Probing Beyond the Standard Model Physics with Neutrinoless Double Beta Decay

Frank Deppisch
f.deppisch@ucl.ac.uk

University College London

Particle Physics Seminar
QMUL, 15 February 2013

Overview

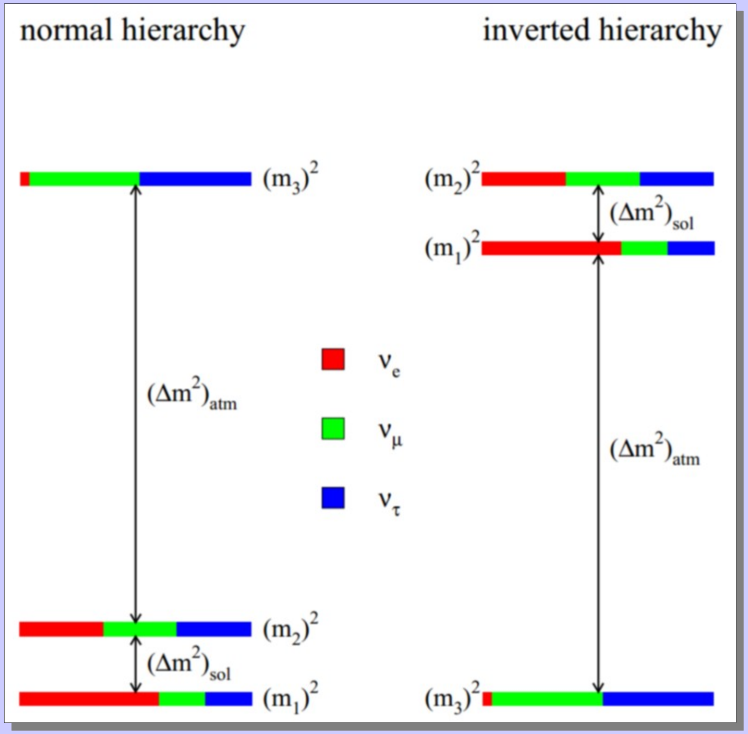
- Neutrinos
  - Oscillations
  - Absolute Mass
- Neutrinoless Double Beta Decay
  - Light Neutrino Exchange
  - Effective Mass and Seesaw
  - New Physics Mechanisms
  - Distinguishing Mechanisms
- LNV at the LHC
- Conclusion

Neutrino Oscillations

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

$$\nu_i = \sum_\alpha U_{i\alpha} \nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)} \nu_i$$

$$\Rightarrow P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.27 \frac{\Delta m^2}{\text{eV}^2} \frac{L/\text{km}}{E/\text{GeV}}\right)$$



- **Solar neutrino oscillations**
  Large mixing
- **Atmospheric oscillations**
  ≈ Maximal mixing
- **Reactor and accelerator neutrinos**

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.021$$

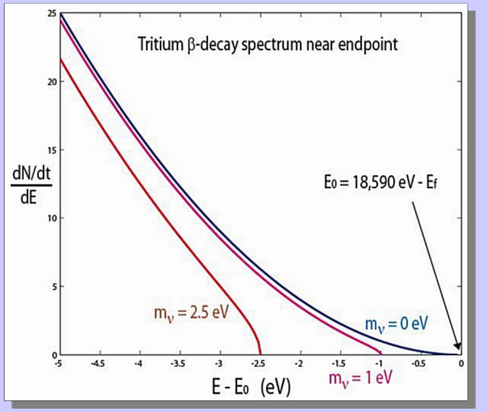
- **Experimental unknowns and anomalies**
  CP violation? Sign of Δm_{23}? Sterile Neutrinos?

Absolute Neutrino Mass

- **Energy endpoint in Beta decay**

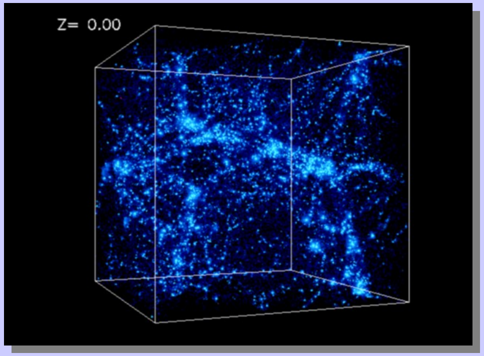
$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 < (2.2\,\mathrm{eV})^2$$

Katrin: $m_\beta \approx 0.2$ eV



- **Impact on Large Scale Structure**

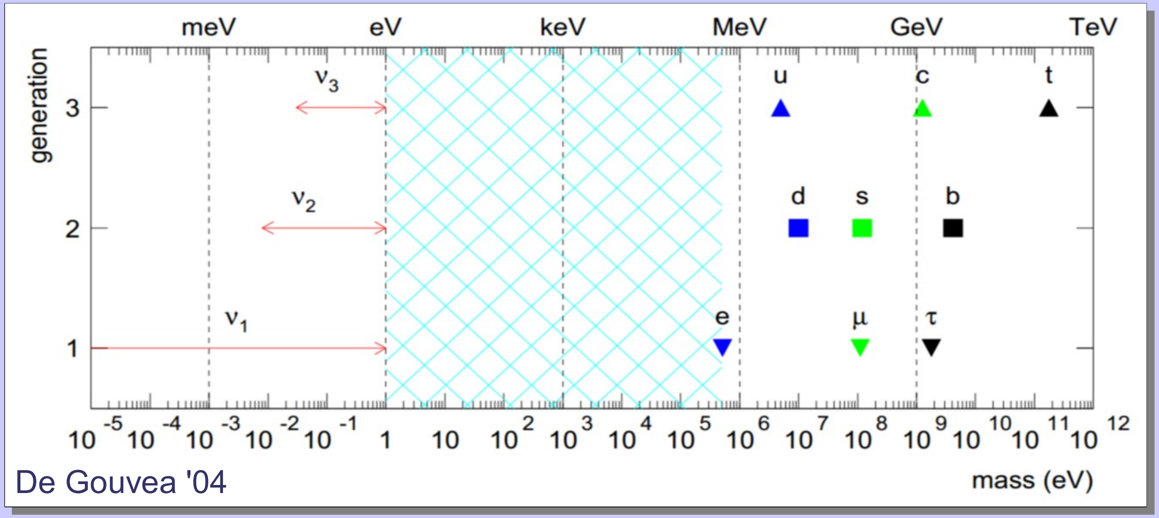
$$\Sigma = \sum_i m_i < 0.4 - 1\,\mathrm{eV}$$



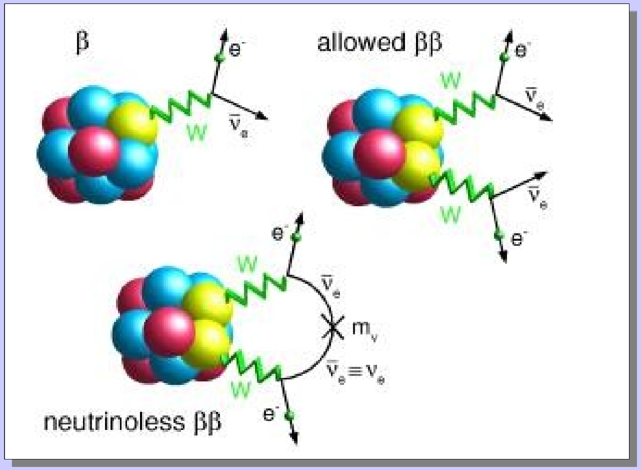
- **Neutrinoless Double Beta Decay**

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| < 0.2 - 2.0\,\mathrm{eV}$$

Future Experiments:
$m_{\beta\beta} \approx 0.01$ eV

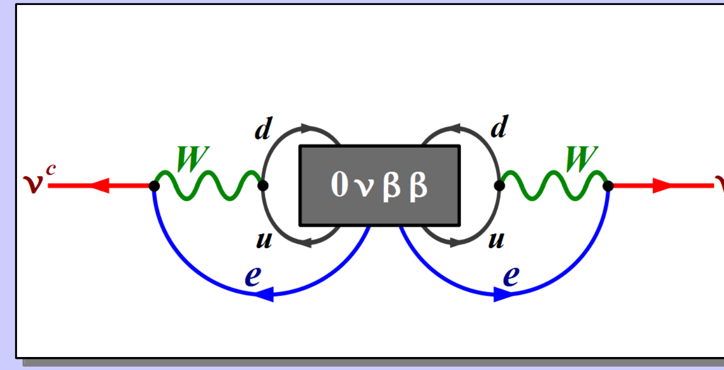


De Gouvea '04



Neutrinoless Double Beta Decay

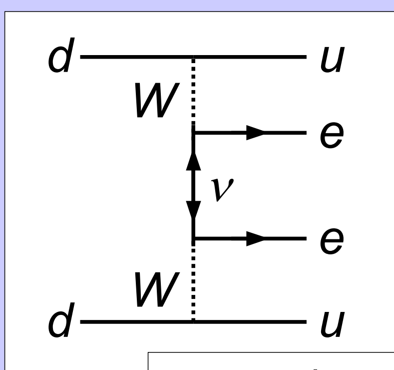
- **Process: $(A, Z) \rightarrow (A, Z+2) + 2e^-$**
- **Uncontroversial detection of $0\nu\beta\beta$ of utmost importance**
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter, Valle '82)



$$\delta m_\nu \approx \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23} \text{ eV}$$

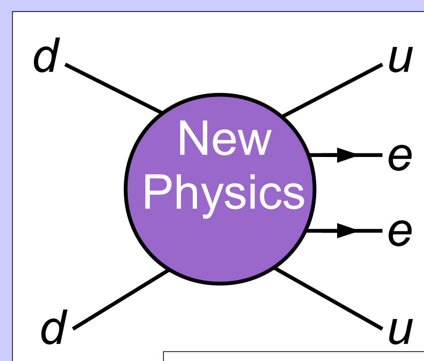
- **Which mechanism triggers the decay?**

Light Neutrino Exchange
(LH Current, Mass Mechanism)



$$T_{1/2}^{-1} \propto \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

General Effective Operator

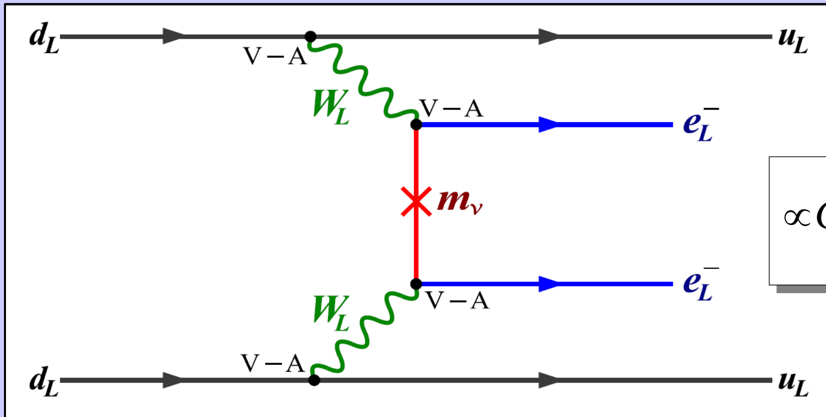


$$T_{1/2}^{-1} \approx 10^{25} \text{ y} \rightarrow M \approx 1 \text{ TeV}$$

$$\bar{u}\,\bar{u}\,\bar{e}\,\bar{e}\,d\,d\,/\,M^5$$

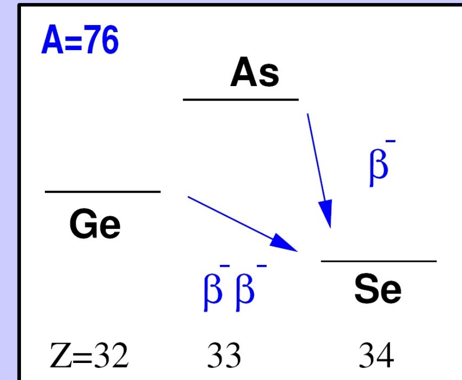
Light Neutrino Exchange

- **Standard Mass Mechanism**



$$\propto G_F^2 \sum_i U_{ei}^2 \gamma_\mu P_L \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu P_L$$

Heidelberg-Moscow
$T_{1/2}(^{76}Ge) \approx 1.9 \cdot 10^{25}$ y
$\langle m_\nu \rangle \approx (0.3 - 0.6)$ eV



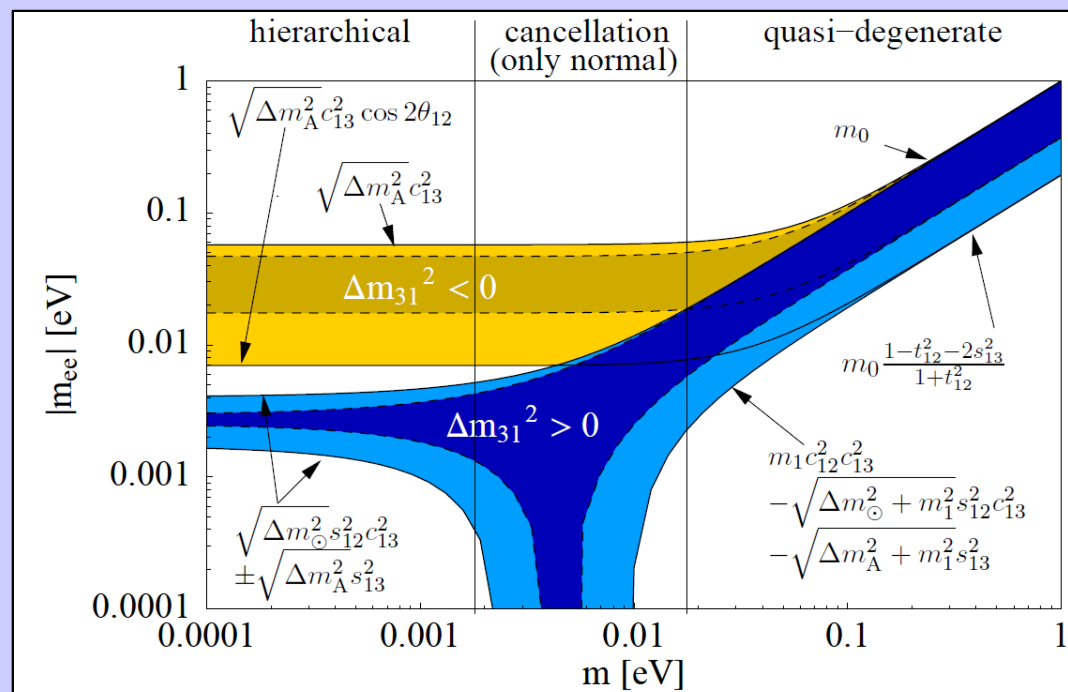
- **Decay Rate**

$$\Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} \left| M^{0\nu} \right|^2$$

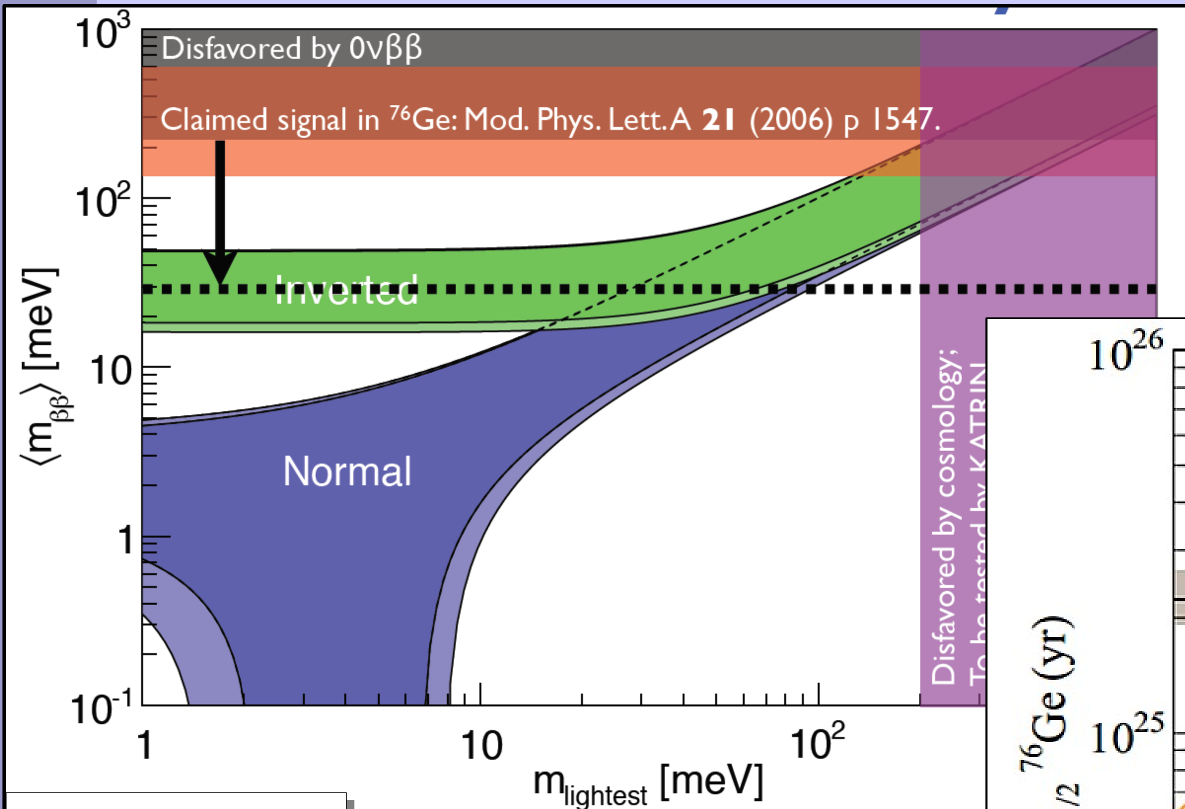
- **Effective Mass**

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| \equiv (m_\nu)_{ee}$$

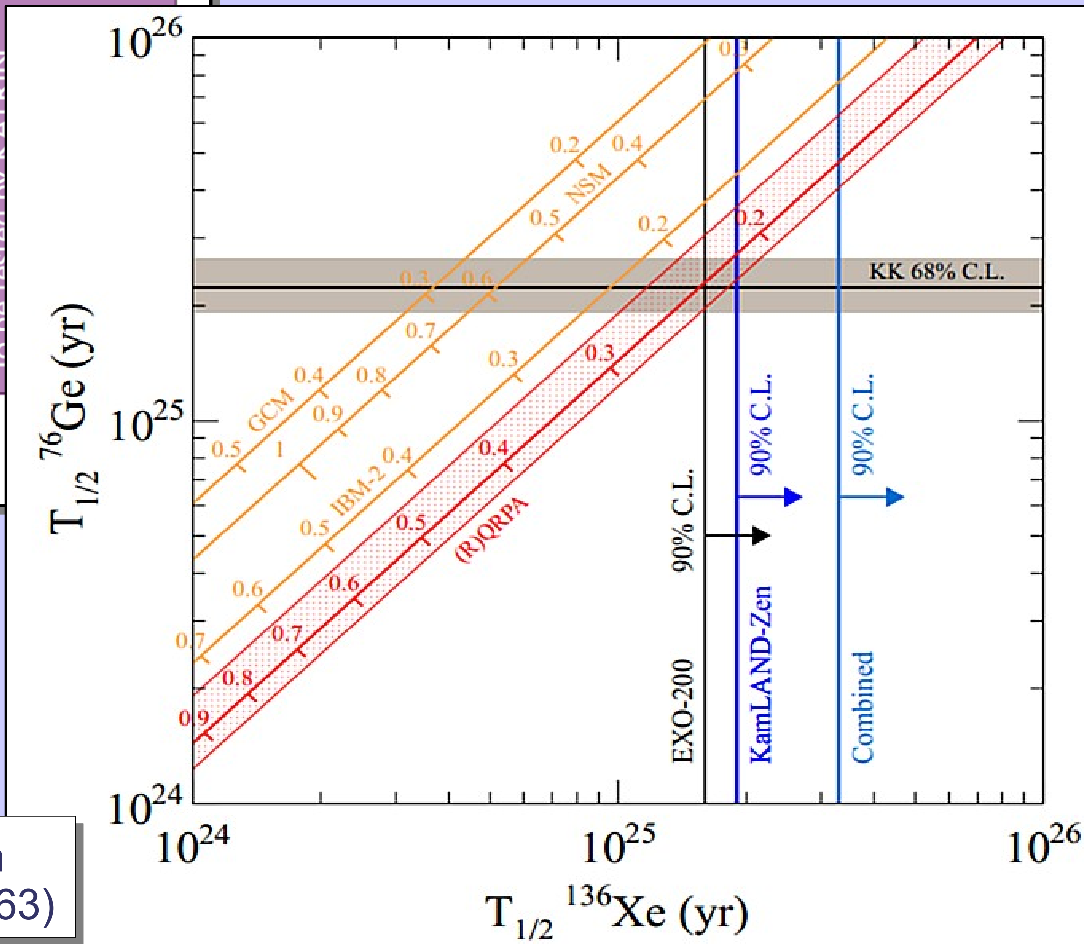
Lindner, Merle, Rodejohann (2005)



Experimental Situation



Detwiler (2012)



KamLAND-Zen (arXiv:1211.3863)

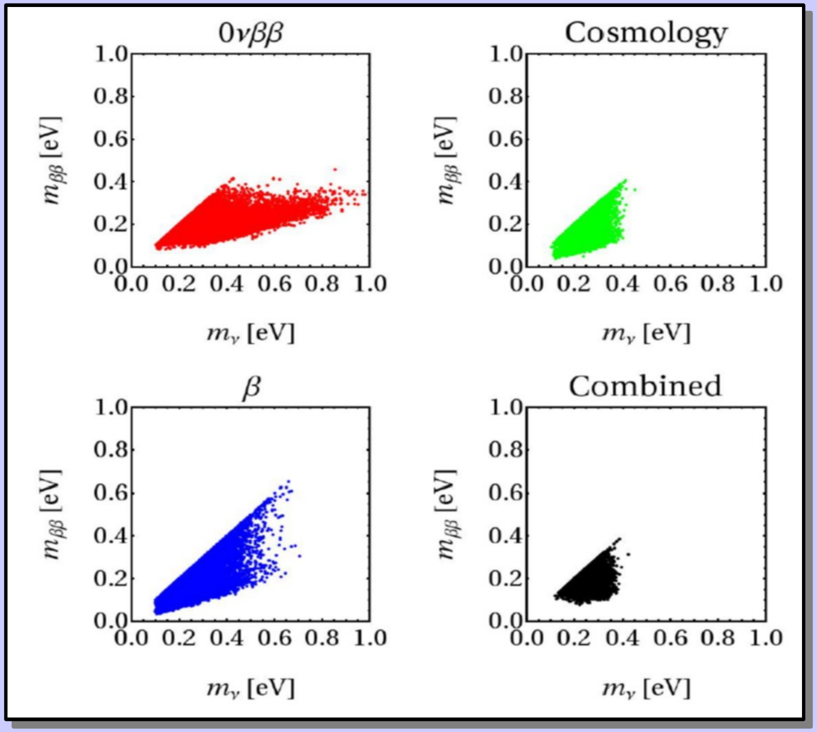
Probing Majorana CP Violation?

- **Effective $0\nu\beta\beta$ Observable**

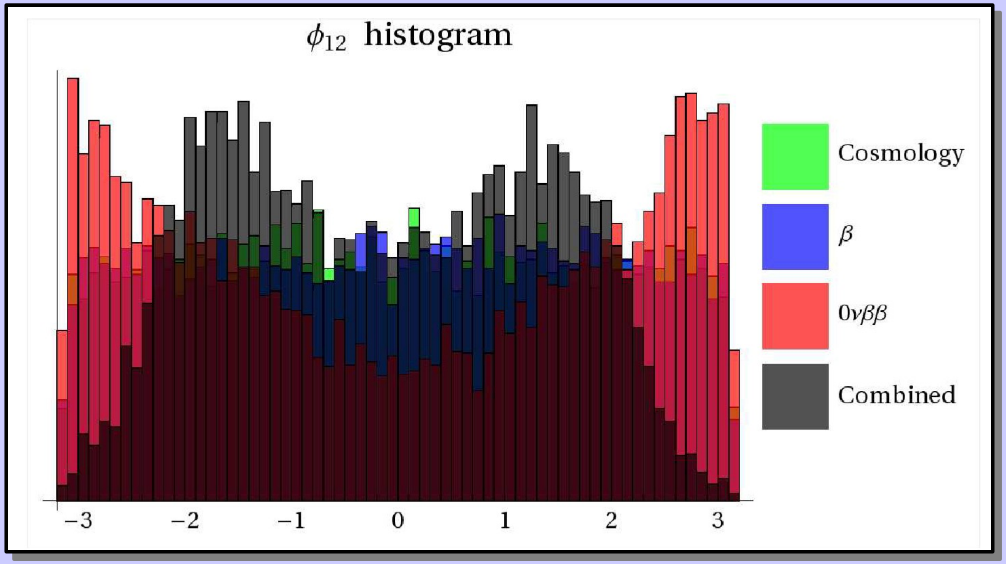
$$m_{\beta\beta} \equiv (m_\nu)_{ee} = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| = \left| m_{\nu_1} |V_{e1}|^2 + m_{\nu_2} |V_{e2}|^2 e^{2i\phi_{12}} + m_{\nu_3} |V_{e3}|^2 e^{2i\phi_{23}} \right|$$
$$\approx m_1^2 \sqrt{1 - \sin^2(2\theta_{12}) \sin^2(\phi_{12})} \quad \text{quasi-deg. neutrinos}$$

- **Interplay of mass probes**

(J. Auger, FFD, O. Lahav, D. Waters, J. Auger, work in progress)

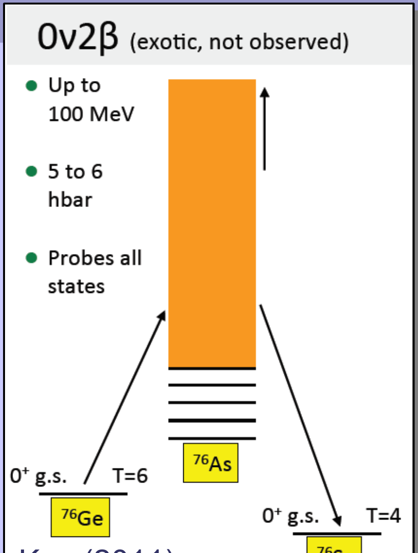


Simulation of observables incl. NME and expected exp. uncertainties with $m_{\nu_1} = 0.25\ \text{eV}, \phi_{12} = \pi/2$

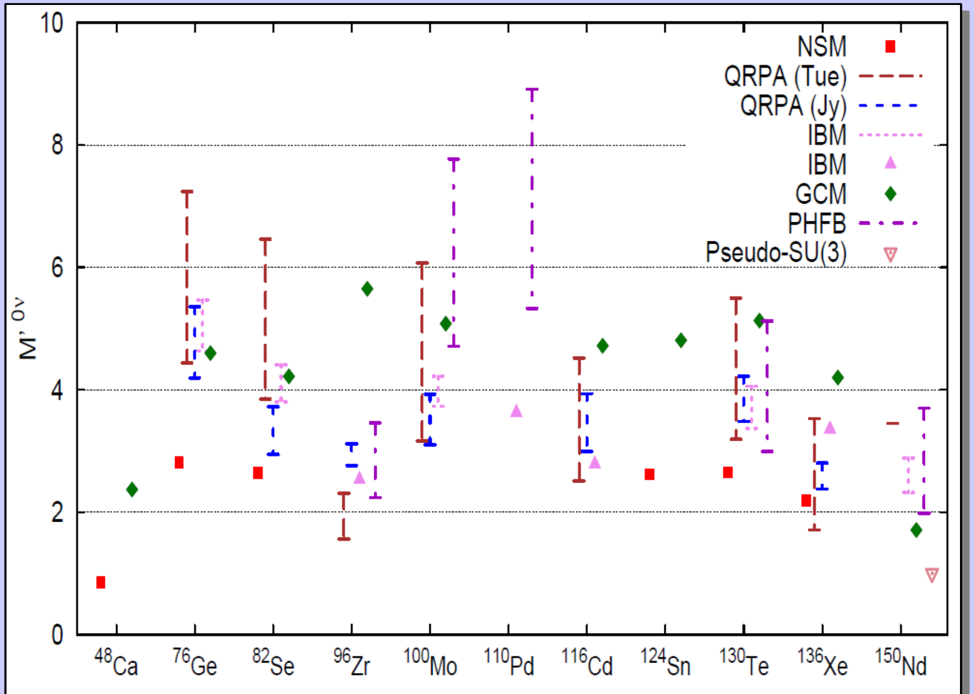


Nuclear Matrix Elements

- **Decay Rate** $$\Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2$$
- **Requires calculation of matrix element of the nuclear transition via intermediate state**
- **Many-body problem not solvable from first principle**
- **Factor 2 – 3 uncertainty between different nuclear models**
  - Shell Models
  - QRPA
  - IBM
- **Important to search for $0\nu\beta\beta$ in several isotopes**



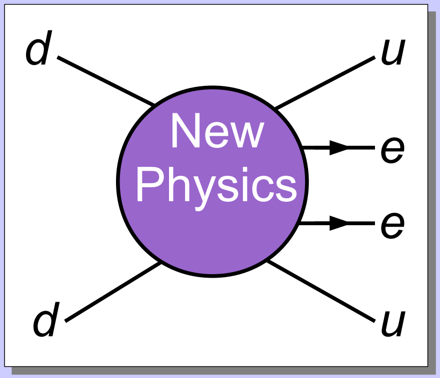
Kay (2011)



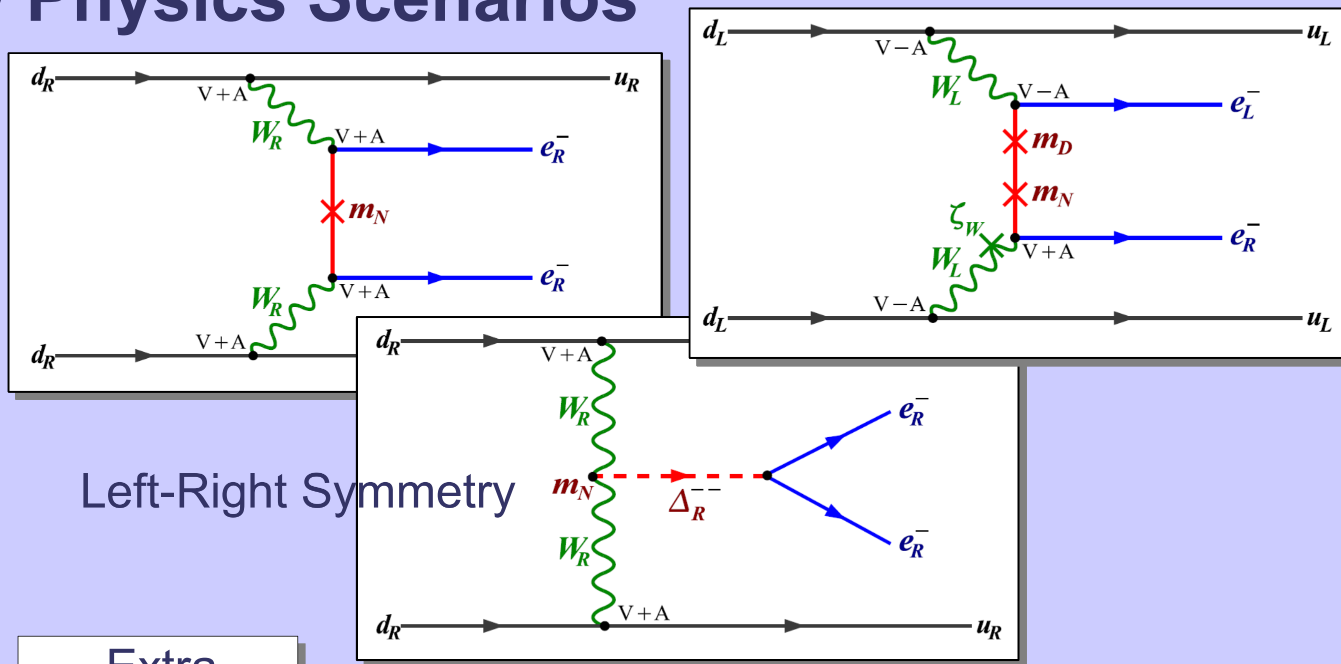
Rodejohann (2012)

New Physics Contributions to $0\nu\beta\beta$

- **Plethora of New Physics Scenarios**



=



Left-Right Symmetry

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

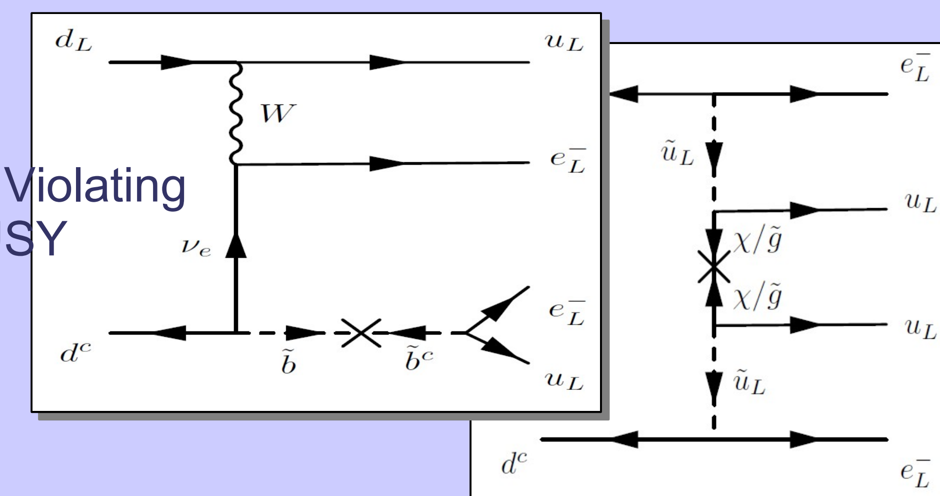
Extra Dimensions

Majorons

Leptoquarks

...

R-Parity Violating SUSY



- **Effective operator for Majorana neutrino mass**

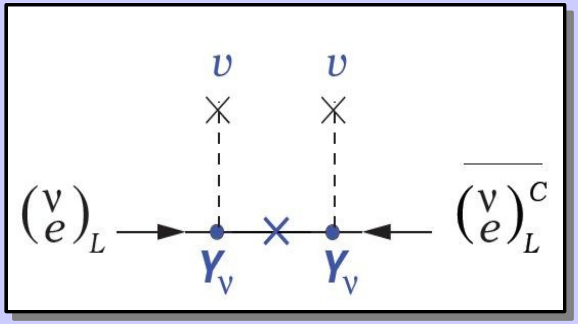
$$L=\frac{1}{2}\frac{h_{ij}}{\Lambda_{\mathrm{LNV}}}(\overline{L_i^c}\cdot\tilde{H})(\tilde{H}^T\cdot L_j)\rightarrow\frac{1}{2}(m_\nu)_{ij}\overline{\nu_i^c}\nu_j$$

Unique dim-5 Operator

- **Seesaw Mechanism**

  Add right-handed neutrinos to the Standard Model particle content, $M\approx 10^{14}\ \mathrm{GeV}$

$$L=L_{\mathrm{SM}}-\frac{1}{2}\bar{\nu}_R M\nu_R^c+\bar{\nu}_R Y_\nu L\cdot H_u$$



- **Light neutrino mass matrix at low energies**

$$m_\nu=m_D^T M^{-1} m_D \ \text{for}\ m_D\ll M_R \qquad m_\nu\approx 0.1\mathrm{eV}\left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2\left(\frac{M}{10^{14}\,\mathrm{GeV}}\right)^{-1}$$

Minimal Left-Right Symmetrical Model

- **Based on** $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Pati & Salam '74
Mohapatra & Senjanovic '75

- **Higgs Sector:**
  Bidoublet (EW Breaking)
  + Left-handed Triplet + Right-handed Triplet
  (Breaking Lepton Number + Parity + $SU(2)_R$)

- **Generating r.h. Neutrino + WR + ZR masses**

$$M_{N_i} \approx M_{W_R} \approx M_{Z_R} \approx < \Delta_R >$$

- **Charged current weak interactions**

$$J_W^{\mu-} = \frac{g_L}{\sqrt{2}} \left(\bar{\nu} U_{LL} + \bar{N}^c U_{LR} \right) \gamma^\mu e_L + \frac{g_R}{\sqrt{2}} \sin \zeta_W \left(\bar{\nu} U_{RL} + \bar{N} U_{RR} \right) \gamma^\mu e_R,$$

$$J_{W'}^{\mu-} = -\frac{g_L}{\sqrt{2}} \sin \zeta_W \left(\bar{\nu} U_{LL} + \bar{N} U_{LR} \right) \gamma^\mu e_L + \frac{g_R}{\sqrt{2}} \left(\bar{N} U_{RR} + \bar{\nu}^c U_{RL} \right) \gamma^\mu e_R,$$

Neutrinoless Double Beta Decay in the LRSM

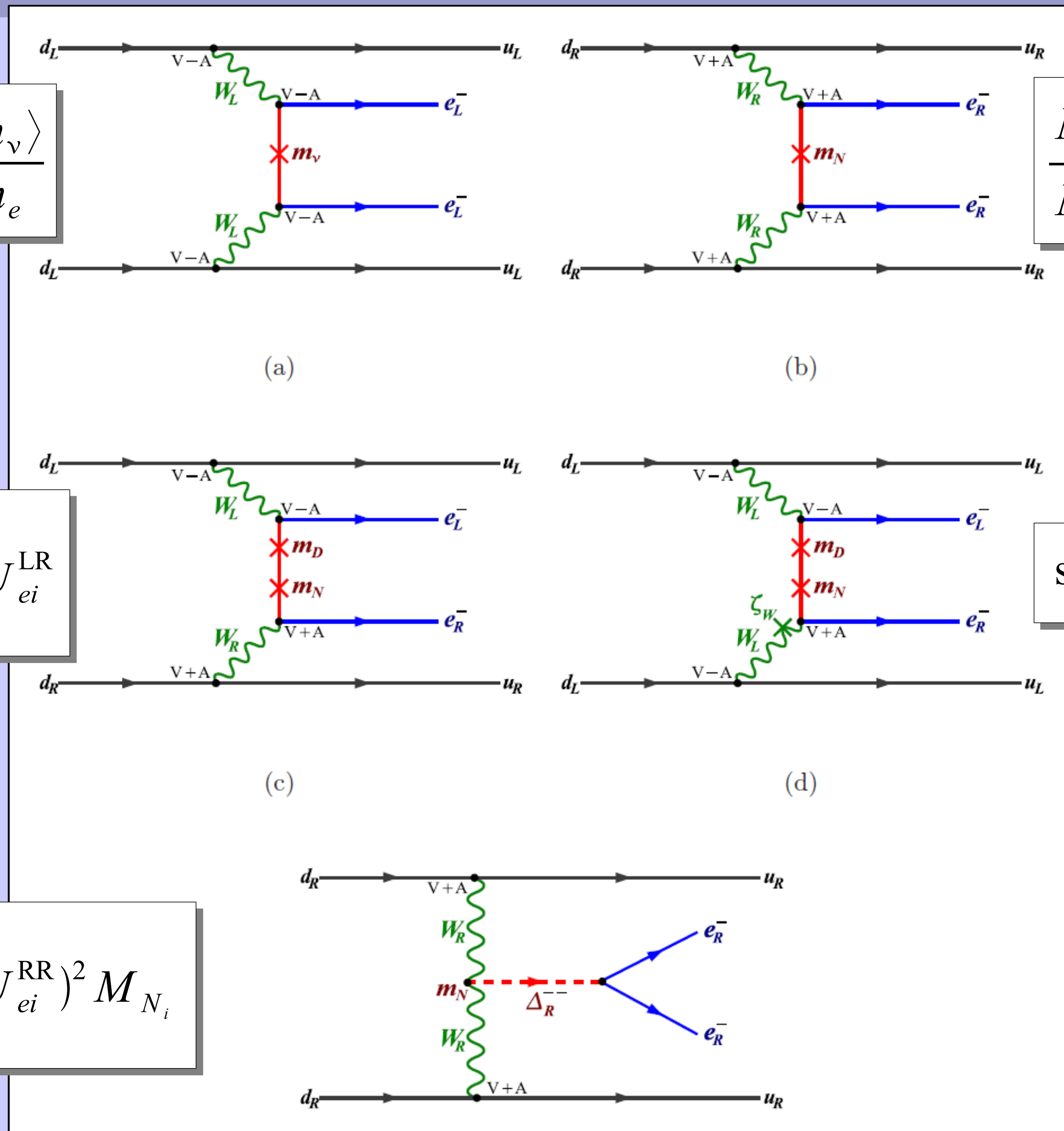
$$\sum_i (U_{ei}^{\mathrm{LL}})^2 \frac{m_{\nu_i}}{m_e} = \frac{\langle m_\nu \rangle}{m_e}$$

$$\frac{M_{W_L}^4}{M_{W_R}^4} \sum_i \frac{(U_{ei}^{\mathrm{RR}})^2}{M_{N_i}}$$

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_i U_{ei}^{\mathrm{LL}} U_{ei}^{\mathrm{LR}}$$

$$\sin^2\zeta \sum_i U_{ei}^{\mathrm{LL}} U_{ei}^{\mathrm{LR}}$$

$$\frac{M_{W_L}^4}{M_{W_R}^4} \frac{m_p}{M_{\Delta_R^{--}}^2} \sum_i (U_{ei}^{\mathrm{RR}})^2 M_{N_i}$$

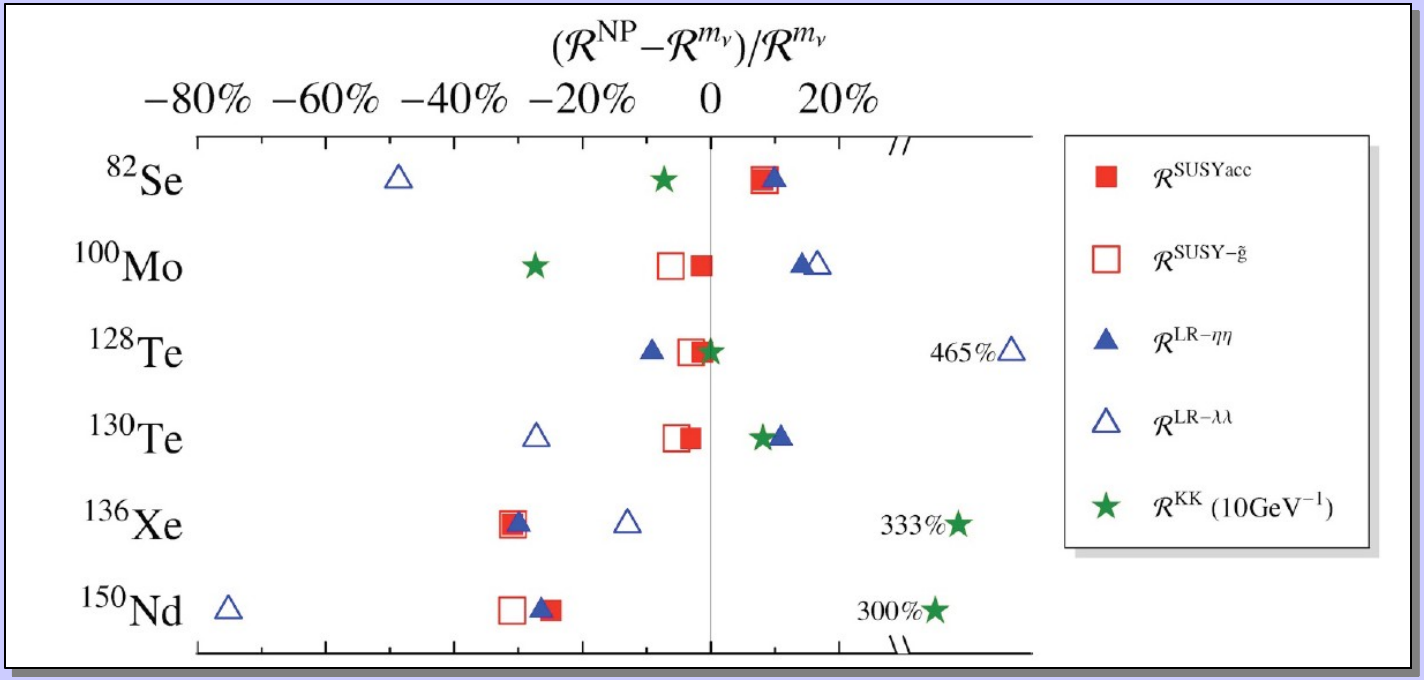


Disentangling New Physics Scenarios

- **Comparison of $0\nu\beta\beta$ in multiple isotopes**
  (FFD, Päs PRL 2007)

$$\frac{T_{1/2}(^{A}\mathrm{X})}{T_{1/2}(^{B}\mathrm{Y})} = \frac{G(^{B}\mathrm{Y})\left|M(^{B}\mathrm{Y})\right|^2}{G(^{A}\mathrm{X})\left|M(^{A}\mathrm{X})\right|^2}$$

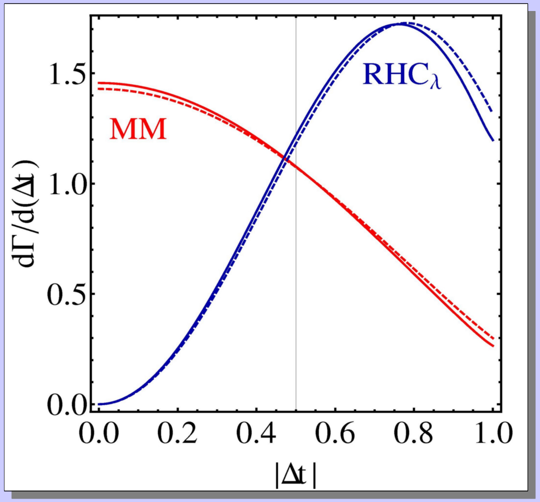
- Depends on $0\nu\beta\beta$ mechanism
- Independent of details of new physics (if one mechanism dominates)
- Important to search for $0\nu\beta\beta$ in several isotopes



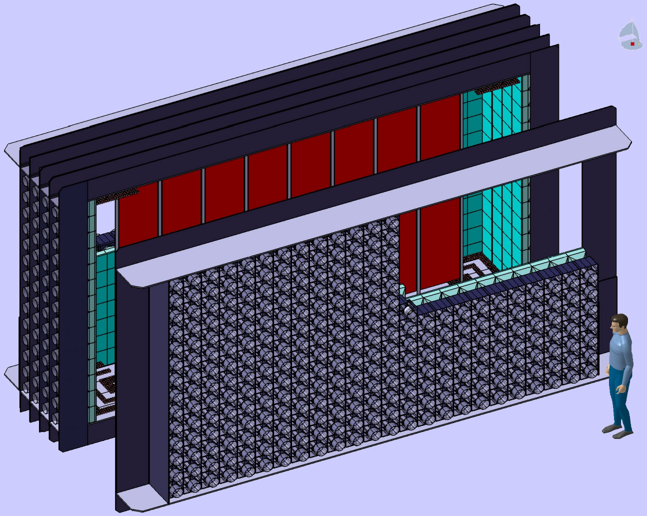
Disentangling New Physics Scenarios

- **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)

$$\frac{d\Gamma}{dE_1\,dE_2\,d\cos\theta} = \frac{\Gamma}{2}\left(1 - k(E_1, E_2)\cos\theta\right) \qquad -1 < k < 1$$

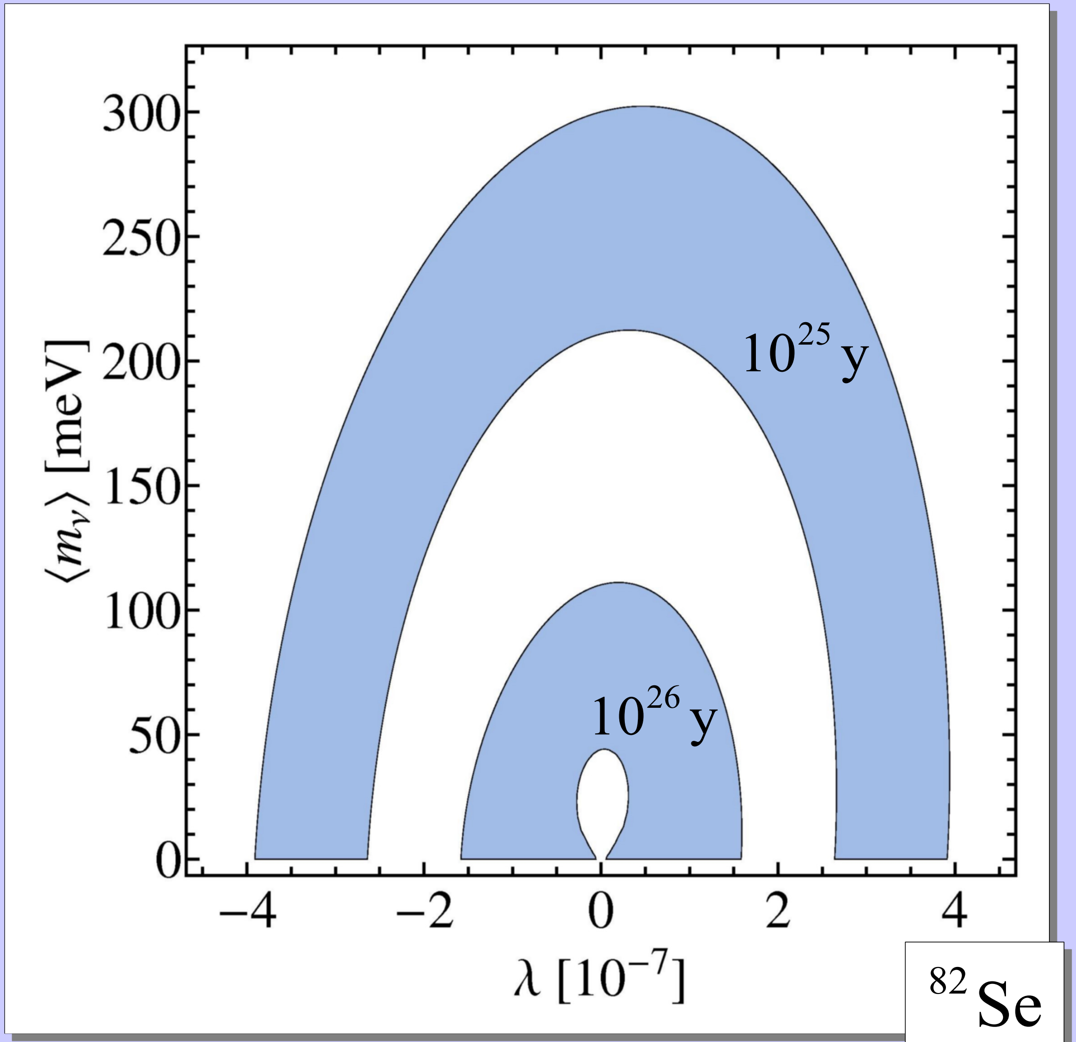


- Linear in $\cos\theta$
- $k(E_1, E_2)$ depends on $0\nu\beta\beta$ mechanism
- Requires measurement of individual electron energies and tracking
- Testable at SuperNEMO
  - Calorimetry and Tracking: Individual electron tracks, vertices and energies
  - Expected sensitivity
    $T_{1/2}$ = 2×10^{26} years
    $\langle m_\nu \rangle$ = 50-90 meV



Angular and Energy Correlations

- **Constraints on the parameter space**
  - Half-life measurement

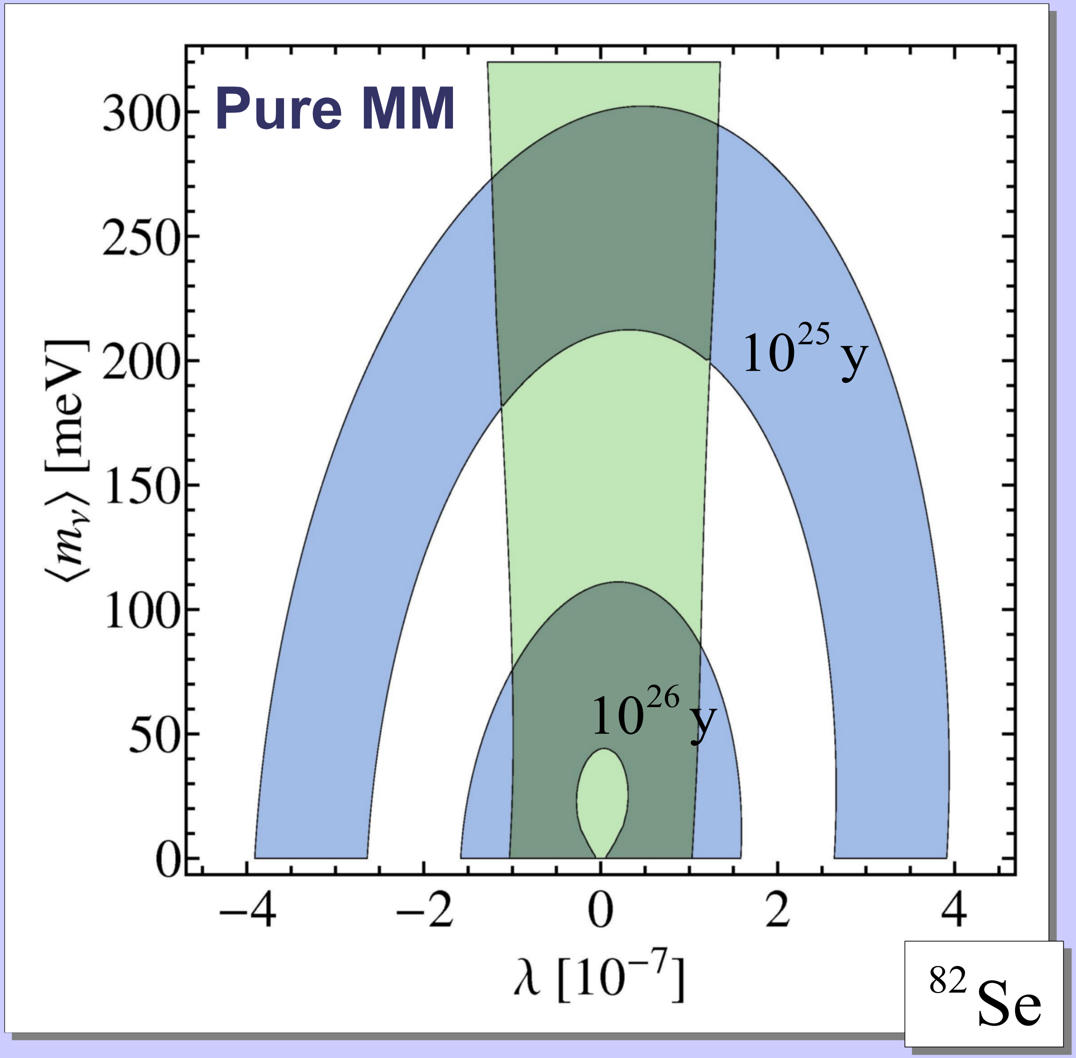


Arnold et al. (2012)

- **Statistical uncertainties from simulation**
- **Theoretical nuclear matrix element uncertainty: 30%**

Angular and Energy Correlations

- **Constraints on the parameter space**
  - Half-life measurement
  - Angular correlation

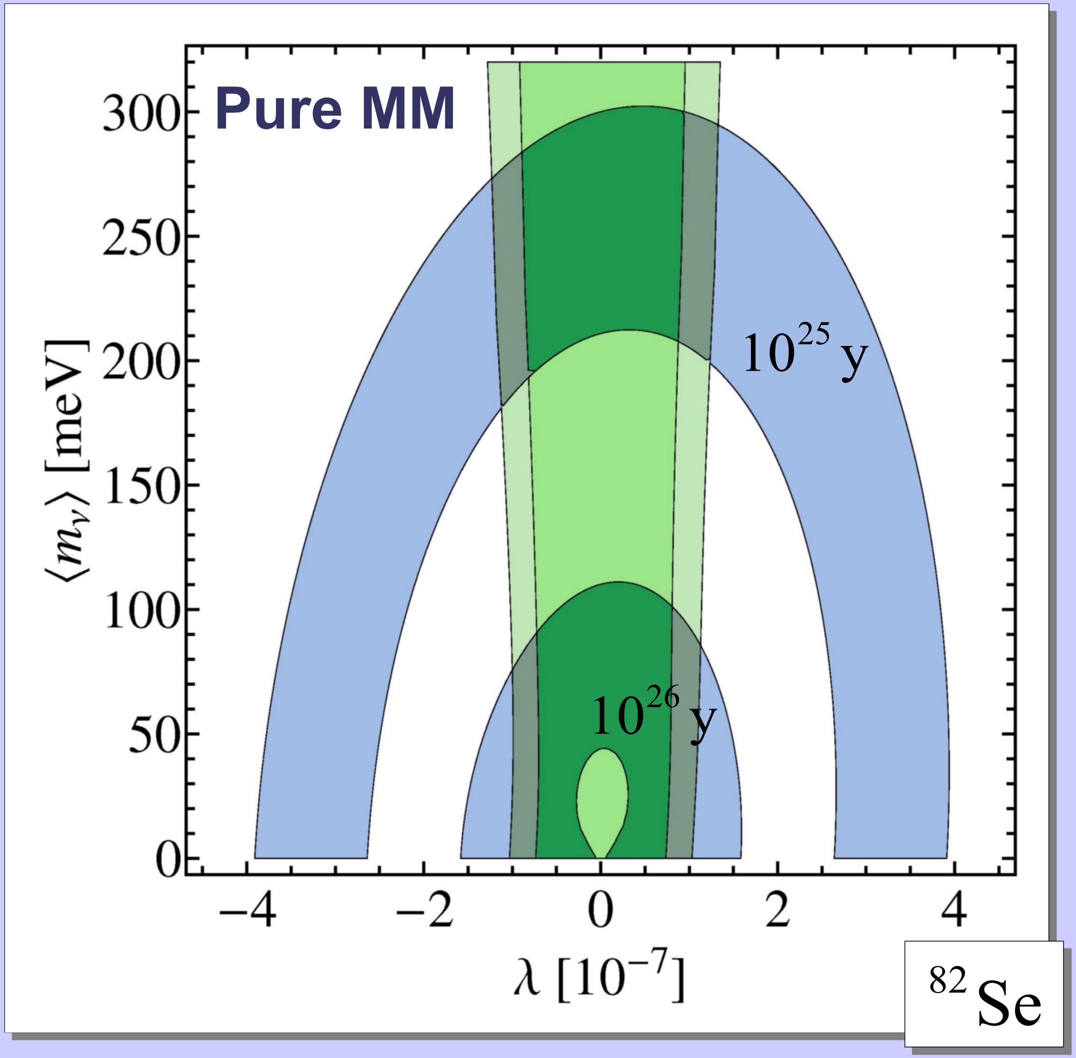


Arnold et al. (2012)

- **Statistical uncertainties from simulation**
- **Theoretical nuclear matrix element uncertainty: 30%**

Angular and Energy Correlations

- **Constraints on the parameter space**
  - Half-life measurement
  - Angular correlation
  - Energy correlation

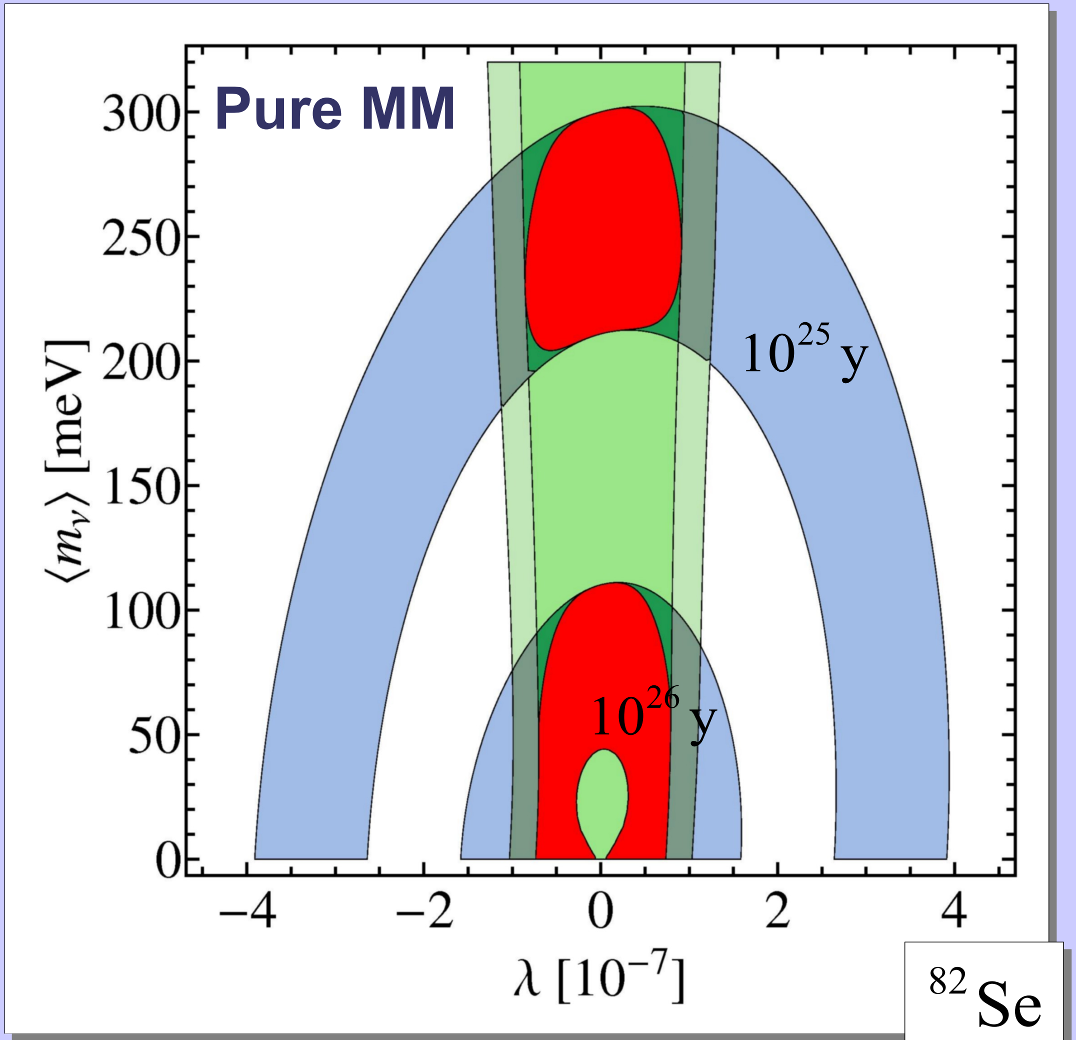


Arnold et al. (2012)

- **Statistical uncertainties from simulation**
- **Theoretical nuclear matrix element uncertainty: 30%**

Angular and Energy Correlations

- **Constraints on the parameter space**
  - Half-life measurement
  - Angular correlation
  - Energy correlation
  - Combined 1σ area

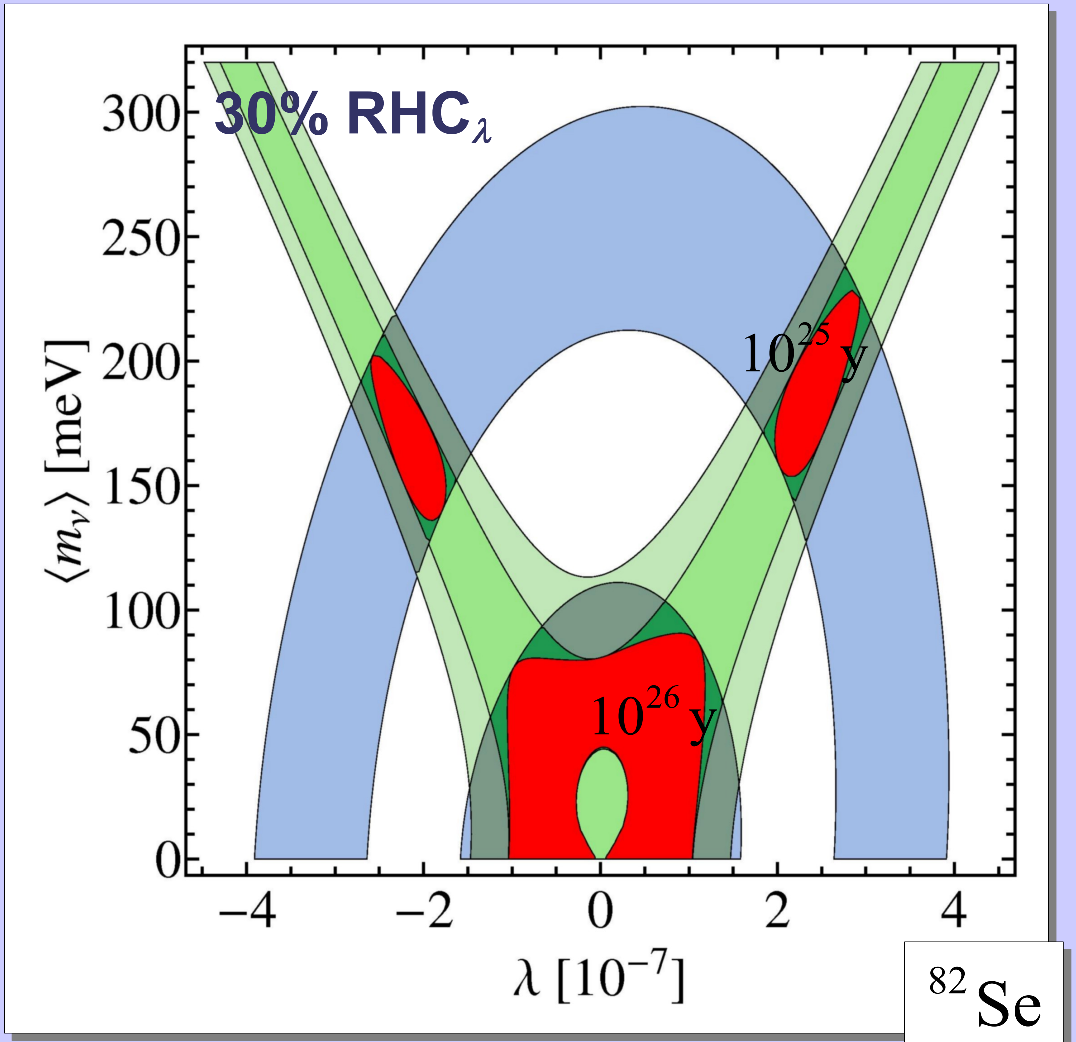


Arnold et al. (2012)

- **Statistical uncertainties from simulation**
- **Theoretical nuclear matrix element uncertainty: 30%**

Angular and Energy Correlations

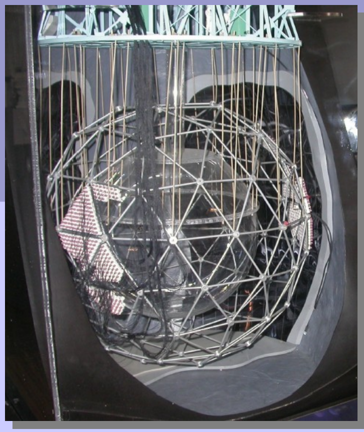
- **Constraints on the parameter space**
  - Half-life measurement
  - Angular correlation
  - Energy correlation
  - Combined 1σ area



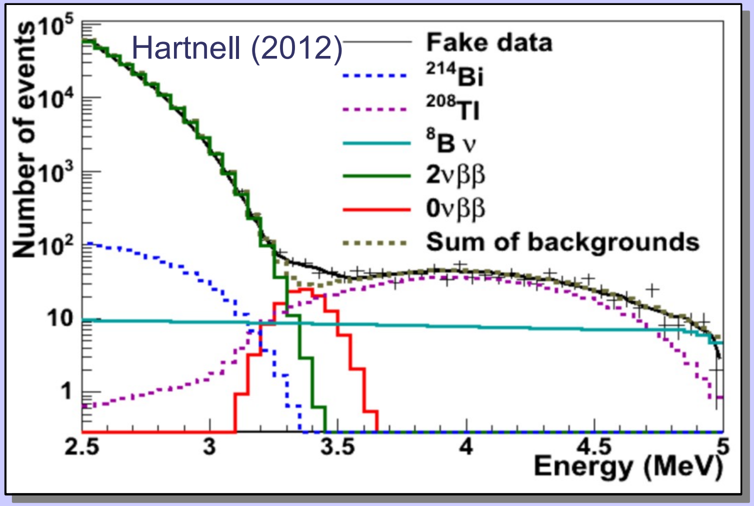
Arnold et al. (2012)

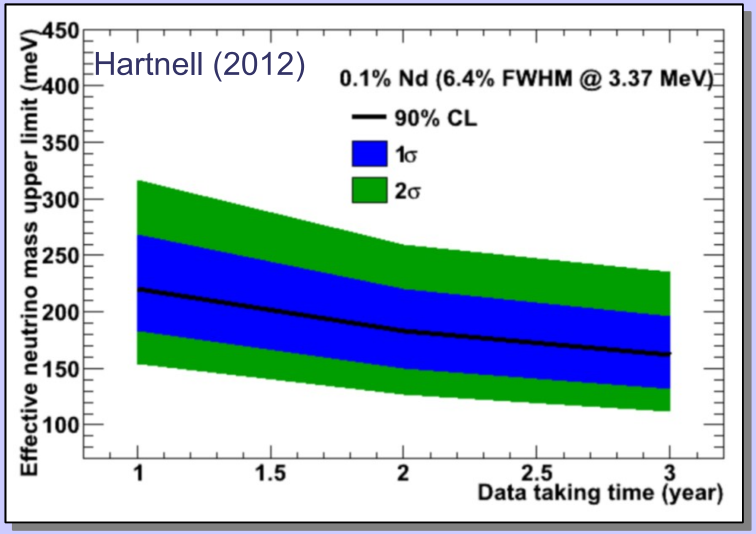
- **Statistical uncertainties from simulation**
- **Theoretical nuclear matrix element uncertainty: 30%**

SNO+

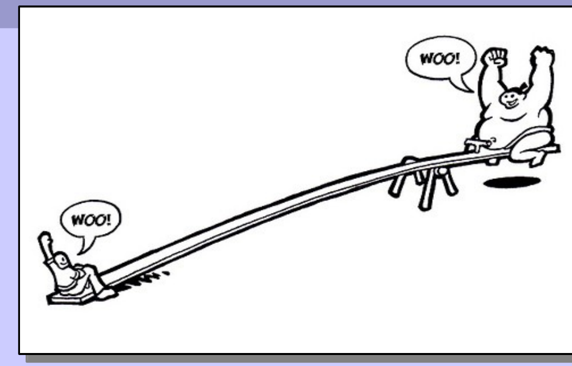


- **Search for low energy solar, geo-, reactor and Supernova neutrinos**
- **Search for $0\nu\beta\beta$ in ^{150}Nd**
  - Loaded in liquid scintillator
    (0.1%, ~ 50 kg ^{150}Nd)
  - Good isotope for $0\nu\beta\beta$ discovery
    (Large phase space, large Q value, good natural abundance)
  - Large nuclear deformation
    (NME uncertainty?)
- **Sensitivity to New Physics?**
  - Work in progress
    J. Hartnell, A. Back (Sussex),
    F. di Lodovico (QMUL), FFD (UCL)
  - Majoron modes
  - Possible upgrades and other isotopes

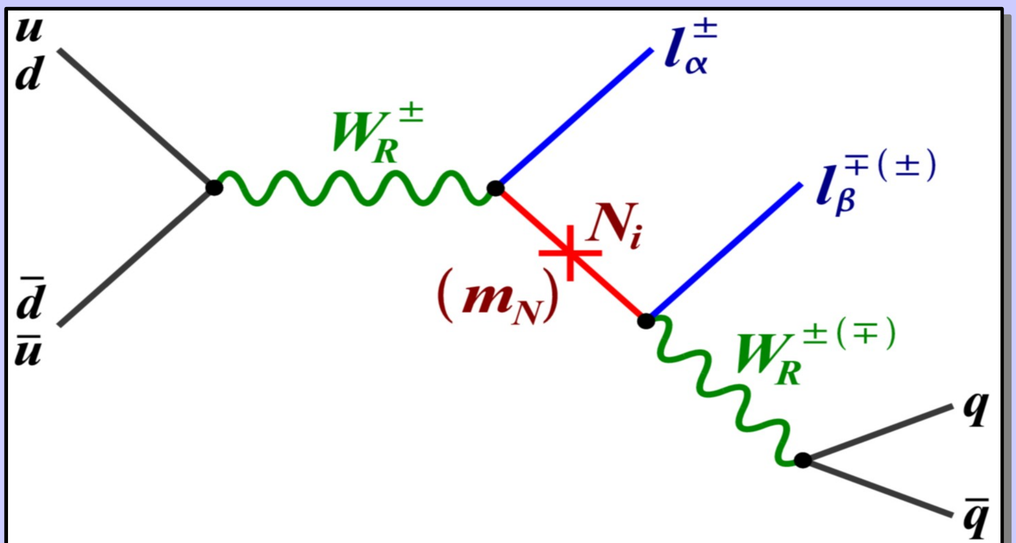




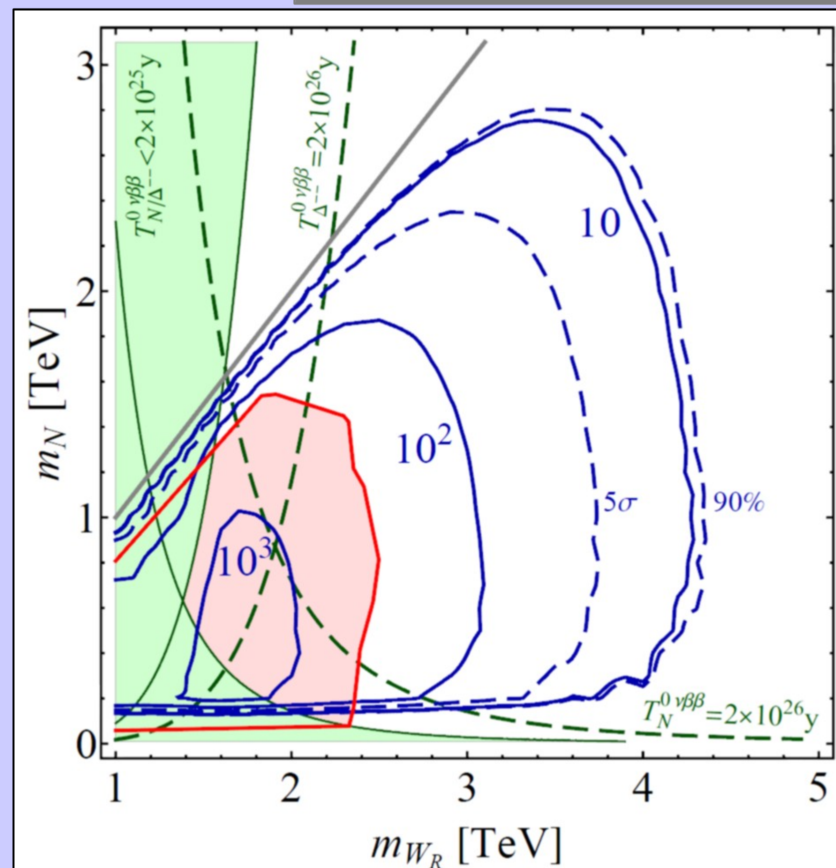
Lepton Number Violation at the LHC



- **Inverse or "Bent" Seesaw mechanism**
- **R-Parity Violating SUSY**
- **Left-Right symmetric models**
  Right-handed neutrinos couple with gauge strength to charged leptons



Probing right-handed neutrino mixing,
Large LFV and LNV rates at LHC



Das, FFD, Kittel, Valle (2012)

Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass

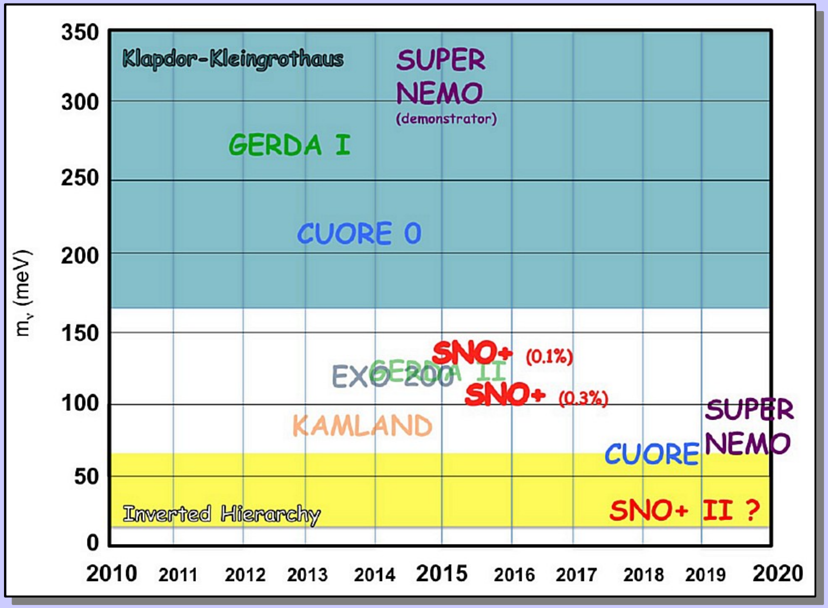
Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass
- **Neutrinos are the only neutral fermions**
  Dirac or Majorana? Lepton Number Violation?

Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass
- **Neutrinos are the only neutral fermions**
  Dirac or Majorana? Lepton Number Violation?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - ***Hope for the best***
    New LNV physics at the EW scale
  - ***Prepared for the worst***
    Only 5-dim operator from LNV
    at the GUT scale

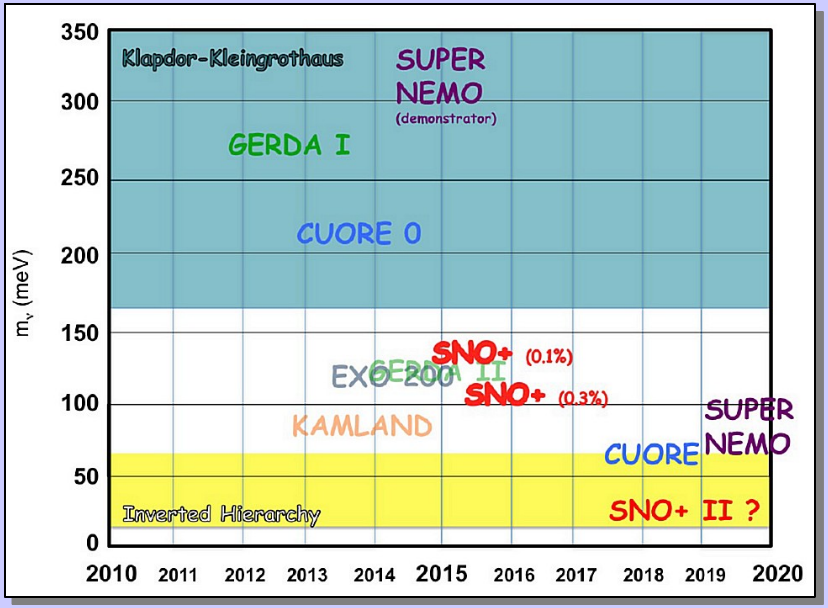
Lefeuvre (2011)



Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass
- **Neutrinos are the only neutral fermions**
  Dirac or Majorana? Lepton Number Violation?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - ***Hope for the best***
    New LNV physics at the EW scale
  - ***Prepared for the worst***
    Only 5-dim operator from LNV
    at the GUT scale

Lefeuvre (2011)



- **Neutrino impact on cosmology**
  Baryogenesis via Leptogenesis?
- **Rich phenomenology in models of neutrino mass generation**
  - Charged lepton flavour violation
  - LFV and LNV processes at the LHC