Neutrinos and physics beyond the Standard Model

Mihai Horoi
Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA

- **Support from NSF grant PHY-1404442 and DOE/SciDAC grants DE-SC0008529/SC0008641 is acknowledged**

DOE: Topical Collaboration

m. Unified description of nuclear reactions
n. Dynamics of fusion/fission
o. Cataclysmic astrophysical events
p. Role of neutrino dynamics in astrophysical phenomena
q. Neutrino-nucleus interactions
r. Calculations of nuclear matrix elements for double beta decay
s. Tests of the Standard Model using nuclei
t. Computationally enabled nuclear theory

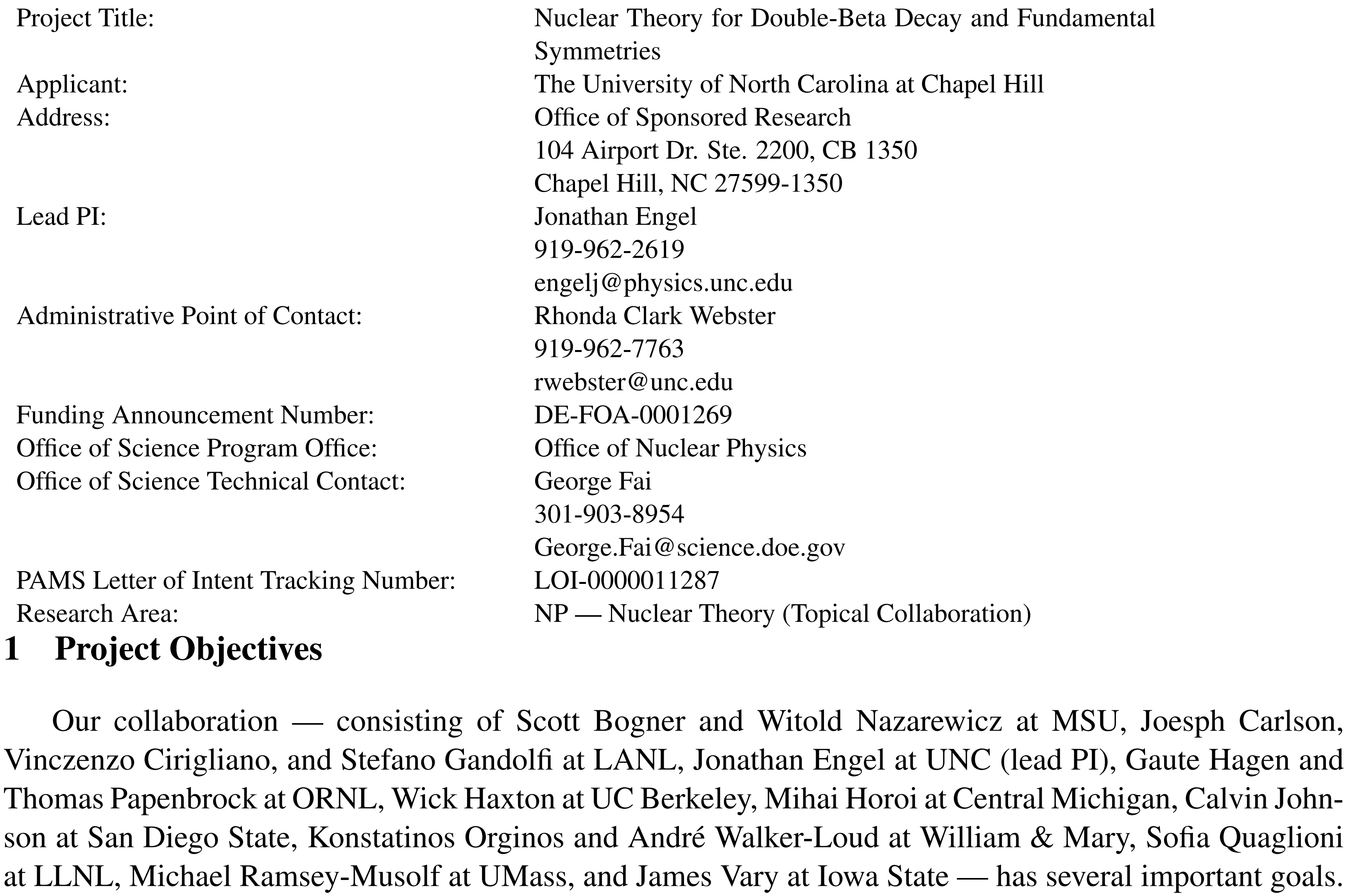
U. S. Department of Energy
Office of Science
Nuclear Physics

Topical Collaborations in Nuclear Theory

Funding Opportunity Number: DE-FOA-0001269
Announcement Type: Initial
CFDA Number: 81.049

Issue Date:	**01/14/2015**
Letter of Intent Due Date:	**03/20/2015 at 5 PM Eastern Time**
Pre-Application Due Date:	**Not Applicable**
Application Due Date:	**04/30/2015 at 5 PM Eastern Time**

DOE: Topical Collaboration



Project Title:	Nuclear Theory for Double-Beta Decay and Fundamental Symmetries
Applicant:	The University of North Carolina at Chapel Hill
Address:	Office of Sponsored Research 104 Airport Dr. Ste. 2200, CB 1350 Chapel Hill, NC 27599-1350
Lead PI:	Jonathan Engel 919-962-2619 engelj@physics.unc.edu
Administrative Point of Contact:	Rhonda Clark Webster 919-962-7763 rwebster@unc.edu
Funding Announcement Number:	DE-FOA-0001269
Office of Science Program Office:	Office of Nuclear Physics
Office of Science Technical Contact:	George Fai 301-903-8954 George.Fai@science.doe.gov
PAMS Letter of Intent Tracking Number:	LOI-0000011287
Research Area:	NP — Nuclear Theory (Topical Collaboration)

1 Project Objectives

Our collaboration — consisting of Scott Bogner and Witold Nazarewicz at MSU, Joesph Carlson, Vinczenzo Cirigliano, and Stefano Gandolfi at LANL, Jonathan Engel at UNC (lead PI), Gaute Hagen and Thomas Papenbrock at ORNL, Wick Haxton at UC Berkeley, Mihai Horoi at Central Michigan, Calvin Johnson at San Diego State, Konstatinos Orginos and André Walker-Loud at William & Mary, Sofia Quaglioni at LLNL, Michael Ramsey-Musolf at UMass, and James Vary at Iowa State — has several important goals.

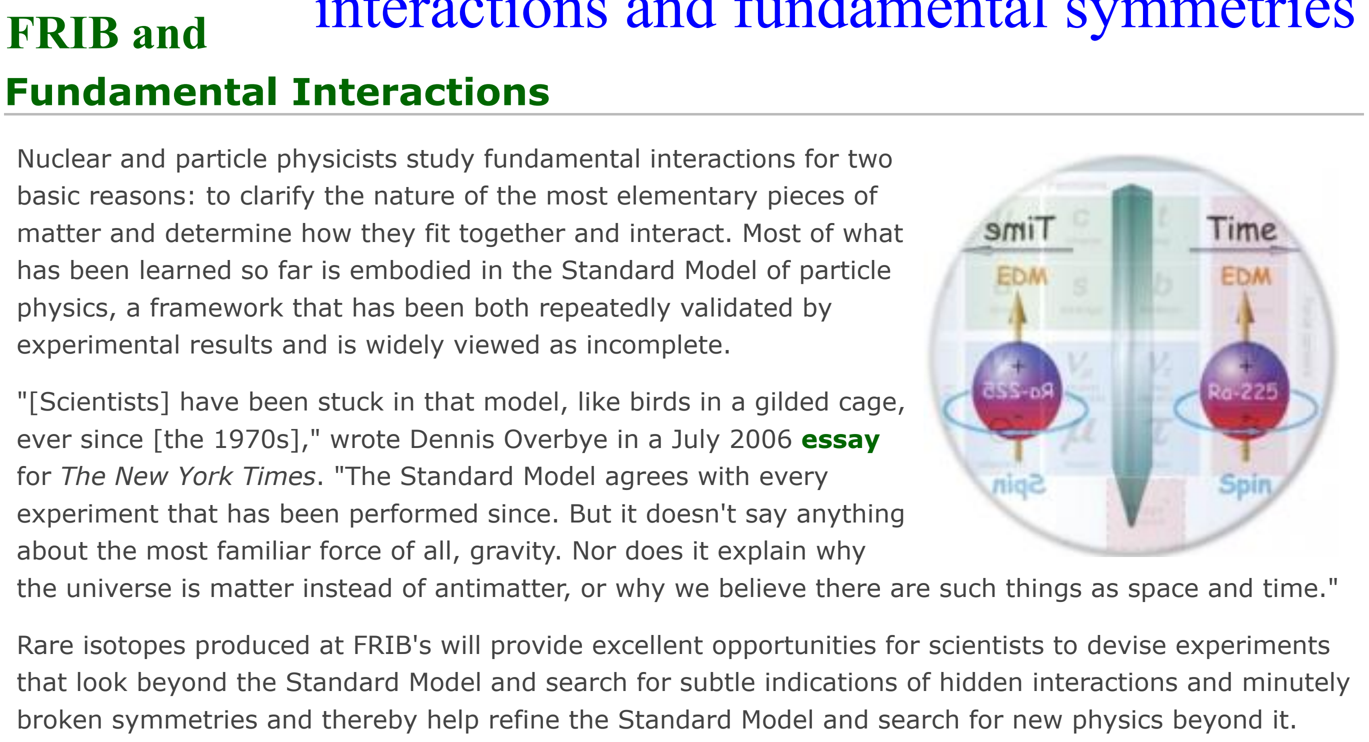
Announcement on the selection of Topical Collaborations in Nuclear Theory recommended for funding

The Office of Nuclear Physics (NP), on the basis of a peer review, has selected the following Topical Collaborations (to start in FY 2016) for funding recommendation:

- Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Collaboration)
  Principal Investigator/Project Director: Jianwei Qiu
  Lead Institution: Brookhaven National Laboratory
  Participating Institutions: Duke University, Jefferson Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, MIT, New Mexico State University, Penn State University at Berks, Old Dominion University, Temple University, University of Arizona, University of Kentucky, University of Maryland, University of Virginia

- Nuclear Theory for Double-Beta Decay and Fundamental Symmetries (DBD Collaboration)
  Principal Investigator/Project Director: Jonathan Engel
  Lead Institution: University of North Carolina at Chapel Hill
  Participating Institutions: Central Michigan University, College of William and Mary, Iowa State University, Michigan State University, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, San Diego State University, University of California Berkeley, University of Massachusetts, University of Tennessee

Nuclei, a laboratory for studying fundamental interactions and fundamental symmetries



FRIB and Fundamental Interactions

Nuclear and particle physicists study fundamental interactions for two basic reasons: to clarify the nature of the most elementary pieces of matter and determine how they fit together and interact. Most of what has been learned so far is embodied in the Standard Model of particle physics, a framework that has been both repeatedly validated by experimental results and is widely viewed as incomplete.

"[Scientists] have been stuck in that model, like birds in a gilded cage, ever since [the 1970s]," wrote Dennis Overbye in a July 2006 **essay** for *The New York Times*. "The Standard Model agrees with every experiment that has been performed since. But it doesn't say anything about the most familiar force of all, gravity. Nor does it explain why the universe is matter instead of antimatter, or why we believe there are such things as space and time."

Rare isotopes produced at FRIB's will provide excellent opportunities for scientists to devise experiments that look beyond the Standard Model and search for subtle indications of hidden interactions and minutely broken symmetries and thereby help refine the Standard Model and search for new physics beyond it.

- Double-beta decay: ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe
- EDM: ^{199}Hg, ^{225}Ra, ^{211}Rn, etc
- PNC: ^{14}N, ^{18}F, ^{19}F, ^{21}Ne (PRL 74, 231 (1995))
- Beta decay: super-allowed, angular correlations, etc

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

Neutrino Masses

PMNS – matrix

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

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

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

- Tritium decay:

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

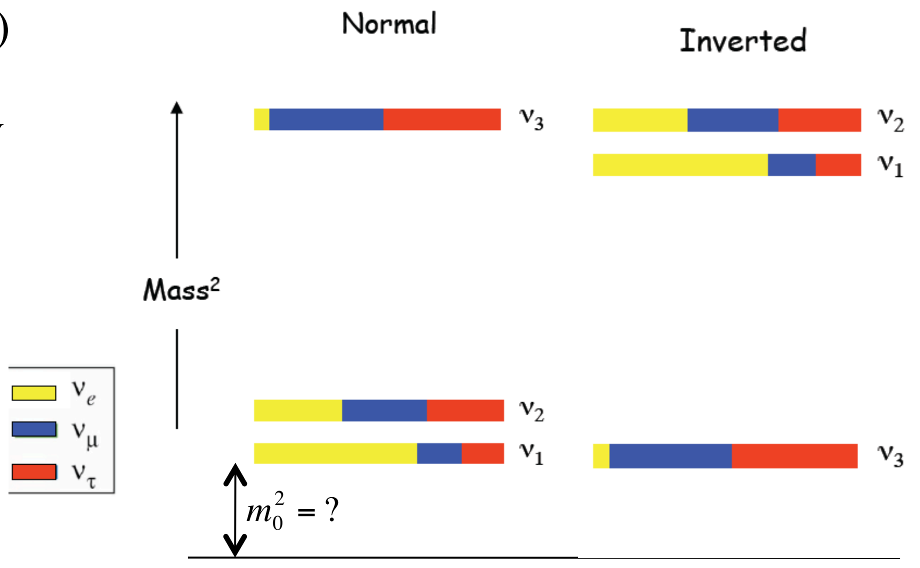
$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < \; 2.2eV\,(Mainz\;\exp.)$$

$$KATRIN\ (to\ take\ data):\ goal\;\; m_{\nu_e} < 0.3eV$$

- Cosmology: CMB power spectrum, BAO, etc,

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

$$Goal: 0.01eV\ (5-10\ y)$$



Two neutrino mass hierarchies

Neutrino Masses

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$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} <$$

$KATRIN$ (to take data): goal $m_{\nu_e} < 0.3eV$

Neutrino oscillations:

- *NH or IH?*
- $\delta_{CP} = ?$
- *Unitarity of* U_{PMNS} ?
- *Are there* $m \sim 1eV$ *sterile neutrinos?*

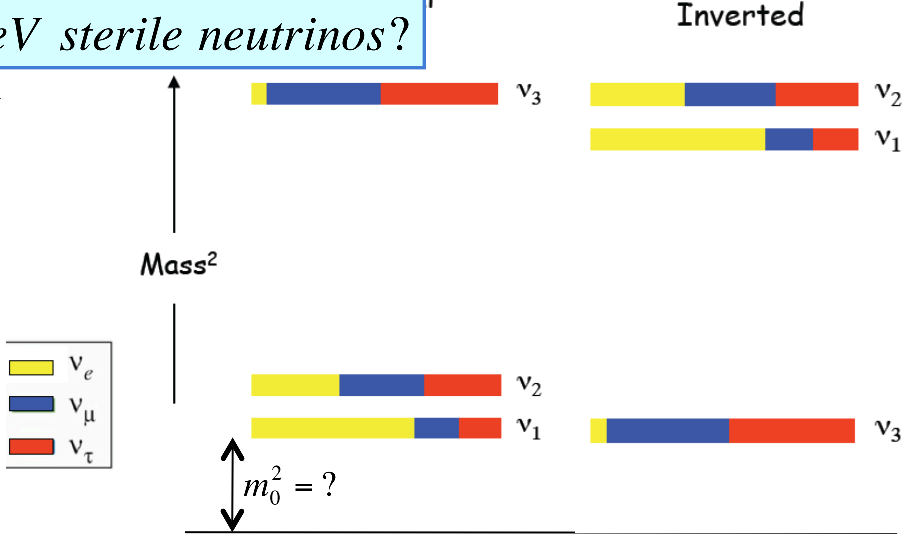
$\times 10^{-5}\ eV^2\,(solar)$

$\times 10^{-3}\ eV^2\,(atmospheric)$

- Cosmology: CMB power spectrum, BAO, etc,

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

$Goal: 0.01eV\ (5-10\ y)$



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Neutrino oscillations :

- NH *or* IH ?
- $\delta_{CP} = ?$
- *Unitarity of* U_{PMNS} ?
- *Are there* $m \sim 1eV$ *sterile neutrinos?*

$\times 10^{-5}\ eV^2\,(solar)$

$4 \times 10^{-3}\ eV^2\,(atmospheric)$

- Tritium decay:

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

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} <$$

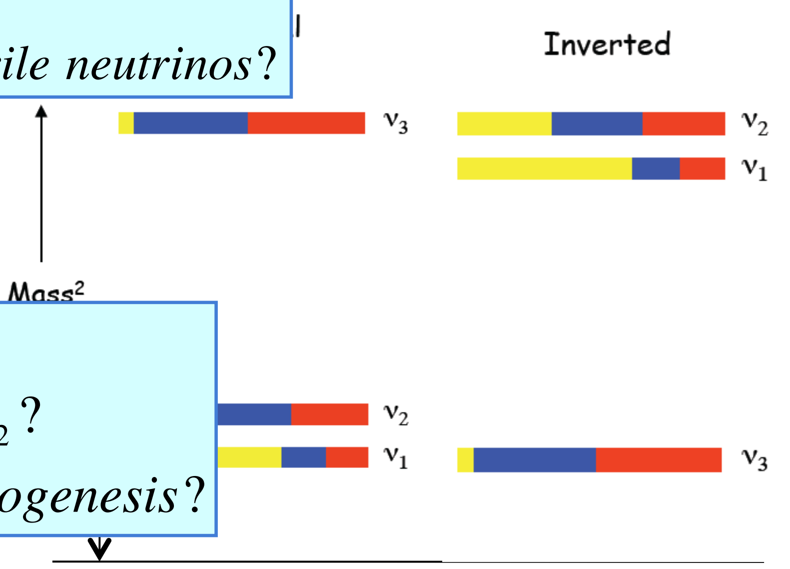
KATRIN (*to take data*): *goal* $m_{\nu_e} < 0.3eV$

- Cosmology: CMB power spectrum, BAO, e

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

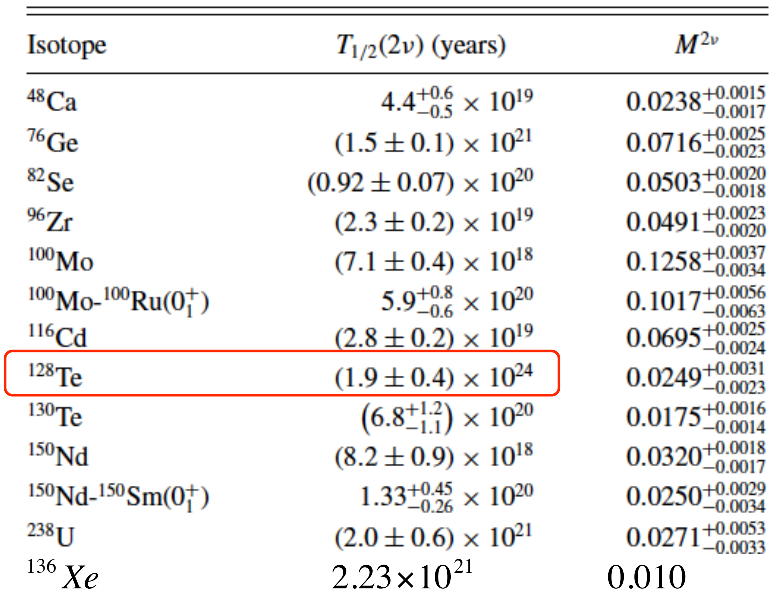
Goal : $0.01eV$ $(5-10\ y)$

- *Dirac or Majorana?*
- *Majorana CPV* α_1, α_2 ?
- *Leptogenesis* $\rightarrow$ *Baryogenesis?*



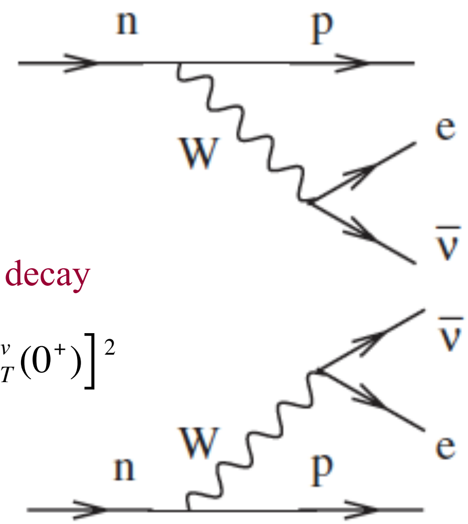
Two neutrino mass hierarchies

Classical Double Beta Decay Problem



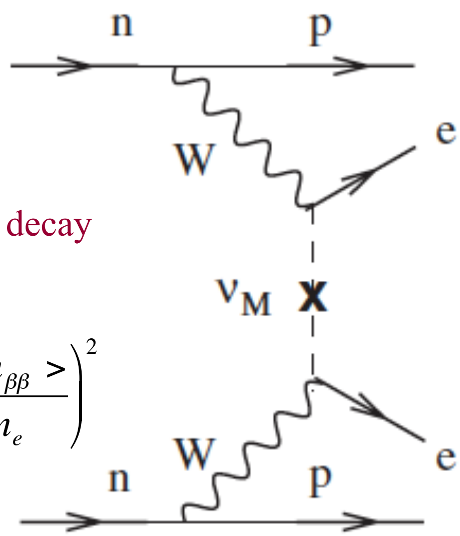
Isotope	$T_{1/2}(2\nu)$ (years)	$M^{2\nu}$
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$	$0.0238^{+0.0015}_{-0.0017}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	$0.0716^{+0.0025}_{-0.0023}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	$0.0503^{+0.0020}_{-0.0018}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	$0.0491^{+0.0023}_{-0.0020}$
^{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}	0.010

A.S. Barabash, PRC 81 (2010)



2-neutrino double beta decay

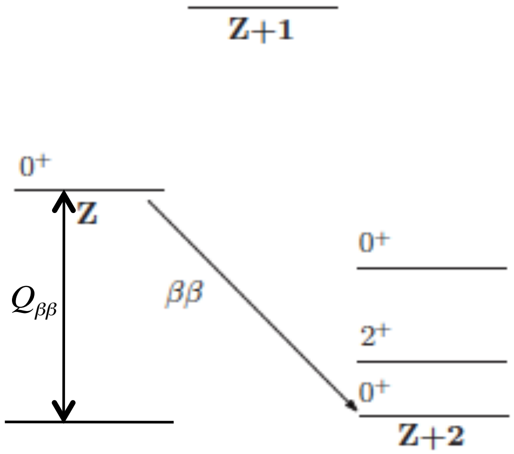
$$T^{-1}_{1/2}(2\nu) = G^{2\nu}(Q_{\beta\beta})\left[M^{2\nu}_{GT}(0^+)\right]^2$$



neutrinoless double beta decay

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

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



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

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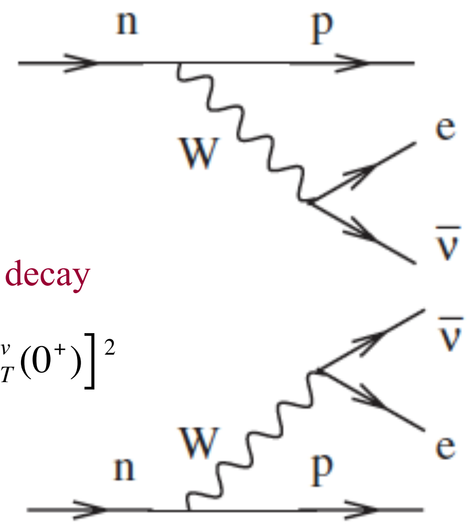
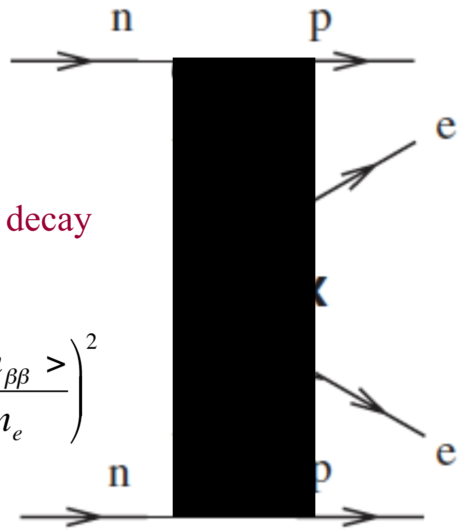


2-neutrino double beta decay

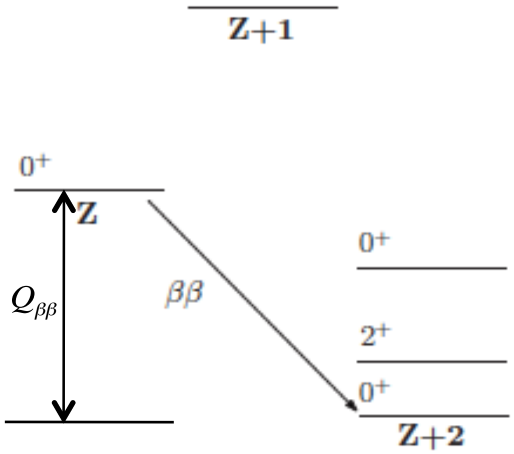
$$T_{1/2}^{-1}(2\nu) = G^{2\nu}(Q_{\beta\beta})\left[M_{GT}^{2\nu}(0^+)\right]^2$$



neutrinoless double beta decay

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

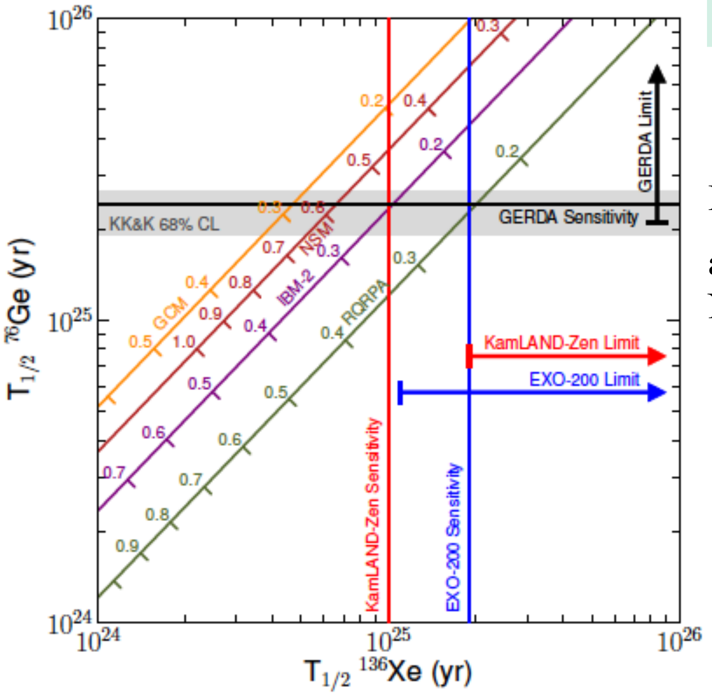
$$\langle m_{\beta\beta}\rangle = \left|\sum_k m_k U_{ek}^2\right|$$



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

^{136}Xe ββ Experimental Results

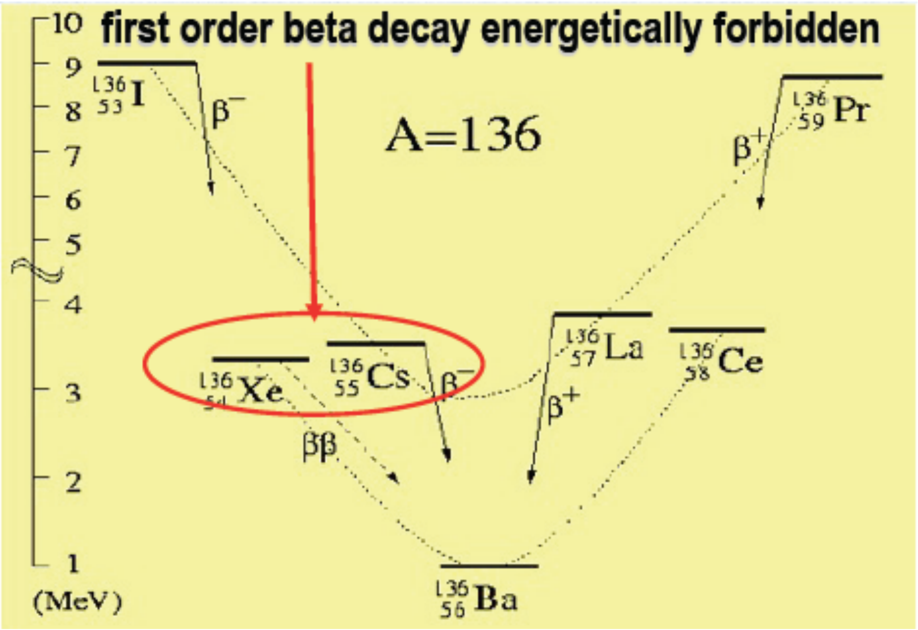
Publication	Experiment	$T^{2\nu}_{1/2}$	$T^{0\nu}_{1/2}$(lim)	$T^{0\nu}_{1/2}$(Sens)
PRL 110, 062502	KamLAND-Zen		> 1.9×10^{25} y	1.1×10^{25} y
PRC 89, 015502	EXO-200	$(2.11 \pm 0.04 \pm 0.21) \times 10^{21}$ y		
Nature 510, 229	EXO-200		>1.1×10^{25} y	1.9×10^{25} y
PRC 85, 045504	KamLAND-Zen	$(2.38 \pm 0.02 \pm 0.14) \times 10^{21}$ y		
		$M^{2\nu}_{\exp} = 0.0191 - 0.0215\ MeV^{-1}$		



EXO-200

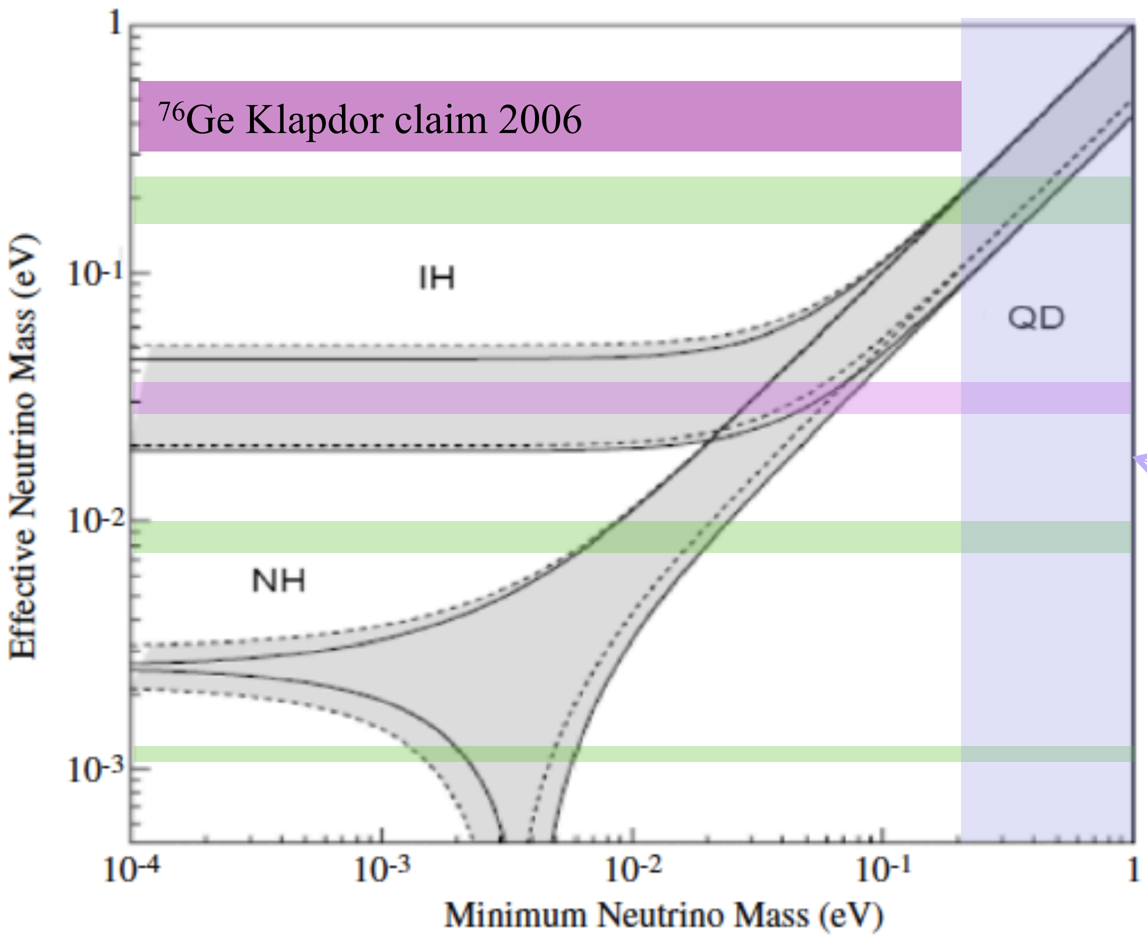
arXiv:1402.6956, Nature 510, 229

M. Horoi



Neutrino ββ effective mass

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



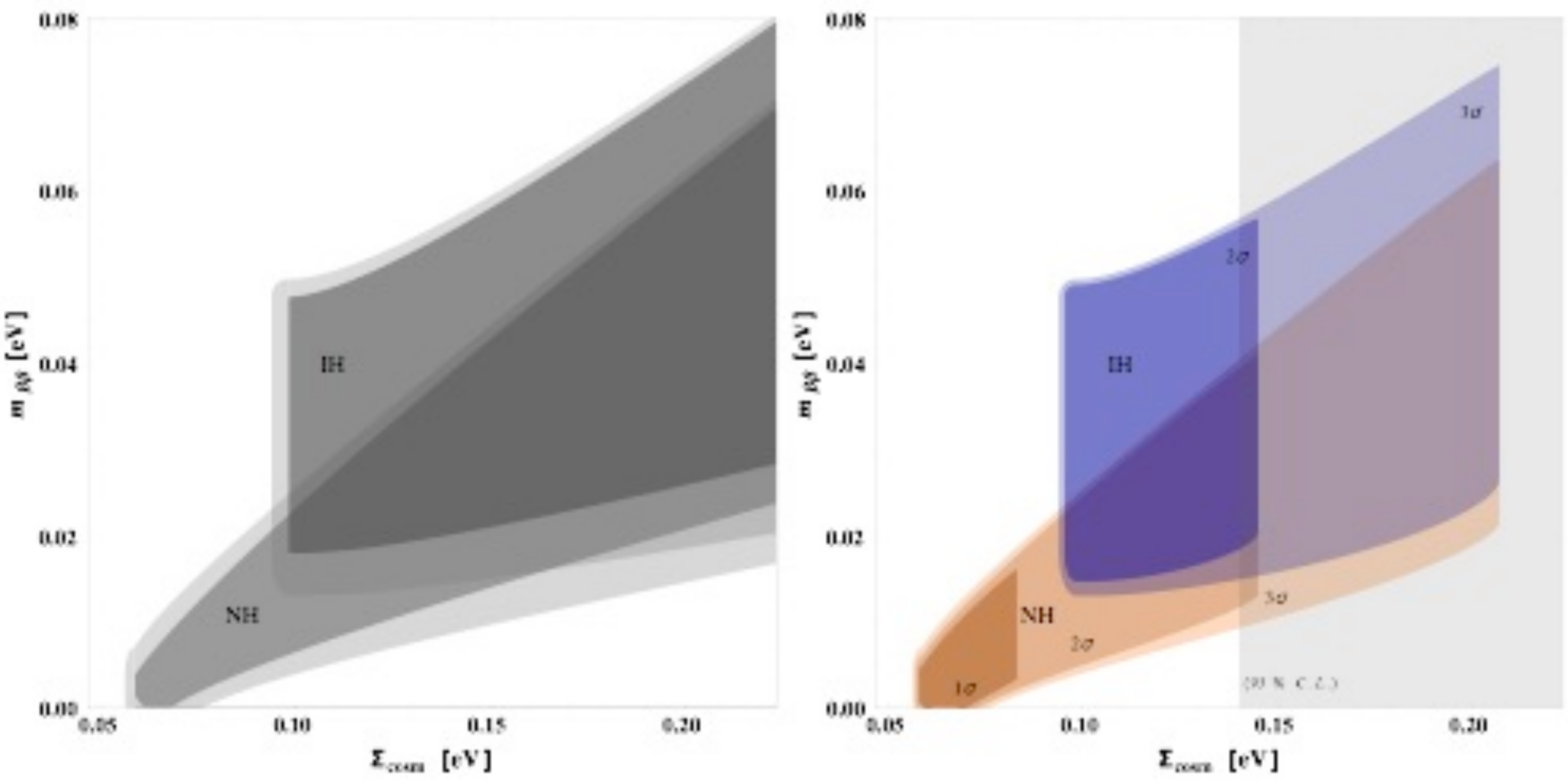
$$\langle m_{\beta\beta}\rangle = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right|$$
$$= \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

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

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

Cosmology constraint

Recent Constraints from Cosmology

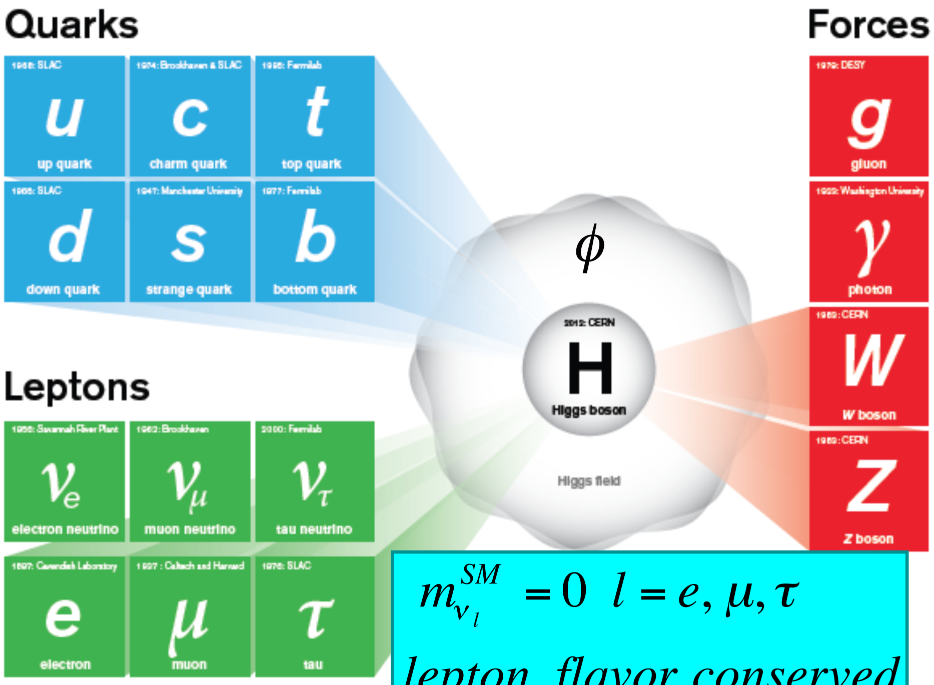


$$\Sigma = m_1 + m_2 + m_3$$

$$\begin{array}{lr}\Sigma < \ \ 84\,\mathrm{meV} & (1\sigma\,\mathrm{C.\,L.}) \\ \Sigma < 146\,\mathrm{meV} & (2\sigma\,\mathrm{C.\,L.}) \\ \Sigma < 208\,\mathrm{meV} & (3\sigma\,\mathrm{C.\,L.})\end{array}$$

arXiV:1505.02722

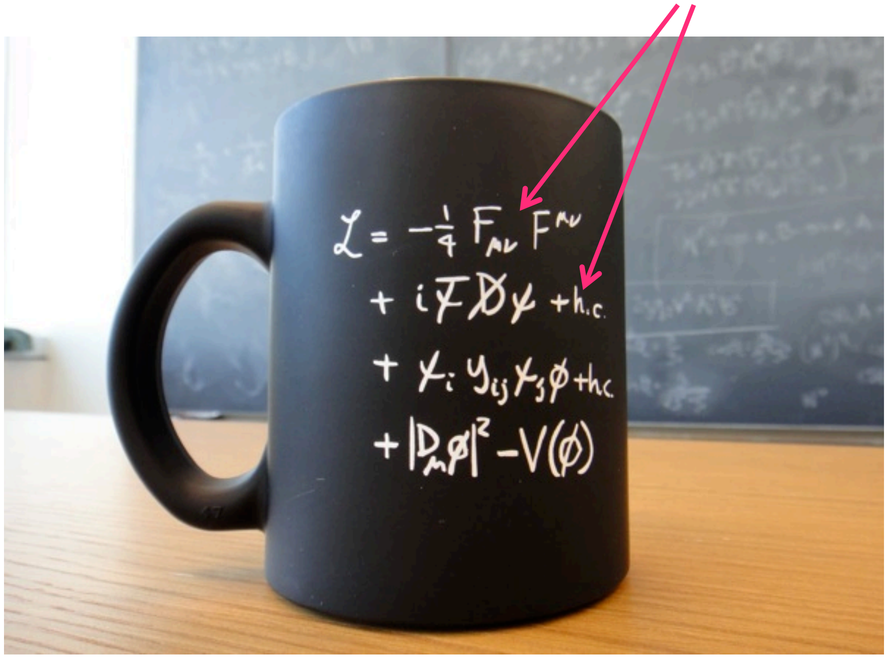
The Minimal Standard Model



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

lepton flavor conserved

?



$SU(2)_L$
doublet

SM fermion masses:

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

$SU(2)_L$
doublet

$SU(2)_L$
singlet

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

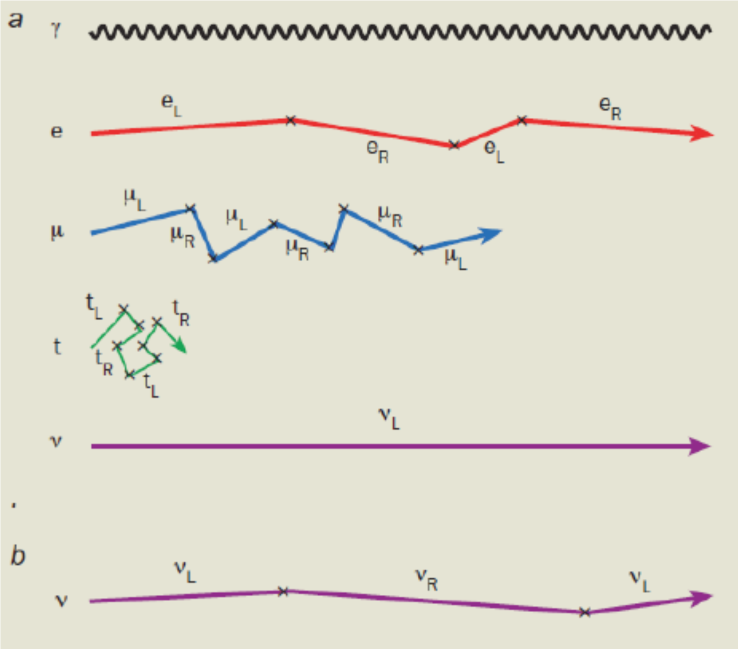
Local Gauge invariance of Lagrangian density $\mathcal{L}$:

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

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

EWSB ↳ $SU(3)_c \times U(1)_{em}$

The origin of Majorana neutrino masses



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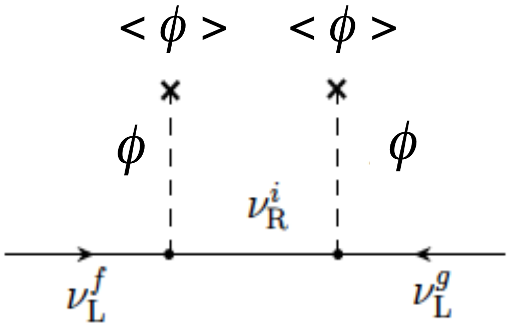


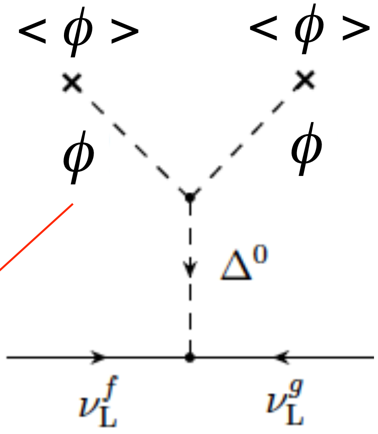
Diagram illustrating the type I see-saw mechanism

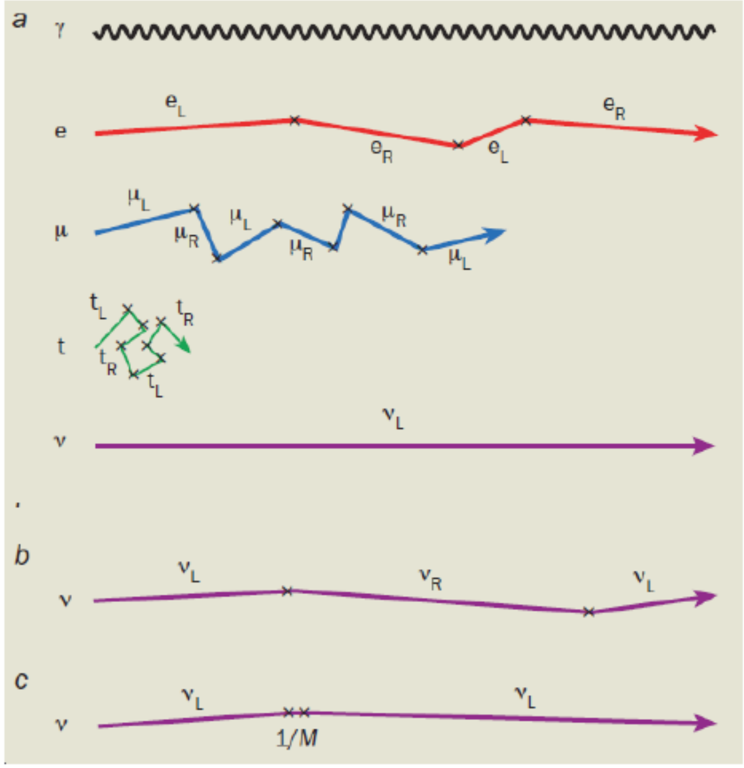
See-saw mechanisms

$$\begin{cases} m_{LL}^{\nu} \approx \dfrac{(100\ GeV)^2}{10^{14}\ GeV} = 0.1\,eV \\ m_{LL}^{\nu} \approx \dfrac{(300\ keV)^2}{1\ TeV} = 0.1\,eV \end{cases}$$

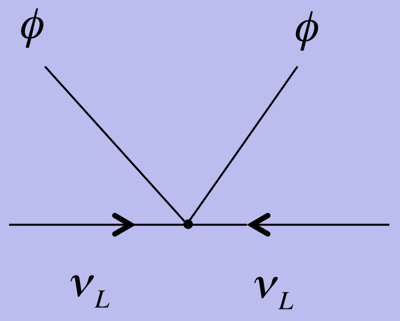
Left-Right Symmetric model

$$m_{LL}^{\nu} \approx m_{LL}^{II} + m_{LL}^{I}$$

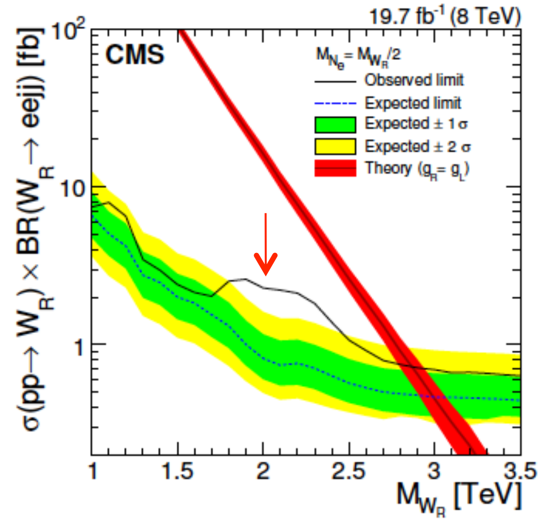




Weinberg's dimension-5 BSM operator contributing to Majorana neutrino mass



W_R search at CMS
arXiv:1407.3683



M. Horoi CMU

Models, ββ, and LHC

◆ Left-right (LR) symmetric model(s):

- Restore LR symmetry (at some scale), needs new iso-triplet Higgs, W_R, new ββ-decay contributions

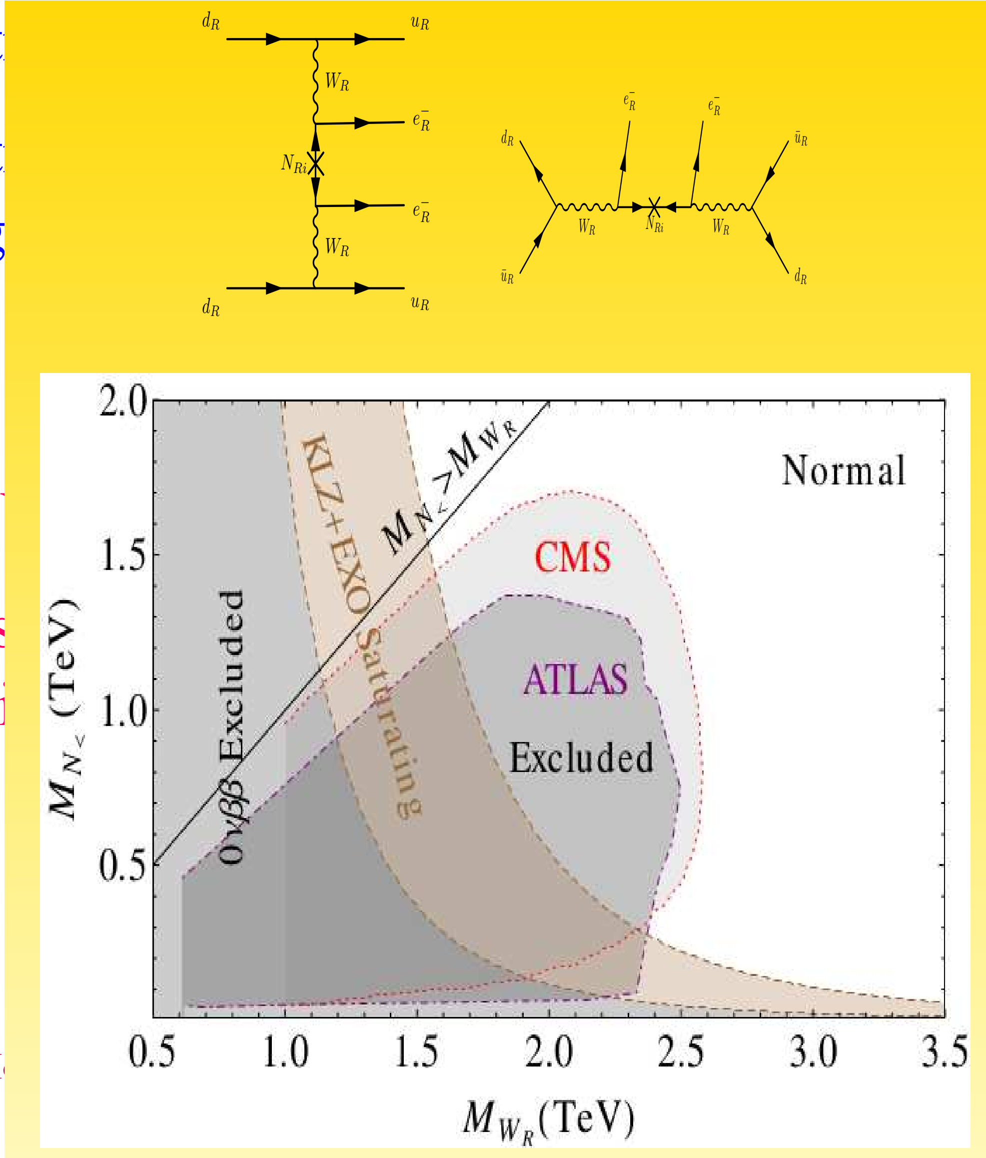
◆ Super-Symmetric (SUSY) model(s):

- Restore fermion-boson symmetry, double the # of particles, may contribute to ββ-decay (R-parity)

Models, ββ, and LHC

- ◆ Left-right (LR) symmet
  - Restore LR symmet new iso-triplet Higg contributions

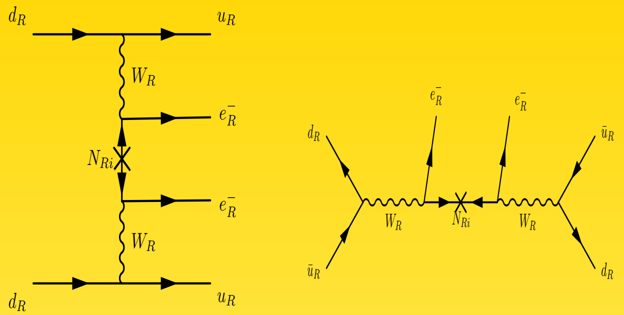
- ◆ Super-Symmetric (SUS
  - Restore fermion-bos particles, may contri



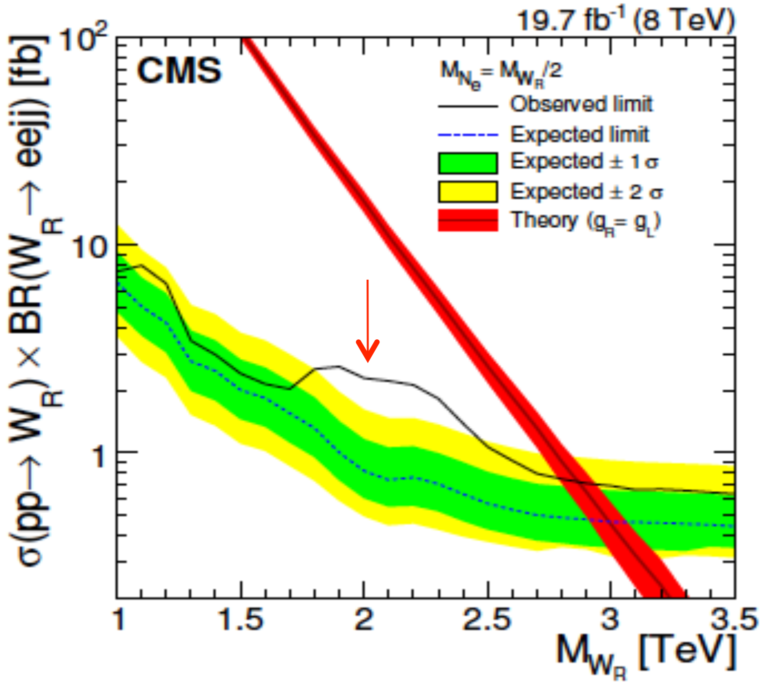
Models, ββ, and LHC

◆ Left-right (LR) symmet

- Restore LR symmet
  Higgs, W_R, new ββ-



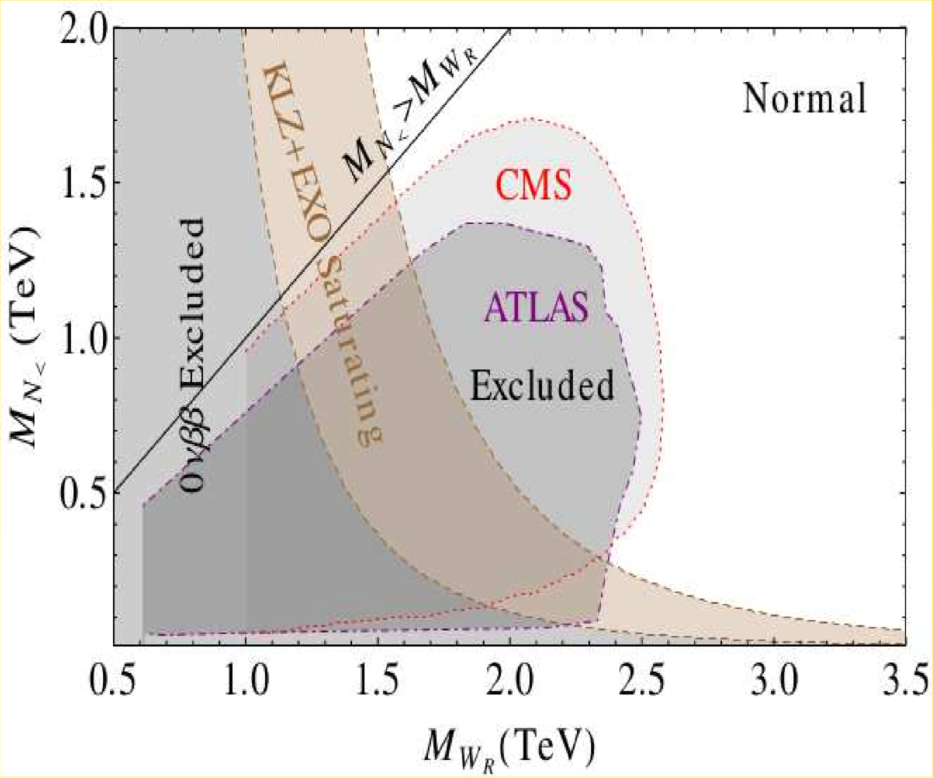
W_R search at CMS arXiv: 1407.3683



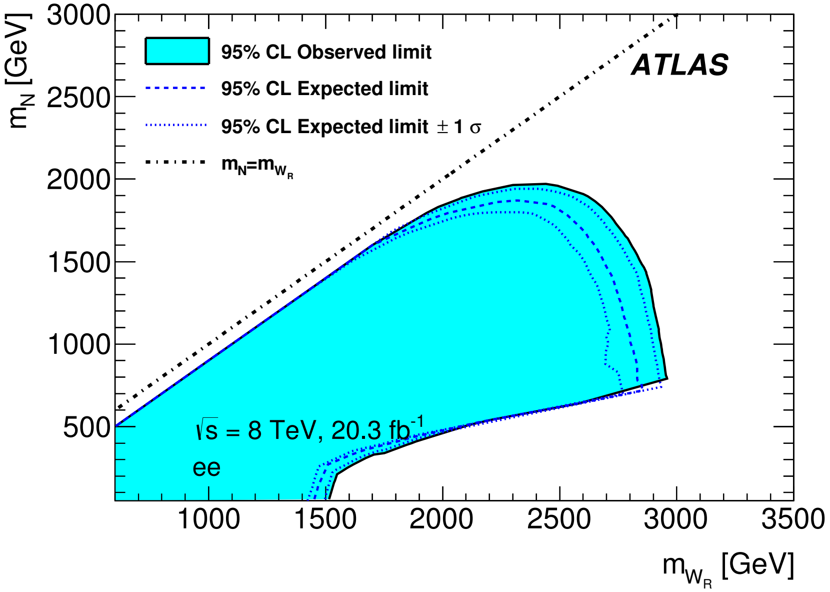
SUS

-bos

ontri

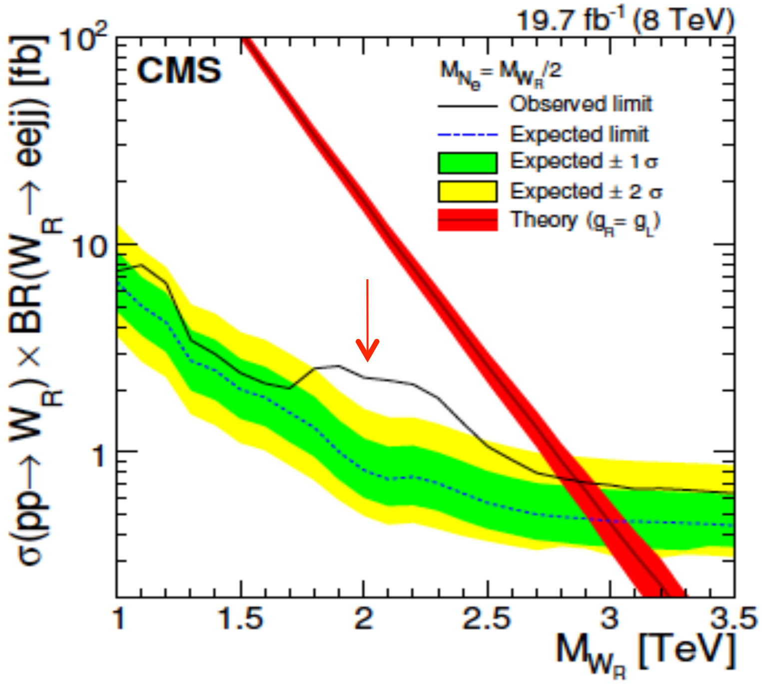


Models, ββ,



- Left-right (LR) symmet
  - Restore LR symmet Higgs, W_R, new ββ-

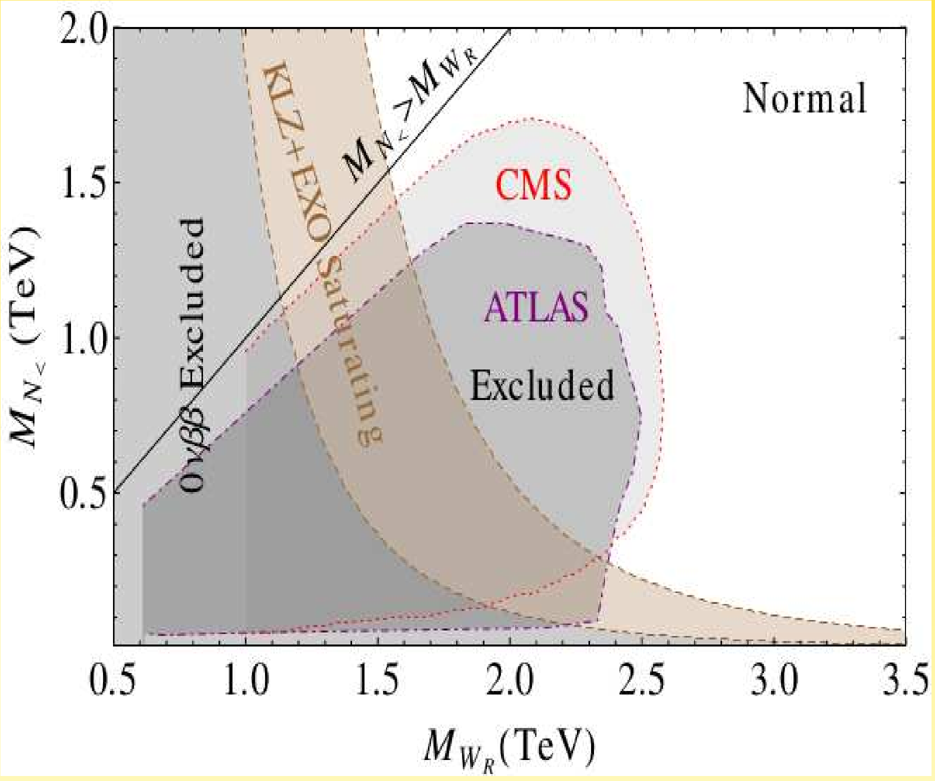
W_R search at CMS arXiv: 1407.3683



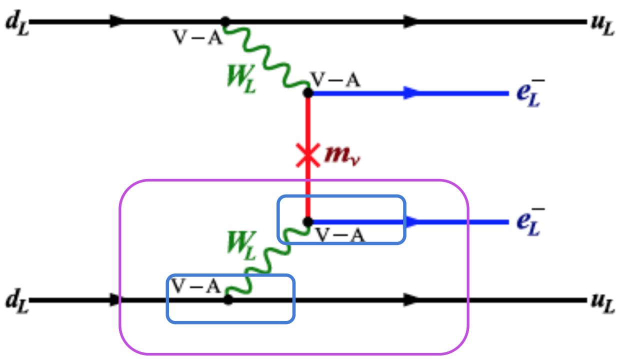
SUSY

-bos

ontri



Low-energy LR contributions to 0νββ decay

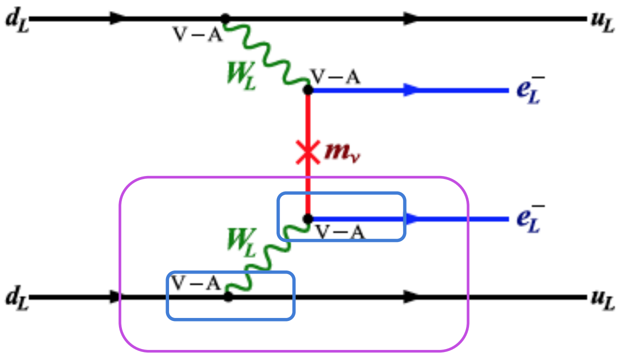


Low-energy effective Hamiltonian

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

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

Low-energy LR contributions to 0νββ decay



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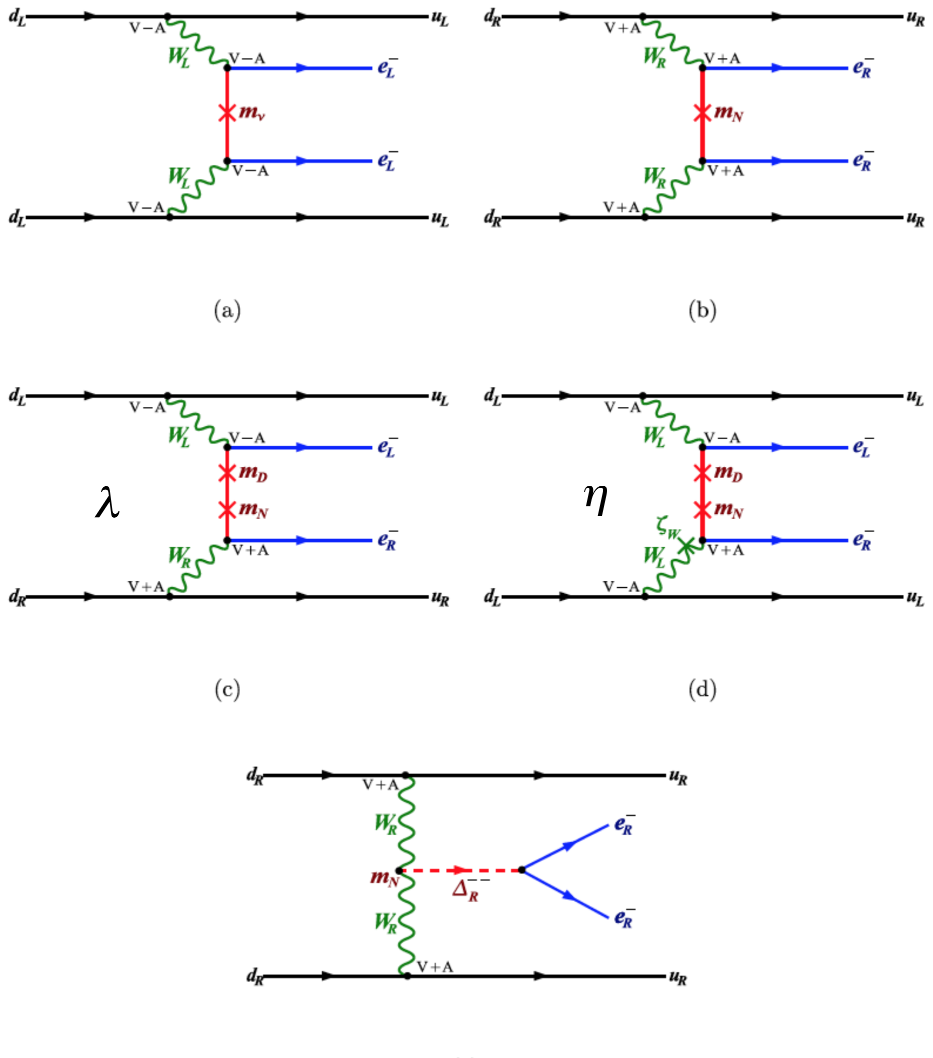
$$j_{L/R}^\mu = \bar{e}\gamma^\mu\left(1 \mp \gamma^5\right)\nu_e$$

$$\nu'_{eL} = \sum_k^{light} U_{ek}\nu_{kL} + \sum_k^{heavy} S_{ek}N_{kR}^c,$$

$$\nu'_{eR} = \sum_k^{light} T_{ek}^*\nu_{iL}^c + \sum_k^{heavy} V_{ek}^*N_{kR},$$

Low-energy LR contributions to 0νββ decay

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



(a) (b)

(c) (d)

(e)

Low-energy effective Hamiltonian

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

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

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

Left – right symmetric model

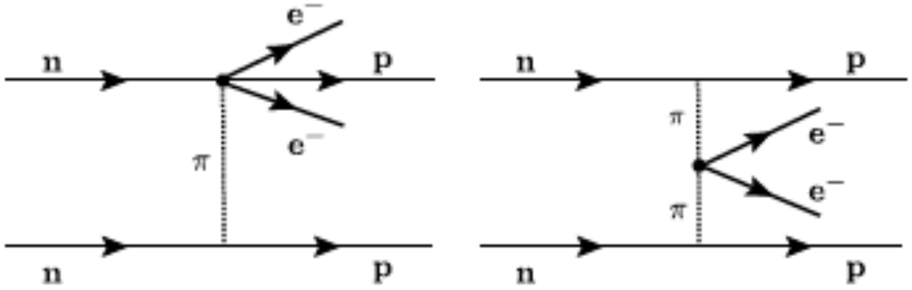
$$-\mathcal{L}\supset \frac{1}{2} h^T_{\alpha\beta}\left(\bar{\nu}_{\beta L}\ \ \bar{e}_{\alpha L}\right)\begin{pmatrix}\Delta^- & -\Delta^0\\ \Delta^{--} & \Delta^-\end{pmatrix}\begin{pmatrix}e^c_R\\ -\nu^c_R\end{pmatrix}+hc$$

No neutrino exchange

More long-range contributions?

$SUSY/w\,R - parity\ v.:\ e.g.\ Rep.\mathrm{Pr}og.Phys.\ 75, 106301(2012)$

Hadronization /w R-parity v. and heavy neutrino



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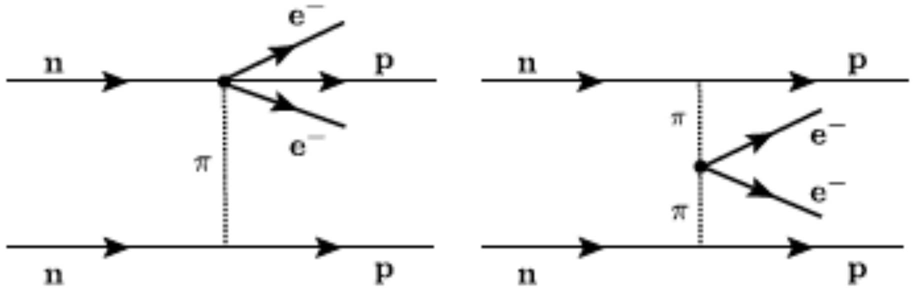


$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}\left|\sum_j M_j\eta_j\right|^2 = G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}\left(\eta_{NL}+\eta_{NR}\right) + \tilde{X}_\lambda < \lambda > + \tilde{X}_\eta < \eta > + M^{(0\lambda')}\eta_{\lambda'} + M^{(0\tilde{q})}\eta_{\tilde{q}} + \cdots\right|^2$$

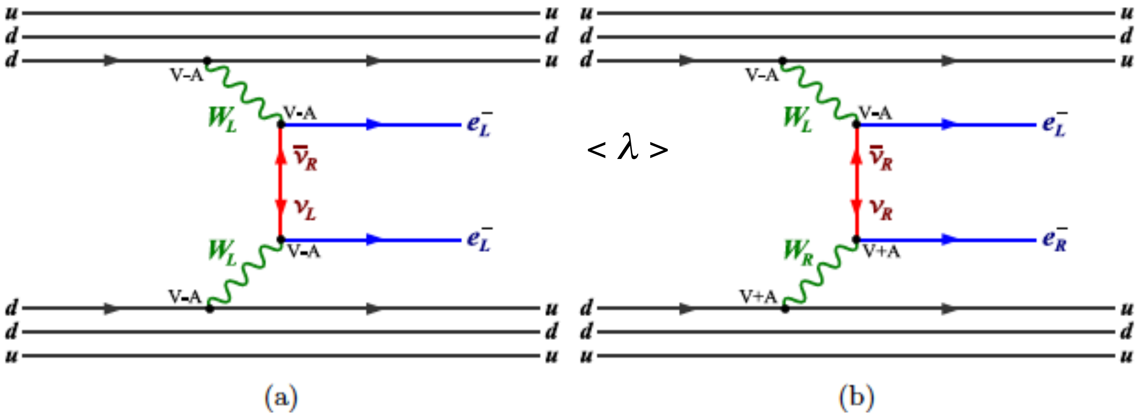
(i) η_{NL} *neglijible in most models*; (ii) $\langle\eta\rangle$ & $\langle\lambda\rangle$ *ruled in/out by energy or angular distributions*

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

DBD signals from different mechanisms

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

arXiv:1005.1241



$$\left[T_{1/2}^{0\nu}\right]^{-1} = \left|M_{GT}^{(0\nu)}\right|^2 \{C_{\nu^2} + C_{\nu\lambda}\cos\phi_1 + C_{\nu\eta}\cos\phi_2 + C_{\lambda^2} + C_{\eta^2} + C_{\lambda\eta}\cos(\phi_1 - \phi_2)\},$$

DBD signals from different mechanisms

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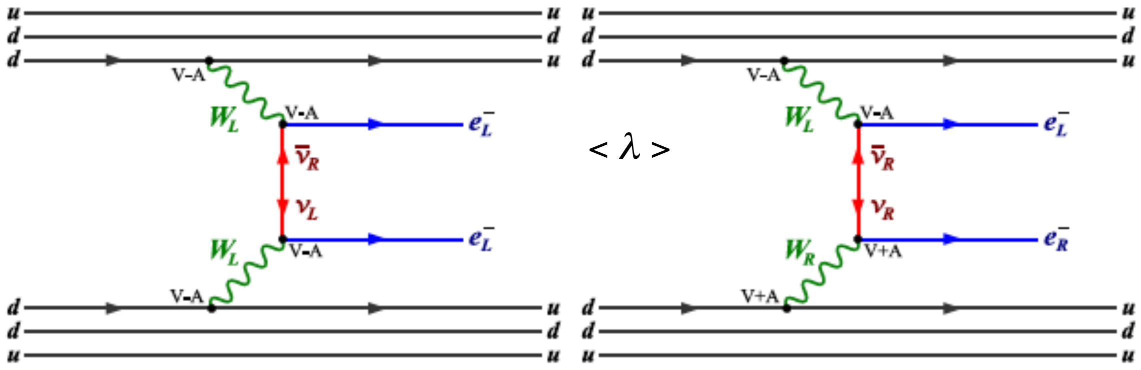


(a) (b)

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \left|M_{GT}^{(0\nu)}\right|^2 \{C_{\nu^2} + C_{\nu\lambda}\cos\phi_1 + C_{\nu\eta}\cos\phi_2 + C_{\lambda^2} + C_{\eta^2} + C_{\lambda\eta}\cos(\phi_1 - \phi_2)\},$$

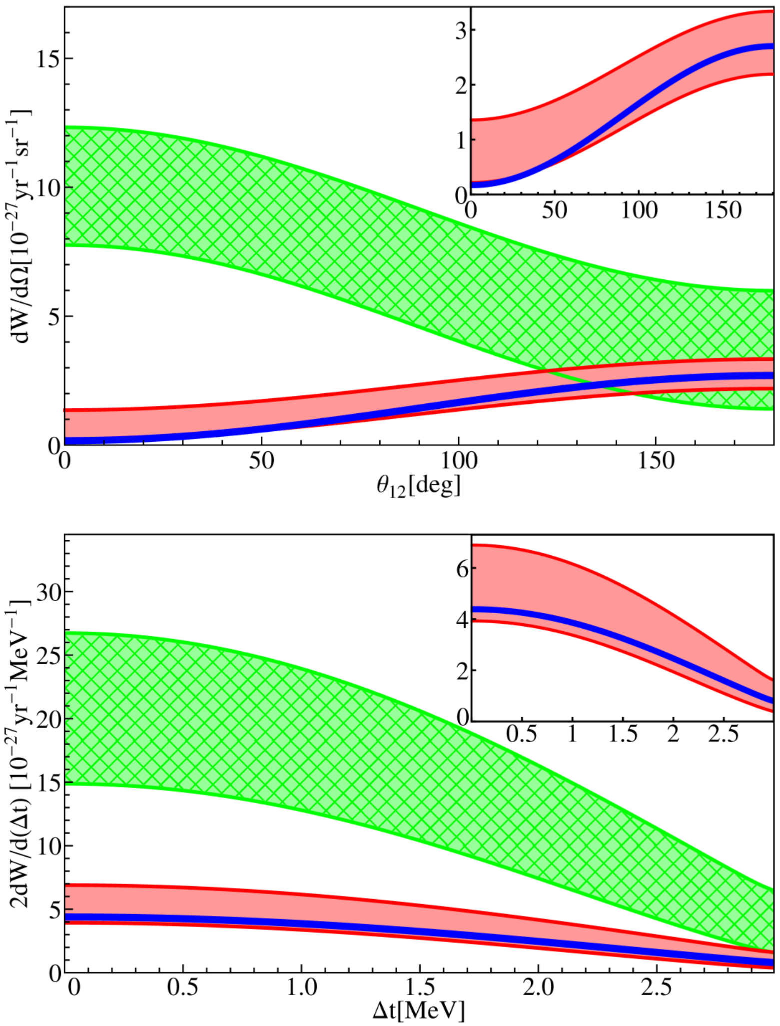
$$\frac{\mathrm{d}^2 W_{0^+\to 0^+}^{0\nu}}{\mathrm{d}\epsilon_1 \mathrm{d}\cos\theta_{12}} = \frac{a_{0\nu}\omega_{0\nu}(\epsilon_1)}{2\,(m_e R)^2}\left[A(\epsilon_1) + B(\epsilon_1)\cos\theta_{12}\right]$$

$$\frac{2\mathrm{d}W_{0^+\to 0^+}^{0\nu}}{\mathrm{d}(\Delta t)} = \frac{2a_{0\nu}}{(m_e R)^2}\,\frac{\omega_{0\nu}(\Delta t)}{m_e c^2} A(\Delta t)$$

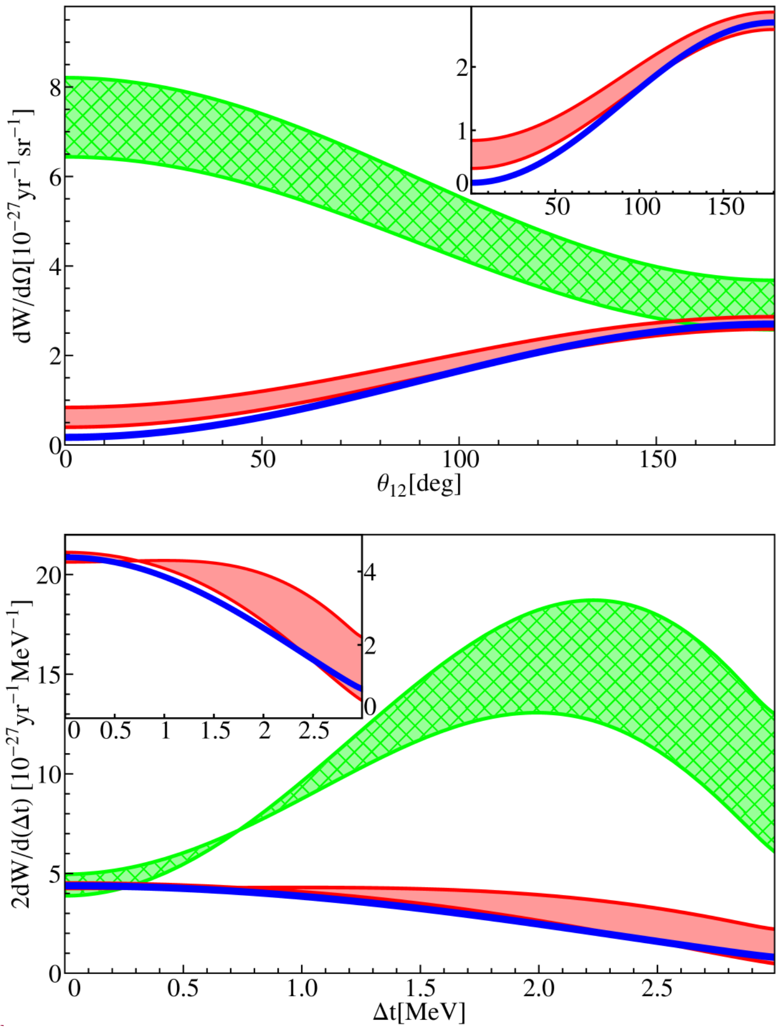
$$t = \varepsilon_{e1} - \varepsilon_{e2}$$

λ and η mechanisms (^{82}Se): look for green

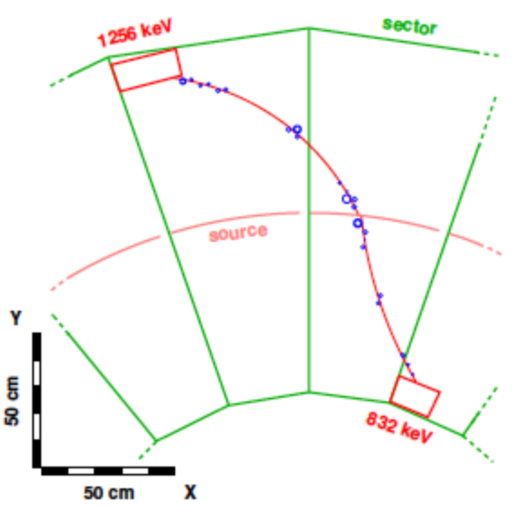
$< \lambda >$ dominates



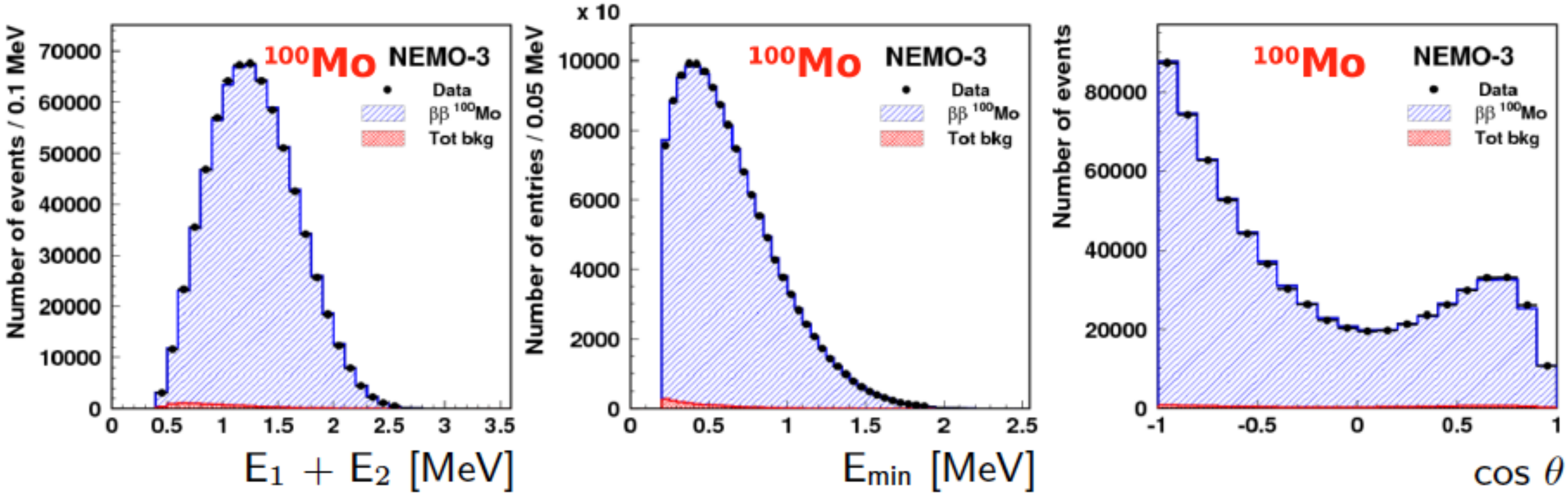
$< \eta >$ dominates



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:
  $\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01 \text{ (stat)} \pm 0.54 \text{ (syst) } 10^{18}$ y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]



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

Two Non-Interfering Mechanisms

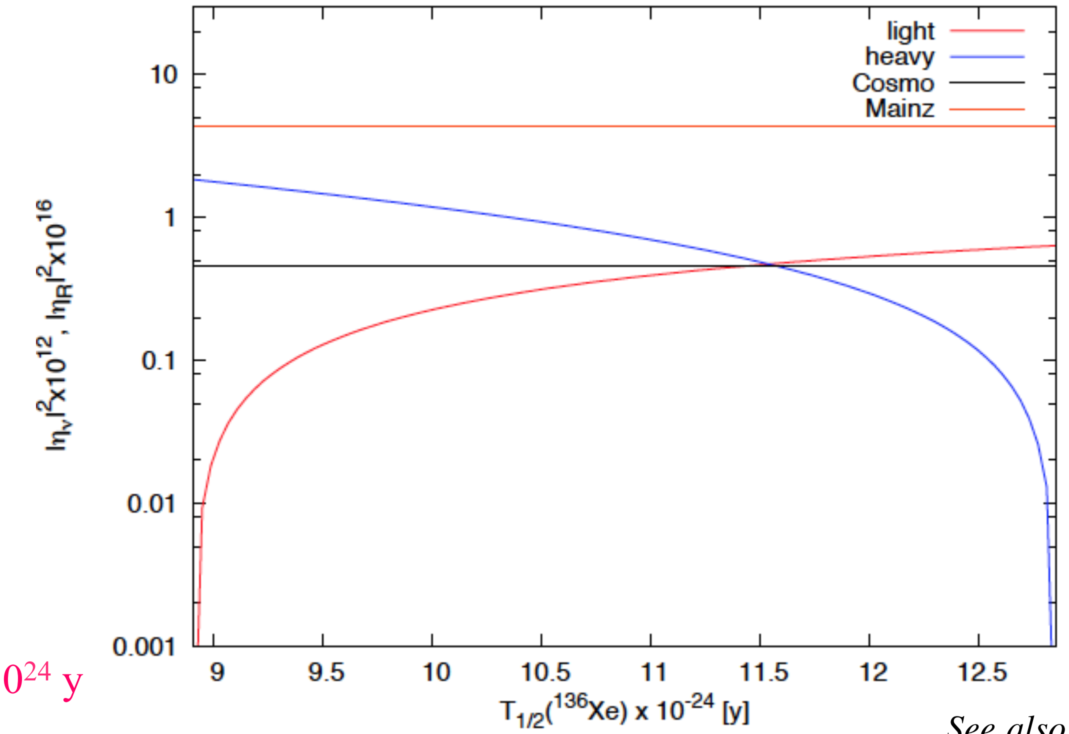
$$\left[T_{1/2}^{0\nu}\right]^{-1} \approx G^{0\nu}\left[\left|M^{(0\nu)}\right|^2 \left|\eta_{\nu L}\right|^2 + \left|M^{(0N)}\right|^2 \left|\eta_{NR}\right|^2\right]$$

No interference terms!

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

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

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



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

See also PRD 83, 113003 (2011)

Two Non-Interfering Mechanisms

$$r(\nu/N) \equiv T_{1/2}^{\nu/N}(1)/T_{1/2}^{\nu/N}(2) = \frac{G_{01}^{0\nu}(2)\left|M^{0\nu/N}(2)\right|^2}{G_{01}^{0\nu}(1)\left|M^{0\nu/N}(1)\right|^2}$$

See also PRD 83, 113003 (2011)

Two Non-Interfering Mechanisms

$$r(\nu/N) \equiv T^{\nu/N}_{1/2}(1)/T^{\nu/N}_{1/2}(2) = \frac{G^{0\nu}_{01}(2)\left|M^{0\nu/N}(2)\right|^2}{G^{0\nu}_{01}(1)\left|M^{0\nu/N}(1)\right|^2}$$

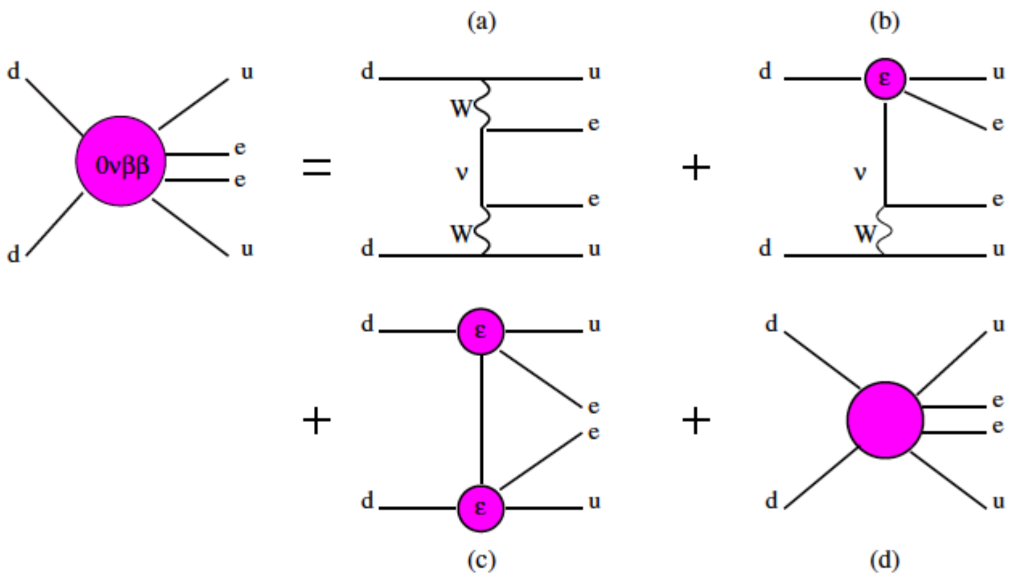
	Ge/Se		Ge/Te		Ge/Xe		Se/Te		Se/Xe		Te/Xe	
	Ge	Se	Ge	Te	Ge	Xe	Se	Te	Se	Xe	Te	Xe
$G^{0\nu}_{01} \times 10^{14}$	0.237	1.018	0.237	1.425	0.237	1.462	1.018	1.425	1.018	1.462	1.425	1.462
$M^{0\nu}(1/2)$	3.57	3.39	3.57	1.93	3.57	1.76	3.39	1.93	3.39	1.76	1.93	1.76
$M^{0N}(1/2)$	202	187	202	136	202	143	187	136	187	143	136	143
$T^{\nu}_{1/2}(1)/T^{\nu}_{1/2}(2)$	3.87		1.76		1.50		0.45		0.39		0.85	
$T^{N}_{1/2}(1)/T^{N}_{1/2}(2)$	3.68		2.73		3.09		0.74		0.84		1.13	
$R(N/\nu)$ present	0.95		1.55		2.06		1.63		2.17		1.33	
$R(N/\nu)$ [45]	1.02		1.39		1.42		1.36		1.39		1.03	

$$R(N/\nu) = r(N)/r(\nu)$$

See also PRD 83,113003 (2011)

Is there a more general description?

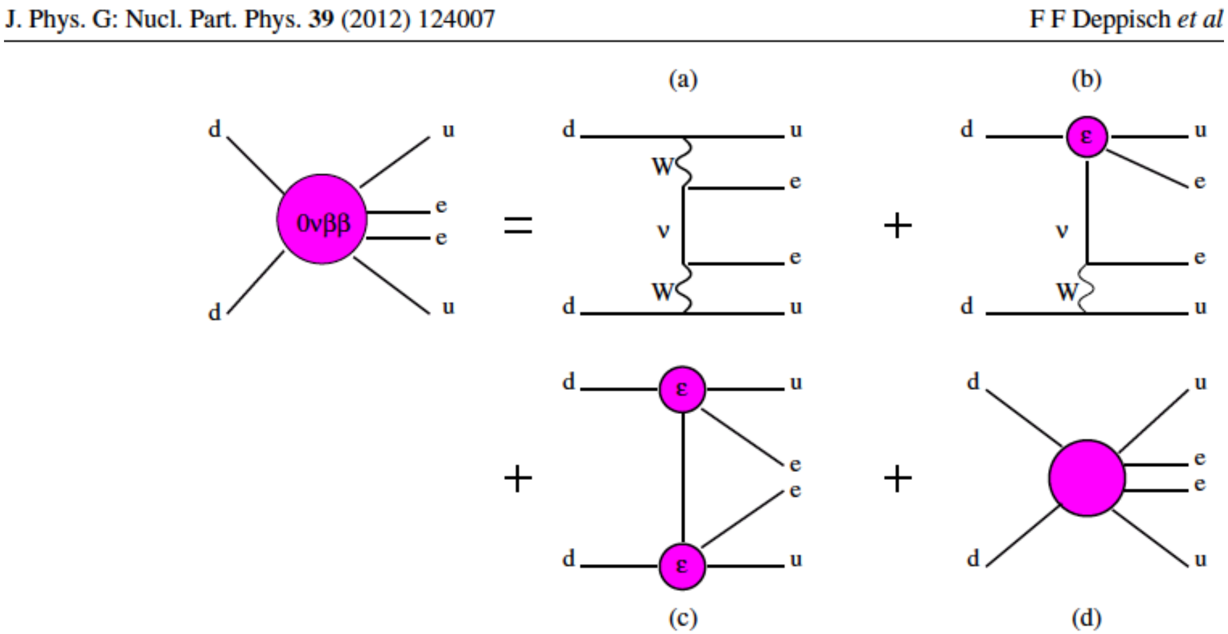
J. Phys. G: Nucl. Part. Phys. **39** (2012) 124007 F F Deppisch *et al*



$$\epsilon \propto \frac{g_{eff}^2}{\Lambda_{eff}^2}$$

$$\epsilon \propto \frac{g_{eff}^4}{\Lambda_{eff}^5} \Rightarrow \Lambda \gtrsim (1-3)\ \mathrm{TeV}$$

Is there a more general description?


J. Phys. G: Nucl. Part. Phys. **39** (2012) 124007 F F Deppisch *et al*

$$G_{01}^{0\nu},\quad G_{06}^{0\nu},\quad G_{09}^{0\nu}$$

Doi, Kotani, Takasugi 1983

$$\epsilon \propto \frac{g_{eff}^2}{\Lambda_{eff}^2}$$

$$\epsilon \propto \frac{g_{eff}^4}{\Lambda_{eff}^5} \Rightarrow \Lambda \gtrsim (1-3)\ \mathrm{TeV}$$

Long-range terms: (a) - (c)

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left\{ j_{V-A}^{\mu} J_{V-A,\mu}^{\dagger} + \sum_{\alpha,\beta} \epsilon_{\alpha}^{\beta} j_{\beta} J_{\alpha}^{\dagger} \right\}$$

$$A_{\beta\beta} \propto T[\mathcal{L}(t_1)\mathcal{L}(t_2)] \propto \left(j_{V-A}J_{V-A}^{+}\right)\left(j_{\alpha}J_{\beta}^{+}\right)$$

$$\alpha,\beta : V-A,\ V+A,\ S+P, S-P,\ T_L,\ T_R$$

Short-range terms: (d)

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \{\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}\}$$

$$A_{\beta\beta} \propto \mathcal{L}$$

$$J^{\mu\nu} = \overline{u}\frac{i}{2}\left[\gamma^{\mu},\gamma^{\nu}\right]\left(1 \pm \gamma^{5}\right)d$$

Summary of 0*ν*DBD mechanisms

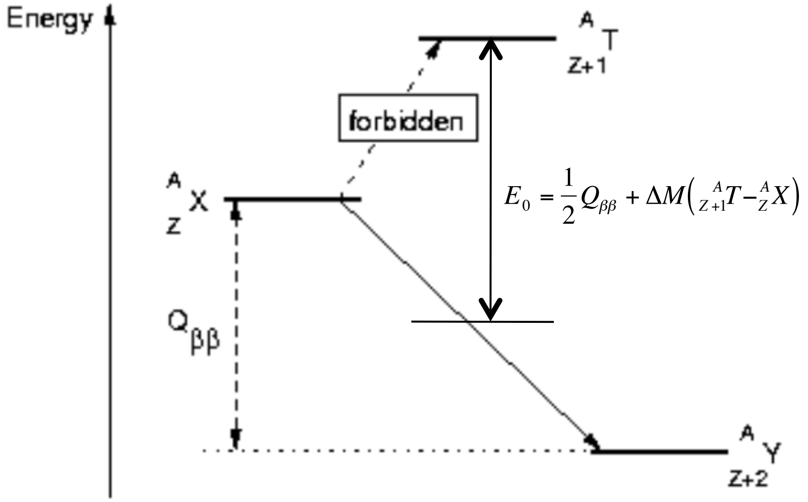
- The mass mechanism (a.k.a. light-neutrino exchange) is likely, and the simplest BSM scenario.
- Low mass sterile neutrino would complicate analysis
- Right-handed heavy-neutrino exchange is possible, and requires knowledge of half-lives for more isotopes.
- η- and λ- mechanisms are possible, but could be ruled in/out by energy and angular distributions.
- Left-right symmetric model may be also (un)validated at LHC/colliders.
- SUSY/R-parity, KK, GUT, etc, scenarios need to be checked, but validated by additional means.

2ν Double Beta Decay (DBD) of ^{48}Ca

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

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

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



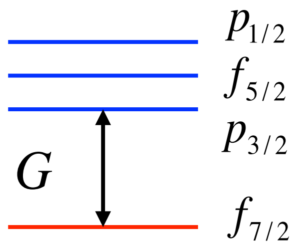
The choice of valence space is important!

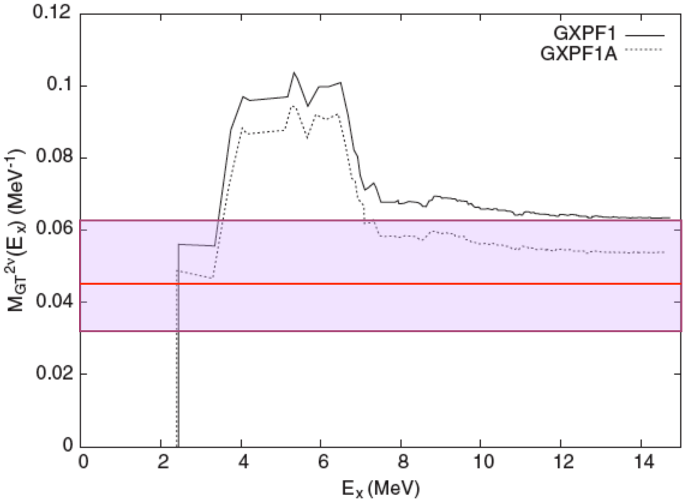
$$B(GT) = \frac{\left|\langle f \| \sigma\cdot\tau \| i\rangle\right|^2}{(2J_i+1)}$$

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

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

Ikeda satisfied in pf !



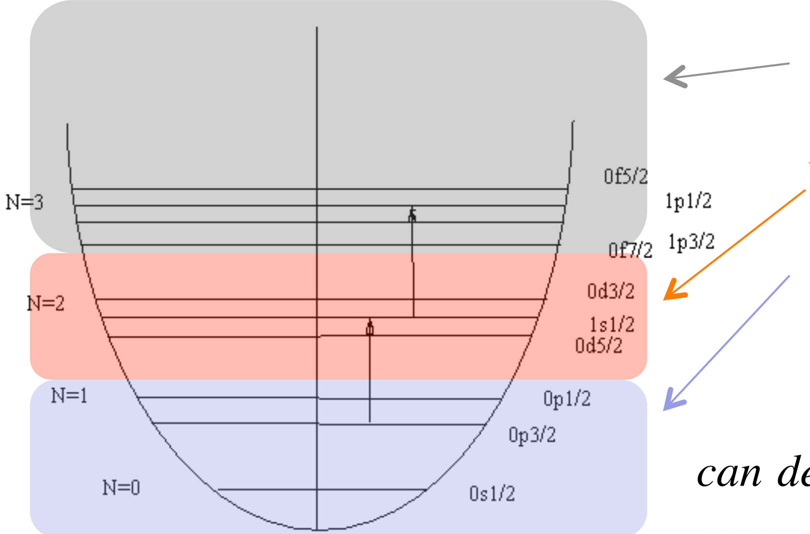


$$\boxed{g_A\sigma\tau \xrightarrow{quenched} 0.74 g_A\sigma\tau}$$

Horoi, Stoica, Brown,

PRC **75**, 034303 (2007)

Shell Model GT Quenching



empty

valence

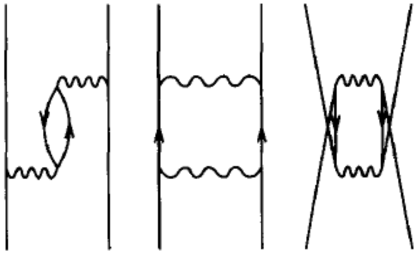
frozen core

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

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

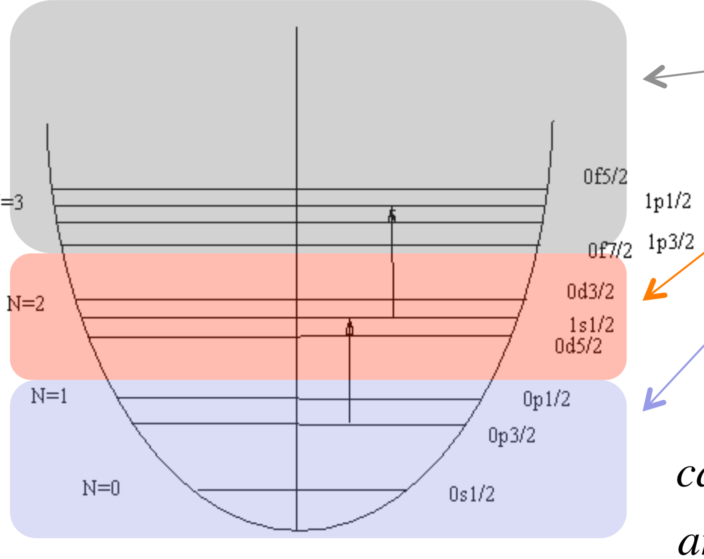
can describe most correlations around the Fermi surface!

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



CENTRAL MICHIGAN UNIVERSITY

Shell Model GT Quenching



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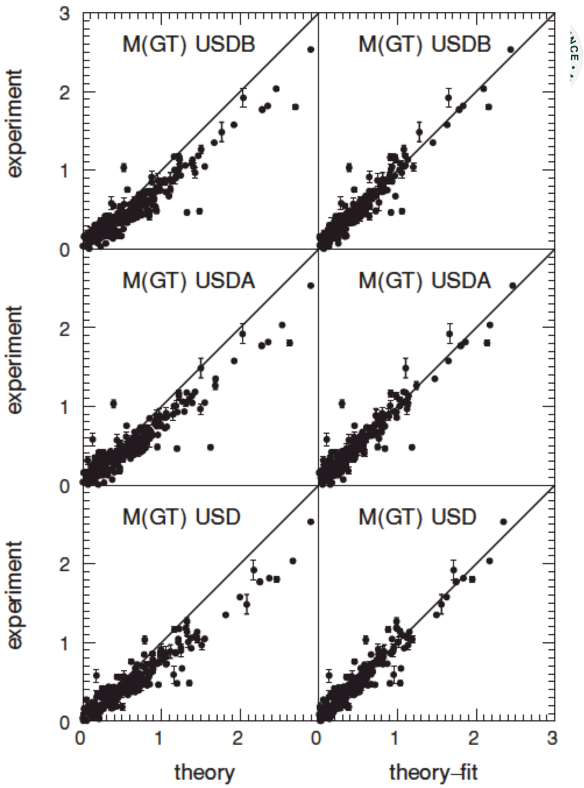
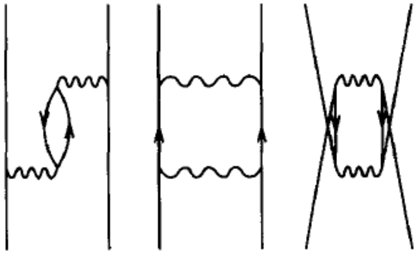
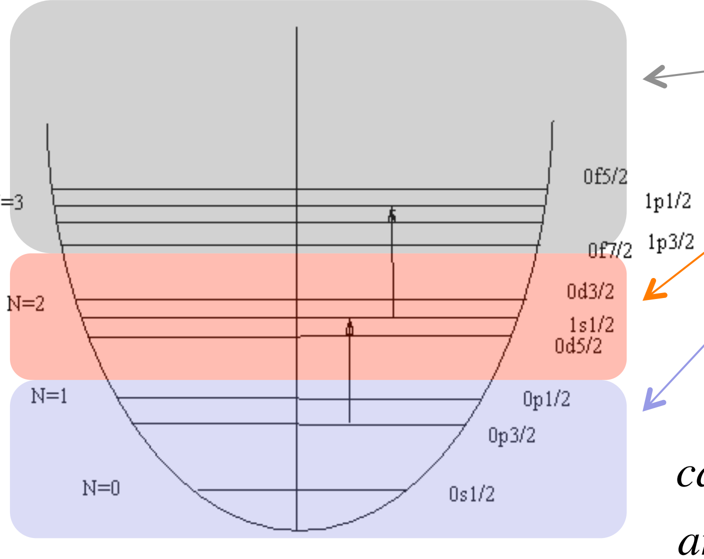


$$\sigma\tau \xrightarrow{quenched} 0.77\sigma\tau$$

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



Shell Model GT Quenching



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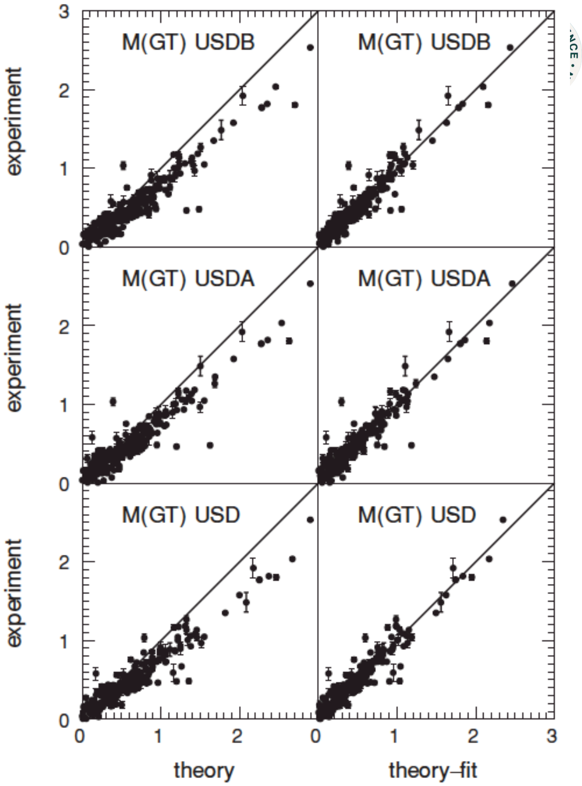
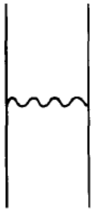


$$\sigma\tau \xrightarrow{quenched} 0.77\sigma\tau$$

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



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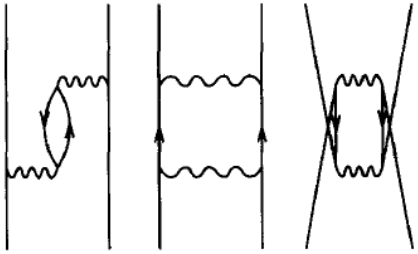


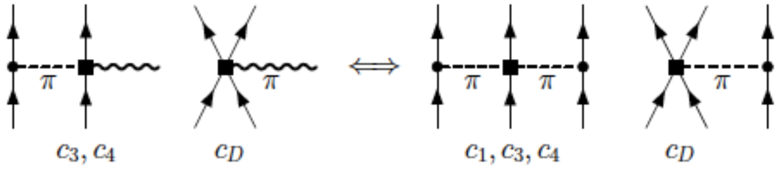


FIG. 1: Chiral 2b currents and 3N force contributions.

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

Closure Approximation and Beyond in Shell Model

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

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

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

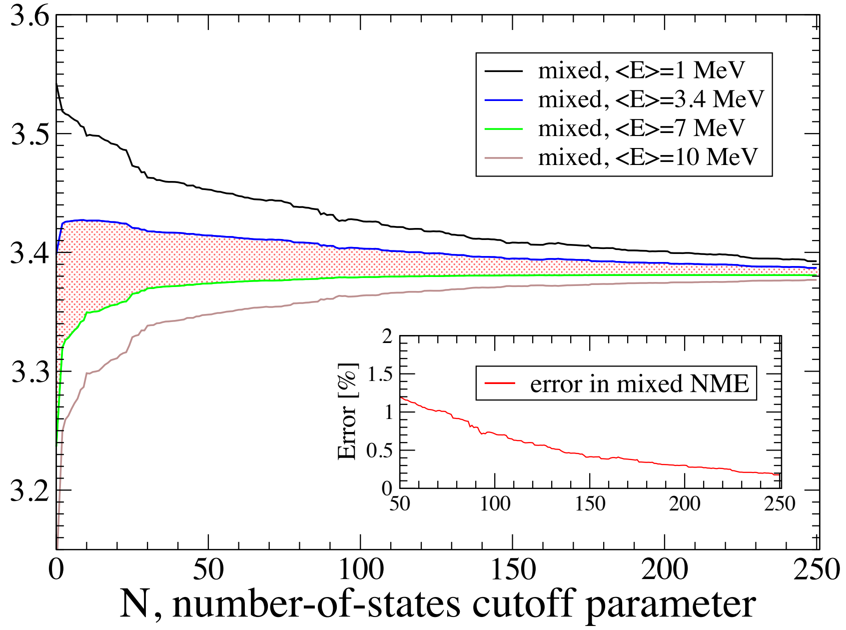
^{82}Se : 10M states

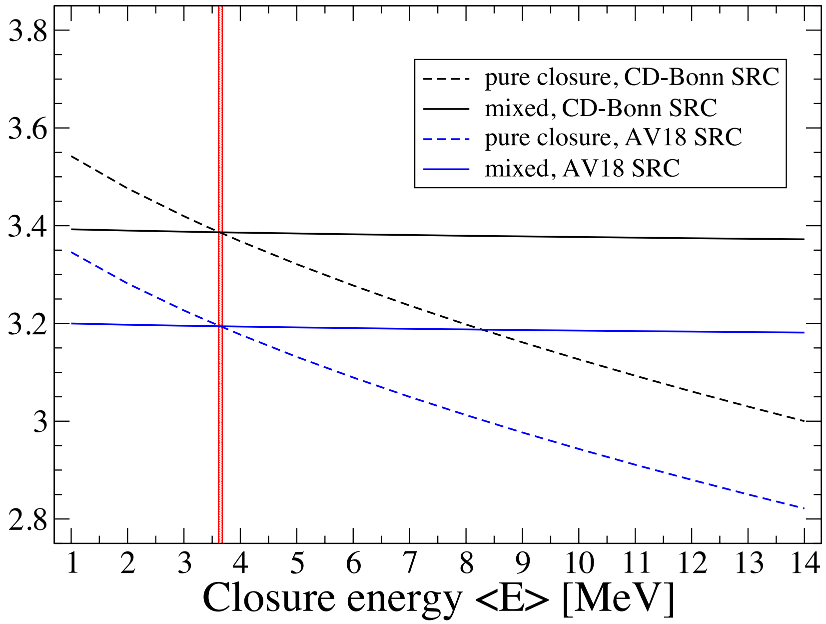
^{130}Te : 22M states

^{76}Ge : 150M states

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

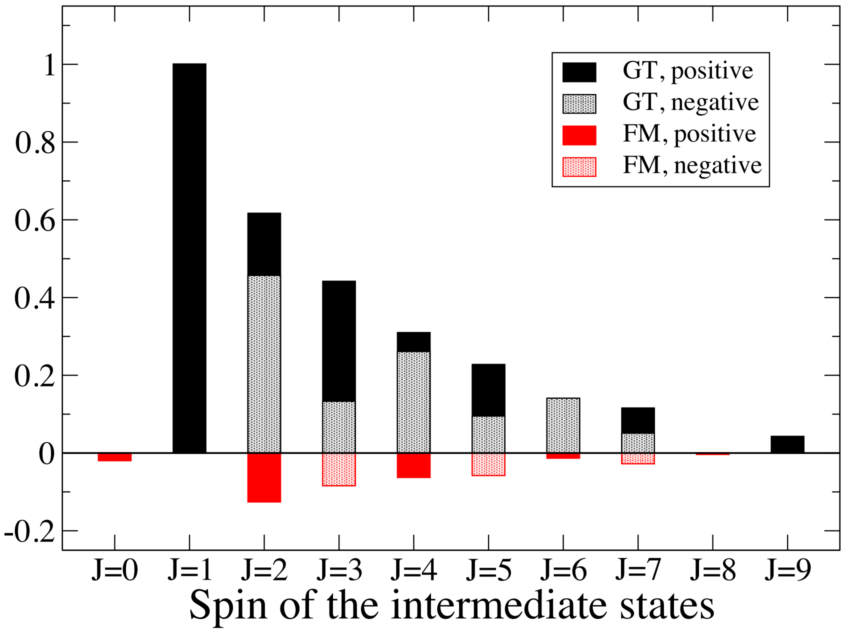
$$\hat{S} = \begin{cases} \sigma_1 \tau_1\, \sigma_2 \tau_2 & Gamow-Teller\ (GT) \\ \tau_1 \tau_2 & Fermi\ (F) \\ \left[3(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\right] \tau_1 \tau_2 & Tensor\ (T) \end{cases}$$





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

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



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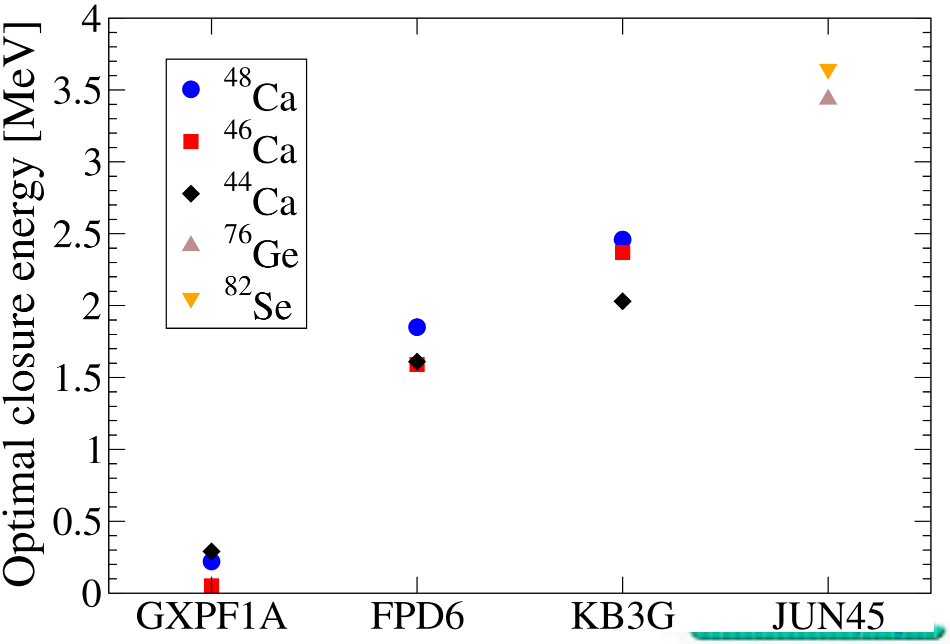
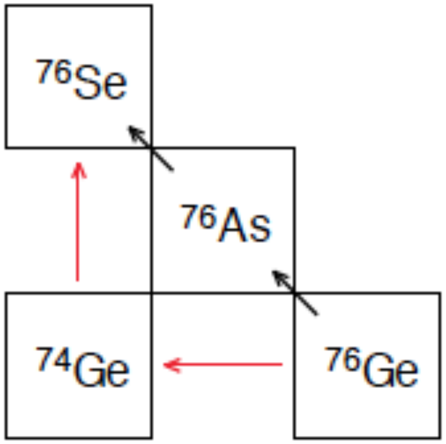
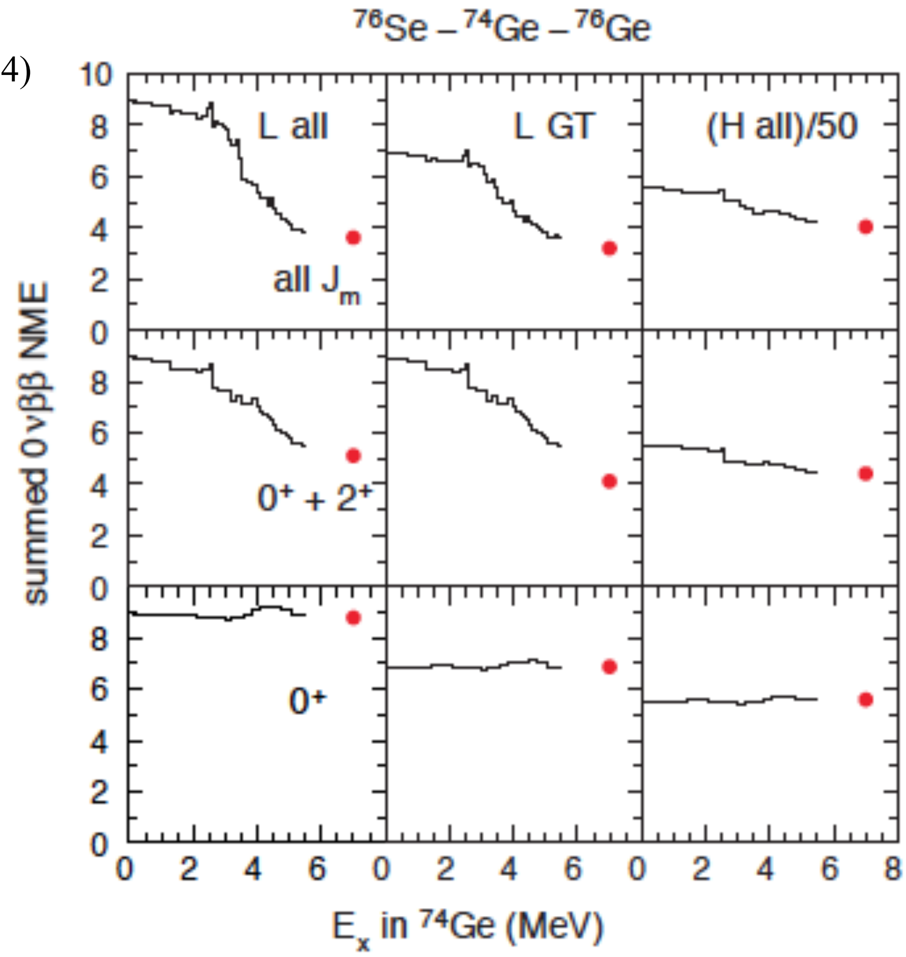


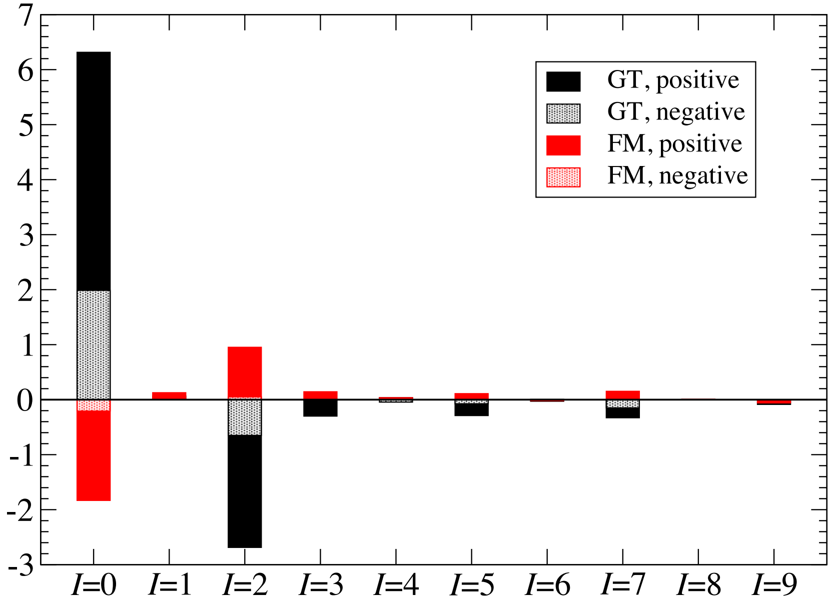
New Approach to calculate NME: New Tests of Nuclear Structure



Brown, Horoi, Senkov

PRL **113**, 262501 (2014)





Spin of the neutron-neutron (proton-proton) pairs

What Experimental Searches Do Exist?

Current Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved Lower Limit (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	61	
SuperNEMO	^{82}Se+	7	
KamLAND-Zen	^{136}Xe	434	
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

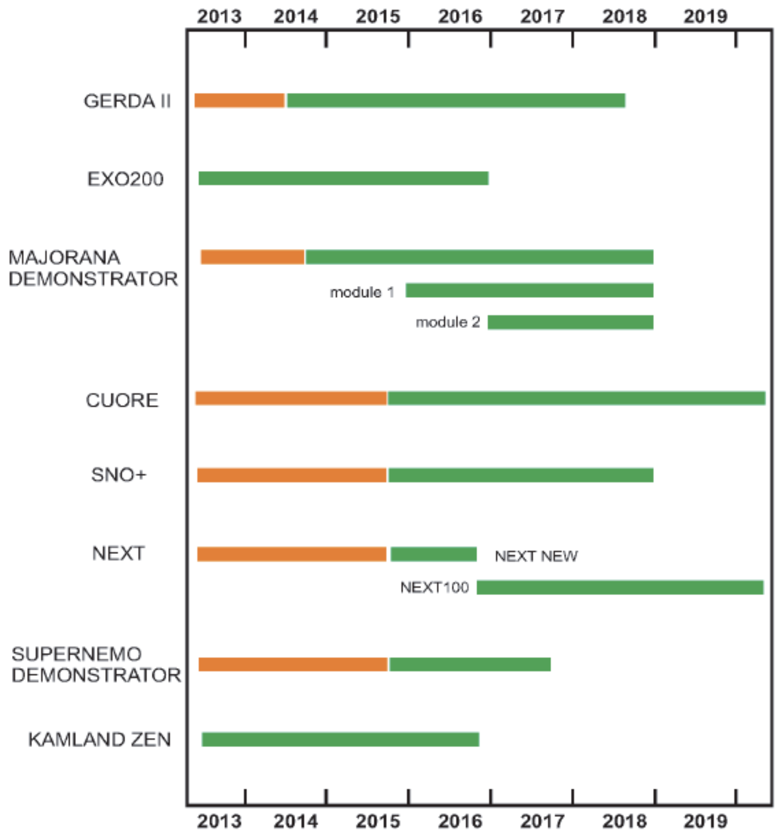
S. Vigdor talk at LRP Town Meeting, Chicago, Sep 28-29, 2014

Goals (DNP14 DBD workshop):

$T_{1/2} > 1 \times 10^{26}\,y$, after ? years

$T_{1/2} > 2.4 \times 10^{26}\,y$, after 3 years

$T_{1/2} > 6 \times 10^{27}\,y$, after 5 years! (nEXO)



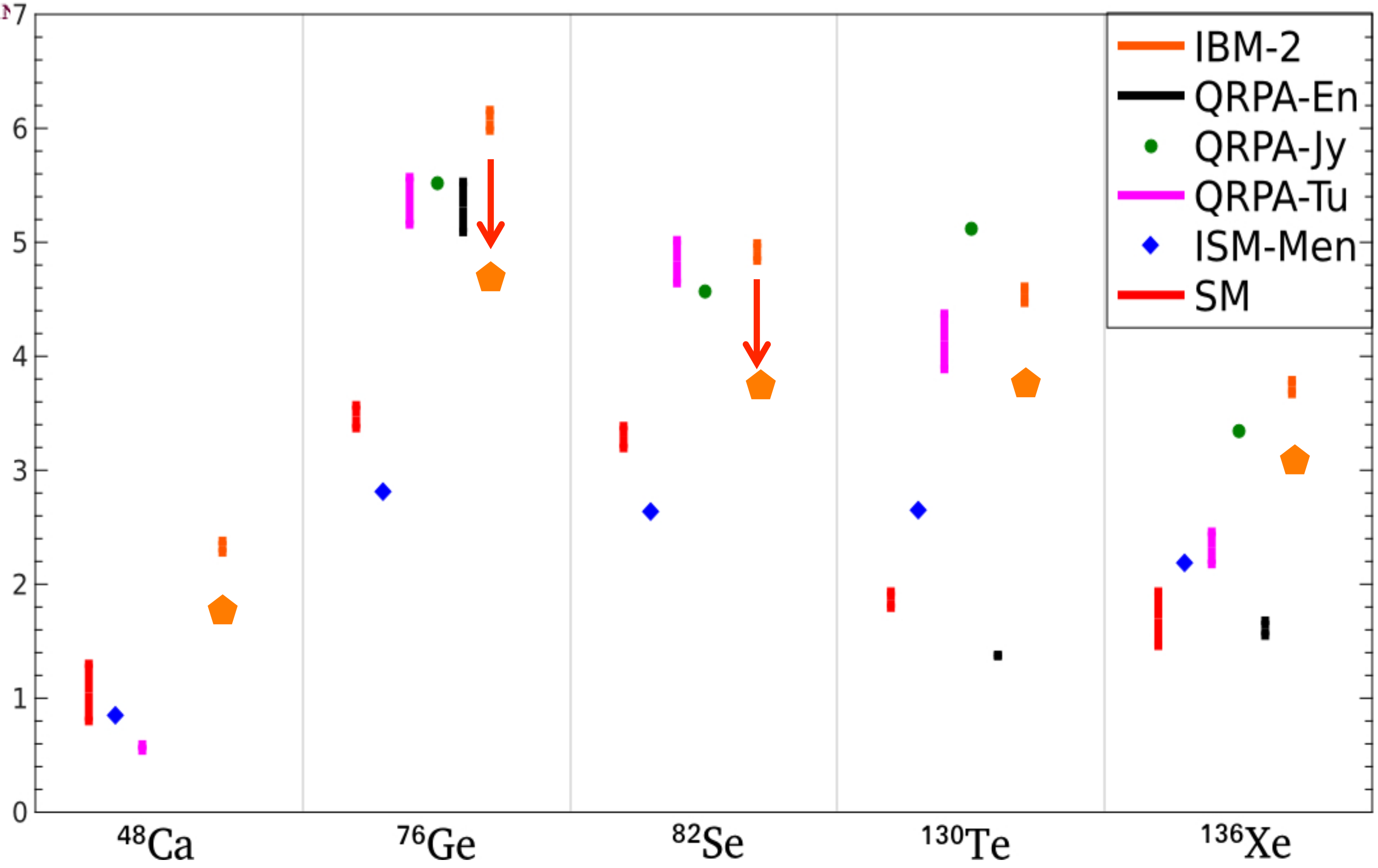
🟧 Construction

🟩 Operation

Able to assess future prospects of different techniques better 2-3 years from now, allowing more intelligent discussion of down-selection.

R&D on new techniques with promise to reduce backgrounds dramatically should also be pursued!

NME for the light-neutrino exchange mechanism



IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013). → ⬟ IBM-2 PRC **91**, 034304 (2015)

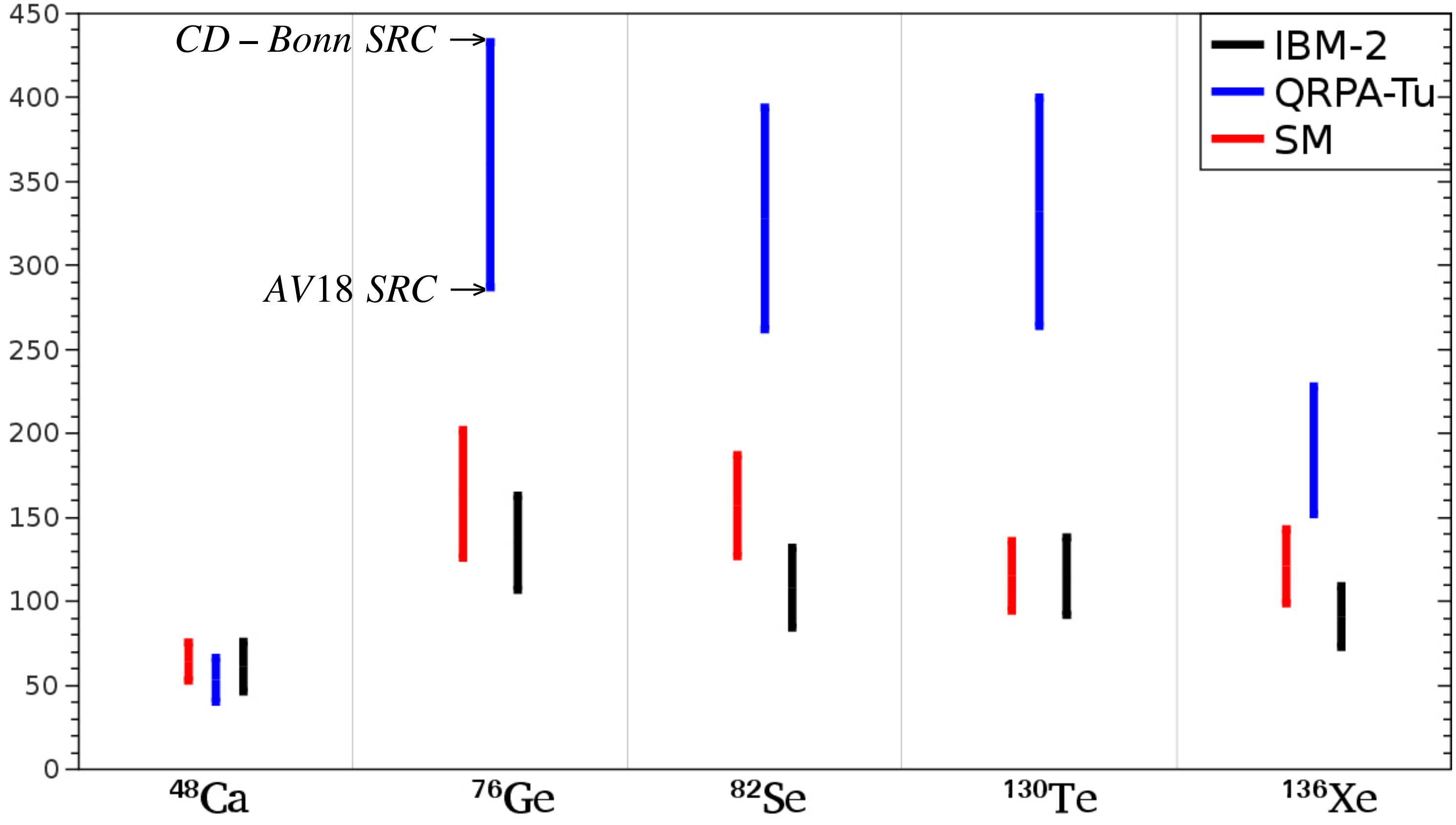
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).

QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077**

ISM-Men J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).
SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **89**, 045502 (2014), PRC **89**, 054304 (2014), PRC **90**, 051301(R) (2014), PRC **91**, 024309 (2015), PRL **110**, 222502 (2013), PRL **113**, 262501(2014).

NME for the heavy-neutrino exchange mechanism



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

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

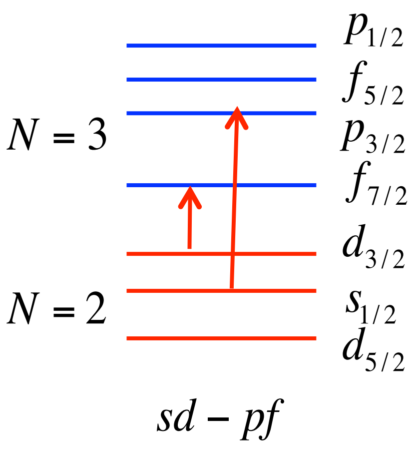
	M(0ν)
0 $\hbar\omega$/ GXPF1A	0.733
0 $\hbar\omega$+2nd ord./GXPF1A	1.301 (77%)

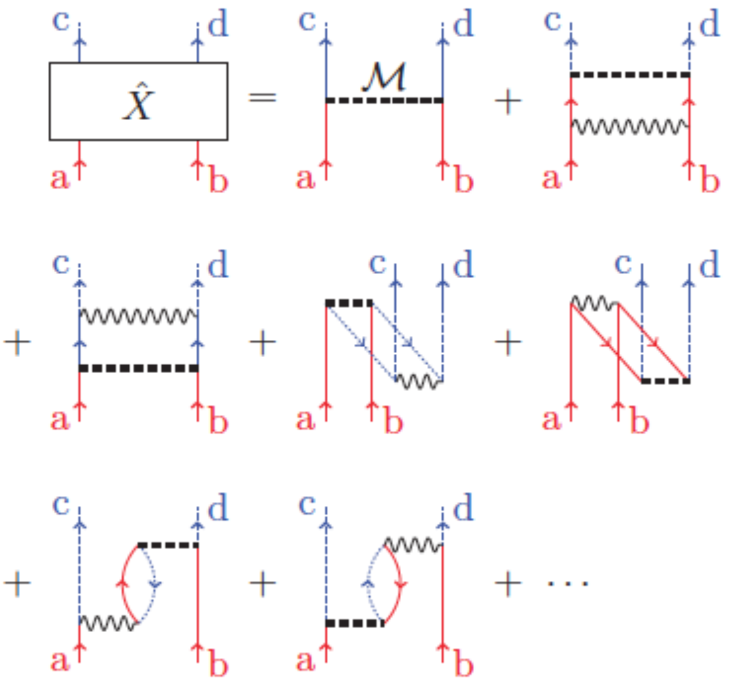
SDPFU: PRC 79, 014310 (2009)

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

arXiv:1308.3815, PRC 89, 045502 (2014)

PRC 87, 064315 (2013)

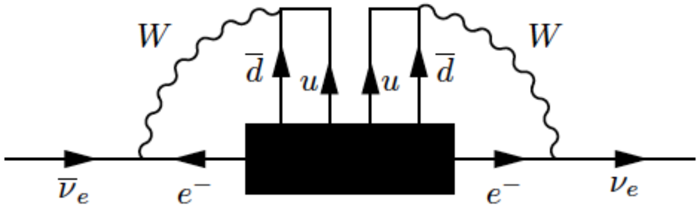




Take-Away Points

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

Black box theorem (all flavors + oscillations)



0νββ observed ⇔

at some level

(i) Neutrinos are Majorana fermions.

(ii) Lepton number conservation is violated by 2 units

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

Regardless of the dominant 0νββ mechanism!

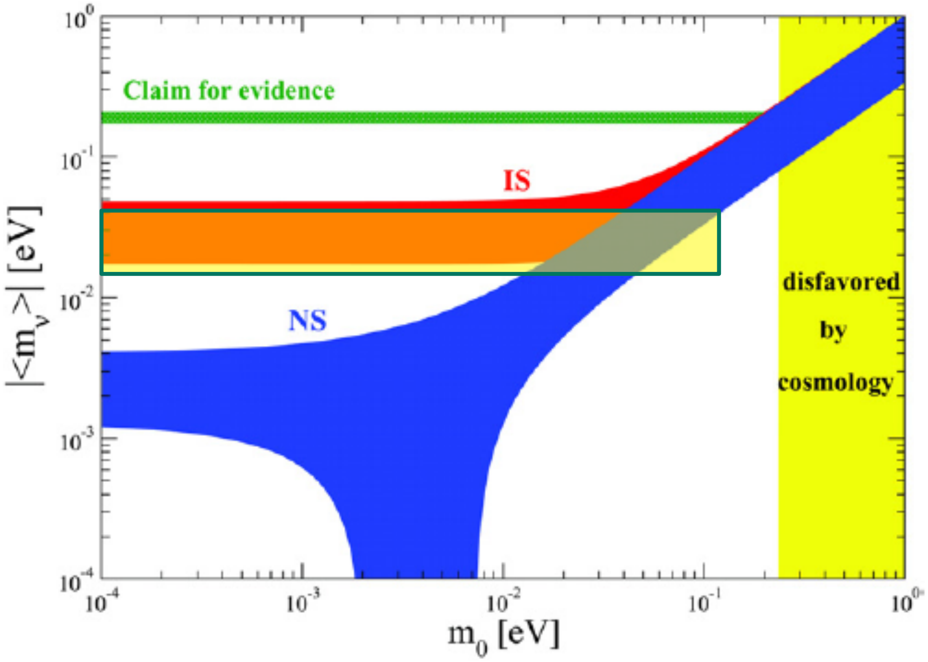
Take-Away Points

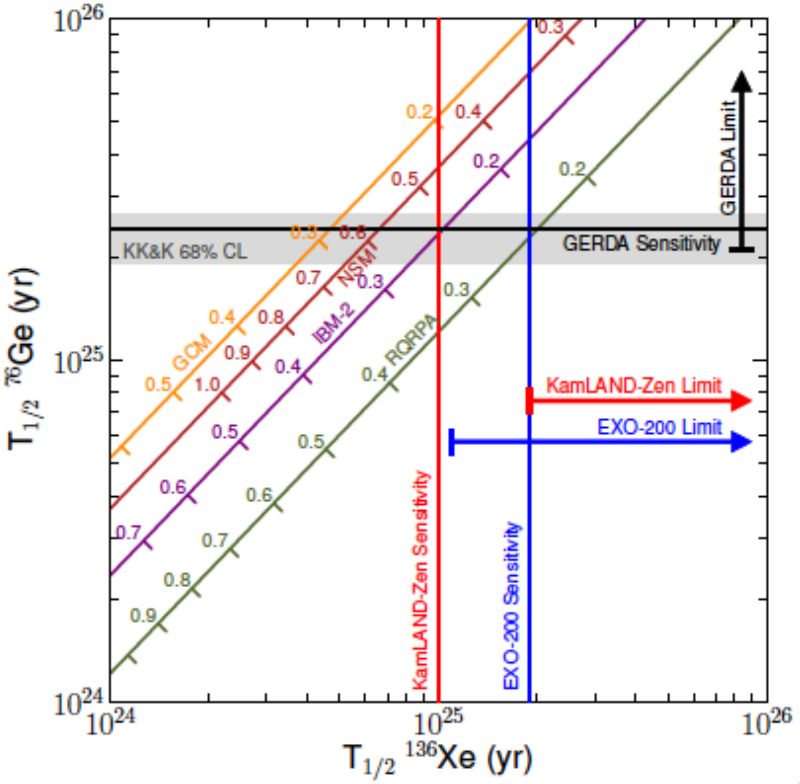
The analysis and guidance of the experimental efforts need **accurate Nuclear Matrix Elements.**

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

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

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





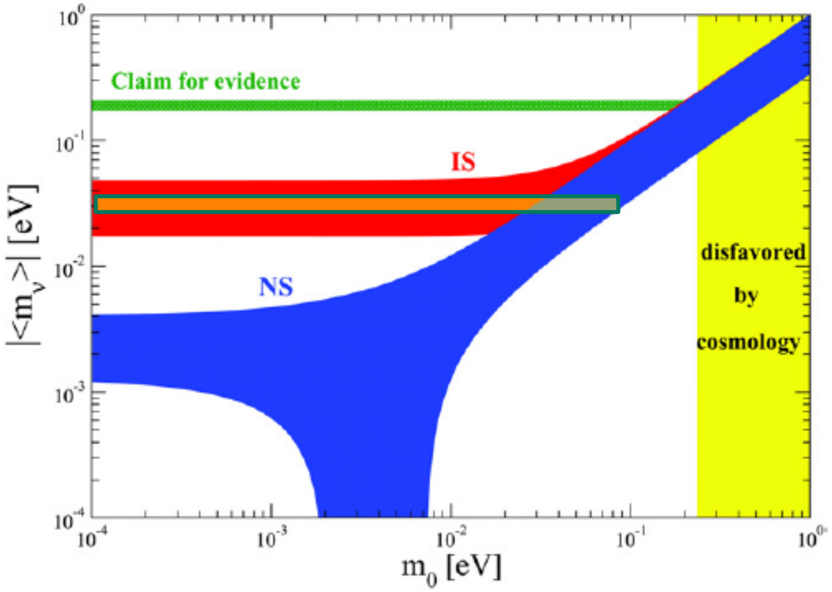
Take-Away Points

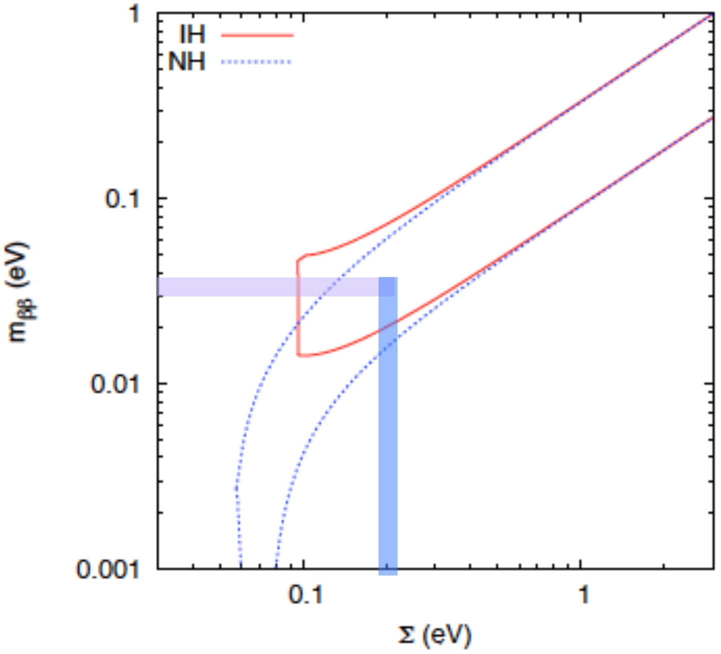
Extracting information about Majorana CP-violation phases may require the mass hierarchy from LBNE(DUNE), cosmology, etc, but also **accurate Nuclear Matrix Elements**.

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

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

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

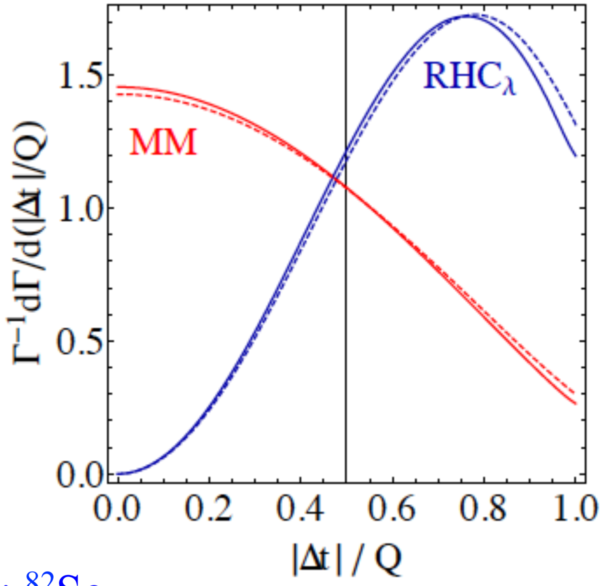




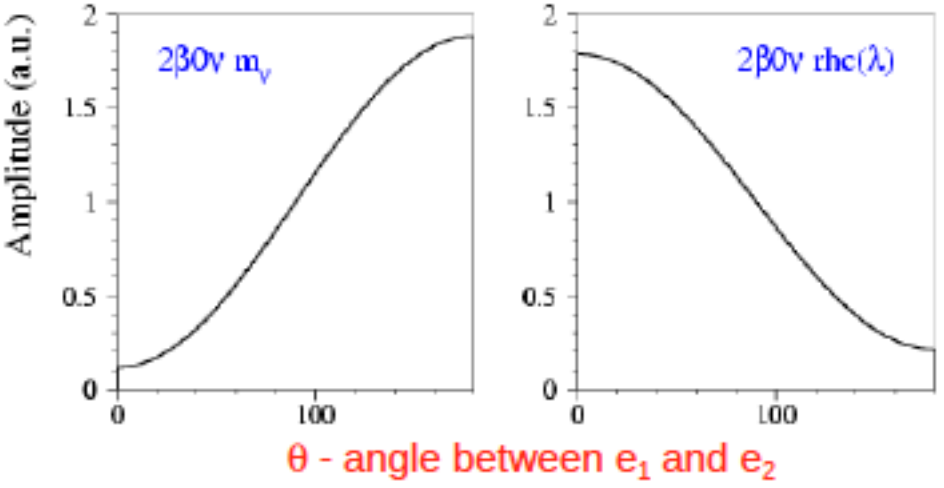
Take-Away Points

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



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

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

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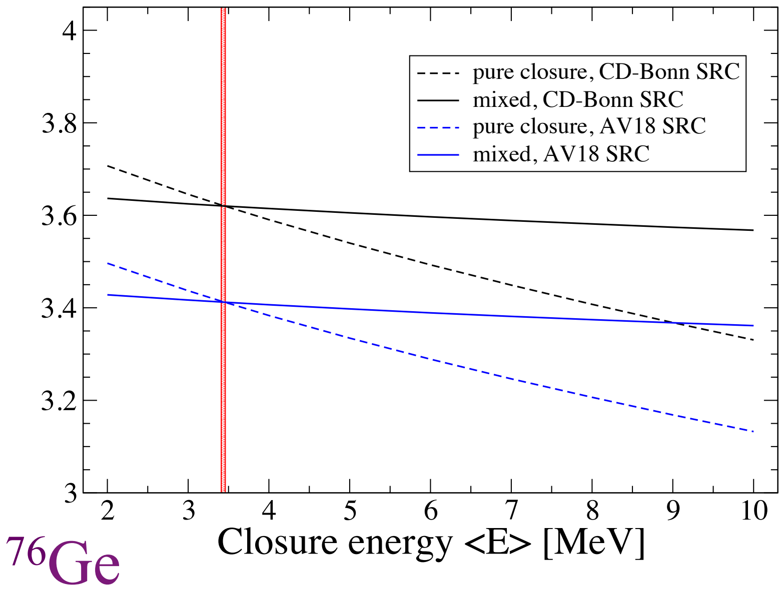
Take-Away Points

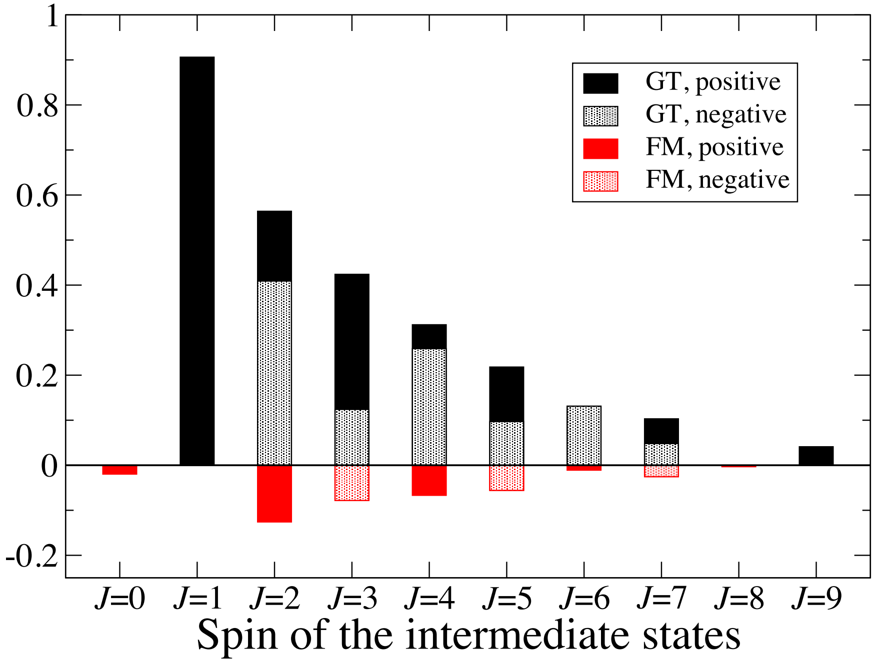
Accurate shell model NME for **different decay mechanisms** were recently calculated.

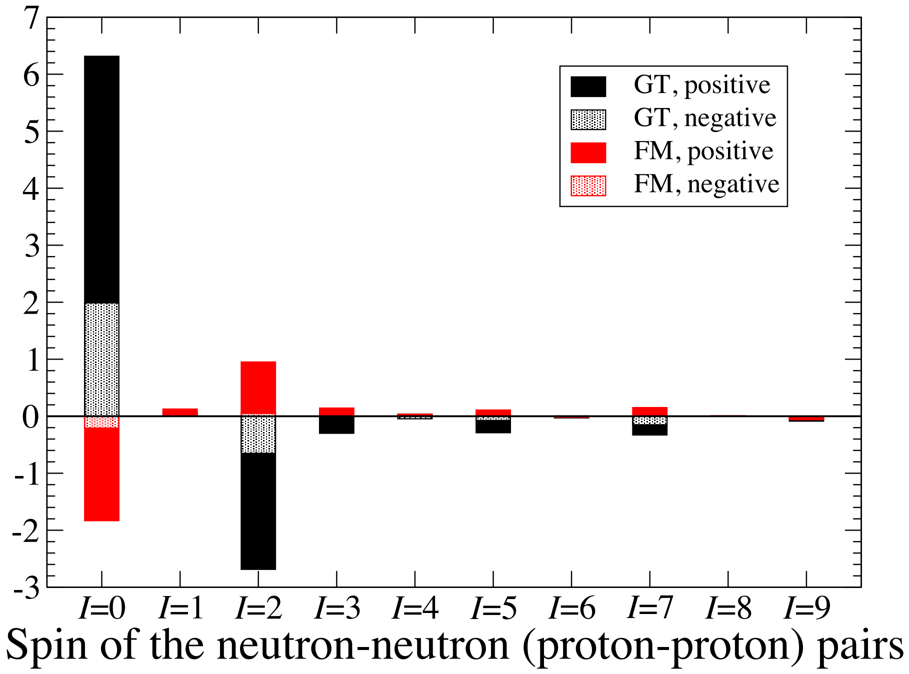
The method provides **optimal closure energies** for the mass mechanism.

Decomposition of the matrix elements can be used for **selective quenching** of classes of states, and for testing nuclear structure.



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





Collaborators:

- Alex Brown, NSCL@MSU
- Roman Senkov, CMU and CUNY
- Andrei Neacsu, CMU
- Jonathan Engel, UNC
- Jason Holt, TRIUMF