Neutrinoless Double Beta Decay

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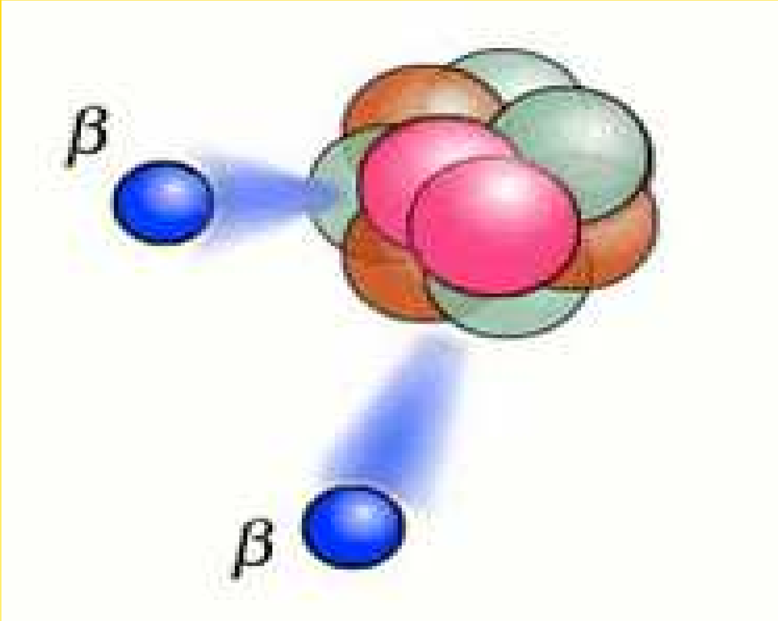
$m_\nu = m_L - m_D^T M_R^{-1} m_D$

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

What is Neutrinoless Double Beta Decay?



For example:

$$^{76}\mathrm{Ge} \quad \rightarrow \quad ^{76}\mathrm{Se}^{++} + 2e^{-}$$

$$L = 0 \qquad\qquad L = +2$$

VIOLATION OF LEPTON NUMBER!

Standard Model of particle physics: lepton number (accidentally) conserved

Two Possibilities

$(A,Z) \to (A,Z+2) + 2\,e^- \quad (0\nu\beta\beta) \Rightarrow$ Lepton Number Violation

- **Standard Interpretation** (neutrino physics)
- **Non-Standard Interpretations** (BSM $\neq$ neutrino physics)

W.R., Int. J. Mod. Phys. **E20**, 1833-1930 (2011); J. Phys. **G39**, 124008 (2012)

Why should we probe Lepton Number Violation?

- L and B <u>*accidentally*</u> conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\,\mathcal{L}_{\rm LNV} + \frac{1}{\Lambda^2}\,\mathcal{L}_{\rm LFV,\,BNV,\,LNV} + \ldots$
- baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majorana neutrinos
- (chiral anomalies: $\partial_\mu J^\mu_{B,L} = c\, G_{\mu\nu}\, \tilde{G}^{\mu\nu} \neq 0$ with $J^B_\mu = \sum \overline{q_i}\, \gamma_\mu\, q_i$ and $J^L_\mu = \sum \overline{\ell_i}\, \gamma_\mu\, \ell_i$)

$\Rightarrow$ Lepton Number Violation as important as Baryon Number Violation

($0\nu\beta\beta$ is much more than a neutrino mass experiment)

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$

- $G_x(Q,Z)$: phase space factor
- $\mathcal{M}_x(A,Z)$: nuclear physics
- η_x: particle physics

Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$

- $G_x(Q,Z)$: phase space factor; calculable
- $\mathcal{M}_x(A,Z)$: nuclear physics; problematic
- η_x: particle physics; interesting

Experimental Aspect

$$(T^{0\nu}_{1/2})^{-1} \propto \begin{cases} a\, M\, \varepsilon\, t & \text{without background} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background} \end{cases}$$

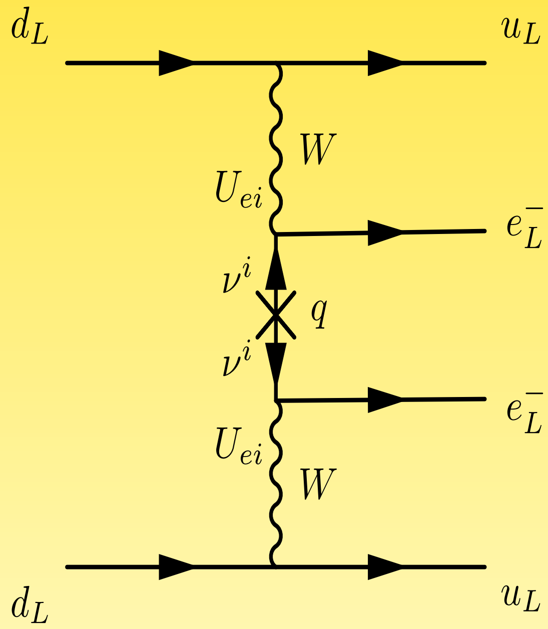
with

- B is background index in counts/(keV kg yr)
- ΔE is energy resolution
- ϵ is efficiency
- $(T^{0\nu}_{1/2})^{-1} \propto$ (particle physics)^2

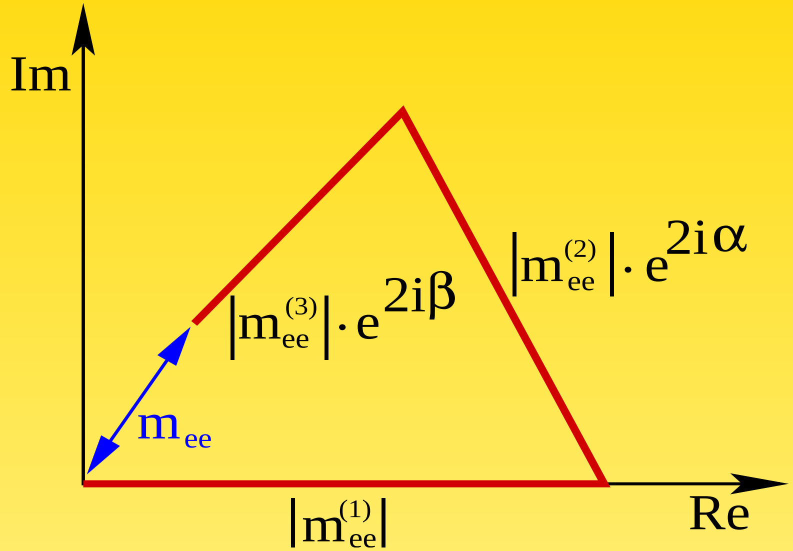
Note: factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

Standard Interpretation

Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution



The effective mass



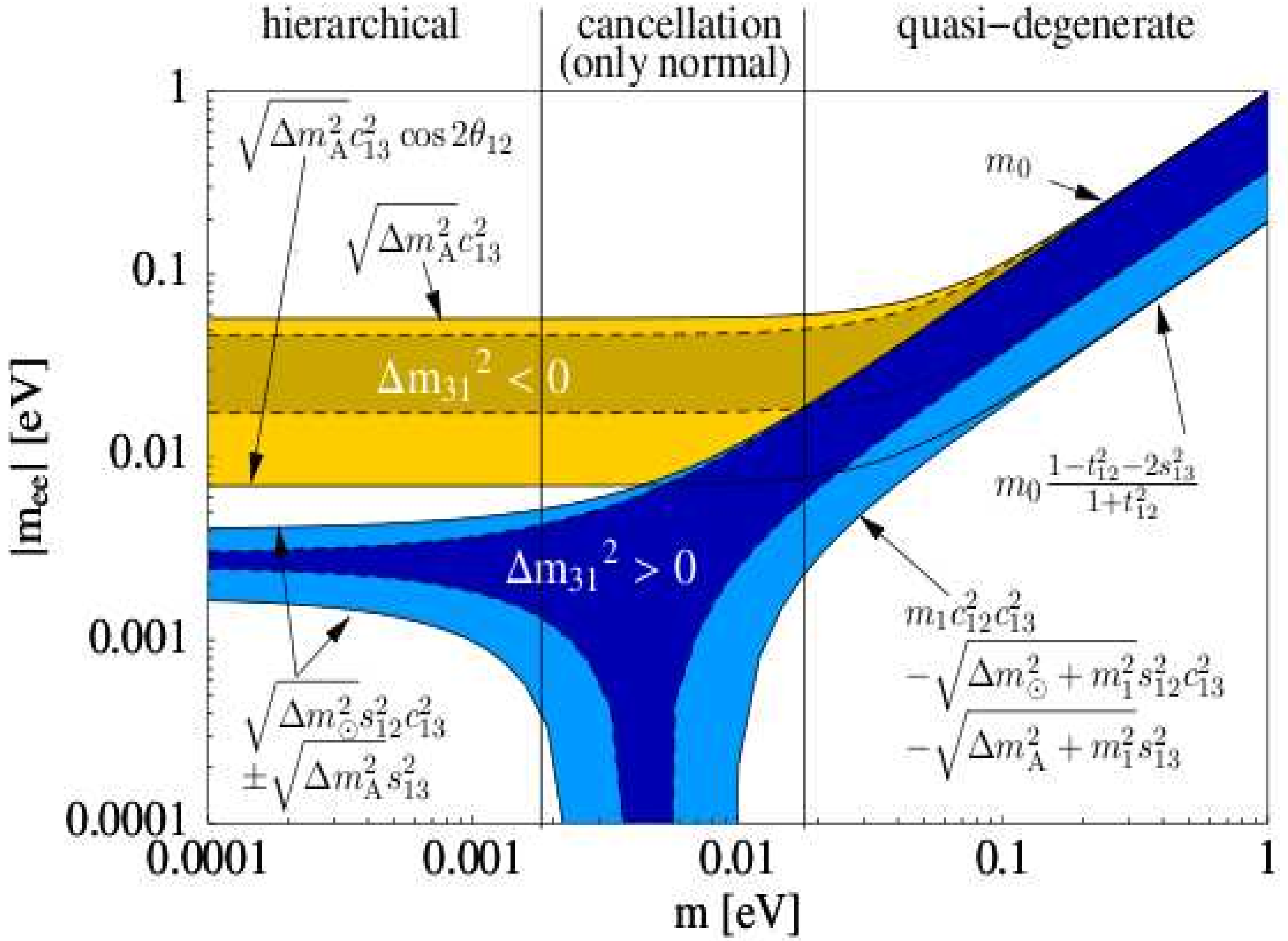
Amplitude proportional to coherent sum (“effective mass”):

$$|m_{ee}| \equiv \left| \sum U_{ei}^2 \, m_i \right| = \left| |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, m_2 \, e^{2i\alpha} + |U_{e3}|^2 \, m_3 \, e^{2i\beta} \right|$$

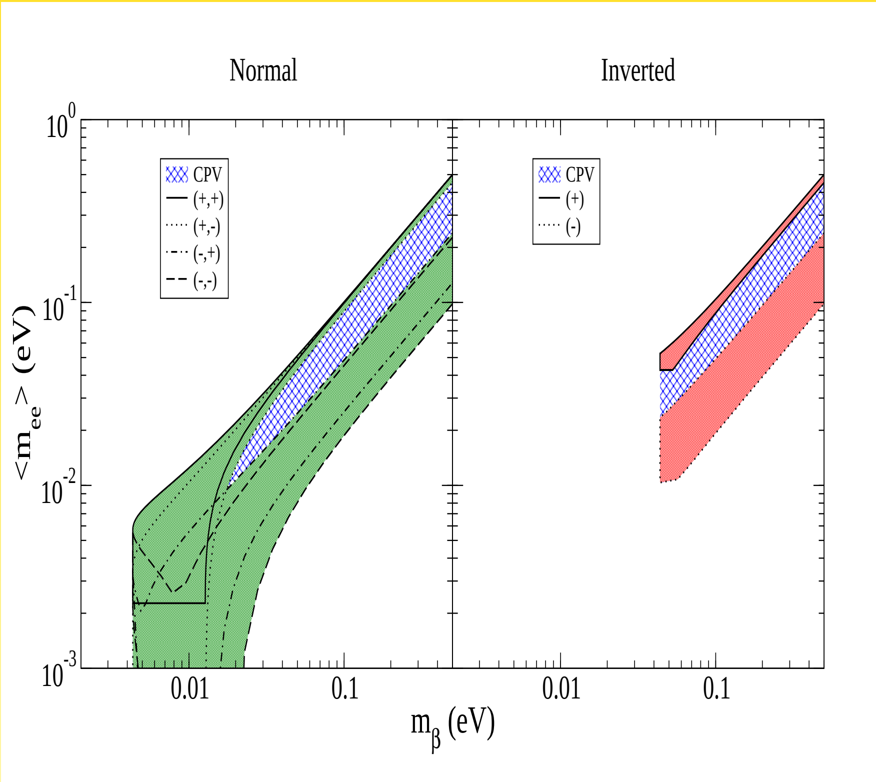
$$= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m^2_{\mathrm{A}}), \alpha, \beta\right)$$

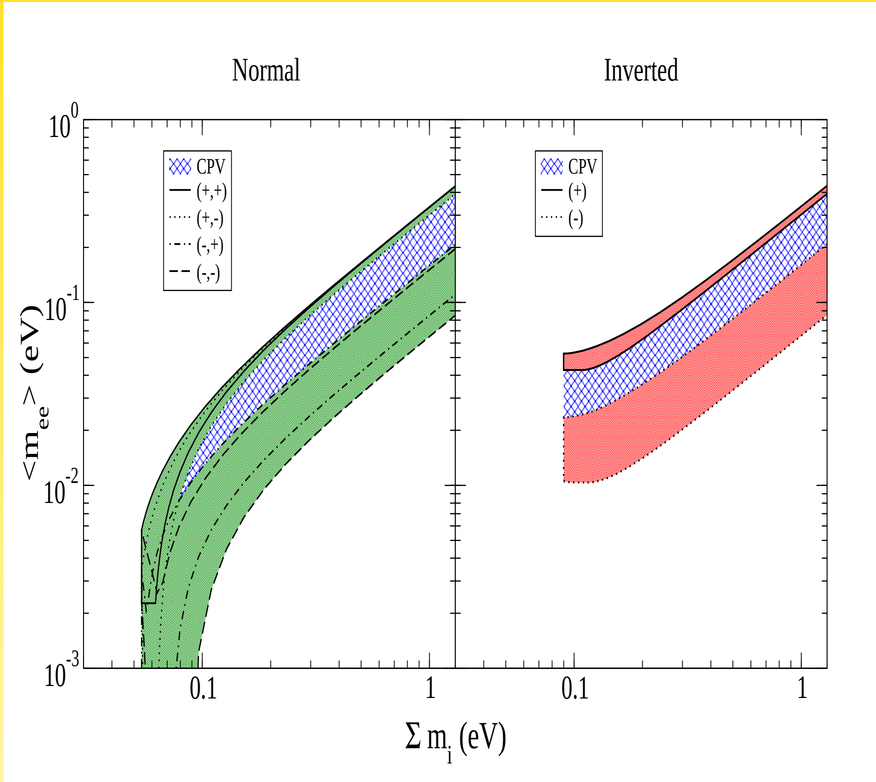
7 out of 9 parameters of neutrino physics!

The usual plot



Plot against other observables





Complementarity of $|m_{ee}| = U_{ei}^2\, m_i$, $m_\beta = \sqrt{|U_{ei}|^2\, m_i^2}$ and $\Sigma = \sum m_i$

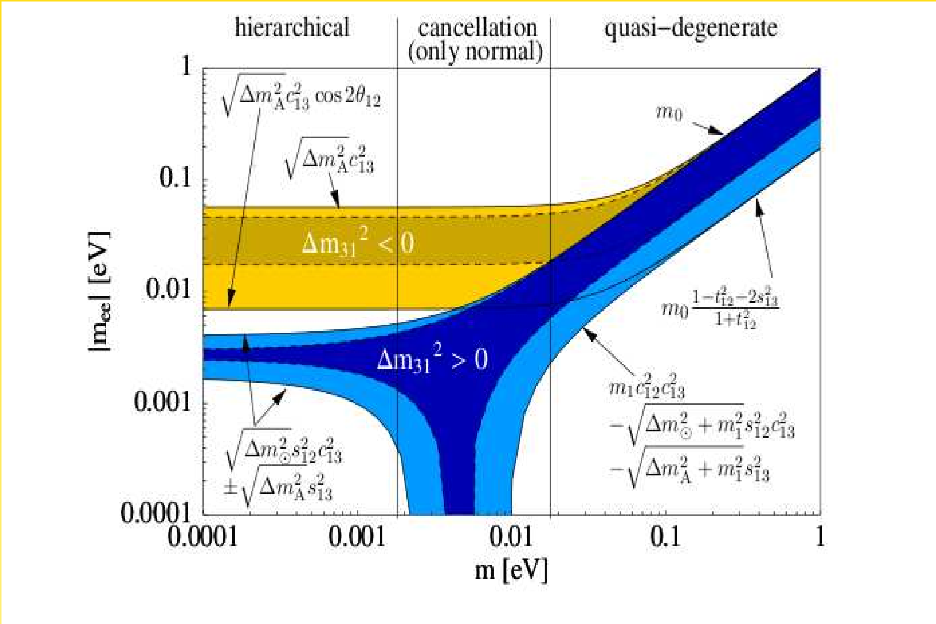
Neutrino Mass

$$m(\text{heaviest}) \gtrsim \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV}$$

3 **complementary** methods to measure neutrino mass:

Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	0.7	0.3	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\lvert \sum U_{ei}^2 m_i \rvert$	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

Inverted Ordering



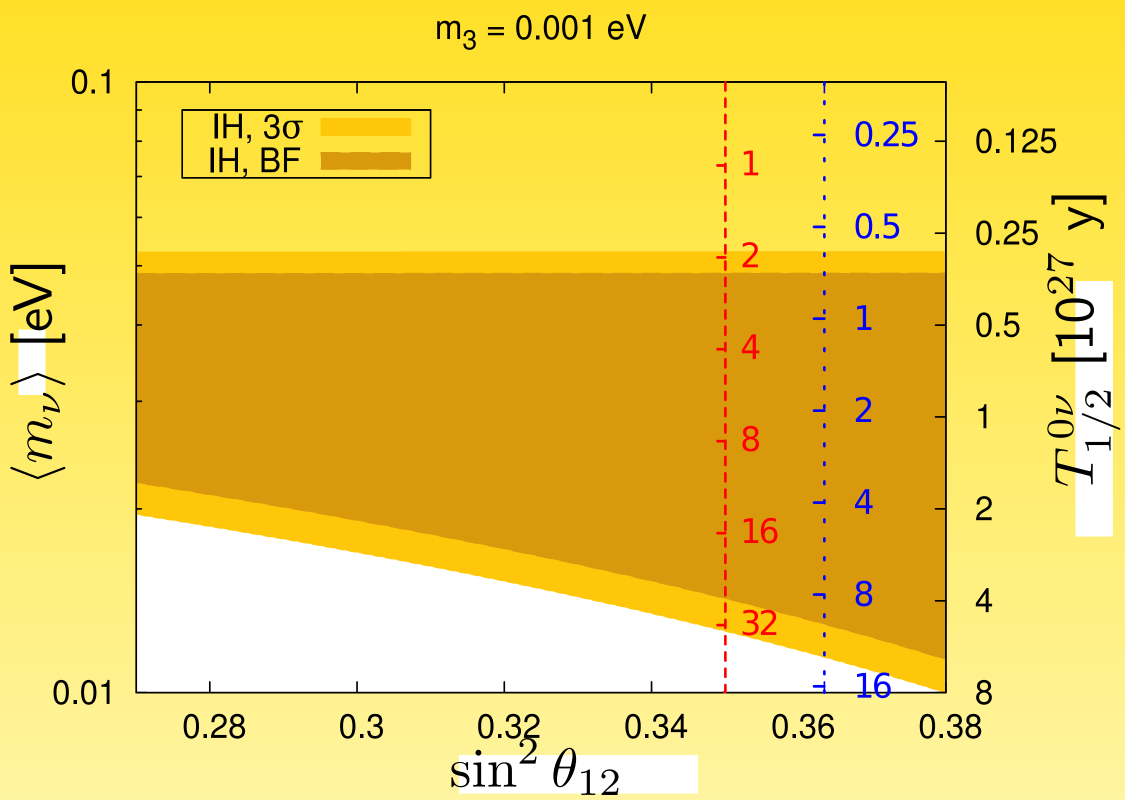
Nature provides 2 scales:

$$|m_{ee}|^{\rm IH}_{\rm max} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \quad \text{and} \quad |m_{ee}|^{\rm IH}_{\rm min} \simeq c_{13}^2 \sqrt{\Delta m_A^2} \cos 2\theta_{12}$$

requires $\mathcal{O}(10^{26} \ldots 10^{27})$ yrs

is the lower limit $|m_{ee}|^{\rm IH}_{\rm min}$ fixed?

Inverted Hierarchy



Dueck, W.R., Zuber, PRD **83**

Ruling out Inverted Hierarchy

$$|m_{ee}|^{\rm IH}_{\rm min} = \left(1 - |U_{e3}|^2\right) \sqrt{|\Delta m^2_{\rm A}|} \, \left(1 - 2 \sin^2 \theta_{12}\right)$$
$$= (0.011 \ldots 0.022) \text{ eV}$$

(want small $|U_{e3}|$, large $|\Delta m^2_{\rm A}|$, small $\sin^2 \theta_{12}$)

Current 3σ range of $\sin^2 \theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|^{\rm IH}_{\rm min}$

$\Rightarrow$ combined factor of ~ 16 in $M \times t \times B \times \Delta E$

$\Rightarrow$ need precision determination of θ_{12}!

Dueck, W.R., Zuber, PRD **83**

Recent Results

- ^{76}Ge:
  - GERDA: $T_{1/2} > 2.1 \times 10^{25}$ yrs
  - GERDA + IGEX + HDM: $T_{1/2} > 3.0 \times 10^{25}$ yrs
- ^{136}Xe:
  - EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yrs **(first run with less exposure:** $T_{1/2} > 1.6 \times 10^{25}$ **yrs. . .)**
  - KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$ yrs

Xe-limit is stronger than Ge-limit when:

$$T_{\rm Xe} > T_{\rm Ge} \, \frac{G_{\rm Ge}}{G_{\rm Xe}} \, \left| \frac{\mathcal{M}_{\rm Ge}}{\mathcal{M}_{\rm Xe}} \right|^2 \text{ yrs}$$

Xe vs. Ge

NME	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	**0.32**	**0.27**	**0.13**	–
ISM(U)	**0.52**	**0.44**	**0.24**	–
IBM-2	**0.27**	**0.23**	**0.16**	–
pnQRPA(U)	**0.28**	**0.24**	**0.17**	–
SRQRPA-B	**0.25**	**0.21**	**0.15**	–
SRQRPA-A	**0.31**	**0.26**	**0.23**	–
QRPA-A	*0.28*	*0.24*	*0.25*	–
SkM-HFB-QRPA	*0.29*	*0.24*	*0.28*	–

Bhupal Dev, Goswami, Mitra, W.R., PRD **88**

Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

10_H $(\leftrightarrow H)$, $\overline{126}_H$ $(\leftrightarrow F)$, 120_H $(\leftrightarrow G)$

Gives relation for mass matrices:

$$m_{\rm up} \propto r(H + sF + it_u\, G)$$

$$m_{\rm down} \propto H + F + iG$$

$$m_D \propto r(H - 3sF + it_D\, G)$$

$$m_\ell \propto H - 3F + it_l\, G$$

$$M_R \propto r_R^{-1} F$$

Numerical fit including RG, Higgs, θ_{13}

$10_H + \overline{126}_H$: 19 free parameters

$10_H + \overline{126}_H + 120_H$: 18 free parameters

20 (19) observables to be fitted

Predictions of $SO(10)$ theories

Model	Fit	$\|m_{ee}\|$ [meV]	m_0 [meV]	M_3 [GeV]	χ^2
$10_H + \overline{126}_H$	NH	0.49	2.40	3.6×10^{12}	23.0
$10_H + \overline{126}_H$ + SS	NH	0.44	6.83	1.1×10^{12}	3.29
$10_H + \overline{126}_H + 120_H$	NH	2.87	1.54	9.9×10^{14}	11.2
$10_H + \overline{126}_H + 120_H$ + SS	NH	0.78	3.17	4.2×10^{13}	6.9×10^{-6}
$10_H + \overline{126}_H + 120_H$	IH	35.52	30.2	1.1×10^{13}	13.3
$10_H + \overline{126}_H + 120_H$ + SS	IH	24.22	12.0	1.2×10^{13}	0.6

Dueck, W.R., JHEP **1309**

Sterile Neutrinos and $0\nu\beta\beta$

- recall: $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH} \sim 0.03$ eV cannot vanish
- $|m_{ee}| = | \underbrace{|U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, m_2 \, e^{2i\alpha} + |U_{e3}^2| \, m_3 \, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 \, m_4 \, e^{2i\Phi_1}}_{m_{ee}^{\rm st}} |$
- sterile contribution to $0\nu\beta\beta$ (assuming 1+3):

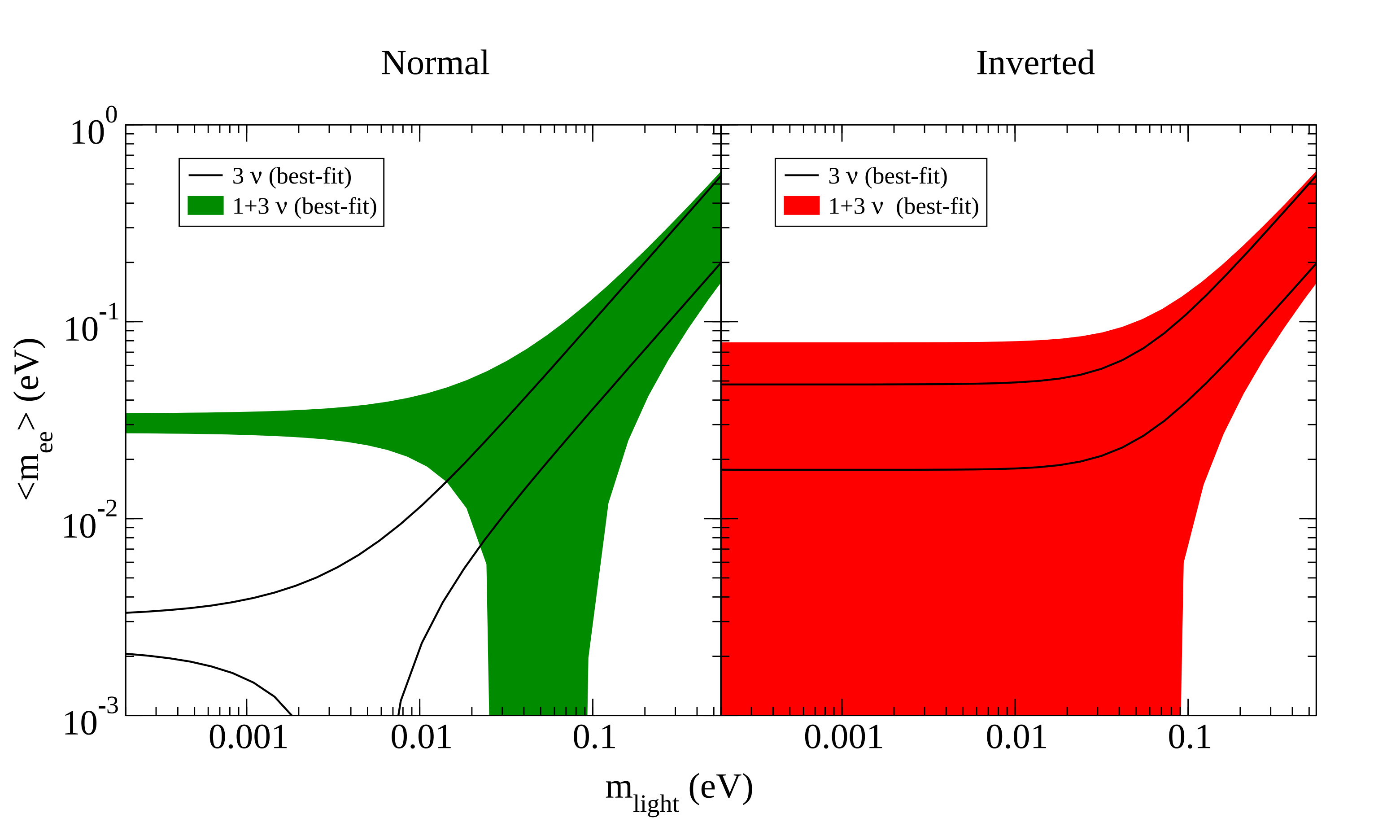
$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}} \, |U_{e4}|^2 \left\{ \begin{array}{l} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

$\Rightarrow$ $|m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

$\Rightarrow$ usual phenomenology gets completely turned around!

Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

Usual plot gets completely turned around!



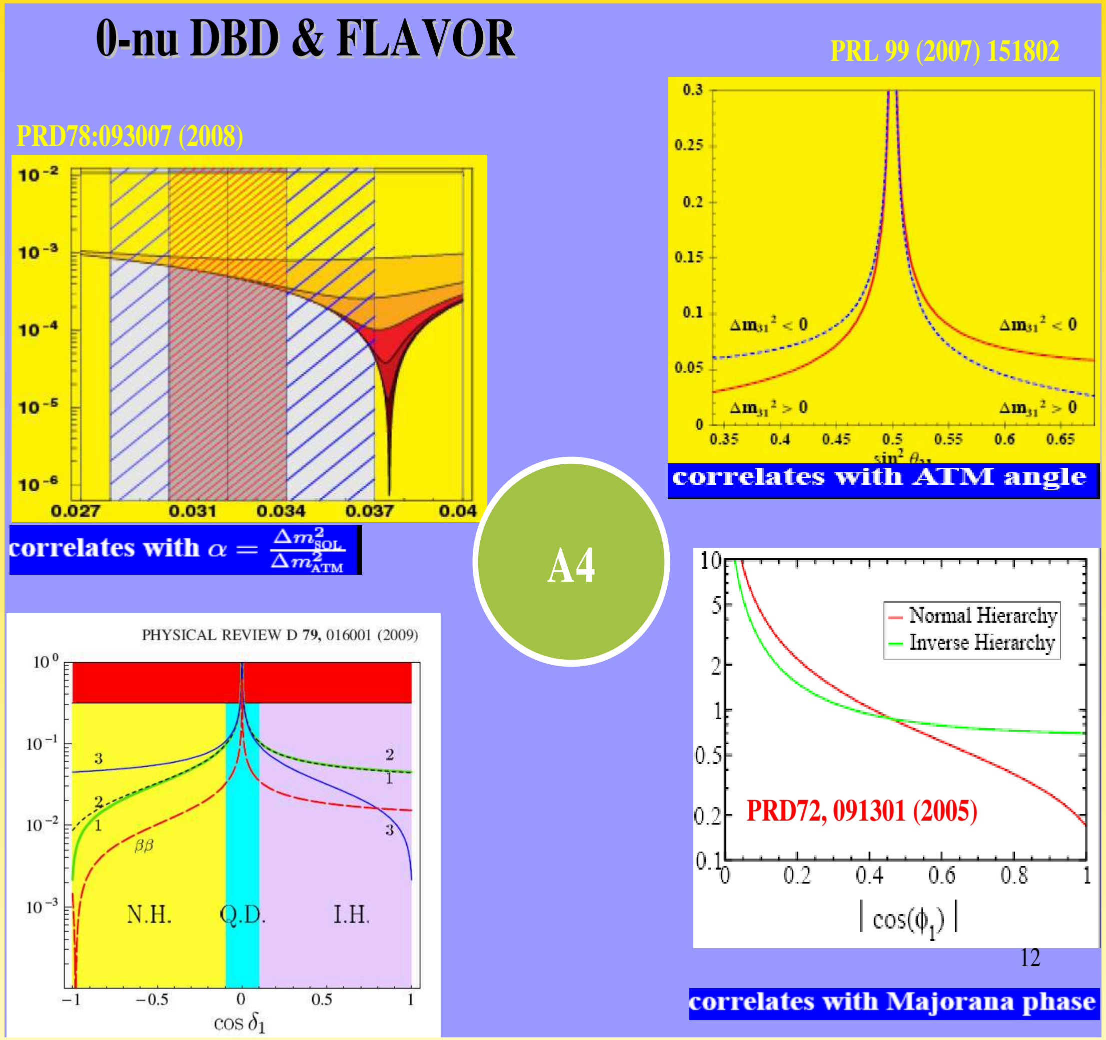
(Flavor Symmetry) Models and Double Beta Decay

1.) Correlations between observables

2.) Neutrino mass sum-rules

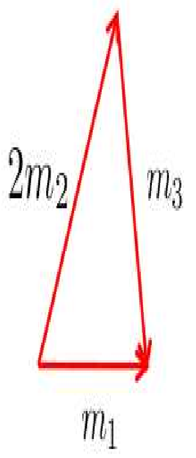
3.) New particles generating $0\nu\beta\beta$

1.) Correlations between observables

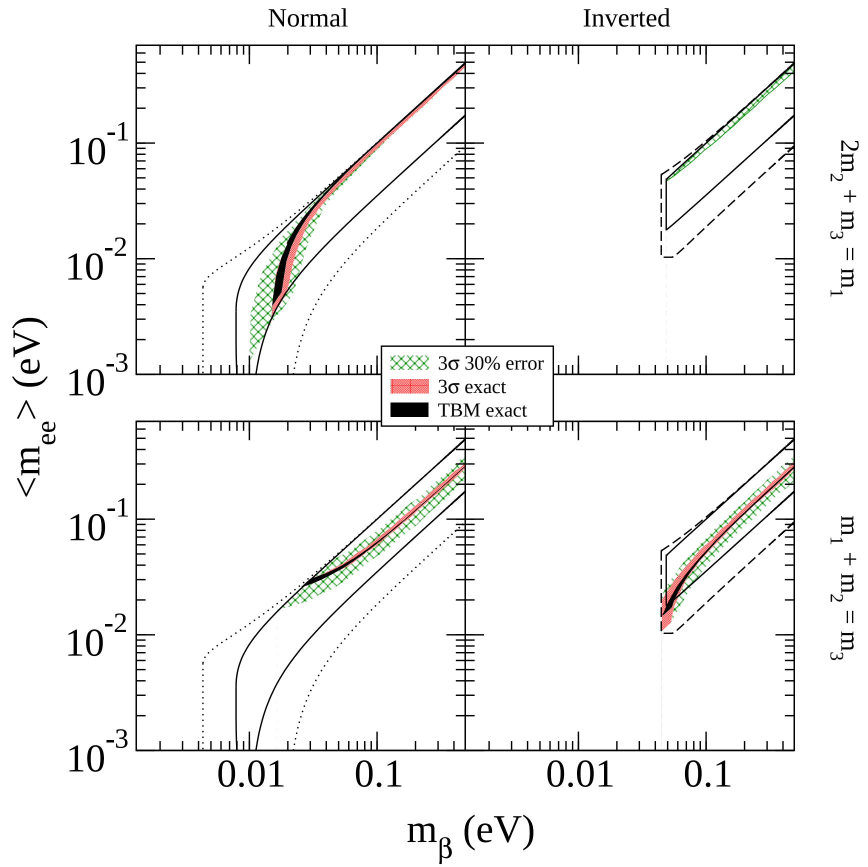


Valle *et al.*; talk by Peinado

2.) Neutrino mass sum-rules



Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4

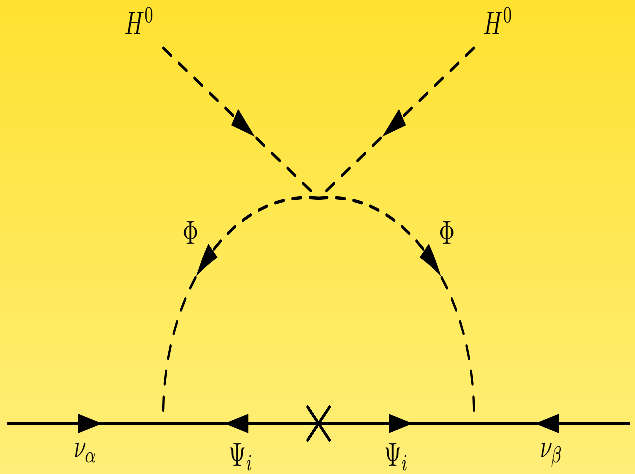


constrains masses and Majorana phases

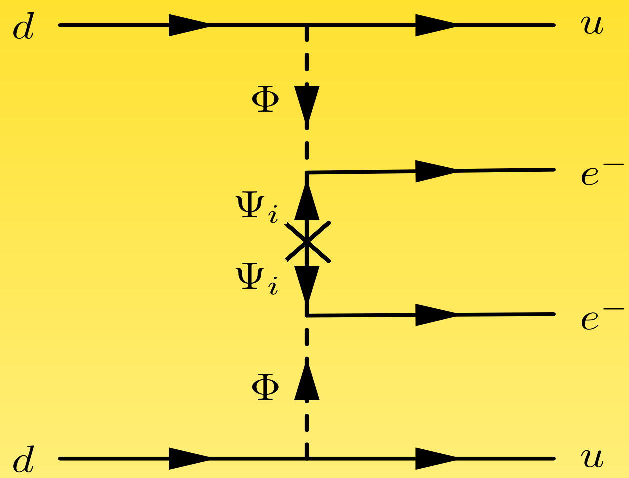
Barry, W.R., NPB **842**

3.) New particles generating $0\nu\beta\beta$

Example: introduce $\Psi_i = (8,1,0)$ and $\Phi = (8,2,\frac{1}{2})$



1-loop m_ν



indirect contribution to $0\nu\beta\beta$:

$$\mathcal{A}_{\rm l} \simeq G_F^2 \, \frac{|m_{ee}|}{q^2}$$

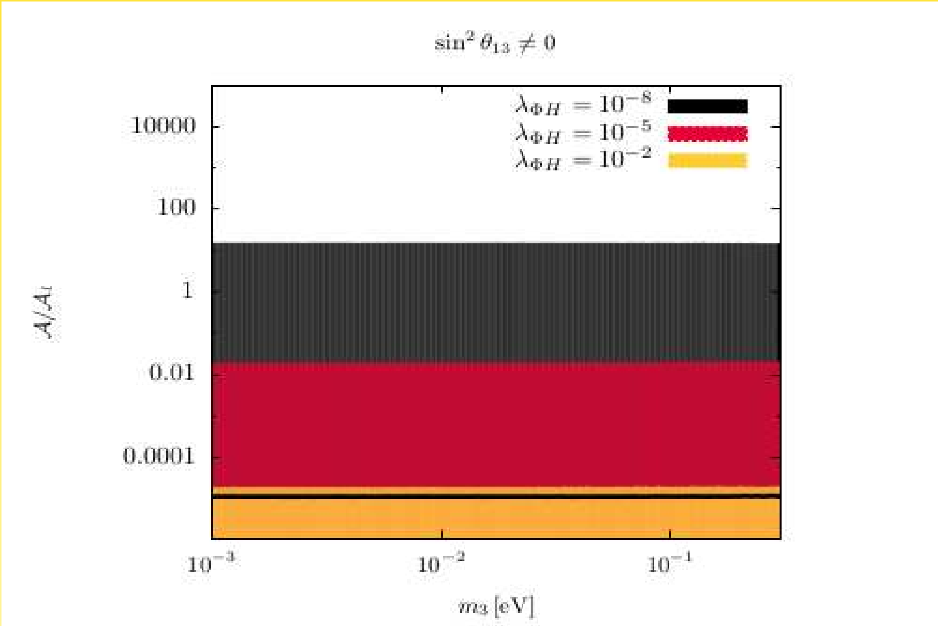
direct contribution to $0\nu\beta\beta$:

$$\mathcal{A} \simeq c_{ud}^2 \, \frac{y_{e\alpha}^2}{M_{\Psi_i} \, M_\Phi^4}$$

Choubey, Dürr, Mitra, W.R., JHEP **1205**

3.) New particles generating $0\nu\beta\beta$

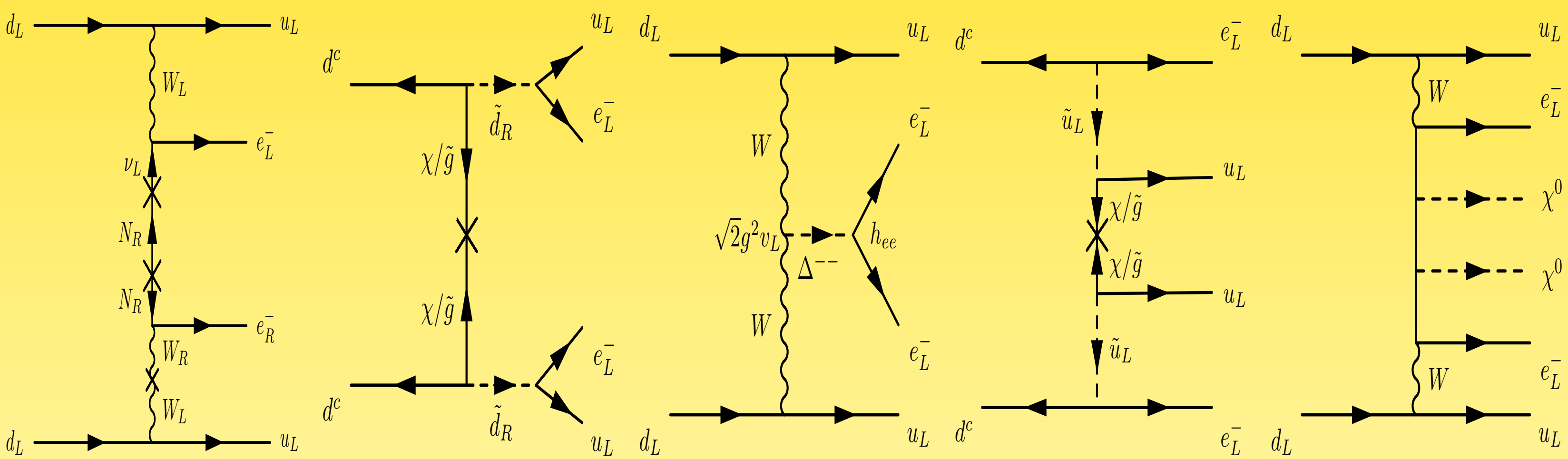
new contribution can dominate over standard one:



see talk by Jose No for another example

Non-Standard Interpretations:

There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism



Clear experimental signature:

KATRIN and/or cosmology see nothing but $0\nu\beta\beta$ does

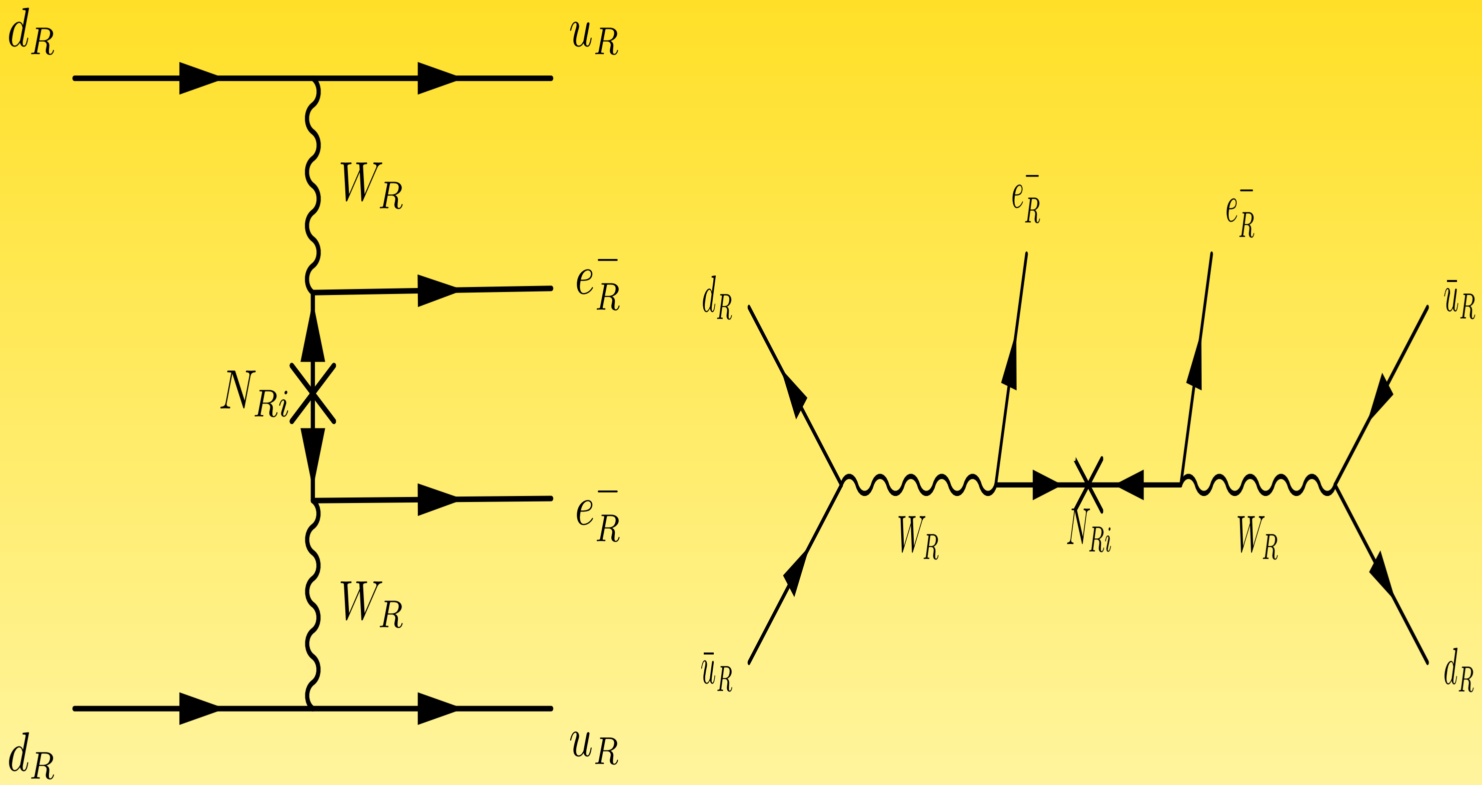
$1 \text{ eV} = 1 \text{ TeV}$

- RPV Supersymmetry
- left-right symmetry
- heavy neutrinos
- color octets
- leptoquarks
- effective operators
- extra dimensions
- ...

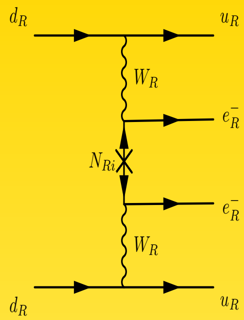
$\Rightarrow$ need to solve the inverse problem...

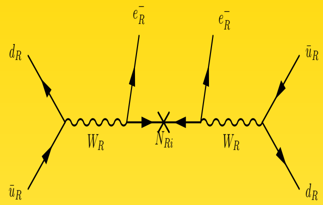
see `talk by Frank Deppisch`

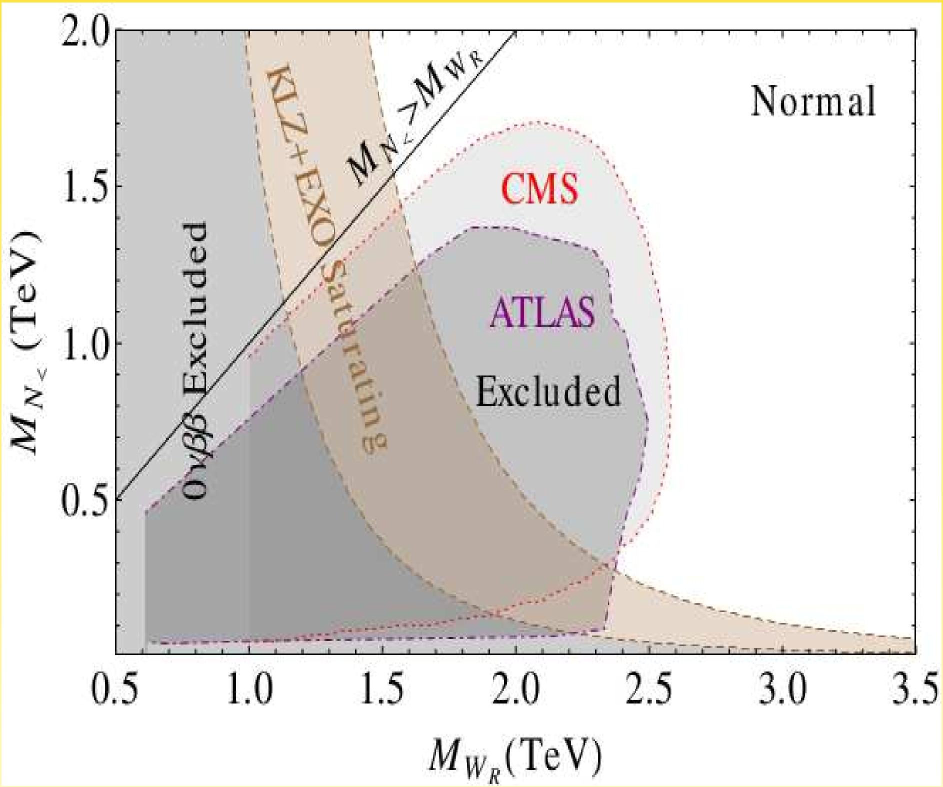
Left-right symmetry



Senjanovic, Keung, 1983; Tello *et al.*; Goswami *et al.*

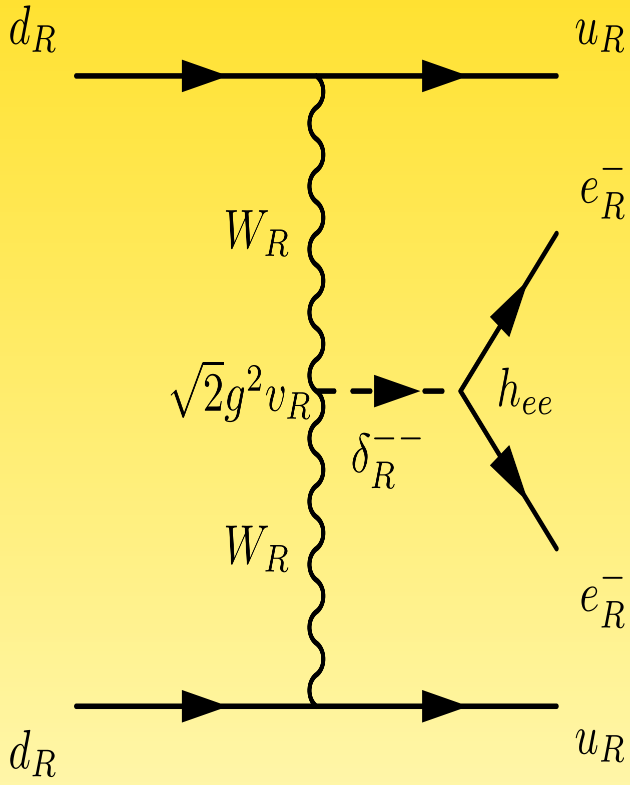


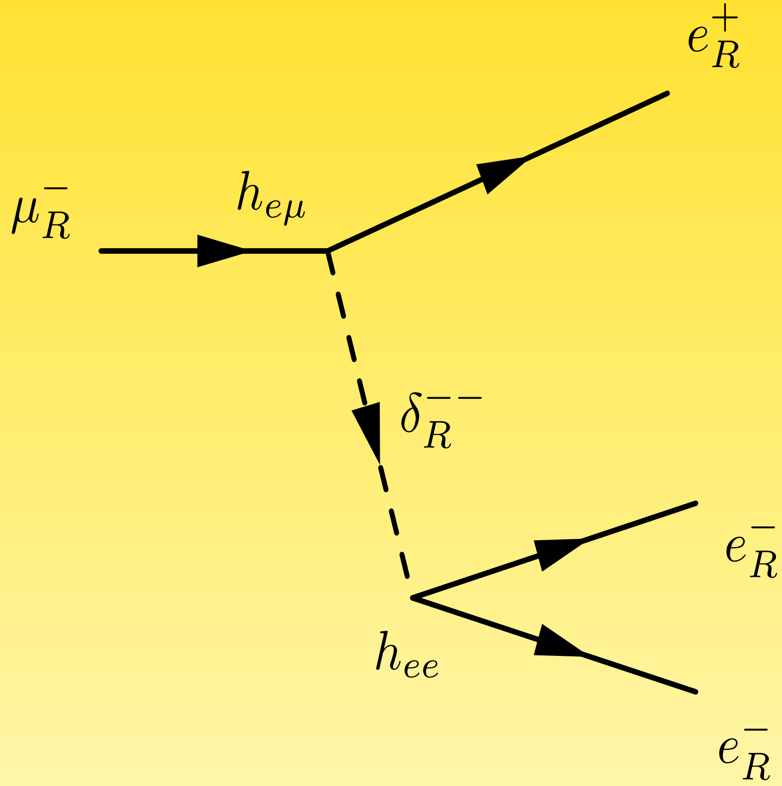




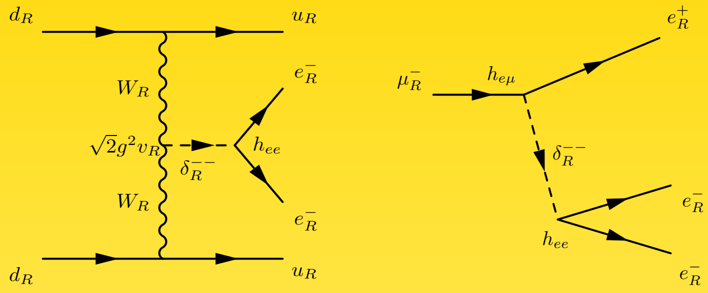
Bhupal Dev, Goswami, Mitra, W.R., Phys. Rev. **D88**

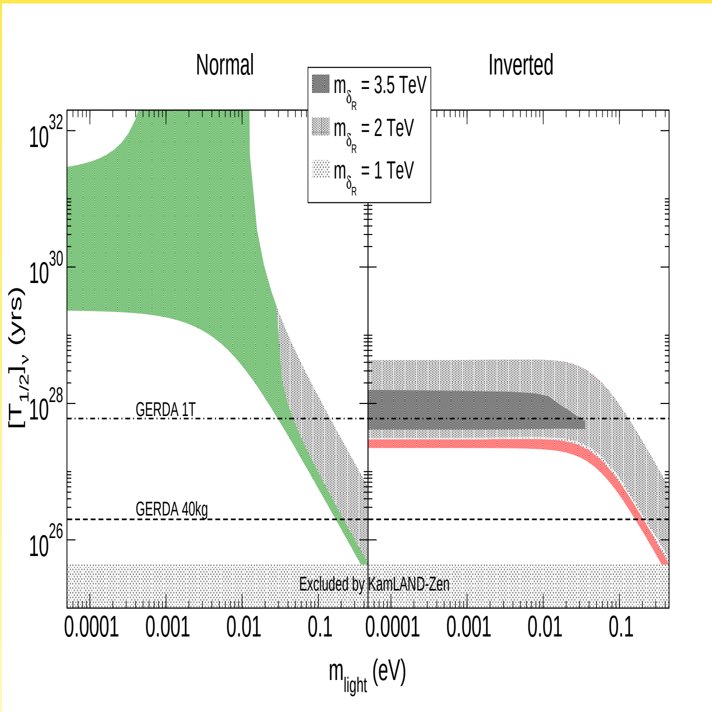
Constraints from Lepton Flavor Violation

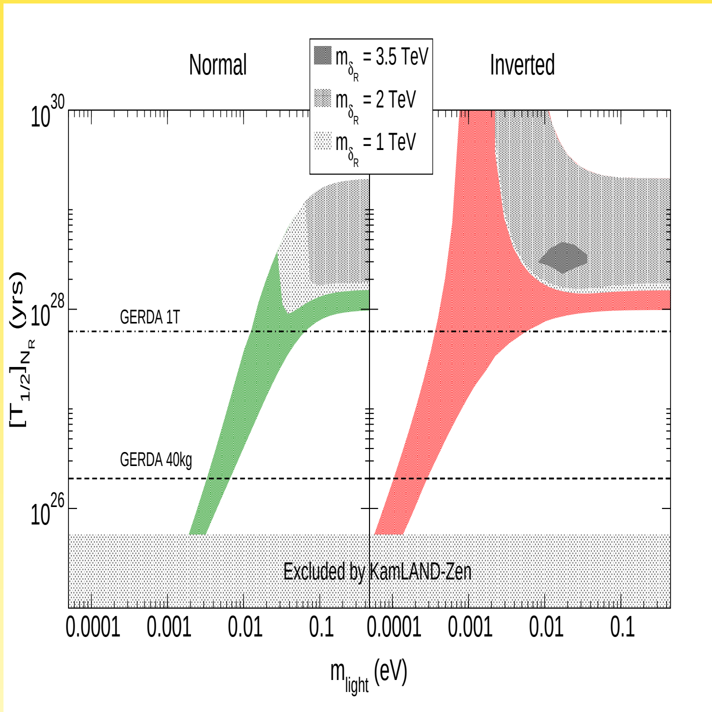




Constraints from Lepton Flavor Violation

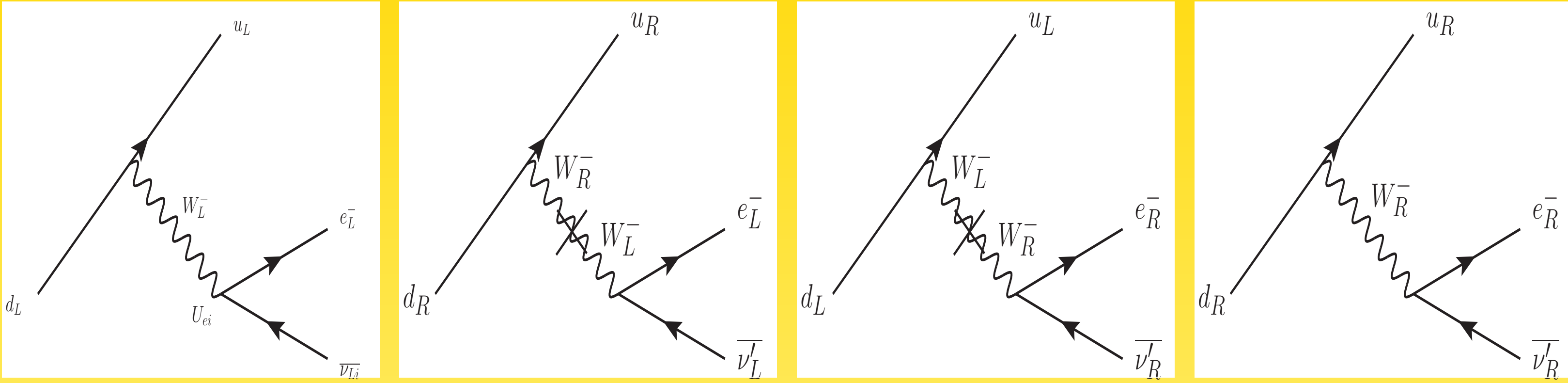






Barry, W.R., JHEP **1309**

Right-handed Currents and KATRIN



$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} = K'(E+m_e)p_e X[1+2C\tan\xi\ \cos\alpha]$$
$$\times\left[|U_{ei}|^2\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+|S_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]$$

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR} = -2K' m_e p_e \mathrm{Re}\left\{\left[\left(\frac{m_{W_L}}{m_{W_R}}\right)^2 + C\tan\xi\, e^{i\alpha}\right]\right.$$
$$\left.\times\left[U_{ei}T_{ei}m_i\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+S_{ei}V_{ei}M_i\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]\right\}$$

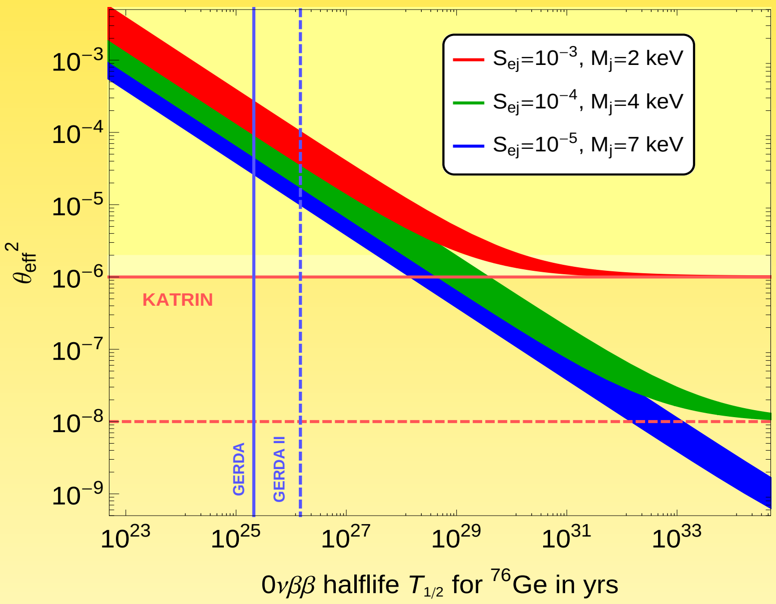
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} \simeq K'(E+m_e)p_e X\left[\frac{m_{W_L}^4}{m_{W_R}^4}+\tan^2\xi+2C\frac{m_{W_L}^2}{m_{W_R}^2}\tan\xi\cos\alpha\right]$$
$$\times|V_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)$$

Right-handed Currents and KATRIN

focus on the case of keV + RH currents:

$$\frac{\mathrm{d}\Gamma/\mathrm{d}E - (\mathrm{d}\Gamma/\mathrm{d}E)_{\rm std}}{(\mathrm{d}\Gamma/\mathrm{d}E)_{\rm std}} \simeq \left(a + b\frac{M}{E_0 - E}\right)\sqrt{1 - \frac{M^2}{(E_0-E)^2}}\,\Theta(E_0 - E - M)$$

connection to $0\nu\beta\beta$!



Barry, Heeck, W.R., 1404.5955

Do Dirac neutrinos mean there is no Lepton Number Violation?

Model based on gauged $B - L$, broken by 4 units

$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...

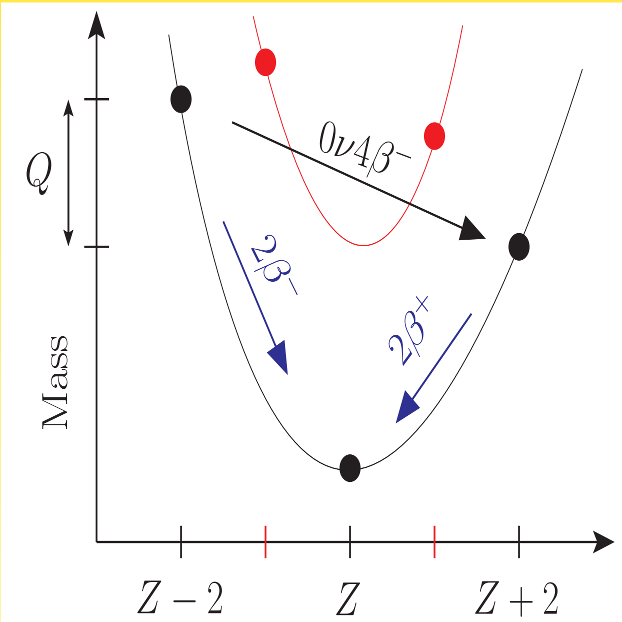
Heeck, W.R., EPL **103**

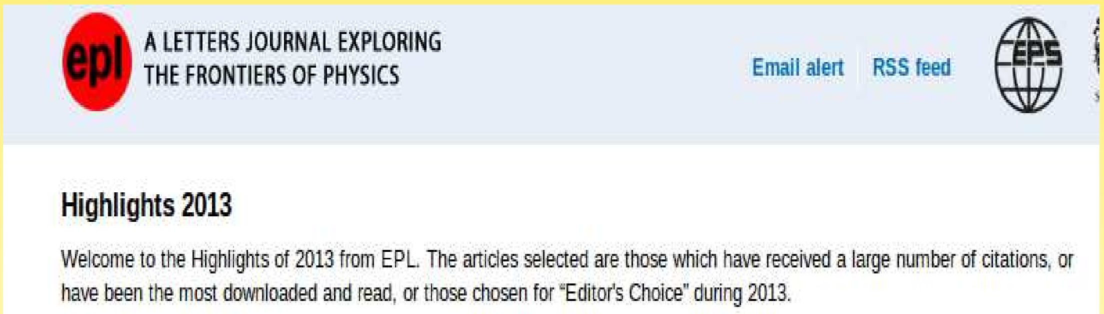
Do Dirac neutrinos mean there is no Lepton Number Violation?

Model based on gauged $B - L$, broken by 4 units

$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed. . .

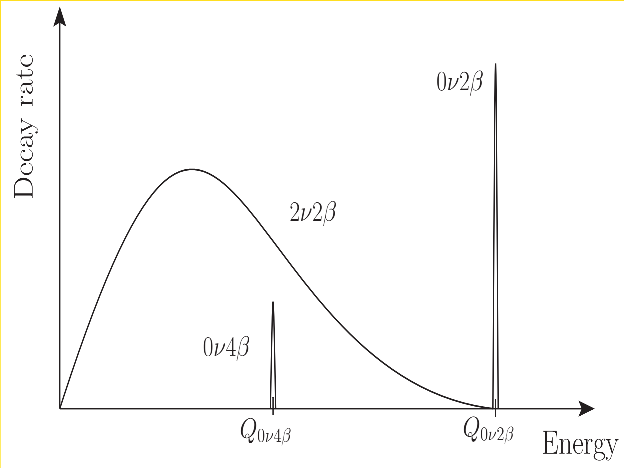
$\Rightarrow$ observable: neutrinoless quadruple beta decay $(A, Z) \to (A, Z + 4) + 4\, e^-$





Heeck, W.R., EPL **103**

Candidates for neutrinoless quadruple beta decay



	$Q_{0\nu 4\beta}$	Other decays	NA
${}^{96}_{40}Zr \to {}^{96}_{44}Ru$	0.629	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}Xe \to {}^{136}_{58}Ce$	0.044	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}Nd \to {}^{150}_{64}Gd$	2.079	$\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6

Heeck, W.R., EPL **103**

Summary

Chi l'ha visto?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Enjoy today's matches!

Wednesday 18th June 2014

FIFA WORLD CUP - GROUP A			
Cameroon	v	Croatia	23:00

FIFA WORLD CUP - GROUP B			
Australia	v	Netherlands	17:00
Spain	v	Chile	20:00