Double-Beta Decay, Nuclear Structure, and Neutrino Physics

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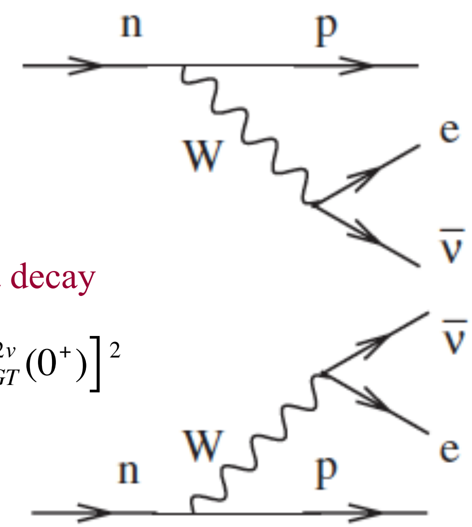
Overview

- Neutrino physics within and beyond the Standard Model
- DBD mechanisms: light Majorana neutrino exchange, right-handed currents, heavy neutrinos, SUSY R-parity violation,…
- ^{48}Ca: 2*ν* and 0*ν* shell-model matrix elements
  - The effect of larger model spaces
  - Beyond closure approximation
- ^{136}Xe, ^{82}Se, and ^{76}Ge results

Classical Double Beta Decay Problem

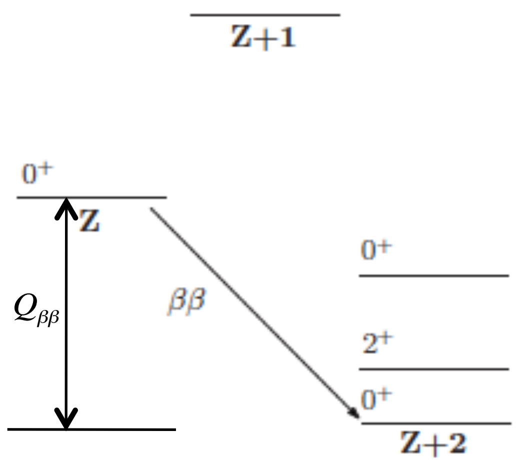
Isotope	$T_{1/2}(2\nu)$ (years)	$M^{2\nu}$
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$	$0.0238^{+0.0015}_{-0.0017}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	$0.0716^{+0.0025}_{-0.0023}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	$0.0503^{+0.0020}_{-0.0018}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	$0.0491^{+0.0023}_{-0.0020}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$	$0.1258^{+0.0037}_{-0.0034}$
^{100}Mo-^{100}Ru(0_1^+)	$5.9^{+0.8}_{-0.6} \times 10^{20}$	$0.1017^{+0.0056}_{-0.0063}$
^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$	$0.0695^{+0.0025}_{-0.0024}$
^{128}Te	$(1.9 \pm 0.4) \times 10^{24}$	$0.0249^{+0.0031}_{-0.0023}$
^{130}Te	$(6.8^{+1.2}_{-1.1}) \times 10^{20}$	$0.0175^{+0.0016}_{-0.0014}$
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$	$0.0320^{+0.0018}_{-0.0017}$
^{150}Nd-^{150}Sm(0_1^+)	$1.33^{+0.45}_{-0.26} \times 10^{20}$	$0.0250^{+0.0029}_{-0.0034}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$	$0.0271^{+0.0053}_{-0.0033}$
^{136}Xe	2.23×10^{21}	0.020

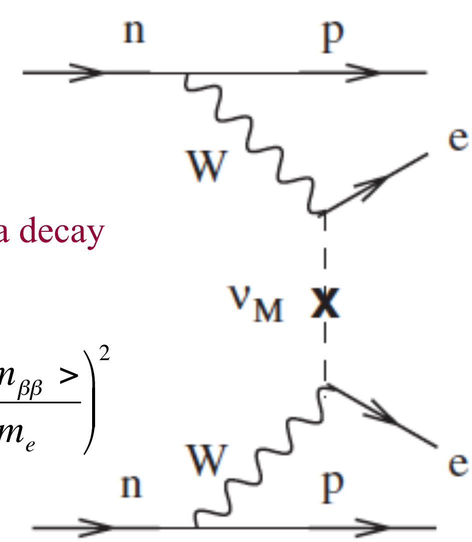
A.S. Barabash, PRC 81 (2010)



2-neutrino double beta decay

$$T_{1/2}^{-1}(2\nu) = G^{2\nu}(Q_{\beta\beta})\left[M_{GT}^{2\nu}(0^+)\right]^2$$





neutrinoless double beta decay

$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2\left(\frac{< m_{\beta\beta} >}{m_e}\right)^2$$

$$\langle m_{\beta\beta}\rangle = \left|\sum_k m_k U_{ek}^2\right|$$

Adapted from Avignone, Elliot, Engel, Rev. Mod. Phys. 80, 481 (2008) -> RMP08

Neutrino Masses

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$
$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

PMNS – matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{12} \equiv \cos\theta_{12},\ s_{12} = \sin\theta_{12},\ etc$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2 (solar)$$
$$|\Delta m^2_{32}| \approx 2.4 \times 10^{-3}\ eV^2 (atmospheric)$$

- Tritium decay:

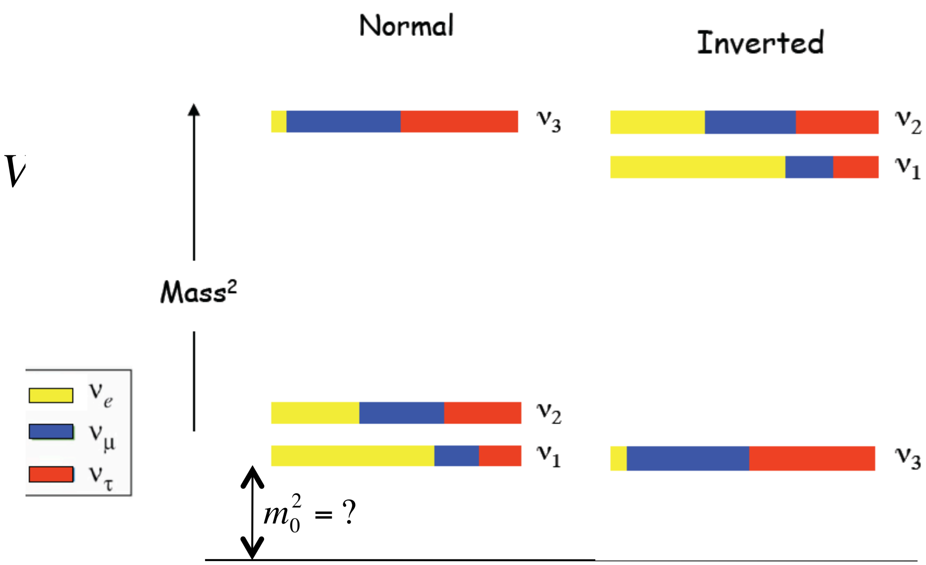
$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.2 eV\ (Mainz\ \exp.)$$

$KATRIN$ exp. ($in\ progress$): $goal\ \ m_{\nu_e} < 0.3 eV$

- Cosmology: CMB power spectrum, BAO, etc,

$$\sum_{i=1}^{3} m_i < 0.23 eV$$



Two neutrino mass hierarchies

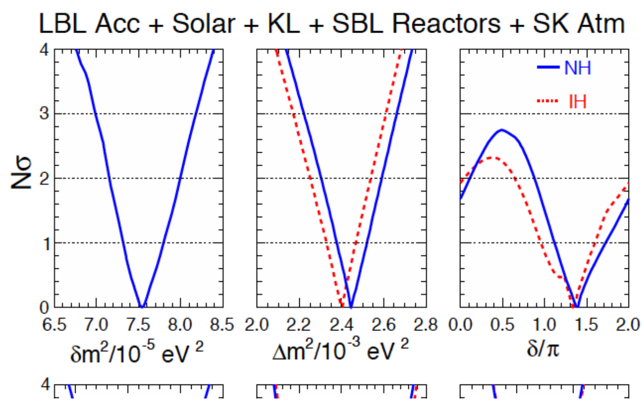
Neutrino Oscillations

$$D = Diag\left[e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1\right]$$

$$U_{PMNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} D$$

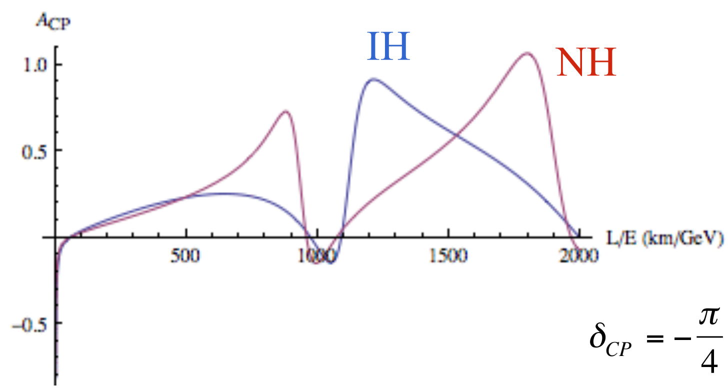
- NH or IH?
- $\delta_{CP} = ?$, θ_{23} octant?

$$|U_{PMNS}| \approx \begin{bmatrix} 0.82 & 0.55 & 0.15 \\ 0.50 & 0.57 & 0.65 \\ 0.27 & 0.61 & 0.74 \end{bmatrix}$$



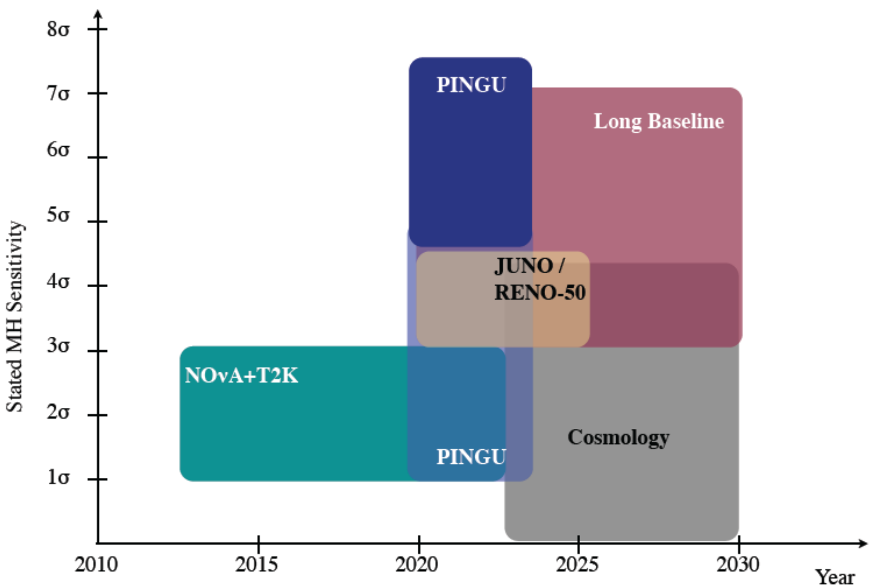
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

LBNE – arXiv:1307.7335



$$\delta_{CP} = -\frac{\pi}{4}$$

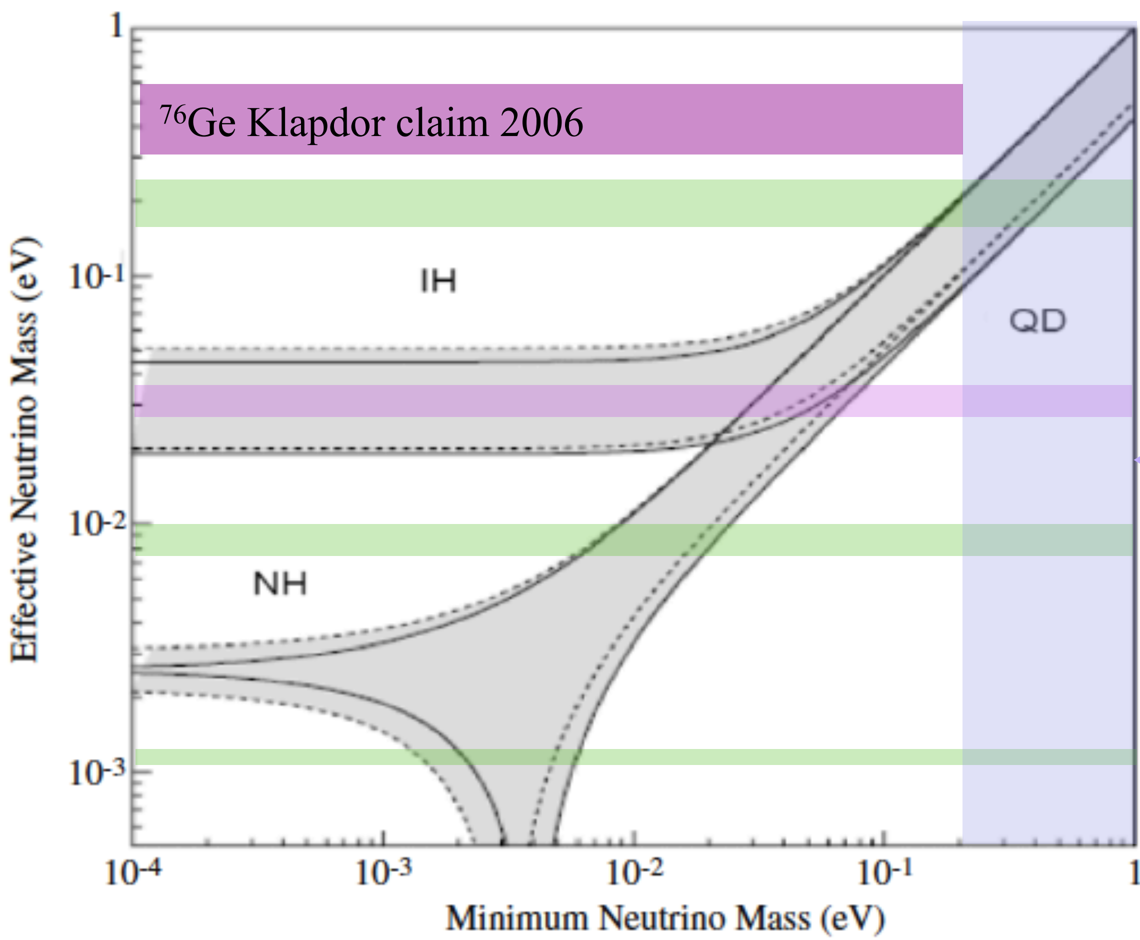
Matter effects not included



- Dirac or Majorana?
- $\alpha_i = ?$
- Unitarity of U_{PMNS}?
- Are there $m \sim 1eV$ sterile neutrinos?
- Leptogenesis? → Baryogenesis

Neutrino ββ effective mass

H. Ejiri / Progress in Particle and Nuclear Physics 64 (2010) 249–257



CMB constraint

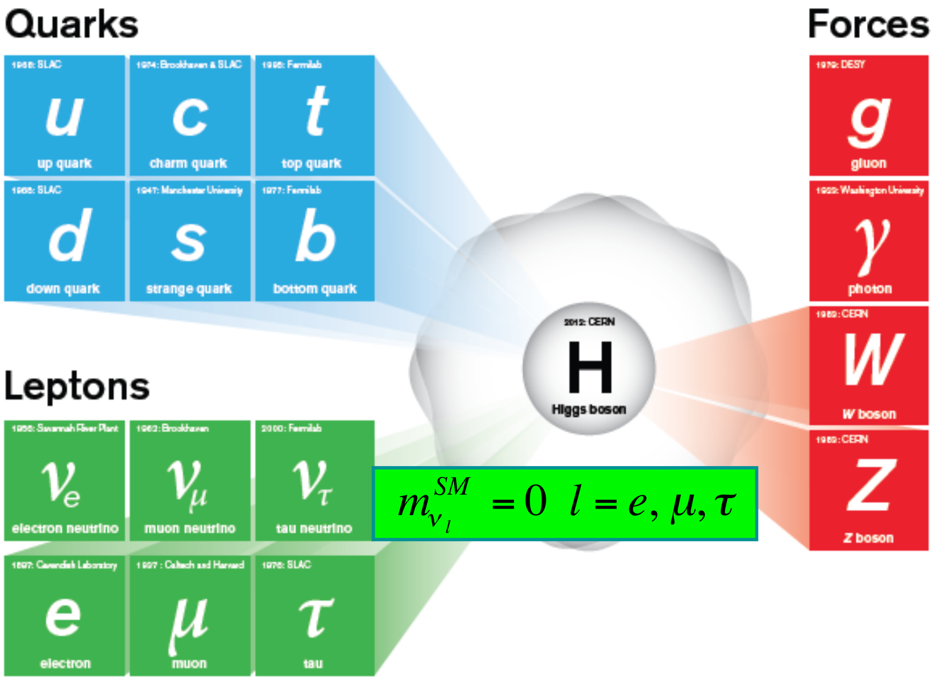
$$\langle m_{\beta\beta} \rangle = \left| \sum_{k=1}^{3} m_k U_{ek}^2 \right|$$

$$= \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

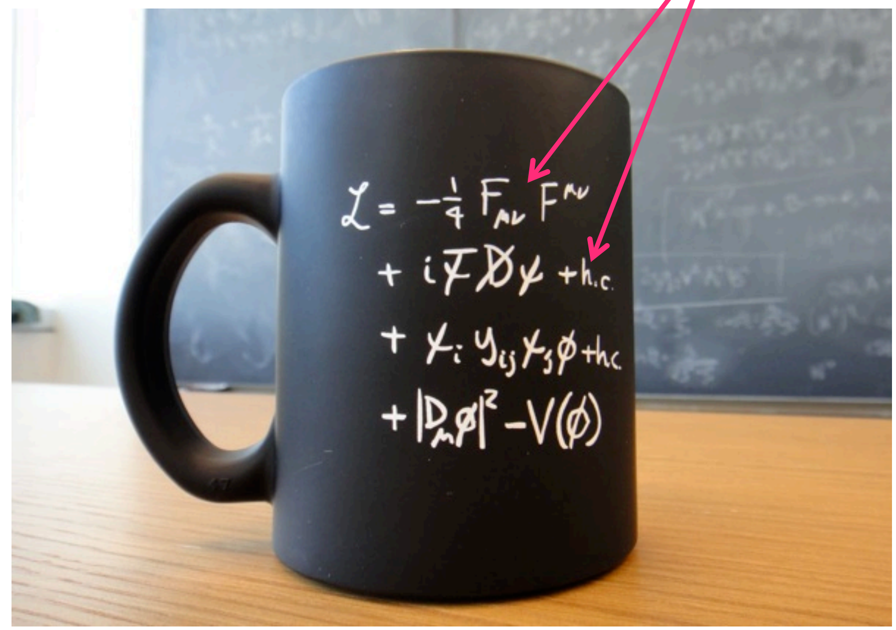
$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta}) \left[M^{0\nu}(0^+) \right]^2 \left(\frac{< m_{\beta\beta} >}{m_e} \right)^2$$

The Minimal Standard Model



$$m_{\nu_l}^{SM} = 0 \quad l = e, \mu, \tau$$



?

$SU(2)_L$ doublet

SM fermion masses:

$$\overline{\psi}_{iL} Y_{ij} \psi_{jR} \phi \rightarrow Y_{ij} < \phi > \overline{\psi}_{iL} \psi_{jR} = \left(m_D\right)_{ij} \overline{\psi}_{iL} \psi_{jR}$$

$SU(2)_L$ doublet $\quad$ $SU(2)_L$ singlet

$\rightarrow$ *neutrino is sterile:* $D_\mu = I\partial_\mu$

Local Gauge invariance of Lagrangian density $\mathcal{L}$:

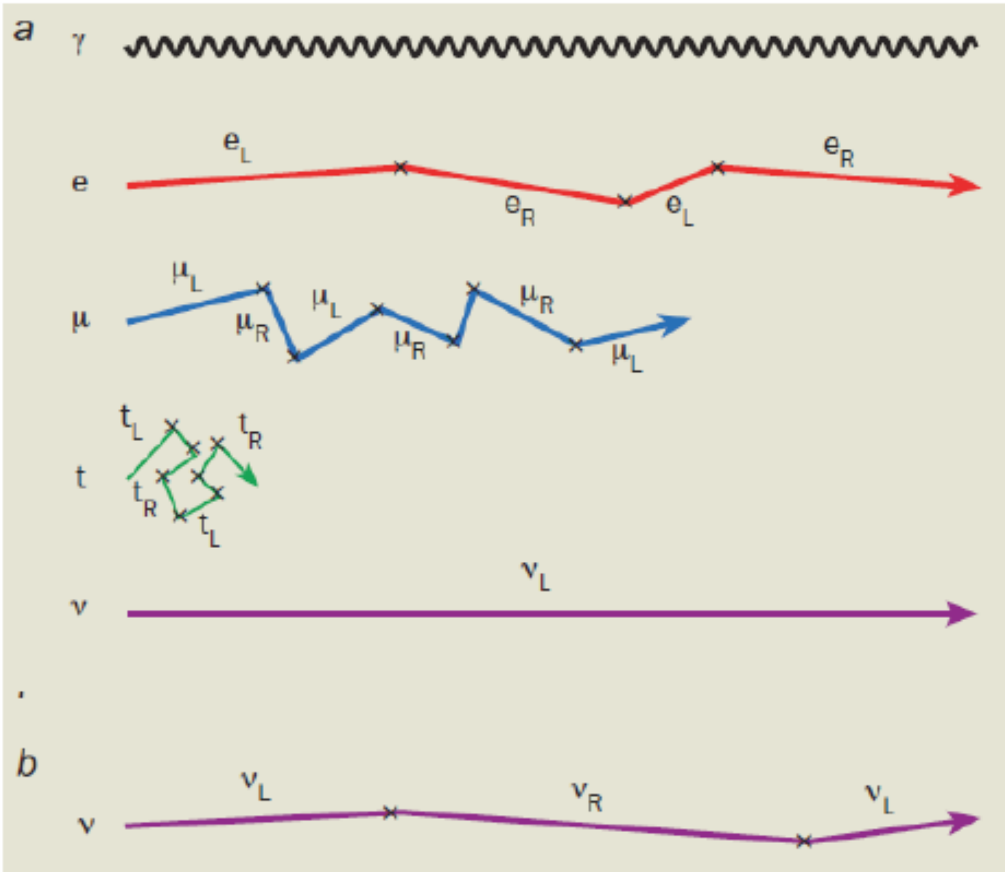
$$\psi \rightarrow U(x)\psi \quad U_{jk}(x) = \delta_{jk} - ig\theta^a(x)\left(T^a\right)_{jk} + O(\theta^2)$$

$$D_\mu = I\partial_\mu - igA_\mu^a(x)T^a$$

$$A_\mu(x) \equiv A_\mu^a(x)T^a \rightarrow U(x)A_\mu(x)U^+(x) + \frac{i}{g}U(x)\partial_\mu U^+(x)$$

$$T^a \in GA \qquad SM\ group: SU(3)_c \times SU(2)_L \times U(1)_Y$$

Fermions masses in the Standard Model



Standard Model photon (m=0)

Standard Model Dirac fermions (m>0)

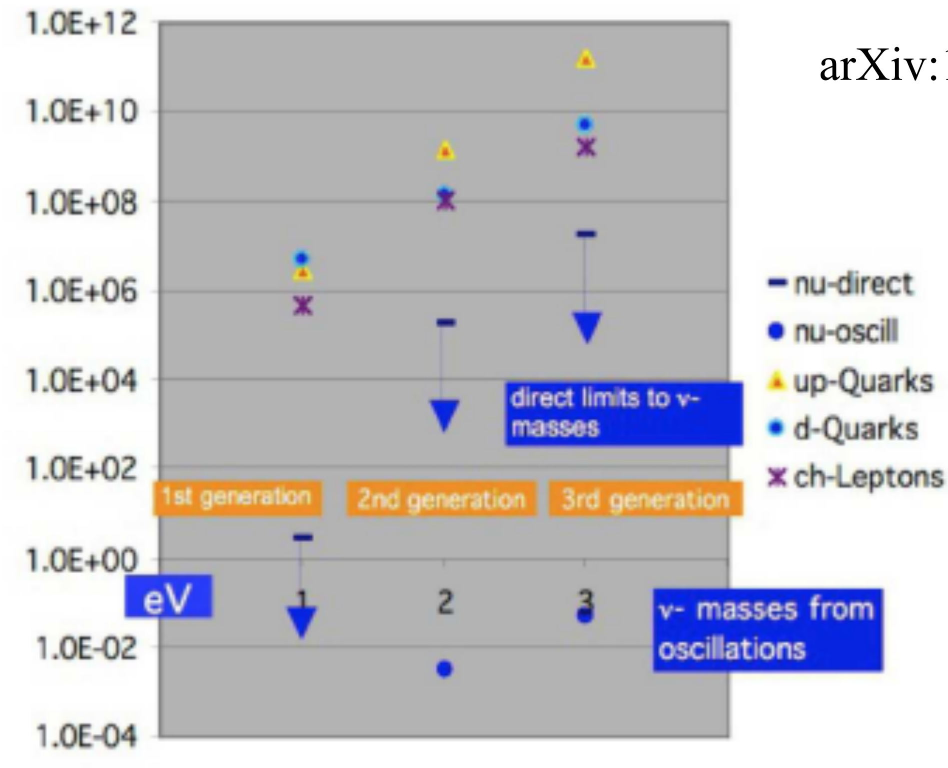
Standard Model neutrino (m=0)

Extended Standard Model Dirac neutrino (m>0)

$$-\mathcal{L} \supset \frac{1}{2}\overline{\psi}_{iL} Y_{ij} \psi_{jR} \phi \rightarrow \frac{1}{2} m_{Dij} \overline{\psi}_{iL} \psi_{jR} \quad \left(m_{Dij} = Y_{ij} < \phi_2 > \right)$$

Too Small Yukawa Couplings?

Standard Model fermion masses



arXiv:1406.5503

$$-\mathcal{L} \supset \frac{1}{2}\overline{\psi}_{iL} Y_{ij} \psi_{jR} \phi \rightarrow \frac{1}{2} m_{Dij} \overline{\psi}_{iL} \psi_{jR} \quad \left(m_{Dij} = Y_{ij}\,\mathrm{v} \right)$$

$$-\mathcal{L} \supset \frac{1}{2} m_{LR} \overline{\nu}_R'^{c}\, \nu_L'^{c}$$

Majorana

The origin of Majorana neutrino masses

$-\mathcal{L} \supset$

$$\frac{1}{2}\left(\overline{\nu'_L}\ \overline{\nu'^c_R}\right)\begin{pmatrix} 0 & m_{LR} \\ m^T_{LR} & M_{RR}\end{pmatrix}\begin{pmatrix}\nu'^c_L \\ \nu'_R\end{pmatrix} + h.c.$$

Type I see-saw

$$m^\nu_{LL} = -m^\nu_{LR} M^{-1}_{RR} m^\nu_{LR} \longrightarrow \begin{cases} m^\nu_{LL} \approx \dfrac{(100\ GeV)^2}{10^{14}\ GeV} = 0.1eV \\ m^\nu_{LL} \approx \dfrac{(300\ keV)^2}{1\ TeV} = 0.1eV \end{cases}$$

$$A_{\beta\beta} \propto \frac{U^2_{ei} m_i}{q^2} - \frac{S^2_{ei}}{M_i}$$

- $U^2_{ei} m_i$ term dominates in most cases

- 1 TeV collider Majorana tests not relevant

- Heavy neutrino dominance requires loop corrections

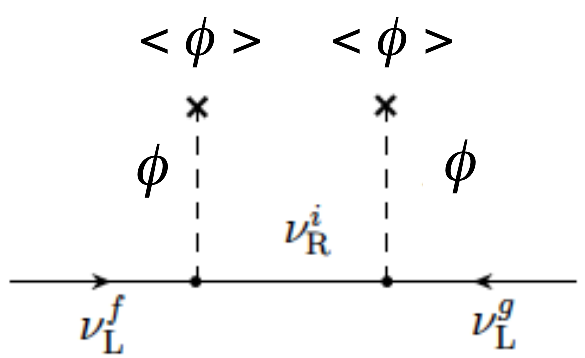
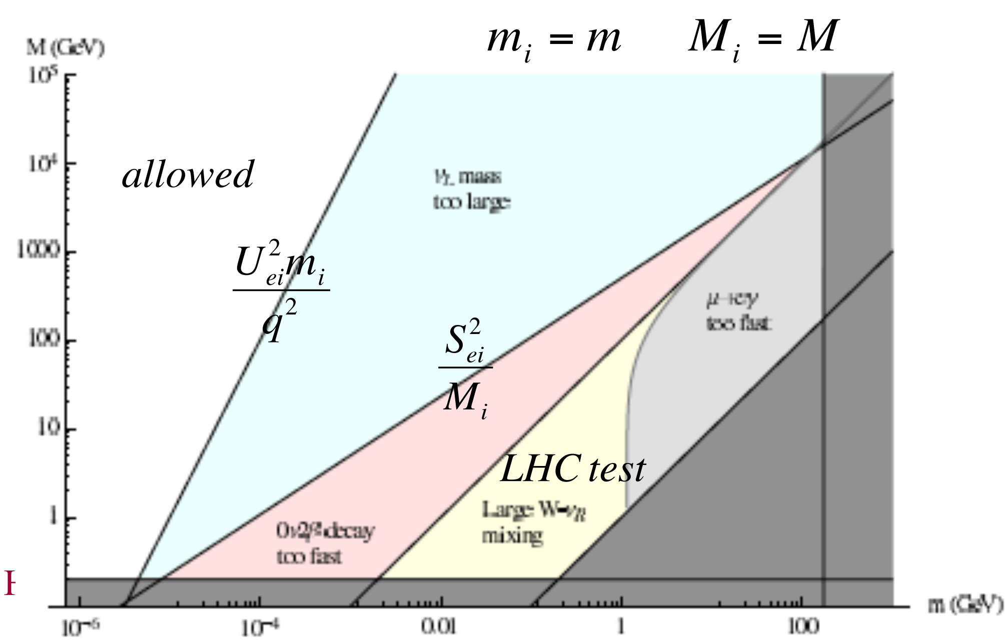


Diagram illustrating the type I see-saw mechanism



arXiv:0710.4947v3

The origin of Majorana neutrino masses

$-\mathcal{L} \supset$

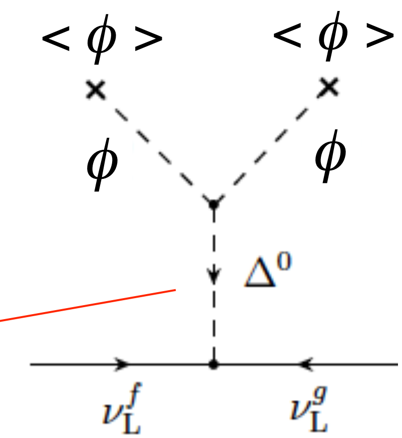
$$\frac{1}{2}\left(\overline{\nu'_L}\;\overline{\nu'^c_R}\right)\begin{pmatrix} 0 & m_{LR} \\ m^T_{LR} & M_{RR}\end{pmatrix}\begin{pmatrix}\nu'^c_L \\ \nu'_R\end{pmatrix} + h.c.$$

$$\frac{1}{2}\left(\overline{\nu'_L}\;\overline{\nu'^c_R}\right)\begin{pmatrix} m_{LL} & m_{LR} \\ m^T_{LR} & M_{RR}\end{pmatrix}\begin{pmatrix}\nu'^c_L \\ \nu'_R\end{pmatrix} + h.c.$$

See-saw mechanisms

$$m^\nu_{LL} = -m^\nu_{LR} M^{-1}_{RR} m^\nu_{LR} \longrightarrow \begin{cases} m^\nu_{LL} \approx \dfrac{(100\ GeV)^2}{10^{14}\ GeV} = 0.1 eV \\ m^\nu_{LL} \approx \dfrac{(300\ keV)^2}{1\ TeV} = 0.1 eV \end{cases}$$

$$m^\nu_{\rm LL} \approx m^{\rm II}_{\rm LL} + m^{\rm I}_{\rm LL}$$



Left-Right Symmetric model

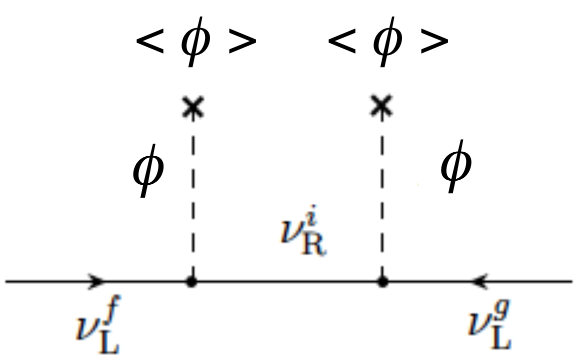
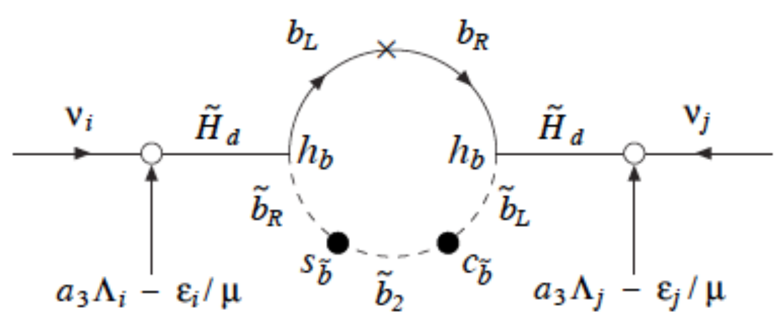


Diagram illustrating the type I see-saw mechanism

GUT/SUSY R-parity v. mechanism



arXiv:0710.4947v3

Majorana neutrino masses

$$-\mathcal{L} \supset \frac{1}{2}\left(\overline{\nu'_L}\ \ \overline{\nu'^c_R}\right)\begin{pmatrix} m_{LL} & m_{LR} \\ m_{LR}^T & M_{RR}\end{pmatrix}\begin{pmatrix}\nu'^c_L \\ \nu'_R\end{pmatrix} + h.c.$$

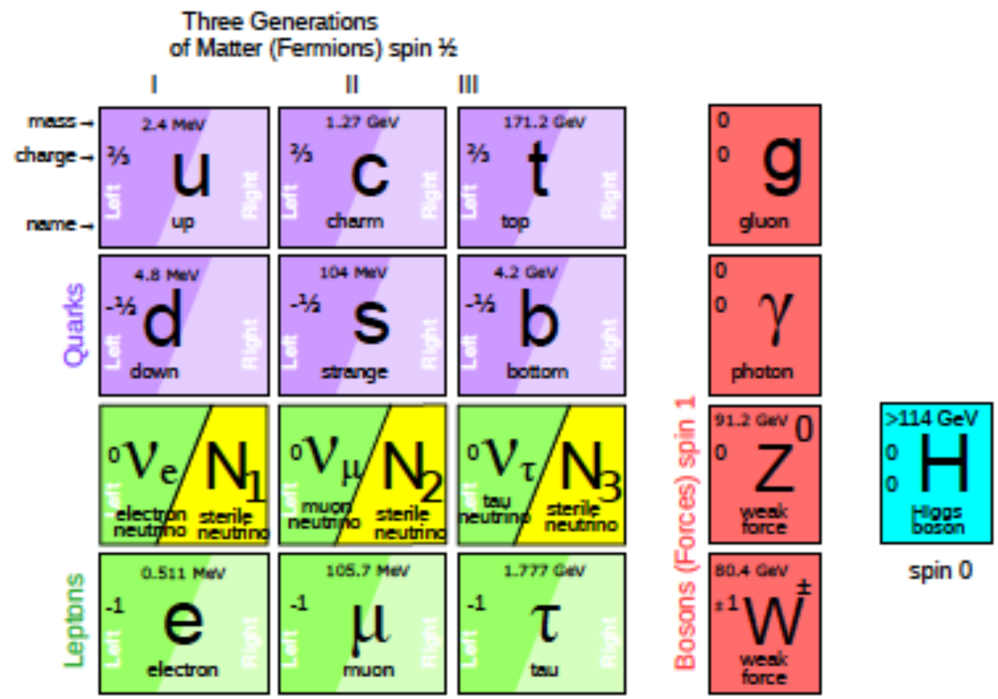
$$\downarrow$$

$$W^+ \, diag(m_1, m_2, m_3, M_1, M_2, \ldots) W$$

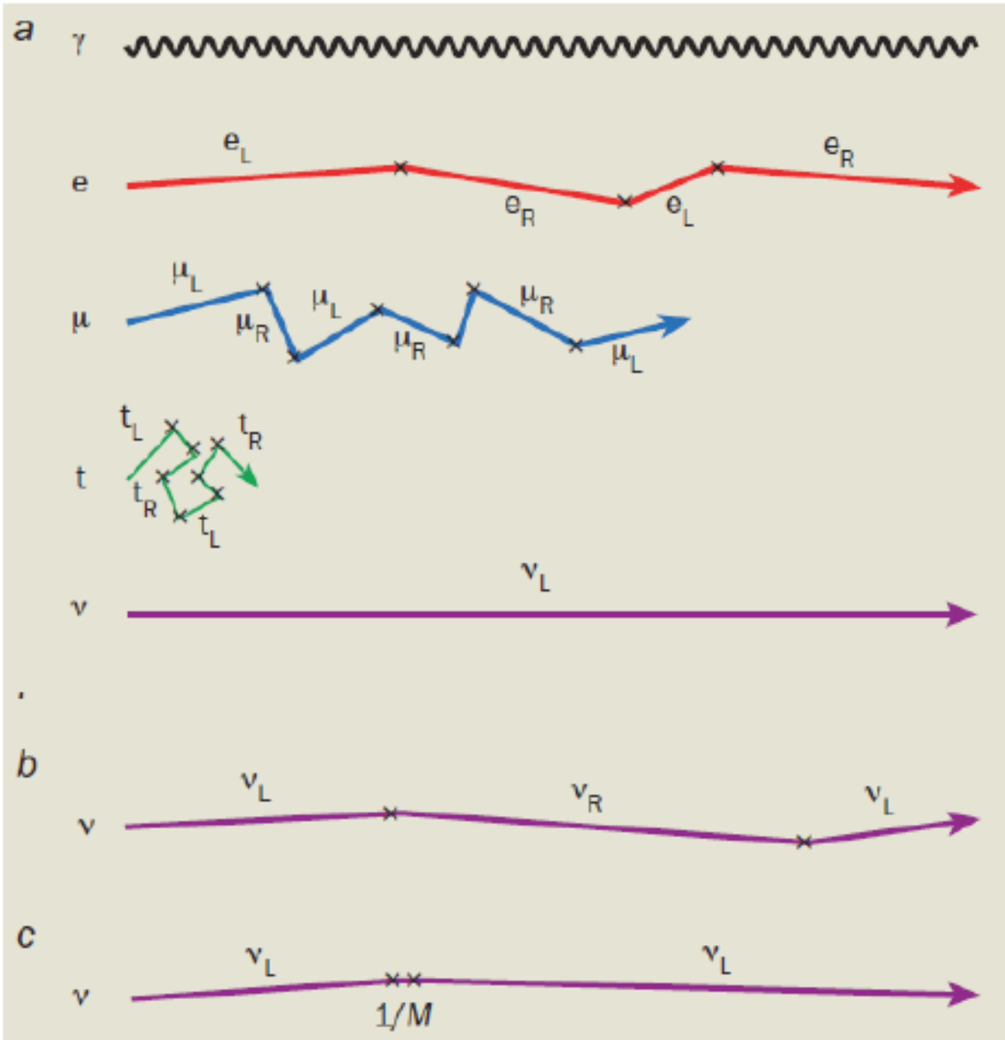
$$\begin{pmatrix}\nu'_L \\ \nu'^c_R\end{pmatrix} = W \begin{pmatrix}\nu_L \\ N^c_R\end{pmatrix} \equiv \begin{pmatrix} U & S \\ T & V\end{pmatrix}\begin{pmatrix}\nu_L \\ N^c_R\end{pmatrix}$$

$$WW^+ = 1 \qquad UU^+ \approx 1 \qquad VV^+ \approx 1$$

$$|S|,\ |T| << 1$$



Fermion masses in and beyond the Standard Model



Standard Model photon (m=0)

Standard Model Dirac fermions (m>0)

Standard Model neutrino (m=0)

Beyond Standard Model Dirac neutrino (m>0)

Beyond Standard Model Majorana neutrino (m>0)

Consequences of Existance of Majorana Neutrinos

- Leptogenesis (ΔL=2) => (SM sphalerons) => Baryogenesis

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.2 \times 10^{-10} \propto 0.01 \sin\delta_{CP}$$

- Exotic (ΔL=2) decays:

$\mu^+ \to e^+ + \gamma$	$BR < 5.7 \times 10^{-13}$
$\mu^+ \to e^+ + e^- + e^+$	$BR < 1.0 \times 10^{-12}$
$\mu^- + A(N,Z) \to e^- + A(N,Z)$	$BR(Au) < 7.0 \times 10^{-13}$

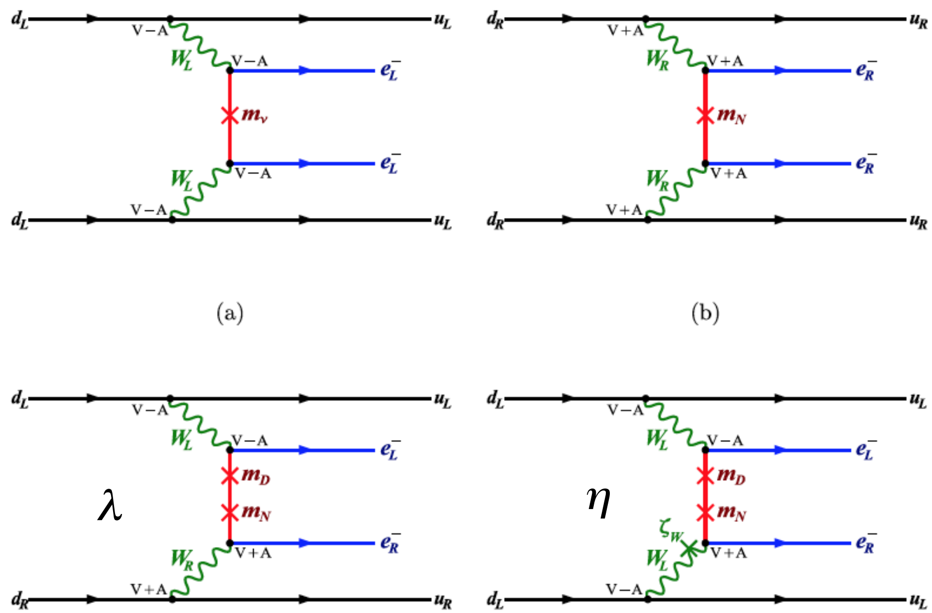
- Larger magnetic moments => Larger decay rates of heavy neutrino

$$\sim 10^{-10} \mu_B (present\ \mathrm{limit}) >> \mu_\nu (Majorana) \approx 10^{-15} \mu_B >> \mu_{ii}^D (Dirac) \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1eV} \right) \mu_B$$

- Different neutrino contribution to Supernovae explosion mechanism => different signals measured on Earth detectors

Possible contributions to 0ββ decay

DAS *et al.* PHYSICAL REVIEW D 86, 055006 (2012)



(a) (b) (c) (d)

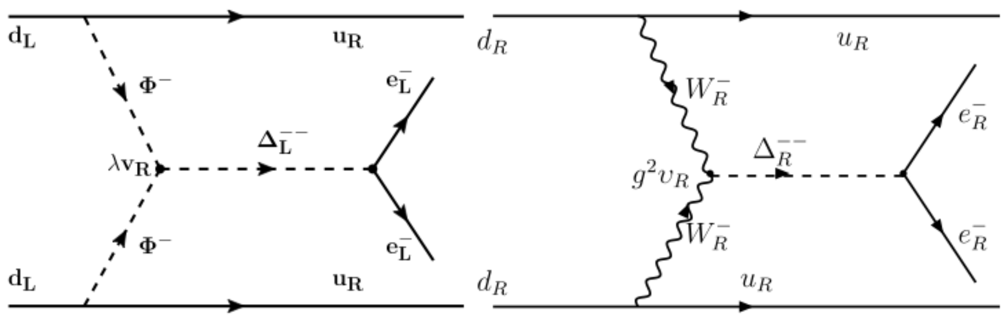
Low-energy effective Hamiltonian

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} j_L^\mu J_{L\mu}^+ + h.c.$$

$$j_{L/R}^\mu = \bar{e}\gamma^\mu\left(1 \mp \gamma^5\right)\nu_e$$

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}}\left[j_L^\mu\left(J_{L\mu}^+ + \kappa J_{R\mu}^+\right) + j_R^\mu\left(\eta J_{L\mu}^+ + \lambda J_{R\mu}^+\right)\right] + h.c.$$

Left – right symmetric model



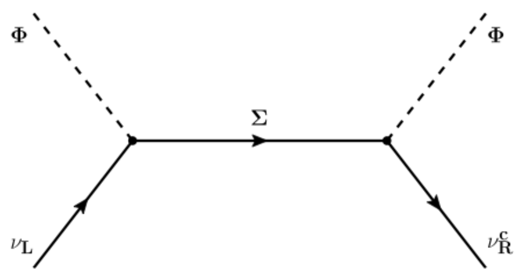
(a) (b)

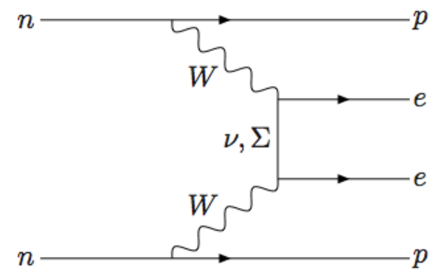
$$-\mathcal{L} \supset \frac{1}{2} h_{\alpha\beta}^T \left(\bar{\nu}_{\beta L} \ \ \bar{e}_{\alpha L}\right)\begin{pmatrix}\Delta^- & -\Delta^0 \\ \Delta^{--} & \Delta^-\end{pmatrix}\begin{pmatrix} e_R^c \\ -\nu_R^c\end{pmatrix} + hc$$

No neutrino exchange

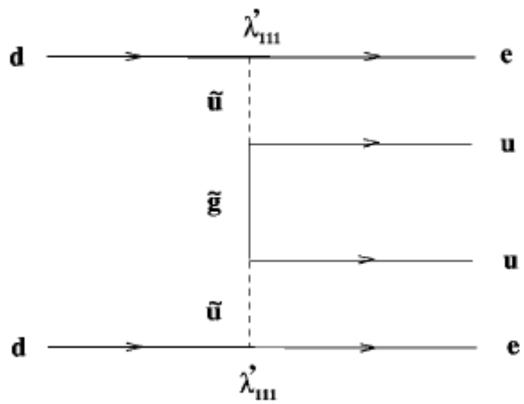
Contributions to 0ββ decay: no neutrino

See-saw type III

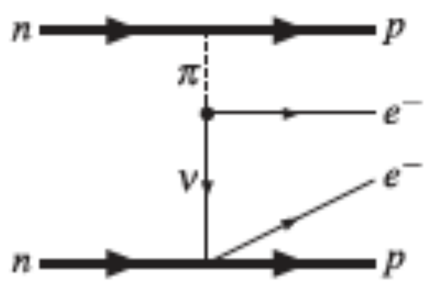




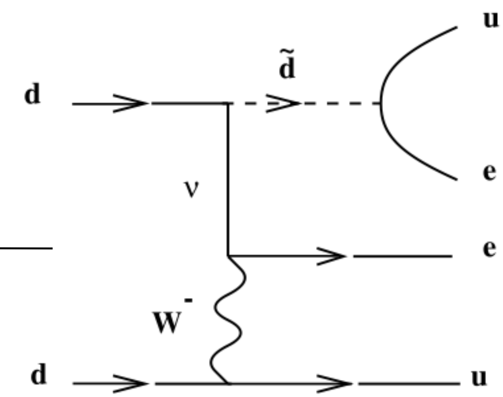
GUT/SUSY R-parity violation



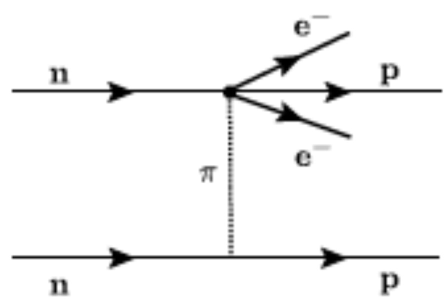
Gluino exchange

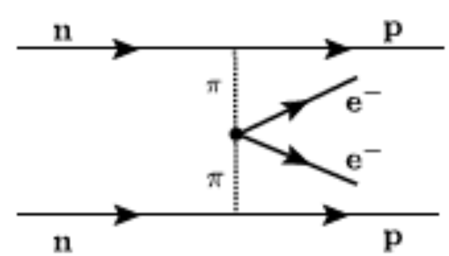


Hadronization /w R-parity v.



Squark exchange





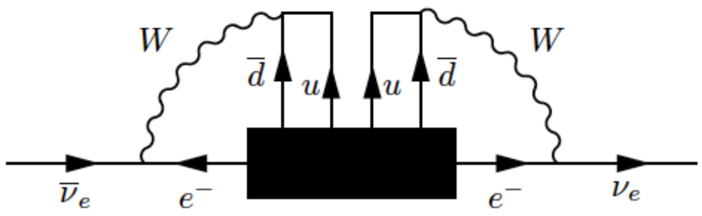
The Black Box Theorems

Black box I (electron neutrino)

J. Schechter and J.W.F Valle, PRD 25, 2951 (1982)

E. Takasugi, PLB 149, 372 (1984)

J.F. Nieves, PLB 145, 375 (1984)



$0\nu\beta\beta$ observed at some level ⇔ (i) Electron neutrinos are Majorana fermions (with m > 0). (ii) Lepton number conservation is violated by 2 units

However:

M. Duerr et al, JHEP 06 (2011) 91

$$\left(\delta m_{\nu_e}\right)_{BB} \sim 10^{-24}\, eV << \sqrt{\left|\Delta m^2_{32}\right|} \approx 0.05\, eV$$

Black box II (all flavors + oscillations)

M. Hirsch, S. Kovalenko, I. Schmidt, PLB 646, 106 (2006)

$0\nu\beta\beta$ observed at some level ⇔ (i) Neutrinos are Majorana fermions. (ii) Lepton number conservation is violated by 2 units

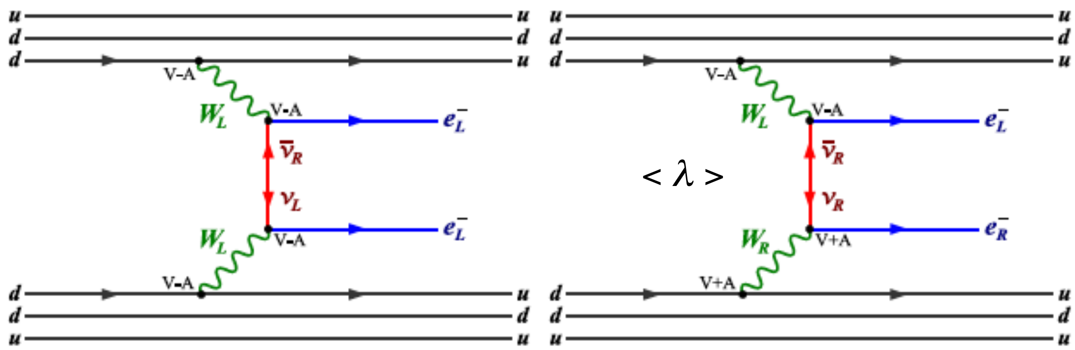
$$(iii)\quad \langle m_{\beta\beta}\rangle = \left|\sum_{k=1}^{3} m_k U^2_{ek}\right| = \left|c^2_{12}c^2_{13}m_1 + c^2_{13}s^2_{12}m_2 e^{i\phi_2} + s^2_{13}m_3 e^{i\phi_3}\right| > 0$$

Regardless of the dominant $0\nu\beta\beta$ mechanism!

DBD signals from different mechanisms

R. Arnold et al.: Probing New Physics Models of Neutrinoless Double Beta Decay with SuperNEMO

arXiv:1005.1241



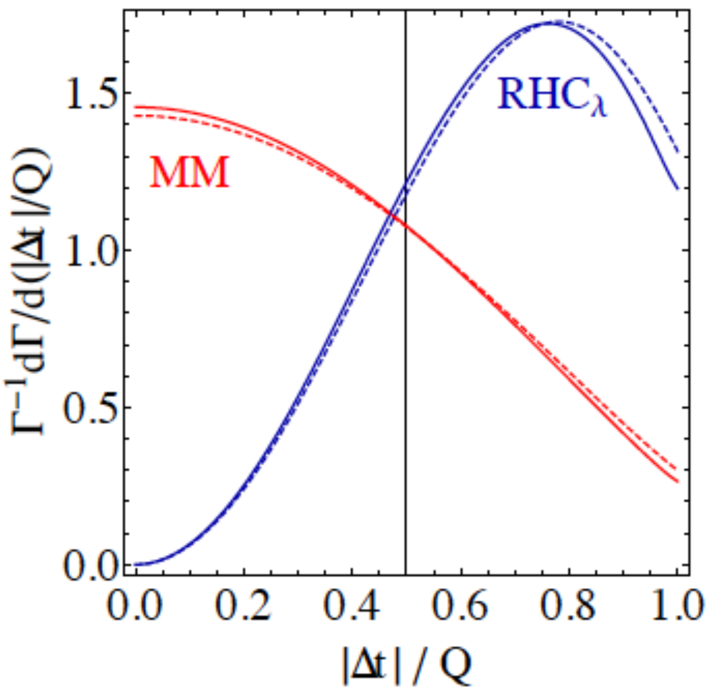
(a) (b)

$$\mu \approx \frac{m_\nu}{m_e}, \quad (10)$$

$$\eta \approx \tan\zeta \sqrt{\frac{m_\nu}{M_R}}, \quad (11)$$

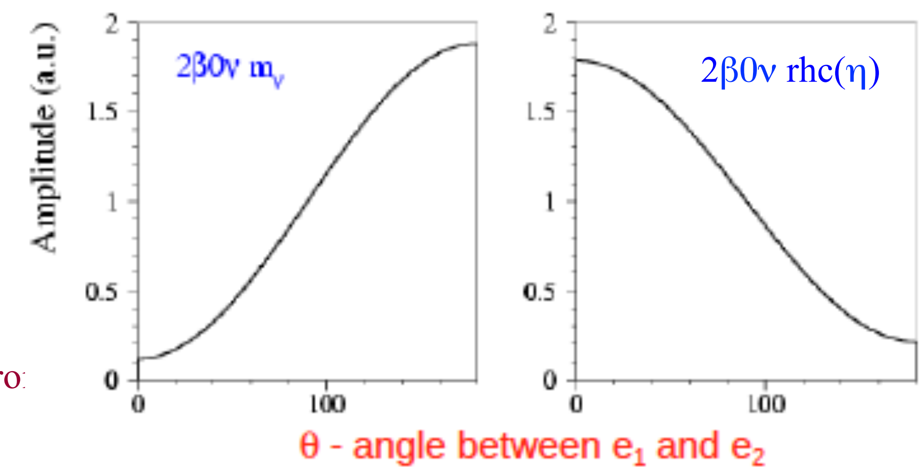
$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}. \quad (12)$$

$$[T_{1/2}]^{-1} = C_{mm}\mu^2 + C_{\lambda\lambda}\lambda^2 + C_{m\lambda}\mu\lambda. \quad (13)$$



Isotope	C_{mm} [y^{-1}]	$C_{\lambda\lambda}$ [y^{-1}]	$C_{m\lambda}$ [y^{-1}]
^{76}Ge	1.12×10^{-13}	1.36×10^{-13}	-4.11×10^{-14}
^{82}Se	4.33×10^{-13}	1.01×10^{-12}	-1.60×10^{-13}
^{150}Nd	7.74×10^{-12}	2.68×10^{-11}	-3.57×10^{-12}

Table 1: Coefficients used in calculating the $0\nu\beta\beta$ decay rate [30].

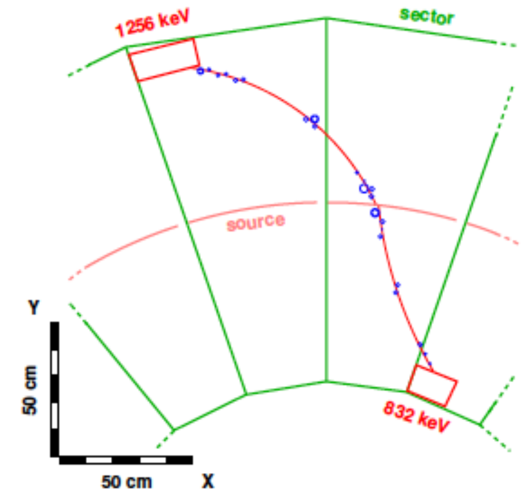


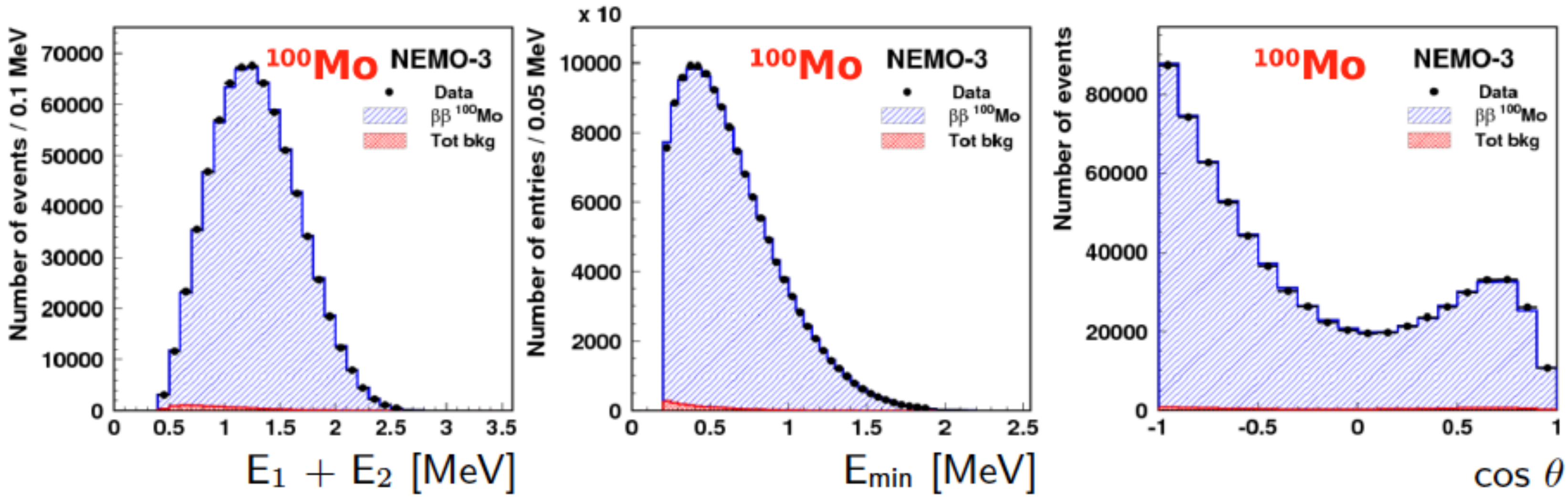
$t = \varepsilon_{e1} - \varepsilon_{e12}$

M. Horo

NEMO-3 $2\nu2\beta$ of ^{100}Mo Measurement

- 6.9 kg of ^{100}Mo
- ~700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3$ %
- Signal to background ratio S/B = 76
- Preliminary half-life:
  $\mathcal{T}^{2\nu}_{1/2} = 7.16 \pm 0.01\ \text{(stat)} \pm 0.54\ \text{(syst)}\ 10^{18}$ y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]

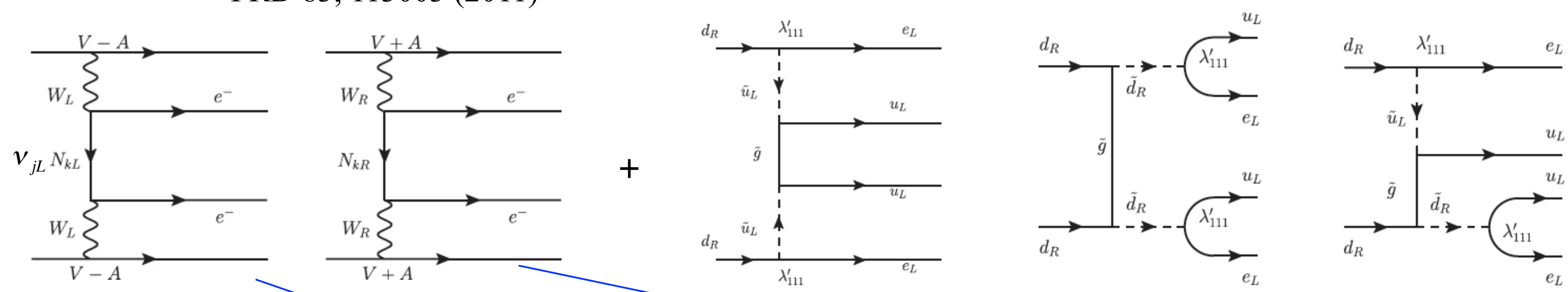




- 0.7 % systematical uncertainty on the $2\nu2\beta$ efficiency above 2 MeV

The DBD half-life

PRD 83, 113003 (2011)



$$\begin{cases} \nu'_{eL} = \sum_k^{light} U_{ek}\nu_{kL} + \sum_k^{heavy} S_{ek}N_{kL} \\ \nu'_{eR} = \sum_k^{light} T^*_{ek}\nu_{kR} + \sum_k^{heavy} V^*_{ek}N_{kR} \end{cases}$$

$$\eta_{\nu L} = \frac{\langle m_{\beta\beta}\rangle}{m_e} \qquad \eta_{NL} = \sum_k^{heavy} S^2_{ek}\frac{m_p}{M_k} \qquad \eta_{NR} = \left(\frac{M_{WL}}{M_{WR}}\right)^4 \sum_k^{heavy} V^2_{ek}\frac{m_p}{M_k}$$

$$\langle\lambda\rangle = \left(\frac{M_{WL}}{M_{WR}}\right)^2 \sum_k^{light} U_{ek}T^*_{ek} \qquad \langle\eta\rangle = \zeta\sum_k^{light} U_{ek}T^*_{ek} \qquad W_R \approx \zeta W_1 + W_2$$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}\left|\sum_j M_j\eta_j\right|^2 = G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}(\eta_{NL}+\eta_{NR}) + \tilde{X}_\lambda < \lambda > + \tilde{X}_\eta < \eta > + M^{(0\lambda')}\eta_{\lambda'} + M^{(0\tilde{q})}\eta_{\tilde{q}} + \cdots\right|^2$$

(i) η_{NL} *neglijible in most models;* *(ii)* $\langle\eta\rangle$ & $\langle\lambda\rangle$ *ruled in/out by energy or angular distributions*

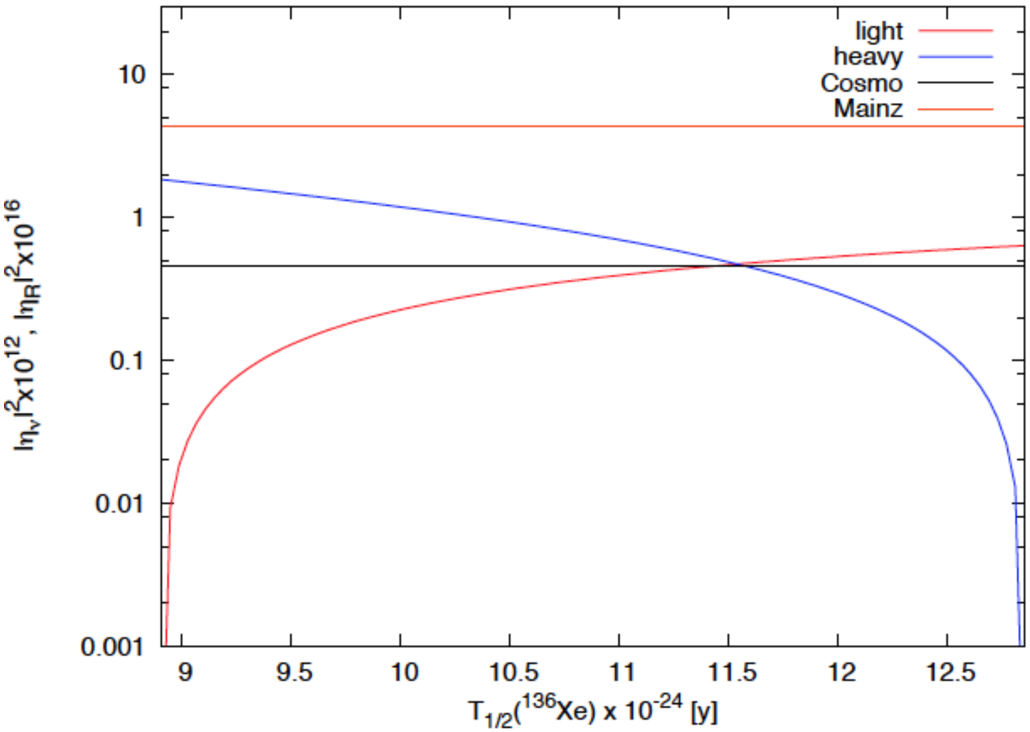
$$\left[T^{0\nu}_{1/2}\right]^{-1} \cong G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}\eta_{NR}\right|^2 \approx G^{0\nu}\left[\left|M^{(0\nu)}\right|^2\left|\eta_{\nu L}\right|^2 + \left|M^{(0N)}\right|^2\left|\eta_{NR}\right|^2\right]$$ *No interference terms!*

Two Non-Interfering Mechanisms

$$|\eta_\nu|, |\eta_{NR}| \Leftarrow \begin{cases} \left[G^{0\nu}_{Ge} T^{0\nu}_{1/2\,Ge}\right]^{-1} = \left|M^{(0\nu)}_{Ge}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Ge}\right|^2 |\eta_{NR}|^2 \\ \left[G^{0\nu}_{Xe} T^{0\nu}_{1/2\,Xe}\right]^{-1} = \left|M^{(0\nu)}_{Xe}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Xe}\right|^2 |\eta_{NR}|^2 \end{cases}$$

$$|\eta_\nu| = \frac{\langle m_{\beta\beta} \rangle}{m_e} \approx 10^{-6}$$

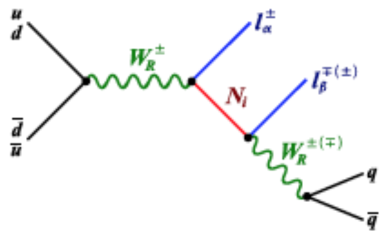
$$|\eta_{NR}| = \left(\frac{M_{WL}}{M_{WR}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k} \approx 10^{-8}$$



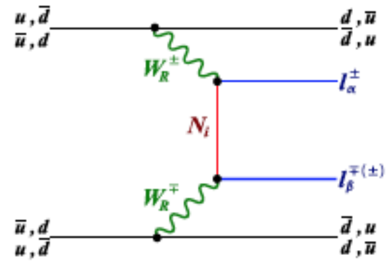
Assume $T_{1/2}(^{76}Ge) = 22.3 \times 10^{24}$ y

Some mechanisms tested at LHC

PRD 86, 055006 (2012)

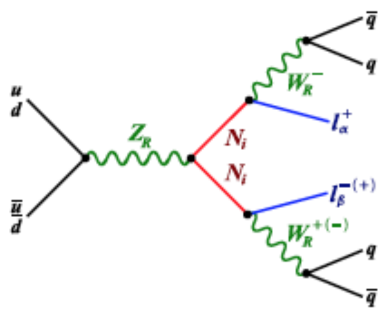


(a)

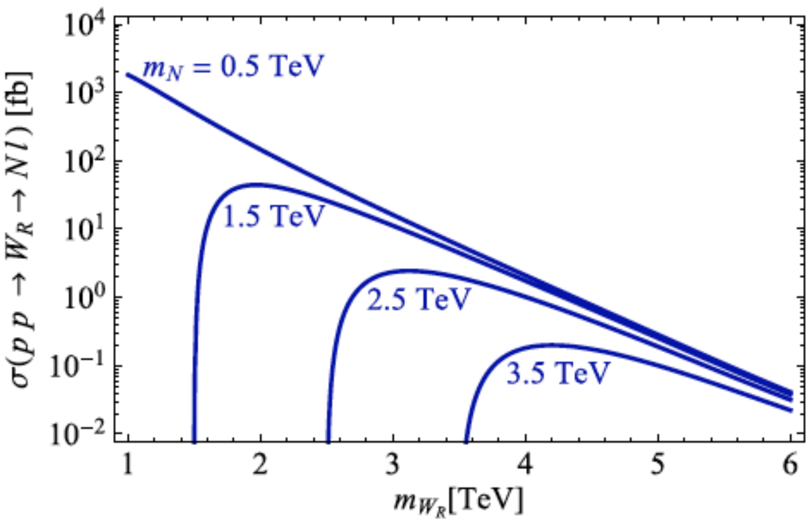


(b)

Left-right symmetric model

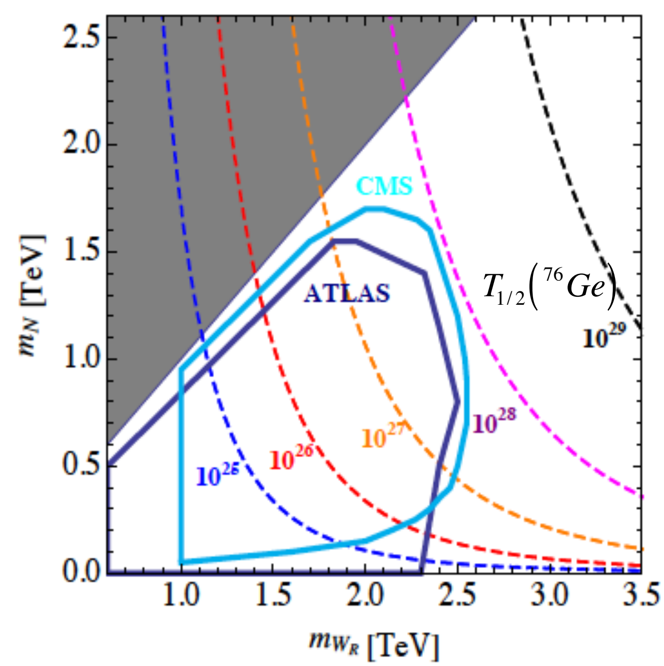


(c)



CMU

arXiv:1307.4849



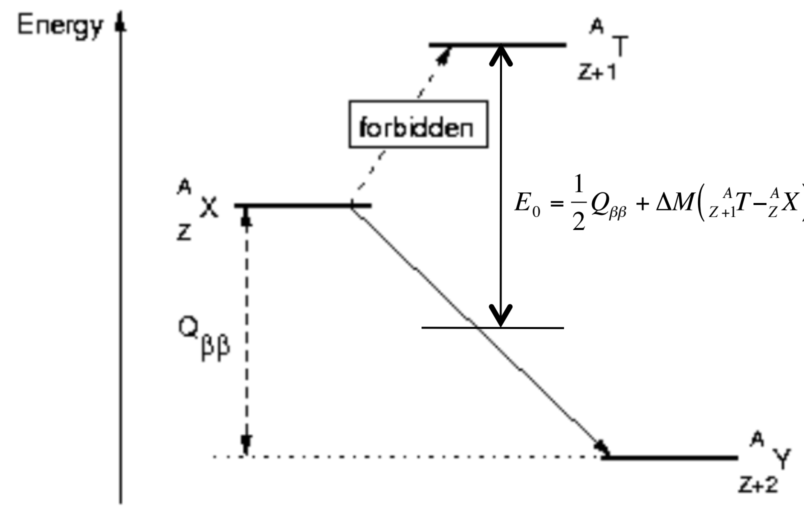
2ν Double Beta Decay (DBD) of ^{48}Ca

CENTRAL MICHIGAN UNIVERSITY

$$T_{1/2}^{-1} = G_{2\nu}(Q_{\beta\beta})\left[M_{GT}^{2\nu}(0^+)\right]^2$$

$$M_{\rm GT}^{2\nu}(0^+) = \sum_k \frac{\langle 0_f \| \sigma\tau^- \| 1_k^+ \rangle \langle 1_k^+ \| \sigma\tau^- \| 0_i \rangle}{E_k + E_0}$$

$$^{48}Ca \xrightarrow{2\nu\,\beta\beta} {}^{48}Ti$$



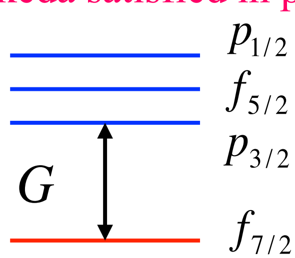
The choice of valence space is important!

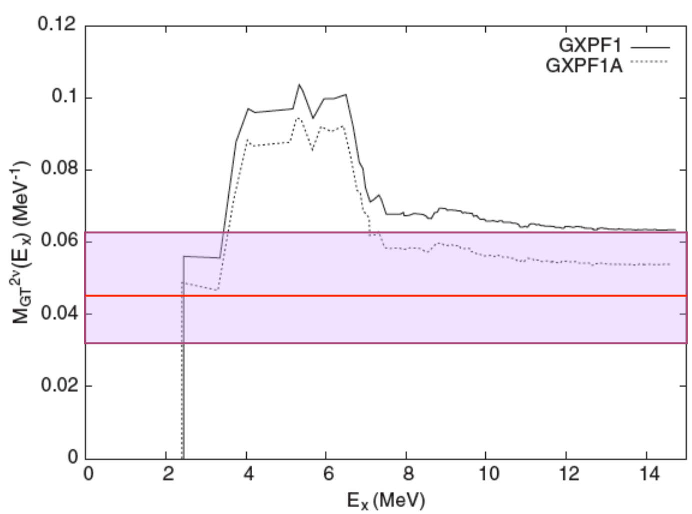
$$B(GT) = \frac{\left|\langle f \| \sigma\cdot\tau \| i \rangle\right|^2}{(2J_i + 1)}$$

ISR	48Ca	48Ti
pf	24.0	12.0
f7 p3	10.3	5.2

$$Ikeda\ sum\ rule(ISR) = \sum B(GT; Z \to Z+1) - \sum B(GT; Z \to Z-1) = 3(N-Z)$$

Ikeda satisfied in pf !





$$g_A\sigma\tau \xrightarrow{quenched} 0.77 g_A\sigma\tau$$

Horoi, Stoica, Brown,

PRC **75**, 034303 (2007)

Nordita 2014

SciDAC Scientific Discovery through Advanced Computing

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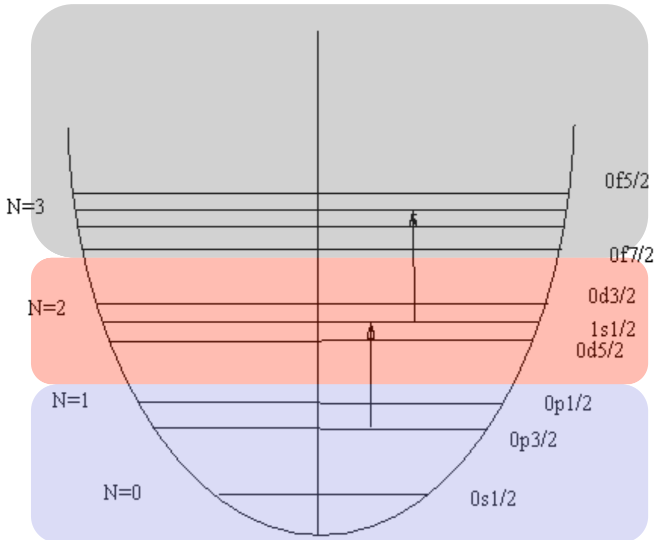
Shell Model GT Quenching



empty

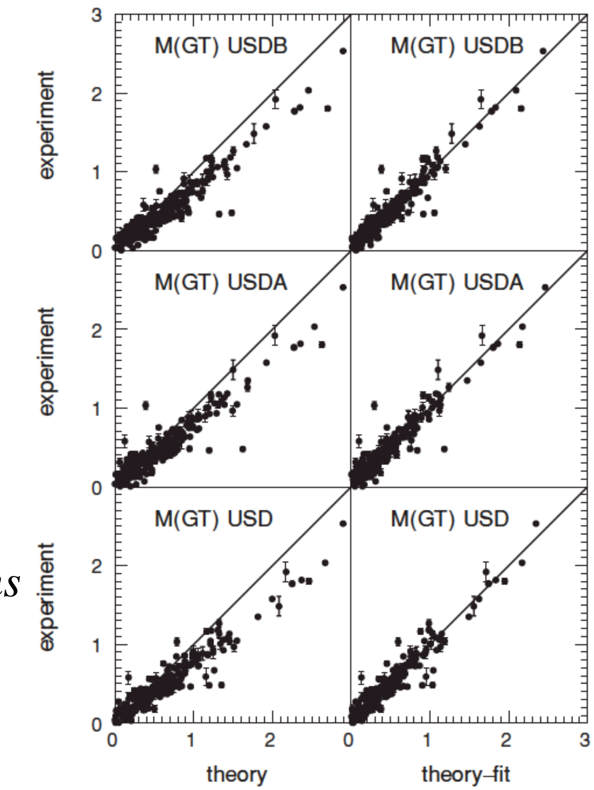
valence

frozen core

$$H_{valence}\Psi = E_n\Psi$$

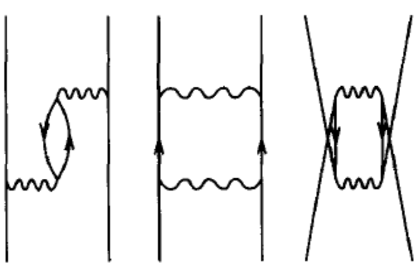
$$H_{valence} = H_{2-body}$$

can describe most correlations around the Fermi surface!



$$\sigma\tau \xrightarrow{quenched} 0.77\sigma\tau$$

core polarization: Phys.Rep. **261**, 125 (1995)



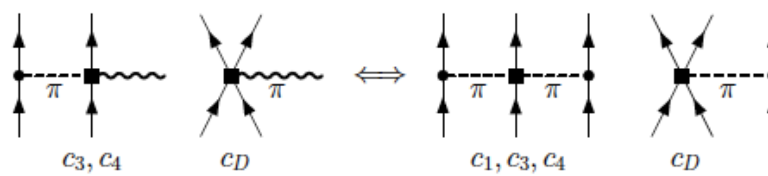


FIG. 1: Chiral 2b currents and 3N force contributions.

J. Menendez, D. Gazit and A. Schwenk, arXiV:1103.3622, PRL

SciDAC Scientific Discovery through Advanced Computing

Double Beta Decay NME for ^{48}Ca

TABLE I. Matrix elements and half-lives for 2ν decay calculated using GXPF1A interaction and two quenching factors. Matrix elements are in MeV^{-1} for transitions to 0^+ states and in MeV^{-3} for transitions to 2^+ states.

	$qf = 0.77$		$qf = 0.74$	
J_n^π	$M^{2\nu}$	$T_{1/2}^{2\nu}$ (yr)	$M^{2\nu}$	$T_{1/2}^{2\nu}$ (yr)
0_1^+	0.054	3.3×10^{19}	0.050	3.9×10^{19}
2_1^+	0.012	8.5×10^{23}	0.010	1.0×10^{24}
0_2^+	0.050	1.6×10^{24}	0.043	1.9×10^{24}

M. Horoi, PRC **87**, 014320 (2013)

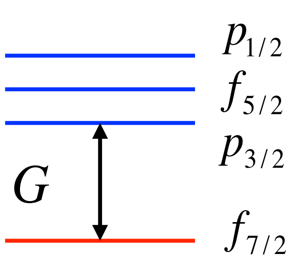
$$M_{GT}^{2\nu}(0^+) = \sum_k \frac{\langle 0_f \| \sigma\tau^- \| 1_k^+ \rangle \langle 1_k^+ \| \sigma\tau^- \| 0_i \rangle}{E_k + E_0}$$

$$\leftarrow \left(T_{1/2}^{2\nu}\right)_{exp} = \left[4.4^{+0.6}_{-0.5}(stat) \pm 0.4(syst)\right] \times 10^{19}\ yr$$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} \left| \tilde{\eta}_{\nu L} M_\nu^{0\nu} + \tilde{\eta}_N M_N^{0\nu} + \eta_{\lambda'} M_{\lambda'}^{0\nu} + \eta_{\tilde{q}} M_{\tilde{q}}^{0\nu} \right|^2,$$

TABLE II. Matrix elements for 0ν decay using the GXPF1A interaction and two SRC models [61], CD-Bonn (SRC1) and Argonne (SRC2). For comparison, the values labeled (a) are taken from Ref. [27], and the value labeled (b) is taken from Ref. [62] for $g_{pp} = 1$ and no SRC.

	Model	$M_\nu^{0\nu}$	$M_N^{0\nu}$	$M_{\lambda'}^{0\nu}$	$M_{\tilde{q}}^{0\nu}$
0_1^+	SRC1	0.90	75.5	618	86.7
	SRC2	0.82	52.9	453	81.8
	others	2.3$^{(a)}$	46.3$^{(a)}$	392$^{(b)}$	
0_2^+	SRC1	0.80	57.2	486	84.2
	SRC2	0.75	40.6	357	80.6



The effect of larger model spaces for ^{48}Ca

M(0v)	SDPFU	SDPFMUP
$0\ \hbar\omega$	0.941	0.623
$0+2\hbar\omega$	1.182 (26%)	1.004 (61%)

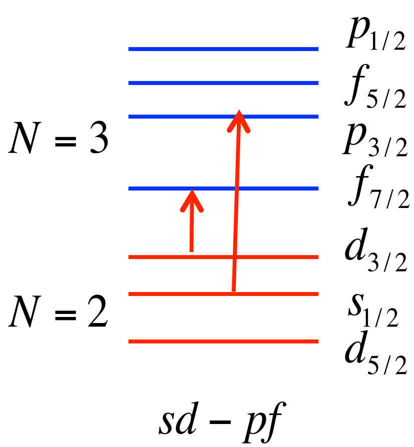
	M(0v)
$0\ \hbar\omega$ / GXPF1A	0.733
$0\ \hbar\omega+2^{nd}$ ord./GXPF1A	1.301 (77%)

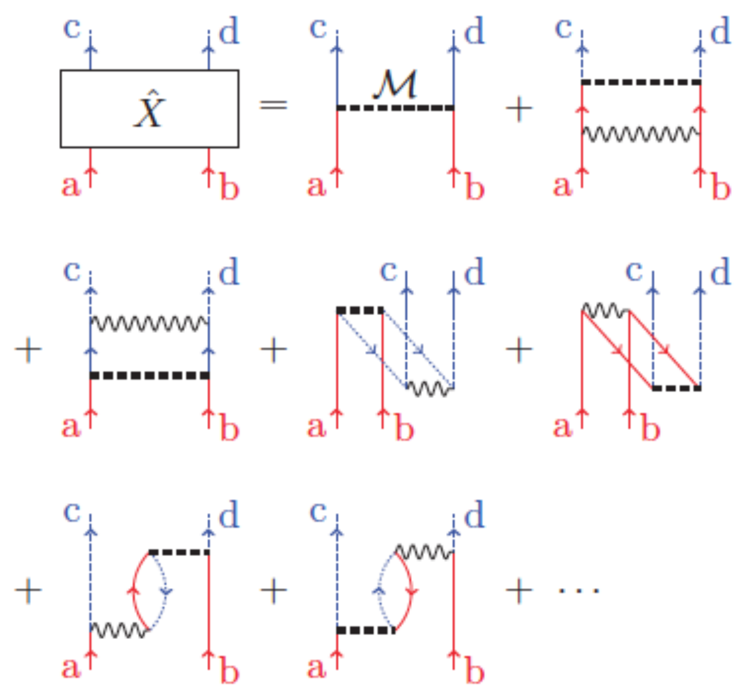
SDPFU: PRC 79, 014310 (2009)

SDPFMUP: PRC 86, 051301(R) (2012)

arXiv:1308.3815, PRC 89, 045502 (2014)

PRC 87, 064315 (2013)





Closure Approximation and Beyond in Shell Model

$$M_S^{0\nu} = \sum_{\substack{\mathcal{J},\, p<p' \\ n<n' \\ p<n}} (\Gamma) \left\langle 0_f^+ \left\| \left[\left(a_p^+ a_{p'}^+ \right)^{\mathcal{J}} \left(\tilde{a}_{n'} \tilde{a}_n \right)^{\mathcal{J}} \right]^0 \right\| 0_i^+ \right\rangle \left\langle p\, p'; \mathcal{J} \left| \int q^2 dq \left[\hat{S} \frac{h(q) j_\kappa(qr) G_{FS}^2 f_{SRC}^2}{q(q + \langle E \rangle)} \tau_{1-}\tau_{2-} \right] \right| n\, n'; \mathcal{J} \right\rangle_{as} - closure$$

$$M_S^{0\nu} = \sum_{\substack{pp'nn' \\ J k \mathcal{J}}} (\tilde{\Gamma}) \left\langle 0_f^+ \left\| \left(a_p^+ \tilde{a}_n \right)^J \right\| J_k \right\rangle \left\langle J_k \left\| \left(a_{p'}^+ \tilde{a}_{n'} \right)^J \right\| 0_i^+ \right\rangle \left\langle p\, p'; \mathcal{J} \left| \int q^2 dq \left[\hat{S} \frac{h(q) j_\kappa(qr) G_{FS}^2 f_{SRC}^2}{q(q + E_k^J)} \tau_{1-}\tau_{2-} \right] \right| n\, n'; \mathcal{J} \right\rangle - beyond$$

Challenge: there are about 100,000 J_k states in the sum for 48Ca

Much more intermediate states for heavier nuclei, such as ^{76}Ge!!!

No-closure may need states out of the model space (not considered).

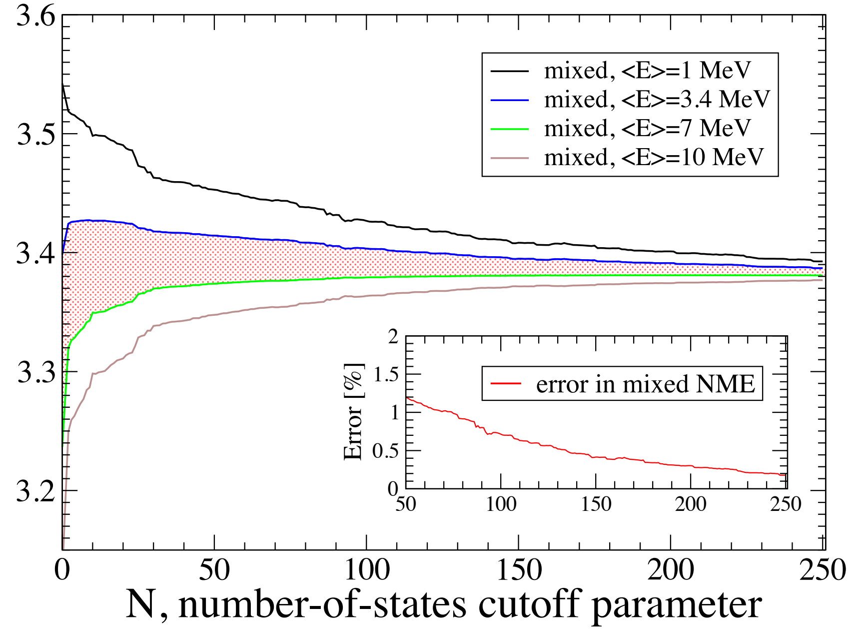
Minimal model spaces

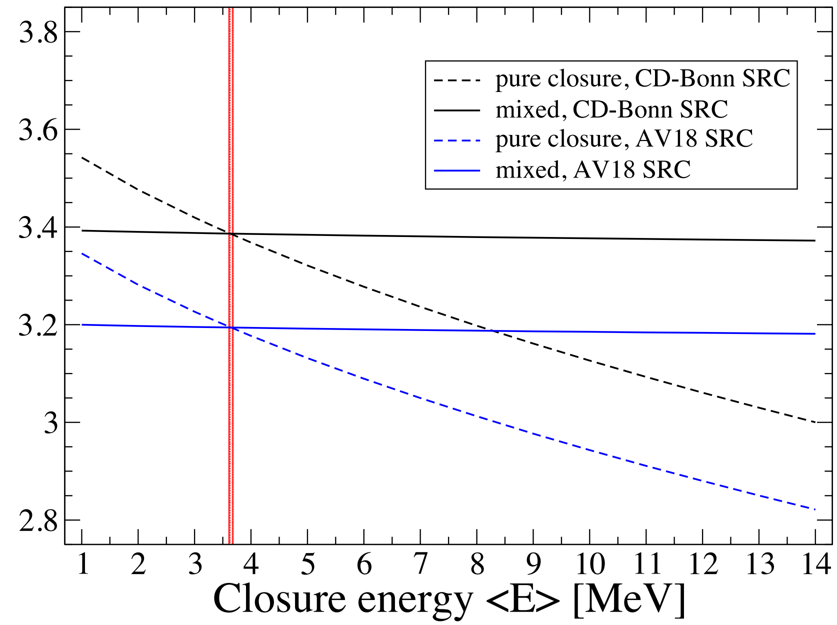
^{82}Se : 10M states

^{130}Te : 22M states

^{76}Ge : 150M states

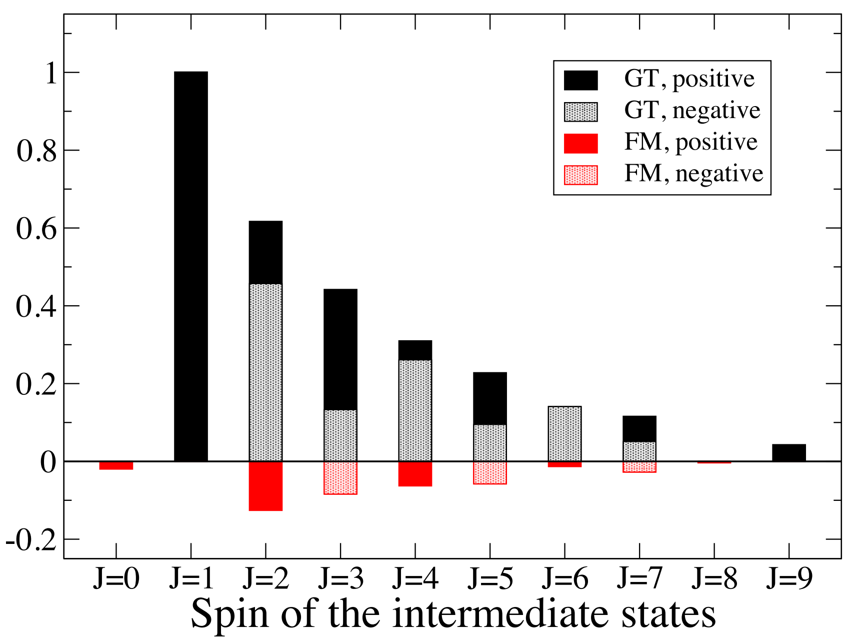
$$\hat{S} = \begin{cases} \sigma_1\tau_1 \sigma_2\tau_2 & Gamow-Teller\ (GT) \\ \tau_1 \tau_2 & Fermi\ (FM) \\ \left[3(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \right] \tau_1 \tau_2 & Tensor\ (T) \end{cases}$$

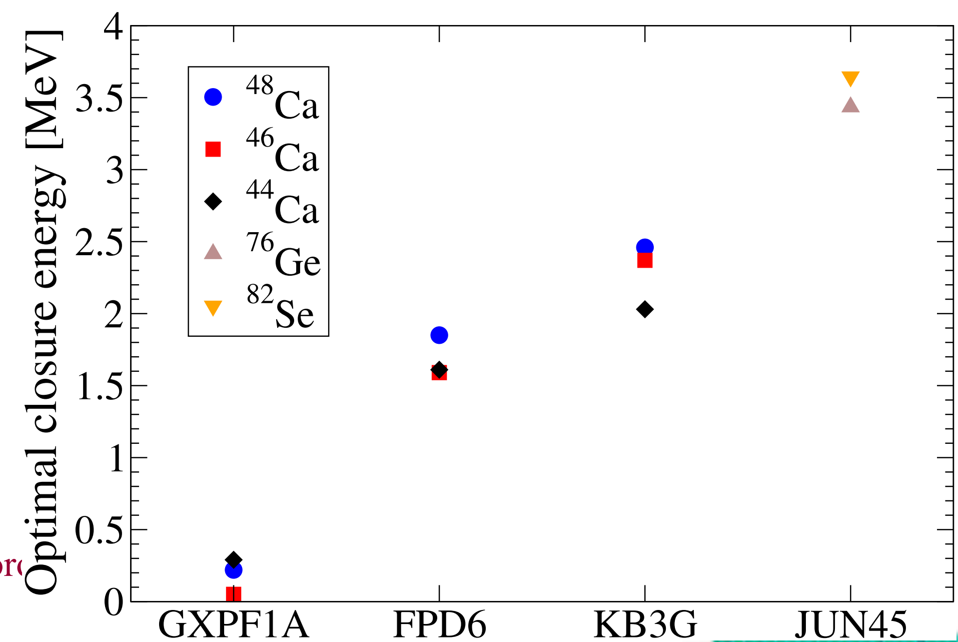


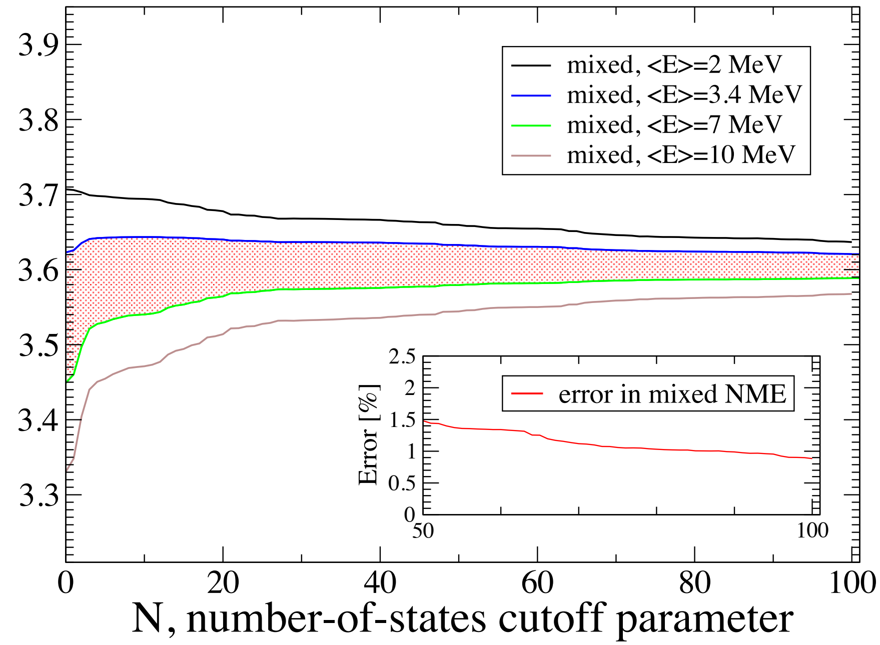


^{82}Se: PRC 89, 054304 (2014)

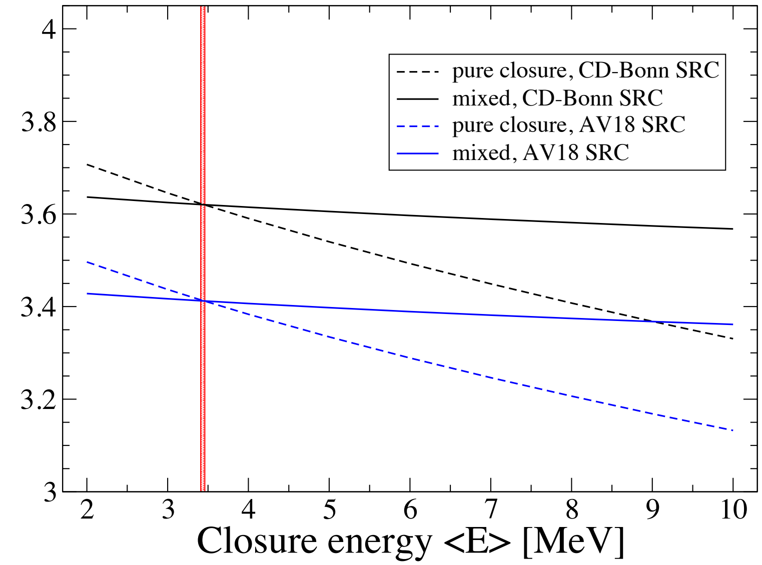
$$M_{mixed}(N) = M_{no-closure}(N) + \left[M_{closure}(N=\infty) - M_{closure}(N)\right]$$



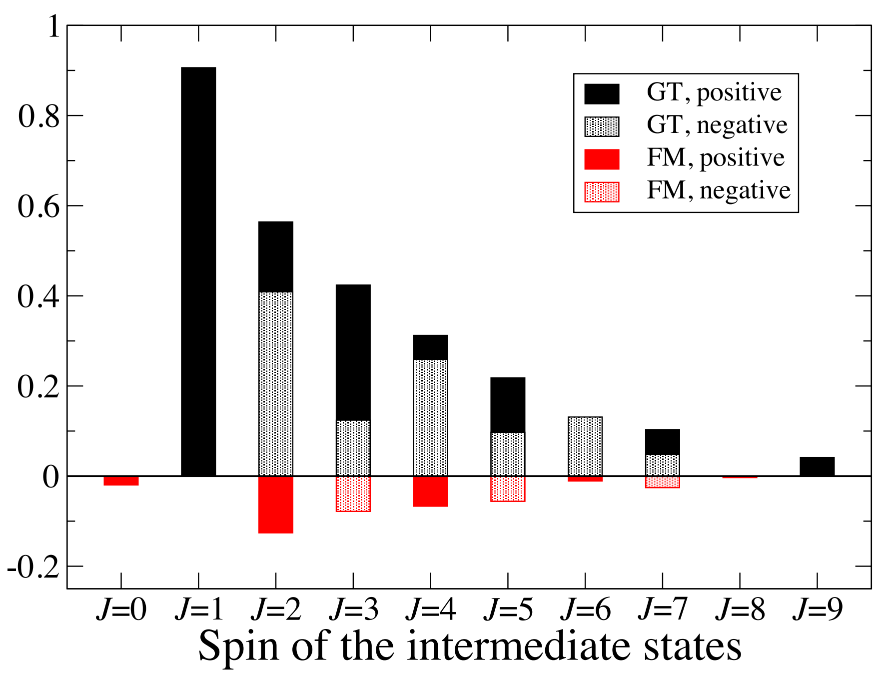


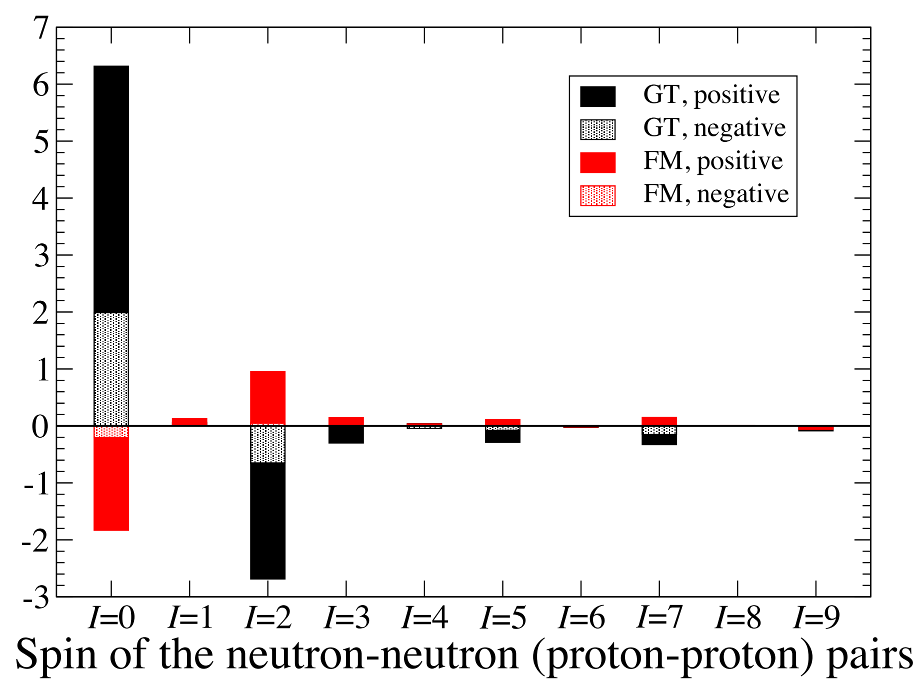


^{76}Ge



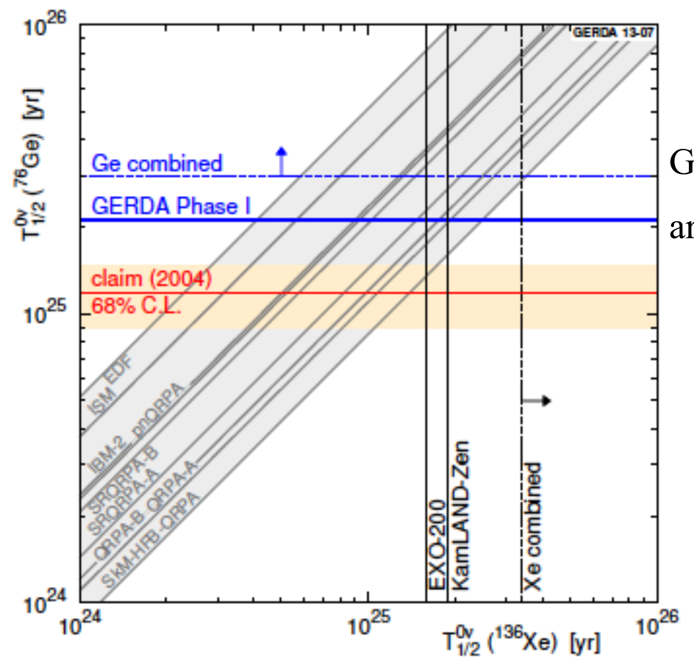
$$M_{mixed}(N) = M_{no-closure}(N) + \left[M_{closure}(N=\infty) - M_{closure}(N) \right]$$





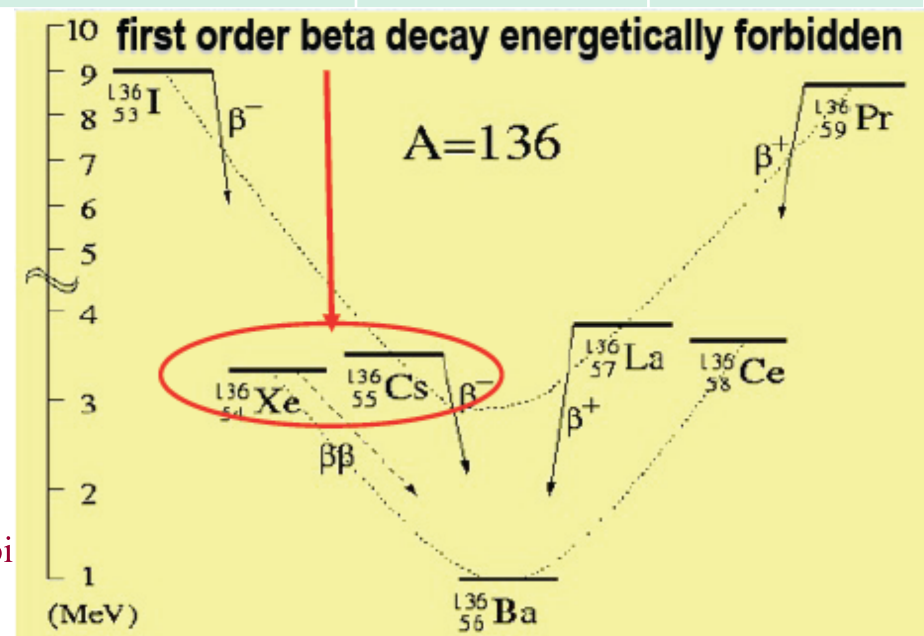
^{136}Xe ββ Experimental Results $M^{2\nu}_{exp} = 0.019\ MeV^{-1}$

Publication	Experiment	$T^{2\nu}_{1/2}$	$T^{0\nu}_{1/2}$	$T^{0\nu}_{1/2}$(Maj)
PRL 110, 062502	KamLAND-Zen		> 1.9×10^{25} y	
PRL 107, 212501	EXO-200	$(2.11\pm0.04\pm0.21)\times10^{21}$ y		
PRL 109, 032505	EXO-200	$(2.23\pm0.017\pm0.22)\times10^{21}$ y	>1.6×10^{25} y	
PRC 85, 045504	KamLAND-Zen	$(2.38\pm0.02\pm0.14)\times10^{21}$ y	>5.7×10^{24} y	
PRC 86, 021601	KamLAND-Zen		>6.2×10^{24} y	>2.6×10^{24} y



GERDA
arXiv:1307.4720

M. Horoi



Other Shell Model Results

Shell Model description of the $\beta\beta$ decay of ^{136}Xe

E. Caurier[a], F. Nowacki[a], A. Poves[b,*]

Physics Letters B 711 (2012) 62–64

$$g_A \sigma\tau \xrightarrow{quenched} q\, g_A \sigma\tau$$

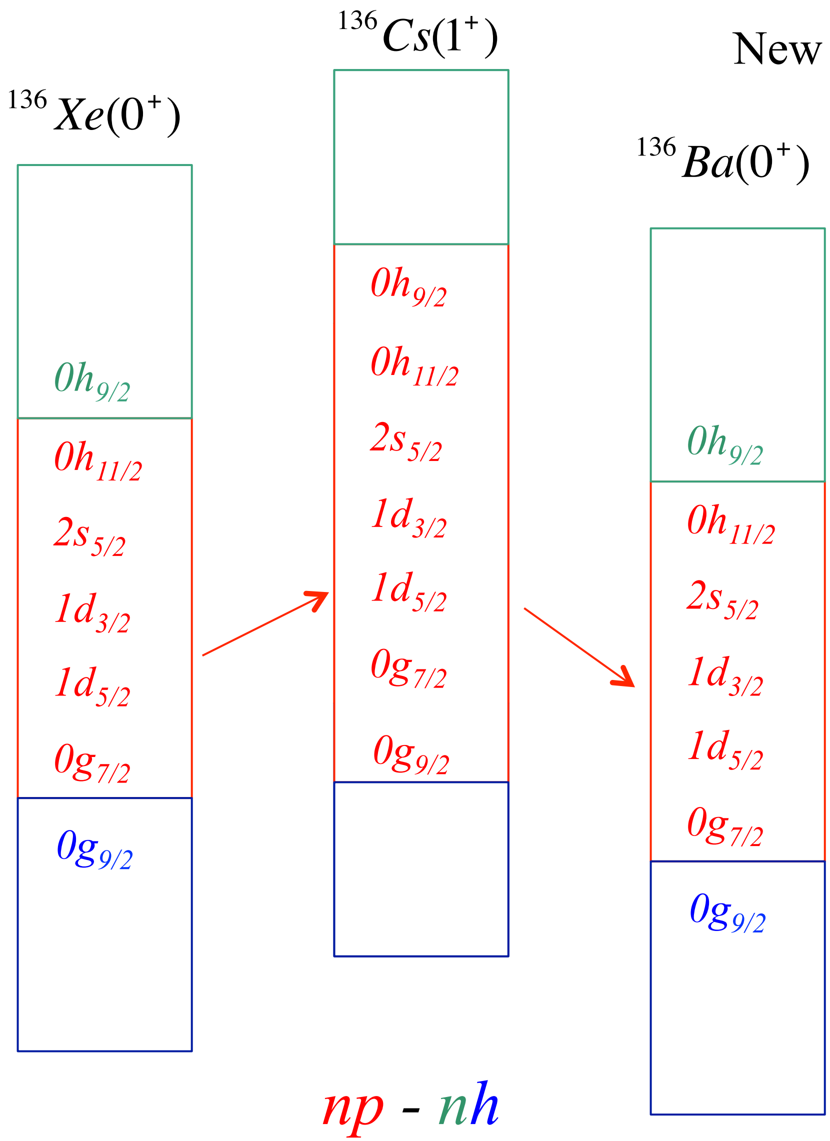
Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.047	kb3
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.048	kb3g
$^{48}Ca \rightarrow {}^{48}Ti$	0.047 ± 0.003	0.74	0.065	gxpf1
$^{76}Ge \rightarrow {}^{76}Se$	0.140 ± 0.005	0.60	0.116	gcn28:50
$^{76}Ge \rightarrow {}^{76}Se$	0.140 ± 0.005	0.60	0.120	jun45
$^{82}Se \rightarrow {}^{82}Kr$	0.098 ± 0.004	0.60	0.126	gcn28:50
$^{82}Se \rightarrow {}^{82}Kr$	0.098 ± 0.004	0.60	0.124	jun45
$^{128}Te \rightarrow {}^{128}Xe$	0.049 ± 0.006	0.57	0.059	gcn50:82
$^{130}Te \rightarrow {}^{130}Xe$	0.034 ± 0.003	0.57	0.043	gcn50:82
$^{136}Xe \rightarrow {}^{136}Ba$	0.019 ± 0.002	0.45	0.025	gcn50:82

$$M^{2\nu}_{GT}(0^+) = \sum_k \frac{\langle 0_f \| \sigma\tau^- \| 1_k^+ \rangle \langle 1_k^+ \| \sigma\tau^- \| 0_i \rangle}{E_k + E_0}$$

$0g_{7/2}\ 1d_{5/2}\ 1d_{3/2}\ 2s_{5/2}\ 0h_{11/2}$ *valence space*

^{136}Xe 2νββ Results $M^{2\nu}_{exp} = 0.019\ MeV^{-1}$



New effective interaction, $\sigma\tau \rightarrow 0.74\,\sigma\tau$ quenching

$0g_{7/2}\ 1d_{5/2}\ 1d_{3/2}\ 2s_{5/2}\ 0h_{11/2}$ *model space*

$$\sum B(GT;Z \rightarrow Z+1) - \sum B(GT;Z \rightarrow Z-1) = 52$$

$Ikeda$: $3(N-Z) = 84$

$$M^{2\nu} = 0.064\ MeV^{-1}$$

$0g_{9/2}\ 0g_{7/2}\ 1d_{5/2}\ 1d_{3/2}\ 2s_{5/2}\ 0h_{11/2}\ 0h_{9/2}$

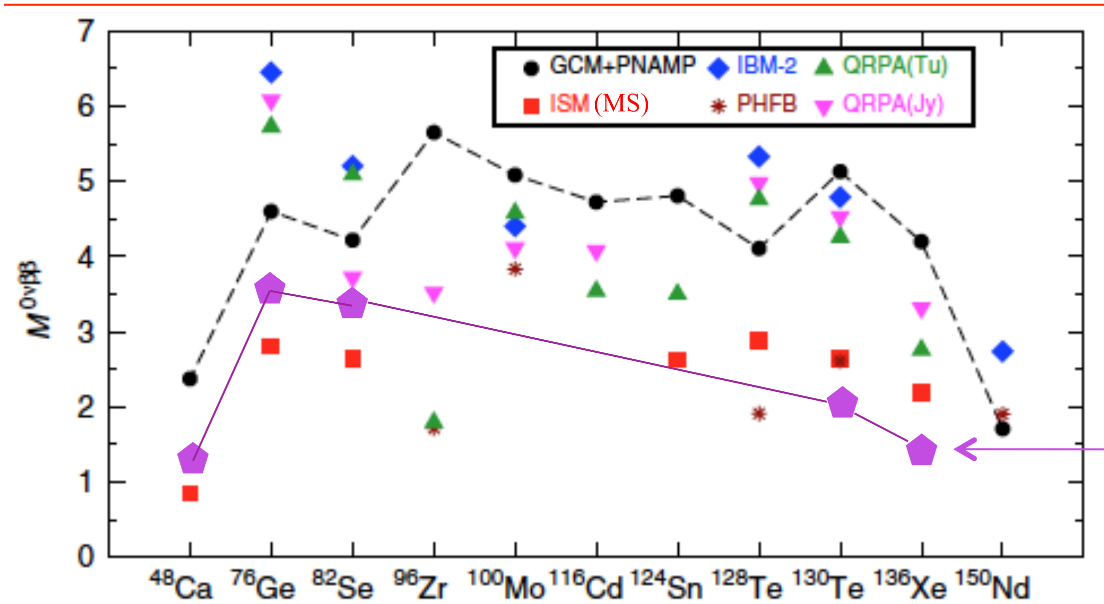
$$\sum B(GT;Z \rightarrow Z+1) - \sum B(GT;Z \rightarrow Z-1) = 84$$

$Ikeda$: $3(N-Z) = 84$

n (0+)	n (1+)	M(2v)
0	0	0.062
0	1	0.091
1	1	0.037
1	2	0.020

CENTRAL MICHIGAN UNIVERSITY

Comparisons of $M^{0\nu}$ $0\nu\beta\beta$ Results



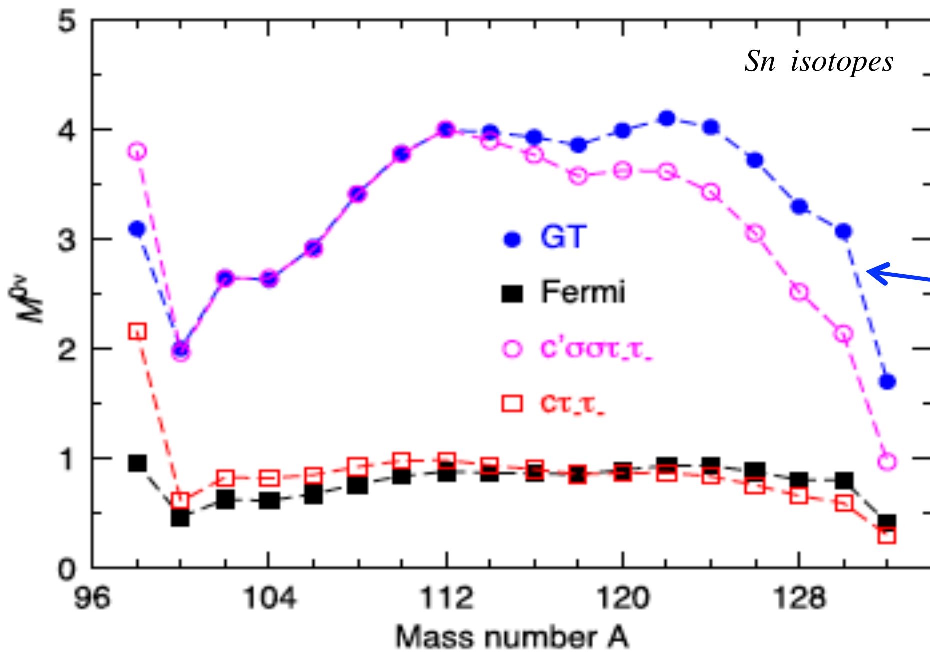
From T. Rodriguez, G. Martinez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010)

⬟ Present Shell Model results:

Phys. Rev. Lett. **110**, 222502 (2013)

PRC **89**, 045502 & **88**, 064312 (2013)

PRC **89**, 054304 (2014)



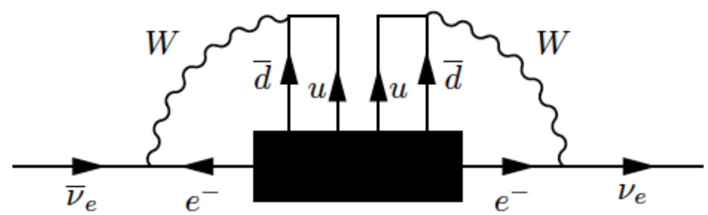
T. Rodriguez, G. Martinez-Pinedo, Phys. Lett. B **719**, 174 (2013)

Large jump down for magic no. of neutrons !!!

MU

Take-Away Points

Observation of 0νββ will signal **New Physics Beyond the Standard Model**.



Black box II (all flavors + oscillations)

0νββ observed ⇔ at some level

(i) Neutrinos are Majorana fermions.

(ii) Lepton number conservation is violated by 2 units

Regardless of the dominant 0νββ mechanism!

$$(iii)\ \langle m_{\beta\beta} \rangle = \left| \sum_{k=1}^{3} m_k U_{ek}^2 \right| = \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right| > 0$$

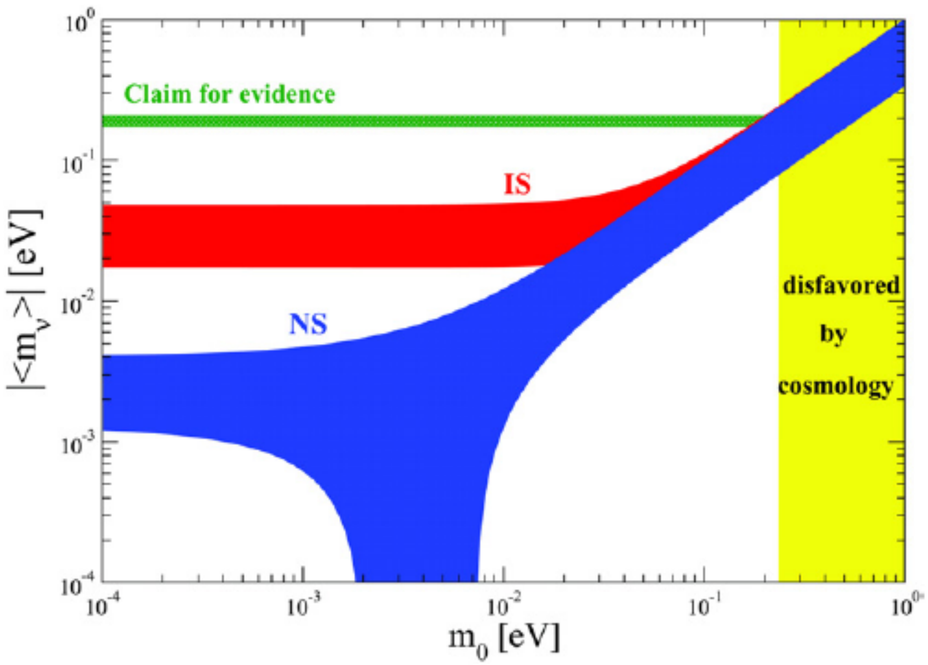
Take-Away Points

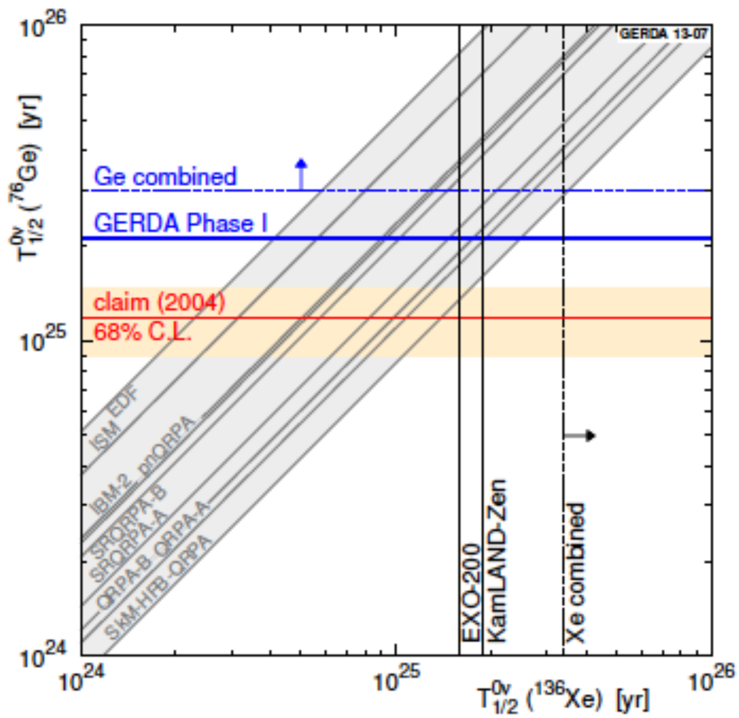
The analysis and guidance of the experimental efforts need **accurate Nuclear Matrix Elements.**

$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2\left(\frac{<m_{\beta\beta}>}{m_e}\right)^2$$

$$\langle m_{\beta\beta}\rangle \equiv \langle m_\nu\rangle = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$





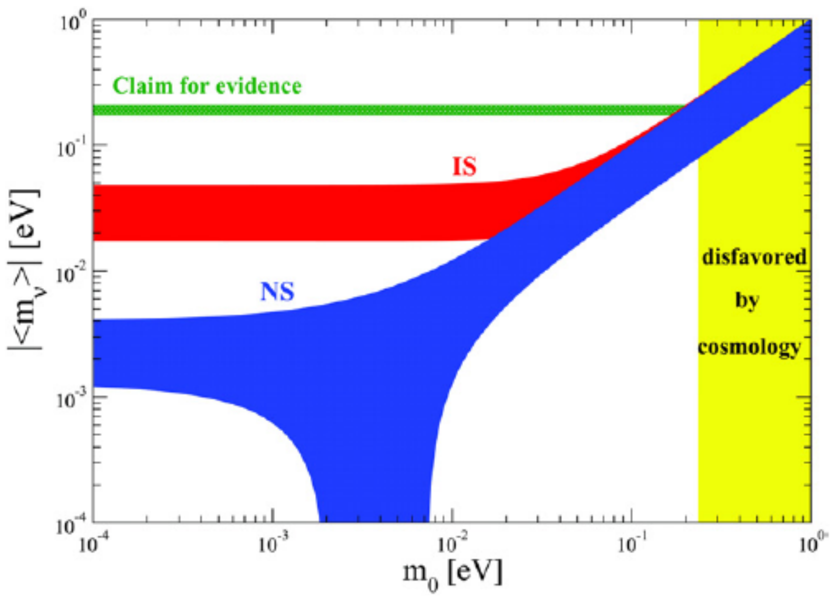
Take-Away Points

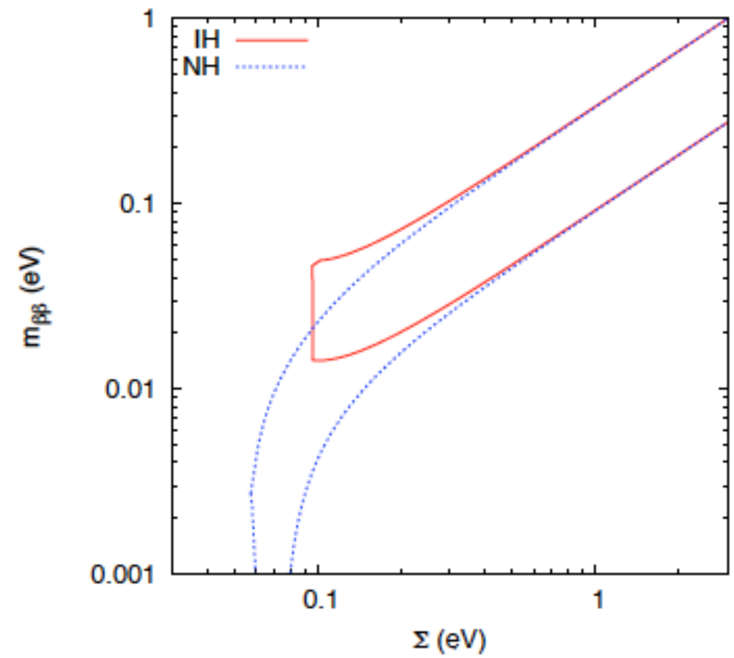
Information about Majorana CP-violation phases may require the mass hierarchy from LBNE, cosmology, etc, but also **accurate Nuclear Matrix Elements**.

$$\langle m_{\beta\beta} \rangle = \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

$$\Sigma = m_1 + m_2 + m_3 \quad \textit{from cosmology}$$

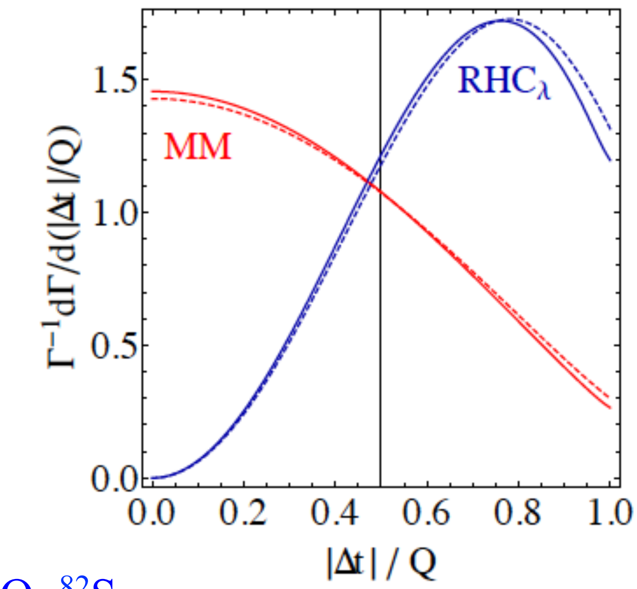




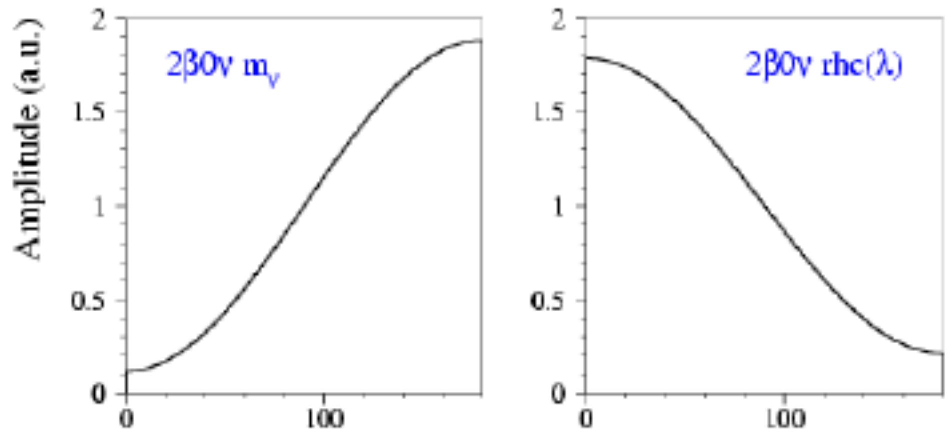
Take-Away Points

Alternative mechanisms to 0νββ need to be carefully tested: many isotopes, energy and angular correlations.

These analyses also require **accurate Nuclear Matrix Elements**.



SuperNEMO; ^{82}Se



θ - angle between e_1 and e_2

$$|\eta_\nu|, |\eta_{NR}| \Leftarrow \begin{cases} \left[G^{0\nu}_{Ge} T^{0\nu}_{1/2\,Ge}\right]^{-1} = \left|M^{(0\nu)}_{Ge}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Ge}\right|^2 |\eta_{NR}|^2 \\ \left[G^{0\nu}_{Xe} T^{0\nu}_{1/2\,Xe}\right]^{-1} = \left|M^{(0\nu)}_{Xe}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Xe}\right|^2 |\eta_{NR}|^2 \end{cases}$$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu} \left|\sum_j M_j \eta_j\right|^2 = G^{0\nu} \left| M^{(0\nu)} \eta_{\nu L} + M^{(0N)} \left(\eta_{NL} + \eta_{NR}\right) + \tilde{X}_\lambda < \lambda > + \tilde{X}_\eta < \eta > + M^{(0\lambda')} \eta_{\lambda'} + M^{(0\tilde{q})} \eta_{\tilde{q}} + \cdots \right|^2$$

Summary and Outlook

- Observation of neutrinoless double beta decay would signal physics beyond the Standard Model: **massive Majorana neutrinos, right-handed currents, SUSY LNV, etc**
- ^{48}Ca and ^{136}Xe cases suggest that 2ν double-beta decay can be described reasonably within the shell model with standard quenching, provided that all spin-orbit partners are included.
- Higher order effects for 0ν NME included: range 1.0 − 1.4
- Reliable 0νββ nuclear matrix elements could be used to identify the dominant mechanism if energy/angular correlations and data for several isotopes become available.
- The effects of the quenching and the missing spin-orbit partners are important (see the ^{136}Xe case), and they need to be further investigated for ^{76}Ge, ^{82}Se and ^{130}Te.