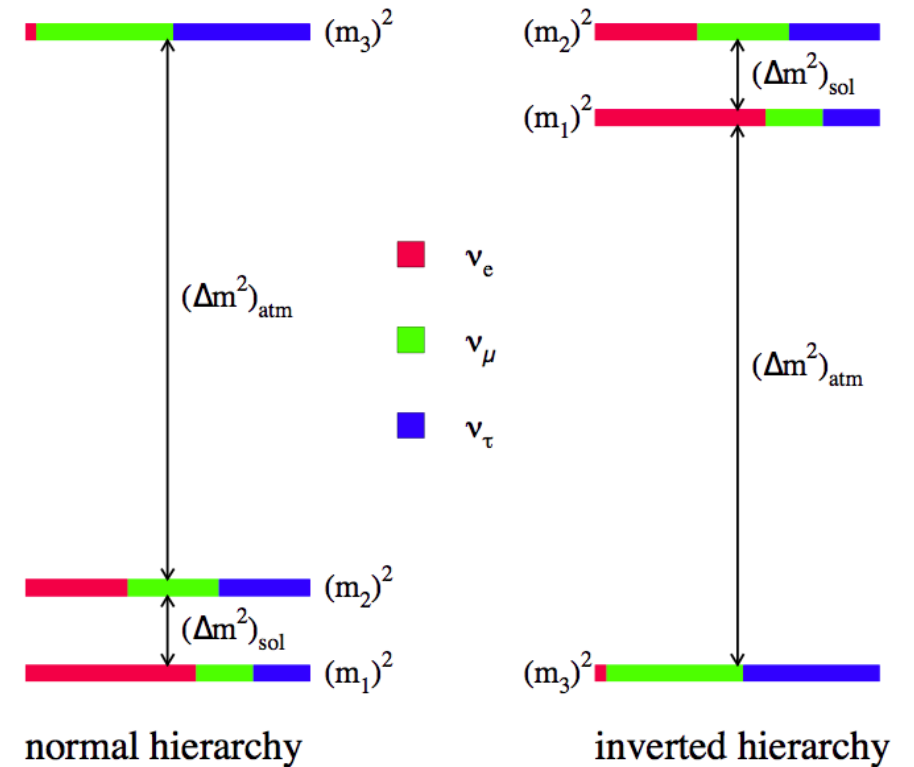
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Flavor eigenstates

Mass eigenstates

Neutrino mass hierarchy



Cahn, Dwyer, Freedman, Haxton et al., arXiv: 1307.5487

NUCLEI AS TEST LABORATORIES



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Look for...

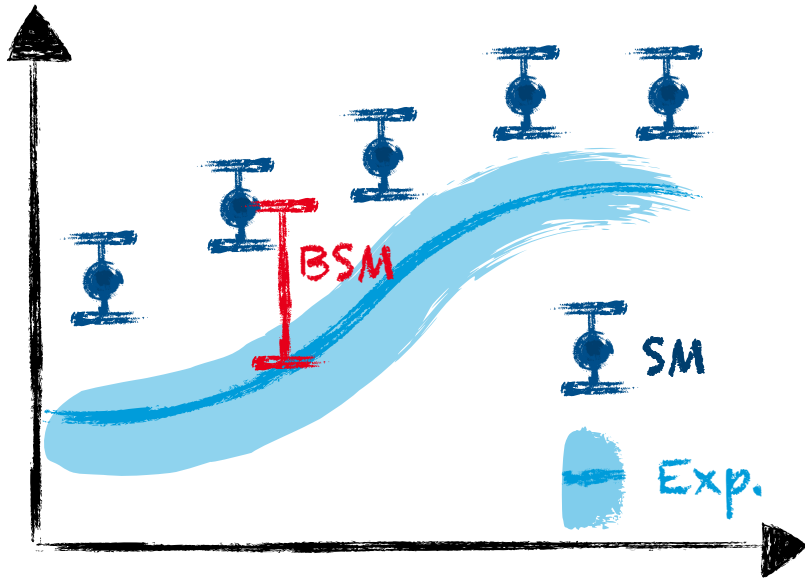
NUCLEI AS TEST LABORATORIES



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Look for...

- Deviations from the Standard Model predictions

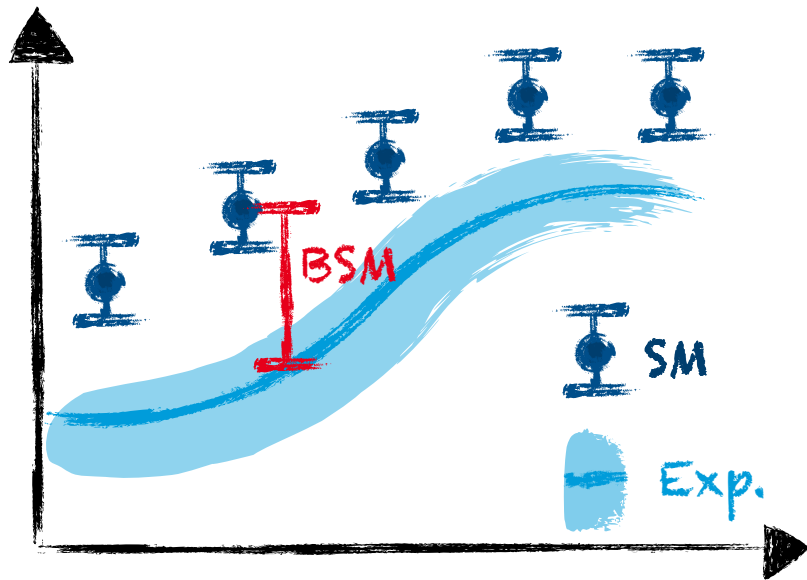


NUCLEI AS TEST LABORATORIES



Look for...

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- Forbidden β decays

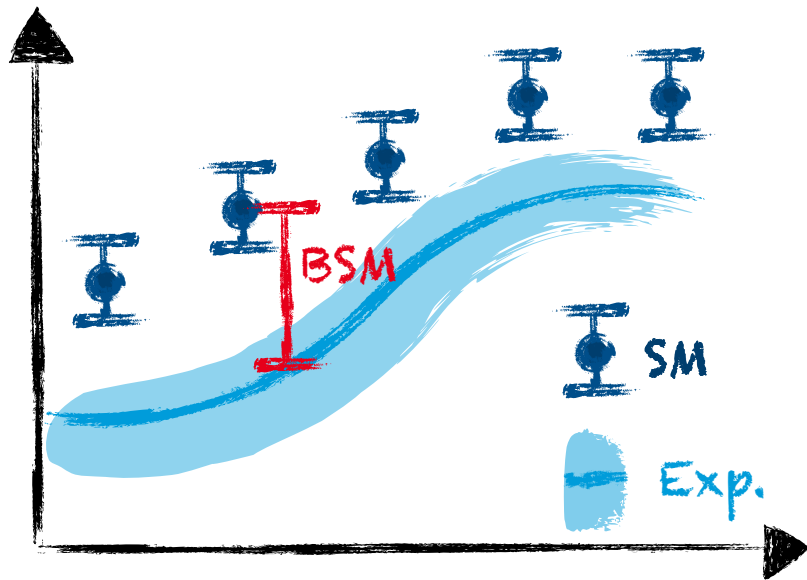
NUCLEI AS TEST LABORATORIES



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Look for...

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- Forbidden β decays
- Superallowed β decay
($0^+ \rightarrow 0^+$ Fermi decay), ...

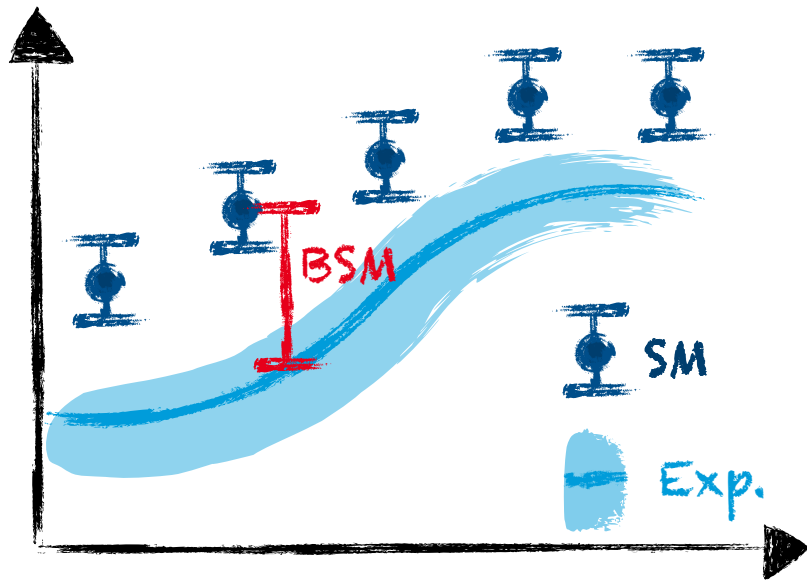
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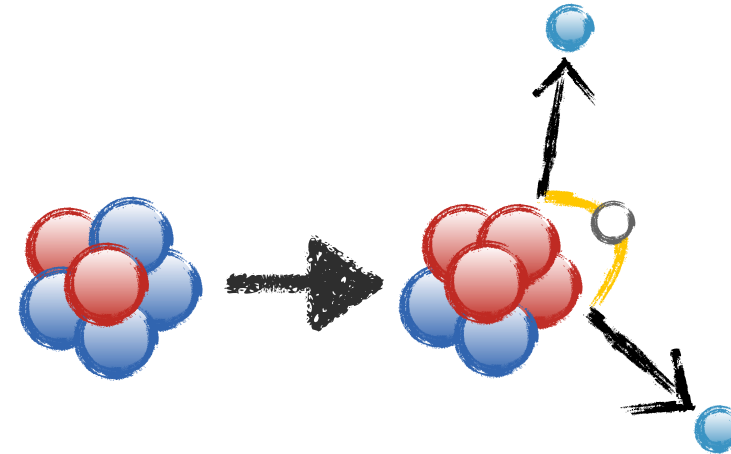
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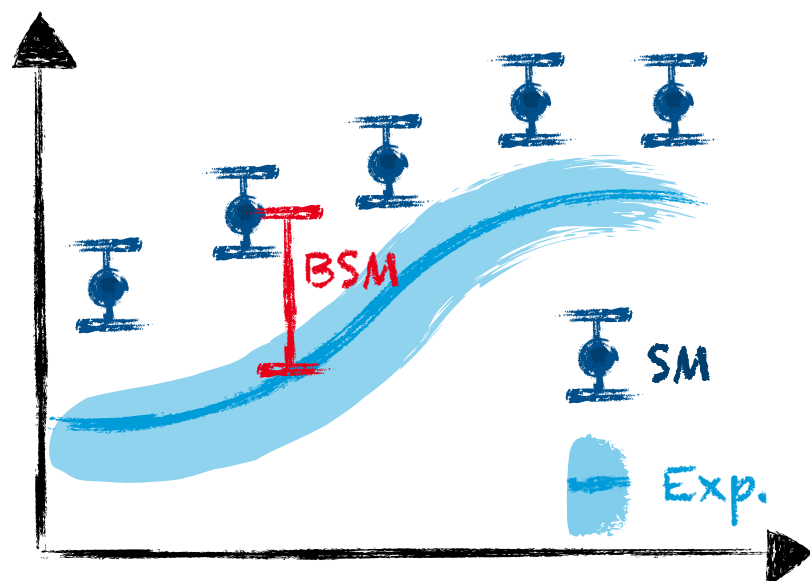
- Phenomena not predicted by the Standard Model



NUCLEI AS TEST LABORATORIES

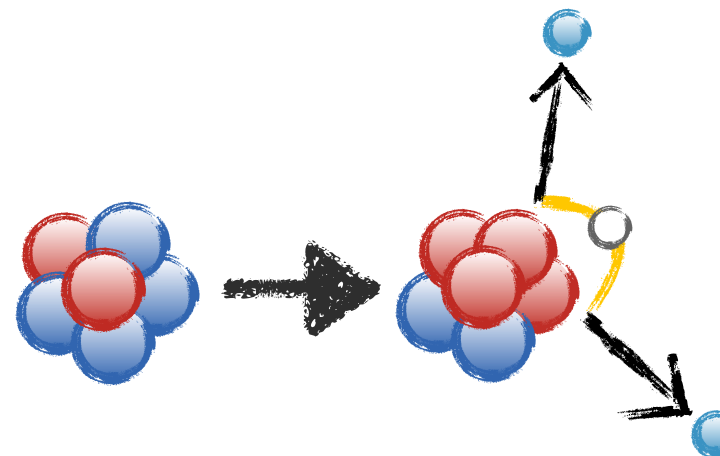
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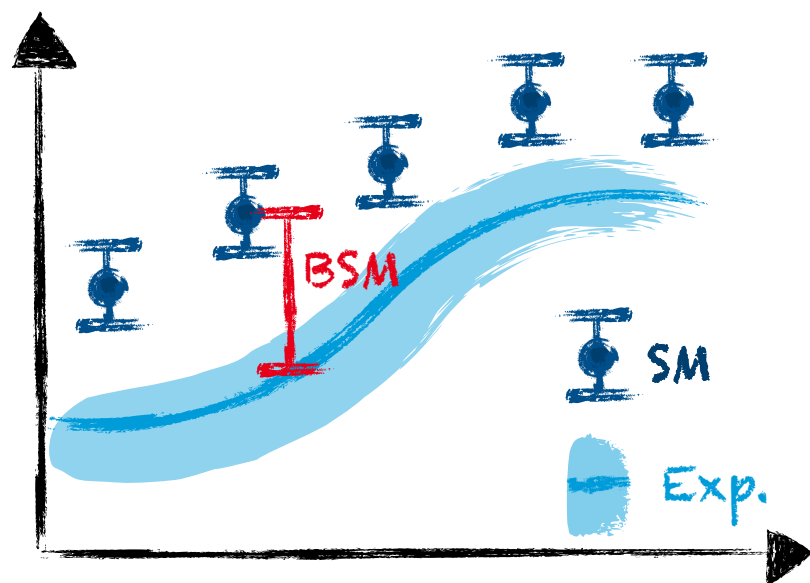


- Neutrinoless double- β decay

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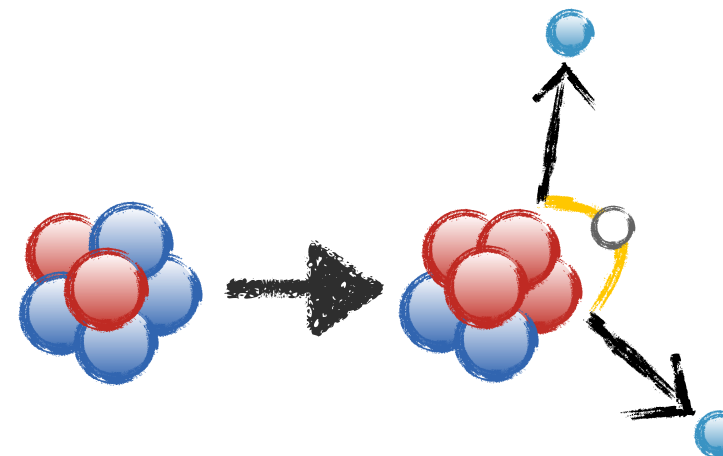
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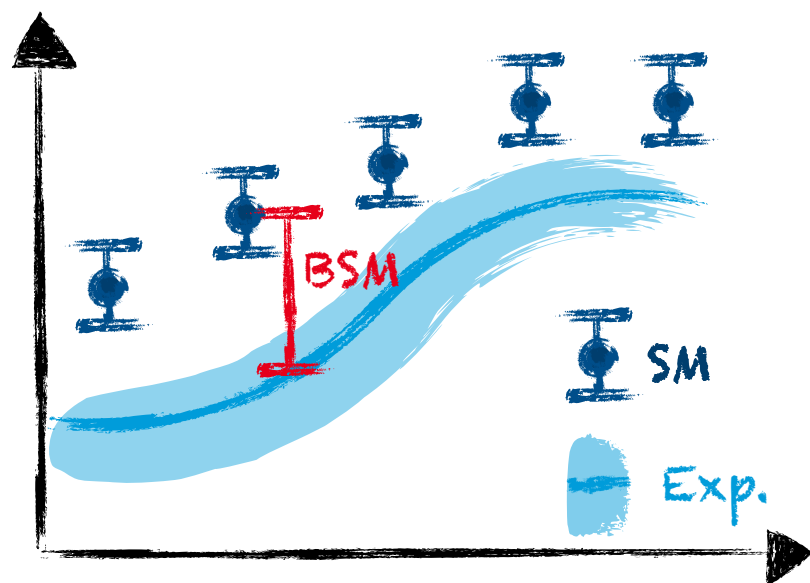


- Neutrinoless double- β decay
- Dark matter scattering from nuclei,

NUCLEI AS TEST LABORATORIES

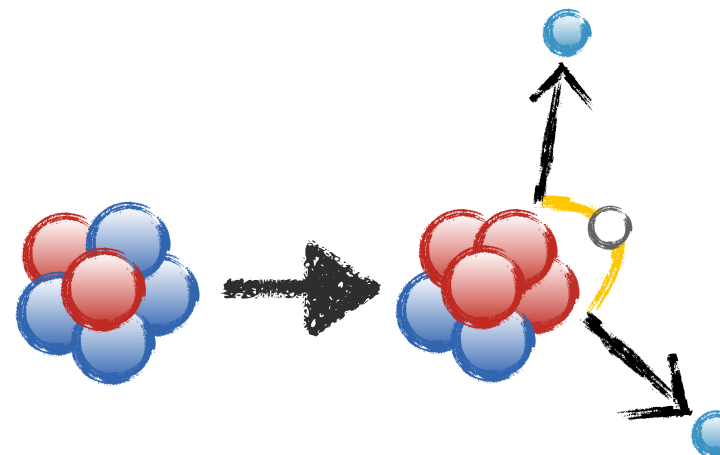
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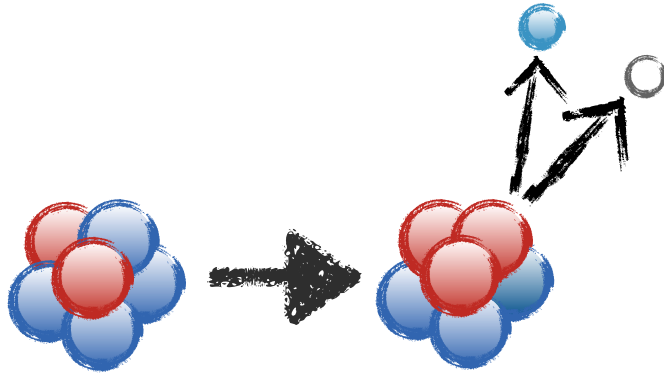


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DOUBLE-BETA DECAY

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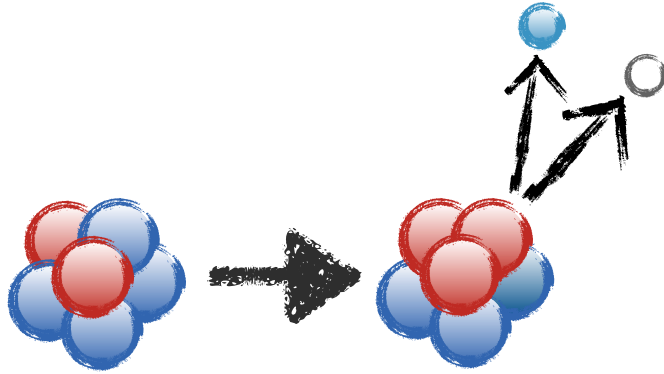
Beta (β^-) decay



*One of the most common
decays*

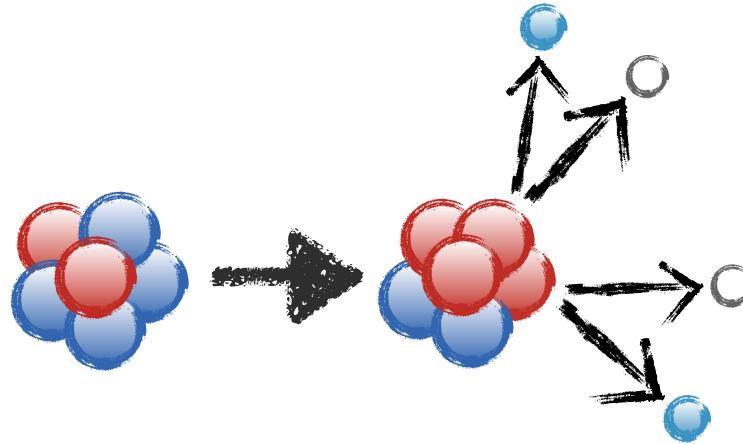
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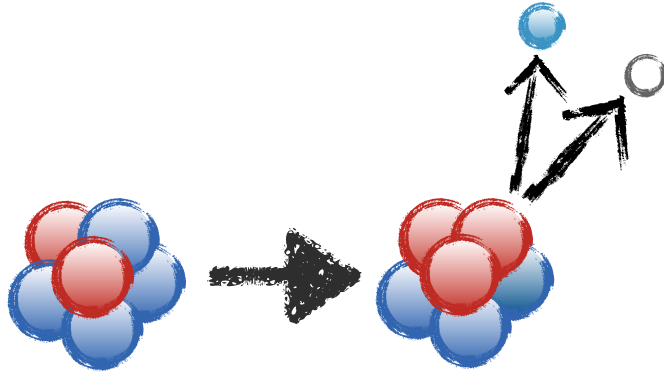
Two-neutrino double- β
($2\nu\beta\beta$) decay



Rarest measured decay

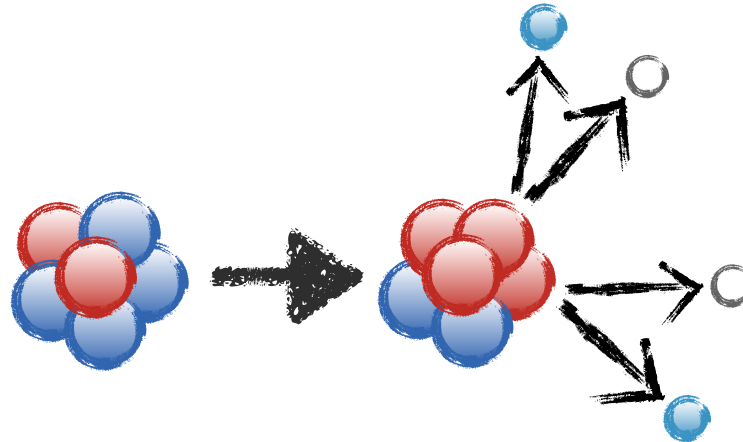
DOUBLE-BETA DECAY

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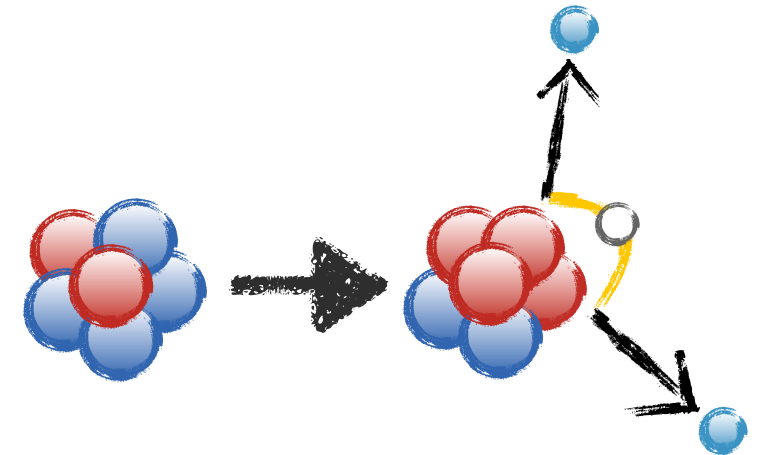
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Two-neutrino double- β ($2\nu\beta\beta$) decay



Rarest measured decay

Neutrinoless double- β ($0\nu\beta\beta$) decay



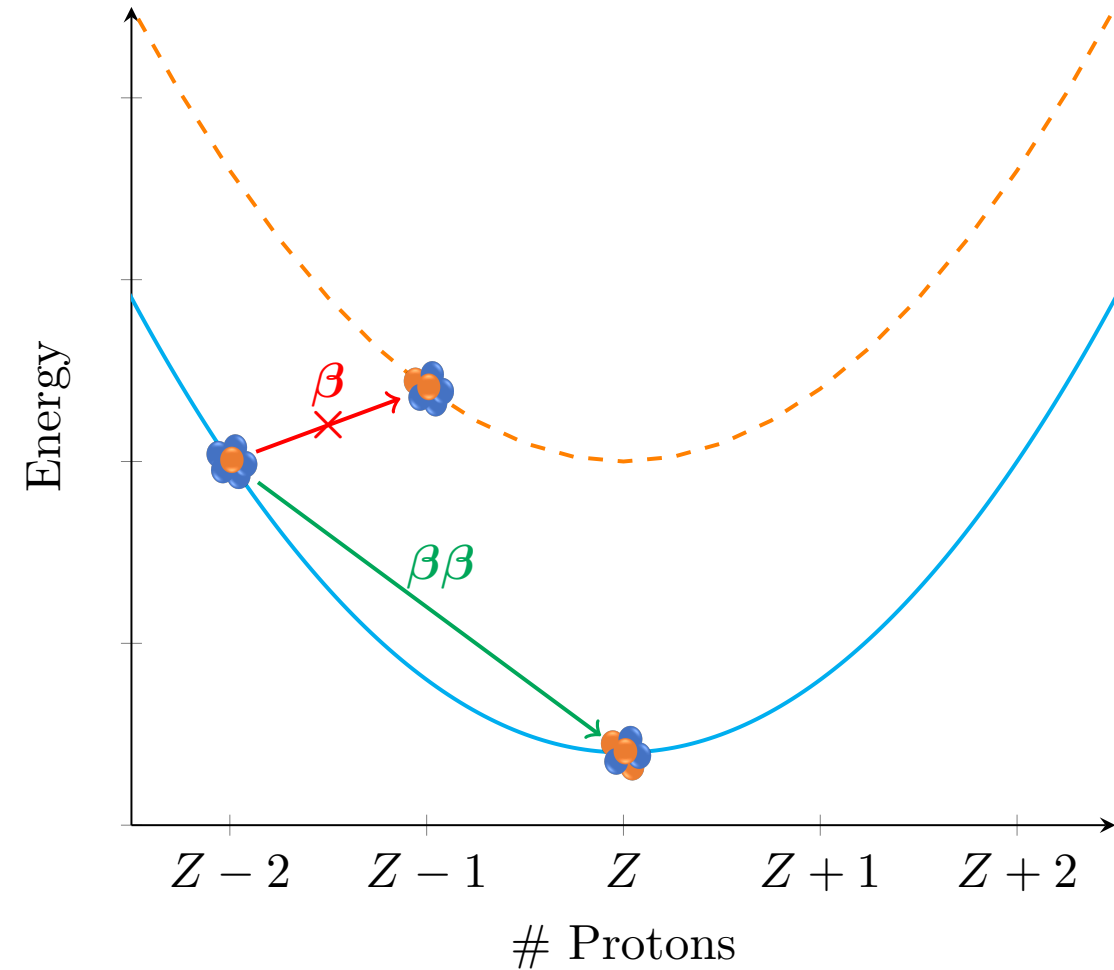
Not yet observed

WHEN CAN NUCLEI DOUBLE-BETA DECAY?



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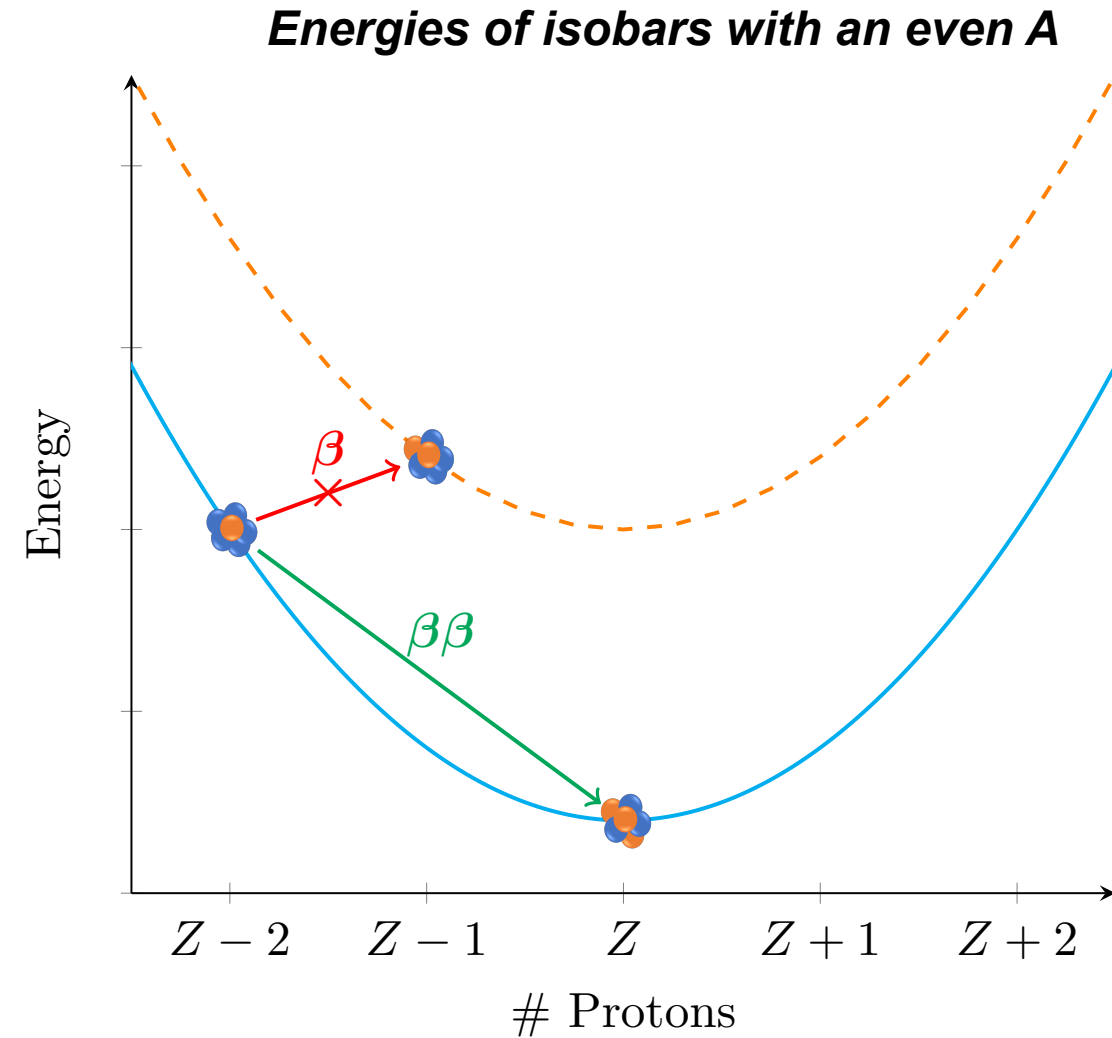
Energies of isobars with an even A



WHEN CAN NUCLEI DOUBLE-BETA DECAY?



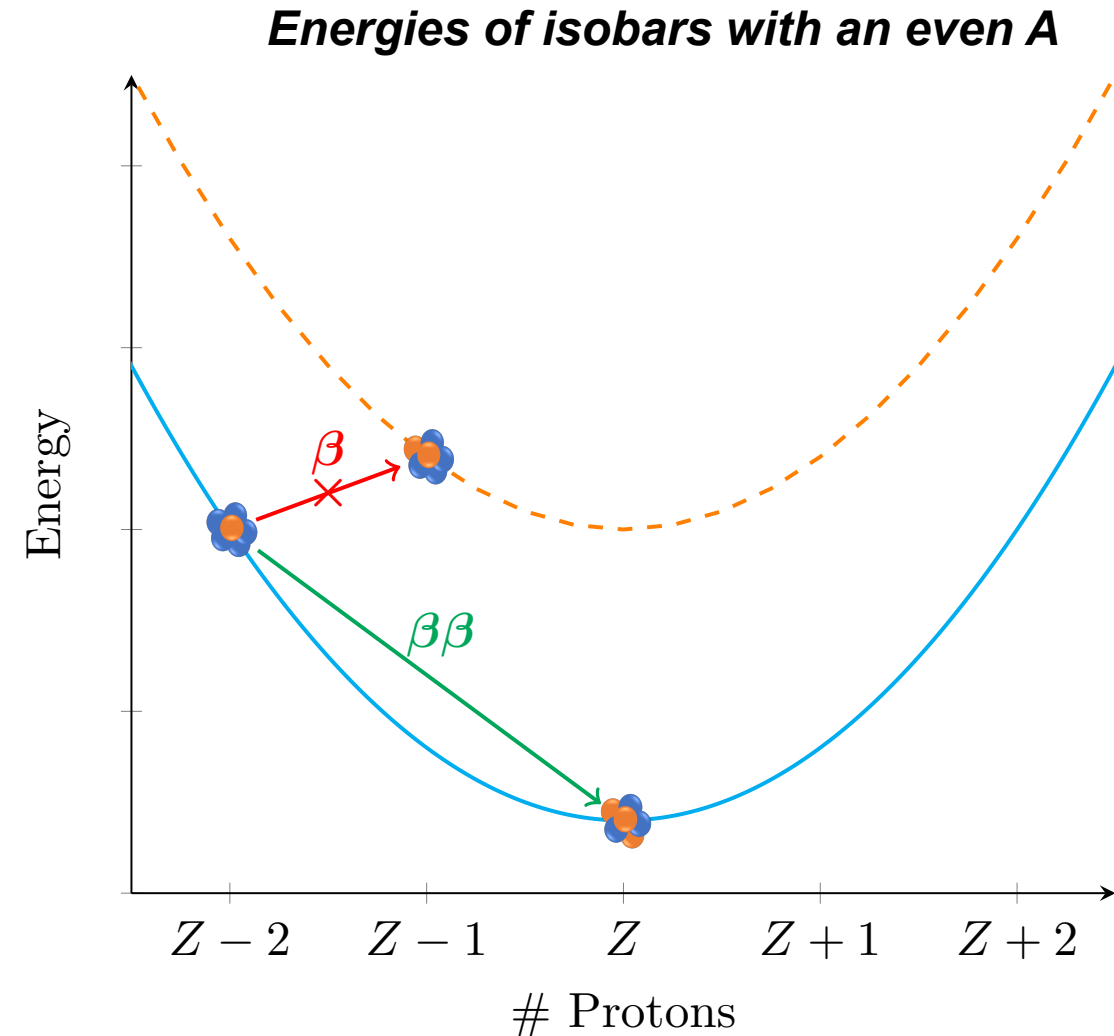
- An atom can lower its energy if its nucleus β decays



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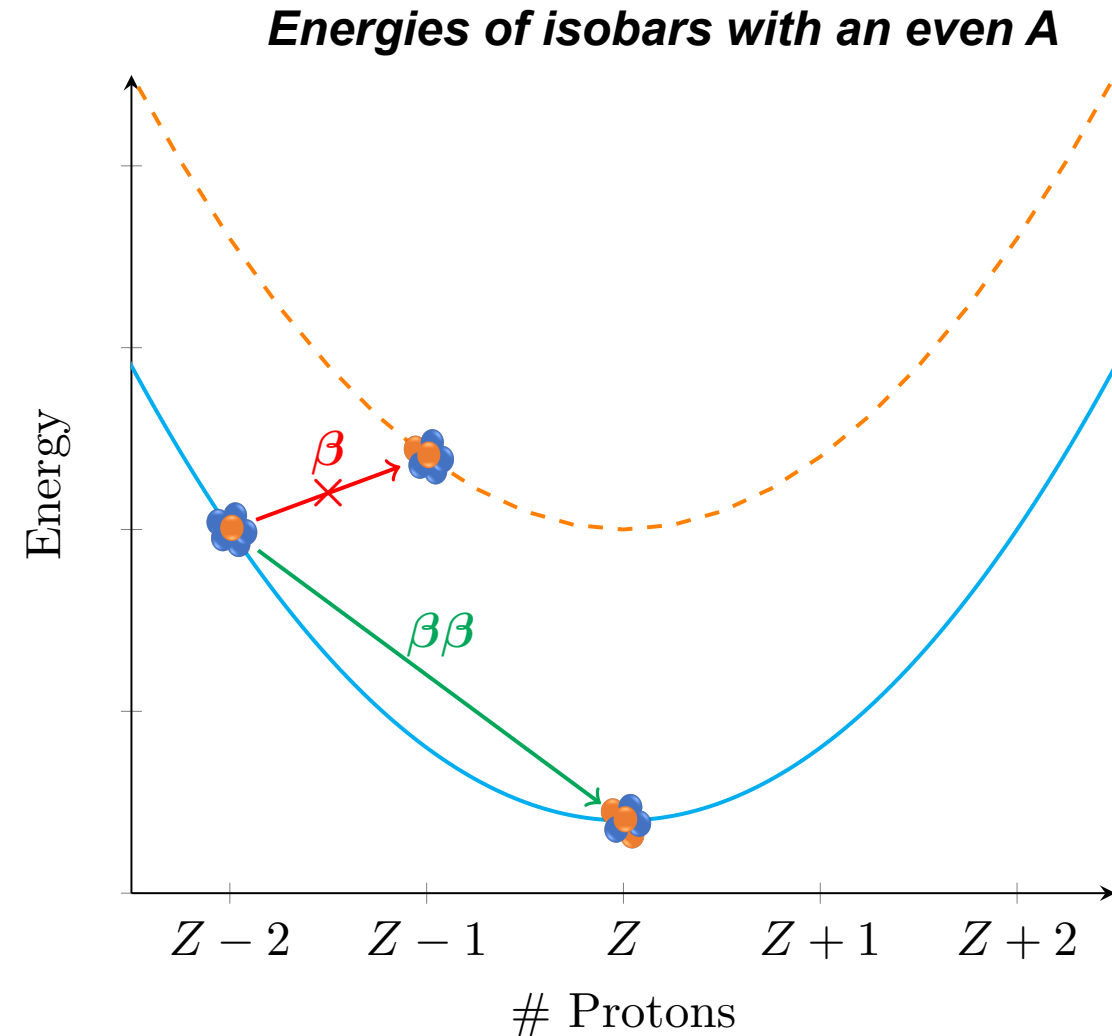
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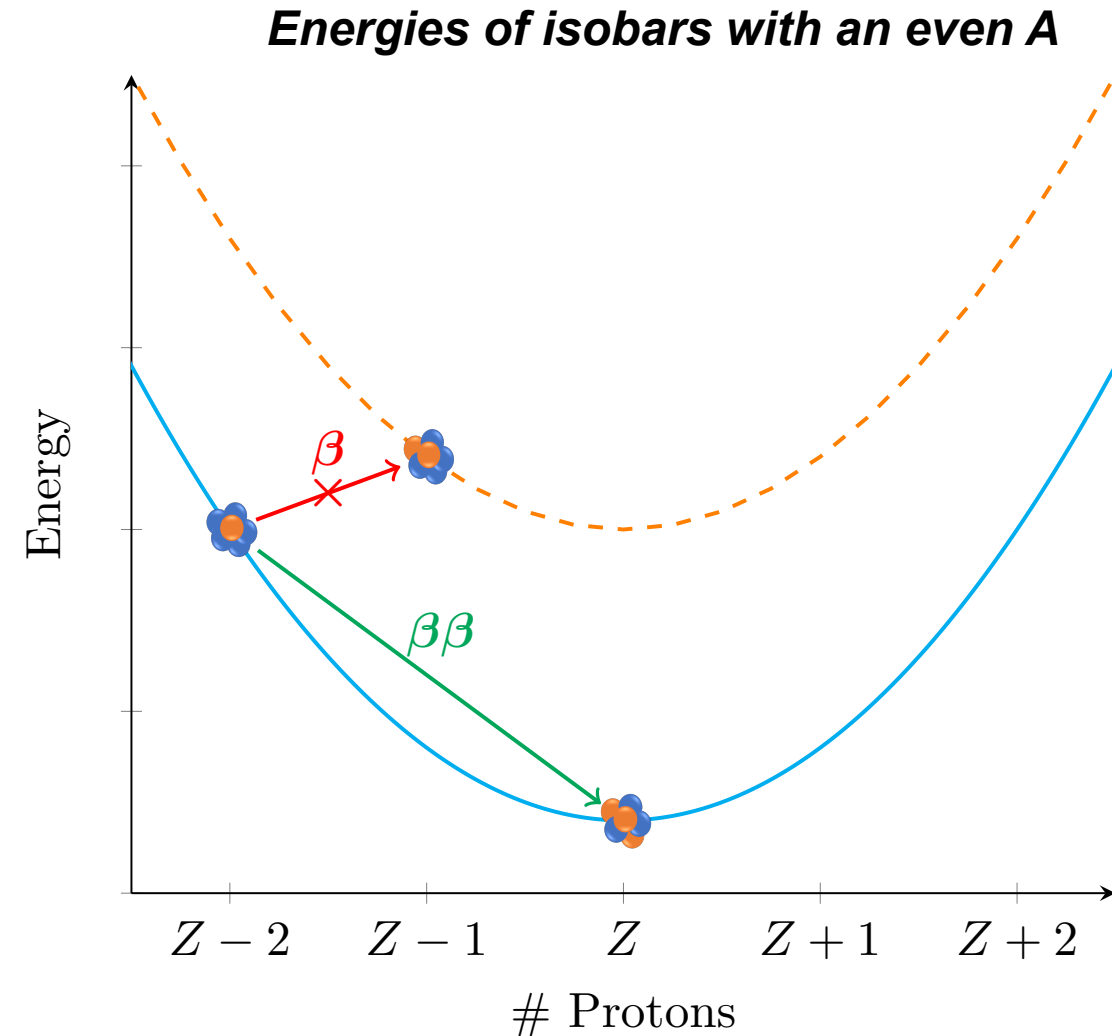
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WHEN CAN NUCLEI DOUBLE-BETA DECAY?



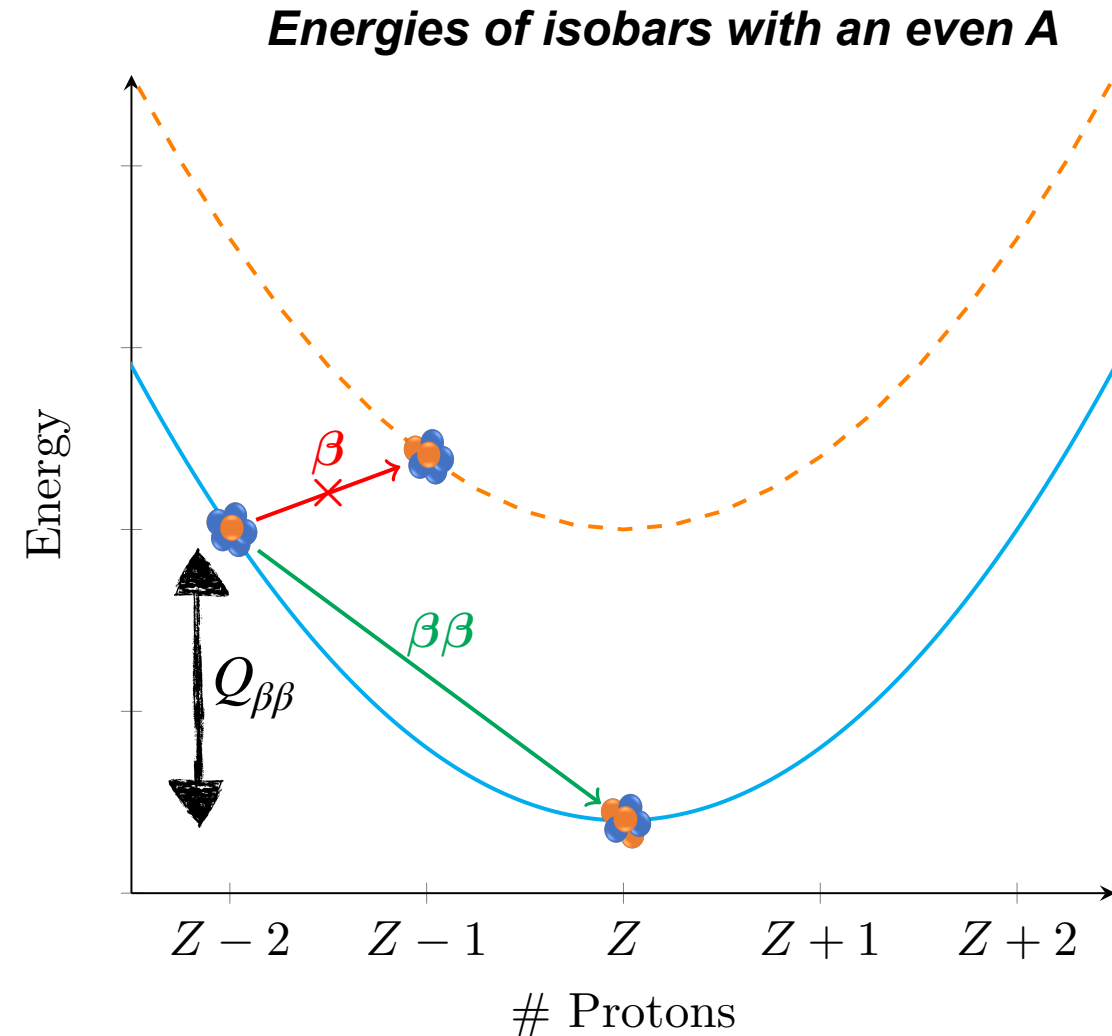
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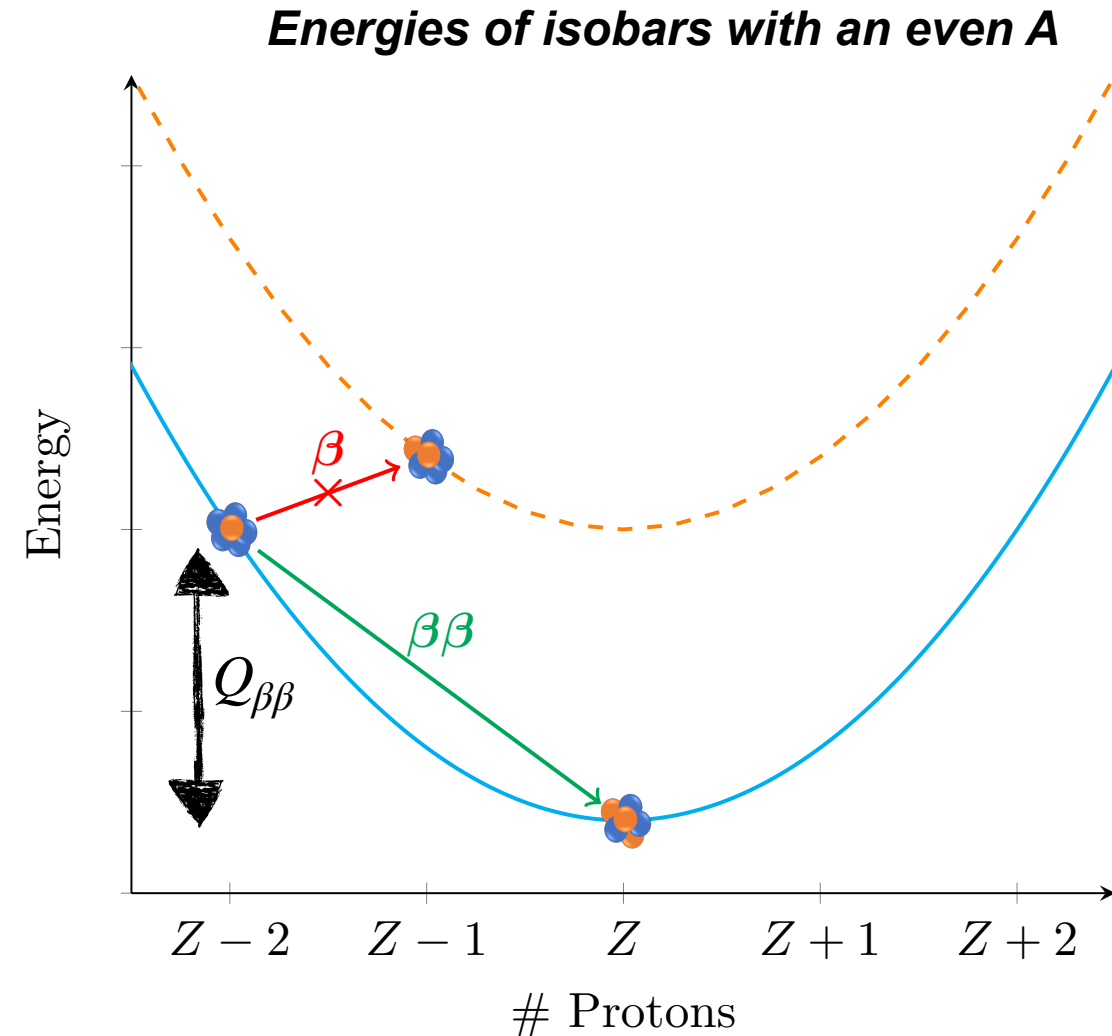
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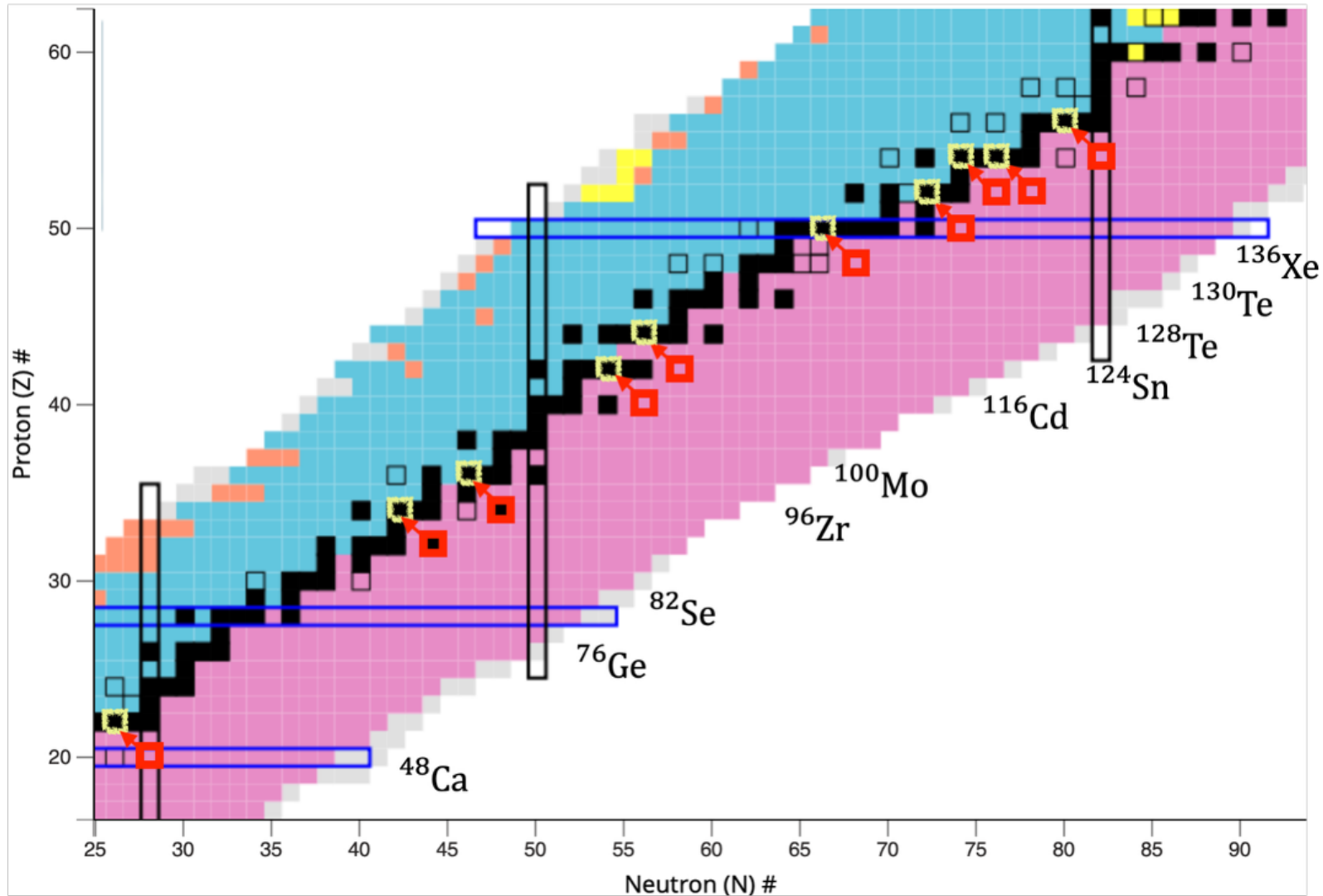
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 - $\Delta E = E_f - E_i > 0$ or
 - $\Delta J \gg 0$



DOUBLE-BETA-DECAY CANDIDATES



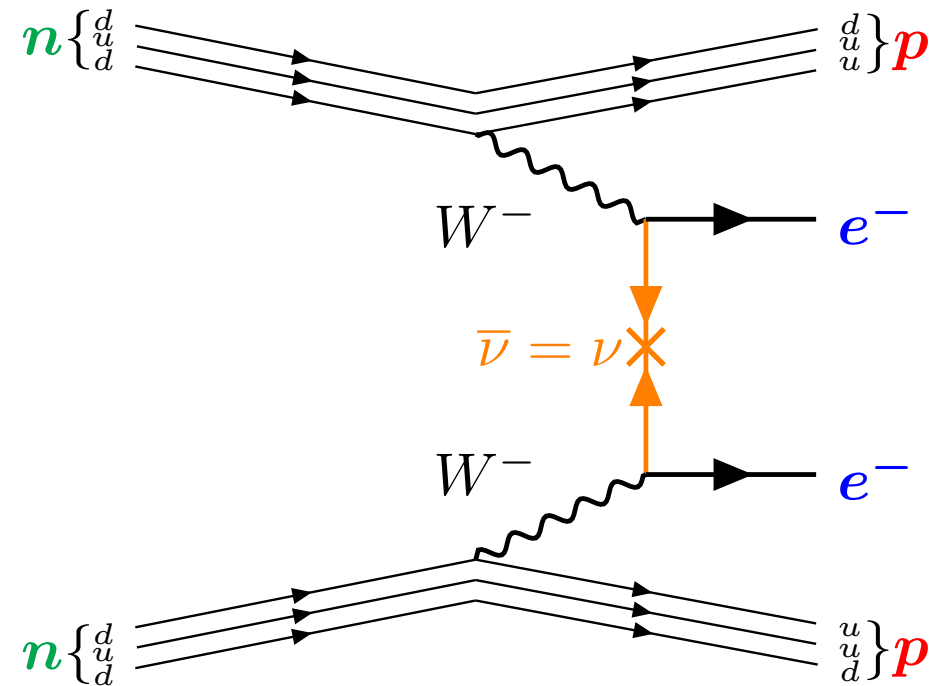
Modified from nndc.bnl.gov/nudat3/

NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY



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$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + \cancel{2\nu_e}$$



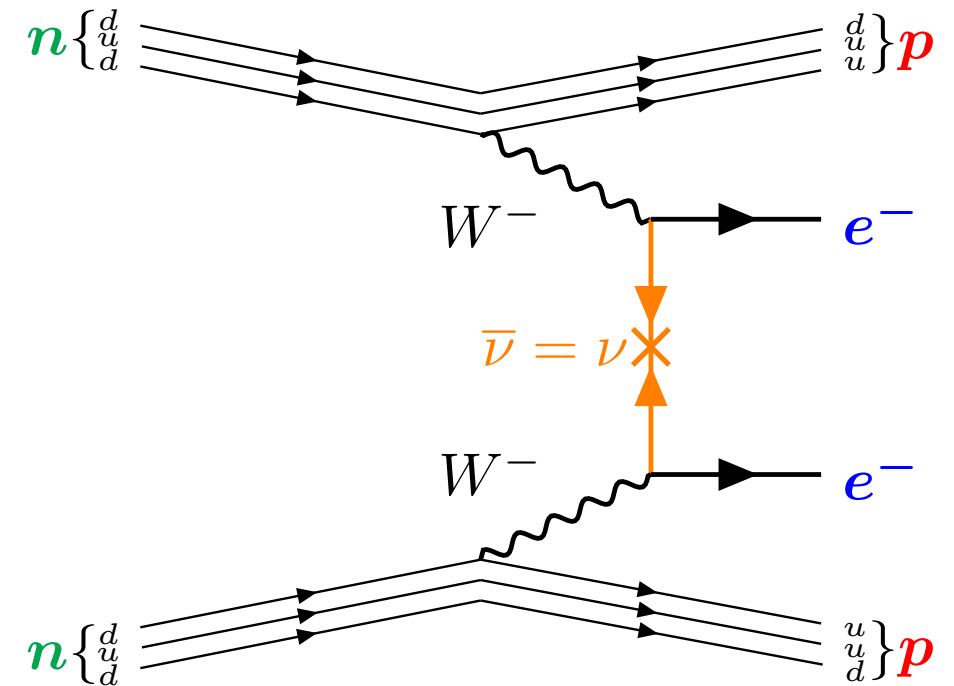
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TECHNISCHE
UNIVERSITÄT
DARMSTADT

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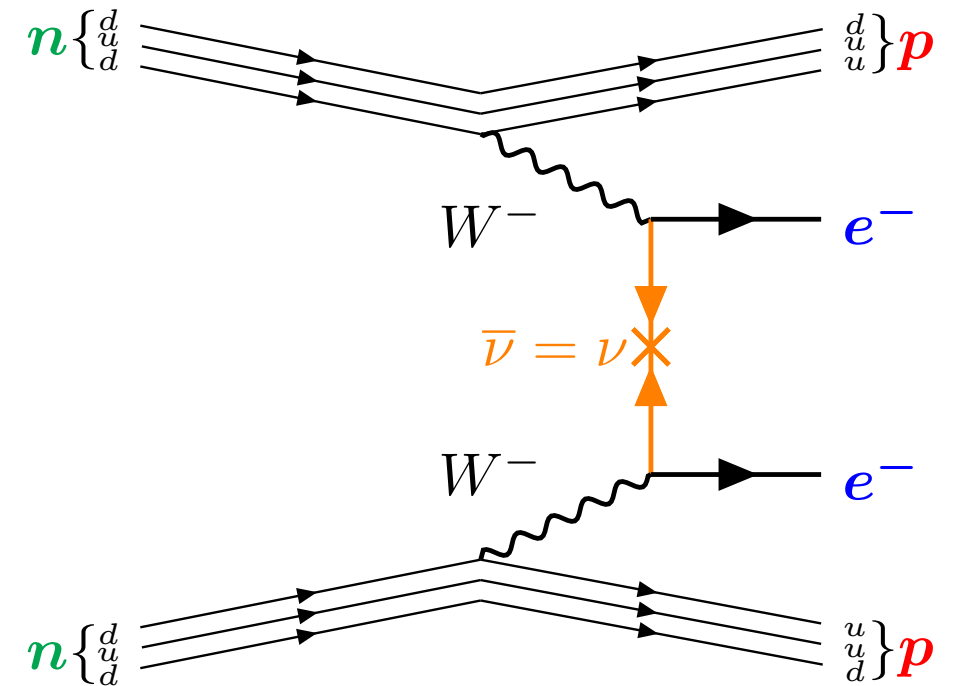


TECHNISCHE
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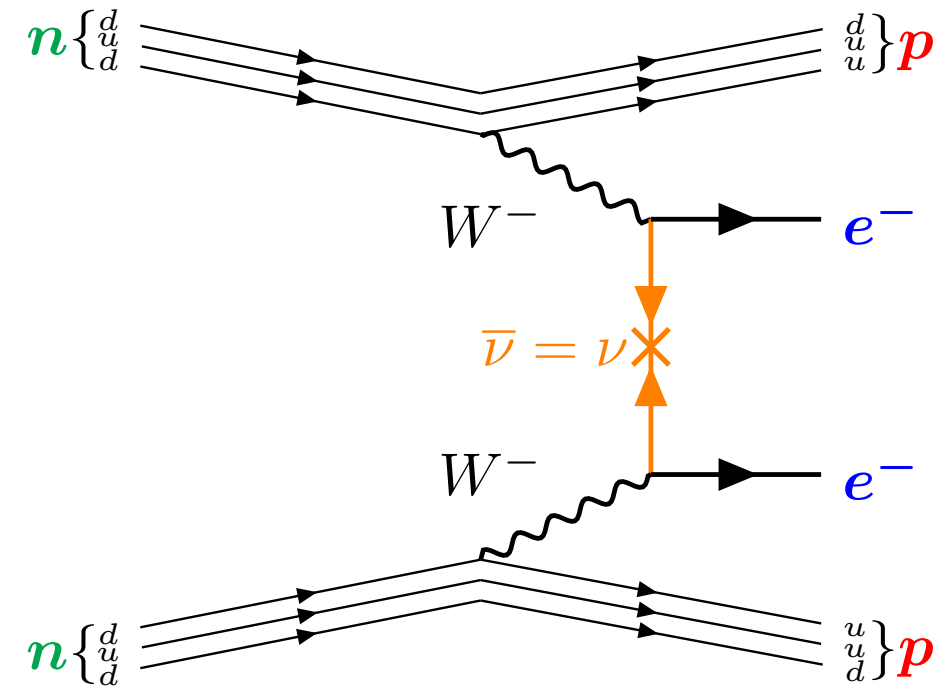


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- Violates lepton-number conservation
- Requires that neutrinos are Majorana particles

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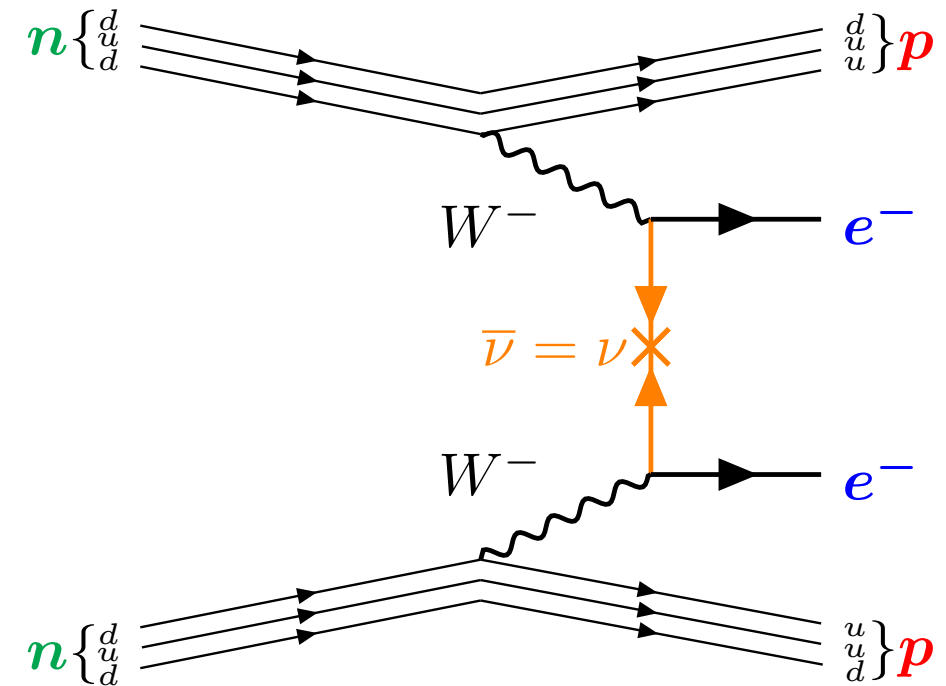


TECHNISCHE
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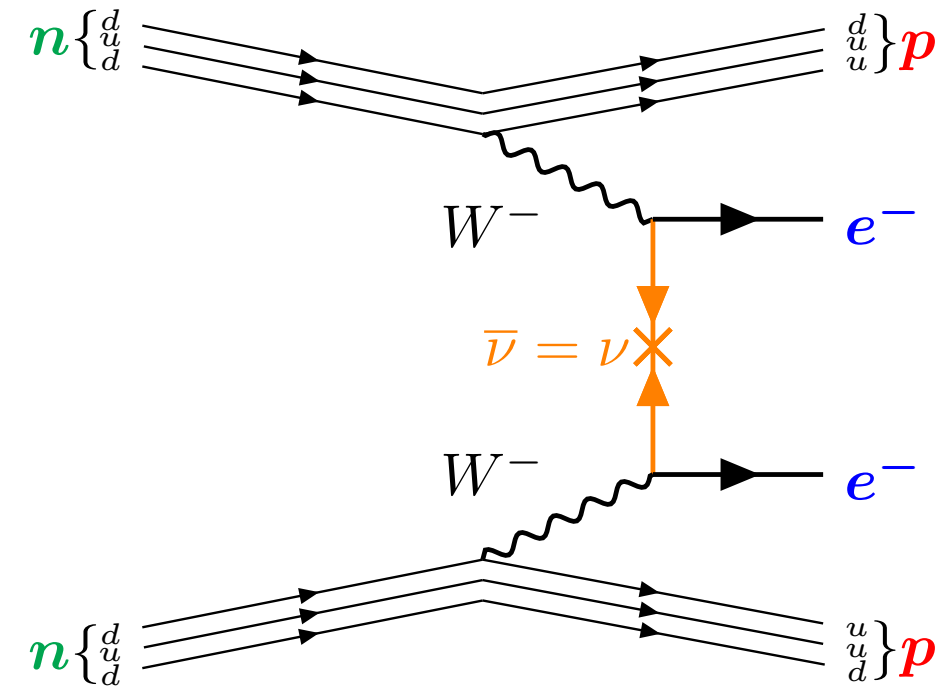
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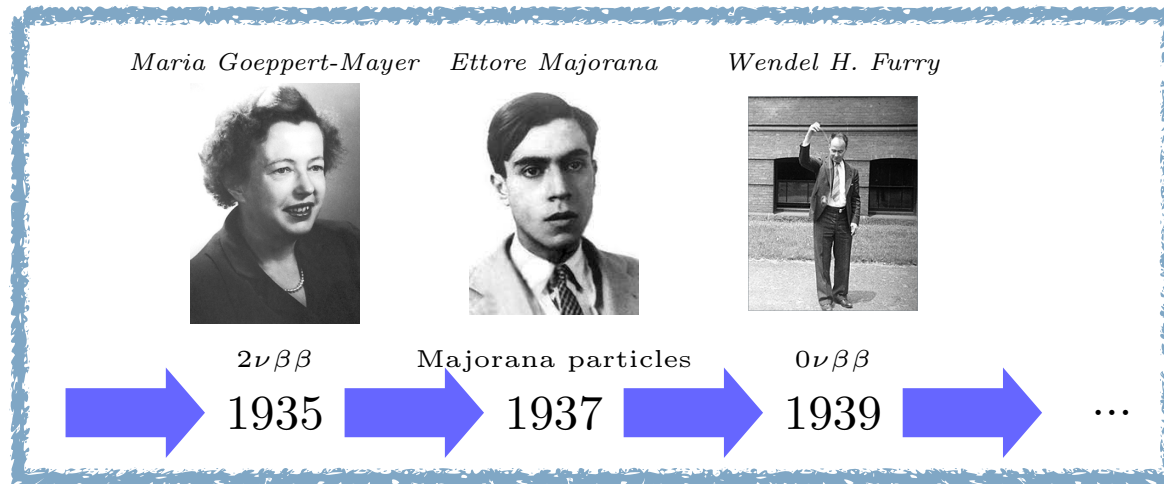
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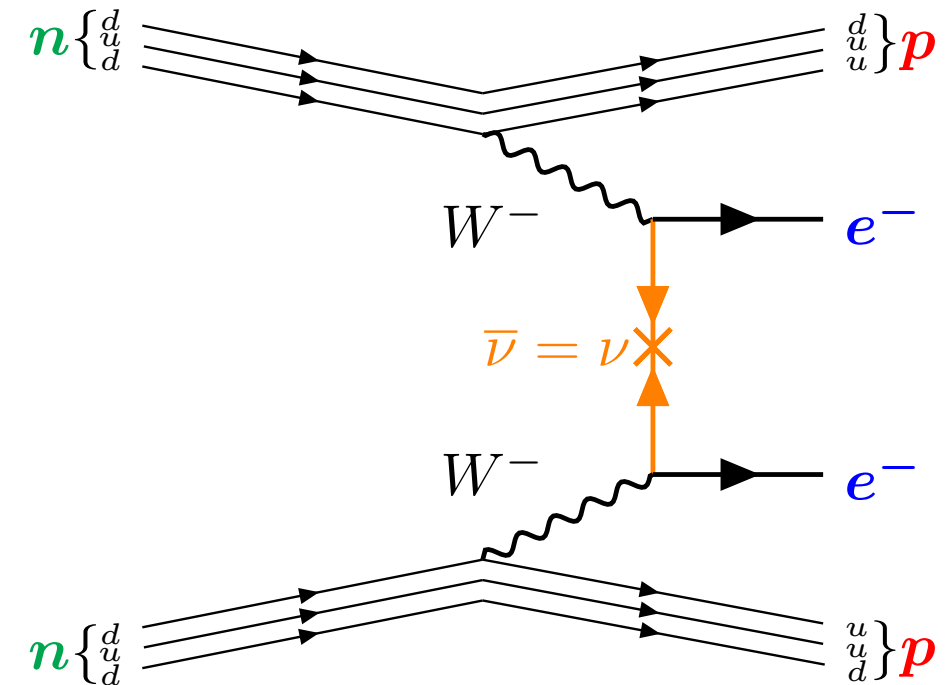
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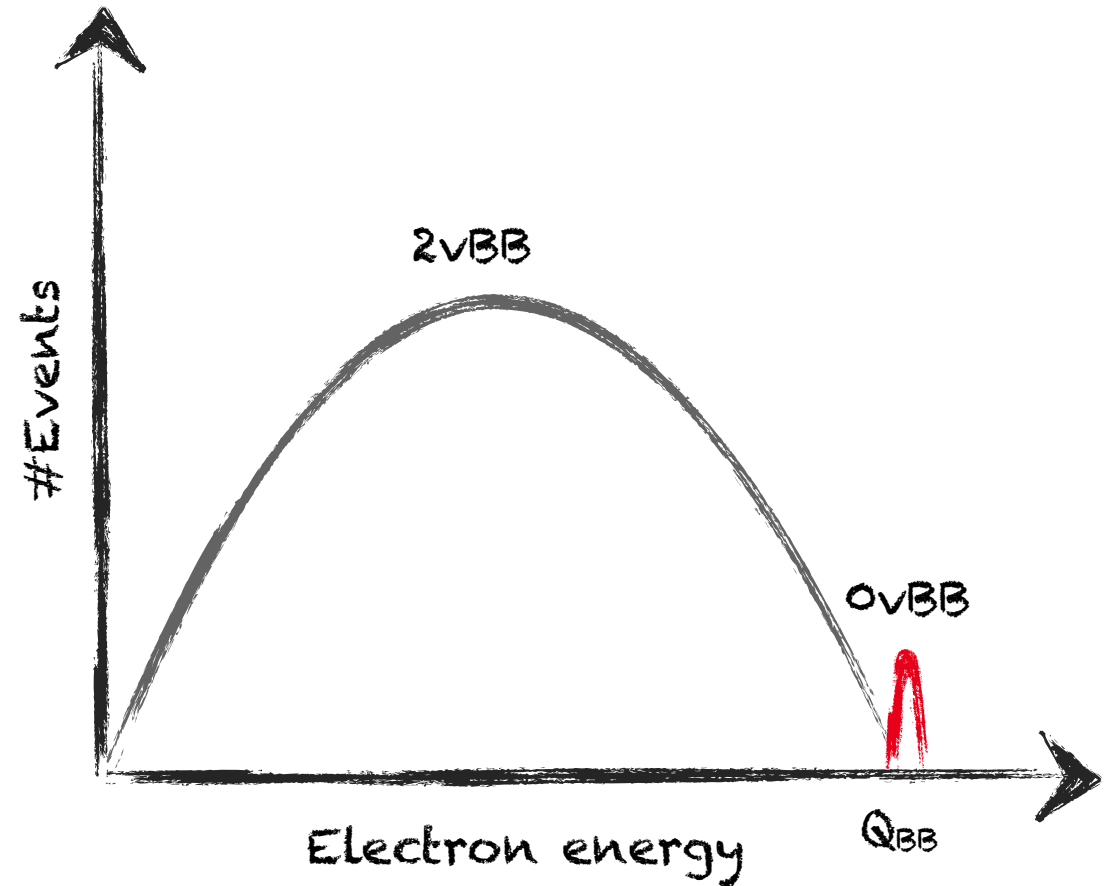


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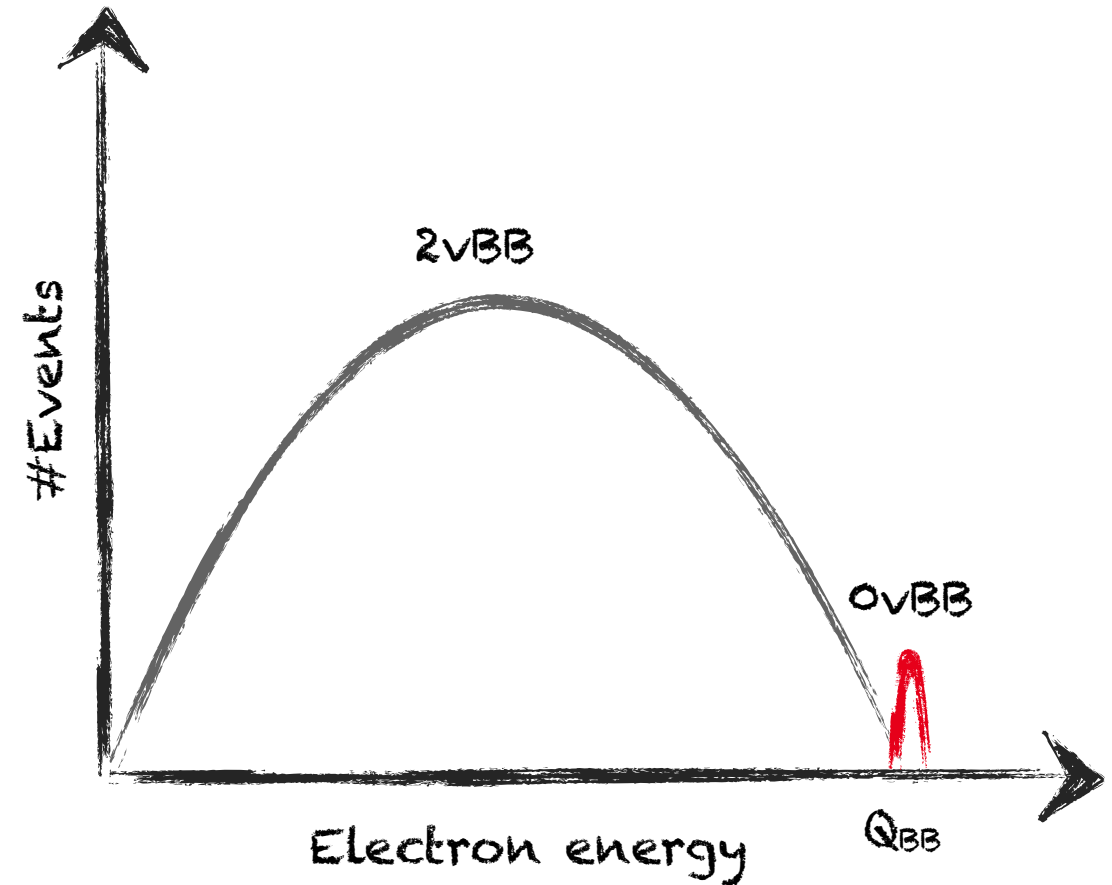
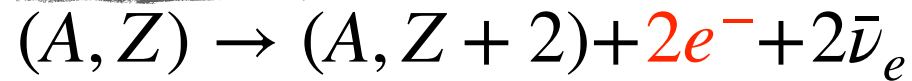
HOW TO MEASURE $\beta\beta$ DECAY?



HOW TO MEASURE $\beta\beta$ DECAY?



- $2\nu\beta\beta$ decay:

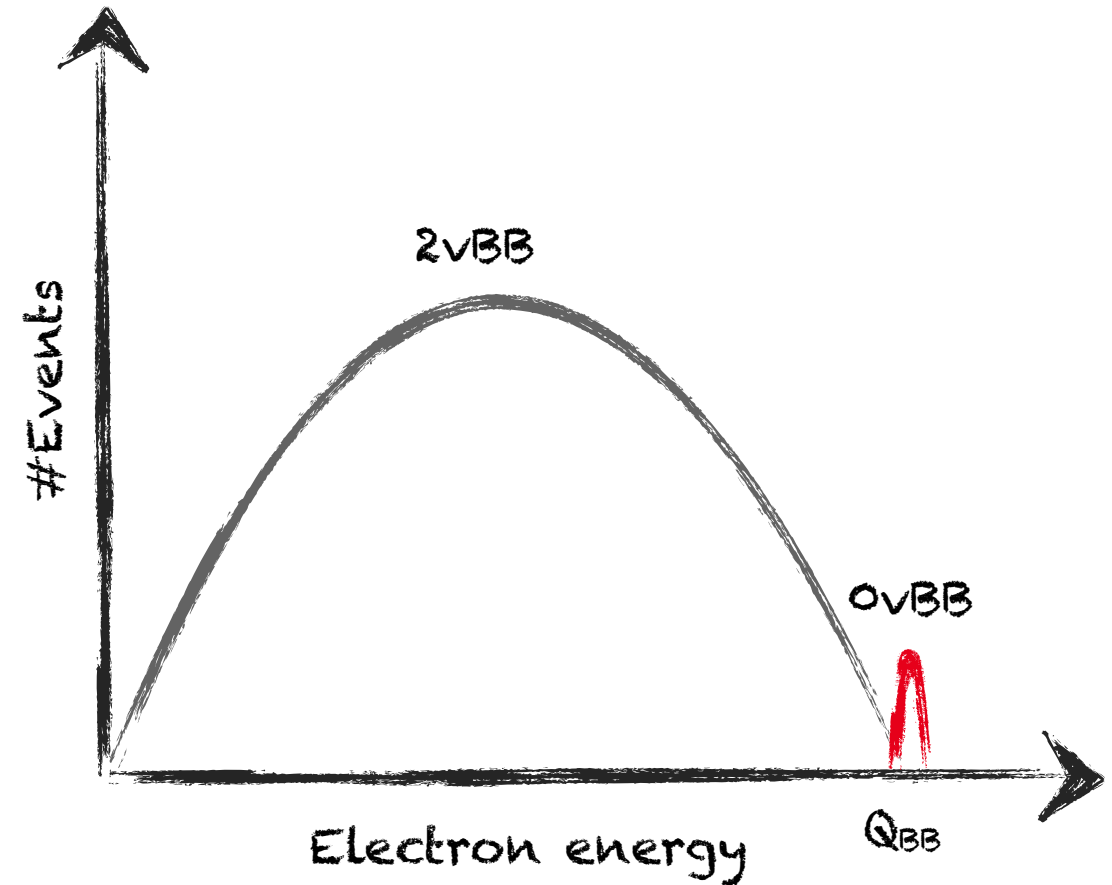


HOW TO MEASURE $\beta\beta$ DECAY?

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HOW TO MEASURE $\beta\beta$ DECAY?

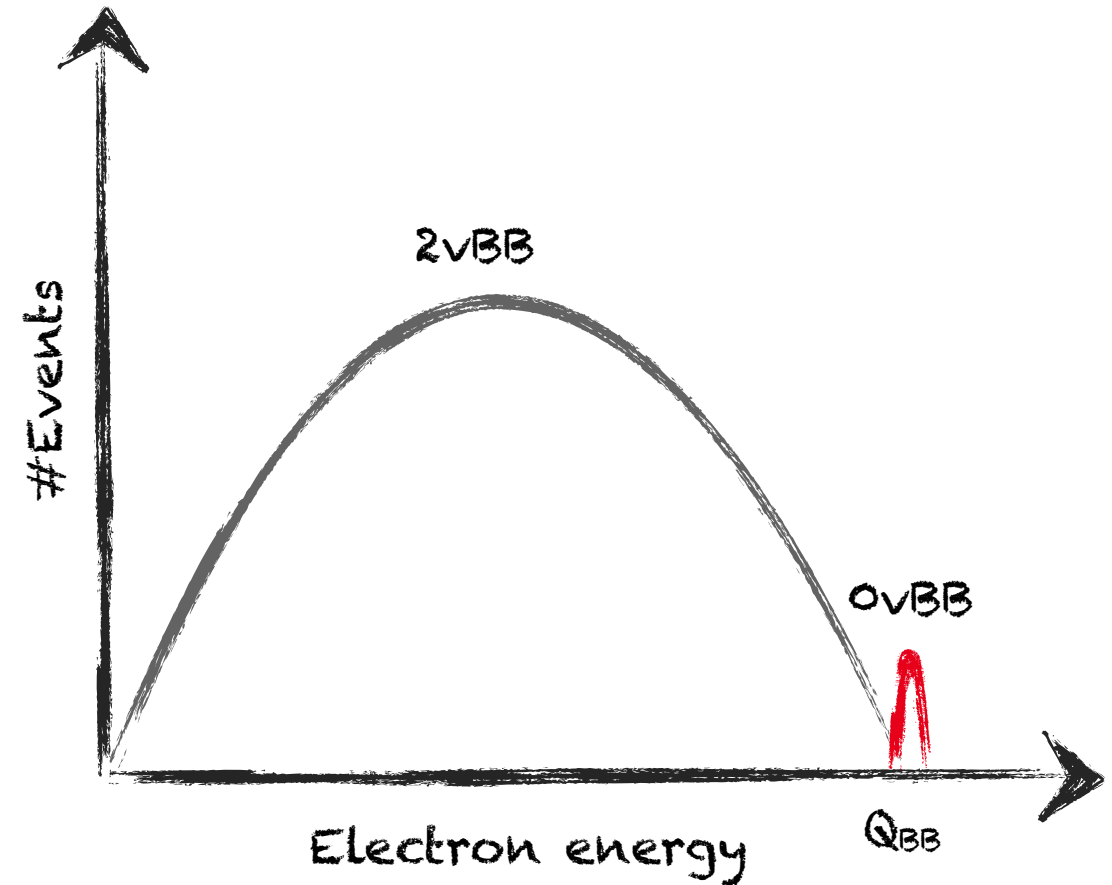
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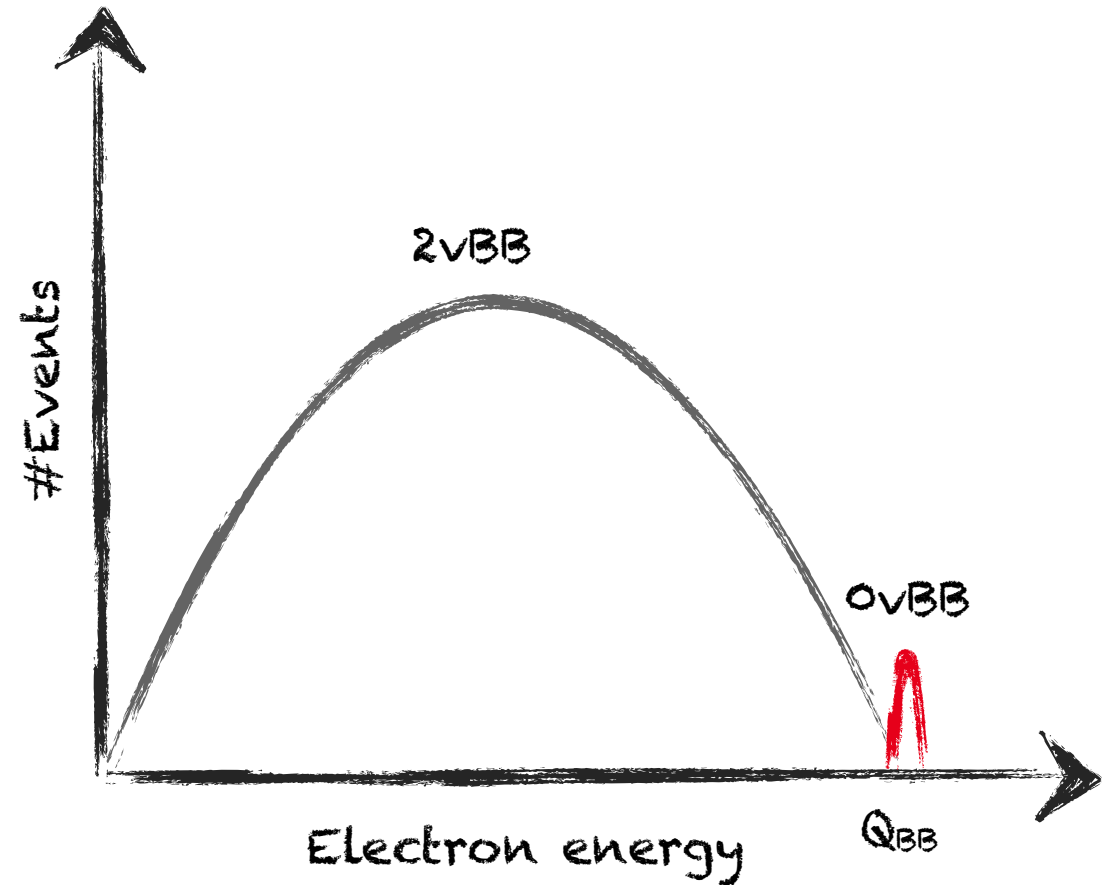
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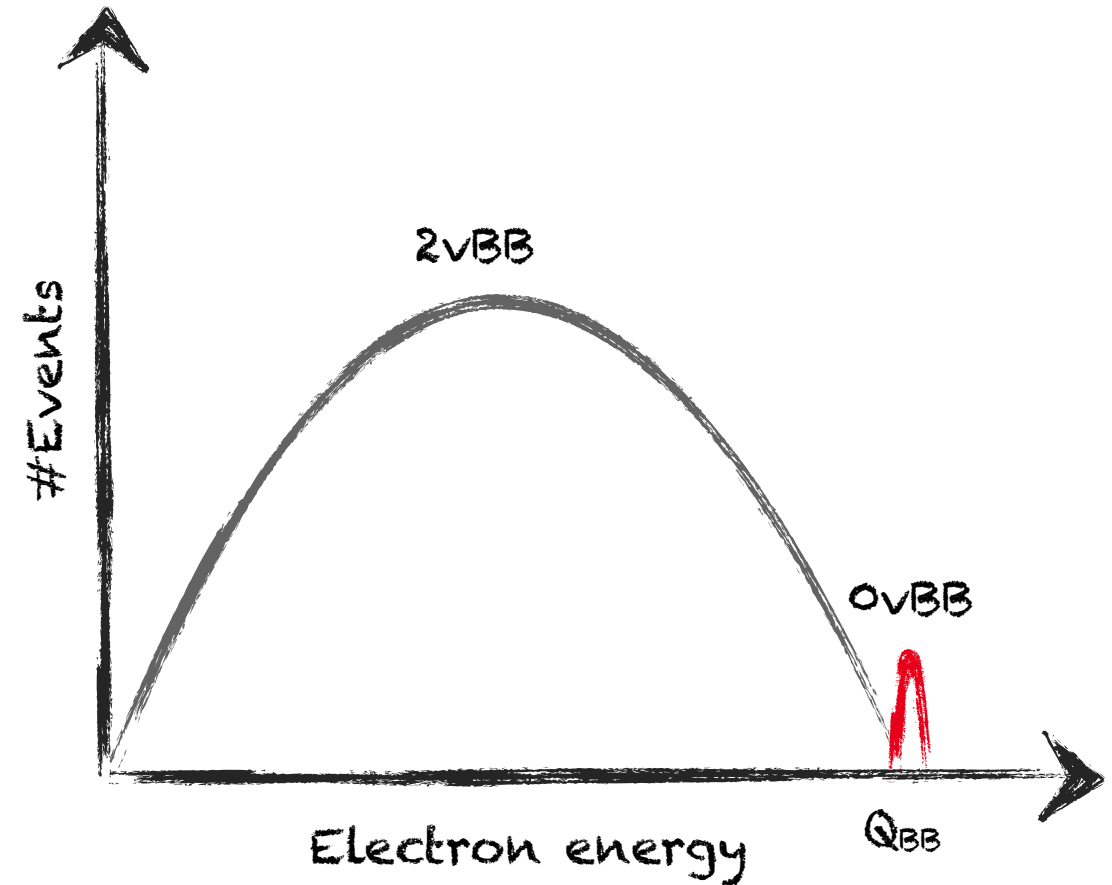
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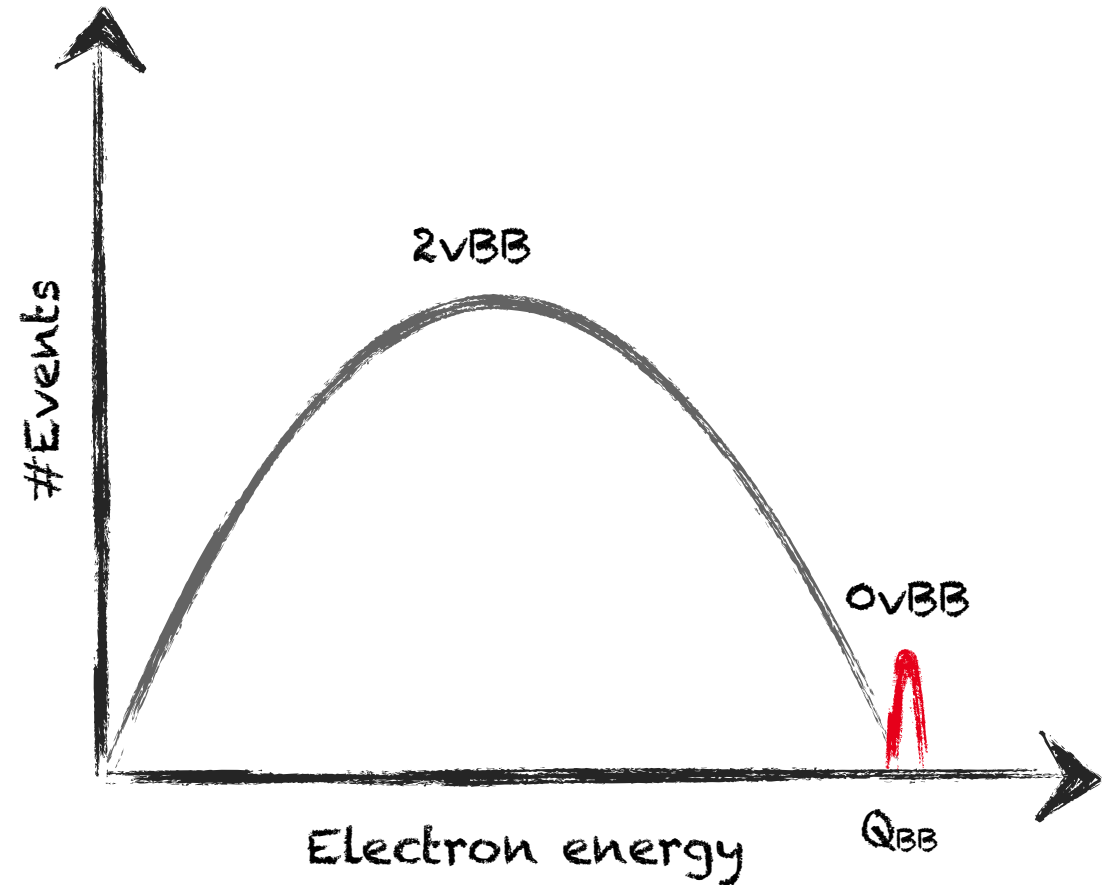
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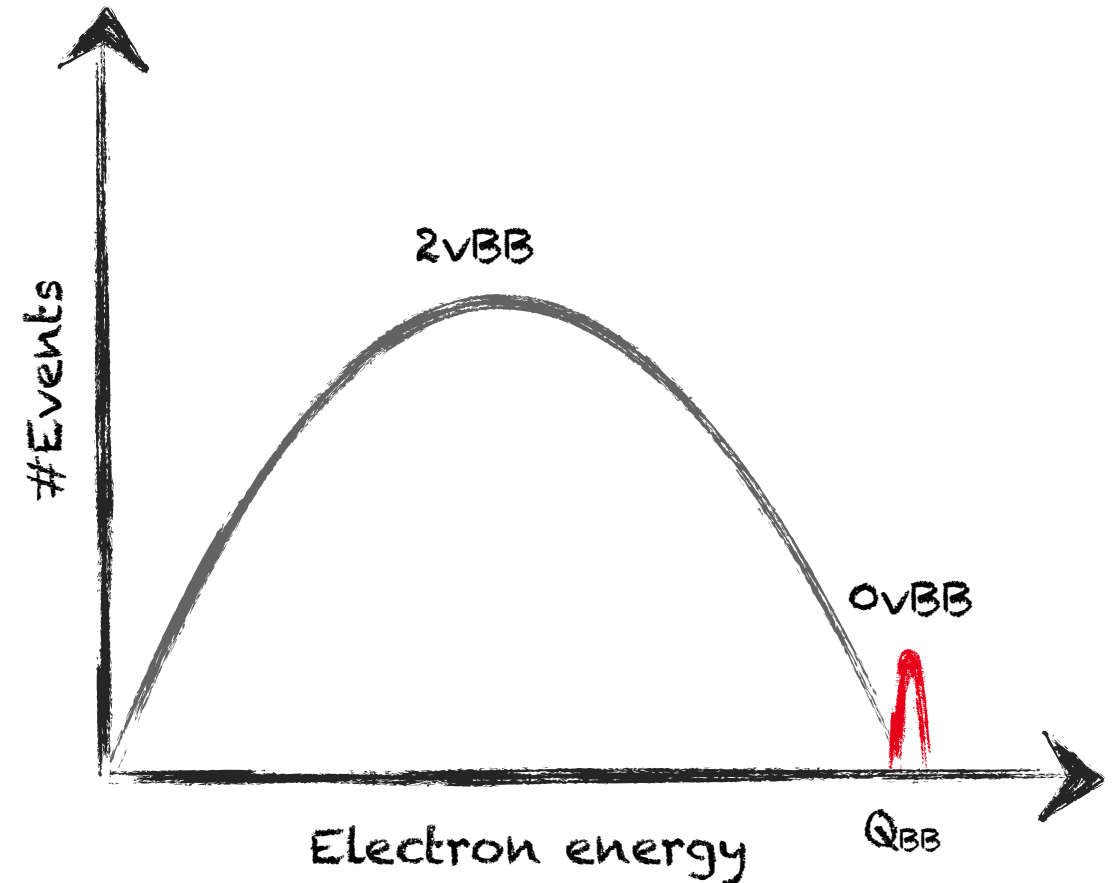
HOW TO MEASURE $\beta\beta$ DECAY?

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- Good candidate isotope has:
 - High natural abundance
 - Large $Q_{\beta\beta}$



DOUBLE-BETA-DECAY EXPERIMENTS



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SNOLAB (Canada):
SNO+ (^{130}Te)

SURF (USA):
MAJORANA (^{76}Ge)
LZ-nat (^{136}Xe)

WIPP (USA):
EXO-200 (^{136}Xe)

LSC (Spain):
NEXT-100 (^{136}Xe)
CROSS (^{100}Mo)

Kamioka (Japan):
KamLAND-Zen (^{136}Xe)

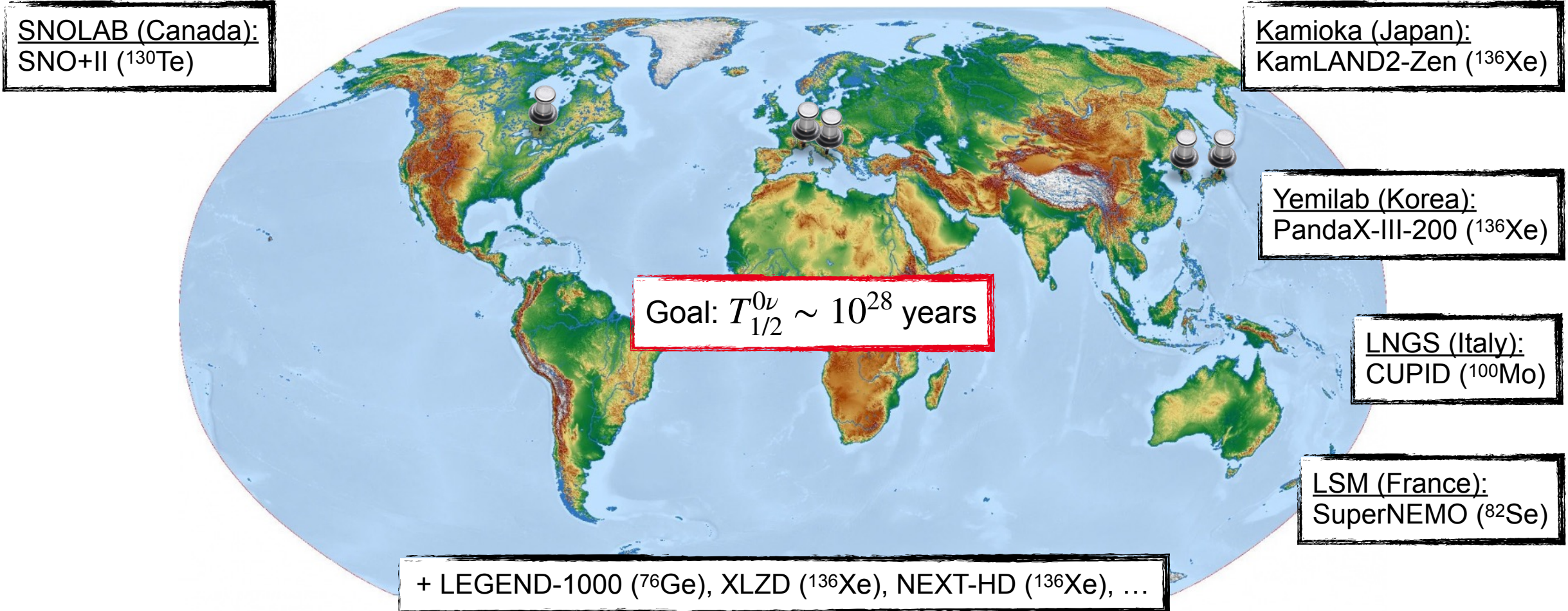
CNJL(China):
PandaX-III-200 (^{136}Xe)

LNGS (Italy):
GERDA (^{76}Ge)
CUORE (^{130}Te)
CUPID-0 (^{82}Se)
LEGEND-200 (^{76}Ge)

LSM (France):
CUPID-Mo (^{100}Mo)
NEMO-3 (^{100}Mo)
SuperNEMO-D (^{82}Se)

Current record:
 $T_{1/2}^{0\nu}({}^{136}\text{Xe}) > 3.8 \times 10^{26}$ years
KamLAND-Zen: arXiv:2406.11438 [hep-ex]

NEXT-GENERATION EXPERIMENTS



$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE



$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE



Half-life to be measured

$$\frac{1}{t_{1/2}^{0\nu}} = g_A^4 G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE



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Majorana mass

$$m_{\beta\beta} = \sum_k (U_{ek})^2 m_k$$

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

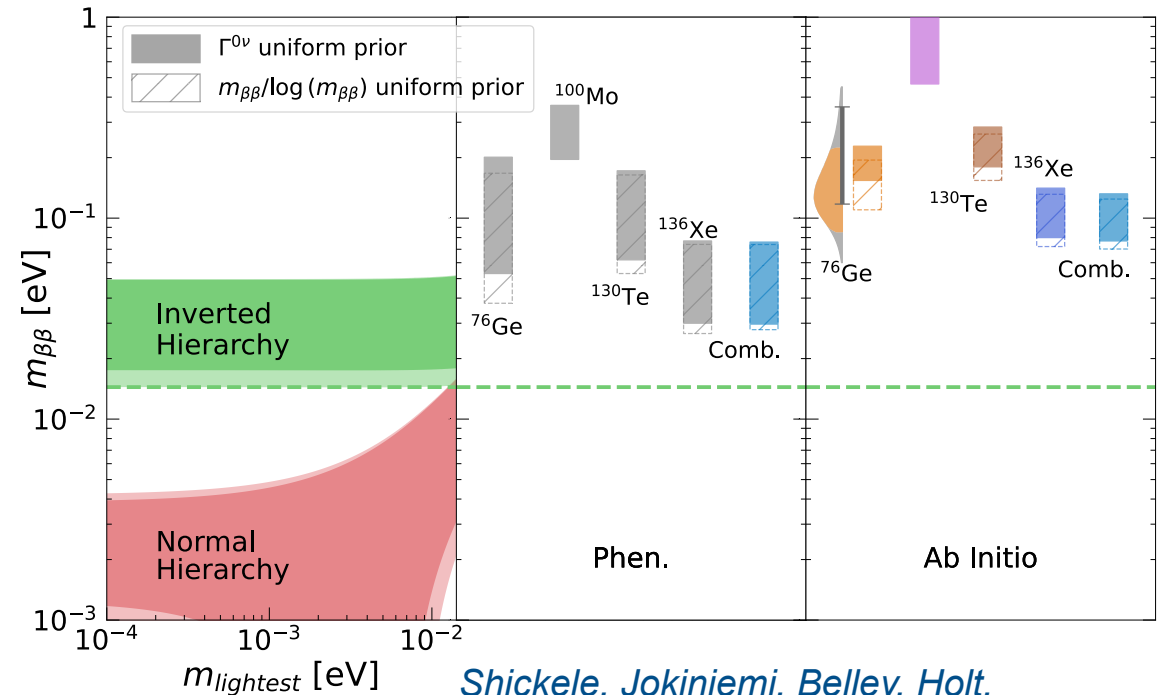


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Shickele, Jokiniemi, Belley, Holt,
Phys. Rev. D 114, 013007 (2026)

$0\nu\beta\beta$ DECAY MEDIATED BY LIGHT-NEUTRINO EXCHANGE

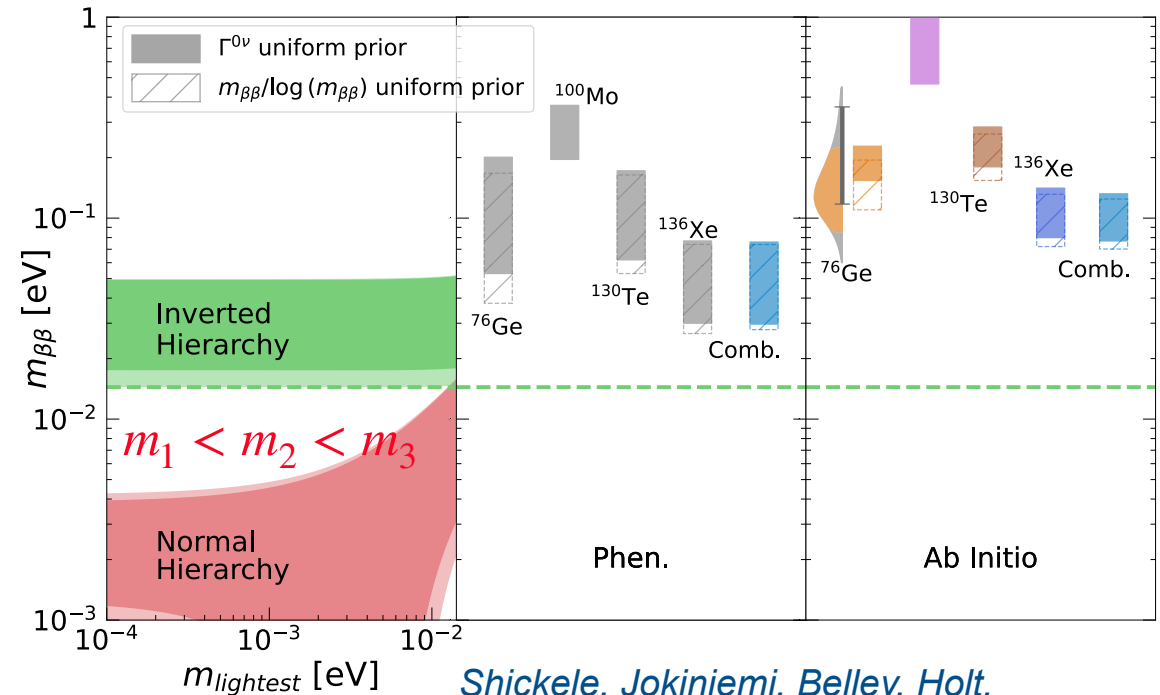


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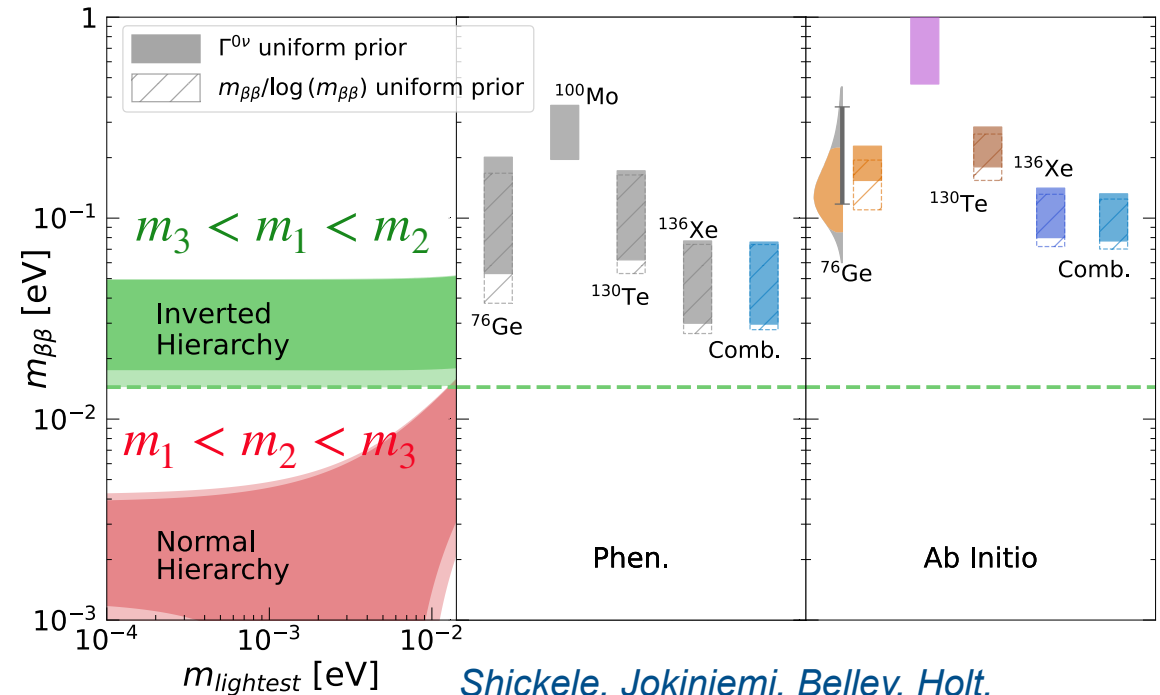


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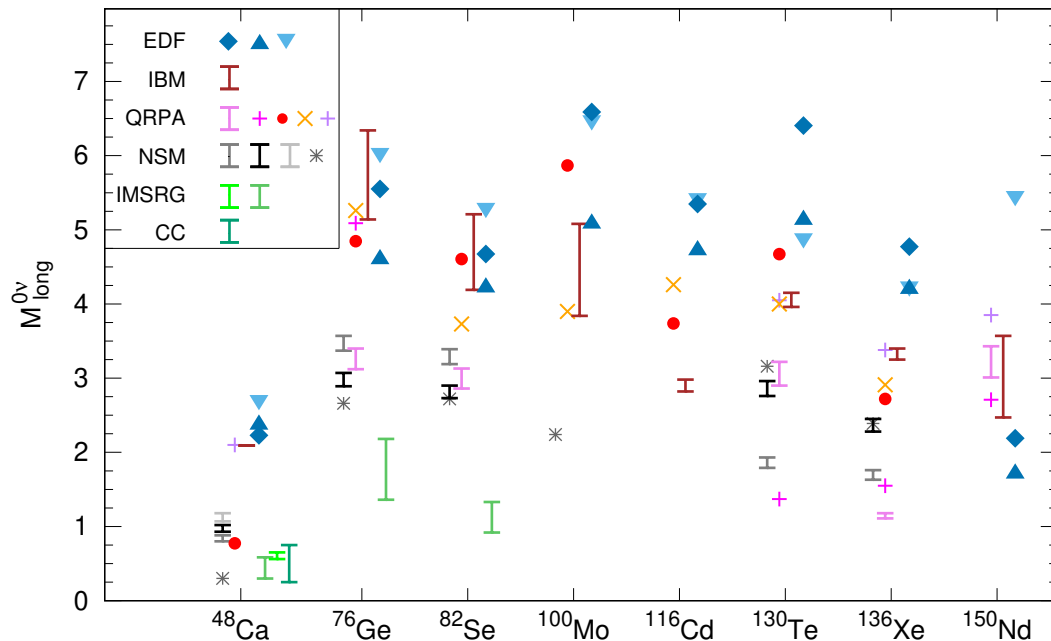
Half-life to be measured

Nuclear matrix element

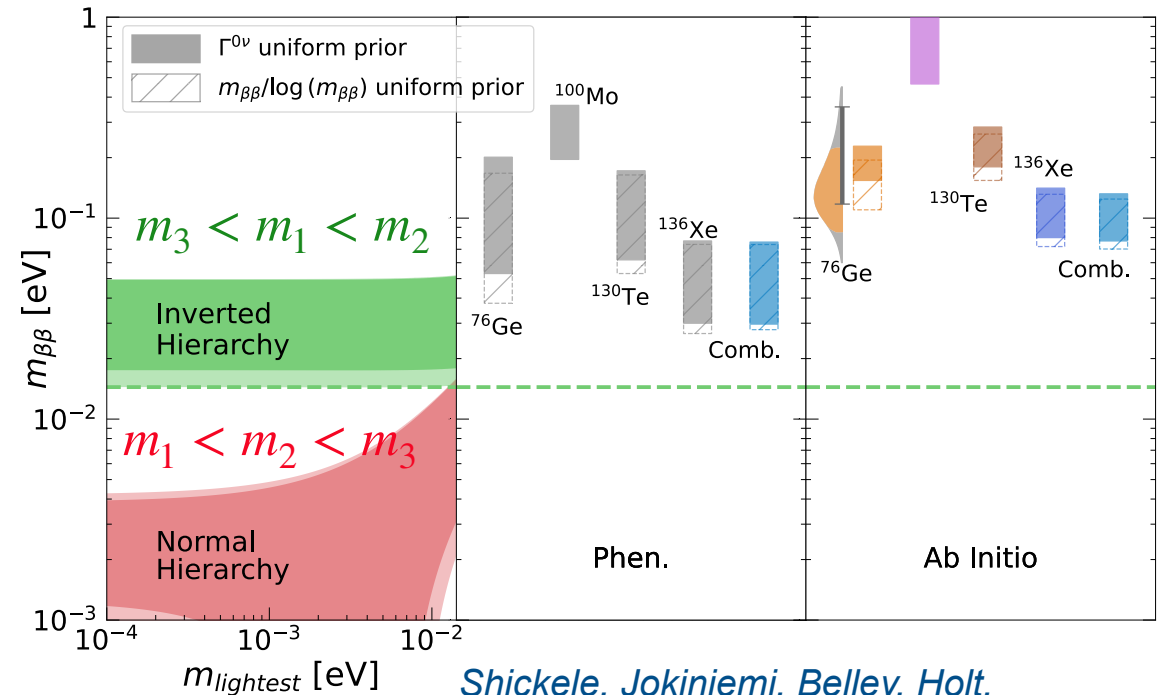
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Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

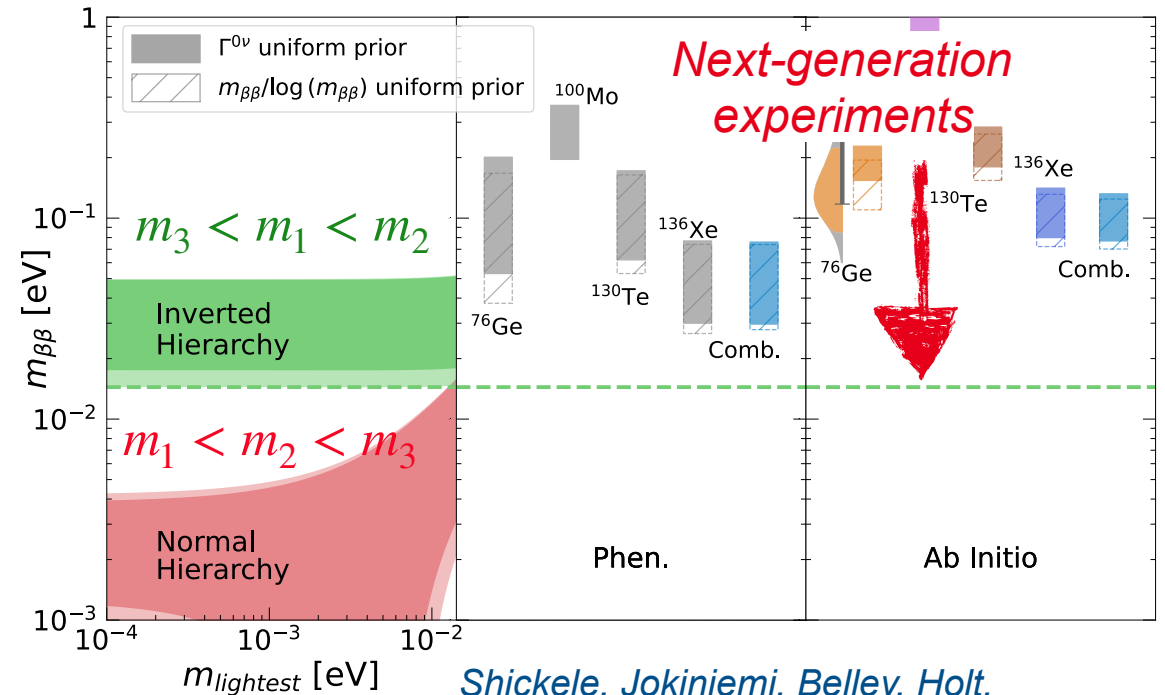


Shickele, Jokiniemi, Belley, Holt,
Phys. Rev. D 114, 013007 (2026)

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*Shickele, Jokiniemi, Belley, Holt,
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THE NUCLEAR MATRIX ELEMENTS

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$$M^{0\nu} = \langle \Psi_f^{(A)} | \mathcal{O}^{0\nu} | \Psi_i^{(A)} \rangle$$

THE NUCLEAR MATRIX ELEMENT

Operator ($nn \rightarrow pp + 2e^-$)



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Initial state wave function
(a 0^+ state)

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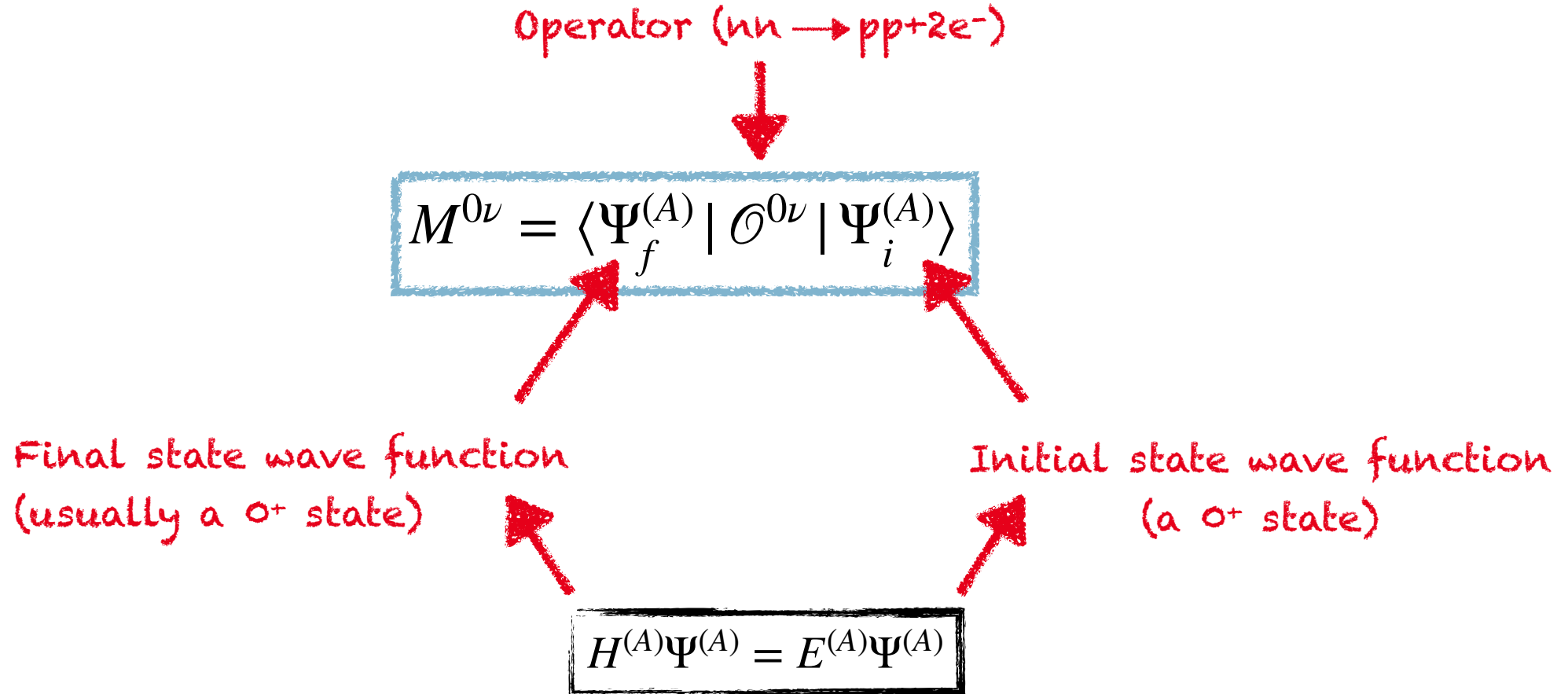


Final state wave function
(usually a 0^+ state)



Initial state wave function
(a 0^+ state)

THE NUCLEAR MATRIX ELEMENT



LIGHT-NEUTRINO EXCHANGE



$$M_L^{0\nu} = \frac{1.2A^{1/3} \text{ fm}}{g_A^2} \langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- [H_F(r) \mathbf{1} + H_{GT}(r) \boldsymbol{\sigma}_n \cdot \boldsymbol{\sigma}_m + H_T(r) S_{nm}] | 0_i^+ \rangle$$

nn → *pp* *Fermi, Gamow-Teller and tensor operators*

■ Neutrino potentials

$$H_X(r) = \frac{2}{\pi} \int dp p^2 j_X(pr) \frac{h_X(p)}{p(p + \langle E \rangle)}, \text{ where } X \in \{F, GT, T\}$$

- Where the h functions contain contributions from **vector** (V), **axial-vector** (A), **pseudoscalar** (P) and **magnetic** (M) currents

$$h_F = h_F^{VV}$$

$$h_{GT} = h_{GT}^{AA} + h_{GT}^{AP} + h_{GT}^{PP} + h_{GT}^{MM}$$

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LIGHT-NEUTRINO EXCHANGE



Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

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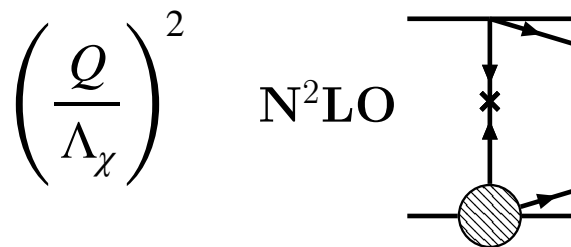
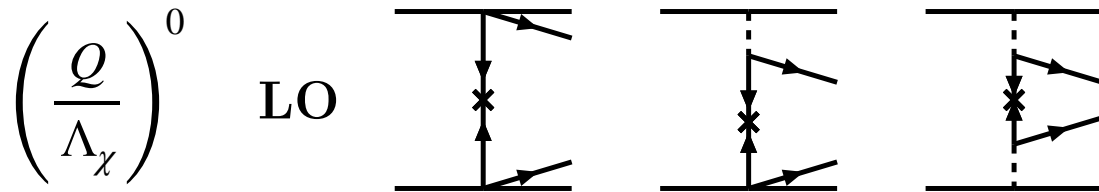
$$h_{GT} = h_{GT}^{AA} + h_{GT}^{AP} + h_{GT}^{PP} + h_{GT}^{MM}$$

$$h_T = h_T^{AP} + h_T^{PP} + h_T^{MM}$$

CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu}$$

$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

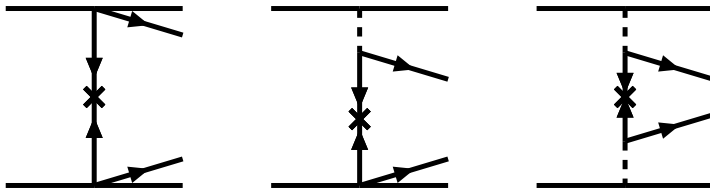
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu}$$

$$M_L^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

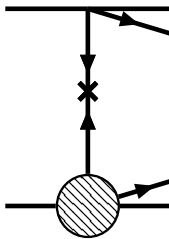
$$\left(\frac{Q}{\Lambda_\chi}\right)^0$$

LO

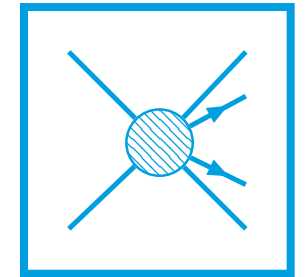


$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

N²LO



15% – 90 %



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

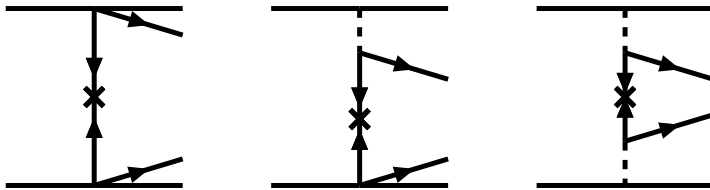
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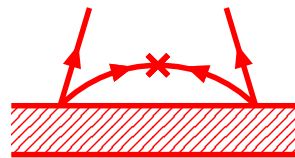
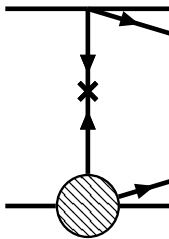
$$\left(\frac{Q}{\Lambda_\chi}\right)^0$$

LO



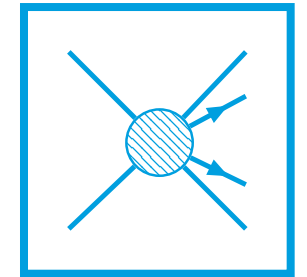
$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

N²LO



5% – 10 %

15% – 90 %



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

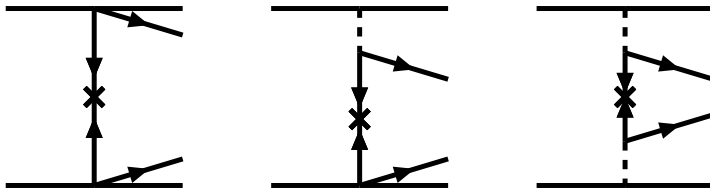
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{\text{loop}}^{0\nu}$$

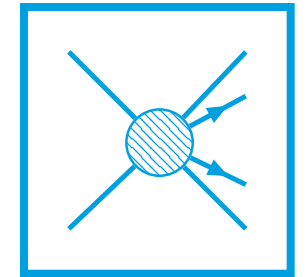
$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

$$\left(\frac{Q}{\Lambda_\chi}\right)^0$$

LO

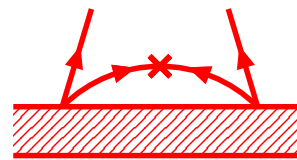
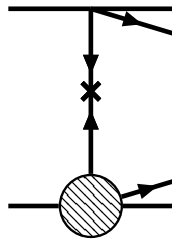


15% – 90 %

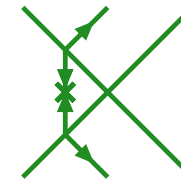


$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

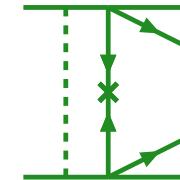
N²LO



5% – 10 %



5% – 10 %



+ ...



V. Cirigliano et al., *Phys. Rev. Lett.* 120, 202001 (2018), *Phys. Rev. C* 100, 055504 (2019)

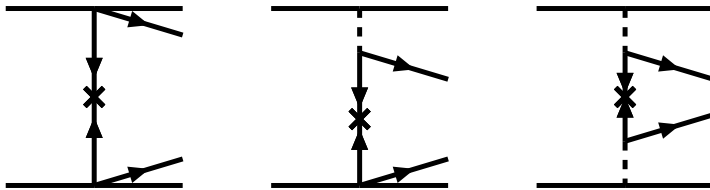
CHIRAL EFFECTIVE THEORY OPERATORS FOR $0\nu\beta\beta$ DECAY

$$M^{0\nu} = M_L^{0\nu} + M_S^{0\nu} + M_{\text{usoft}}^{0\nu} + M_{\text{loop}}^{0\nu}$$

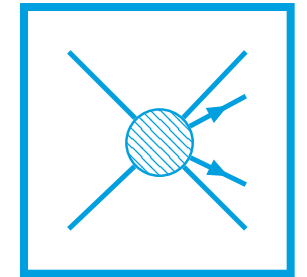
$$M_L^{0\nu} = M_{\text{GT}}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

$$\left(\frac{Q}{\Lambda_\chi}\right)^0$$

LO

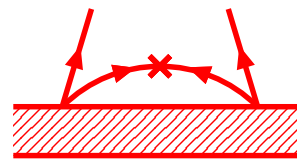
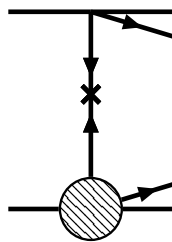


15% – 90 %

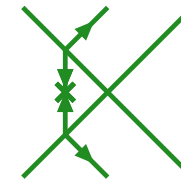


$$\left(\frac{Q}{\Lambda_\chi}\right)^2$$

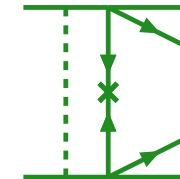
N²LO



5% – 10 %



5% – 10 %



+ ...

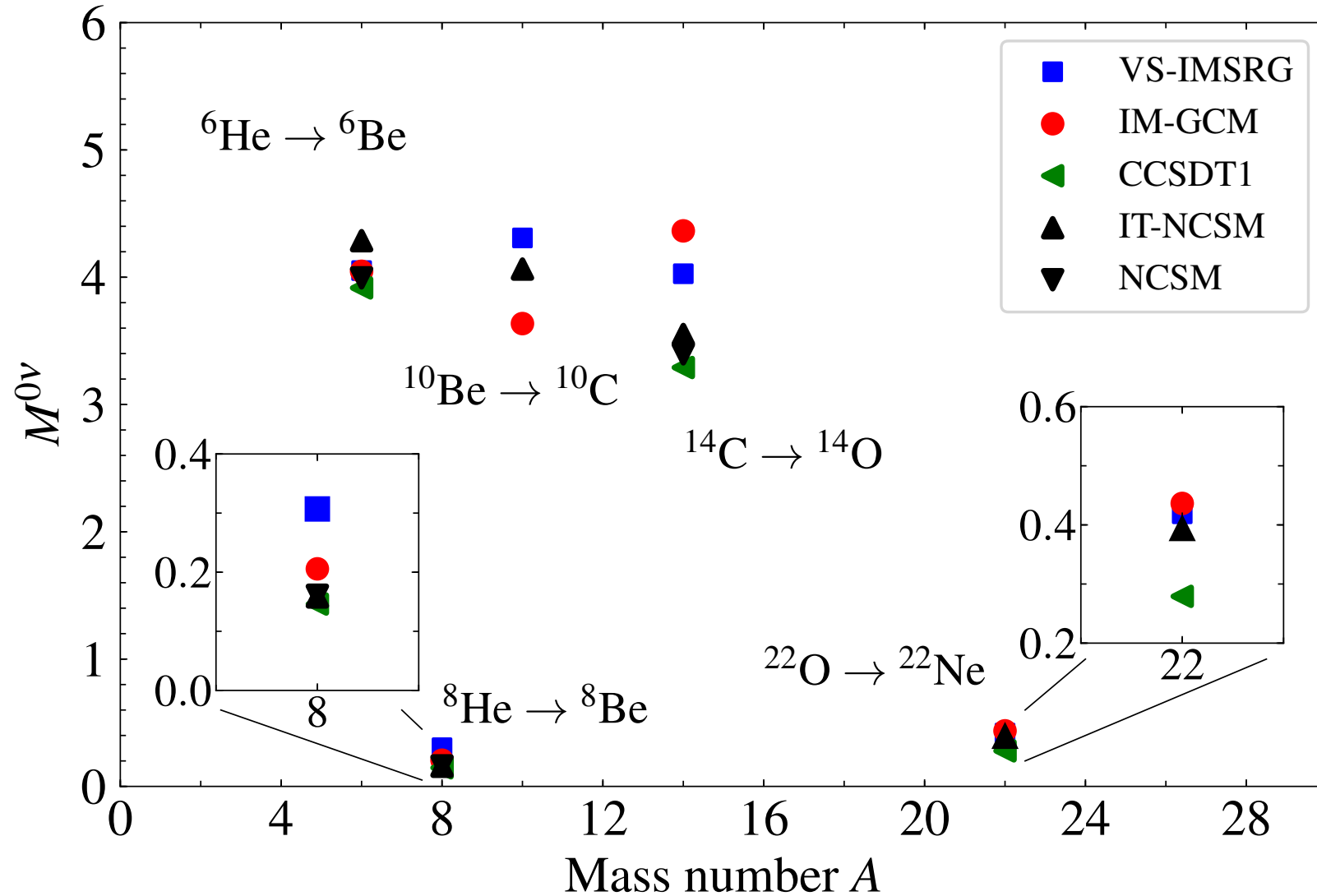


N³LO

3-nucleon potentials *Chambers-Wall et al. arXiv:2510.21564*

V. Cirigliano et al., Phys. Rev. Lett. 120, 202001 (2018), Phys. Rev. C 100, 055504 (2019)

AB INITIO NUCLEAR MATRIX ELEMENTS

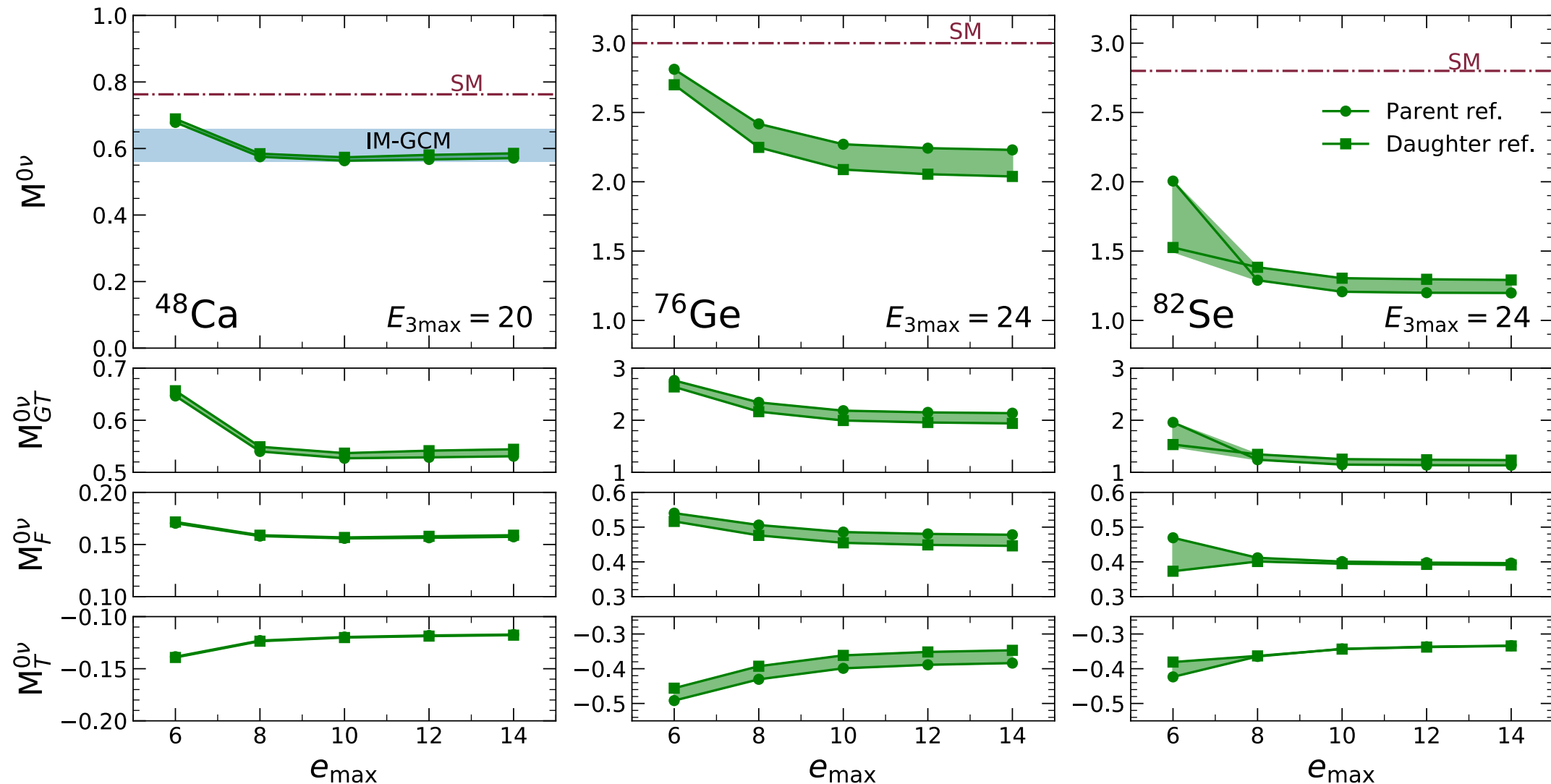


Yao, Belley, Wirth, Miyagi, Payne, Stroberg, Hergert, Holt, Phys. Rev. C 103, 014315 (2021)

AB INITIO NUCLEAR MATRIX ELEMENTS



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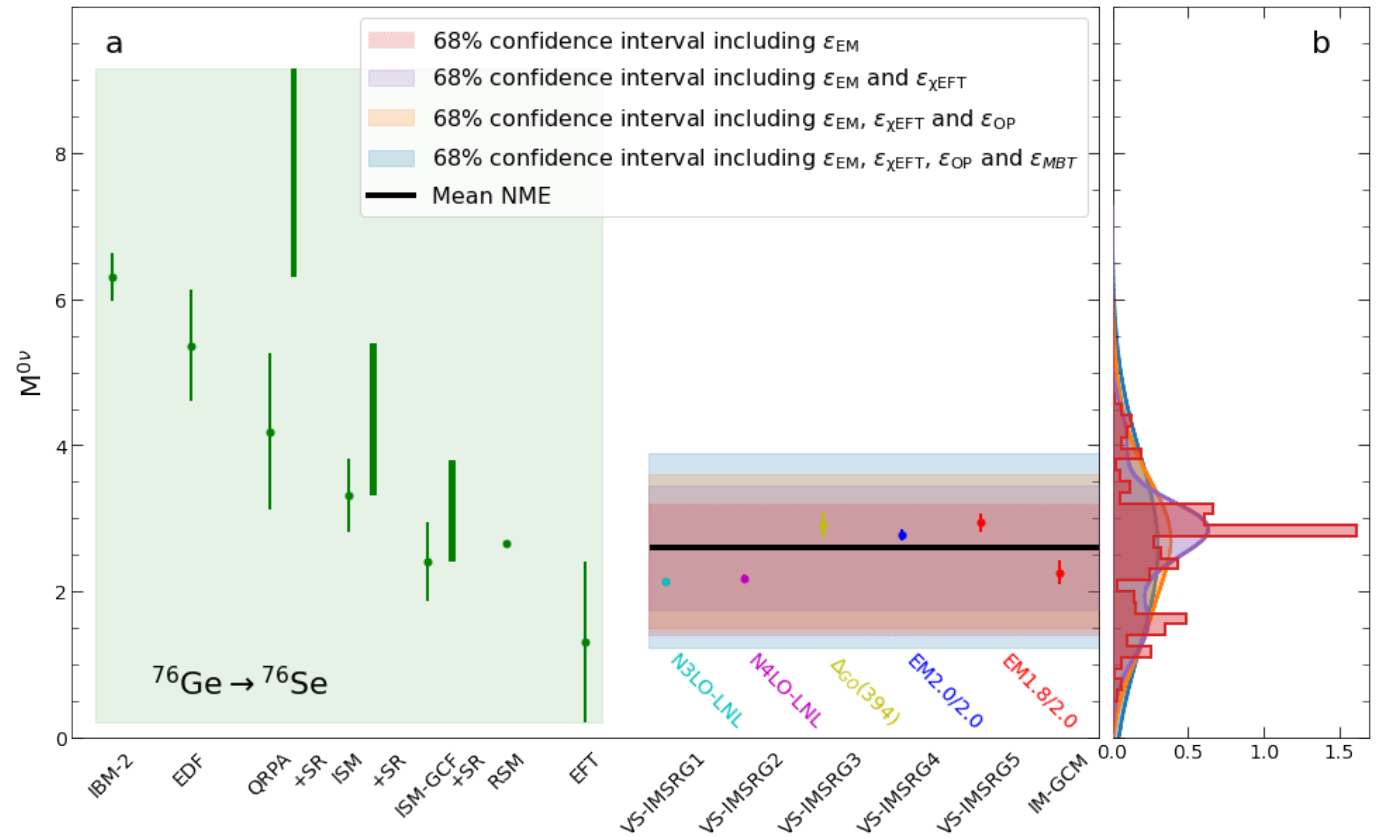
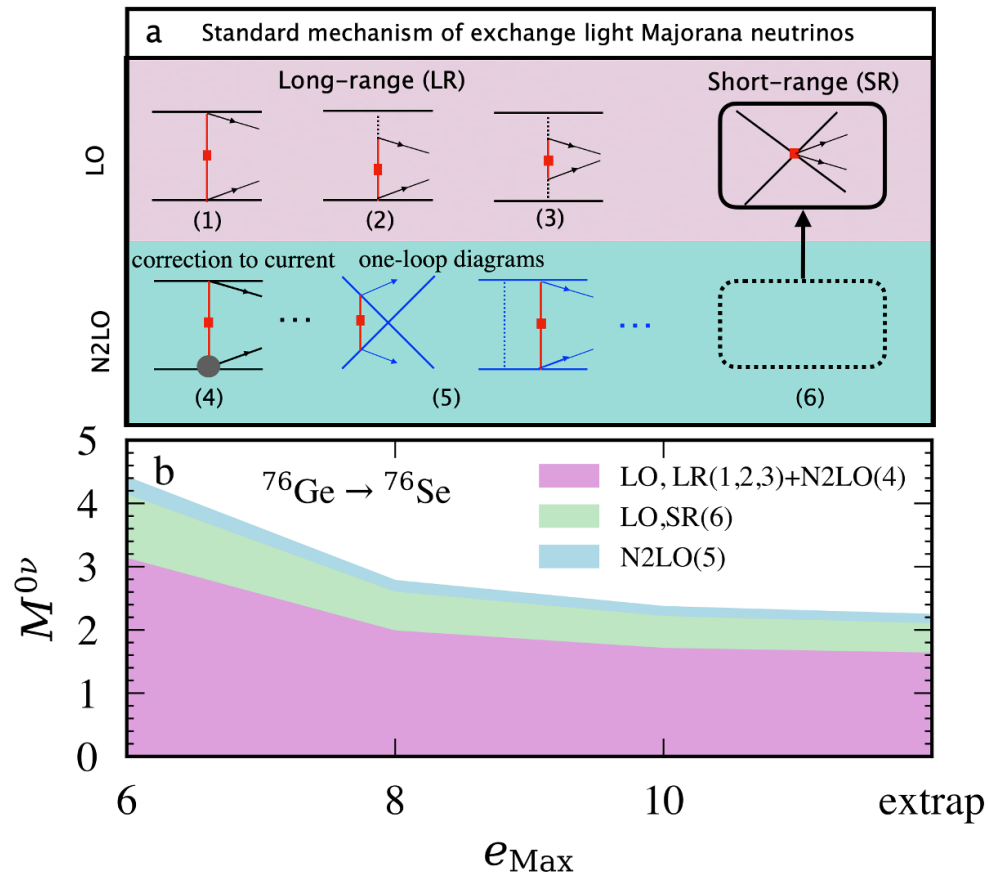
Belley, Payne, Stroberg, Miyagi, Holt, Phys. Rev. Lett. 126, 042502 (2021)

UNCERTAINTY QUANTIFICATION



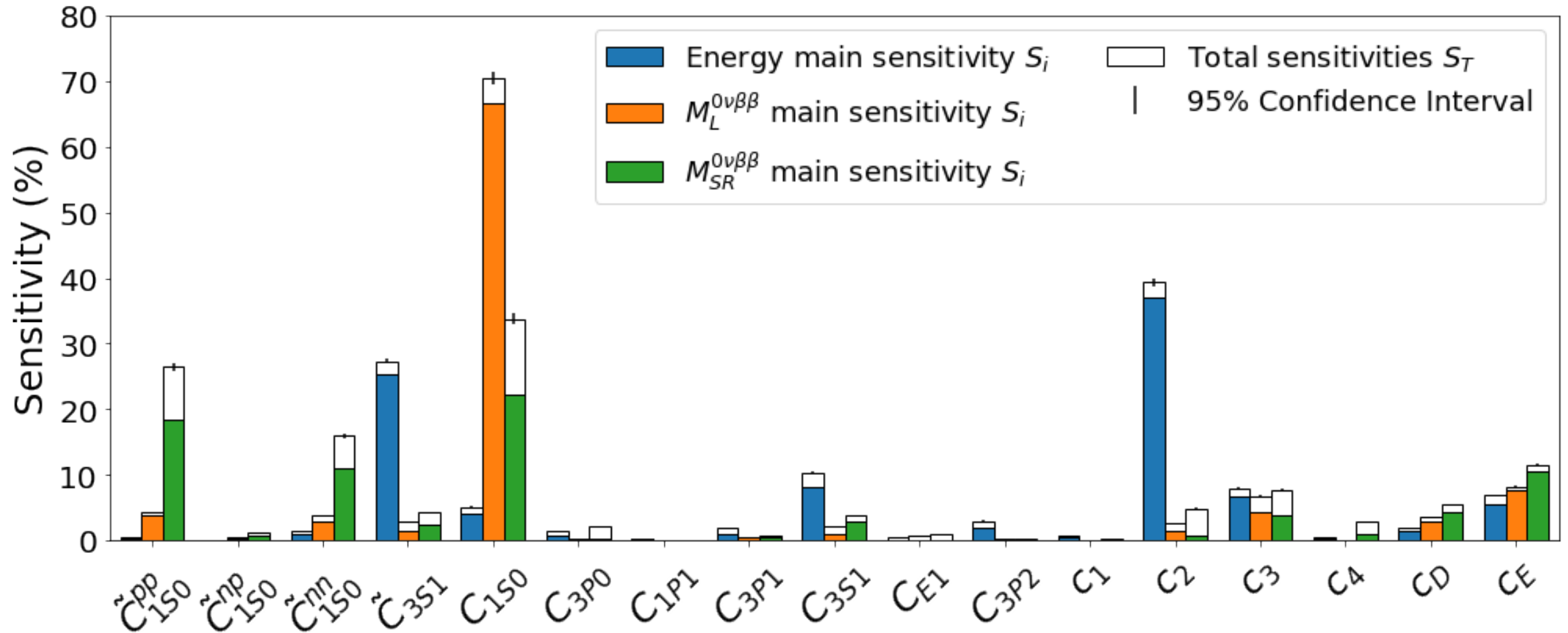
TECHNISCHE
UNIVERSITÄT
DARMSTADT

Ab initio calculations based on consistent Hamiltonians and operators based on χ EFT allow for uncertainty quantification



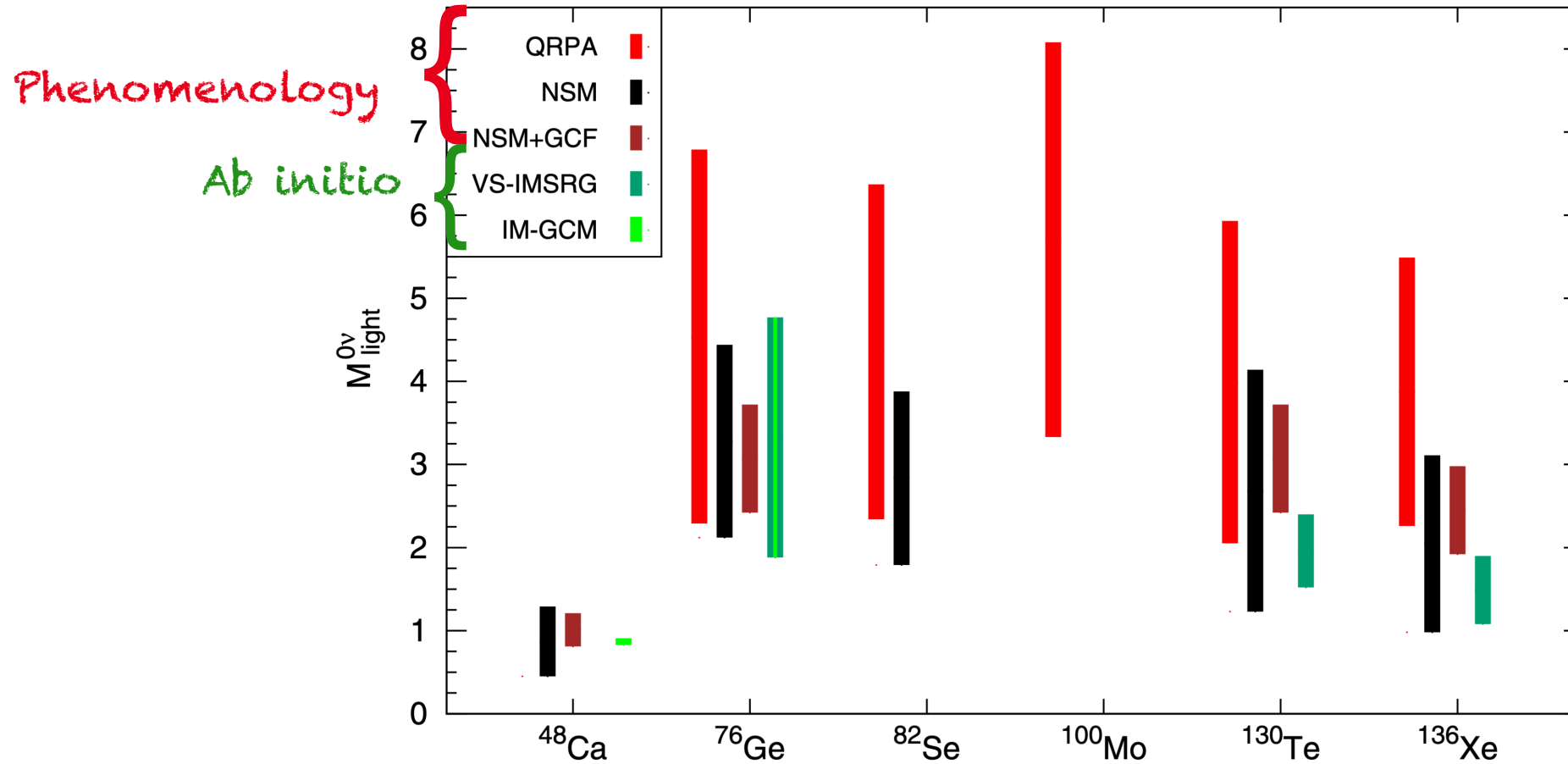
Belley, Yao, Bally, Pitcher, Engel, et al., Phys. Rev. Lett. 132, 182502 (2024)

SENSITIVITY ANALYSIS



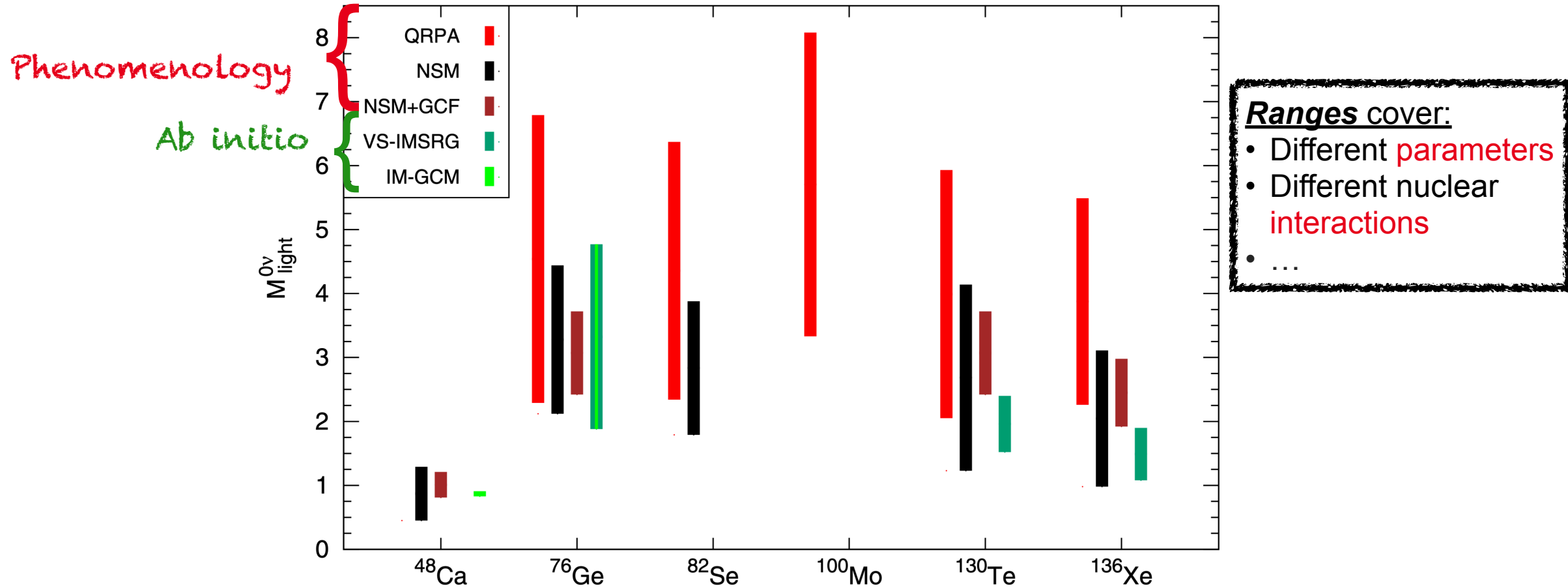
Belley, Pitcher, Miyagi, Stroberg, Holt, Phys. Rev. C 113, 014319 (2026)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



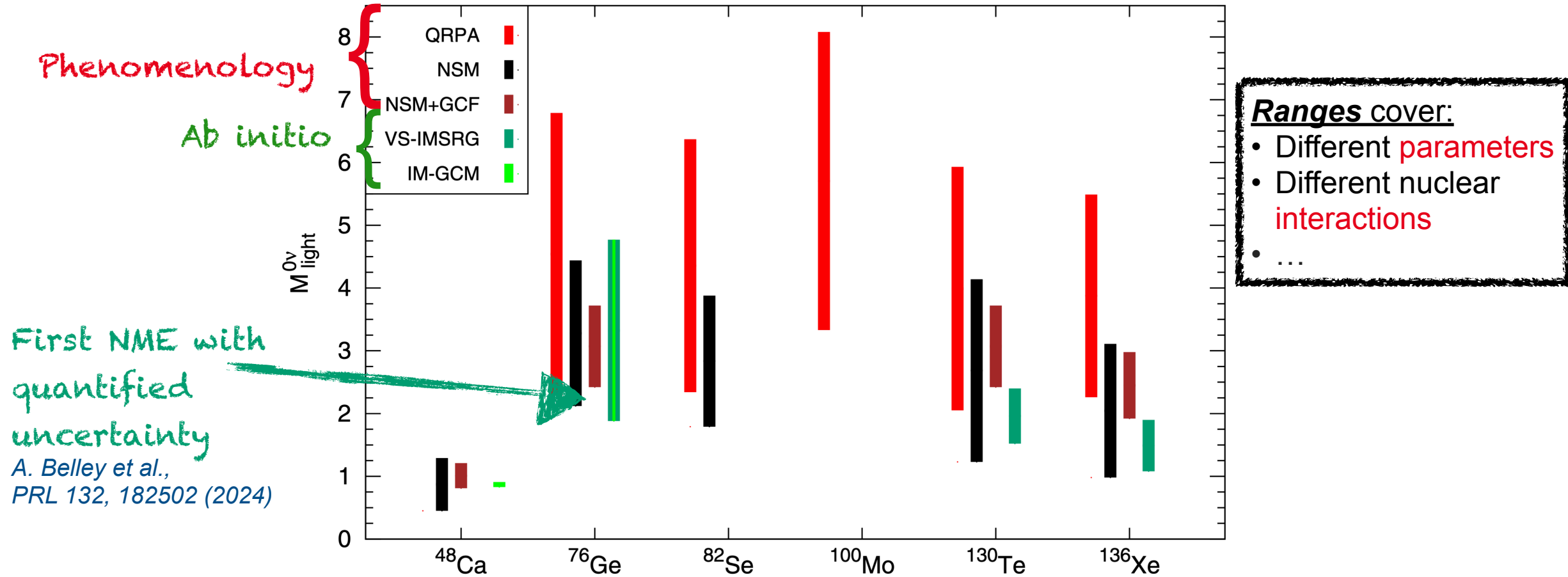
Gómez-Cadenas et al., *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



Gómez-Cadenas et al., *La Rivista del Nuovo Cimento* 46, 619 (2023)

CURRENT STATUS OF THE NUCLEAR MATRIX ELEMENTS



Gómez-Cadenas et al., *La Rivista del Nuovo Cimento* 46, 619 (2023)



GLOBAL NEUTRINO-MASS LIMITS

GLOBAL LIMITS FOR MAJORANA MASSES



$$\frac{\Gamma^{0\nu}(A, Z)}{\ln 2} = \frac{1}{t_{1/2}^{0\nu}(A, Z)} = g_A^4 G^{0\nu}(A, Z) |M^{0\nu}(A, Z)|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

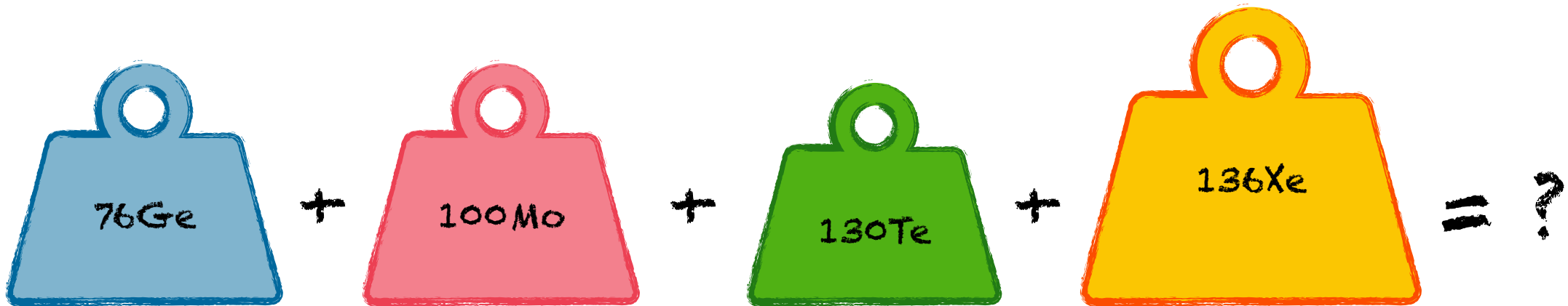


Figure idea stolen from T. Shickele

GLOBAL LIMITS FOR MAJORANA MASSES



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- Experiments probe Majorana mass with different isotopes

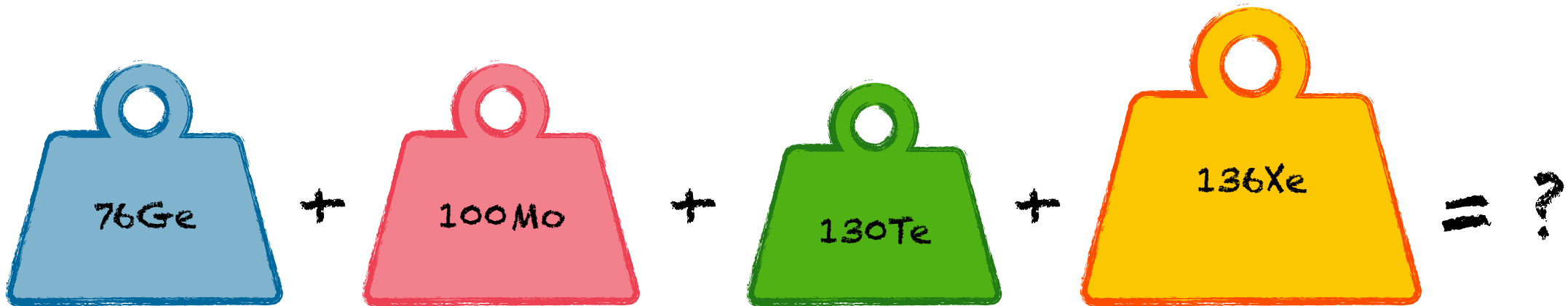


Figure idea stolen from T. Shickele

GLOBAL LIMITS FOR MAJORANA MASSES



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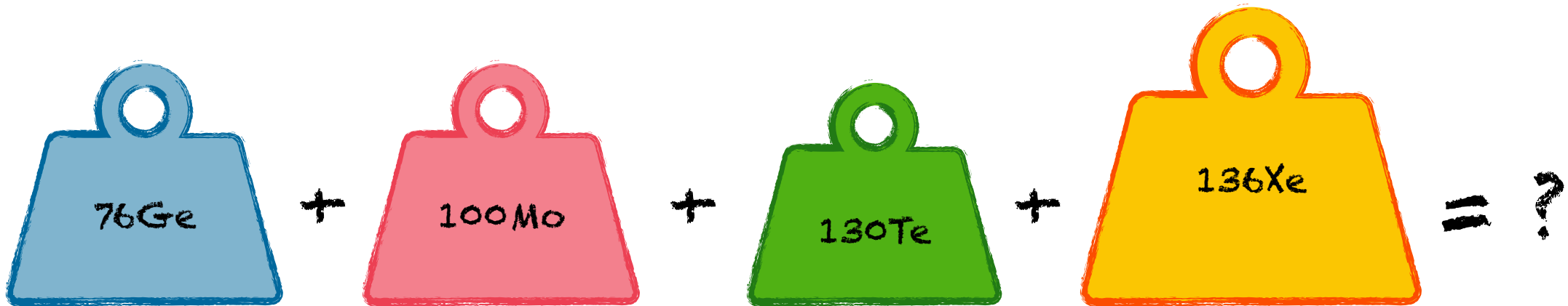


Figure idea stolen from T. Shickele

GLOBAL LIMITS FOR MAJORANA MASSES



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- Experiments probe Majorana mass with different isotopes
 - How to combine these into **global Majorana-mass limits**?

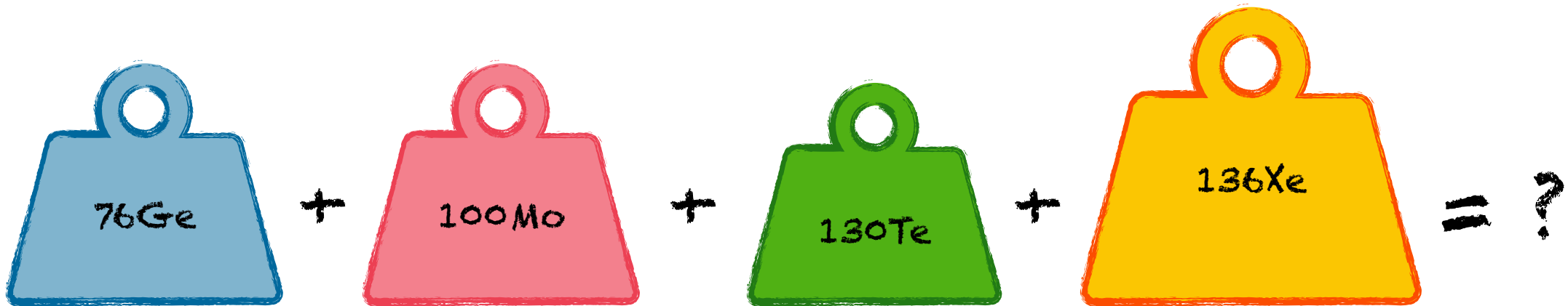


Figure idea stolen from T. Shickele

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Biller, Phys. Rev. D 104, 012002 (2021)



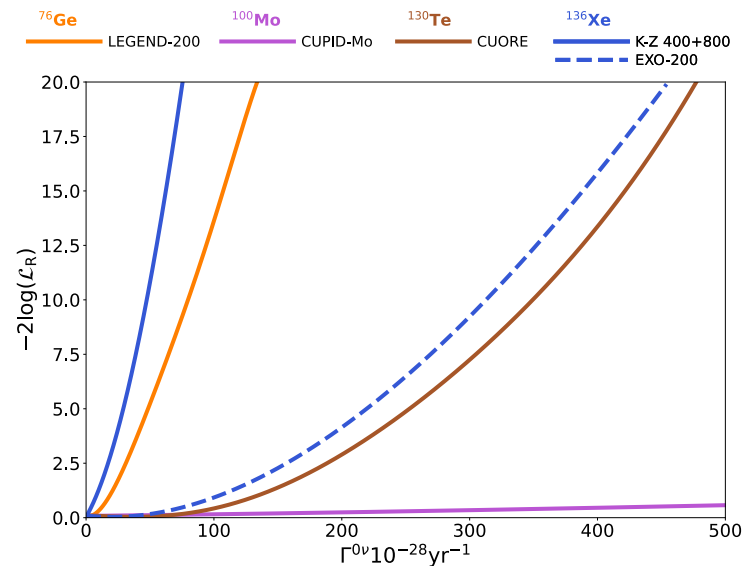
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$$P(m_{\beta\beta} | \text{Data}) \propto \mathcal{L}(\text{Data} | m_{\beta\beta}) \pi(m_{\beta\beta})$$

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Biller, Phys. Rev. D 104, 012002 (2021)

Likelihood functions from current experiments:



Shickele, Jokiniemi, Belley, Holt, Phys. Rev. D 114, 013007 (2026)

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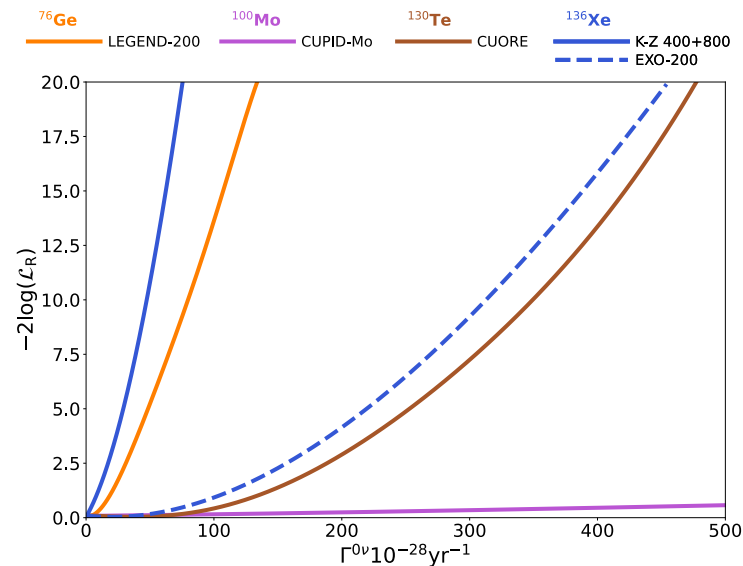
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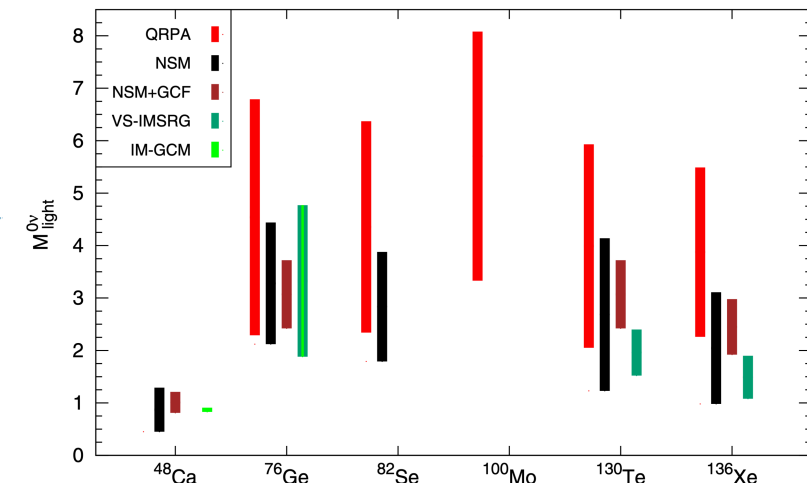
Shickele, Jokiniemi, Belley, Holt, Phys. Rev. D 114, 013007 (2026)

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Nuclear matrix elements

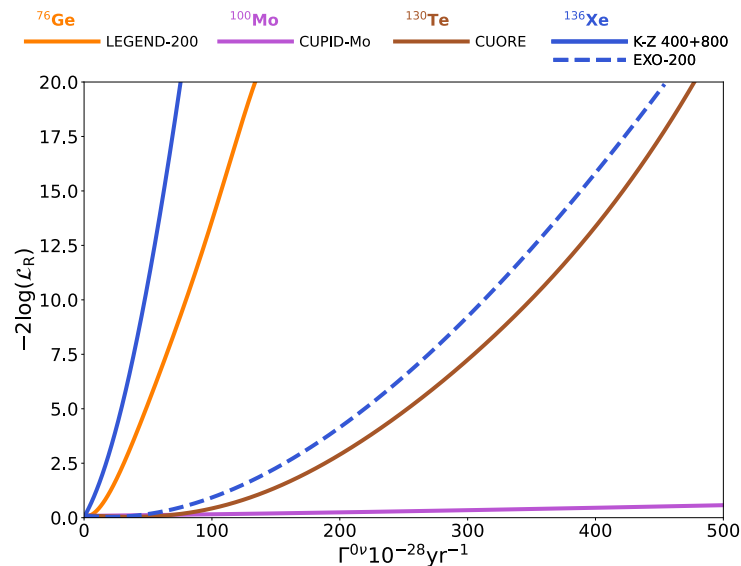


*Gómez-Cadenas, Martín-Albo, Menéndez et al.,
La Rivista del Nuovo Cimento 46, 619 (2023)*

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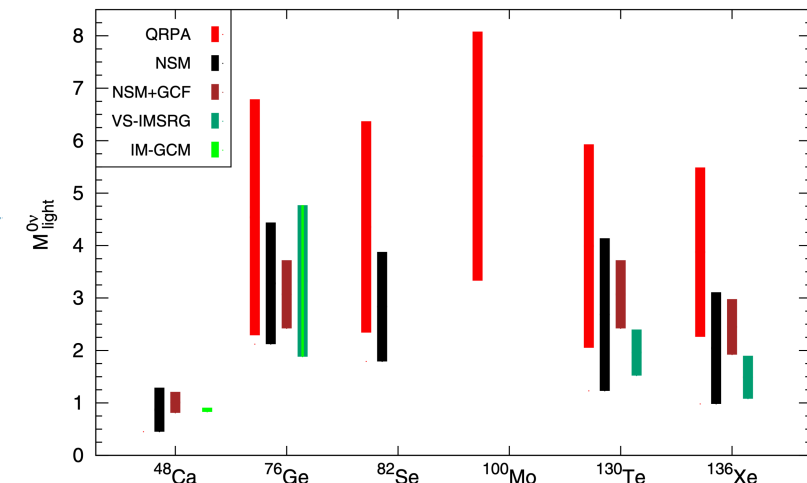
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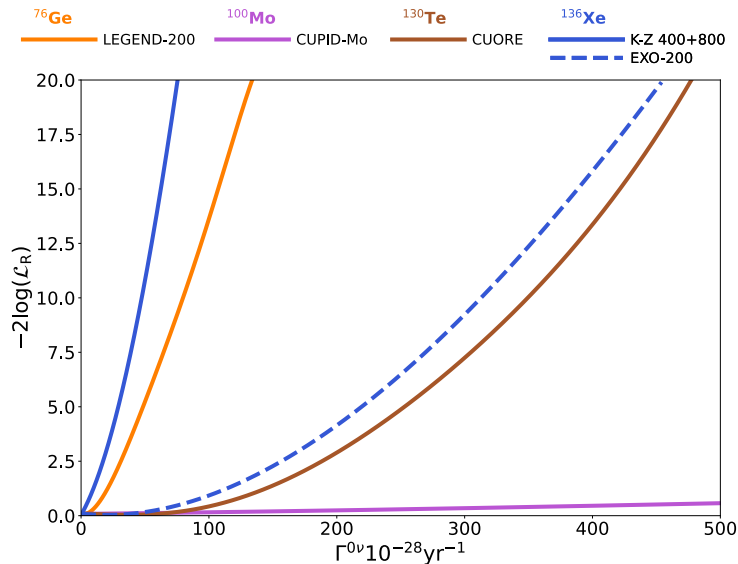


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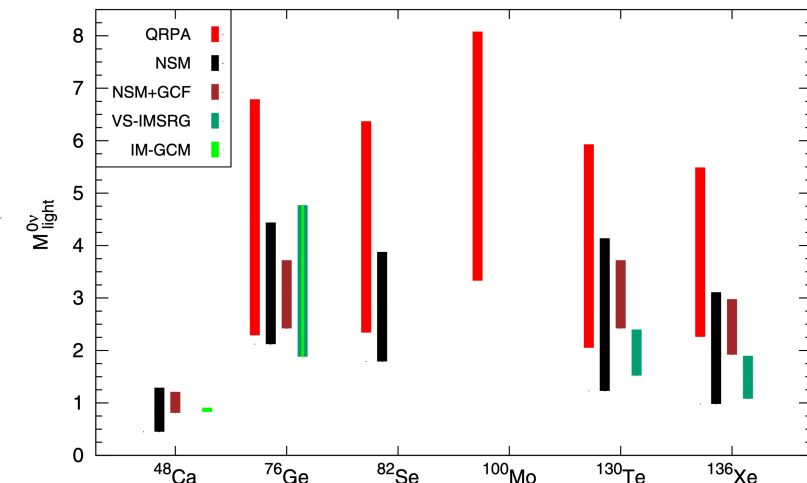
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Prior:

- Uniform in $m_{\beta\beta}$ OR
- Uniform in $\Gamma^{0\nu}$ (or $m_{\beta\beta}^2$) OR
- Uniform in $\log(m_{\beta\beta})$

Nuclear matrix elements



Gómez-Cadenas, Martín-Albo, Menéndez et al.,
La Rivista del Nuovo Cimento 46, 619 (2023)

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Biller, Phys. Rev. D 104, 012002 (2021)

90% credible interval global limits for $m_{\beta\beta}$

Prior:

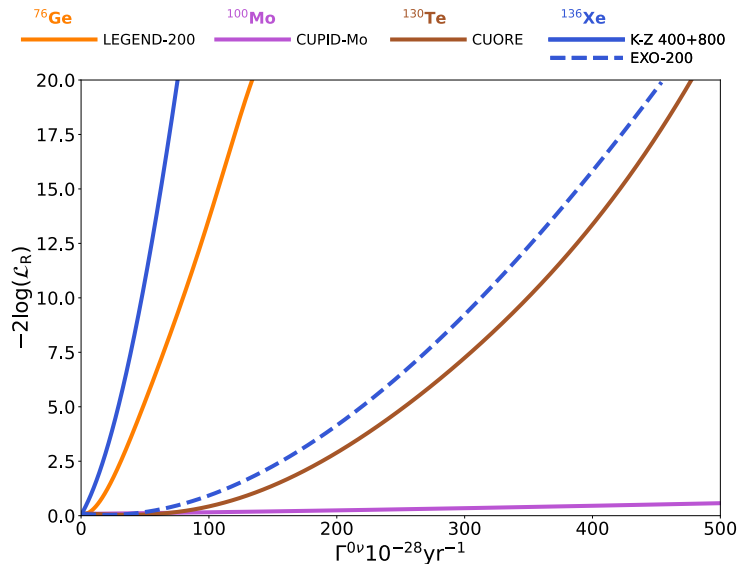
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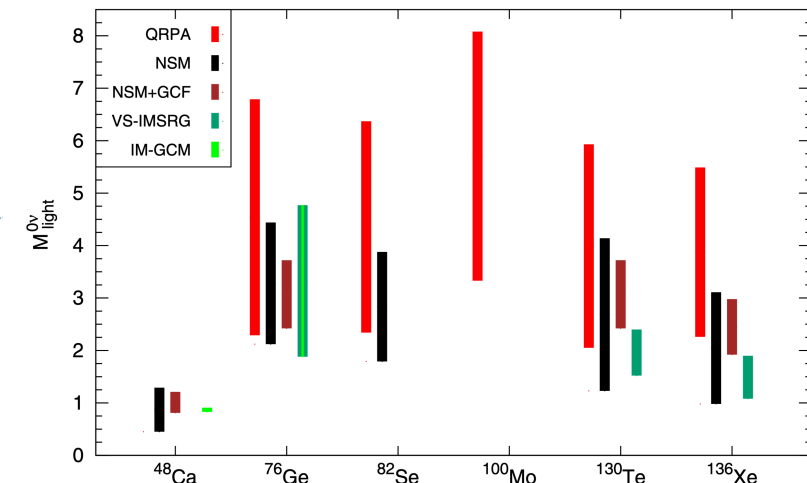
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Shickele, Jokiniemi, Belley, Holt, Phys. Rev. D 114, 013007 (2026)

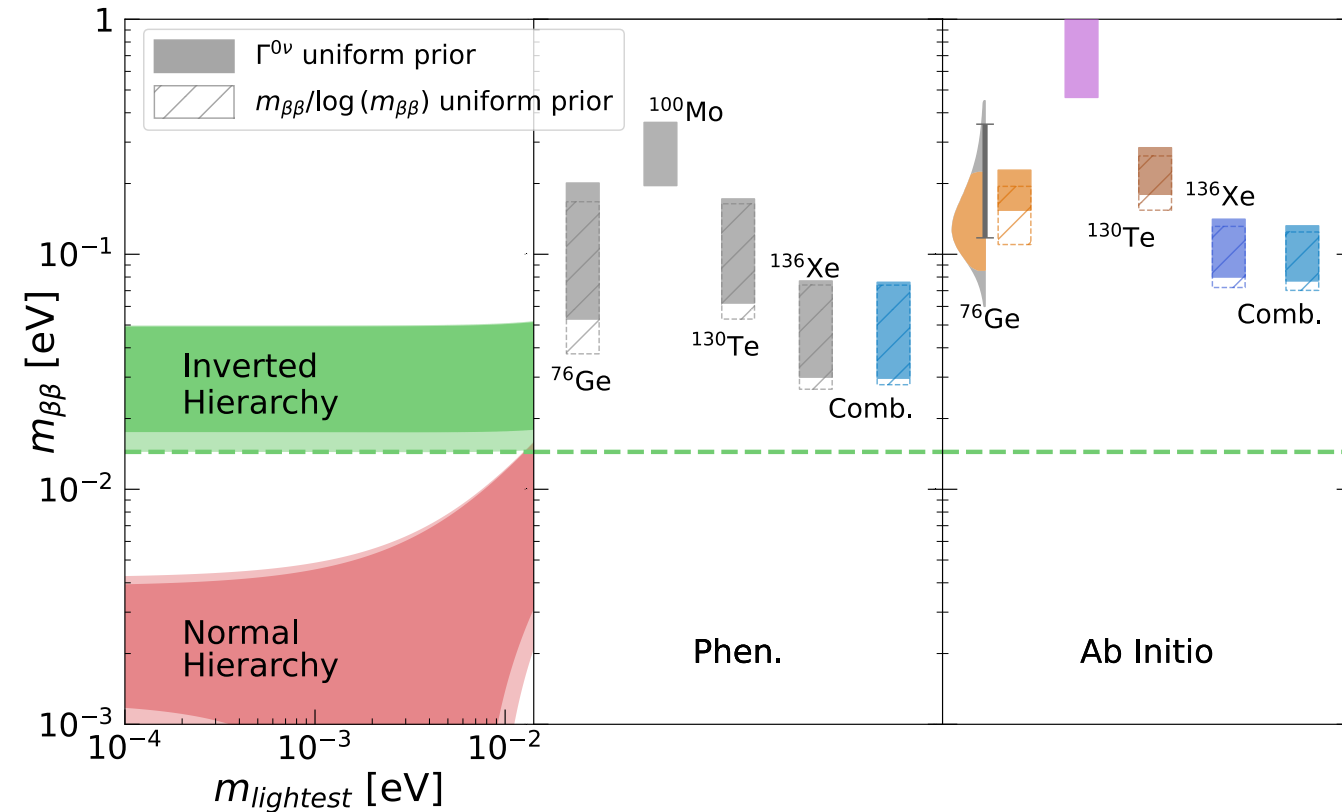
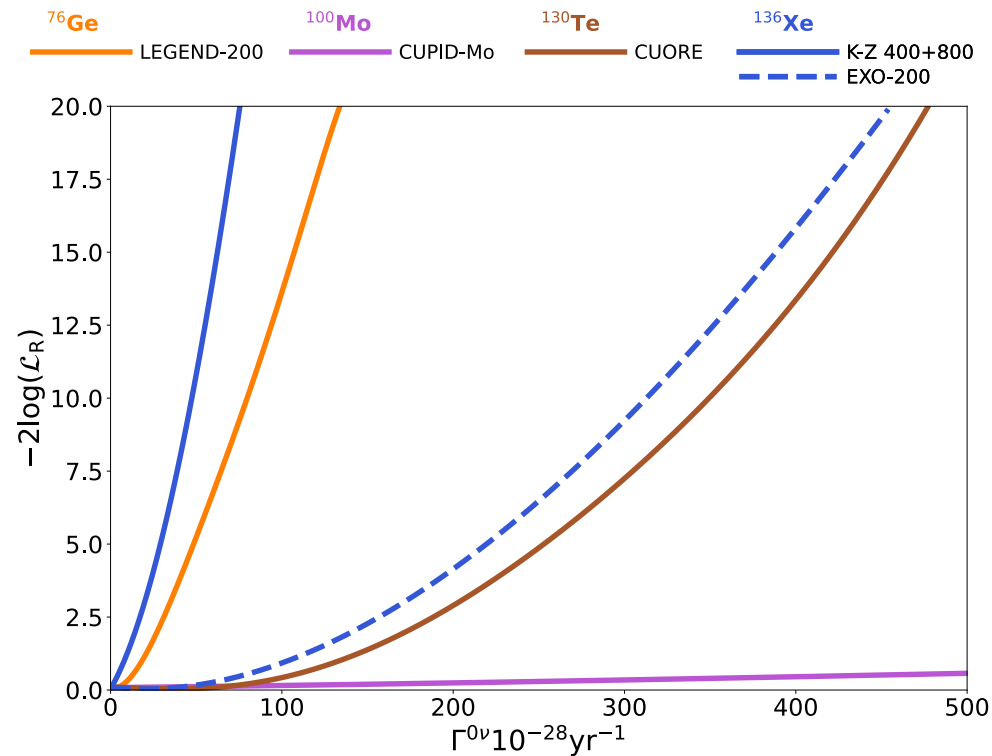
Nuclear matrix elements



Gómez-Cadenas, Martín-Albo, Menéndez et al.,
La Rivista del Nuovo Cimento 46, 619 (2023)

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Current best limits

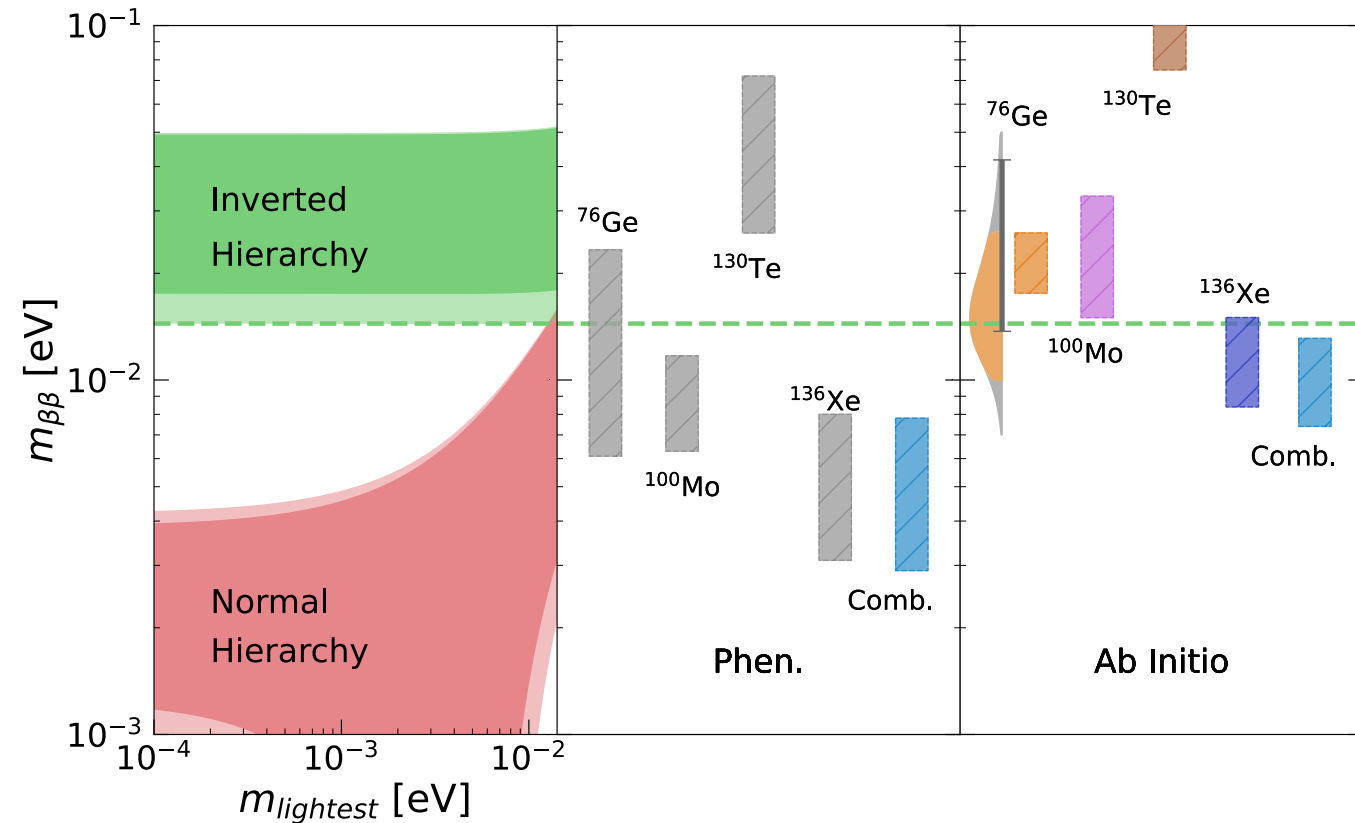
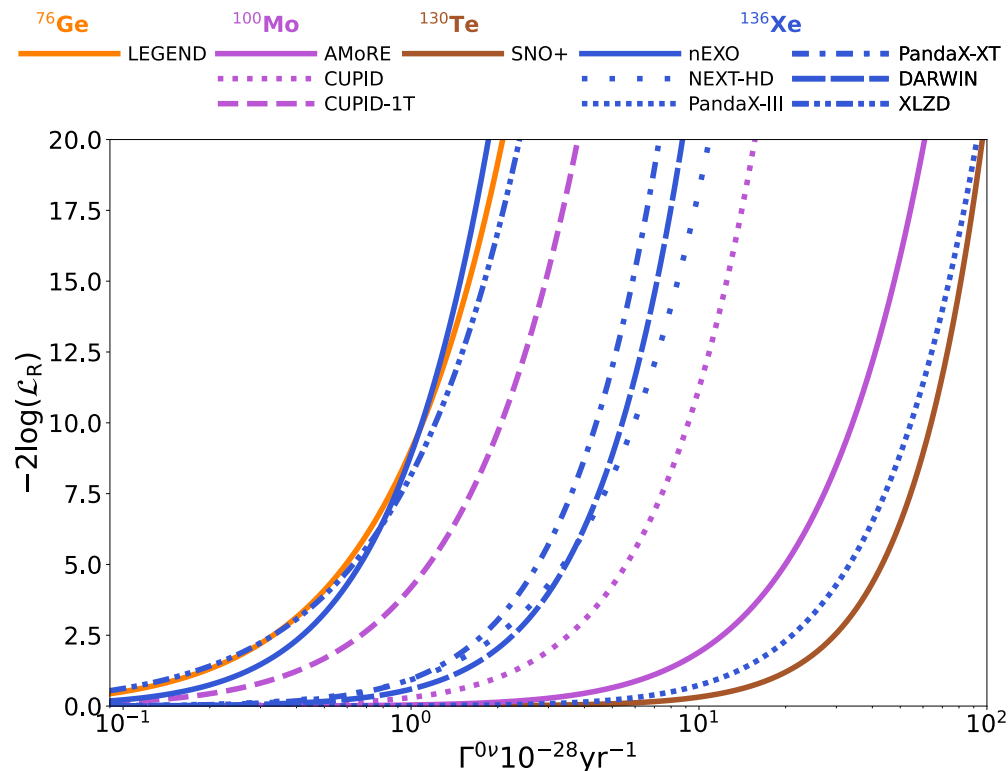


Shickele, Jokiniemi, Belley, Holt, *Phys. Rev. D* 114, 013007 (2026)

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Next-generation experiments

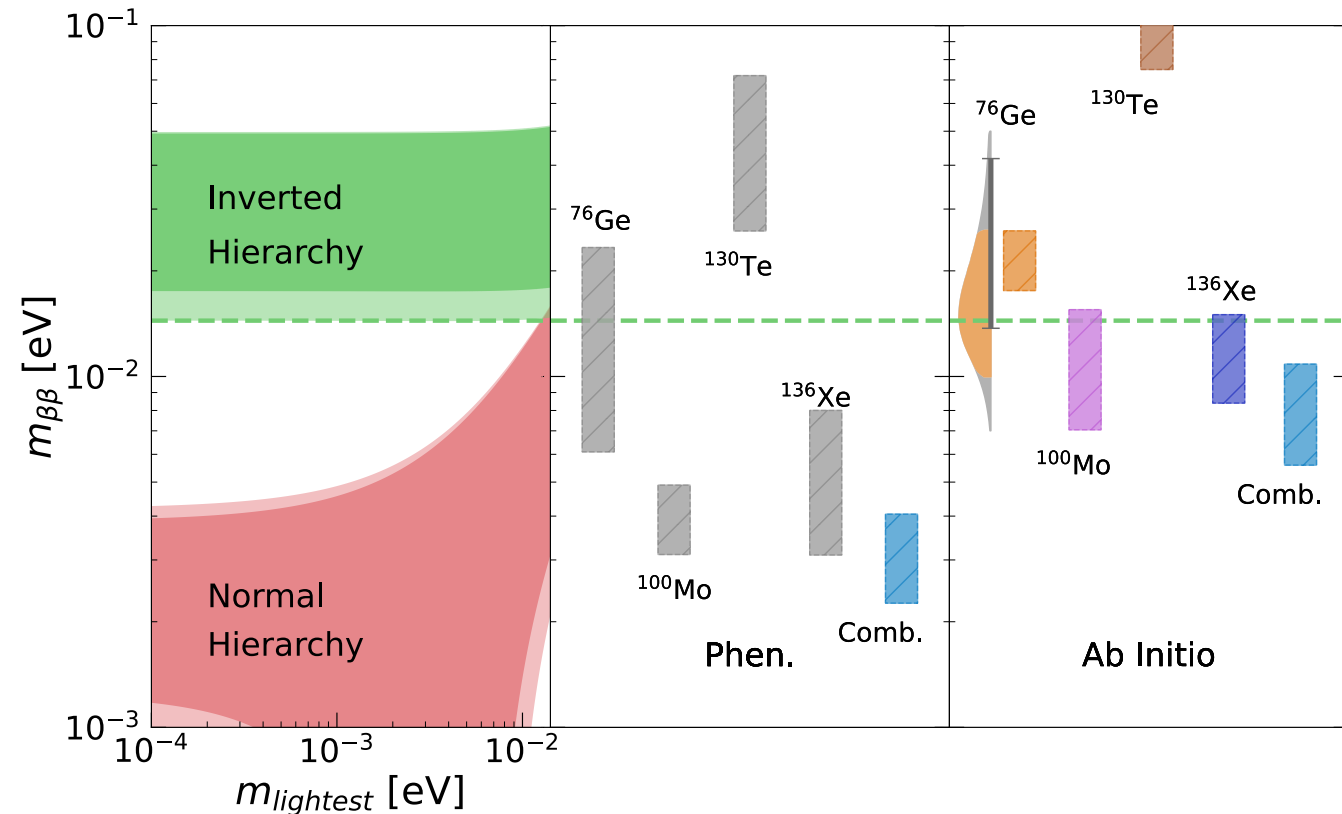
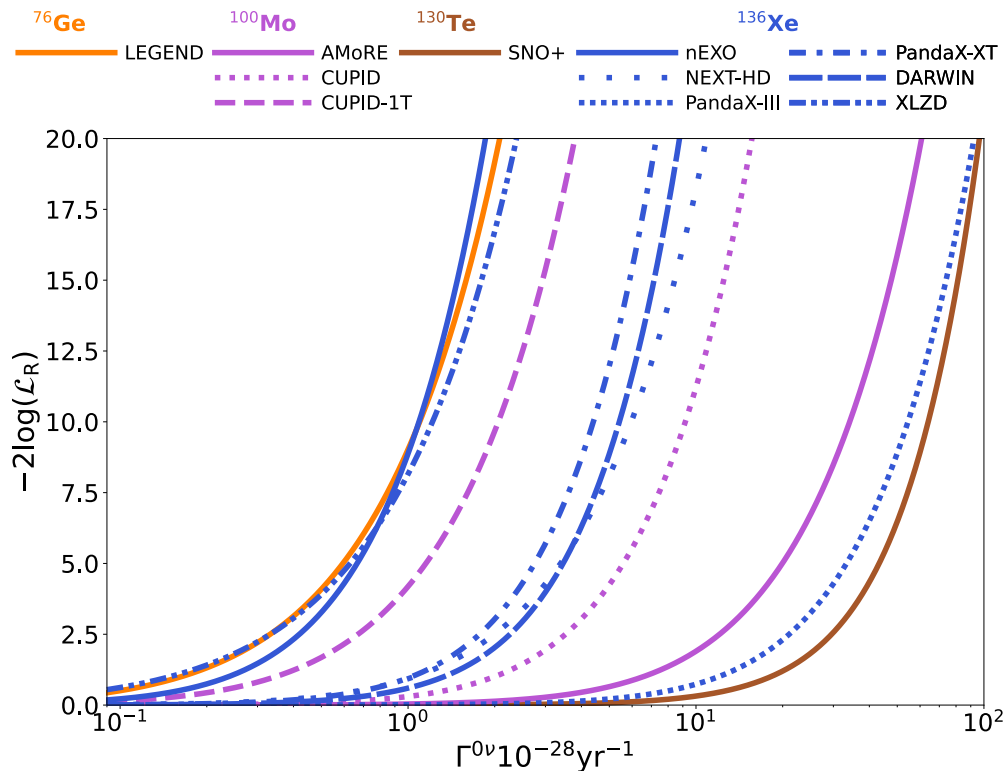
No CUPID-1T



Shickele, Jokiniemi, Belley, Holt, Phys. Rev. D 114, 013007 (2026)

Next-generation experiments

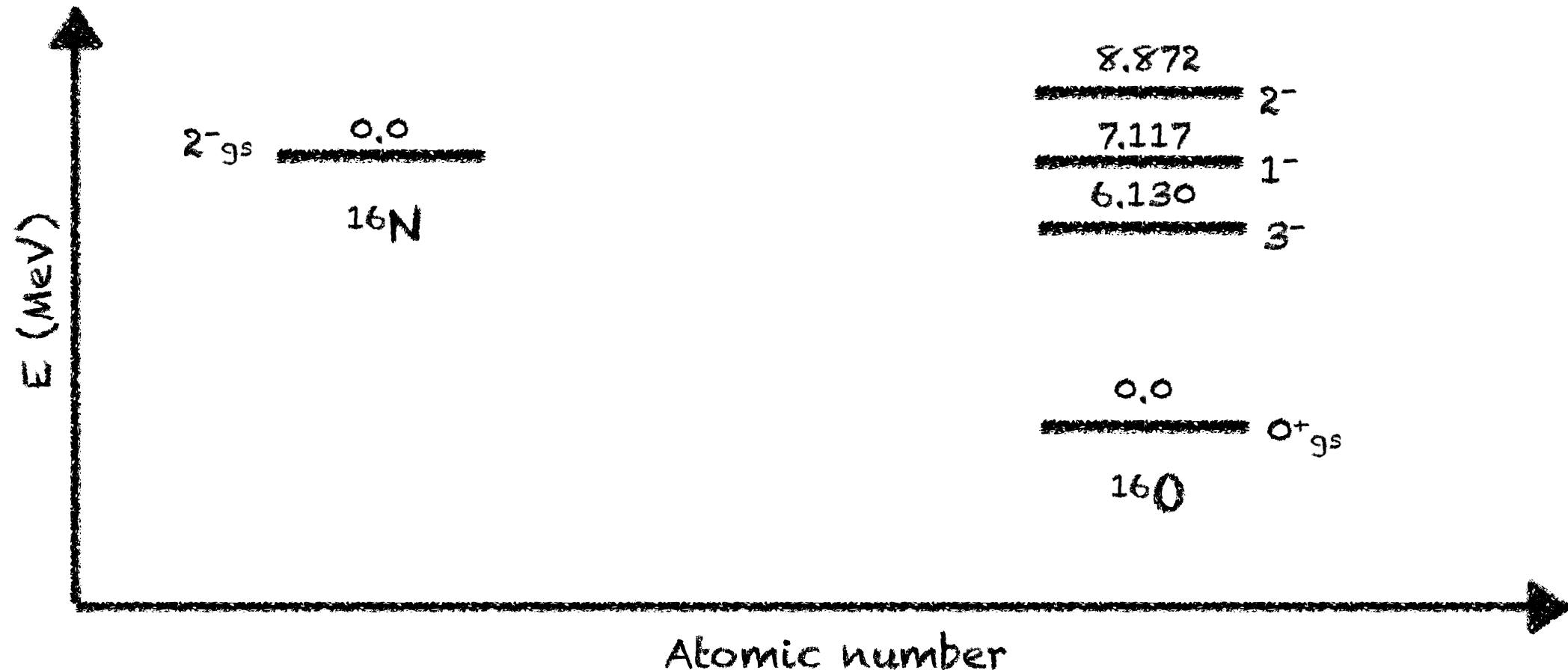
With CUPID-1T



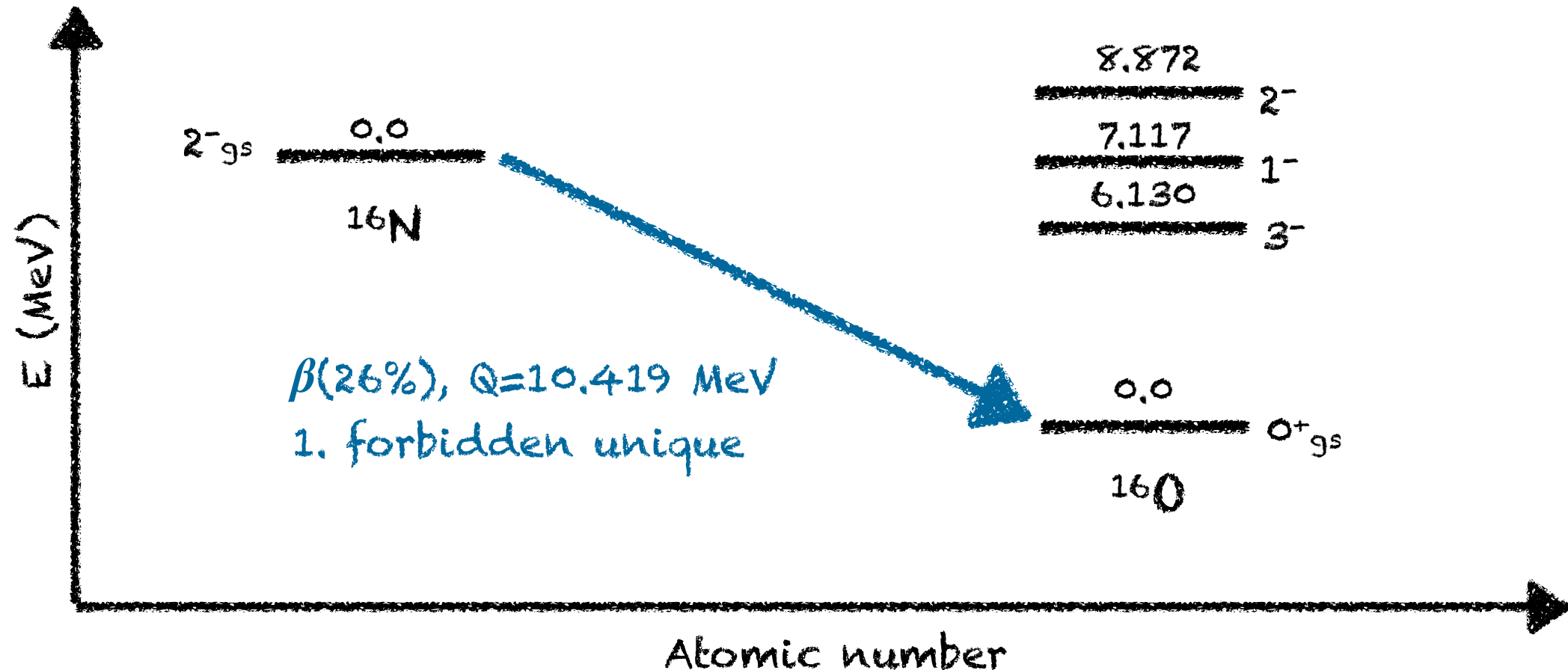
Shickele, Jokiniemi, Belley, Holt, Phys. Rev. D 114, 013007 (2026)

PRECISION BETA-DECAY SEARCHES

FORBIDDEN β DECAY OF ^{16}N



FORBIDDEN β DECAY OF ^{16}N



PRECISION β DECAY STUDIES FOR BSM PHYSICS



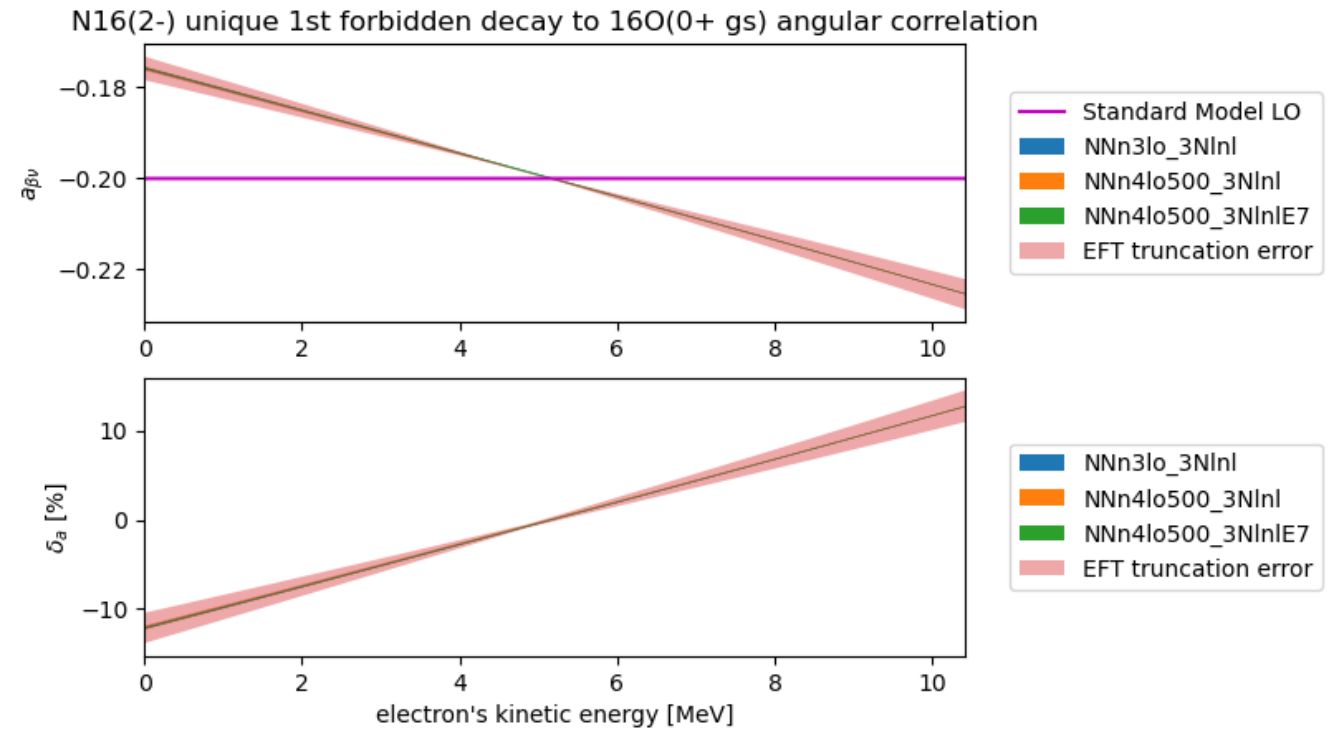
$$d\Gamma \propto |\langle \Psi_f | \hat{H}_W | \Psi_i \rangle|^2 \propto 1 + b_F \frac{m_e}{\epsilon} + a \vec{\beta} \cdot \hat{v} + a_2 [\beta^2 - (\hat{\beta} \cdot \hat{v})^2]$$

Glick-Magid, Gazit, *Phys. Rev. D* 107, 075031 (2023)

$$b_F = 0 + \delta b + \frac{C_T^+}{C_A} \sim 10^{-3}$$

$$a = -\frac{1}{5} \left(1 + \delta a - \frac{|C_T^+|^2 + |C_T^-|^2}{4|C_A|^2} \right)$$

$$a_2 = \frac{1}{5} \left(1 + \delta a_2 - \frac{|C_T^+|^2 + |C_T^-|^2}{4|C_A|^2} \right)$$



Glick-Magid, Gazda, Gazit, Forssén, Jokiniemi, Navrátil,
in preparation

PRECISION β DECAY STUDIES FOR BSM PHYSICS



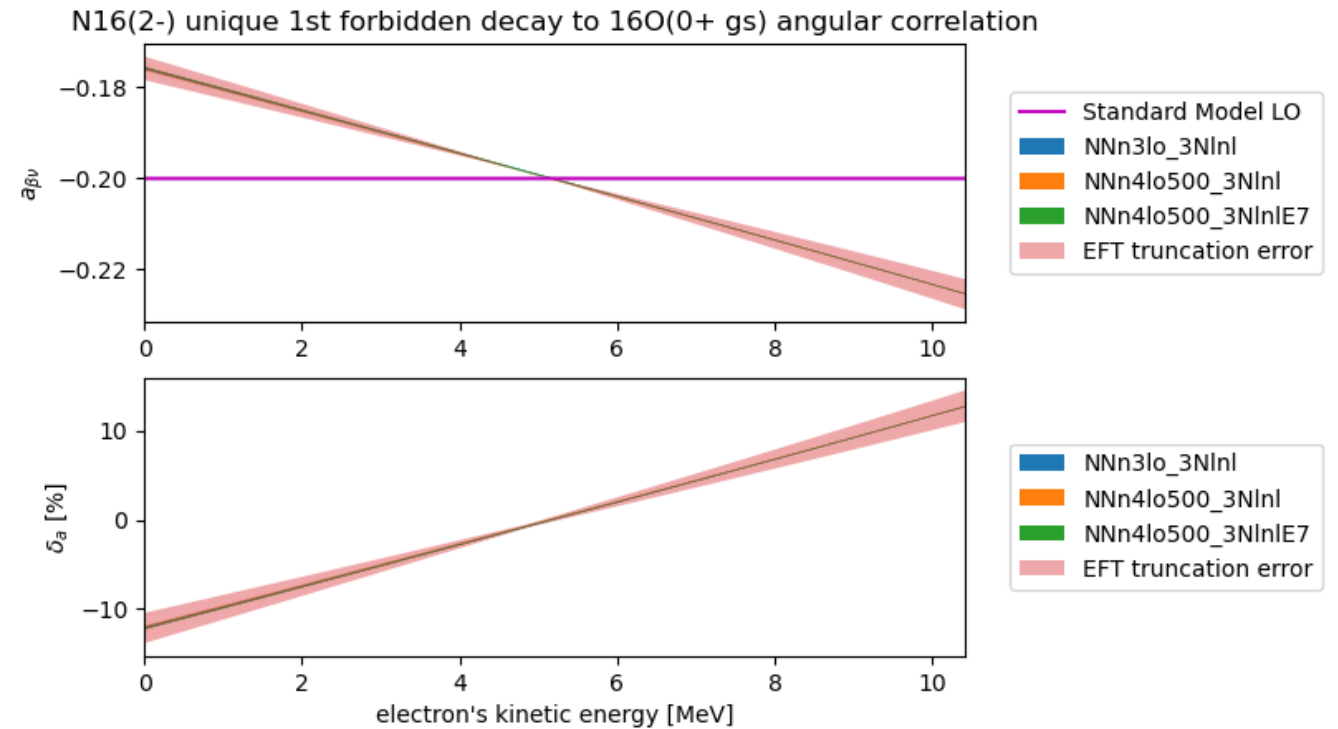
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Glick-Magid, Gazda, Gazit, Forssén, Jokiniemi, Navrátil,
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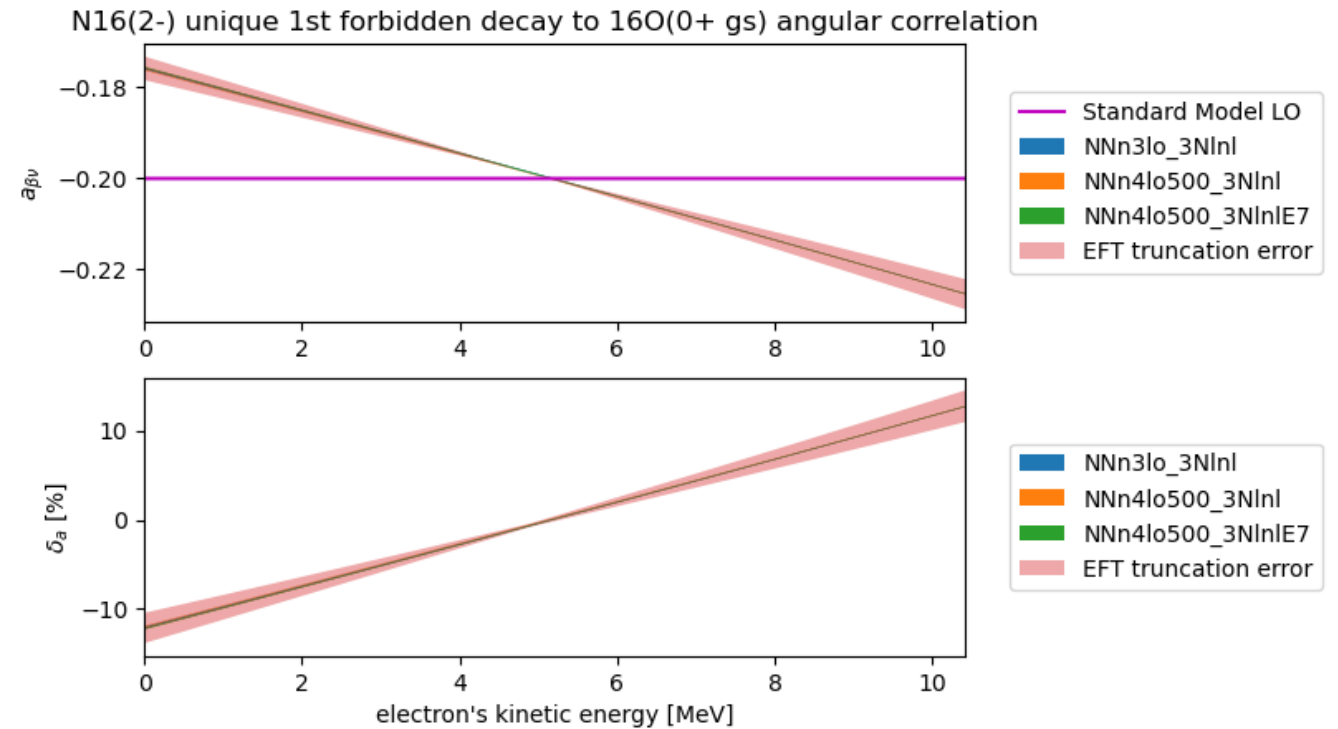
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Glick-Magid, Gazda, Gazit, Forssén, Jokiniemi, Navrátil,
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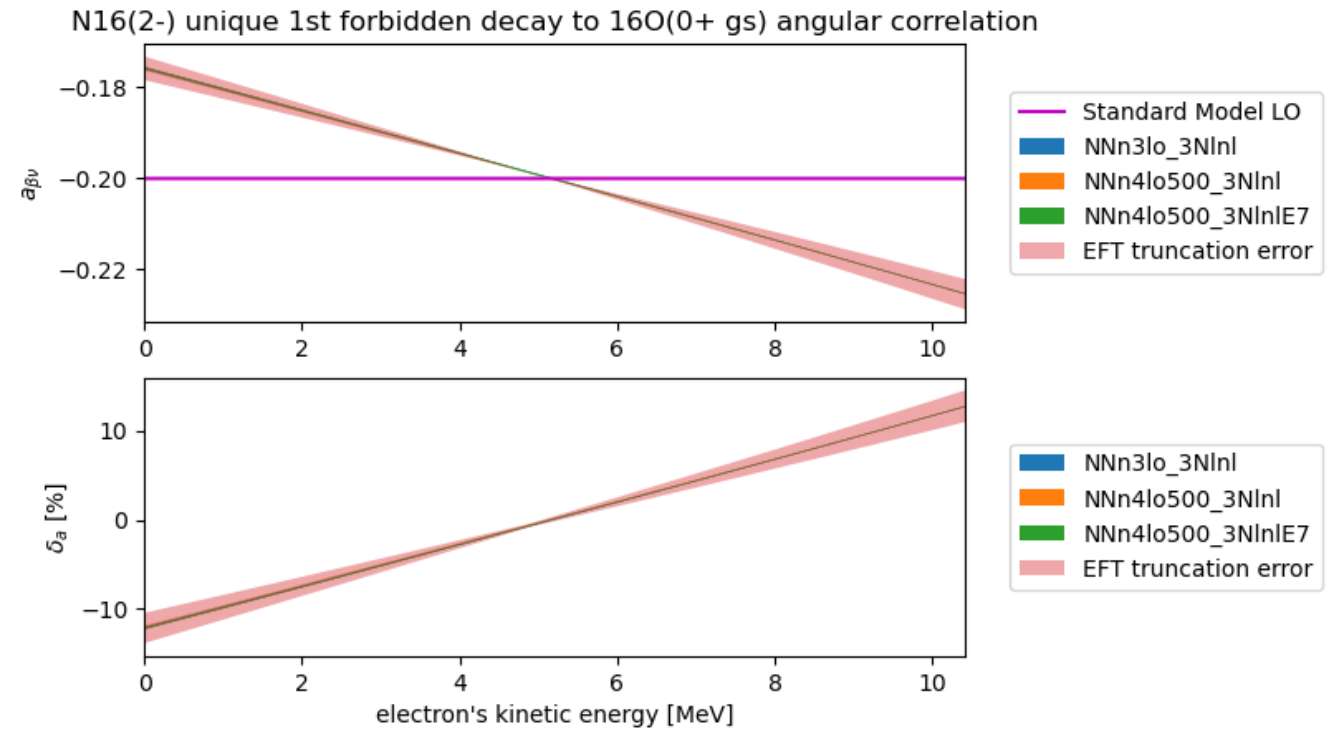
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Glick-Magid, Gazit, *Phys. Rev. D* 107, 075031 (2023)

$$b_F = \underbrace{0}_{\text{SM}} + \underbrace{\delta b}_{\text{SM corr.}} + \underbrace{\frac{C_T^+}{C_A}}_{\text{BSM}} \sim 10^{-3}$$

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Glick-Magid, Gazda, Gazit, Forssén, Jokiniemi, Navrátil,
in preparation

TAKE-HOME MESSAGES

- Our current knowledge on particles in the Universe and interactions between them is based on the Standard Model of Particle Physics
- There are some phenomena that the standard model cannot explain: matter-antimatter asymmetry of the Universe, neutrino masses, dark matter, ...
- Atomic nuclei, forming most of the known Universe, can be used as test laboratories to look for physics beyond the standard model
 - One can look for deviations from Standard model predictions in processes involving nuclei
 - One can look for processes not predicted by the standard model
- Neutrinoless double-beta decay is a hypothetical beyond-standard-model process subject to active research worldwide
- One can also look for deviations from the Standard Model in precision beta decay searches
- Beyond-standard-model searches call for reliable *ab initio* nuclear-theory predictions with quantified uncertainties

Questions?

✉ lotta.jokiniemi@tu-darmstadt.de