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Probing New Physics with Double Beta Decay

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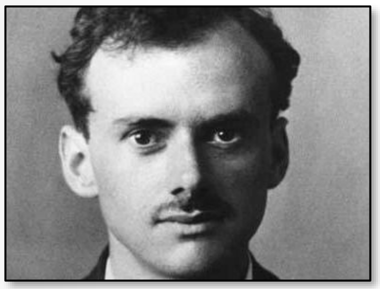
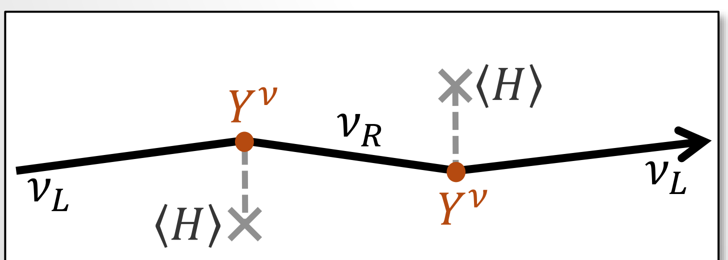
Dirac versus Majorana

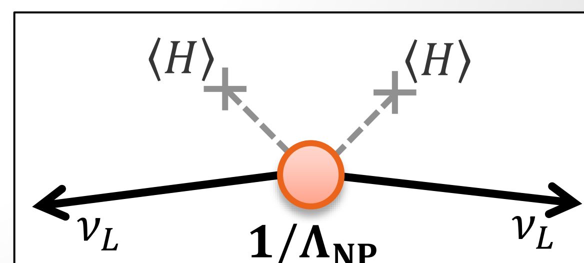
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass



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

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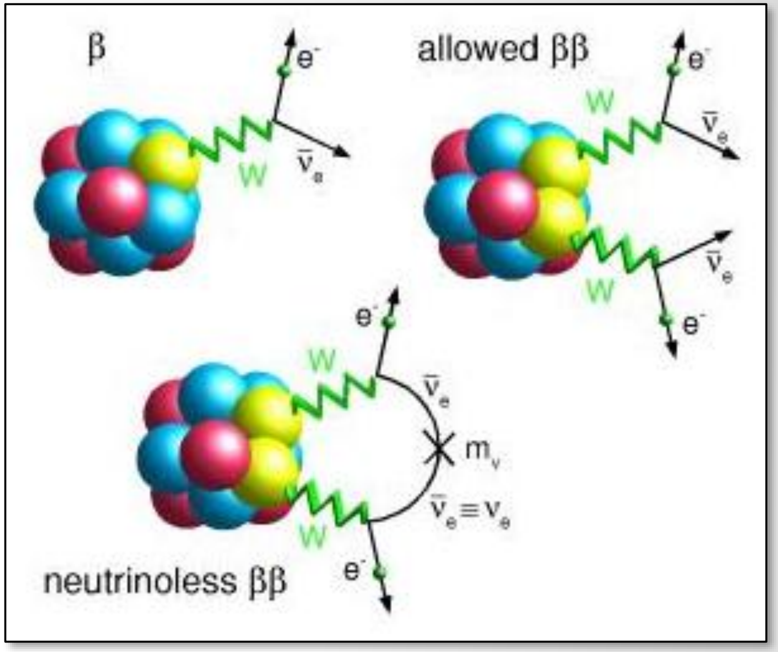
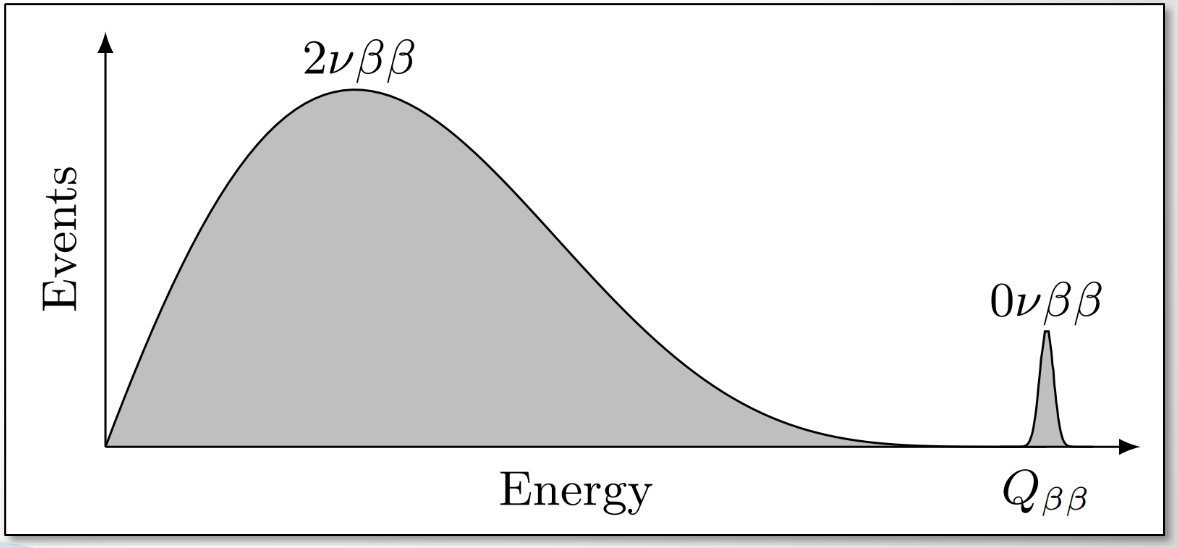
- Single beta decay
  $$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A, Z) \to (A, Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by massive Majorana neutrinos





Neutrinoless Double β Decay

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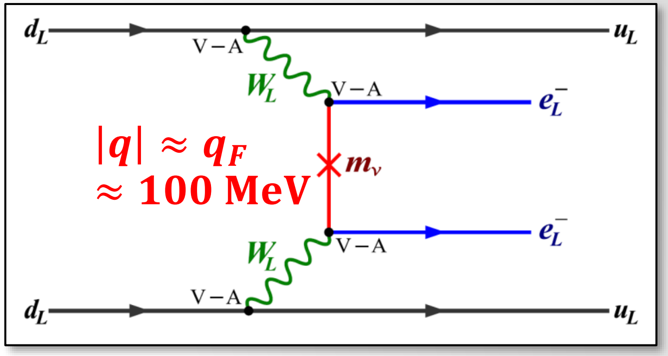
- Half-life

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

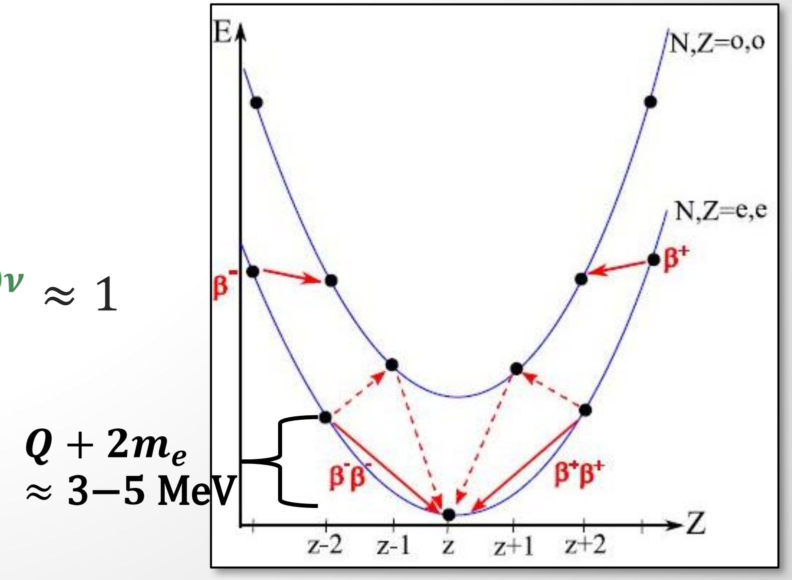


- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\boxed{\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}} \rightarrow m_{\beta\beta}$$

- 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

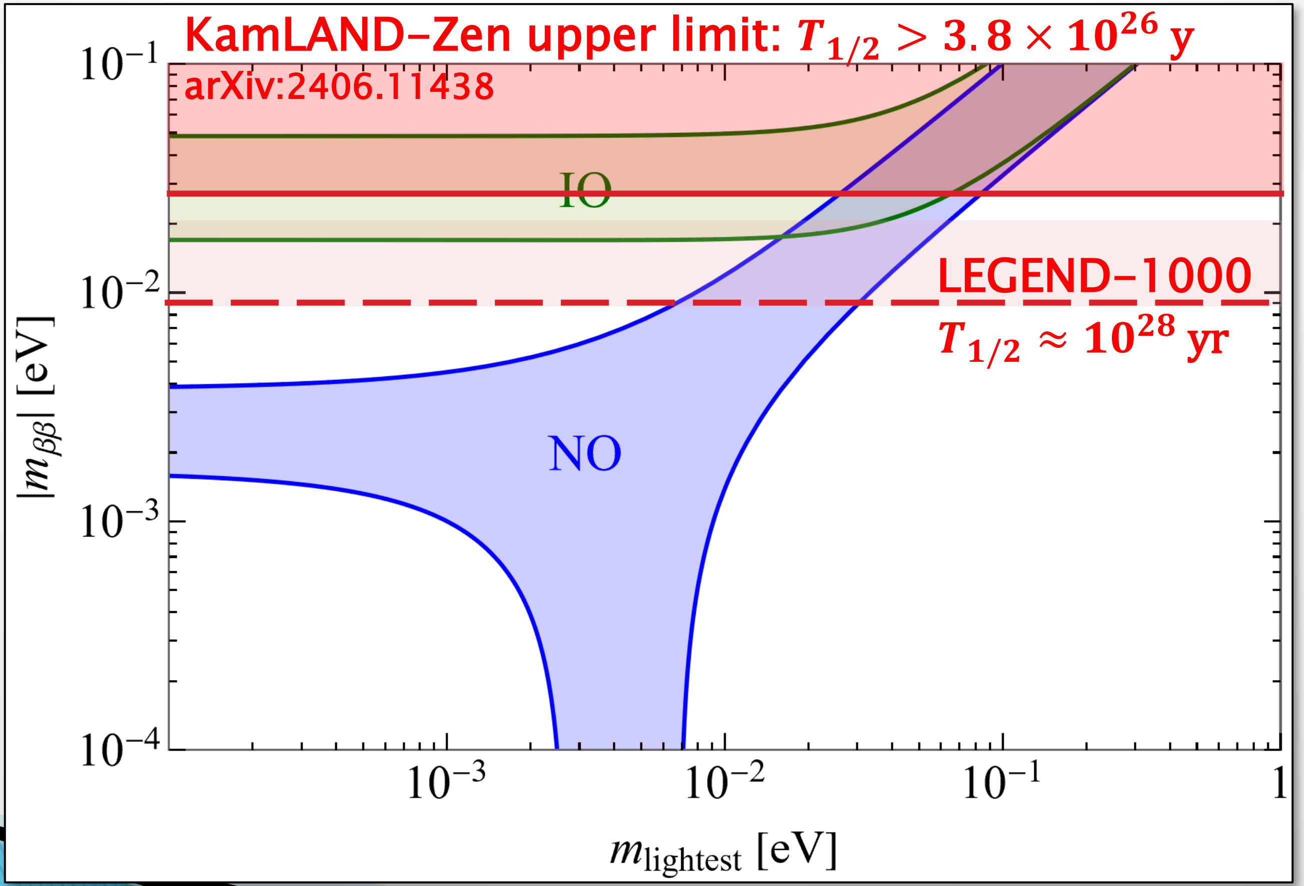
$$\boxed{\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{0.1\ \mathrm{eV}}\right)^2}$$



Three Active Neutrinos

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

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}| \underbrace{\approx}_{\text{degenerate } \nu \text{ \& } \theta_{13} \approx 0} m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2(\phi_{12}/2)}$$



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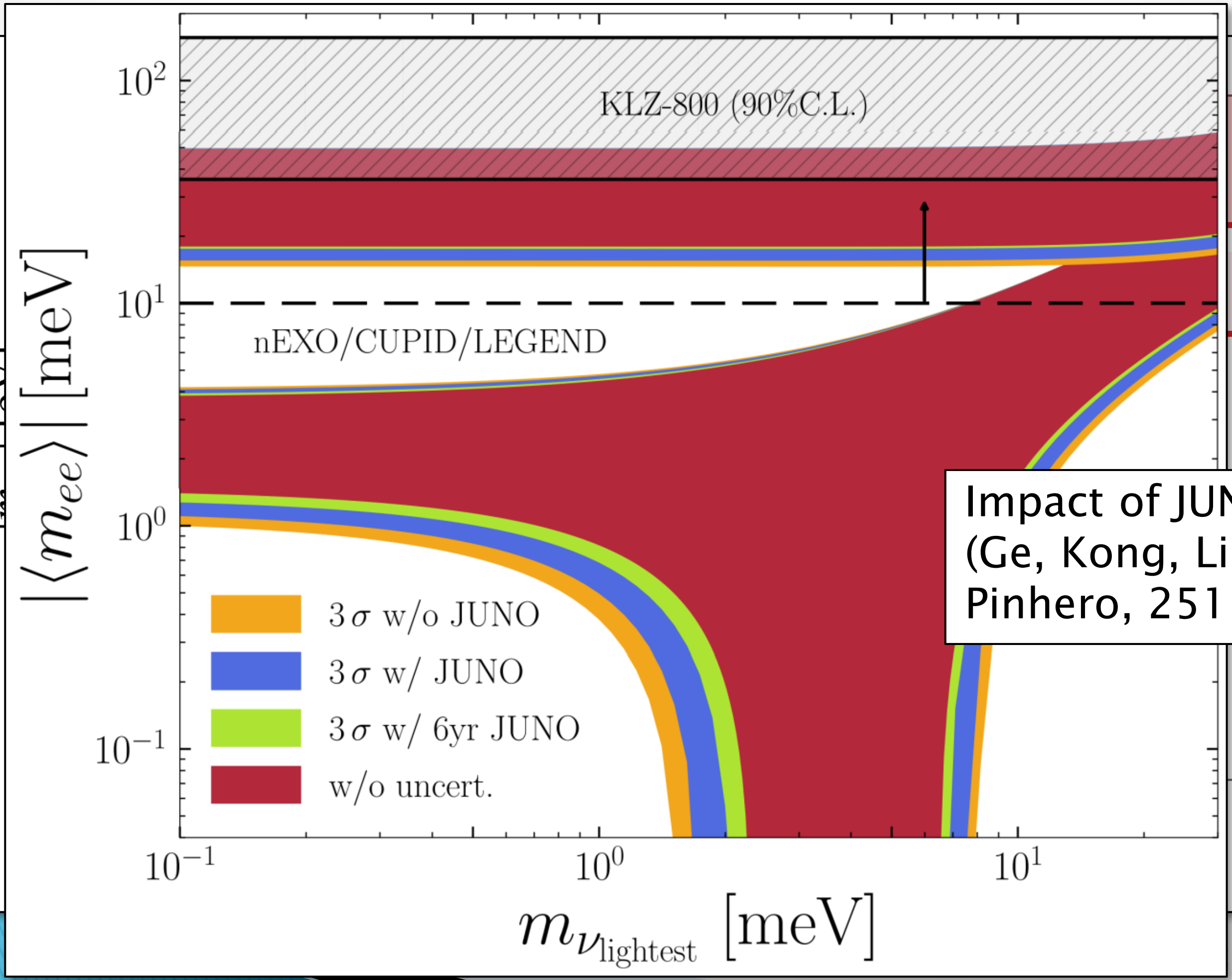
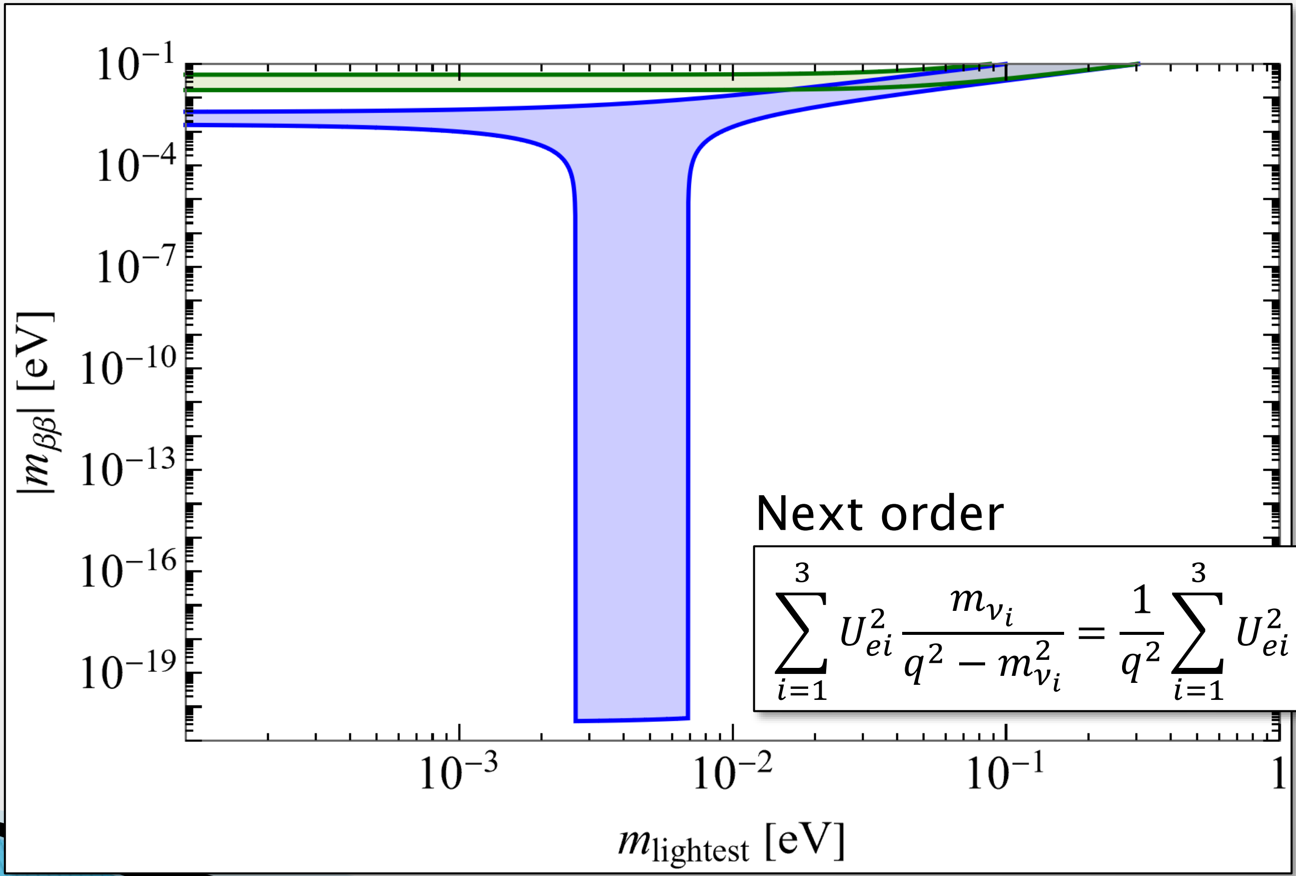


Impact of JUNO (first) data (Ge, Kong, Lindner, Pinhero, 2511.15391)

Three Active Neutrinos

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

$$\boxed{m_{\beta\beta} = 0 \not\rightarrow \Gamma_{0\nu\beta\beta} = 0}$$

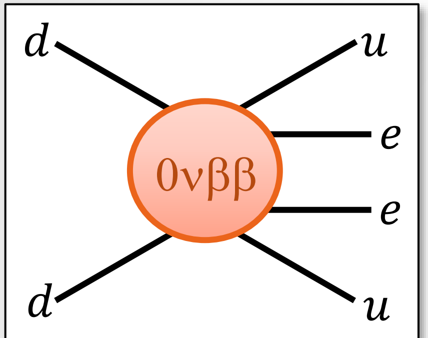


Next order

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

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

- Plethora of New Physics scenarios



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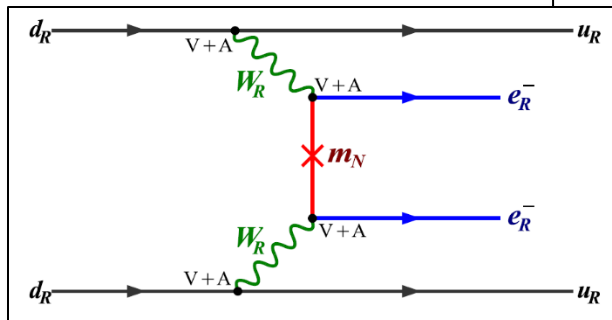
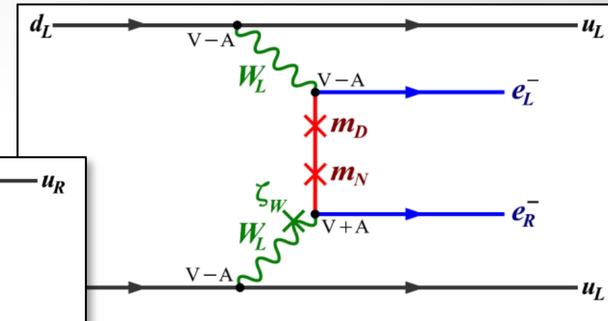
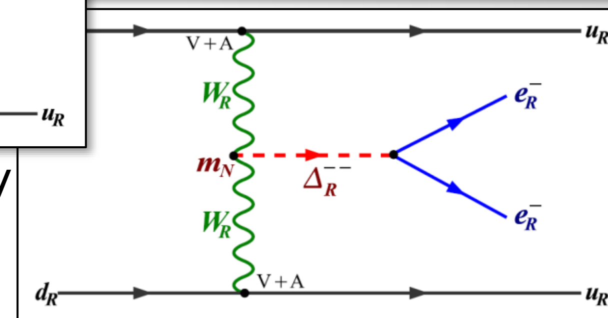
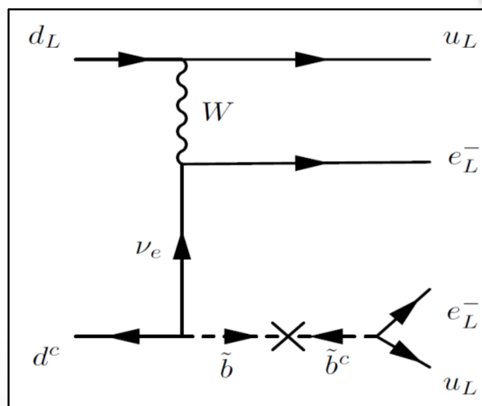


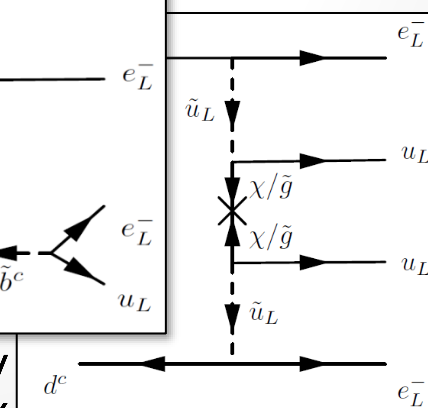




Left-Right Symmetry

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





R-Parity Violating SUSY

Extra Dimensions

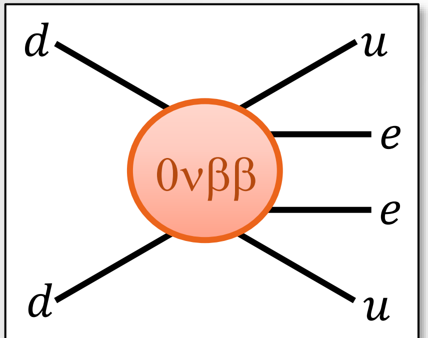
Majorons

Leptoquarks

...

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

- Plethora of New Physics scenarios



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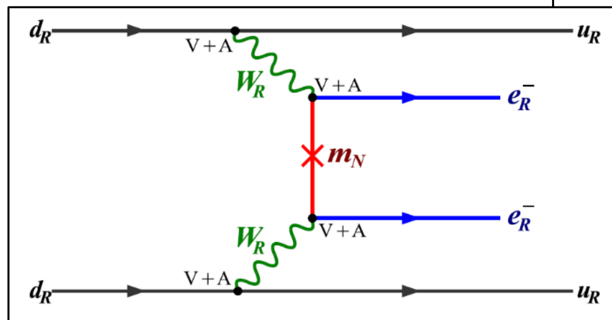
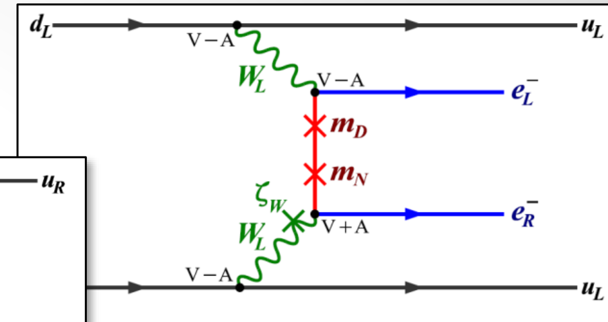
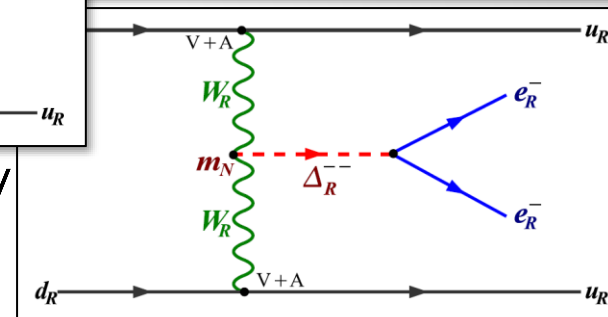


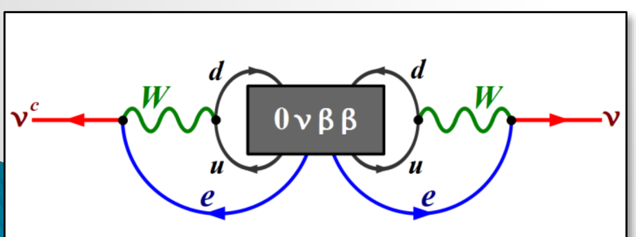


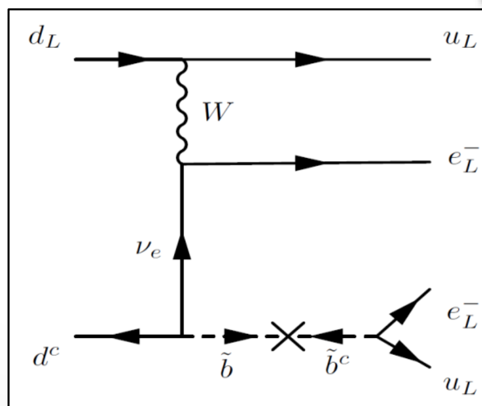


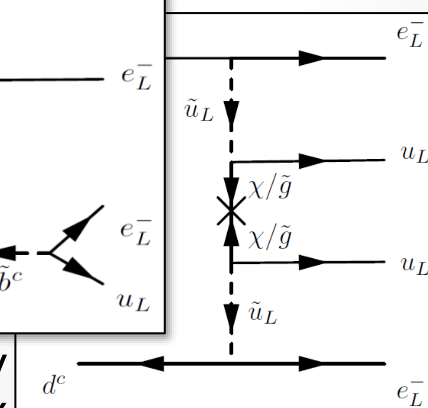
Left–Right Symmetry

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

- Neutrinos still Majorana
  Schechter, Valle, Phys.Rev.D 25 (1982) 2951







R–Parity Violating SUSY

Extra Dimensions

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…

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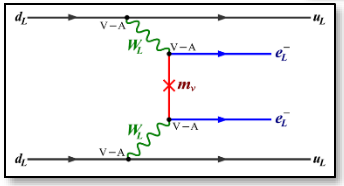
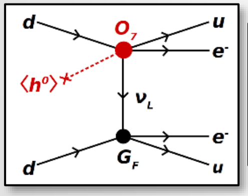
New Physics and $0\nu\beta\beta$

- Decay modes, rates and NP sensitivity
  - $2\nu\beta\beta$ (SM) $\boxed{\Gamma^{2\nu}_{SM} = G_F^4 Q^{11} p_F^{-2} \approx \left(10^{19}\, yr\right)^{-1}}$
  - $0\nu\beta\beta$ via Majorana neutrinos

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



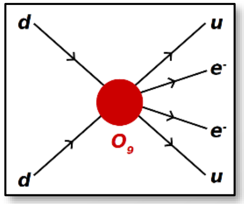
  - $0\nu\beta\beta$ via BSM 7-dim LNV operator



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

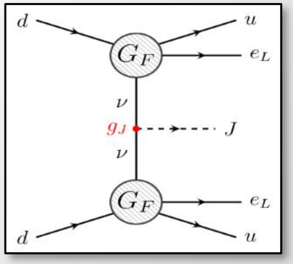
  - $0\nu\beta\beta$ via BSM 9-dim LNV operator

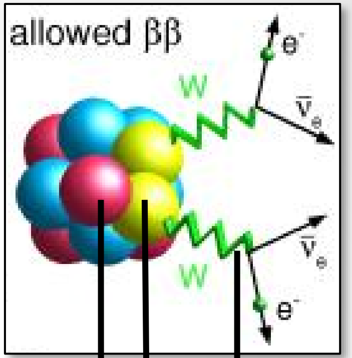
$$\boxed{\Gamma^{0\nu}_{SR} = \Lambda^{-10} Q^5 p_F^6 \approx \left(\frac{4\, TeV}{\Lambda}\right)^{10} \left(10^{25}\, yr\right)^{-1}}$$



  - $0\nu\beta\beta J$ ordinary Majoron emission

$$\boxed{\Gamma^{0\nu J} = g^2 G_F^4 Q^7 p_F^2 \approx \left(\frac{g}{10^{-5}}\right)^2 \left(10^{21}\, yr\right)^{-1}}$$





$Q \sim 1\, MeV$ energy release

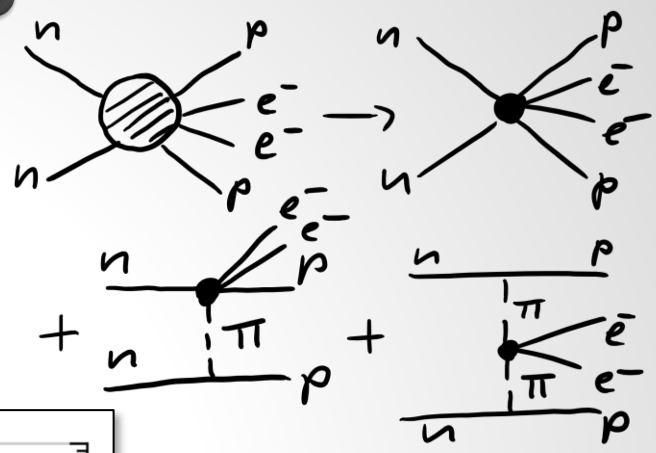
$G_F \sim 10^{-5} GeV^{-2} \sim v_{EW}^{-2}$ electroweak scale

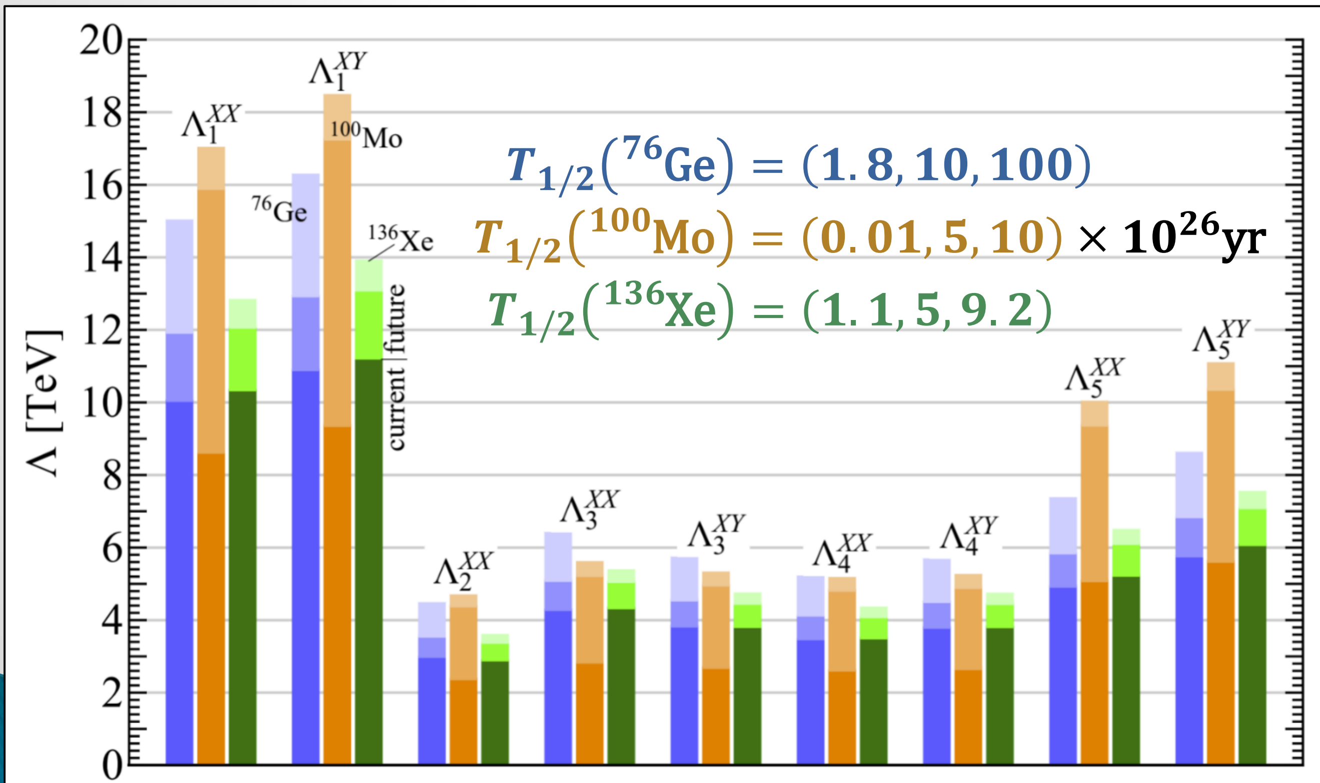
$p_F \sim 100\, MeV \sim 1\, fm^{-1}$ inter-nucleon distance

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

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

- Limits on short-range operators
  - NMEs from IBM-2 with $g_A = 1.0$ and short-range correlations in Argonne parametrization





Pion-mediated contributions

- R-parity violating SUSY (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
- Chiral EFT with Pion operators from Lattice QCD (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)

Falsifying Baryogenesis

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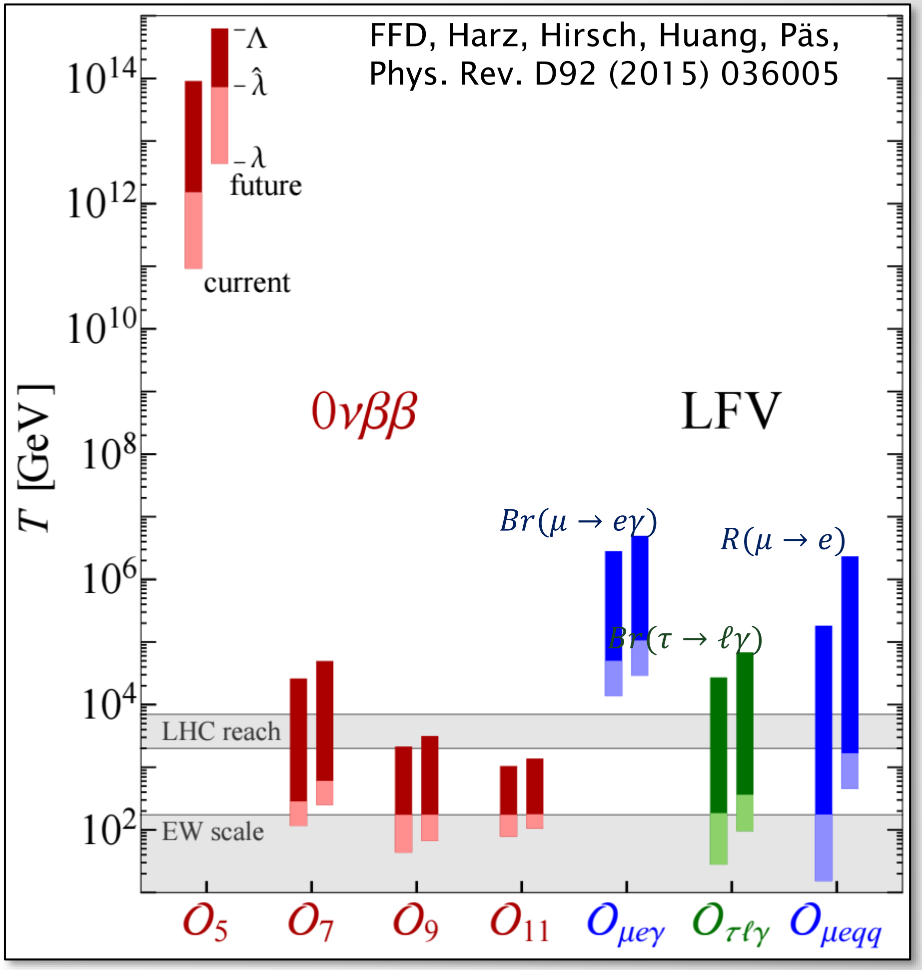
FFD, Harz, Hirsch, PRL 112 (2014) | FFD, Harz, Hirsch, Huang, Päs, PRD 92 (2015)

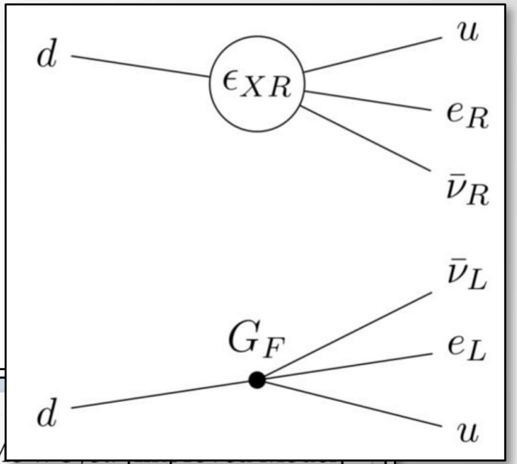
- LNV processes lead to washout of lepton asymmetry in early universe
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**

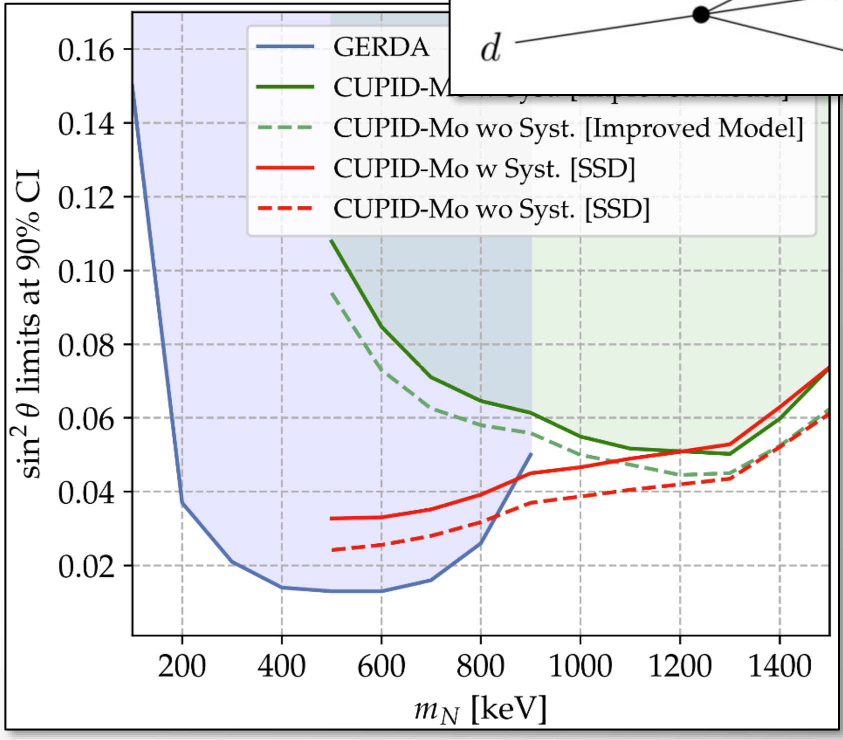


New Physics in $2\nu\beta\beta$

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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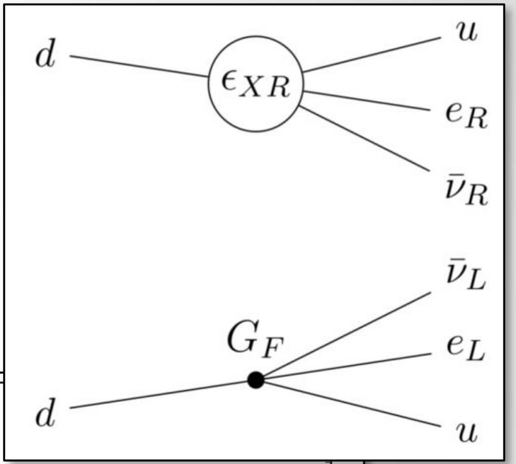
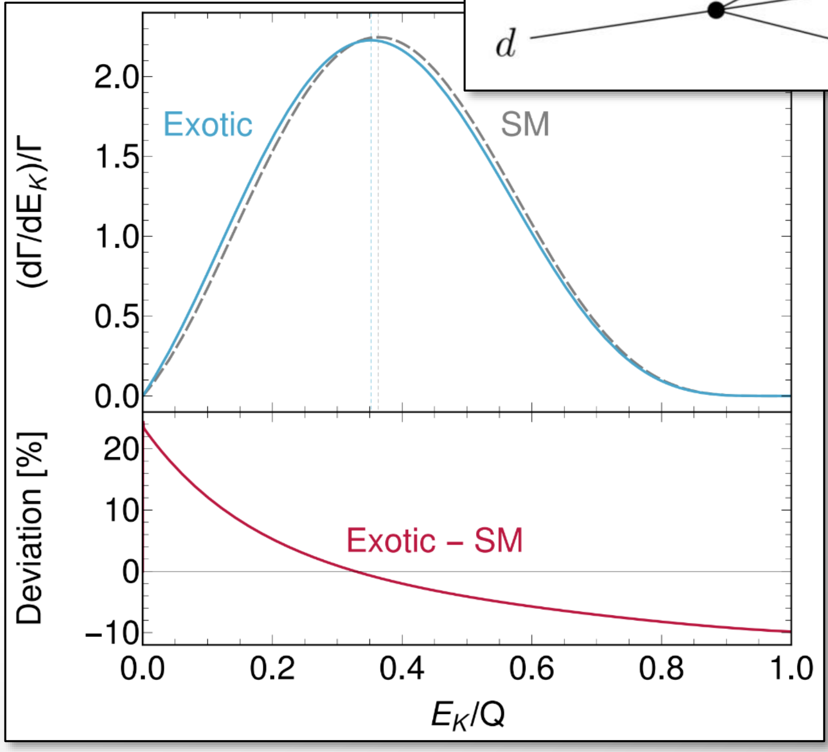
- Lepton number conserving RH currents
    - LEGEND analysis ongoing





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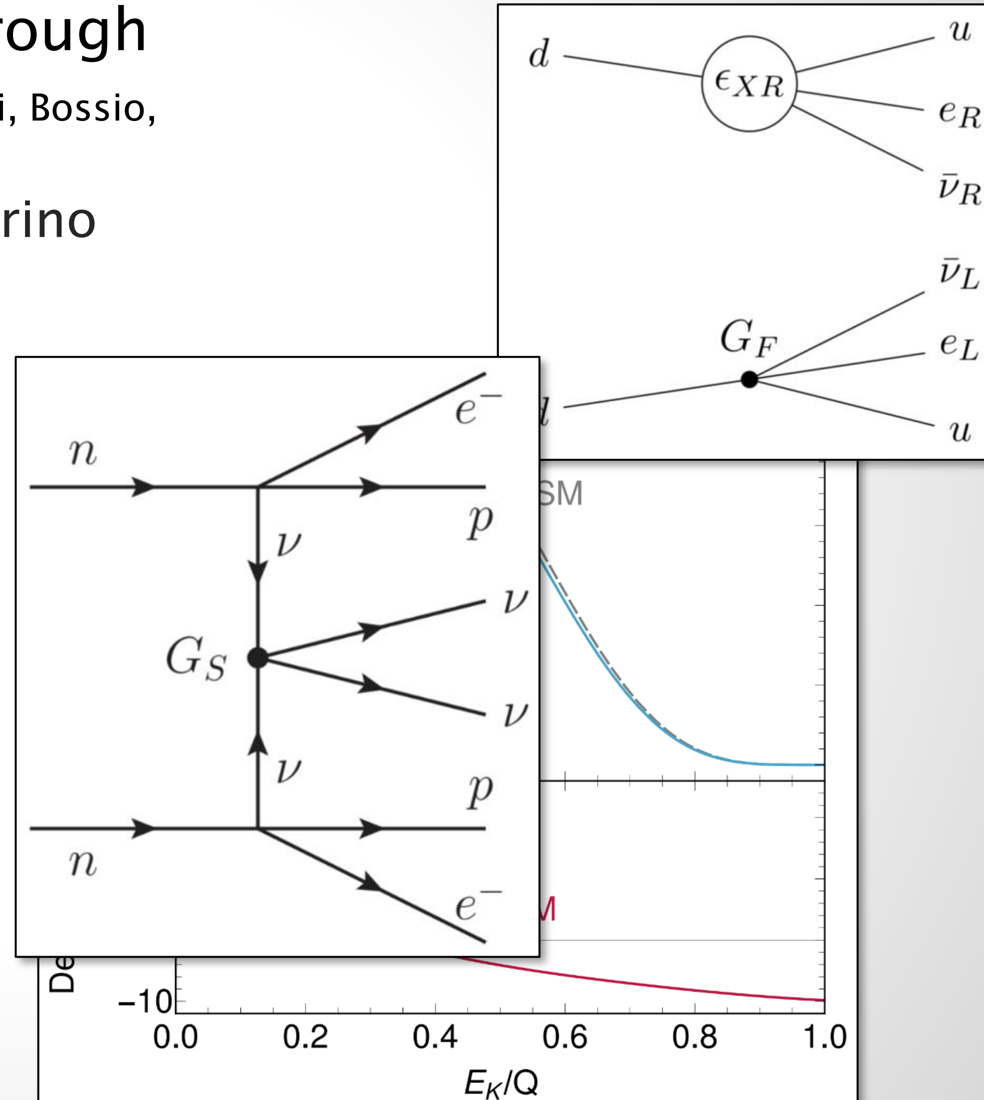
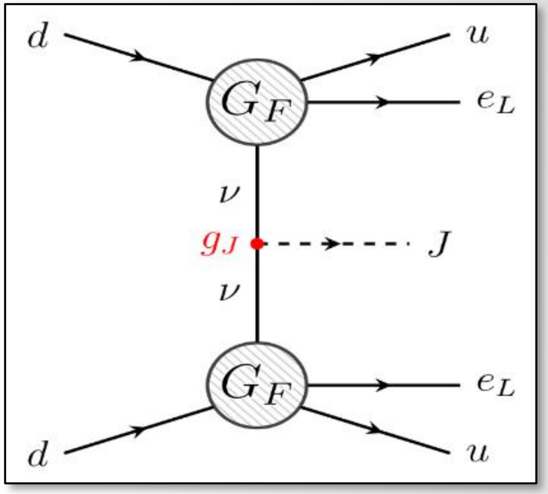
- Neutrino self-interactions

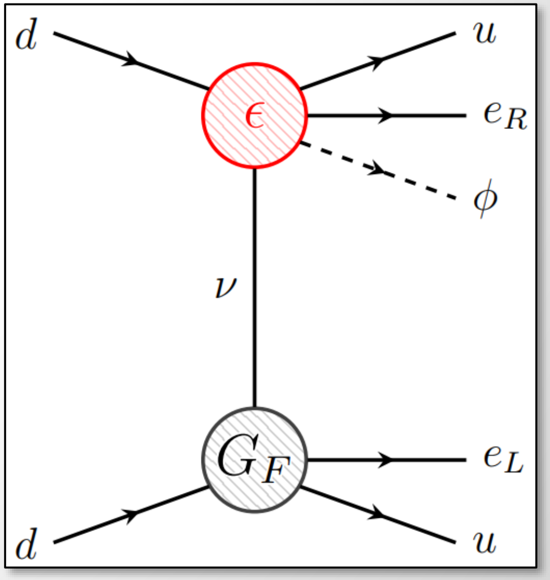


Exotic Particle Emission

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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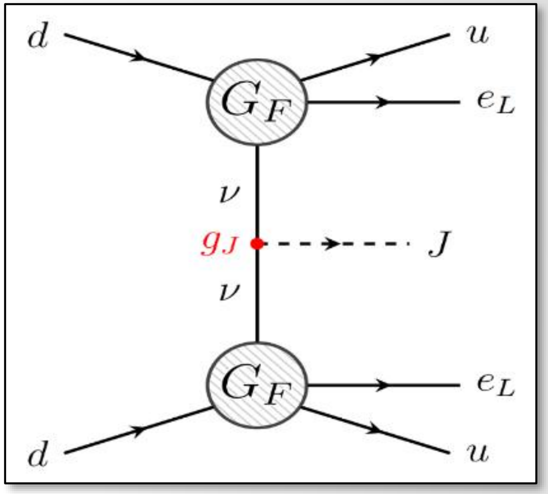
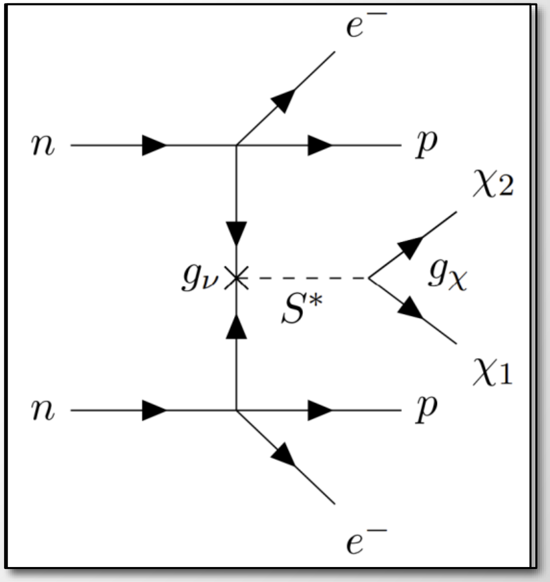
  - Non-standard energy distribution
  - Searched for in EXO-200: $T_{1/2} > 4 \times 10^{24}$ y (PRD 104 (2021) 11, 112002)
- Dirac neutrinos coupled to massive, L-charged “Majoron” S and dark fermions χ

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

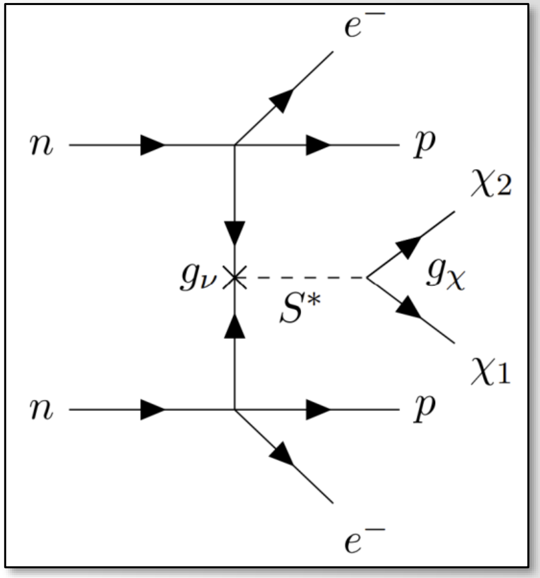
  - Z_2 symmetry to forbid mixing
  - Self-interacting neutrinos and self-interacting (potentially) DM





Neutrinos coupled to DS

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606



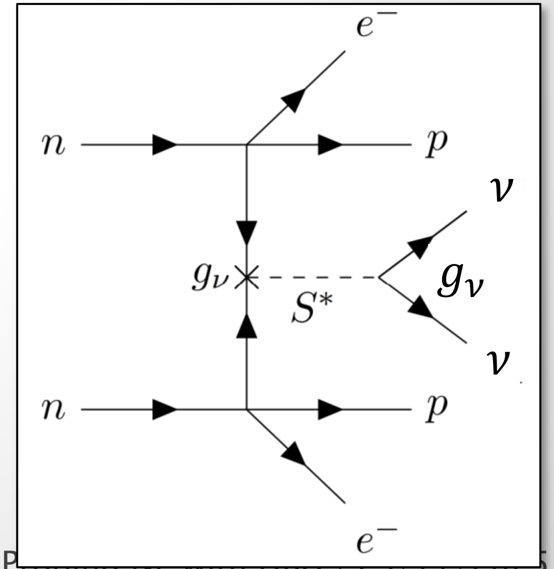
- Model I’: Dirac neutrinos coupled to massive, L-charged scalar S and dark fermions χ

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

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

- Model I: No Z_2, mixing terms allow

$$\begin{aligned}-\mathcal{L} = {} & m_\nu \overline{\nu'_R}\nu'_L + m_{\nu\chi}\overline{\chi'_R}\nu'_L + m_{\chi\nu}\overline{\nu'_R}\chi'_L + M\overline{\chi'_R}\chi'_L \\ & + \left(a_\nu \overline{\nu'^c_L}\nu'_L S^* + b_\nu \overline{\nu'^c_R}\nu'_R S^* + a_{\nu\chi}\overline{\nu'^c_L}\chi'_L S^* + b_{\nu\chi}\overline{\nu'^c_R}\chi'_R S^* + a_\chi \overline{\chi'^c_L}\chi'_L S^* + b_\chi \overline{\chi'^c_R}\chi'_R S^*\right) + \text{h.c.}.\end{aligned}$$

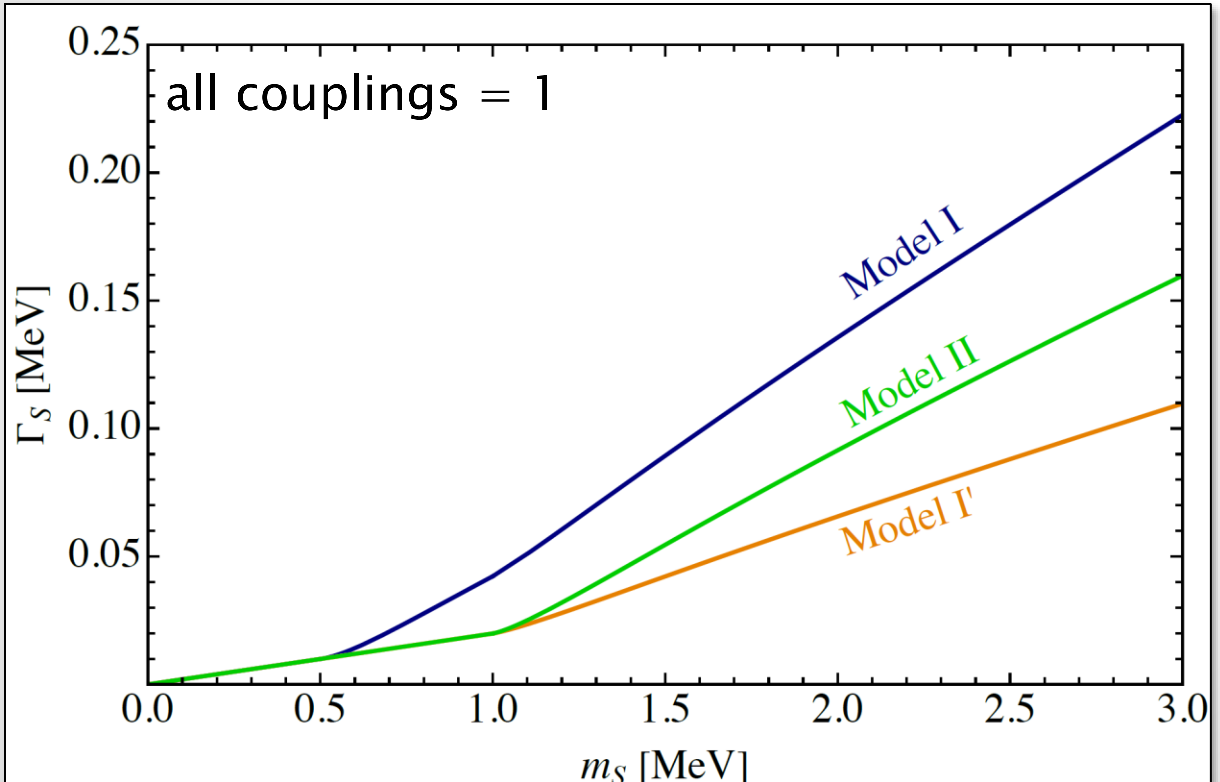


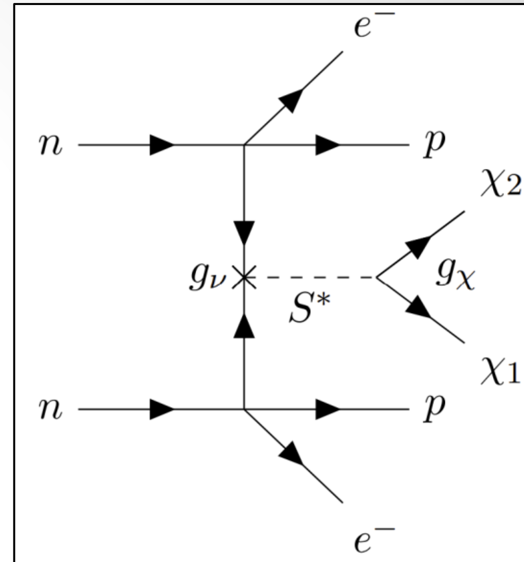
- Dirac neutrinos not required, but here, no constraints from $0\nu\beta\beta$

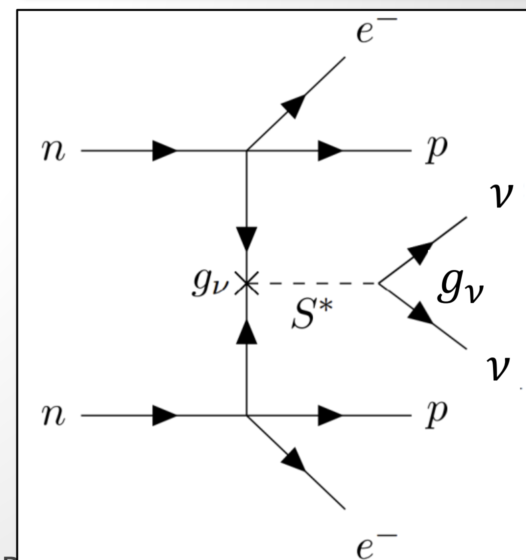
Neutrinos coupled to DS

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Small but sizeable S decay width possible







Neutrinos coupled to DS

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Rich double beta decay phenomenology
  - $2\chi_S\beta\beta$

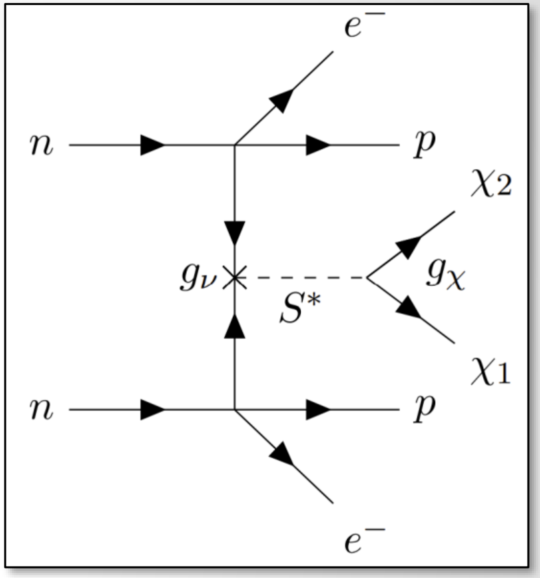
$$\frac{d\Gamma_S^{2\chi}}{dT} = \kappa_{0\nu}\left(\frac{m_e}{2R}\right)^2 |\mathcal{M}_{0\nu}|^2 |a_\nu|^2 \left\{\left(|a_\chi|^2 + |b_\chi|^2\right) I_1(T) - 2\mathrm{Re}\left[a_\chi^* b_\chi\right] I_2(T)\right\} g(T) \times \Theta(Q - m_{\chi_1} - m_{\chi_2} - T),$$

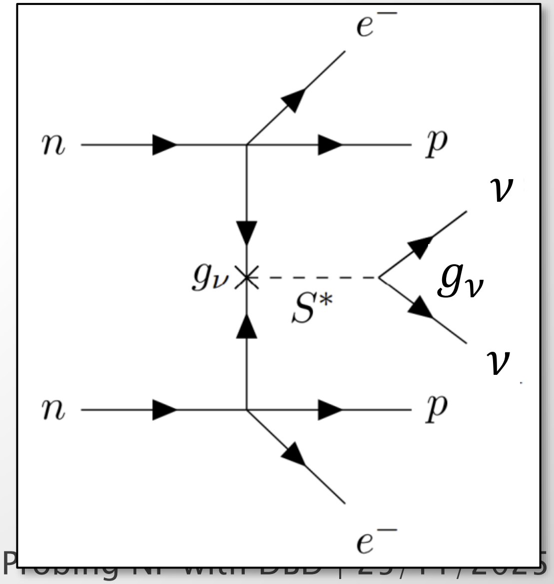
$$I_1(T) = \frac{1}{4(2\pi)^4}\int_{m_{\chi_1}}^{Q-T-m_{\chi_2}} dE_3 \left\{\frac{m_S^2 - m_{\chi_1}^2 - m_{\chi_2}^2}{2m_S\Gamma_S}\left[\arctan\zeta_+(E_3) + \arctan\zeta_-(E_3)\right] + \frac{1}{4}\log\left[\frac{\zeta_-^2(E_3)+1}{\zeta_+^2(E_3)+1}\right]\right\},$$

$$I_2(T) = \frac{1}{4(2\pi)^4}\frac{m_{\chi_1}m_{\chi_2}}{m_S\Gamma_S}\int_{m_{\chi_1}}^{Q-T-m_{\chi_2}} dE_3\left[\arctan\zeta_+(E_3) + \arctan\zeta_-(E_3)\right].$$

  - $2\nu_S\beta\beta$
    - Including interference with SM $2\nu\beta\beta$

$$\zeta_\pm(E_3) = \frac{2|\mathbf{p}_3||\mathbf{p}_4|(x\pm 1)}{m_S\Gamma_S x}$$

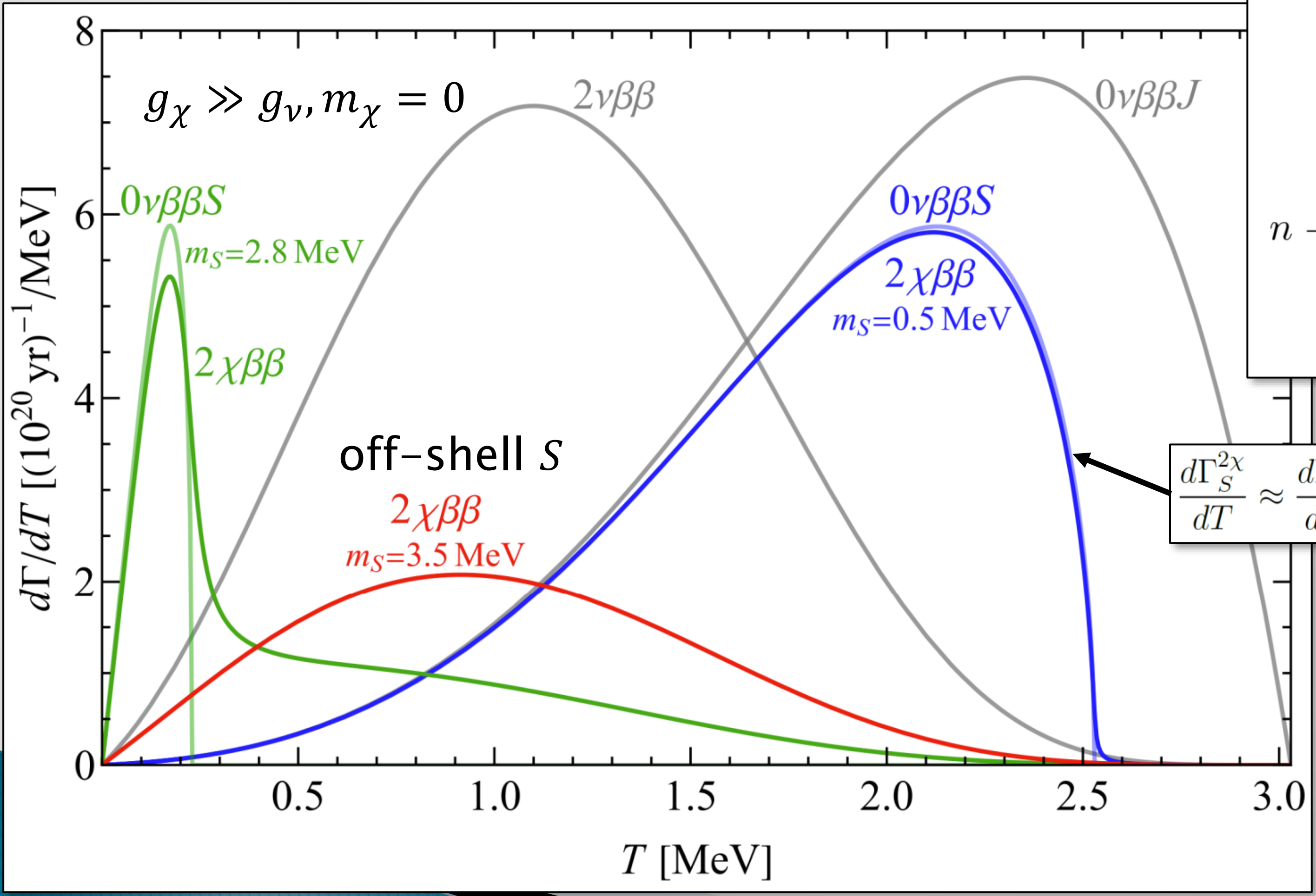


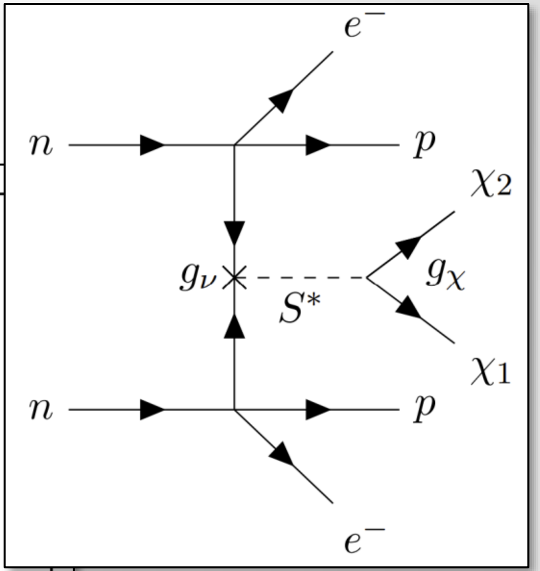


Neutrinos coupled to DS

Boudjema, FFD, Herrero, Majumdar, Senapati, 2511.13606

- Finite S width/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

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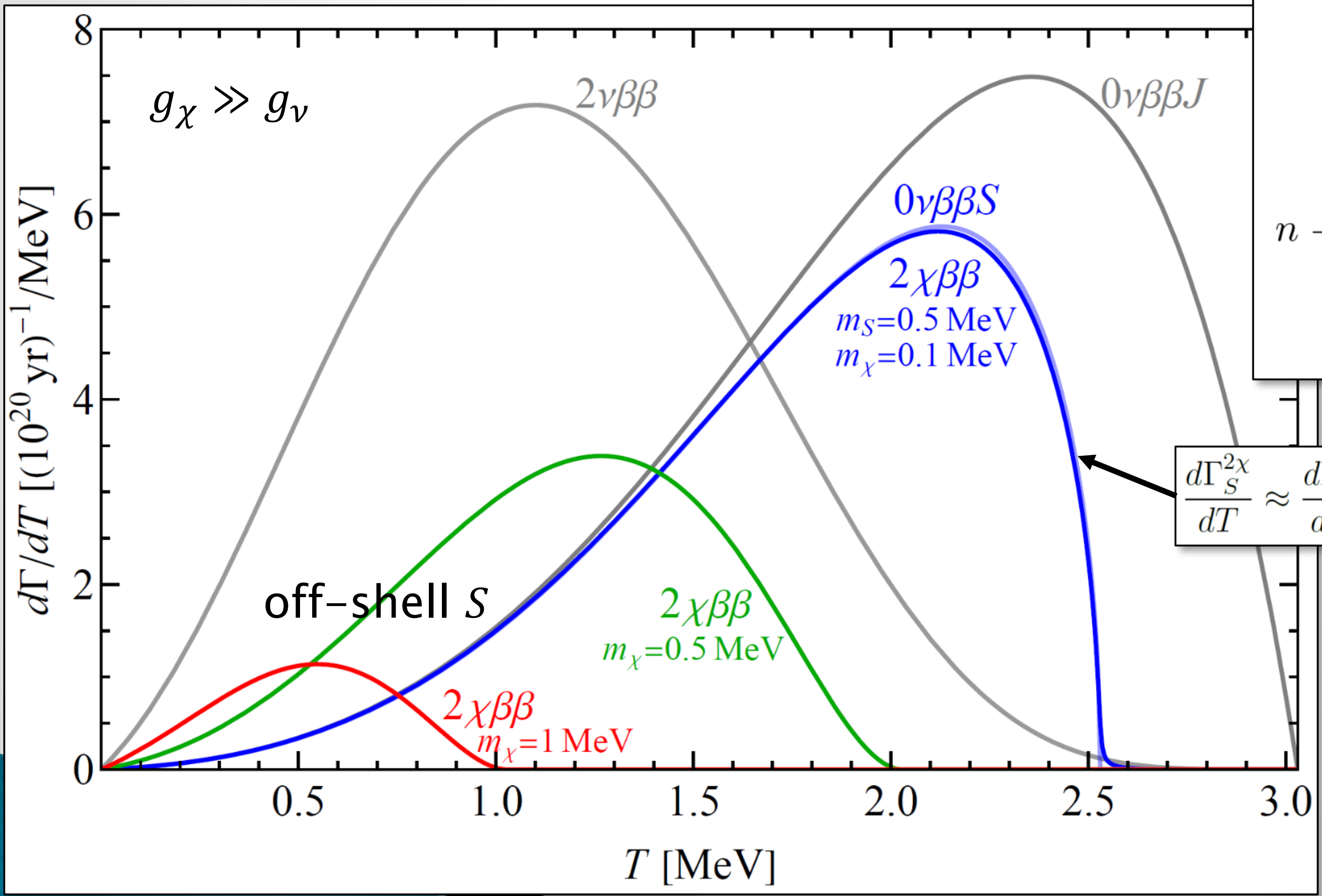

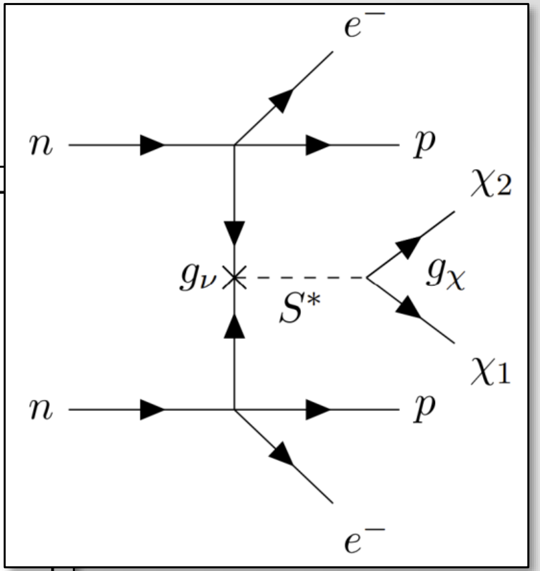

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On-shell S in narrow-width approximation

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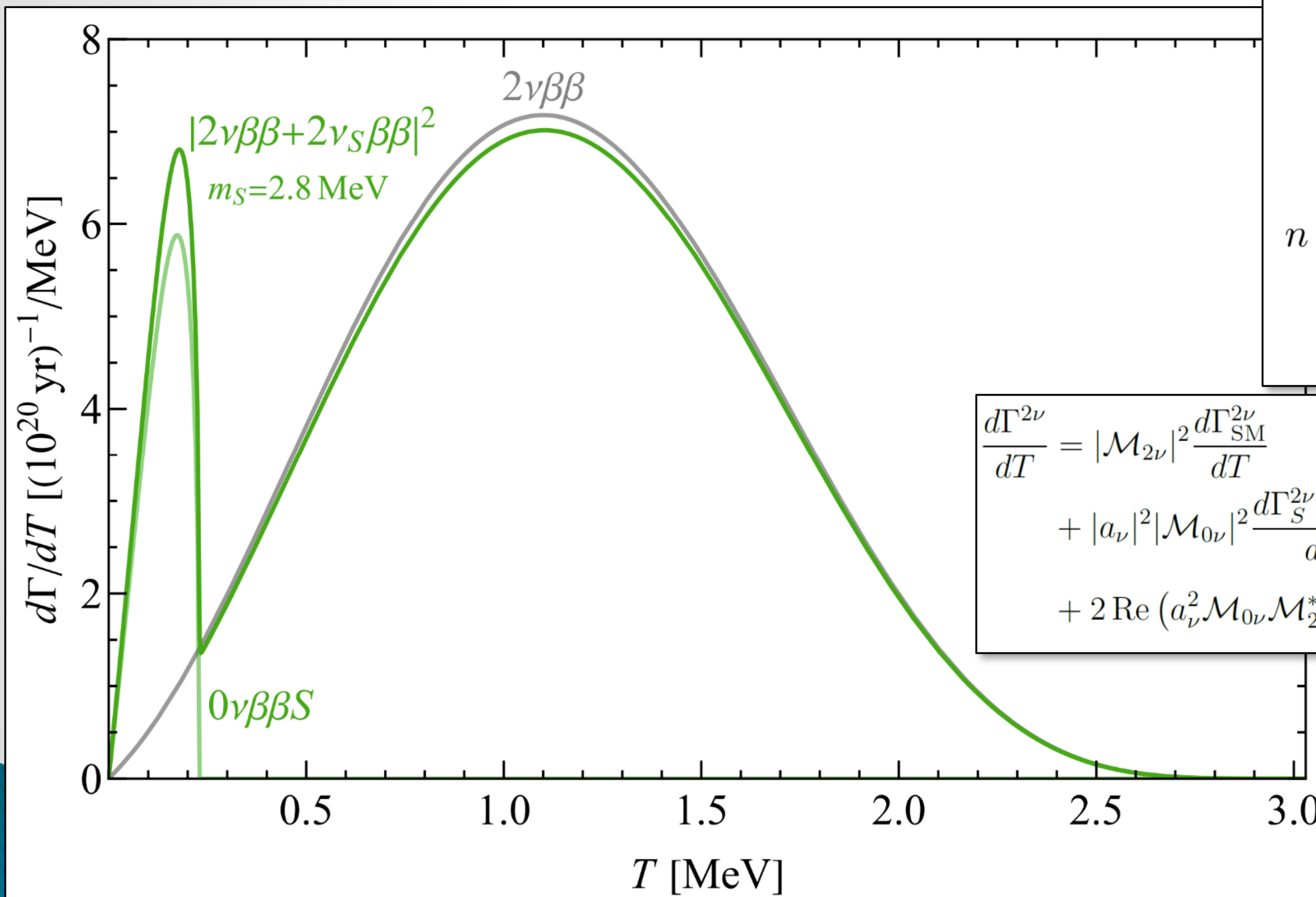
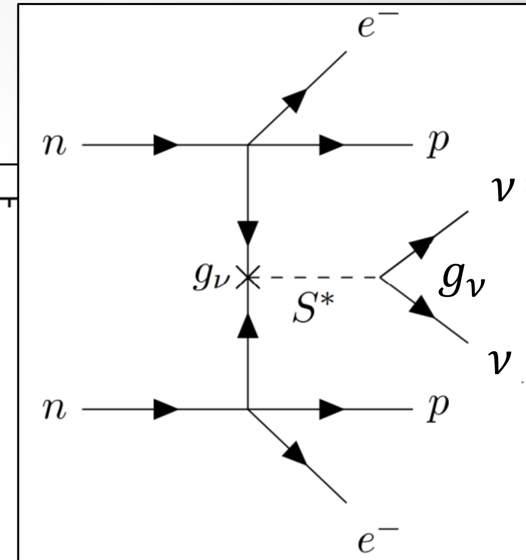
- $2\nu_S\beta\beta$ and interference with SM $2\nu\beta\beta$





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

Neutrinos coupled to DS

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- Sensitivity of current and future double beta decay searches

Isotope	Experiment	$\mathcal{E}$ [kg · yr]	$T_{\min}$ [keV]	ΔT [keV]	σ_f [%]
^{76}Ge	GERDA II [67]	104	500	15	1.9
	LEGEND-1000 [68]	7.0×10^3	100	2.5	0.5
^{100}Mo	NEMO-3 [10]	34	500	100	1.8
	CUPID-1T [69]	1.7×10^3	100	5	0.5
^{136}Xe	KamLAND-Zen [5]	126	100	50	0.3
	nEXO [70]	1.9×10^4	100	5	0.5

Isotope	m_{iso} [g/mol]	Q [MeV]	$(T_{1/2}^{2\nu})_{\exp}$ [yr]	$\langle \mathcal{M}_{2\nu} \rangle$	$\delta\mathcal{M}_{2\nu}$	$\langle \mathcal{M}_{0\nu} \rangle$	$\delta\mathcal{M}_{0\nu}$
$^{76}_{32}$Ge	72.6	2.04	1.9×10^{21}	0.10	0.22	4.3	1.2
$^{100}_{42}$Mo	96.0	3.03	7.1×10^{18}	0.19	0.27	4.9	1.5
$^{136}_{54}$Xe	131	2.46	2.2×10^{21}	0.016	0.19	2.6	1.1

Neutrinos coupled to DS

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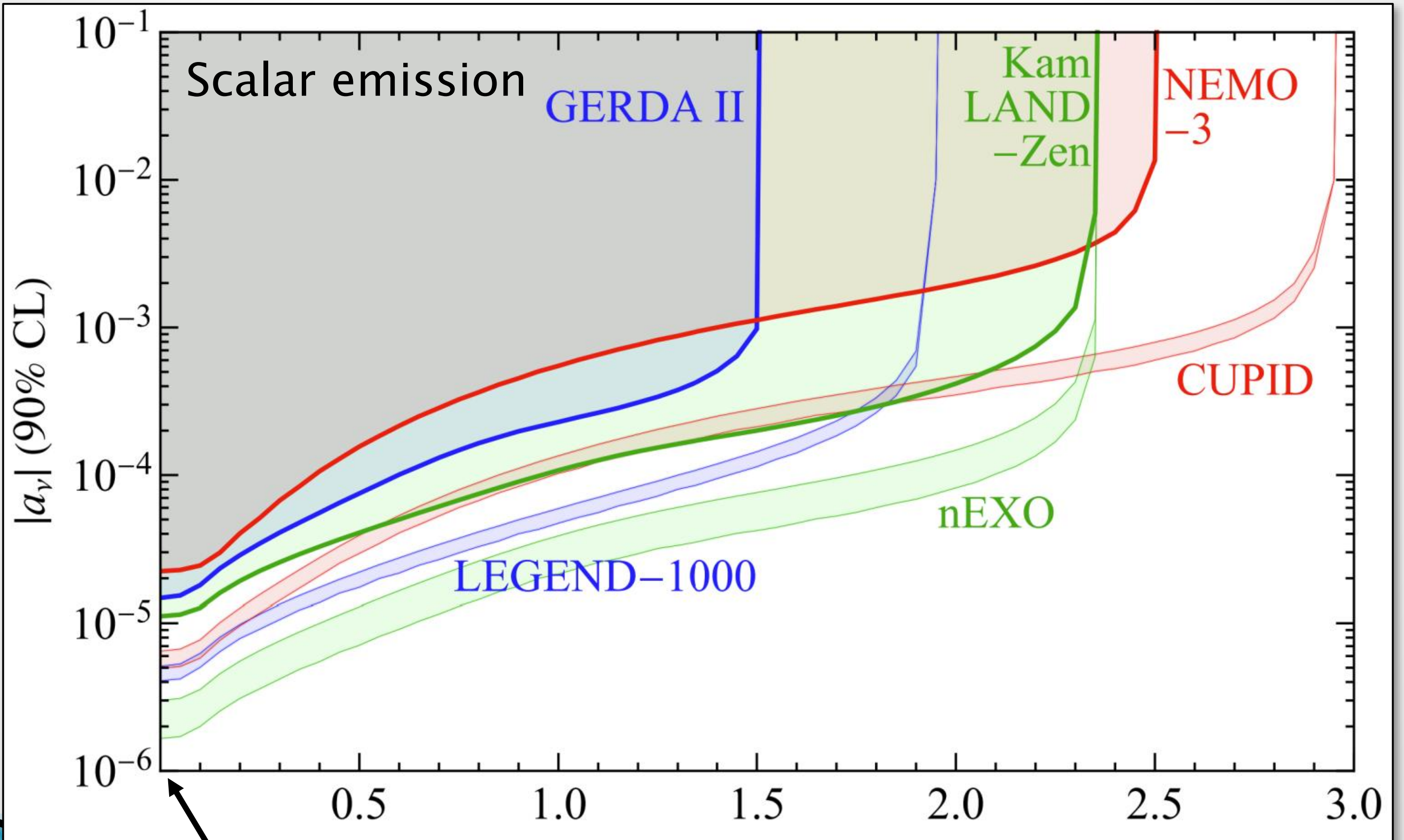
- Sensitivity of current and future double beta decay searches



Ordinary Majoron $m_S = 0$

Neutrinos coupled to DS

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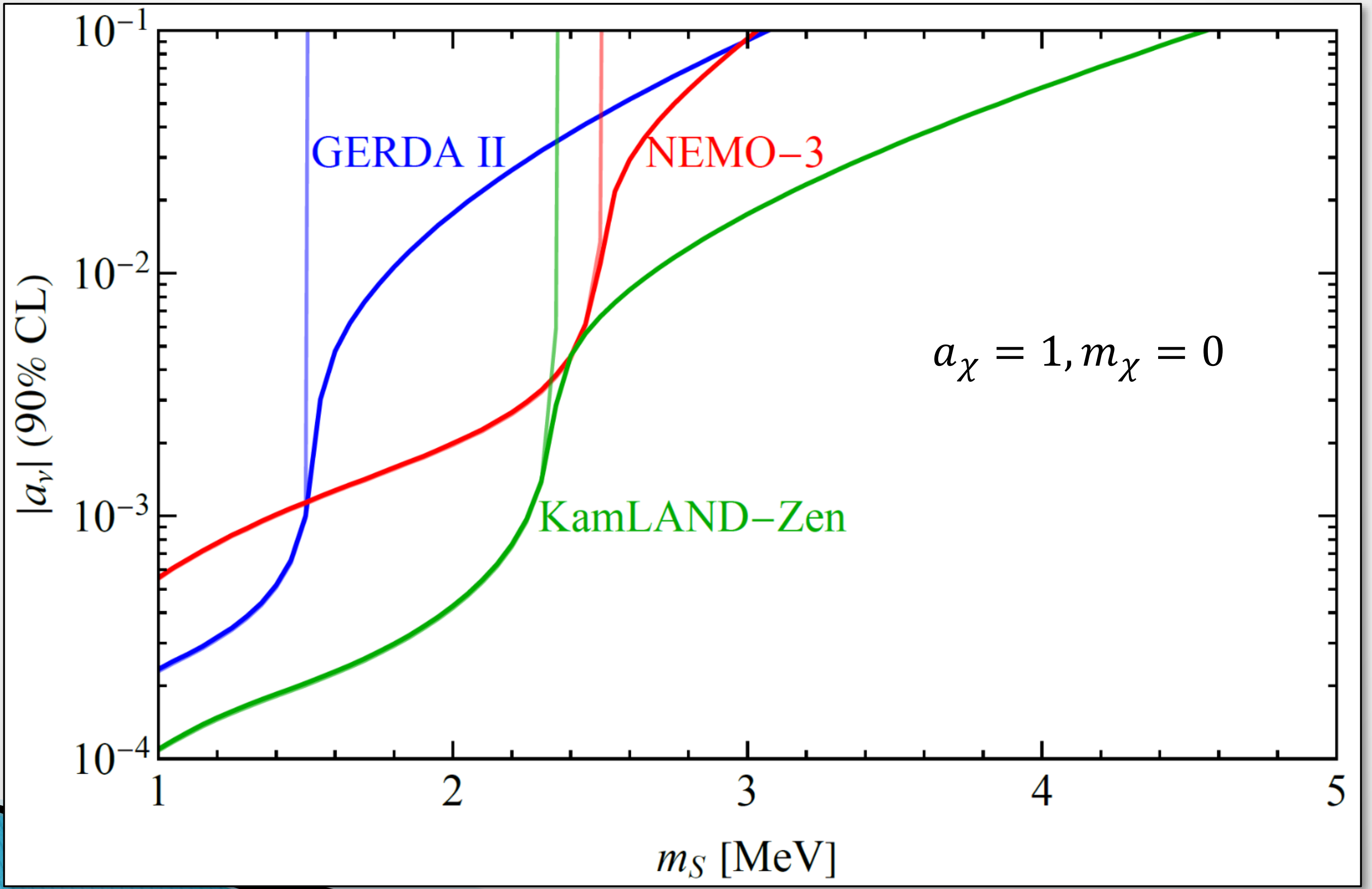
- Modification from interference and off-shell S



Neutrinos coupled to DS

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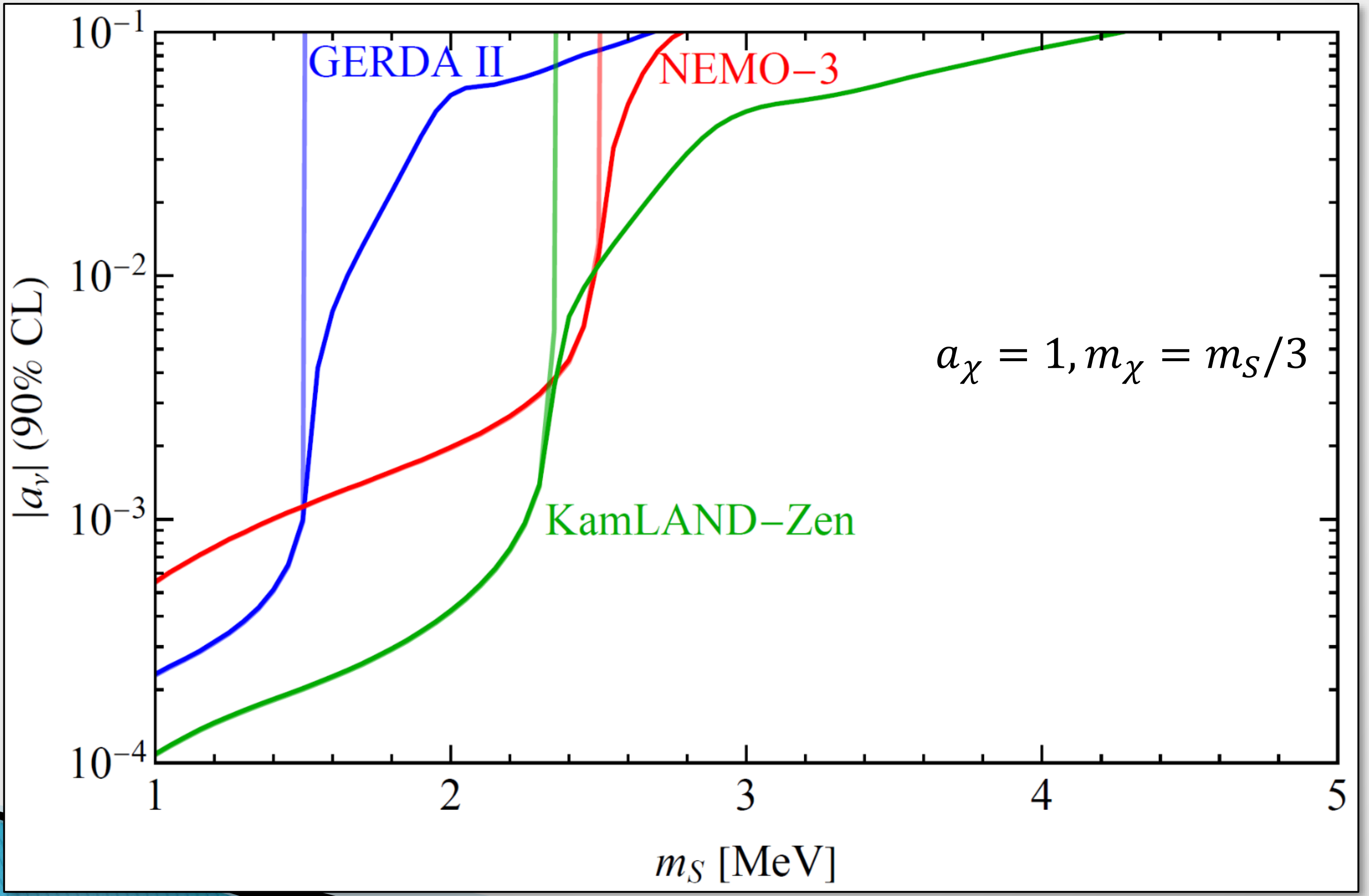

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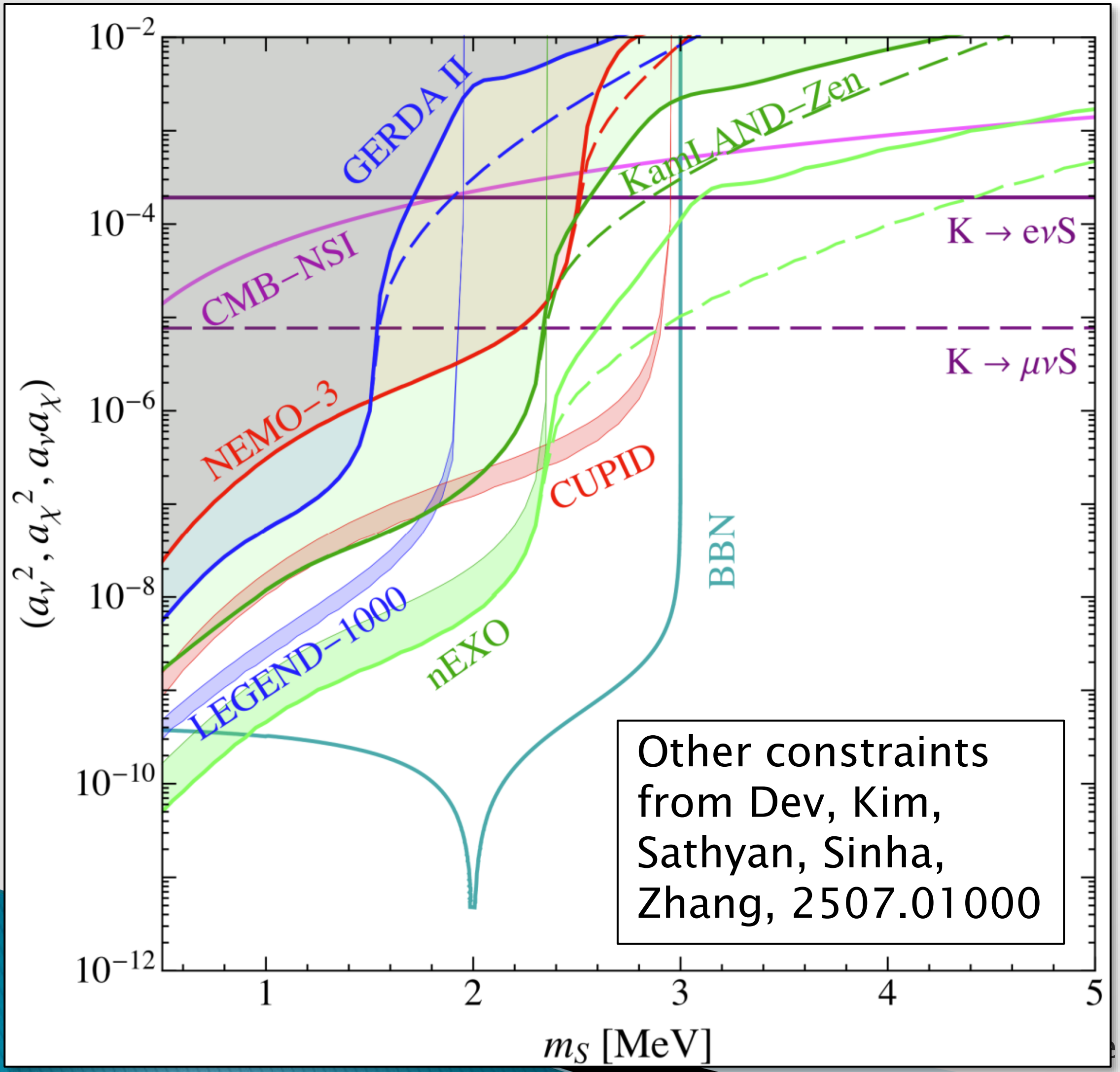
- Comparison with other constraints

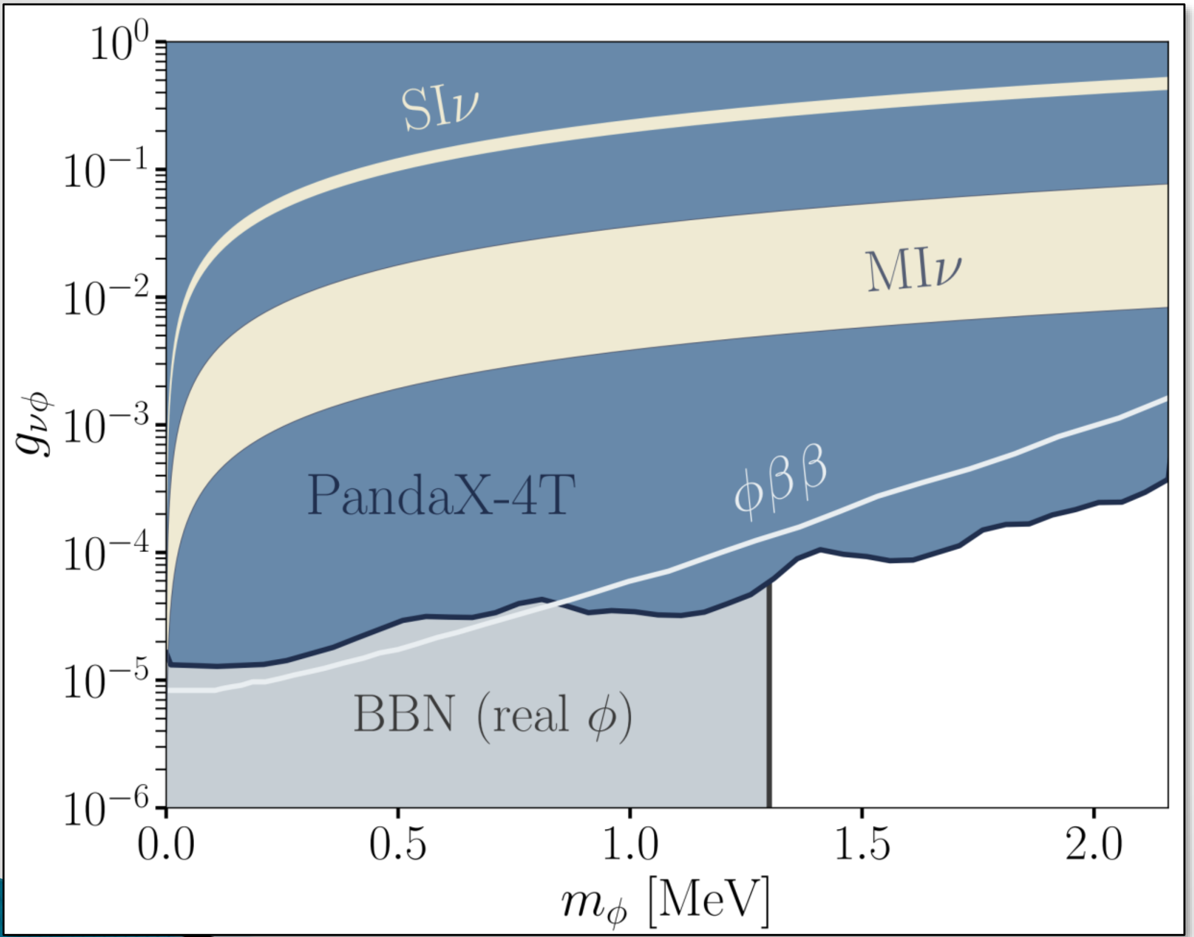


- Cosmology
  - Thermal relic χ?
  - DM–ν collisional damping
  - BBN
  - Neutrino reheating from DM annihilations
  - Impact of ν NSI on free-streaming (CMB)
- Astrophysics
  - Supernovae cooling
- Terrestrial
  - Kaon decays $K \to e\nu S$
  - Z-width, … for higher m_S

Neutrinos coupled to DS

University College London

- Recent search at PandaX-4T (PandaX collaboration, arXiv:2511.13515)



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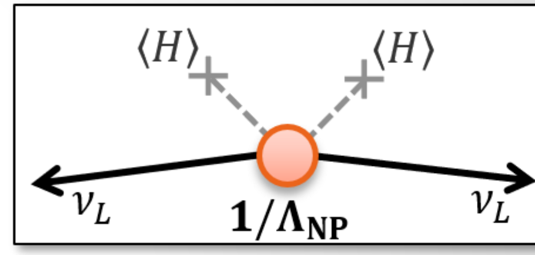
Conclusion

- **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 at scales $m_N \approx 1\ \mathrm{eV} - 100\ \mathrm{TeV}$
  - Falsify high-scale baryogenesis scenarios

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

- **$2\nu\beta\beta$ spectrum sensitive to New Physics**
  - Non-standard ν interactions, sterile ν
  - Neutrino self-interactions and DS interactions
    - Strongest terrestrial limits $|g_{\nu_e S}| < 10^{-5} - 10^{-1}$ for $m_S < 3 - 5\ \mathrm{MeV}$
    - Synergy and overlap with cosmological considerations