LOEWE
Exzellente Forschung für Hessens Zukunft

SFB 1245

TECHNISCHE UNIVERSITÄT DARMSTADT

CONSTRAINING NEUTRINO PROPERTIES BY DOUBLE-BETA DECAY

Lotta Jokiniemi (she/her)

Institut für Kernphysik, Theoriezentrum, TU Darmstadt

PAINT2026 – Workshop on Progress in Ab Initio Nuclear Theory, TRIUMF, February 25, 2026

TECHNISCHE UNIVERSITÄT DARMSTADT

COLLABORATORS

T. Shickele, J. D. Holt

A. Todd

A. Belley

F. Deppisch

TECHNISCHE UNIVERSITÄT DARMSTADT

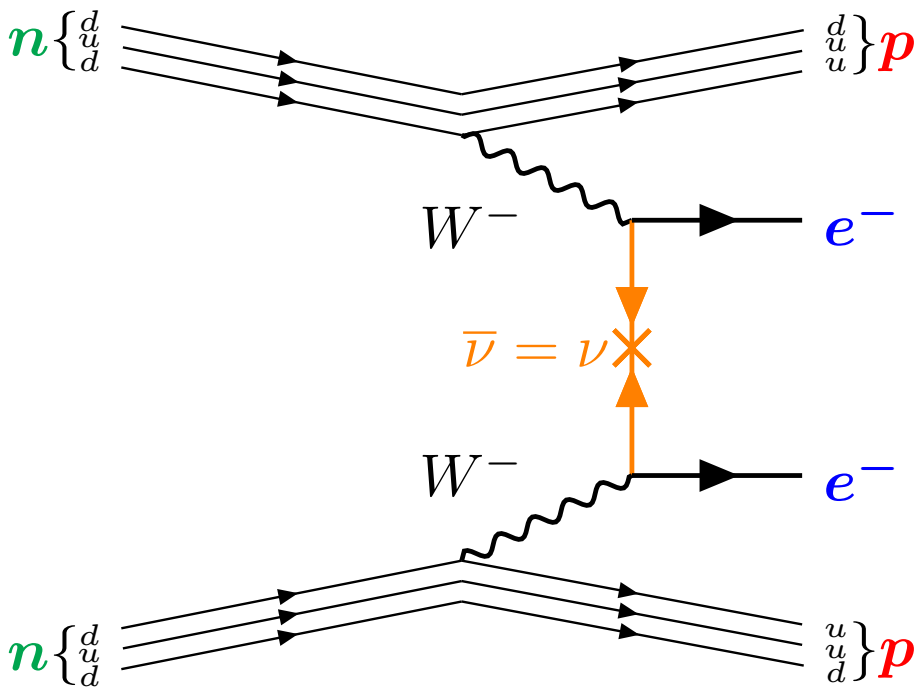
OUTLINE

TECHNISCHE UNIVERSITÄT DARMSTADT

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

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

L: 0 → 0 + 2 (-2)



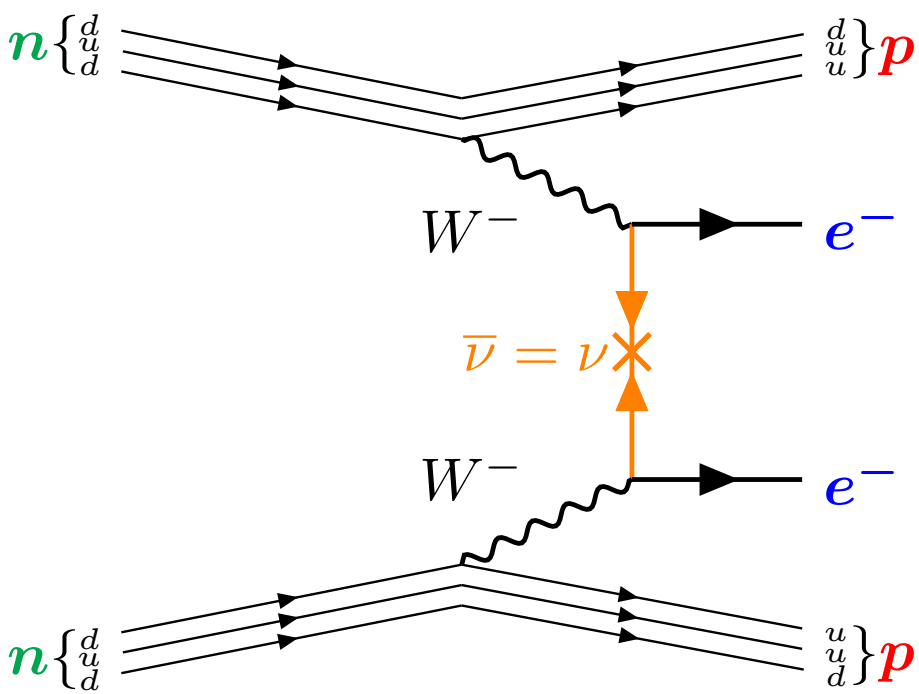
TECHNISCHE UNIVERSITÄT DARMSTADT

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

- **Violates lepton-number conservation**

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

L: 0 → 0 + 2 (-2)



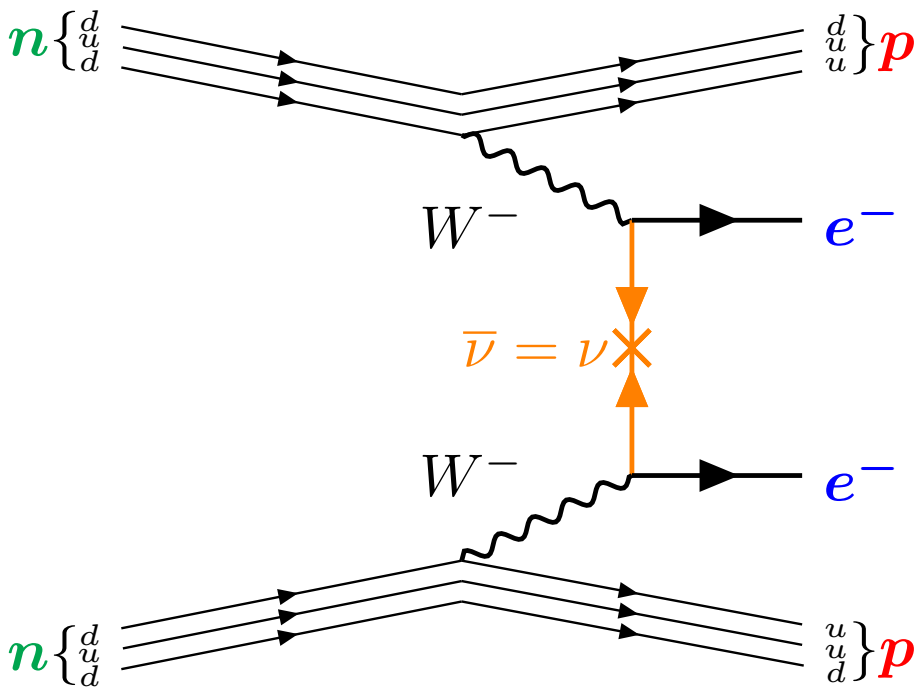
TECHNISCHE UNIVERSITÄT DARMSTADT

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

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

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

L: 0 → 0 + 2 (-2)



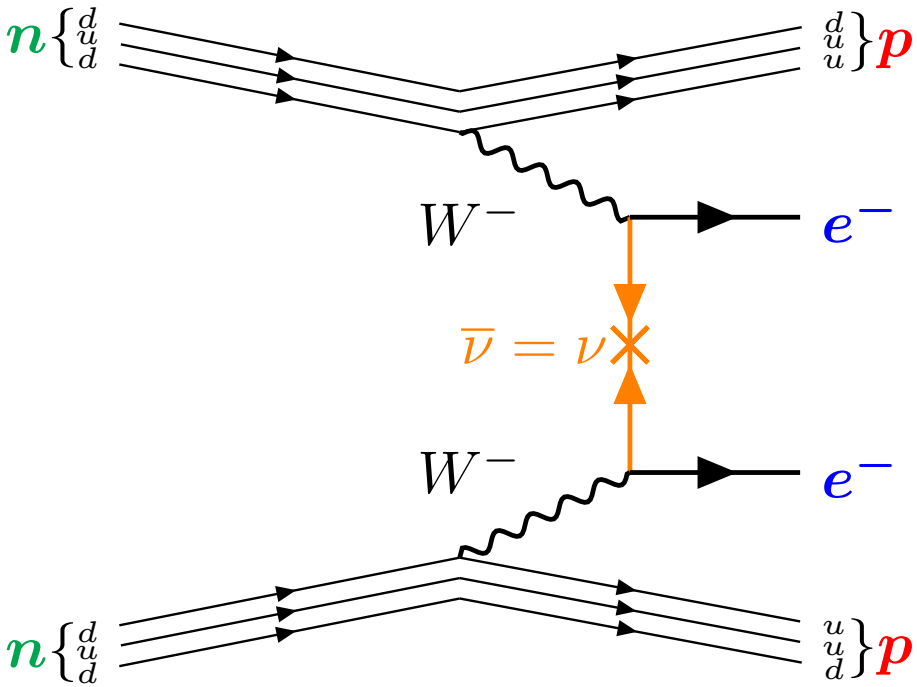
TECHNISCHE UNIVERSITÄT DARMSTADT

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

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t_{1/2}^{0\nu} \gtrsim 10^{25}$ **years**

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

L: 0 → 0 + 2 (-2)



TECHNISCHE UNIVERSITÄT DARMSTADT

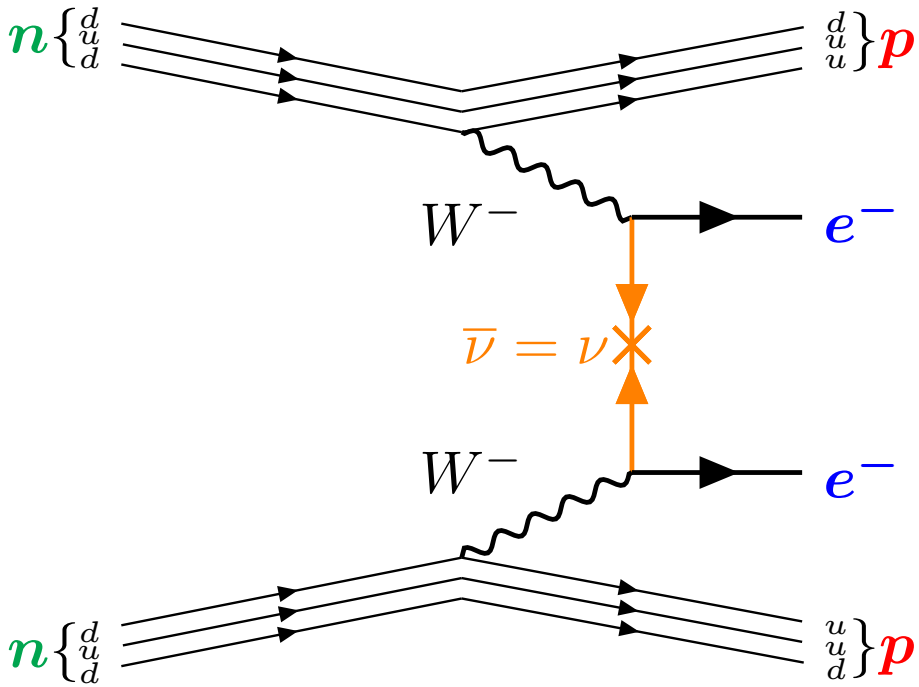
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t^{0\nu}_{1/2} \gtrsim 10^{25}$ **years**

  ($t^{2\nu}_{1/2} \approx 10^{20}$ years, Age of the Universe $\approx 10^{10}$ years)

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

L: 0 → 0 + 2 (-2)



TECHNISCHE UNIVERSITÄT DARMSTADT

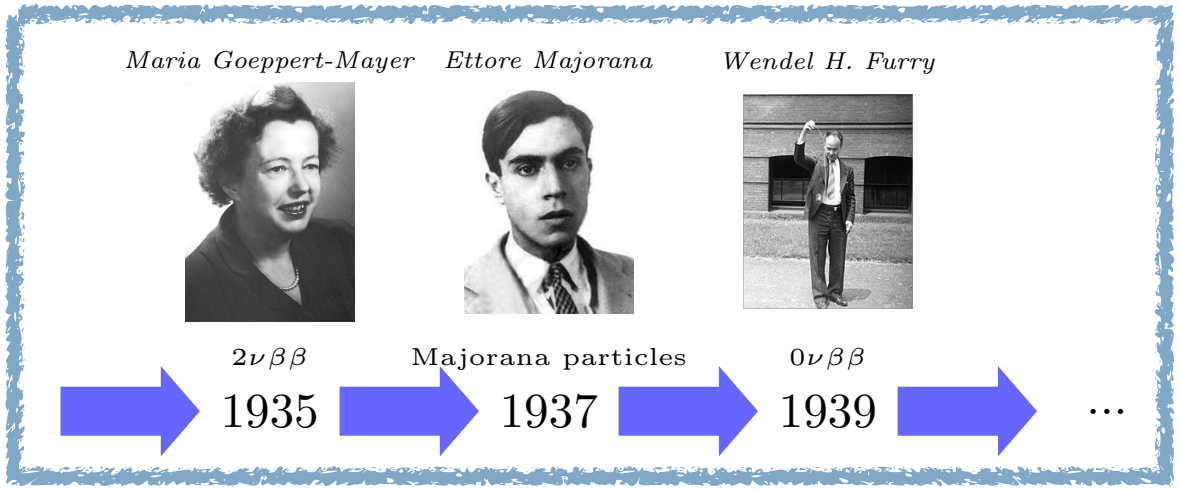
NEUTRINOLESS DOUBLE-BETA ($0\nu\beta\beta$) DECAY

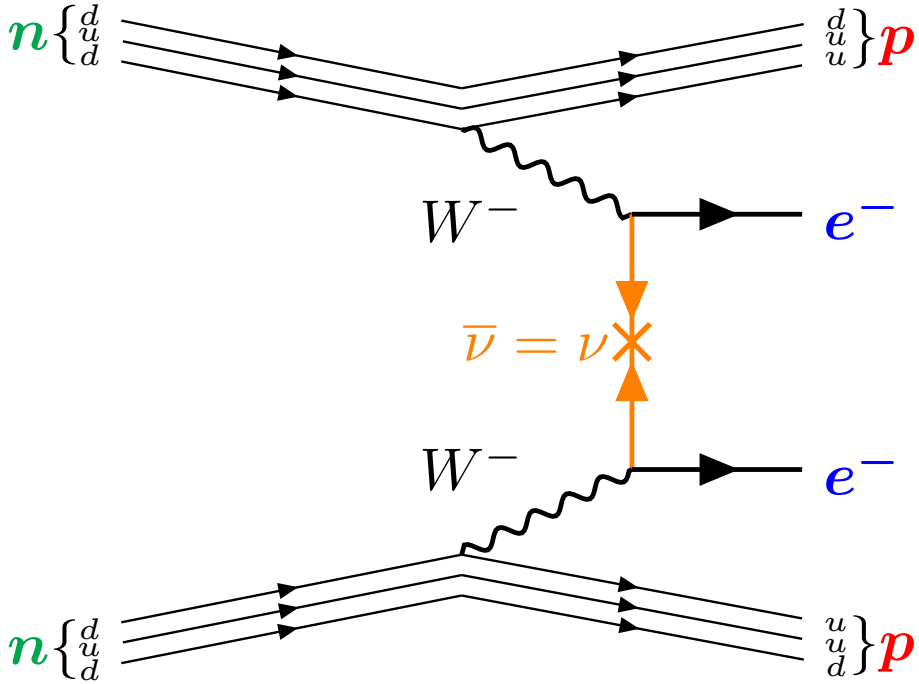
- **Violates lepton-number conservation**
- Requires that **neutrinos are Majorana particles**
- If observed, $t^{0\nu}_{1/2} \gtrsim 10^{25}$ **years**

  ($t^{2\nu}_{1/2} \approx 10^{20}$ *years, Age of the Universe* $\approx 10^{10}$ *years*)

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

L: 0 → 0 + 2 (-2)





TECHNISCHE UNIVERSITÄT DARMSTADT

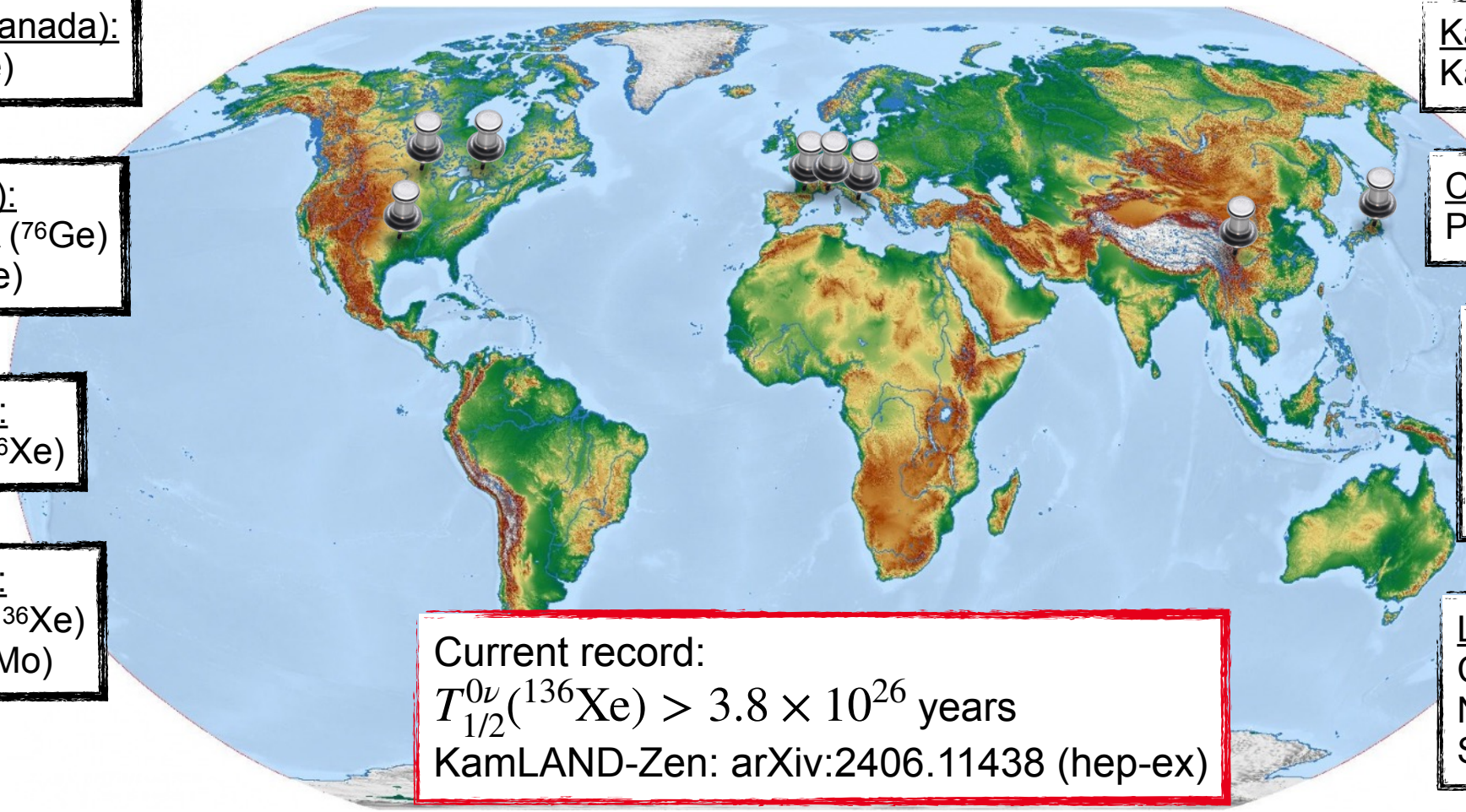
DOUBLE-BETA-DECAY EXPERIMENTS

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:
$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 3.8 \times 10^{26}$ years
KamLAND-Zen: arXiv:2406.11438 (hep-ex)

TECHNISCHE UNIVERSITÄT DARMSTADT

NEXT-GENERATION EXPERIMENTS

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

Kamioka (Japan):
KamLAND2-Zen (^{136}Xe)

Yemilab (Korea):
PandaX-III-200 (^{136}Xe)

Goal: $T^{0\nu}_{1/2} \sim 10^{28}$ years

LNGS (Italy):
CUPID (^{100}Mo)

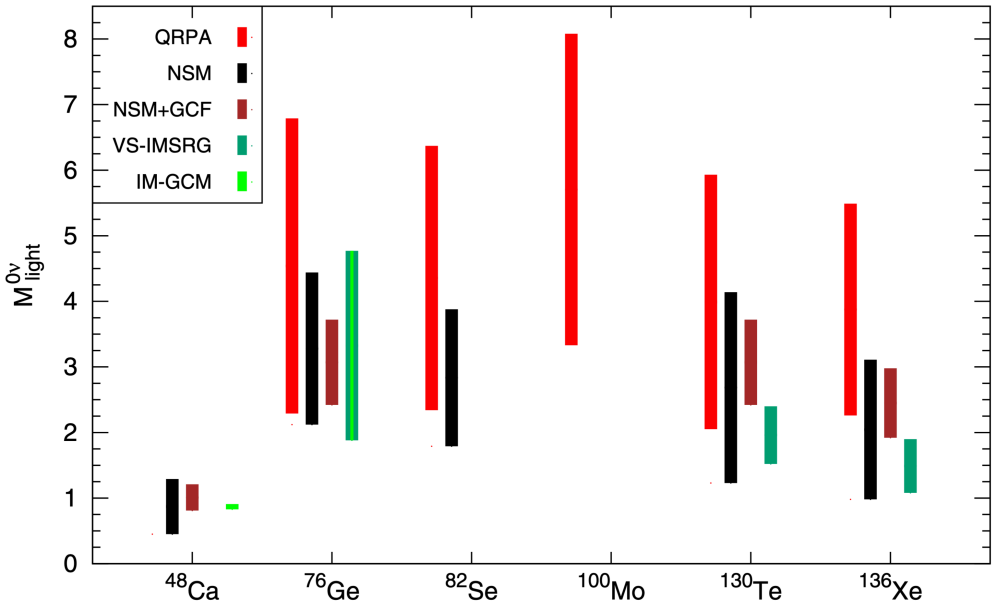
LSM (France):
SuperNEMO (^{82}Se)

+ LEGEND-1000 (^{76}Ge), nEXO/XLZD (^{136}Xe), NEXT-HD (^{136}Xe), Darwin (^{136}Xe), …

TECHNISCHE UNIVERSITÄT DARMSTADT

$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

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



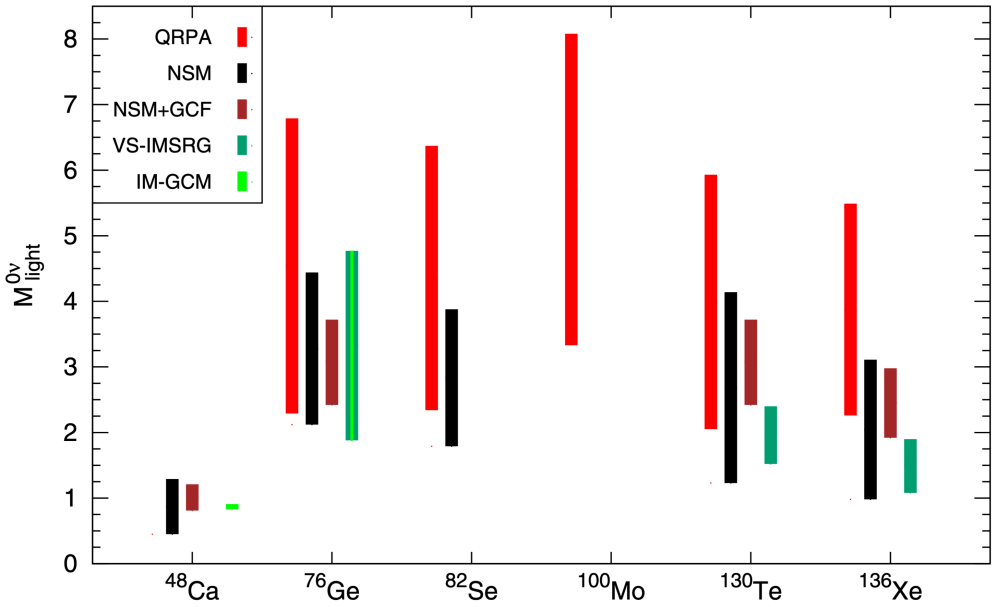
Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)

TECHNISCHE UNIVERSITÄT DARMSTADT

$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

Observable

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



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)

TECHNISCHE UNIVERSITÄT DARMSTADT

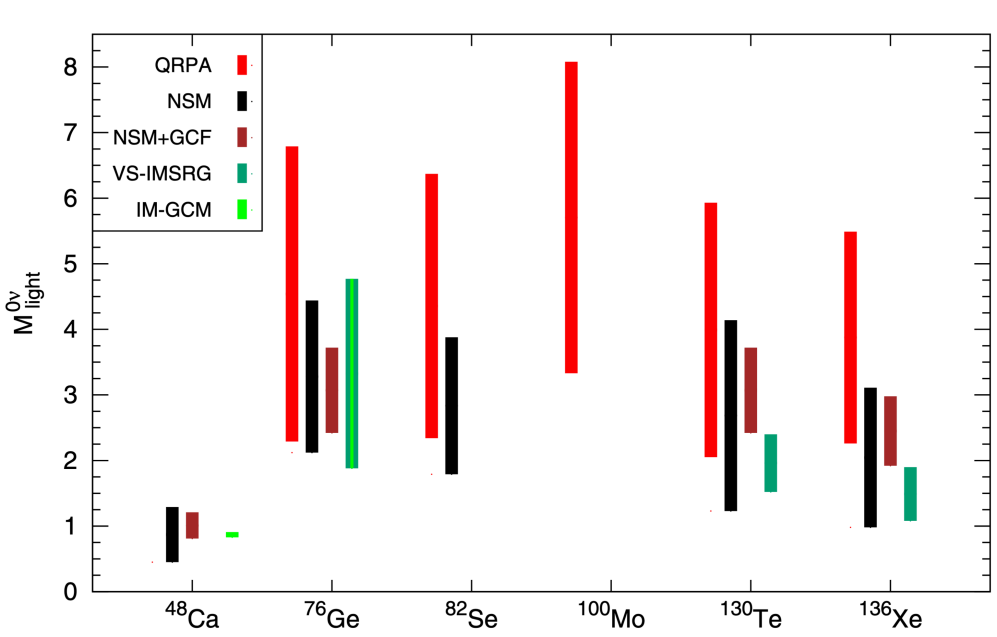
$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

Observable

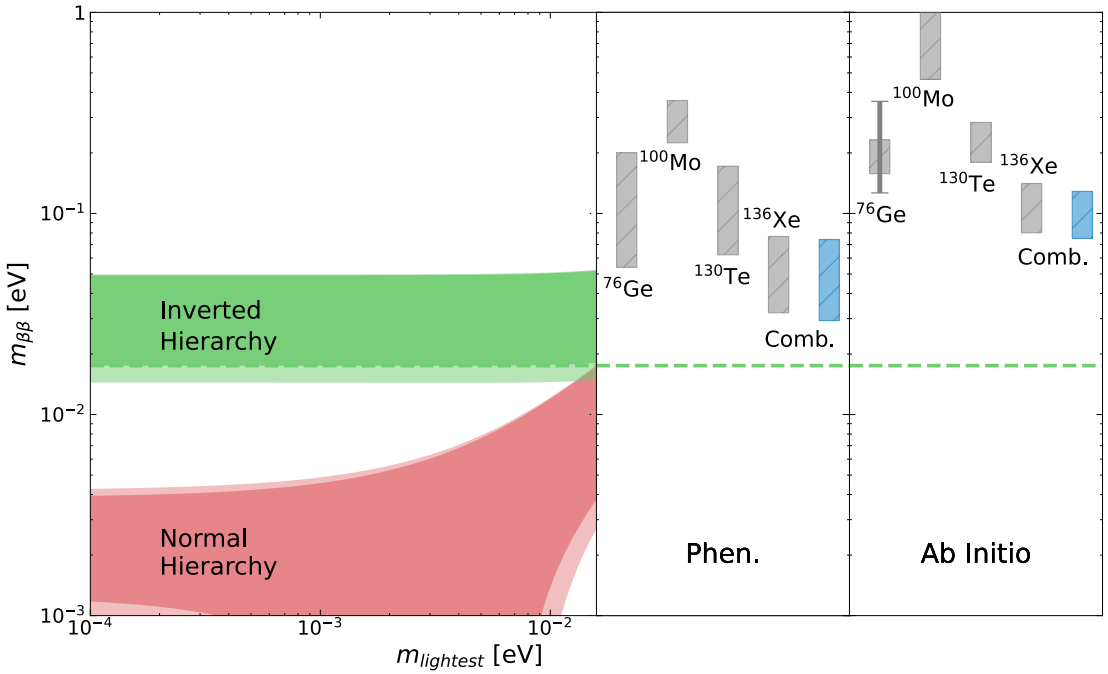
$$\frac{\Gamma^{0\nu}(A,Z)}{\ln 2} = \frac{1}{t^{0\nu}_{1/2}(A,Z)} = g_A^4 G^{0\nu}(A,Z)\,|M^{0\nu}(A,Z)|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

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



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

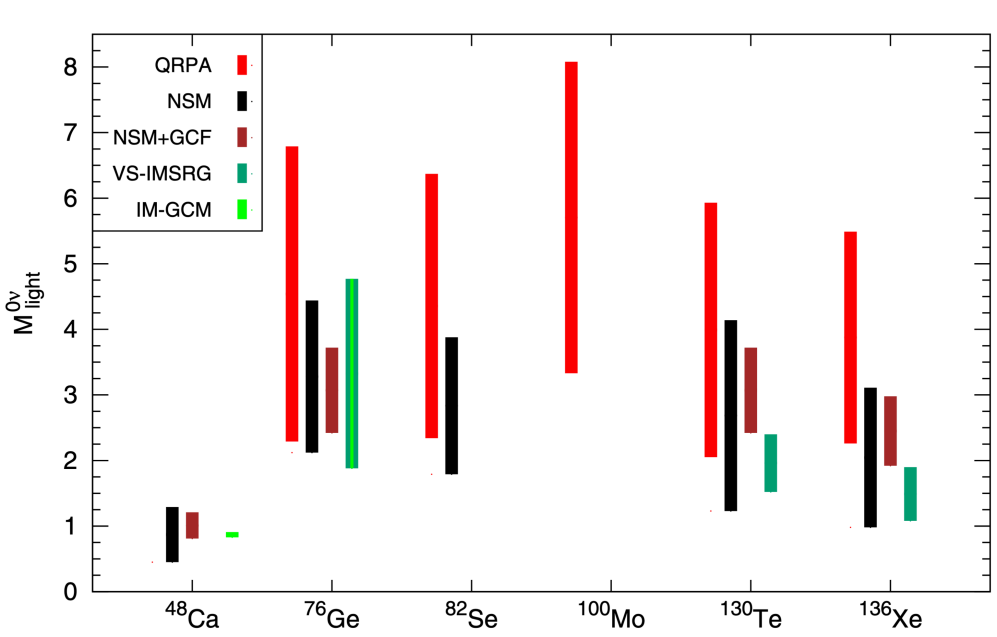
$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

Observable

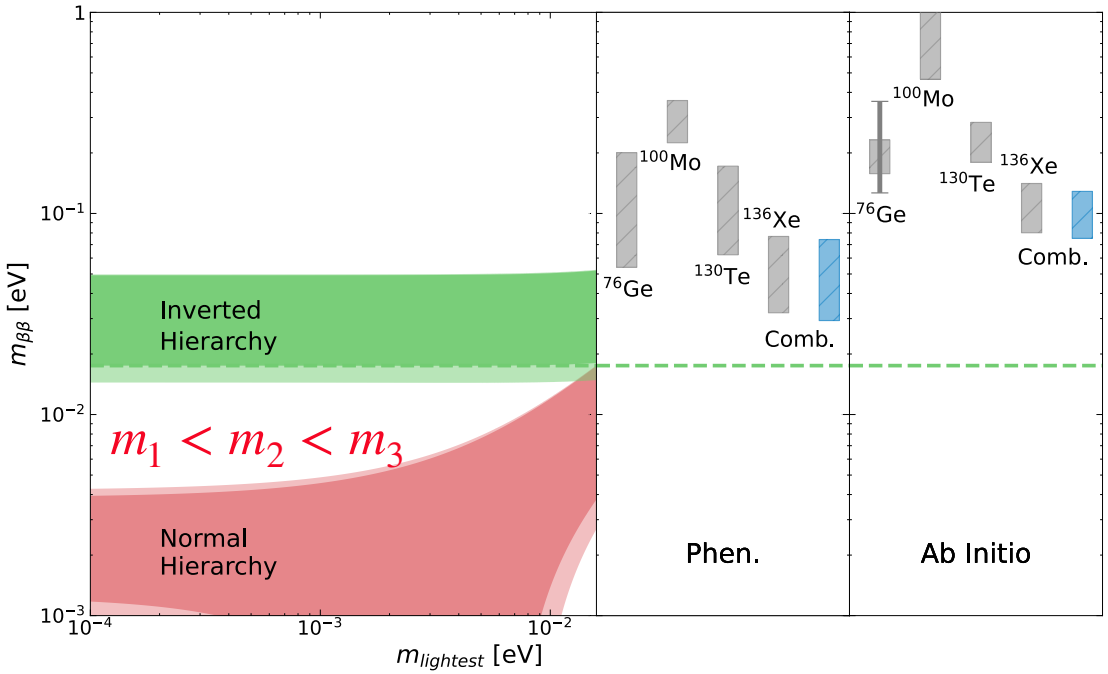
$$\frac{\Gamma^{0\nu}(A,Z)}{\ln 2} = \frac{1}{t^{0\nu}_{1/2}(A,Z)} = g_A^4 G^{0\nu}(A,Z)\,|M^{0\nu}(A,Z)|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

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



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

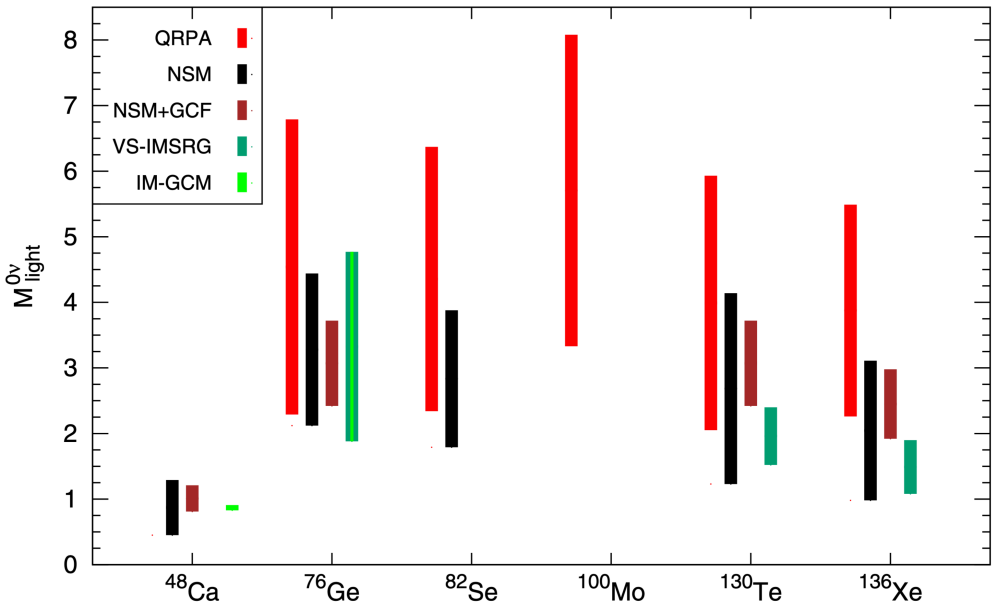
$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

Observable

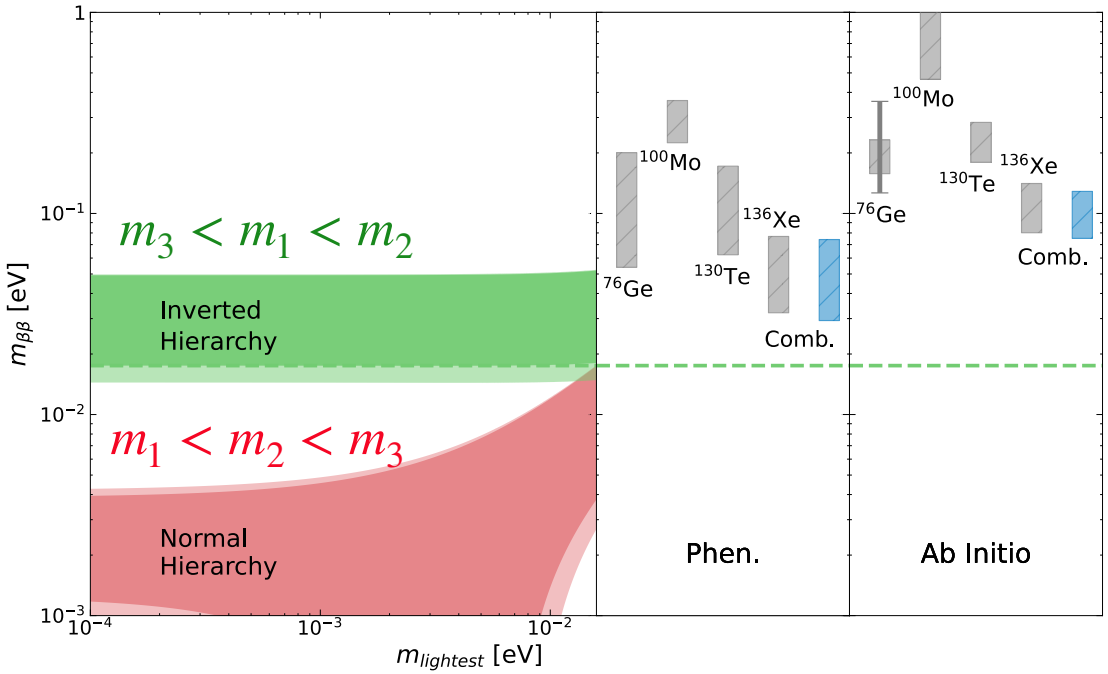
$$\frac{\Gamma^{0\nu}(A,Z)}{\ln 2} = \frac{1}{t^{0\nu}_{1/2}(A,Z)} = g_A^4 G^{0\nu}(A,Z)\,|M^{0\nu}(A,Z)|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Majorana mass

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



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

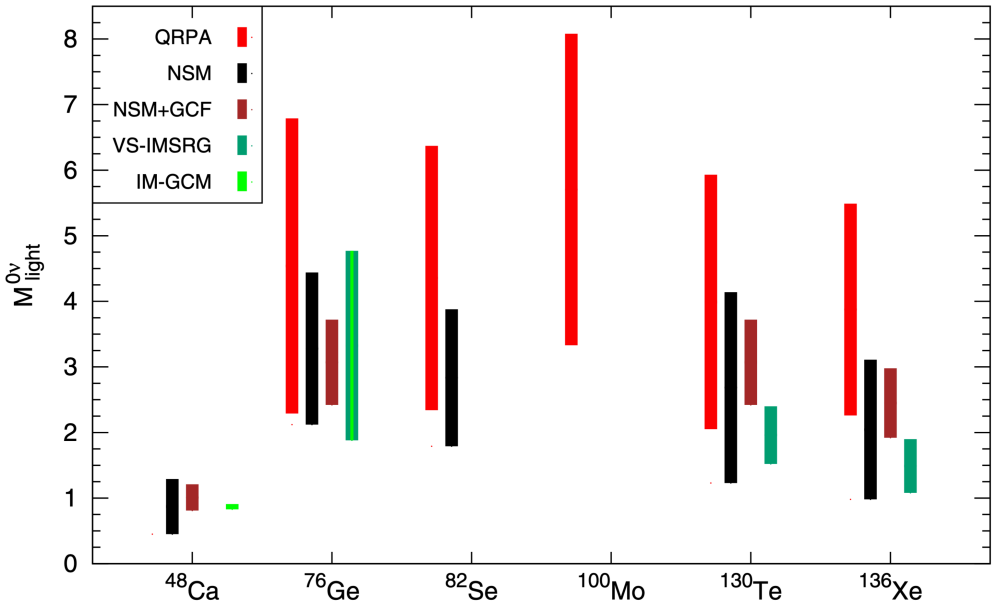
Observable

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

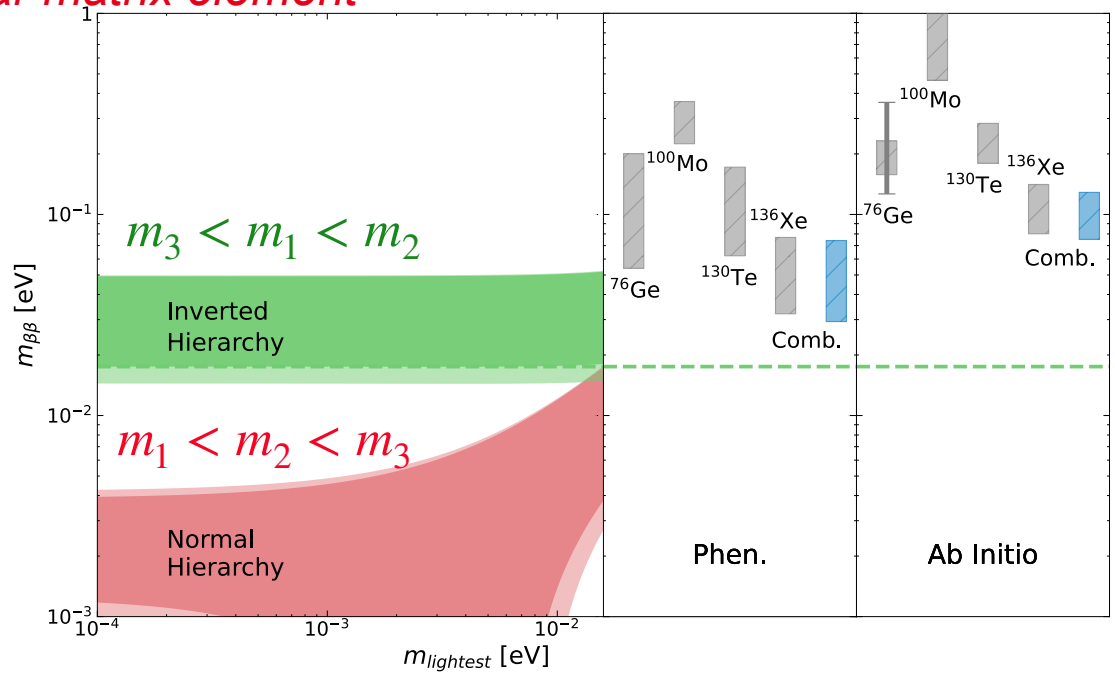
Majorana mass

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

Nuclear matrix element



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

$0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

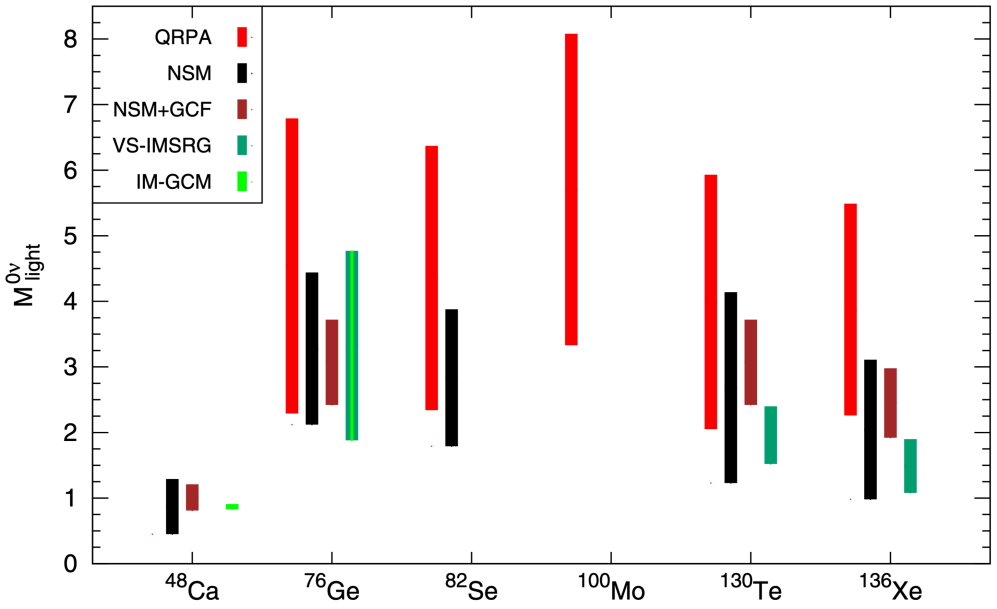
Observable

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

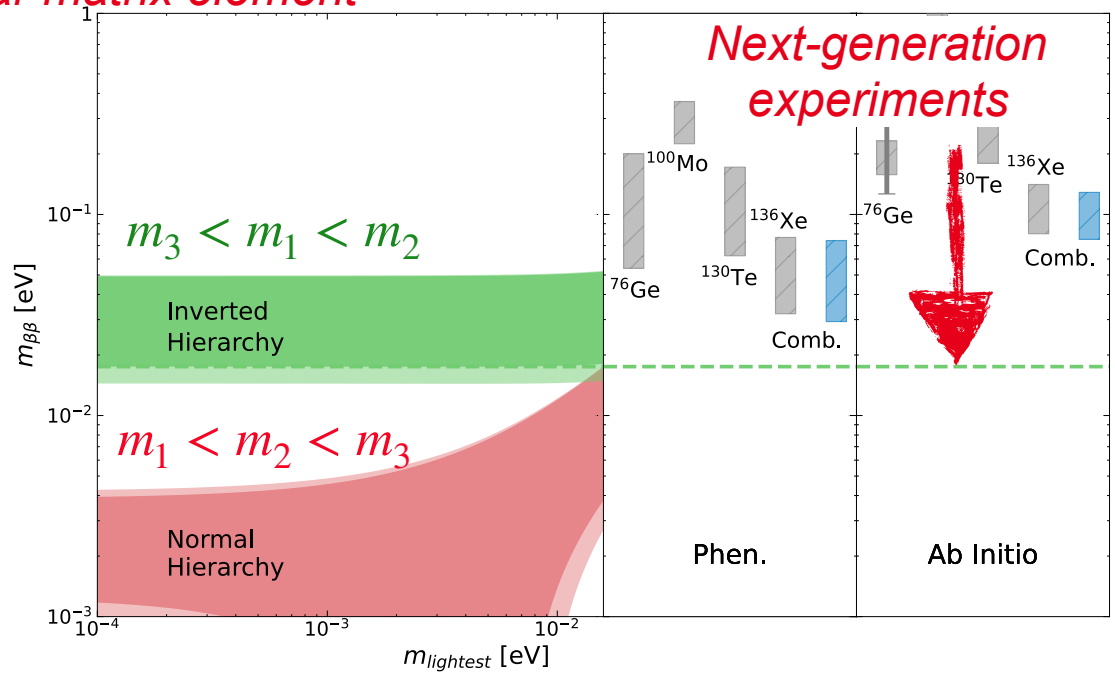
Majorana mass

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

Nuclear matrix element



Gómez-Cadenas, Martín-Albo, Menéndez, Mezzetto, Monrabal, Sorel, La Rivista del Nuovo Cimento 46, 619 (2023)



Shickele, Jokiniemi, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

THE NUCLEAR MATRIX ELEMENT

$$M^{0\nu} = \langle \Psi^{(A)}_f \,|\, \mathcal{O}^{0\nu} \,|\, \Psi^{(A)}{}_i \rangle$$

TECHNISCHE UNIVERSITÄT DARMSTADT

THE NUCLEAR MATRIX ELEMENT

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

$$M^{0\nu} = \langle \Psi^{(A)}_f \mid \mathcal{O}^{0\nu} \mid \Psi^{(A)}_i \rangle$$

TECHNISCHE UNIVERSITÄT DARMSTADT

THE NUCLEAR MATRIX ELEMENT

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

$$M^{0\nu} = \langle \Psi^{(A)}_f \mid \mathcal{O}^{0\nu} \mid \Psi^{(A)}_i \rangle$$

Initial state wave function

TECHNISCHE UNIVERSITÄT DARMSTADT

THE NUCLEAR MATRIX ELEMENT

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

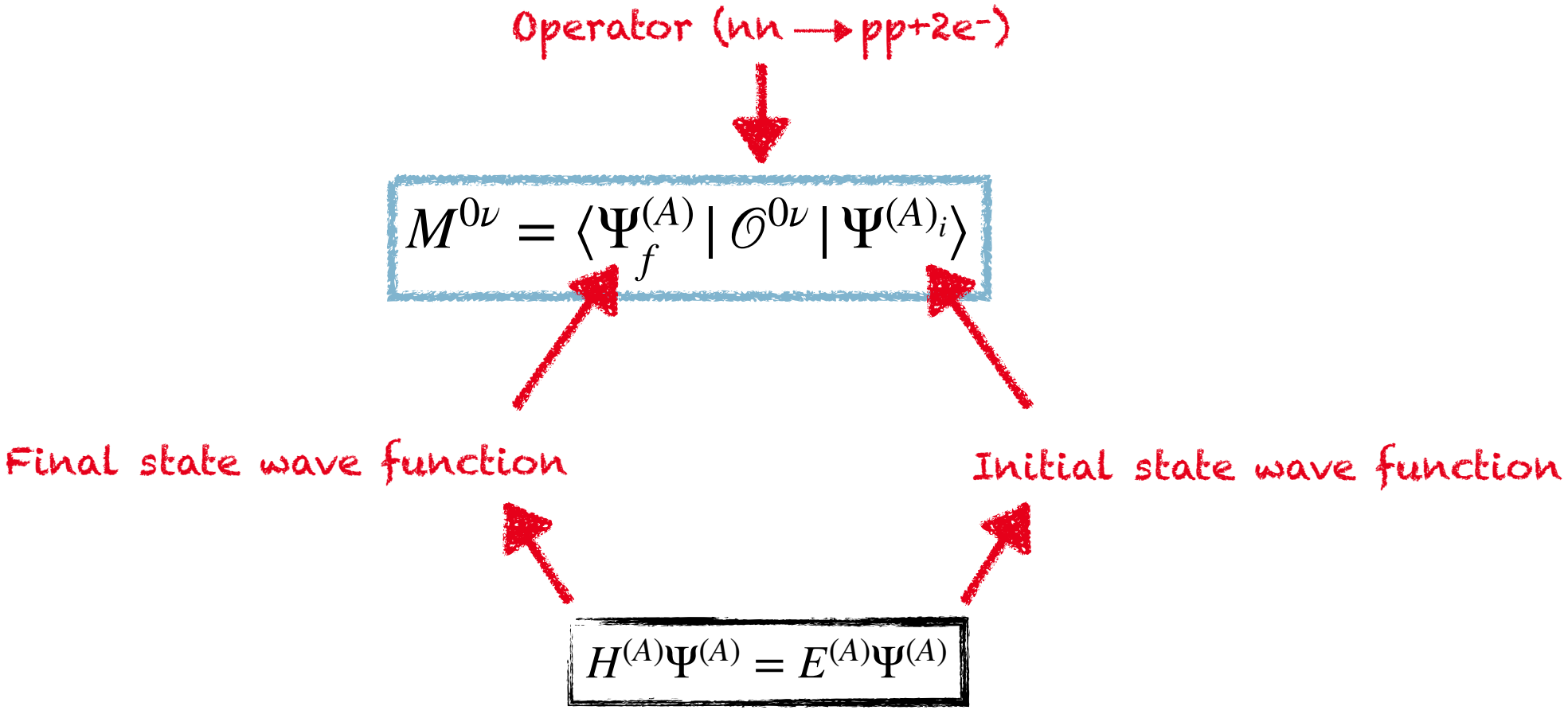
$$M^{0\nu} = \langle \Psi^{(A)}_f \mid \mathcal{O}^{0\nu} \mid \Psi^{(A)}_i \rangle$$

Final state wave function

Initial state wave function

TECHNISCHE UNIVERSITÄT DARMSTADT

THE NUCLEAR MATRIX ELEMENT



TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n \qquad \mathcal{O}^{(m,n)}_{\mathrm{F}} = 1$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n \qquad \mathcal{O}^{(m,n)}_{\mathrm{F}} = 1 \qquad \mathcal{O}^{(m,n)}_{\mathrm{T}} = 3[(\boldsymbol{\sigma}_m \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_n \cdot \hat{\mathbf{r}})] - \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n \qquad \mathcal{O}^{(m,n)}_{\mathrm{F}} = 1 \qquad \mathcal{O}^{(m,n)}_{\mathrm{T}} = 3[(\boldsymbol{\sigma}_m \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_n \cdot \hat{\mathbf{r}})] - \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

nn → pp

TECHNISCHE UNIVERSITÄT DARMSTADT

NUCLEAR MATRIX ELEMENT FOR $0\nu\beta\beta$ DECAY WITH LIGHT-NEUTRINO EXCHANGE

$$M^{0\nu} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

$$\mathcal{O}^{(m,n)}_{\mathrm{GT}} = \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n \qquad \mathcal{O}^{(m,n)}_{\mathrm{F}} = 1 \qquad \mathcal{O}^{(m,n)}_{\mathrm{T}} = 3[(\boldsymbol{\sigma}_m \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_n \cdot \hat{\mathbf{r}})] - \boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n$$

$$M^{0\nu}_{\mathrm{X}} = \frac{2R}{\pi g_{\mathrm{A}}^2} \times \langle 0^+_f \| \sum_{m,n} \tau^-_m \tau^-_n \, \mathcal{O}^{(m,n)}_{\mathrm{X}} \int \frac{j_0(qr) h_{\mathrm{X}}(q^2)\, q^2}{q(q+E)} \mathrm{d}q \| 0^+_i \rangle$$

Neutrino potential

nn → pp

Neutrino propagator:

$$\frac{1}{\omega(\omega+E)},$$

where

$$\omega = \sqrt{q^2 + m_N^2}$$

TECHNISCHE UNIVERSITÄT DARMSTADT

OUTLINE

1 Introduction

2 **Effective field theory for neutrinoless double-beta decay with light-neutrino exchange**

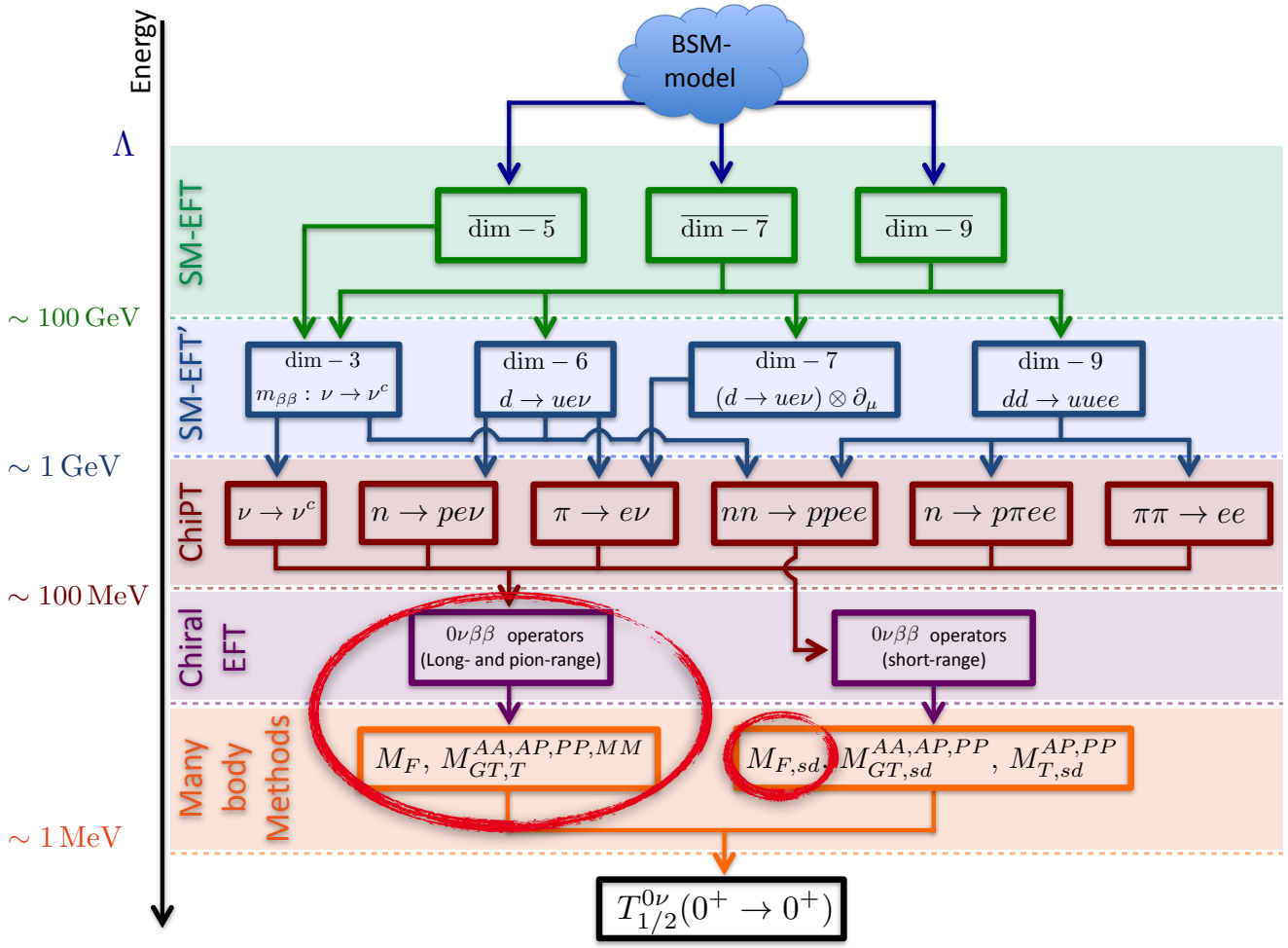
3 Global limits for Majorana masses

4 Different decay mechanisms

5 Summary and Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

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



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12, 097 (2018)

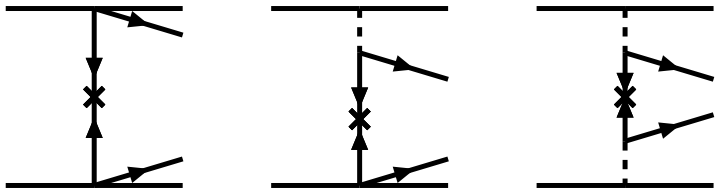
TECHNISCHE UNIVERSITÄT DARMSTADT

CHIRAL EFFECTIVE THEORY FOR LIGHT-NEUTRINO EXCHANGE

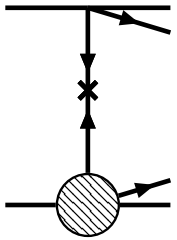
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}}$$

$$M^{0\nu}_{\mathrm{L}} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

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



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



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

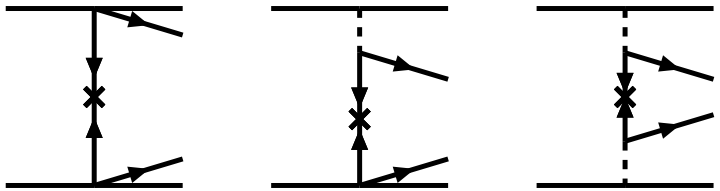
TECHNISCHE UNIVERSITÄT DARMSTADT

CHIRAL EFFECTIVE THEORY FOR LIGHT-NEUTRINO EXCHANGE

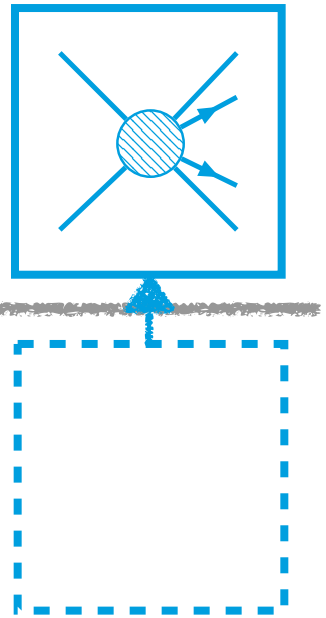
$$M^{0\nu} = M_{\mathrm{L}}^{0\nu} + M_{\mathrm{S}}^{0\nu}$$

$$M_{\mathrm{L}}^{0\nu} = M_{\mathrm{GT}}^{0\nu} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M_{\mathrm{F}}^{0\nu} + M_{\mathrm{T}}^{0\nu}$$

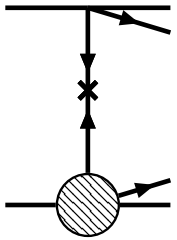
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO



15% – 90 %



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



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

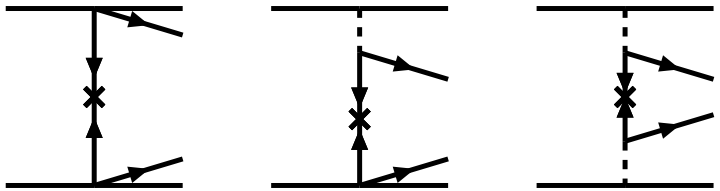
TECHNISCHE UNIVERSITÄT DARMSTADT

CHIRAL EFFECTIVE THEORY FOR LIGHT-NEUTRINO EXCHANGE

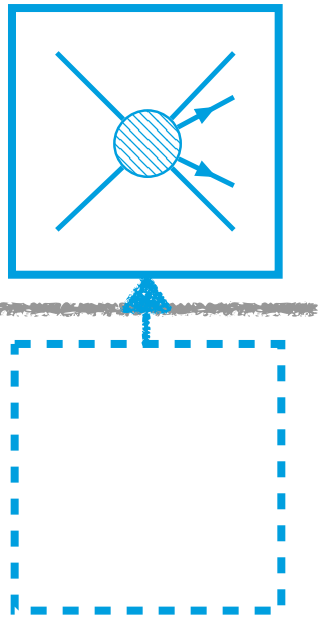
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}}$$

$$M^{0\nu}_{\mathrm{L}} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

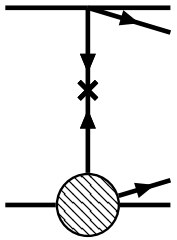
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO

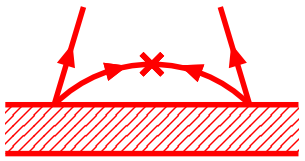


15% – 90 %



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





5% – 10 %

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

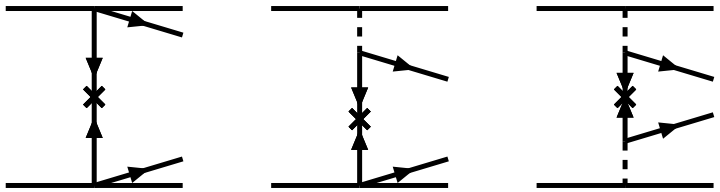
TECHNISCHE UNIVERSITÄT DARMSTADT

CHIRAL EFFECTIVE THEORY FOR LIGHT-NEUTRINO EXCHANGE

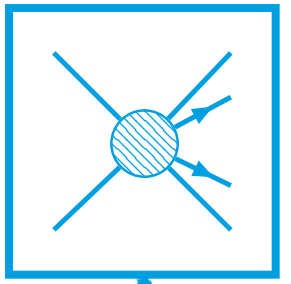
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}} + M^{0\nu}_{\mathrm{loop}}$$

$$M^{0\nu}_{\mathrm{L}} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

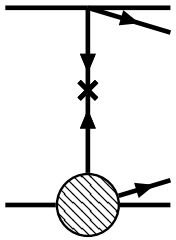
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO

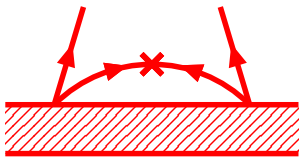


15% – 90 %

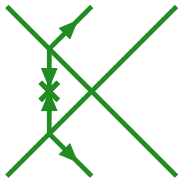


$\left(\frac{Q}{\Lambda_\chi}\right)^2$ N^{2}LO

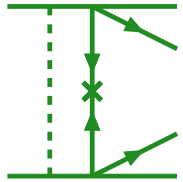




5% – 10 %



5% – 10 %



+…

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

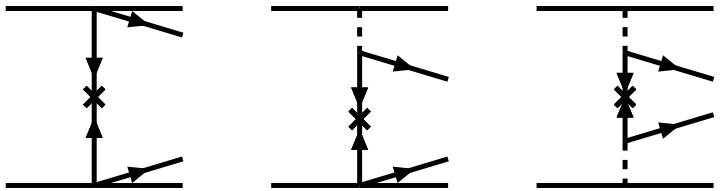
TECHNISCHE UNIVERSITÄT DARMSTADT

CHIRAL EFFECTIVE THEORY FOR LIGHT-NEUTRINO EXCHANGE

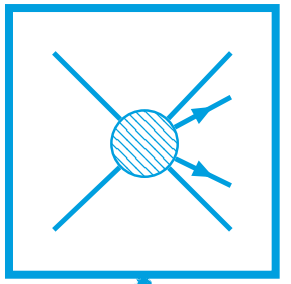
$$M^{0\nu} = M^{0\nu}_{\mathrm{L}} + M^{0\nu}_{\mathrm{S}} + M^{0\nu}_{\mathrm{usoft}} + M^{0\nu}_{\mathrm{loop}}$$

$$M^{0\nu}_{\mathrm{L}} = M^{0\nu}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0\nu}_{\mathrm{F}} + M^{0\nu}_{\mathrm{T}}$$

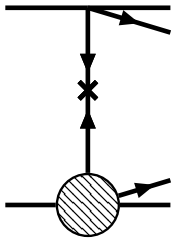
$\left(\frac{Q}{\Lambda_\chi}\right)^0$ LO

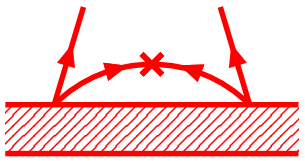


15% – 90 %

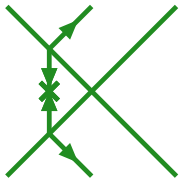


$\left(\frac{Q}{\Lambda_\chi}\right)^2$ N^{2}LO

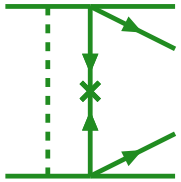




5% – 10 %



5% – 10 %



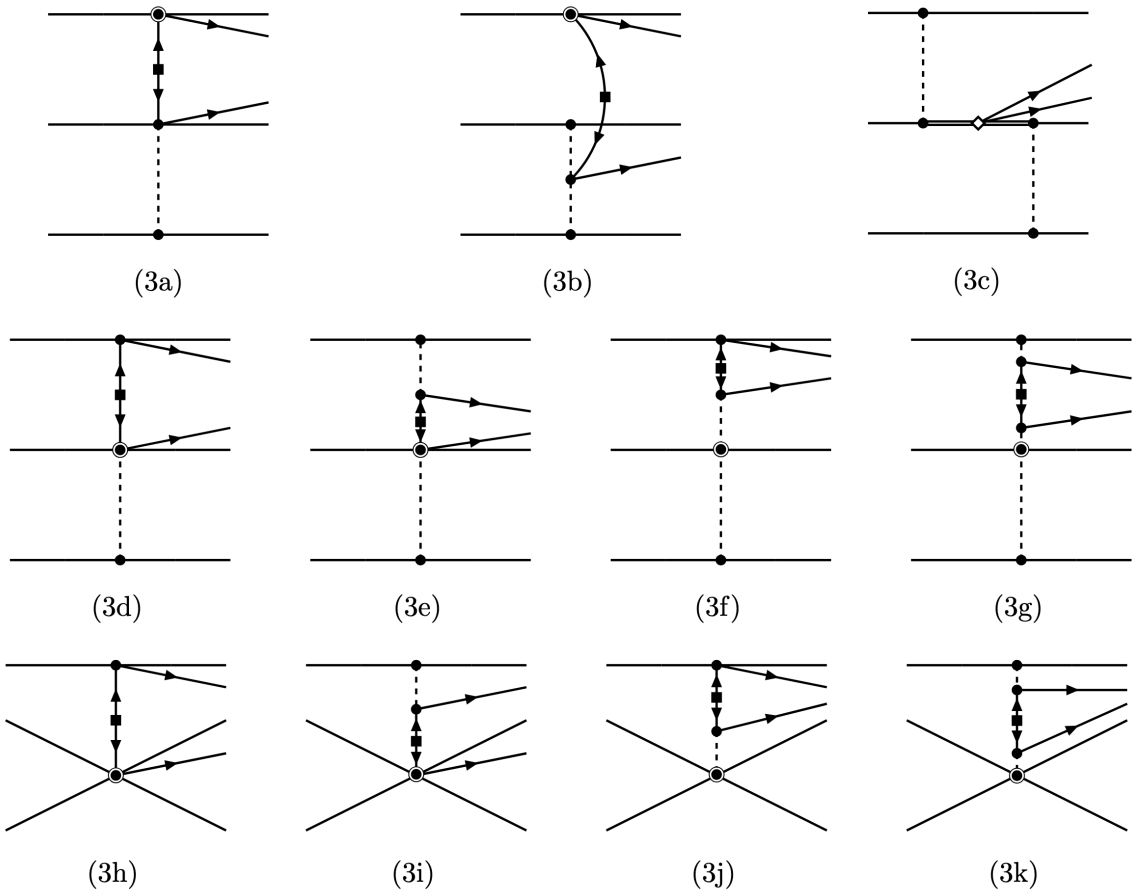
+…

N^{3}LO 3-nucleon potentials

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

TECHNISCHE UNIVERSITÄT DARMSTADT

THREE-NUCLEON POTENTIALS

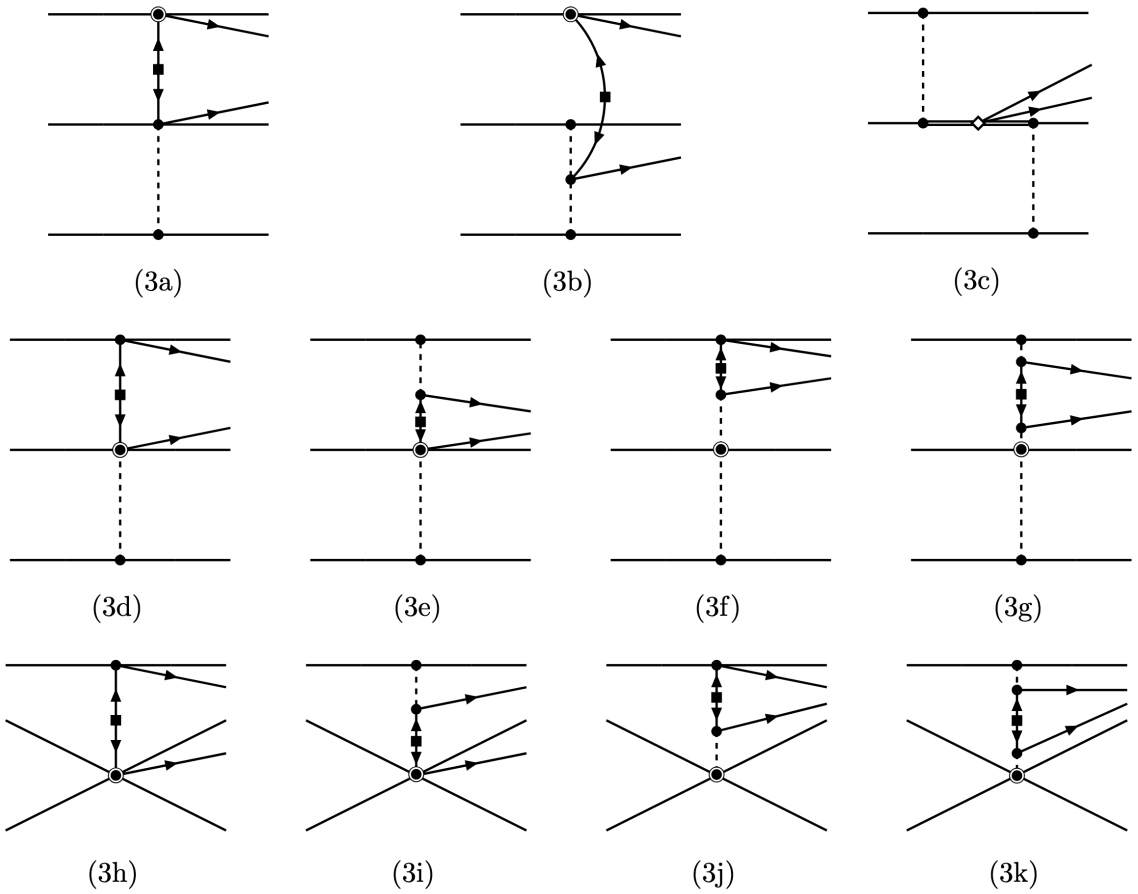


Chambers-Wall, Lieffers, King, Mereghetti, Pastore, Piarulli, Wiringa, arXiv:2510.21564

TECHNISCHE UNIVERSITÄT DARMSTADT

THREE-NUCLEON POTENTIALS

- Additional three-nucleon diagrams enter at N^2LO (Δ-full) and N^3LO

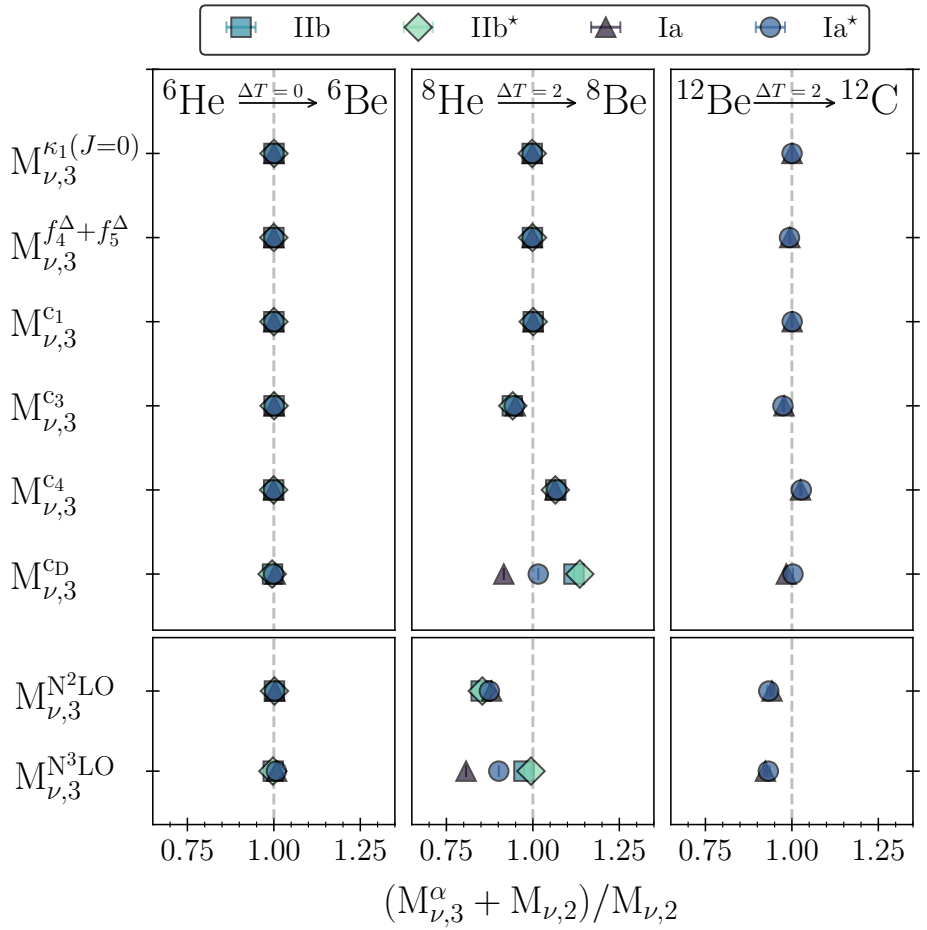


Chambers-Wall, Lieffers, King, Mereghetti, Pastore, Piarulli, Wiringa, arXiv:2510.21564

TECHNISCHE UNIVERSITÄT DARMSTADT

THREE-NUCLEON POTENTIALS

- Additional three-nucleon diagrams enter at N²LO (Δ-full) and N³LO
- These three-nucleon diagrams **moderately reduce** the matrix elements of **light nuclei**

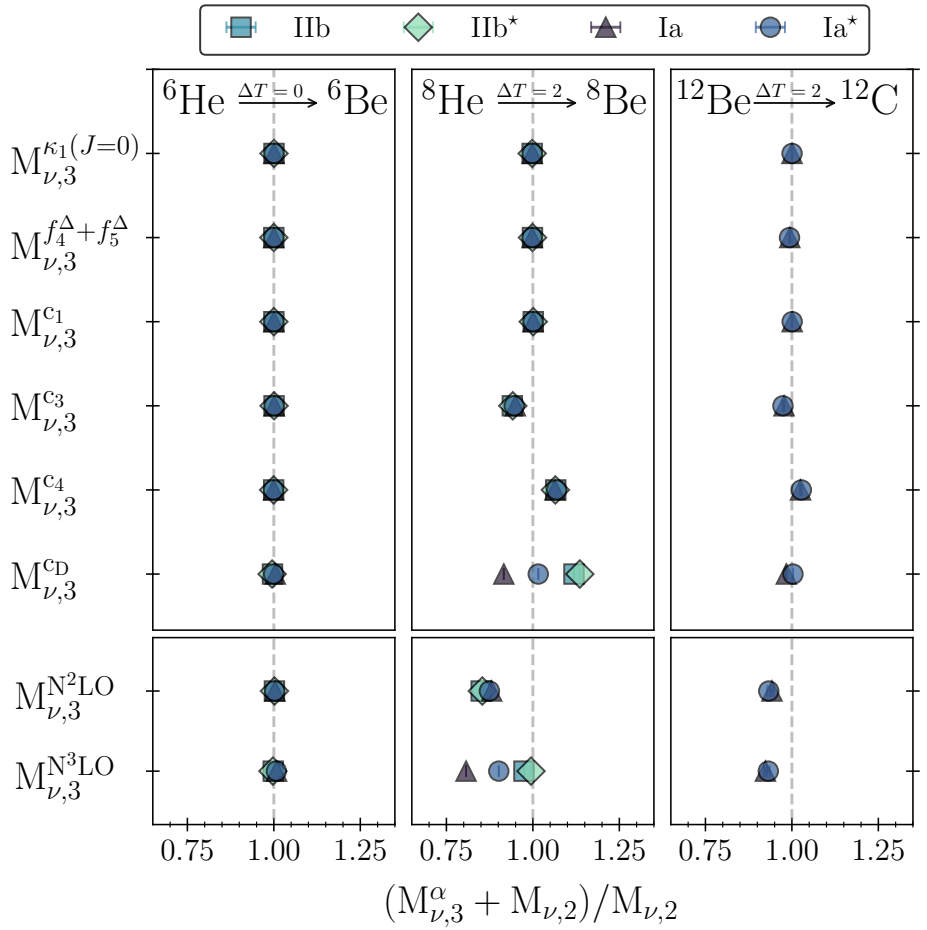


Chambers-Wall, Lieffers, King, Mereghetti, Pastore, Piarulli, Wiringa, arXiv:2510.21564

TECHNISCHE UNIVERSITÄT DARMSTADT

THREE-NUCLEON POTENTIALS

- Additional three-nucleon diagrams enter at N²LO (Δ-full) and N³LO
- These three-nucleon diagrams **moderately reduce** the matrix elements of **light nuclei**
- **What is the effect in experimentally relevant nuclei?**

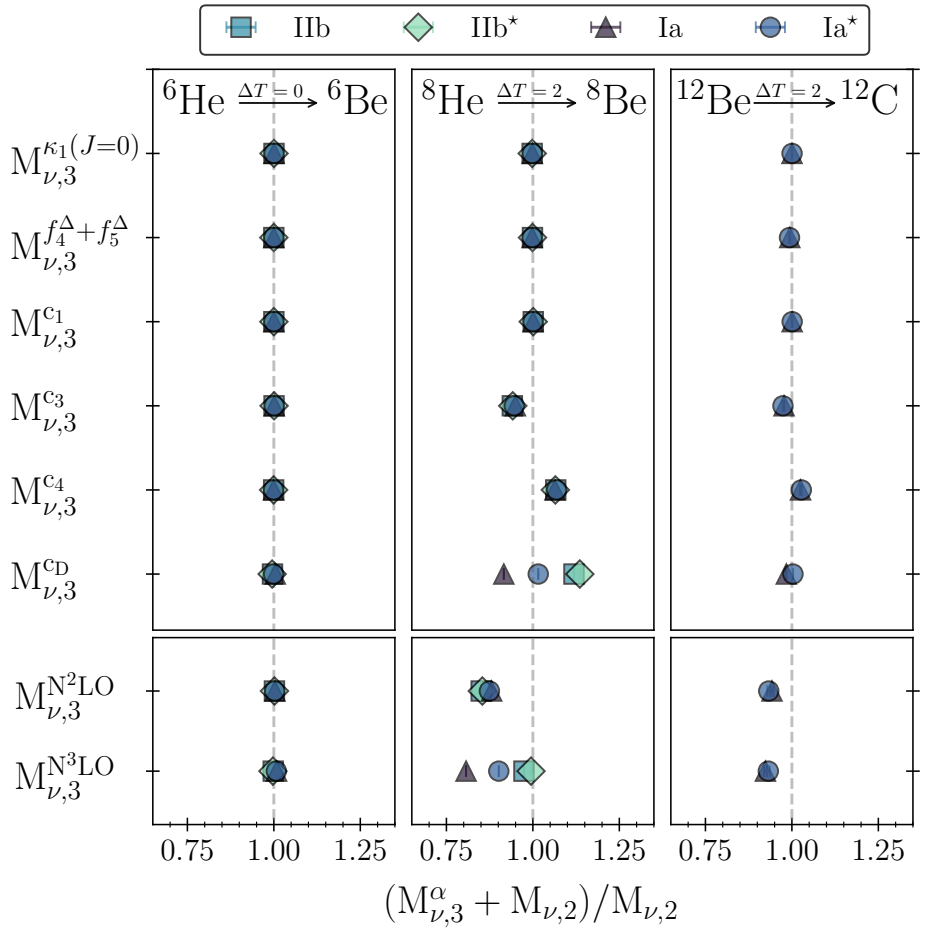


Chambers-Wall, Lieffers, King, Mereghetti, Pastore, Piarulli, Wiringa, arXiv:2510.21564

TECHNISCHE UNIVERSITÄT DARMSTADT

THREE-NUCLEON POTENTIALS

- Additional three-nucleon diagrams enter at N²LO (Δ-full) and N³LO
- These three-nucleon diagrams **moderately reduce** the matrix elements of **light nuclei**
- **What is the effect in experimentally relevant nuclei?**
  - Work in progress in the VS-IMSRG framework



Chambers-Wall, Lieffers, King, Mereghetti, Pastore, Piarulli, Wiringa, arXiv:2510.21564

TECHNISCHE UNIVERSITÄT DARMSTADT

OUTLINE

1 Introduction

2 Effective field theory for neutrinoless double-beta decay with light-neutrino exchange

3 **Global limits for Majorana masses**

4 Different decay mechanisms

5 Summary and Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

GLOBAL LIMITS FOR MAJORANA MASSES

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

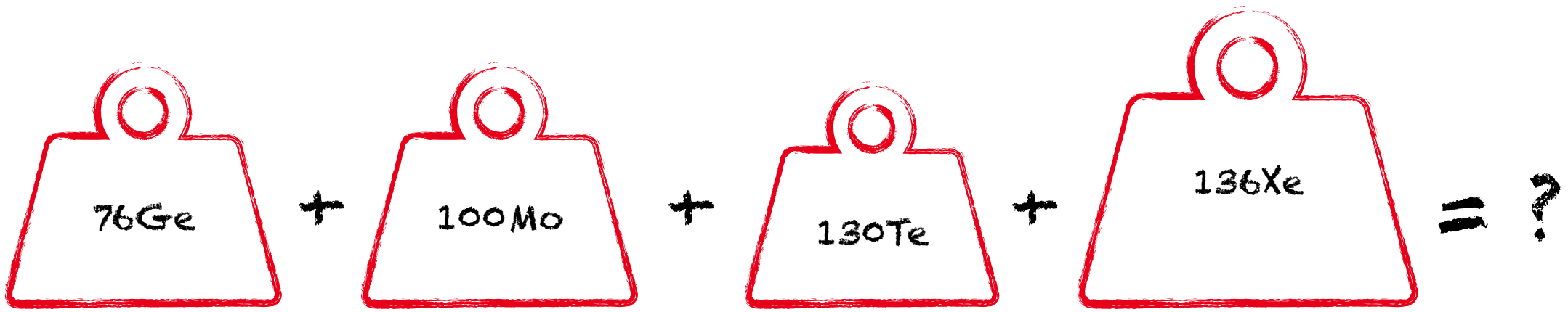


Figure idea stolen from T. Shickele

GLOBAL LIMITS FOR MAJORANA MASSES

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

- Experiments probe Majorana mass with different isotopes

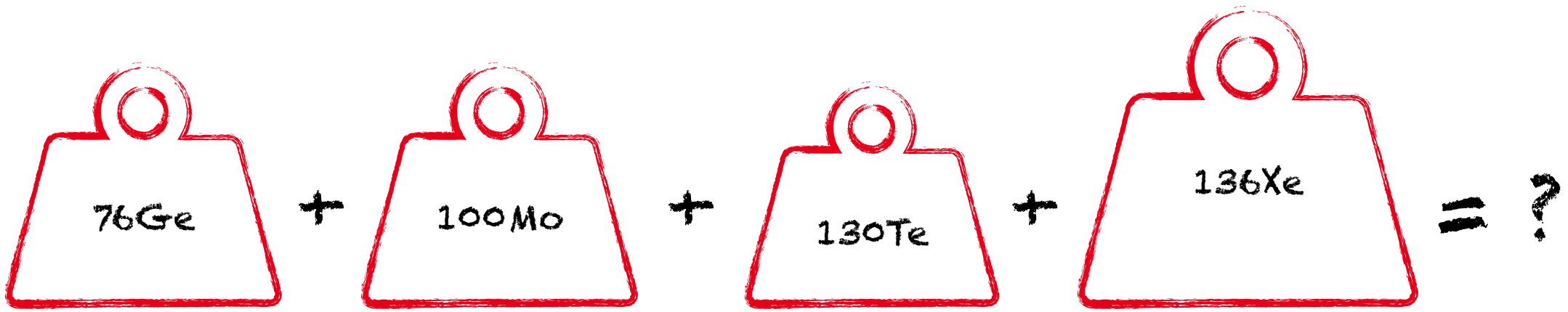


Figure idea stolen from T. Shickele

GLOBAL LIMITS FOR MAJORANA MASSES

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

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

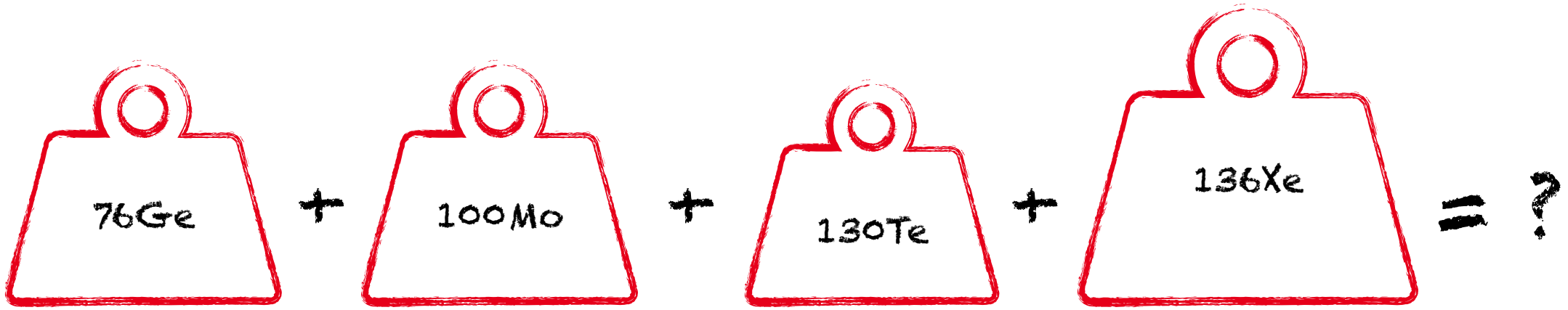


Figure idea stolen from T. Shickele

COMBINED CONSTRAINTS FOR MAJORANA MASSES

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

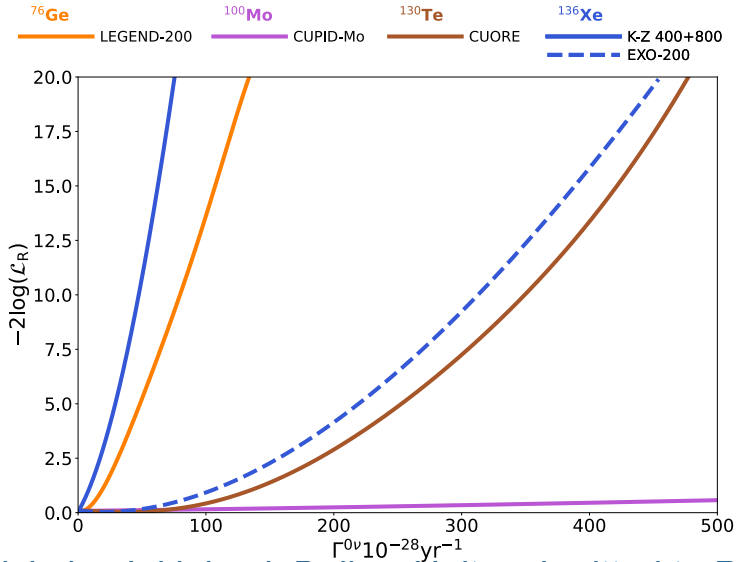
$$\mathrm{P}(m_{\beta\beta}\,|\,\mathrm{Data}) \propto \mathscr{L}(\mathrm{Data}\,|\,m_{\beta\beta})\pi(m_{\beta\beta})$$

TECHNISCHE UNIVERSITÄT DARMSTADT

COMBINED CONSTRAINTS FOR MAJORANA MASSES

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

Likelihood functions from current experiments:



Shickele, Jokiniemi, Belley, Holt, submitted to PRD

$$\mathrm{P}(m_{\beta\beta}\,|\,\mathrm{Data}) \propto \mathscr{L}(\mathrm{Data}\,|\,m_{\beta\beta})\pi(m_{\beta\beta})$$

Combined likelihood:

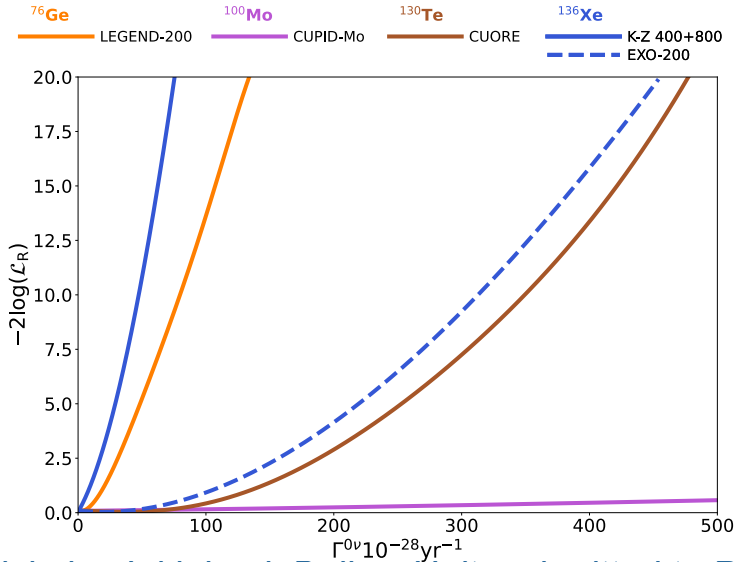
$$\mathscr{L}_{\mathrm{R,Comb}} = \prod_{i}^{n} \mathscr{L}_{\mathrm{R},i}$$

TECHNISCHE UNIVERSITÄT DARMSTADT

COMBINED CONSTRAINTS FOR MAJORANA MASSES

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

Likelihood functions from current experiments:



Shickele, Jokiniemi, Belley, Holt, submitted to PRD

$$\mathrm{P}(m_{\beta\beta}\,|\,\mathrm{Data}) \propto \mathscr{L}(\mathrm{Data}\,|\,m_{\beta\beta})\pi(m_{\beta\beta})$$

Combined likelihood:

$$\mathscr{L}_{\mathrm{R,Comb}} = \prod_{i}^{n} \mathscr{L}_{\mathrm{R},i}$$

Prior:

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

TECHNISCHE UNIVERSITÄT DARMSTADT

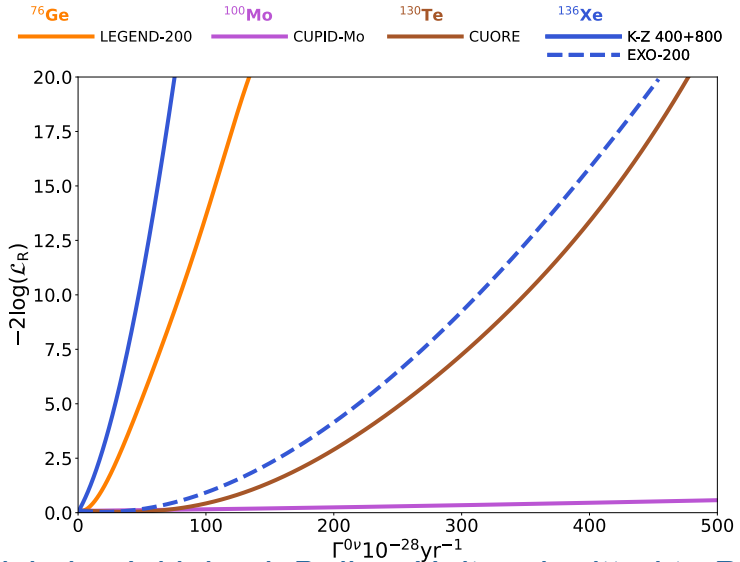
COMBINED CONSTRAINTS FOR MAJORANA MASSES

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

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

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

Likelihood functions from current experiments:



Shickele, Jokiniemi, Belley, Holt, submitted to PRD

Combined likelihood:

$$\mathcal{L}_{\text{R,Comb}} = \prod_i^n \mathcal{L}_{\text{R},i}$$

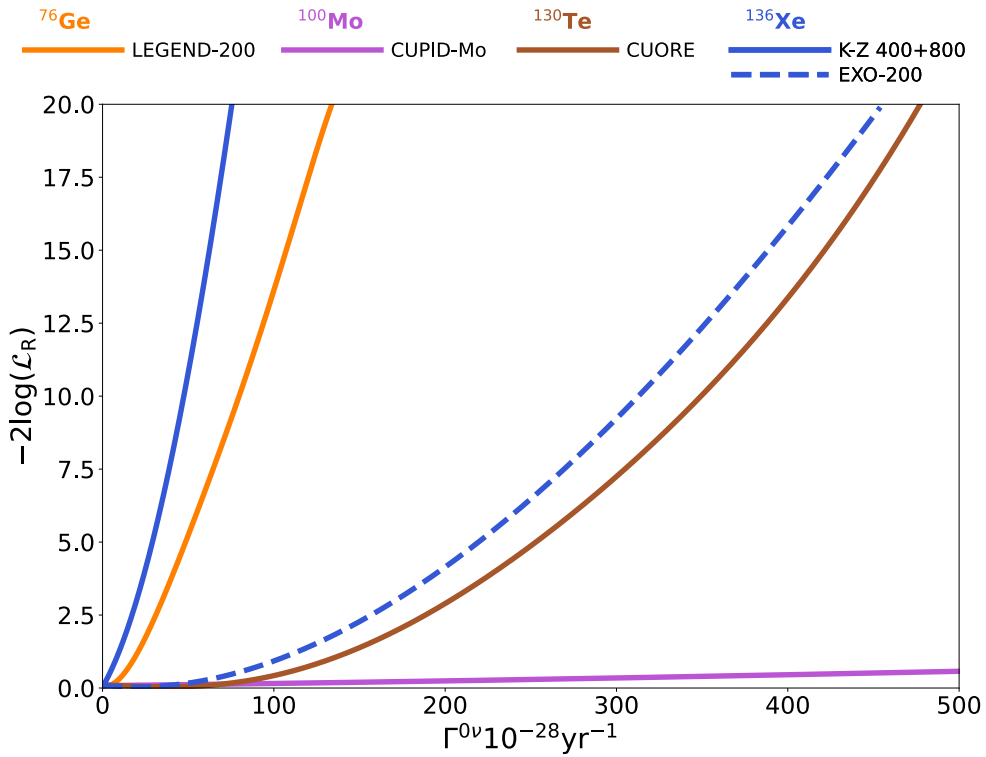
Prior:

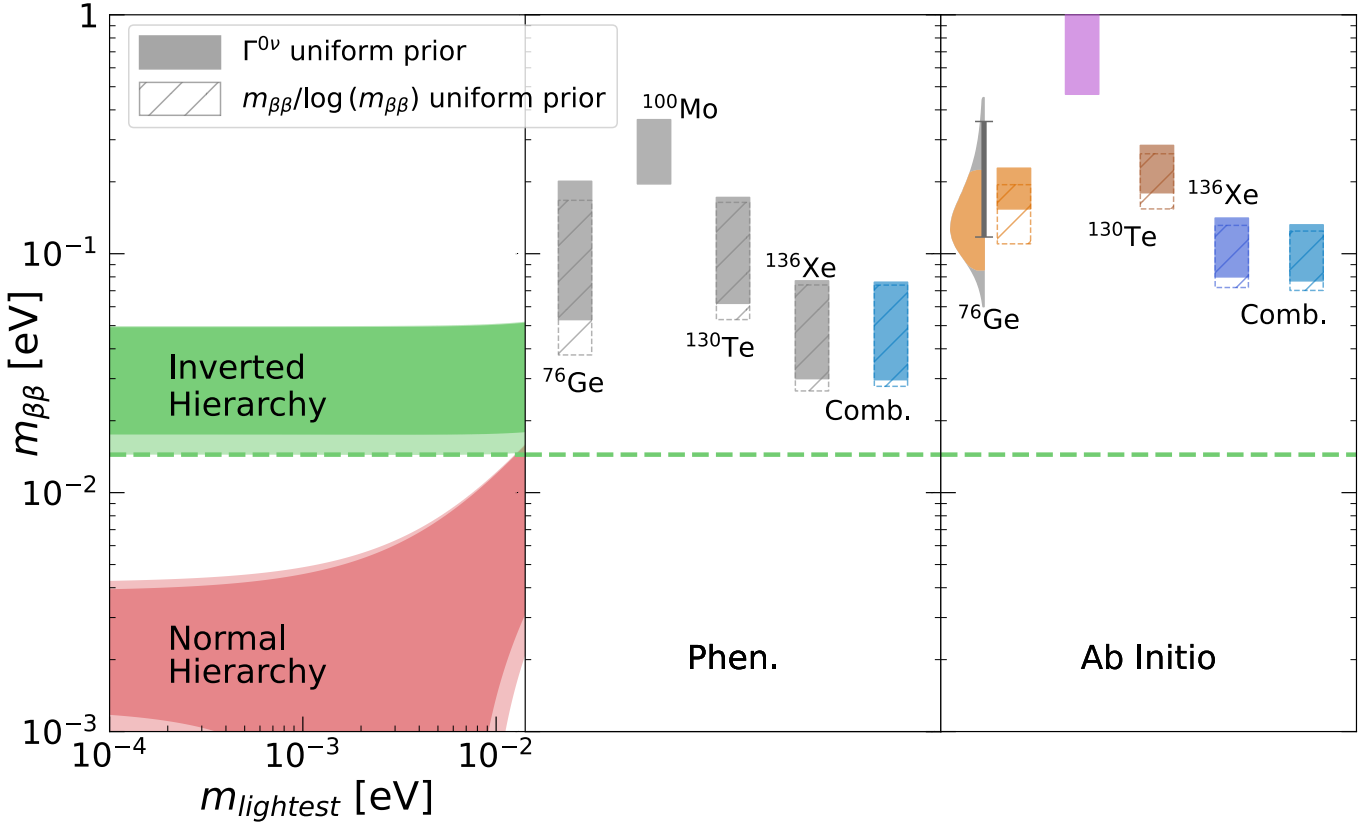
- Uniform in $m_{\beta\beta}$
- Uniform in $\Gamma^{0\nu}$ (or $m_{\beta\beta}^2$)
- Uniform in $\log(m_{\beta\beta})$

TECHNISCHE UNIVERSITÄT DARMSTADT

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Current best limits



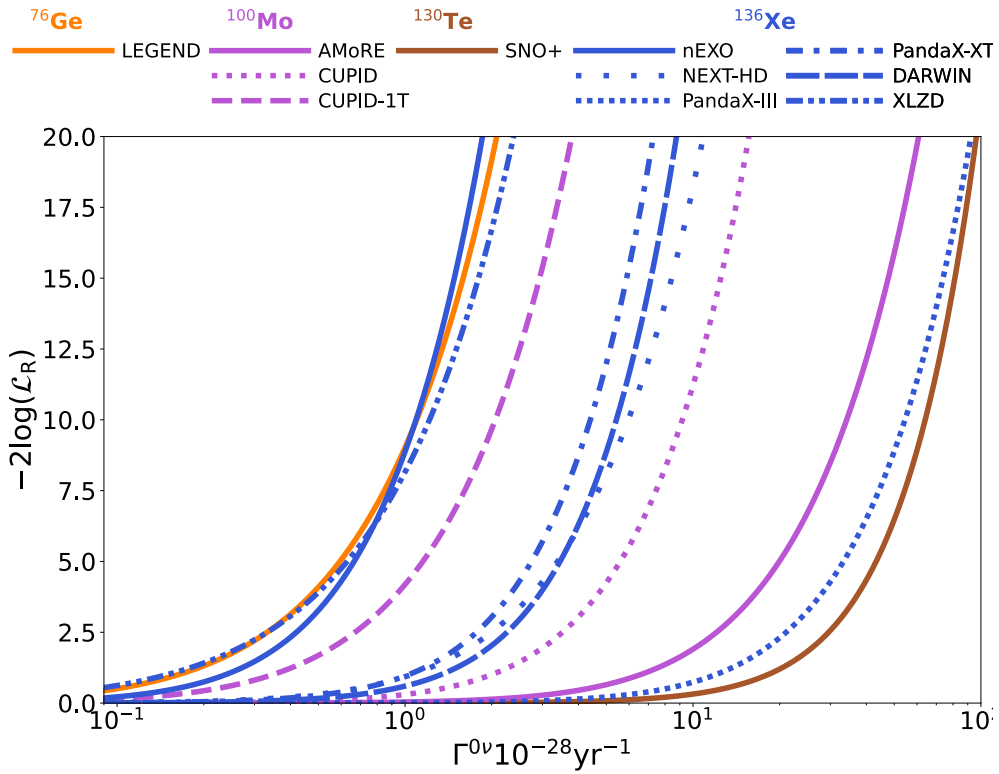


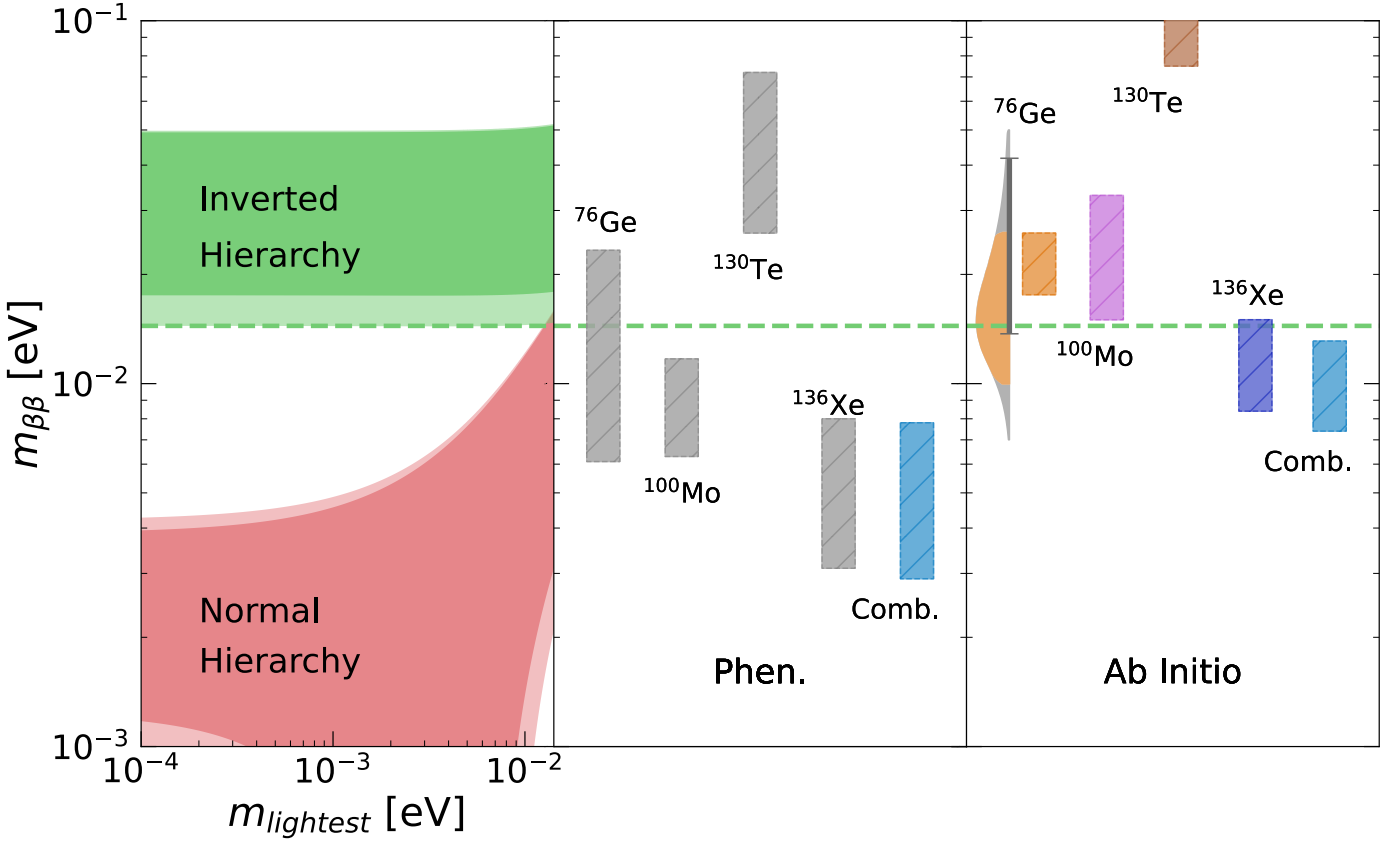
Shickele, Jokiniemi, Belley, Holt, submitted to PRD

TECHNISCHE UNIVERSITÄT DARMSTADT

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Next-generation experiments *No CUPID-1T*



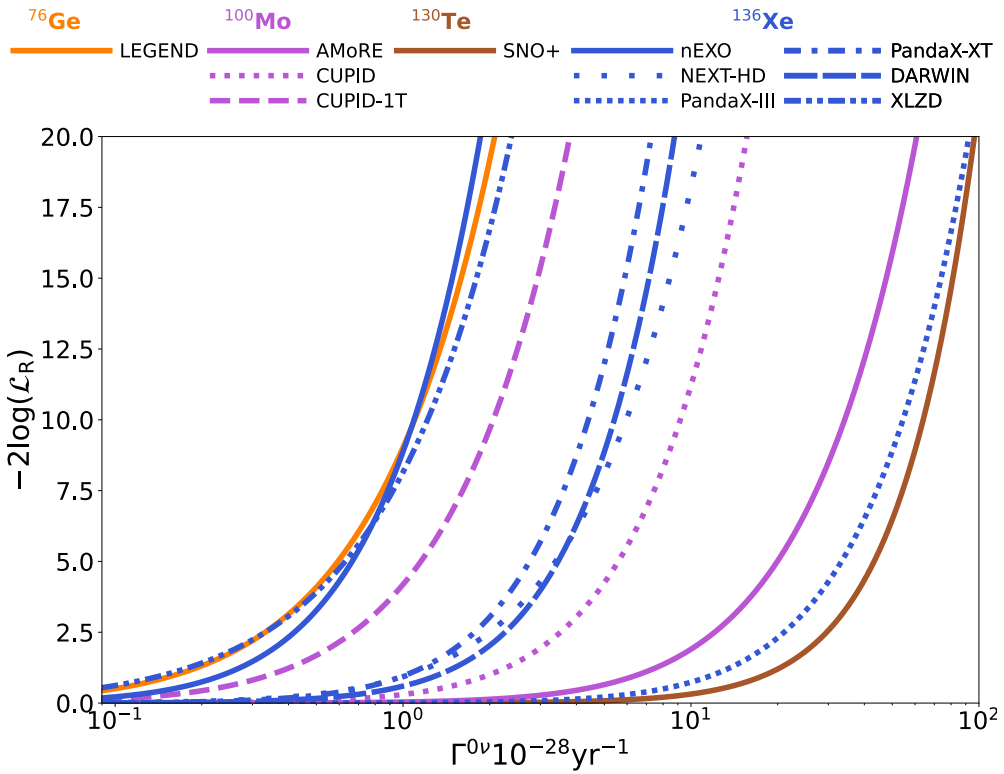


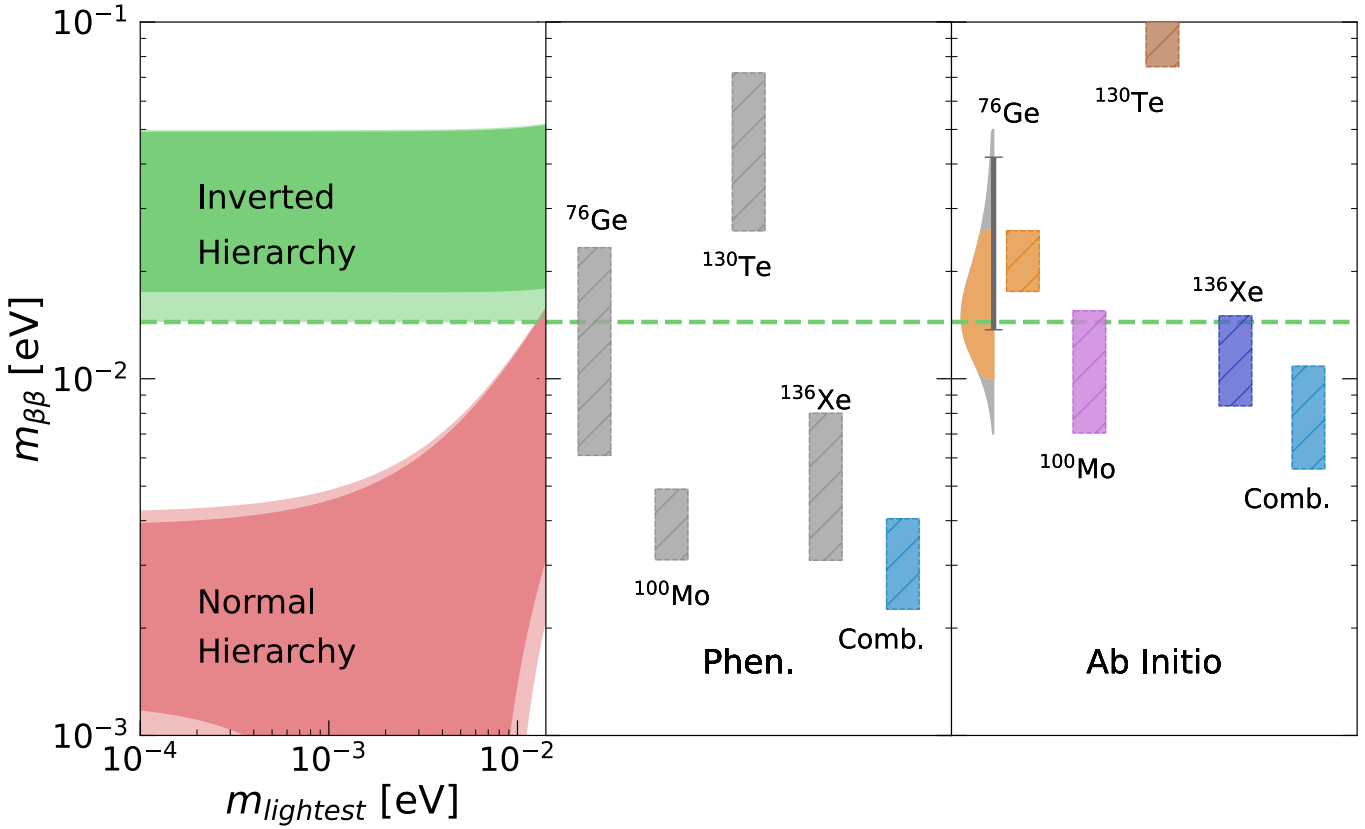
Shickele, Jokiniemi, Belley, Holt, submitted to PRD

TECHNISCHE UNIVERSITÄT DARMSTADT

COMBINED CONSTRAINTS FOR MAJORANA MASSES

Next-generation experiments *With CUPID-1T*





Shickele, Jokiniemi, Belley, Holt, submitted to PRD

TECHNISCHE UNIVERSITÄT DARMSTADT

OUTLINE

1 Introduction

2 Effective field theory for neutrinoless double-beta decay with light-neutrino exchange

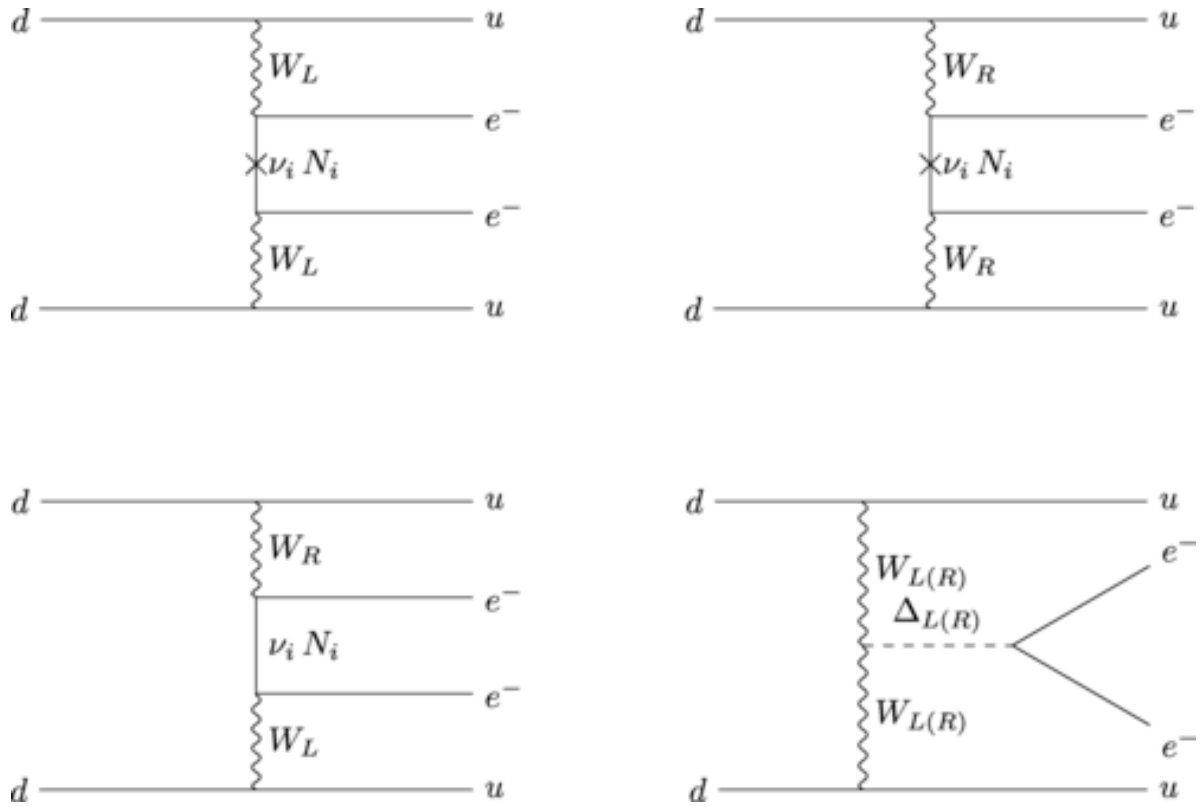
3 Global limits for Majorana masses

4 **Different decay mechanisms**

5 Summary and Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

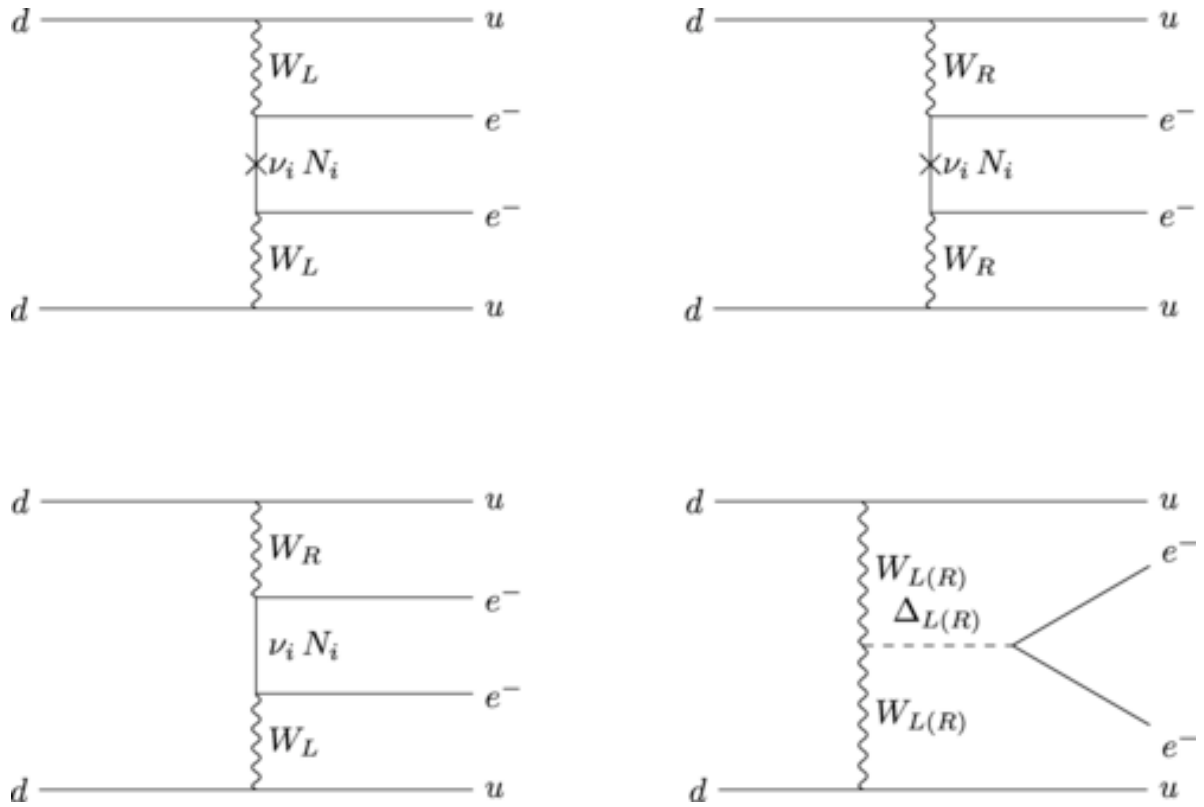


*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios

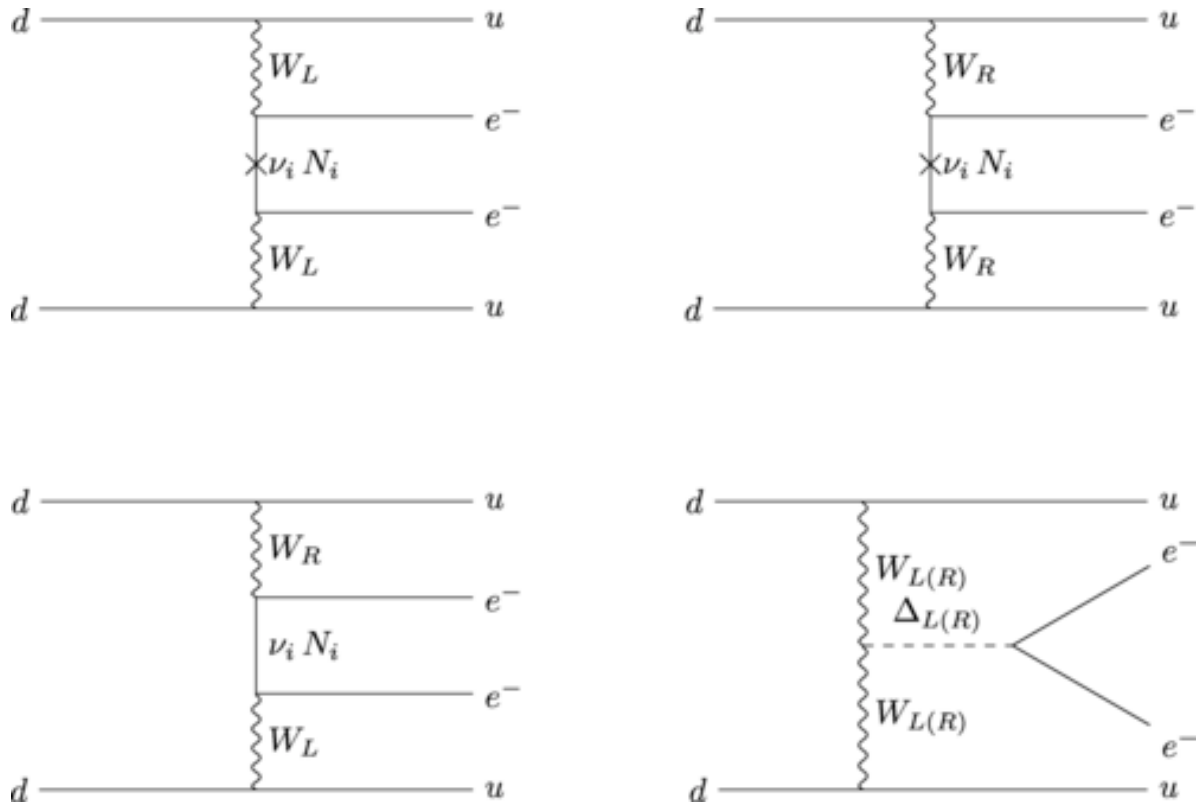


*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)

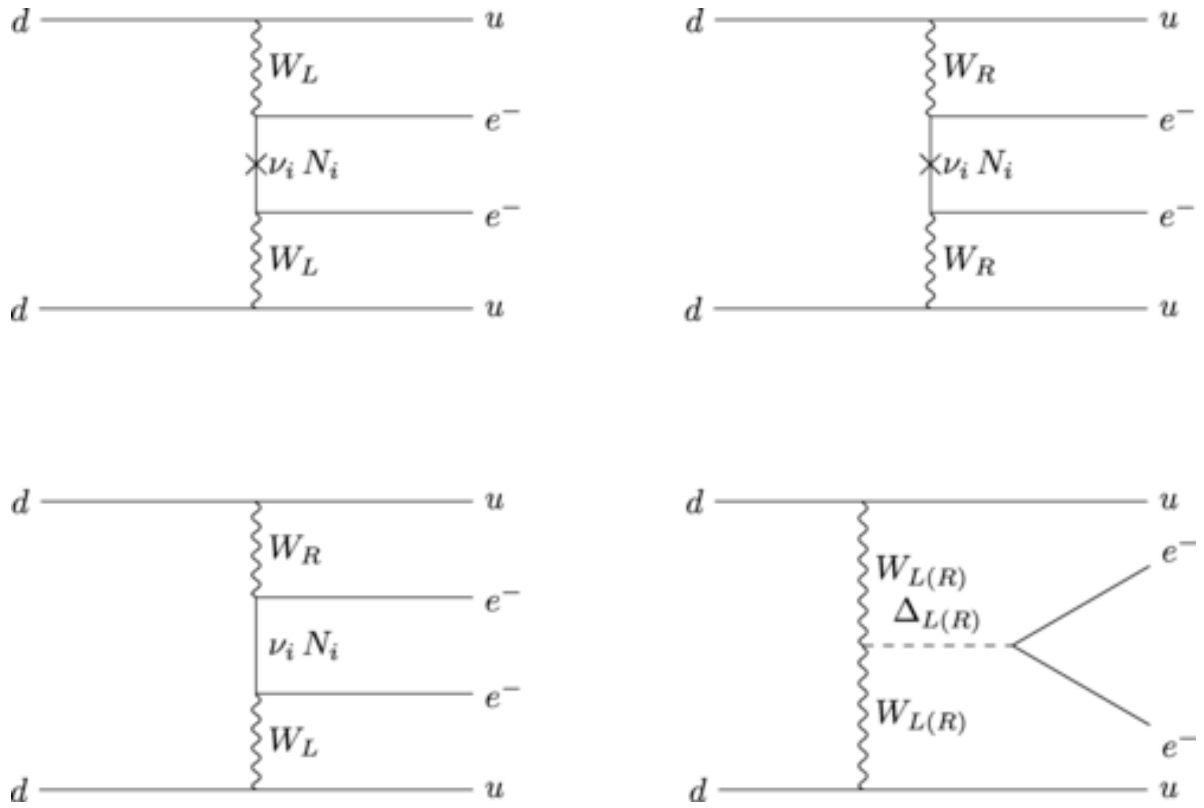


*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)
  - R-parity violating SUSY

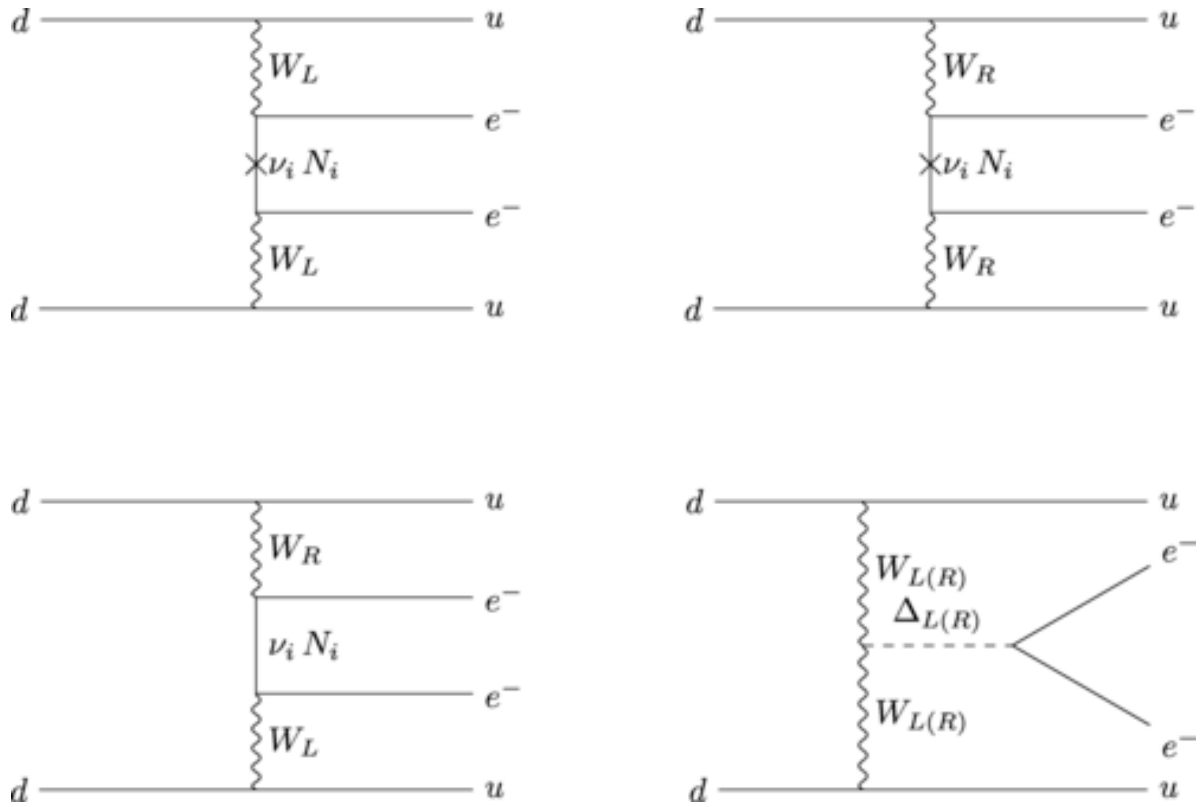


*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)
  - R-parity violating SUSY
  - leptoquarks, …



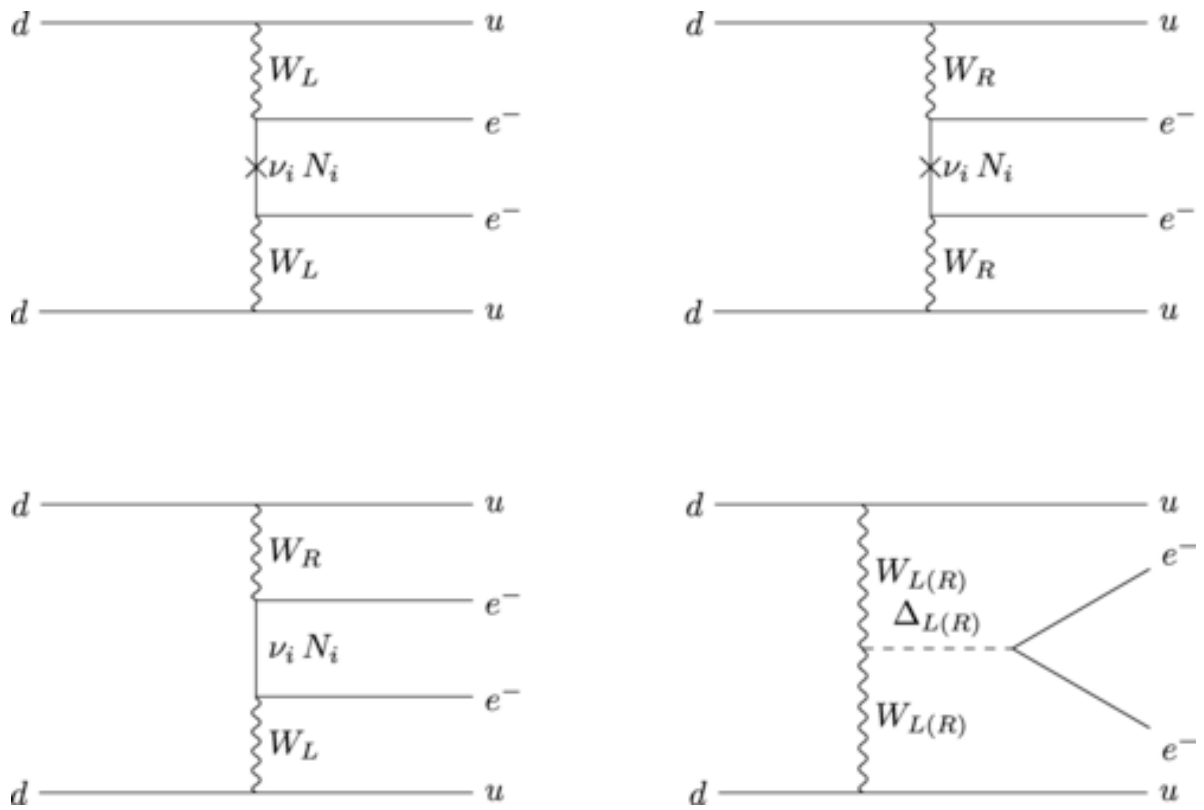
*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)
  - R-parity violating SUSY
  - leptoquarks, …
- If light-neutrino-exchange is not the driving mechanism, **no direct connection to Majorana mass**

$$\frac{1}{T^{0\nu}_{1/2}} = g_{\mathrm{A}}^4 G^{0\nu} \left| M^{0\nu}_{\mathrm{light}} m_{\beta\beta} + \ldots \right|^2$$



*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

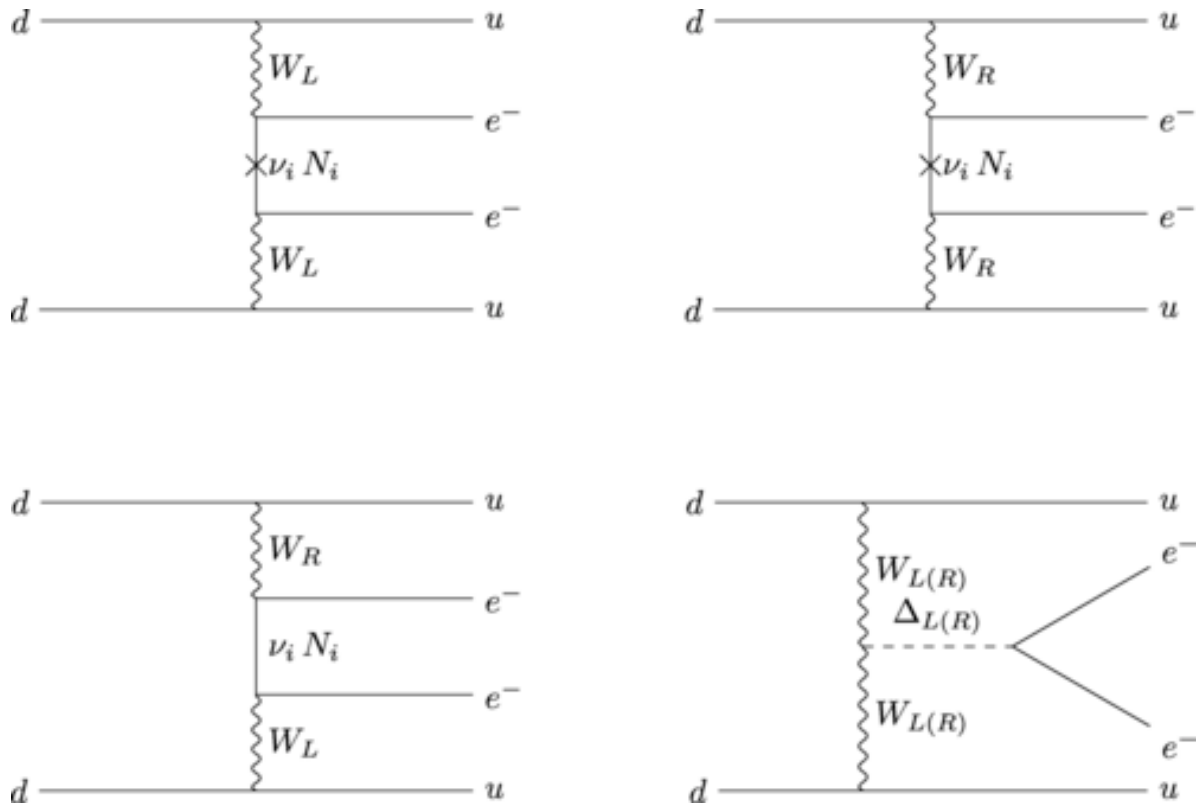
TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)
  - R-parity violating SUSY
  - leptoquarks, …
- If light-neutrino-exchange is not the driving mechanism, **no direct connection to Majorana mass**

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} \left| M^{0\nu}_{\text{light}} m_{\beta\beta} + \ldots \right|^2$$

- Experiments cannot tell which mechanism plays a role



*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

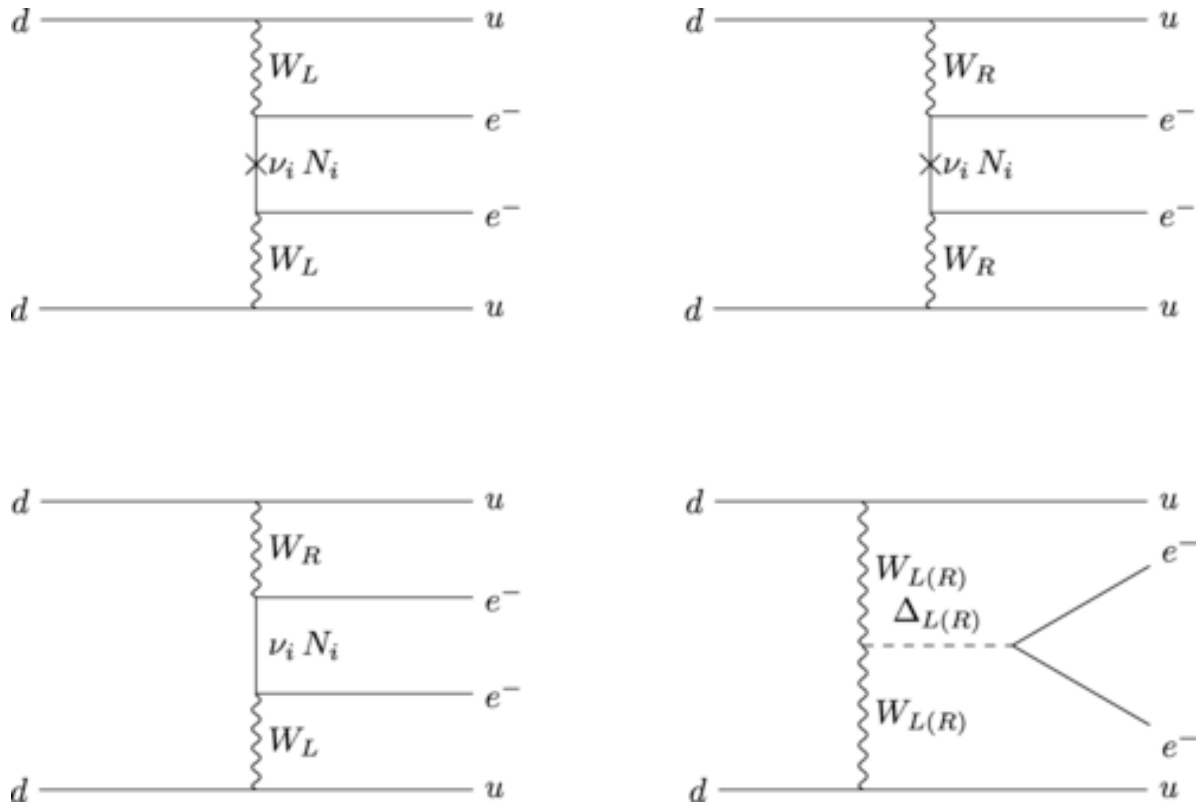
TECHNISCHE UNIVERSITÄT DARMSTADT

DIFFERENT DECAY SCENARIOS

- Many possible scenarios
  - left-right symmetric models (heavy neutrino (N_i), …)
  - R-parity violating SUSY
  - leptoquarks, …
- If light-neutrino-exchange is not the driving mechanism, **no direct connection to Majorana mass**

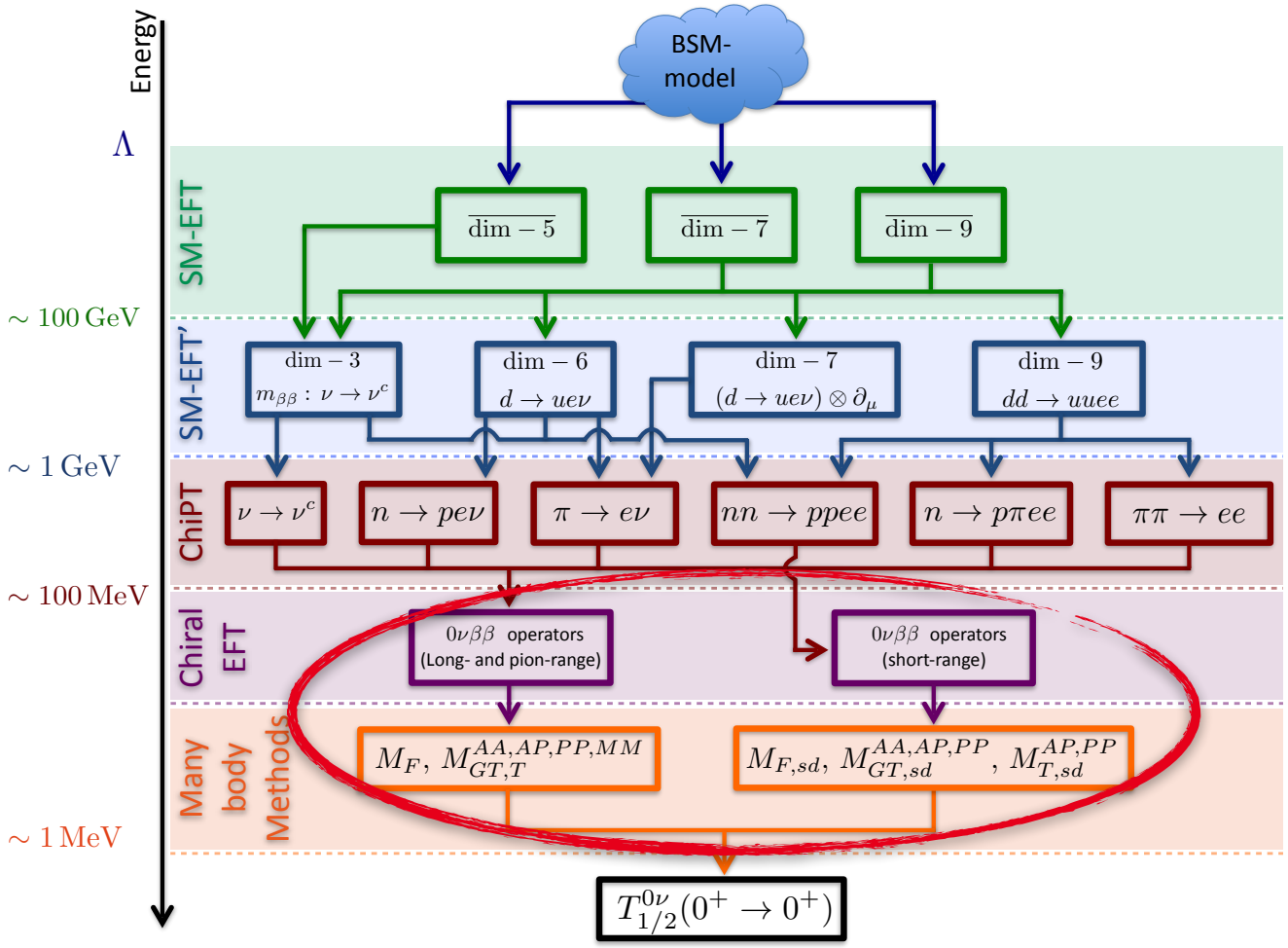
$$\frac{1}{T^{0\nu}_{1/2}} = g_{\mathrm{A}}^4 G^{0\nu} \left| M^{0\nu}_{\mathrm{light}} m_{\beta\beta} + \ldots \right|^2$$

- Experiments cannot tell which mechanism plays a role
  - **Need nuclear-theory input**



*Gráf, Lindner, Scholer, Phys. Rev. D **106**, 035022 (2022)*

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



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 12, 097 (2018)

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM MASSIVE NEUTRINOS

$$A_\nu(m_i) = \begin{cases} A_\nu^{(\mathrm{pot},<)}(m_i) + A_\nu^{(\mathrm{hard})}(m_i) + A_\nu^{(\mathrm{usoft})}(m_i), & m_i < 100\ \mathrm{MeV}, \\ A_\nu^{(\mathrm{pot})}(m_i) + A_\nu^{(\mathrm{hard})}(m_i), & 100\ \mathrm{MeV} < m_i < 2\ \mathrm{GeV}, \\ A_\nu^{(9)}(m_i), & 2\ \mathrm{GeV} \leq m_i\,. \end{cases}$$

Dekens, de Vries, Castillo et al., JHEP 09, 201 (2024)

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM MASSIVE NEUTRINOS

$$A_\nu(m_i) = \begin{cases} A_\nu^{(\mathrm{pot},<)}(m_i) + A_\nu^{(\mathrm{hard})}(m_i) + A_\nu^{(\mathrm{usoft})}(m_i), & m_i < 100\ \mathrm{MeV}, \\ A_\nu^{(\mathrm{pot})}(m_i) + A_\nu^{(\mathrm{hard})}(m_i), & 100\ \mathrm{MeV} < m_i < 2\ \mathrm{GeV}, \\ A_\nu^{(9)}(m_i), & 2\ \mathrm{GeV} \leq m_i\,. \end{cases}$$

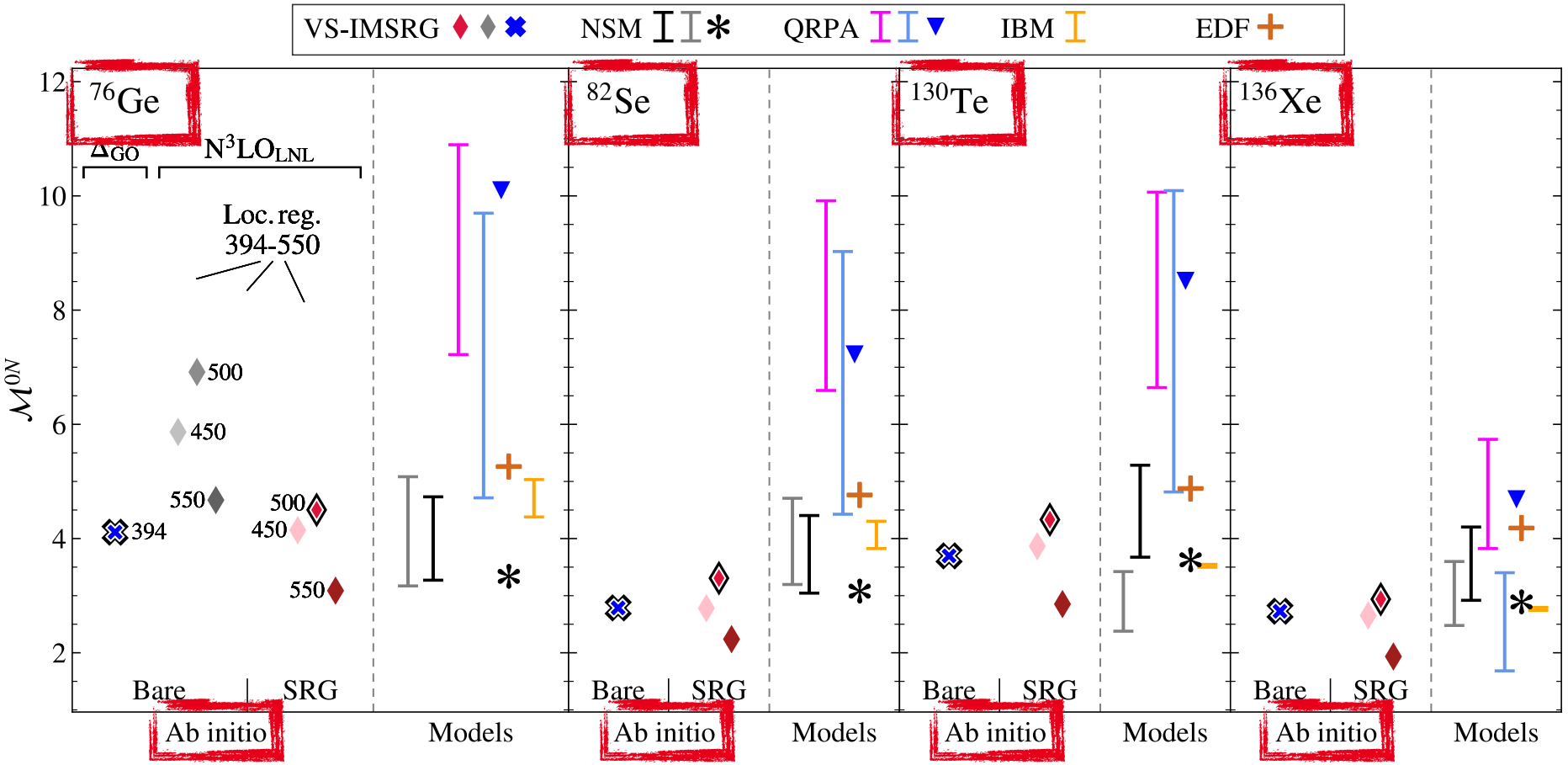
Dekens, de Vries, Castillo et al., JHEP 09, 201 (2024)

- Hard neutrinos: $k_0 \sim |\mathbf{k}| \sim \Lambda_\chi \rightarrow M_{\mathrm{sd}}^X$
- Soft neutrinos: $k_0 \sim |\mathbf{k}| \sim m_\pi \rightarrow$ Loop diagrams
- Potential neutrinos: $k_0 \sim |\mathbf{k}|^2/m_N \sim k_F^2/m_N \rightarrow M_{\mathrm{ld}}^X$
- Ultrasoft neutrinos: $k_0 \sim |\mathbf{k}| \sim k_F^2/m_N \rightarrow$ Coherent contribution

TECHNISCHE UNIVERSITÄT DARMSTADT

SHORT-RANGE NUCLEAR MATRIX ELEMENTS

$$M^{0N} = M^{0N}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{0N}_{\mathrm{F}} + M^{0N}_{\mathrm{T}}$$

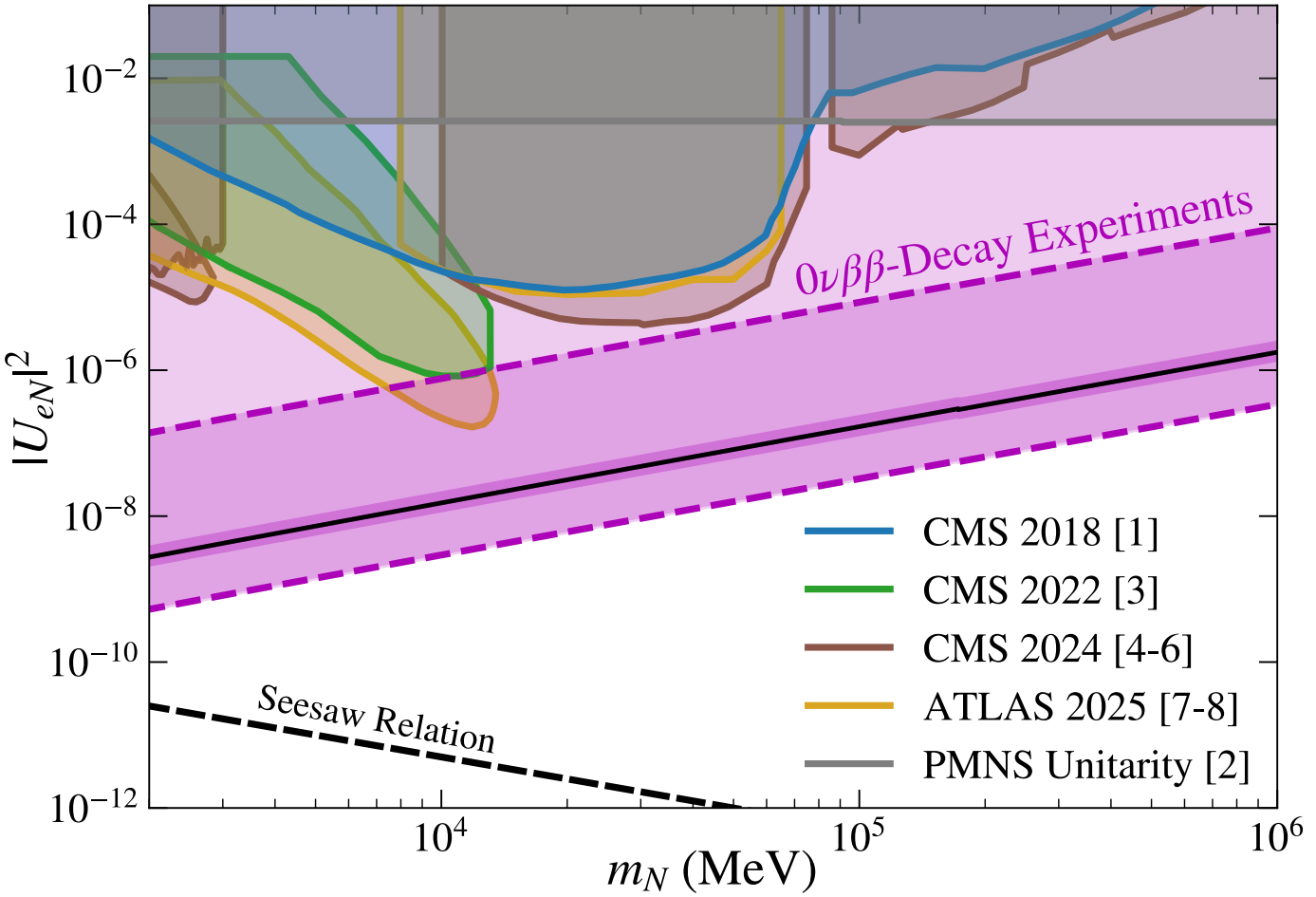


Todd, Shickele, Belley, Jokiniemi, Holt, submitted to PRL

TECHNISCHE UNIVERSITÄT DARMSTADT

TOY MODEL: 3+1 SCENARIO

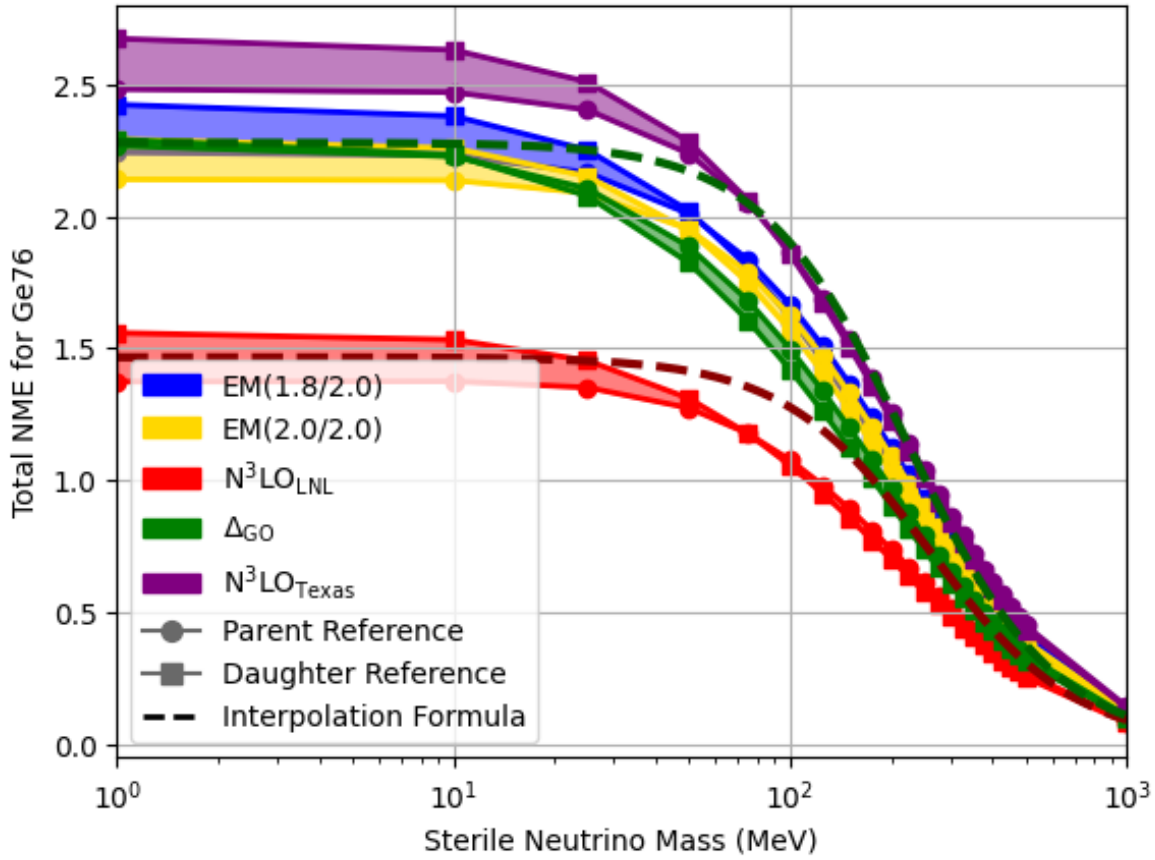
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_R \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{eN} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu N} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau N} \\ U_{R1} & U_{R2} & U_{R3} & U_{RN} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_N \end{pmatrix}$$



Todd, Shickele, Belley, Jokiniemi, Holt, submitted to PRL

TECHNISCHE UNIVERSITÄT DARMSTADT

LIGHT STERILE-NEUTRINO EXCHANGE



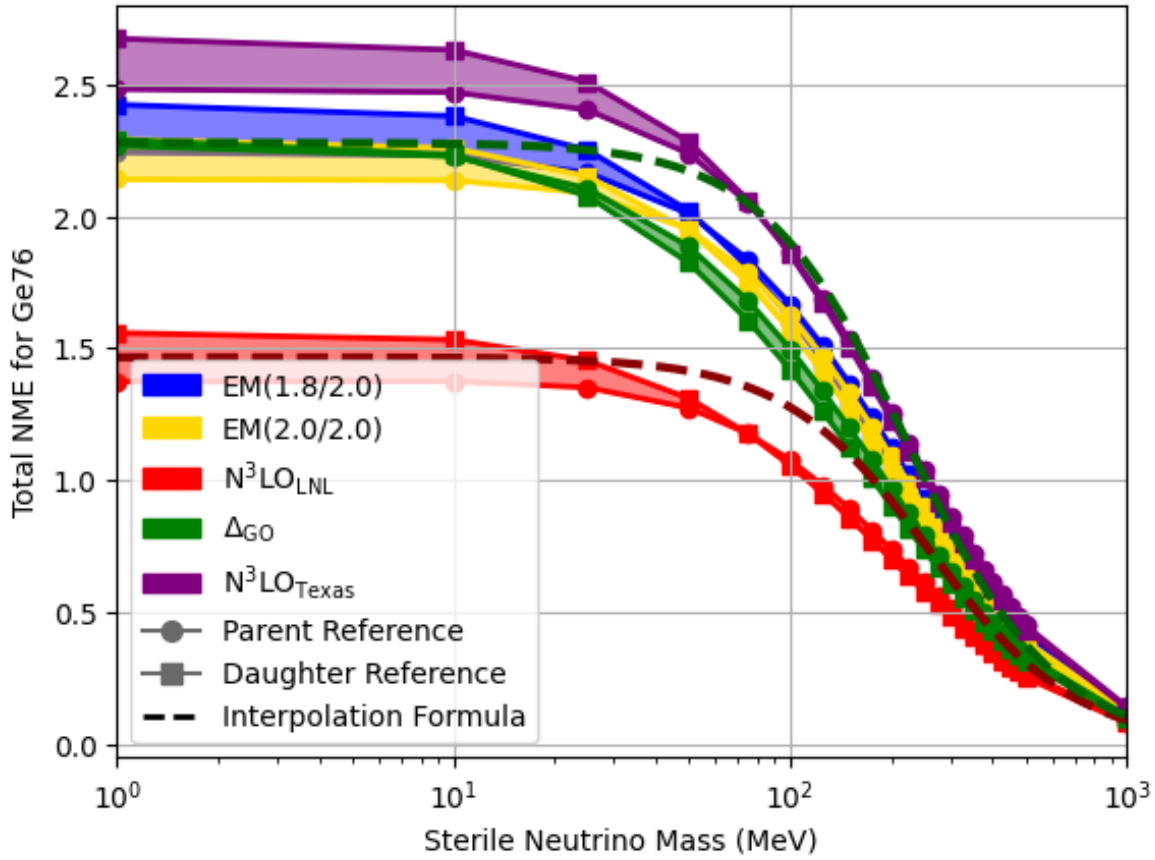
Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

LIGHT STERILE-NEUTRINO EXCHANGE

- When $m_N \sim 100$ **MeV** $\sim q$, the nuclear matrix elements are sensitive to the neutrino mass

  Dekens et al, JHEP 09 (2024) 201



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

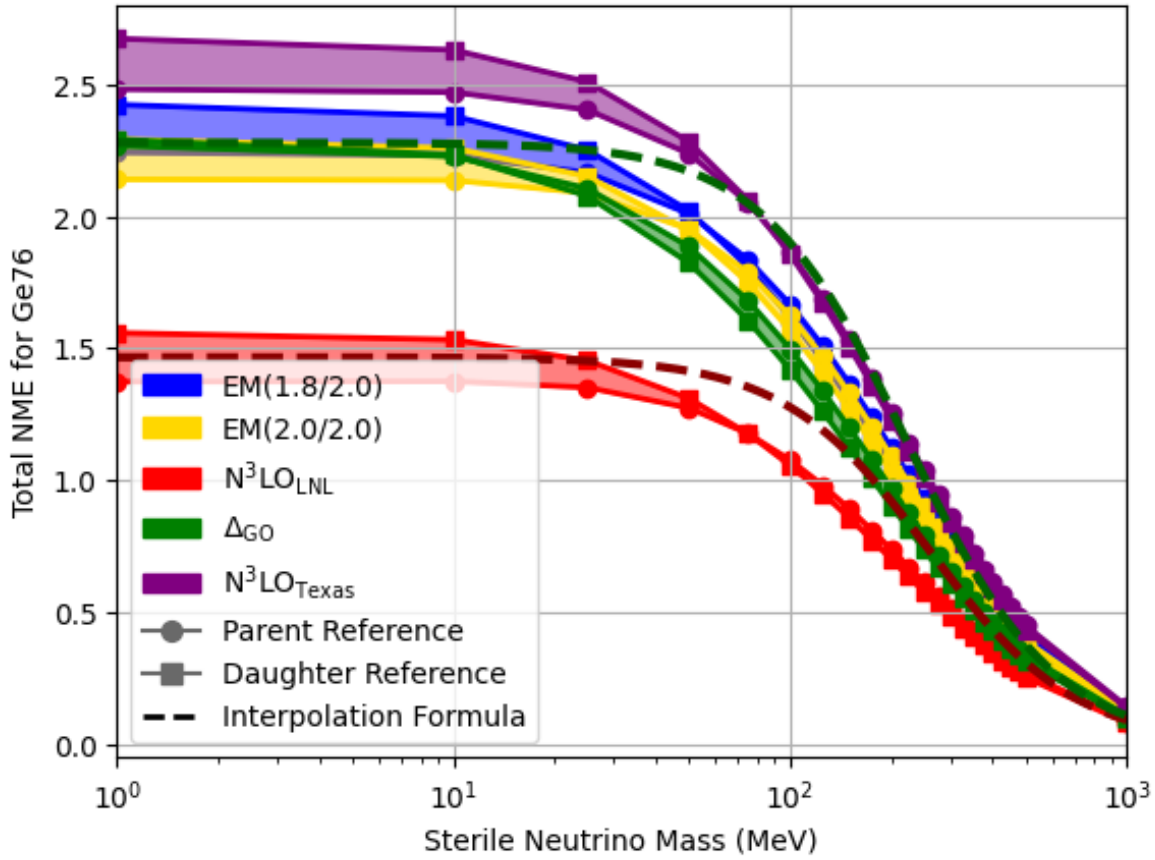
TECHNISCHE UNIVERSITÄT DARMSTADT

LIGHT STERILE-NEUTRINO EXCHANGE

- When $m_N \sim 100$ **MeV** $\sim q$, the nuclear matrix elements are sensitive to the neutrino mass
  Dekens et al, JHEP 09 (2024) 201
- In the literature, mostly an **interpolation formula**

$$M^{0\nu}(m_N) = M^{0\nu}_{\mathrm{L}} \frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_N^2}, \ \langle p^2 \rangle = m_e m_p \, | M^{0\nu}_{\mathrm{S}} / M^{0\nu}_{\mathrm{L}} |$$

  is used



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

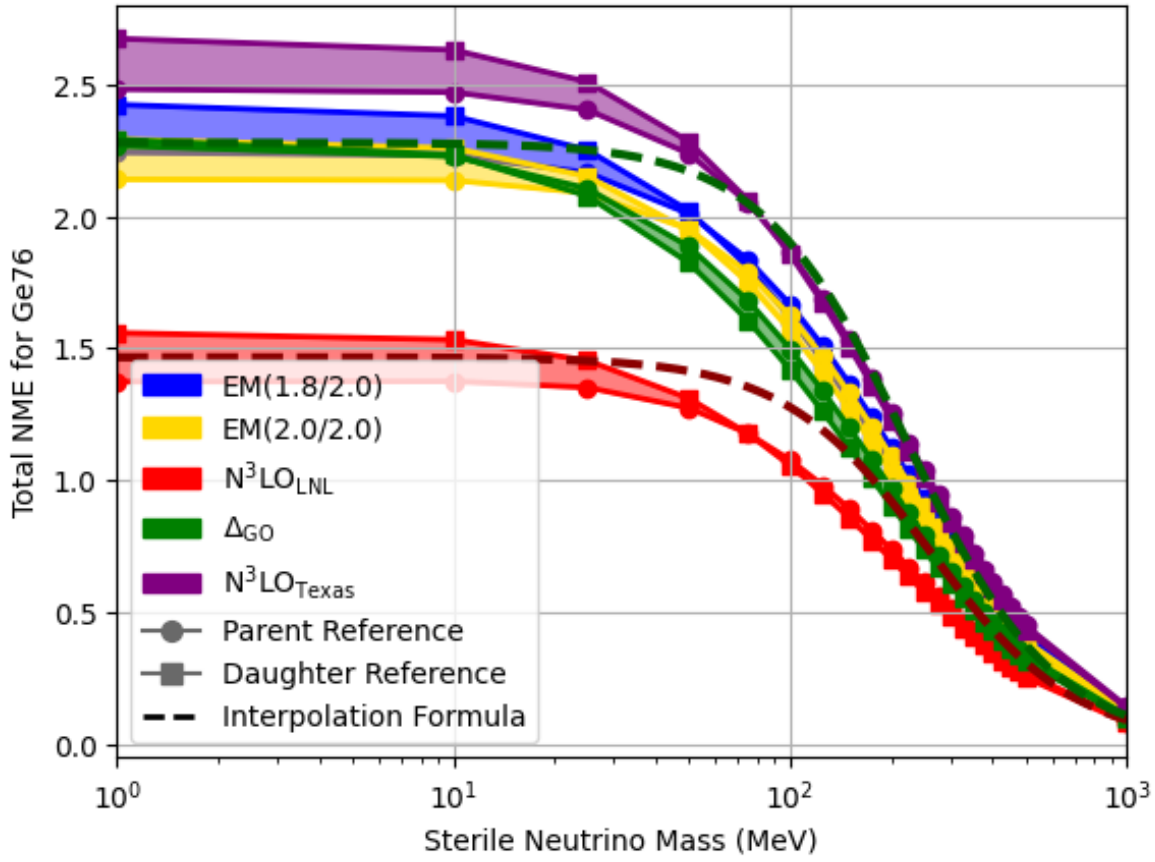
TECHNISCHE UNIVERSITÄT DARMSTADT

LIGHT STERILE-NEUTRINO EXCHANGE

- When $m_N \sim 100$ **MeV** $\sim q$, the nuclear matrix elements are sensitive to the neutrino mass
  Dekens et al, JHEP 09 (2024) 201
- In the literature, mostly an **interpolation formula**

$$M^{0\nu}(m_N) = M^{0\nu}_{\mathrm{L}} \frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_N^2}, \ \langle p^2 \rangle = m_e m_p \, |M^{0\nu}_{\mathrm{S}}/M^{0\nu}_{\mathrm{L}}|$$

  is used
- **Including the mass-dependence explicitly we see deviations from interpolation formula**



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

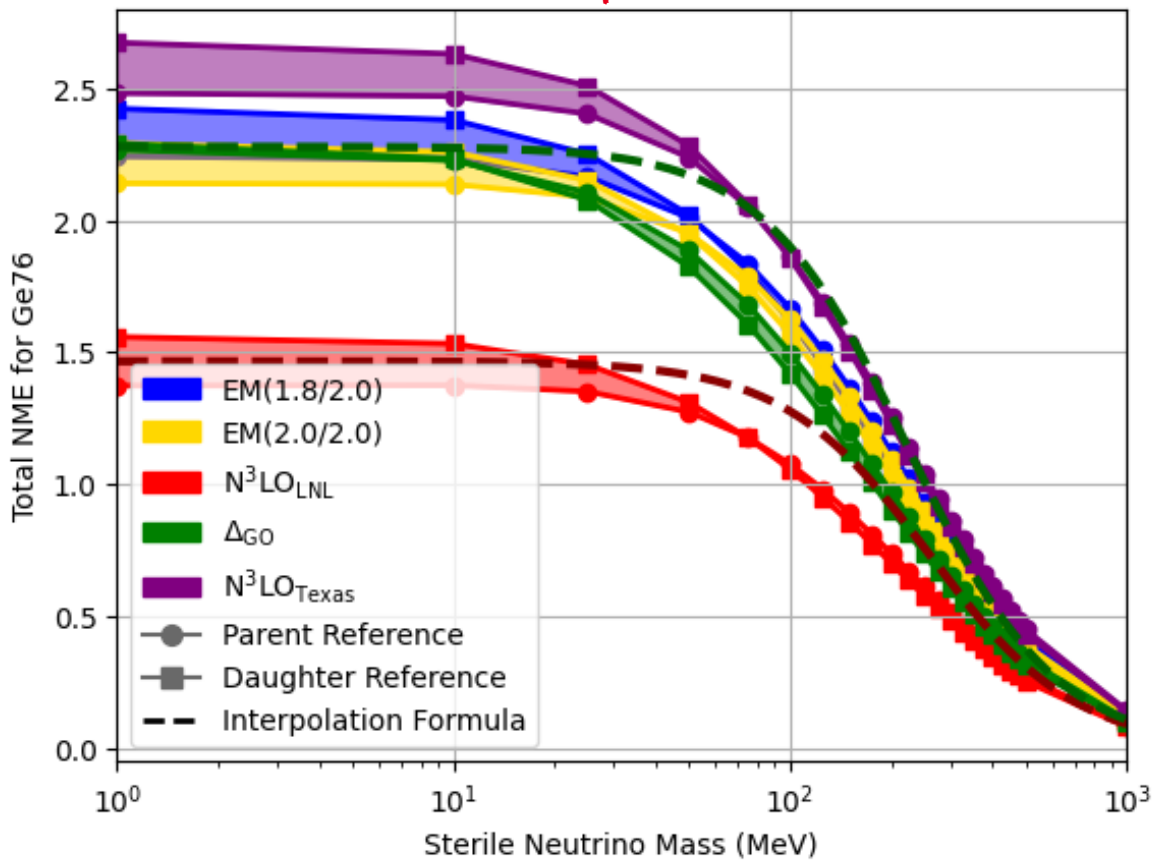
LIGHT STERILE-NEUTRINO EXCHANGE

- When $m_N \sim 100$ **MeV** $\sim q$, the nuclear matrix elements are sensitive to the neutrino mass
  Dekens et al, JHEP 09 (2024) 201
- In the literature, mostly an **interpolation formula**

$$M^{0\nu}(m_N) = M^{0\nu}_{\mathrm{L}} \frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_N^2}, \ \langle p^2 \rangle = m_e m_p \, | M^{0\nu}_{\mathrm{S}} / M^{0\nu}_{\mathrm{L}} |$$

  is used
- **Including the mass-dependence explicitly we see deviations from interpolation formula**

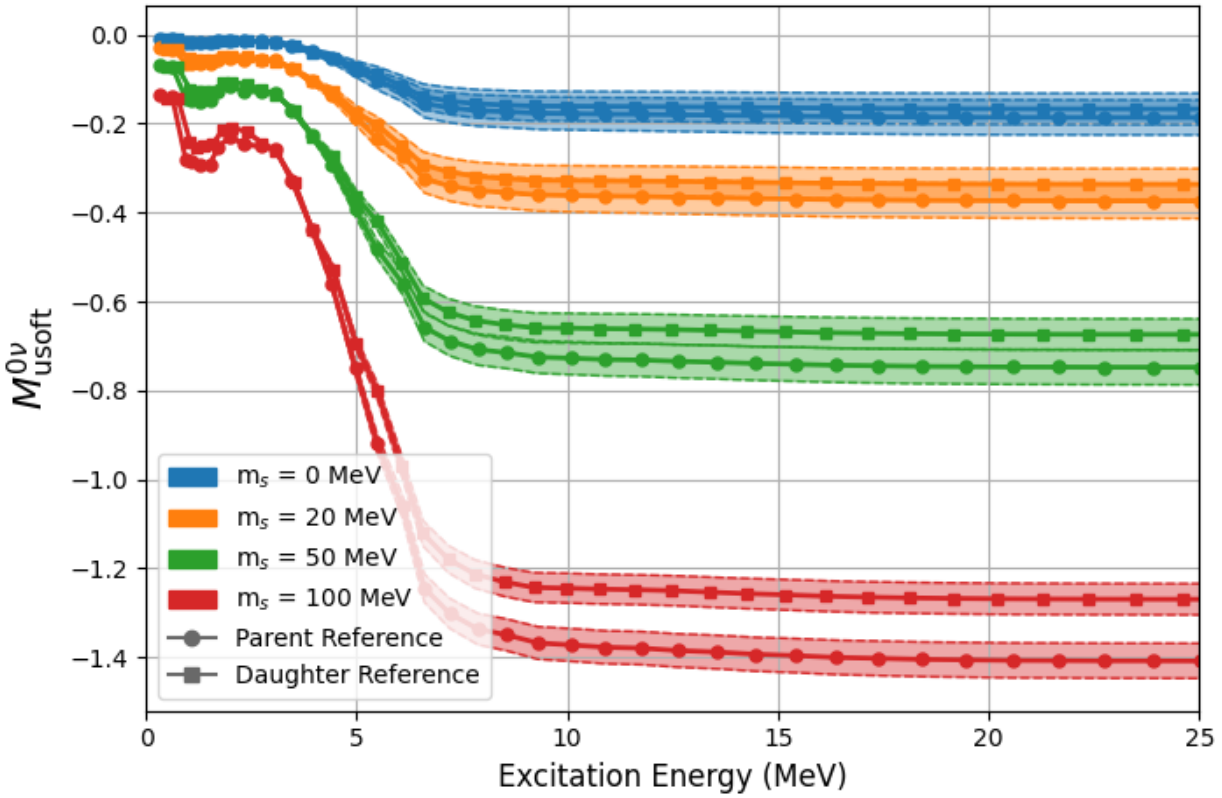
See T. Shickele's poster for details



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM ULTRASOFT AND HARD NEUTRINOS



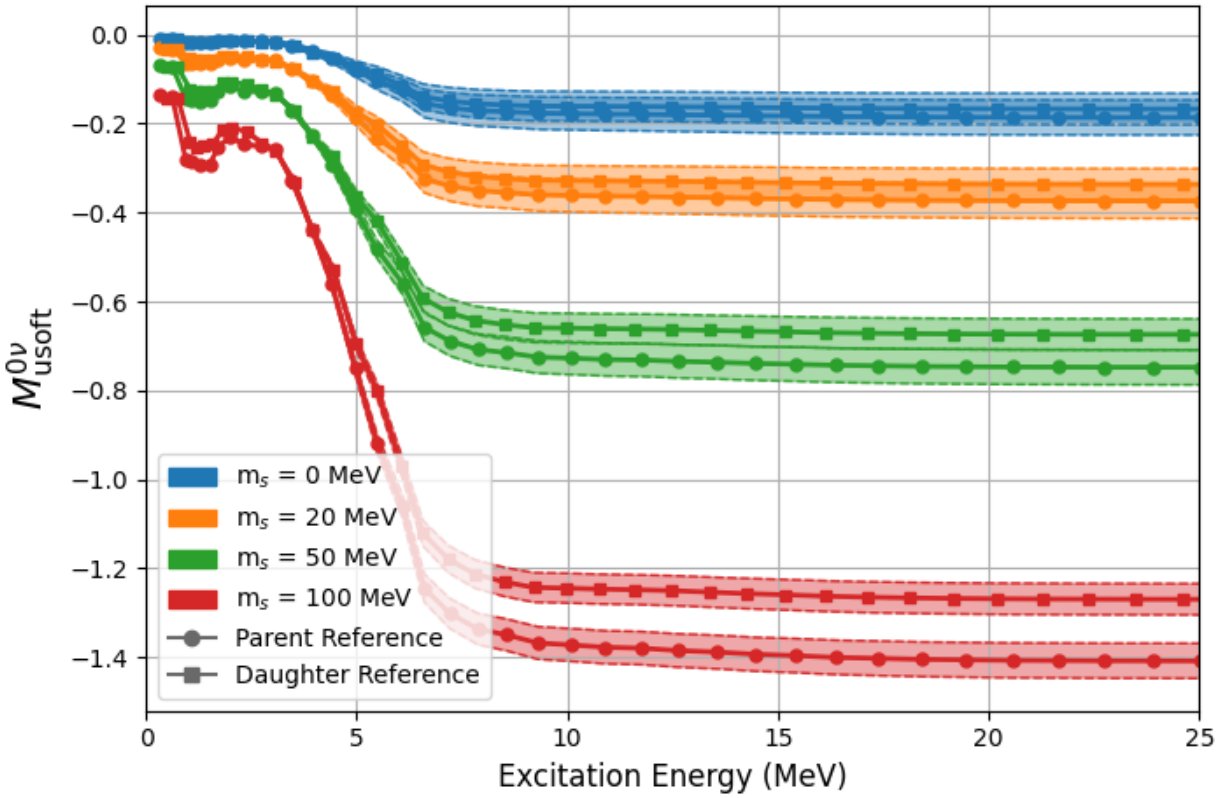
Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM ULTRASOFT AND HARD NEUTRINOS

- Coherent contribution from ultrasoft ($k_0 \sim |\mathbf{k}| \sim k_F^2/m_N$) neutrinos

$$A_\nu^{(\mathrm{usoft})}(m_i) \propto \sum_n \langle 0_f^+ | \mathcal{J}^\pi | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_\mu | 0_i^+ \rangle \times \left(f(m_i, \Delta E_1) + f(m_i, \Delta E_2) \right)$$



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM ULTRASOFT AND HARD NEUTRINOS

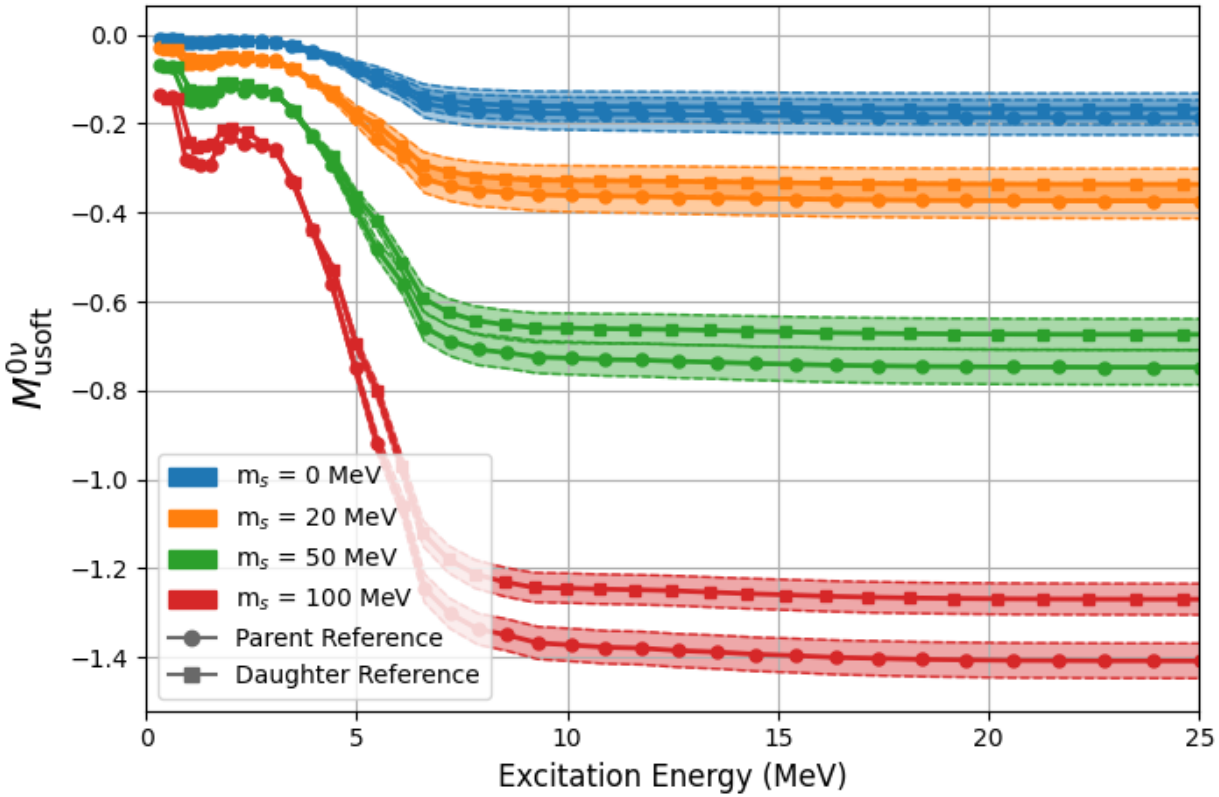
- Coherent contribution from ultrasoft ($k_0 \sim |\mathbf{k}| \sim k_F^2/m_N$) neutrinos

$$A_\nu^{(\mathrm{usoft})}(m_i) \propto \sum_n \langle 0_f^+ | \mathcal{J}^\pi | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_\mu | 0_i^+ \rangle \times \left(f(m_i, \Delta E_1) + f(m_i, \Delta E_2) \right)$$

- Contact term from hard ($k_0 \sim |\mathbf{k}| \sim \Lambda_\chi$) neutrinos

$$A_\nu^{(\mathrm{hard})}(m_i) \propto g_\nu^{NN}(m_i) M_{\mathrm{F,sd}}$$

Cirigliano, Dekens, Urrutia Quiroga, JHEP04(2025)181



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM ULTRASOFT AND HARD NEUTRINOS

See T. Shickele's poster for details

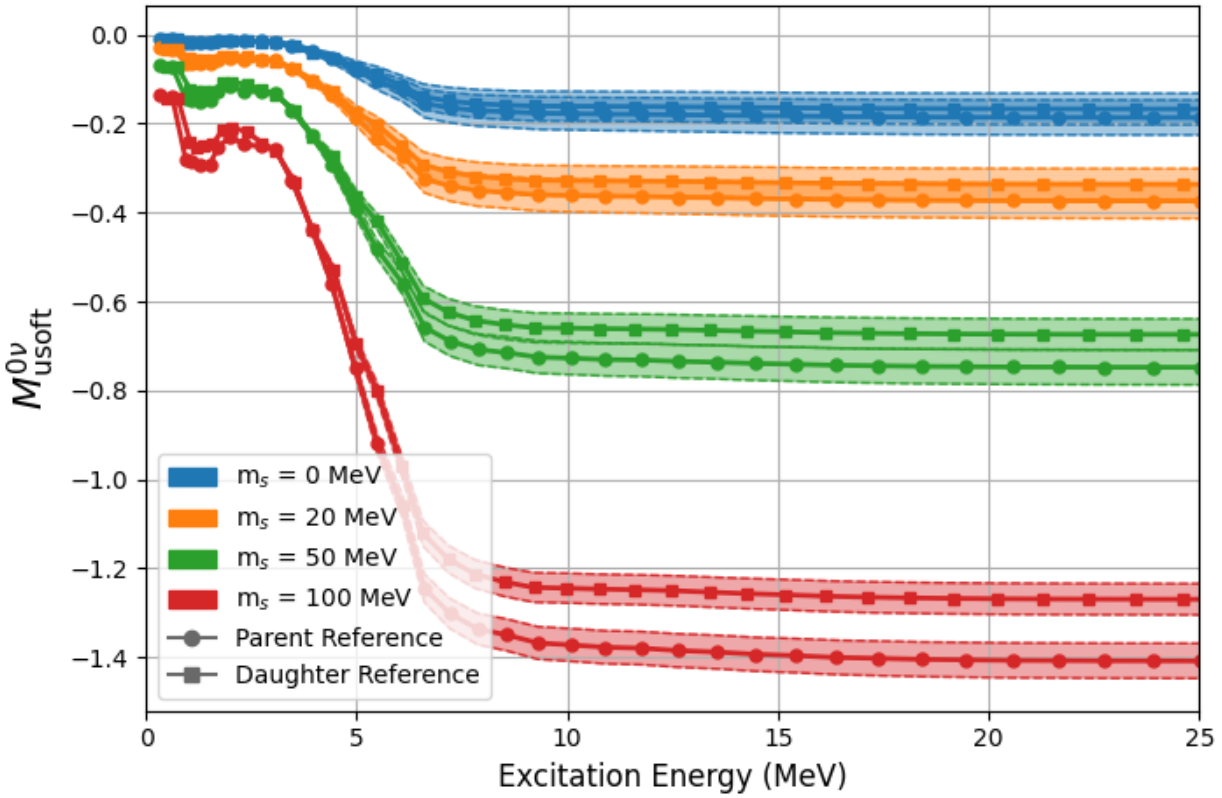
- Coherent contribution from ultrasoft ($k_0 \sim |\mathbf{k}| \sim k_F^2/m_N$) neutrinos

$$A_\nu^{(\mathrm{usoft})}(m_i) \propto \sum_n \langle 0_f^+ | \mathcal{J}^\pi | 1_n^+ \rangle \langle 1_n^+ | \mathcal{J}_\mu | 0_i^+ \rangle \times \left(f(m_i, \Delta E_1) + f(m_i, \Delta E_2) \right)$$

- Contact term from hard ($k_0 \sim |\mathbf{k}| \sim \Lambda_\chi$) neutrinos

$$A_\nu^{(\mathrm{hard})}(m_i) \propto g_\nu^{NN}(m_i) M_{\mathrm{F,sd}}$$

Cirigliano, Dekens, Urrutia Quiroga, JHEP04(2025)181

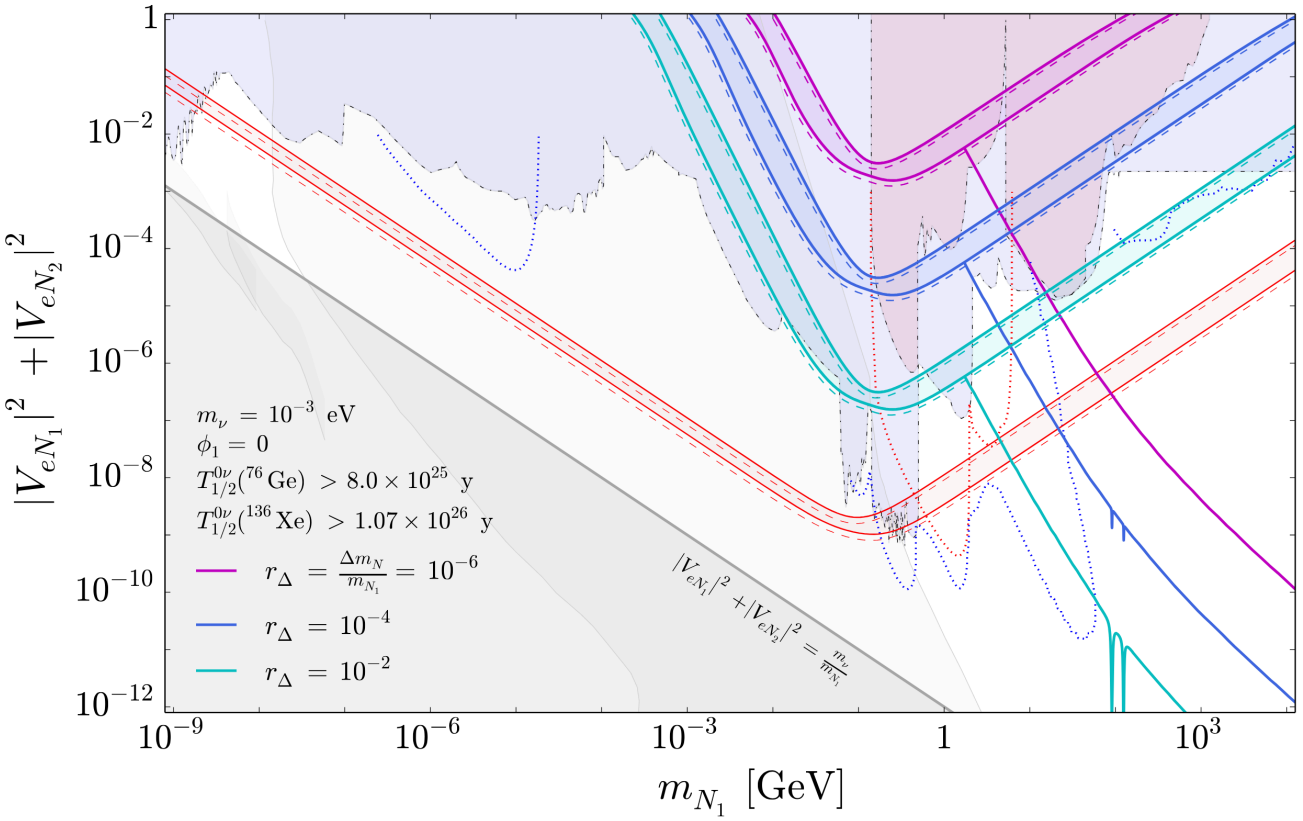


Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

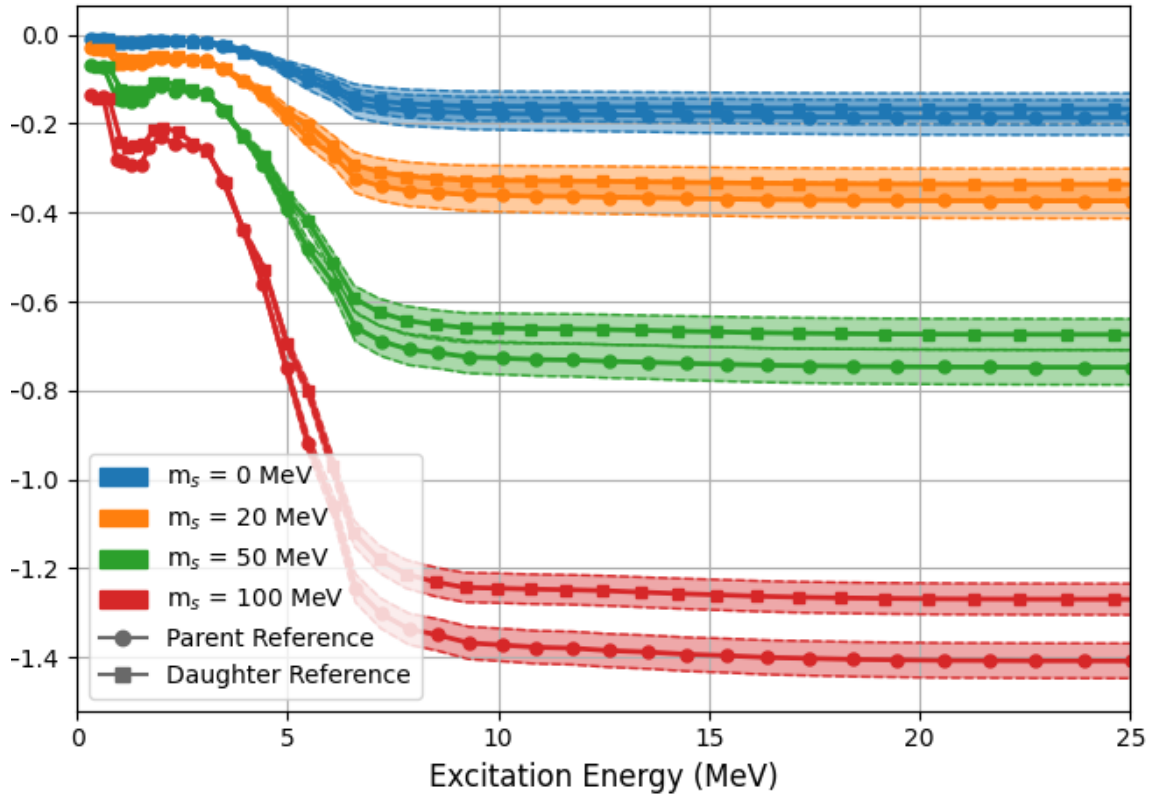
TECHNISCHE UNIVERSITÄT DARMSTADT

CONTRIBUTION FROM ULTRASOFT AND HARD NEUTRINOS

See T. Shickele's poster for details



Bolton, Deppisch, Dev, JHEP 2020, 170 (2020)



Shickele, Jokiniemi, Deppisch, Belley, Holt, in preparation

TECHNISCHE UNIVERSITÄT DARMSTADT

SUMMARY AND OUTLOOK

- $0\nu\beta\beta$ decay is a robust yet challenging probe for beyond-standard-model physics and neutrino properties
- χEFT analysis of the operators allows for uncertainty quantification in *ab initio* framework
- Next-generation experiments likely to fully cover the inverted-hierarchy band of neutrino masses
- Reliable nuclear-theory predictions needed to distinguish $0\nu\beta\beta$-decay mechanism

TODO

- Correlated nuclear matrix elements
- Two-body currents
- Different mechanisms,…