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(More than) Exotic $0\nu\beta\beta$ Decay with Majoron-like Emission

Frank Deppisch
f.deppisch@ucl.ac.uk
University College London

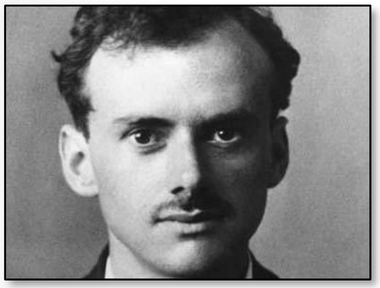
with Ricardo Cepedello, Lorena González, Chandan Hati, Martin Hirsch

Phys.Rev.Lett. 122 (2019) 181801

MEDEX’19 | Prague | 27-31/05/2019

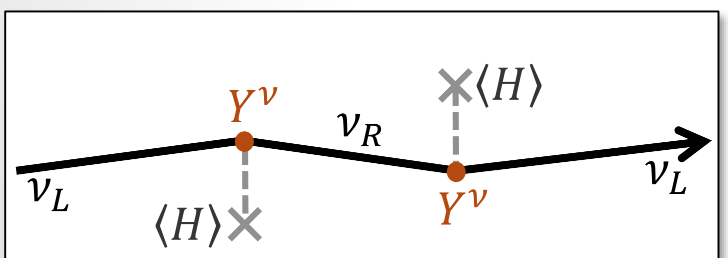
Dirac vs Majorana

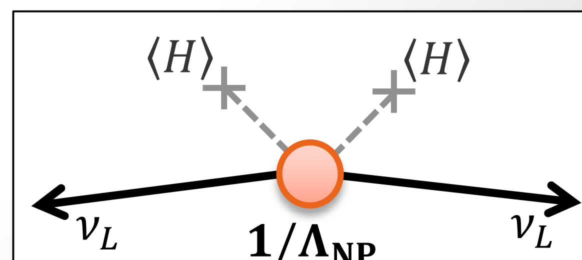
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass



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 and ν Nature

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- Single beta decay

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

  - Tritium decay, KATRIN: $\boldsymbol{m_\beta \approx 0.2}$ **eV**
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $\boldsymbol{m_\beta \approx 0.05}$ **eV**

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

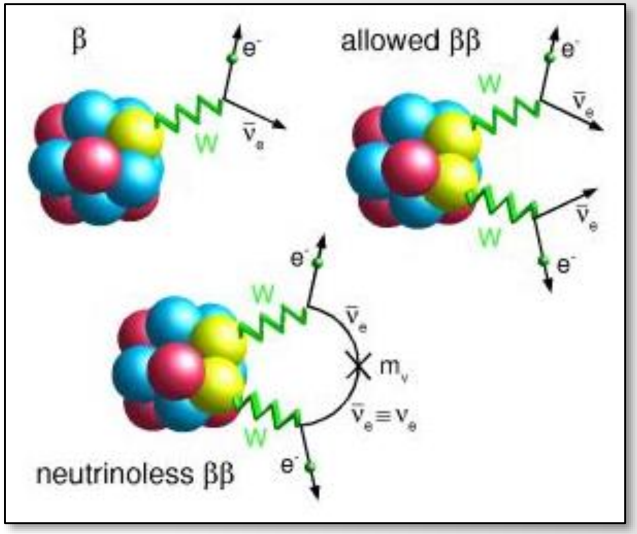
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

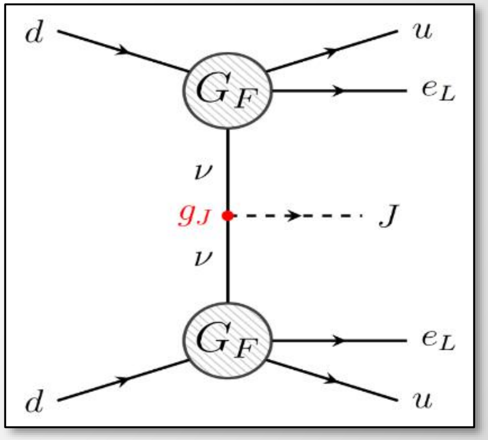
- Neutrinoless double beta ($0\nu\beta\beta$) decay

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

  - Violation of lepton number
  - Mediated by Majorana neutrinos

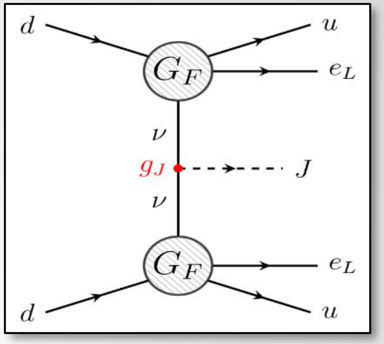
- Majoron assisted double beta ($0\nu\beta\beta J$) decay
  - Missing energy → lepton number violated?

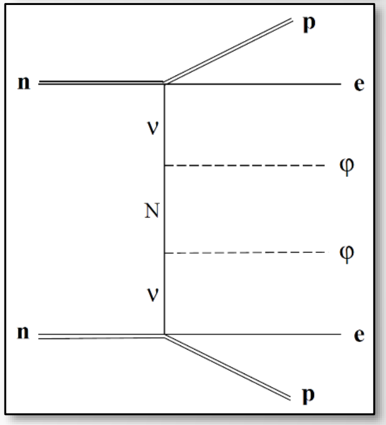


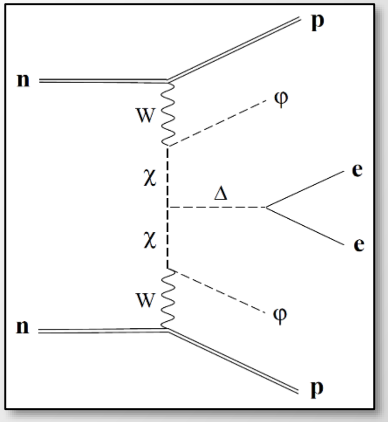


Majorons and MLPs

- Emission of one or more neutral bosons
  - Majoron model of neutrino mass generation
  - "Majoron-like" boson J with coupling to ν, e.g. $g_{ij}\bar{\nu}_i\gamma_5\nu_j J$







Bamert, Burgess, Mohapatra '95

Majorons and MLPs

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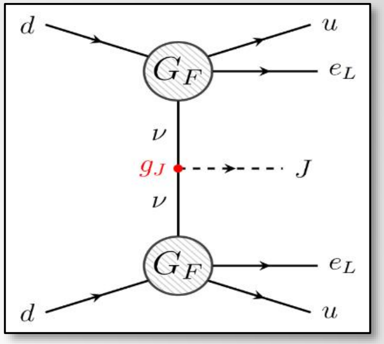
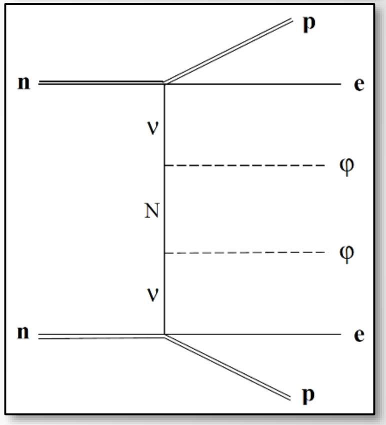
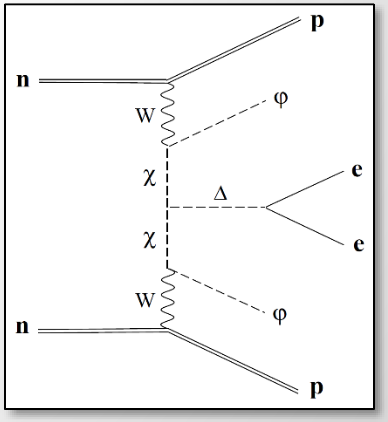
- Emission of one or more neutral bosons
  - Majoron model of neutrino mass generation
  - "Majoron-like" boson J with coupling to ν, e.g. $g_{ij}\bar{\nu}_i\gamma_5\nu_j J$
  - Light scalar associated with Weinberg-like operator (Blum, Nir, Shavit, Phys. Lett. B785 (2018) 354)

$$\mathcal{L}_{d=6} = -\frac{\mathcal{Y}_{\alpha\beta}}{\Lambda^2}\phi(HL_\alpha)(HL_\beta)$$

  - Extensions with derivative couplings or two-Majoron emission







Bamert, Burgess, Mohapatra '95

Majorons and MLPs

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- Standard Majoron classes

Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ [10^{23}yr]	$\mathcal{M}^{0\nu\chi}$	$G^{0\nu\chi}$ [yr^{-1}]	$\langle g \rangle$
IB	1	χ	no	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IC	1	χ	yes	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
ID	3	$\chi\chi$	no	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	yes	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IF	2	χ	bulk field	0	> 1.8	–	–	–
IIB	1	χ	no	-2	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IIC	3	χ	yes	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$
IID	3	$\chi\chi$	no	-1	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	yes	-1	> 0.3	$10^{-3\pm1}$	$1.21 \cdot 10^{-18}$	$< 2.2^{+4.9}_{-1.4}$
IIF	3	χ	gauge boson	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$

GERDA, Eur. Phys. J. C75 (2015) 9, 416

Majorons and MLPs

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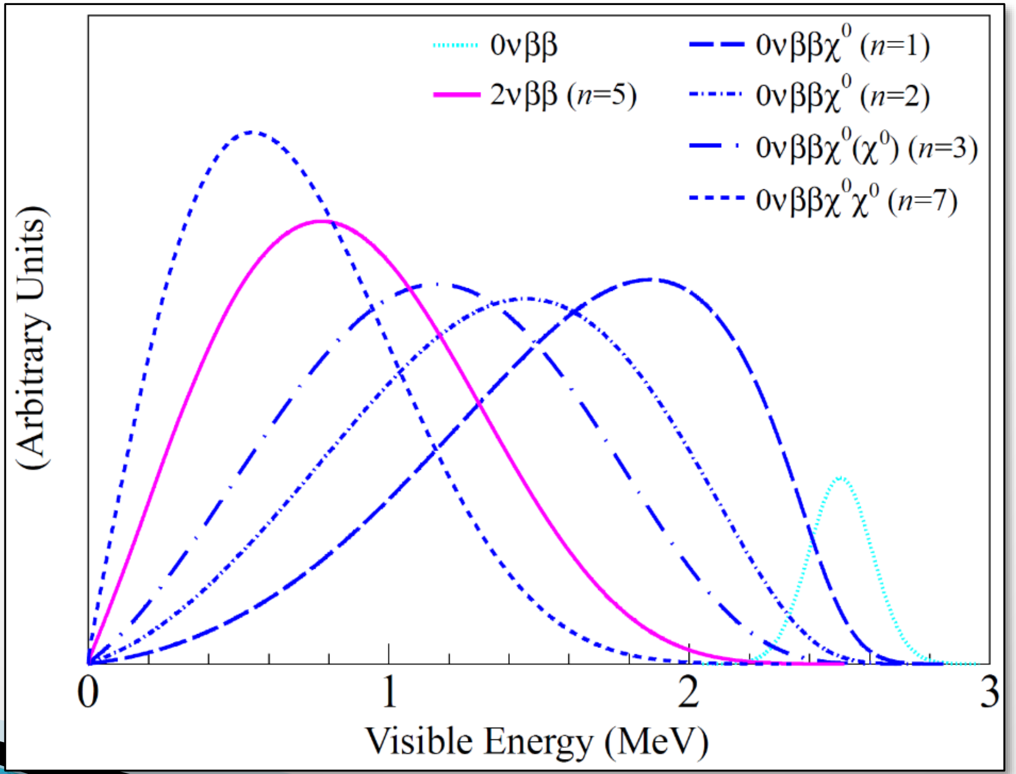
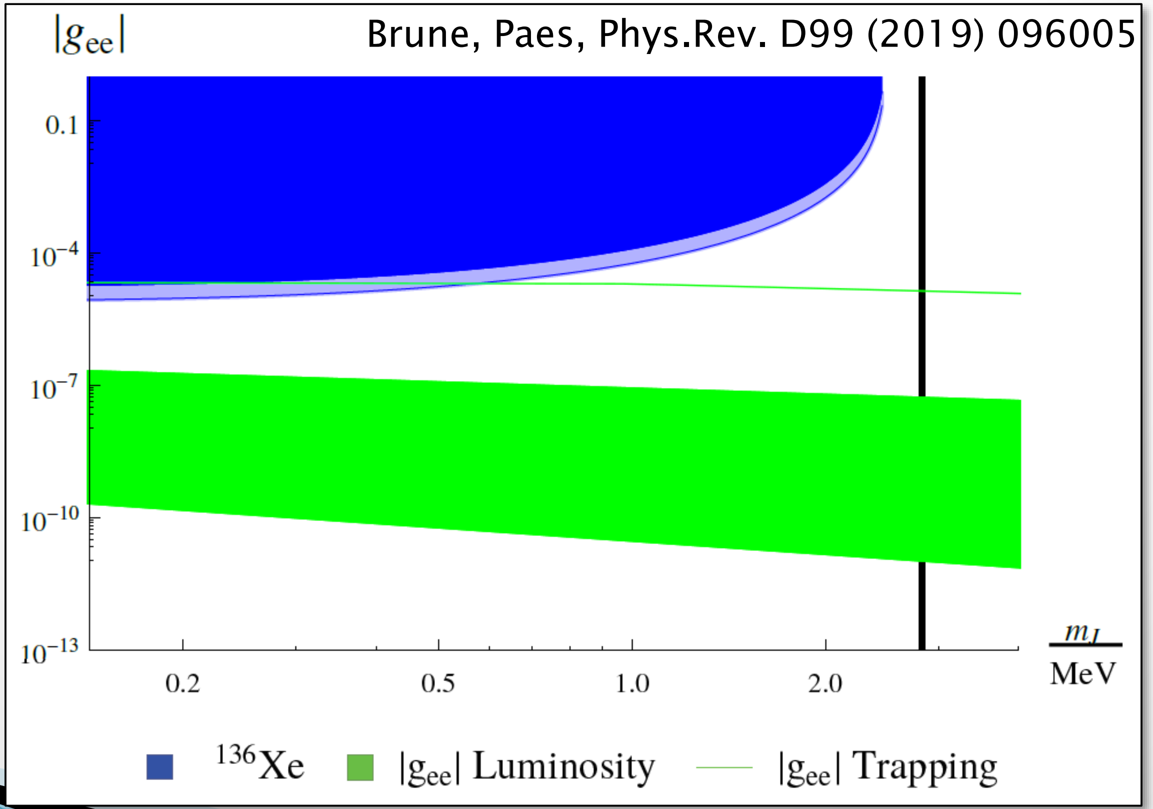
- Standard Majoron classes
- Different electron energy distribution

$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \; [p_1 \varepsilon_1 F(\varepsilon_1)] \; [p_2 \varepsilon_2 F(\varepsilon_2)]$$



Astrophysical Effects

- If massive, Majoron can be Dark Matter
  - Singlet Majoron Model
    (Garcia-Cely, Heeck, JHEP 05 (2017)102)
- Strong constraints from Supernovae



Majorons and RH Currents

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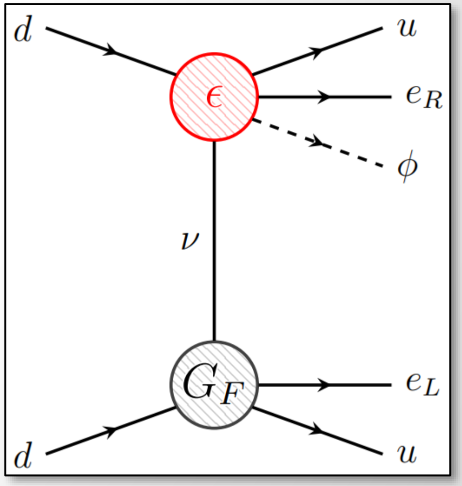
- Effective RH lepton currents with massless scalar ϕ

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$

- Giving rise to long-range contribution to $0\nu\beta\beta\phi$ decay

$$\mathcal{M} = \epsilon_{RX}^\phi \frac{(G_F\cos\theta_C)^2}{\sqrt{2}m_p} \sum_N \int d^3x d^3y \int \frac{d^3q}{2\pi^2\omega} \phi(\mathbf{y}) e^{i\mathbf{q}(\mathbf{x}-\mathbf{y})} \times \left\{ \left[\frac{J_{LX}^{\rho\sigma}(\mathbf{x},\mathbf{y}) u_{\rho\sigma}^L(E_1\mathbf{x}, E_2\mathbf{y})}{\omega + \mu_N - \frac{1}{2}(E_1 - E_2 - E_\phi)} - \frac{J_{XL}^{\rho\sigma}(\mathbf{x},\mathbf{y}) u_{\rho\sigma}^R(E_1\mathbf{x}, E_2\mathbf{y})}{\omega + \mu_N - \frac{1}{2}(E_1 - E_2 + E_\phi)} \right] - \left[E_1 \leftrightarrow E_2 \right] \right\}$$

  - No suppression with ν mass



- Calculation follows long-range η and λ $0\nu\beta\beta$ modes

Doi, Kotani, Takasugi, Prog. Theor. Phys. Suppl. 83 (1985) 1

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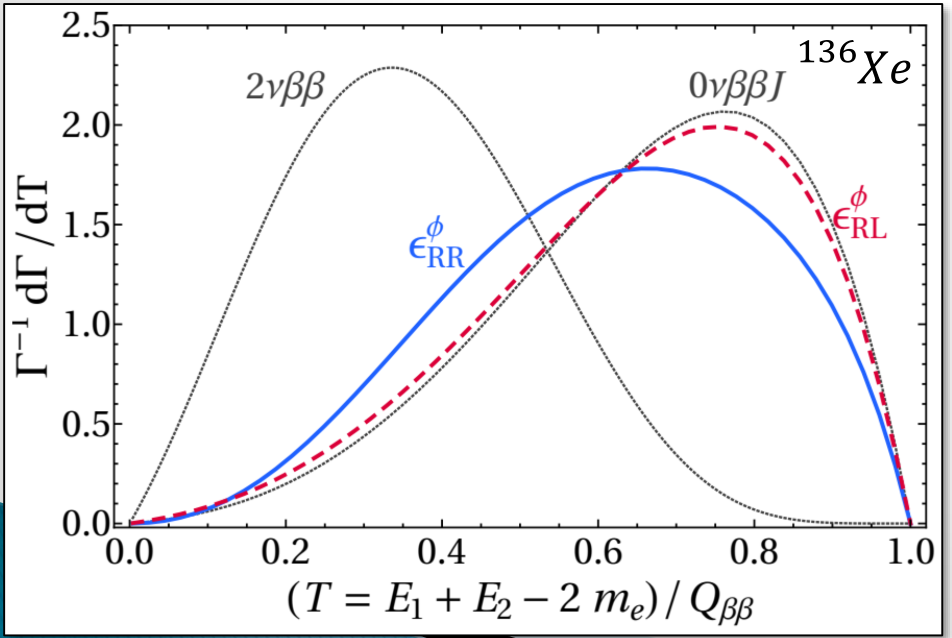
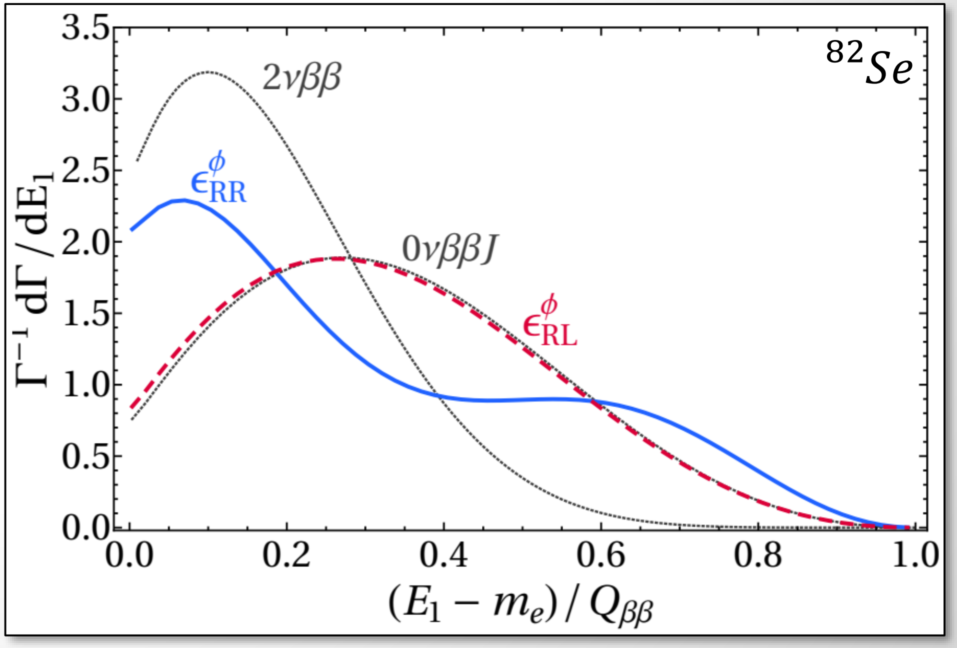
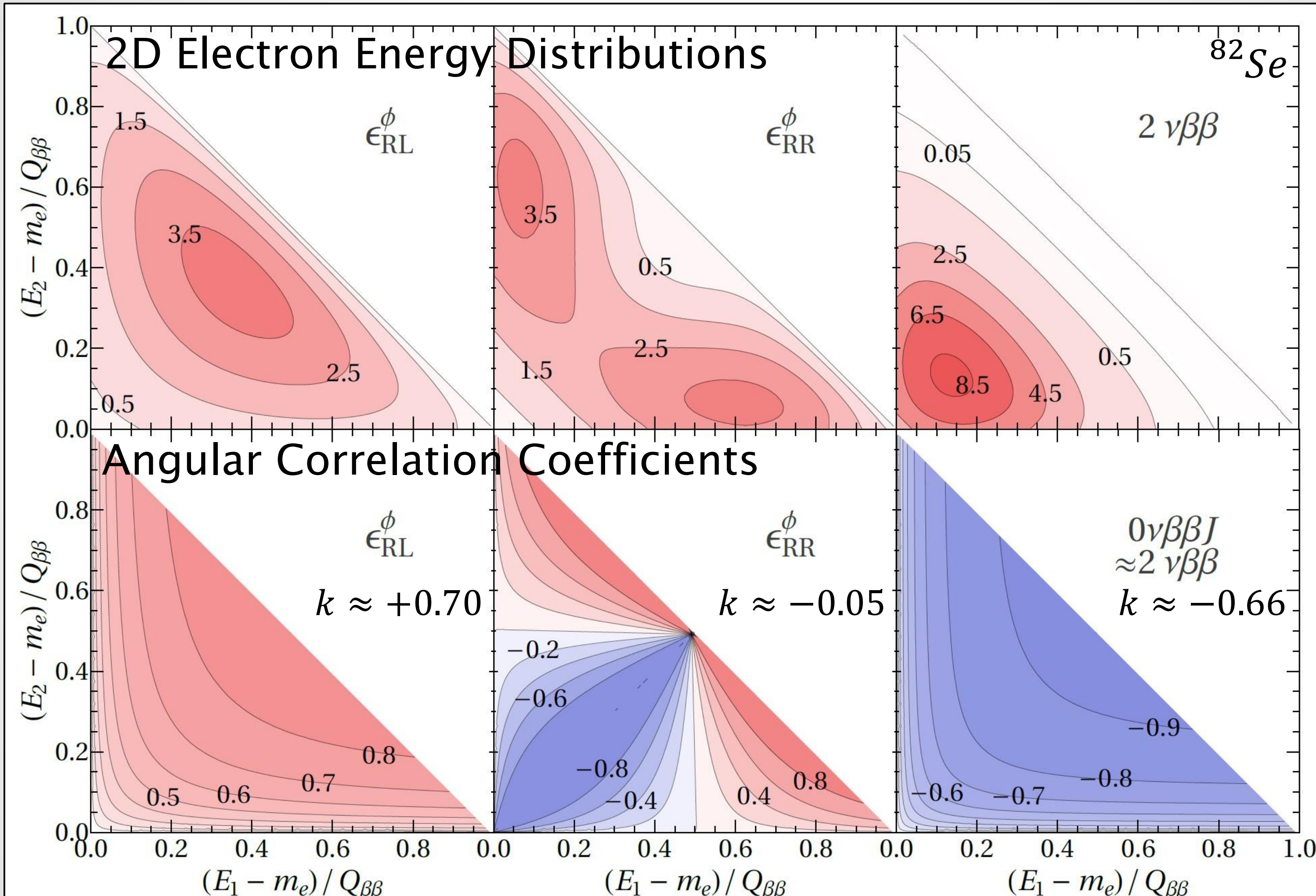
- Non-standard total and single electron energy distributions





Majorons and RH Currents



Average Angular Correlation $\dfrac{d\Gamma}{d\cos\theta} = \dfrac{\Gamma}{2}(1 + k\cos\theta)$

Majorons and RH Currents

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- Sensitivity (massless ϕ, recasting single Majoron searches)

Isotope	$T_{1/2}$ [y]	$\lvert\epsilon^{\phi}_{RL}\rvert$	$\lvert\epsilon^{\phi}_{RR}\rvert$
^{82}Se	3.7×10^{22} [14]	4.1×10^{-4}	4.6×10^{-2}
^{136}Xe	2.6×10^{24} [13]	1.1×10^{-4}	1.1×10^{-2}
^{82}Se	1.0×10^{24}	8.0×10^{-5}	8.8×10^{-3}
^{136}Xe	1.0×10^{25}	5.7×10^{-5}	5.8×10^{-3}

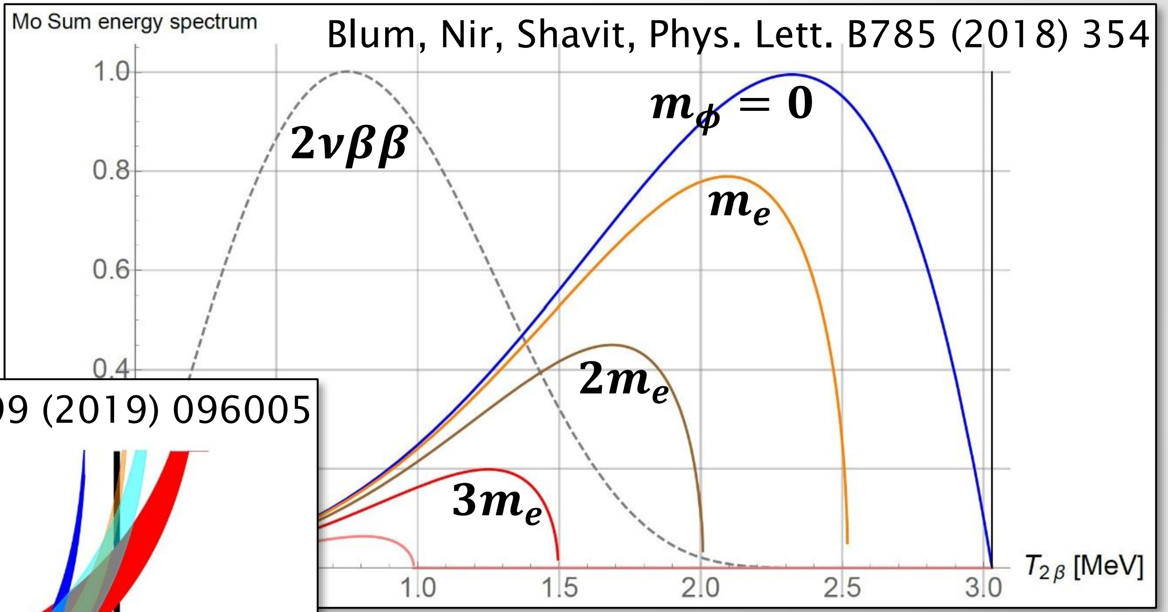
- Standard long-range NMEs

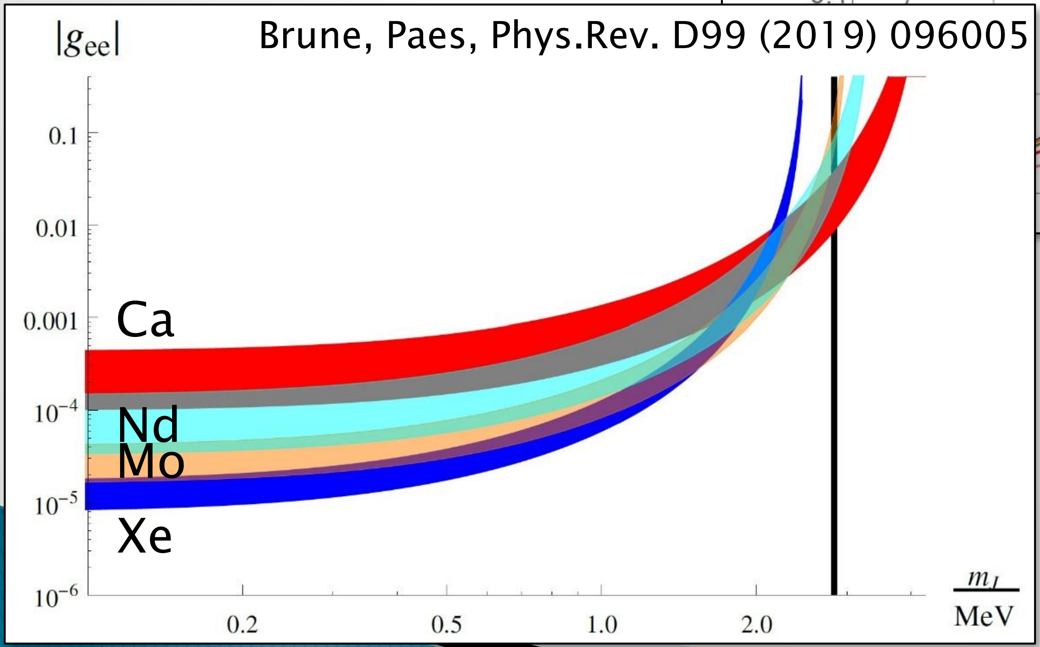
Isotope	$Q_{\beta\beta}$ [MeV]	M_{GT}	χ_F	$\chi_{GT\omega}$	$\chi_{F\omega}$	χ'_{GT}	χ'_F	χ_T	χ_R	χ_P
^{82}Se	2.99	2.993	−0.134	0.947	−0.131	1.003	−0.103	0.004	1.086	0.430
^{136}Xe	2.46	1.770	−0.158	0.908	−0.149	1.092	−0.167	−0.031	0.955	0.256

Horoi, Neacsu, Phys. Rev. D93 (2016) 113014
Caurier et al., Phys. Rev. Lett. 77 (1996) 1954, Eur. Phys. J. A36 (2008) 195

Majorons and RH Currents

- Sensitivity modification for massive ϕ
  - Suppression of phase space
  - Decrease of $S/\sqrt{B}$





UV Model: LR Symmetry

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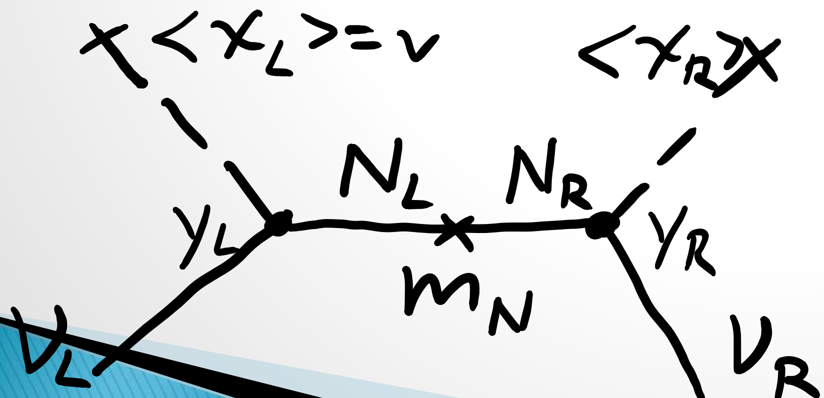
- Extended Gauge Symmetry

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

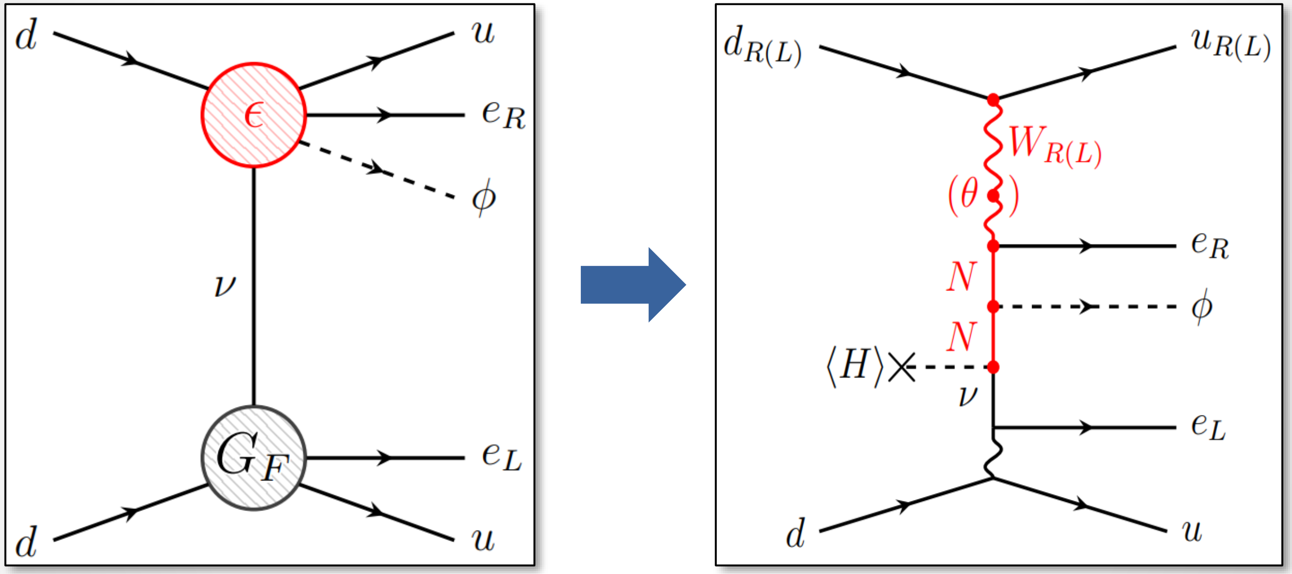
- Minimal LR model: $X = B - L$
- We consider $X \neq B - L$ broken but $B - L$ conserved
- Dirac neutrinos (and charged SM fermions) via Dirac seesaw via heavy, vector-like fermions
  (Bolton, FFD, Hati, arXiv:1902.05802)

Field	$SU(2)_L$	$SU(2)_R$	$B-L$	ζ	X	$SU(3)_C$
q_L	2	1	1/3	0	1/3	3
q_R	1	2	1/3	0	1/3	3
ℓ_L	2	1	-1	0	-1	1
ℓ_R	1	2	-1	0	-1	1
$U_{L,R}$	1	1	1/3	+1	4/3	3
$D_{L,R}$	1	1	1/3	-1	-2/3	3
$E_{L,R}$	1	1	-1	-1	-2	1
$N_{L,R}$	1	1	-1	+1	0	1
χ_L	2	1	0	+1	1	1
χ_R	1	2	0	+1	1	1
ϕ	1	1	2	-2	0	1



UV Model: LR Symmetry

- UV Diagram



- Sensitivity from ϵ_{RL}^{ϕ}

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

UV Model: Leptoquarks

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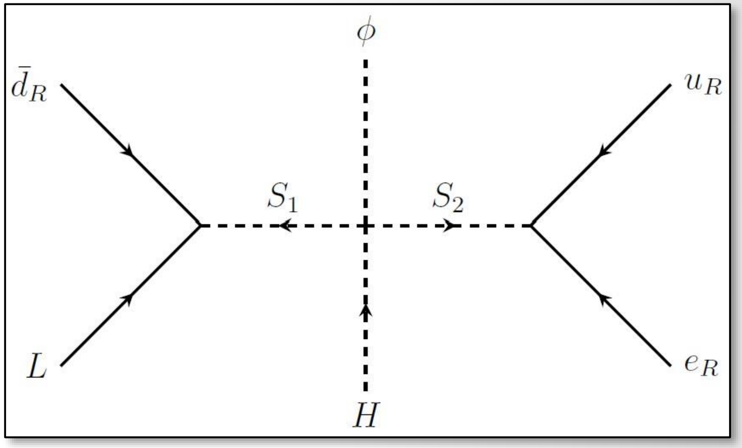
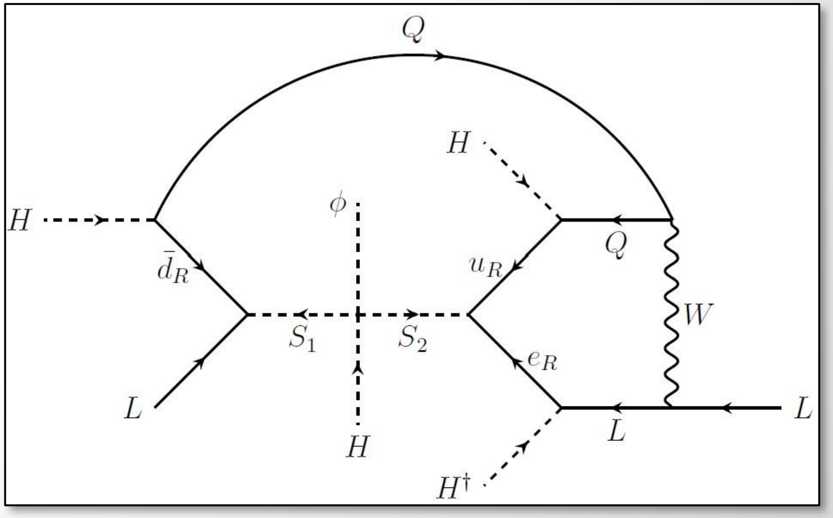
- Add heavy scalar leptoquarks $S_1(3,2,1/6)$, $S_2(3^*,1,1/3)$
  - Effective operator at tree level
  - Lepton number conserved if $L(S_1) = L(S_2) = -1$, $L(\phi) = -2$



  - LNV and Majorana neutrino mass at two-loop if $\langle\phi\rangle \neq 0$



Conclusion

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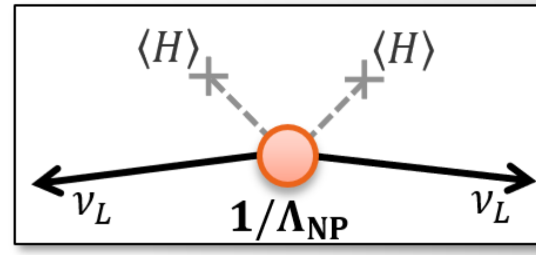
- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Standard interpretation: New Physics near GUT scale breaking lepton number
  - Important to look for alternative scenarios
    - If missing energy, lepton number may not be broken
    - Neutrino mass may be associated with exotic light particles
- **Majoron emission with RH currents**
  - Example of novel decay mode
  - Other possibilities?



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