



New Physics with Neutrinoless Double Beta Decay

Frank Deppisch
University College London

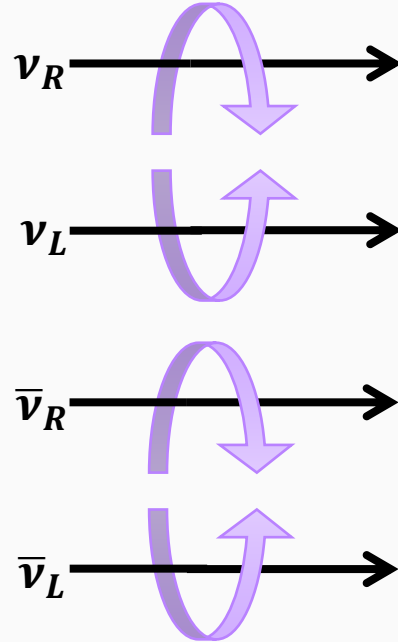
2nd Workshop on next generation $0\nu\beta\beta$
searches in Xe | Old Trafford
14-18/09/2026



Dirac versus Majorana

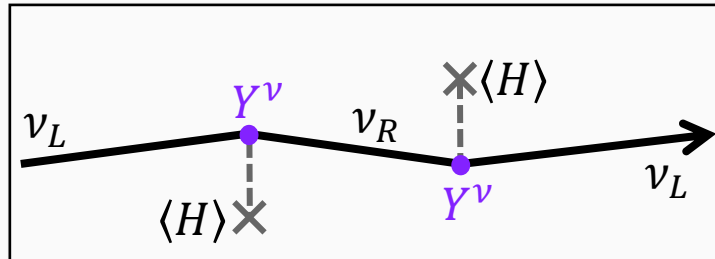
- Two possibilities to define neutrino mass

Dirac

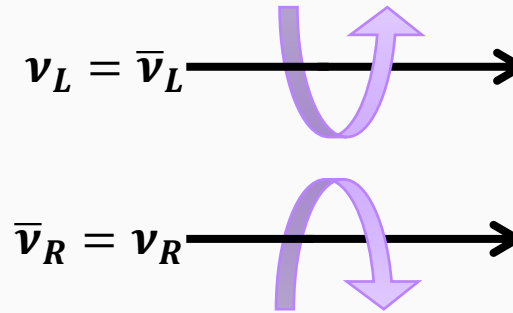


$$m_D \bar{\psi} \psi = m_D (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

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



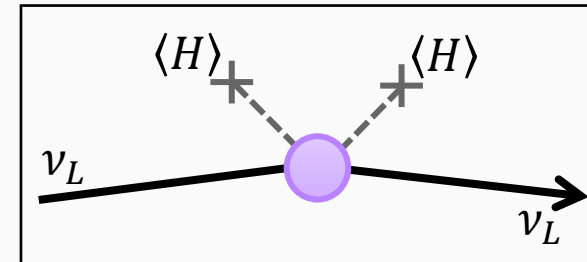
Majorana



$$\bar{\nu}_R = \nu_R$$

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

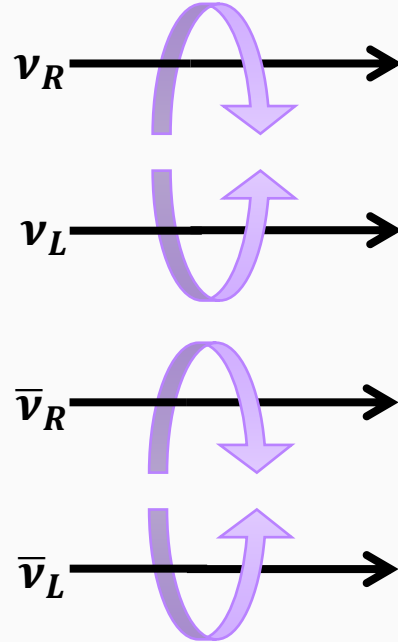
Majorana mass, using only a left-handed
neutrino $\rightarrow$ Lepton Number Violation



Dirac versus Majorana

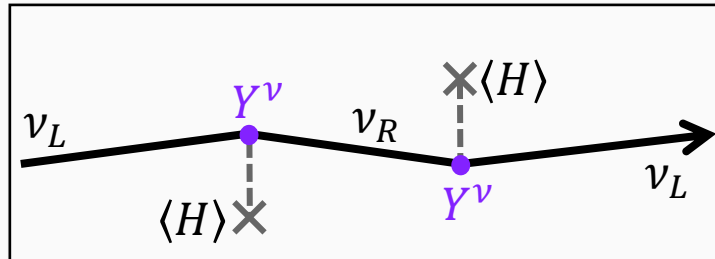
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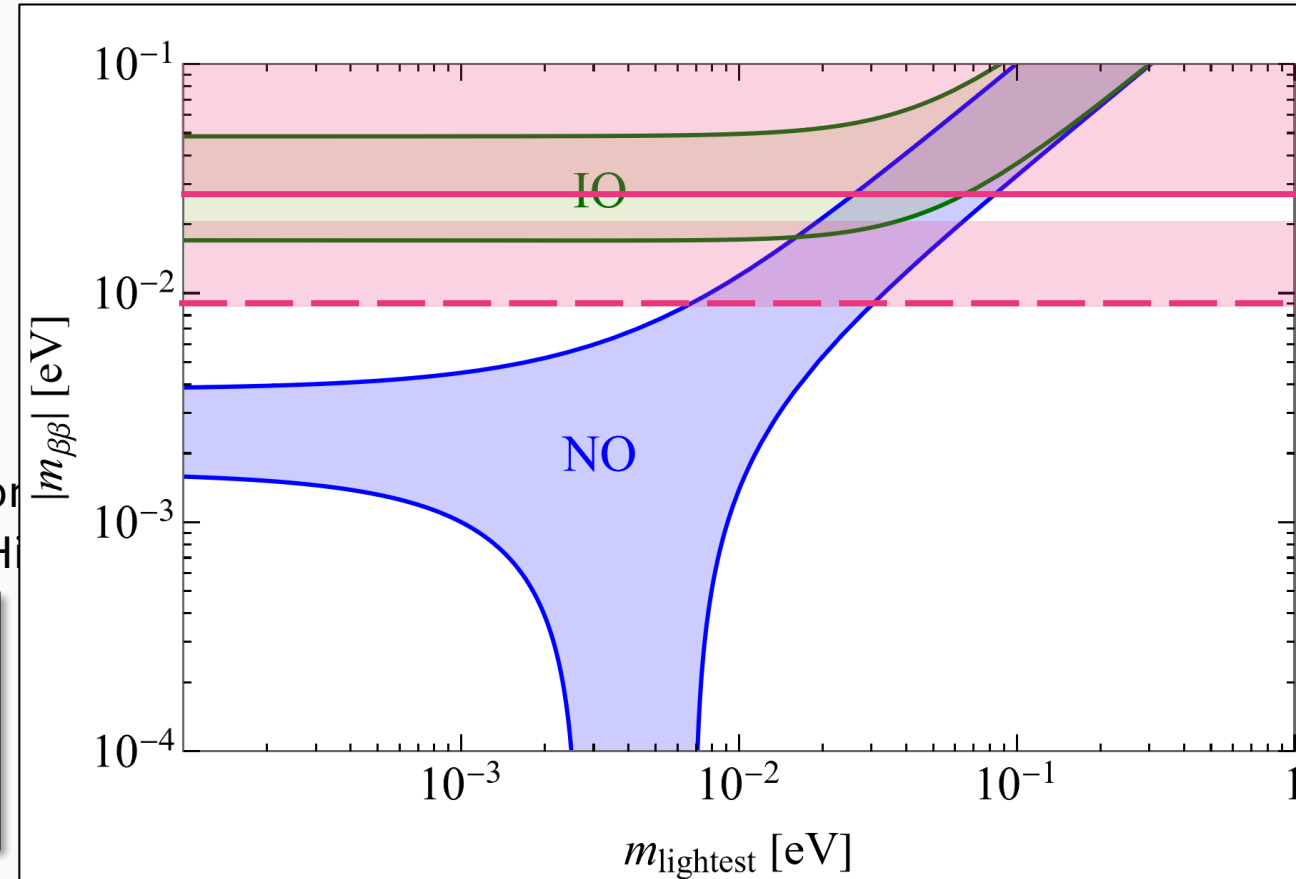


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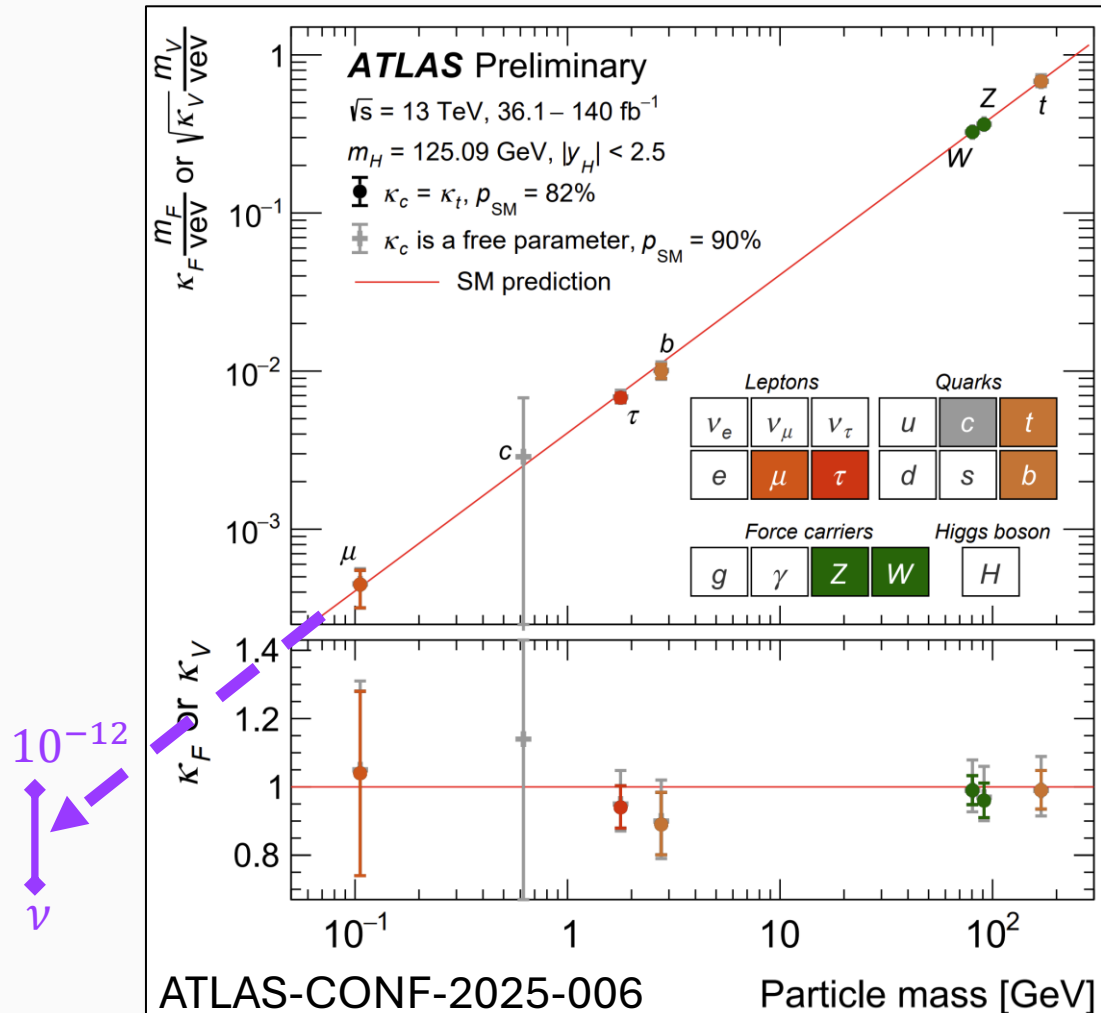
Majorana



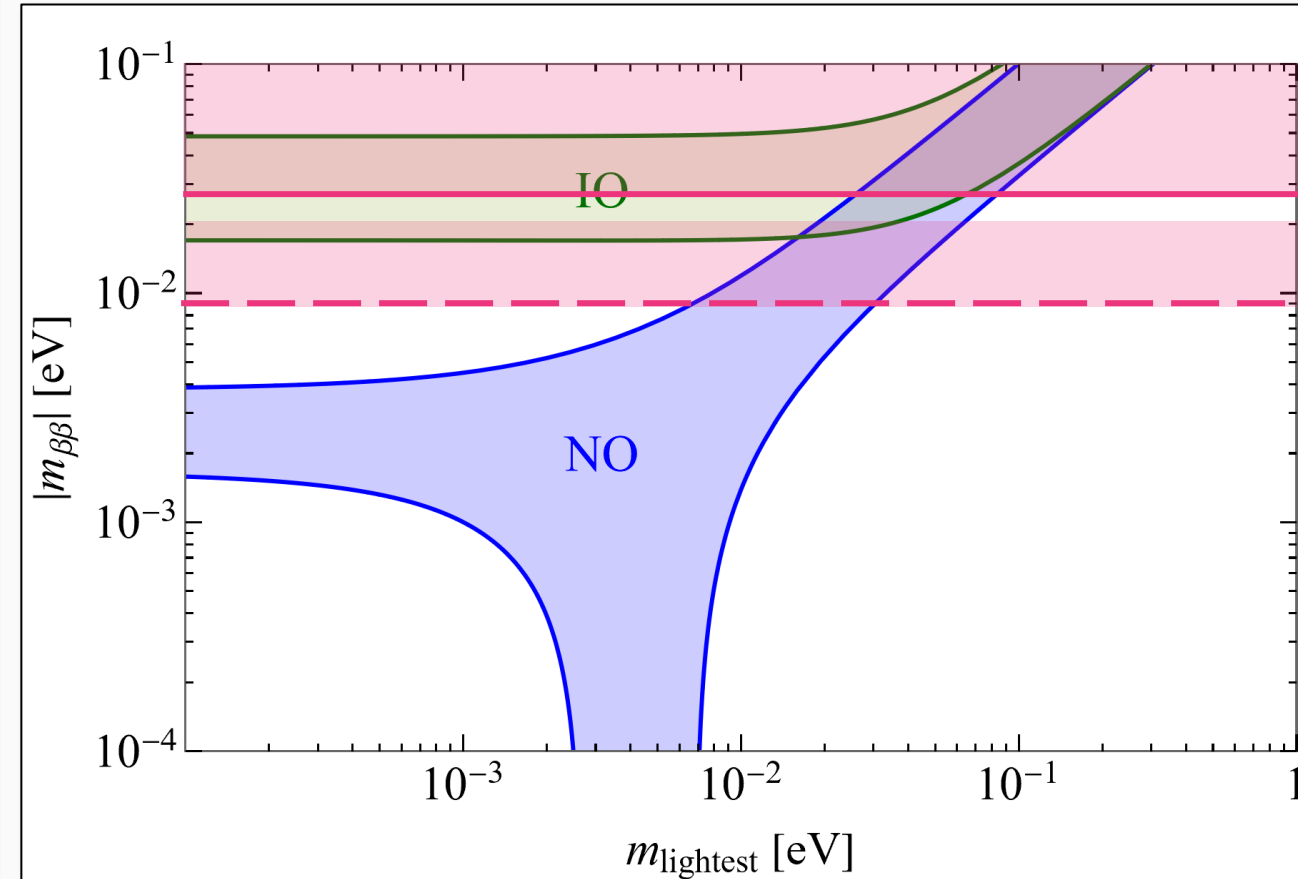
Dirac versus Majorana

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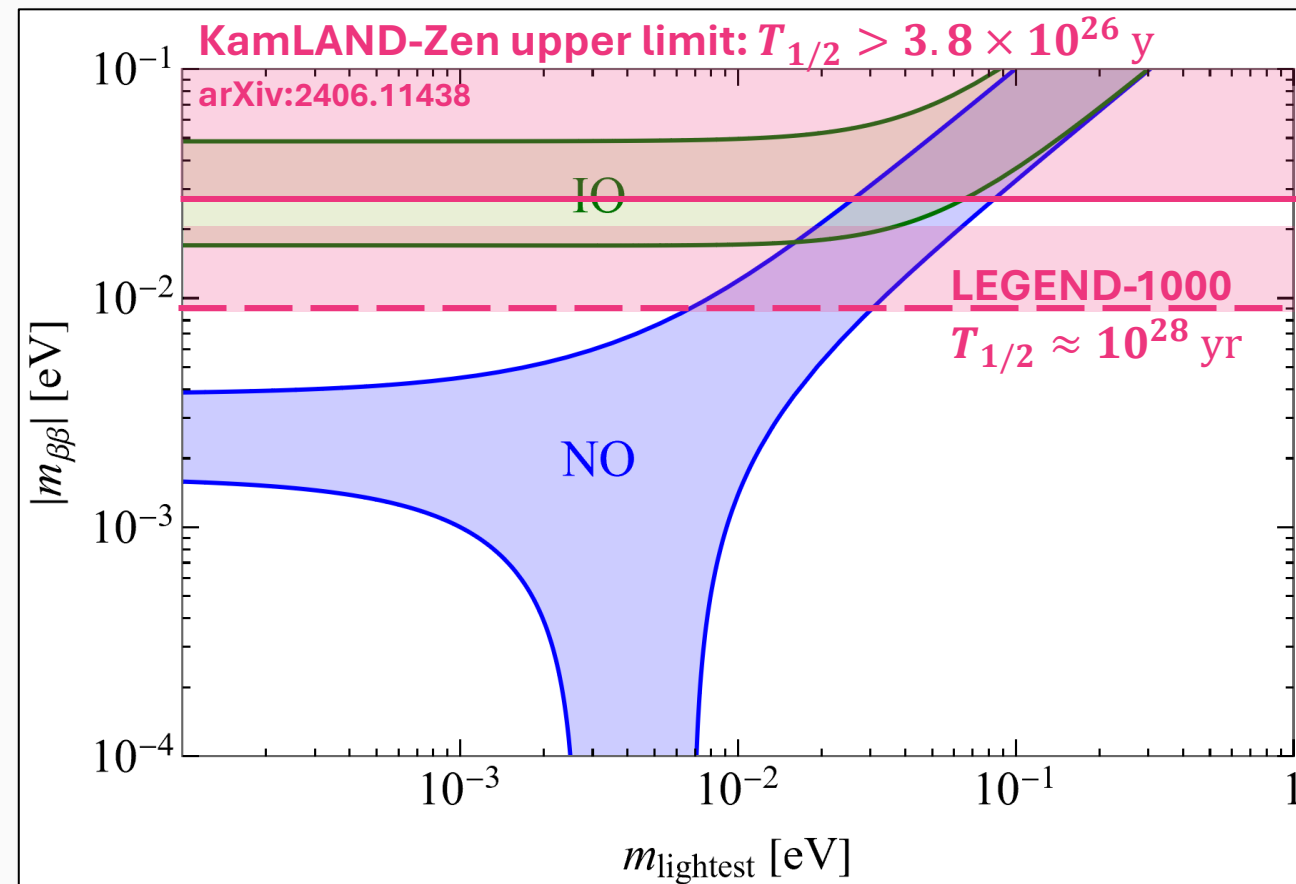
Three Active Majorana Neutrinos

Effective $0\nu\beta\beta$ Mass

degenerate ν & $\theta_{13} \approx 0$

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

- $m_{\beta\beta} \neq 0$
does not imply CPV
 - but depends on CP phases
untestable in oscillations
- $m_{\beta\beta} \neq 0$ implies LNV



Three Active Majorana Neutrinos

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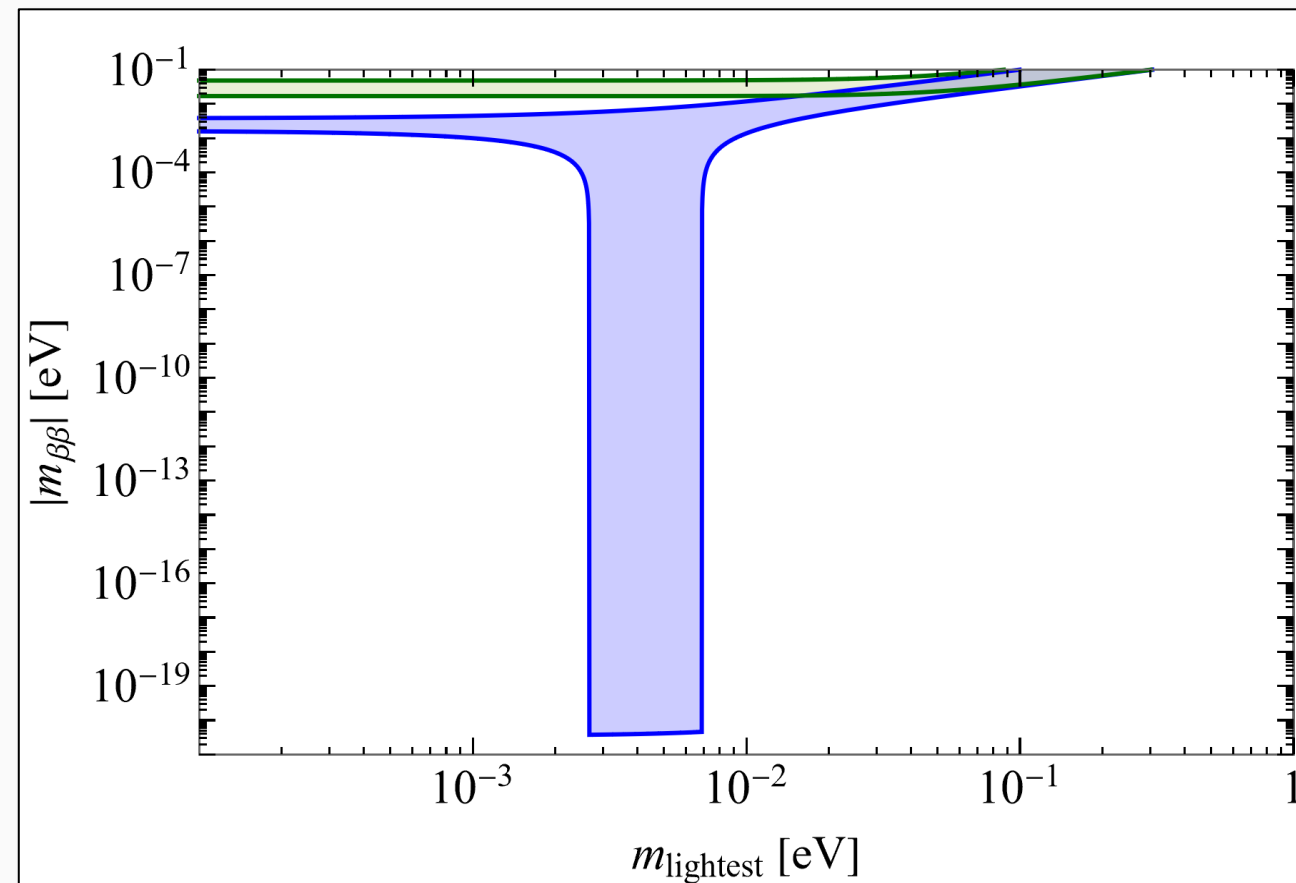
- but depends on CP phases
untestable in oscillations

■ $m_{\beta\beta} \neq 0$ implies LNV

■ $m_{\beta\beta} = 0$ (NO) does not imply LNC

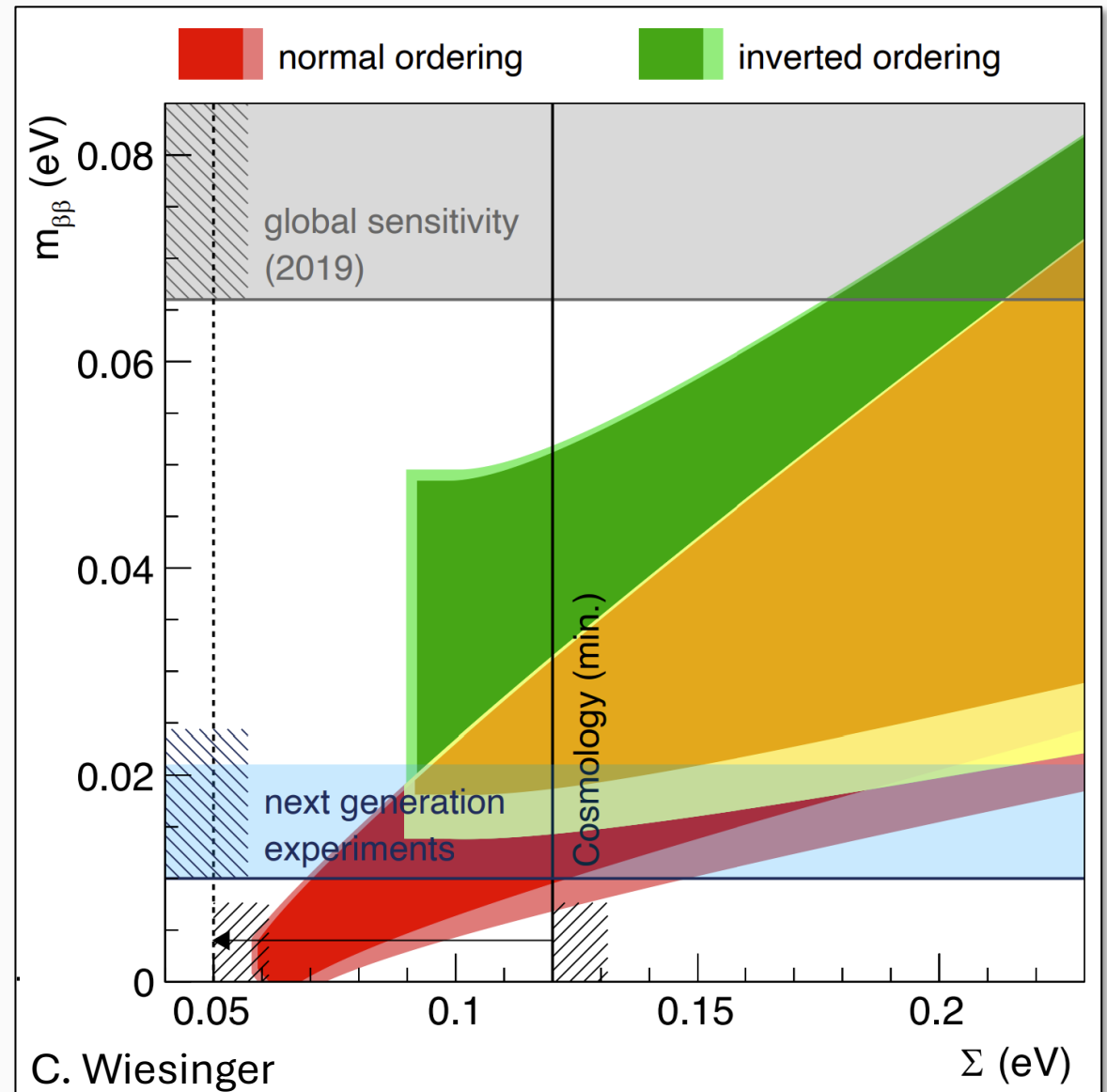
- Next order

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



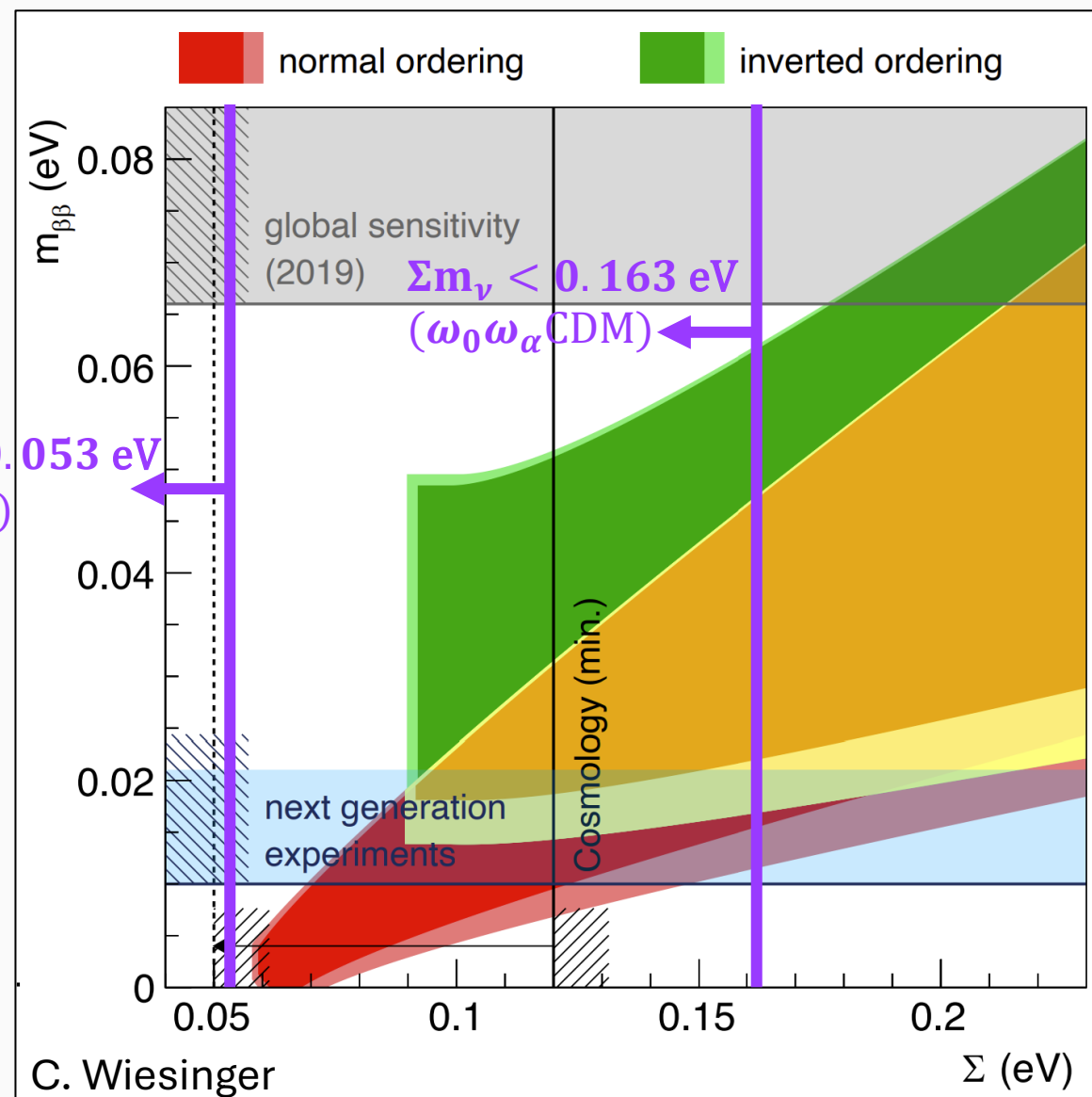
Three Active Majorana Neutrinos

- 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



Three Active Majorana Neutrinos

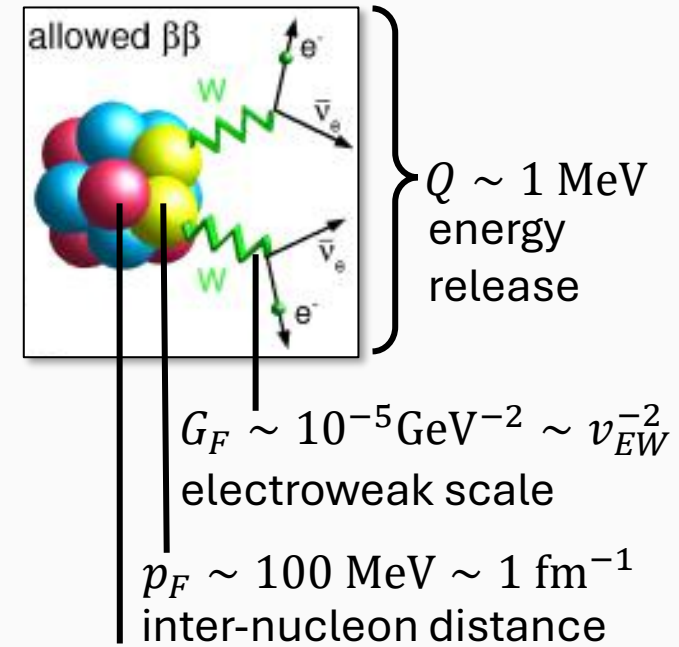
- Effective $0\nu\beta\beta$ Mass
 - Next generation experiments probing IO scenario
 - Pathways to explore NO scenario
- Concordance or tension with other neutrino mass measurements
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 - Cosmology
 - Maximal tension with DESI DR2 + CMB (Planck) (Phys. Rev. D 112 (2025) 083513)



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

- Decay modes, rates and NP sensitivity

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

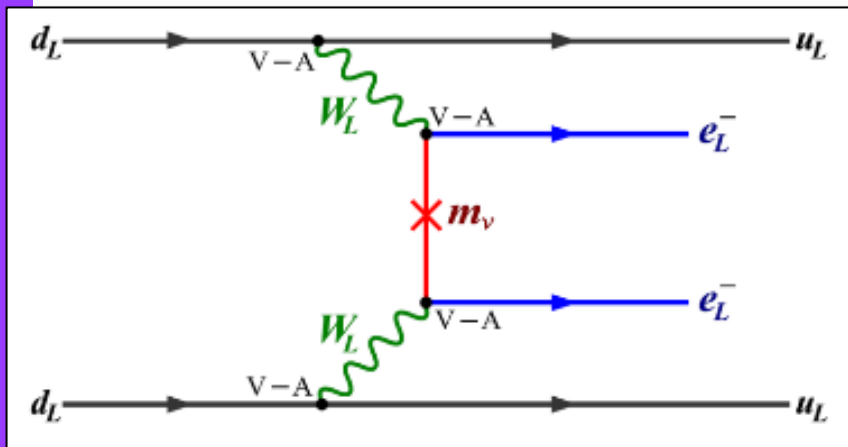
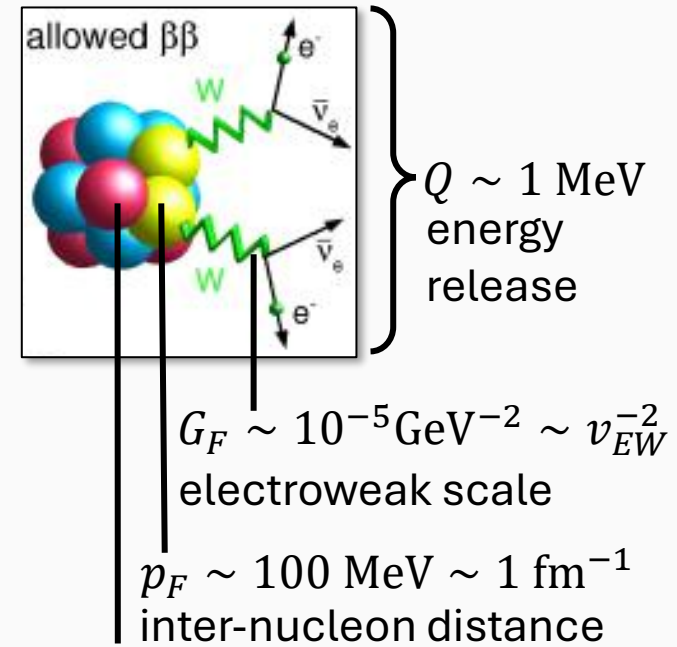


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$0\nu\beta\beta$ via Mass Mechanism $\Gamma_{m_\nu}^{0\nu} = m_\nu^2 G_F^4 Q^5 p_F^2 \approx \left(\frac{m_\nu}{0.1 \text{ eV}}\right)^2 (10^{25} \text{ yr})^{-1}$



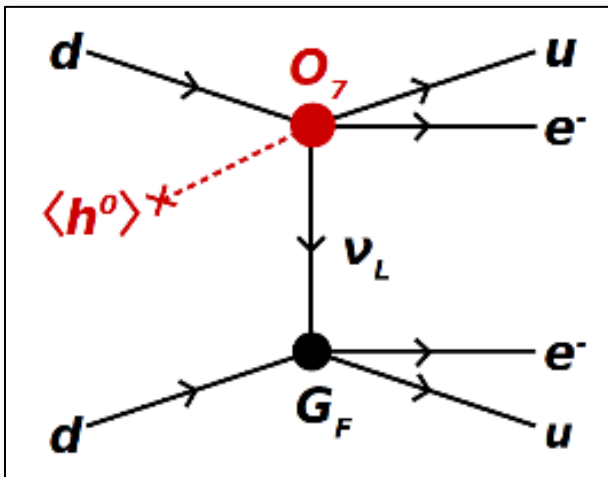
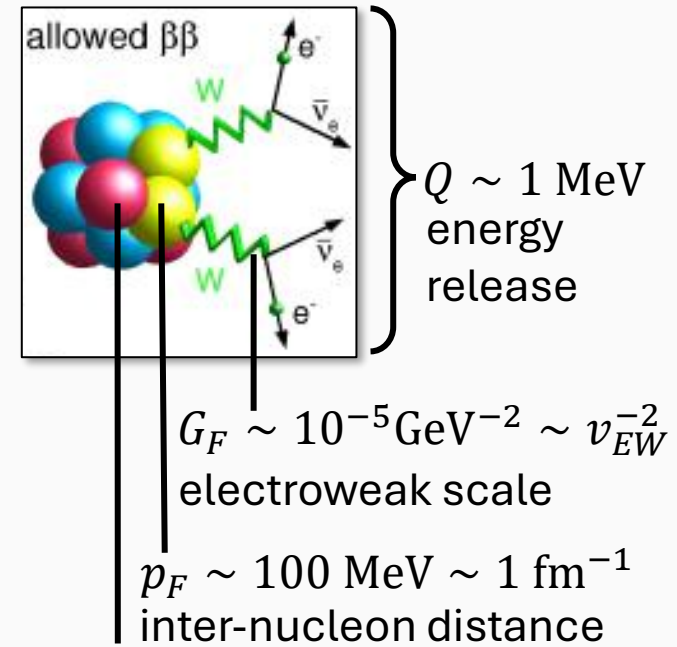
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$0\nu\beta\beta$ via 7-dim LNV Operator $\Gamma_{LR}^{0\nu} = \Lambda^{-6} G_F Q^5 p_F^4 \approx \left(\frac{20 \text{ TeV}}{\Lambda}\right)^6 (10^{25} \text{ yr})^{-1}$



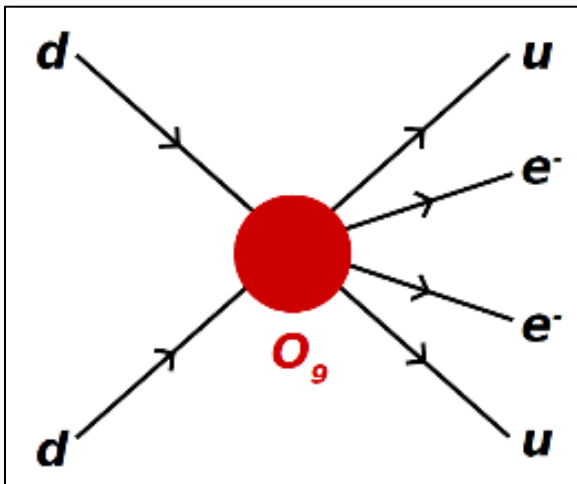
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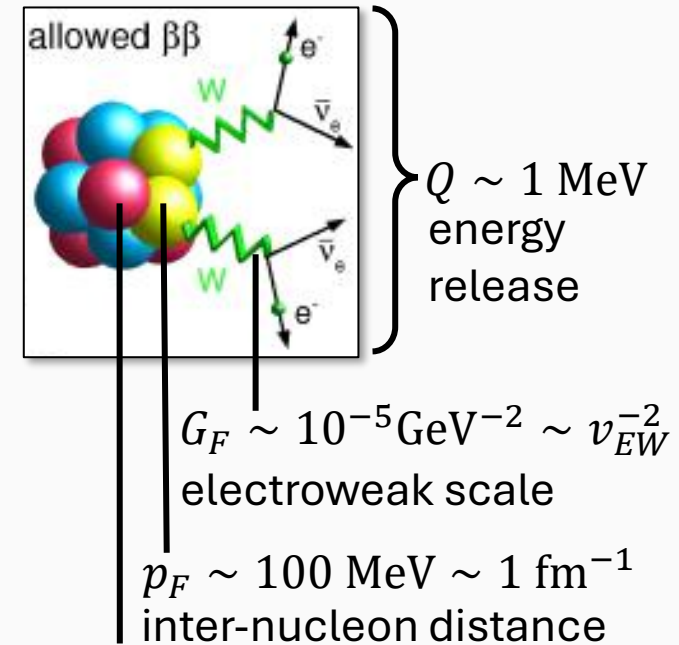
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$0\nu\beta\beta$ via 9-dim LNV Operator

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



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

- Decay modes, rates and NP sensitivity

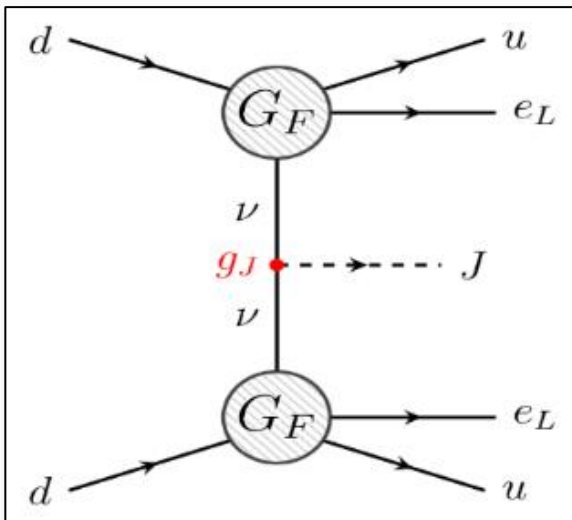
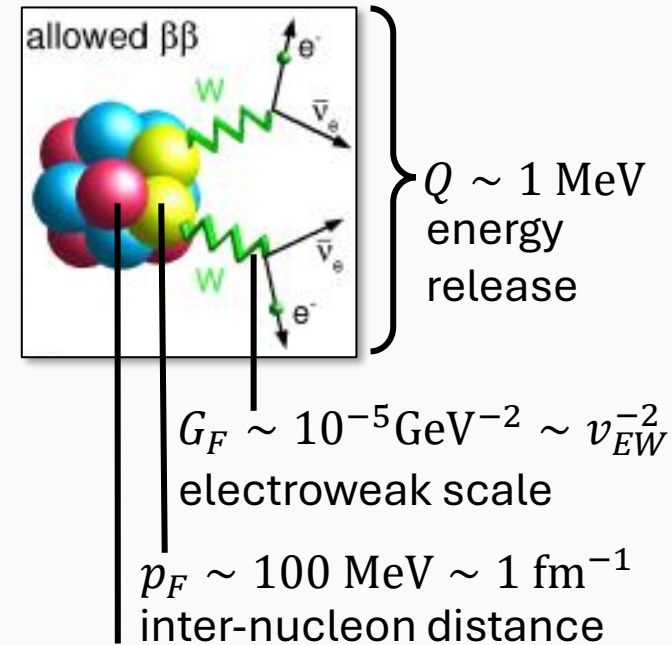
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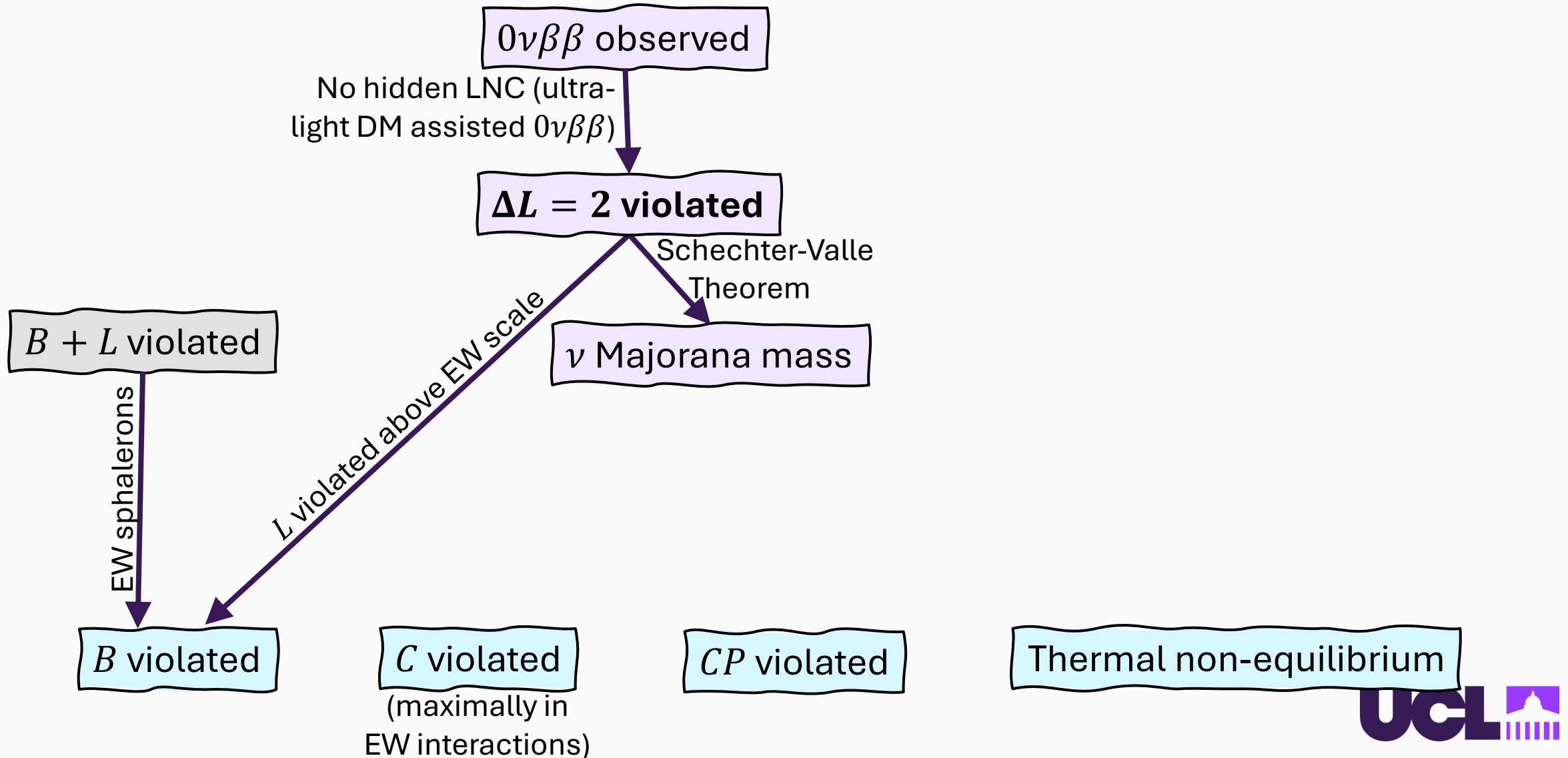
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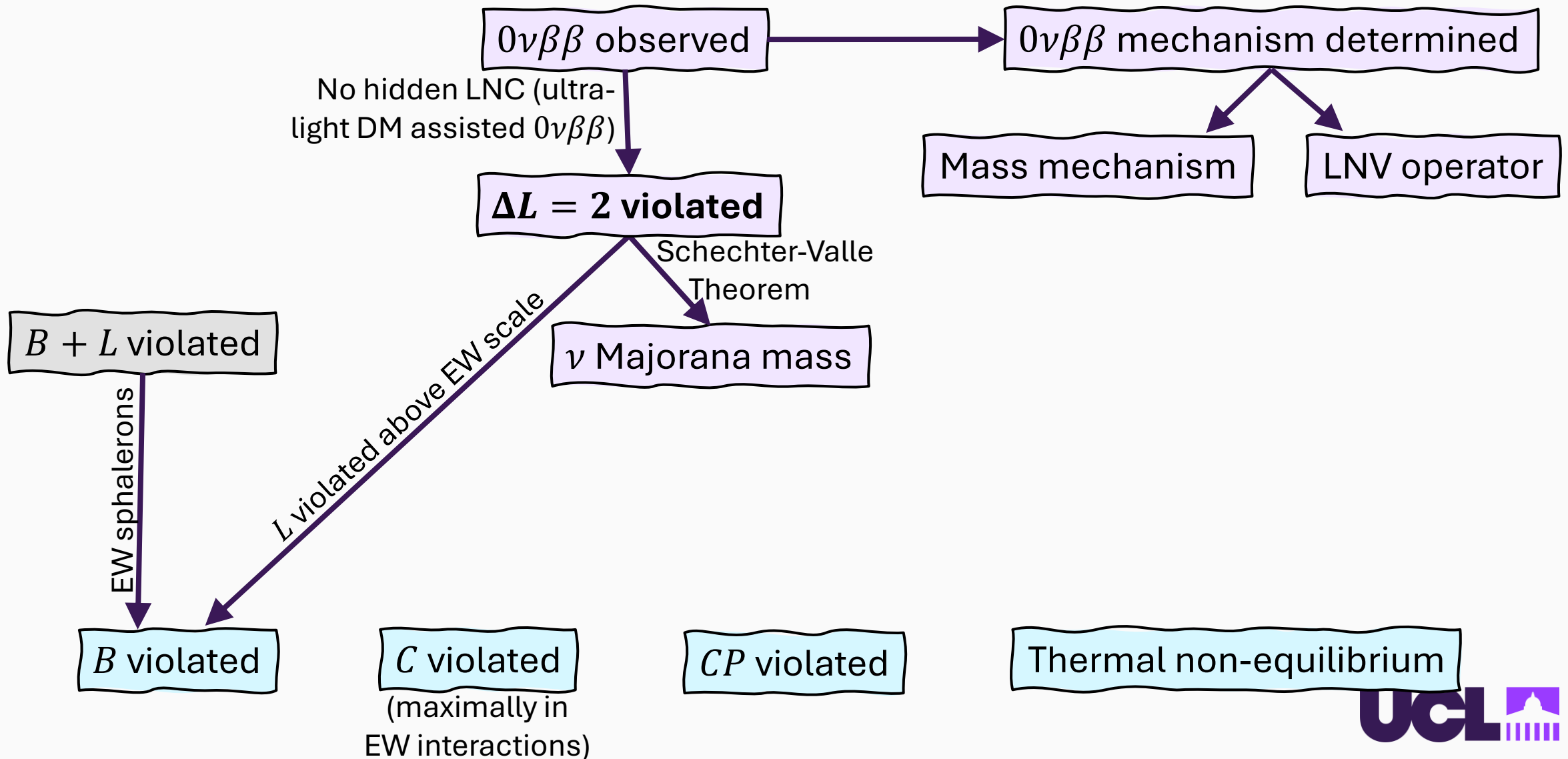
$0\nu\beta\beta J$ Ordinary Majoron Emission $\Gamma^{0\nu J} = g^2 G_F^4 Q^7 p_F^2 \approx \left(\frac{g}{10^{-5}}\right)^2 (10^{21} \text{ yr})^{-1}$



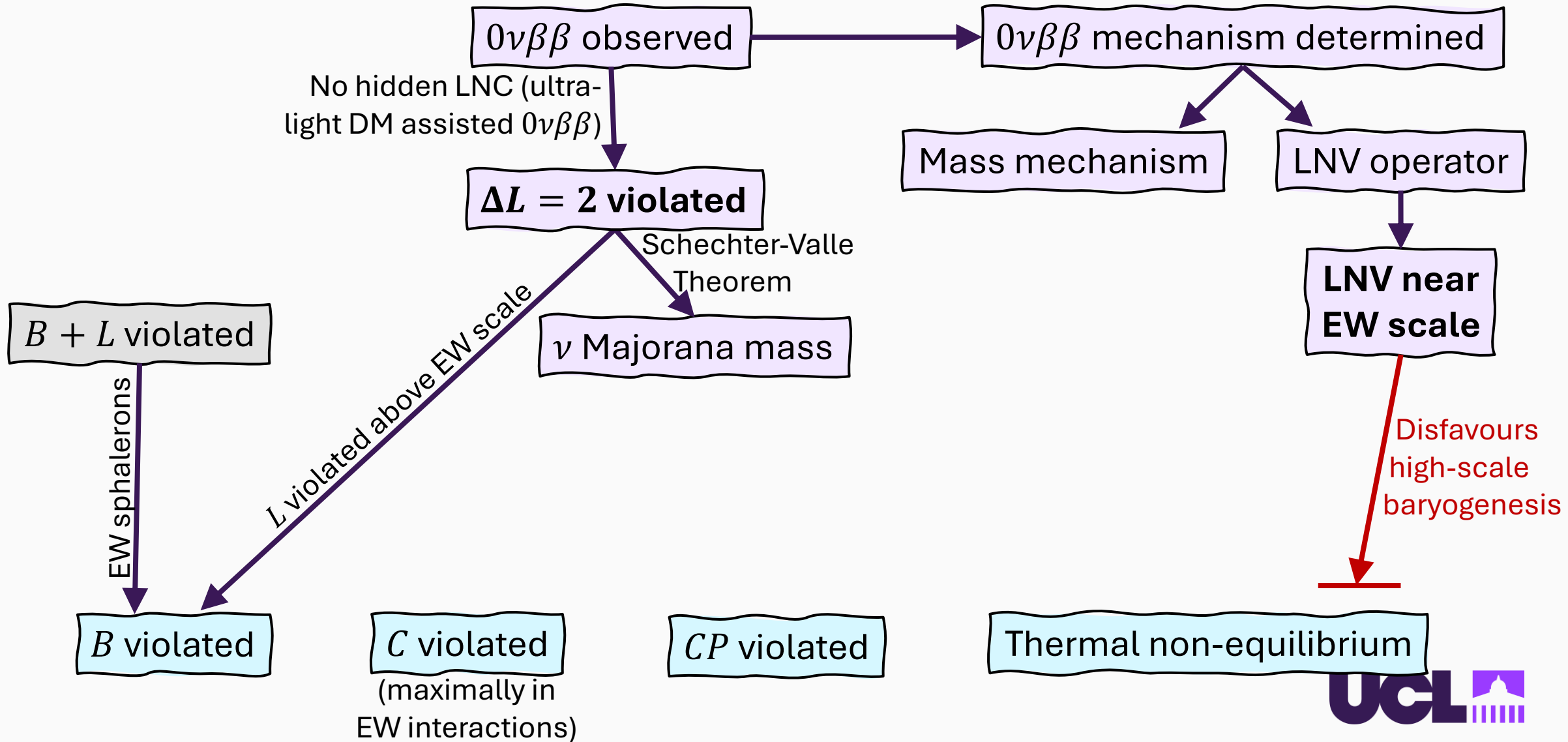
Implications of $0\nu\beta\beta$



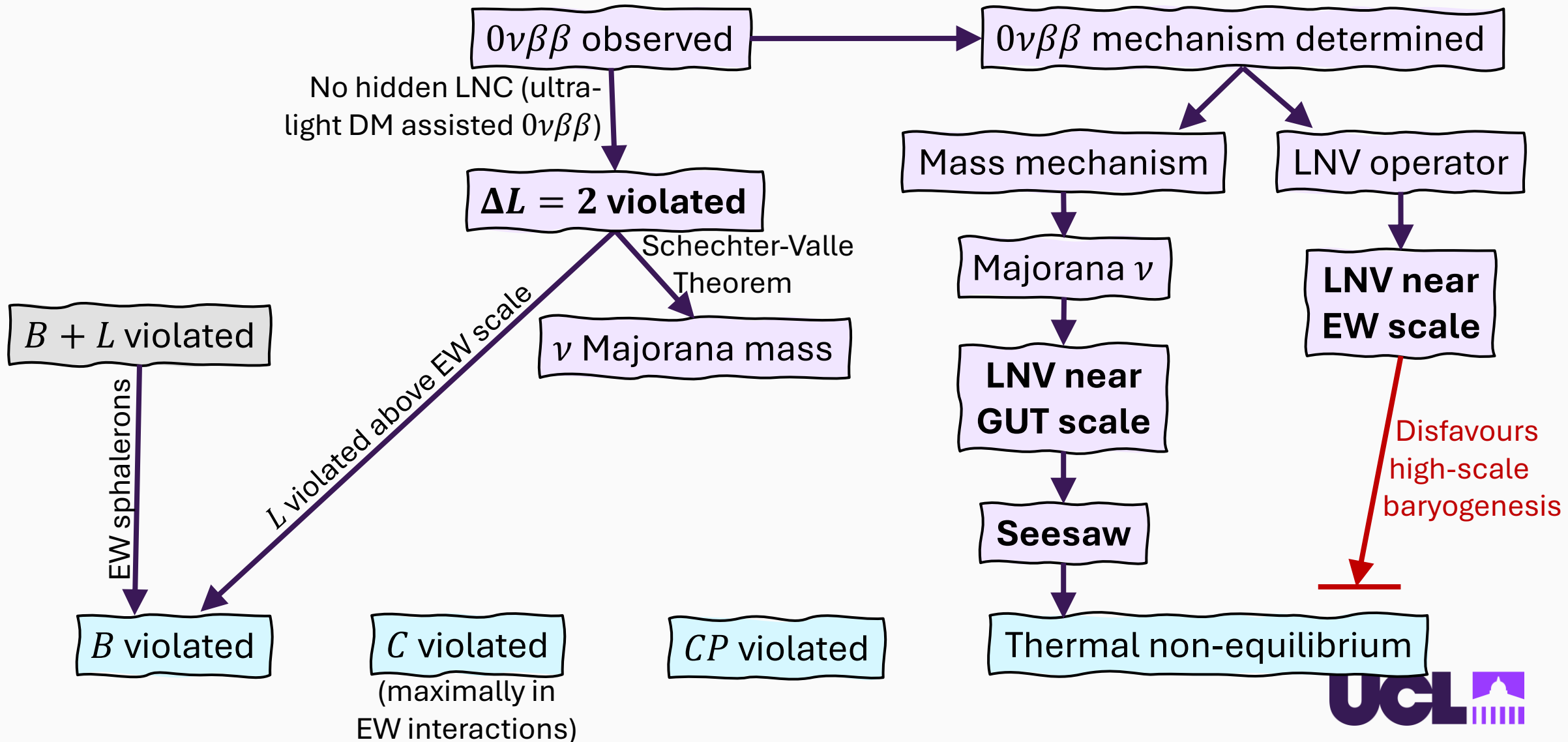
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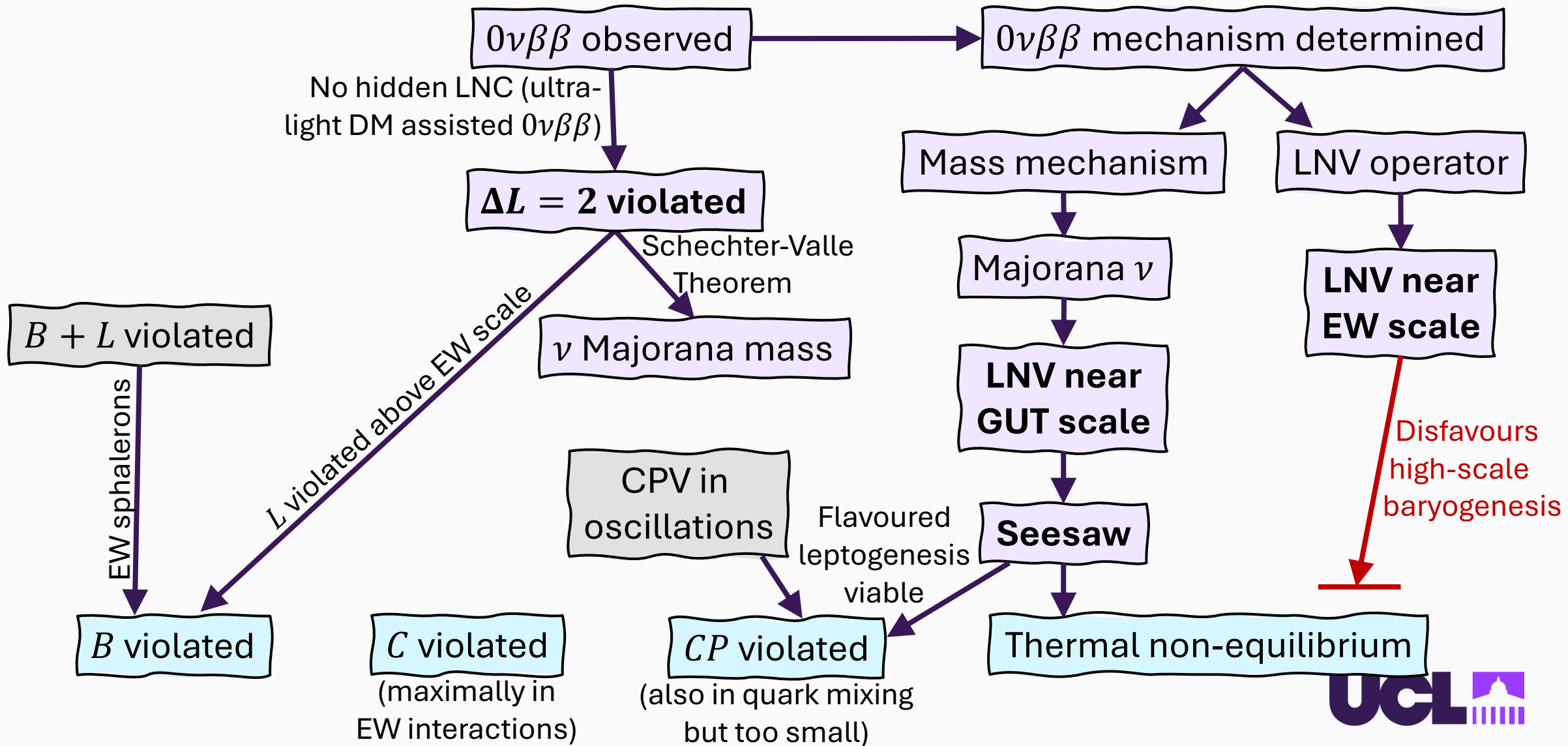
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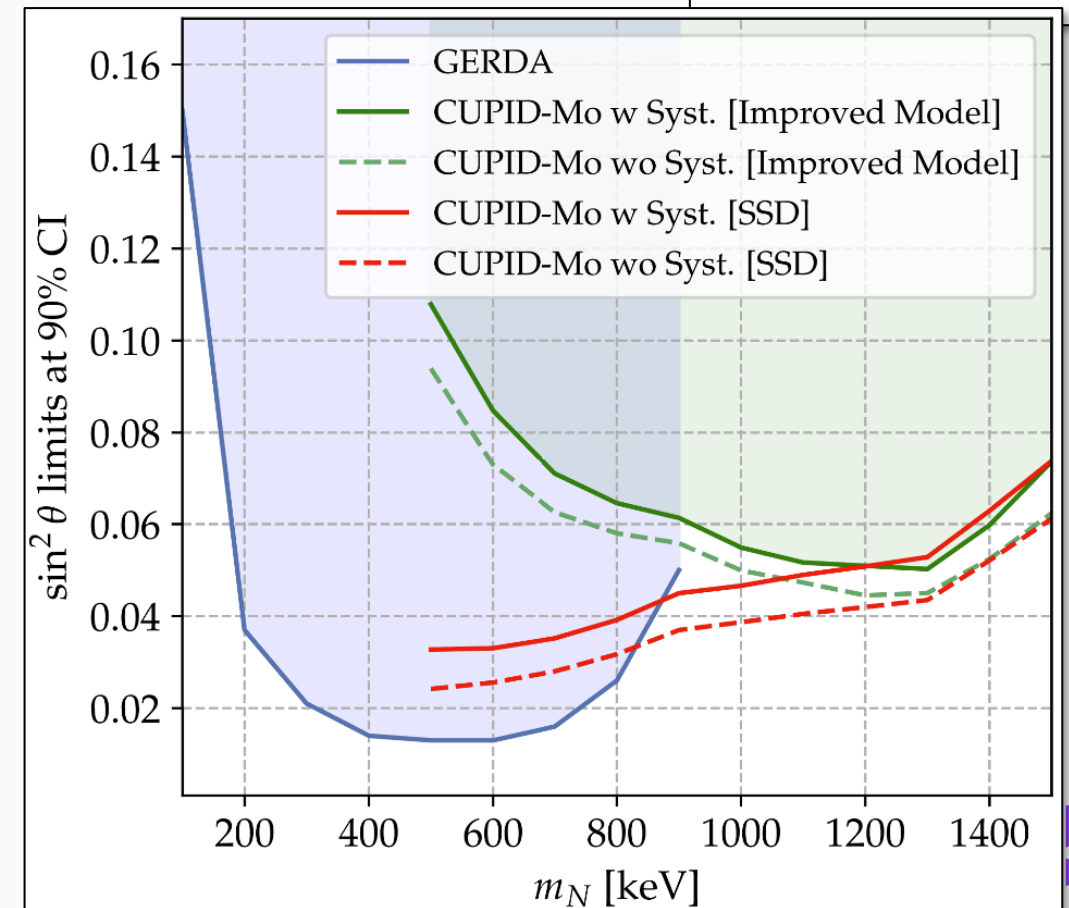
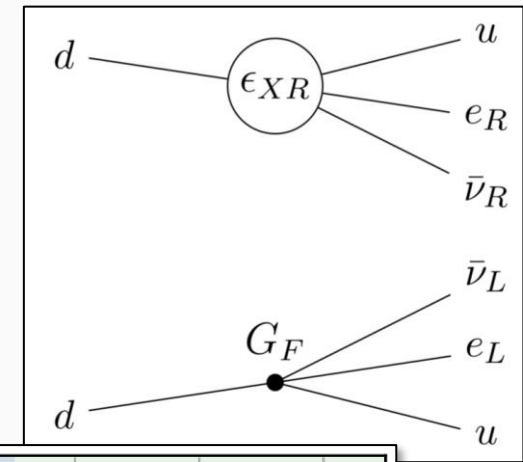
New Physics in $2\nu\beta\beta$

■ 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)



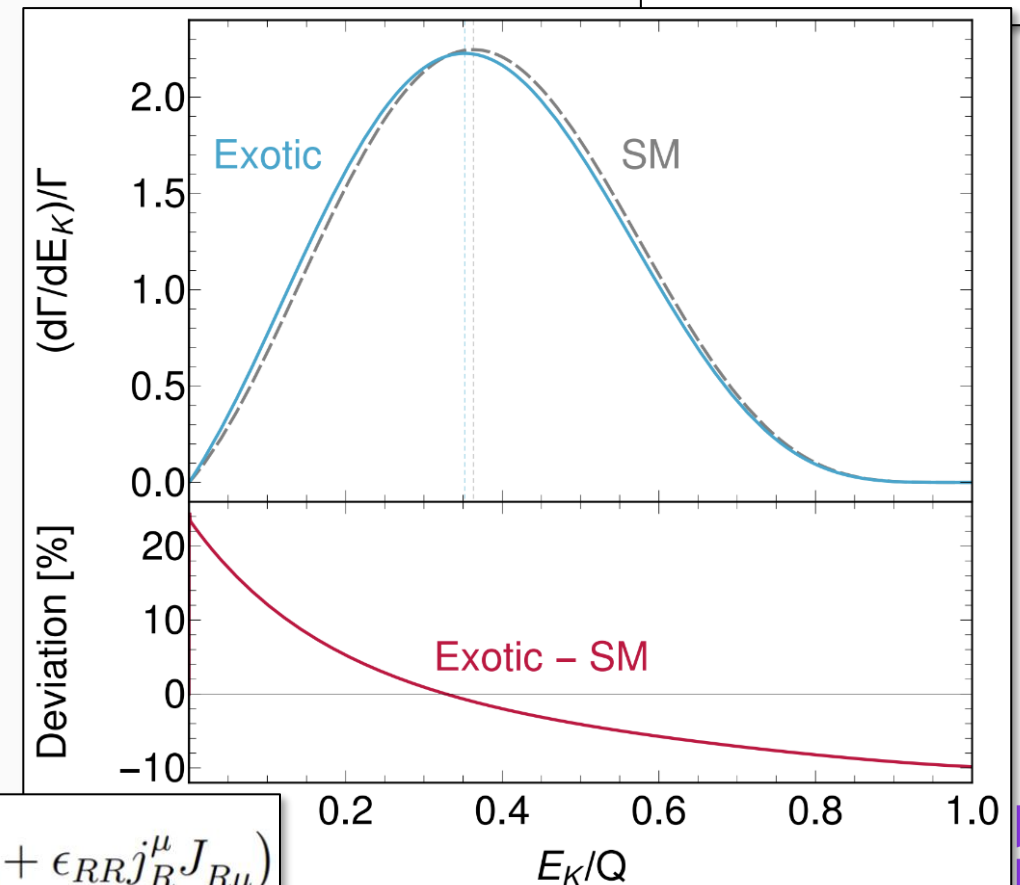
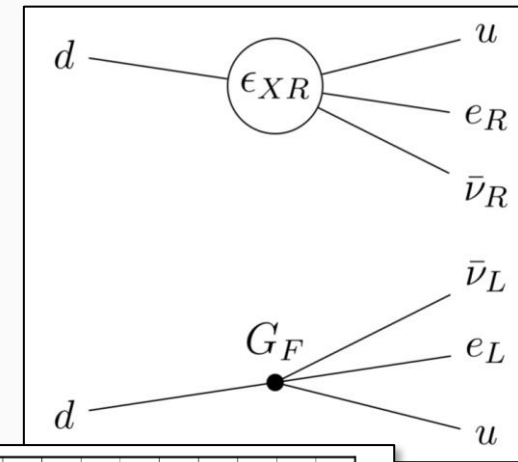
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 - CUPID-0 (2603.17602)
- Lepton number conserving RH currents (FFD, Graf, Simkovic, Phys. Rev. Lett. 125 (2020) 17, 171801)



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



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

■ Neutrino self-interactions

- Same signature as SM $2\nu\beta\beta$ decay

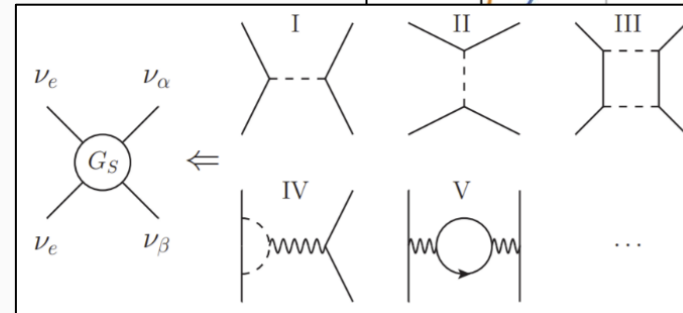
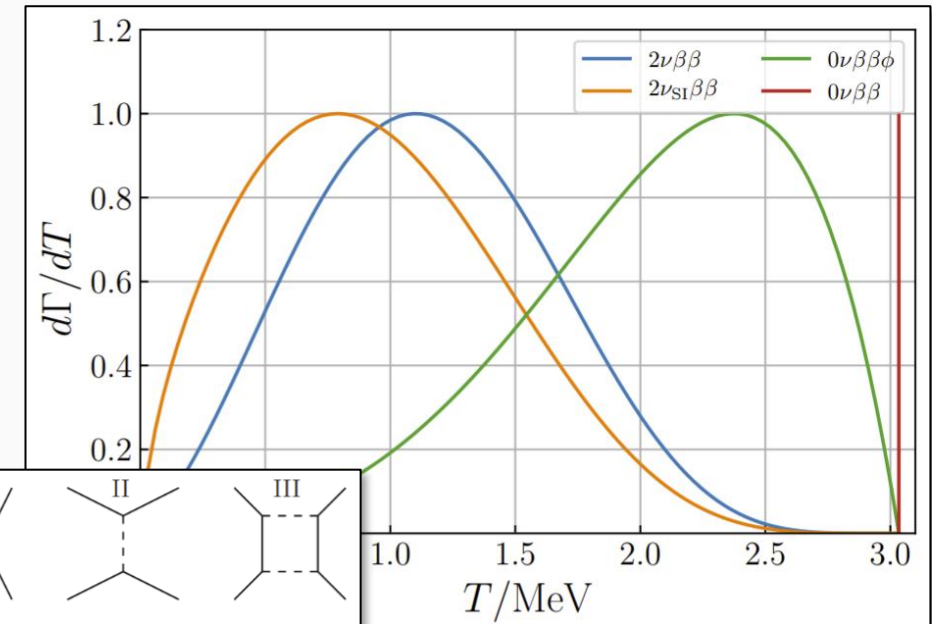
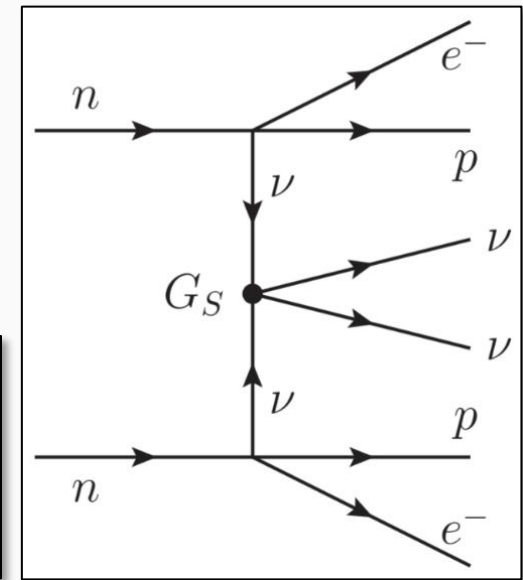
$$\Gamma_{2\nu} + \Gamma_{\nu\text{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}$$

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

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

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



Neutrinos coupled to Dark Sectors

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

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

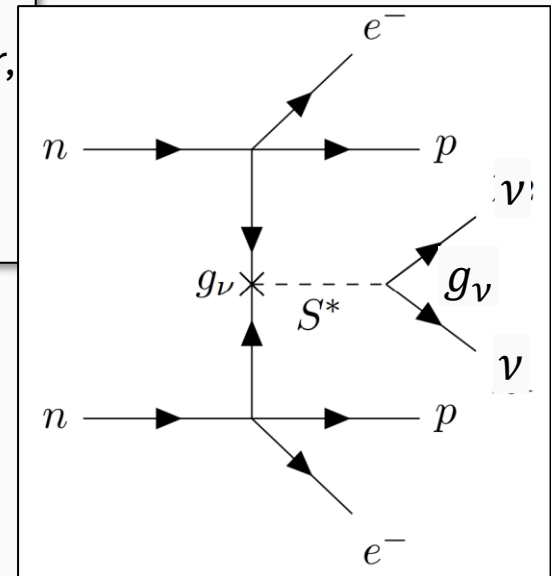
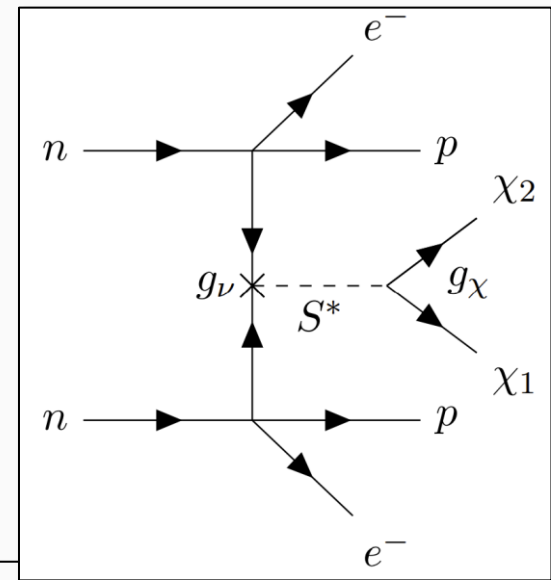
- Z_2 symmetry to forbid mixing
- Self-interacting neutrinos and self-interacting (potentially) DM

- Model I: No Z_2 , mixing terms allowed

$$-\mathcal{L} = m_\nu \bar{\nu}'_R \nu'_L + m_{\nu\chi} \bar{\chi}'_R \nu'_L + m_{\chi\nu} \bar{\nu}'_R \chi'_L + M \bar{\chi}'_R \chi'_L \\ + (a_\nu \bar{\nu}'_L \nu'_L S^* + b_\nu \bar{\nu}'_R \nu'_R S^* + a_{\nu\chi} \bar{\nu}'_L \chi'_L S^* + b_{\nu\chi} \bar{\nu}'_R \chi'_R S^* + a_\chi \bar{\chi}'_L \chi'_L S^* + b_\chi \bar{\chi}'_R \chi'_R S^*) + \text{h.c.}.$$

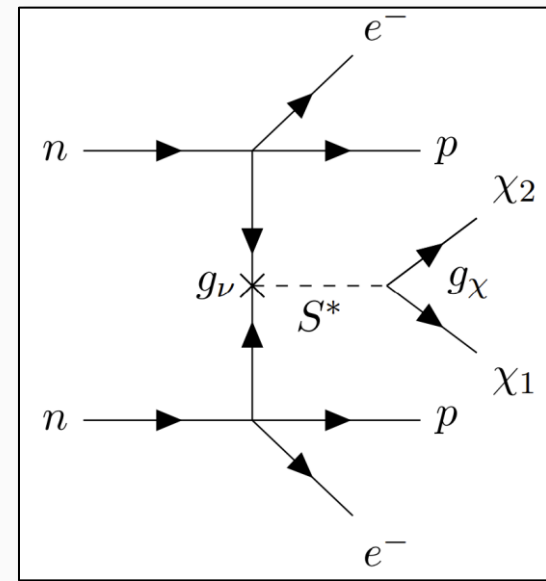
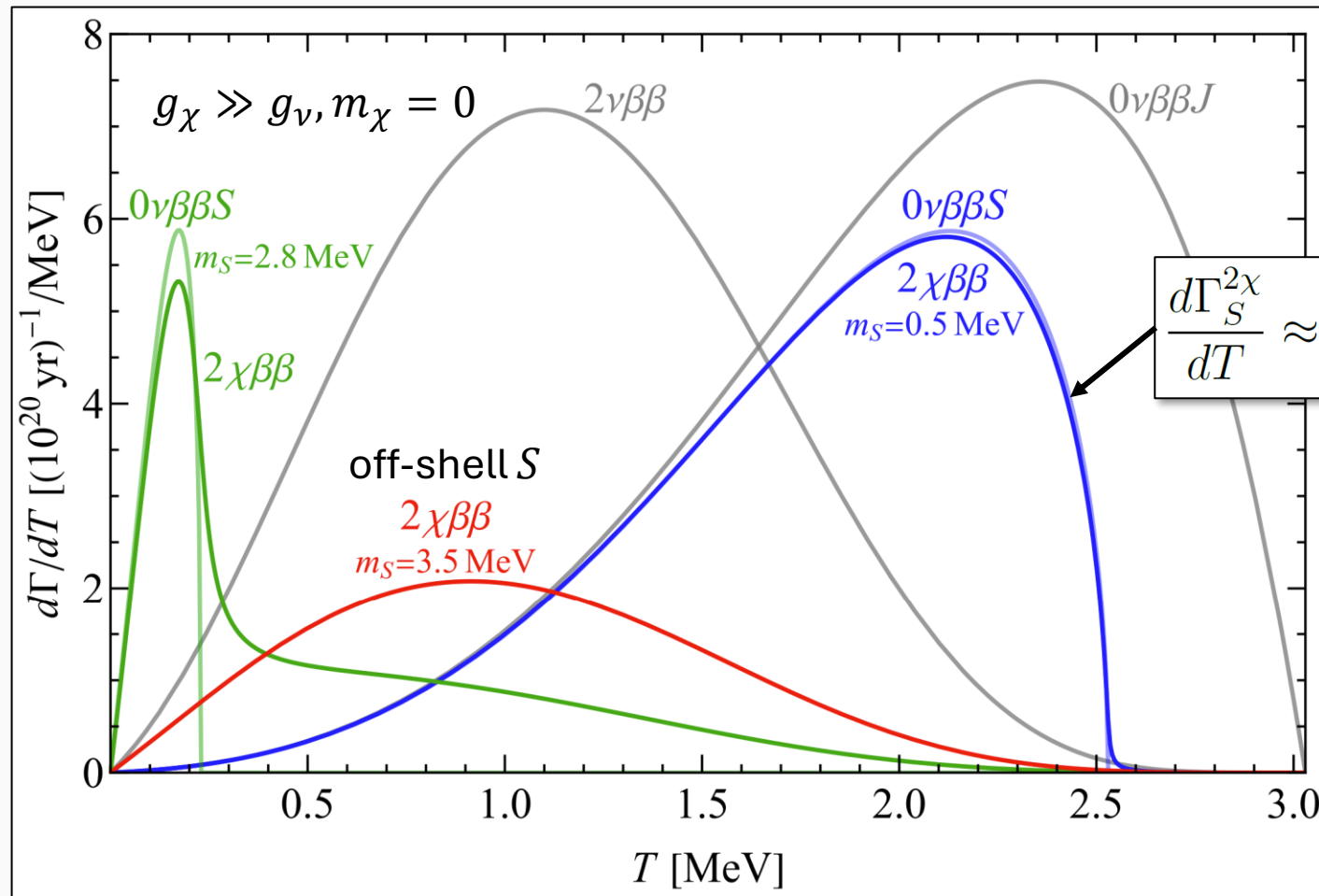
- Applicable to Majorana neutrinos, but constraints from $0\nu\beta\beta$

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



Neutrinos coupled to Dark Sectors

- Finite S width and off-shell S



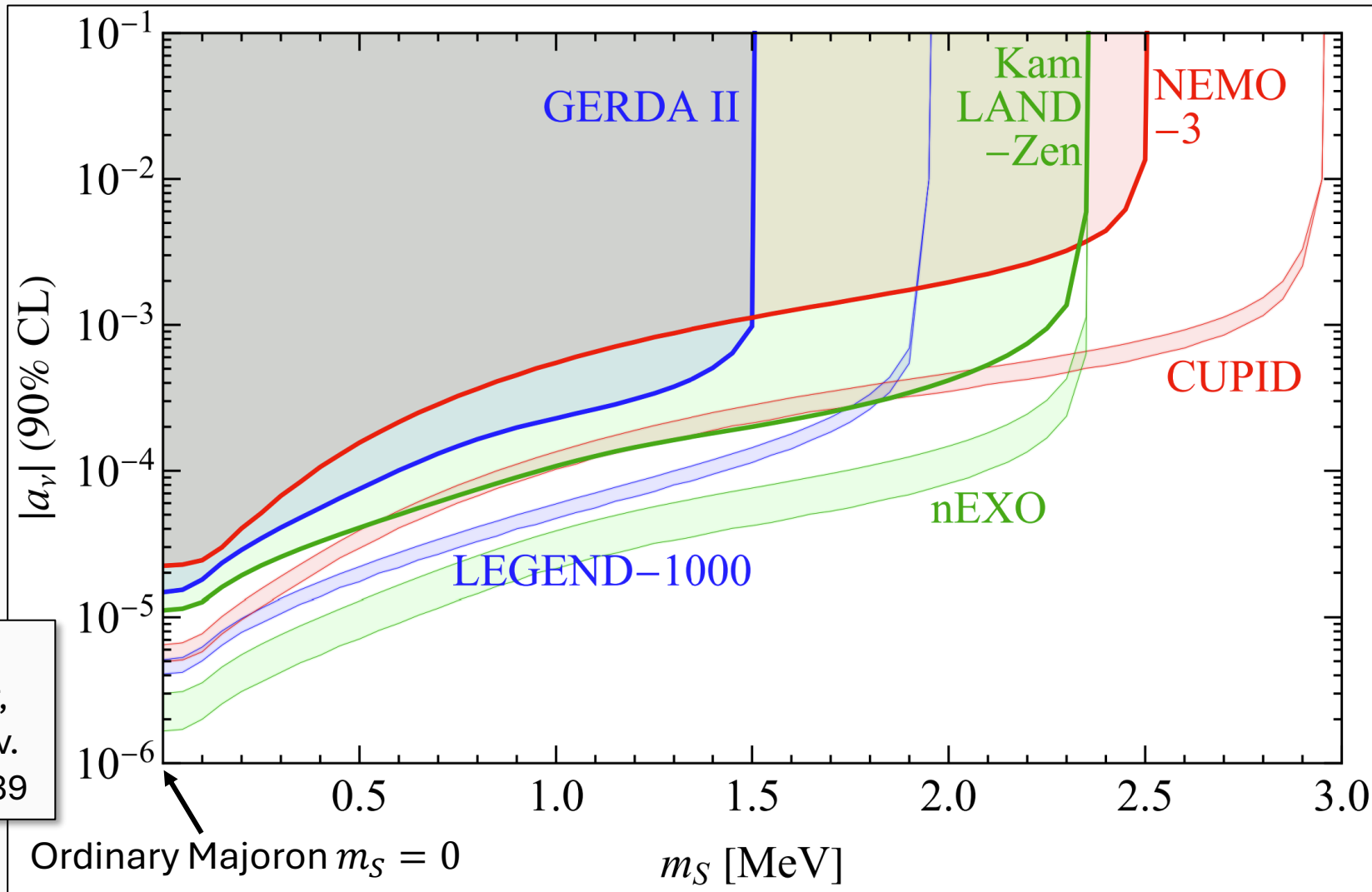
On-shell S in narrow-width approximation

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

Neutrinos coupled to Dark Sectors

- Sensitivity of double beta decay searches

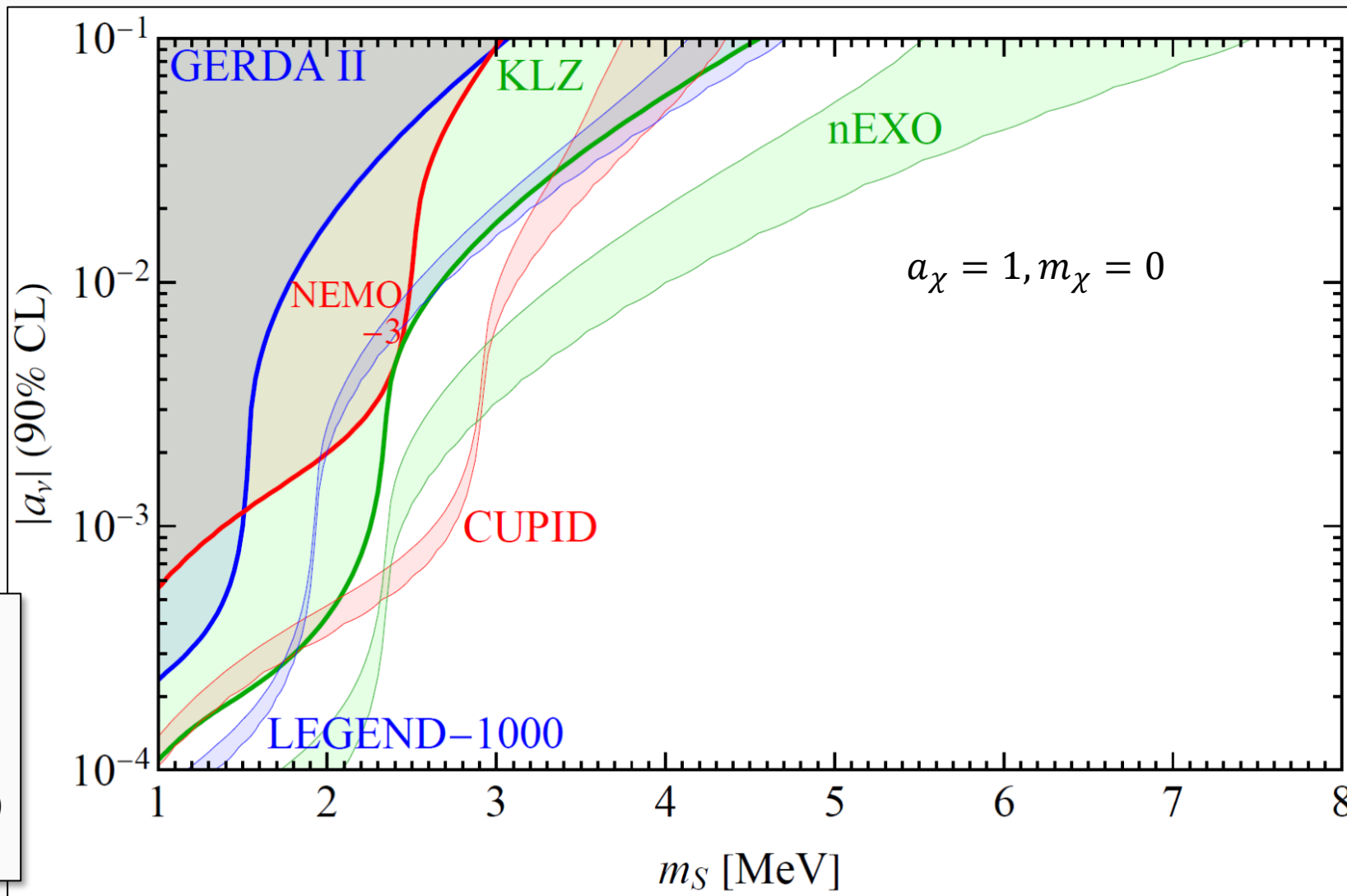
Also see exp.
PandaX search:
Phys. Rev. Lett. 136
(2026) 241802



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

Neutrinos coupled to Dark Sectors

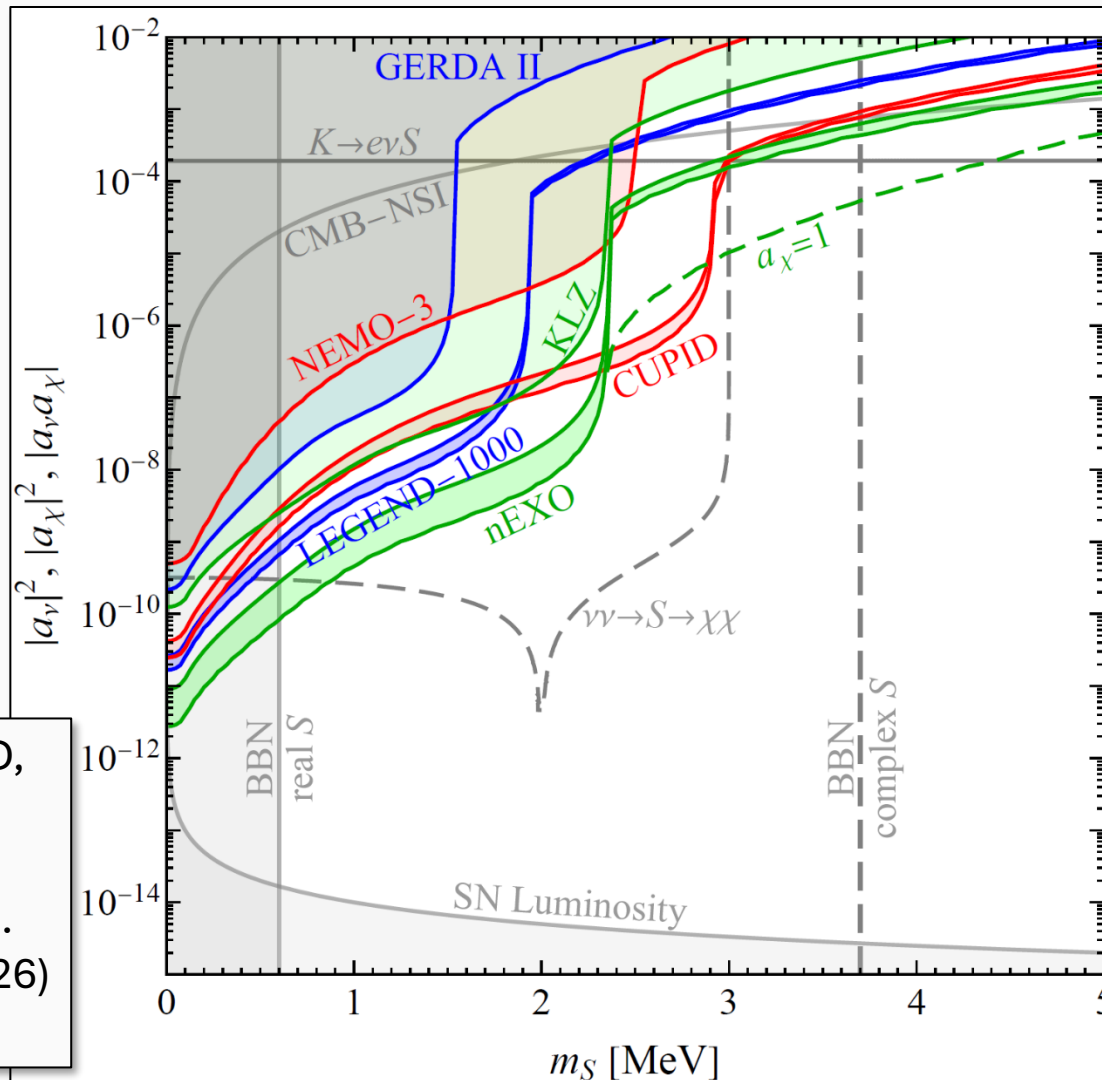
- Modification from interference and off-shell S



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

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

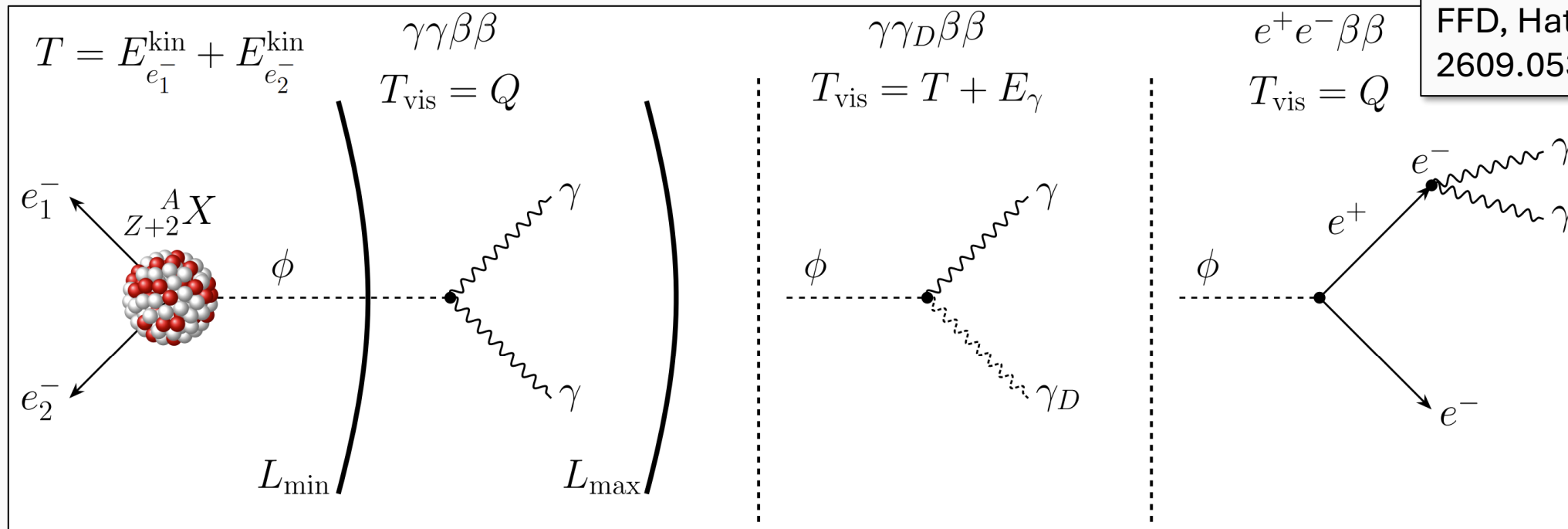
- Kaon decays $K \rightarrow e\nu S$
- Z-width, ... for higher m_S

Long-lived Particles from Double Beta Decay

- Massive Majoron has macroscopic decay length

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

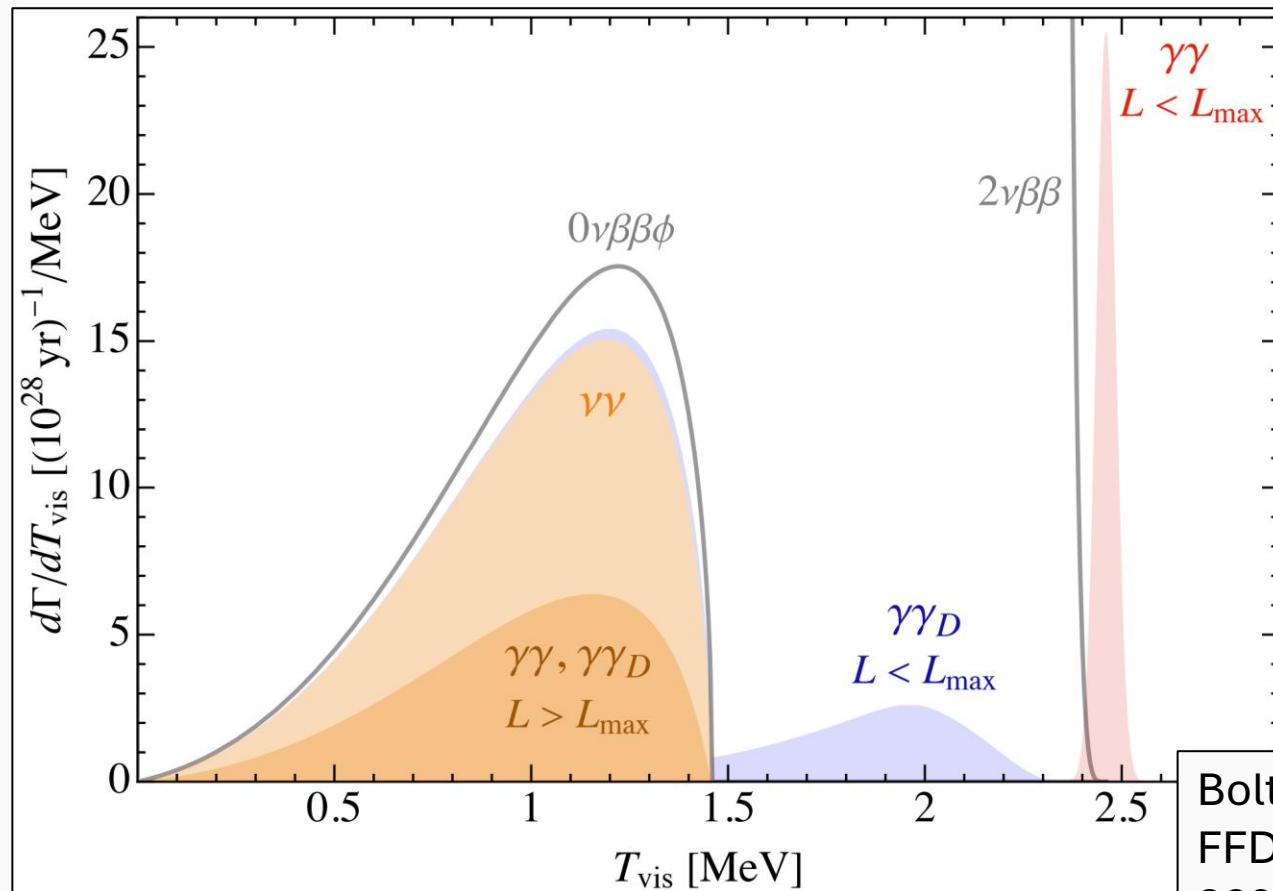
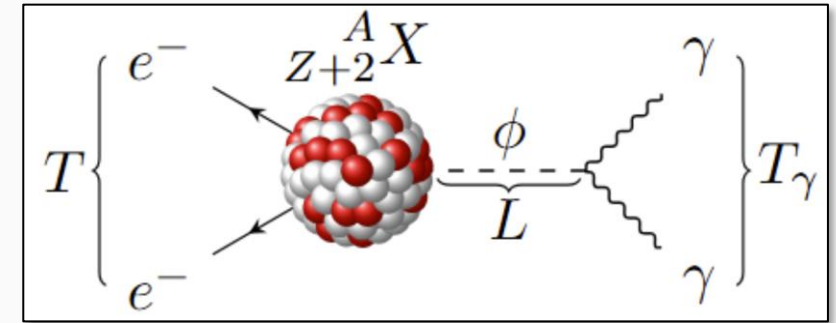
- Couple to photons, dark photons and e^+e^-
- Displaced signatures $\gamma\gamma\beta\beta$, $\gamma\gamma_D\beta\beta$, $e^+e^-\beta\beta$



Bolton, Boudjema,
FFD, Hati, Majumdar,
2609.05352

Long-lived Particles from Double Beta Decay

- Displaced energy deposition at endpoint and distorted Majoron spectrum



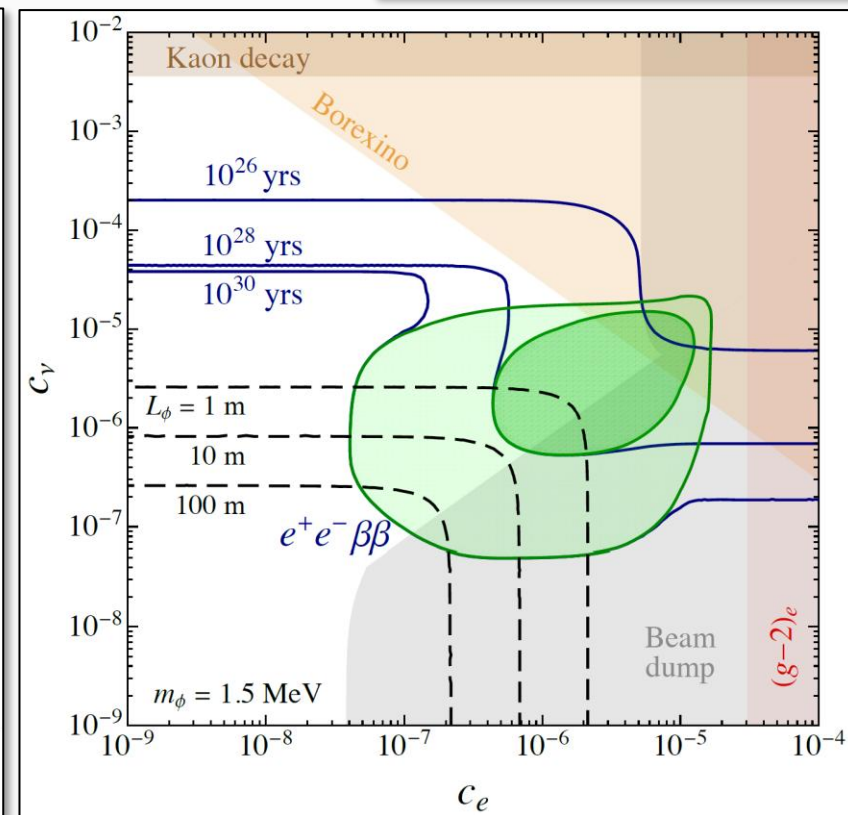
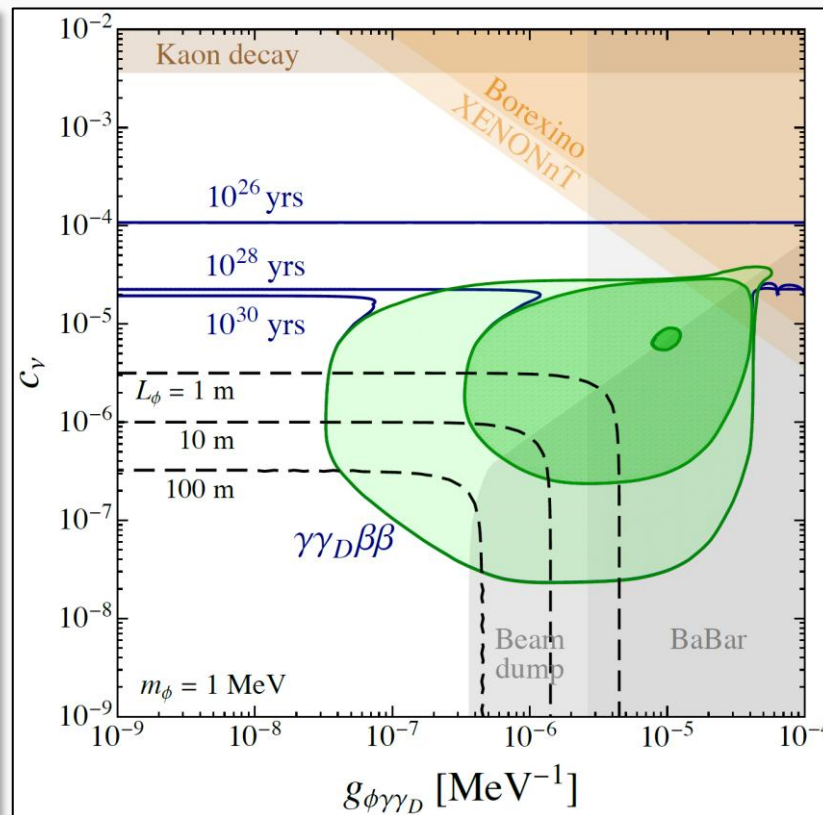
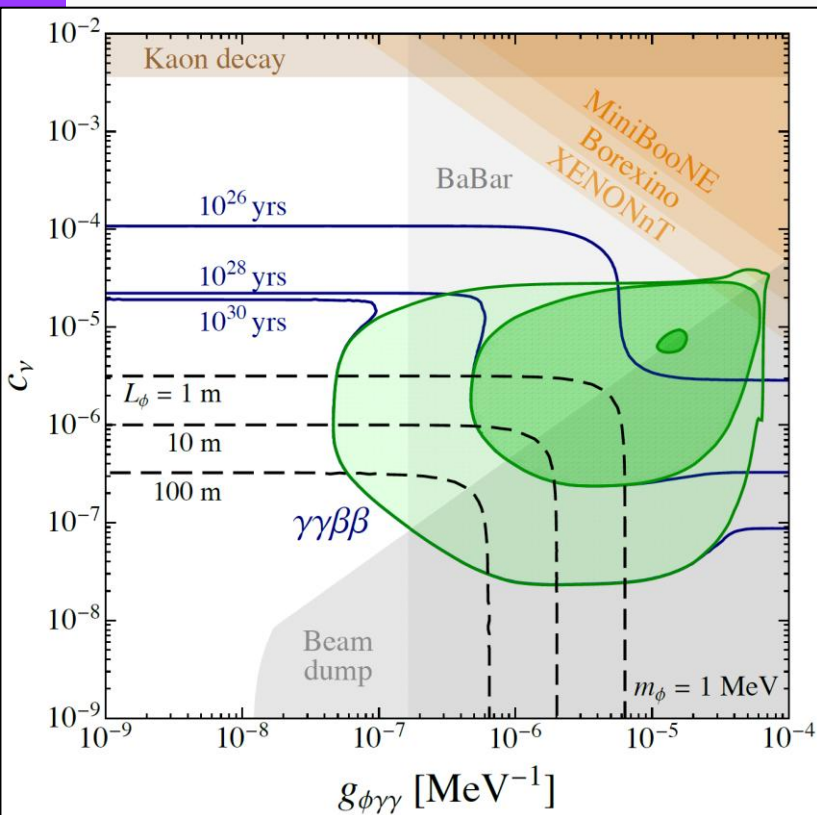
- Fully visible energy deposition for $\gamma\gamma\beta\beta$, $e^+e^-\beta\beta$ if decaying inside detector
- Novel spectrum for $\gamma\gamma_D\beta\beta$
- Distorted Majoron spectrum if decaying outside (or to $\nu\nu$)

Bolton, Boudjema,
FFD, Hati, Majumdar,
2609.05352

Long-lived Particles from Double Beta Decay

- Displaced energy deposition at endpoint and distorted Majoron spectrum
- Sensitivity at KamLAND-Zen, nEXO, n²EXO

Bolton, Boudjema,
FFD, Hati, Majumdar,
2609.05352



Conclusions

- **Neutrino conundrum**

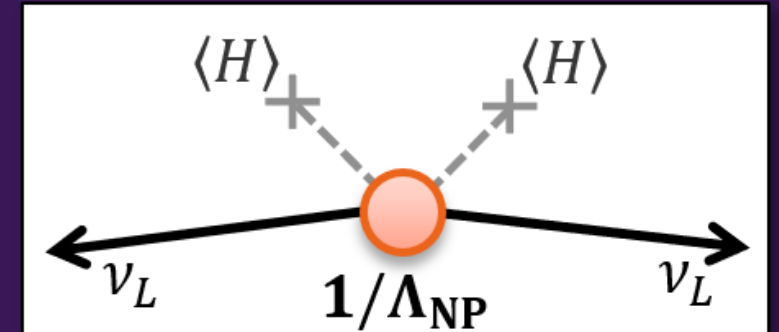
- Much lighter than other fermions
- Only neutral fermions: Dirac or Majorana?

- **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

- **Portal to New Physics**

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



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