UCL
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Neutrinoless Double Beta Decay Overview

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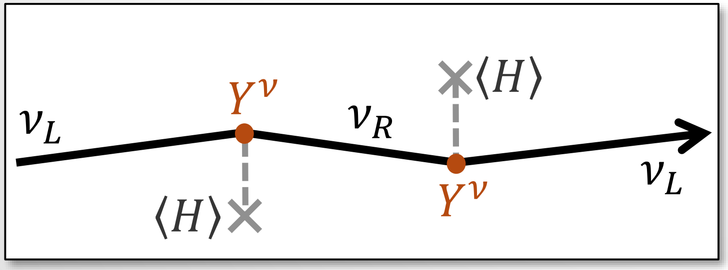
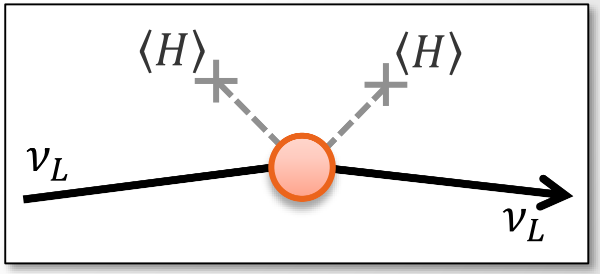
Dirac vs Majorana

- 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 decays

- Single beta decay

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

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

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

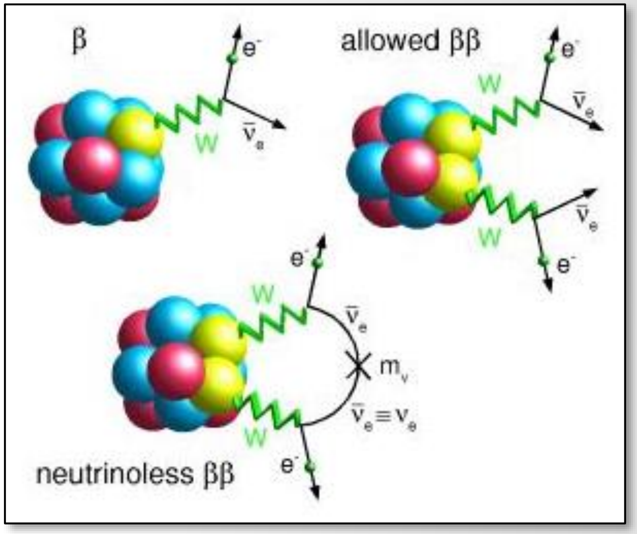
- Neutrinoless double beta ($0\nu\beta\beta$) decay

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

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

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

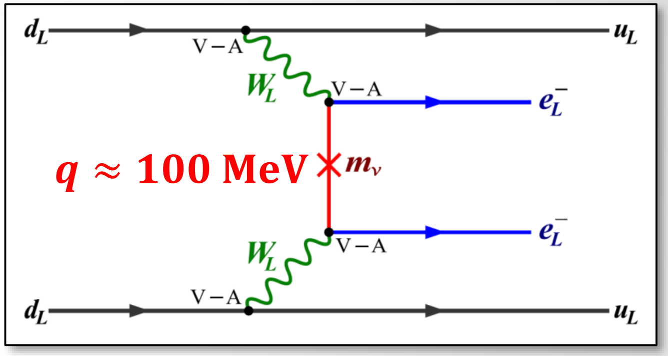
$$(A,Z) \to (A,Z+2) + 2e^- + n\chi$$



$0\nu\beta\beta$

- Half-life

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



- Particle Physics

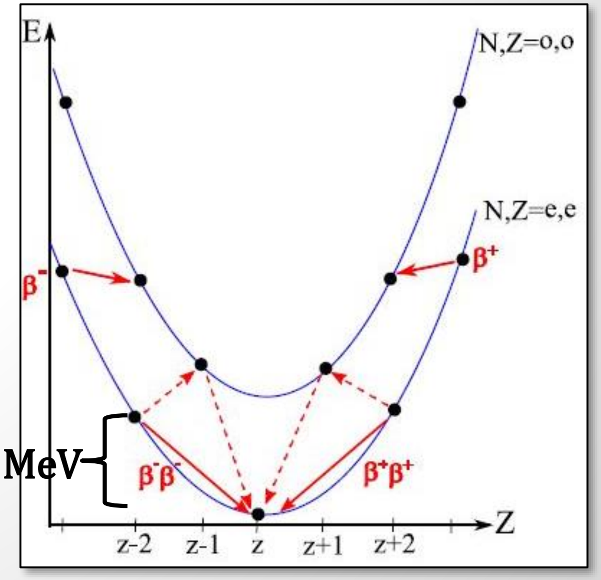
$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\cancel{\not{q}}+m_{\nu_i}}{q^2-m_{\nu_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2}\boxed{\sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i}} \rightarrow \boldsymbol{m_{\beta\beta}}$$

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

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

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

$Q \approx 2-4$ MeV



Three Active Neutrinos

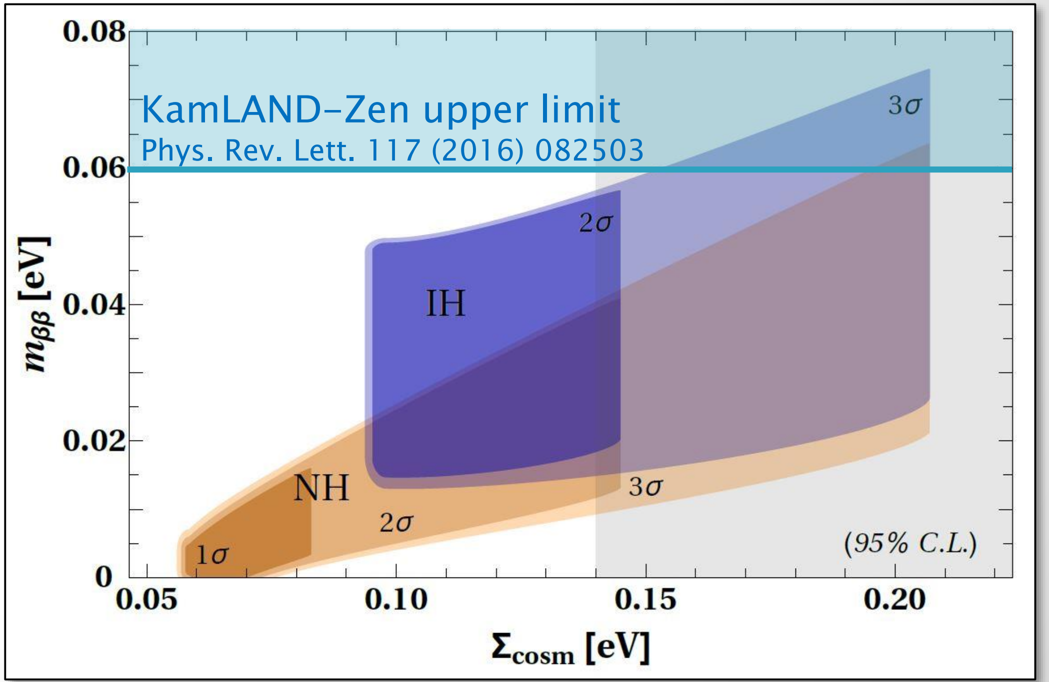
- Effective $0\nu\beta\beta$ Mass

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

- Degenerate Regime

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

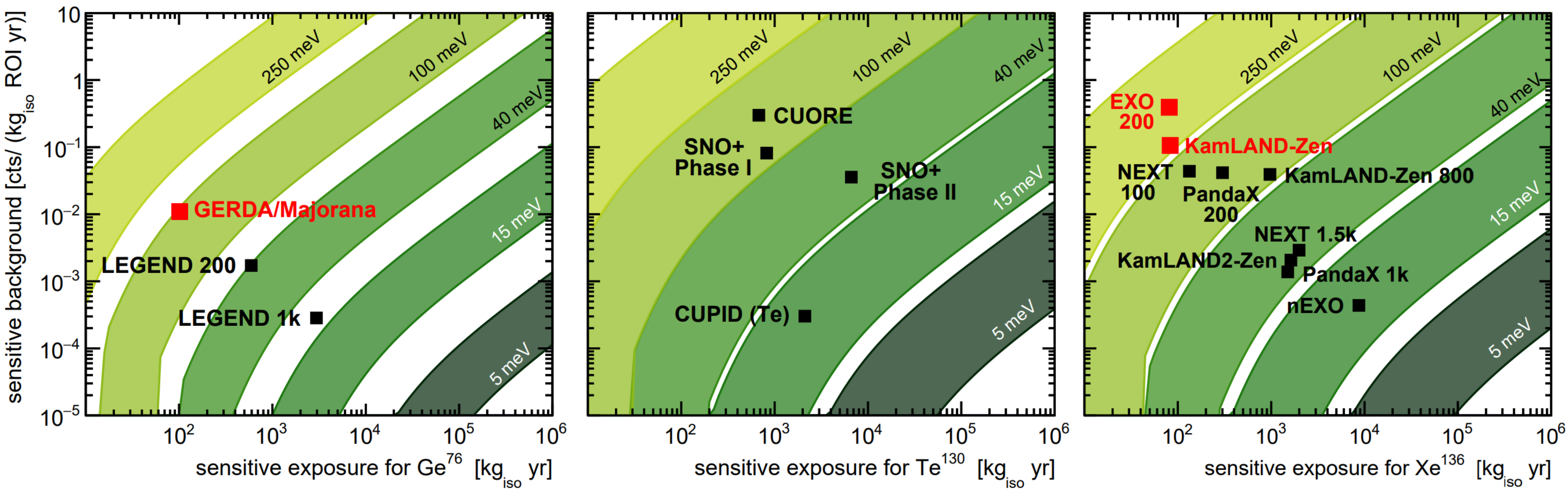
- Uncertainty from unknown Majorana phases
- Accidental cancellation for NH possible



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

Three Active Neutrinos

- Experimental Sensitivity



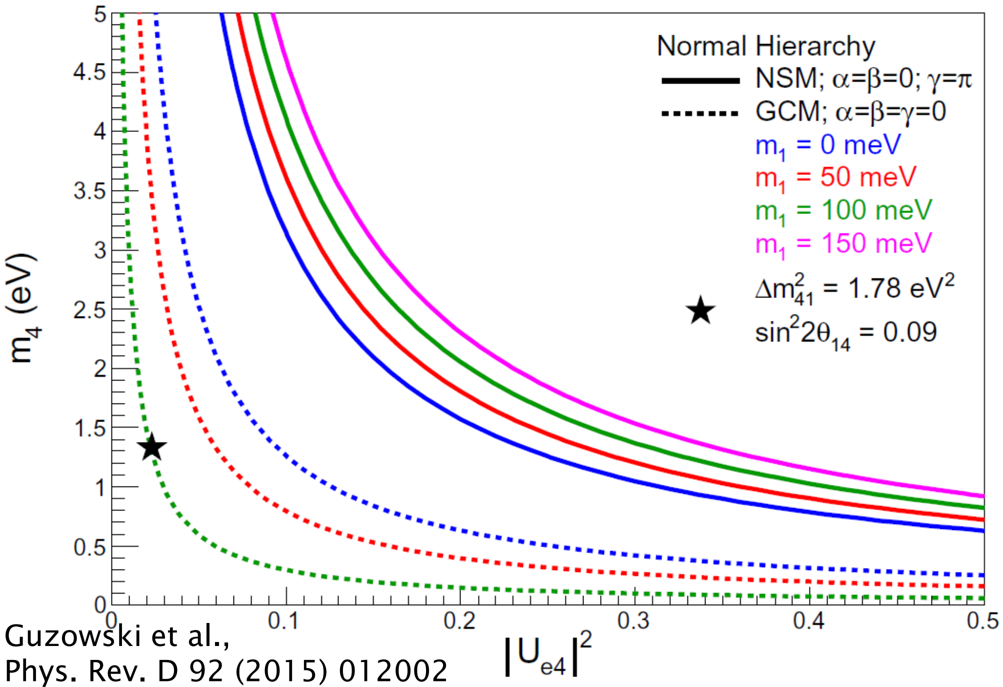
Agostini, Benato, Detwiler
arXiv:1705.02996

Light Sterile Neutrinos

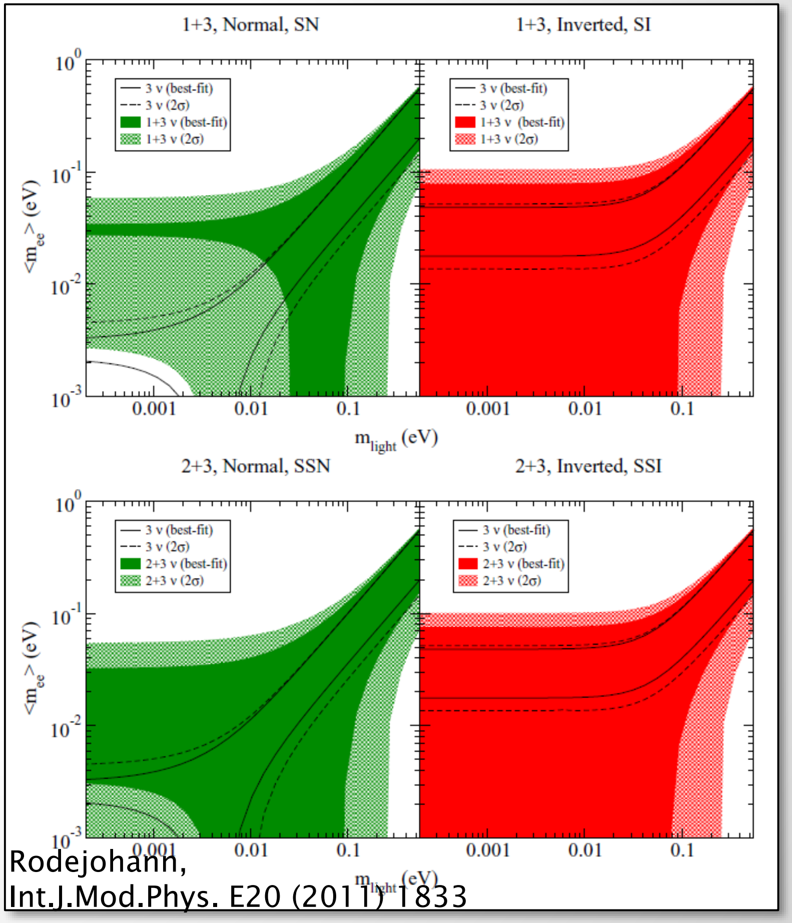
- Effective $0\nu\beta\beta$ Mass

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i(\phi_{13}-2\delta)} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots$$

- Dependence on new mass, mixing, phase



Guzowski et al.,
Phys. Rev. D 92 (2015) 012002



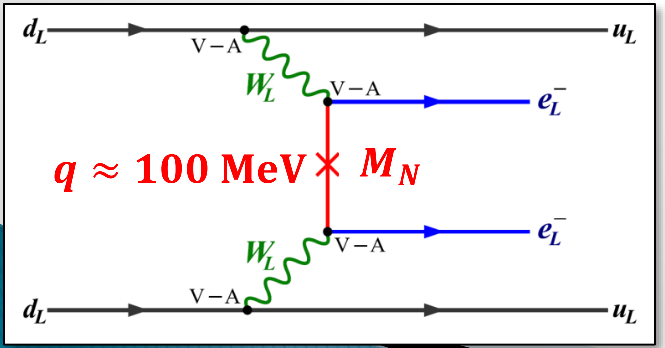
Rodejohann,
Int.J.Mod.Phys. E20 (2011) 1833

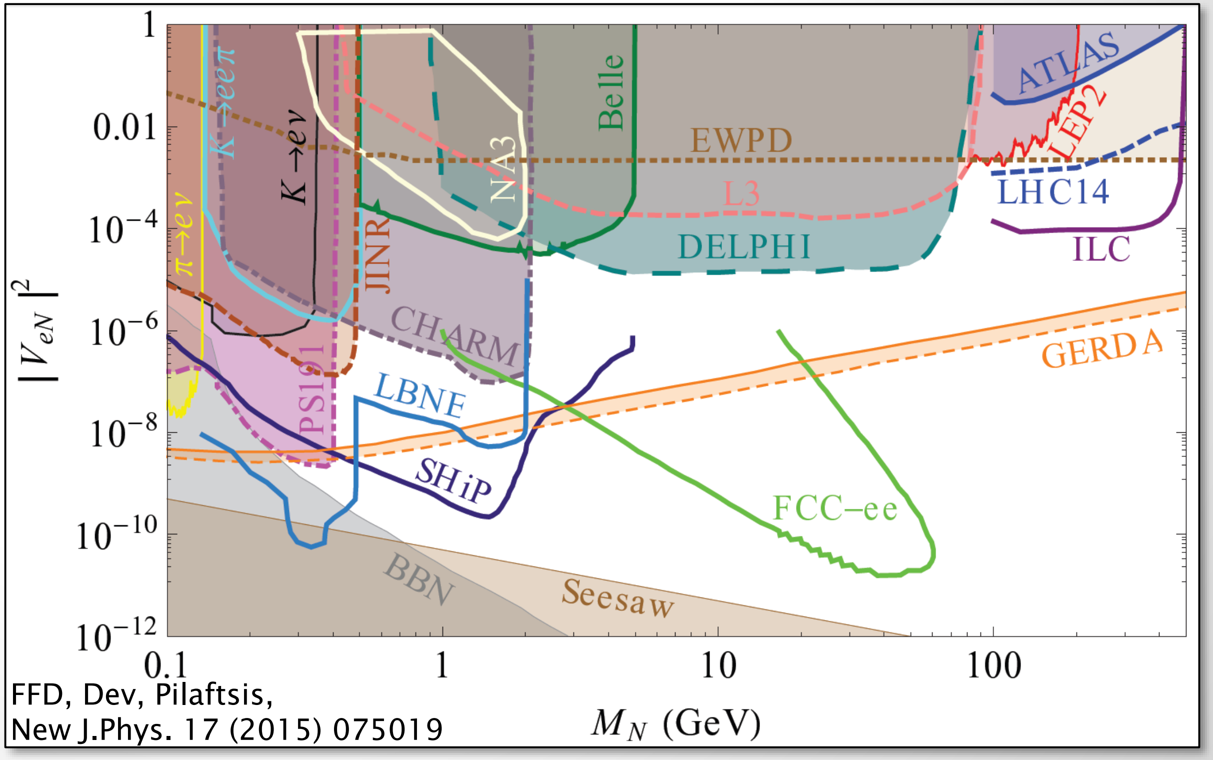
Heavy Sterile Neutrinos

- with mass larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\cancel{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\boxed{\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}}} \rightarrow \left\langle \frac{1}{M_N}\right\rangle_{\beta\beta}$$

- Nuclear matrix elements change
  - Short-range operator
- Many other probes





FFD, Dev, Pilaftsis,
New J.Phys. 17 (2015) 075019

Nuclear Matrix Elements

- Hadronic current

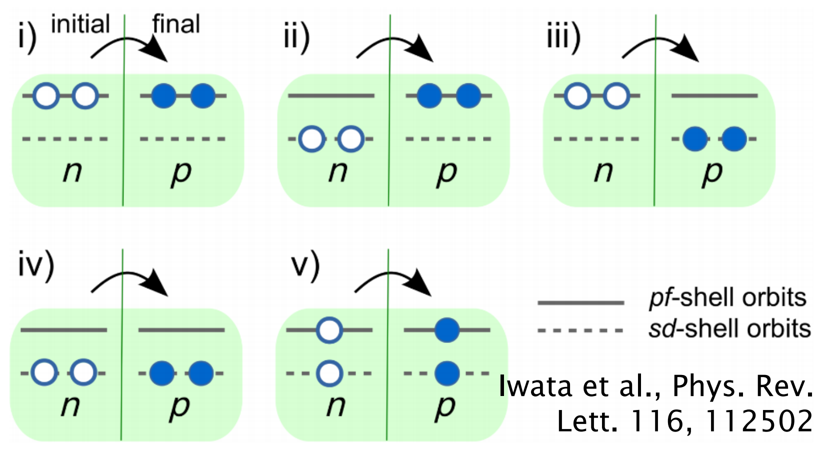
$$J^\mu(q) = g_V\gamma^\mu - g_A\gamma^\mu\gamma^5 + \frac{ig_M}{2m_N}\sigma^{\mu\nu}q_\nu - g_P\gamma^5 q^\mu$$

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

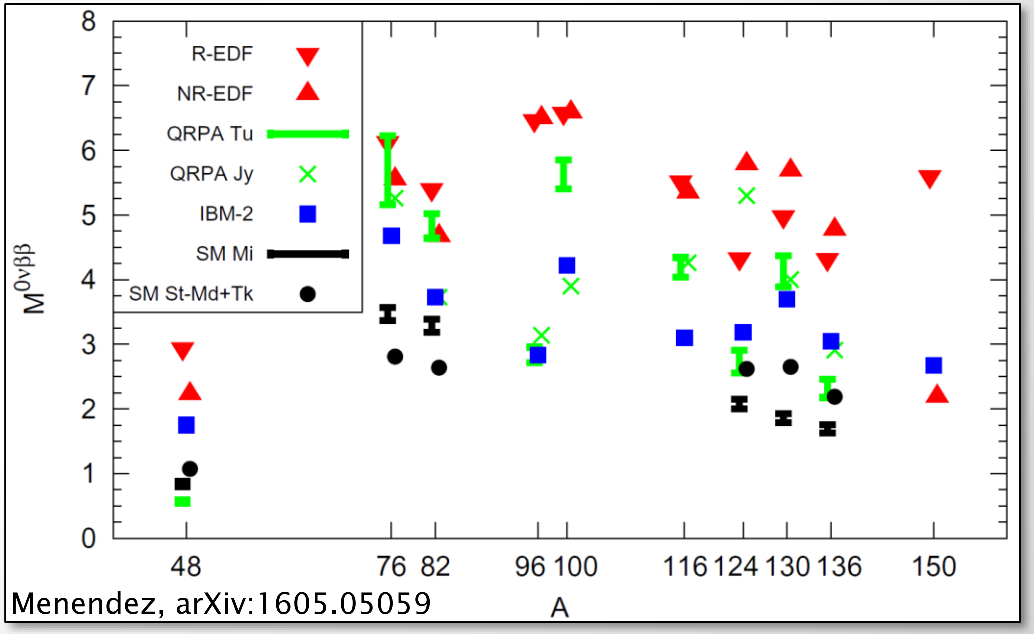
$$M^{0\nu} = g_A^2\left(M_{GT} - \frac{g_V^2}{g_A^2}M_F + M_T\right)$$

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

IBM-3 MCSM GFMC IBM NCSM NR-EDF BCS ISM IBM-1 EDF QRPA IMSRG HFB CCEI GCM RPA R-EDF USDB abinitio IBM-4 IBM-2 RQRPA



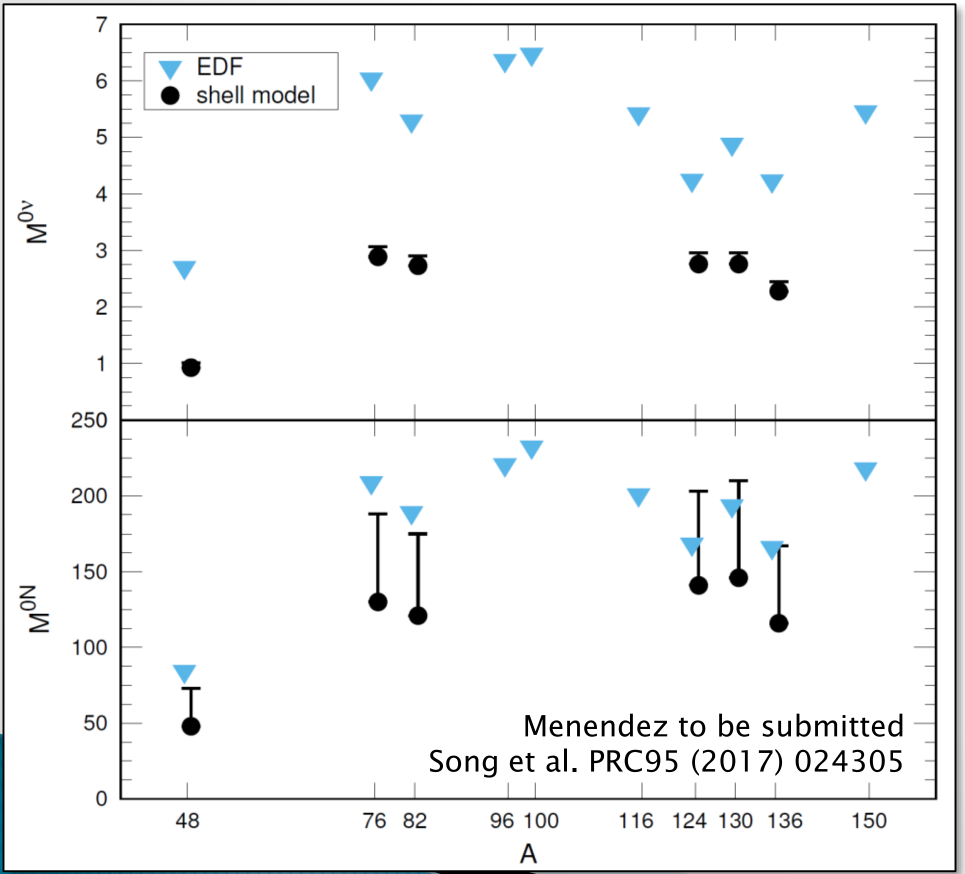
Iwata et al., Phys. Rev. Lett. 116, 112502



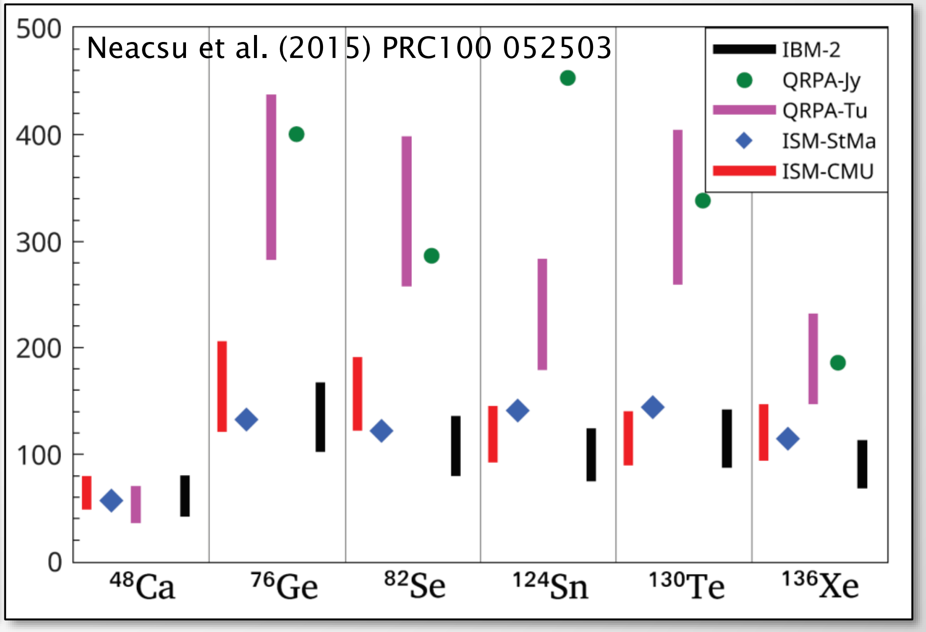
Menendez, arXiv:1605.05059

Nuclear Matrix Elements

- Heavy Neutrino Exchange
  - NMEs less uncertain?
  - Talk by J. Menendez at INT Seattle



Menendez to be submitted
Song et al. PRC95 (2017) 024305



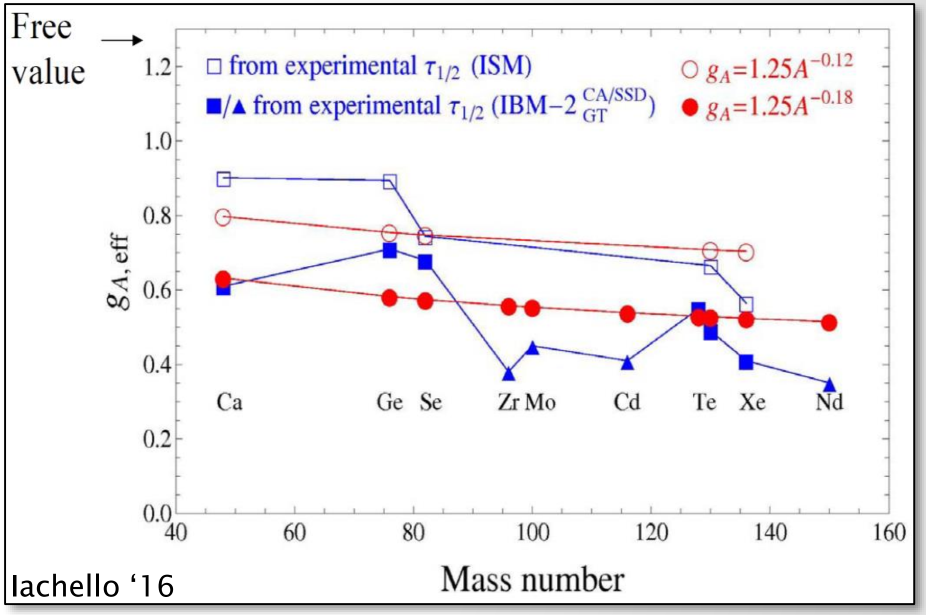
Neacsu et al. (2015) PRC100 052503

Quenching of g_A?

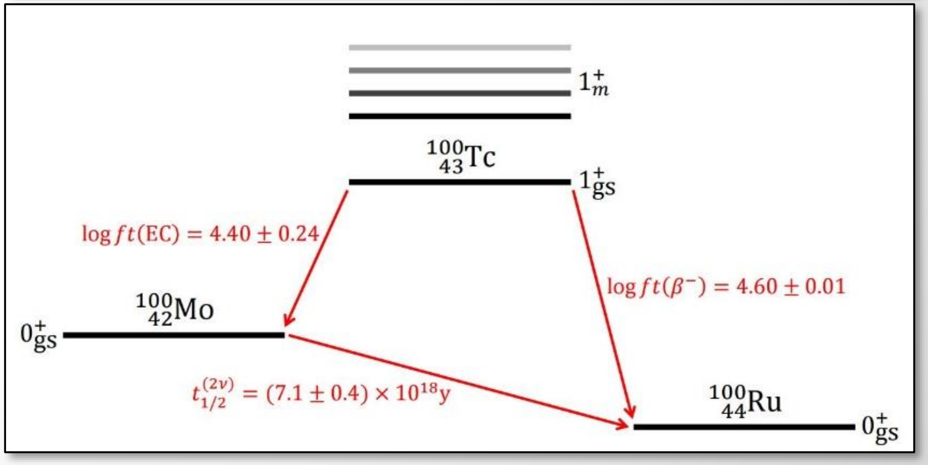
- Nuclear matrix element

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

- Axial-vector coupling g_A
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of 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

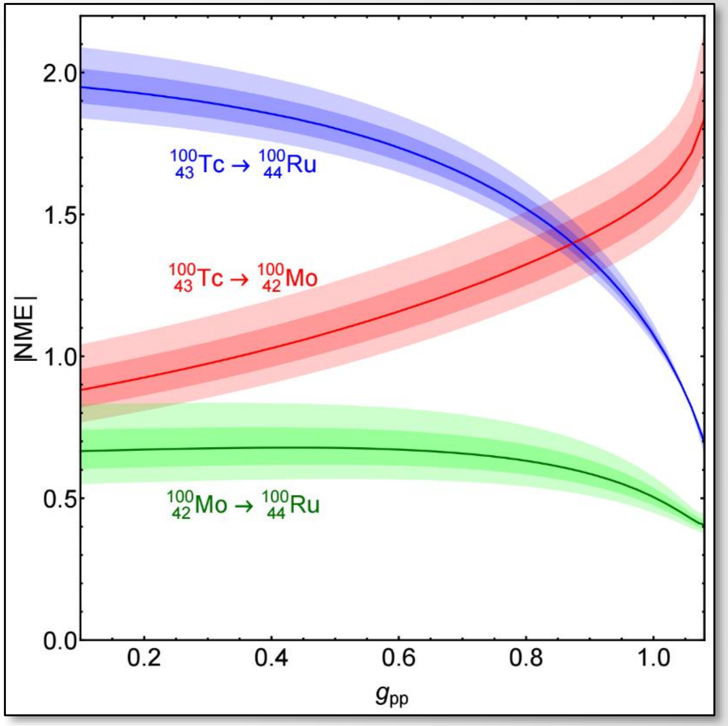


Quenching of g_A?

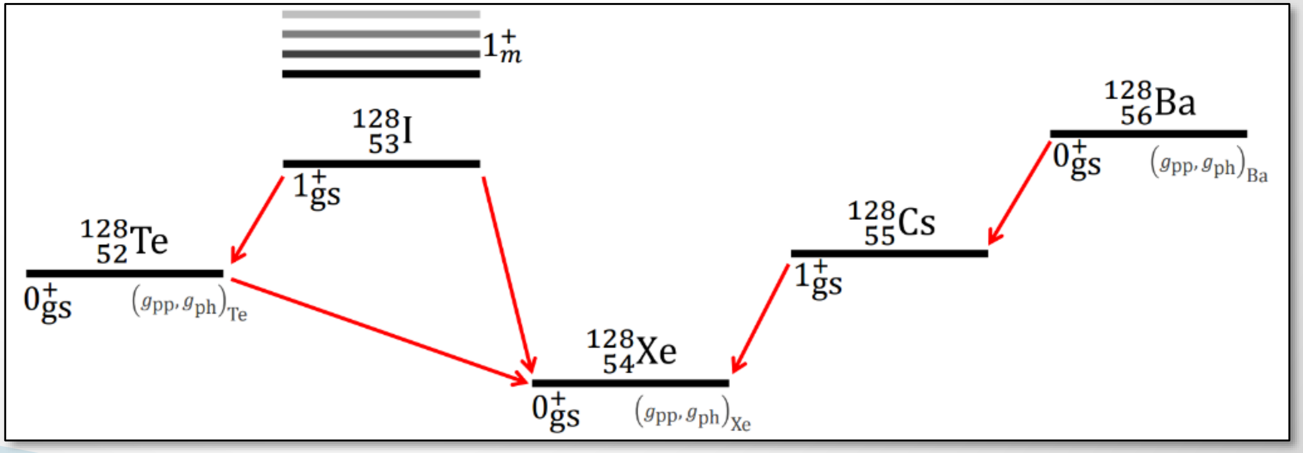
- Comparison with measured single beta / electron capture rates
  - Fit of model parameters g_A and g^i_{pp} (per even-even isotope)

$$\log ft = \log_{10}\left(f_0 t_{1/2}[s]\right) = \log_{10}\left(\frac{6147}{B_{GT}}\right)$$

$$B_{GT} = \frac{g_A^2}{2J+1}\left|M_{GT}(g_{pp}, g_{ph}\right|^2$$

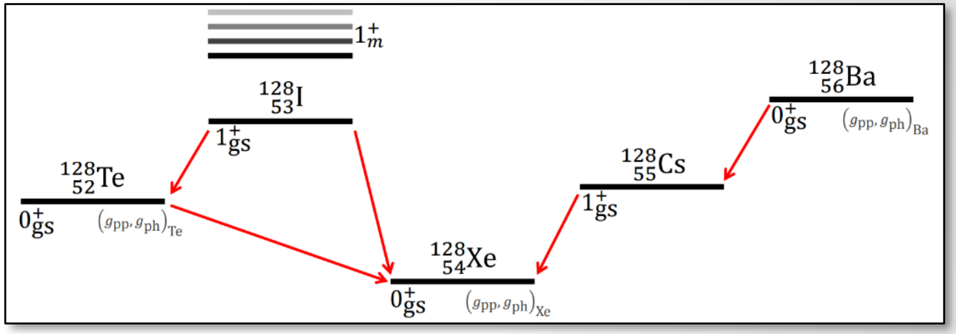


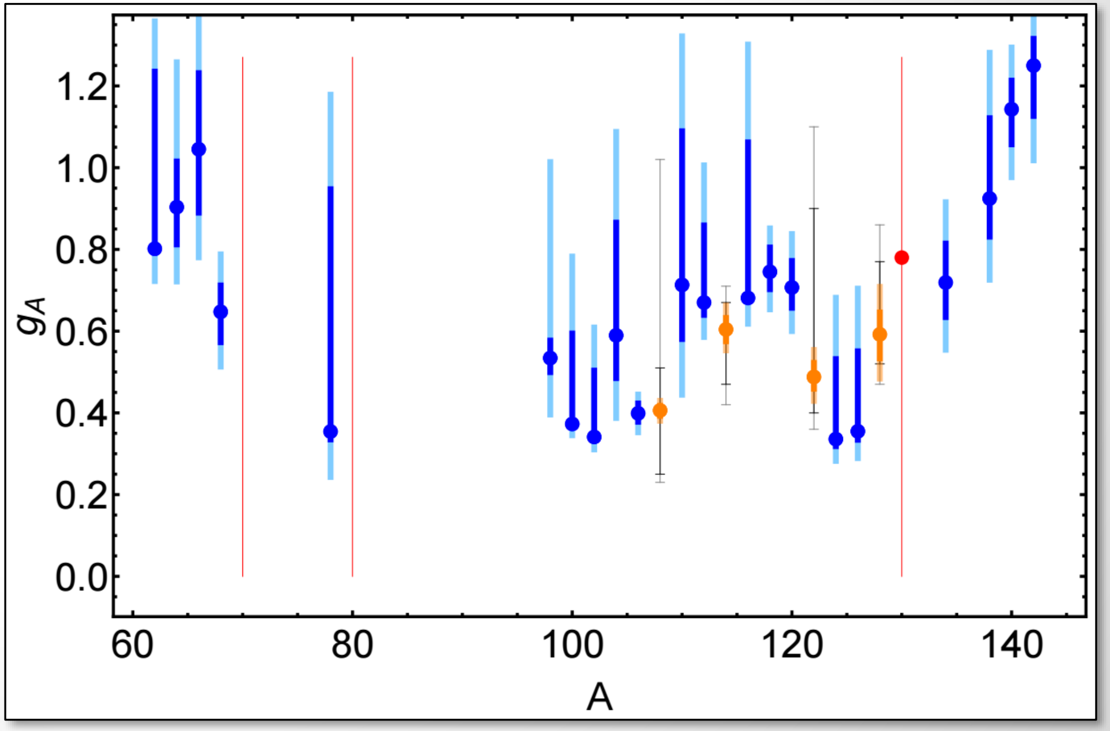
FFD, Suhonen, Phys. Rev. C 94 (2016) 5, 055501



Quenching of g_A?

- Comparison with measured single beta / electron capture rates
  - Fit of model parameters g_A and g^i_{pp} (per even-even isotope)
  - Taking into account all isotopes
  - Comparison with $2\nu\beta\beta$
  - Quenching of g_A (mass number dependent), including large errors





FFD, Suhonen, Phys. Rev. C 94 (2016) 5, 055501

Quenching of g_A?

- Single beta / EC / $2\nu\beta\beta$ analysis relevant for $0\nu\beta\beta$?

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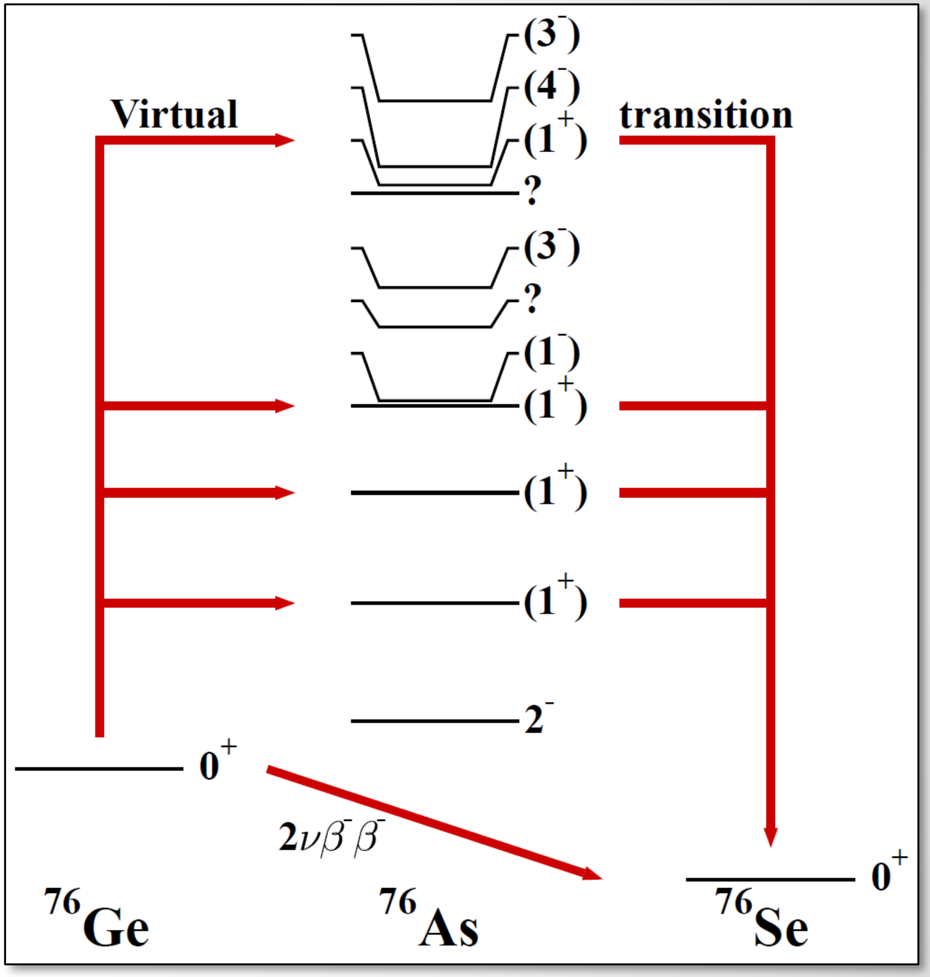
Unclear!

- Processes different at nucleon level
- Probing different transitions
- Incorporate more experimental information
  - Higher, forbidden beta decays
  - Charge exchange reactions
  - Muon capture



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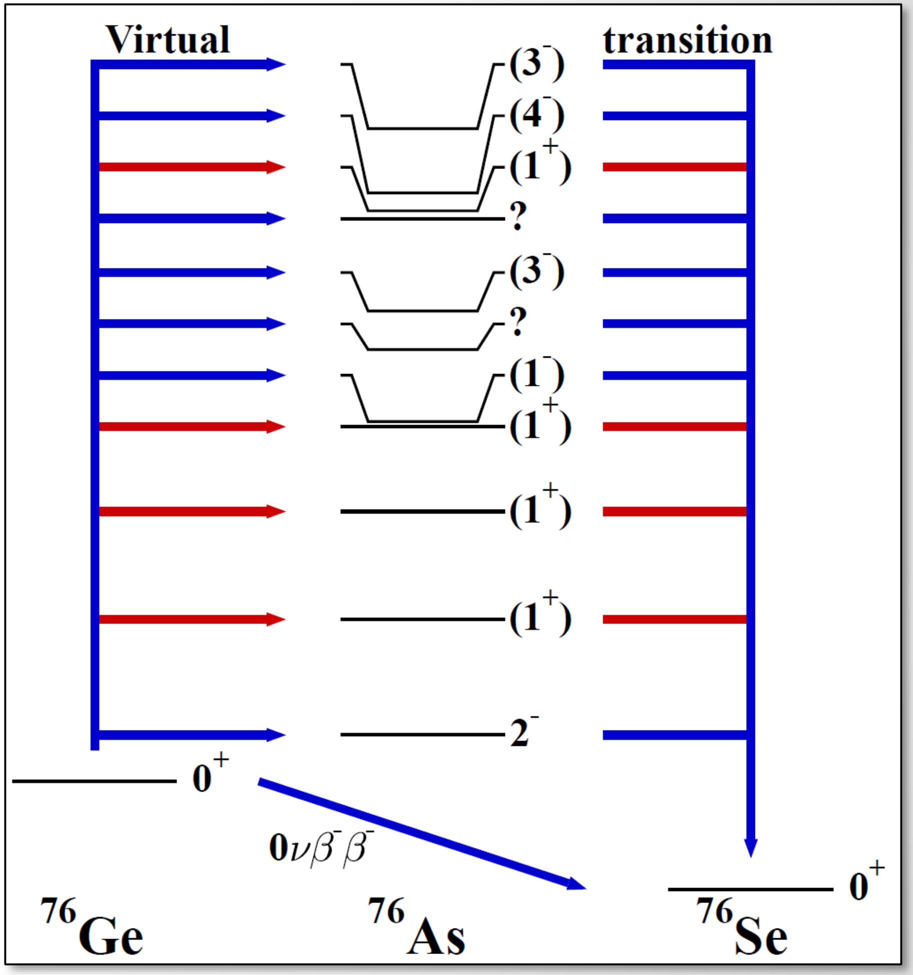
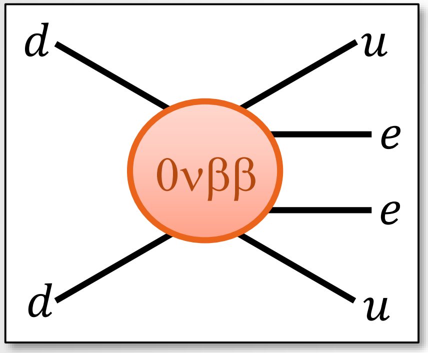


New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios



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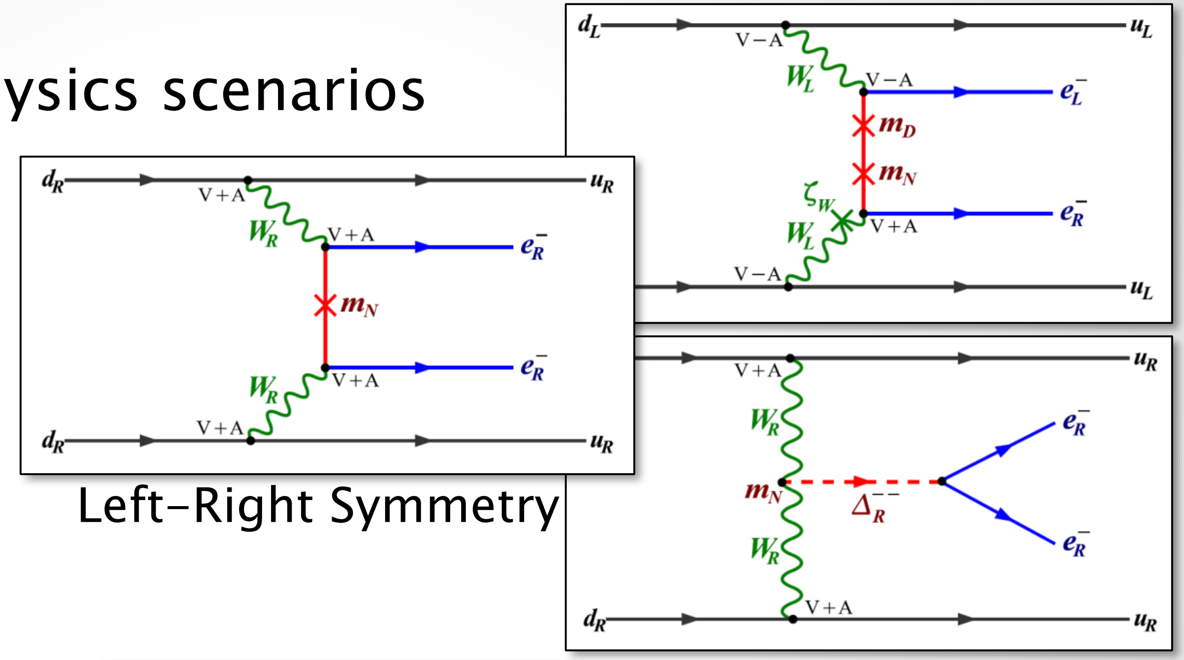
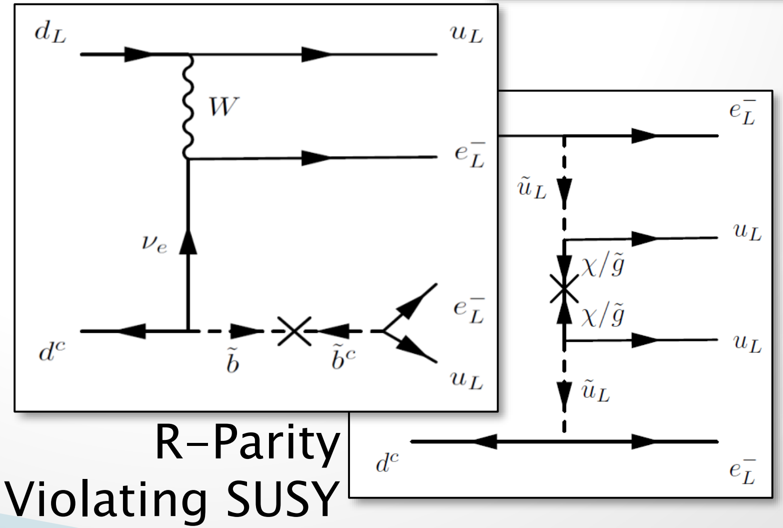
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^{2}$$



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

…

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

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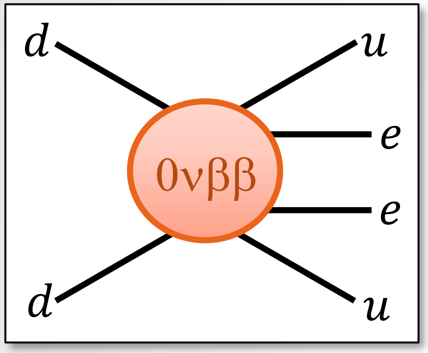

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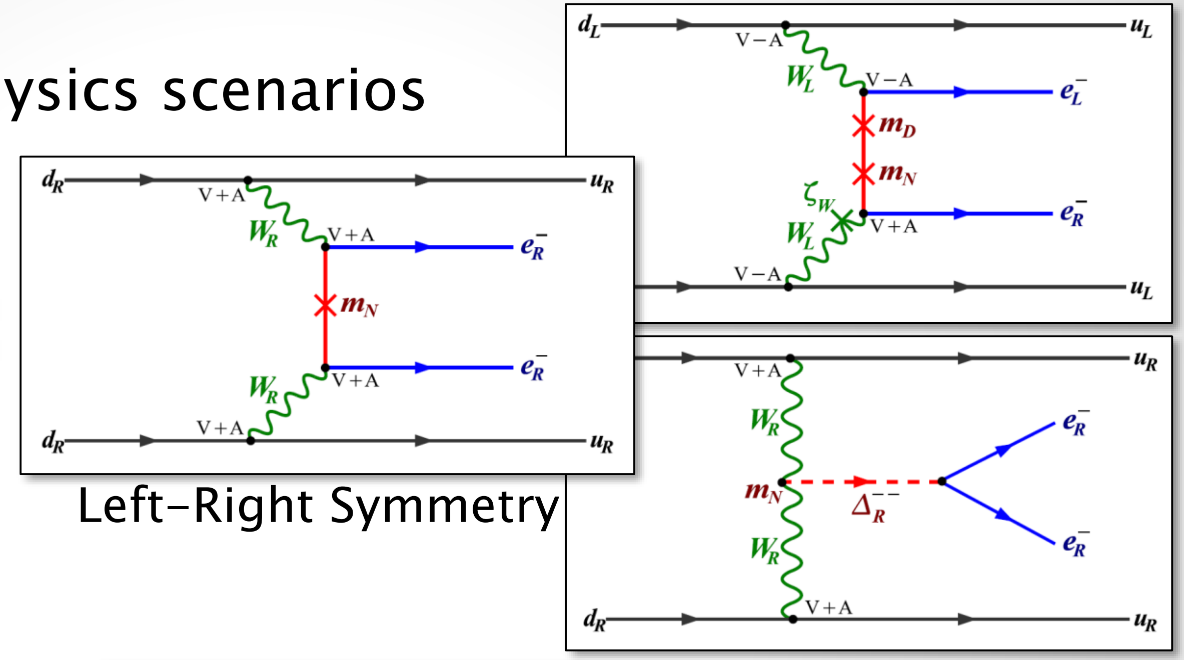
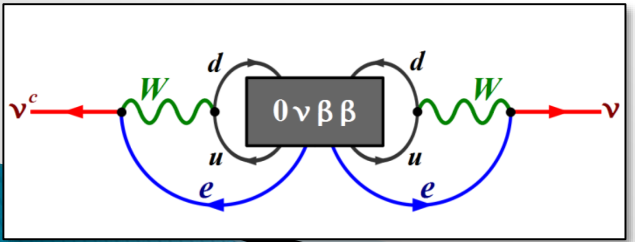
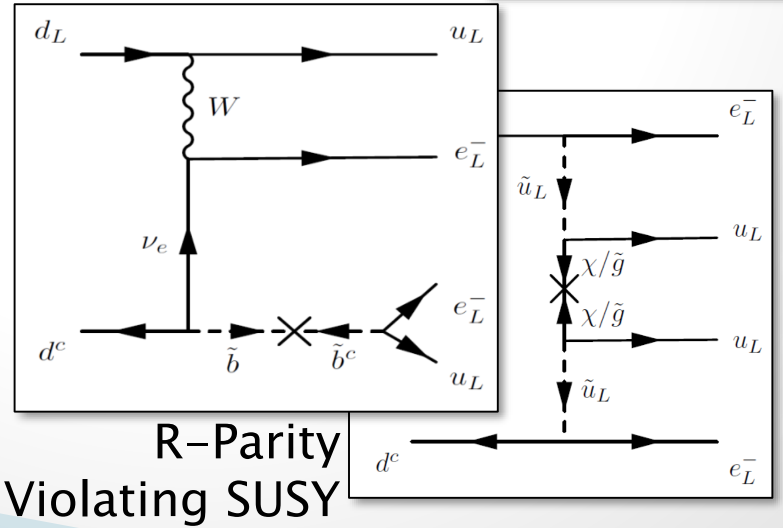


Left-Right Symmetry

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

- Neutrinos still Majorana





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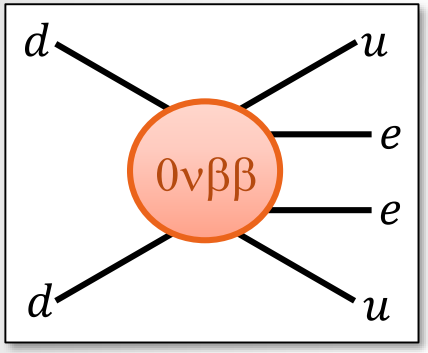
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry



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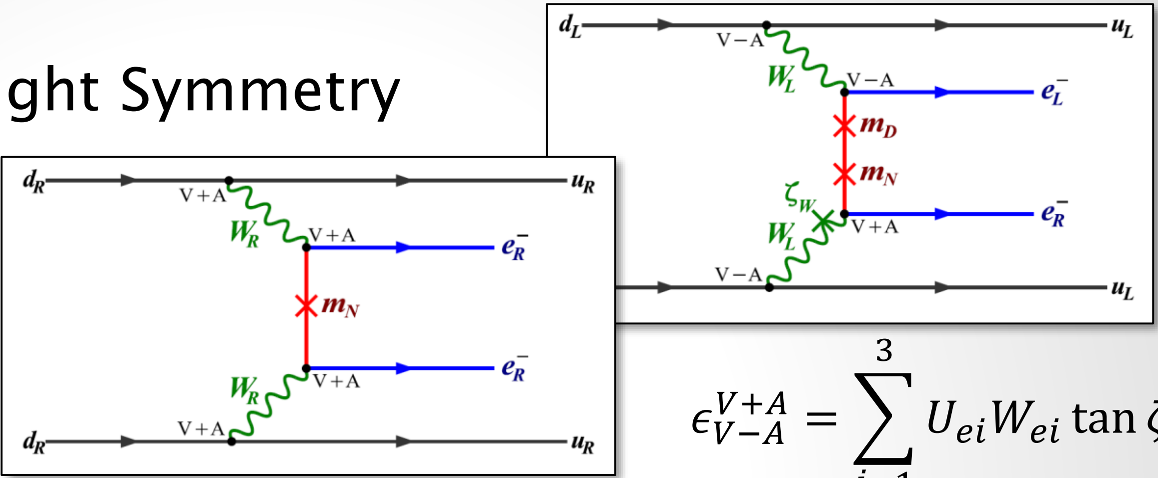


$$\boxed{T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2}$$

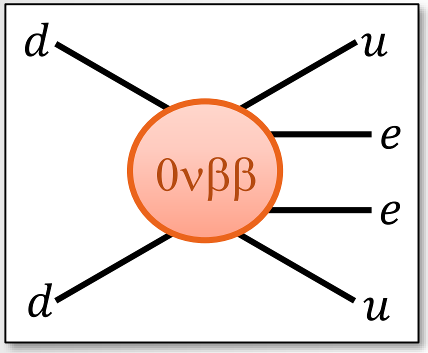
$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\,\mathrm{TeV})^5}$$

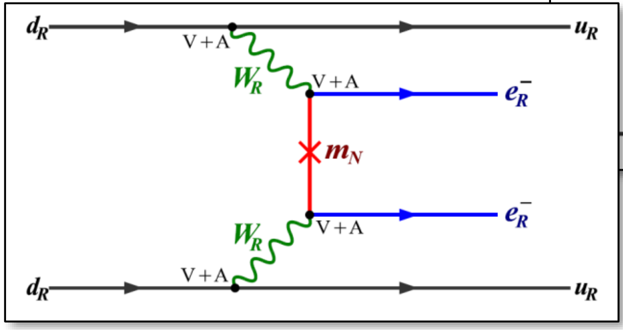
$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\,\mathrm{TeV})^3}$$

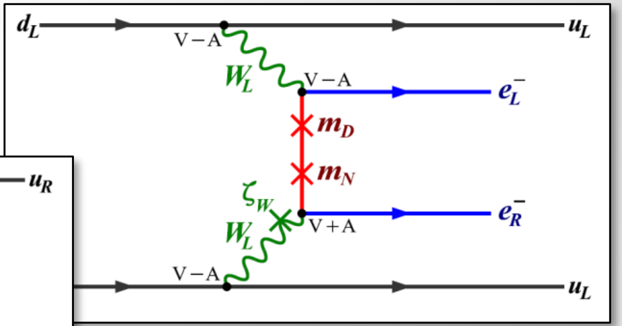
- $0\nu\beta\beta$ probes the TeV scale

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

- Examples in Left-Right Symmetry







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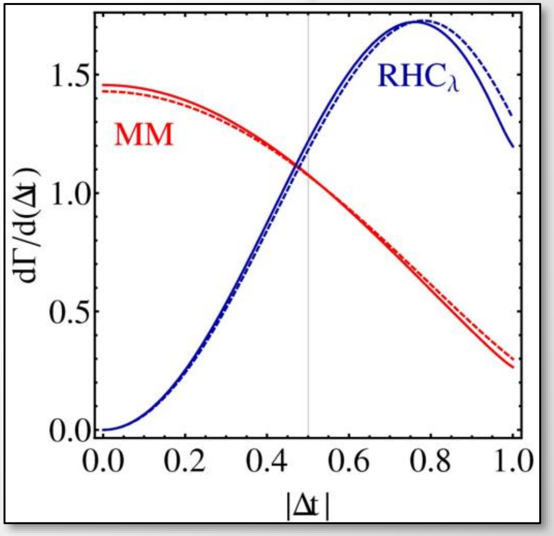
Modified angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06)

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

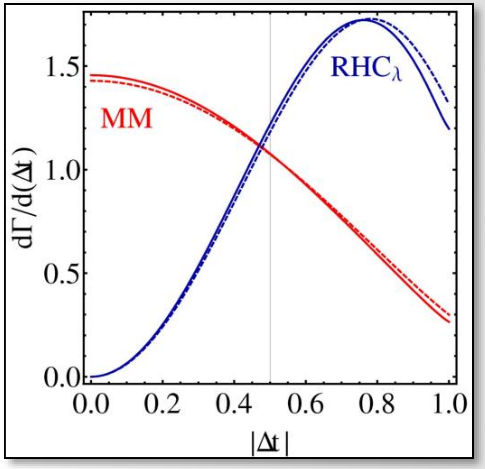


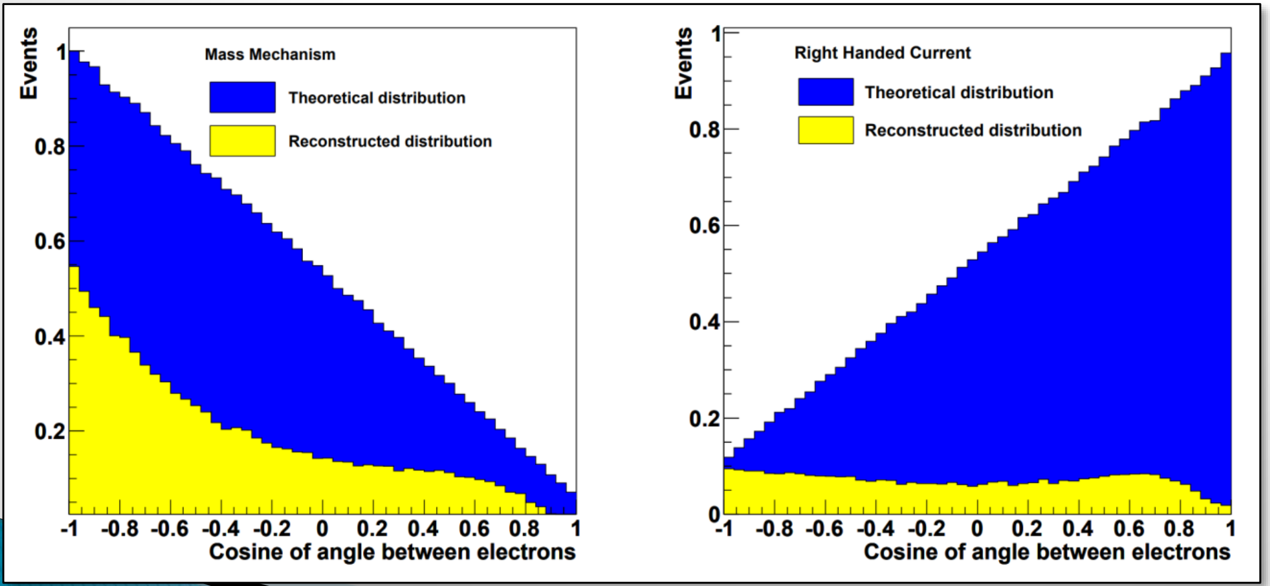
Disentangling New Physics Contributions

- Angular and energy distribution of emitted electrons
  (Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

$$\boxed{\frac{d\Gamma}{dE_{e_1}dE_{e_2}d\cos\theta} = \frac{\Gamma}{2}\left(1 - k\left(E_{e_1}, E_{e_2}\right)\cos\theta\right), \qquad -1 < k < 1}$$

  - Linear in $\cos\theta$
  - $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta\beta$ mechanism





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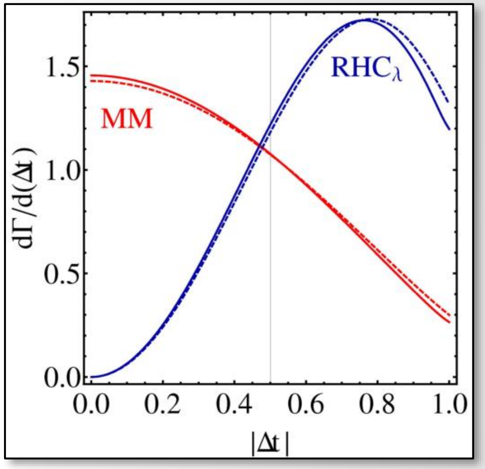

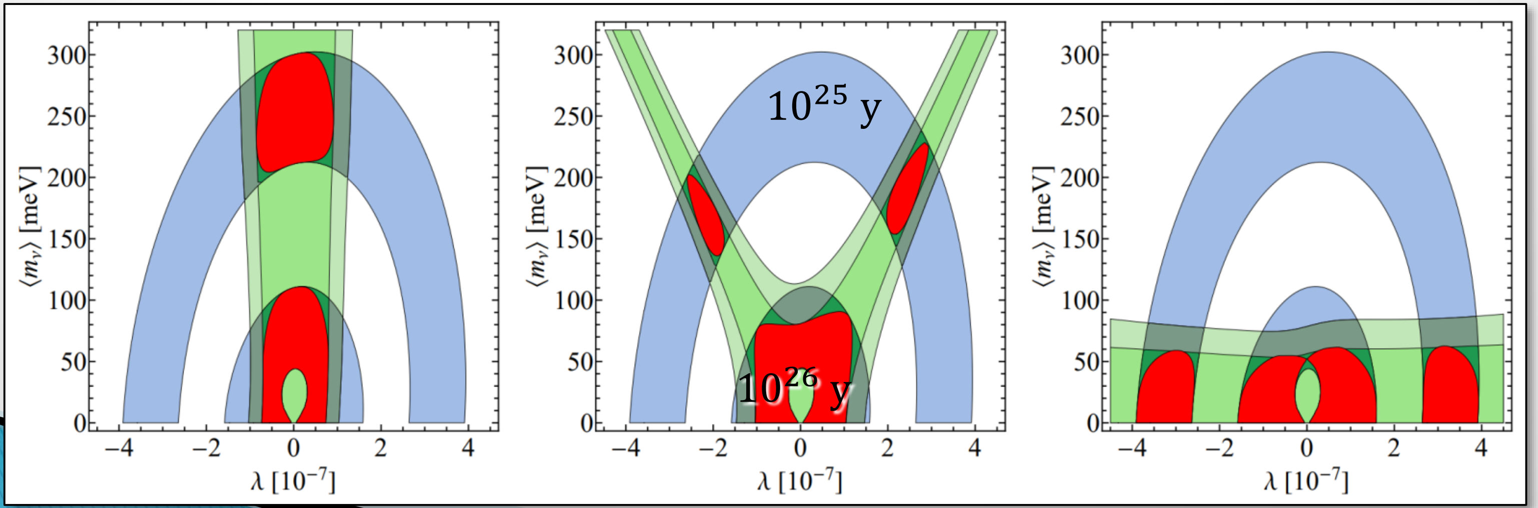

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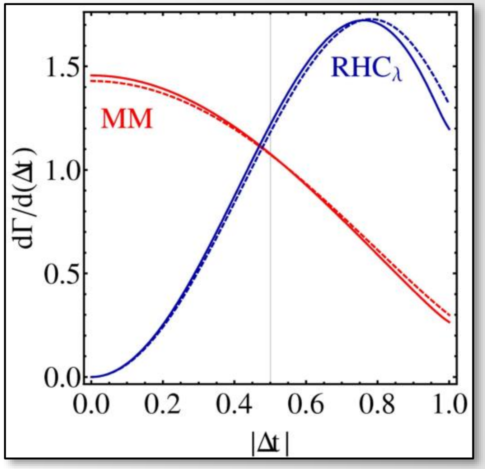
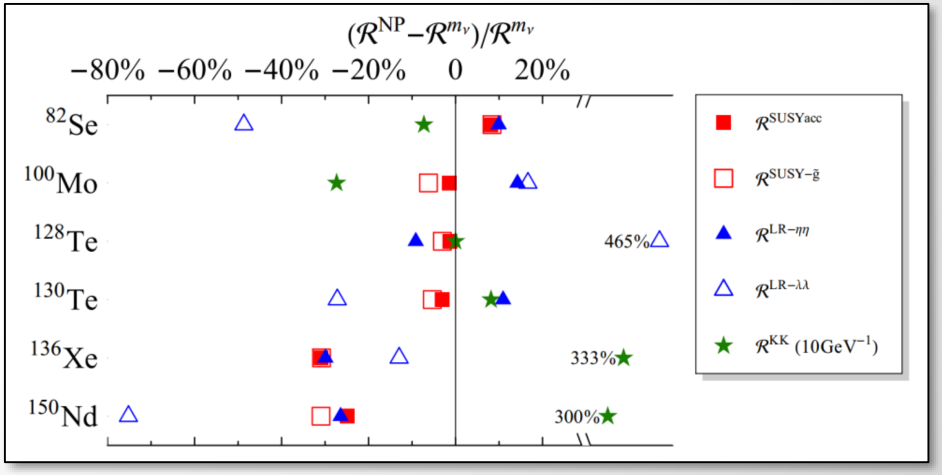


  - Linear in $\cos\theta$
  - $k(E_{e_1},E_{e_2})$ depends on $0\nu\beta\beta$ mechanism

- Comparison of $0\nu\beta\beta$ in multiple isotopes
  (FFD, Päs PRL 2007, Meroni et al. 2013)
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics
    (if one mechanism dominates)

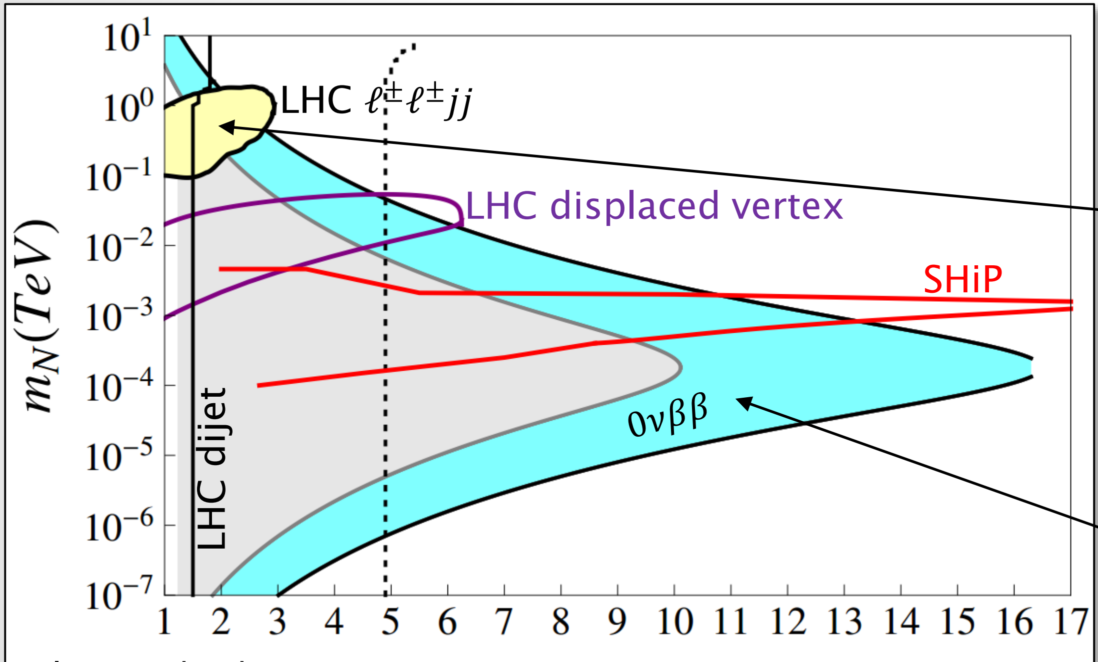
$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



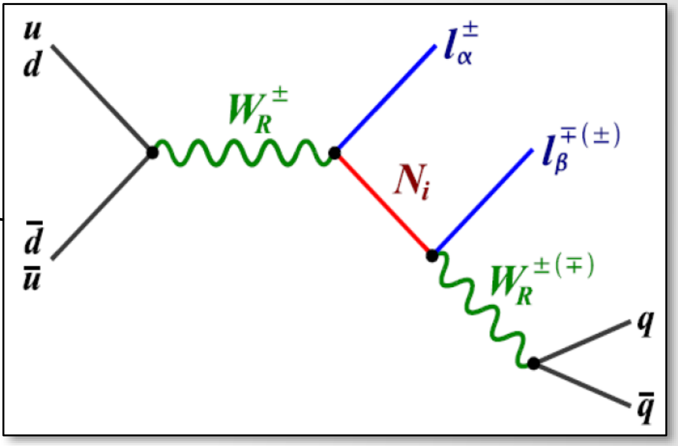
$0\nu\beta\beta$ vs LHC

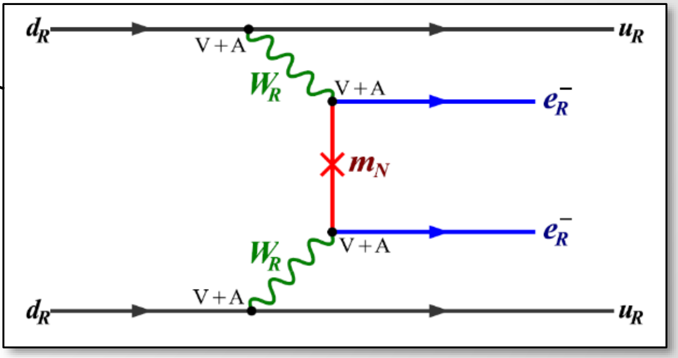
- Example of Left-Right Symmetry

(Mohapatra, Senjanovic ‘75)



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

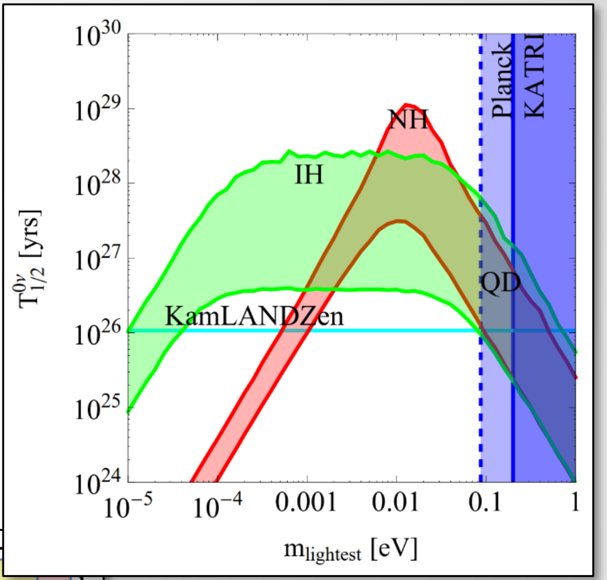




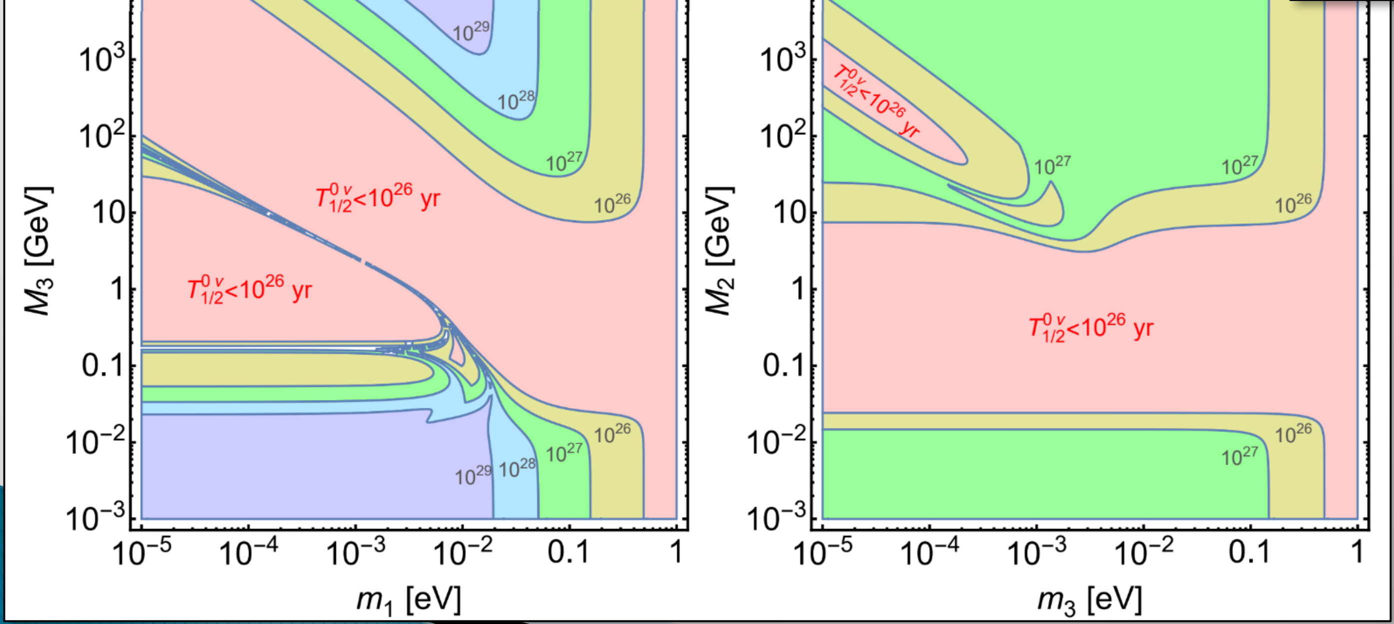
$0\nu\beta\beta$ vs LHC

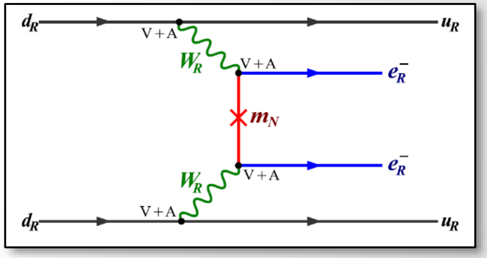
University College London

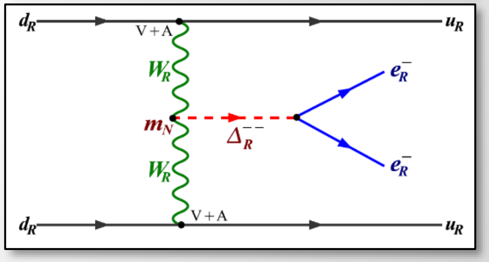
- Example of Left-Right Symmetry
  (Mohapatra, Senjanovic '75)
  - Correlation of contributions, e.g. Seesaw II dominance with $m_\nu \propto M_N$



FFD, Hati, Patra, Pritimita, Sarkar '17





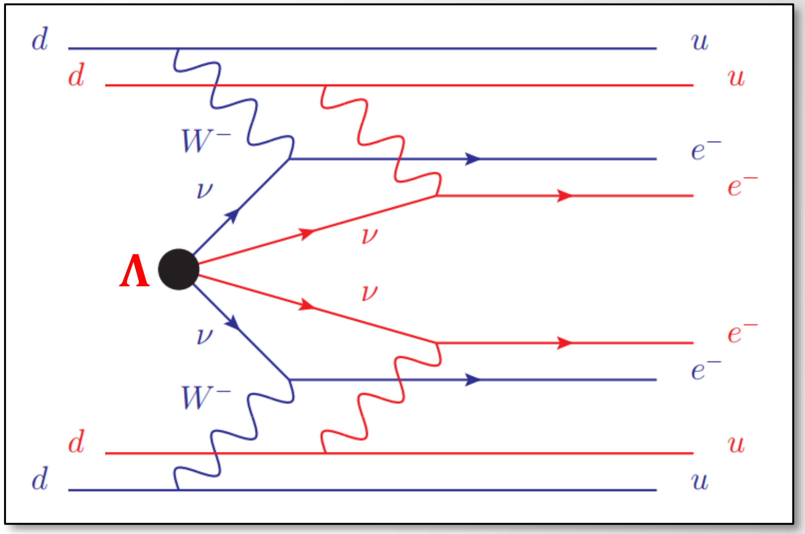


Quadruple $0\nu\beta\beta\beta\beta$

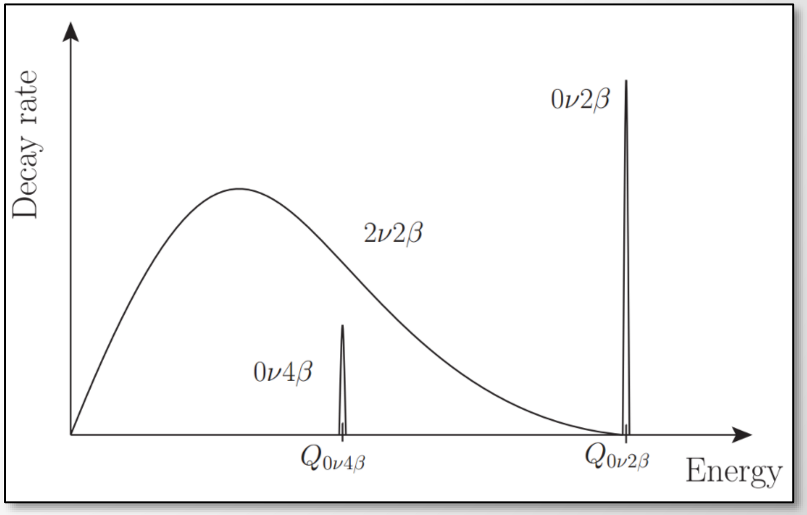
- $(A, Z) \rightarrow (A, Z+4) + 4e^-$
- Possible for new physics violating lepton number $\Delta L = 4$
(Heeck, Rodejohann, EP Lett. 103 (2013) 32001)
- Dirac neutrinos despite lepton number violation
- Challenging to probe

$$\frac{T_{1/2}^{0\nu4\beta}}{T_{1/2}^{2\nu2\beta}} \approx 10^{46}\left(\frac{\Lambda}{\mathrm{TeV}}\right)^4 > 120$$

NEMO-3



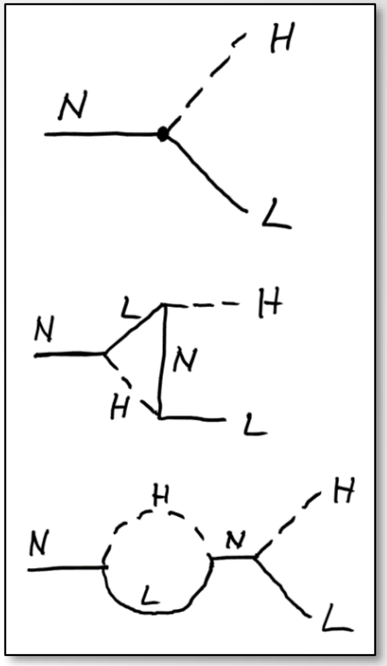
Heeck, Rodejohann,
EP Lett. 103 (2013) 32001



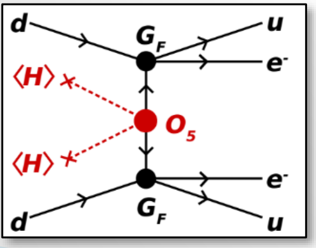
Baryon Asymmetry Generation and Washout

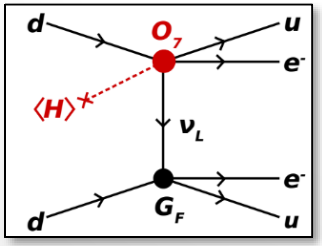
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

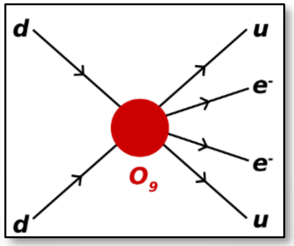
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

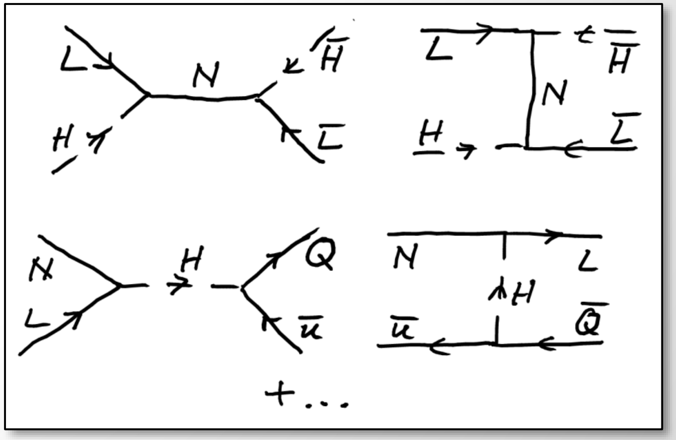


- What if we observe lepton number violating processes in $0\nu\nu\beta$?



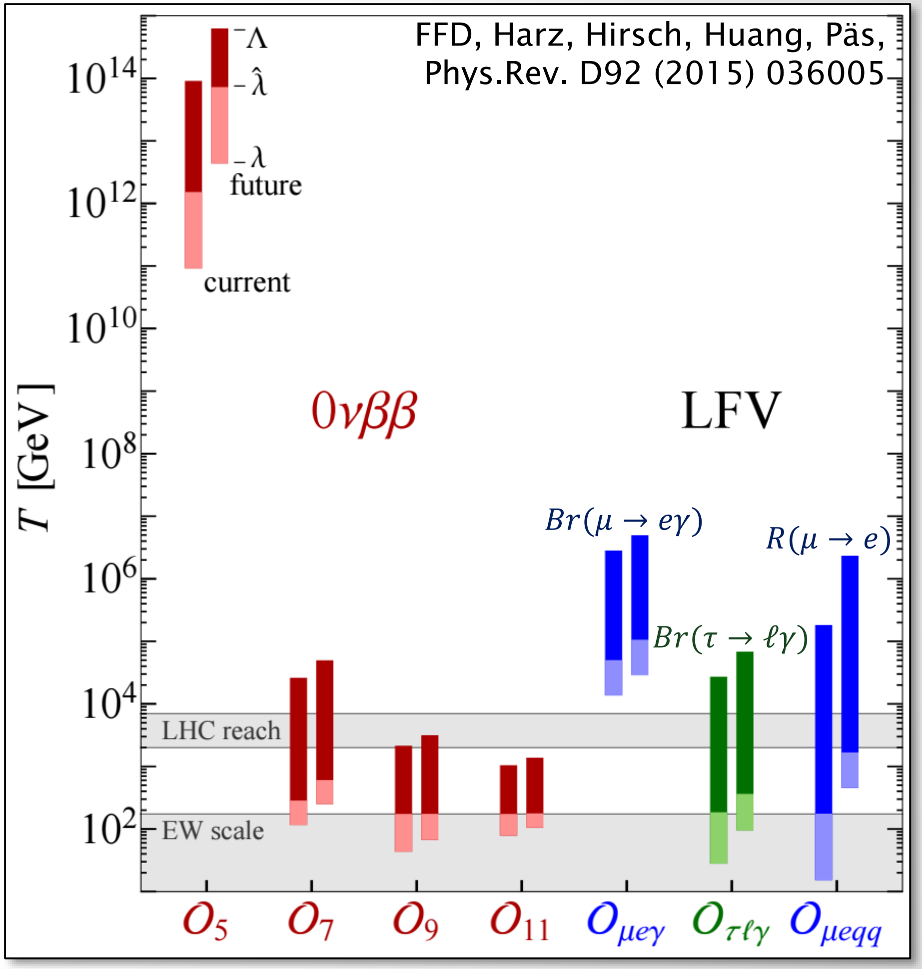






Baryon Asymmetry
Lepton Asymmetry Washout

- 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



FFD, Harz, Hirsch, Huang, Päs,
Phys.Rev. D92 (2015) 036005

Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Mechanism of neutrino mass generation? At what scale?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Discovery → Majorana ν → Physics near GUT scale? LNV @ TeV?
  - Exclusion → Dirac ν? → Fine-tuned SM?
- **Challenging nuclear physics**
  - Effort to calculate NMEs from first principles
  - Quenching (if any) needs to be understood quantitatively
- **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