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Double Beta Decay as a Probe of New Physics

Frank Deppisch

f.deppisch@ucl.ac.uk

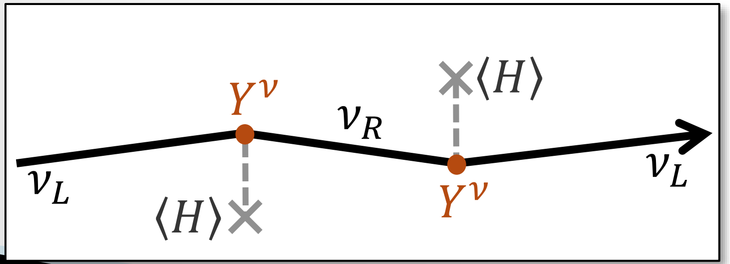
University College London

Workshop on
Neutrinos and Related New Physics
Zhuhai | 28/11-01/12/2025

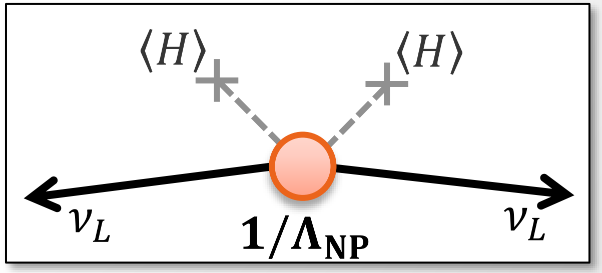
Dirac versus Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with $m_\nu / \Lambda_{EW} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Beta Decay and Neutrino Mass

- Single beta decay

  $$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

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

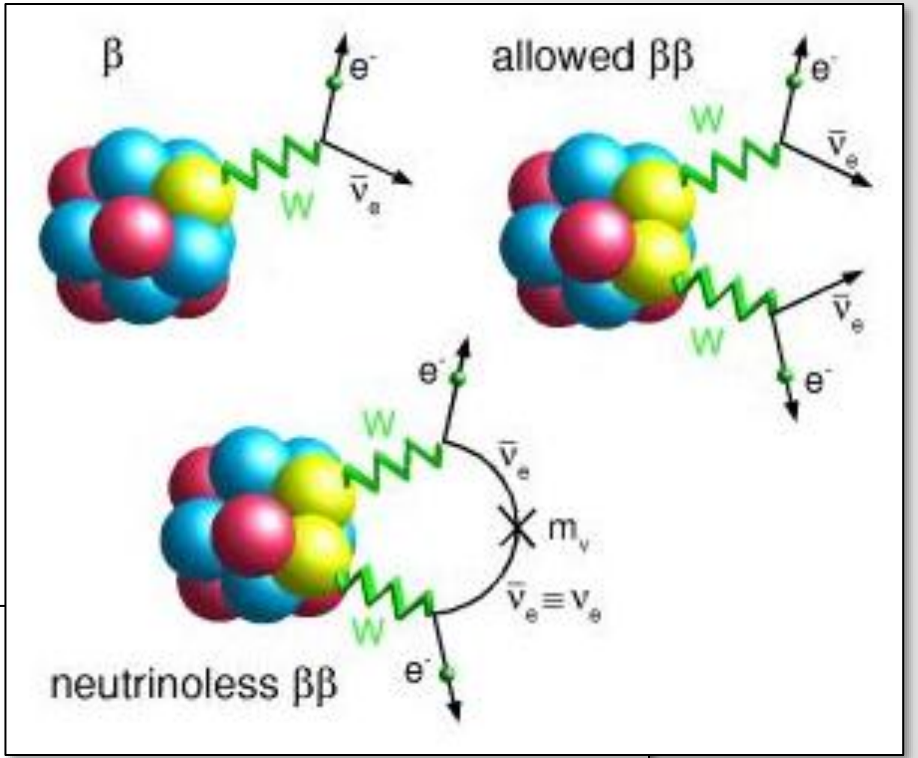
  $$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

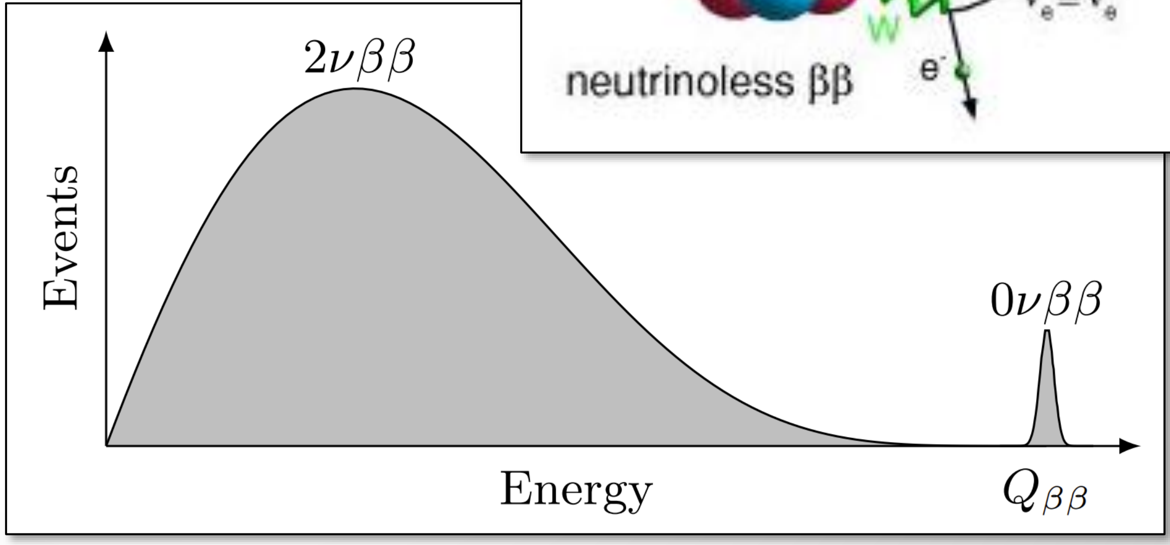
  - SM-allowed in certain isotopes
- Neutrinoless double beta ($0\nu\beta\beta$) decay

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

  - Violation of lepton number
  - Mediated by massive Majorana neutrinos

See talk by Hao Ma
for experimental overview





Neutrinoless Double Beta Decay

- Half-life

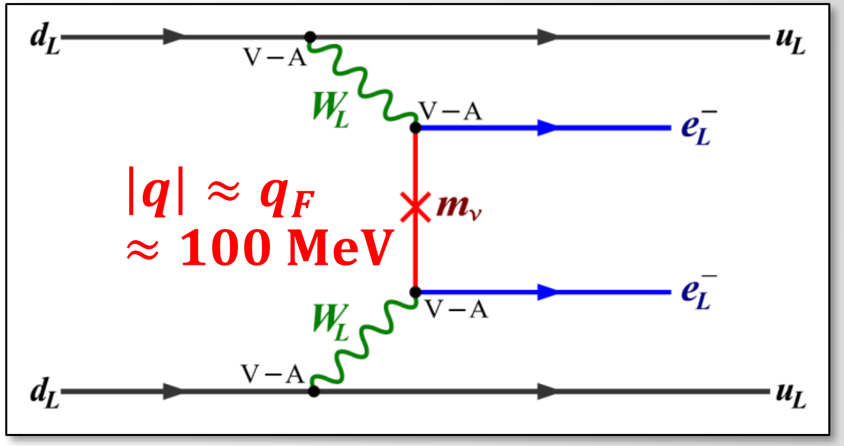
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$

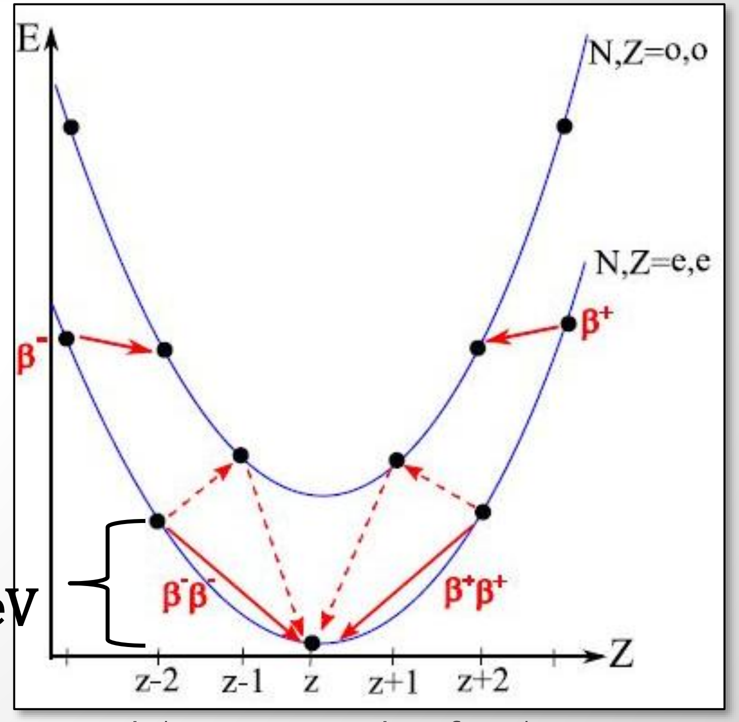
- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\cancel{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \boxed{\sum_{i=1}^{3} U_{ei}^2 m_{\nu_i}} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$, but large uncertainties, factor 2–3

See talk by Jiangmin Yao





$Q + 2m_e$
$\approx$ 3–5 MeV

Three Active Neutrinos

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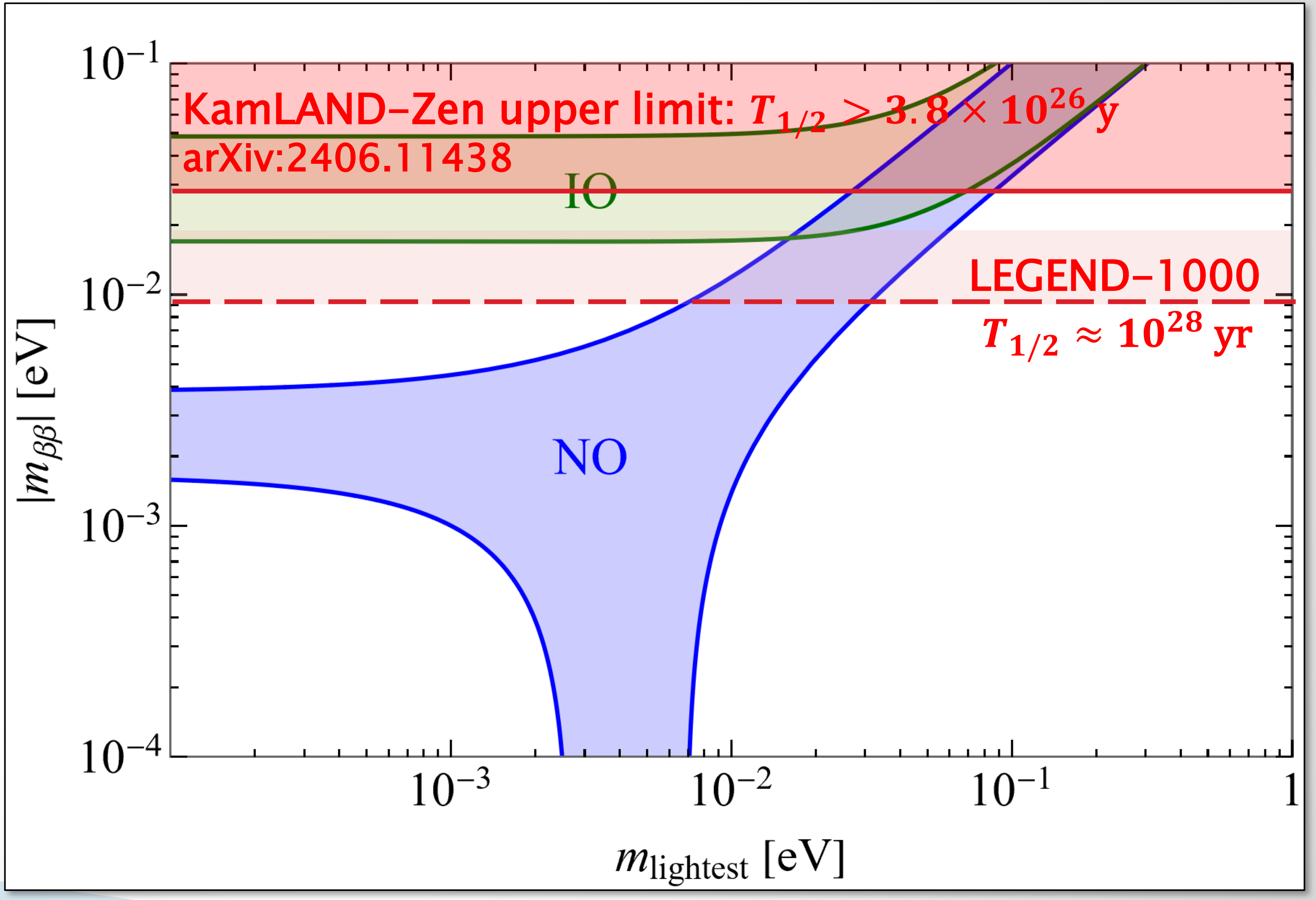
- Effective $0\nu\beta\beta$ Mass

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}|$$



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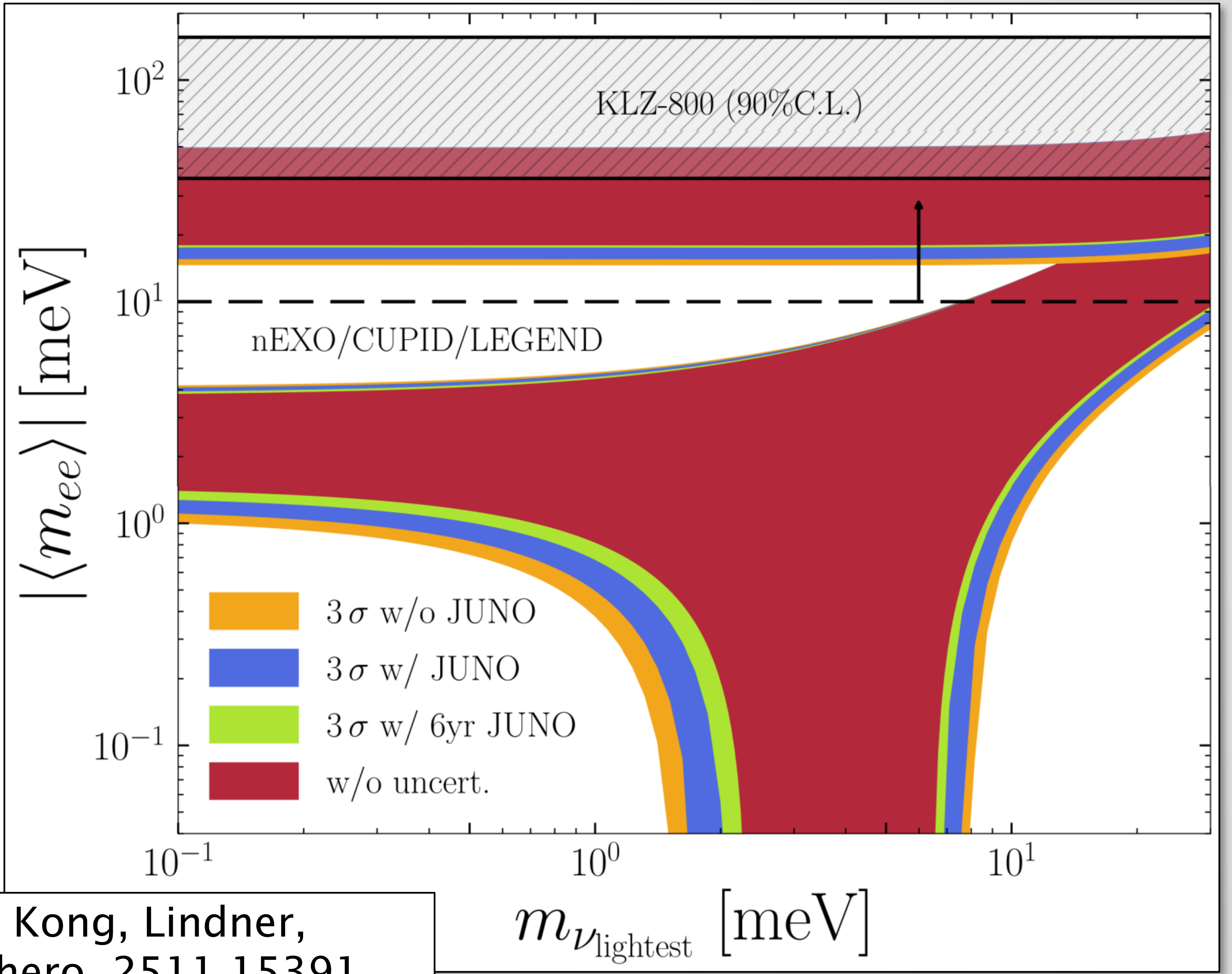
- Impact of JUNO Data



Ge, Kong, Lindner, Pinhero, 2511.15391

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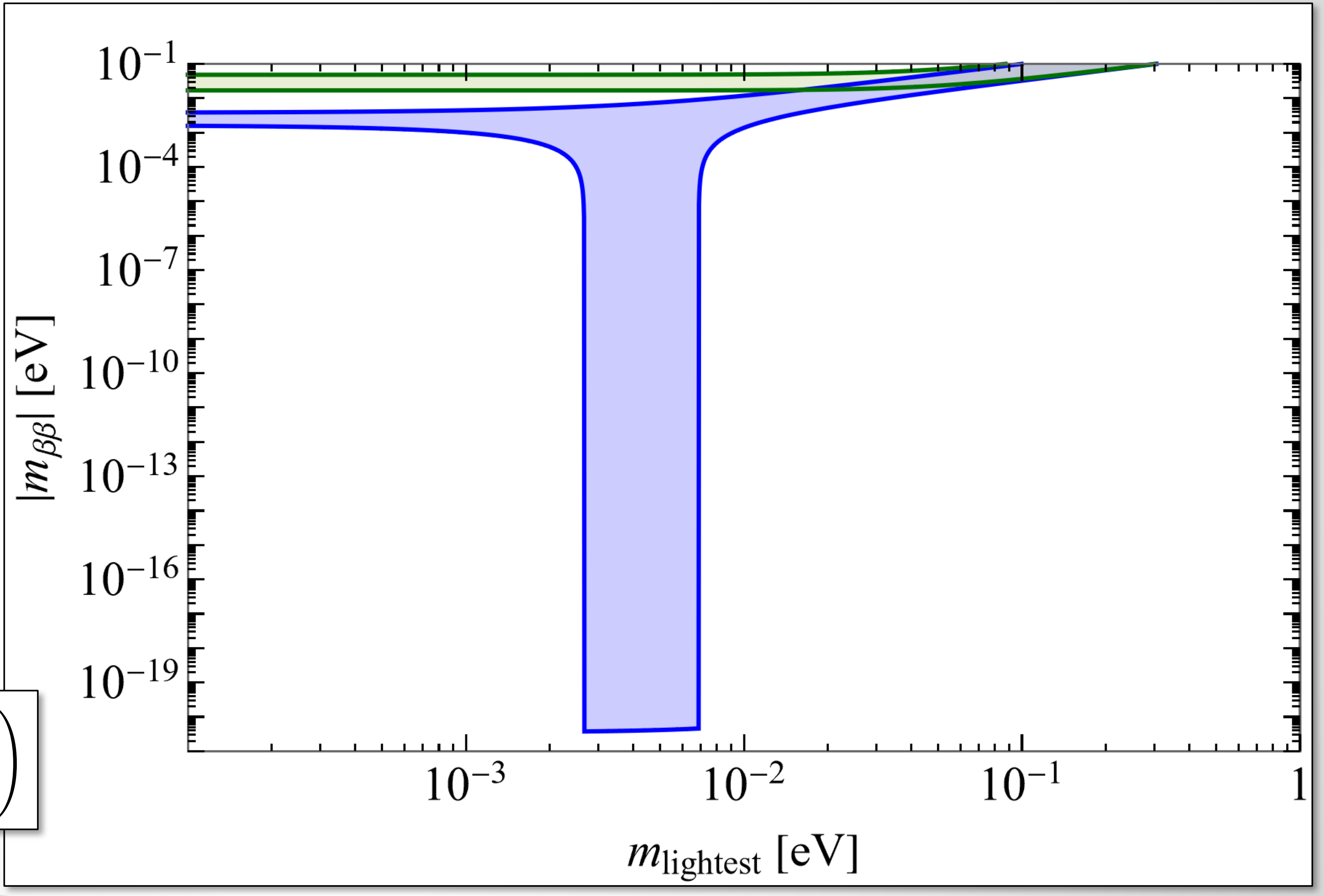
- Impact of JUNO Data
- Vanishing $m_{\beta\beta}$

$$m_{\beta\beta} = 0 \not\Rightarrow \Gamma_{0\nu\beta\beta} = 0$$

  - Next Order

$$\sum_{i=1}^{3} U_{ei}^2 \frac{m_{\nu_i}}{q^2 - m_{\nu_i}^2} = \frac{1}{q^2} \sum_{i=1}^{3} U_{ei}^2 \left(m_{\nu_i} + \frac{m_{\nu_i}^3}{q^2} \right)$$



Neutrino Mass Probes

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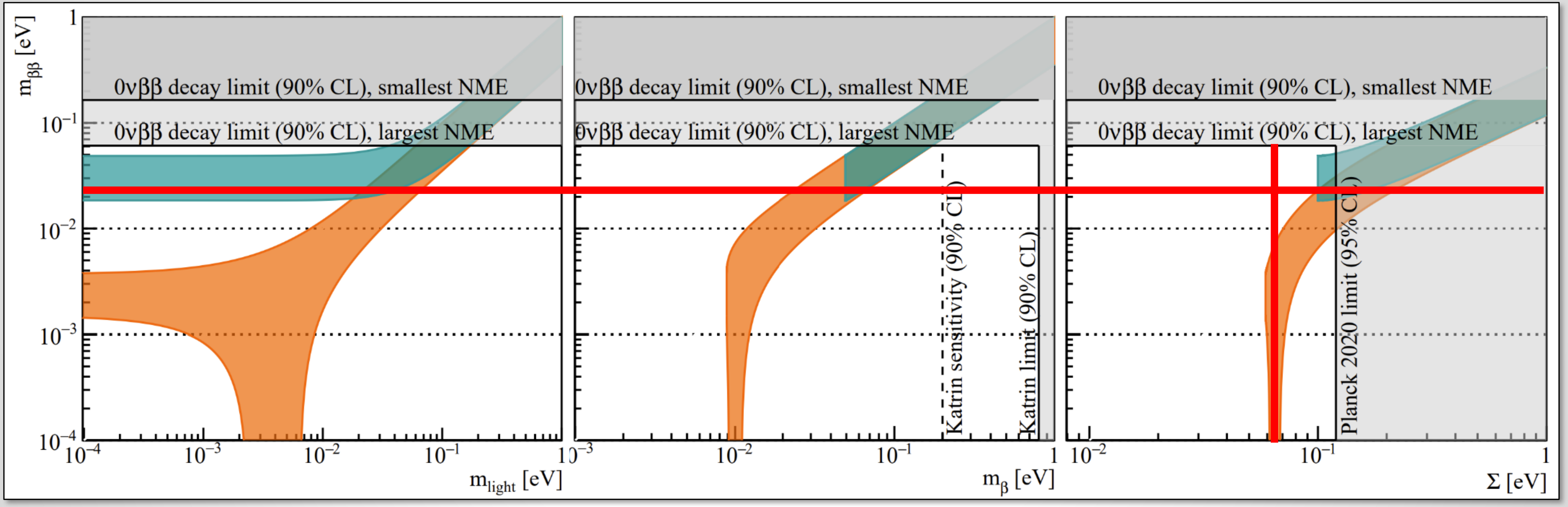
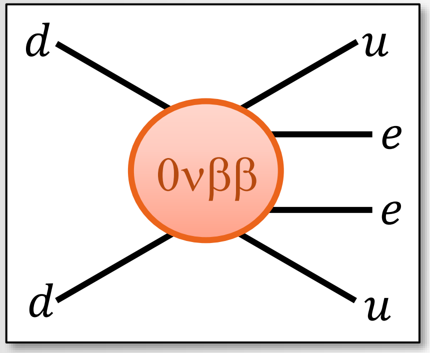
- Concordance (or lack thereof) with oscillations, cosmology and tritium decay



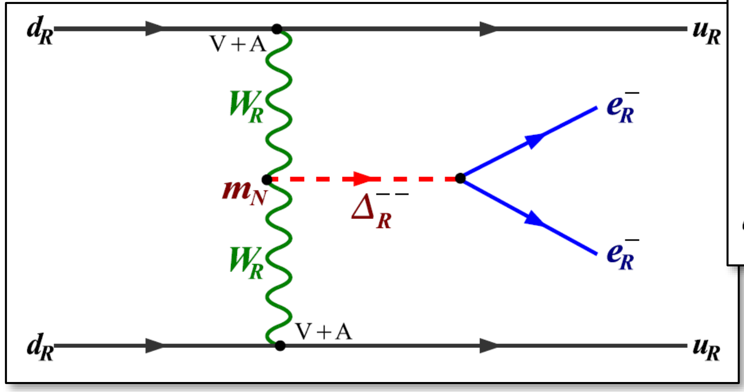
Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002

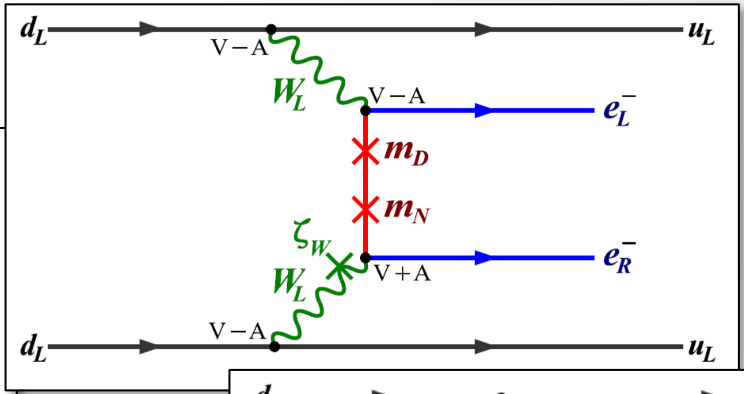
New Physics and $0\nu\beta\beta$

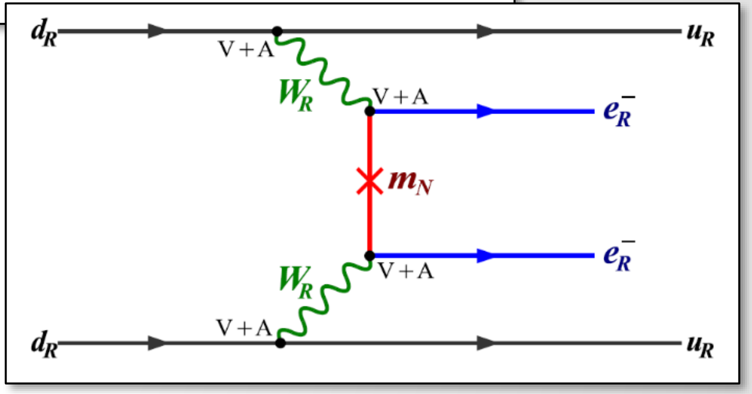
- Plethora of New Physics scenarios



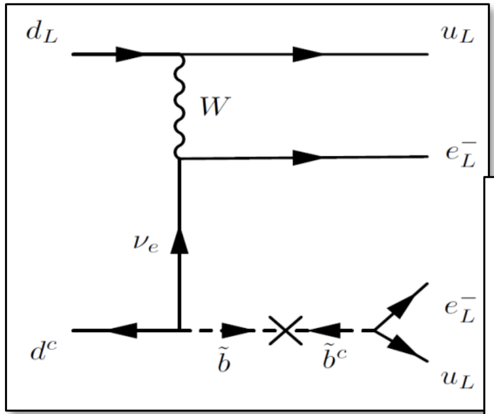
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

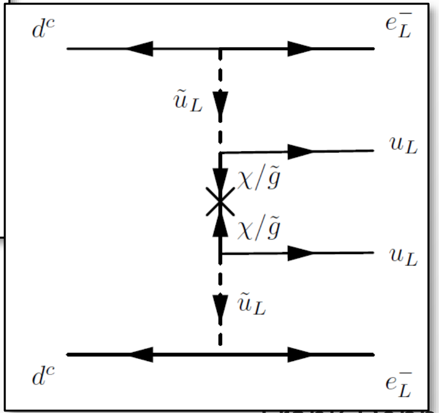






Left-Right Symmetry





R-Parity Violating SUSY

Extra Dimensions

Leptoquarks

…

New Physics and $0\nu\beta\beta$

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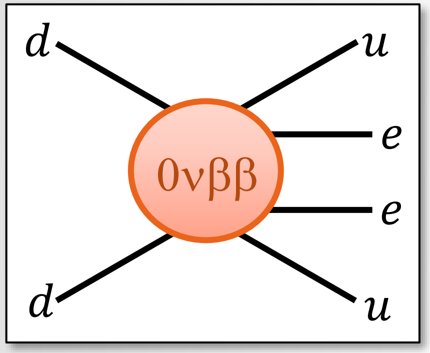
- Plethora of New Physics scenarios



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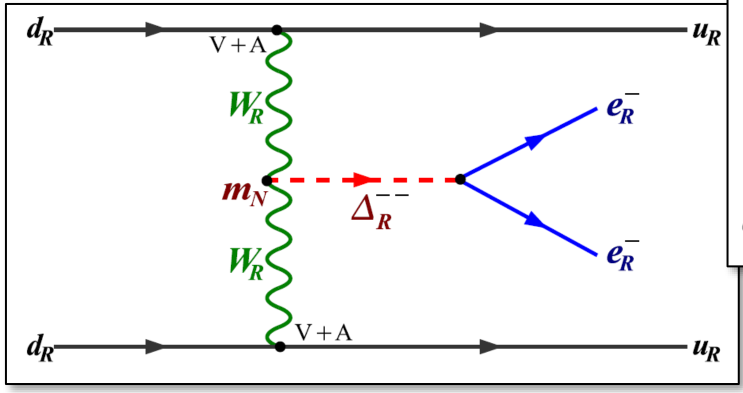

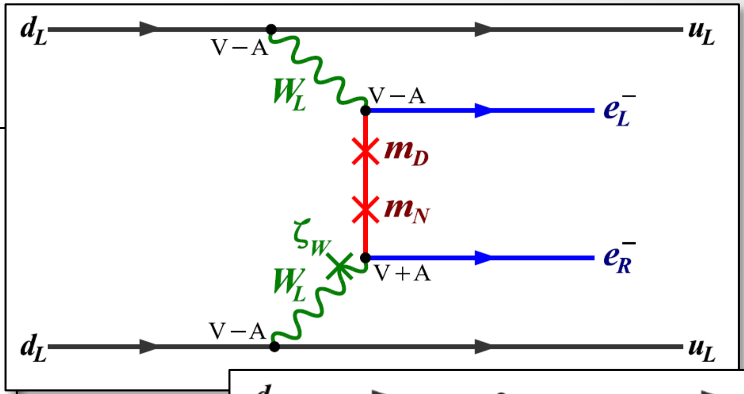

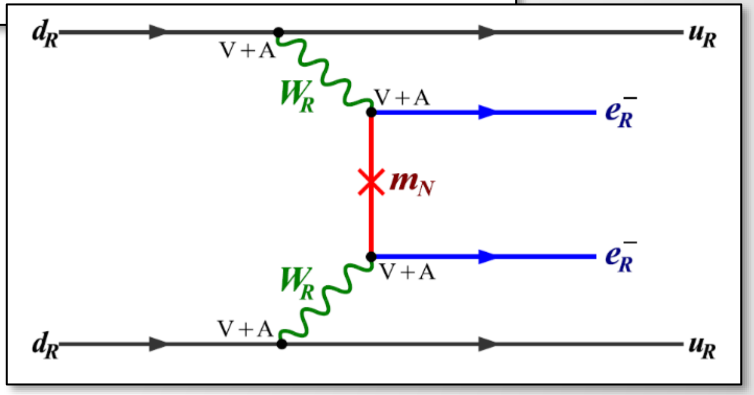

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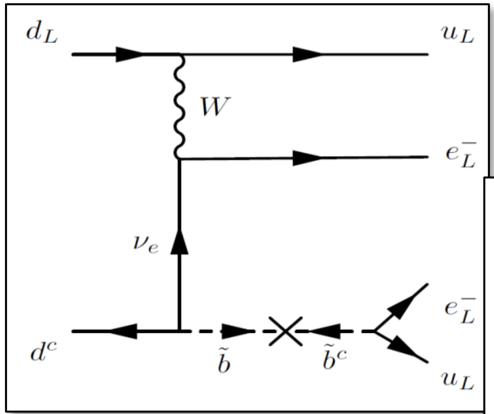

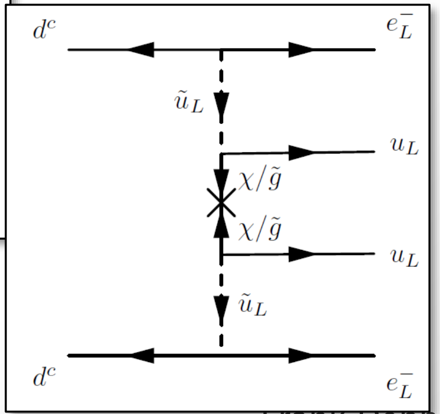

R-Parity Violating SUSY

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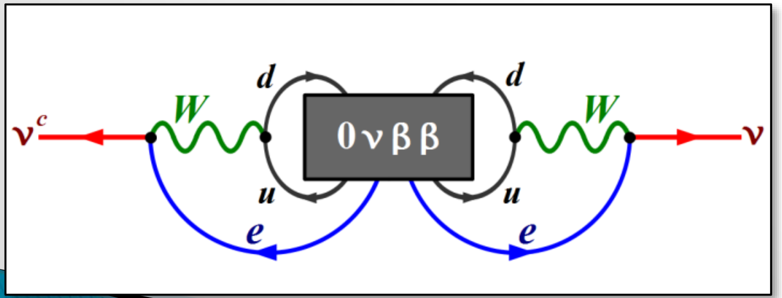
...

- Neutrinos still Majorana



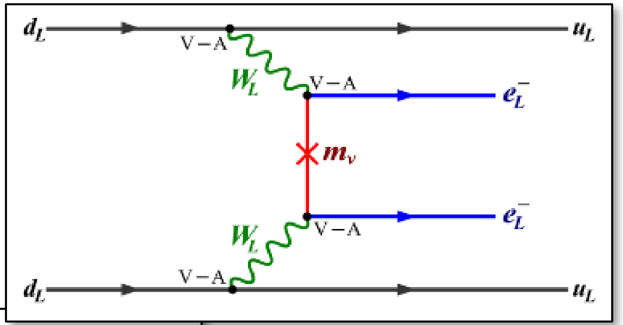
New Physics and $0\nu\beta\beta$

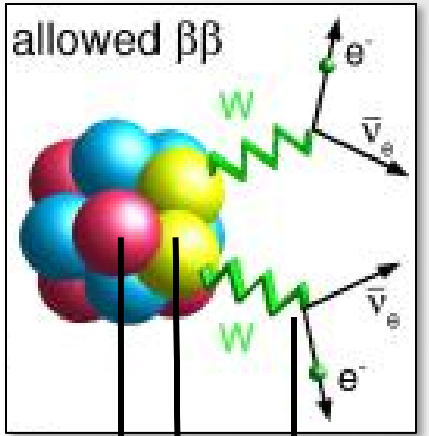
- Decay modes, rates and NP sensitivity
  - $2\nu\beta\beta$ (SM)

$$\boxed{\Gamma^{2\nu}_{SM} \approx G_F^4 Q^{11} p_F^{-2} \approx \left(10^{19}\ yr\right)^{-1}}$$

  - $0\nu\beta\beta$ via Majorana neutrinos

$$\boxed{\Gamma^{0\nu}_{m_\nu} \approx m_\nu^2 G_F^4 Q^5 p_F^2 \approx \left(\frac{m_\nu}{0.1\ eV}\right)^2 \left(10^{25}\ yr\right)^{-1}}$$





$Q \sim 1\ MeV$
energy
release

$G_F \sim 10^{-5} GeV^{-2} \sim v_{EW}^{-2}$
electroweak scale

$p_F \sim 100\ MeV \sim 1\ fm^{-1}$
inter-nucleon distance

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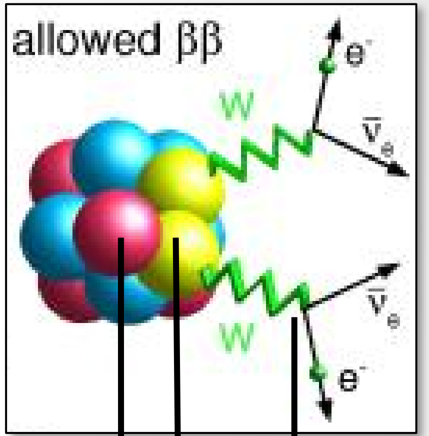
  - $0\nu\beta\beta$ via BSM 7-dim LNV operator

$$\boxed{\Gamma^{0\nu}_{LR} \approx \Lambda^{-6} G_F Q^5 p_F^4 \approx \left(\frac{20\,TeV}{\Lambda}\right)^6 \left(10^{25}\,yr\right)^{-1}}$$



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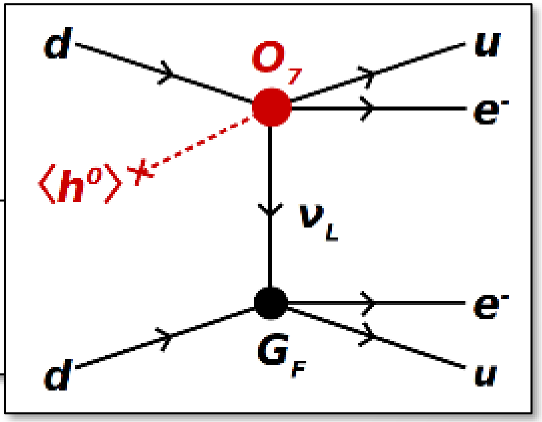

See talk by Xia-Dong Ma

New Physics and $0\nu\beta\beta$

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- Decay modes, rates and NP sensitivity
  - $2\nu\beta\beta$ (SM)

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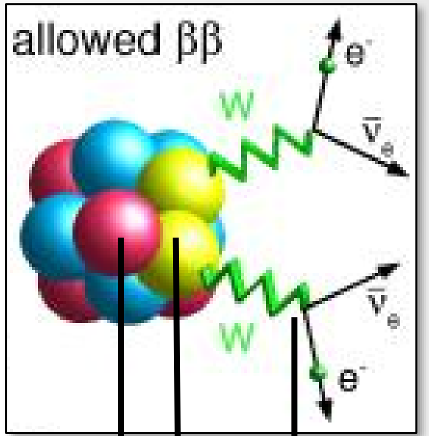
  - $0\nu\beta\beta$ via BSM 9-dim LNV operator

$$\boxed{\Gamma^{0\nu}_{SR} \approx \Lambda^{-10} Q^5 p_F^6 \approx \left(\frac{4\,TeV}{\Lambda}\right)^{10} \left(10^{25}\,yr\right)^{-1}}$$



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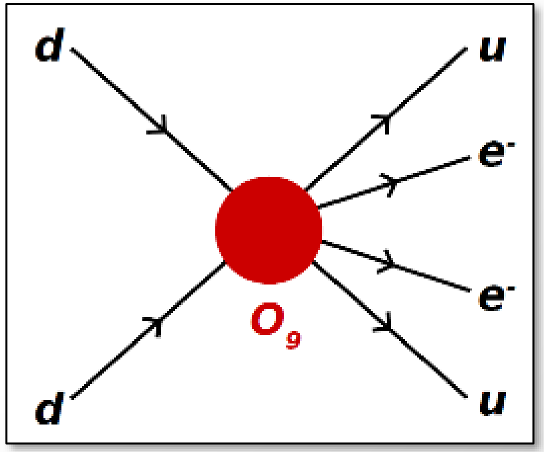
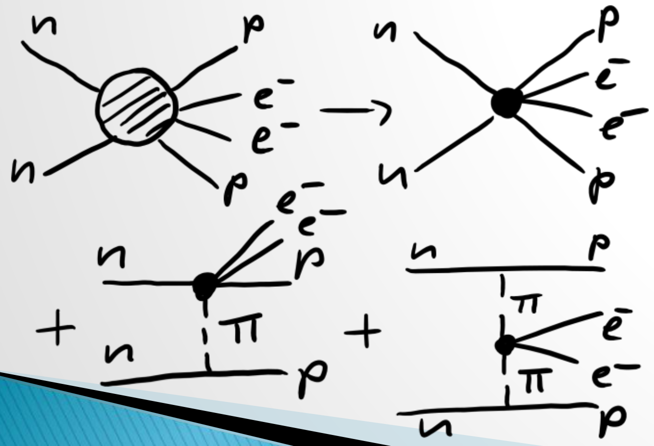
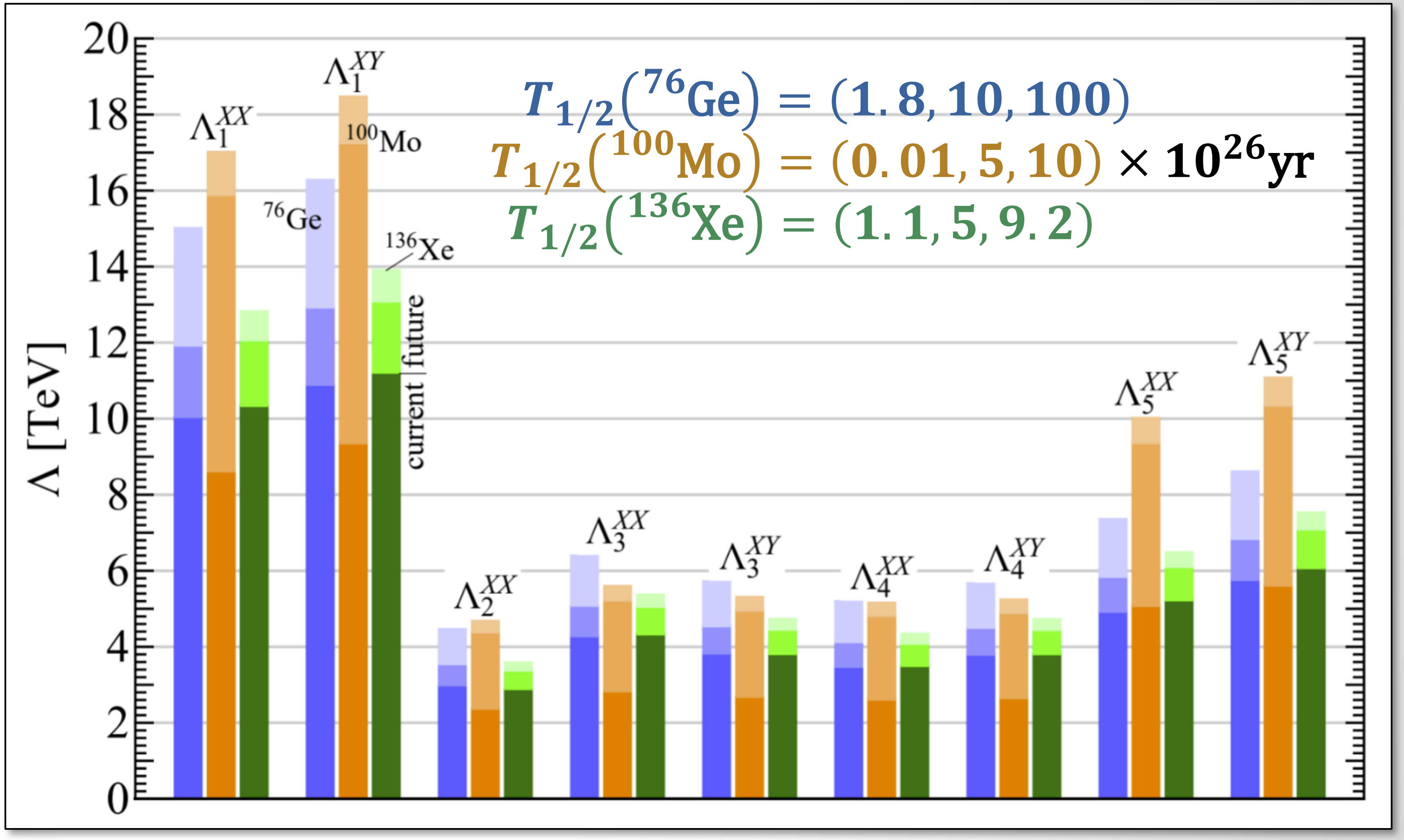


New Physics and $0\nu\beta\beta$

FFD, Graf, Iachello, Kotila, PRD 102 (2020)

- Limits on short-range operators
  - NMEs from IBM-2 with $g_A = 1.0$
  - Pion-mediated contributions, e.g., R-parity violating SUSY (Faessler, Kovalenko, Simkovic, Schwieger, PRL 78 (1997) 183)

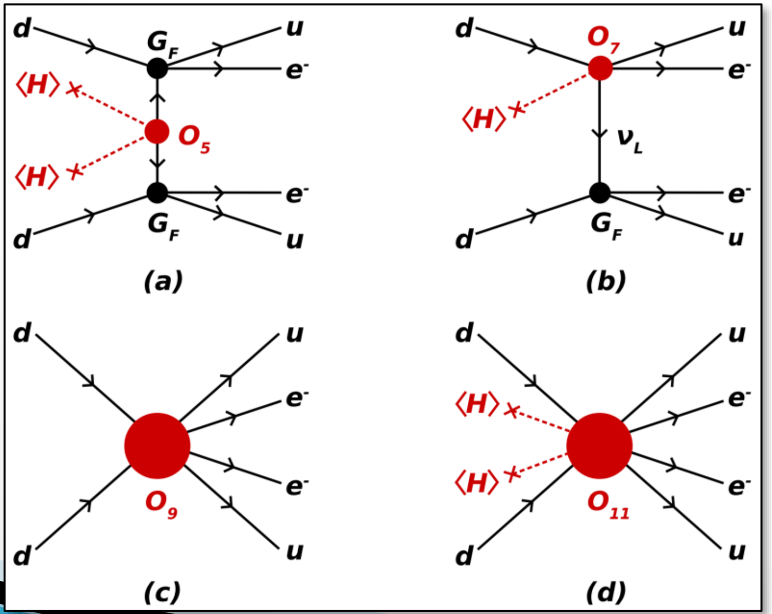


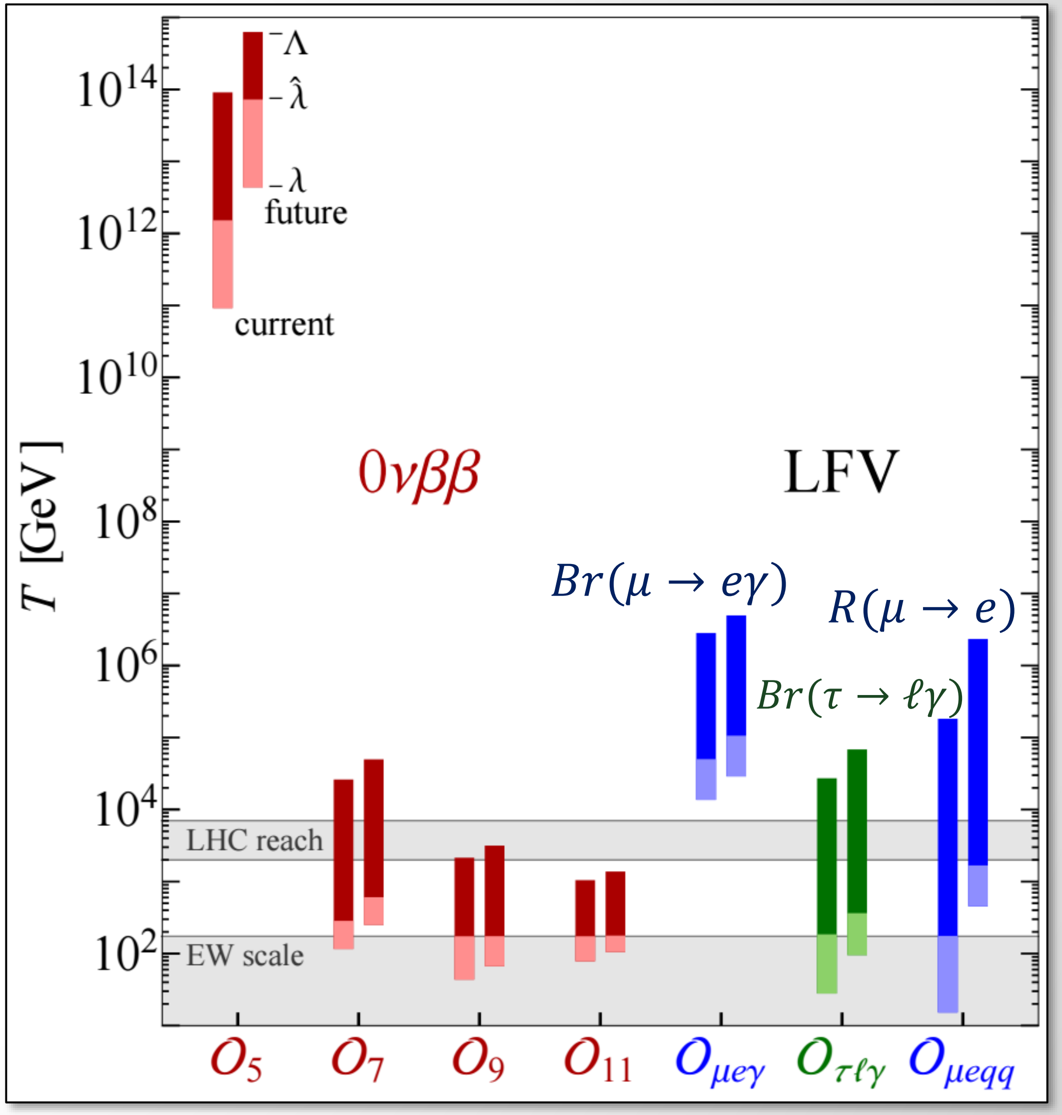


Falsifying Baryogenesis

FFD, Harz, Hirsch, PRL 112 (2014) | FFD, Harz, Hirsch, Huang, Päs, PRD 92 (2015)

- LNV processes lead to washout of lepton asymmetry in early universe
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**

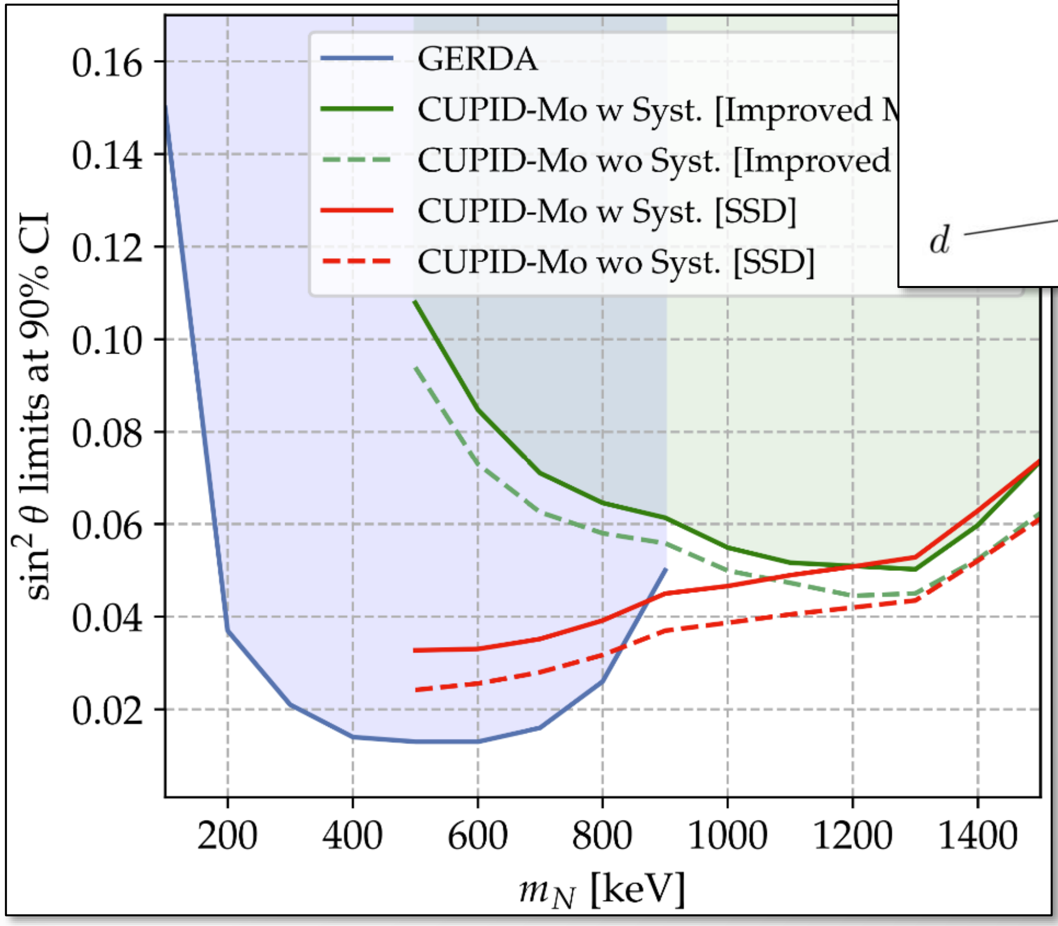


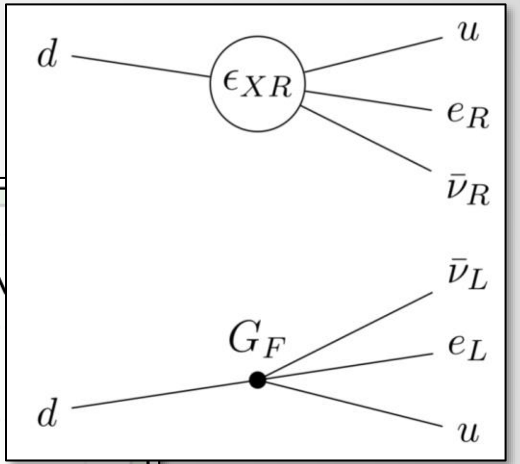


New Physics in $2\nu\beta\beta$

FFD, Graf, Simkovic, PRL 125 (2020) | FFD, Graf, Rodejohann, Xu, PRD 102 (2020)

- Sterile neutrino search through energy endpoint (also: Agostini, Bossio, Ibarra, Marcano, PLB 815 (2021))
  - Emission of one sterile neutrino in double beta decay: $\nu N\beta\beta$
  - Observed limits:
    - GERDA (JCAP 12 (2022) 012)
    - CUPID-Mo (Eur.Phys.J.C 84 (2024) 9)





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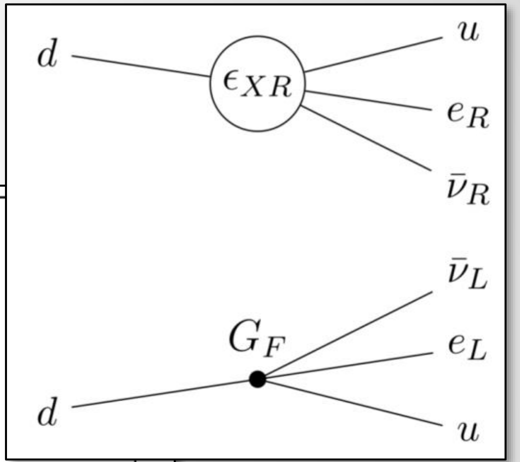
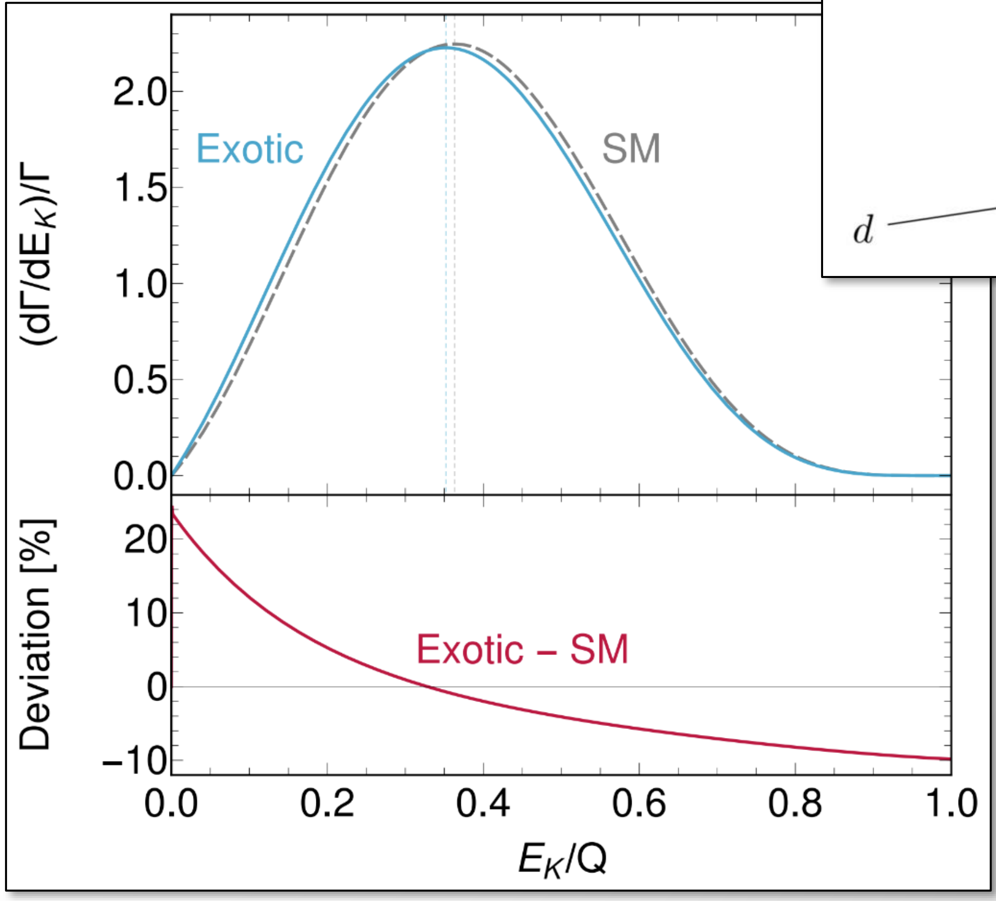
  - LEGEND analysis ongoing





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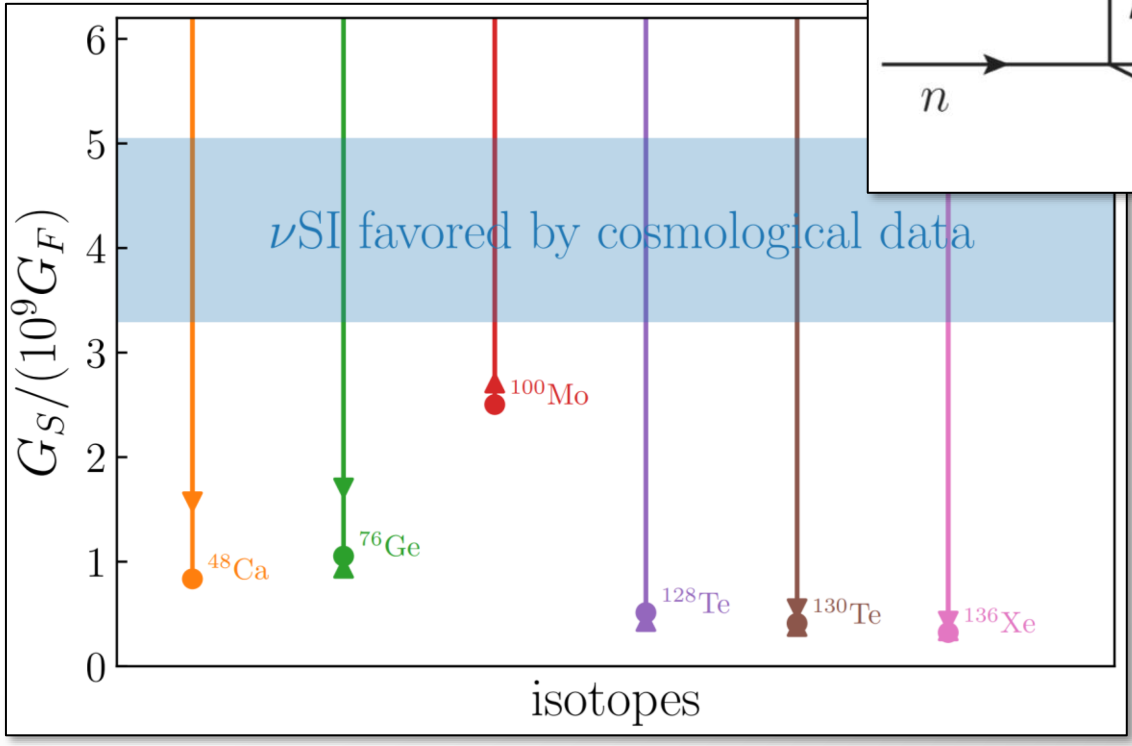
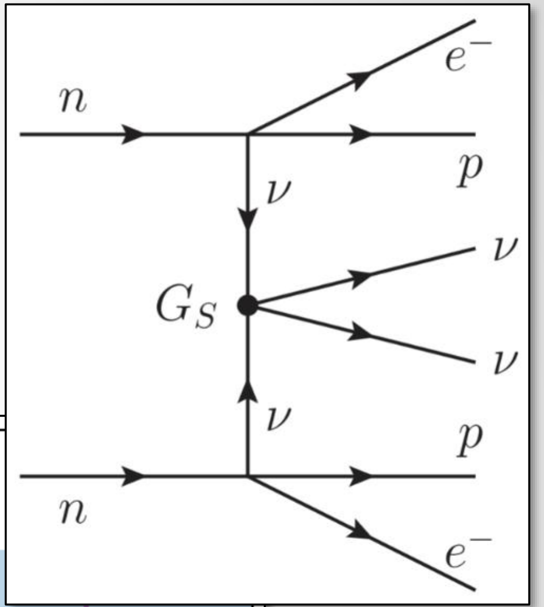
- Neutrino self-interactions
  - Excluding νSI motivated by Hubble tension





Exotic Particle Emission

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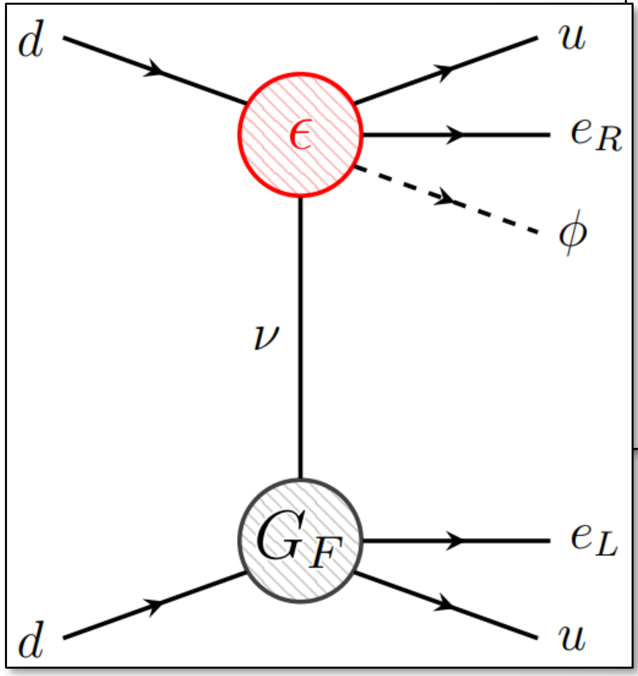
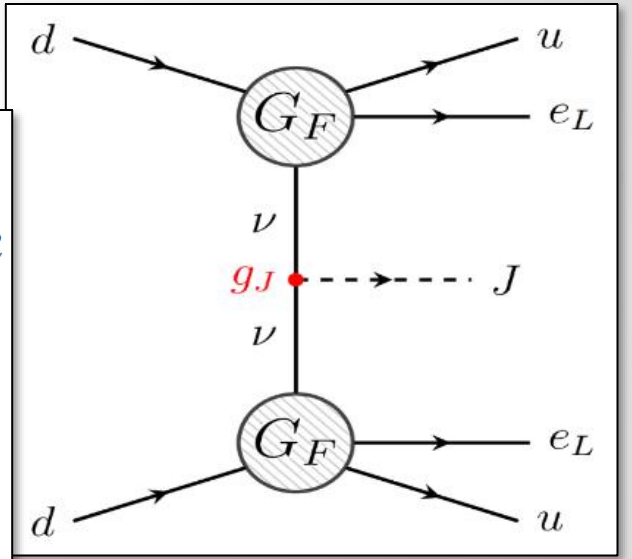
Cepedello, FFD, González, Hati, Hirsch, PRL 122 (2019) | Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Majoron(-like) J emission
- Majoron-like ϕ emission assisted by RH current
  - Non-standard energy distribution
  - Searched for in EXO-200: $T_{1/2} > 4 \times 10^{24}$ y (PRD 104 (2021) 11, 112002)





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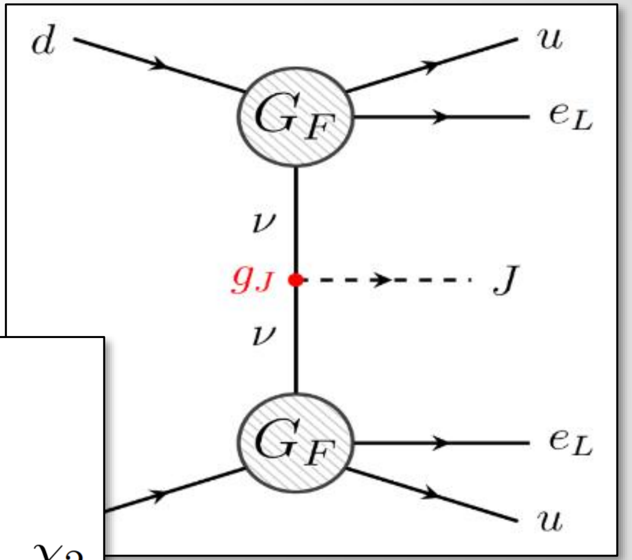
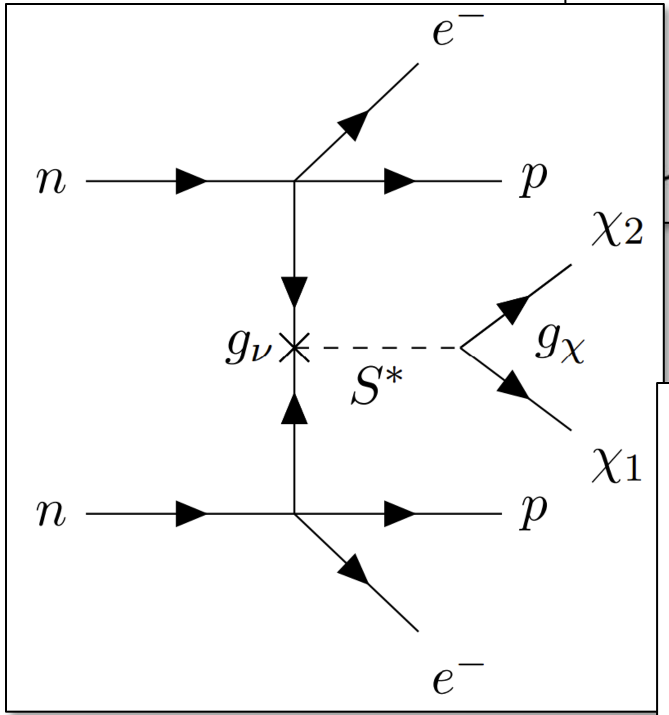
- Dirac neutrinos coupled to massive, L-charged scalar S and fermion χ

$$-\mathcal{L} = \overline{\nu^c}\,(a_\nu P_L + b_\nu P_R)\,\nu S^* + \overline{\chi^c}\,(a_\chi P_L + b_\chi P_R)\,\chi S^* + \text{h.c.}.$$

  - Z_2 symmetry to forbid mixing
  - Self-interacting neutrinos and self-interacting (potentially) DM



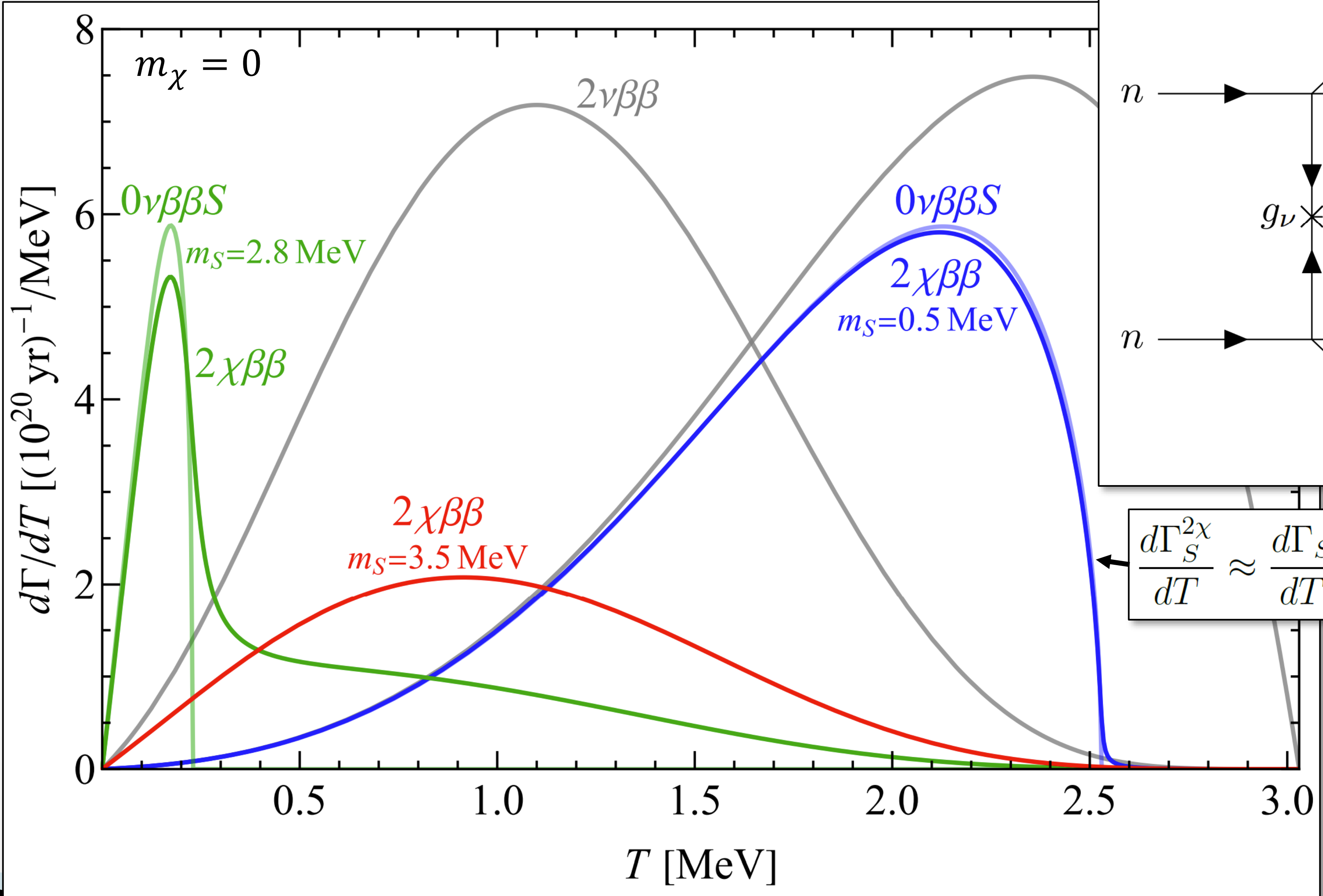


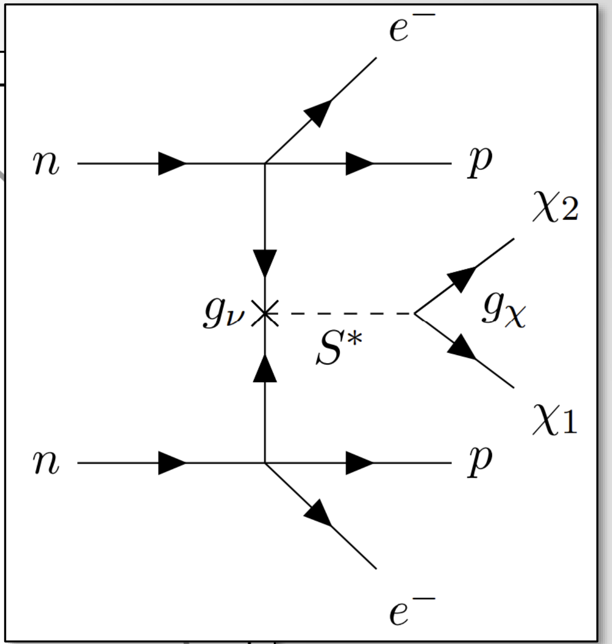
See talk by Michael Ramsey-Musolf; PandaX, 2511.13515; De Vries, Graf, Plakkot, Stary, 2511.19173

Neutrinos coupled to Dark Sector

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Finite width S
- Off-shell S





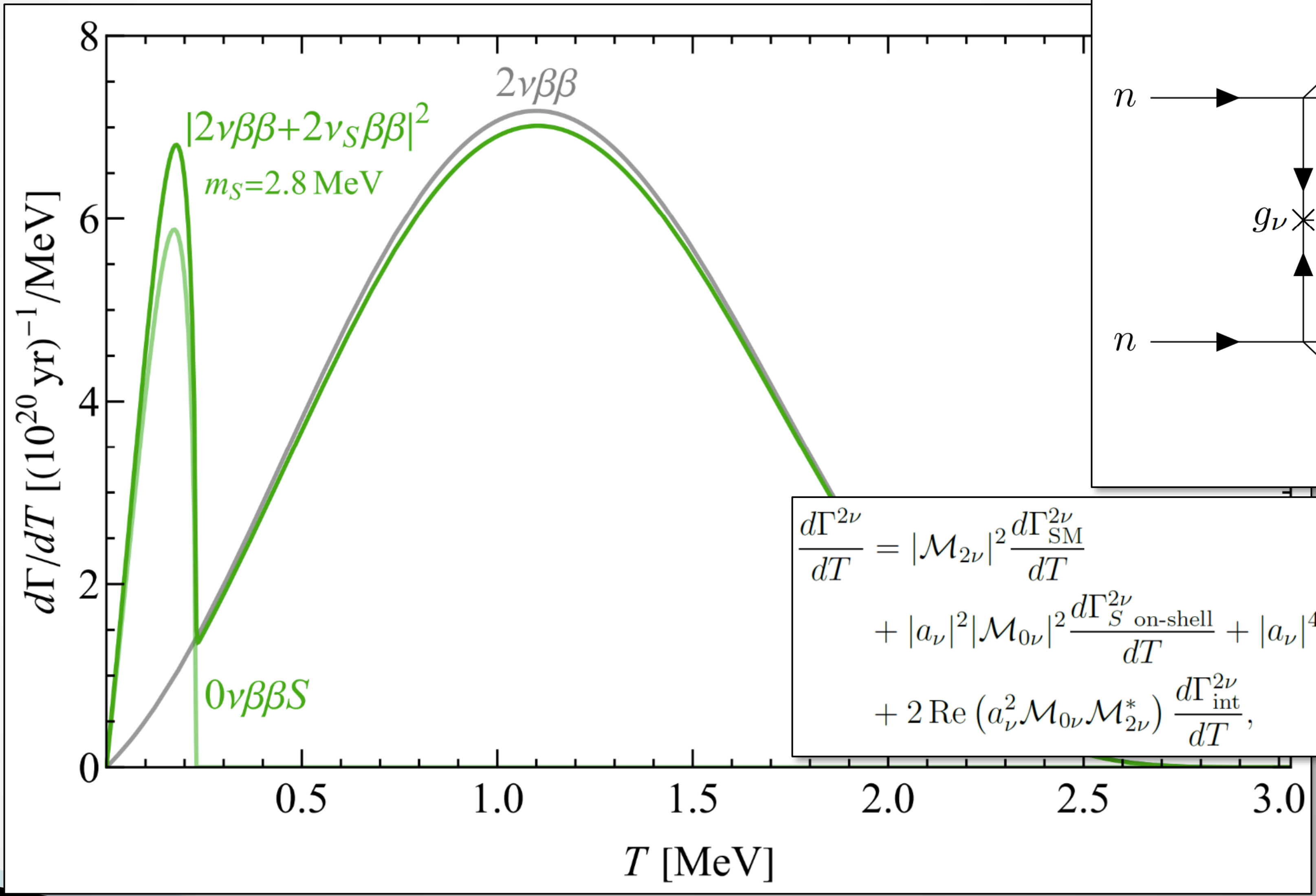
$$\frac{d\Gamma_S^{2\chi}}{dT} \approx \frac{d\Gamma_S}{dT} \times \mathrm{Br}(S \to \chi\chi)$$

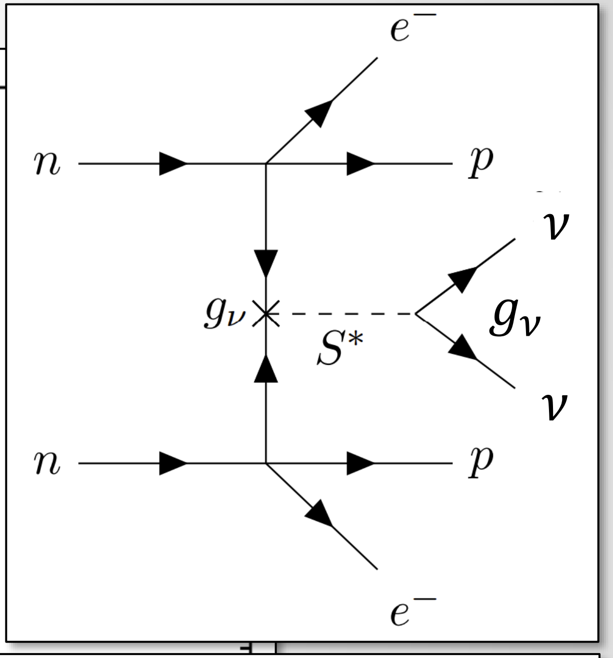
On-shell S in narrow-width approximation

Neutrinos coupled to Dark Sector

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Finite width S
- Off-shell S
- $2\nu_S\beta\beta$ and interference with SM $2\nu\beta\beta$





$$\frac{d\Gamma^{2\nu}}{dT} = |\mathcal{M}_{2\nu}|^2 \frac{d\Gamma^{2\nu}_{\rm SM}}{dT} + |a_\nu|^2 |\mathcal{M}_{0\nu}|^2 \frac{d\Gamma^{2\nu}_{S\ \text{on-shell}}}{dT} + |a_\nu|^4 |\mathcal{M}_{0\nu}|^2 \frac{d\Gamma^{2\nu}_{S\ \text{off-shell}}}{dT} + 2\,\mathrm{Re}\left(a_\nu^2 \mathcal{M}_{0\nu}\mathcal{M}^*_{2\nu}\right) \frac{d\Gamma^{2\nu}_{\rm int}}{dT},$$

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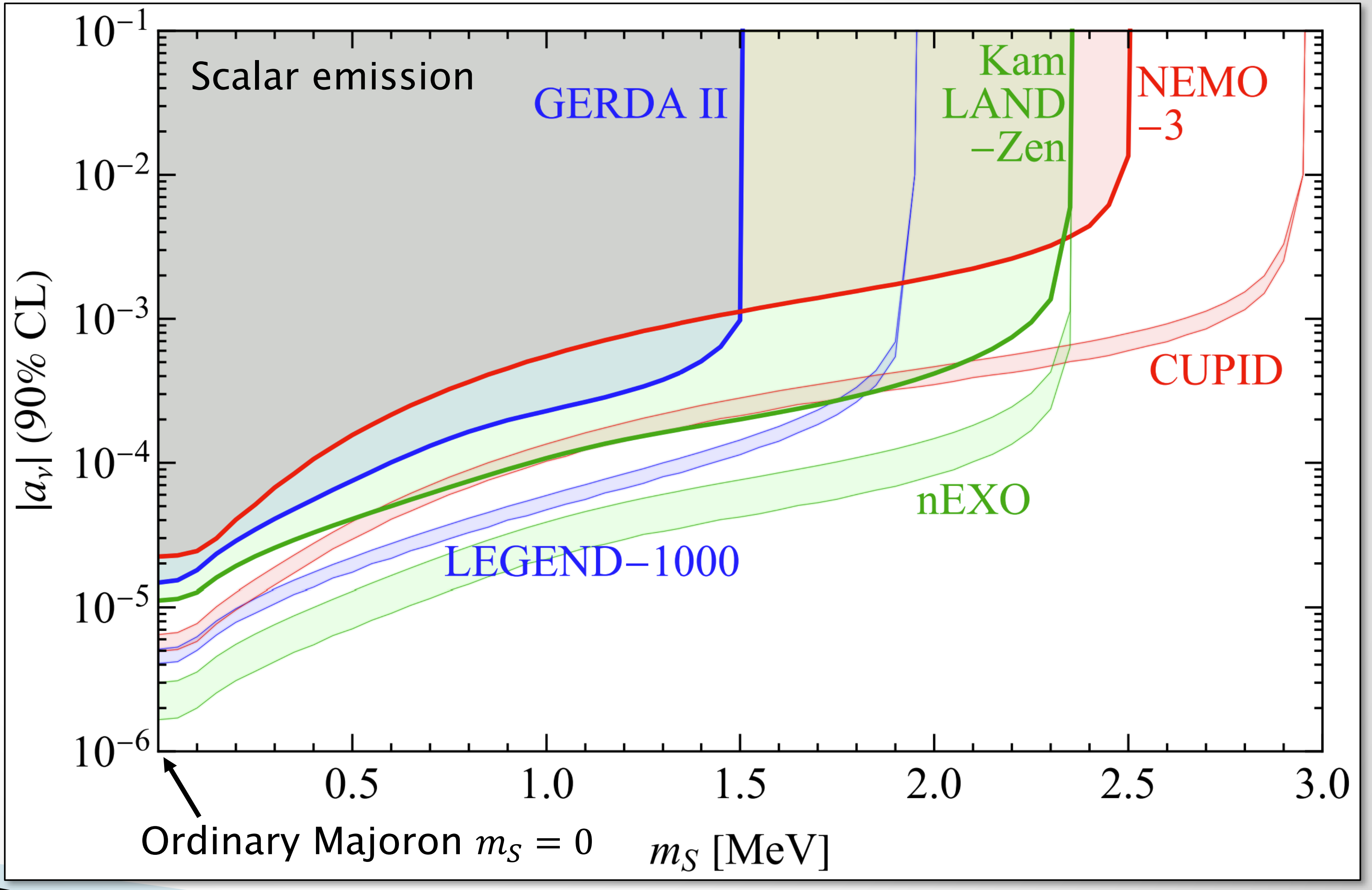
- Finite width S
- Off-shell S
- $2\nu_S\beta\beta$ and interference with SM $2\nu\beta\beta$
- Sensitivity of current and future double beta searches



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Neutrinos coupled to Dark Sector

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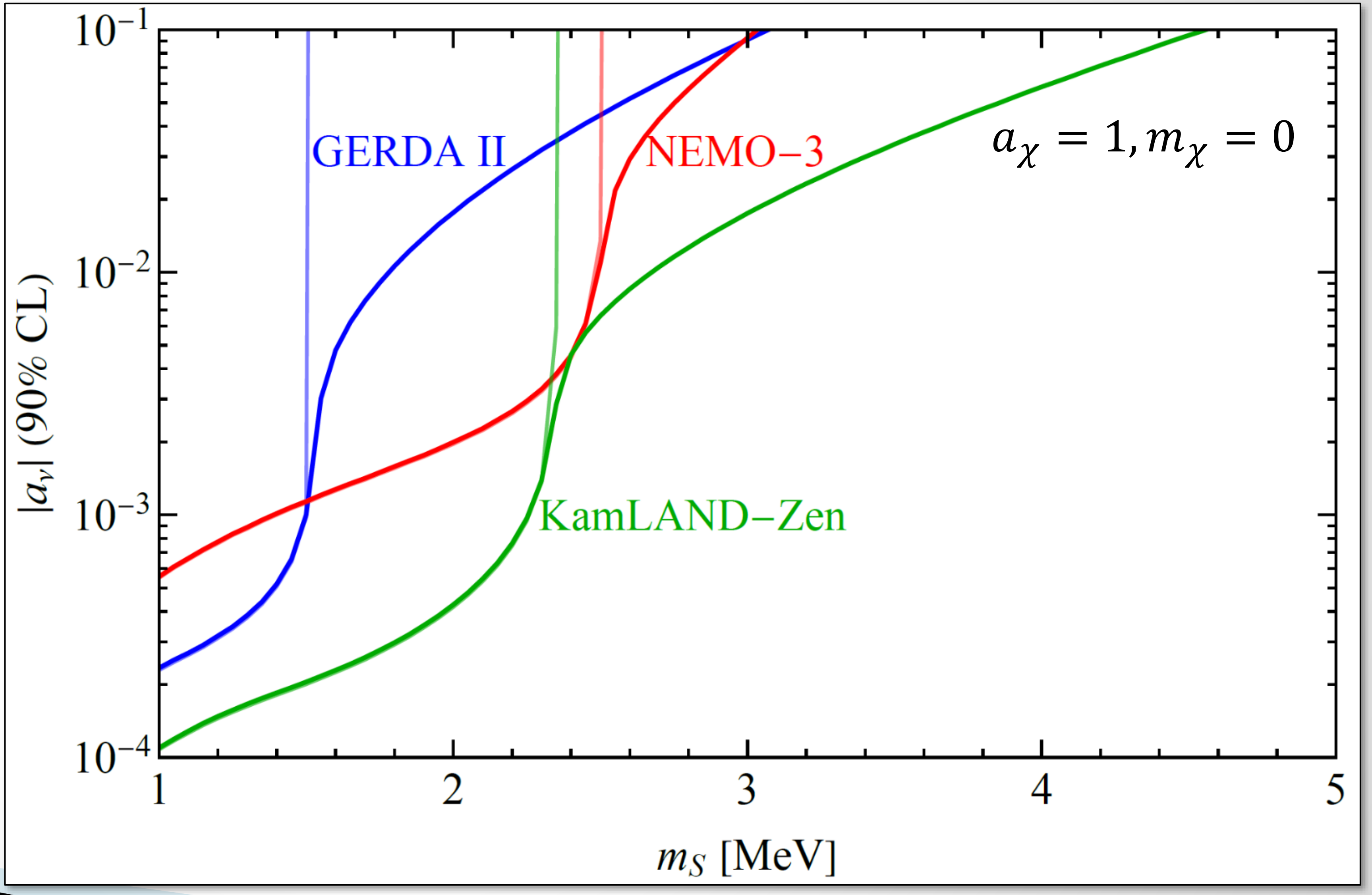
- Finite width S
- Off-shell S
- $2\nu_S\beta\beta$ and interference with SM $2\nu\beta\beta$
- Sensitivity of current and future double beta searches
  - Modification from interference and off-shell S



Conclusion

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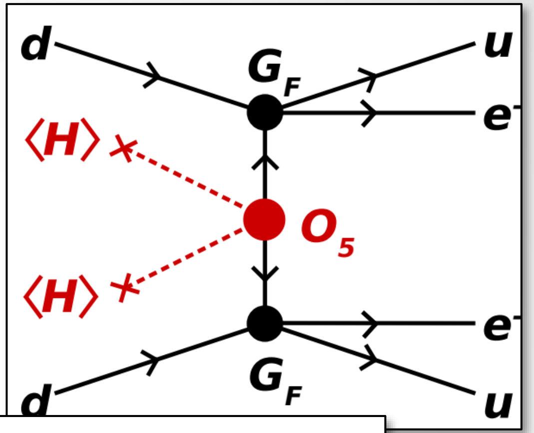
- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana?
  - Mechanism of neutrino mass generation?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Prove neutrino Majorana nature
  - LNV physics near GUT scale and $\Lambda \approx 1\,\mathrm{eV} - 100\,\mathrm{TeV}$
  - Falsify high-scale baryogenesis scenarios
- **$2\nu\beta\beta$ spectrum sensitive to New Physics**
  - Non-standard ν interactions, sterile ν
  - Neutrino self-interactions and dark sector interactions
    - Strongest terrestrial limits $|g_{\nu_e S}| < 10^{-5} - 10^{-1}$ for $m_S < 3 - 5\,\mathrm{MeV}$



$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\,\mathrm{y}} \approx \left(\frac{\Lambda_{\mathrm{NP}}}{10^{15}\,\mathrm{GeV}}\right)^2$$