UCL University College London

Theory of Lepton Number and Lepton Flavour Violation

Frank Deppisch
f.deppisch@ucl.ac.uk

University College London

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Lepton Flavour versus Lepton Number Violation

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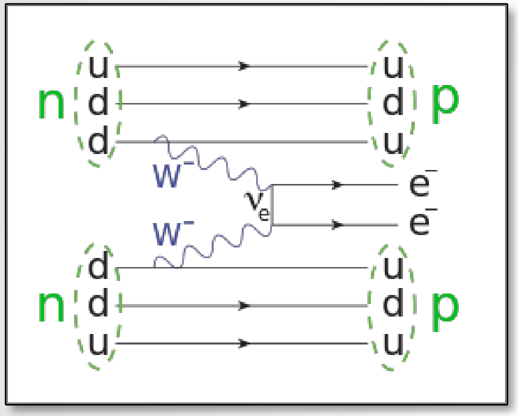
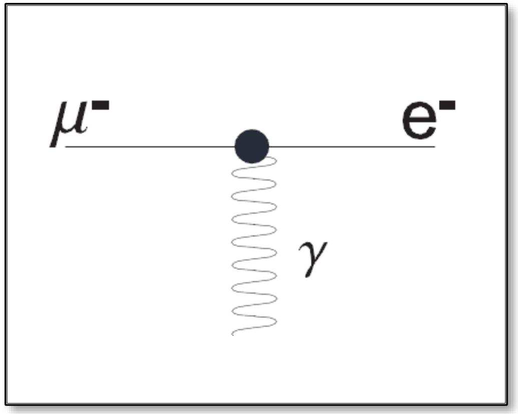
Neutrinoless double beta decay



$\Delta L_e = 2, \Delta L_\mu = 0, \Delta L = 2$

Lepton Number Violation

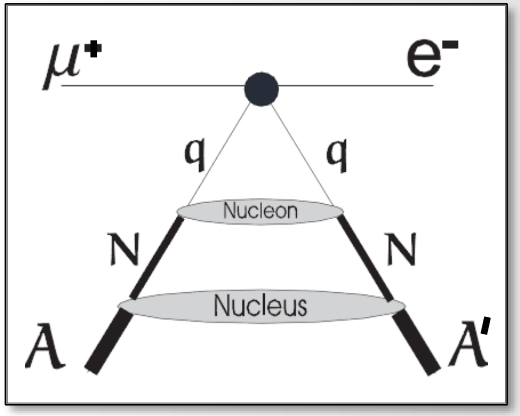
$\mu^- \to e^- \gamma$



$\Delta L_e = 1, \Delta L_\mu = -1, \Delta L = 0$

Lepton Flavour Violation

$\mu^+ \to e^-$ conversion in nuclei



$\Delta L_e = 1, \Delta L_\mu = 1, \Delta L = 2$

Lepton Flavour Violation + Lepton Number Violation

Lepton Flavour versus Lepton Number Violation

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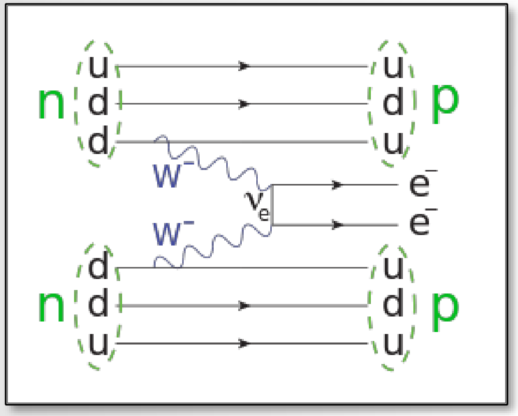
Neutrinoless double beta decay



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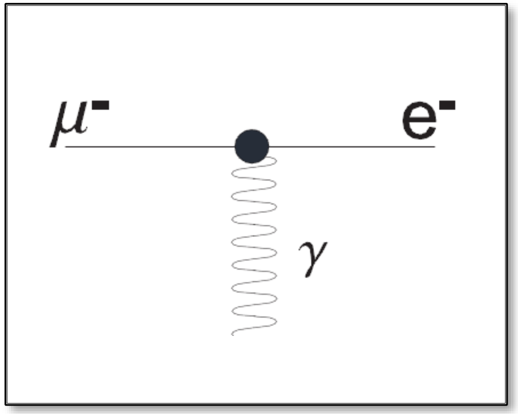

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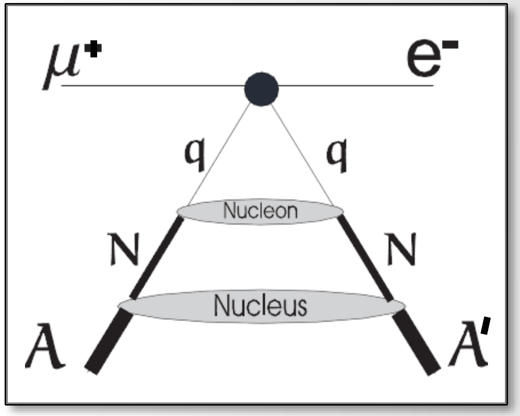

$\Delta L_e = 1, \Delta L_\mu = 1, \Delta L = 2$

Lepton Flavour Violation + Lepton Number Violation

nobelprize.org

Neutrino Oscillations

Dirac vs Majorana

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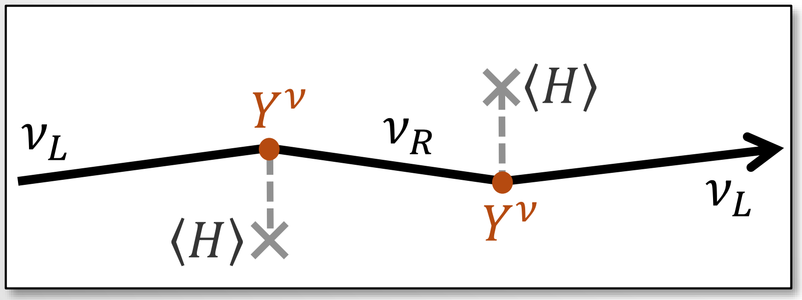
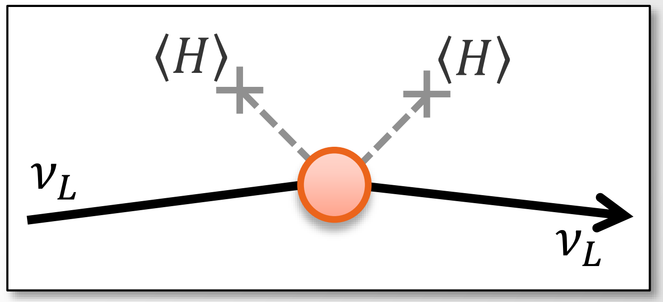
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

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





Neutrino Oscillations

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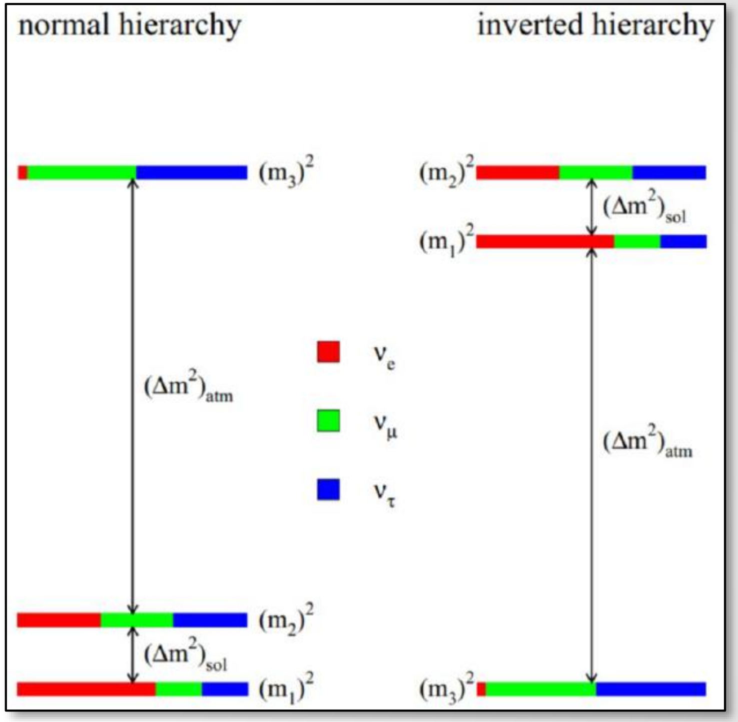
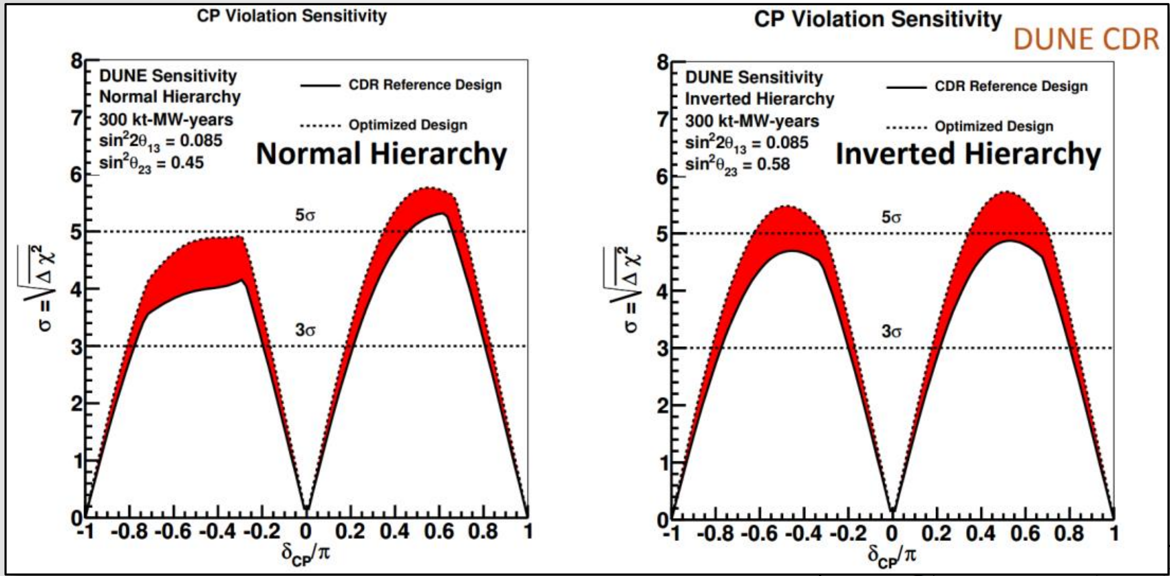
- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation

$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



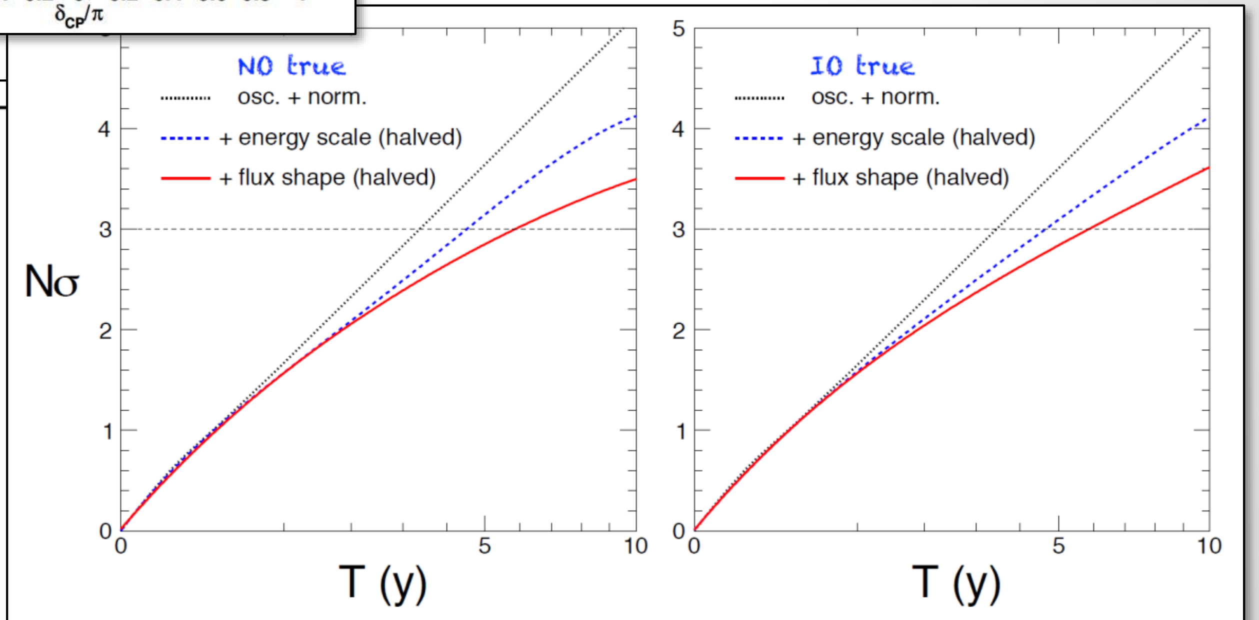
- Era of neutrino precision physics
  - Current errors ~ 1–10%
- Experimental unknowns and anomalies
  - CP Violation? Sign of Δm_{23}? Octant of θ_{23}? Sterile Neutrinos?

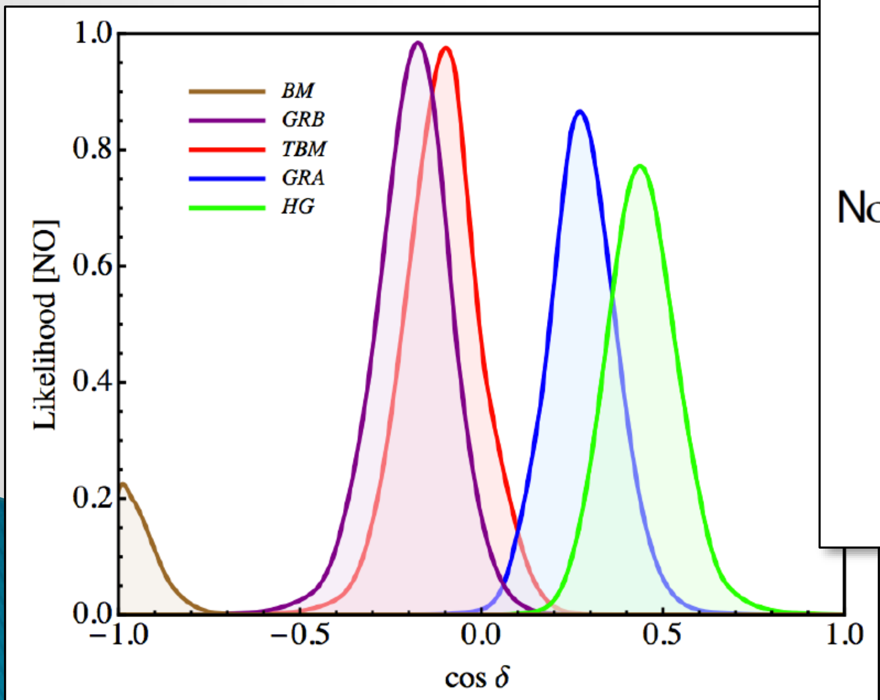
Neutrino Oscillations



Dune sensitivity to CP violating phase

JUNO sensitivity to mass ordering (Marrone et al. '15)





Impact on flavour models (Girardi '14)

Beta decays

- Single beta decay

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

- Allowed double beta ($2\nu\beta\beta$) decay

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

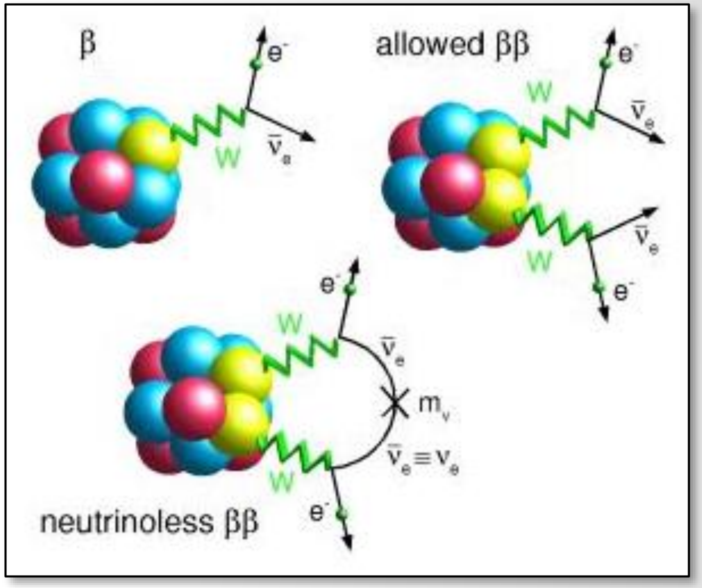
- Neutrinoless double beta ($0\nu\beta\beta$) decay

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

  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Variants
    - $0\nu\beta^+\beta^+$: $(A,Z) \to (A,Z-2) + 2e^+$
    - $0\nu\beta^+\text{EC}$: $(A,Z) + e^- \to (A,Z-2) + e^+$
    - $0\nu\text{ECEC}$: $(A,Z) + 2e^- \to (A,Z-2)^*$

- Majoron-assisted $0\nu\beta\beta$ decay

$$(A,Z) \to (A,Z+2) + 2e^- + n\chi$$



$0\nu\beta\beta$

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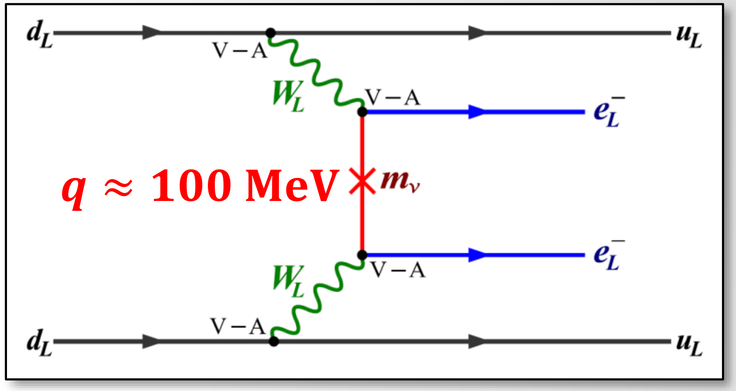


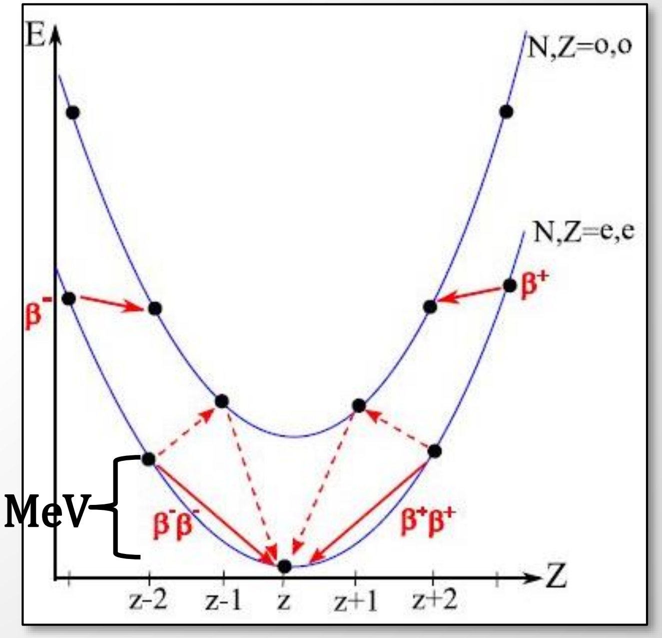
- Half-life

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

- Particle Physics

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

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$



$$T_{1/2}^{-1} \propto \frac{|m_{\beta\beta}|^2}{q^4} G_F^4 Q^5$$

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

$Q \approx 2$–4 MeV

$0\nu\beta\beta$

- Half–life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2$$

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- Atomic Physics
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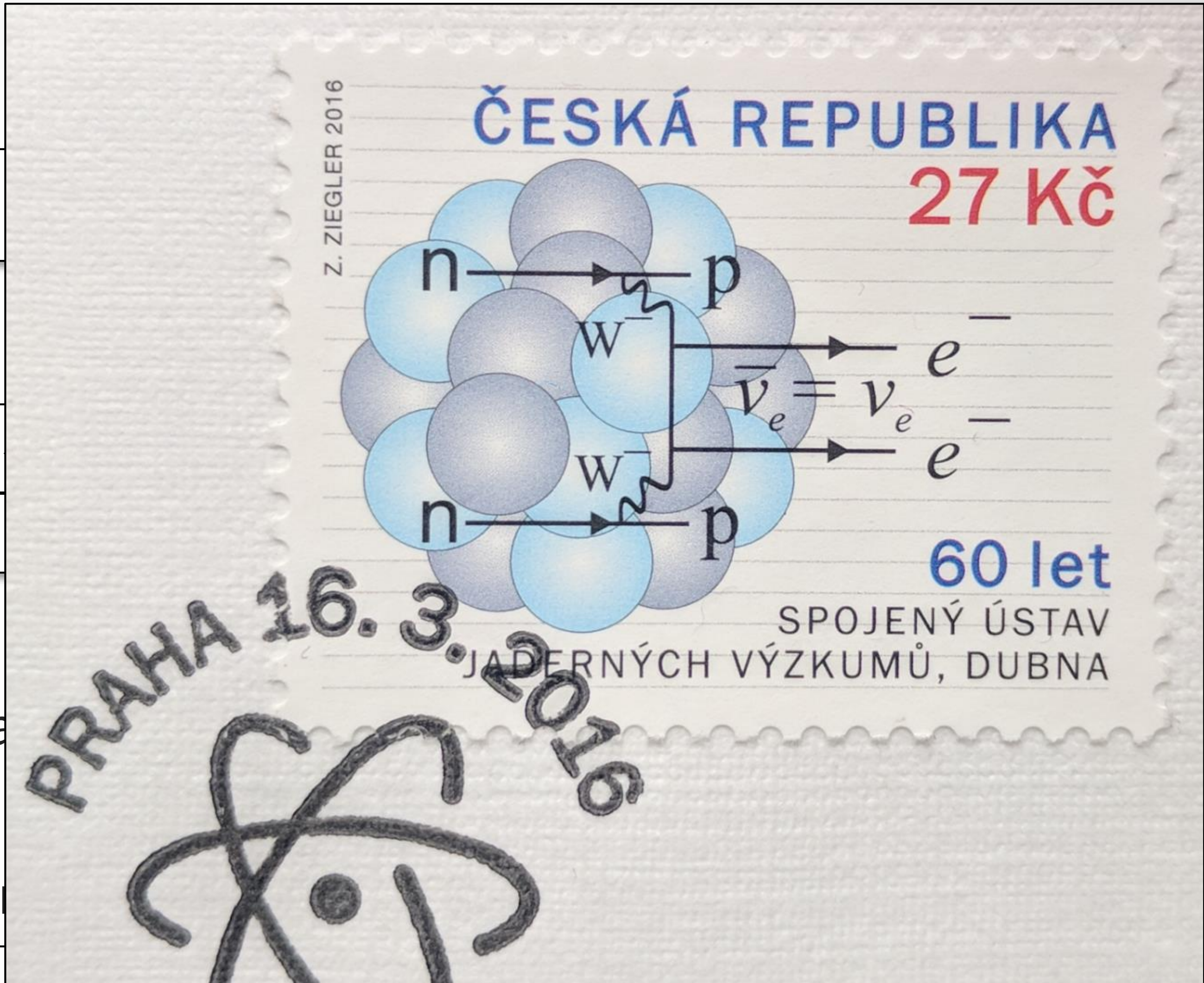
- Nuclear Physics
  - Nuclear transition



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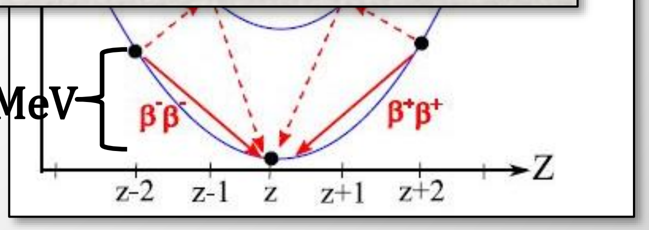

$0\nu\beta\beta$ – Light Neutrinos

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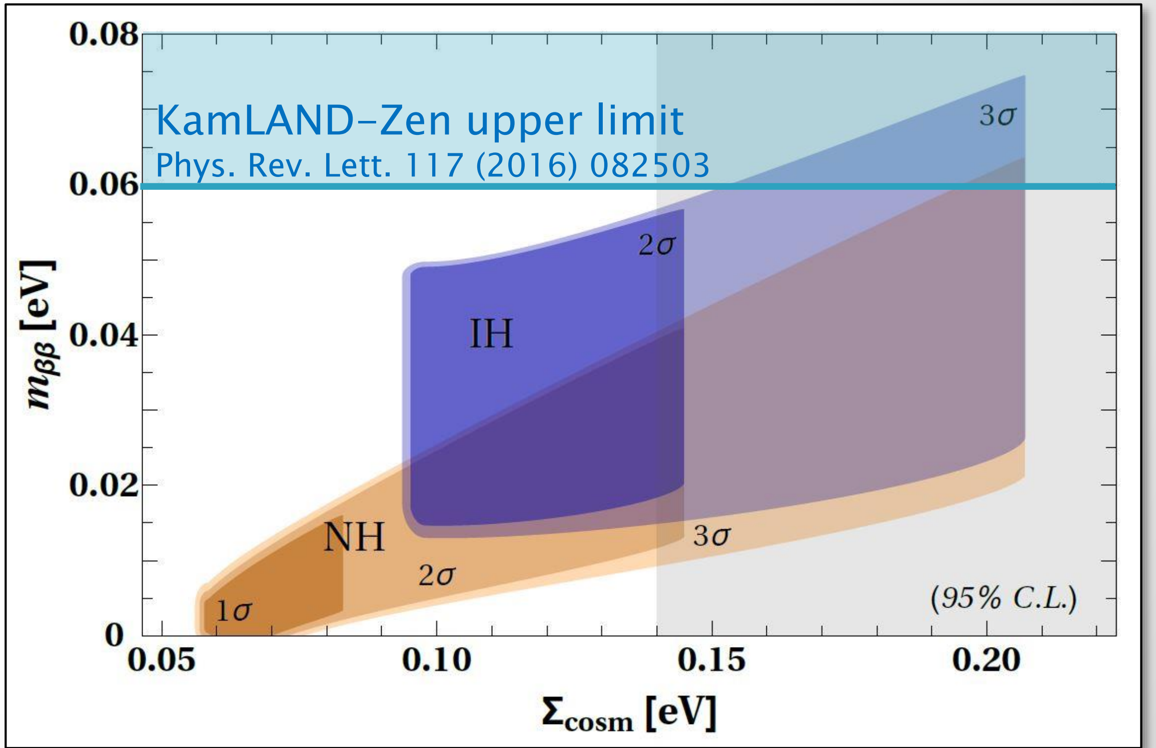
- Effective $0\nu\beta\beta$ Mass

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

- Degenerate Regime

$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases
- Accidental cancellation for NH possible



Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

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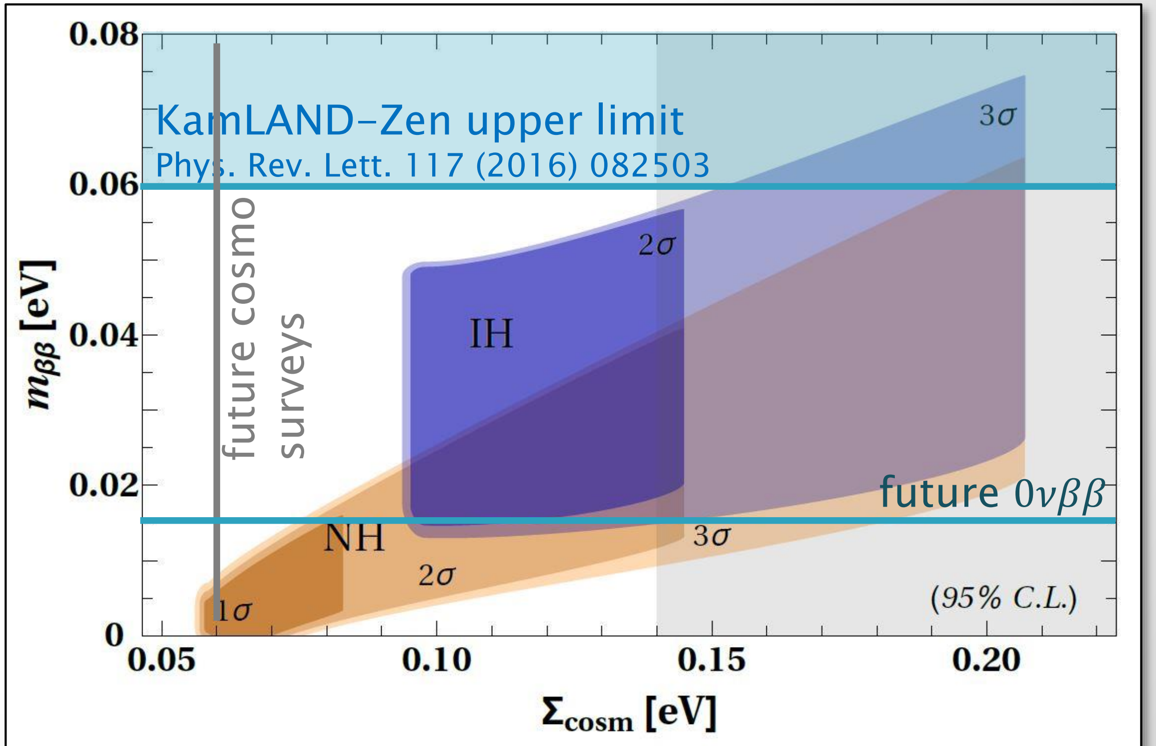

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$0\nu\beta\beta$ – Light Neutrinos

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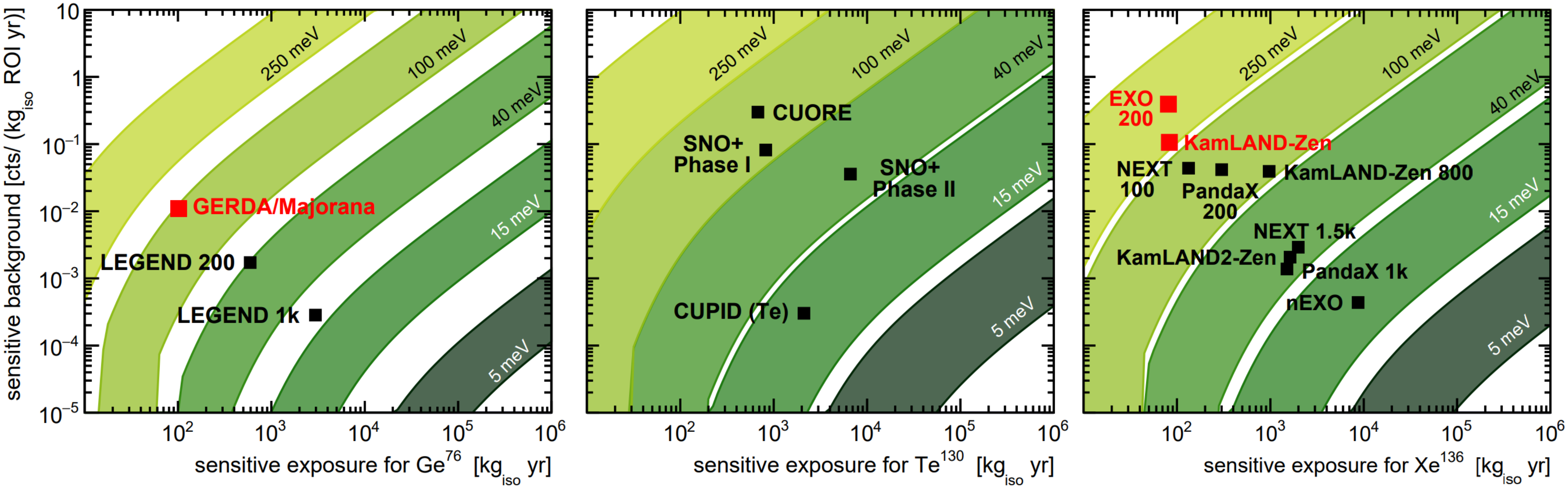
- Experimental Sensitivity



Agostini, Benato, Detwiler
arXiv:1705.02996

Nuclear Matrix Elements

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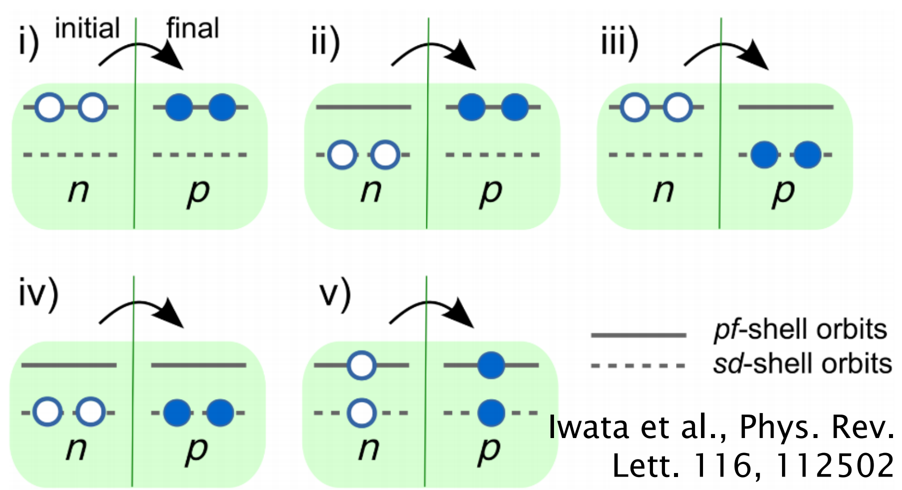
- Hadronic current

$$J^{\mu}(q) = g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5 + \frac{i g_M}{2 m_N}\sigma^{\mu\nu} q_\nu - g_P \gamma^5 q^{\mu}$$

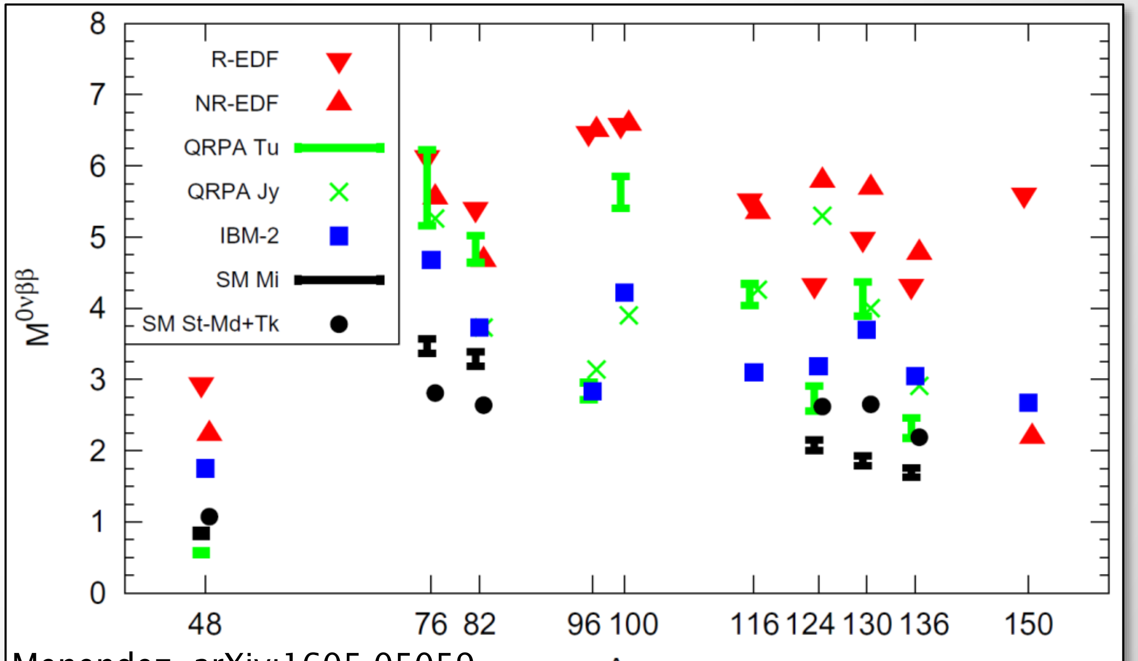
- Nuclear Matrix Element $M^{0\nu}$

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_V^2}{g_A^2} M_F + M_T \right)$$

  - Many–body problem
  - Factor 2 – 3 uncertainty between nuclear models



Iwata et al., Phys. Rev. Lett. 116, 112502



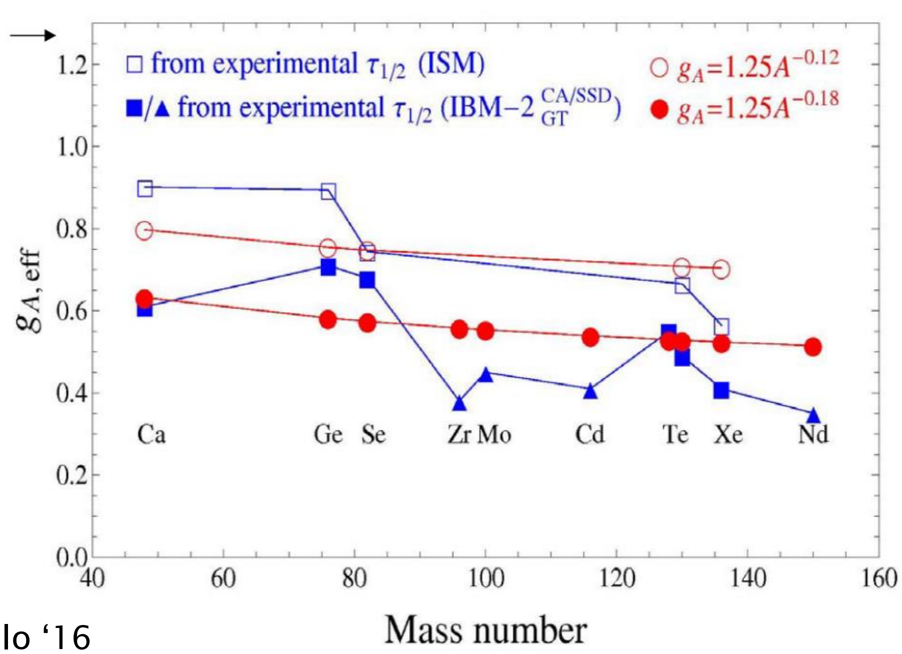
Menendez, arXiv:1605.05059

Quenching of g_A?

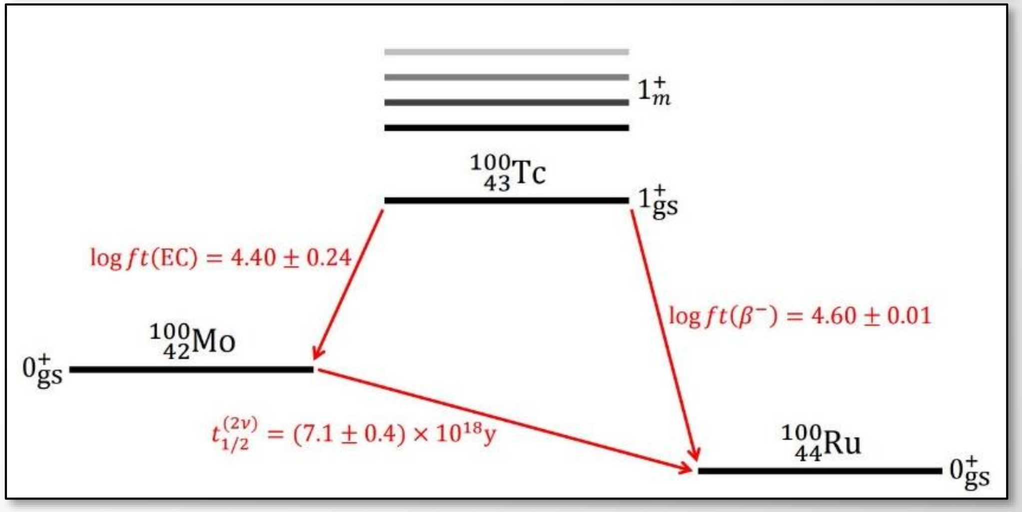
- Nuclear matrix element

$$M^{0\nu} = g_A^2\left(M_{GT} - \frac{g_V^2}{g_A^2}M_F + M_T\right)$$

- Axial–vector coupling g_A
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of single β and $2\nu\beta\beta$ decay with theory: $g_A \approx 0.6–0.8$
  - If applicable to $0\nu\beta\beta$, reduction of sensitivity
  - Genuine effect or short–coming of models?



Iachello '16



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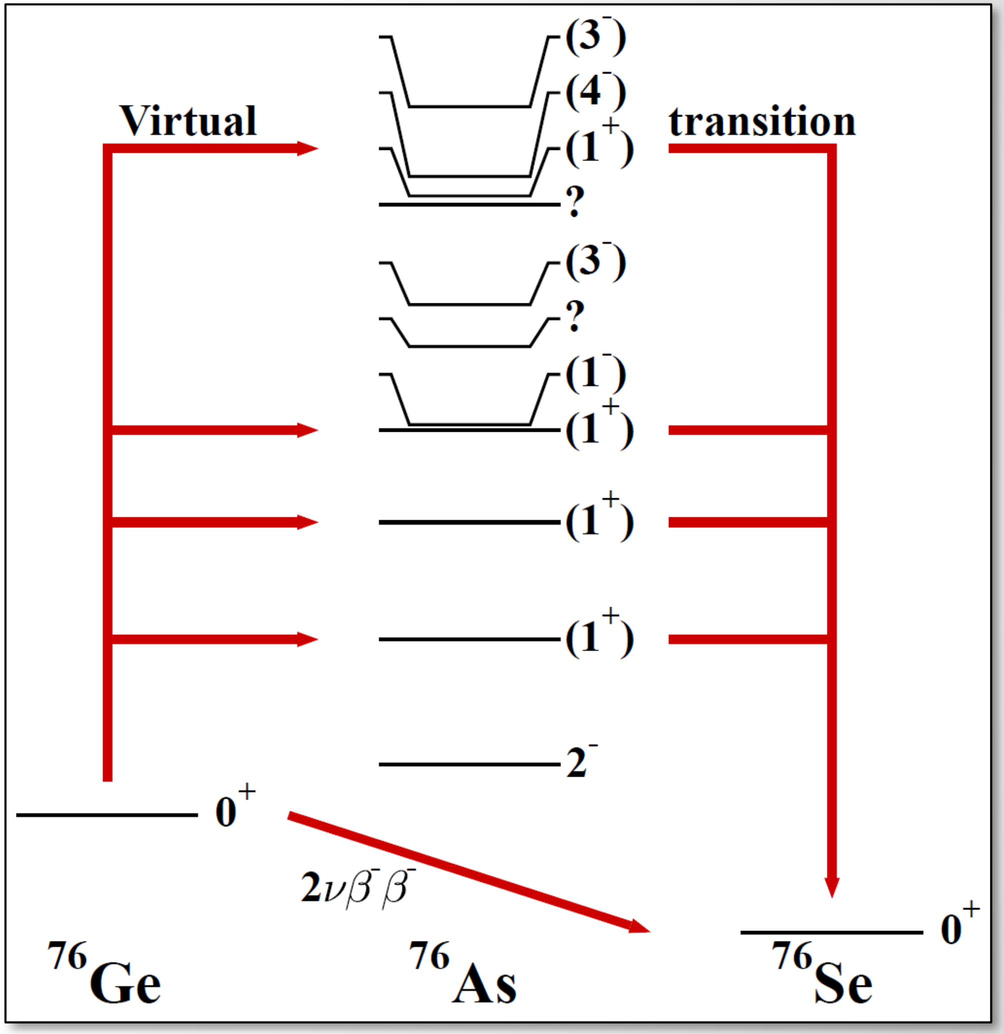

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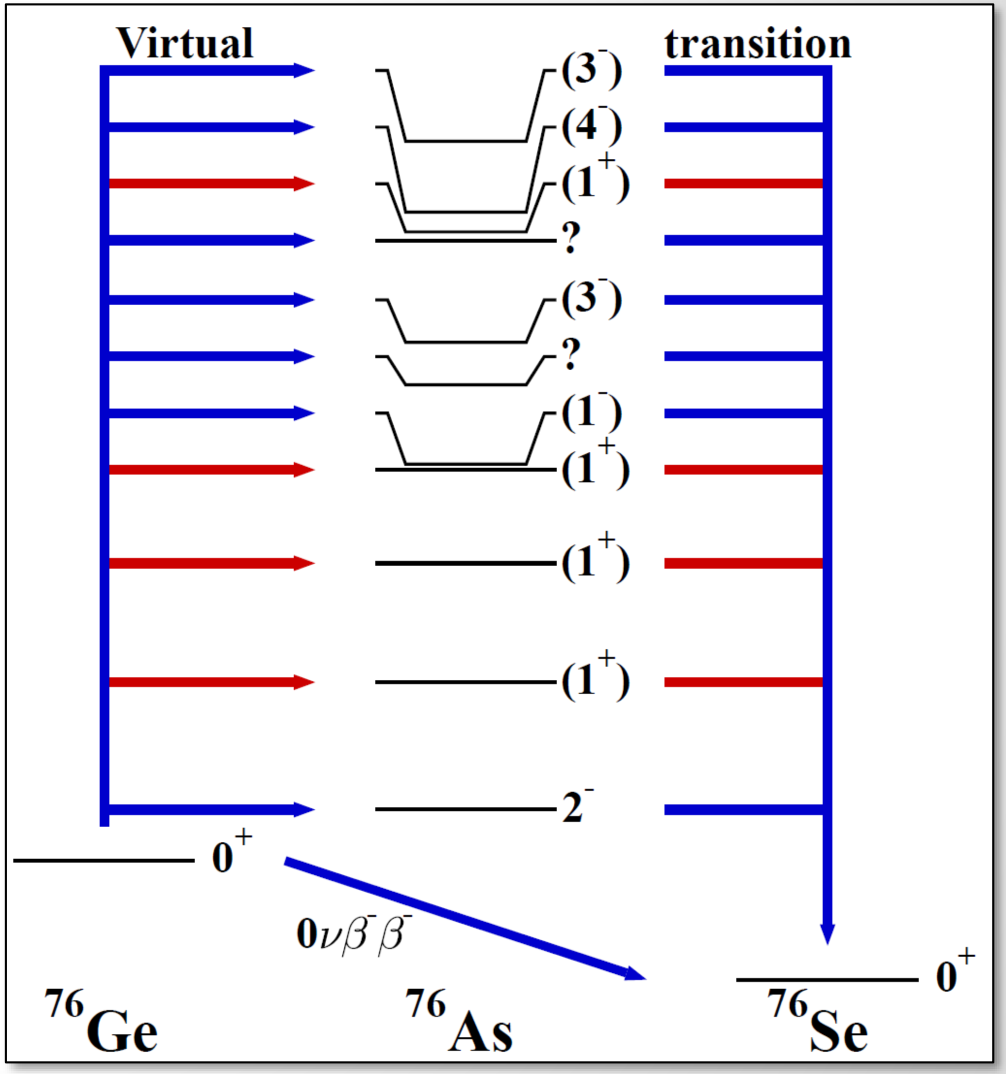
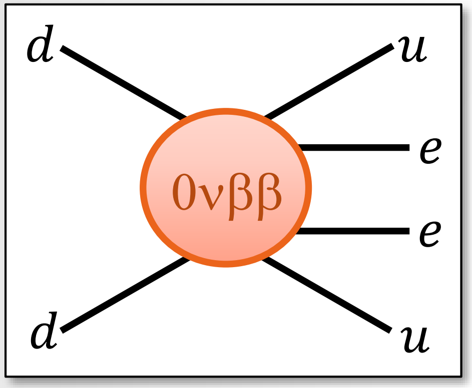


New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios



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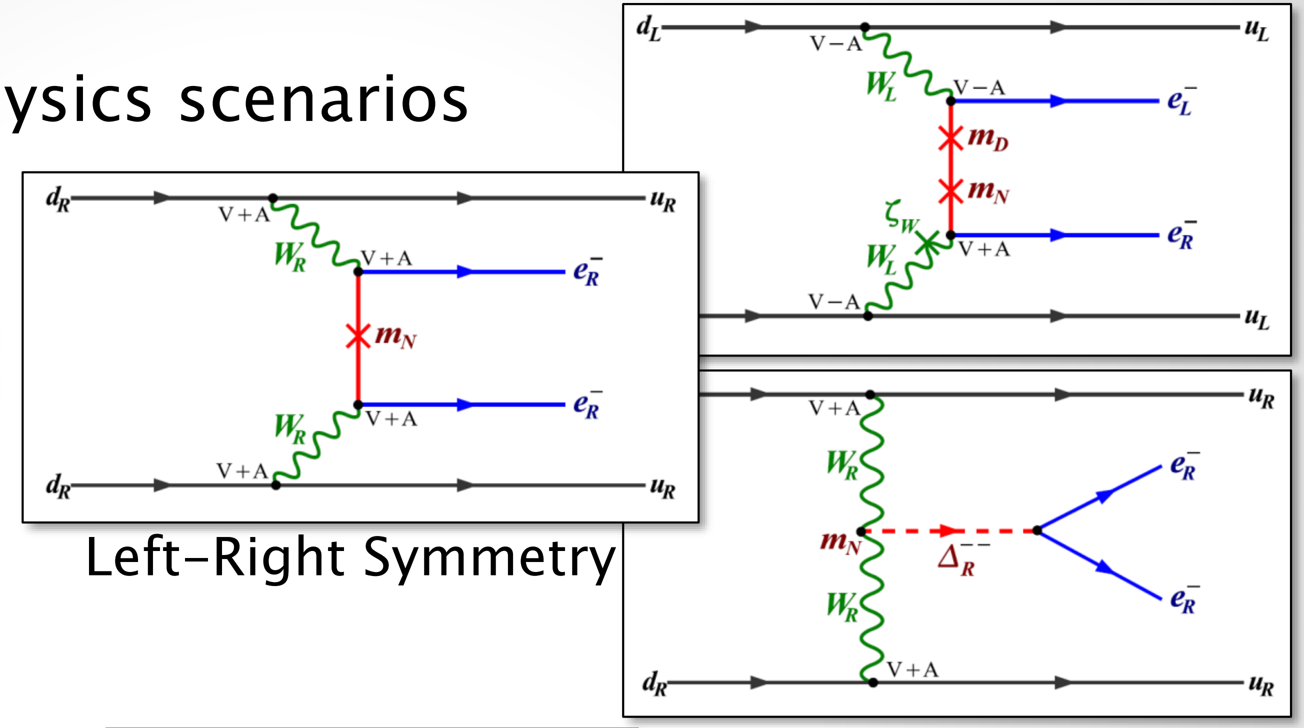
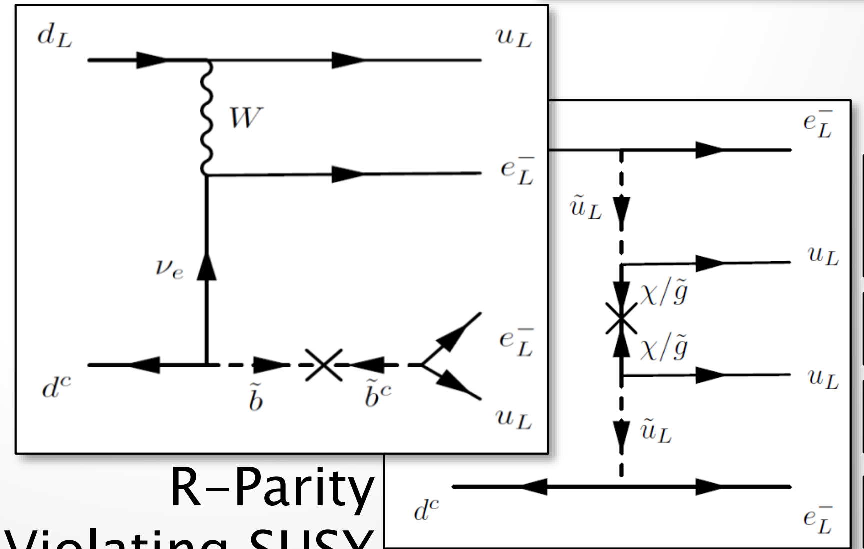
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$



Left–Right Symmetry



R–Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

…

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

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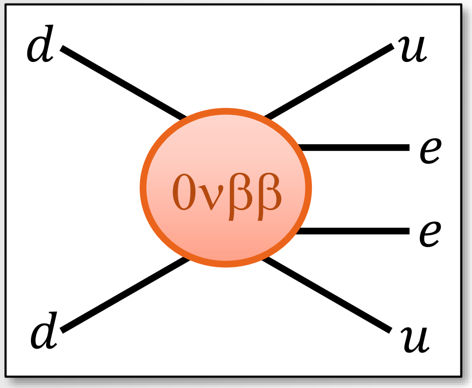
- Plethora of New Physics scenarios



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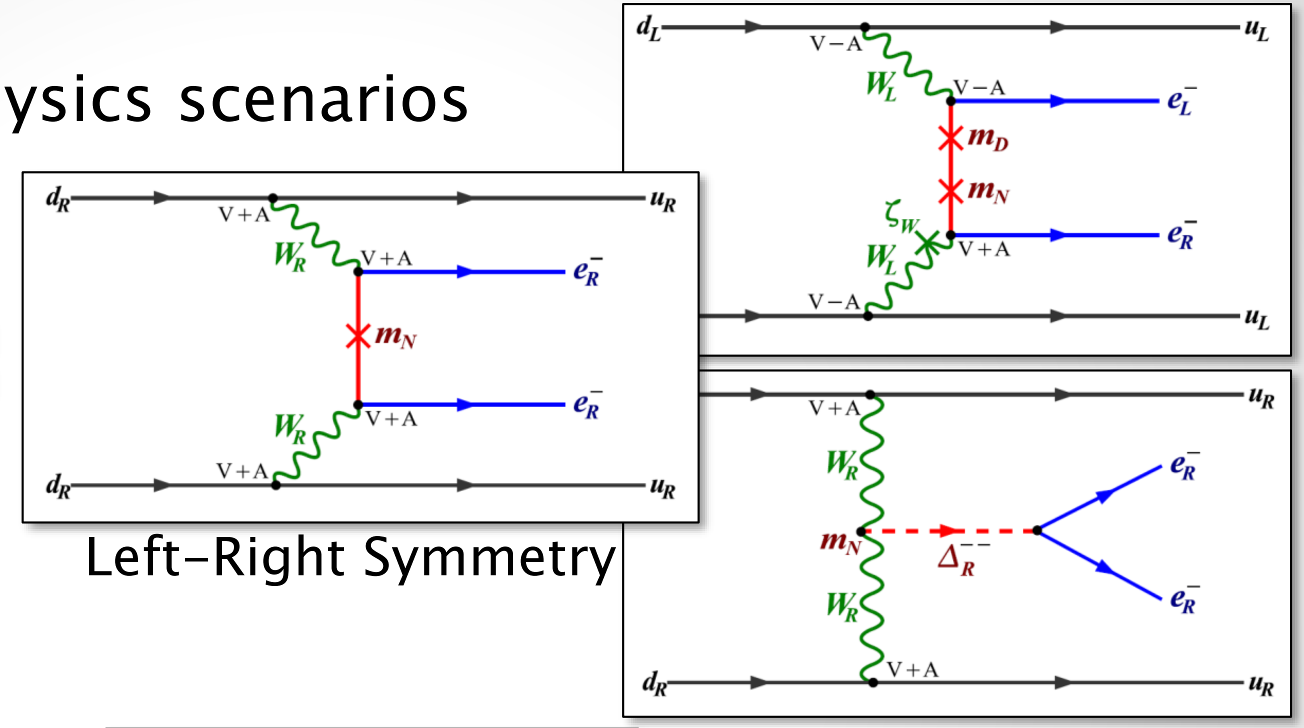

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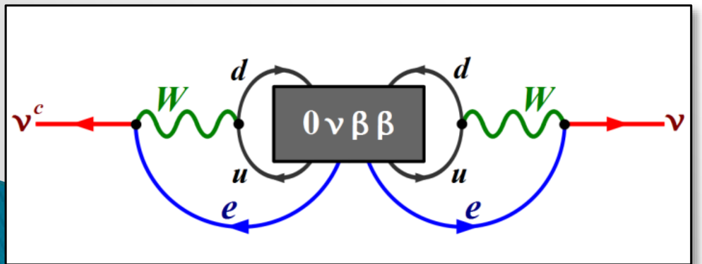
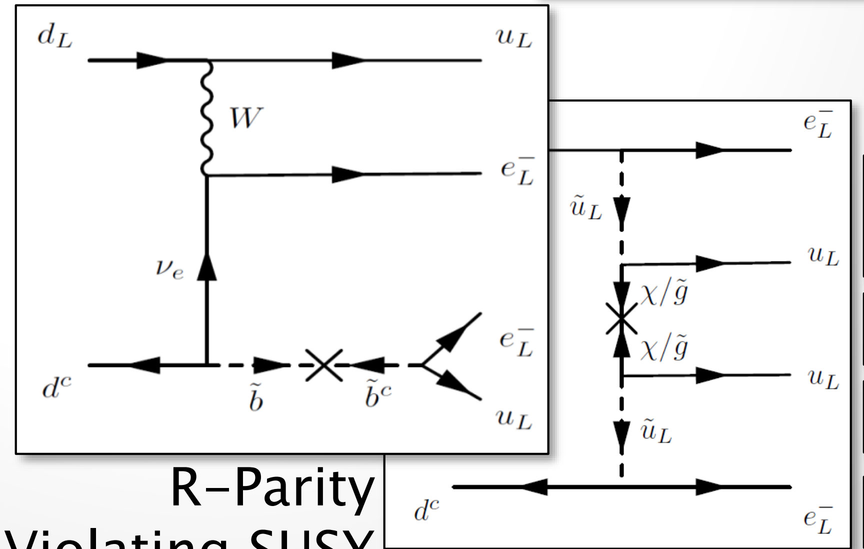




R–Parity Violating SUSY

- Neutrinos still Majorana

Extra Dimensions

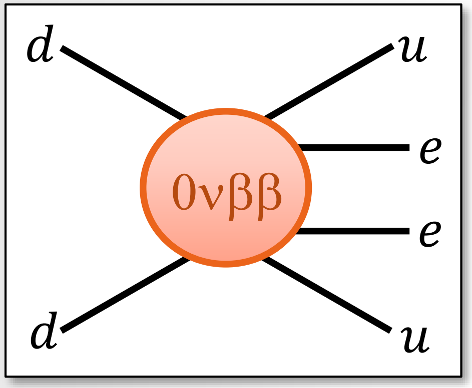
Majorons

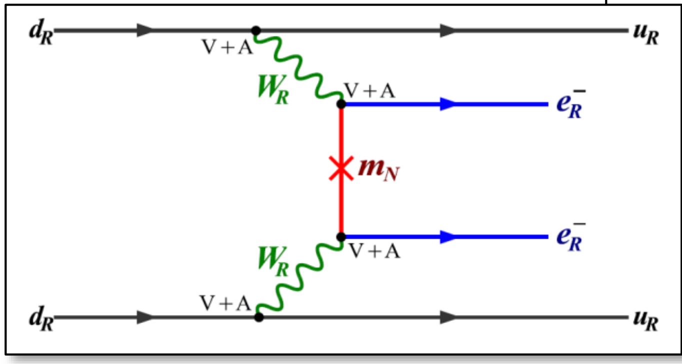
Leptoquarks

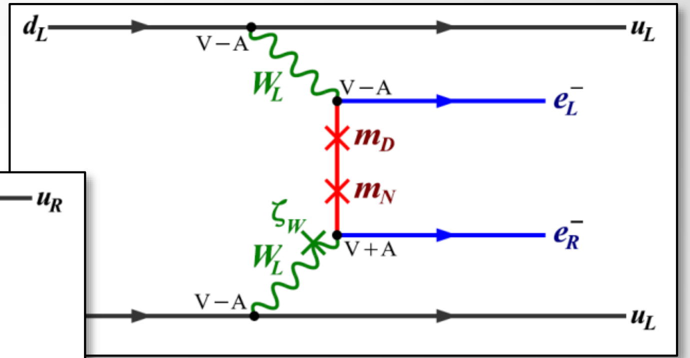
...

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

- Examples in Left–Right Symmetry







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

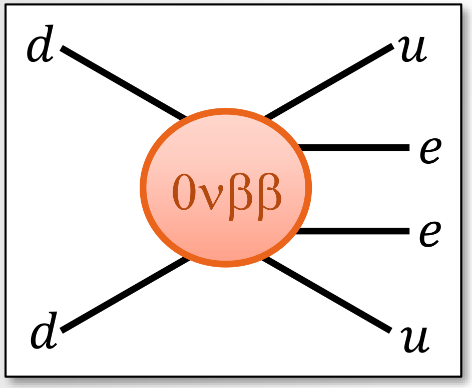
$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \text{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan \zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \text{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale

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

- Examples in Left-Right Symmetry



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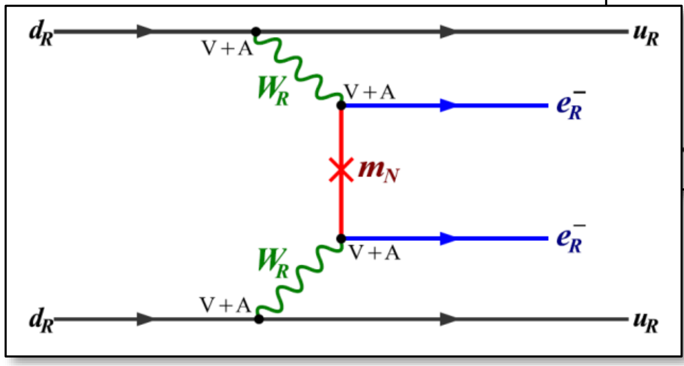

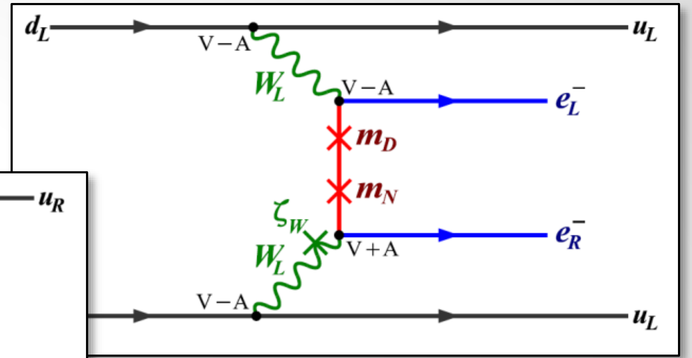

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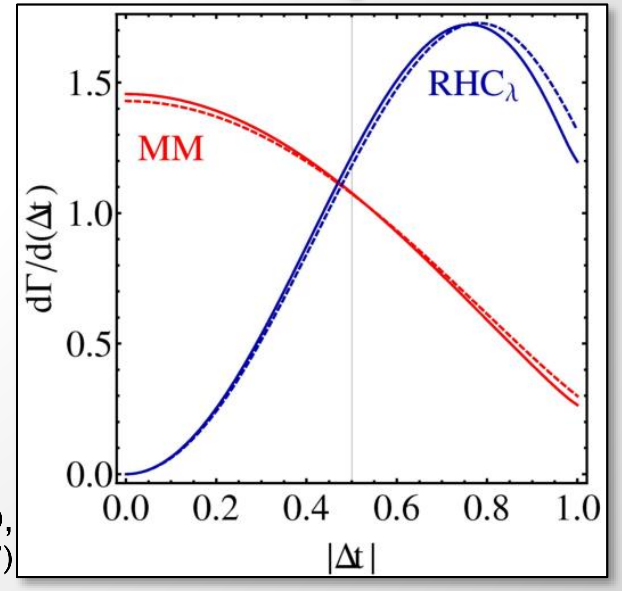
- $0\nu\beta\beta$ probes the TeV scale

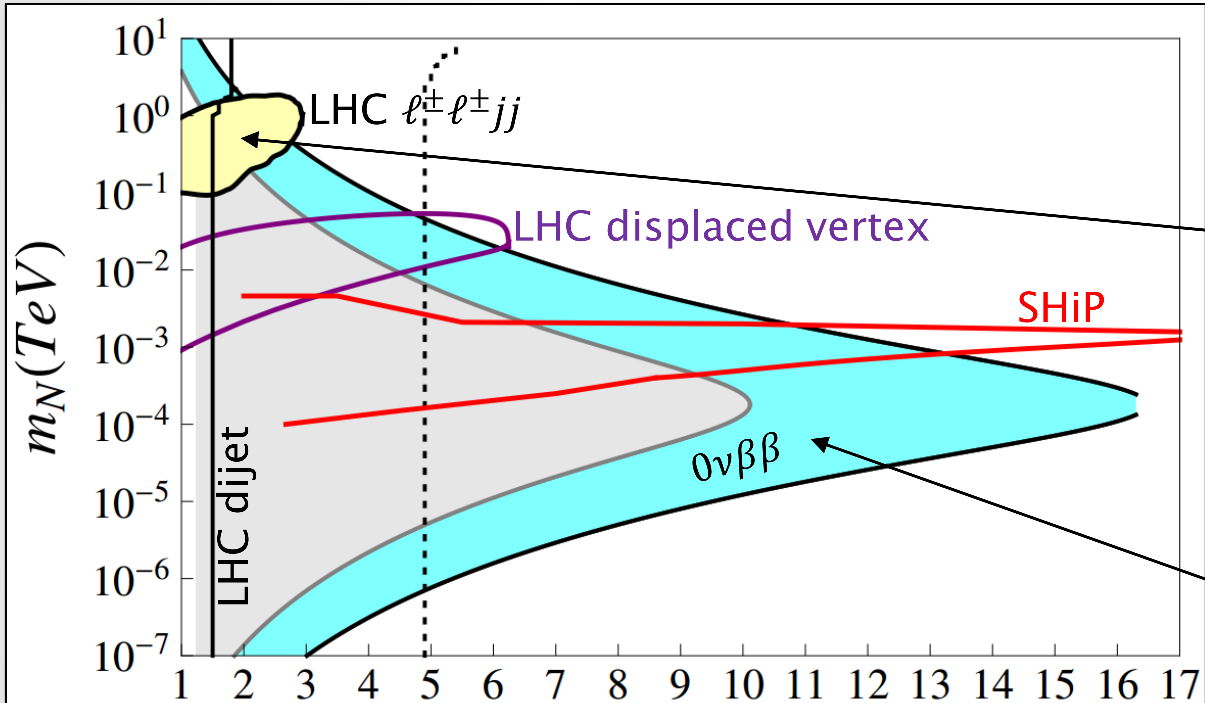
Modified angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06)



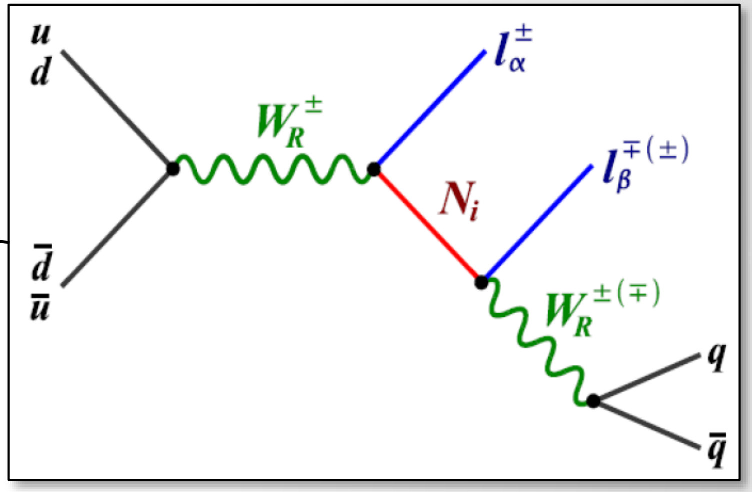
FFD, SuperNEMO, Eur.Phys.J. C70 (2010) 927)

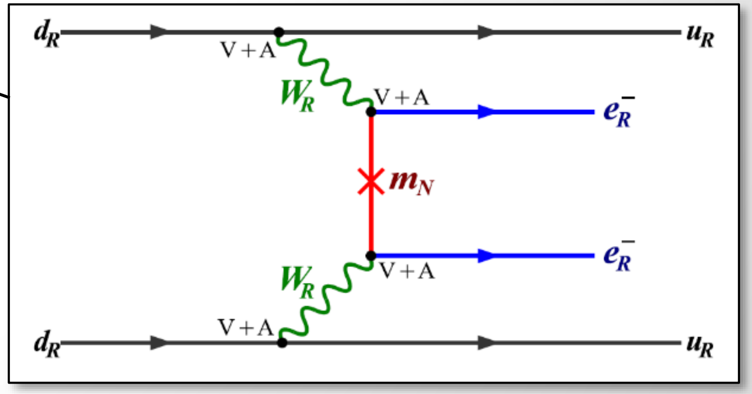
$0\nu\beta\beta$ vs LHC

- Example of Left-Right Symmetry
  (Mohapatra, Senjanovic '75)



Helo, Hirsch, Phys. Rev. D92 (2015), 073017

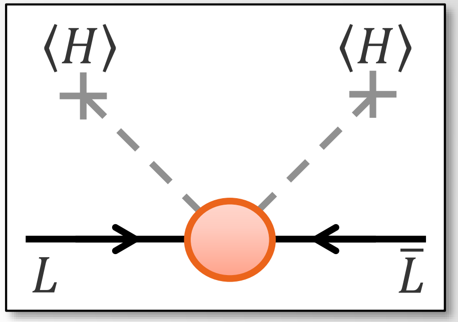




Neutrino Mass Models

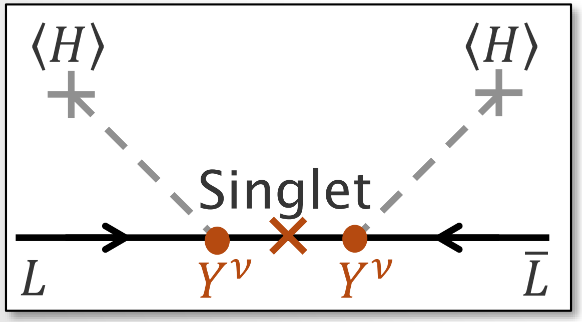
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

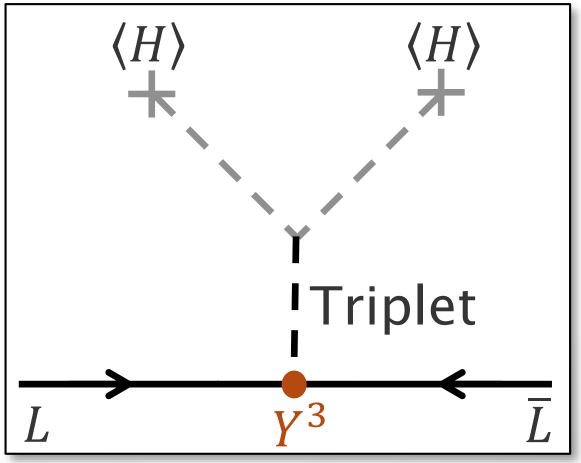


- Seesaw Mechanism

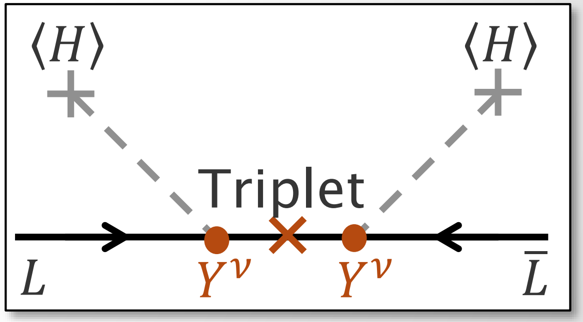
Seesaw I



Seesaw II



Seesaw III



Neutrino Mass Models

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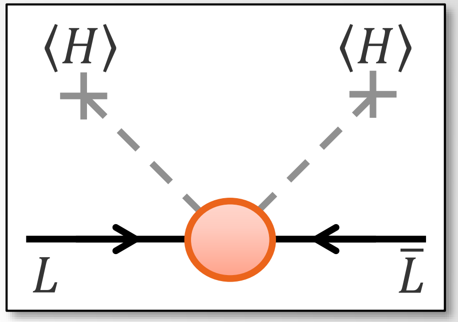
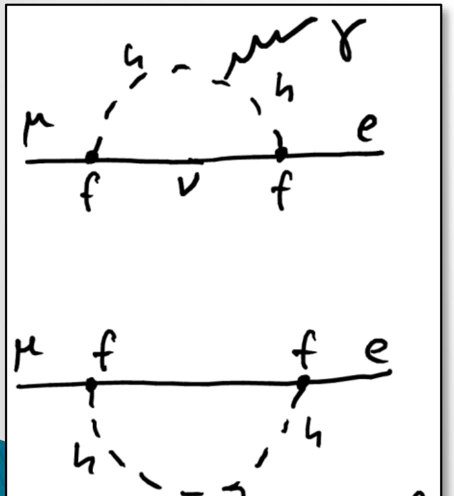
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

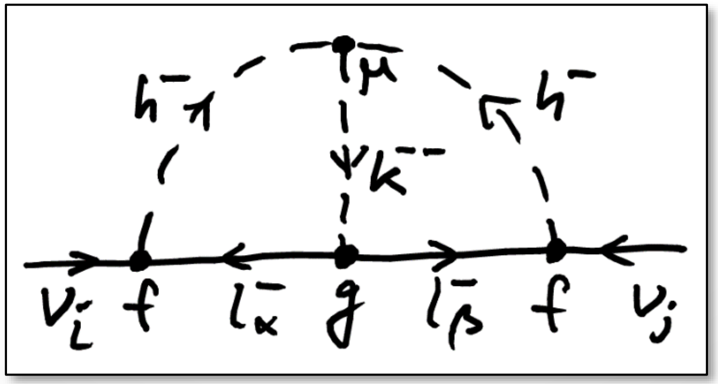
$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$



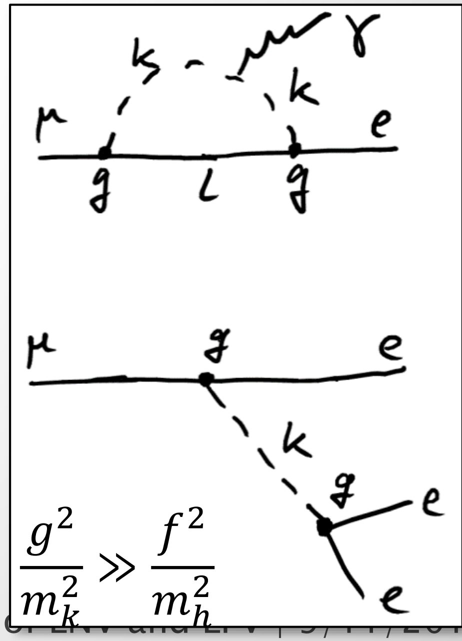
- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. Babu–Zee model (Zee '85, Babu '88)



$$\frac{f^2}{m_h^2} \gg \frac{g^2}{m_k^2}$$



Neutrino masses
suppressed at 2–loop



$$\frac{g^2}{m_k^2} \gg \frac{f^2}{m_h^2}$$

Heavy Sterile Neutrinos

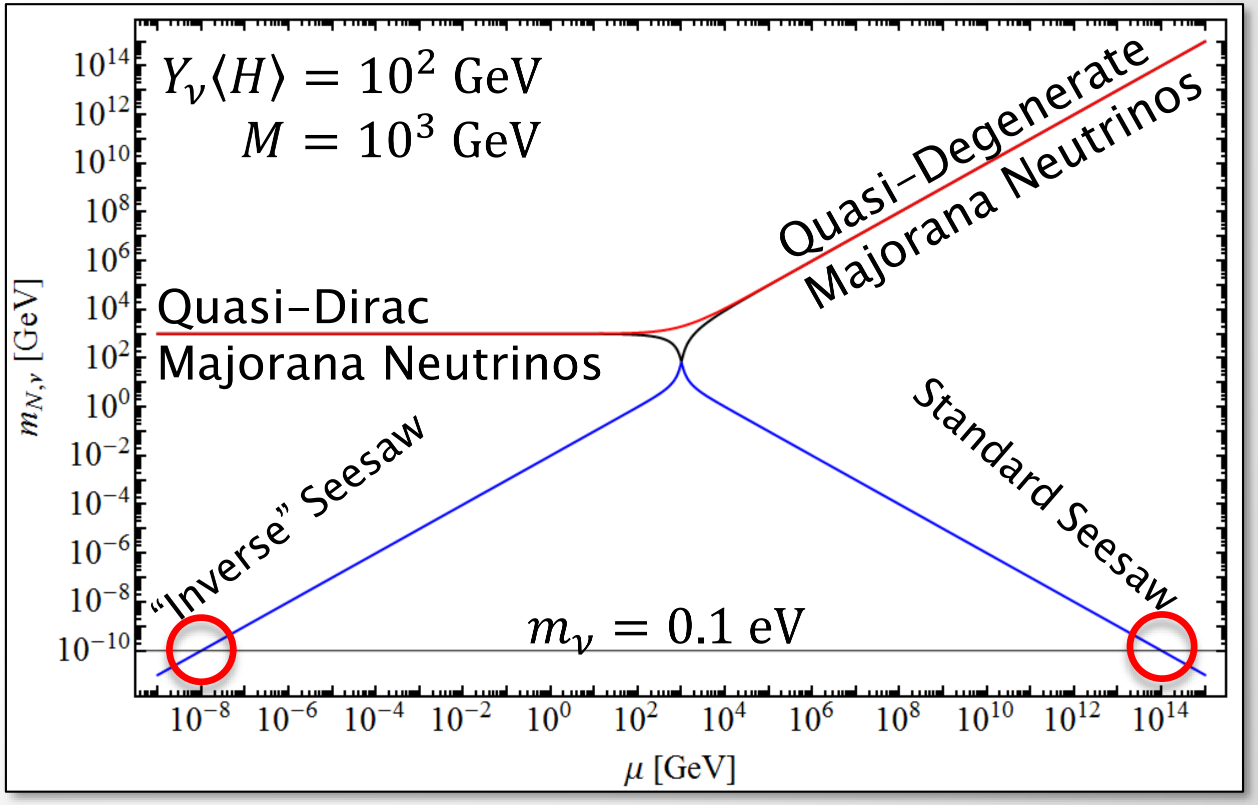
- Correct light neutrino masses for TeV scale heavy neutrinos
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings
    - CLFV remains small

$$V^{LR} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$$

  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

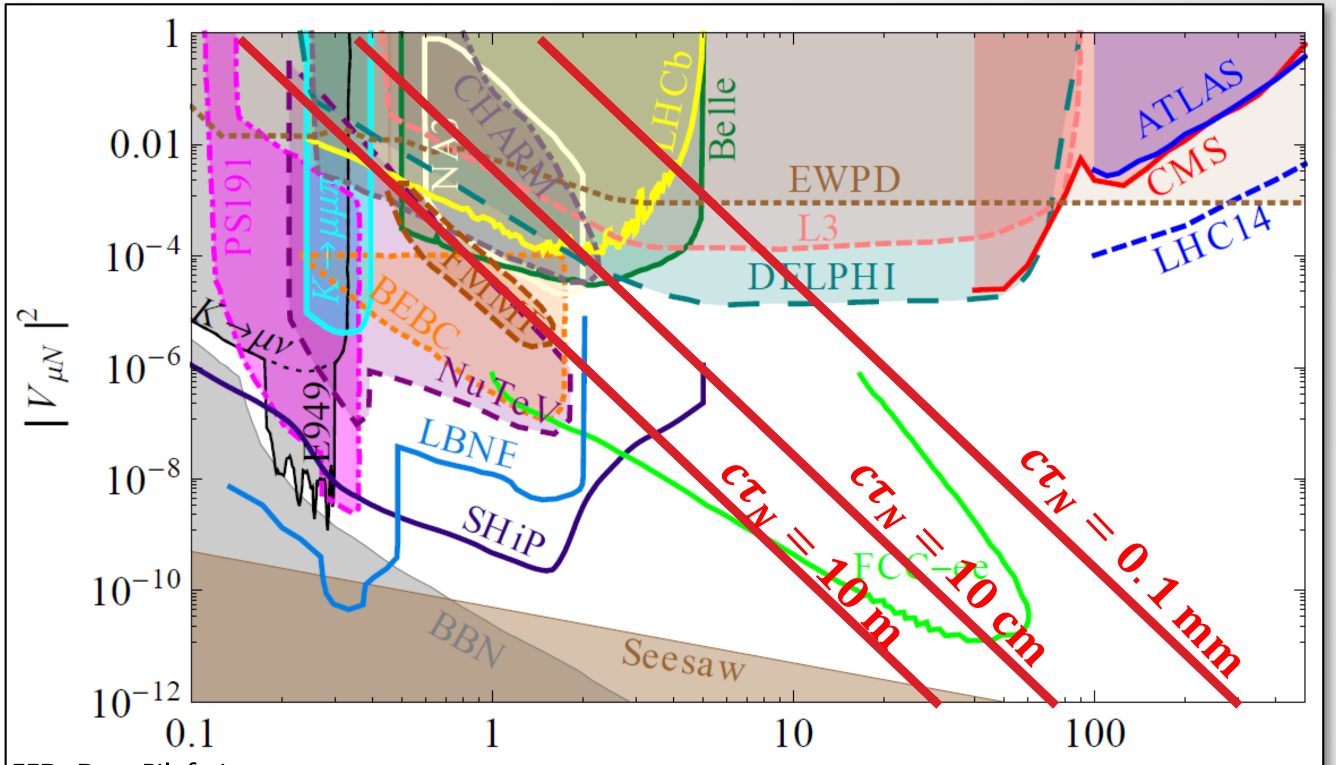
$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

    - Potentially large CLFV
    - In the limit $\mu \to 0$, no LNV but CLFV

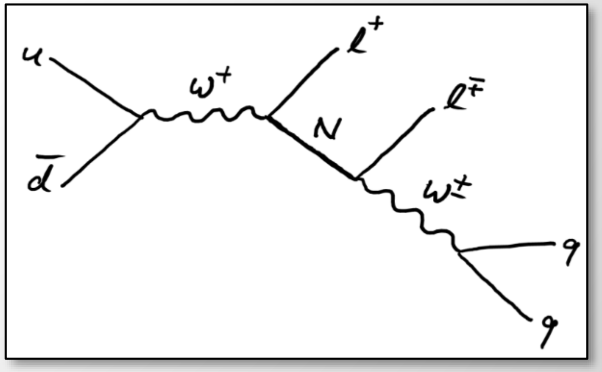


Heavy Sterile Neutrinos

- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
  - GERDA
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$
  - Belle
- Beam Dump Experiments
  - e.g. PS191, CHARM
  - LBNE
- LNV Meson Decays
  - $K \to ee\pi$
  - SHiP
- Z Decays
  - LEP: L3, Delphi
  - FCC-ee
- Electroweak Precision Tests
  - EWPD: Fit of electroweak precision observables, lepton universality observables



FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019



Heavy Sterile Neutrinos

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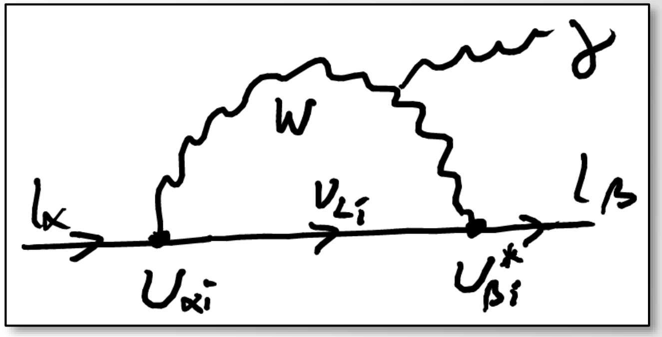
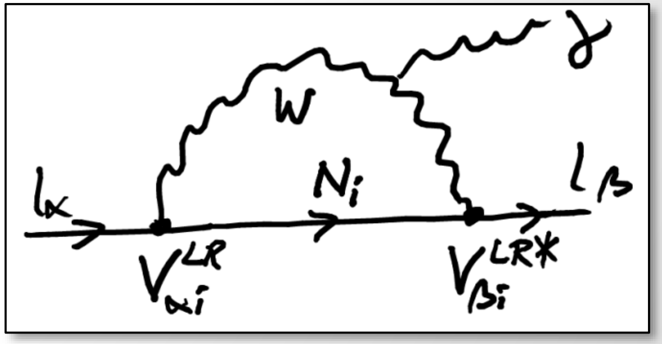
- CLFV in the Seesaw Mechanism
  - Light neutrino exchange
    - Negligible due to small neutrino masses



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei}\, \frac{\Delta m^2_{1i}}{m_W^2}\right|^2 \approx 10^{-56}$$

  - Heavy neutrino exchange
    - Sizable for TeV scale heavy neutrinos and large LR mixing $V^{LR} \approx 10^{-2}$



$$Br(\mu \to e\gamma) \approx 4\times 10^{-3}\left|\sum_i V^{LR*}_{\mu i} V^{LR}_{ei}\, G\left(\frac{m^2_{N_i}}{m_W^2}\right)\right|^2$$
$$\approx 10^{-11}\left(\frac{V^{LR}}{10^{-2}}\right)^4$$

$$\mathcal{U}^\nu = \begin{pmatrix} U & V^{LR} \\ (V^{LR})^\intercal & U^R \end{pmatrix}$$

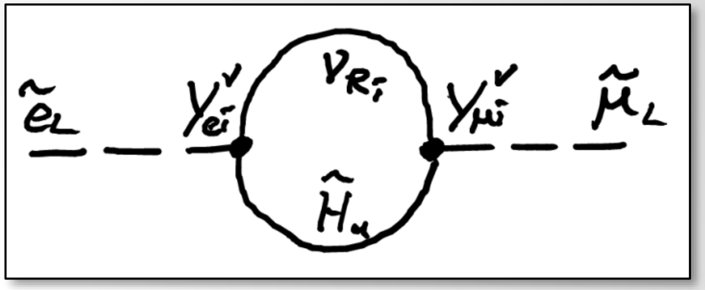
SUSY Seesaw

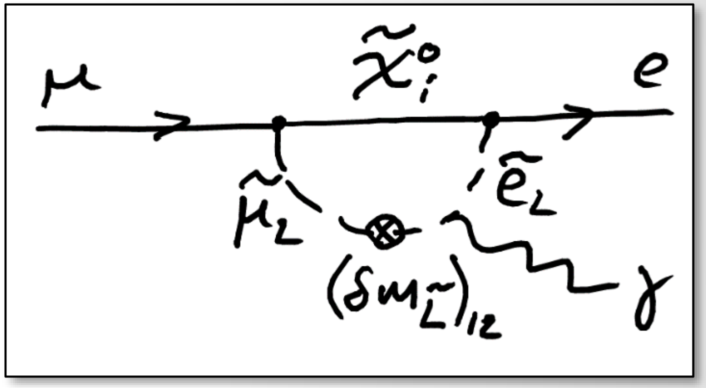
- Neutrino flavour mixing radiatively induces slepton flavour mixing
(Borzumati, Masiero '86)

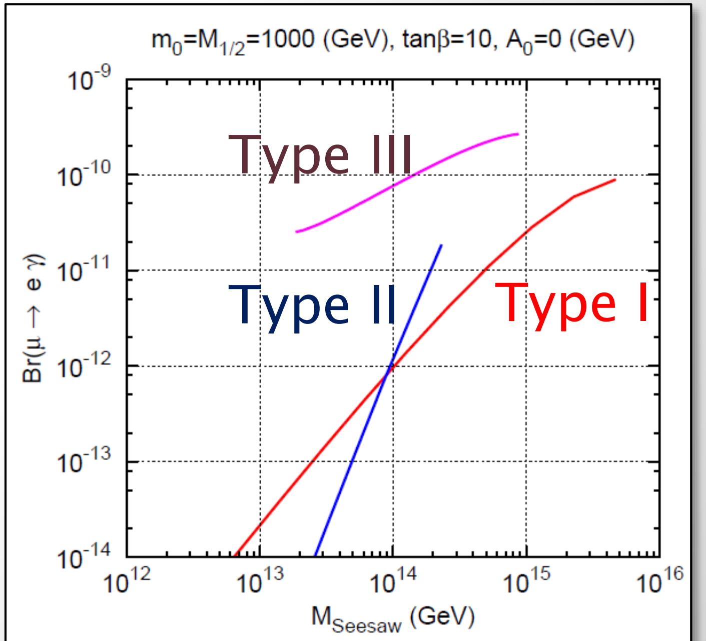
- Correlation between slepton and neutrino flavour mixing (Type I)

$$(\delta m_{\tilde{L}}^2) = \begin{pmatrix} \delta_{11} & \delta_{12} & \delta_{13} \\ \delta_{12}^* & \delta_{22} & \delta_{23} \\ \delta_{13}^* & \delta_{23}^* & \delta_{33} \end{pmatrix} \propto \left(Y^{\nu\dagger} \cdot Y^\nu\right) \log(M_X / M_{\nu_R})$$

- Induces observable charged LFV rates despite high scale Seesaw $M_{\nu_R} \approx 10^{14}$ GeV

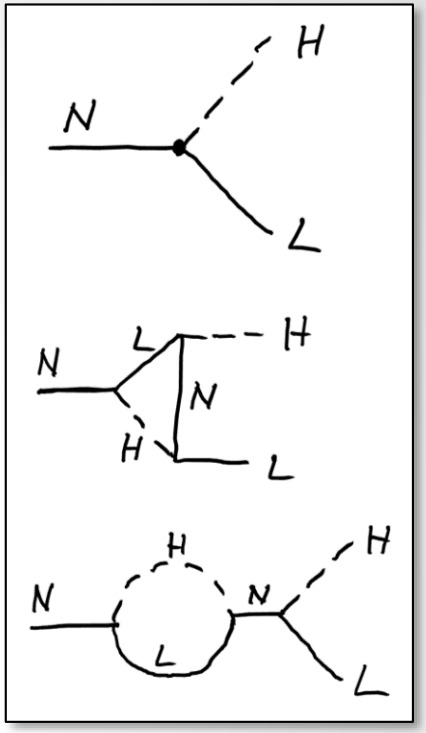






Esteves et al. '11

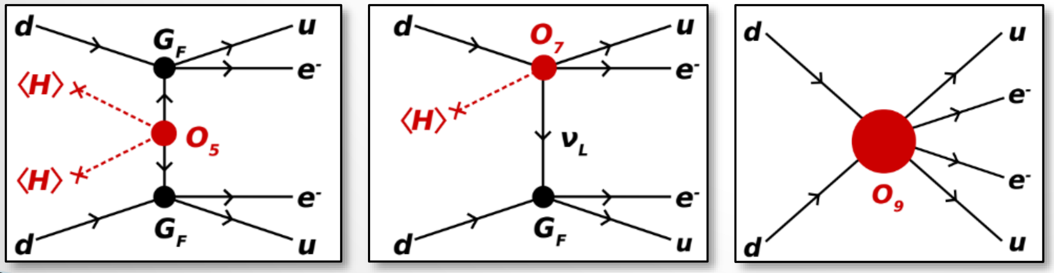
Baryon Asymmetry Generation and Washout

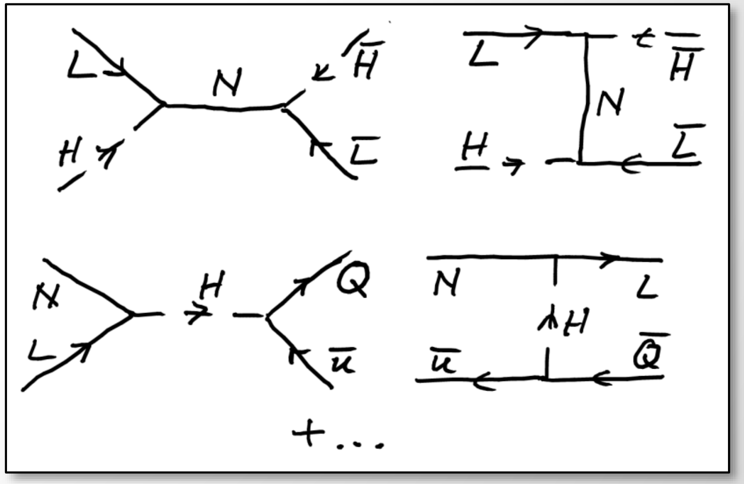


- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

- What if we observe lepton number violating processes in $0\nu\nu\beta$?





Baryon Asymmetry
Lepton Asymmetry Washout

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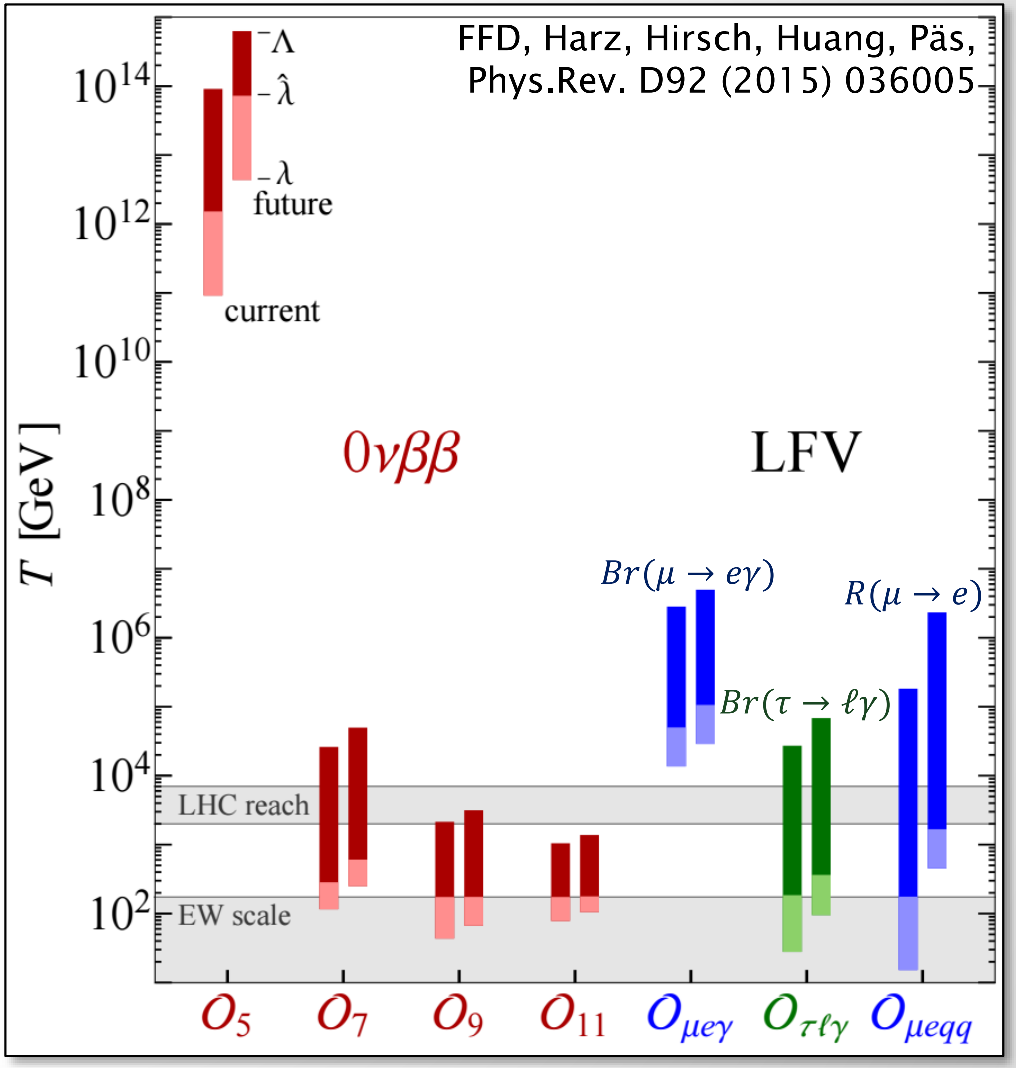
- Compare $0\nu\beta\beta$ rate with lepton asymmetry washout in the early Universe
- Observation of lepton number violation
  - gives information at what temperatures operators are in equilibrium
  - corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - **can falsify high-scale baryogenesis scenarios**



Conclusion

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- **Neutrinos much lighter than other fermions**
  - LNV! Dirac or Majorana? Lepton Number Violation?
- **LNV and LFV are crucial probes for BSM physics**
  - Test mechanisms and scale of neutrino mass generation
  - How is lepton number/flavour approximately protected
    - High scale, small couplings, symmetry?
- **Neutrinoless double beta decay**
  - Discovery → Majorana ν → Physics near GUT scale? LNV @ TeV?
  - Exclusion → Dirac ν? → Fine–tuned SM?
- **Strong Synergy with LHC+LFV searches**
  - LHC can deep–probe anatomy of $0\nu\beta\beta$ LNV operators
  - Observation of LNV+LFV would strongly constrain baryogenesis