Neutrino Mass and Light New Physics in Double Beta Decay

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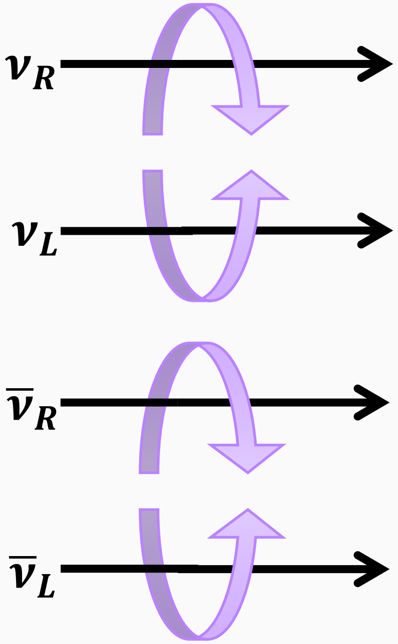
INT26-6a Workshop | U. of Washington
Seattle | 20-24/07/2026

Dirac versus Majorana

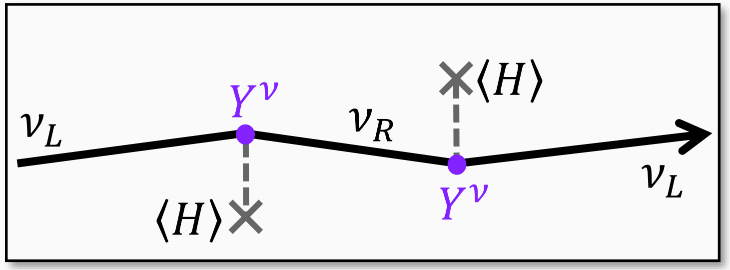
- Two possibilities to define neutrino mass

Dirac

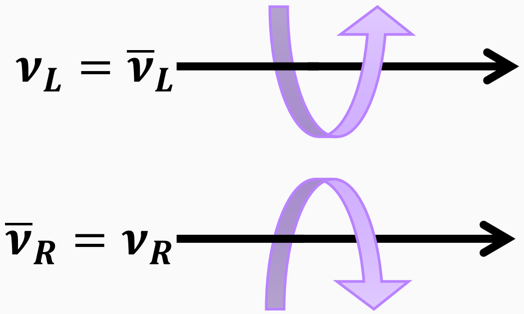


$$\boxed{m_D\bar{\psi}\psi = m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)}$$

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

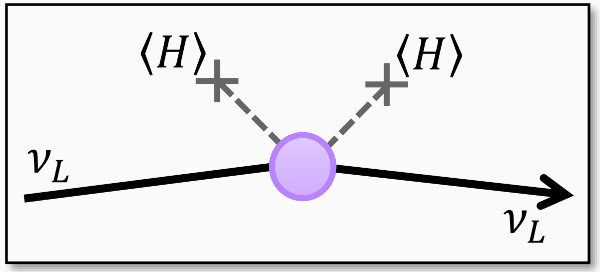


Majorana



$$\boxed{\frac{1}{2} m_M \psi_L^T C^{-1} \psi_L}$$

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



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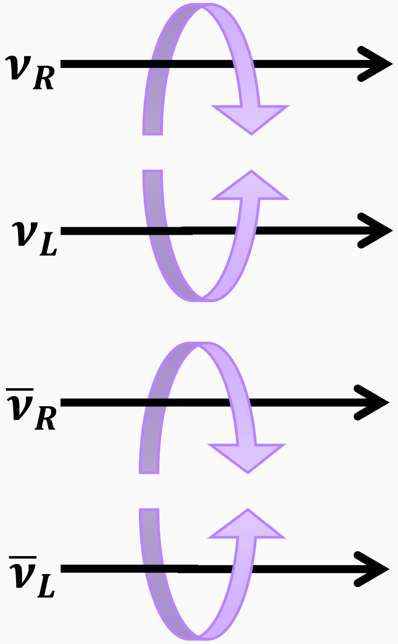

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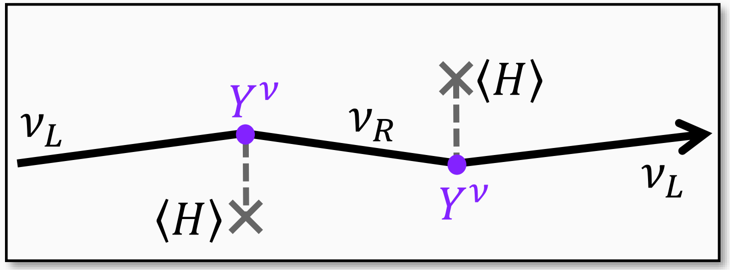

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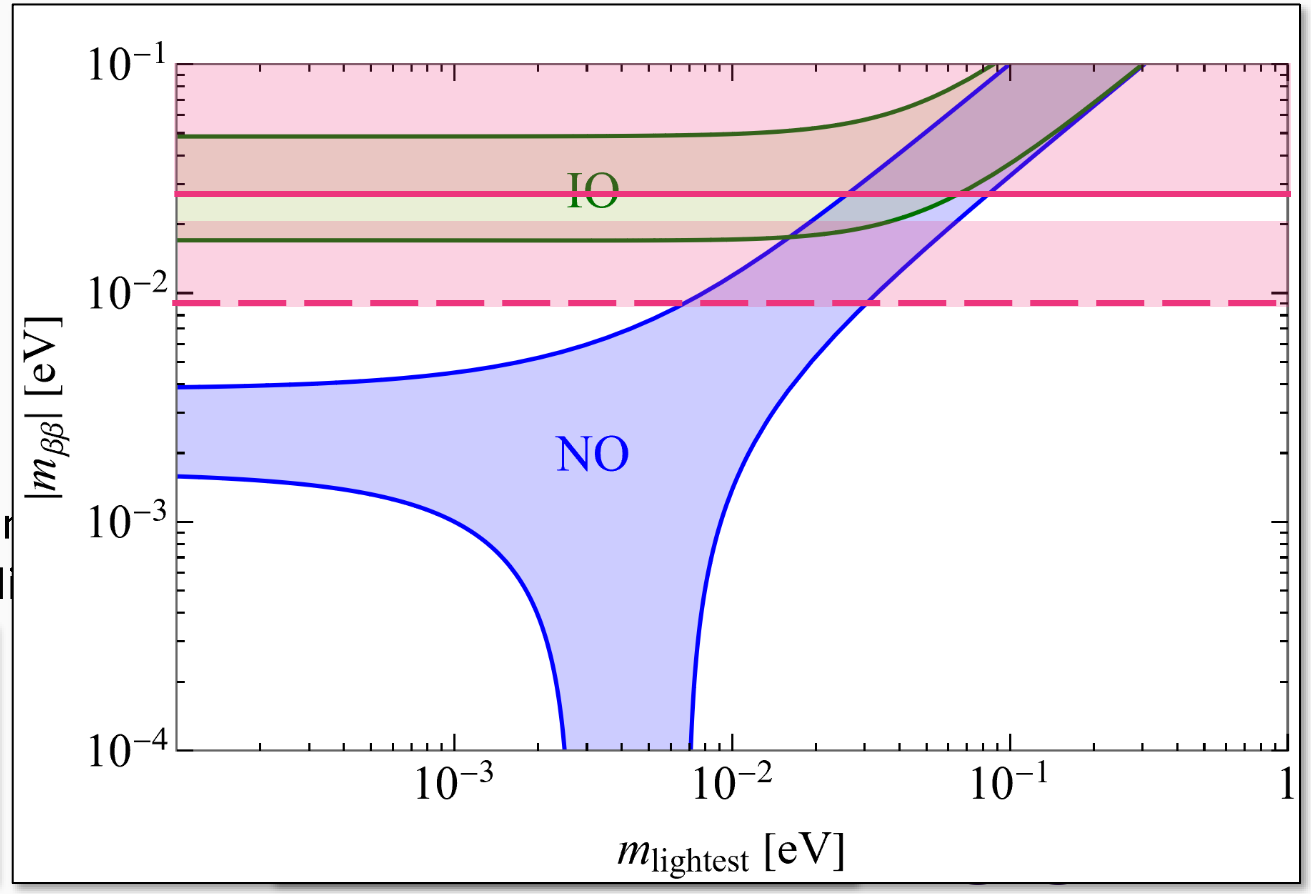

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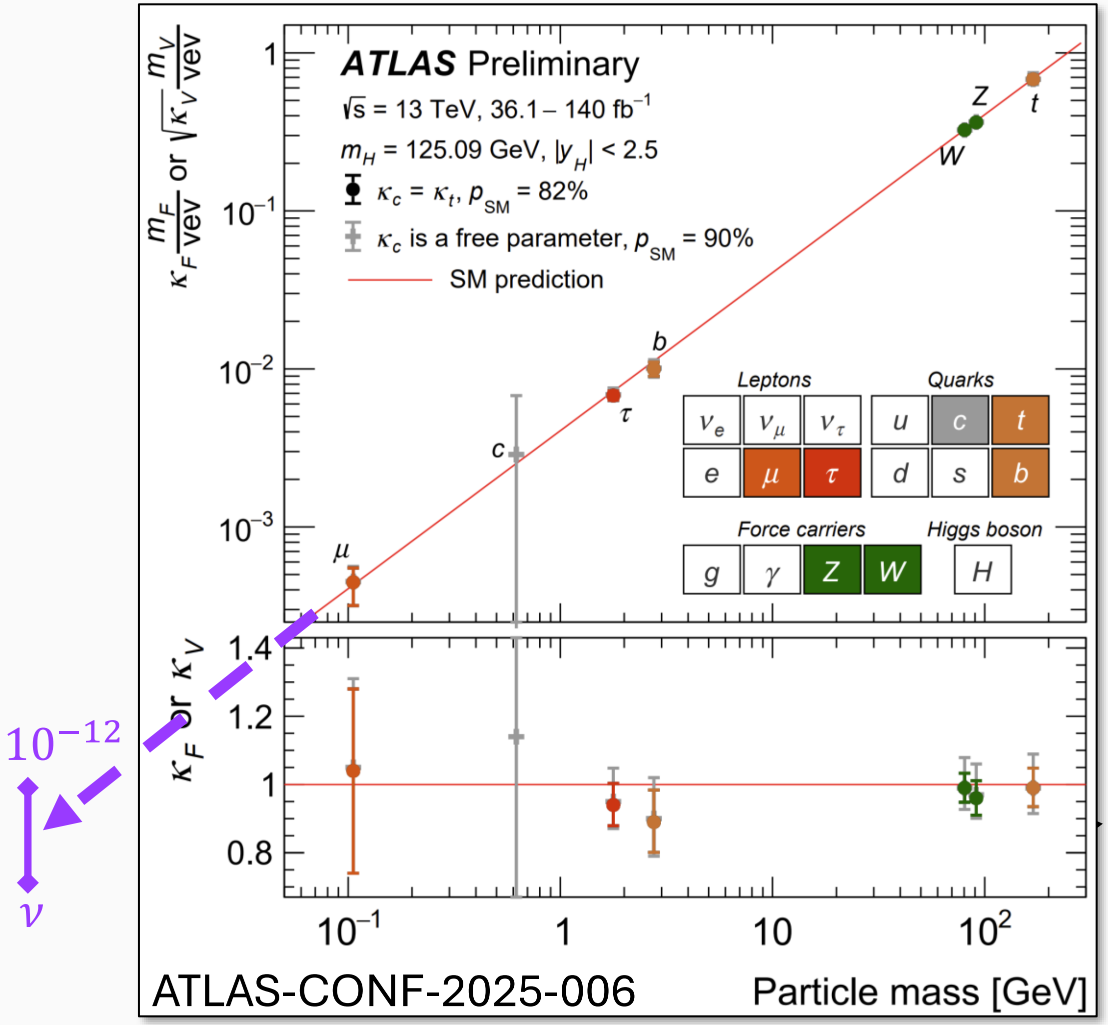
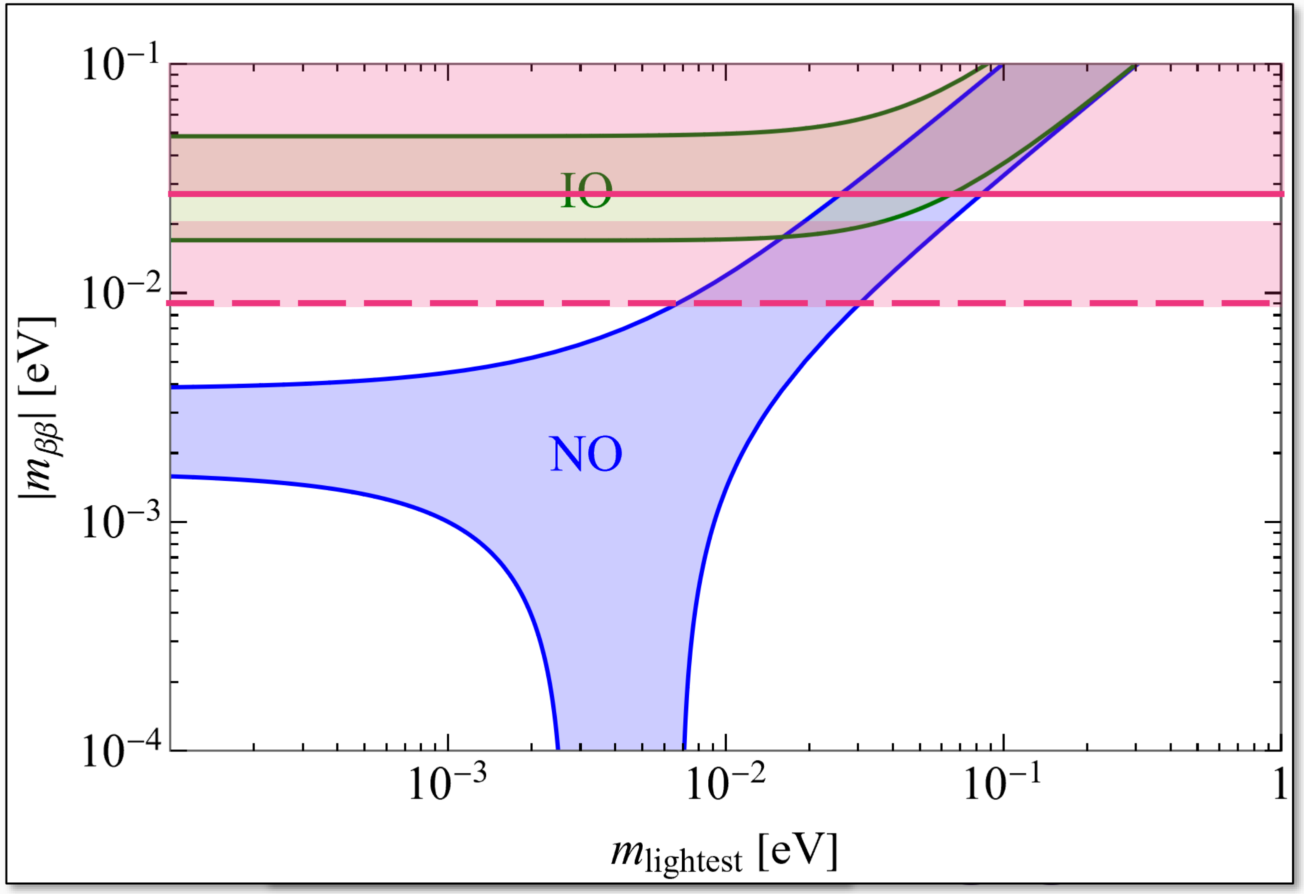


Majorana



Dirac versus Majorana

- Origin of neutrino masses beyond the Standard Model
- Crucial role of total lepton number L symmetry
  - Arises accidentally as global $U(1)_L$ in SM gauge symmetry

$$\boxed{\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}$$

    particle content and renormalizability
  - L broken non-perturbatively but $B - L$ conserved
- Global symmetries expected to be broken gravitational effects?

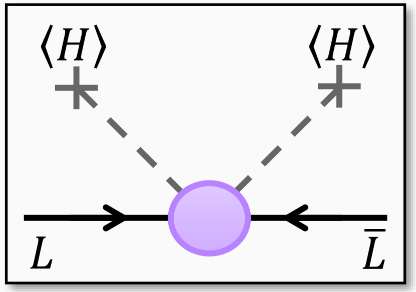
$$\boxed{m_\nu \approx \frac{v^2}{M_{\mathrm{Planck}}} \approx 10^{-5}\ \mathrm{eV}}$$

  - Too small to explain oscillations but too large as subdominant splitting
  - Connection to matter-antimatter asymmetry

Dirac versus Majorana

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

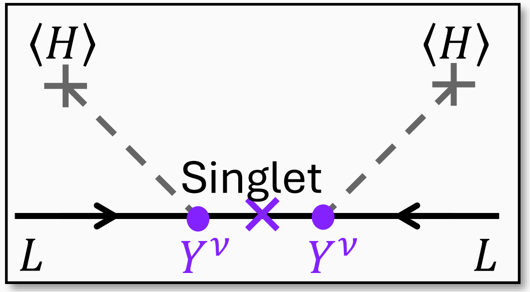
$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}\left(\bar{L}_i^c \cdot H\right)\left(H^T \cdot L_j\right) \xrightarrow[\langle H\rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$



- Seesaw Mechanism
  - Sterile neutrino mass scale unknown

$$m_\nu \approx 0.1\ \mathrm{eV}\left(\frac{Y_\nu\langle H\rangle}{100\ \mathrm{GeV}}\right)^2\left(\frac{10^{14}\ \mathrm{GeV}}{M_N}\right)$$

Seesaw I



$M_N \approx 10^{14}$ GeV	Naïve Seesaw, GUTs
$\gtrsim 10^9$ GeV	Thermal Leptogenesis
$\approx 10^2$ GeV	Resonant Leptogenesis, LHC
≈ 1 keV	Dark Matter Candidate
≈ 1 eV	Oscillations, Cosmology, $0\nu\beta\beta$
$\ll 1$ eV	Quasi-Dirac neutrinos

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Neutrinoless Double Beta Decay

- Half-life

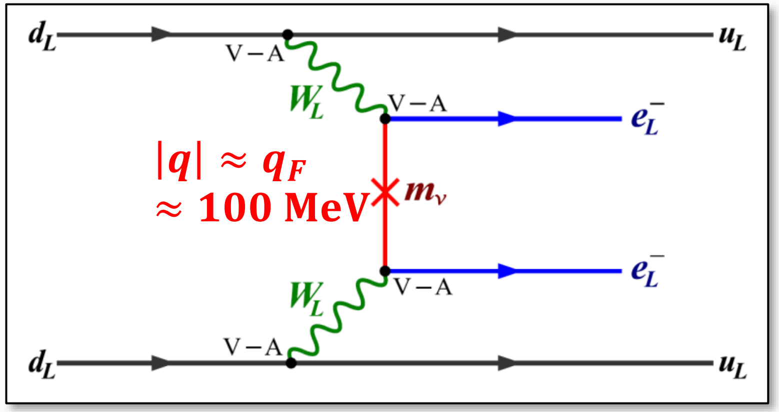
$$\boxed{T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} \left|M^{0\nu}\right|^2}$$

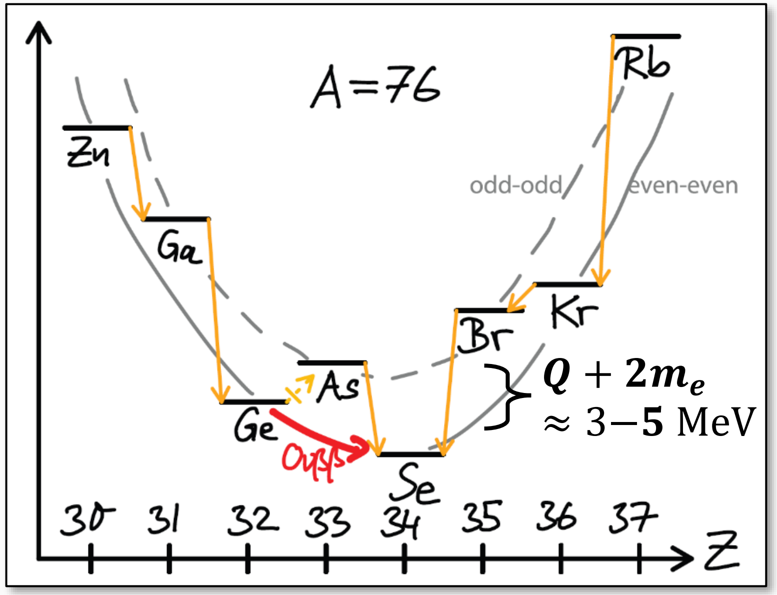
- Particle Physics

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

- 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

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

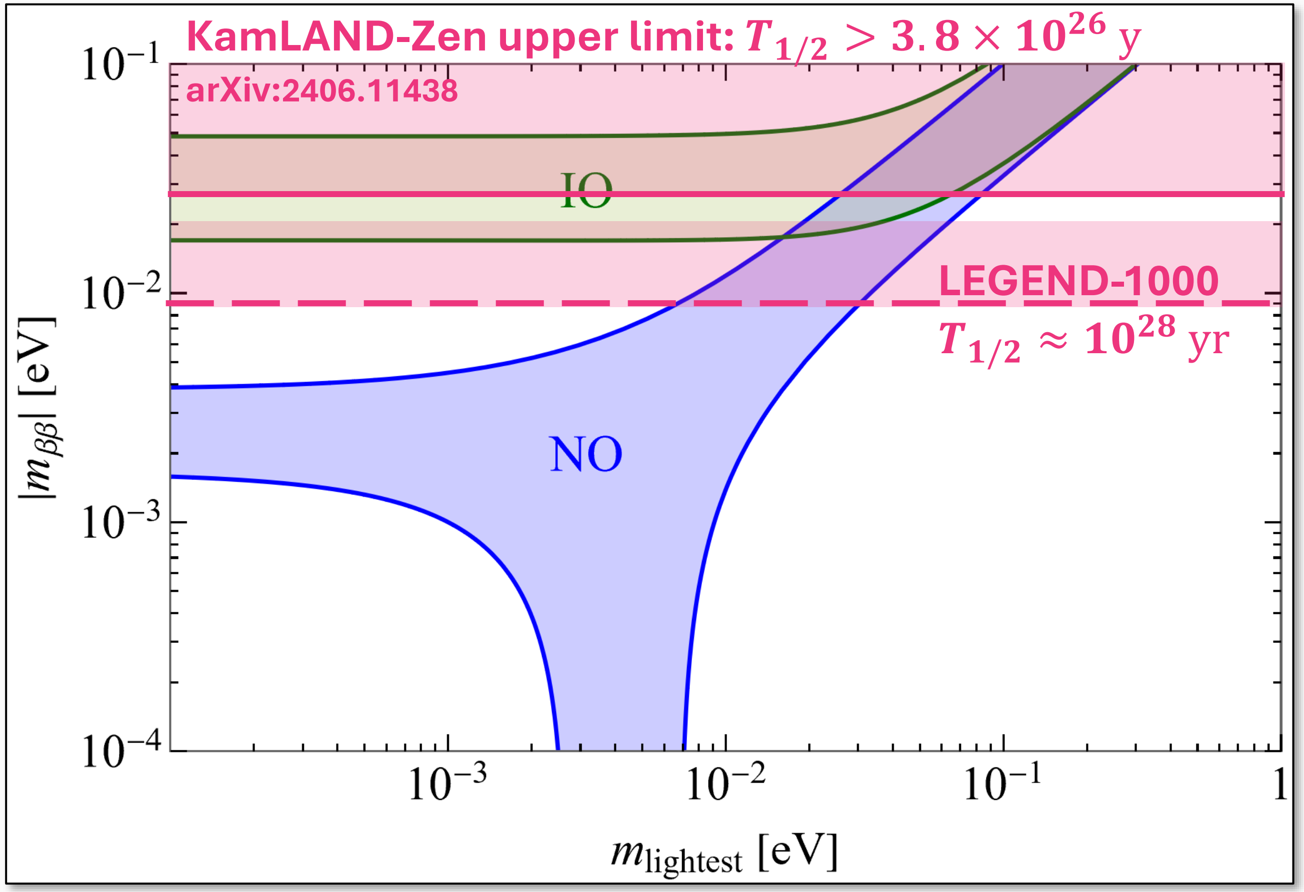




Three Active Majorana Neutrinos

- 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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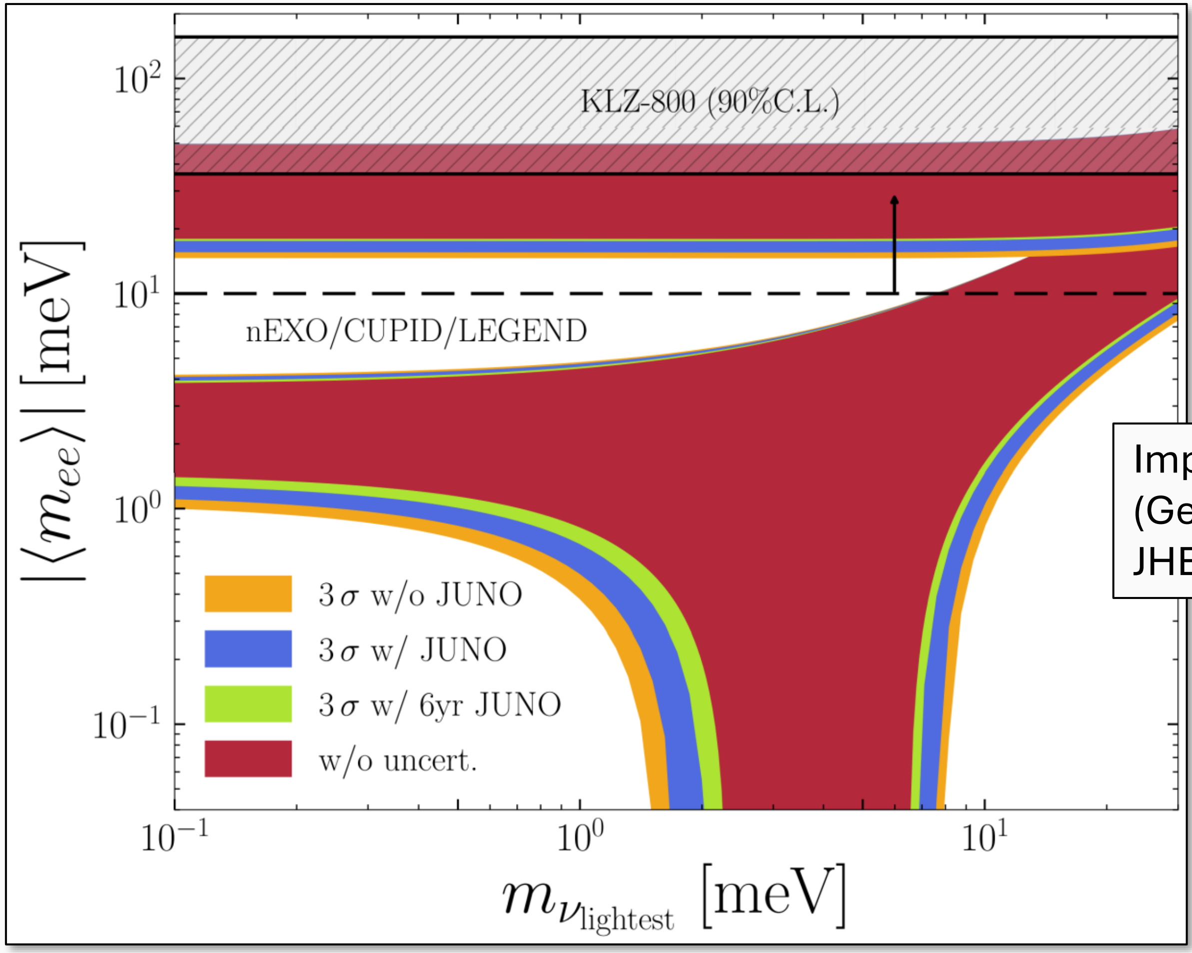

Impact of JUNO (first) data (Ge, Kong, Lindner, Pinhero, JHEP 03 (2026) 105)

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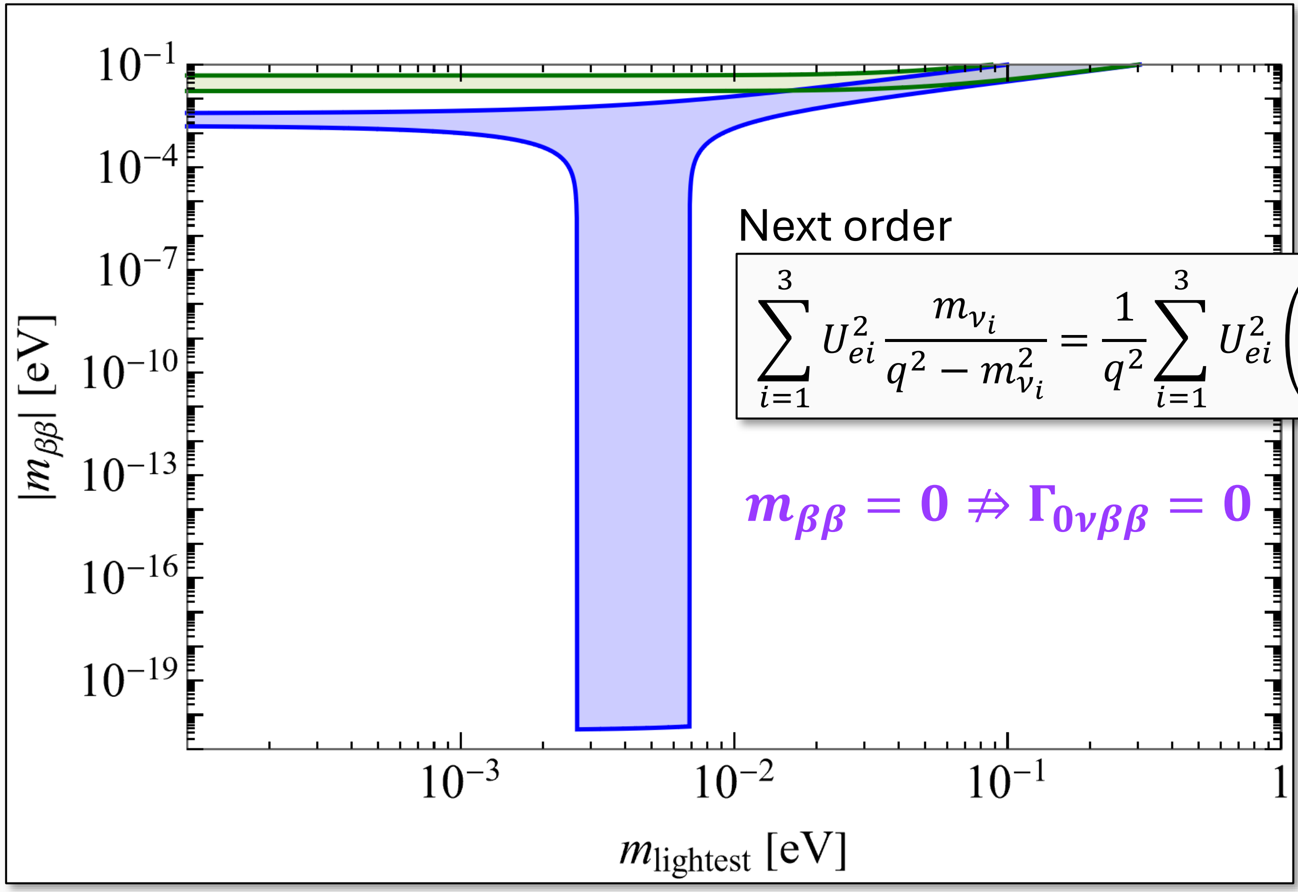


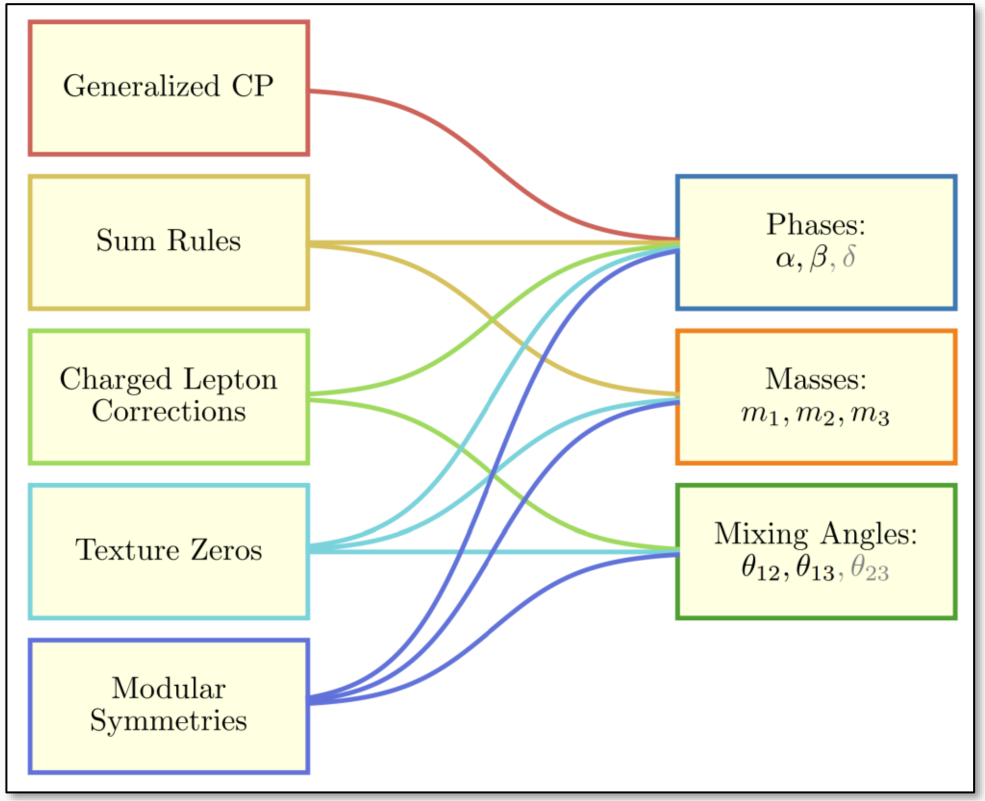
Next order

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

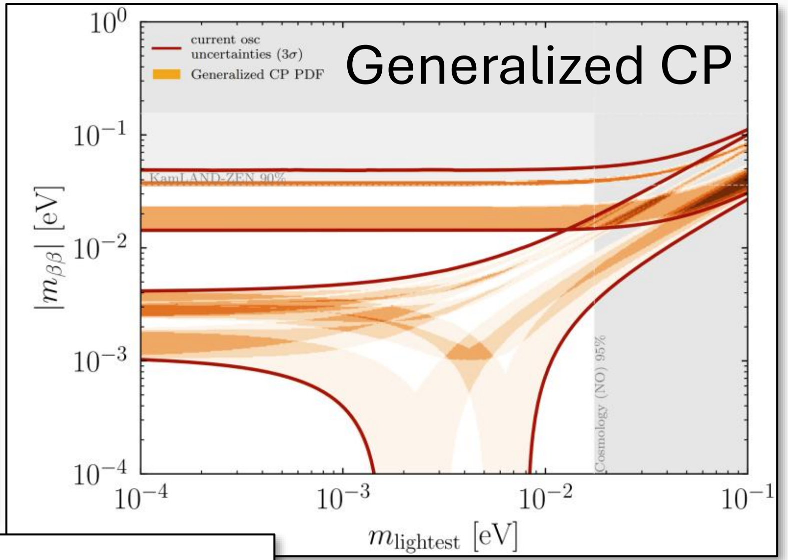
$$\boldsymbol{m_{\beta\beta} = 0 \nRightarrow \Gamma_{0\nu\beta\beta} = 0}$$

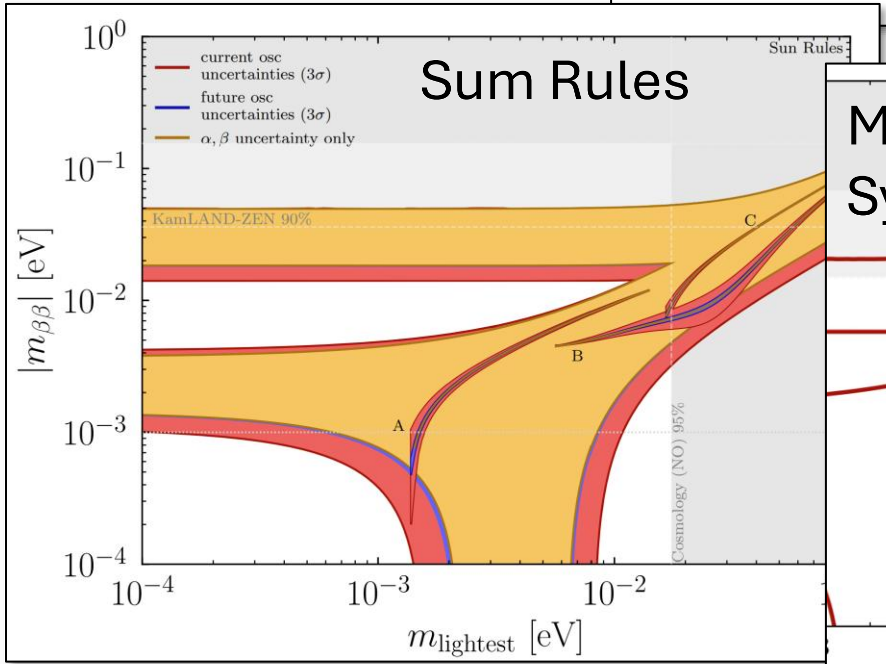
Three Active Majorana Neutrinos

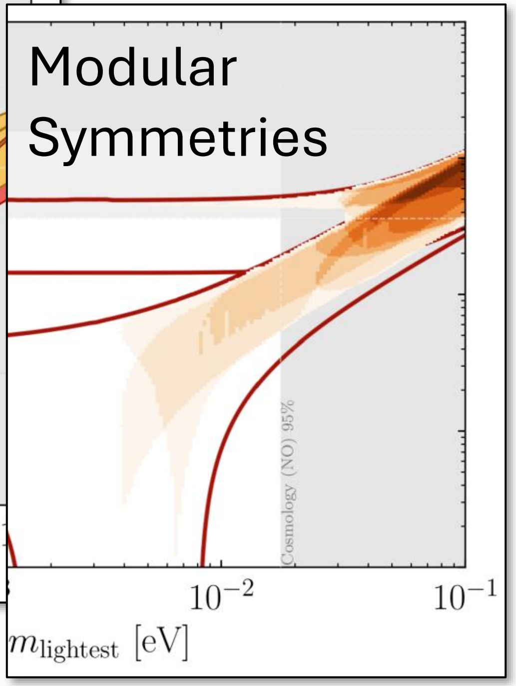
- Neutrino flavour and CP models
  - Predicting/restricting masses, angles and phases, and thus $m_{\beta\beta}$



Denton, Gehrlein, Phys. Rev. D 109 (2024) 055028

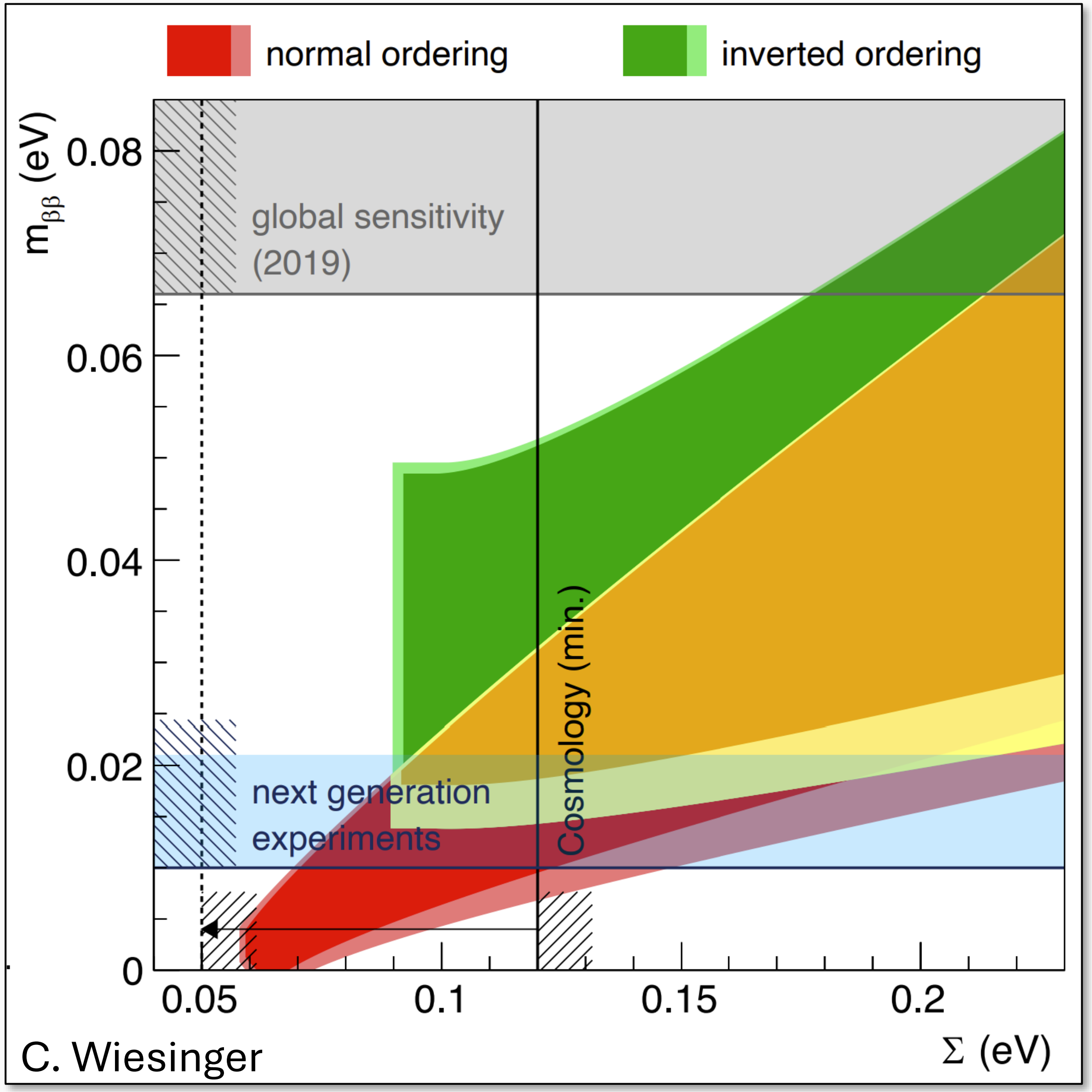






Three Active Majorana Neutrinos

- Effective $0\nu\beta\beta$ Mass
  - Next generation experiments probing IO scenario
  - Pathways to explore NO scenario
- Concordance or tension with other neutrino mass measurements
  - Tritium decay
  - Cosmology



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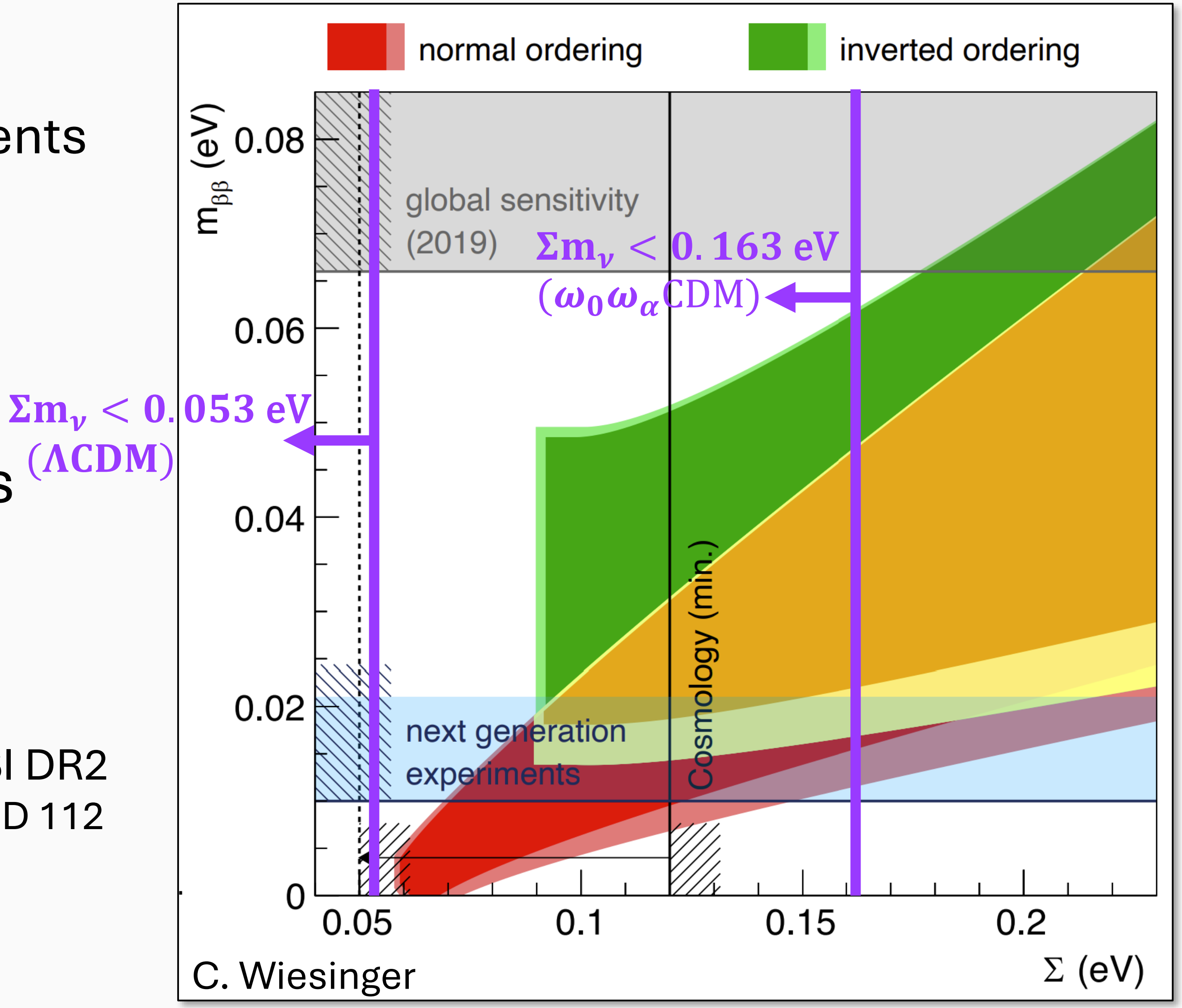
    - Maximal tension with DESI DR2 + CMB (Planck) (Phys. Rev. D 112 (2025) 083513)

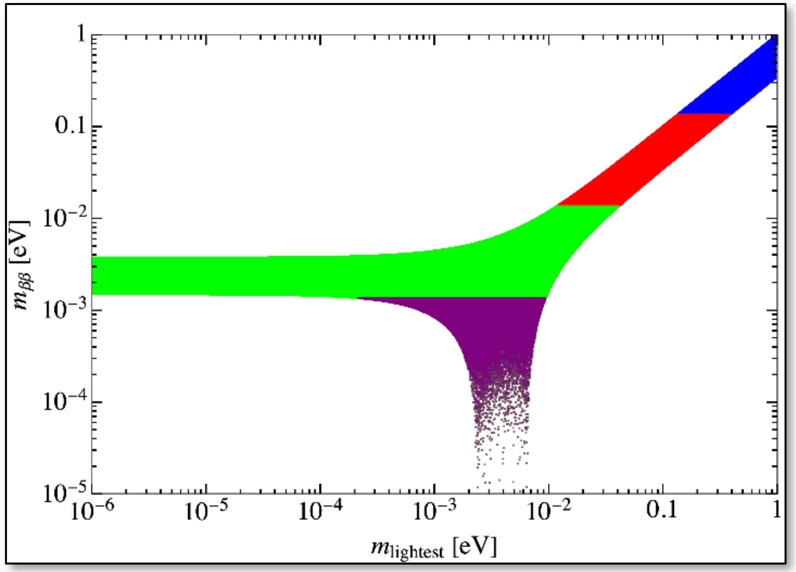


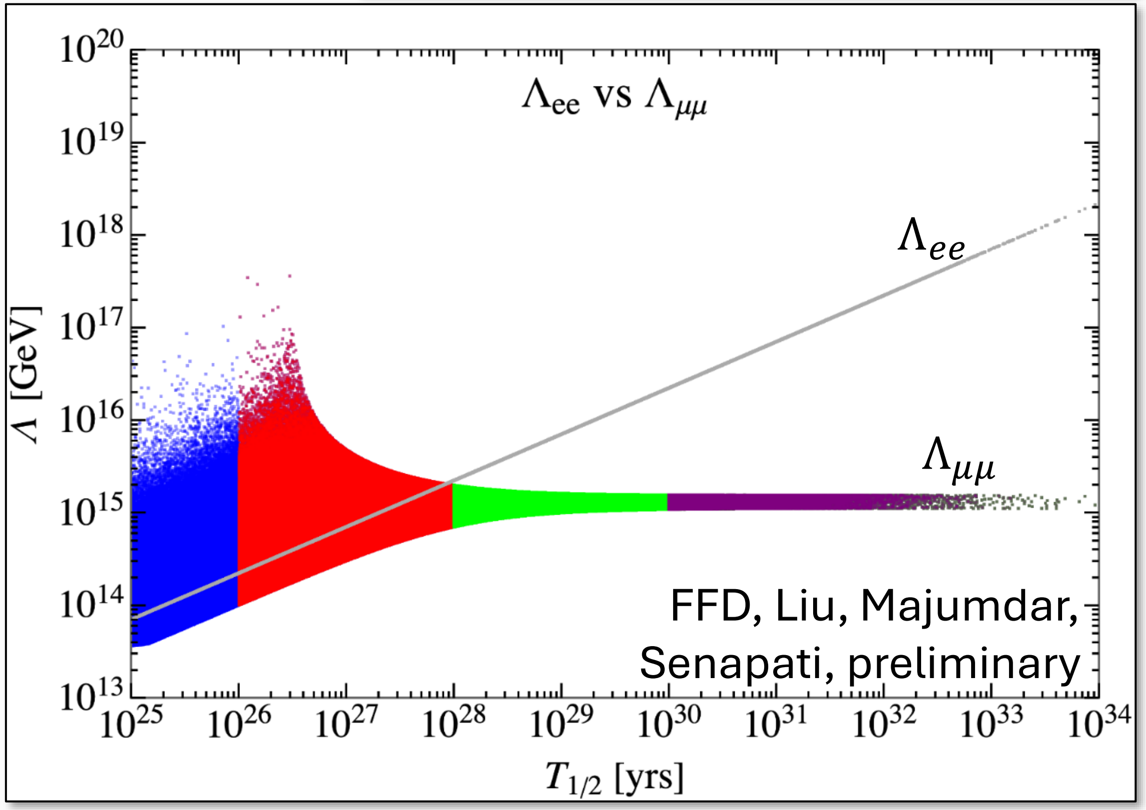
Constraining Weinberg Operator

- Minimal SM extension for Majorana neutrinos

$$L = L_{SM} + \frac{1}{2}\Lambda_{\alpha\beta}^{-1}\left(\overline{L_\alpha^c}\cdot\tilde{H}^*\right)\left(\tilde{H}^+\cdot L_\beta\right) + \text{h.c.}$$

- Reconstruct operator scales from oscillation and $0\nu\beta\beta$ data
  - Best NO fit oscillation values and fixed NME
  - $m_{ee} = m_{\beta\beta} \rightarrow \Lambda_{ee}$ directly from $0\nu\beta\beta$
  - Variation over $m_{lightest}$ and Majorana phases





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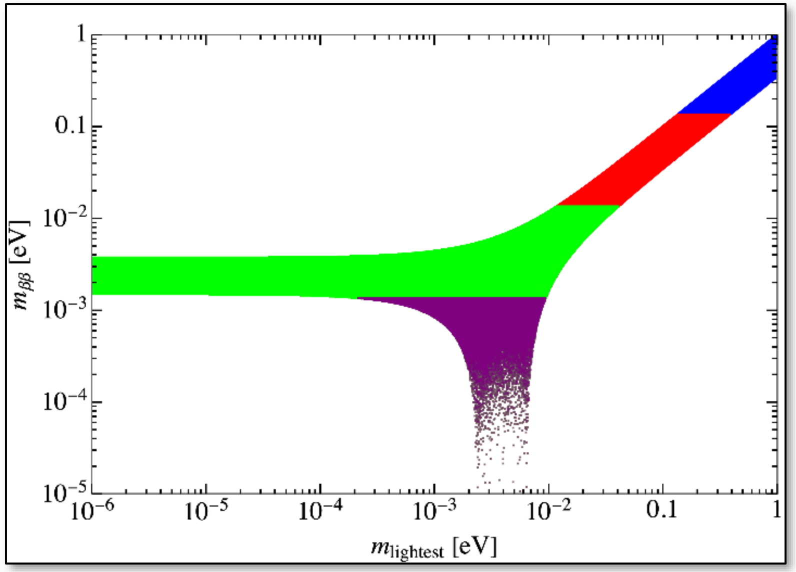
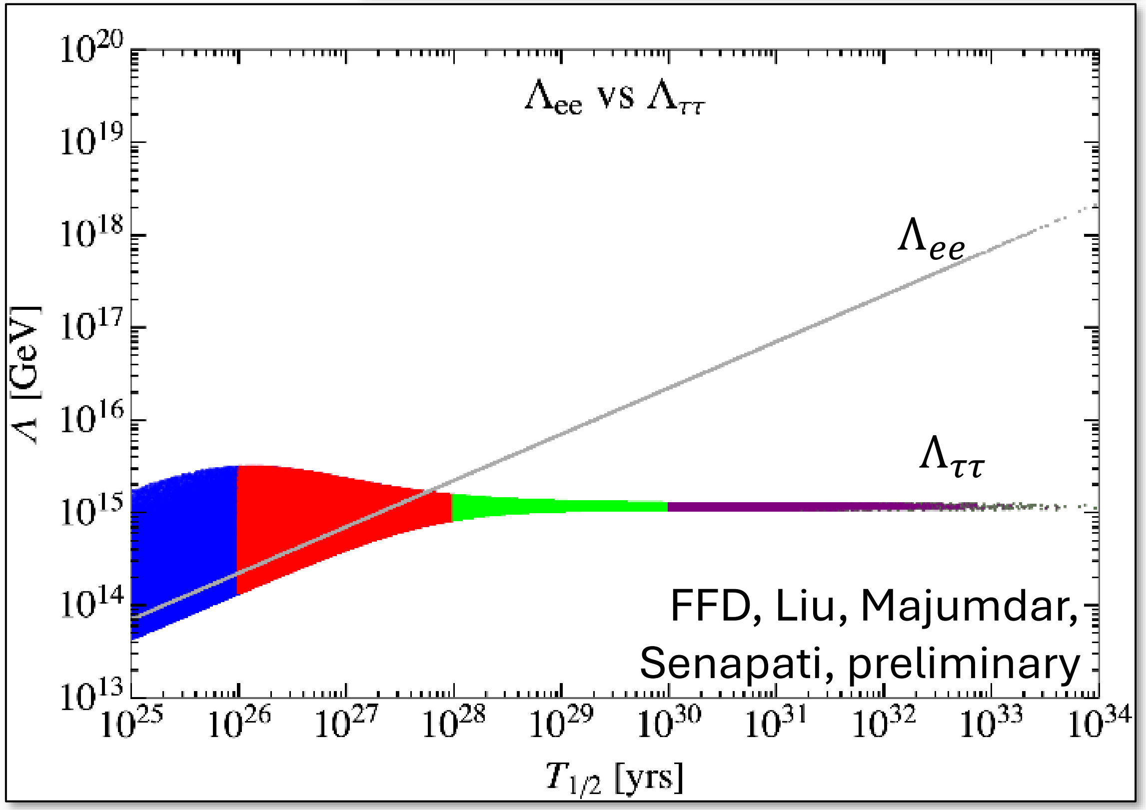
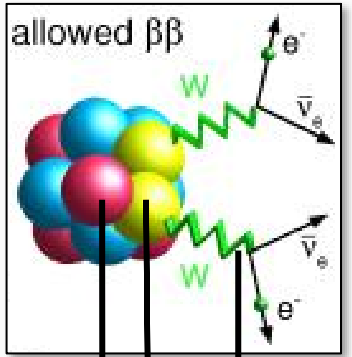




New Physics and $0\nu\beta\beta$

- Decay modes, rates and NP sensitivity

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



$Q \sim 1$ MeV
energy release

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

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

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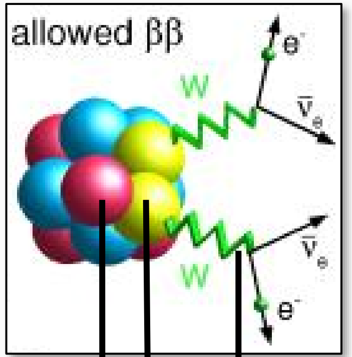

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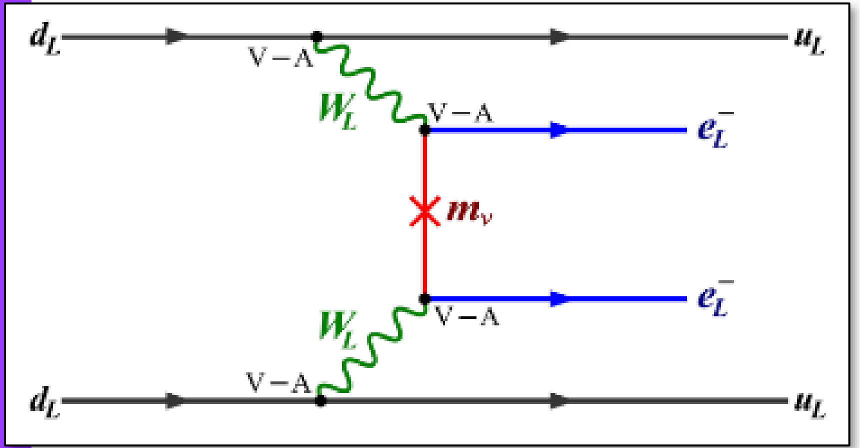

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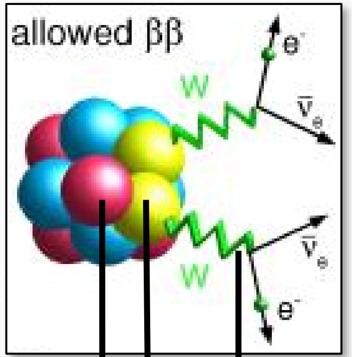
$0\nu\beta\beta$ via 7-dim LNV Operator $\boxed{\Gamma^{0\nu}_{LR} = \Lambda^{-6} G_F\ Q^5 p_F^4 \approx \left(\frac{20\ \text{TeV}}{\Lambda}\right)^6 \left(10^{25}\ yr\right)^{-1}}$



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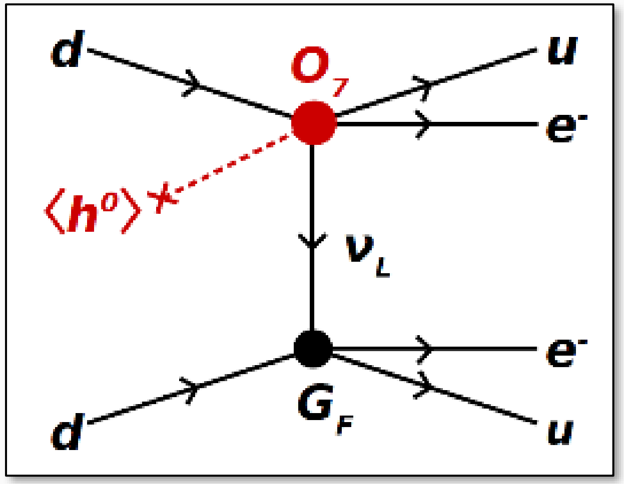

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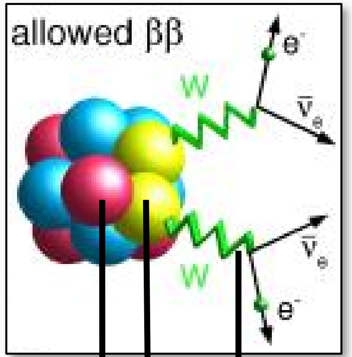

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$$\Gamma_{SM}^{2\nu} = G_F^4 Q^{11} p_F^{-2} \approx \left(10^{19}\ yr\right)^{-1}$$

$0\nu\beta\beta$ via Mass Mechanism

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

$0\nu\beta\beta$ via 7-dim LNV Operator

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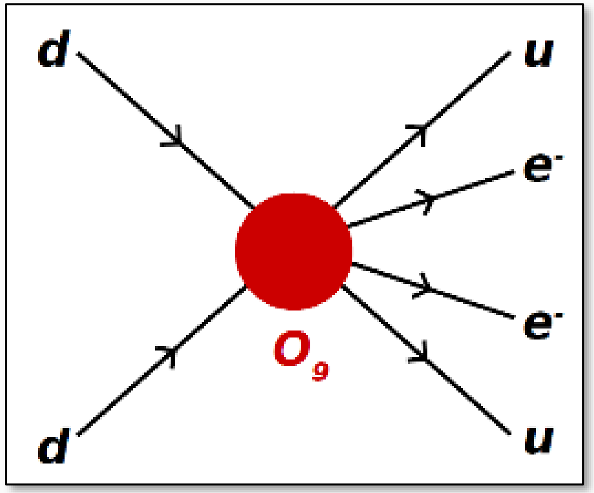

$0\nu\beta\beta$ via 9-dim LNV Operator

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

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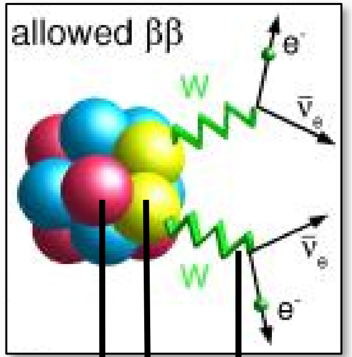

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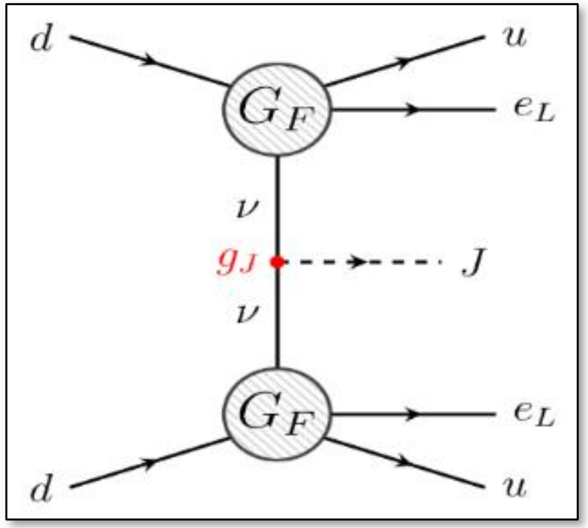

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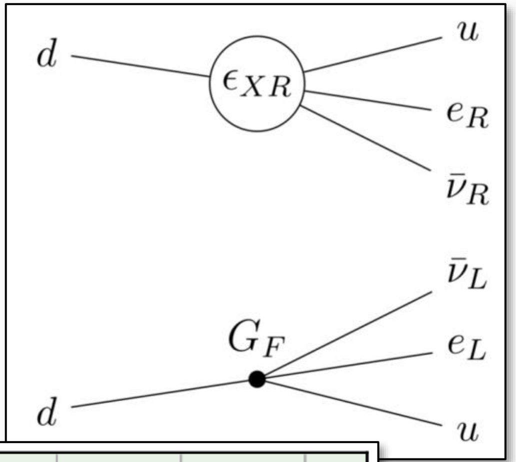
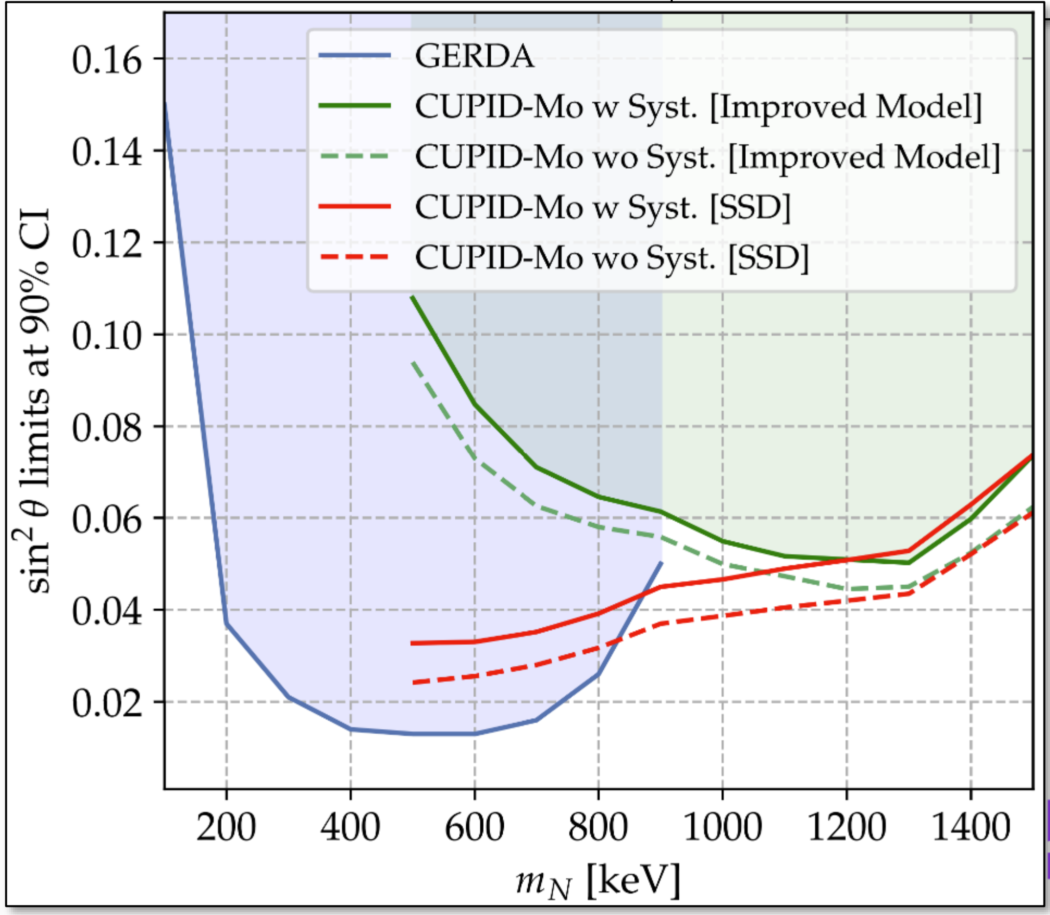
$0\nu\beta\beta J$ Ordinary Majoron Emission

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

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

- Sterile neutrino search through energy endpoint
  Bolton, FFD, Graf, Simkovic, Phys. Rev. D 103 (2021) 055019;
  Agostini, Bossio, Ibarra, Marcano, Phys. Lett. B 815 (2021)
  - Emission of one sterile neutrino in double beta decay: $\nu N\beta\beta$
  - Same principle as endpoint searches in single β decays
  - Observed limits:
    - GERDA (JCAP 12 (2022) 012)
    - CUPID-Mo (Eur. Phys. J. C 84 (2024) 9)
    - CUPID-0 (2603.17602)





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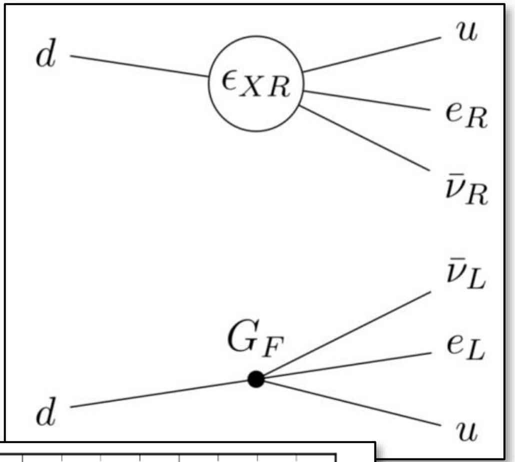
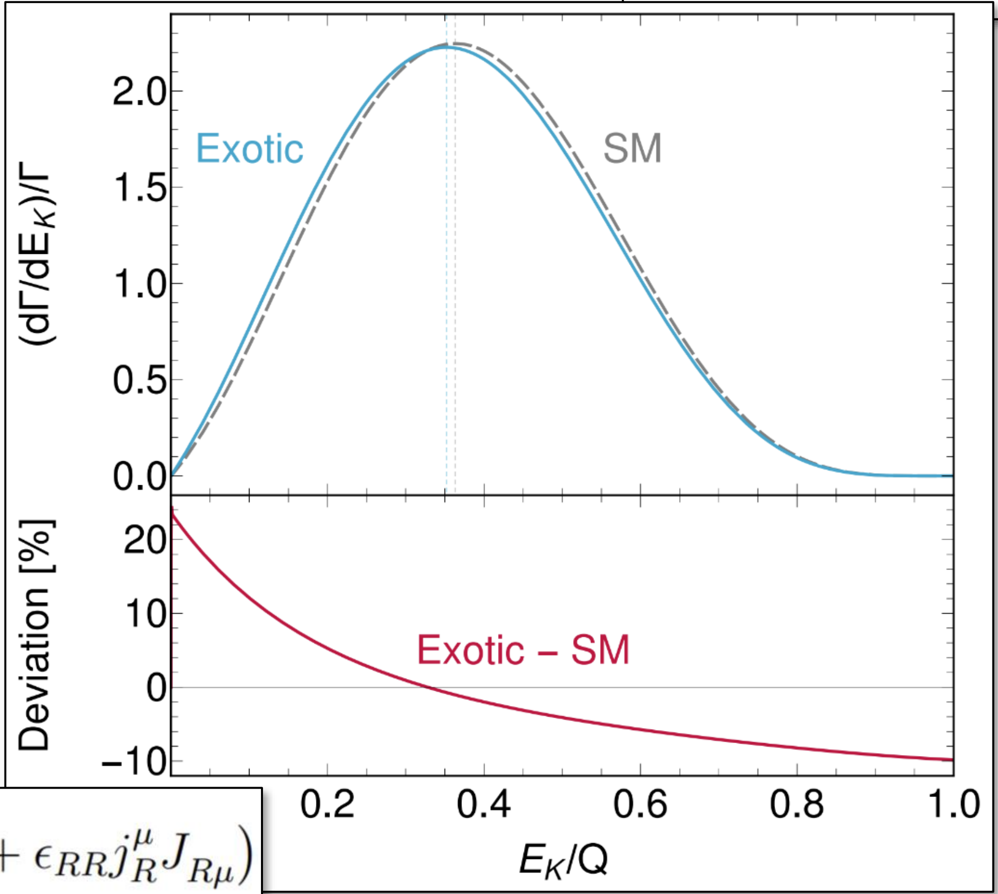
    - CUPID-0 (2603.17602)
  - Lepton number conserving RH currents (FFD, Graf, Simkovic, Phys. Rev. Lett. 125 (2020) 17, 171801)





$$\frac{G_F \cos\theta_C}{\sqrt{2}} \left((1+\delta_{\rm SM}+\epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu}\right)$$

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

- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

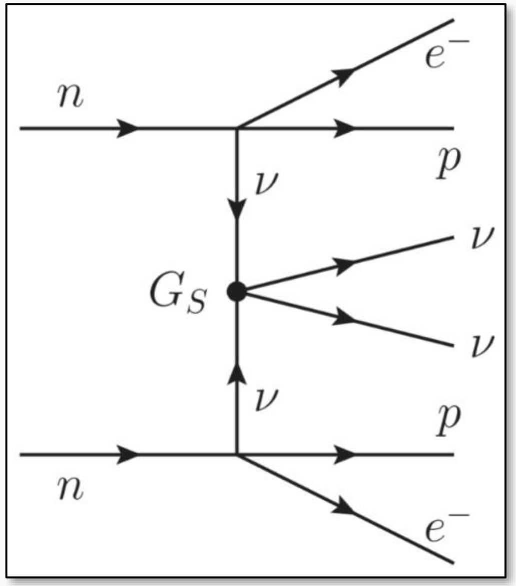
$$\boxed{\Gamma_{2\nu} + \Gamma_{\nu\mathrm{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}}$$

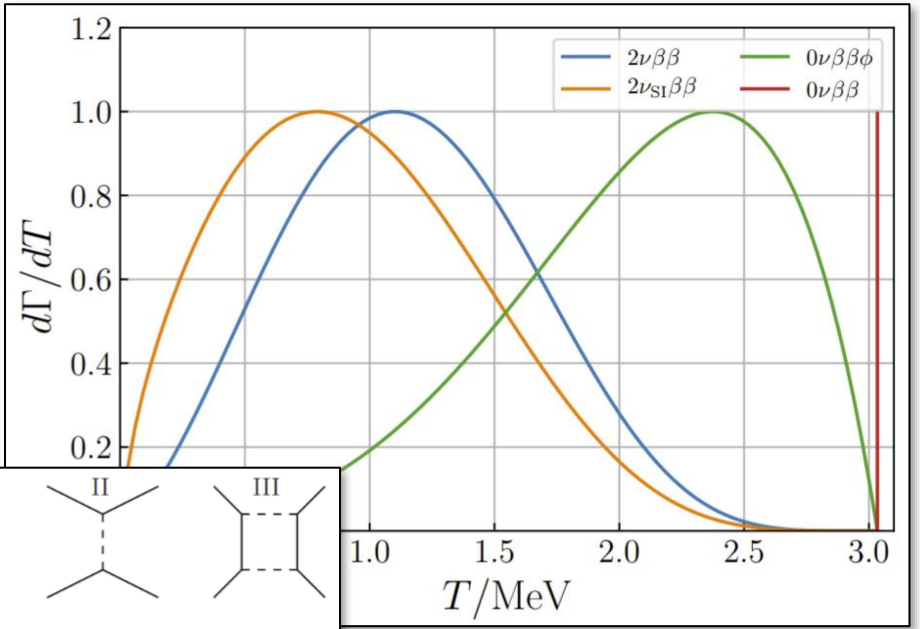
  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Non-observation of enhanced rate

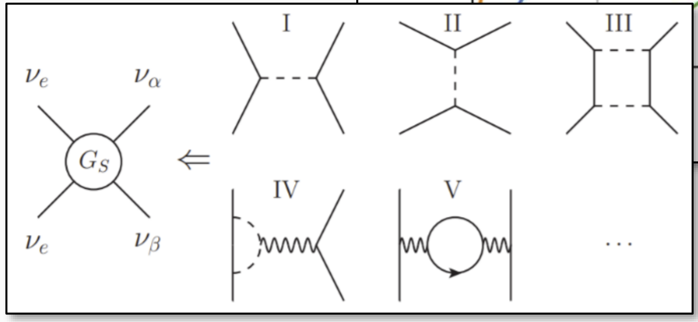
$$\boxed{\Gamma_{\nu\mathrm{SI}} / \Gamma_{2\nu}^{\mathrm{ex}} < 1}$$

excludes regime $G_S \approx 4 \times 10^9\, G_F$ suggested to resolve Hubble tension (Kreisch, Cyr-Racine, Doré, Phys. Rev. D 101 (2020) 12, 123505)

FFD, Graf, Rodejohann, Xu, Phys. Rev. D 102 (2020) 5, 051701

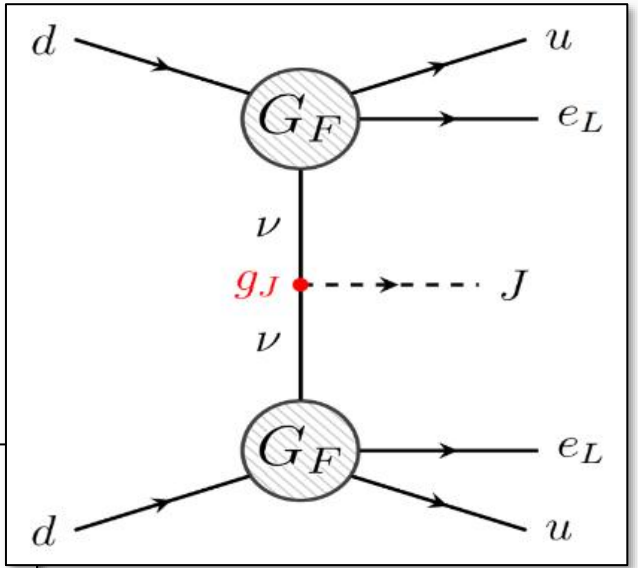




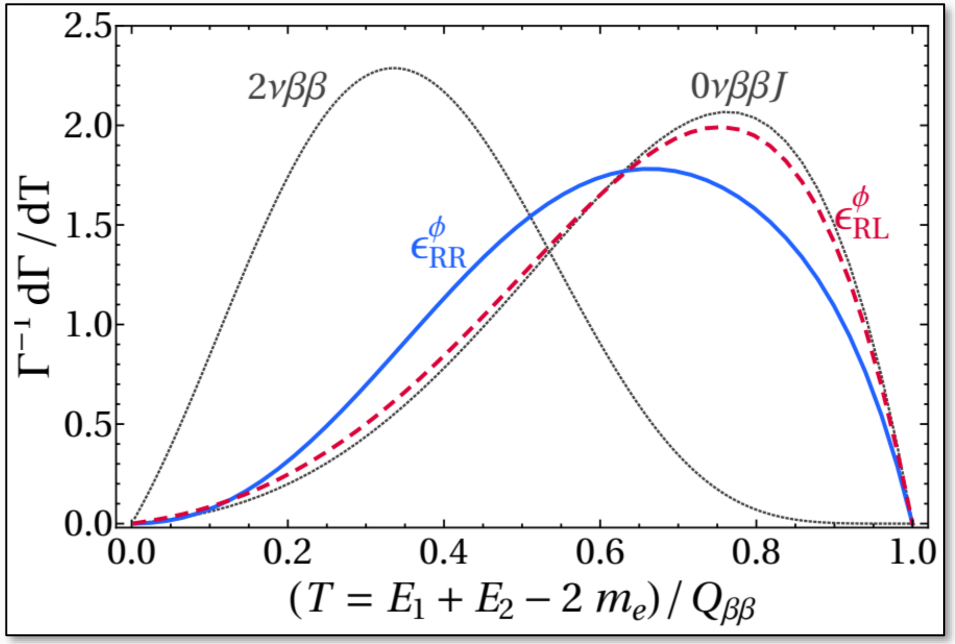


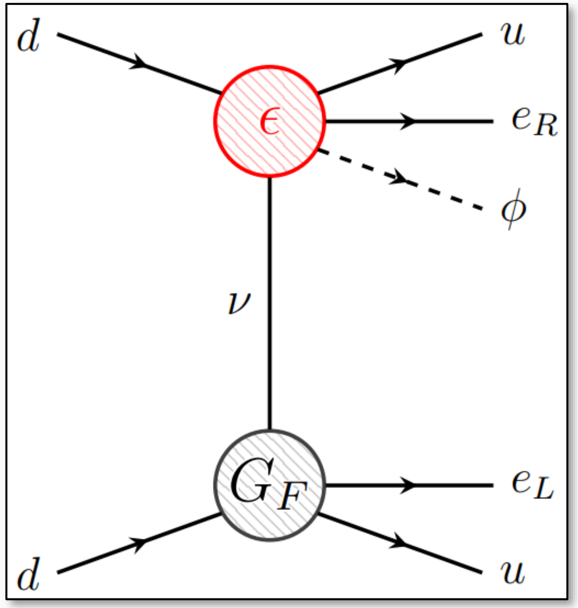
Exotic Particle Emission

- 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
  (Phys. Rev. D 104 (2021) 11, 112002)



Cepedello, FFD, González, Hati, Hirsch, Phys. Rev.Lett. 122 (2019) 18, 181801

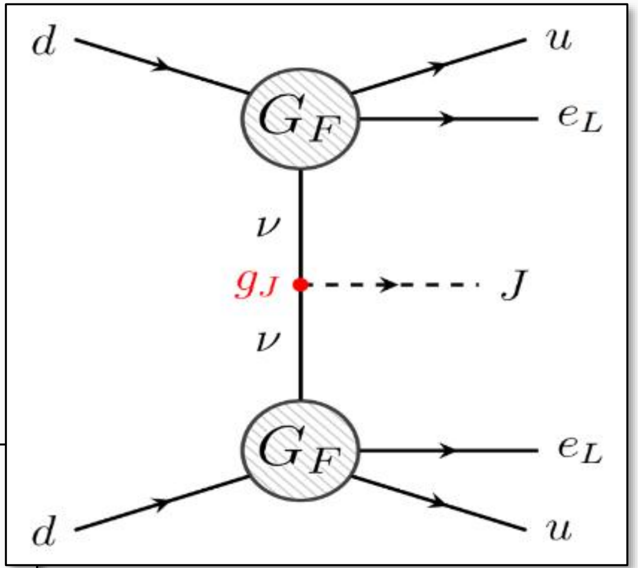




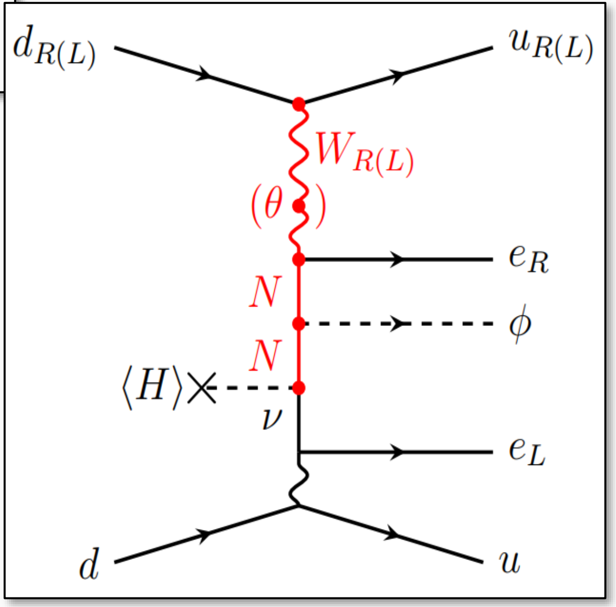
Exotic Particle Emission

- 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)
- Sensitivity to Left-Right symmetric model with Dirac neutrinos

$$\frac{T_{1/2}^{\mathrm{Xe}}}{10^{25}\ \mathrm{y}} \approx \left(\frac{1.4 \times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \mathrm{TeV}}\right)^4 \left(\frac{m_N}{100\ \mathrm{MeV}}\right)^4$$



Cepedello, FFD, González, Hati, Hirsch, Phys. Rev.Lett. 122 (2019) 18, 181801



Neutrinos coupled to Dark Sectors

- Dirac neutrinos coupled to massive, L-charged "Majoron" S and dark fermions χ

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

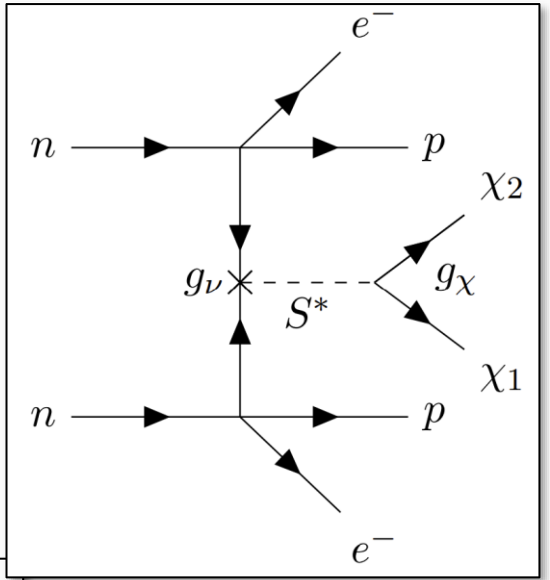
  - Z_2 symmetry to forbid mixing
  - Self-interacting neutrinos and self-interacting (potentially) DM

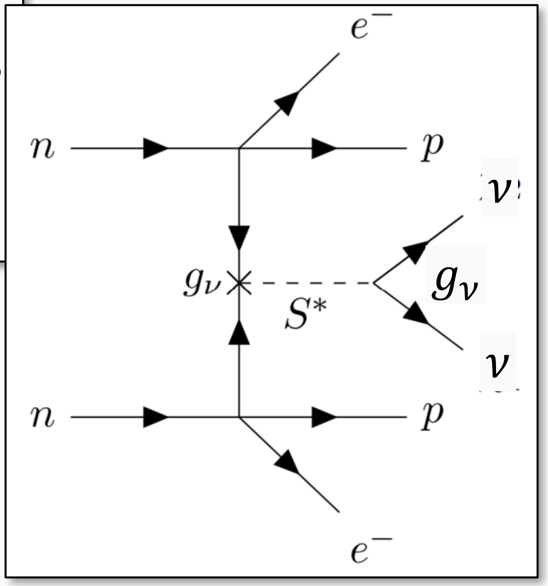
- Model I: No Z_2, mixing terms allowed

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

- Applicable to Majorana neutrinos, but constraints from $0\nu\beta\beta$

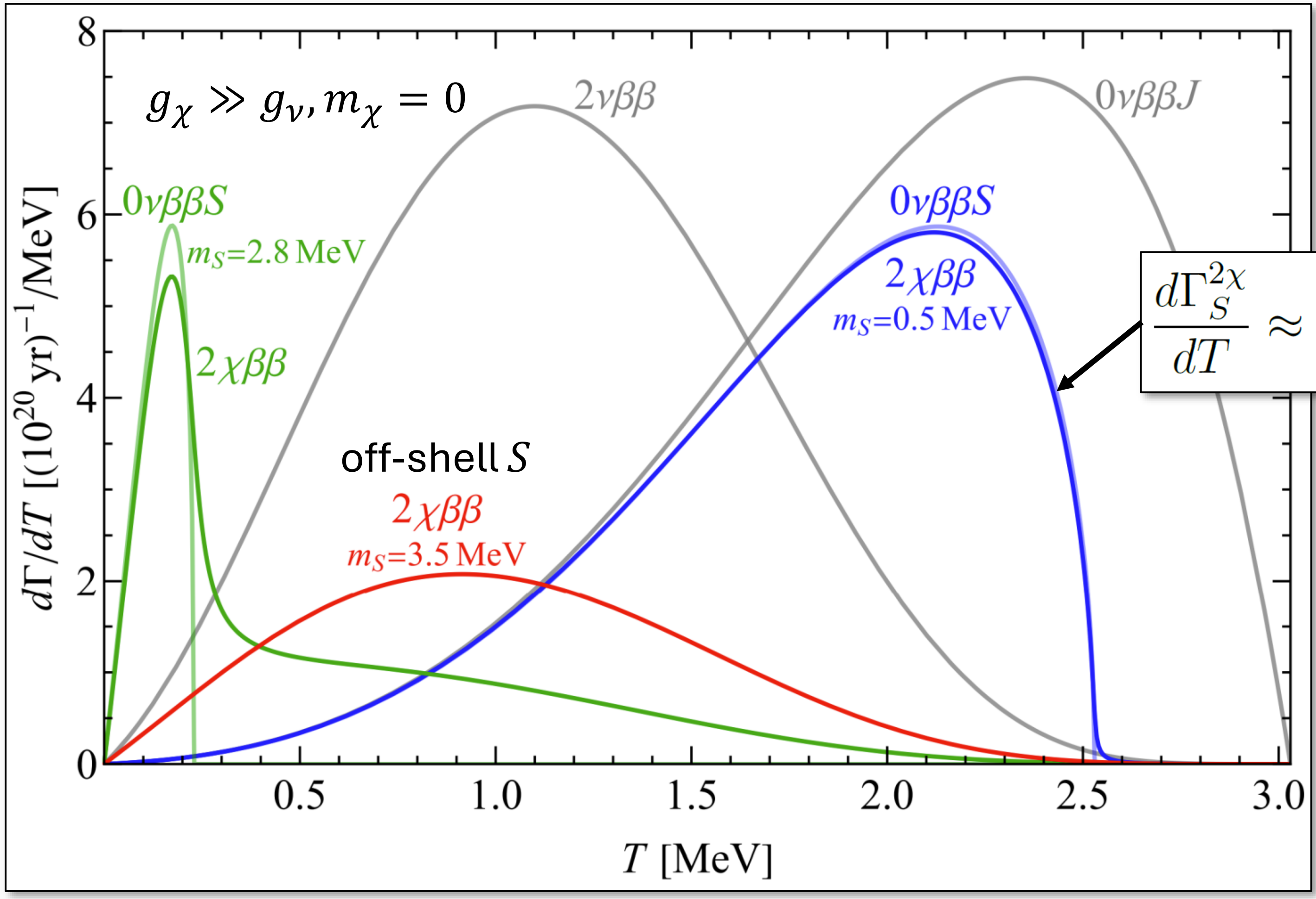
Boudjema, FFD, Herrero, Majumdar, Senapati, Phys. Rev. D 113 (2026) 075039

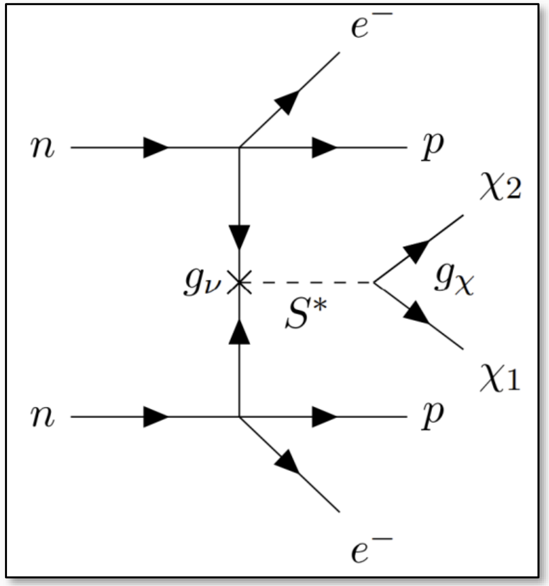




Neutrinos coupled to Dark Sectors

- Finite S width and off-shell S





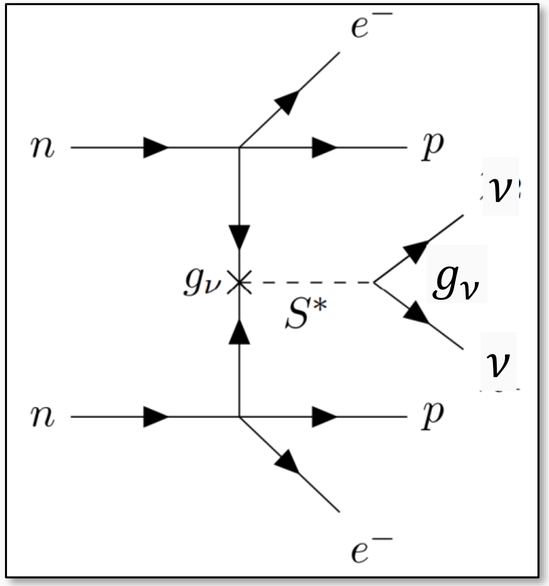
$$\frac{d\Gamma_S^{2\chi}}{dT} \approx \frac{d\Gamma_S}{dT} \times \mathrm{Br}(S \to \chi\chi)$$

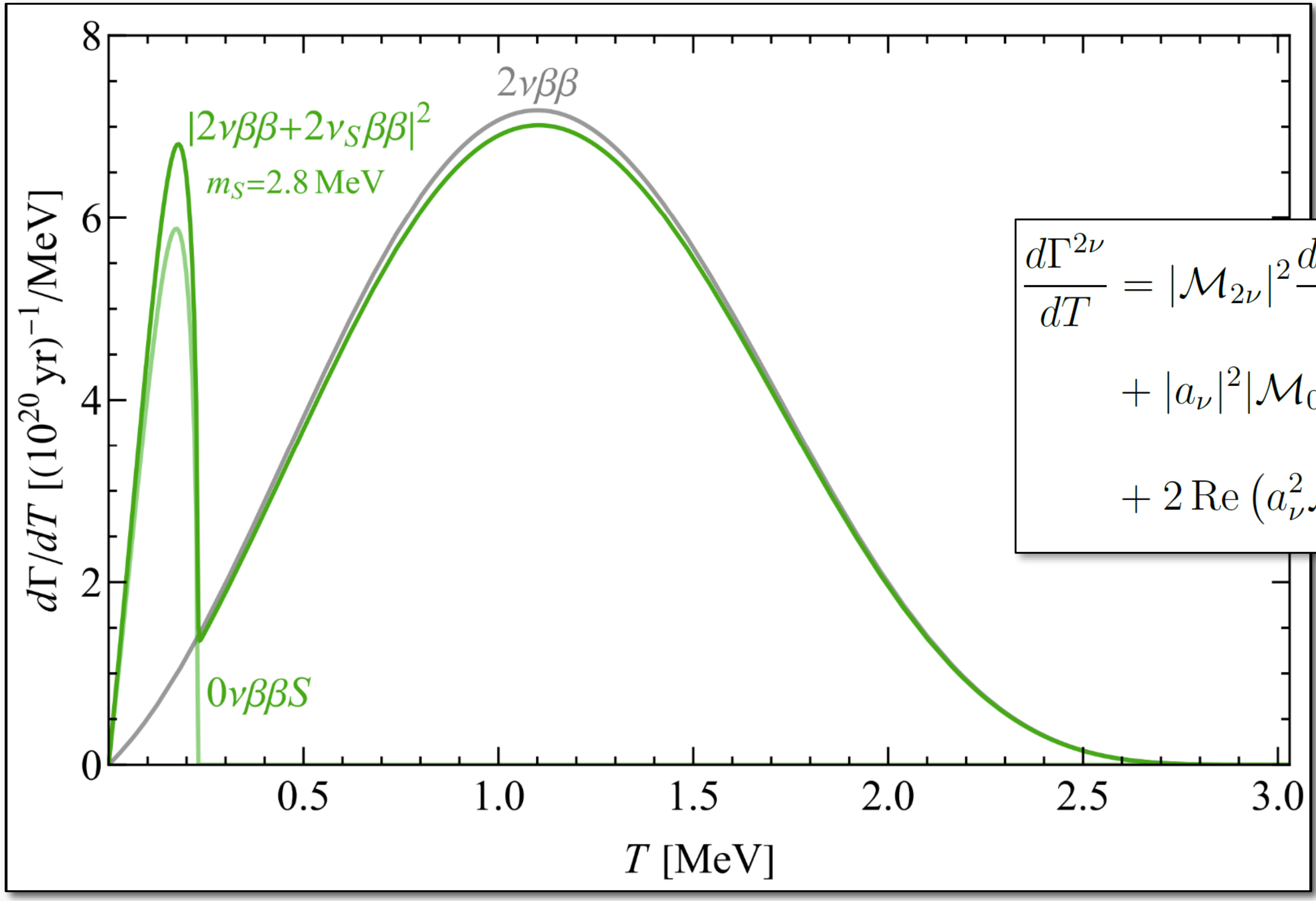
On-shell S in narrow-width approximation

Boudjema, FFD, Herrero, Majumdar, Senapati, Phys. Rev. D 113 (2026) 075039

Neutrinos coupled to Dark Sectors

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



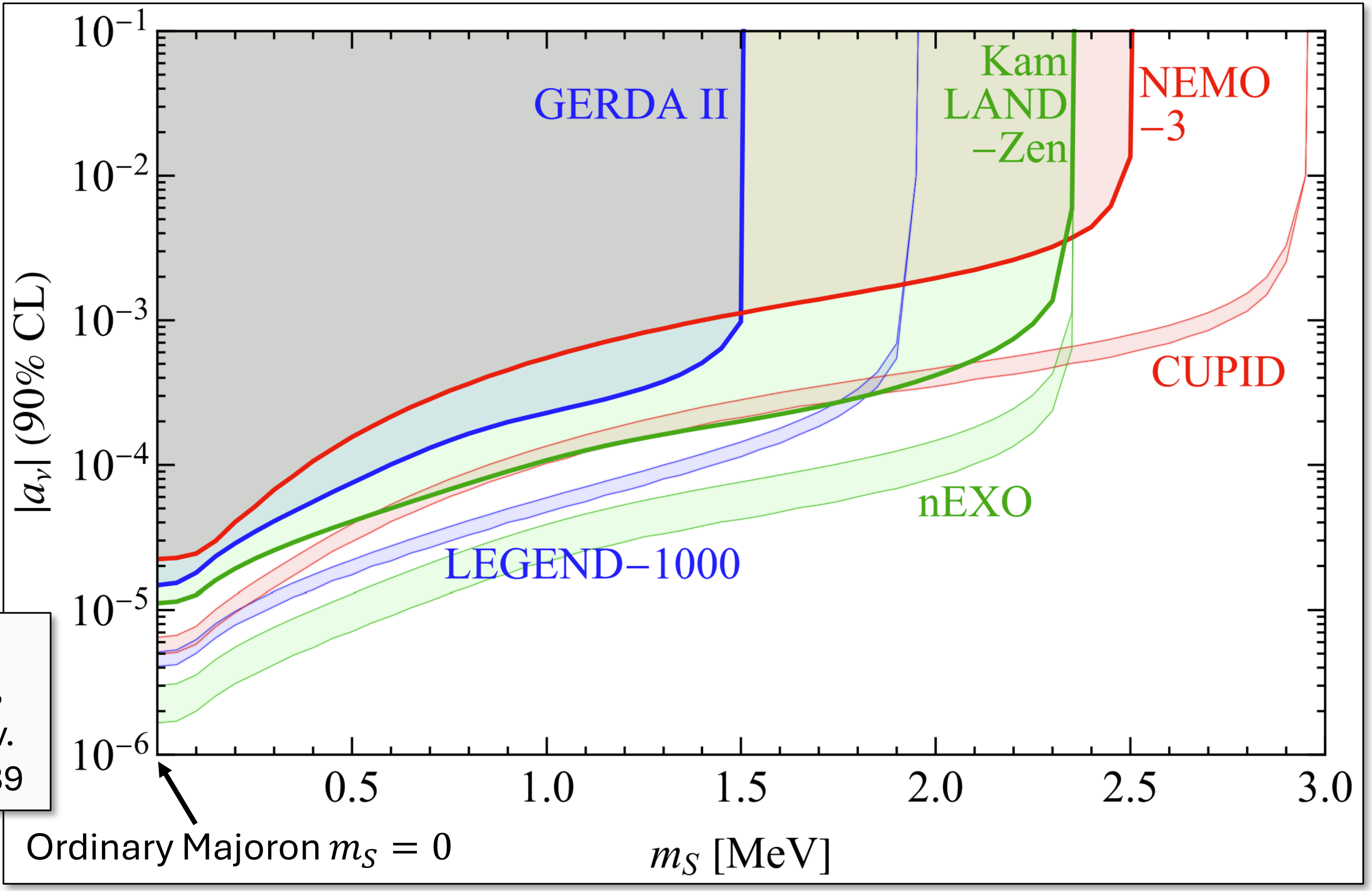


$$
\begin{aligned}
\frac{d\Gamma^{2\nu}}{dT} &= |\mathcal{M}_{2\nu}|^2 \frac{d\Gamma^{2\nu}_{\mathrm{SM}}}{dT} \\
&+ |a_\nu|^2 |\mathcal{M}_{0\nu}|^2 \frac{d\Gamma^{2\nu}_{S\ \text{on-shell}}}{dT} + |a_\nu|^4 |\mathcal{M}_{0\nu}|^2 \frac{d\Gamma^{2\nu}_{S\ \text{off-shell}}}{dT} \\
&+ 2\,\mathrm{Re}\left(a_\nu^2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

Boudjema, FFD, Herrero, Majumdar, Senapati, Phys. Rev. D 113 (2026) 075039

Neutrinos coupled to Dark Sectors

- Sensitivity of double beta decay searches



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Neutrinos coupled to Dark Sectors

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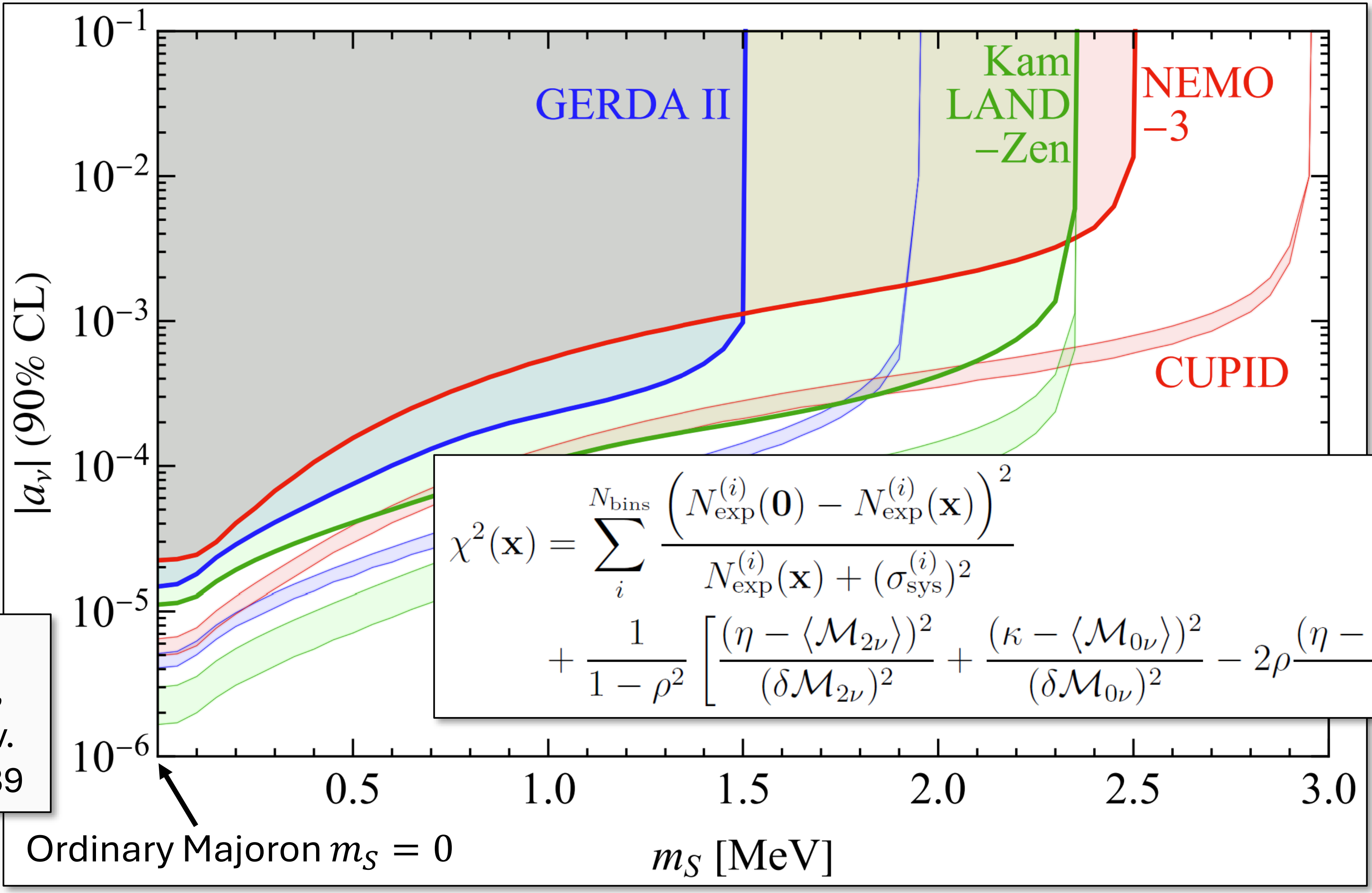
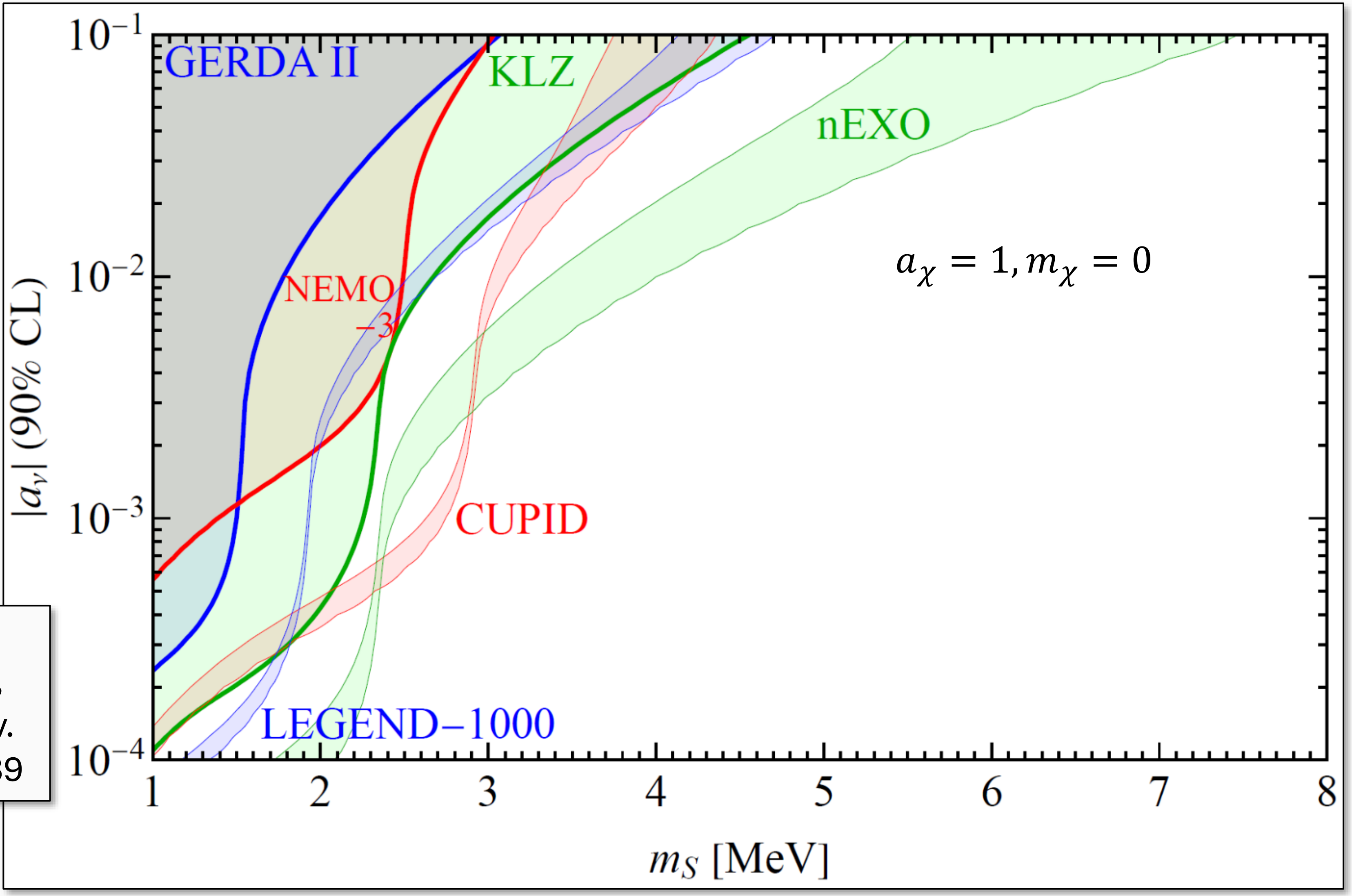


$$\chi^2(\mathbf{x}) = \sum_i^{N_{\rm bins}} \frac{\left(N_{\rm exp}^{(i)}(\mathbf{0}) - N_{\rm exp}^{(i)}(\mathbf{x})\right)^2}{N_{\rm exp}^{(i)}(\mathbf{x}) + (\sigma_{\rm sys}^{(i)})^2} + \frac{1}{1-\rho^2}\left[\frac{(\eta - \langle\mathcal{M}_{2\nu}\rangle)^2}{(\delta\mathcal{M}_{2\nu})^2} + \frac{(\kappa - \langle\mathcal{M}_{0\nu}\rangle)^2}{(\delta\mathcal{M}_{0\nu})^2} - 2\rho\frac{(\eta - \langle\mathcal{M}_{2\nu}\rangle)(\kappa - \langle\mathcal{M}_{0\nu}\rangle)}{\delta\mathcal{M}_{2\nu}\cdot\delta\mathcal{M}_{0\nu}}\right]$$

Boudjema, FFD, Herrero, Majumdar, Senapati, Phys. Rev. D 113 (2026) 075039

Neutrinos coupled to Dark Sectors

- Modification from interference and off-shell S



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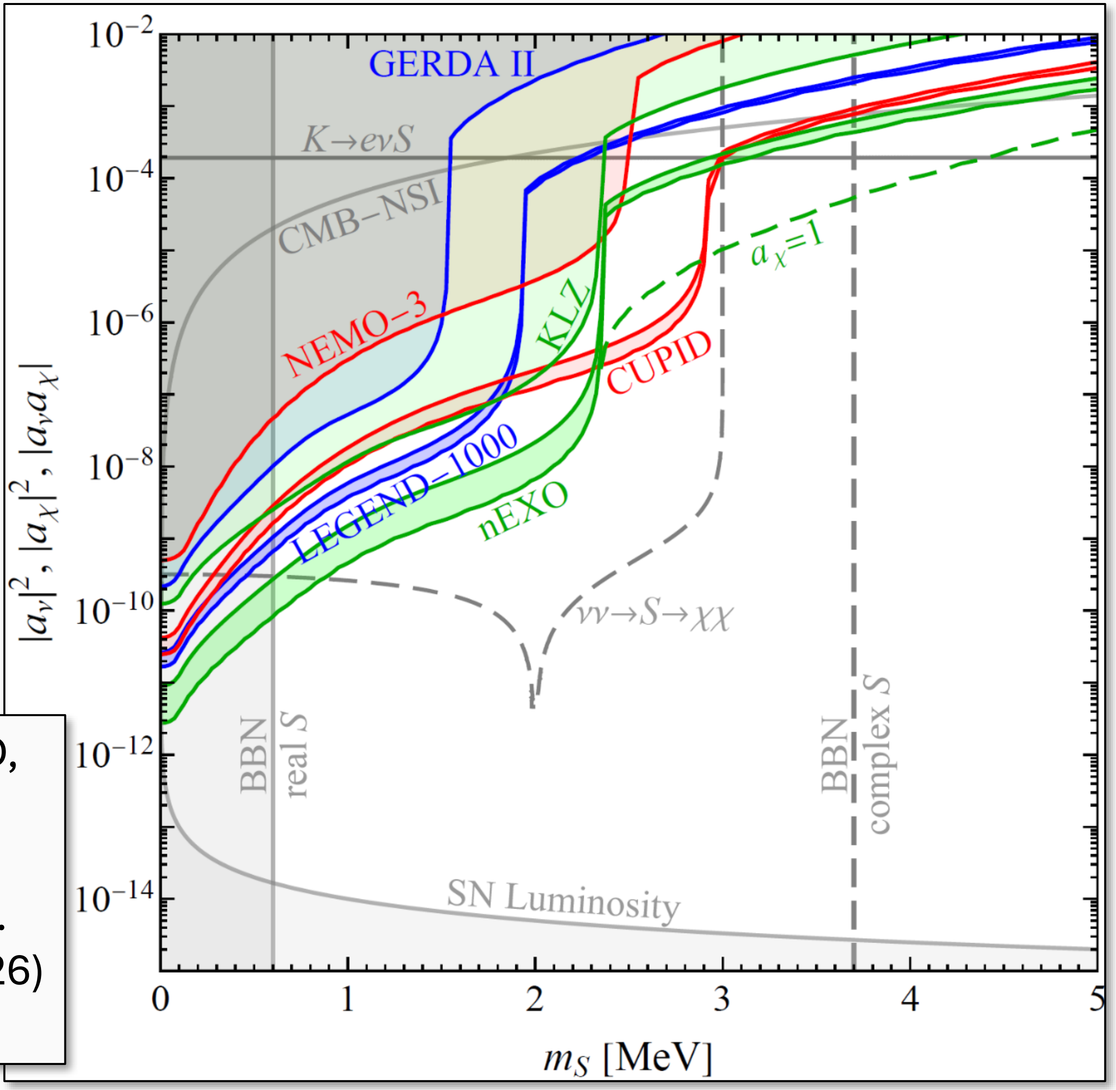
Neutrinos coupled to Dark Sectors

- Comparison with other constraints

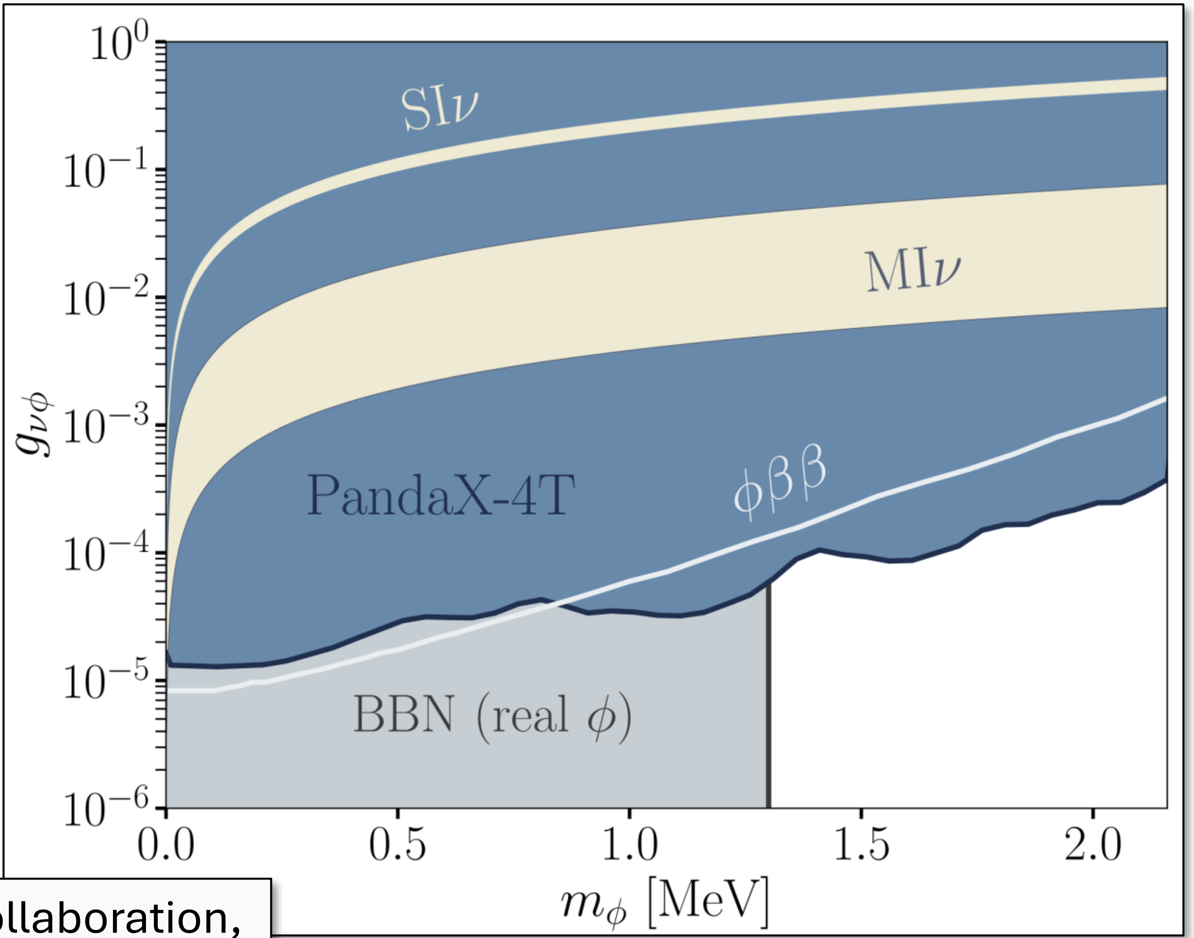


Boudjema, FFD, Herrero, Majumdar, Senapati, Phys. Rev. D 113 (2026) 075039

- 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 Dark Sectors

- Recent search at PandaX-4T



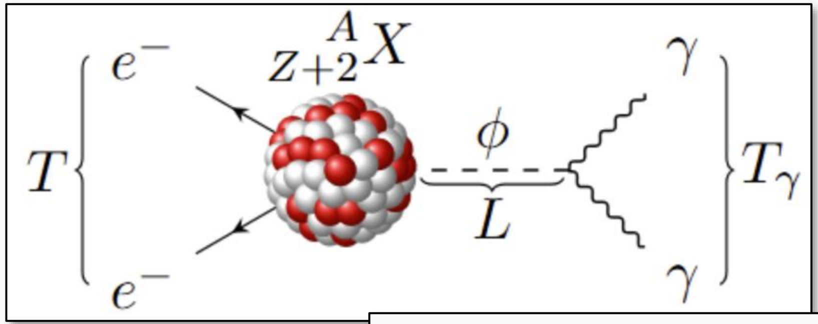
PandaX collaboration, Phys. Rev. Lett. 136 (2026) 241802

- 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

Long-lived Particles from Double Beta Decay

- If it exists, a massive Majoron is starting to have a macroscopic decay length

$$L \approx 0.1\ \mathrm{cm} \times \left(\frac{10^{-4}}{c_\nu}\right)^2 \left(\frac{1\ \mathrm{MeV}}{m_\phi}\right)$$



Bolton, Boudjema, FFD, Hati, Majumdar, 2608.xxxxx

- Coupling to electrons and photons

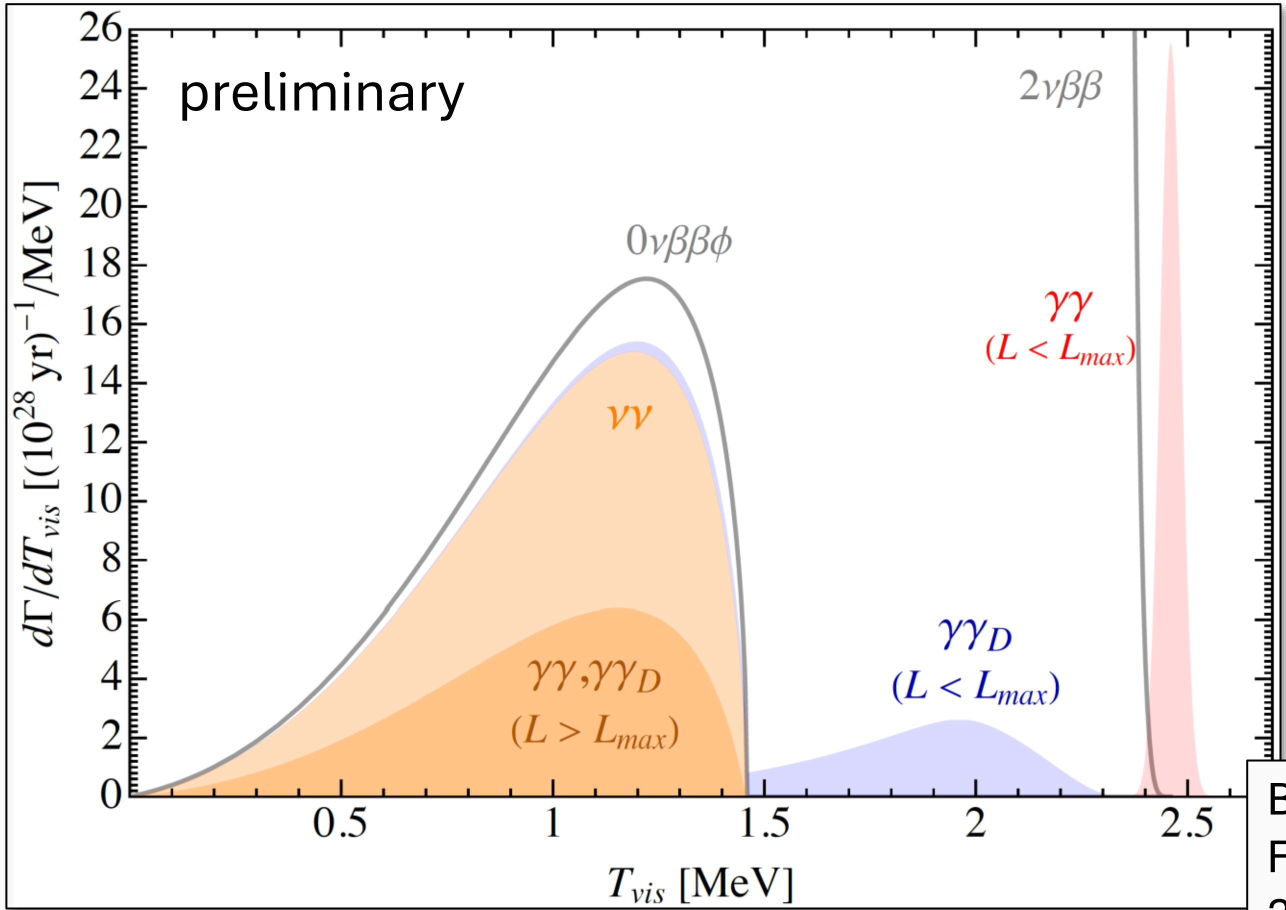
$$\mathcal{L} = \frac{1}{2} c_\nu^{\alpha\beta} (\bar{\nu}_\alpha P_L \nu_\beta)\phi + c_e^{\alpha\beta} (\bar{e}_\alpha P_L e_\beta)\phi + \mathrm{h.c.},$$

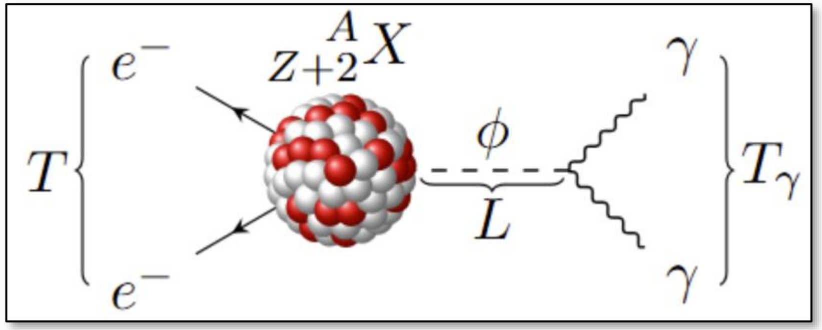
$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{\phi\gamma\gamma_D}}{2} \phi F_{\mu\nu} \tilde{F}_D^{\mu\nu},$$

- Displaced signatures $\gamma\gamma\beta\beta$, $\gamma\gamma_D\beta\beta$, $e^+e^-\beta\beta$
  - Segmented detectors or large fiducial volumes

Long-lived Particles from Double Beta Decay

- Displaced energy deposition and distorted Majoron spectrum



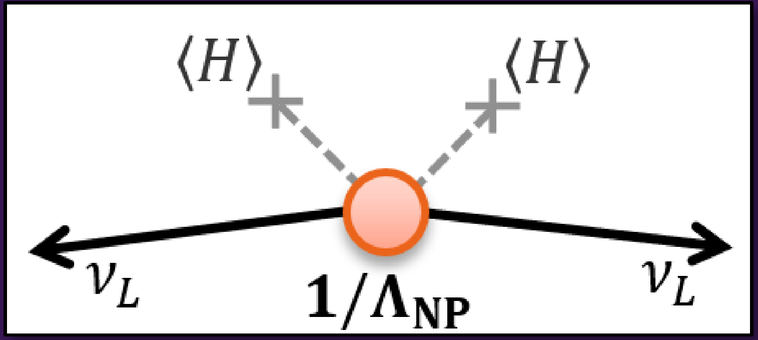


- Fully visible energy deposition for $\gamma\gamma\beta\beta$, $e^+e^-\beta\beta$
- Sensitivity strongly dependent on experiment
- Ideal sensitivity to couplings $c_\nu \approx 10^{-7}$, $c_e \approx 10^{-6}$, $g_{\phi\gamma\gamma} \approx 10^{-6}\ \mathrm{MeV}^{-1}$

Bolton, Boudjema, FFD, Hati, Majumdar, 2608.xxxxx

Conclusions

- **Neutrino conundrum**
  - Much lighter than other fermions
  - Only neutral fermions: Dirac or Majorana?
- **Absolute neutrino mass and nature**
  - Tritium decay and cosmological observations to probe last mass parameter of SM
  - $0\nu\beta\beta$ as crucial test of neutrino nature and lepton number symmetry of SM
  - $0\nu\beta\beta$ sensitive to high-scale lepton number violating New Physics up to GUT scales



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

- **Portal to New Physics**
  - Mechanism of neutrino mass generation
  - Exotic neutrino interactions and light New Physics in $2\nu\beta\beta$