UCL University College London

Neutrinoless Double Beta Decay and BSM Physics

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Dirac vs Majorana

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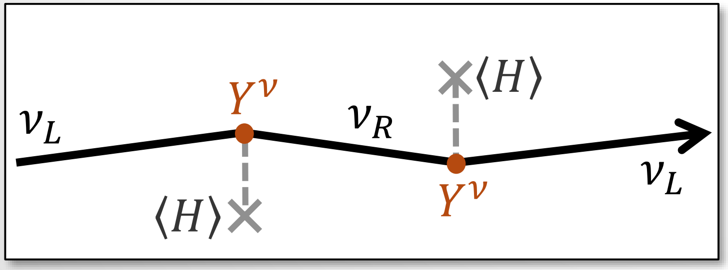
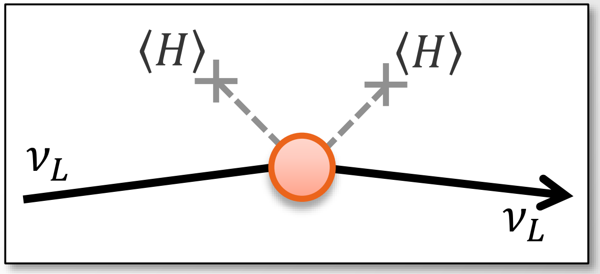
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

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

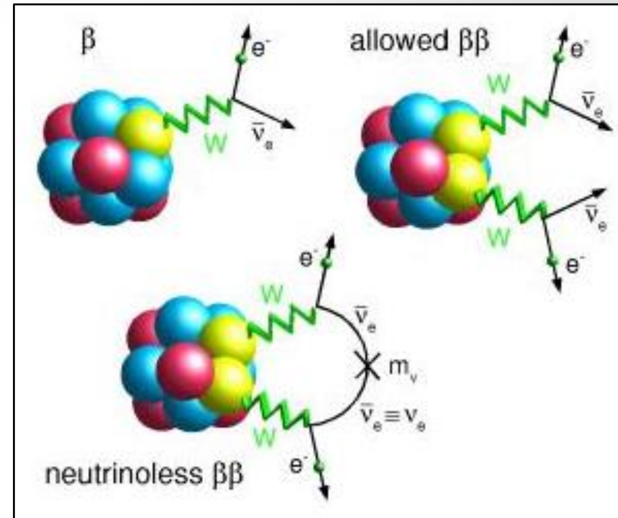


Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation



Absolute Neutrino Mass
Beta Decays

- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^{-} + \bar{\nu}_e$$
  - Tritium decay, KATRIN: $m_\nu \approx 0.2$ eV
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos



Absolute Neutrino Mass
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- Single beta c
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  - Tritium deca
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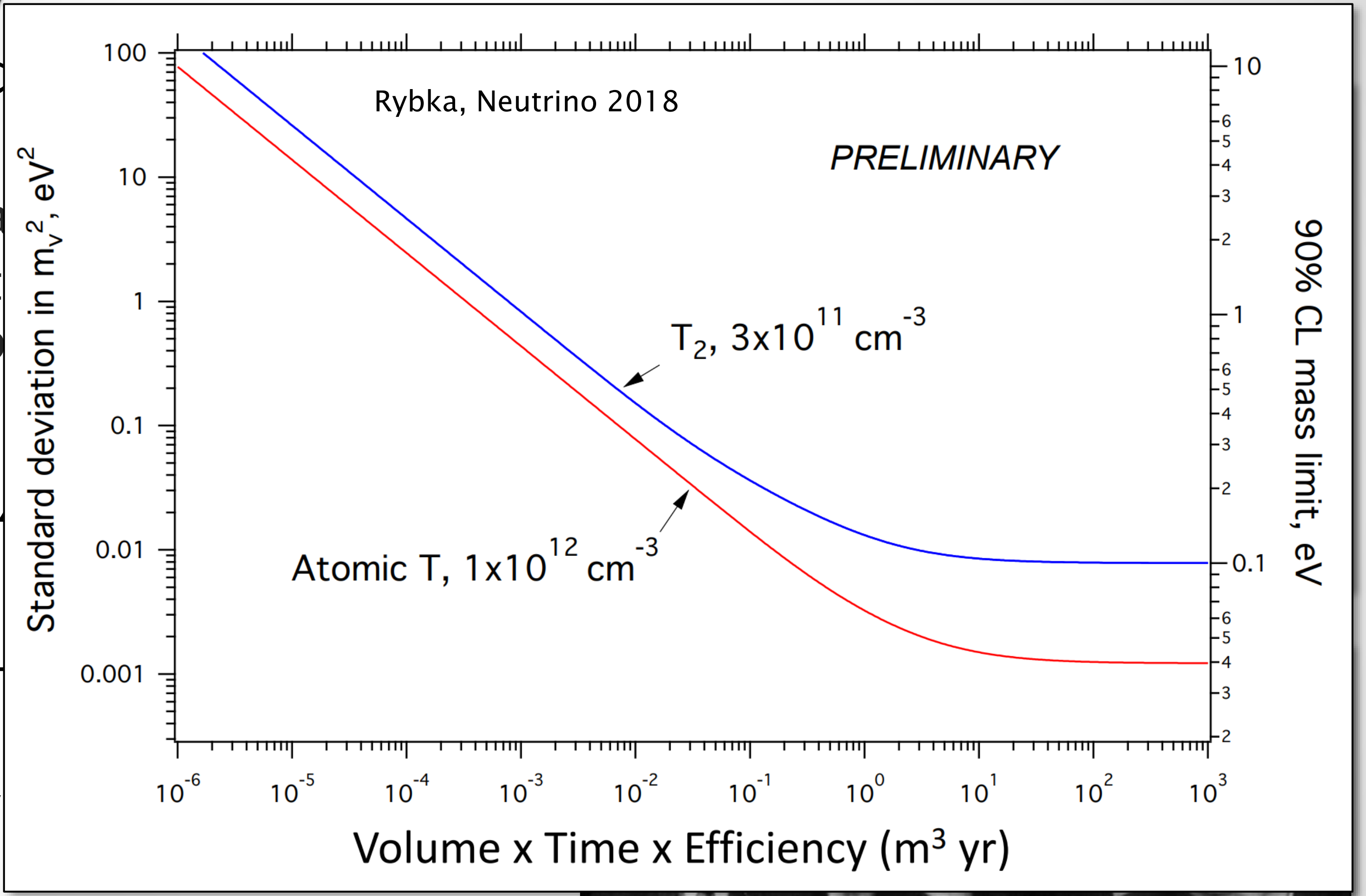
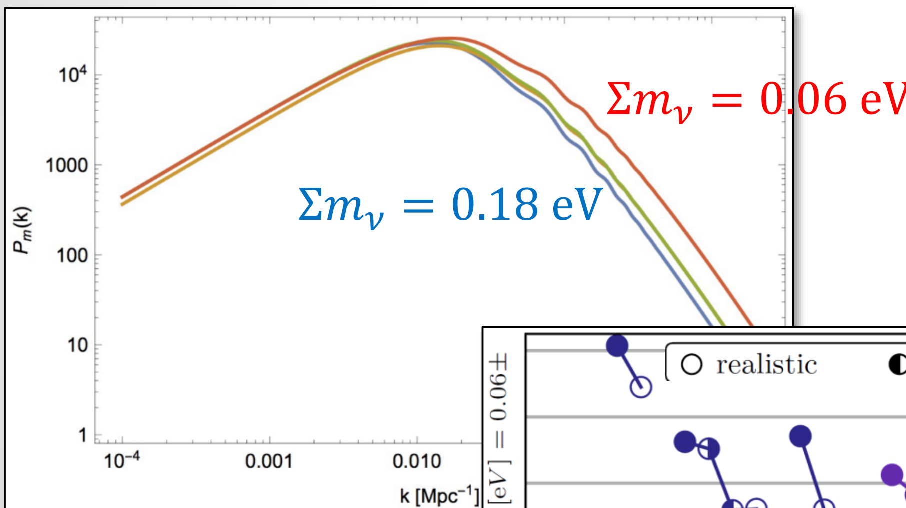
- Neutrinoless
  (A, Z) -
  - Violation of
  - Mediated by



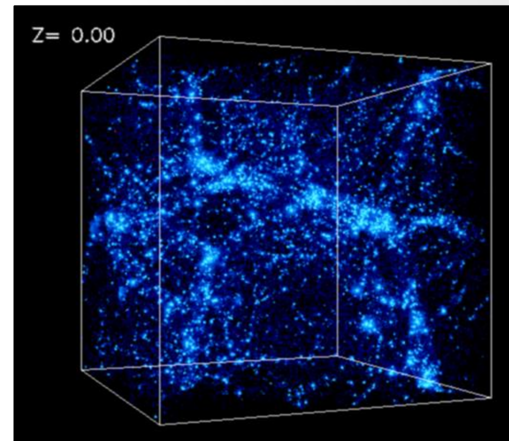
Absolute Neutrino Mass Cosmology

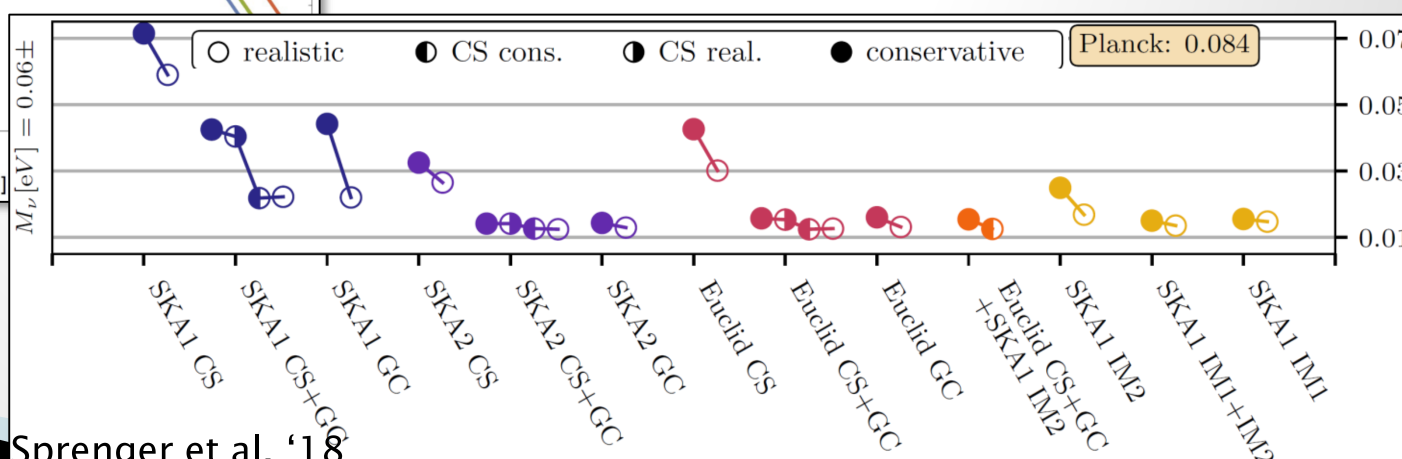
- Impact on large scale structures of the Universe
  - Light sterile neutrinos = extra DOFs of radiation
  - Sensitive to sum of neutrino masses

$$n_{eff} < 3.4, \quad \sum m_\nu < 0.15 - 0.25 \text{ eV}$$



Gerbino, Lattanzi '18



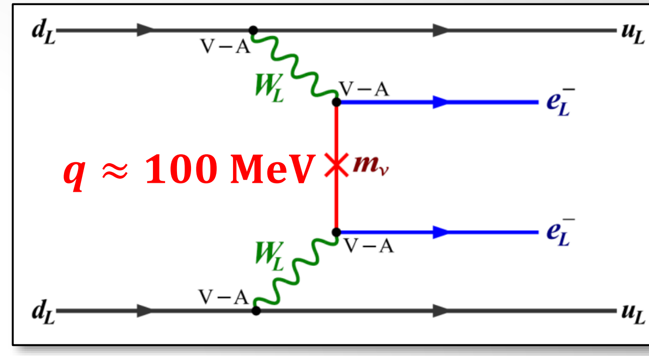


Sprenger et al. '18

$0\nu\beta\beta$

- Half-life

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



- Particle Physics

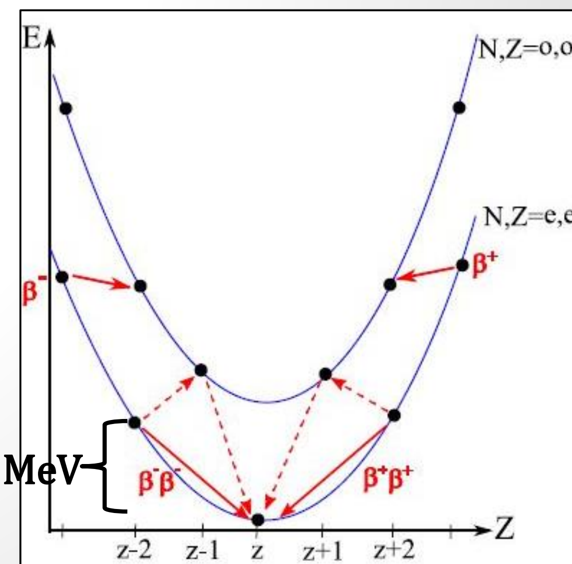
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

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

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

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

$Q \approx 2\text{–}4$ MeV



$0\nu\beta\beta$

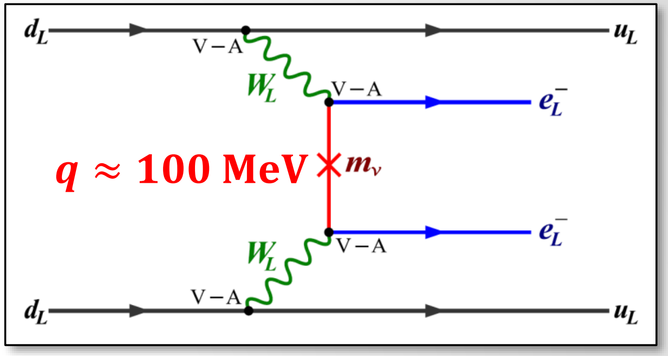
- Effective $0\nu\beta\beta$ Mass

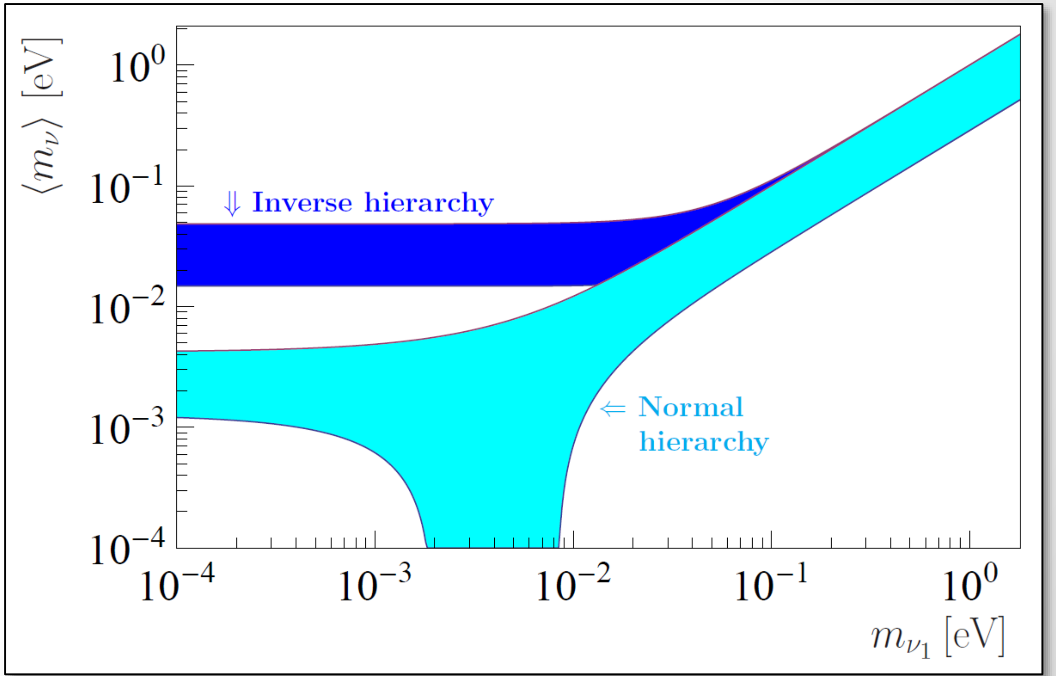
$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

- 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





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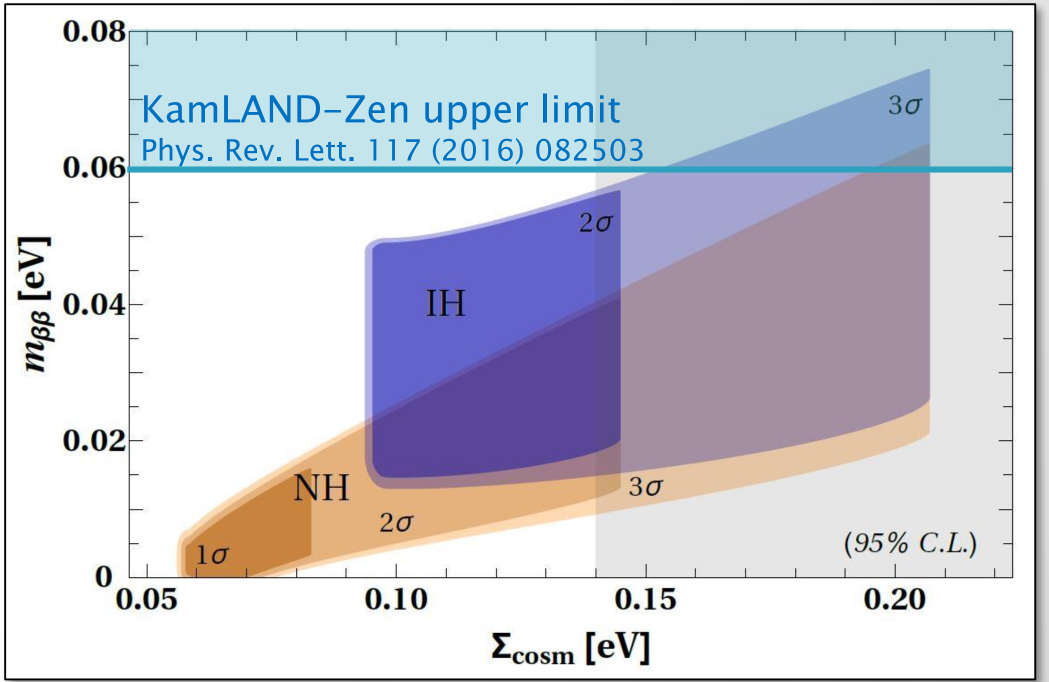

Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

$0\nu\beta\beta$

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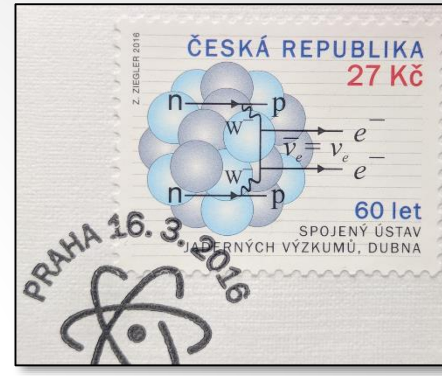
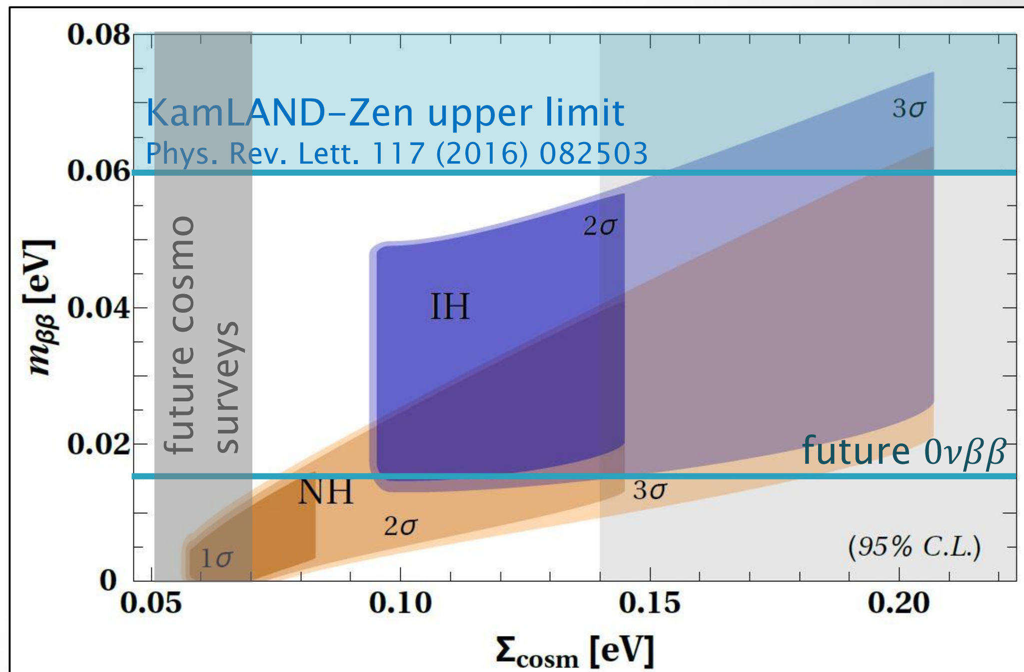
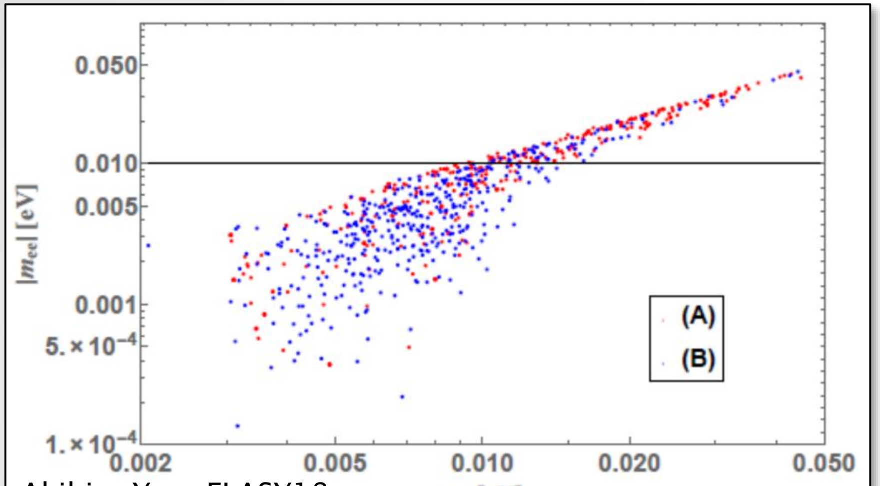




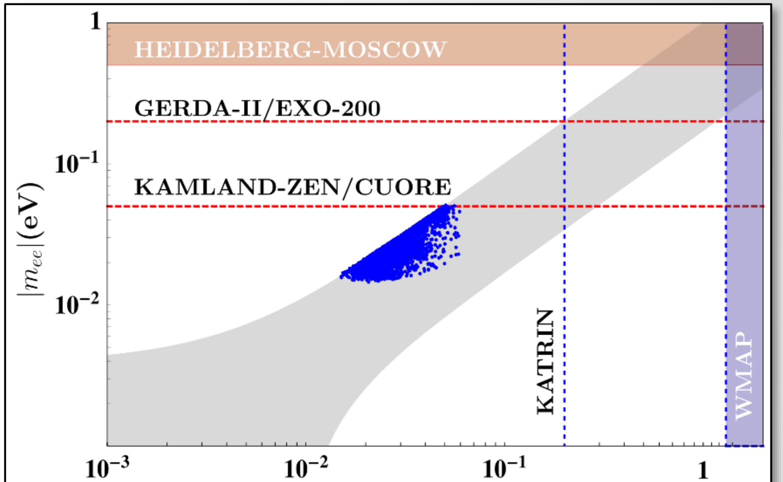
Dell'Oro, Marcocci, Viel, Vissani, Adv. High Energy Phys. (2016) 2162659

$0\nu\beta\beta$

Impact of Symmetries and Textures

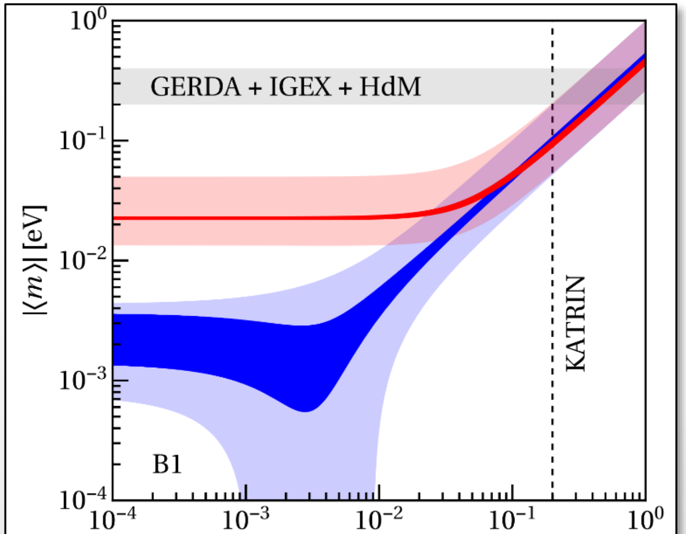


Akihiro Yuu, FLASY18

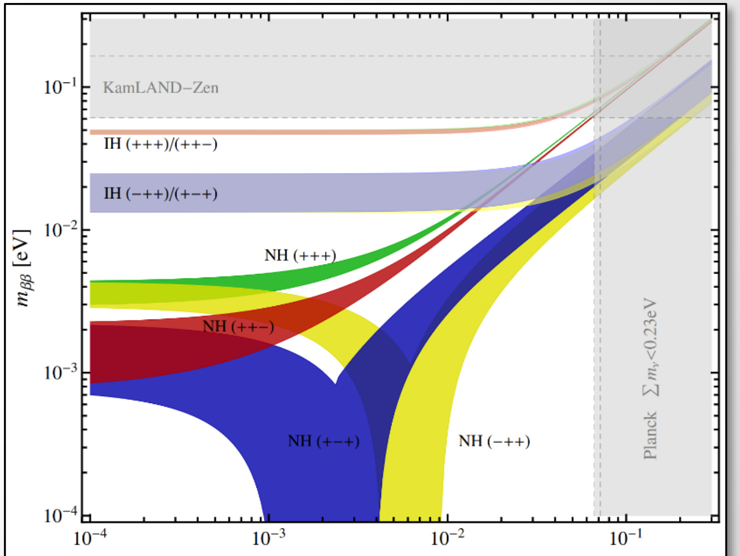


King et al. ‘13

- Focus on testable range and interplay with cosmology priors?

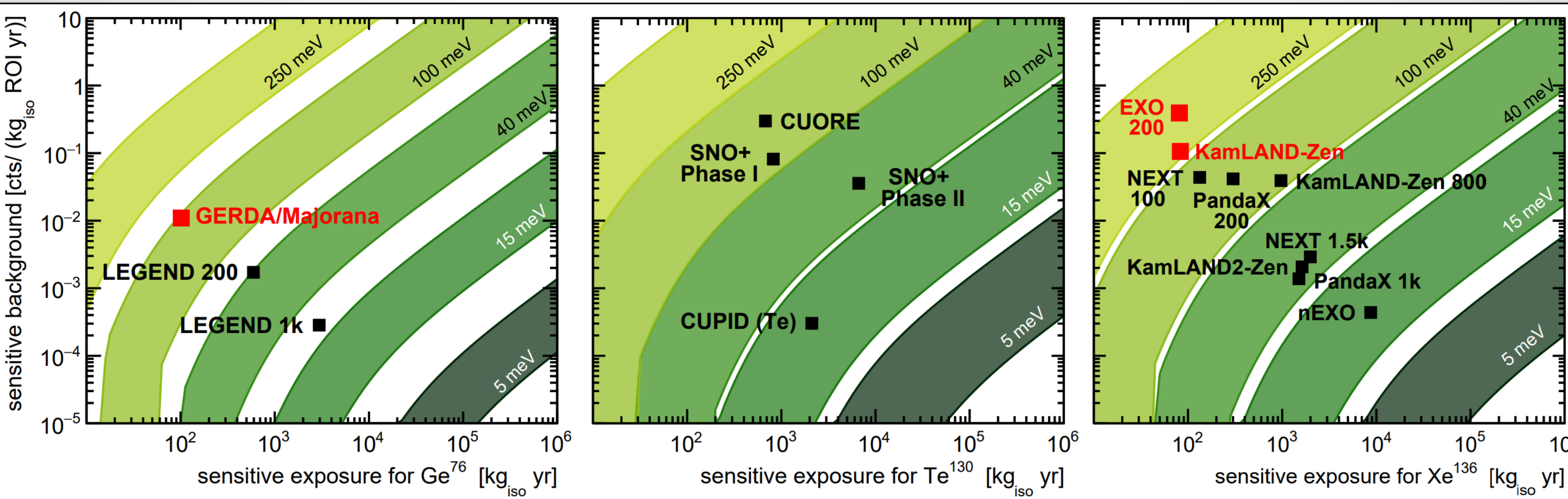


Girardi et al. ‘16



Mohapatra, Nishi ‘15

$0\nu\beta\beta$
Experimental Sensitivity



Agostini, Benato, Detwiler
arXiv:1705.02996

Nuclear Matrix Elements

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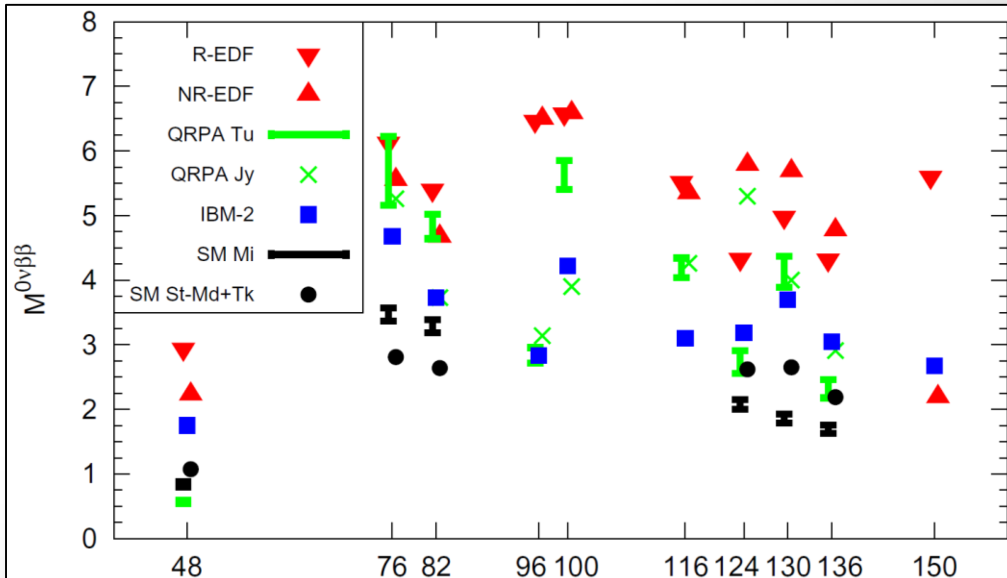
- Hadronic current

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

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

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

  - Dependence on isotope and operator
  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models



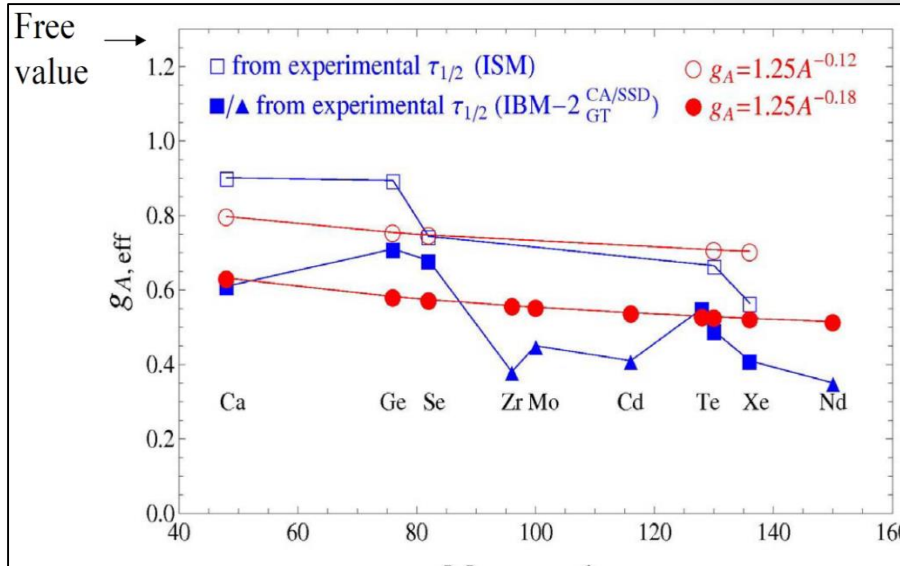
Menendez, arXiv:1605.05059

Quenching of g_A?

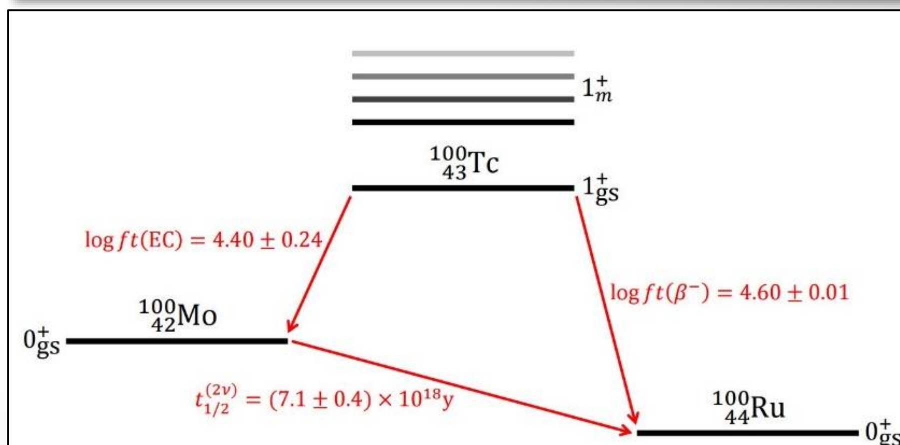
- Nuclear matrix element

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

- 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 $0\nu\beta\beta$, strong reduction of sensitivity
  - Genuine effect or short-coming of models?



Iachello '16



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

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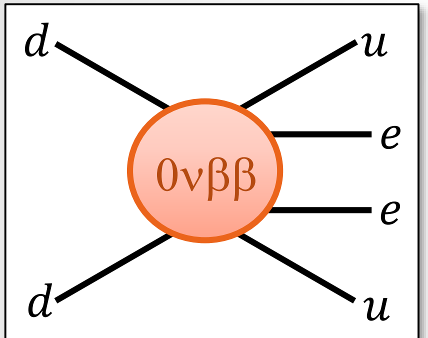
- Plethora of New Physics scenarios



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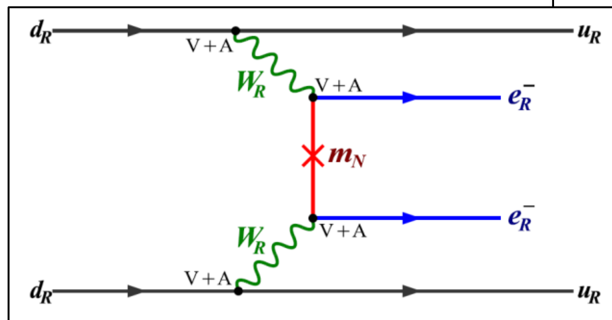
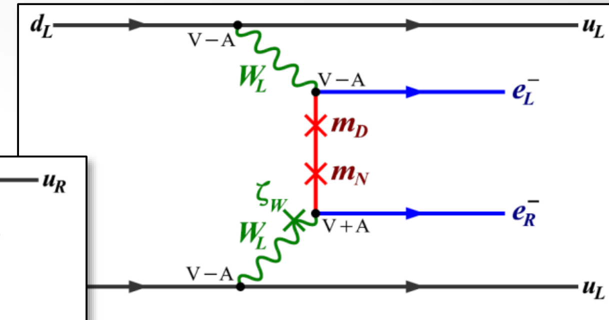
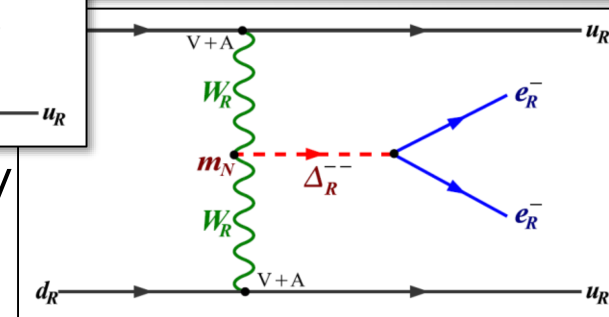
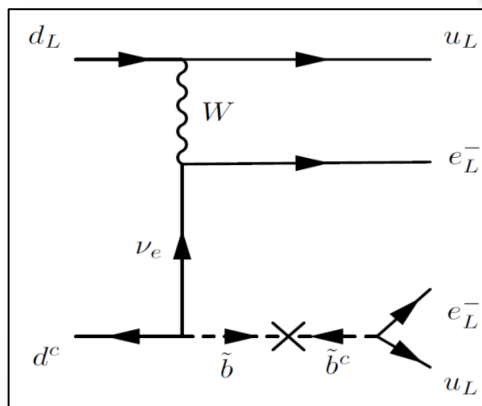
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2$$

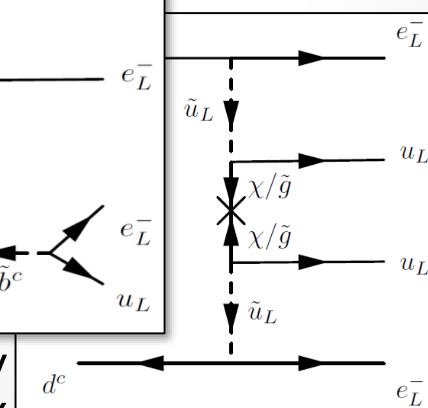






Left-Right Symmetry





R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...

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

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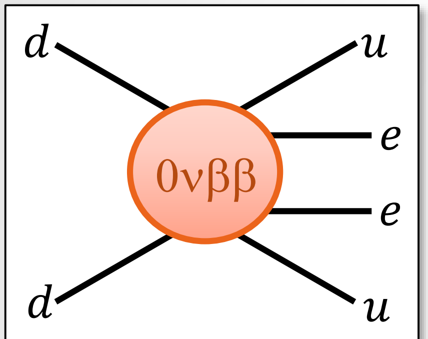
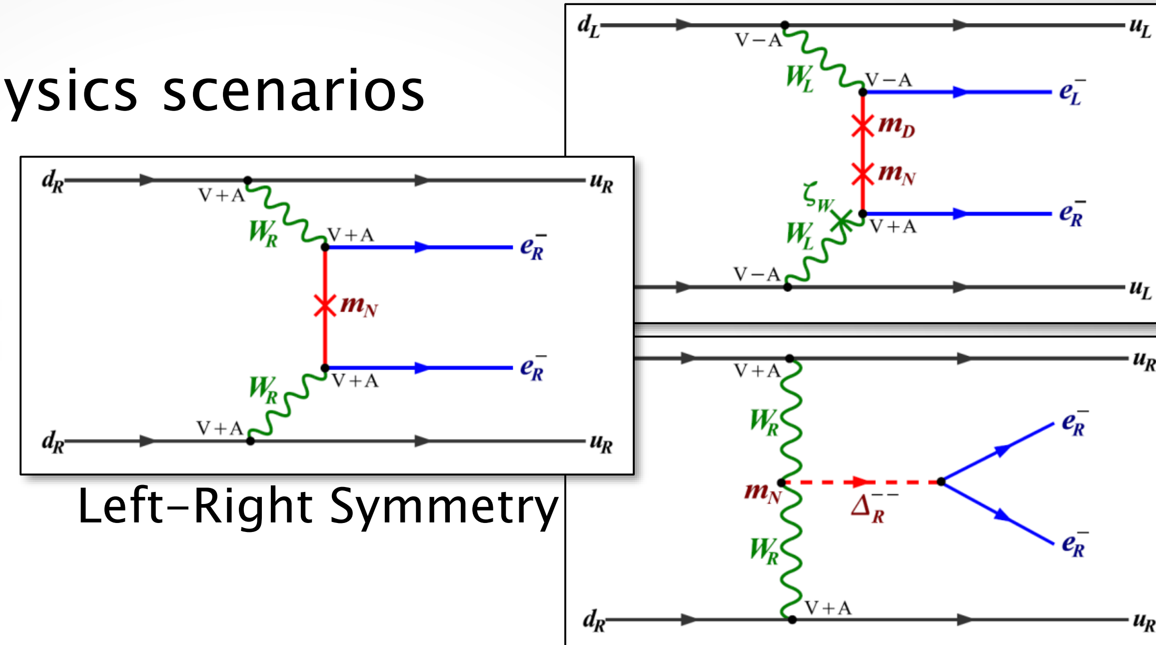
- Plethora of New Physics scenarios

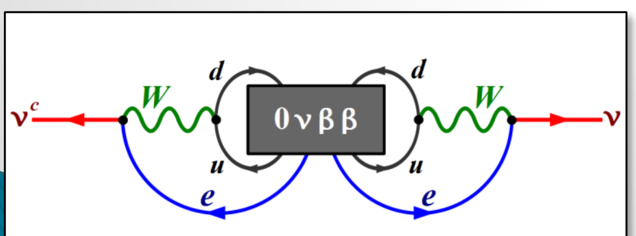


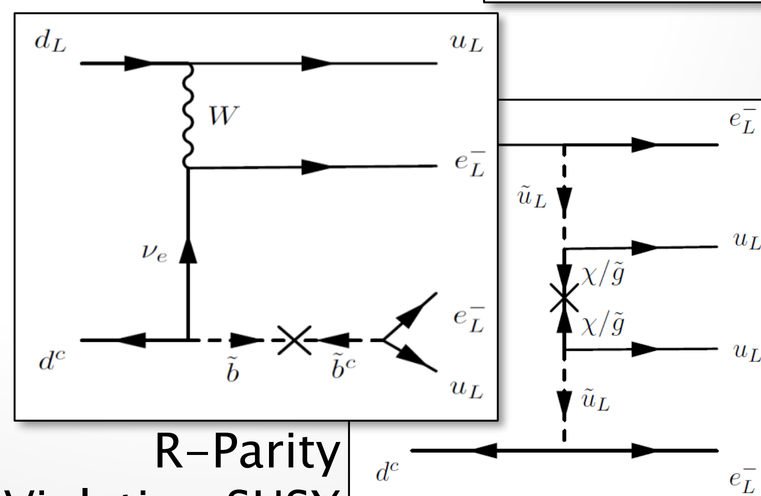
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$



Left-Right Symmetry

- Neutrinos still Majorana





R-Parity Violating SUSY

Extra Dimensions

Majorons

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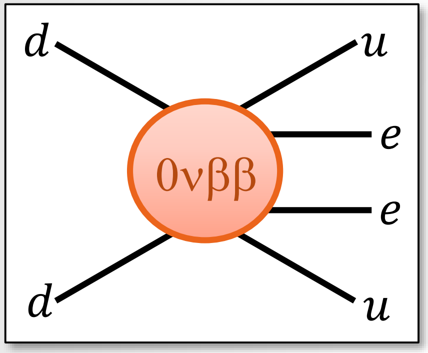
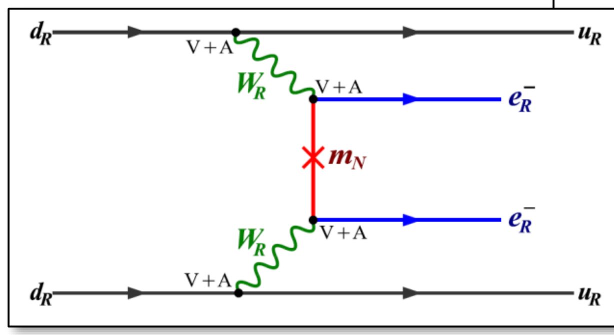
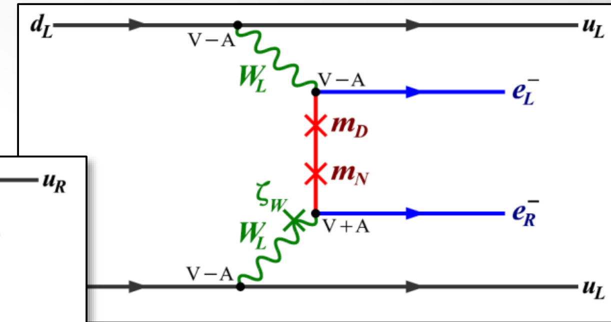
...

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

- Examples in Left-Right Symmetry







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

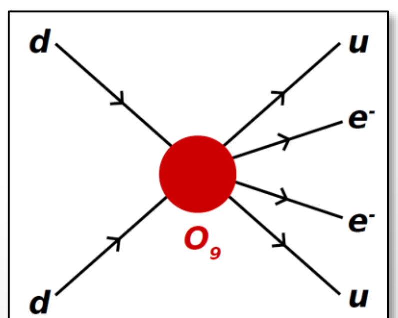
$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4}$$

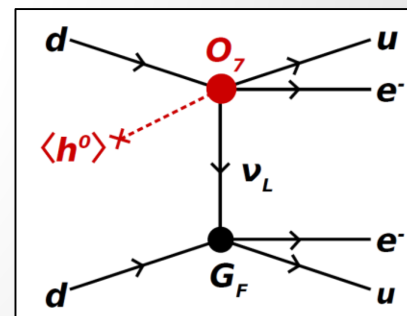
$$\approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W$$

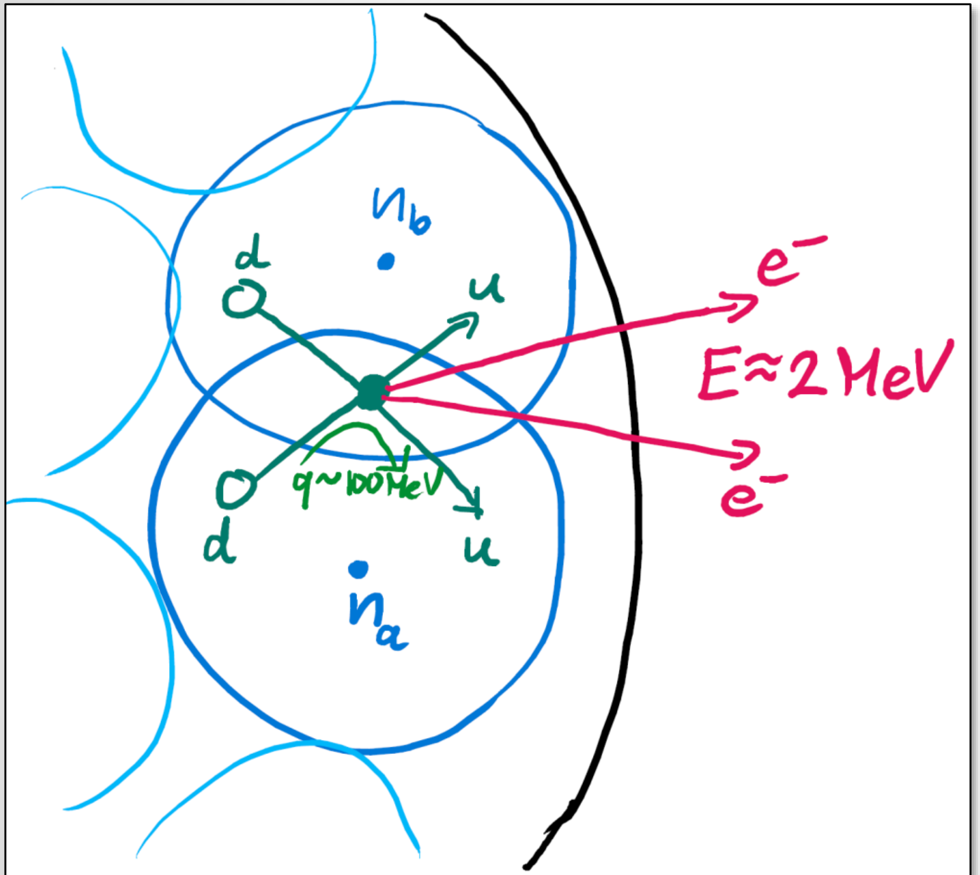
$$\approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators





Short-Range Mechanisms



- Re-evaluation of limits on short-range operators
  (L. Graf, FFD, Iachello, Kotila '18)
  - General parton level operators (Paes et al. '01)
  - Nucleon currents

$$\langle p|\, \bar{u}(1 \pm \gamma_5) d\, |n\rangle = \bar{N}\tau^+ \left[F_S(q^2) \pm F_{PS}(q^2)\gamma_5\right] N',$$

$$\langle p|\, \bar{u}\gamma^\mu (1 \pm \gamma_5) d\, |n\rangle = \bar{N}\tau^+ \left[F_V(q^2)\gamma^\mu - i\frac{F_W(q^2)}{2m_p}\sigma^{\mu\nu}q_\nu\right] N' \pm \bar{N}\tau^+ \left[F_A(q^2)\gamma^\mu\gamma_5 - \frac{F_P(q^2)}{2m_p}\gamma_5 q^\mu\right] N',$$

  - Form factors with enhancement for

$$F_{PS}(q^2) = \frac{g_{PS}}{(1+q^2/m_{PS}^2)^2}\frac{1}{1+q^2/m_\pi^2}, \quad g_{PS} = 349$$

$$F_P(q^2) = \frac{g_A}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}\frac{4m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right)$$

(Pion-mediated contributions in chiral EFT)

Short-Range Mechanisms

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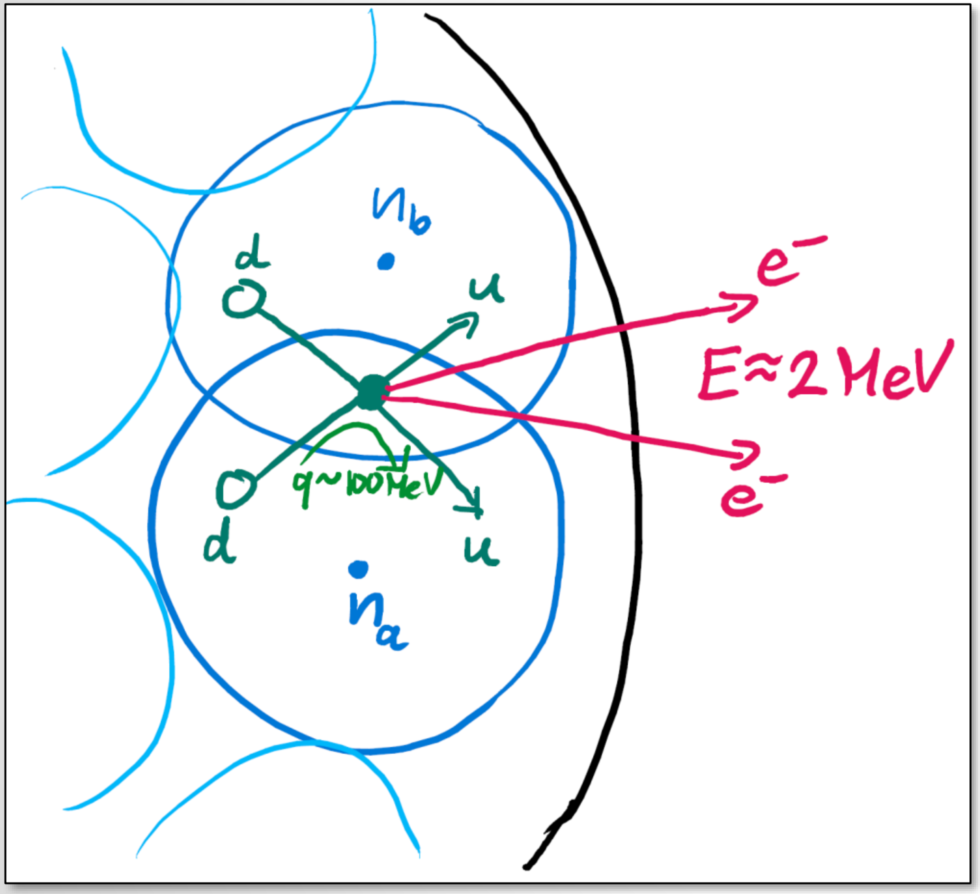

- Re-evaluation of limits on short-range operators
  (L. Graf, FFD, Iachello, Kotila '18)
  - Nuclear Matrix Elements in the Interacting Boson Model – work in progress, exact calculation of new NMEs still outstanding

$$M'_{GT} = \left\langle \frac{\boldsymbol{q}^2}{m_p^2} h(\boldsymbol{q}^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle \approx \frac{(0.1\ \mathrm{GeV})^2}{(1\ \mathrm{GeV})^2} M_{GT}$$

Short–Range Mechanisms

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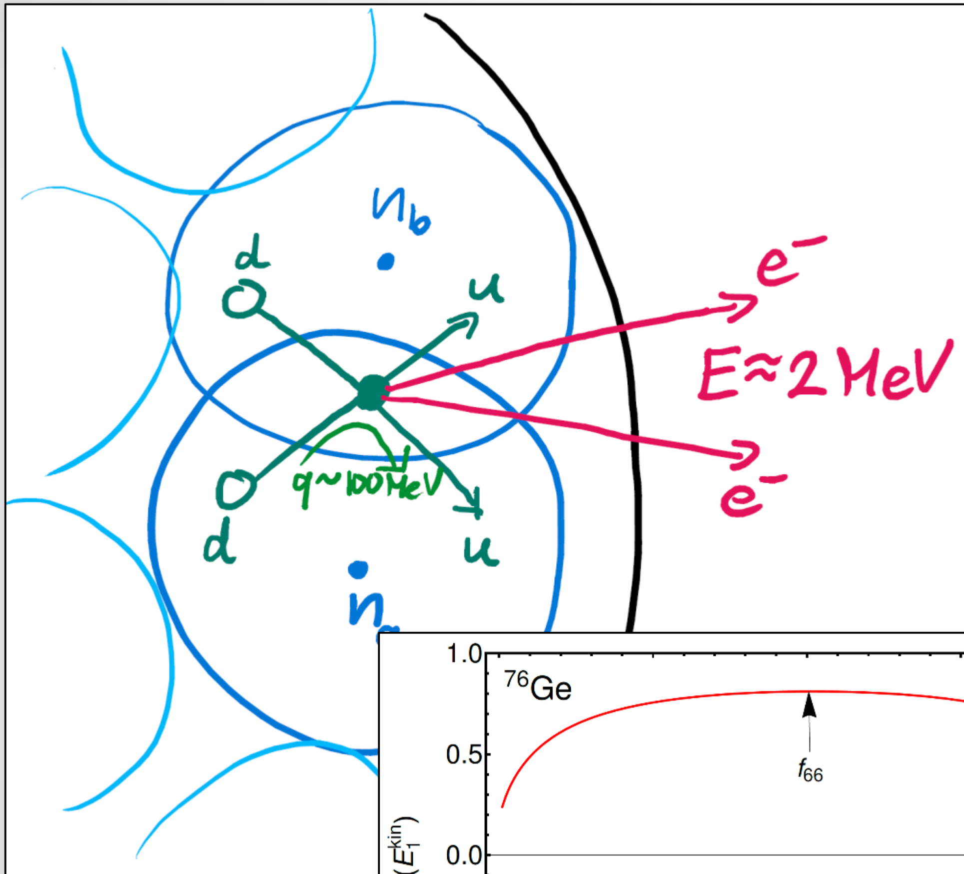
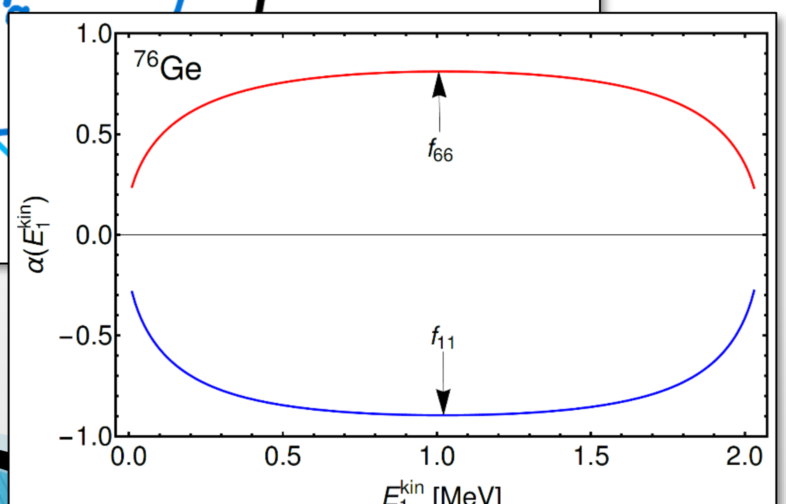
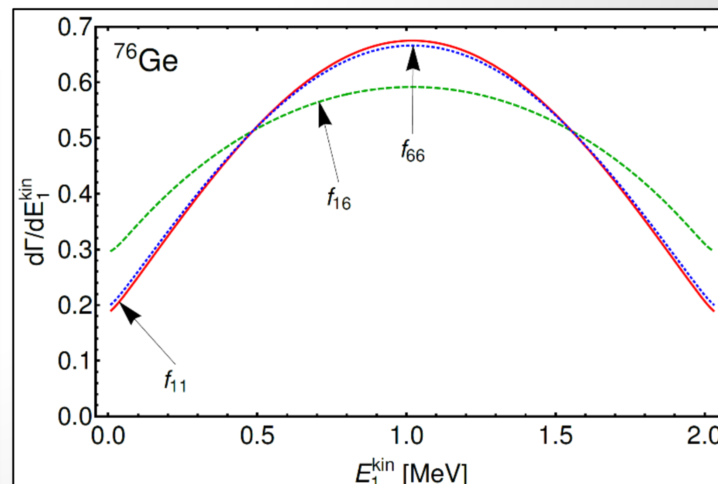
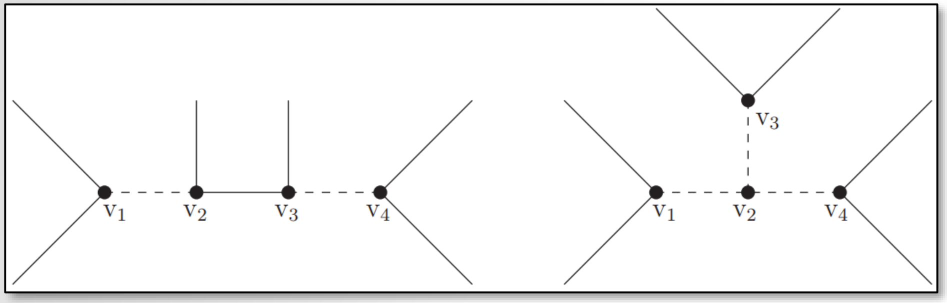


- Re–evaluation of limits on short–range operators
  (L. Graf, FFD, Iachello, Kotila '18)
  - Numerical determination of electron wavefunctions, including nuclear Coulomb potential and electron cloud screening ➔ Electron energy and angular distribution





Short-Range Mechanisms



#	Decomposition	Mediator $(Q_{em}, SU(3)_c)$: S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(-1, \mathbf{1} \oplus \mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \bar{\mathbf{3}})$	$(+1/3, \bar{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \bar{\mathbf{3}})$

Helo, Hirsch, Kovalenko, Paes '13

- Re-evaluation of limits on short-range operators
  (L. Graf, FFD, Iachello, Kotila '18)
  - Improved limits on effective interactions and NP scales

$$\frac{1}{\Lambda_{NP}^5} = \frac{G_F^2}{2m_p}\epsilon_i$$

JJj ($|\epsilon_1^{RR,LL}|$, $|\epsilon_1^{LR}|$) · $J_{\mu\nu}J^{\mu\nu}j$ ($|\epsilon_2^{XX}|$) · $J_\mu J^\mu j$ ($|\epsilon_3^{RR,LL}|$, $|\epsilon_3^{LR}|$) · $J_\mu J^{\mu\nu} j_\nu$ ($|\epsilon_4^{XX}|$) · $J_\mu J j^\mu$ ($|\epsilon_5^{RR,LL}|$, $|\epsilon_5^{RL,LR}|$)

	$T_{1/2}^{exp}$ [y]	$\lvert\epsilon_1^{RR,LL}\rvert$	$\lvert\epsilon_1^{LR}\rvert$	$\lvert\epsilon_2^{XX}\rvert$	$\lvert\epsilon_3^{RR,LL}\rvert$	$\lvert\epsilon_3^{LR}\rvert$	$\lvert\epsilon_4^{XX}\rvert$	$\lvert\epsilon_5^{RR,LL}\rvert$	$\lvert\epsilon_5^{RL,LR}\rvert$
^{76}Ge	$> 5.3 \times 10^{25}$ [68]	1.5	1.5	190	66	91	250	60	50
^{130}Te	$> 2.8 \times 10^{24}$ [69]	3.5	3.4	420	140	210	550	140	120
^{136}Xe	$> 1.1 \times 10^{26}$ [70]	0.57	0.57	84	27	38	110	23	19

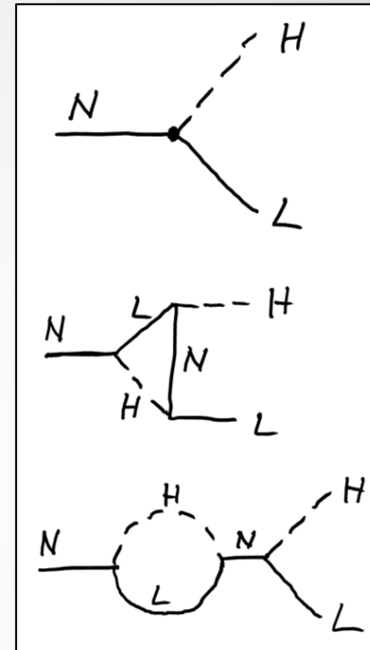
preliminary

$\times 10^{-10}$

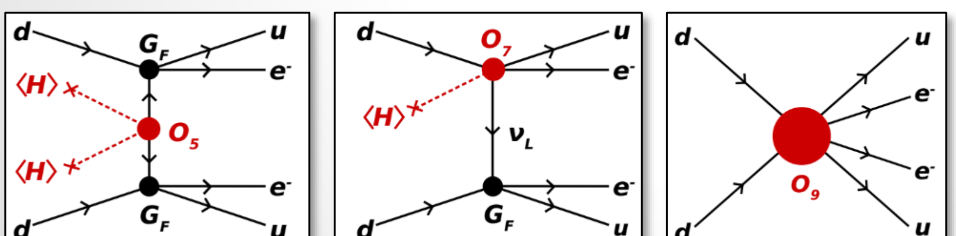
Baryon Asymmetry Generation and Washout

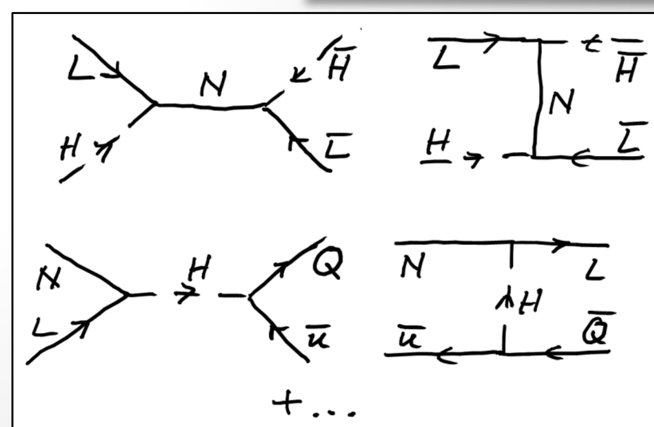
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

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



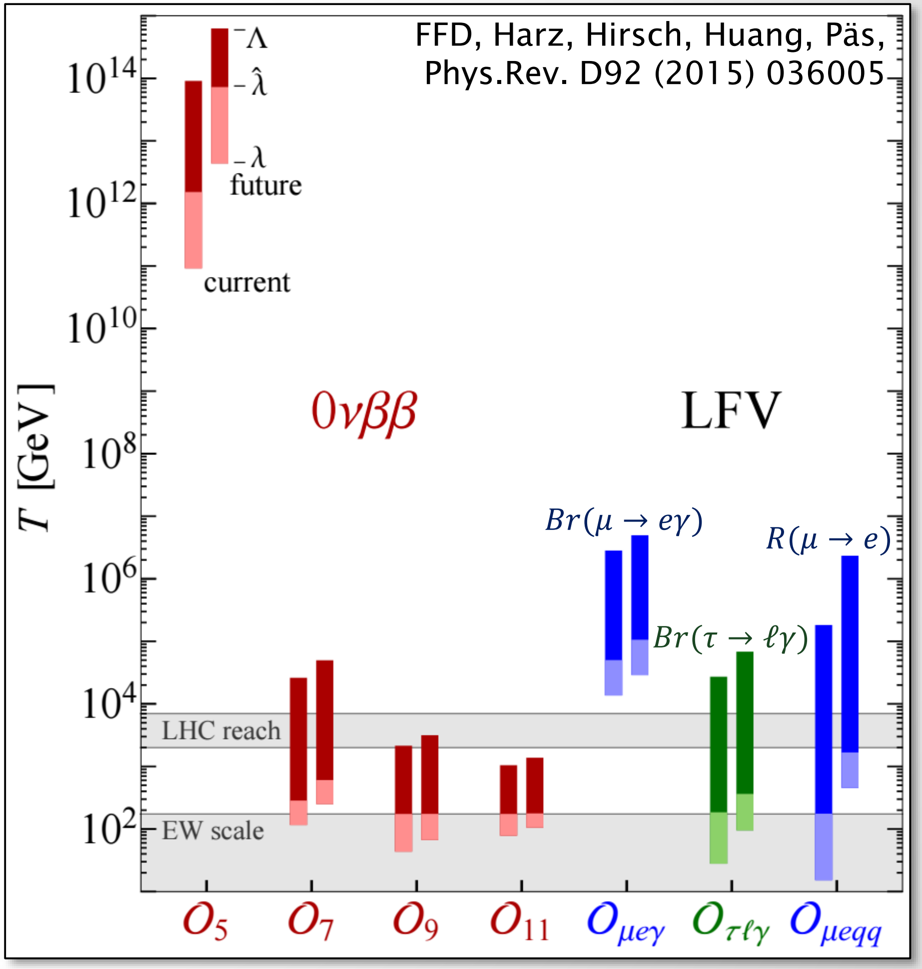
- What if we observe lepton number violating processes in $0\nu\beta\beta$?





Baryon Asymmetry
Lepton Asymmetry Washout

- Temperature ranges of strong equilibration
  - Assumes observation of corresponding process!
- Observation of LN(F)V
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



Washout via $0\nu\beta\beta$ operators

University College London

- 9D and 11D Operators

$\mathcal{O}$	Operator	m_ν	LR	ϵ_{LR}	SR	ϵ_{SR}
1^{H^4}	$L^iL^jH^kH^l\overline{H}^tH_t\overline{H}^uH_u\epsilon_{ik}\epsilon_{jl}$	$\frac{v^2}{\Lambda}f^2\left(\frac{v}{\Lambda}\right)$	–	–	–	–
1^{y_e}	$L^iL^jH^kH^l(\overline{L}^tH_t\bar{e^c})\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	–	–	–	–
1^{y_d}	$L^iL^jH^kH^l(\overline{Q}^tH_t\bar{d^c})\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_d y^{\text{ex}}_{d\vert u}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}$	–	–
2^{H^2}	$L^iL^jL^ke^cH^l\overline{H}^tH_t\varepsilon_{ij}\varepsilon_{kl}$	$\frac{y_e}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	–	–	–	–
$3_a^{H^2}$	$L^iL^jQ^kd^cH^l\overline{H}^tH_t\epsilon_{ij}\epsilon_{kl}$	$\frac{y_dg^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{T_R}_{T_R}$	–	–
$3_b^{H^2}$	$L^iL^jQ^kd^cH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
$4_a^{H^2}$	$L^iL^j\overline{Q}_i\bar{u^c}H^k\overline{H}^tH_t\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
6	$L^iL^j\overline{Q}_k\bar{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
7	$L^iQ^j\bar{e^c}\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_e^{\text{ex}}g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
8^{H^2}	$L^i\bar{e^c}\bar{u^c}d^cH^j\overline{H}^tH_t\epsilon_{ij}$	$\frac{y_e^{\text{ex}}y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon^{V+A}_{V+A}$	–	–
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_e^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	–	–	–	–
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	$\epsilon^{T_R}_{T_R}$	$\frac{g^2}{16\pi^2}\frac{1}{\Lambda^5}$	ϵ_1
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{1}{\Lambda^5}$	ϵ_1
12_a	$L^iL^j\overline{Q}_i\bar{u^c}\overline{Q}_j\bar{u^c}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}$	ϵ_1
12_b^*	$L^iL^j\overline{Q}_k\bar{u^c}\overline{Q}_l\bar{u^c}\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{g^2y_d^{\text{ex}}y_u^{\text{ex}}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
13	$L^iL^j\overline{Q}_i\bar{u^c}L^le^c\epsilon_{jl}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	–	–
14_a	$L^iL^j\overline{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}$	$\epsilon^{T_R}_{T_R}$	$\frac{g^2}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
14_b	$L^iL^j\overline{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}$	$\frac{1}{\Lambda^5}$	ϵ_1
15	$L^iL^jL^kd^c\overline{L}_i\bar{u^c}\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
16	$L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	–	–
17	$L^iL^jd^cd^c\bar{d^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{T_R}_{T_R}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{y_d^{\text{ex}}y_e^{\text{ex}}}{16\pi^2}\frac{1}{\Lambda^5}$	$2\epsilon_5$
18	$L^iL^jd^cu^c\bar{u^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{T_R}_{T_R}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{y_e^{\text{ex}}y_u^{\text{ex}}}{16\pi^2}\frac{1}{\Lambda^5}$	$2\epsilon_5$
19	$L^iQ^jd^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij}$	$\frac{y_e^{\text{ex}}y_d^2y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_5$
20	$L^id^c\overline{Q}_i\bar{u^c}\bar{e^c}\bar{u^c}$	$\frac{y_e^{\text{ex}}y_dy_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_5$
61	$L^iL^jH^kH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	–	–	–	–
66	$L^iL^jH^kH^l\epsilon_{ik}Q^rd^c\overline{H}_r\epsilon_{jl}$	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{1}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
71	$L^iL^jH^kH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_uy^{\text{ex}}_{d\vert u}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}$	–	–
76	$\bar{e^c}\bar{e^c}d^cd^c\bar{u^c}\bar{u^c}$	$\frac{y_e^{\text{ex}2}y_d^2y_u^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_dy_uy_e^{\text{ex}}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_3^{LLz}$

$\mathcal{O}$	Operator	m_ν	LR	ϵ_{LR}	SR	ϵ_{SR}
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_ey_e^{\text{ex}}y_u^{\text{ex}}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_ey_e^{\text{ex}}y_u^{\text{ex}}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y^{\text{ex}}_{d\vert(e)}y_d^{\text{ex}}y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert\epsilon^{V+A}_{V+A}$	–	–
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{y_u^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
26_a	$L^iL^jQ^kd^c\overline{L}_i\bar{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_ey_d}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
26_b	$L^iL^jQ^kd^c\overline{L}_k\bar{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
27_a	$L^iL^jQ^kd^c\overline{Q}_i\bar{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{y_d^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
27_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{y_d^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
28_a	$L^iL^jQ^kd^c\overline{Q}_j\bar{u^c}H^l\overline{H}_i\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{v^2}{\Lambda^7}$	ϵ_1
28_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{u^c}H^l\overline{H}_i\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}$	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
28_c	$L^iL^jQ^kd^c\overline{Q}_l\bar{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
29_a	$L^iL^jQ^ku^c\overline{Q}_k\bar{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\text{ex}}y_u^{\text{ex}}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
29_b	$L^iL^jQ^ku^c\overline{Q}_l\bar{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\text{ex}}y_u^{\text{ex}}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
30_a	$L^iL^j\overline{L}_i\bar{e^c}\overline{Q}_k\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_ey_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
30_b	$L^iL^j\overline{L}_m\bar{e^c}\overline{Q}_n\bar{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	–	–
31_a	$L^iL^j\overline{Q}_i\bar{d^c}\overline{Q}_k\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
31_b	$L^iL^j\overline{Q}_m\bar{d^c}\overline{Q}_n\bar{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
32_a	$L^iL^j\overline{Q}_j\bar{u^c}\overline{Q}_k\bar{u^c}H^k\overline{H}_i$	$\frac{y_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
32_b	$L^iL^j\overline{Q}_m\bar{u^c}\overline{Q}_n\bar{u^c}H^k\overline{H}_i\epsilon_{jk}\epsilon^{mn}$	$\frac{y_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\text{ex}2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
34	$\bar{e^c}\bar{e^c}L^iQ^je^cd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e^{\text{ex}}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{e\vert u\vert(d)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V\pm A}$	–	–
35	$\bar{e^c}\bar{e^c}L^ie^c\overline{Q}_j\bar{u^c}H^jH^k\epsilon_{ik}$	$\frac{y_e^{\text{ex}}y_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{e\vert d\vert(u)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert 2\epsilon^{V+A}_{V\pm A}$	–	–
36	$\bar{e^c}\bar{e^c}Q^id^cQ^jd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e^{\text{ex}2}y_d^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y_dy_e^{\text{ex}}y^{\text{ex}}_{e\vert u\vert(d)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V\pm A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
37	$\bar{e^c}\bar{e^c}Q^id^c\overline{Q}_j\bar{u^c}H^jH^k\epsilon_{ik}$	$\frac{y_e^{\text{ex}2}y_dy_ug^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{g^2y_e^{\text{ex}}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
38	$\bar{e^c}\bar{e^c}\overline{Q}_i\bar{u^c}\overline{Q}_j\bar{u^c}H^iH^j$	$\frac{y_e^{\text{ex}2}y_u^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y^{\text{ex}}_{e\vert d\vert(u)}y_e^{\text{ex}}y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert 2\epsilon^{V+A}_{V\pm A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
40_a	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{d\vert u\vert u\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V\pm A}$	–	–
43_a	$L^iL^jL^kd^c\overline{L}_l\bar{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
44_c	$L^iL^jQ^ke^c\overline{Q}_l\bar{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$	$\frac{g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	–	–
47_a	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{d\vert u\vert(e)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V-A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
47_d	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{d\vert u\vert(e)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V-A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
53	$L^iL^jd^cd^c\bar{u^c}\bar{u^c}\overline{H}_i\overline{H}_j$	$\frac{y_d^2y_u^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y_dy_uy^{\text{ex}}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
54_a	$L^iQ^jQ^kd^c\overline{Q}_i\bar{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_e^{\text{ex}}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\text{ex}}_{e\vert(d)\vert u}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V\mp A}$	–	–
54_d	$L^iQ^jQ^kd^c\overline{Q}_l\bar{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$	$\frac{y_e^{\text{ex}}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	$\frac{v^2}{\Lambda^7}$	$2\epsilon_5$
55_a	$L^iQ^j\overline{Q}_i\overline{Q}_k\bar{e^c}\bar{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_e^{\text{ex}}y_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	$\frac{v^2}{\Lambda^7}$	$2\epsilon_5$
59	$L^iQ^jd^cd^c\bar{e^c}\bar{u^c}H^k\overline{H}_i\epsilon_{jk}$	$\frac{y_e^{\text{ex}}y_d^2y_u}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{V+A}_{V+A}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon_5$
60	$L^id^c\overline{Q}_j\bar{u^c}\bar{e^c}\bar{u^c}H^j\overline{H}_i$	$\frac{y_e^{\text{ex}}y_dy_u^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{V+A}_{V+A}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon_5$

Baryon Asymmetry
Lepton Asymmetry Washout

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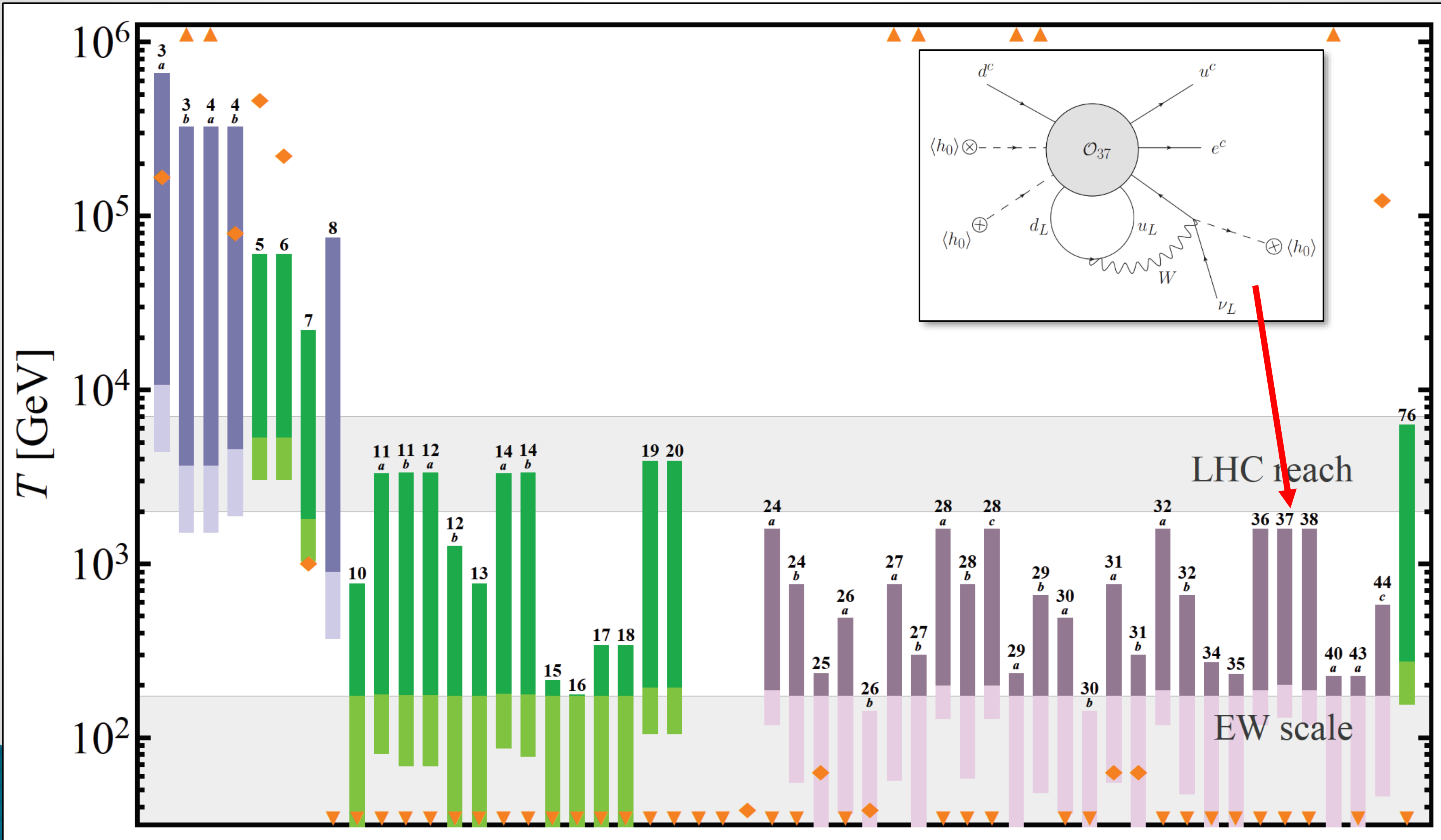
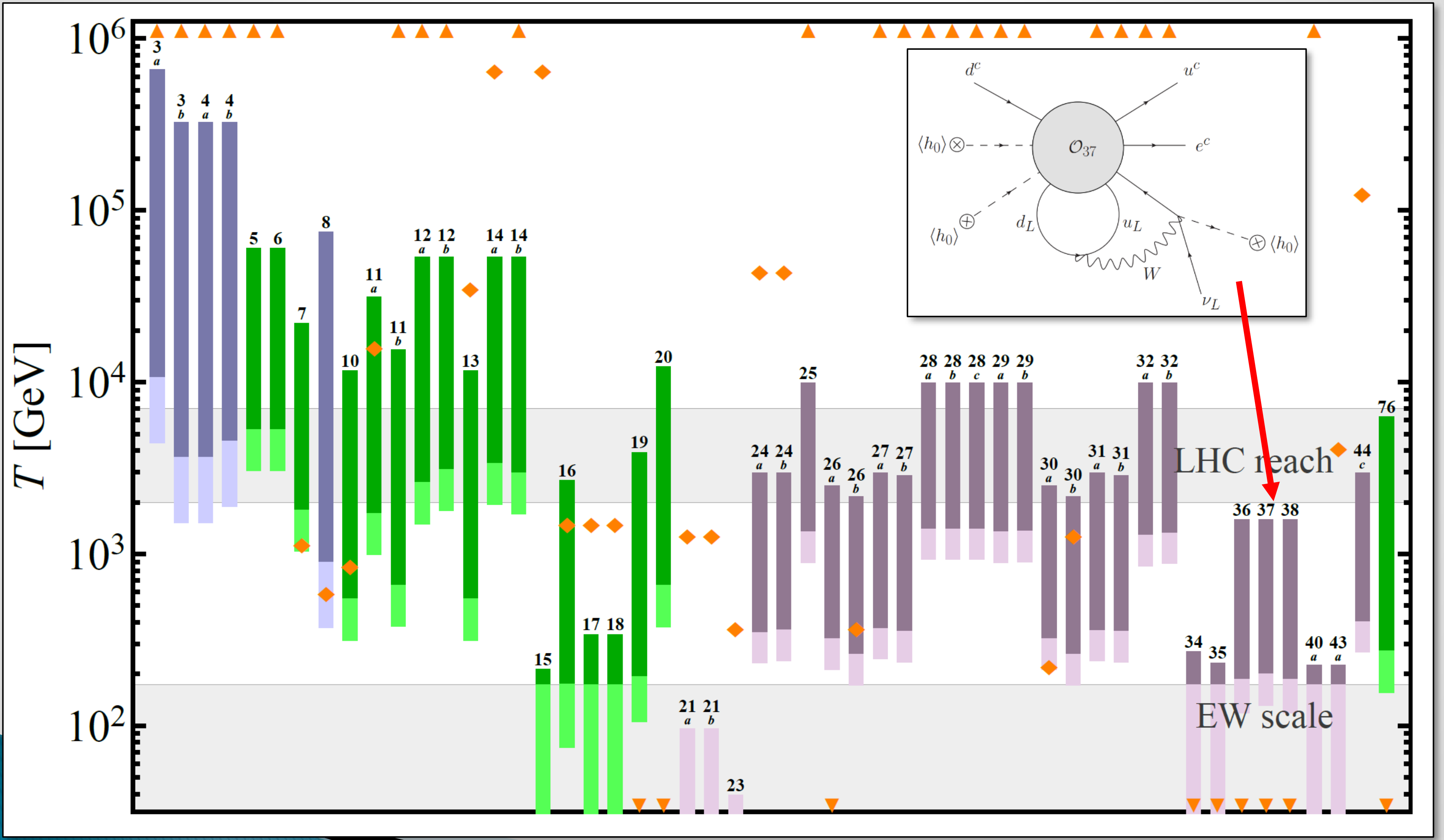


Baryon Asymmetry
Lepton Asymmetry Washout



Conclusion

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- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - New LNV physics at the LHC scale?
  - Standard Mass Mechanism?
    - 5-dim operator from LNV at GUT scale
  - Experimentally and theoretically challenging
- **Importance of probing LNV around the TeV scale**
  - E.g. searches for heavy neutral leptons at the LHC
  - Can we rule out mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe