Neutrinoless Double Beta Decay: Neutrinos and Beyond

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24/09/2012

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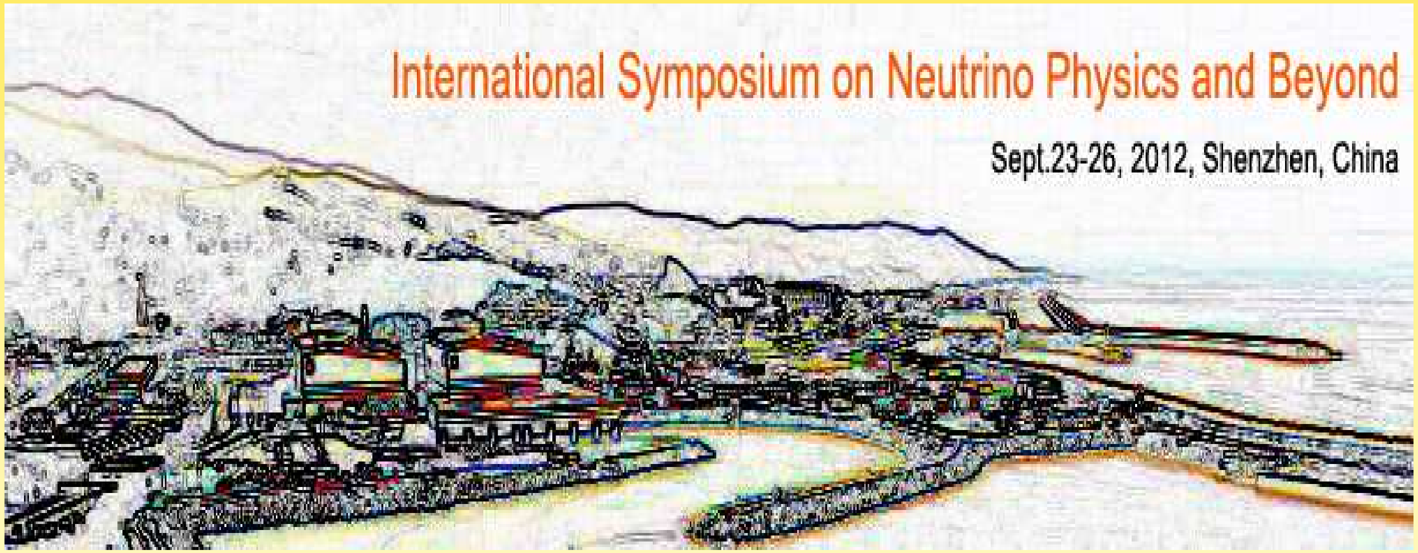
MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology



Outline

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

- **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

- **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

reviews on $0\nu\beta\beta$:

Int. J. Mod. Phys. **E20**, 1833 (2011); Focus issue J. Phys. **G** [1206.2560]

Interpretation of Experiments

Master formula:

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

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

Interpretation of Experiments

Master formula:

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

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

Upcoming/running experiments: exciting time!!

best limit was from 2001...

Name	Isotope	source = detector; calorimetric with			source ≠ detector
		high energy res.	low energy res.	event topology	event topology
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA	^{116}Cd (and ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
DCBA	^{82}Se or ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LUCIFER	^{82}Se or ^{100}Mo or ^{116}Cd	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se or ^{100}Mo or ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+	^{150}Nd(?)	–	✓	–	–
SuperNEMO	^{82}Se or ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

multi-isotope determination good for 3 reasons

3 Reasons for Multi-isotope determination

1.) credibility

2.) test NME calculation

$$\frac{T_{1/2}^{0\nu}(A_1, Z_1)}{T_{1/2}^{0\nu}(A_2, Z_2)} = \frac{G(Q_2, Z_2)\,|\mathcal{M}(A_2, Z_2)|^2}{G(Q_1, Z_1)\,|\mathcal{M}(A_1, Z_1)|^2}$$

systematic errors drop out, ratio sensitive to NME model

3.) test mechanism

$$\frac{T_{1/2}^{0\nu}(A_1, Z_1)}{T_{1/2}^{0\nu}(A_2, Z_2)} = \frac{G_x(Q_2, Z_2)\,|\mathcal{M}_x(A_2, Z_2)|^2}{G_x(Q_1, Z_1)\,|\mathcal{M}_x(A_1, Z_1)|^2}$$

particle physics drops out, ratio of NMEs sensitive to mechanism

Experimental Aspects

particle physics:

$$(T^{0\nu}_{1/2})^{-1} \propto \text{ (particle physics)}^2$$

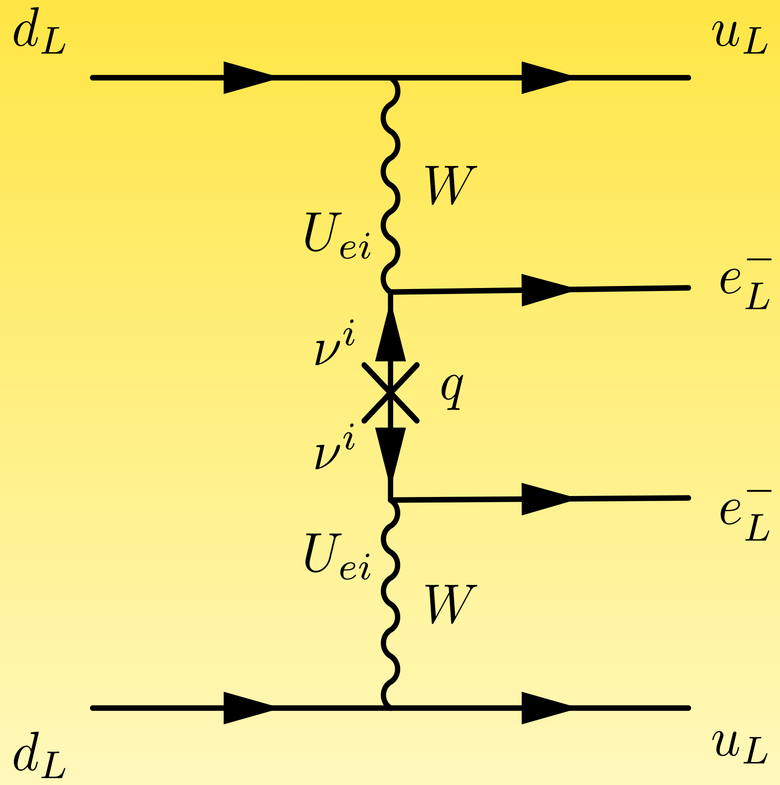
experimentally:

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

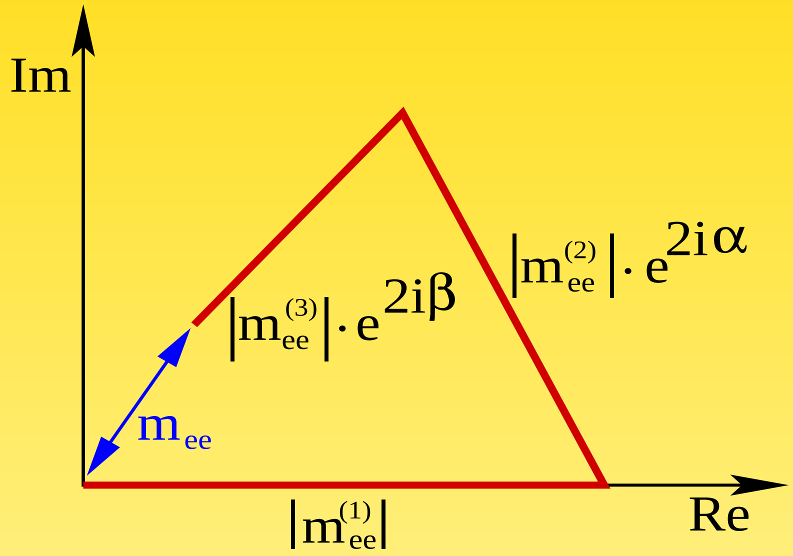
Note: factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

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



$\Delta L \neq 0$: Neutrinoless Double Beta Decay

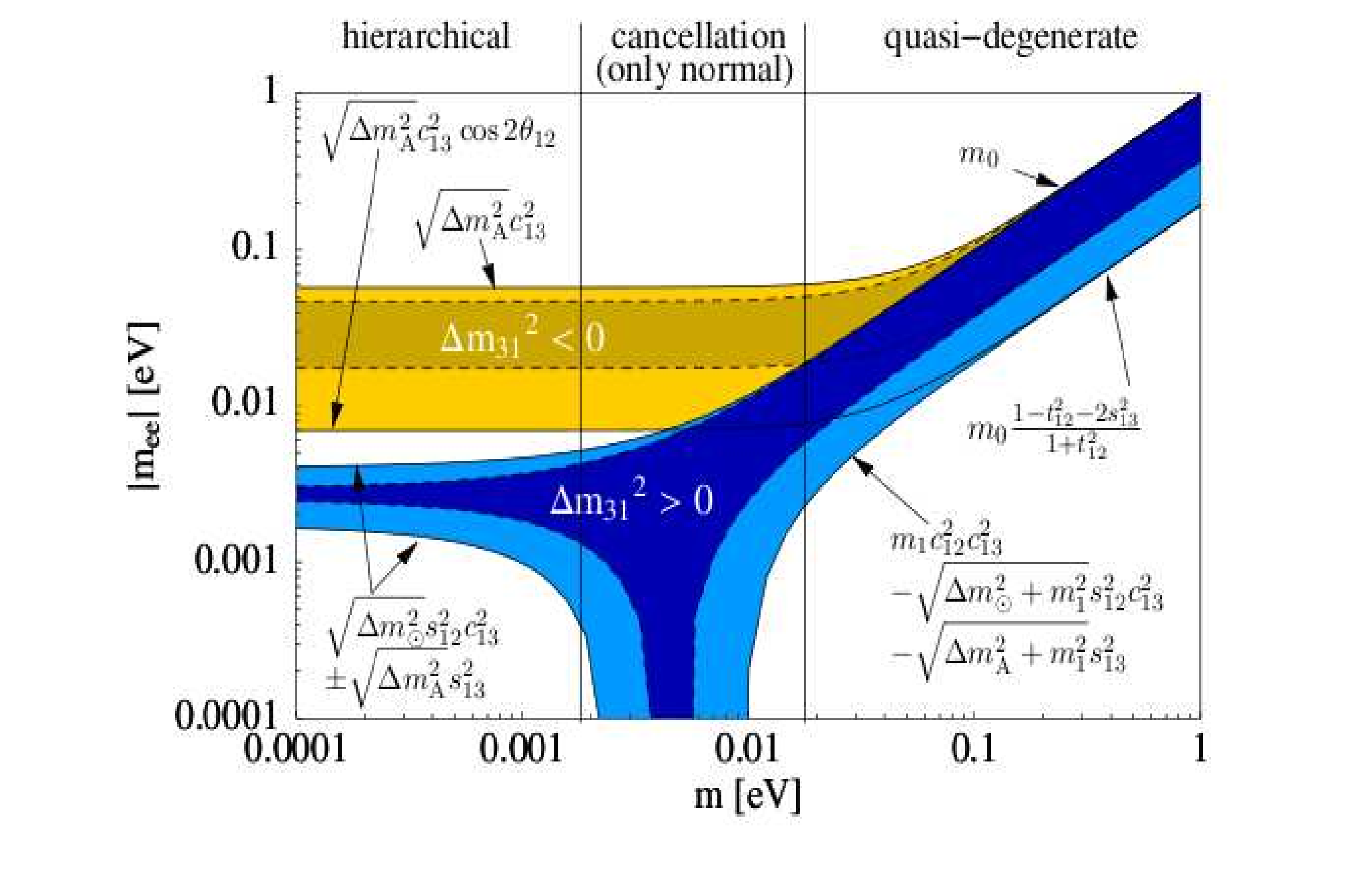


Amplitude proportional to coherent sum (“effective mass”):

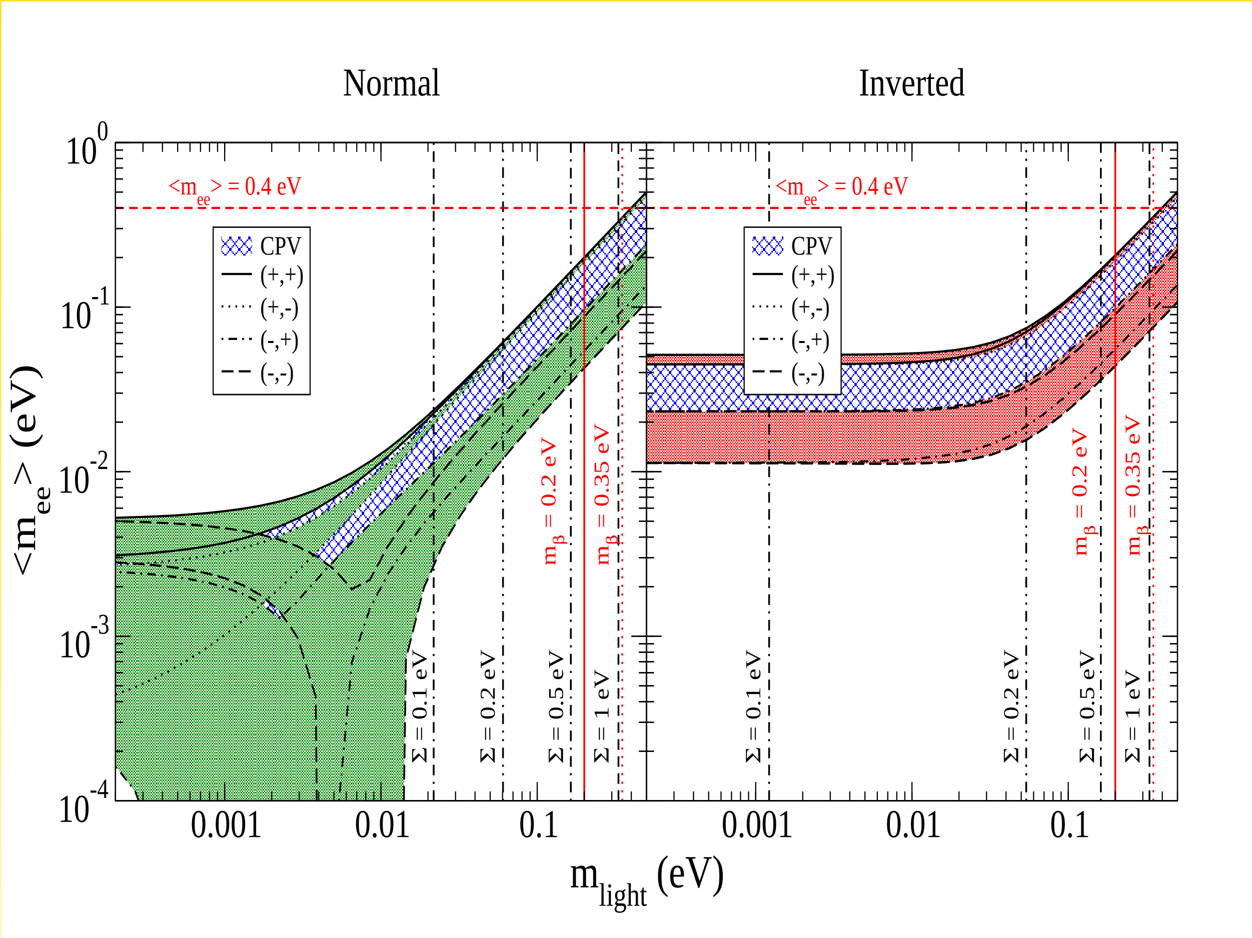
$$\boxed{|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|}$$

7 out of 9 parameters of m_ν!

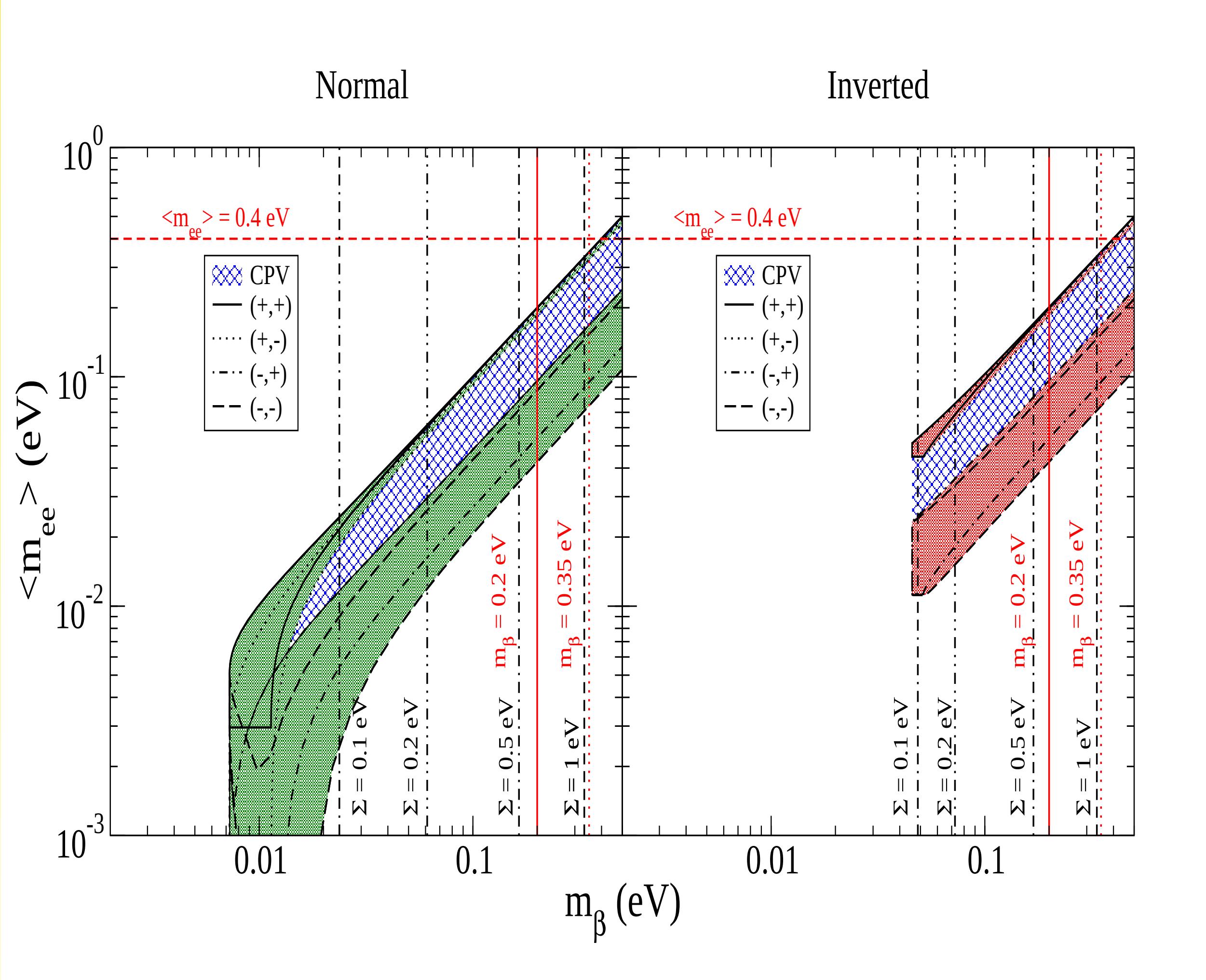
The usual plot



The usual plot

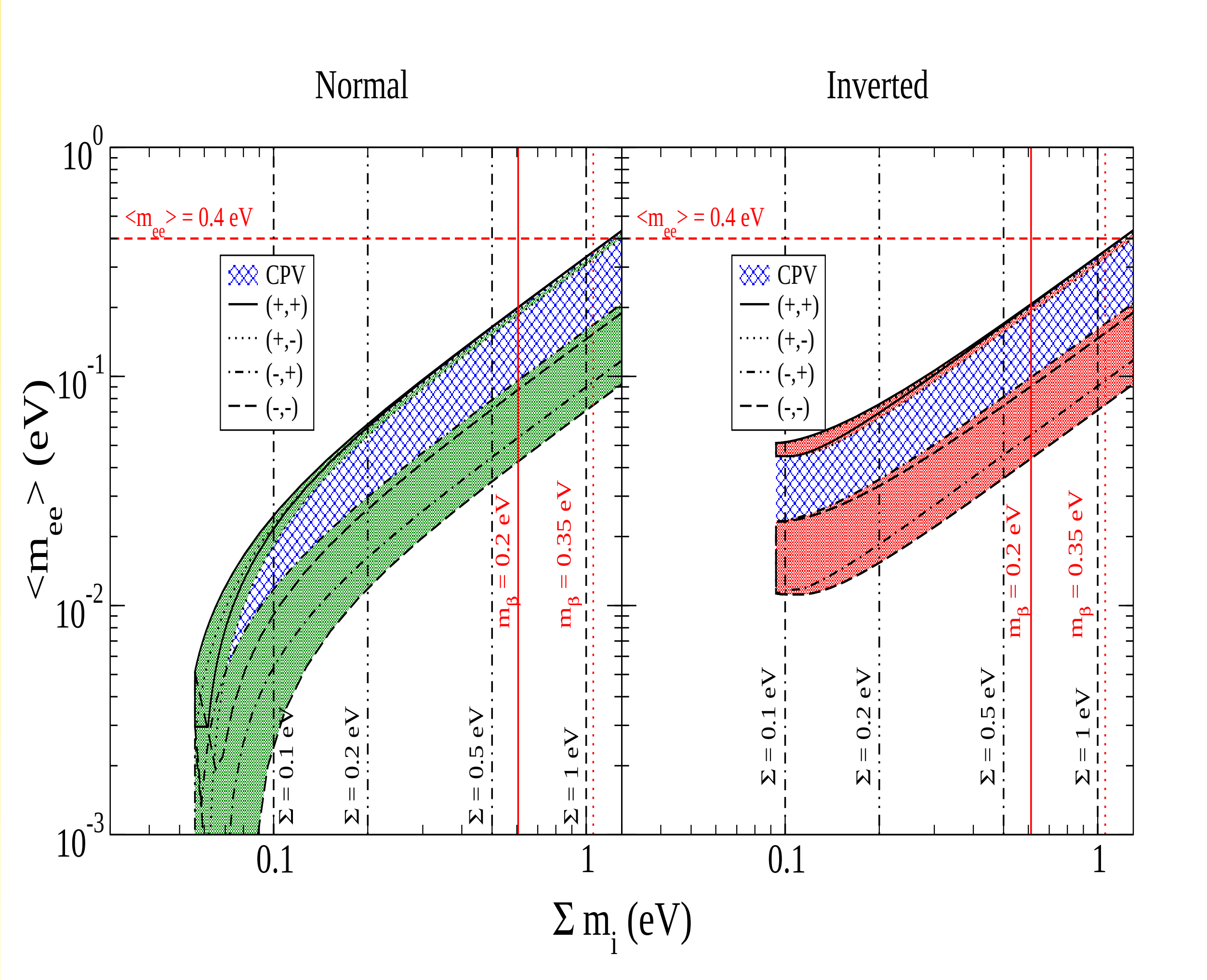


Plot against other observables



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

Plot against other observables

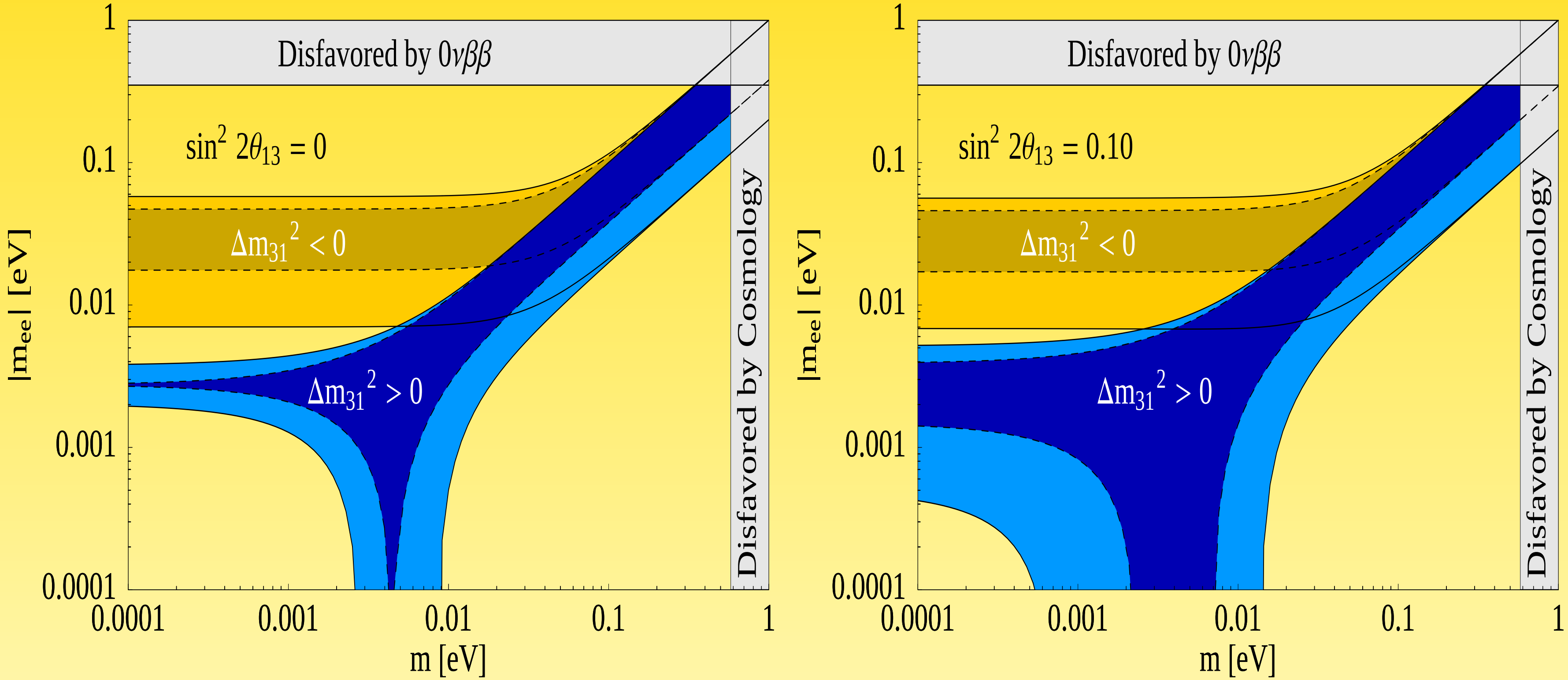


Complementarity of $|m_{ee}| = U_{ei}^2 \, m_i$ and $m_\beta = \sqrt{|U_{ei}|^2 \, m_i^2}$ and $\Sigma = \sum m_i$

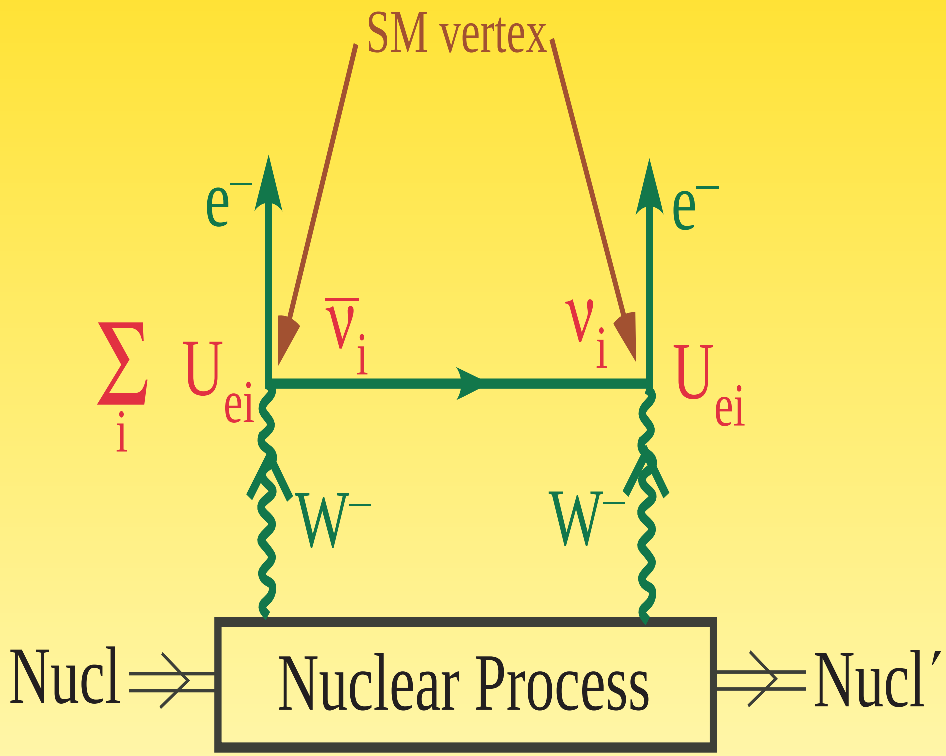
Neutrino Mass Matrix

		KATRIN		$0\nu\beta\beta$		cosmology	
		yes	no	yes	no	yes	no
KATRIN	yes	–	–	QD + Majorana	QD + Dirac	QD	N-SC
	no	–	–	N-SI	low IH or NH or Dirac	$m_\nu \lesssim 0.1$ eV or N-SC	NH
$0\nu\beta\beta$	yes	•	•	–	–	(IH or QD) + Majorana	N-SC or N-SI
	no	•	•	–	–	low IH or (QD + Dirac)	NH
cosmology	yes	•	•	•	•	–	–
	no	•	•	•	•	–	–

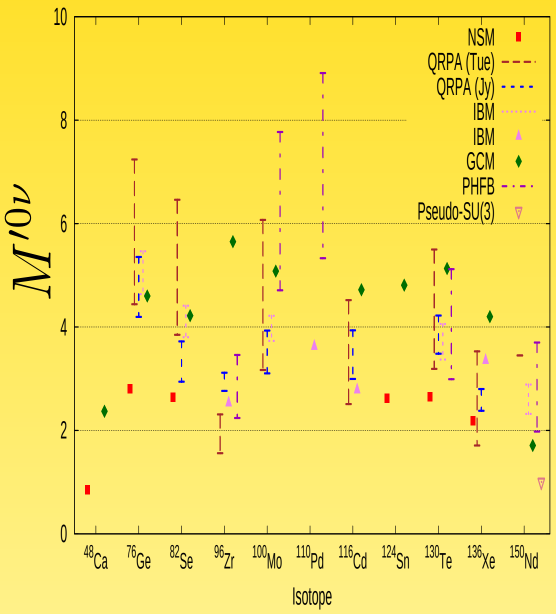
$0\nu\beta\beta$ and U_{e3}

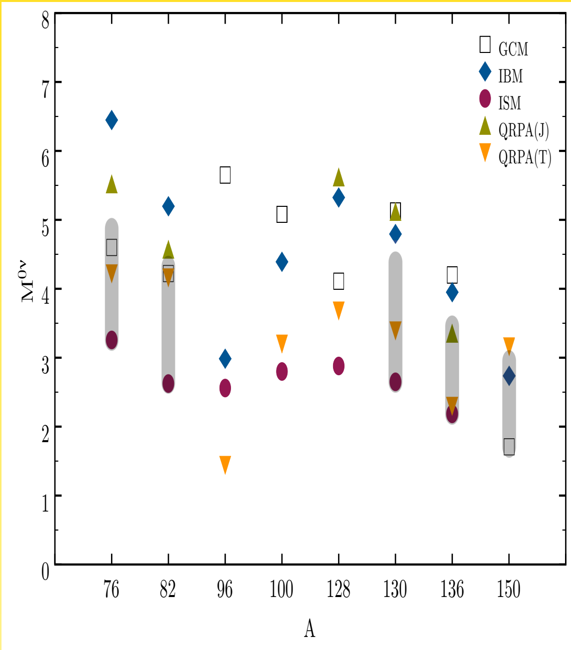


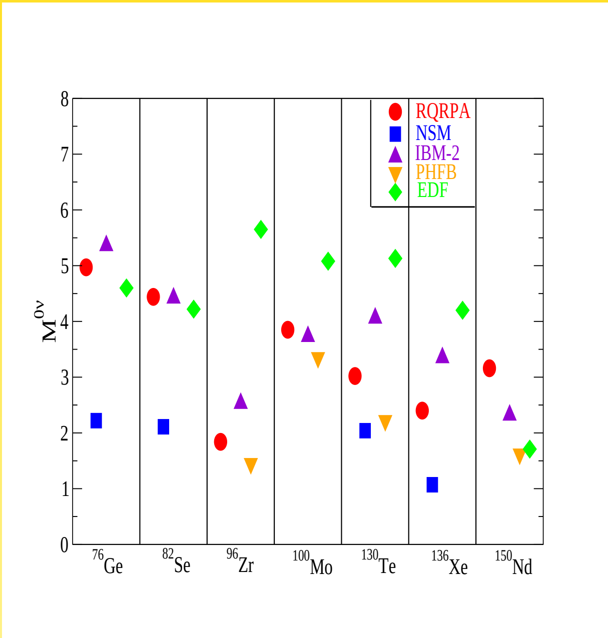
From life-time to particle physics: Nuclear Matrix Elements



From life-time to particle physics: Nuclear Matrix Elements







`Dueck, W.R., Zuber, PRD` **83** `Gomez-Cadenas` *et al.*`, 1109.5515` `Vogel, 1208.1992`

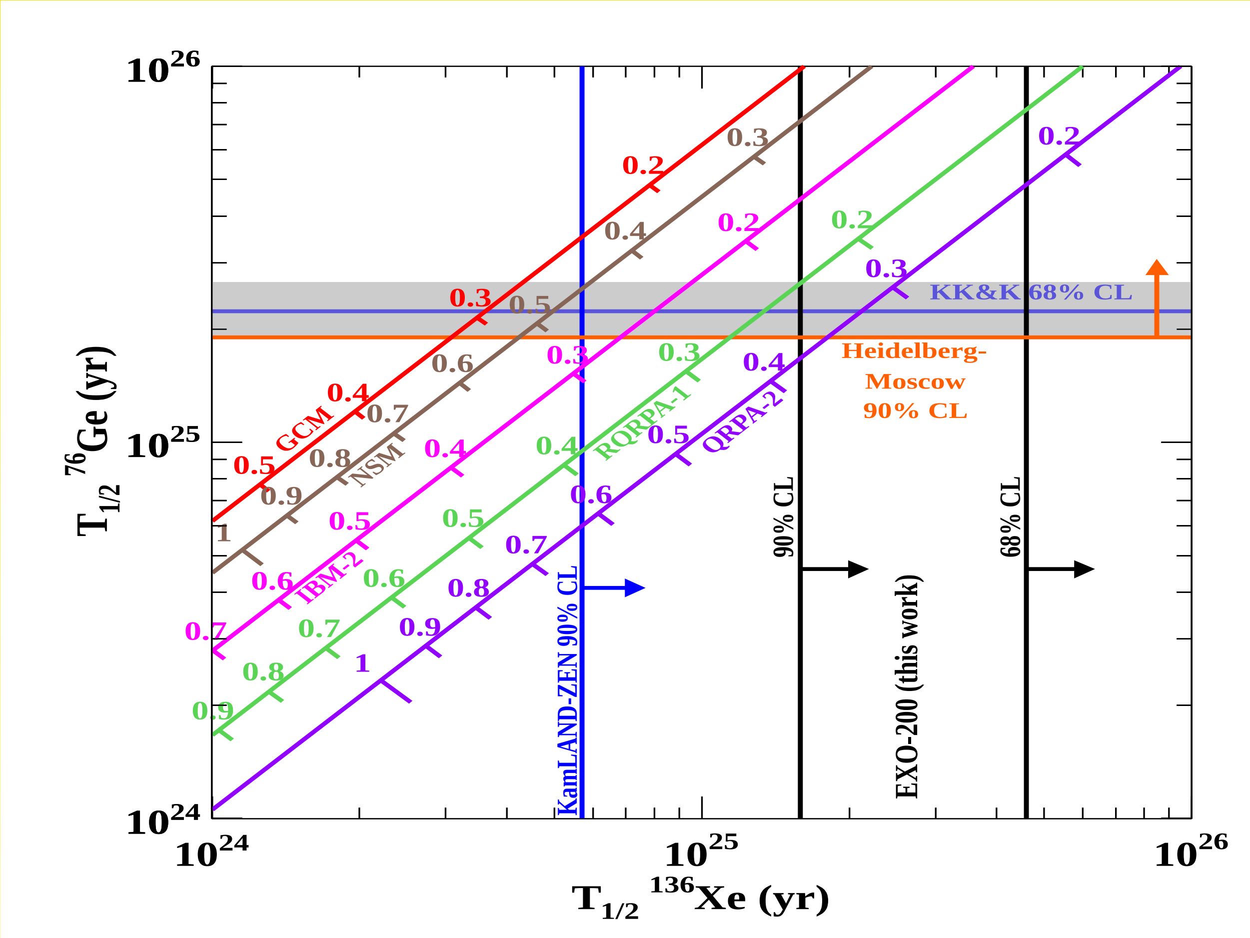
(current) uncertainty of factor 2 to 3, directly translates into uncertainty on particle physics parameter

Isotope	$T^{0\nu}_{1/2}$ [yrs]	Experiment	$\|m_{ee}\|^{\rm lim}_{\rm min}$ [eV]	$\|m_{ee}\|^{\rm lim}_{\rm max}$ [eV]	
^{48}Ca	5.8×10^{22}	CANDLES	3.55	9.91	$\times 0.98$
^{76}Ge	1.9×10^{25}	HDM	0.21	0.53	$\times 1.04$
	1.6×10^{25}	IGEX	0.25	0.63	$\times 1.04$
^{82}Se	3.2×10^{23}	NEMO-3	0.85	2.08	$\times 1.04$
^{96}Zr	9.2×10^{21}	NEMO-3	3.97	14.39	$\times 1.06$
^{100}Mo	1.0×10^{24}	NEMO-3	0.31	0.79	$\times 1.06$
^{116}Cd	1.7×10^{23}	SOLOTVINO	1.22	2.30	$\times 1.06$
^{130}Te	2.8×10^{24}	CUORICINO	0.27	0.57	$\times 1.09$
^{136}Xe	1.6×10^{25}	EXO-200	0.15	0.36	$\times 1.10$
^{150}Nd	1.8×10^{22}	NEMO-3	2.35	5.08	$\times 1.12$

(recent reevaluation of phase space factors by `Iachello+Kotila`)

HDM limit reached/improved by EXO-200 !

EXO-200 vs. Klapdor



EXO, 1205.5608

↔ talk by O'Sullivan

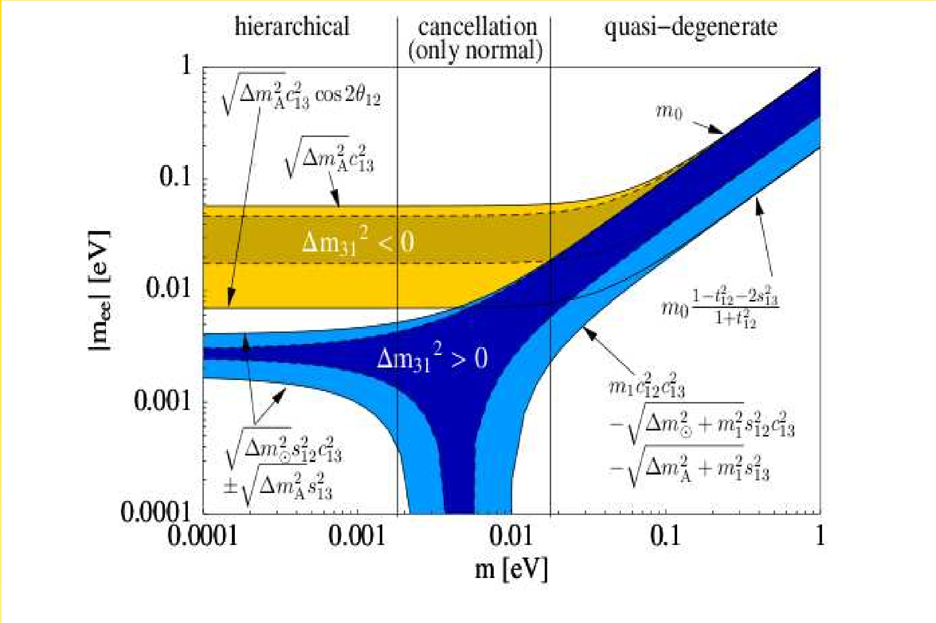
Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011	0.17-0.42
		40	2×10^{26}	in progress	$\sim$ 2012	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26}*$	in progress	$\sim$ 2013	0.018-0.037
			$2.1 \times 10^{26}**$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013	0.06-0.16
		1000	6×10^{27}	R&D	$\sim$ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	$\sim$ 2011	0.073-0.18
		1000	8×10^{26}	R&D	$\sim$ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	$\sim$ 2011	0.03-0.07
		1000	10^{27}	R&D	$\sim$ 2013-15	0.02-0.046
SNO+	^{150}Nd	132	1.8×10^{25}	in progress	$\sim$ 2014	0.09-0.18

(with *same* lifetime: ^{150}Nd and ^{100}Mo do best...)

With $0\nu\beta\beta$ one can

- test Majorana nature of neutrinos
- probe neutrino mass scale
- test inverted ordering
- extract Majorana phase
- test flavor symmetry models: neutrino mass “sum-rules”

Inverted Ordering



Nature provides 2 scales:

$$\langle m_\nu \rangle^{\text{IH}}_{\text{max}} \simeq c_{13}^2 \sqrt{\Delta m_{\rm A}^2} \quad \text{and} \quad \langle m_\nu \rangle^{\text{IH}}_{\text{min}} \simeq c_{13}^2 \sqrt{\Delta m_{\rm A}^2} \cos 2\theta_{12}$$

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

Ruling out Inverted Hierarchy

$$|m_{ee}|_{\rm min}^{\rm IH} = \left(1 - |U_{e3}|^2\right) \sqrt{|\Delta m_{\rm A}^2|}\,\left(1 - 2\sin^2\theta_{12}\right) = \left\{ \begin{array}{cc} (0.016 \ldots 0.020)~{\rm eV} & 1\sigma \\ (0.013 \ldots 0.024)~{\rm eV} & 3\sigma \end{array} \right.$$

- small $|U_{e3}|$
- large $|\Delta m_{\rm A}^2|$
- small $\sin^2\theta_{12}$

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

$\Rightarrow$ 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**

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

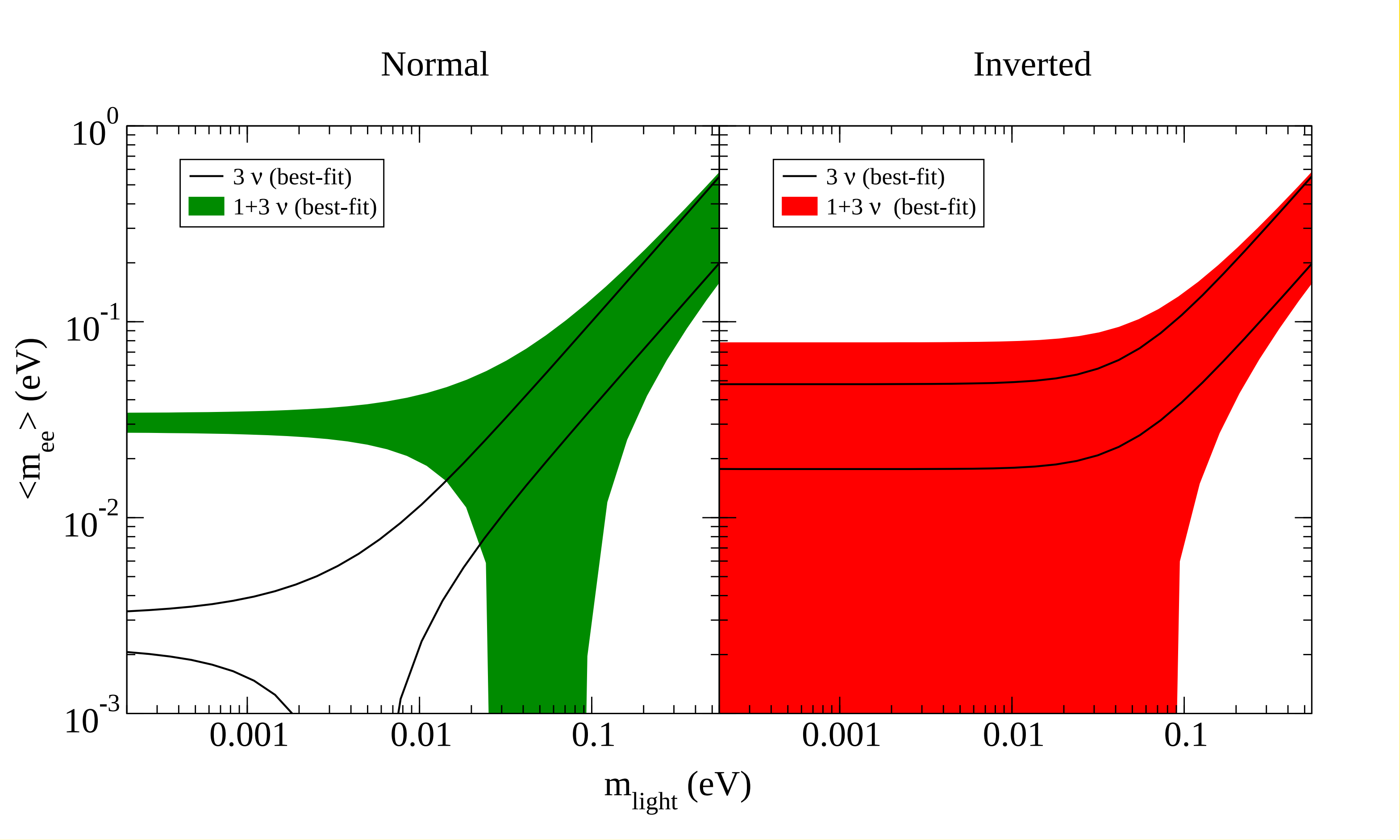
- recall: $|m_{ee}|^{\rm act}_{\rm NH}$ can vanish and $|m_{ee}|^{\rm act}_{\rm IH} \sim 0.02$ eV cannot vanish
- $|m_{ee}| = \left| \underbrace{|U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}^2|\, m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2\, m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}} \right|$
- $\Delta m^2_{\rm st} \simeq 1.8$ eV^2 and $|U_{e4}| \simeq 0.13$ ($\leftrightarrow$ `talk by Giunti`)
- sterile contribution to $0\nu\beta\beta$ (assuming 1+3):

$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \simeq 0.03 \text{ eV} \left\{ \begin{array}{l} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

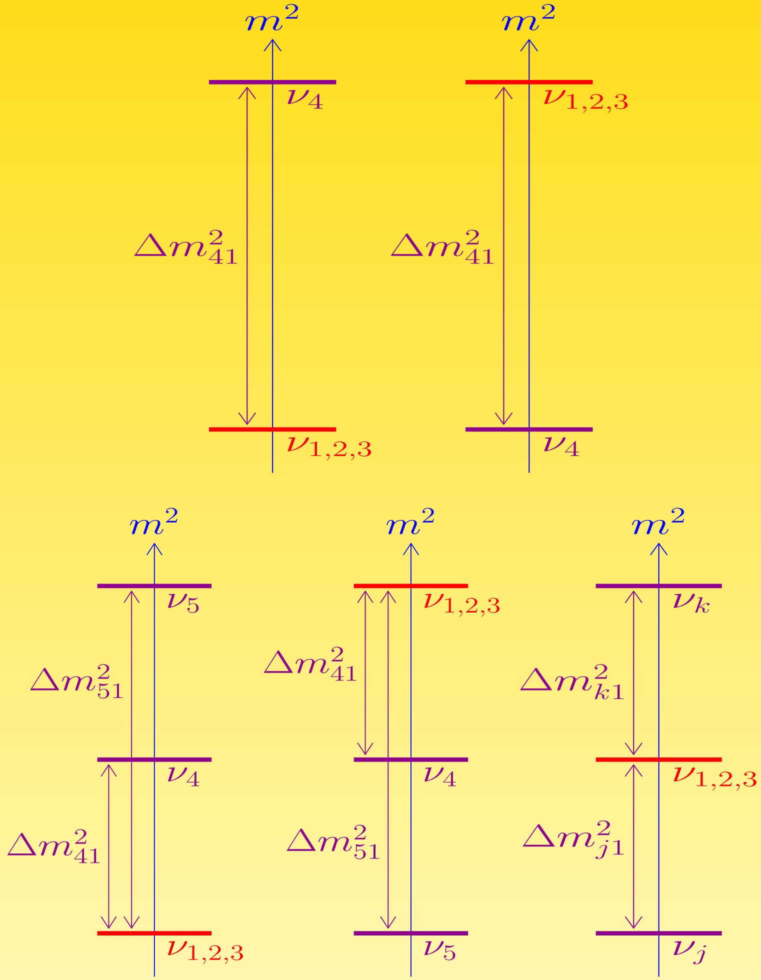
- $\Rightarrow$ $|m_{ee}|_{\rm NH}$ cannot vanish and $|m_{ee}|_{\rm IH}$ can vanish!

usual phenomenology gets completely turned around!

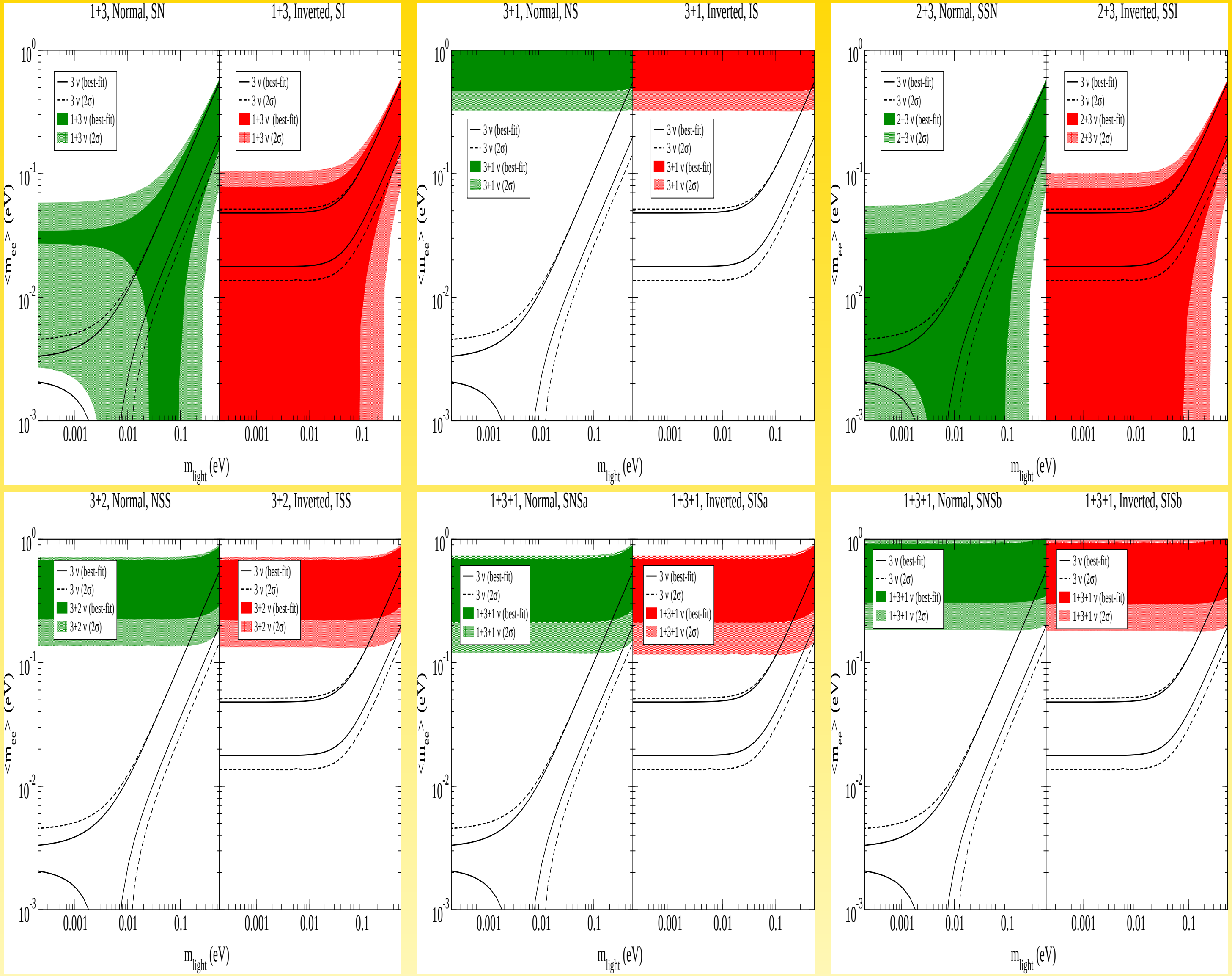
Usual plot gets completely turned around!



Mass Orderings



3 active neutrinos can be normally or inversely ordered



Barry, W.R., Zhang, JHEP **1107**

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

- if the eV-steriles are from seesaw: individual cancellations in flavor symmetry models, e.g.:

$$U_{e2}^2\, m_2 + U_{e4}^2\, m_4 = 0$$

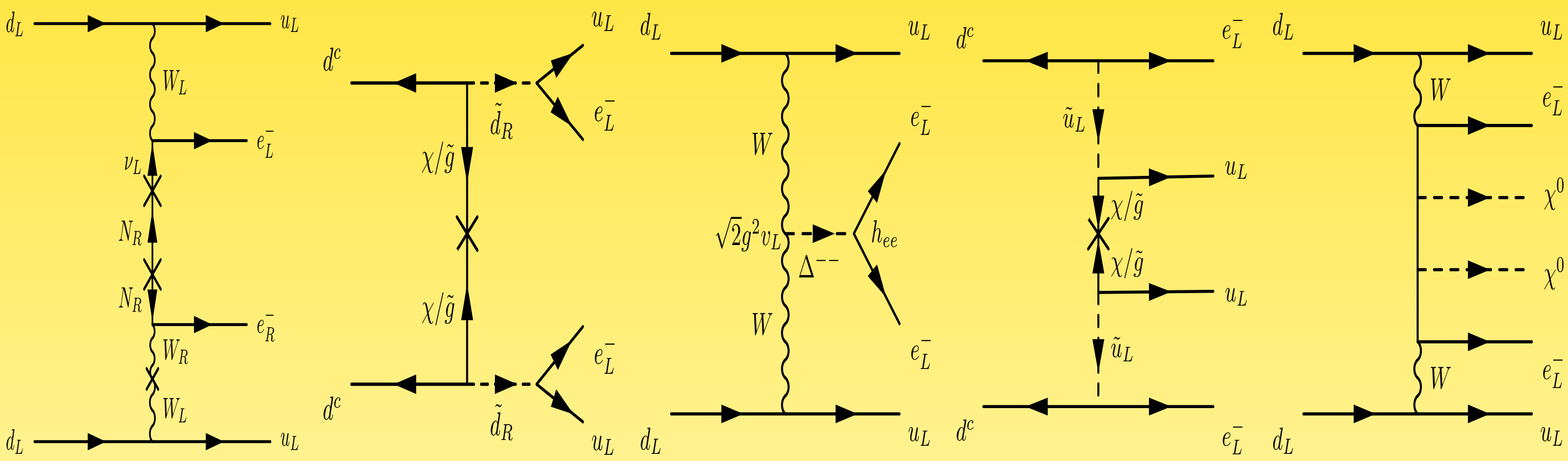
- if seesaw scale is below 100 MeV: No double beta decay!

$$\sum_{i=1}^{6} U_{ei}^2\, m_i = 0 \text{ since } \mathcal{M} = \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_R \end{array} \right) = U \left(\begin{array}{cc} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{array} \right) U^T$$

Barry, W.R., Zhang, JCAP **1201**

Non-Standard Interpretations:

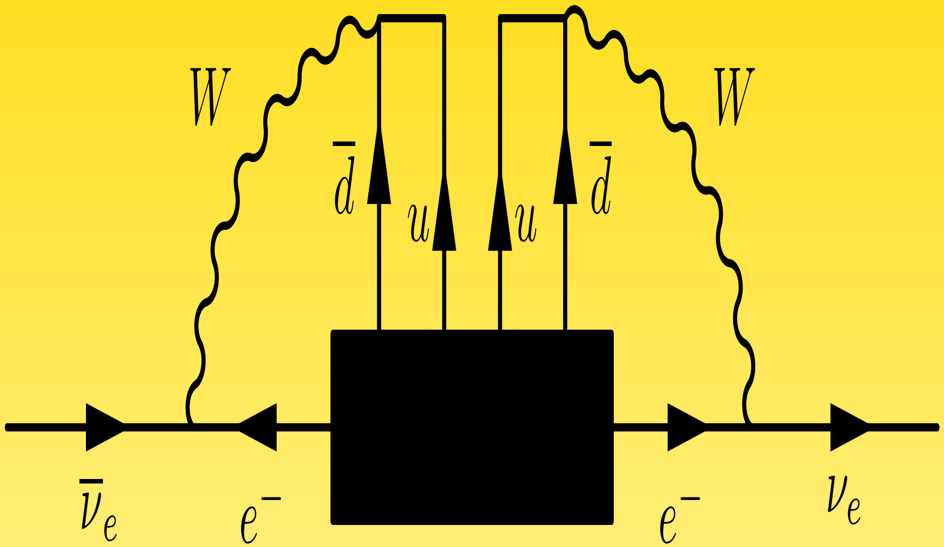
There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism



Clear experimental signature:

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

Schechter-Valle theorem: no matter what process, neutrinos are Majorana:



is 4 loop diagram: $m_\nu \sim \frac{1}{(16\pi^2)^4} \frac{\mathrm{MeV}^5}{m_W^4} \lesssim 10^{-23}\,\mathrm{eV}$

explicit calculation: Duerr, Lindner, Merle, 1105.0901

note: often there are 1-loop diagrams leading to m_ν: direct vs. indirect contribution (Choubey, Duerr, Mitra, W.R., 1201.3031)

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\| U_{ei}^2 \, m_i \right\|$	0.4 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\| \frac{S_{ei}^2}{M_i} \right\|$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\| \frac{V_{ei}^2}{M_i \, M_{W_R}^4} \right\|$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\| \frac{(M_R)_{ee}}{m_{\Delta_R}^2 \, M_{W_R}^4} \right\|$	10^{-15} GeV^{-5}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\| \frac{U_{ei} \, \tilde{S}_{ei}}{M_{W_R}^2} \right\|$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan \zeta \, \left\| U_{ei} \, \tilde{S}_{ei} \right\|$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\left\| \lambda'^2_{111} \right\|}{\Lambda^5_{\rm SUSY}}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\| \sin 2\theta^b \, \lambda'_{131} \, \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}} \right) \right\|$ $\sim \frac{G_F}{q} m_b \frac{\left\| \lambda'_{131} \, \lambda'_{113} \right\|}{\Lambda^3_{\rm SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\left\| \langle g_\chi \rangle \right\|$ or $\left\| \langle g_\chi \rangle \right\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

Distinguishing Mechanisms

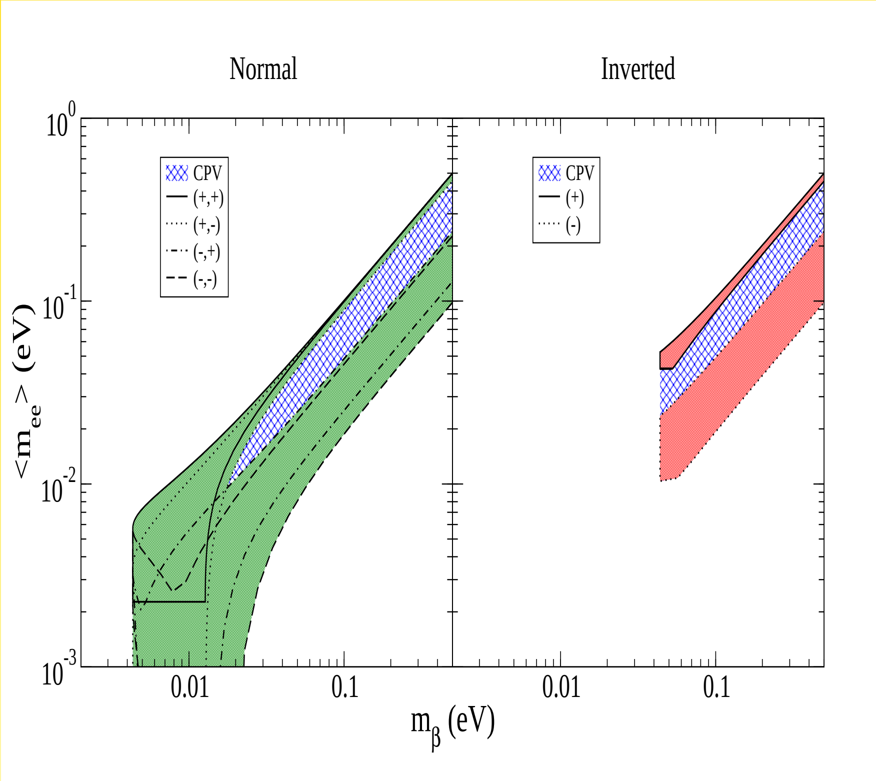
The inverse problem of $\mathbf{0}\nu\beta\beta$

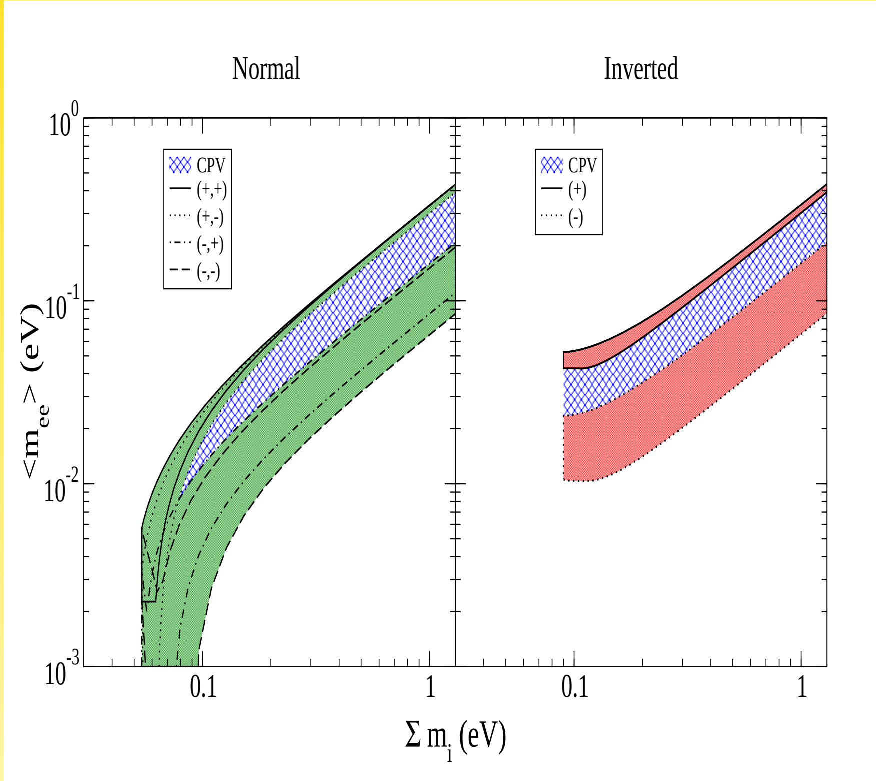
1.) Other observables (LHC, LFV, KATRIN, cosmology,...)

2.) Decay products (individual e^- energies, angular correlations, spectrum,...)

3.) Nuclear physics (multi-isotope, 0νECEC, $0\nu\beta^+\beta^+$,...)

1.) Distinguishing via other Observables





standard mechanism: KATRIN, cosmology

Energy Scale:

Note: *standard amplitude* for light Majorana neutrino exchange:

$$\mathcal{A}_{\rm l} \simeq G_F^2 \, \frac{|m_{ee}|}{q^2} \simeq 7 \times 10^{-18} \left(\frac{|m_{ee}|}{0.5 \text{ eV}}\right) \text{GeV}^{-5} \simeq 2.7 \text{ TeV}^{-5}$$

if new heavy particles are exchanged:

$$\mathcal{A}_{\rm h} \simeq \frac{c}{M^5}$$

$\Rightarrow$ for $0\nu\beta\beta$ holds:

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

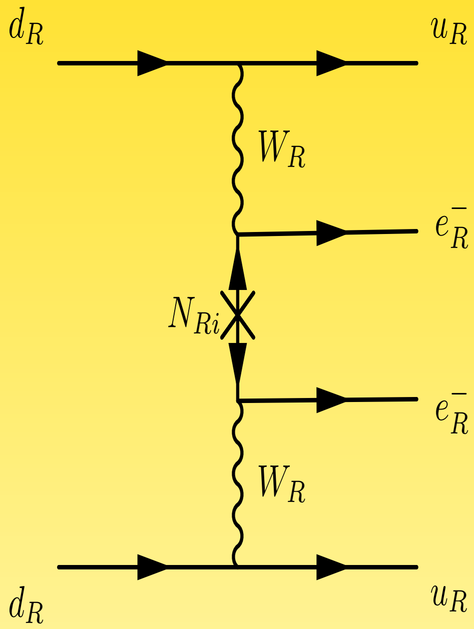
$\Rightarrow$ Phenomenology in colliders, LFV

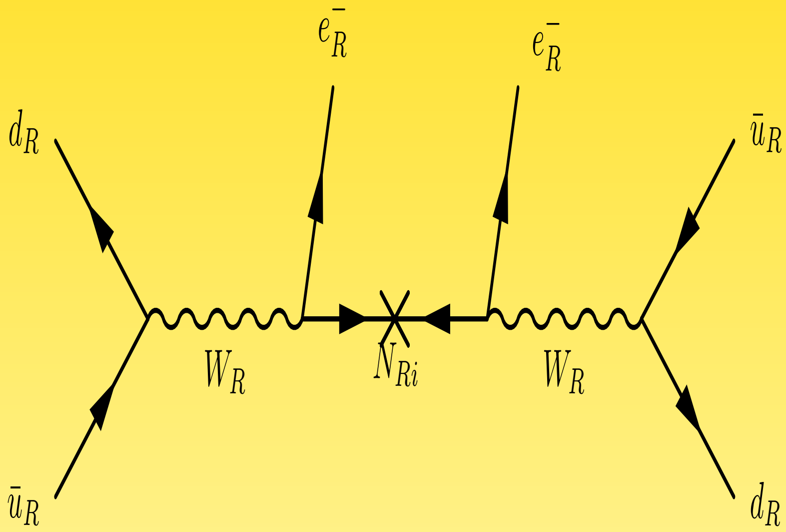
Examples

- R-parity violating supersymmetry (`Allanach, Paes, Kom`)
- TeV seesaw neutrinos (`Ibarra, Petcov` *et al.*; `Mitra, Senjanovic, Vissani`)
- Left-right symmetric theories (`Senjanovic` *et al.*; `Goswami` *et al.*)
- Color seesaw (`Choubey, Duerr, Mitra, W.R.`)

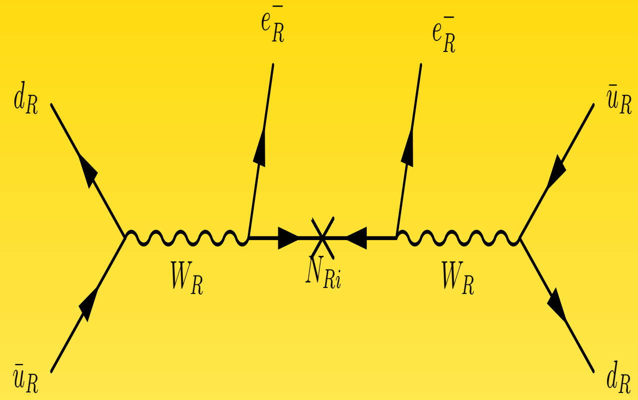
...focus only on one example here...

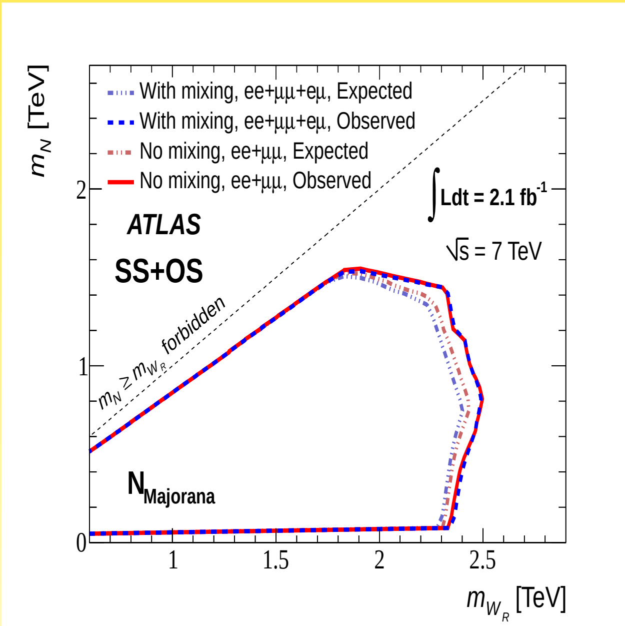
Left-right symmetry

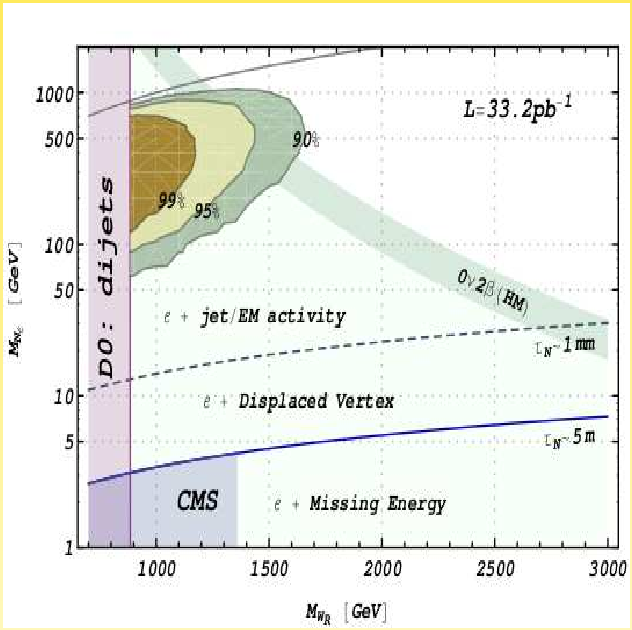




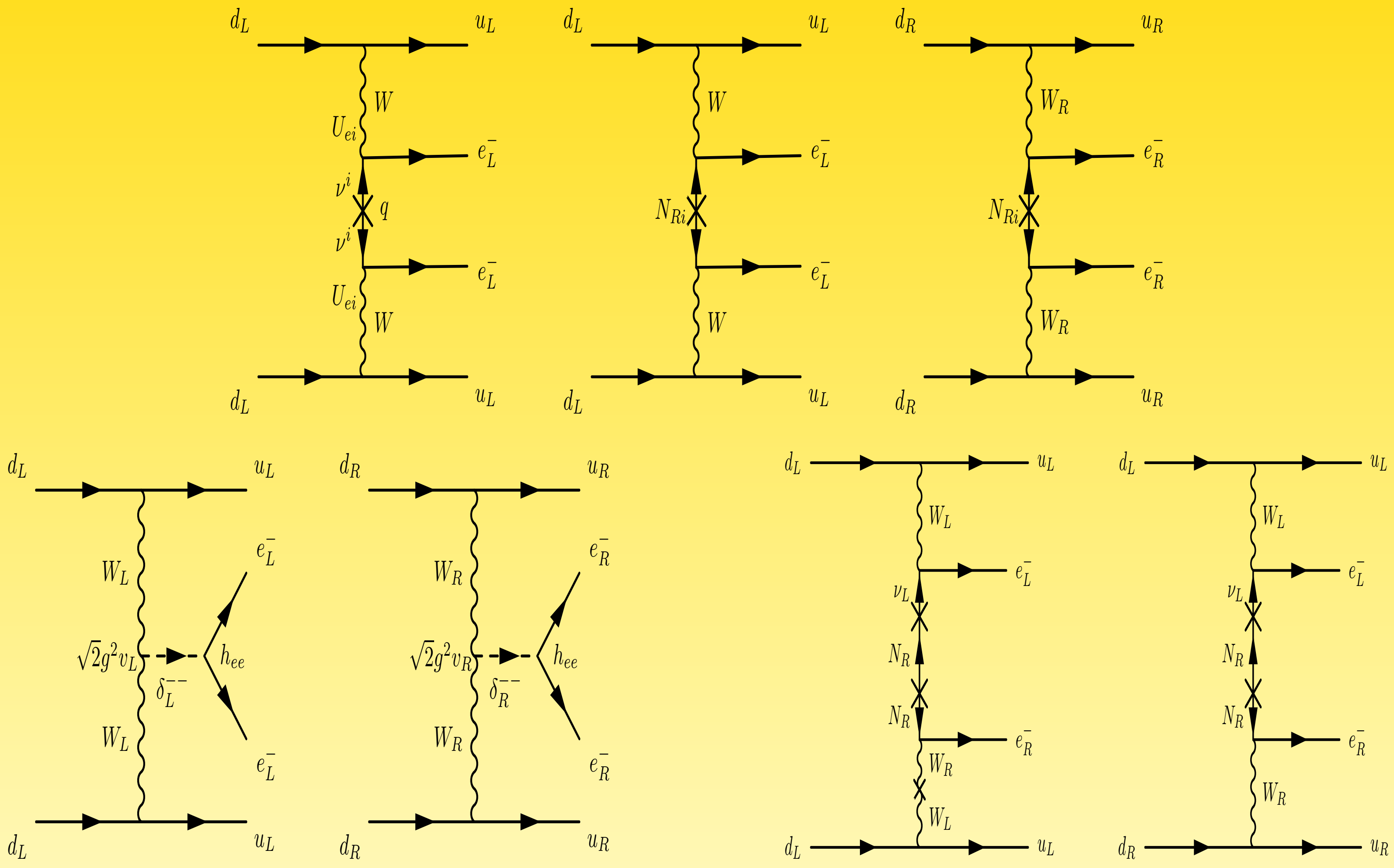
Senjanovic *et al.*, 1011.3522; 1103.1627


d_R
e_R^-
e_R^-
$\bar{u}_R$
W_R
N_{Ri}
W_R
$\bar{u}_R$
d_R

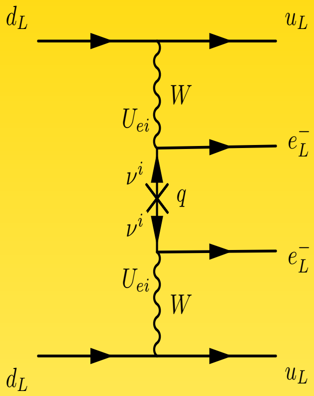

With mixing, ee+μμ+eμ, Expected
With mixing, ee+μμ+eμ, Observed
No mixing, ee+μμ, Expected
No mixing, ee+μμ, Observed
$\int L dt = 2.1\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7$ TeV
ATLAS
SS+OS
$m_N \geq m_{W_R}$ forbidden
$N_{Majorana}$
m_N [TeV]
m_{W_R} [TeV]

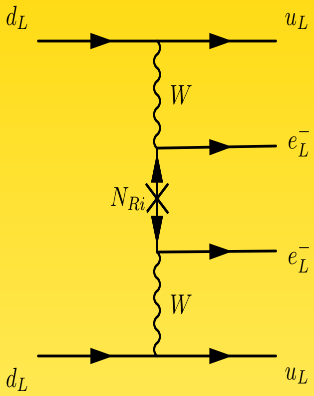

$L=33.2\mathrm{pb}^{-1}$
90%
99%
95%
D0: dijets
$0\nu2\beta$ (HM)
e + jet/EM activity
τ_N~1 mm
e + Displaced Vertex
τ_N~5 m
CMS
e + Missing Energy
M_{W_R} [GeV]
[GeV]

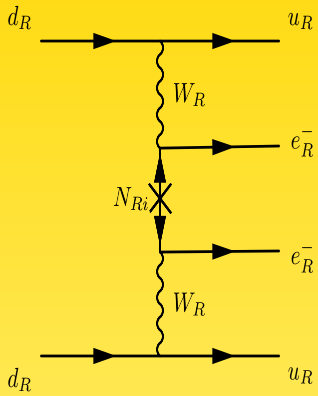
Left-right symmetry



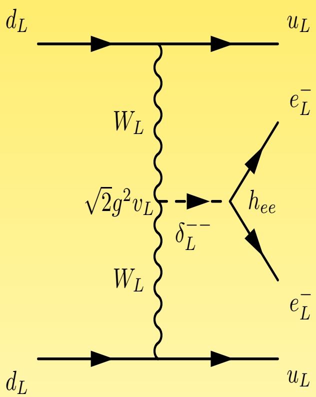
Left-right symmetry

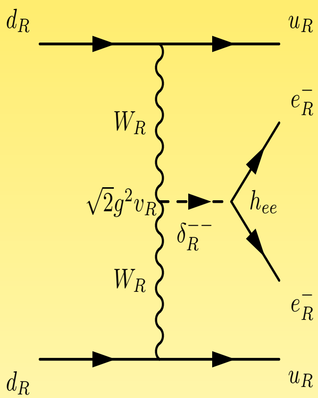


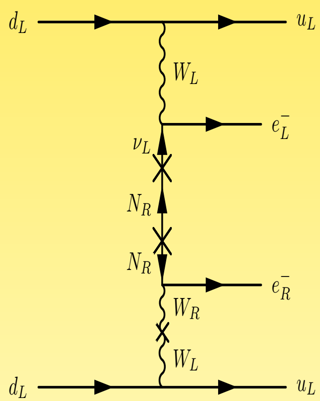


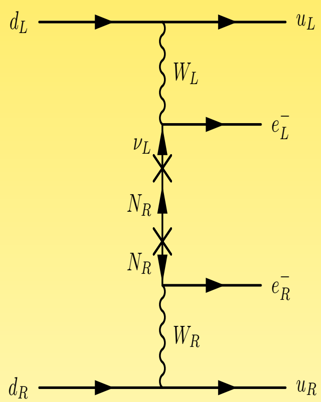


$$U_{ei}^2\, m_i \qquad \frac{S_{ei}^2}{M_i} \qquad \frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



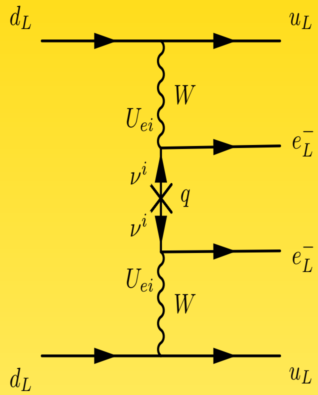




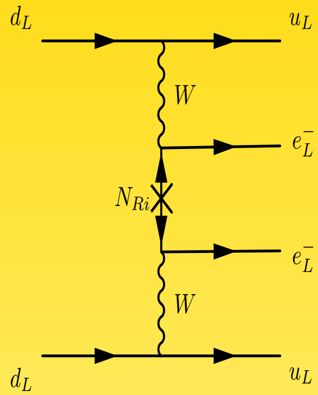


$$\le \frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2} \qquad \frac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2} \qquad U_{ei}\, T_{ei} \tan\zeta \qquad \frac{U_{ei}\, T_{ei}}{M_{W_R}^2}$$

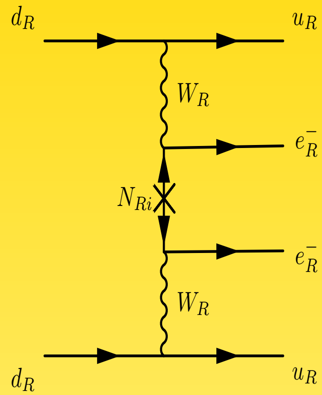
Left-right symmetry



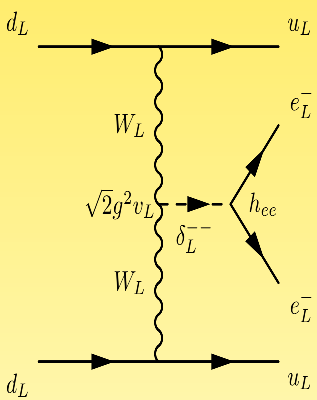
0.4 eV



2×10^{-8} GeV^{-1}



4×10^{-16} GeV^{-5}



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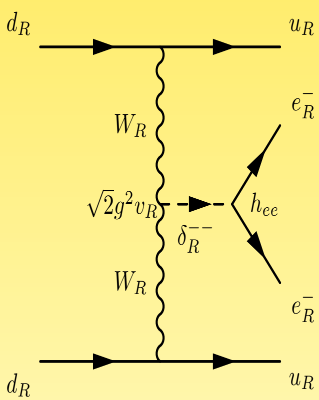
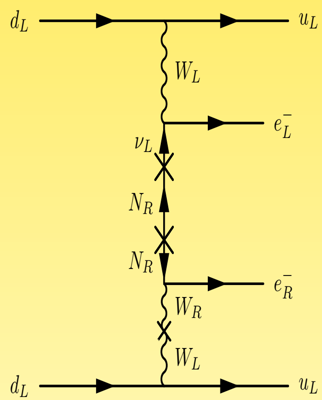
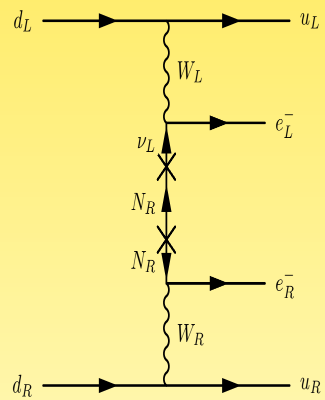


10^{-15} GeV^{-5}



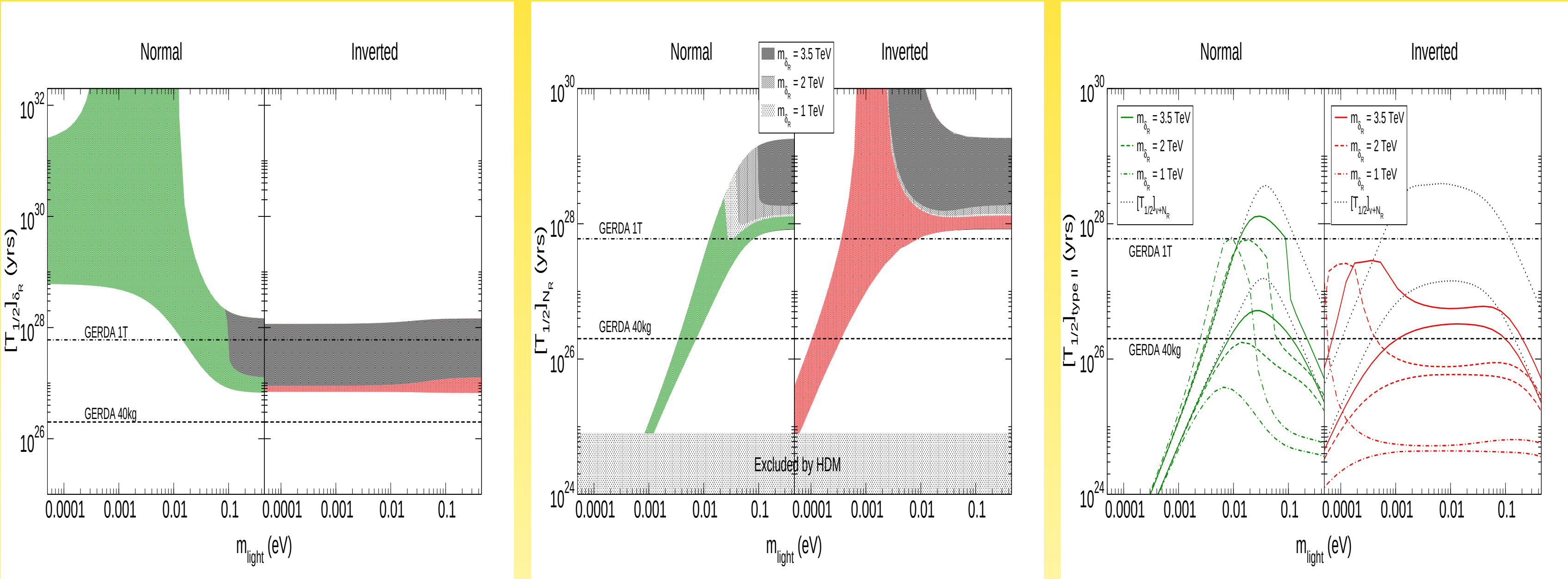
6×10^{-9}



1.4×10^{-10} GeV^{-2}

Interplay of diagrams in left-right symmetry

Interference of diagrams, constraints from LFV, neutrino data,. . .

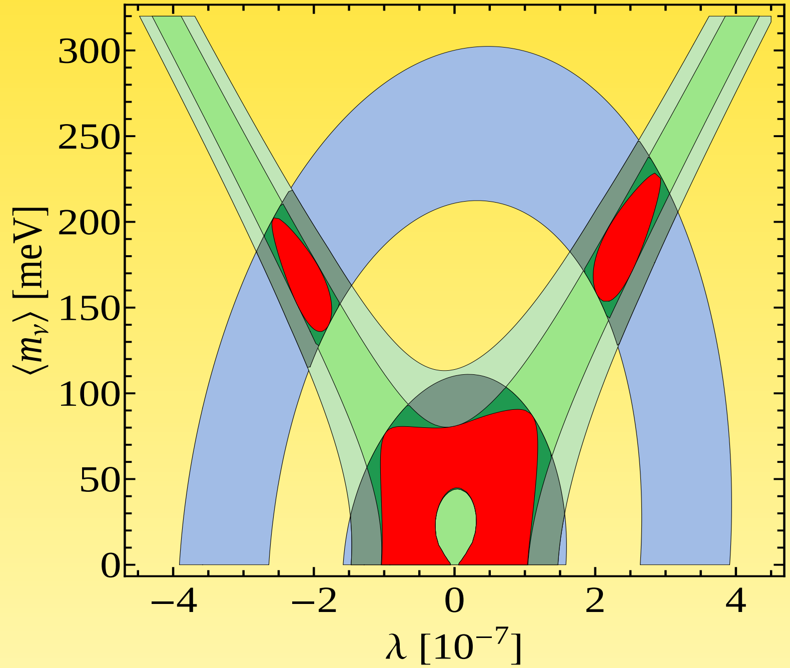


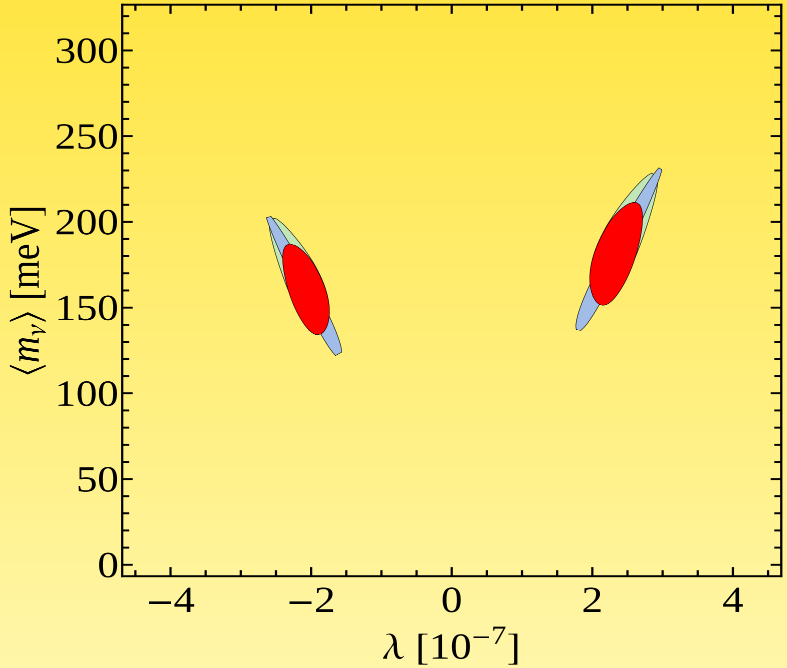
Barry, W.R., to appear; see also Goswami *et al.*, 1204.2527

2.) Distinguishing via decay products

Defining asymmetries

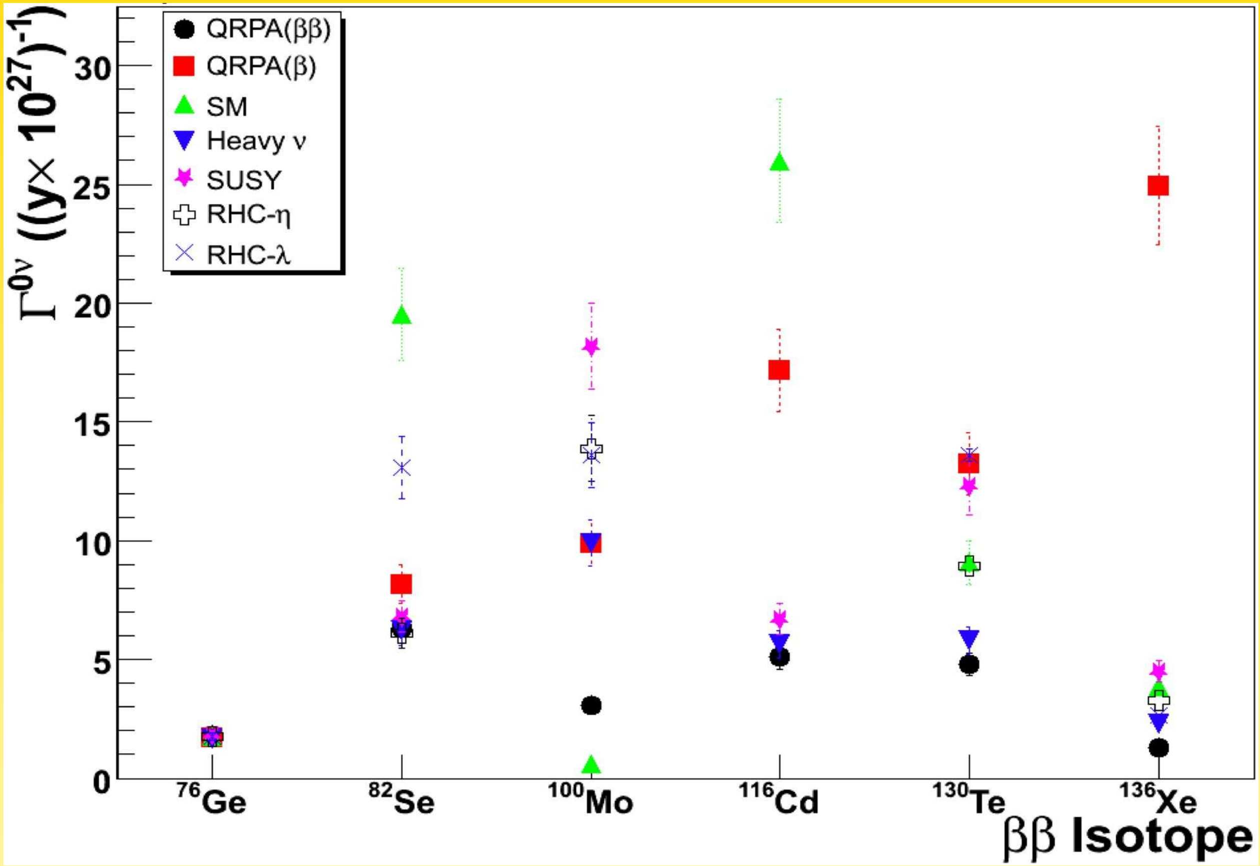
$A_\theta = (N_+ - N_-)/(N_+ + N_-)$ and $A_E = (N_> - N_<)/(N_> + N_<)$





SuperNEMO: Arnold *et al.*, 1005.1241

3.) Distinguishing via nuclear physics

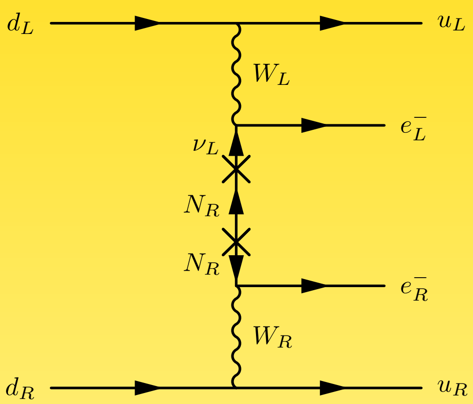


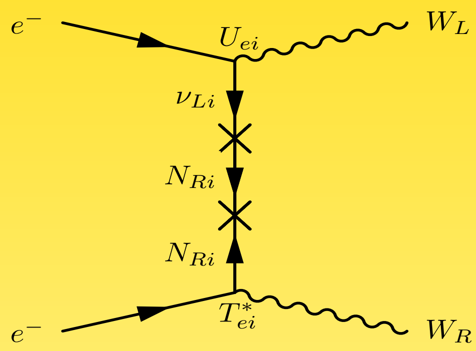
Gehman, Elliott, hep-ph/0701099

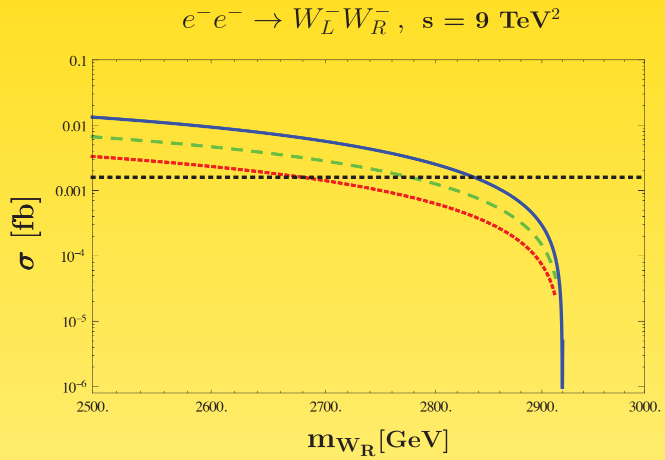
3 to 4 isotopes necessary to disentangle mechanism

Cleanest Probe: $e^- e^-$ collisions: "inverse $0\nu\beta\beta$"

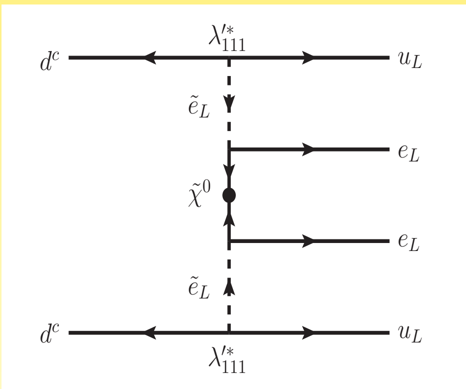
- LR-symmetry: (Barry, Dorame, W.R., 1204.3365)

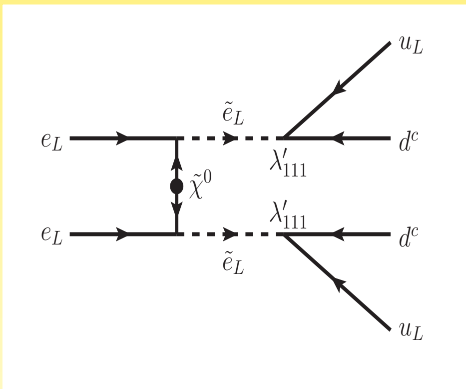


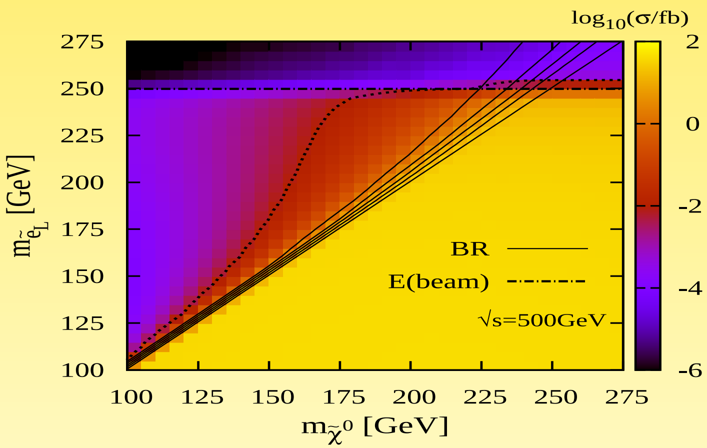




- SUSY: (Kom, W.R., 1110.3220)







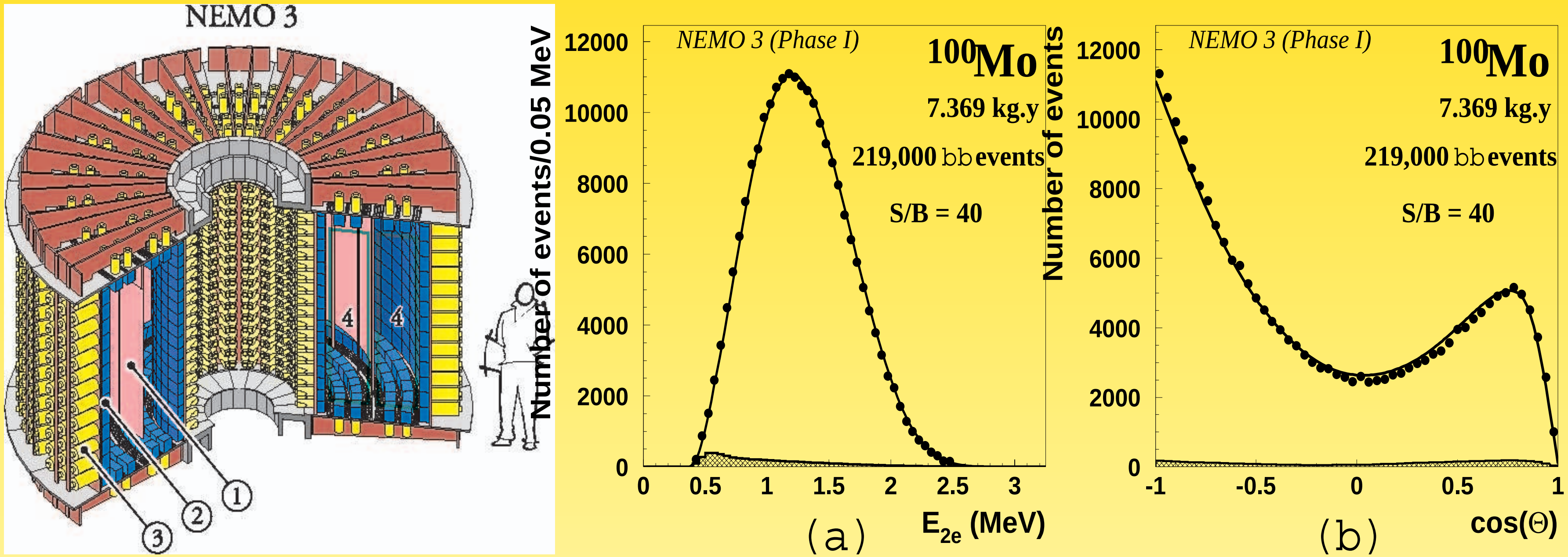
Summary

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.

2.) Distinguishing via decay products

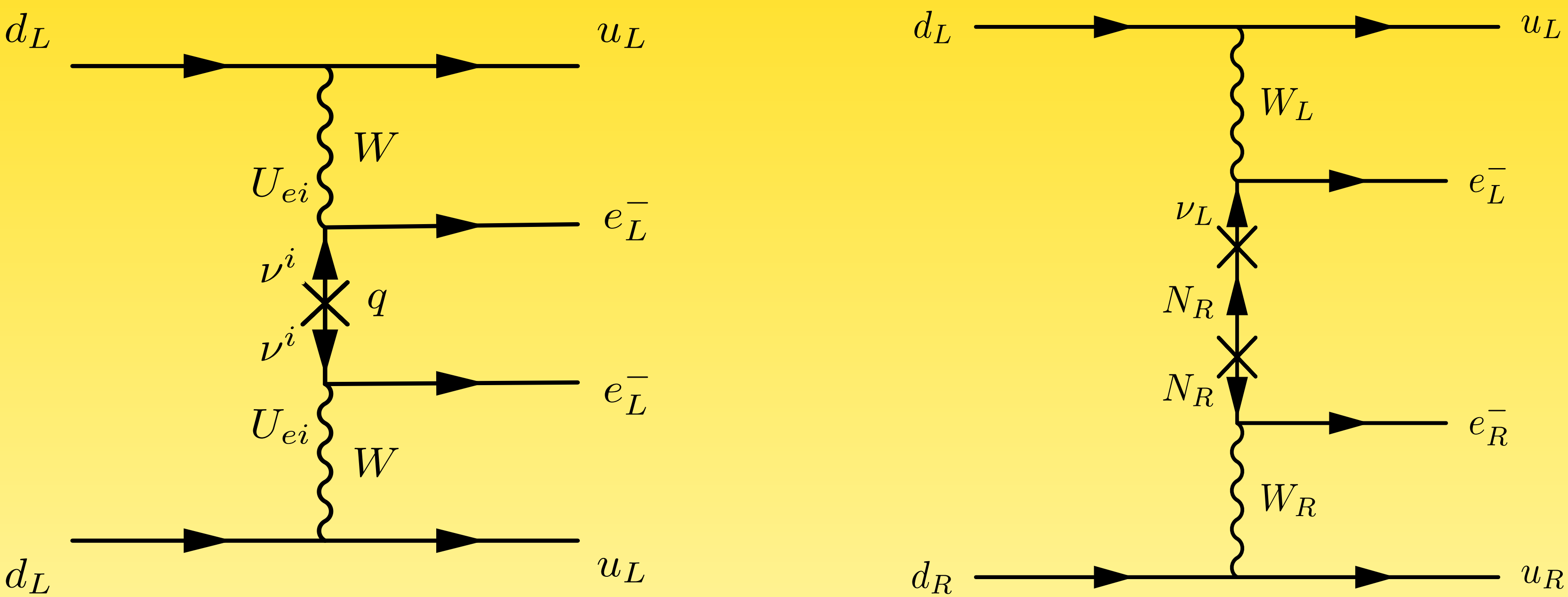
SuperNEMO



- source foils in between plastic scintillators
- individual electron energy, and their relative angle!

2.) Distinguishing via decay products

Consider standard plus λ-mechanism



$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta) \qquad \frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$$

Arnold *et al.*, 1005.1241

EXO-200 vs. Klapdor

$$T_{\mathrm{Ge}}^{-1} = G_{\mathrm{Ge}} \left|\mathcal{M}_{\mathrm{Ge}}\right|^2 \left|m_{ee}\right|^2 = \left(2 \times 10^{25}\,\mathrm{yrs}\right)^{-1}$$

$$T_{\mathrm{Xe}}^{-1} = G_{\mathrm{Xe}} \left|\mathcal{M}_{\mathrm{Xe}}\right|^2 \left|m_{ee}\right|^2 \leq \left(1.6 \times 10^{25}\,\mathrm{yrs}\right)^{-1}$$

Ge-claim is ruled out when

$$T_{\mathrm{Xe}} \geq 2.9 \times 10^{24} \left|\frac{\mathcal{M}_{\mathrm{Ge}}}{\mathcal{M}_{\mathrm{Xe}}}\right|^2 \mathrm{yrs}$$

With compilation from `Vogel, 1208.1992`:

$$\left|\frac{\mathcal{M}_{\mathrm{Ge}}}{\mathcal{M}_{\mathrm{Xe}}}\right|^2 \simeq \begin{cases} 4.0 & (\mathrm{RQRPA}) & \Rightarrow T_{\mathrm{Xe}} \geq 1.2 \times 10^{25}\,\mathrm{yrs} \\ 4.2 & (\mathrm{NSM}) & \Rightarrow T_{\mathrm{Xe}} \geq 1.2 \times 10^{25}\,\mathrm{yrs} \\ 2.5 & (\text{IBM-2}) & \Rightarrow T_{\mathrm{Xe}} \geq 7.3 \times 10^{24}\,\mathrm{yrs} \\ 1.2 & (\mathrm{EDF}) & \Rightarrow T_{\mathrm{Xe}} \geq 3.5 \times 10^{24}\,\mathrm{yrs} \end{cases}$$

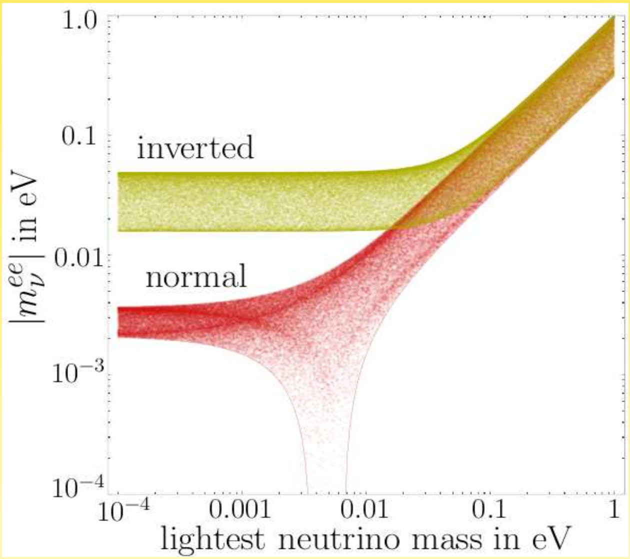
Simple and interesting scenario

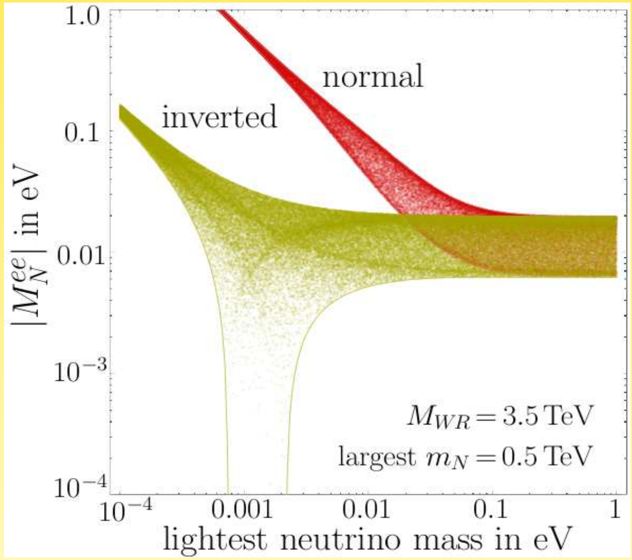
$$m_\nu = M_L - m_D\, M_R^{-1}\, m_D^T = v_L\, h - m_D\, (v_R\, f)^{-1}\, m_D^T$$

suppose M_L dominates in m_ν and $h = f$: $\Rightarrow M_R \propto m_\nu$

Triplet can mediate $\mu \to 3e$ at tree-level: $m_\Delta \gg M_i$

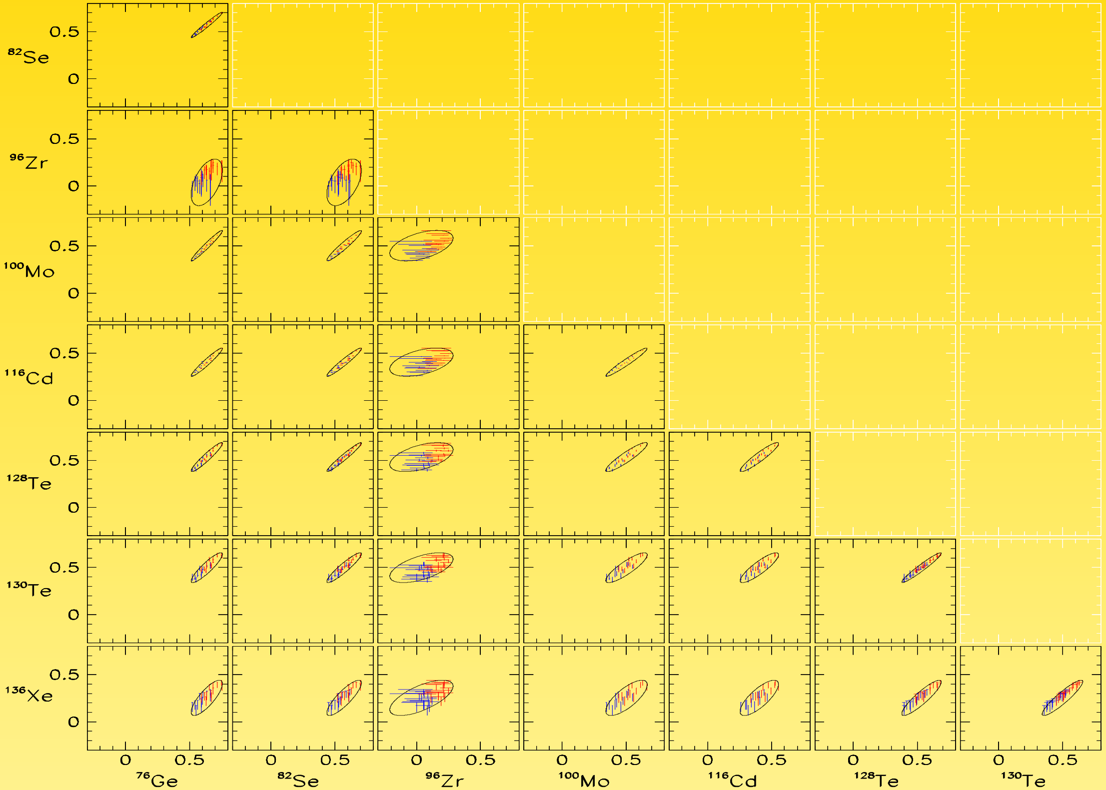
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$





Tello *et al.*, 1011.3522

to better estimate error range: correlations need to be understood:



`Faessler, Fogli` *et al.*`, PRD` **79**

ellipse major axis: SRC (blue, red) and g_A

ellipse minor axis: g_{pp}

Flavor Symmetry Models

suppose your model predicts TBM:

$$(m_\nu)_{\rm TBM} = \begin{pmatrix} x & y & y \\ \cdot & z+x & y-z \\ \cdot & \cdot & z+x \end{pmatrix}$$

$$m_1 = x - y \ , \ \ m_2 = x + 2y \ , \ \ m_3 = x - y + 2z$$

if $z = y + x/2$, then:

$$m_1 = x - y \ , \ \ m_2 = x + 2y \ , \ \ m_3 = 2x + y$$

and one has a neutrino mass sum-rule

$$m_1 + m_2 = m_3$$

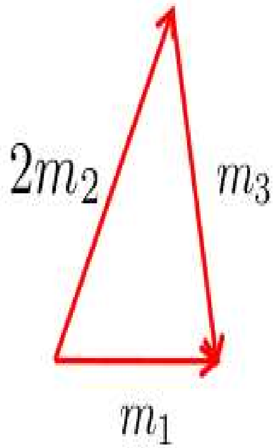
The Zoo (of A_4 models)

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
A1				-	[1–14] [15]$^{\#}$
A2	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[16–18]
A3				$\underline{1}, \underline{3}$	[19]
B1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[4, 20–27]$^{\#}$ [28–30]* [31–45]
B2				$\underline{1}, \underline{3}$	[46]$^{\#}$
C1				-	[2, 47, 48]
C2	$\underline{3}$	$\underline{3}$	-	$\underline{1}$	[49, 50] [51]$^{\#}$
C3				$\underline{1}, \underline{3}$	[52]
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[53]
D1				-	[54, 55]$^{\#}$ [56, 57]* [58]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[59] [60]*
D3				$\underline{1}'$	[61]*
D4				$\underline{1}', \underline{3}$	[62]*
E	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[63, 64]
F	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$	[65]
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	-	[66]
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	-	-	[67]
I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[68]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 69, 70]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	$\underline{1}$	[71]*
L	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}$	-	[72]*
M	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[73, 74]
N	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}', \underline{1}''$	-	[75]

Barry, W.R., PRD **81**, updated regularly on

http://www.mpi-hd.mpg.de/personalhomes/jamesb/Table_A4.pdf

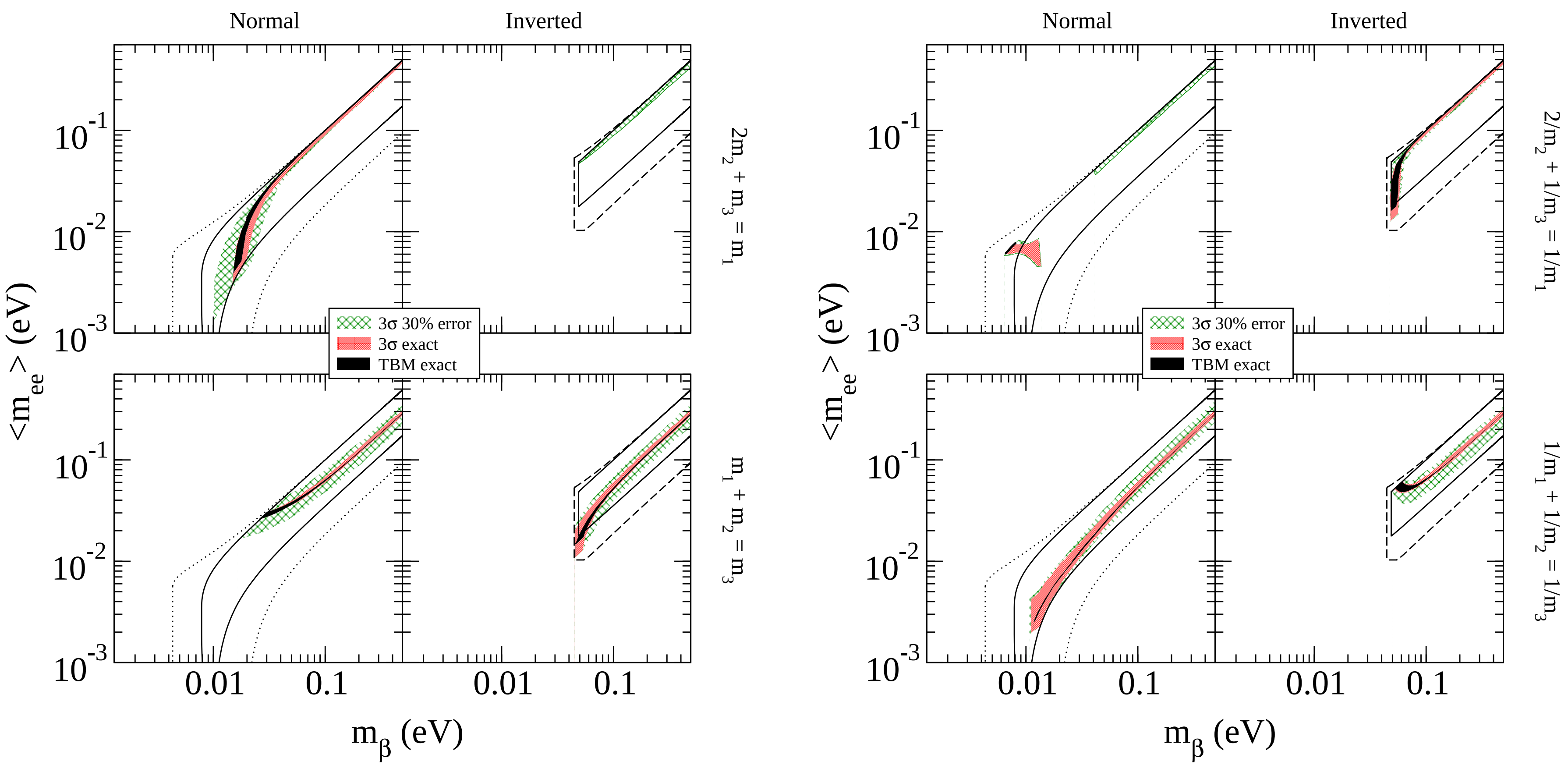
Sum-rules in Models and $0\nu\beta\beta$



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**



$$m_1 + m_2 - m_3 = \epsilon\, m_{\rm max}$$

stable: new solutions not before $\epsilon \simeq 0.2$