Neutrinoless Double Beta Decay and Particle Physics

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WHEPP12
12/01/12

Outline

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

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

review on $0\nu\beta\beta$ and particle physics:

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

Why should we probe Lepton Number Violation (LNV)?

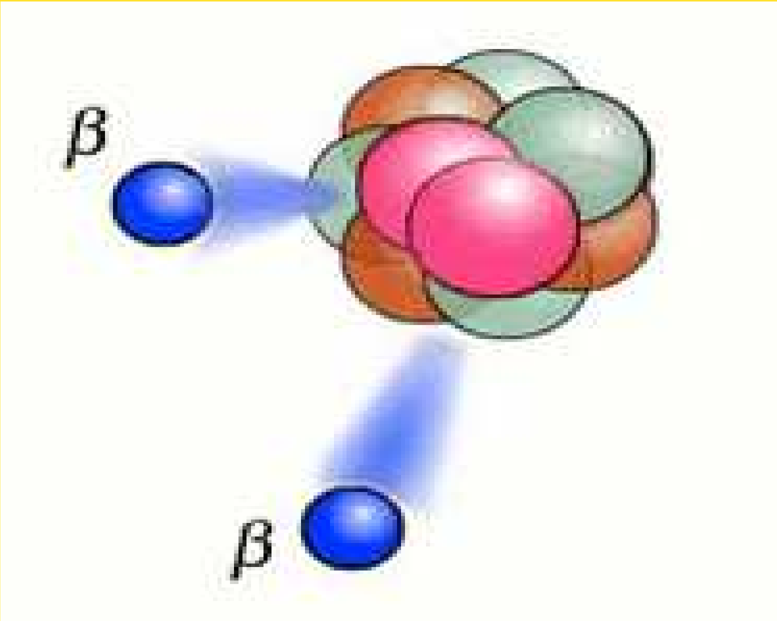
- L and B *accidentally* conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\,\mathcal{L}_{\rm LNV} + \frac{1}{\Lambda^2}\,\mathcal{L}_{\rm LFV,\,BNV,\,LNV} + \ldots$
- baryogenesis: B is violated
- B, L often connected in GUTs
- GUTs have seesaw and Majorana neutrinos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

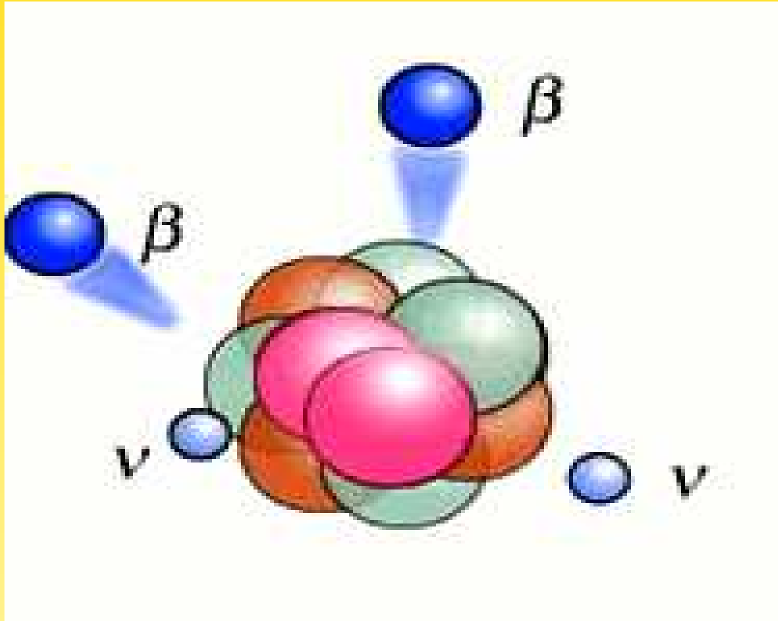
$\Rightarrow$ Lepton Number Violation as important as Baryon Number Violation

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

What is Neutrinoless Double Beta Decay?

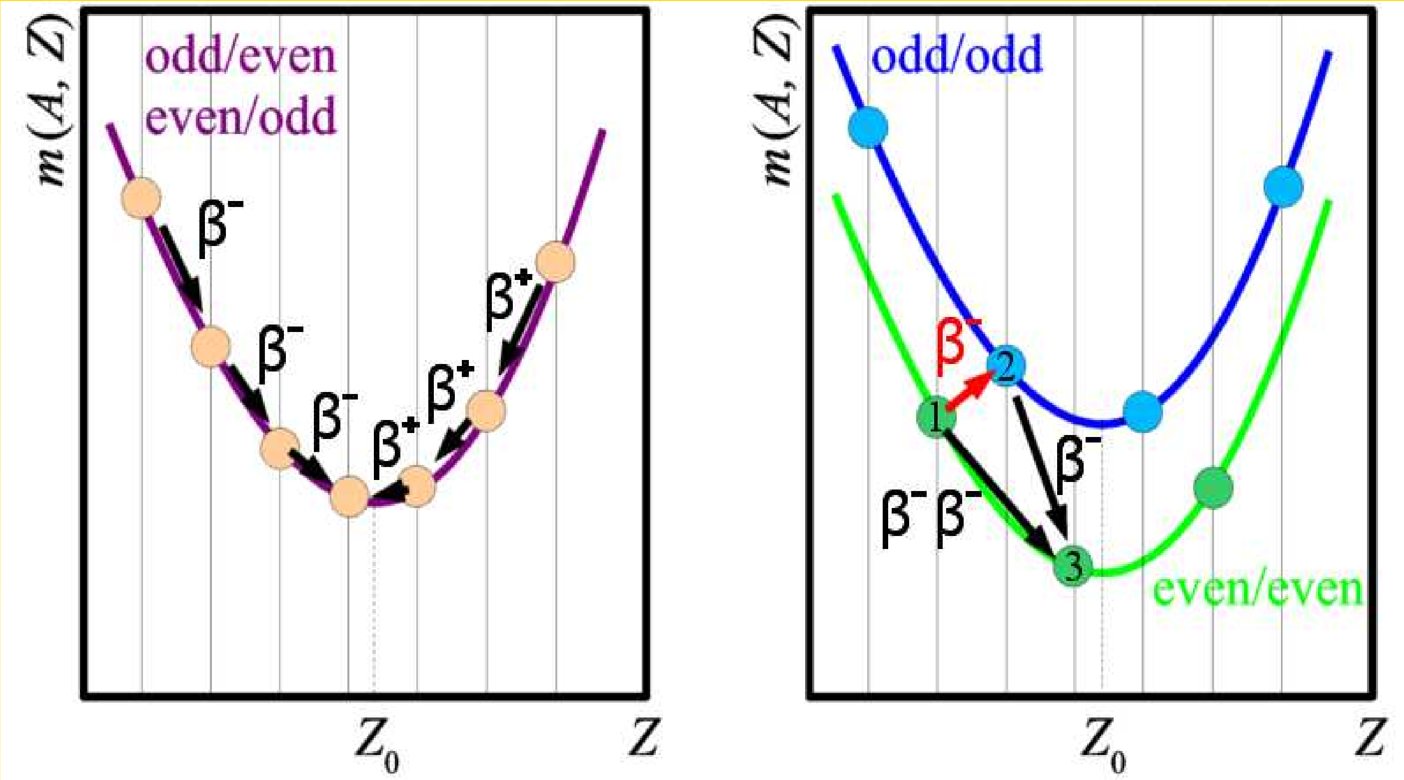
$$(A, Z) \rightarrow (A, Z + 2) + 2\, e^- \quad (0\nu\beta\beta)$$





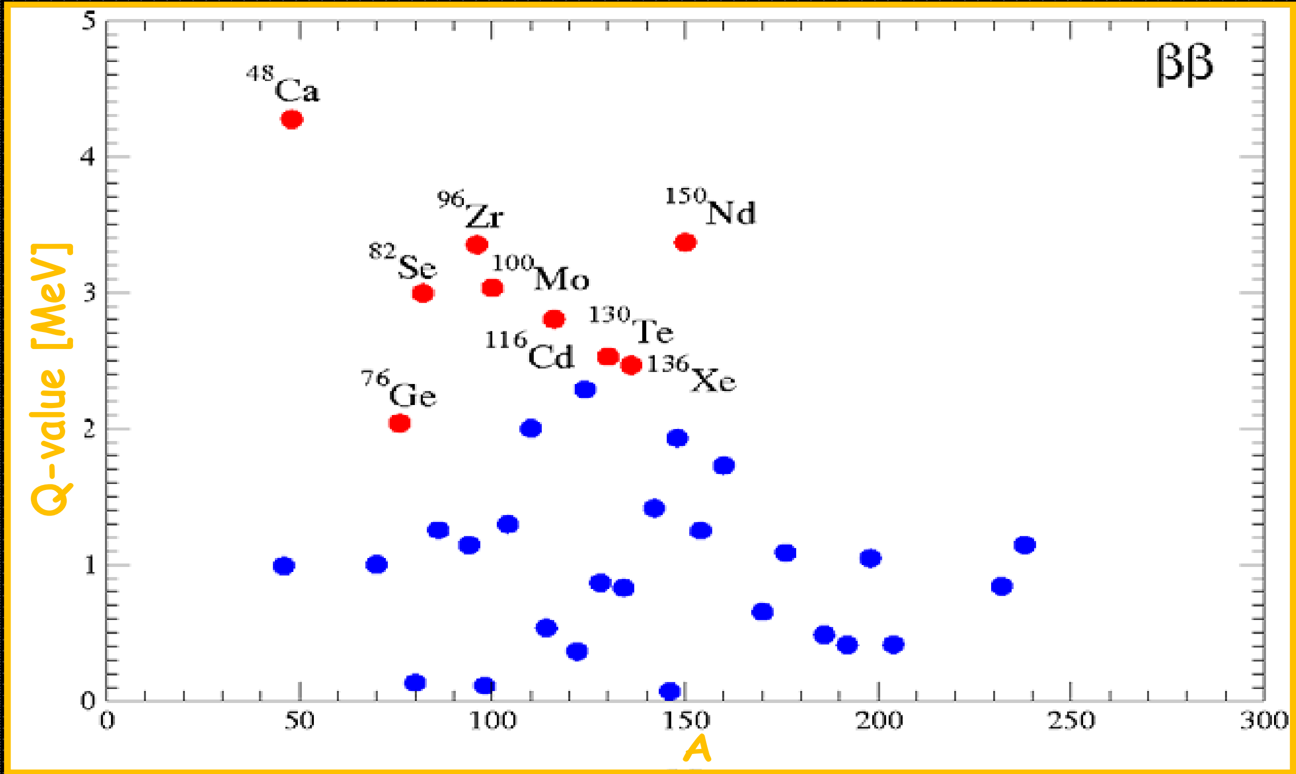
- second order in weak interaction: $\Gamma \propto G_F^4 \Rightarrow$ rare!
- not to be confused with $(A, Z) \rightarrow (A, Z + 2) + 2\, e^- + 2\, \bar{\nu}_e \quad (2\nu\beta\beta)$ (which occurs more often but is still rare)

Need to forbid single β decay:



- $E_{\text{Bindung}} = E_{\text{Volumen}} - E_{\text{Oberfläche}} - E_{\text{Coulomb}} - E_{\text{Symmetrie}} \pm E_{\text{Paarbildung}}$
- $\Rightarrow$ even/even $\rightarrow$ even/even
- either direct ($0\nu\beta\beta$) or two simultaneous decays with virtual (energetically forbidden) intermediate state ($2\nu\beta\beta$)

How many nuclei in this condition?



Slide by A. Giuliani

Upcoming experiments: exciting time!!

current best limit is from 2001...

Name	Isotope	source = detector; calorimetric with			source ≠ detector
		high energy res.	low energy res.	event topology	event topology
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

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Status	Start of data-taking
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011
		40	2×10^{26}	in progress	$\sim$ 2012
		1000	6×10^{27}	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	$\sim$ 2013
			$2.1 \times 10^{26**}$		
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013
		1000	6×10^{27}	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	in progress	$\sim$ 2011
		1000	8×10^{26}	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-15
KamLAND-Zen	^{136}Xe	400	4×10^{26}	in progress	$\sim$ 2011
		1000	10^{27}	R&D	$\sim$ 2013-15
SNO+	^{150}Nd	56	4.5×10^{24}	in progress	$\sim$ 2012
		500	3×10^{25}	R&D	$\sim$ 2015

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

3 Reasons for Multi-isotope determination

1.) credibility

2.) test NME calculation

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

systematic errors drop out, ratio sensitive to NME model

3.) test mechanism

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

particle physics drops out, ratio of NMEs sensitive to mechanism

Experimental Aspects

particle theory:

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

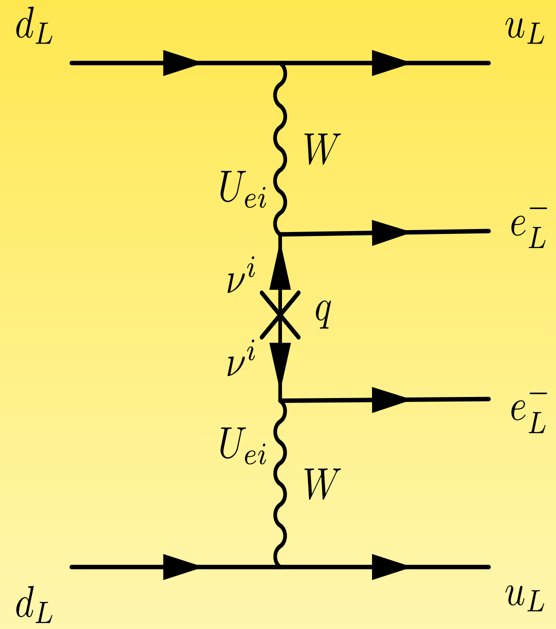
experimentally:

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

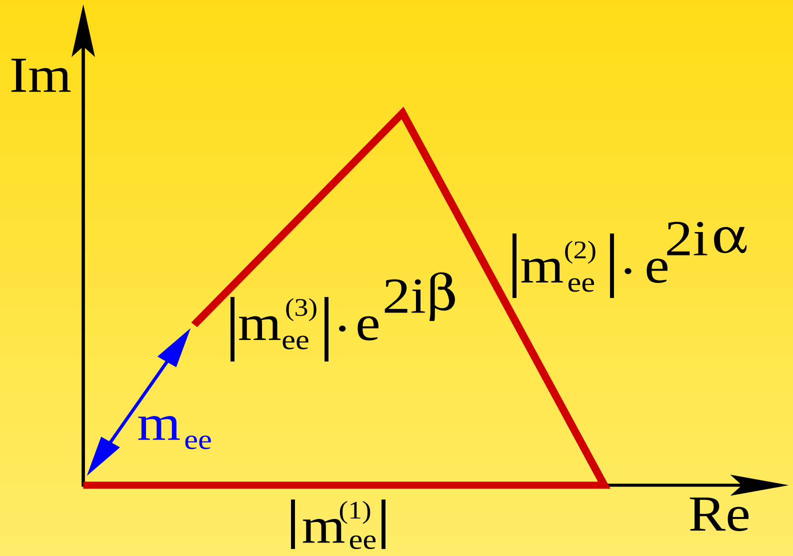
Note: factor 2 in particle physics is combined factor of 16 in $M \times t \times B \times \Delta E$

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

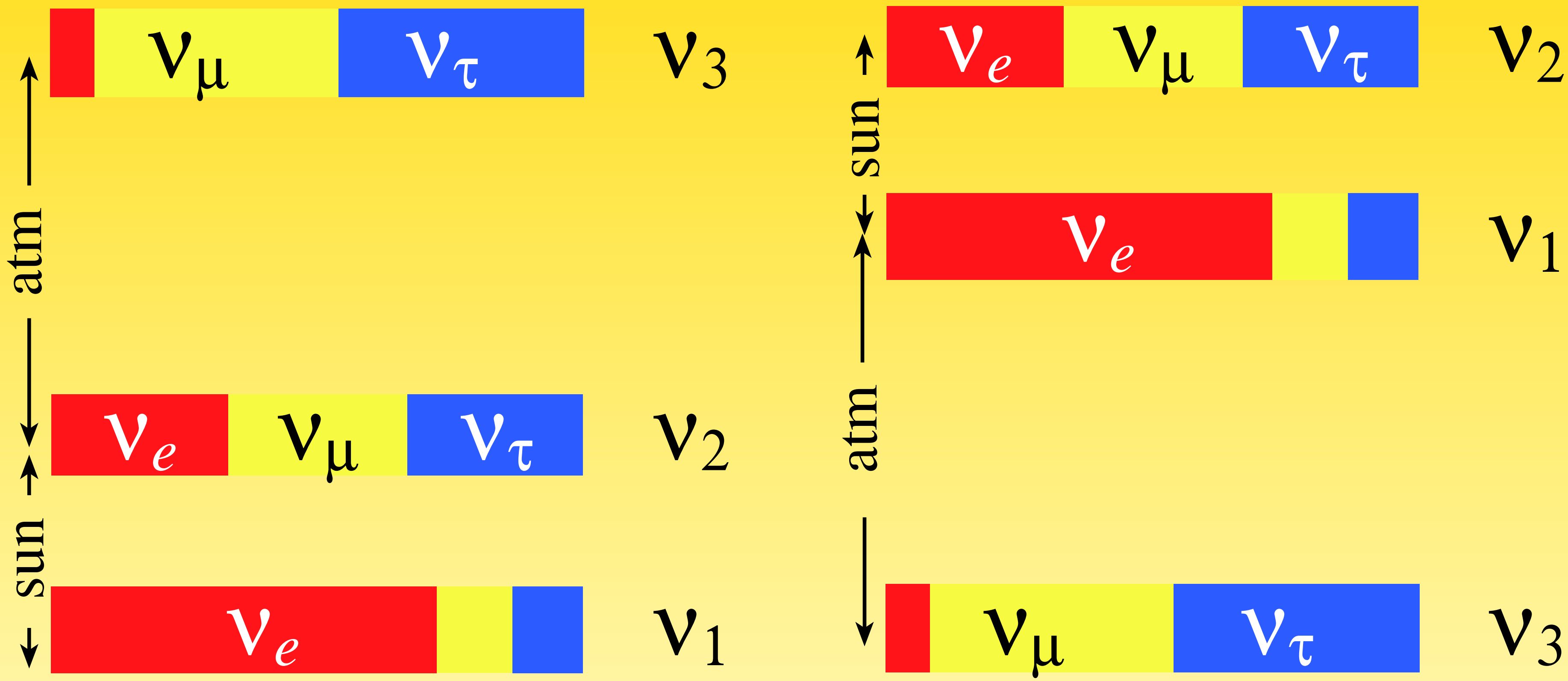


Amplitude proportional to coherent sum ("effective mass"):

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

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

7 out of 9 parameters of m_ν!



ν_μ
ν_τ
ν_3
atm
ν_e
ν_μ
ν_τ
ν_2
sun
ν_e
ν_1
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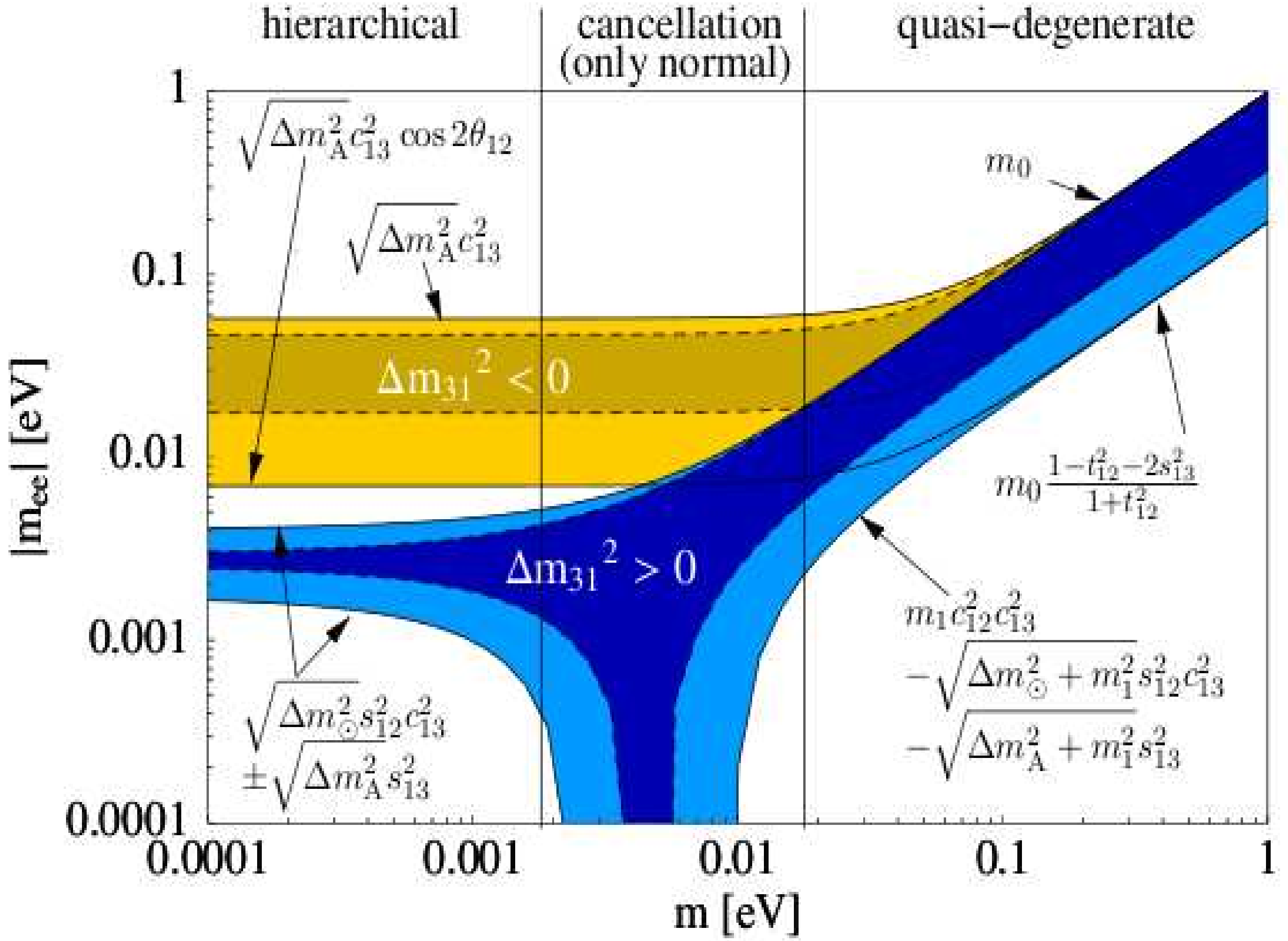
ν_τ
ν_2
sun
ν_e
ν_1
atm
ν_μ
ν_τ
ν_3

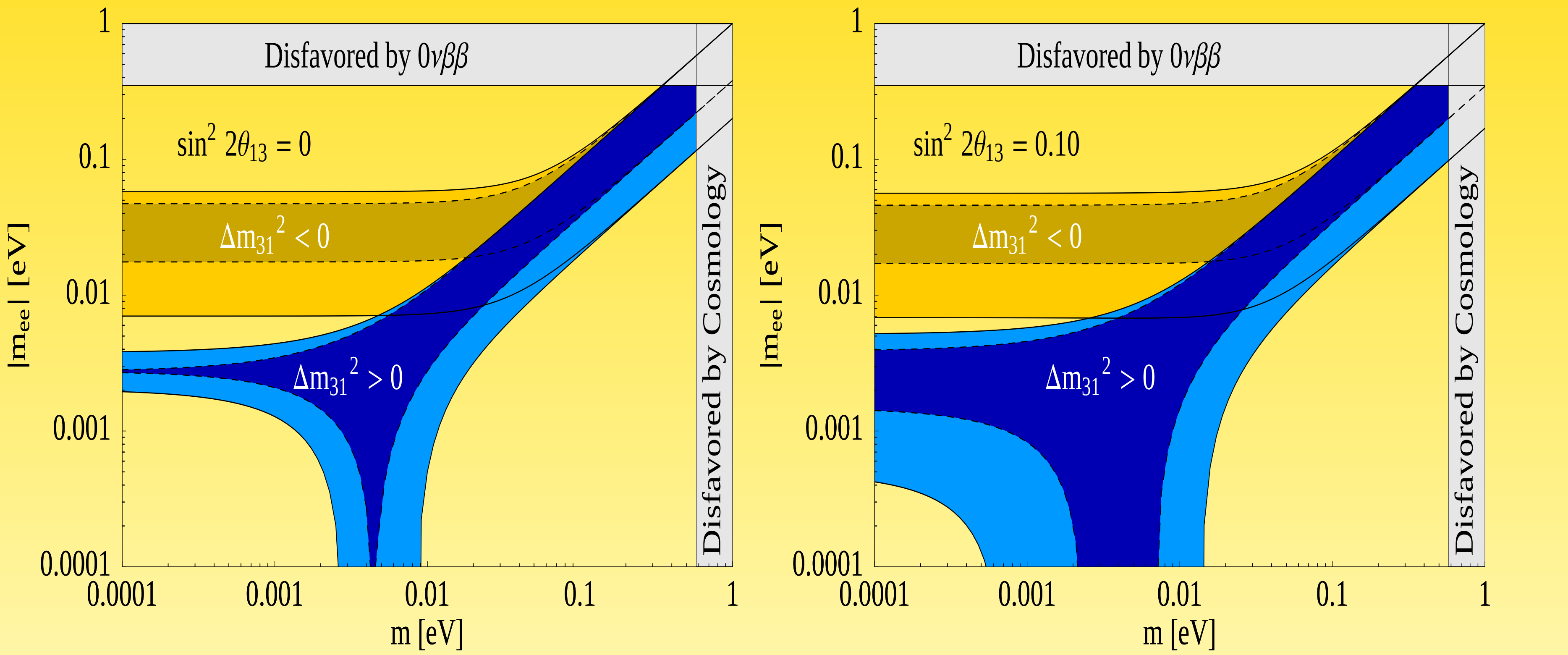
The usual plot



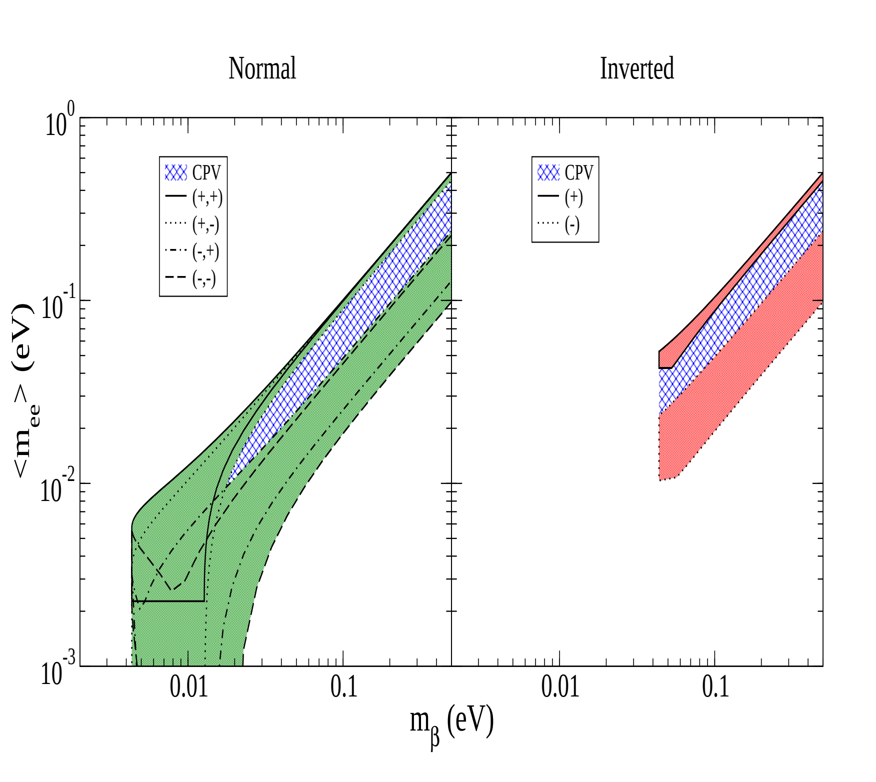
Crucial points

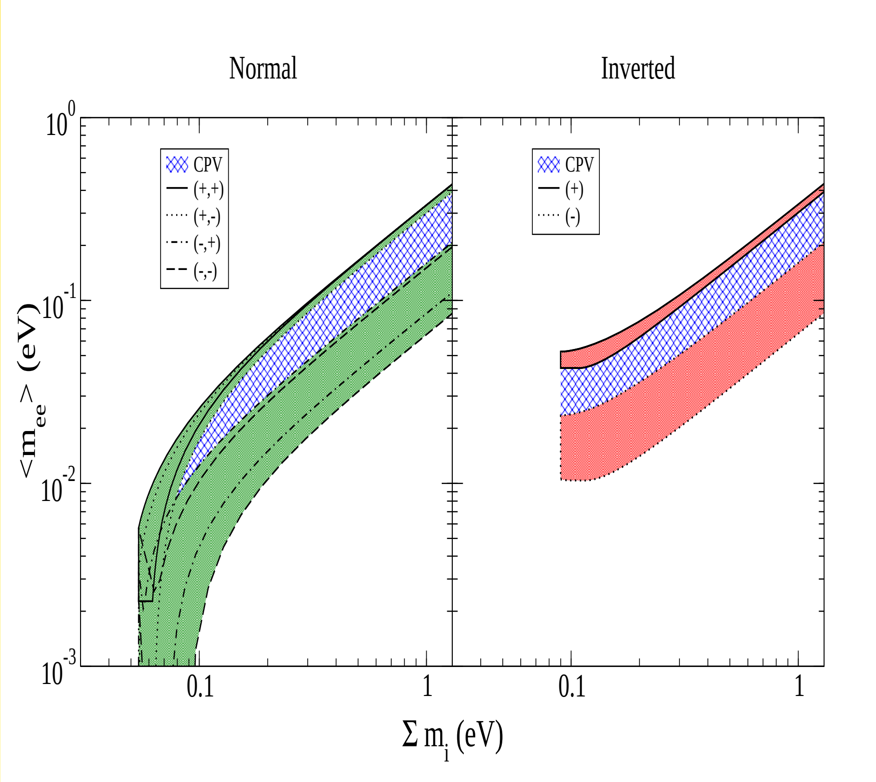
- NH: can be zero!
- IH: cannot be zero! $|m_{ee}|_{\rm min}^{\rm inh} = \sqrt{\Delta m_{\rm A}^2}\, c_{13}^2 \, \cos 2\theta_{12}$
- gap between $|m_{ee}|_{\rm min}^{\rm inh}$ and $|m_{ee}|_{\rm max}^{\rm nor}$
- QD: cannot be zero! $|m_{ee}|_{\rm min}^{\rm QD} = m_0 \, c_{13}^2 \, \cos 2\theta_{12}$
- QD: cannot distinguish between normal and inverted ordering

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



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 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	•	•	•	•	–	–

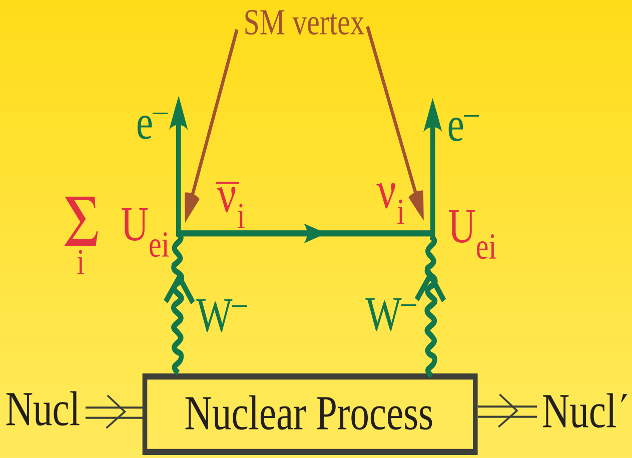
Which mass ordering with which life-time?

	Σ	m_β	$\lvert m_{ee}\rvert$
NH	$\sqrt{\Delta m_{\rm A}^2}$	$\sqrt{\Delta m_\odot^2 + \lvert U_{e3}\rvert^2 \Delta m_{\rm A}^2}$	$\left\lvert\sqrt{\Delta m_\odot^2} + \lvert U_{e3}\rvert^2 \sqrt{\Delta m_{\rm A}^2}\, e^{2i(\alpha-\beta)}\right\rvert$
	$\simeq 0.05$ eV	$\simeq 0.01$ eV	~ 0.003 eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{28-29}$ yrs
IH	$2\sqrt{\Delta m_{\rm A}^2}$	$\sqrt{\Delta m_{\rm A}^2}$	$\sqrt{\Delta m_{\rm A}^2}\sqrt{1-\sin^2 2\theta_{12}\sin^2\alpha}$
	$\simeq 0.1$ eV	$\simeq 0.05$ eV	~ 0.03 eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{26-27}$ yrs
QD	$3m_0$	m_0	$m_0\sqrt{1-\sin^2 2\theta_{12}\sin^2\alpha}$
			$\gtrsim 0.1$ eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{25-26}$ yrs

(for 10^{26} yrs you need 10^{26} atoms, which are 10^3 mols, which are 100 kg)

From life-time to particle physics: Nuclear Matrix Elements

From life-time to particle physics: Nuclear Matrix Elements



- 2 point-like Fermi vertices; "long-range" neutrino exchange; momentum exchange $q \simeq 1/r \simeq 0.1$ GeV
- NME $\leftrightarrow$ overlap of decaying nucleons...
- different approaches (QRPA, NSM, IBM, GCM, pHFB) imply uncertainty
- plus uncertainty due to model details
- plus convention issues (Cowell, PRC **73**; Smolnikov, Grabmayr, PRC **81**; Dueck, W.R., Zuber, PRD **83**)

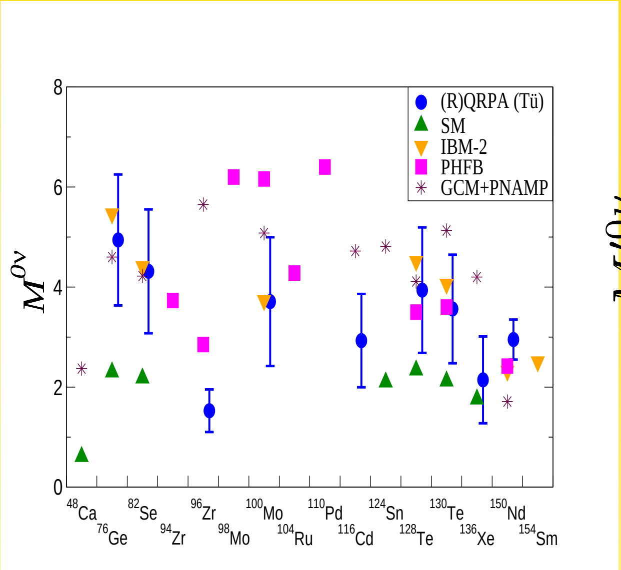
typical model for NME: set of single particle states with a number of possible wave function configurations; solve $\mathcal{H}$ in a mean background field

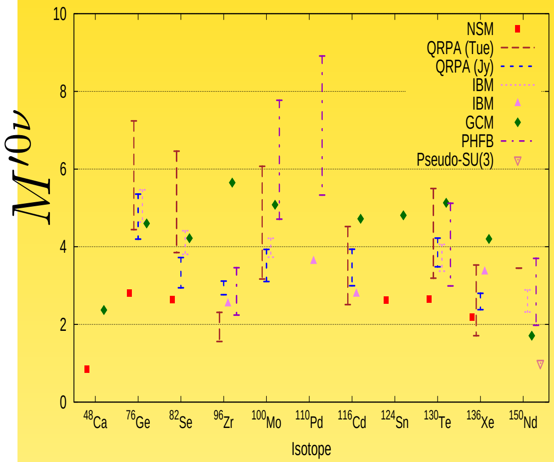
- Quasi-particle Random Phase Approximation (QRPA) **(many single particle states, few configurations)**
- Nuclear Shell Model (NSM) **(many configurations, few single particle states)**
- Interacting Boson Model (IBM) **(many single particle states, few configurations) (many single particle states, few configurations)**
- Generating Coordinate Method (GCM) **(many single particle states, few configurations)**
- projected Hartree-Fock-Bogoliubov model (pHFB)

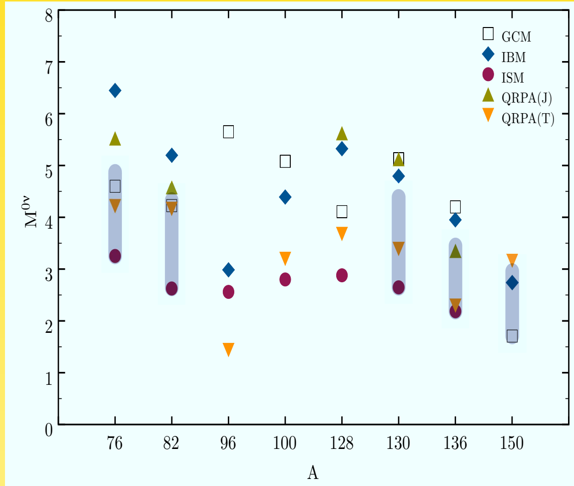
tends to overestimate NMEs

tends to underestimate NMEs

From life-time to particle physics: Nuclear Matrix Elements

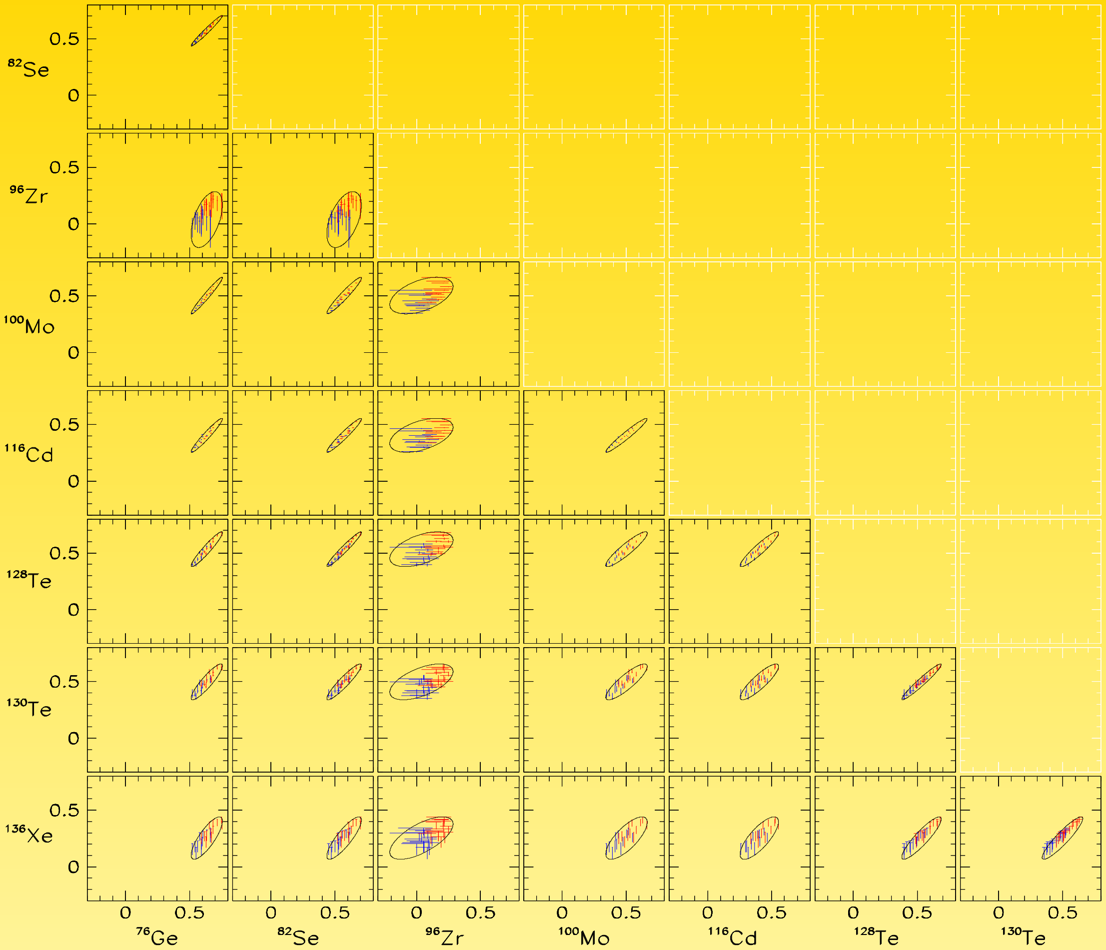






`Faessler, 1104.3700` `Dueck, W.R., Zuber, PRD` **83** `Gomez-Cadenas` *et al.*`, 1109.5515`

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}

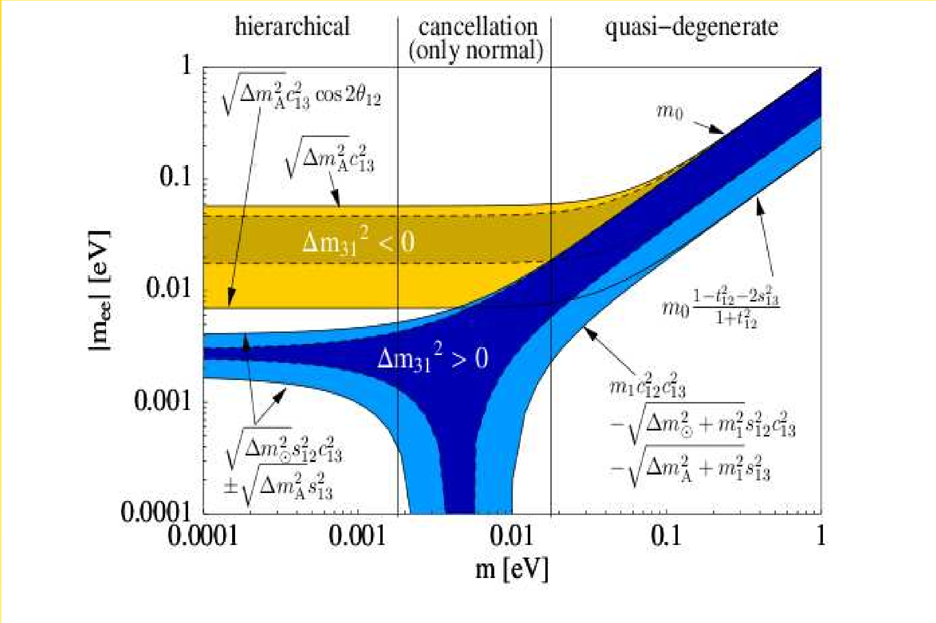
$0\nu\beta\beta$ and Neutrino physics

Isotope	$T_{1/2}^{0\nu}$ [yrs]	Experiment	$\lvert m_{ee} \rvert_{\rm min}^{\rm lim}$ [eV]	$\lvert m_{ee} \rvert_{\rm max}^{\rm lim}$ [eV]
^{48}Ca	5.8×10^{22}	CANDLES	3.55	9.91
^{76}Ge	1.9×10^{25}	HDM	0.21	0.53
	1.6×10^{25}	IGEX	0.25	0.63
^{82}Se	3.2×10^{23}	NEMO-3	0.85	2.08
^{96}Zr	9.2×10^{21}	NEMO-3	3.97	14.39
^{100}Mo	1.0×10^{24}	NEMO-3	0.31	0.79
^{116}Cd	1.7×10^{23}	SOLOTVINO	1.22	2.30
^{130}Te	2.8×10^{24}	CUORICINO	0.27	0.57
^{136}Xe	5.0×10^{23}	DAMA	0.83	2.04
^{150}Nd	1.8×10^{22}	NEMO-3	2.35	5.08

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [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}	in progress	$\sim$ 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}	in progress	$\sim$ 2011	0.03-0.07
		1000	10^{27}	R&D	$\sim$ 2013-15	0.02-0.046
SNO+	^{150}Nd	56	4.5×10^{24}	in progress	$\sim$ 2012	0.15-0.32
		500	3×10^{25}	R&D	$\sim$ 2015	0.06-0.12

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

Inverted Ordering

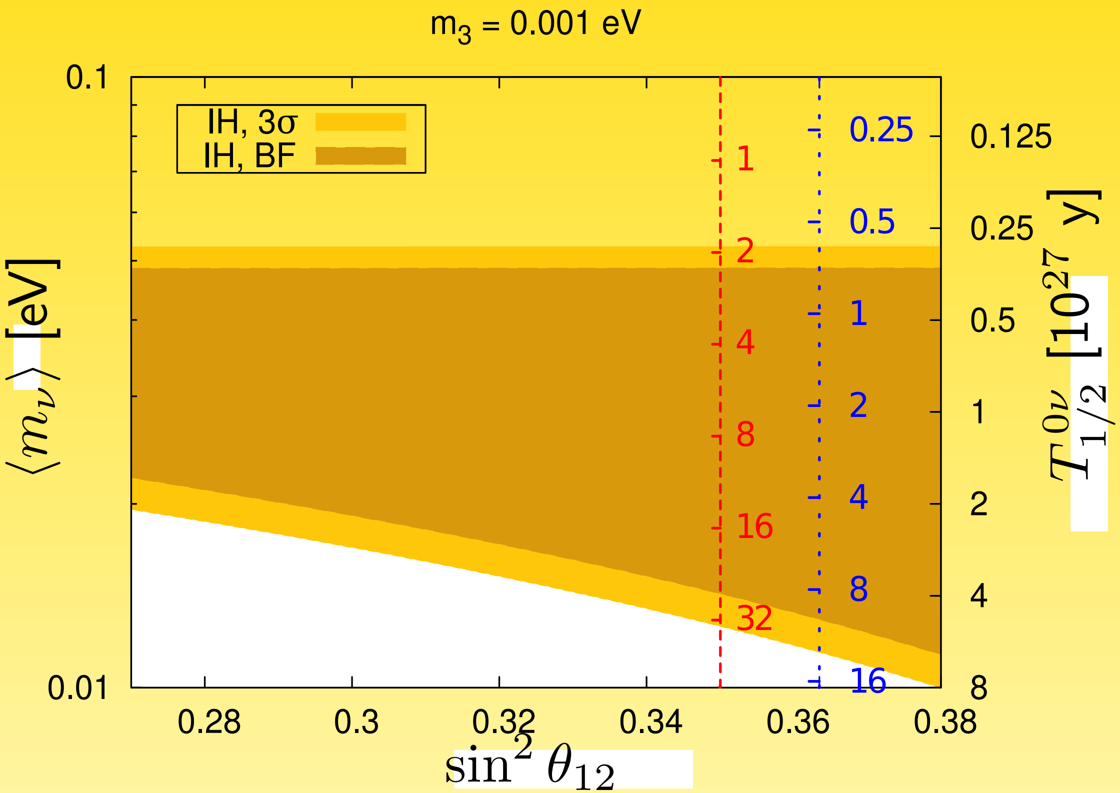


Nature provides 2 scales:

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

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

Ruling out Inverted Hierarchy



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

Ruling out Inverted Hierarchy

$$|m_{ee}|_{\rm min}^{\rm IH} = \left(1 - |U_{e3}|^2\right) \sqrt{|\Delta m_{\rm A}^2|} \left(1 - 2 \sin^2 \theta_{12}\right) = \left\{ \begin{array}{cc} (0.015 \ldots 0.020) \text{ eV} & 1\sigma \\ (0.010 \ldots 0.024) \text{ eV} & 3\sigma \end{array} \right.$$

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

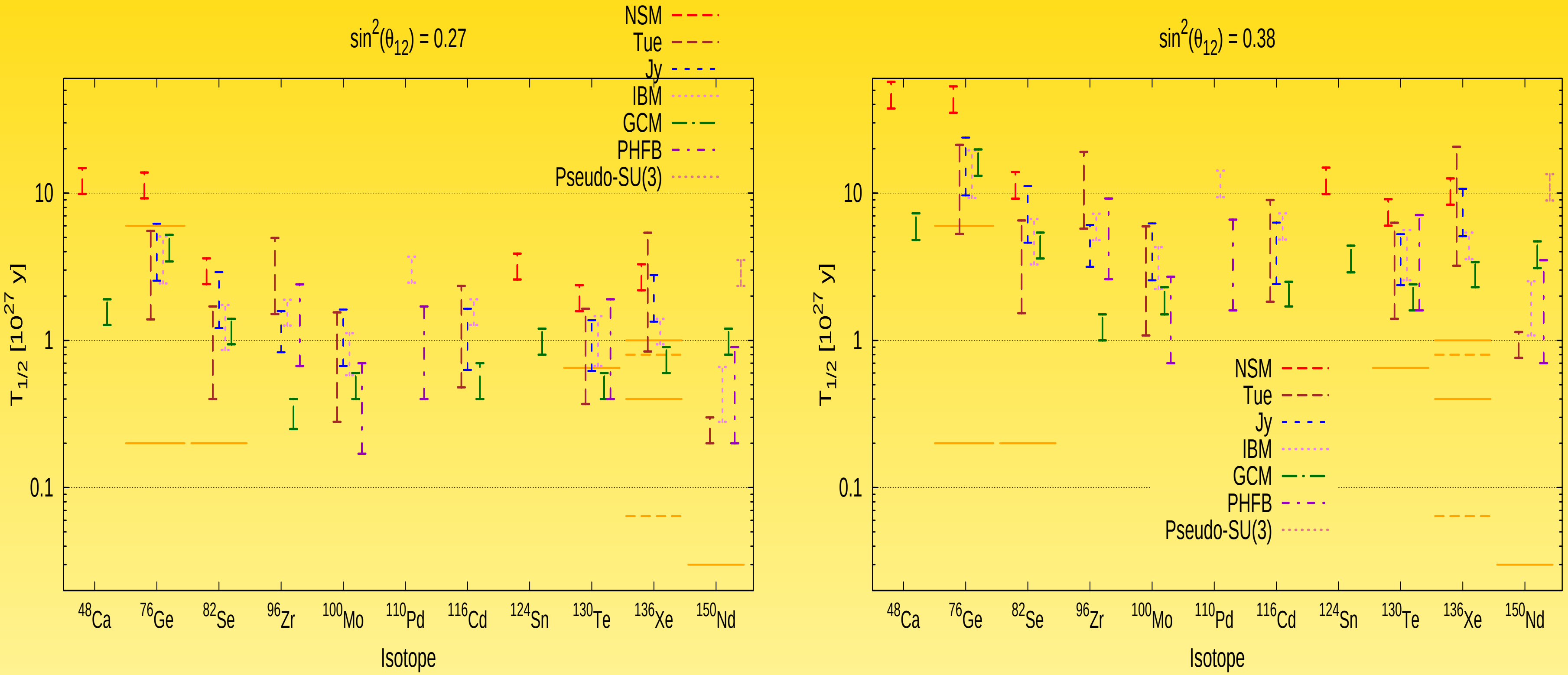
Current 3σ range of $\sin^2 \theta_{12}$ gives factor of 2 uncertainty for $|m_{ee}|_{\rm min}^{\rm IH}$

$\Rightarrow$ 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**

Ruling out Inverted Hierarchy

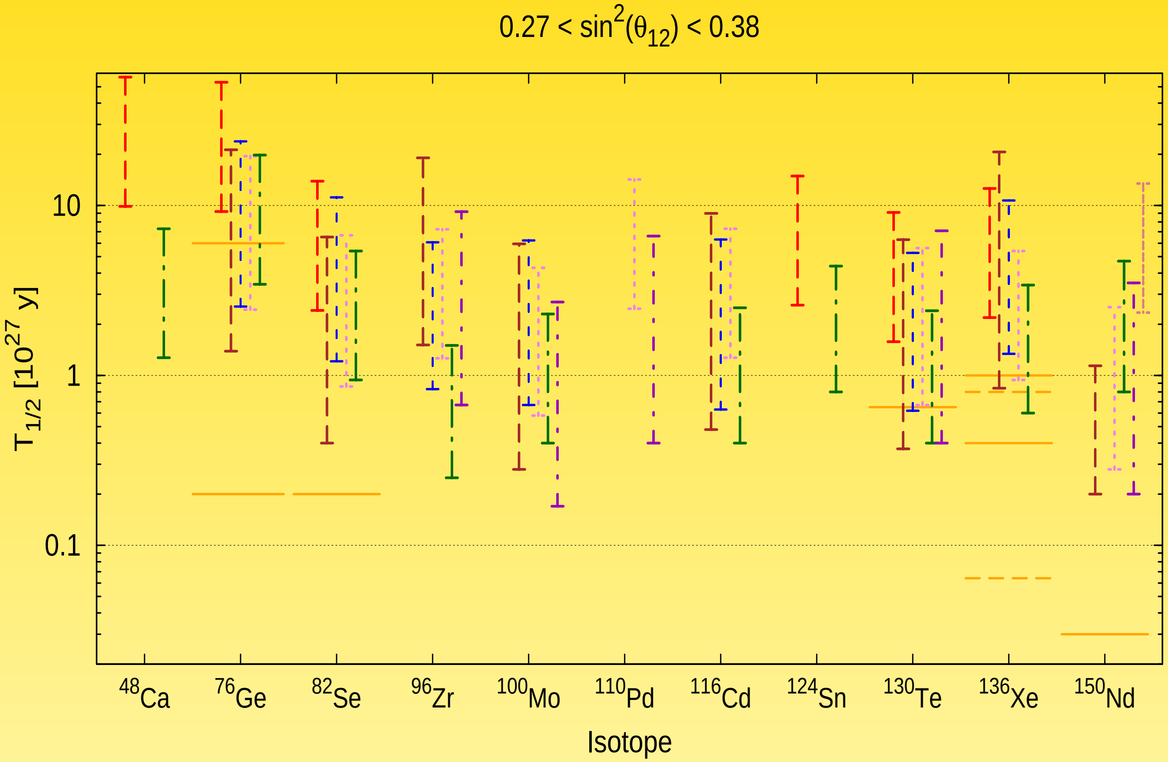


$\sin^2\theta_{12} = 0.27$ $\sin^2\theta_{12} = 0.38$

spread due to NMEs **and due to θ_{12}!!**

Note: ^{100}Mo and ^{150}Nd do best...

Ruling out Inverted Hierarchy

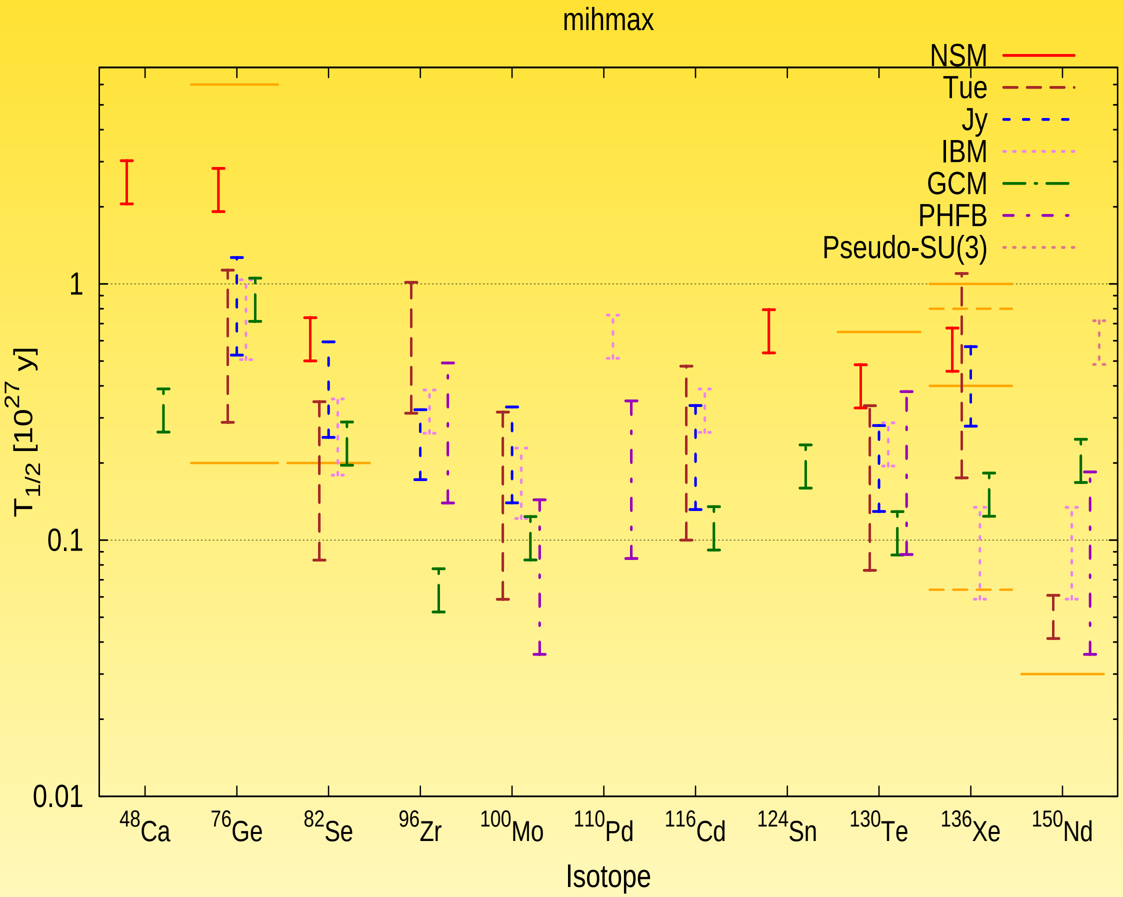


spread due to NMEs **and due to θ_{12}!!**

Note: ^{100}Mo and ^{150}Nd do best...

Testing Inverted Hierarchy

lifetime to enter the IH regime



Tri-bimaximal Mixing

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

`Harrison, Perkins, Scott (2002)`

with mass matrix

$$(m_\nu)_{\rm TBM} = U_{\rm TBM}^\ast \, m_\nu^{\rm diag} \, U_{\rm TBM}^\dagger = \begin{pmatrix} A & B & B \\ \cdot & \frac{1}{2}(A+B+D) & \frac{1}{2}(A+B-D) \\ \cdot & \cdot & \frac{1}{2}(A+B+D) \end{pmatrix}$$

$$A = \frac{1}{3}\left(2\,m_1 + m_2\,e^{-2i\alpha}\right)\,, \quad B = \frac{1}{3}\left(m_2\,e^{-2i\alpha} - m_1\right)\,, \quad D = m_3\,e^{-2i\beta}$$

$\Rightarrow$ Flavor symmetries...

Flavor Symmetry Models

suppose your model predicts TBM:

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

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

if $z = y + x/2$:

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

and one has a neutrino mass sum-rule

$$m_1 + m_2 = m_3$$

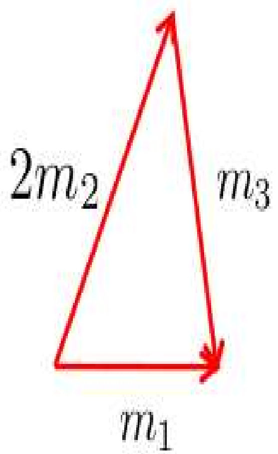
The Zoo (of A_4 models)

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

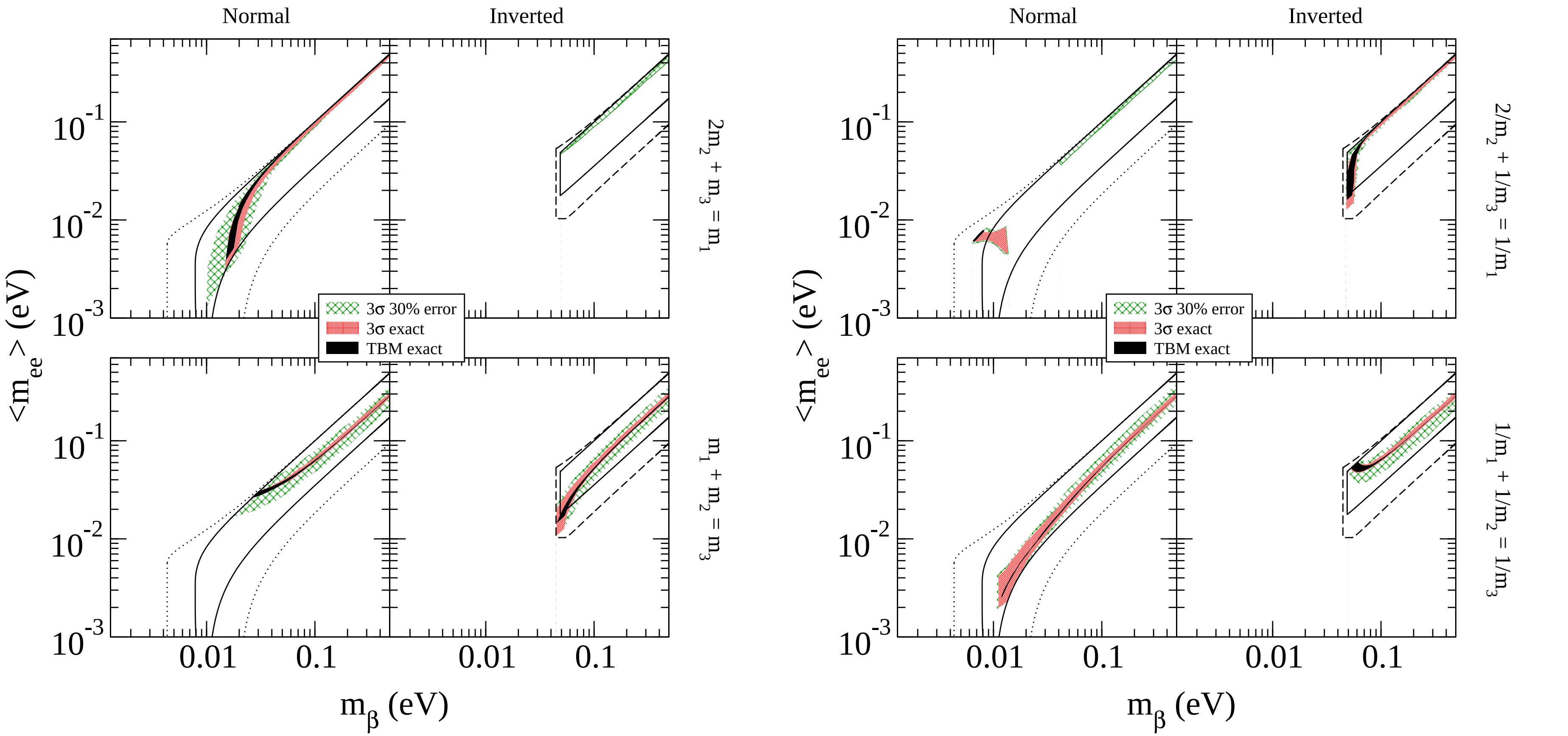
Sum-rules in Models and $0\nu\beta\beta$



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 $\epsilon \simeq 0.2$

Sterile Neutrinos??

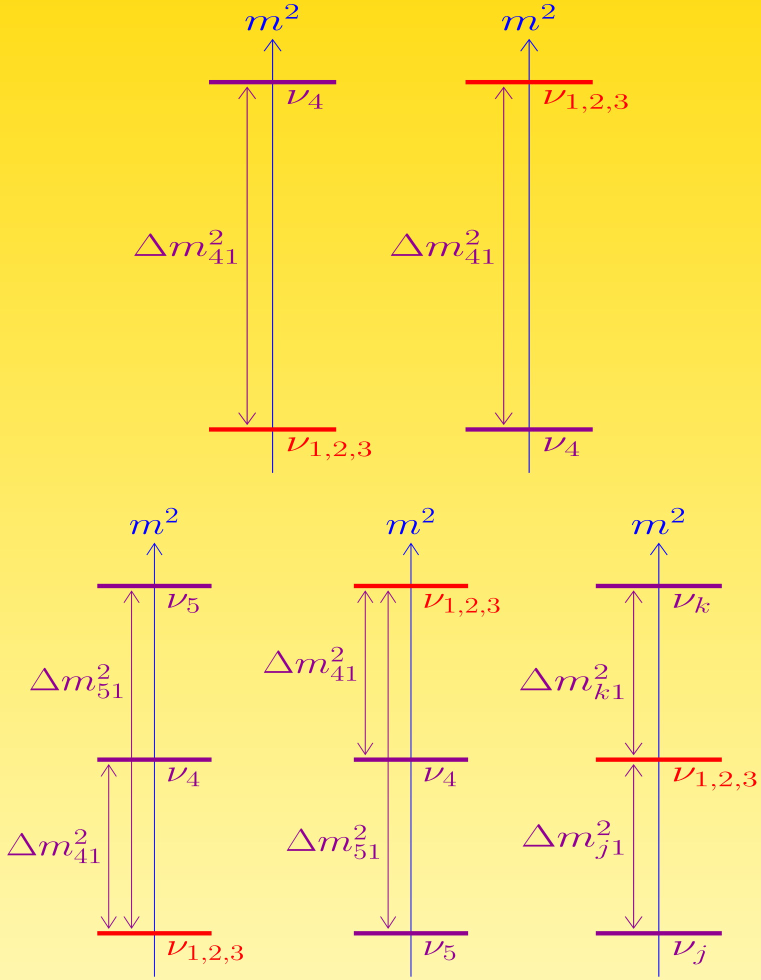
- LSND/MiniBooNE
- cosmology
- BBN
- r-process nucleosynthesis in Supernovae
- reactor anomaly (Mention *et al.*, PRD **83**)

	$\Delta m^2_{41}[\mathrm{eV}^2]$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\Delta m^2_{51}[\mathrm{eV}^2]$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$
3+2/2+3	0.47	0.128	0.165	0.87	0.138	0.148
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163

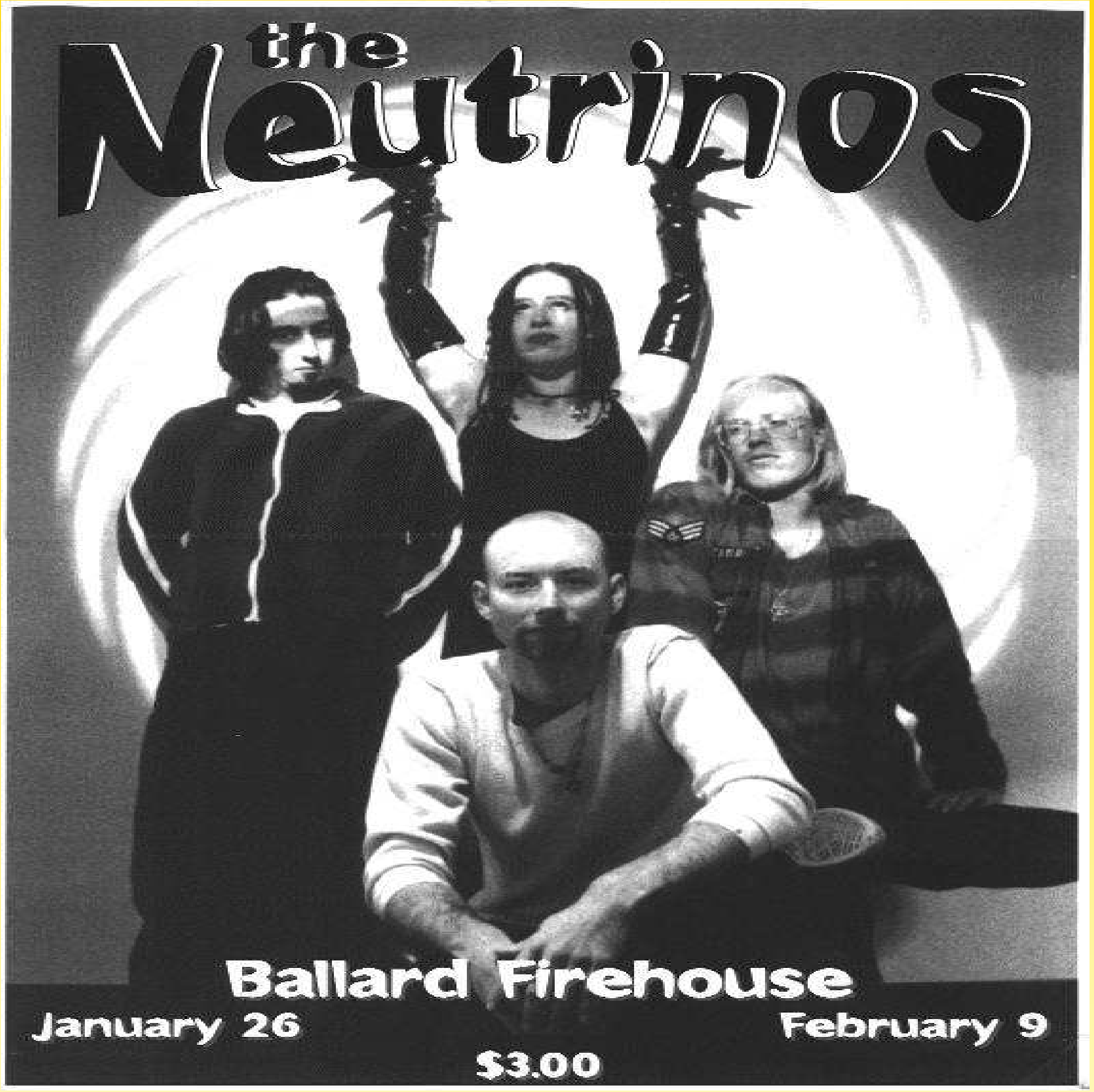
or $\Delta m^2_{41} = 1.78$ eV^2 and $|U_{e4}|^2 = 0.151$

Kopp, Maltoni, Schwetz, 1103.4570

Mass Orderings



3 active neutrinos can be normally or inversely ordered



Which one is sterile?

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
- $|m_{ee}| = |\underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2\, e^{2i\alpha} + |U_{e3}^2| m_3\, e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 m_4\, e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- $\Delta m^2_{\rm st} \simeq 1$ eV^2 and $|U_{e4}| \simeq 0.15$
- sterile contribution to $0\nu\beta\beta$:

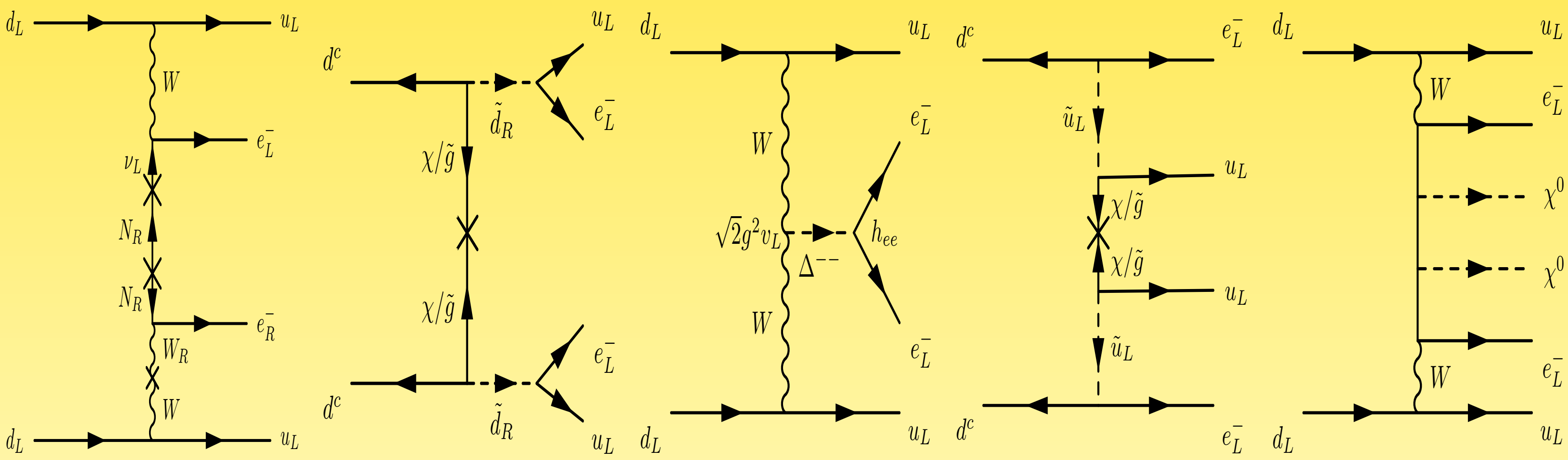
$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\,|U_{e4}|^2 \simeq 0.02 \text{ eV} \left\{ \begin{array}{c} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{array} \right.$$

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

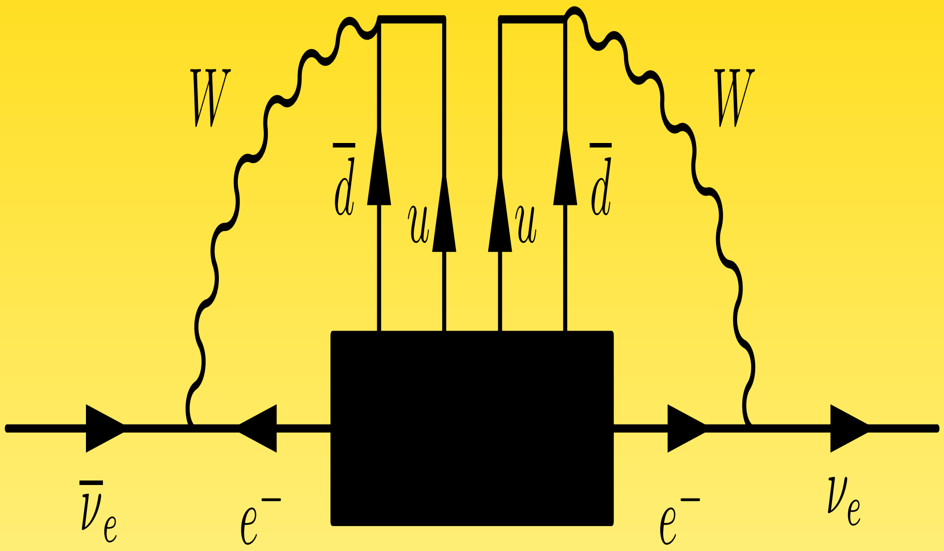
Barry, W.R., Zhang, JHEP **1107**

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



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



Blackbox diagram is 4 loop:

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

explicit calculation: Duerr, Lindner, Merle, 1105.0901

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\lvert U_{ei}^2 \, m_i \right\rvert$	0.5 eV	oscillations, cosmology, neutrino mass
heavy neutrino exchange	$\left\lvert \frac{S_{ei}^2}{M_i} \right\rvert$	2×10^{-8} GeV^{-1}	LFV, collider
heavy neutrino and RHC	$\left\lvert \frac{V_{ei}^2}{M_i \, M_{W_R}^4} \right\rvert$	4×10^{-16} GeV^{-5}	flavor, collider
Higgs triplet and RHC	$\left\lvert \frac{(M_R)_{ee}}{m_{\Delta_R}^2 \; M_{W_R}^4} \right\rvert$	10^{-15} GeV^{-1}	flavor, collider e^- distribution
λ-mechanism with RHC	$\left\lvert \frac{U_{ei} \, \tilde{S}_{ei}}{M_{W_R}^2} \right\rvert$	1.4×10^{-10} GeV^{-2}	flavor, collider, e^- distribution
η-mechanism with RHC	$\tan\zeta \, \left\lvert U_{ei} \, \tilde{S}_{ei} \right\rvert$	6×10^{-9}	flavor, collider, e^- distribution
short-range $\not{R}$	$\frac{\left\lvert \lambda'^2_{111} \right\rvert}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\lvert \sin 2\theta^b \, \lambda'_{131} \, \lambda'_{113} \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2} \right) \right\rvert$ $\sim \frac{G_F}{q} m_b \frac{\left\lvert \lambda'_{131} \, \lambda'_{113} \right\rvert}{\Lambda_{\rm SUSY}^3}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\lvert\langle g_\chi \rangle\rvert$ or $\lvert\langle g_\chi \rangle\rvert^2$	$10^{-4} \ldots 1$	spectrum, cosmology

Distinguishing Mechanisms

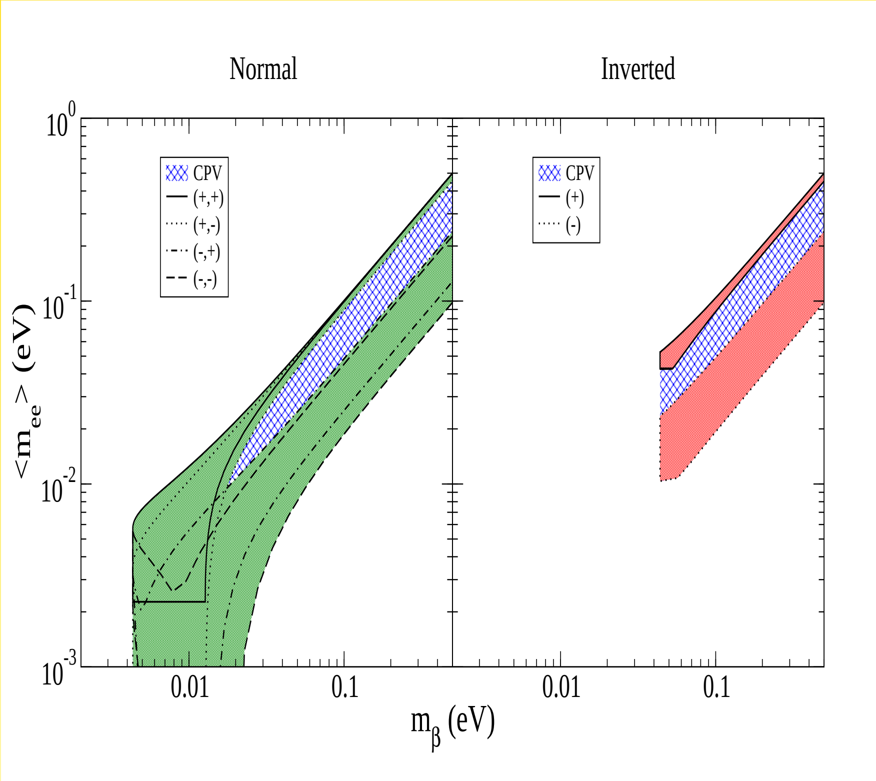
The inverse problem of 0$\nu\beta\beta$

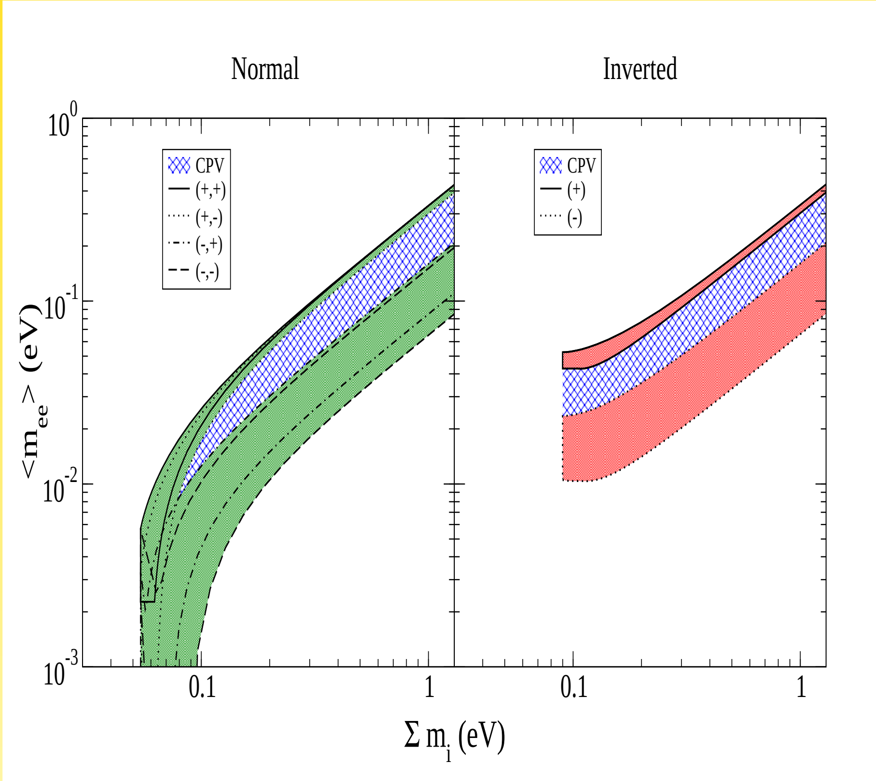
1.) Other observables (LHC, LFV, KATRIN, cosmology,...)

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:

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

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

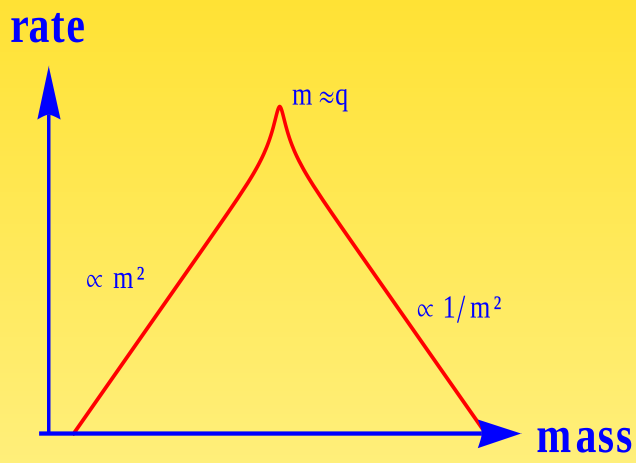
$$\boxed{1 \text{ eV} = 1 \text{ TeV}}$$

$\Rightarrow$ Phenomenology in colliders, LFV

Examples

- Fermions and no RHC:

$$\mathcal{A} \propto \frac{m}{q^2 - m^2} \rightarrow \begin{cases} m & \text{for } q^2 \gg m^2 \\ \frac{1}{m} & \text{for } q^2 \ll m^2 \end{cases}$$

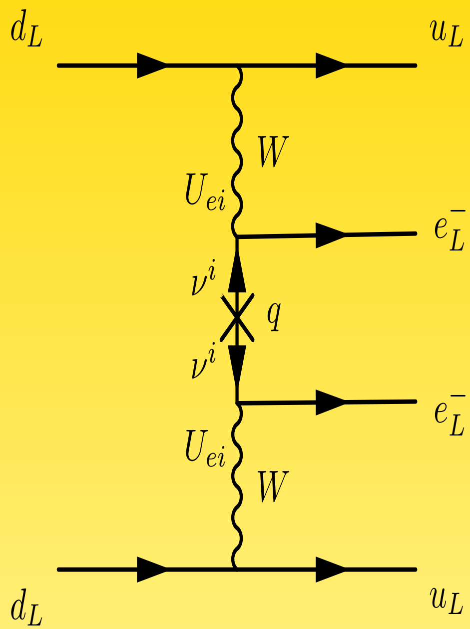


Note: maximum $\mathcal{A}$ corresponds to $m \simeq \langle q \rangle$: limits on $\mathcal{O}(m_K)$ Majorana neutrinos from $K^+ \rightarrow \pi^- \mu^+ e^+$

- heavy scalar:

$$\mathcal{A} \propto \frac{1}{q^2 - m^2} \rightarrow \frac{1}{m^2}$$

Heavy neutrinos



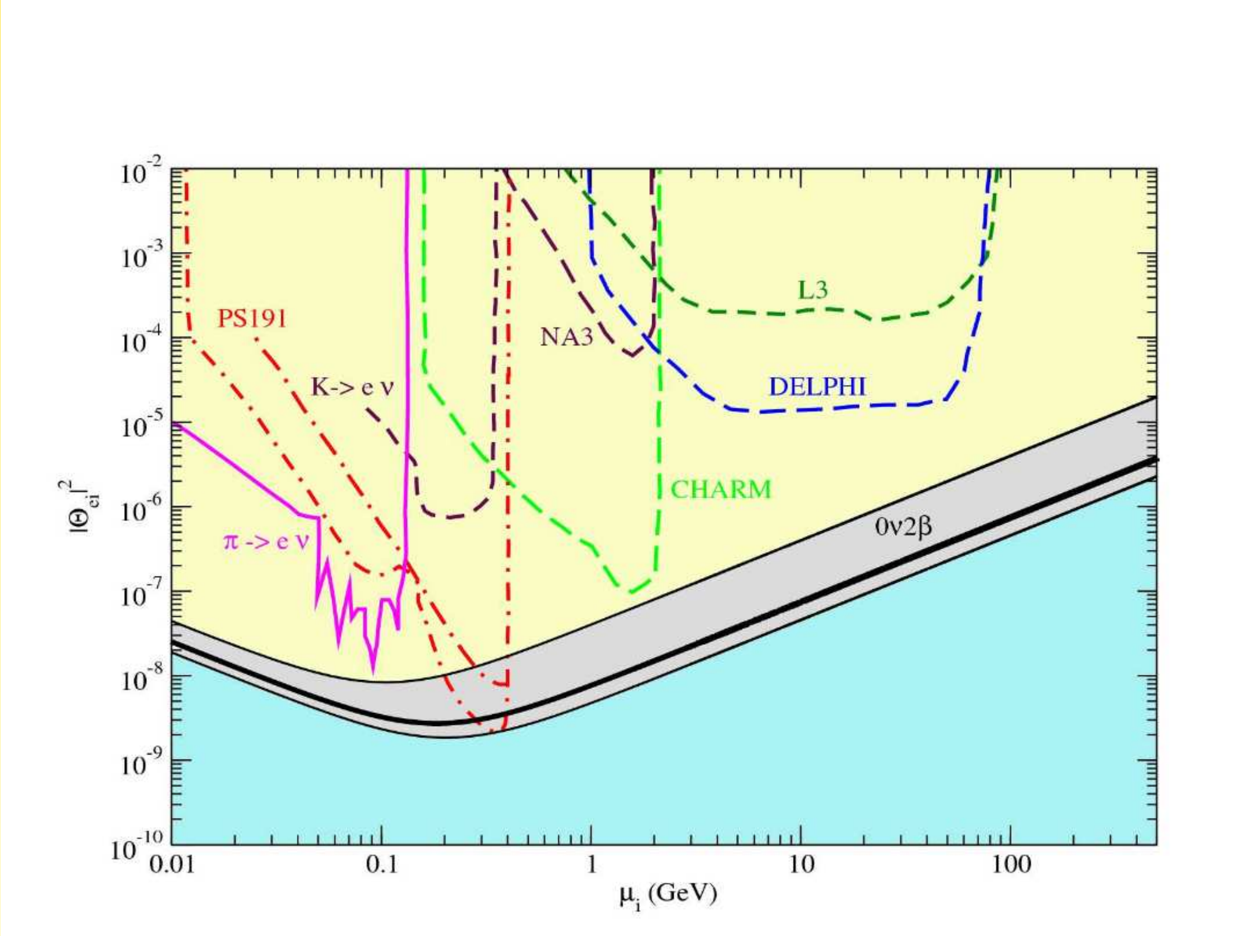
same diagram with $U \to S$

$$\mathcal{A}_{\rm h} = G_F^2 \frac{S_{ei}^2}{M_i} \equiv G_F^2 \, \langle \frac{1}{m} \rangle \;\Rightarrow \langle \frac{1}{m} \rangle \;\leq 5 \times 10^{-8} \text{ GeV}^{-1}$$

literature value: 2×10^{-8} GeV^{-1} ...

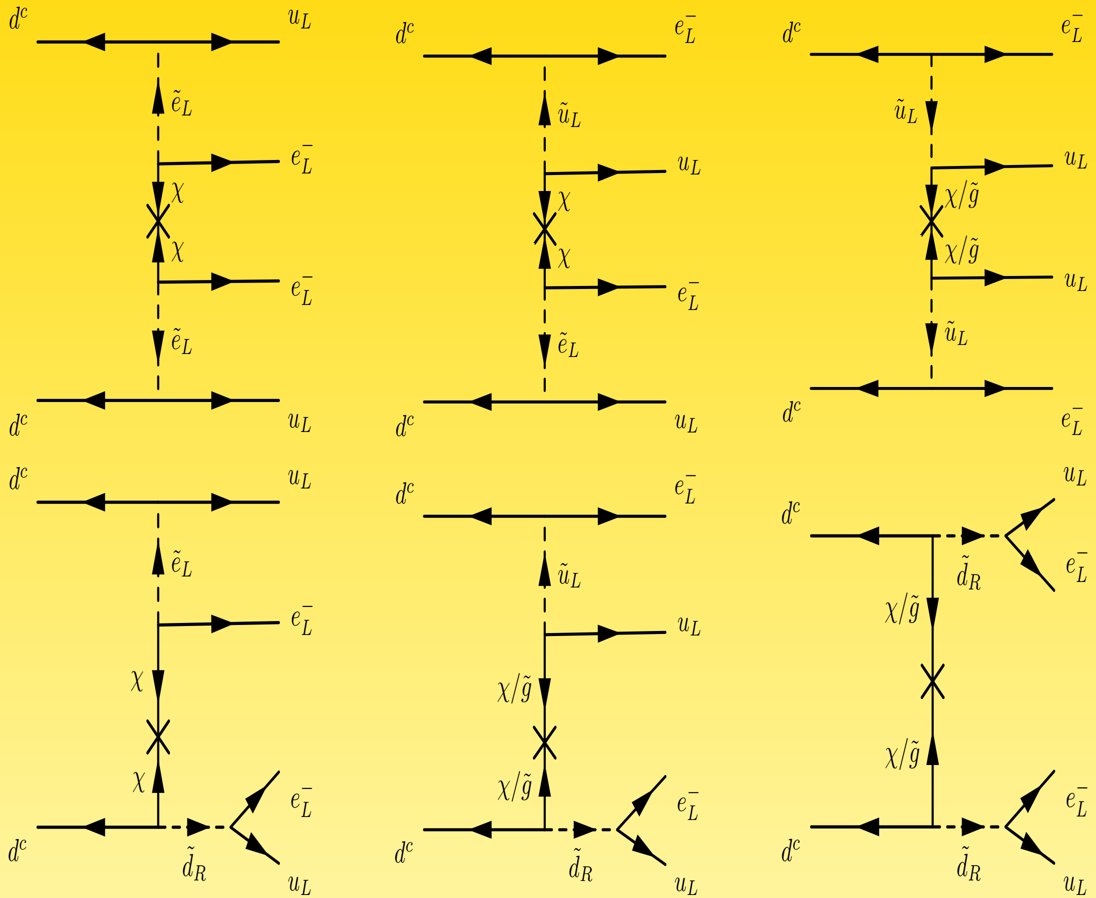
$\Rightarrow$ comparison on amplitude level is fine

Heavy neutrinos



Mitra, Senjanovic, Vissani, 1108.0004

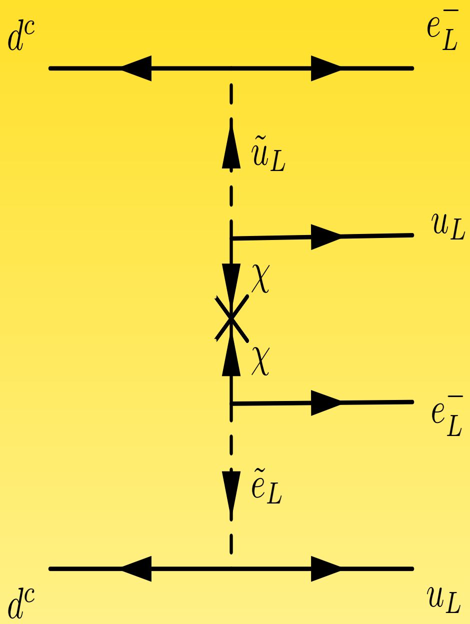
Supersymmetry: short range

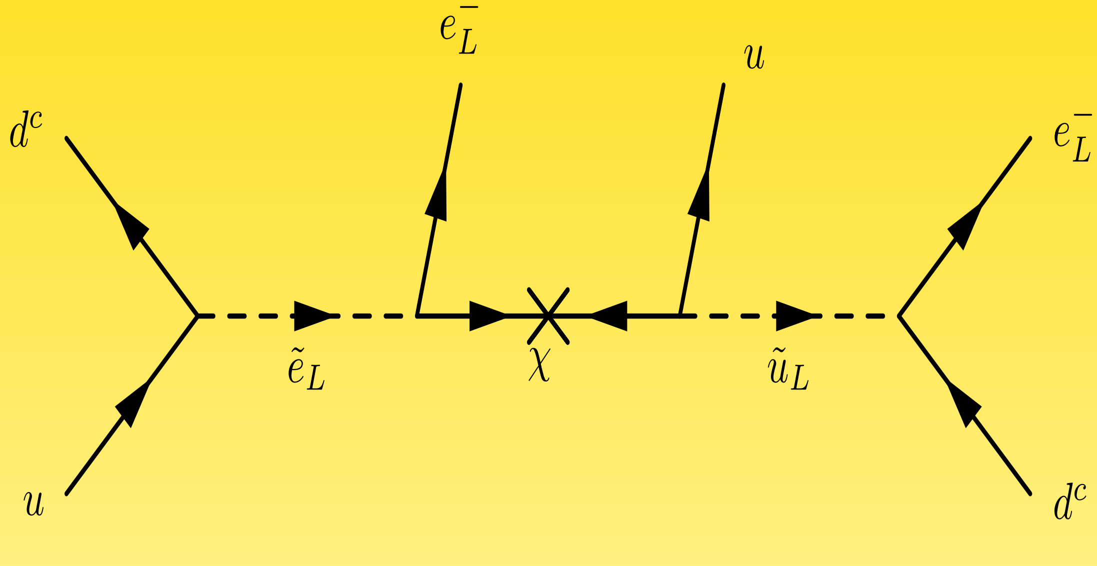


$$\mathcal{A}_{\not{R}_1} \simeq \frac{\lambda'^2_{111}}{\Lambda^5_{\mathrm{SUSY}}}$$

Supersymmetry: short range

interplay with LHC:



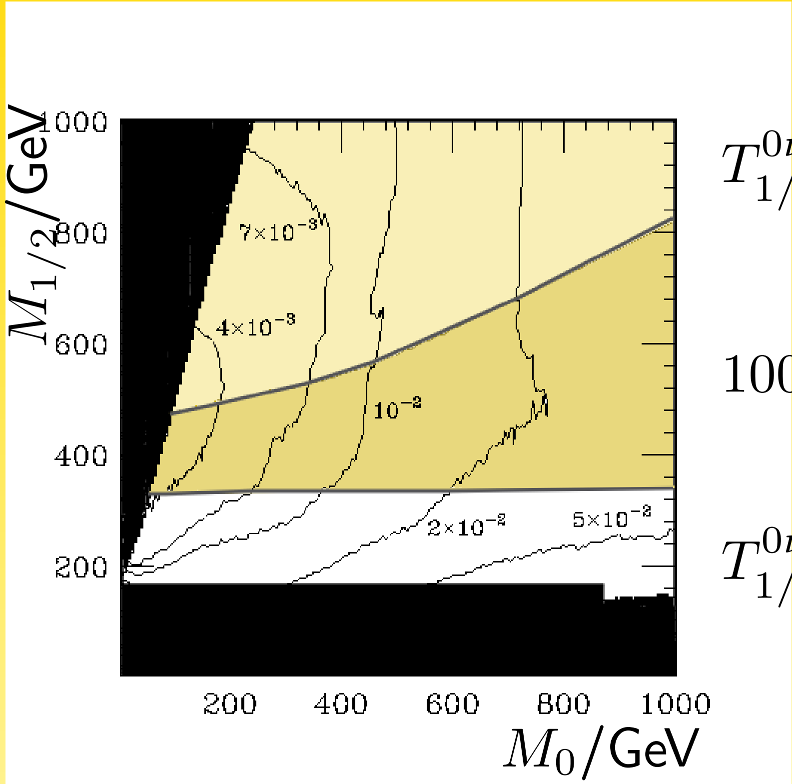


"resonant selectron production"

$$\hat{\sigma} \propto \frac{\lambda'^2_{111}}{\hat{s}}$$

Allanach, Kom, Paes, 0903.0347

$\tan\beta = 10,\ A_0 = 0,\ 10\ \text{fb}^{-1}$



$T_{1/2}^{0\nu\beta\beta}(\text{Ge}) > 1 \times 10^{27}$ yrs

$100 > T_{1/2}^{0\nu\beta\beta}(\text{Ge})/10^{25}$ yrs > 1.9

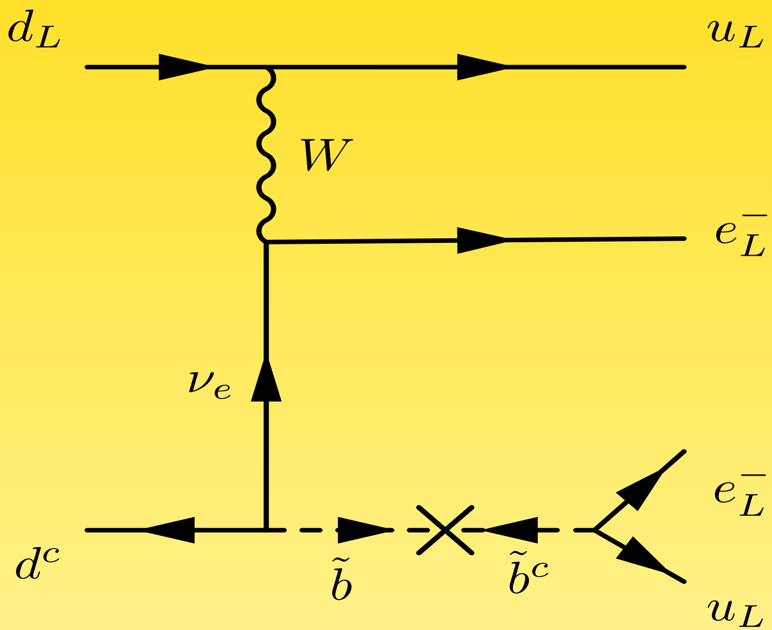
$T_{1/2}^{0\nu\beta\beta}(\text{Ge}) < 1.9 \times 10^{25}$ yrs

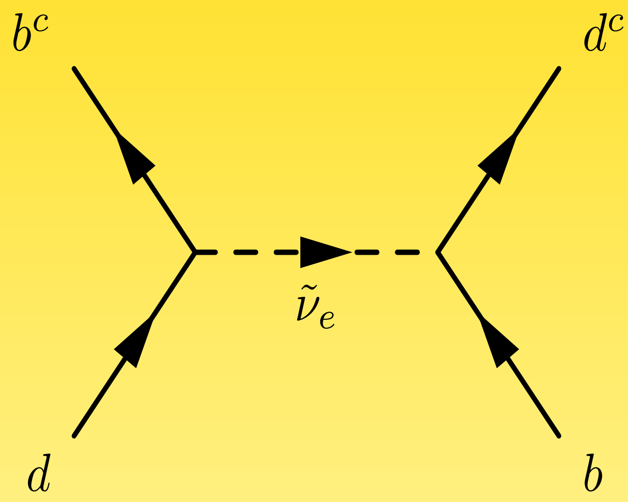
→ observation in white region in conflict with $0\nu\beta\beta$

→ if $0\nu\beta\beta$ observed: dark yellow region tests $\not{R}$ SUSY mechanism

→ light yellow region: no significant $\not{R}$ contribution to $0\nu\beta\beta$

Supersymmetry: long range





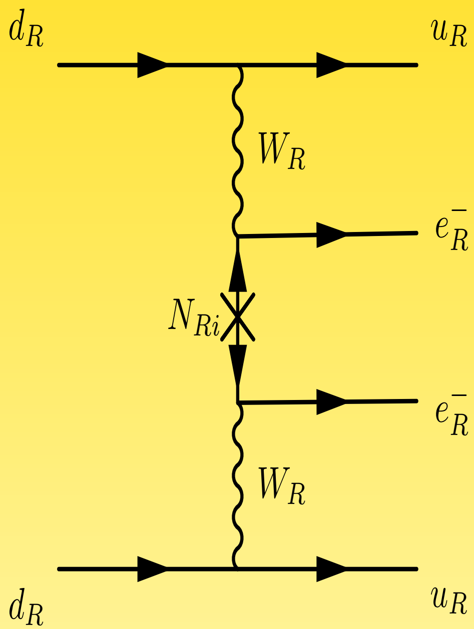
$$\mathcal{A}^b_{\not R_2} \simeq G_F \, \frac{1}{q} \, U_{ei} \, m_b \, \frac{\lambda'_{131} \, \lambda'_{113}}{\Lambda^3_{\rm SUSY}}$$

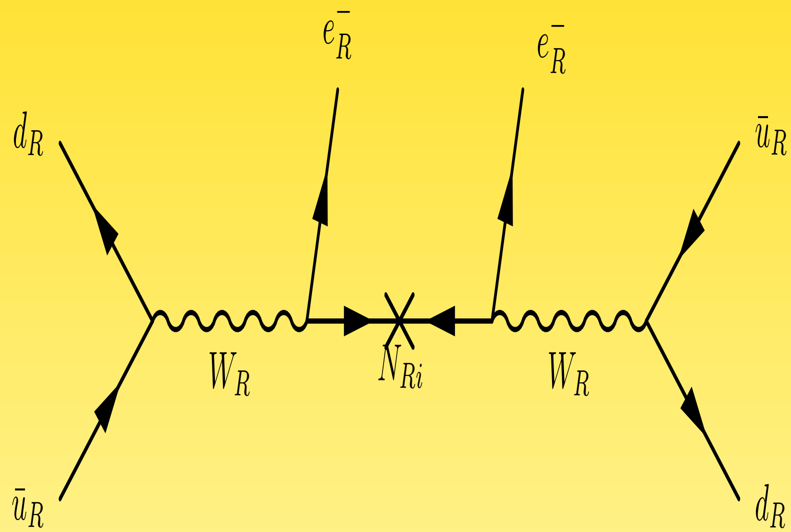
$0\nu\beta\beta$

$$\frac{\lambda'_{131} \, \lambda'_{113}}{\Lambda^2_{\rm SUSY}}$$

B^0-$\bar{B}^0$ mixing

Left-right symmetry





Tello *et al.*, 1011.3522

"Inverse $0\nu\beta\beta$"

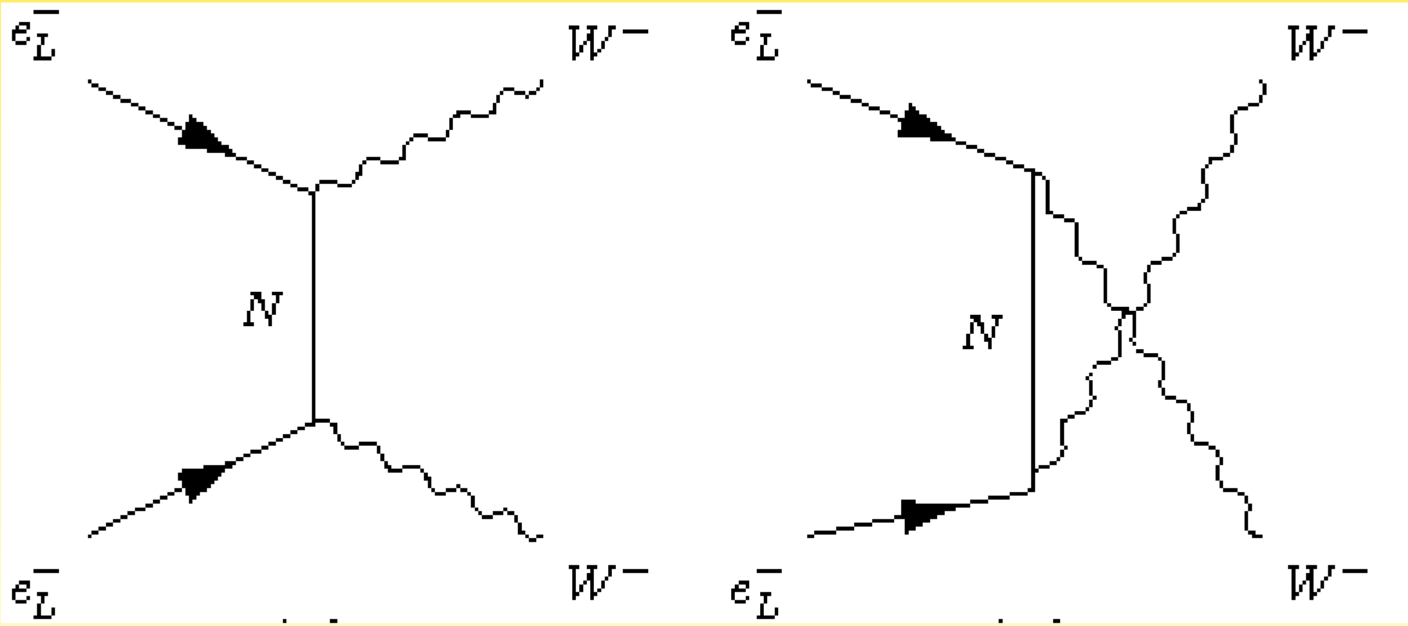
this is not

$$^{76}\mathrm{Se}^{++} + e^- + e^- \to {}^{76}\mathrm{Ge}$$

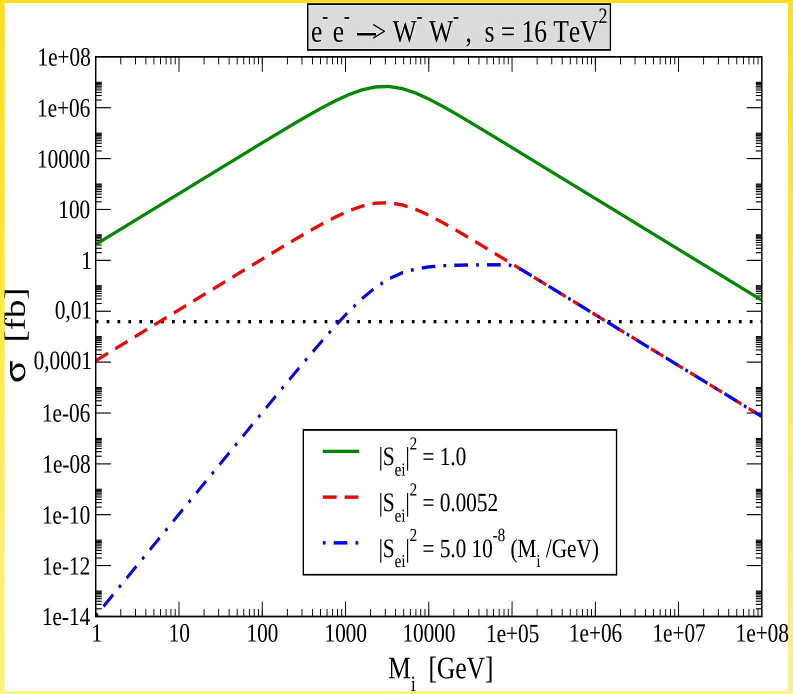
but rather

$$e^- + e^- \to W^- + W^-$$

Rizzo; Heusch, Minkowski; Gluza, Zralek; Cuypers, Raidal;...



Inverse Neutrinoless Double Beta Decay



W.R., PRD **81**

$$\frac{d\sigma}{d\cos\theta} = \frac{G_F^2}{32\,\pi}\left\{\sum (m_\nu)_i\,\mathcal{U}_{ei}^2\left(\frac{t}{t-(m_\nu)_i}+\frac{u}{u-(m_\nu)_i}\right)\right\}^2$$

Inverse Neutrinoless Double Beta Decay

Extreme limits:

- light neutrinos:

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\,\pi}\,|m_{ee}|^2 \leq 4.2 \cdot 10^{-18} \left(\frac{|m_{ee}|}{1\,\mathrm{eV}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ way too small

- heavy neutrinos:

$$\sigma(e^- e^- \to W^- W^-) = 2.6 \cdot 10^{-3} \left(\frac{\sqrt{s}}{\mathrm{TeV}}\right)^4 \left(\frac{S_{ei}^2/M_i}{5 \cdot 10^{-8}\,\mathrm{GeV}^{-1}}\right)^2 \mathrm{fb}$$

$\Rightarrow$ too small

- $\sqrt{s} \to \infty$:

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2\,(m_\nu)_i\right)^2$$

$\Rightarrow$ amplitude grows with $\sqrt{s}$? Unitarity??

Unitarity

high energy limit $\sqrt{s} \to \infty$:

$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left(\sum \mathcal{U}_{ei}^2 \, (m_\nu)_i \right)^2$$

$\leftrightarrow$ amplitude grows with $\sqrt{s}$?

Answer: exact see-saw relation $\mathcal{U}_{ei}^2 \, (m_\nu)_i = 0$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} = \mathcal{U} \begin{pmatrix} m_\nu^{\rm diag} & 0 \\ 0 & M_R^{\rm diag} \end{pmatrix} \mathcal{U}^T$$

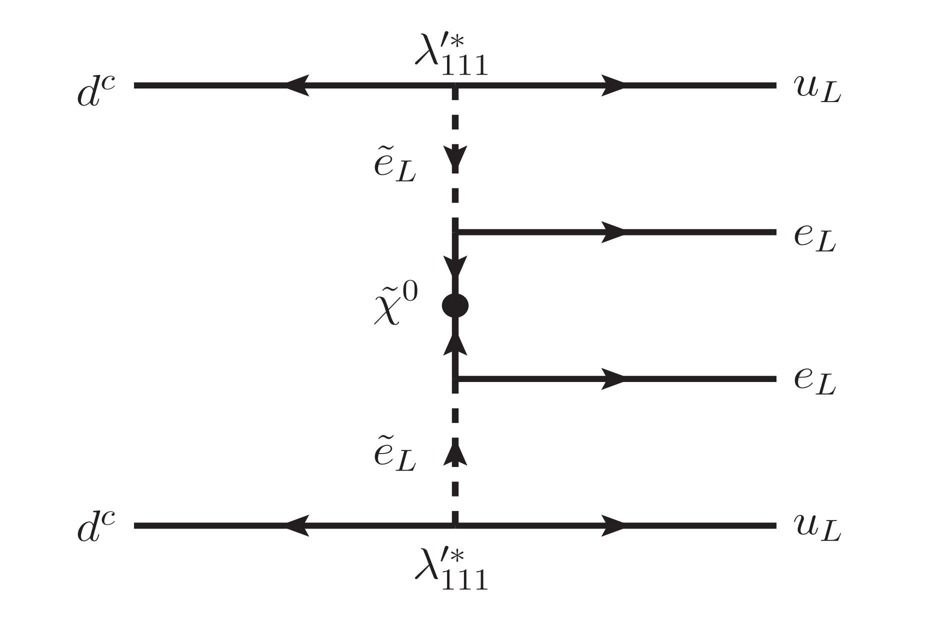
if Higgs triplet is present: unitarity also conserved

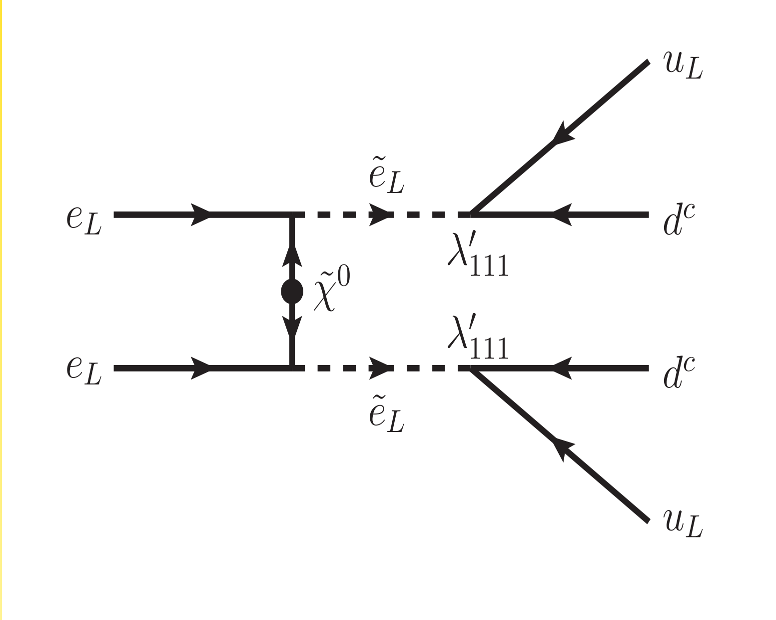
$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F^2}{4\pi} \left((\mathcal{U}_{ei}^2 \, (m_\nu)_i - (m_L)_{ee} \right)^2 = 0$$

W.R., PRD **81**

Inverse $0\nu\beta\beta$ and RPV SUSY

$$\mathcal{W} = \lambda'_{111} L_1 Q_1 D_1^c \;\Rightarrow\; e^- e^- \longrightarrow 4 \text{ jets}$$





$0\nu\beta\beta$

resonant selectron production

via *gauge* interactions

Cross section

$$\sigma(e_L^- e_L^- \to \tilde{e}_L^- \tilde{e}_L^-) = \frac{\pi\alpha^2 |g_L|^4}{s} \frac{2m_{\tilde{\chi}^0}^2}{s + 2m_{\tilde{\chi}^0}^2 - 2m_{\tilde{e}_L}^2} \left[L + \frac{2\lambda}{(s + 2m_{\tilde{\chi}^0}^2 - 2m_{\tilde{e}_L}^2)^2 - \lambda^2} \right]$$

where

$$L = \ln \frac{s + 2m_{\tilde{\chi}^0}^2 - 2m_{\tilde{e}_L}^2 + \lambda}{s + 2m_{\tilde{\chi}^0}^2 - 2m_{\tilde{e}_L}^2 - \lambda}$$

$$\lambda = \lambda(s, m_{\tilde{e}_L}^2, m_{\tilde{e}_L}^2) = \sqrt{s^2 - 4sm_{\tilde{e}_L}^2}$$

Keung, Littenberg, 1983

adjustable parameters

$$m_{\tilde{\chi}^0}\,, \quad m_{\tilde{g}}\,, \quad m_{\tilde{e}_L}\,, \quad m_{\tilde{u}_L}\,, \quad m_{\tilde{d}_R}\,, \quad \lambda'_{111}$$

squarks and gluinos decoupled;

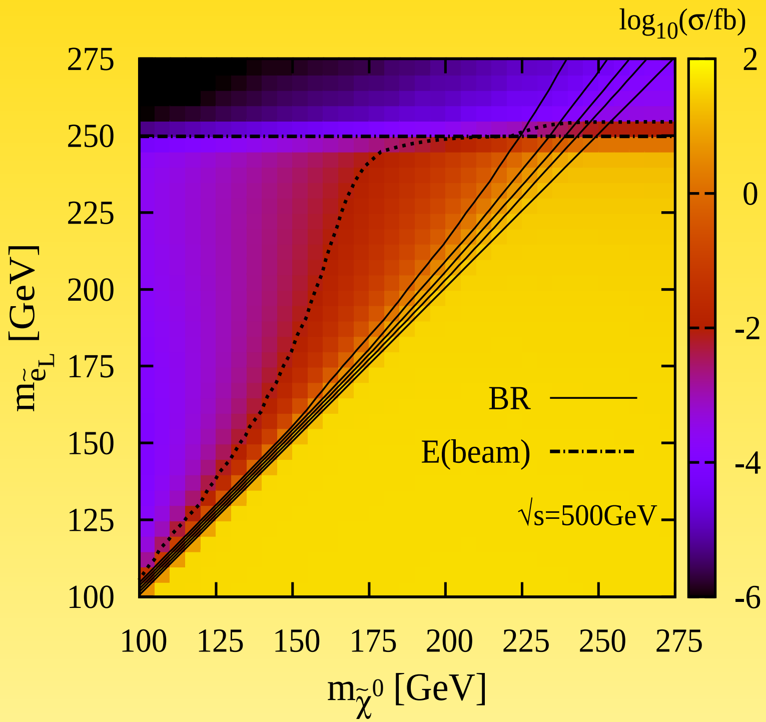
competing decays $\tilde{e}_L \to e\,\tilde{\chi}^0$ and $\tilde{e}_L \to jj$

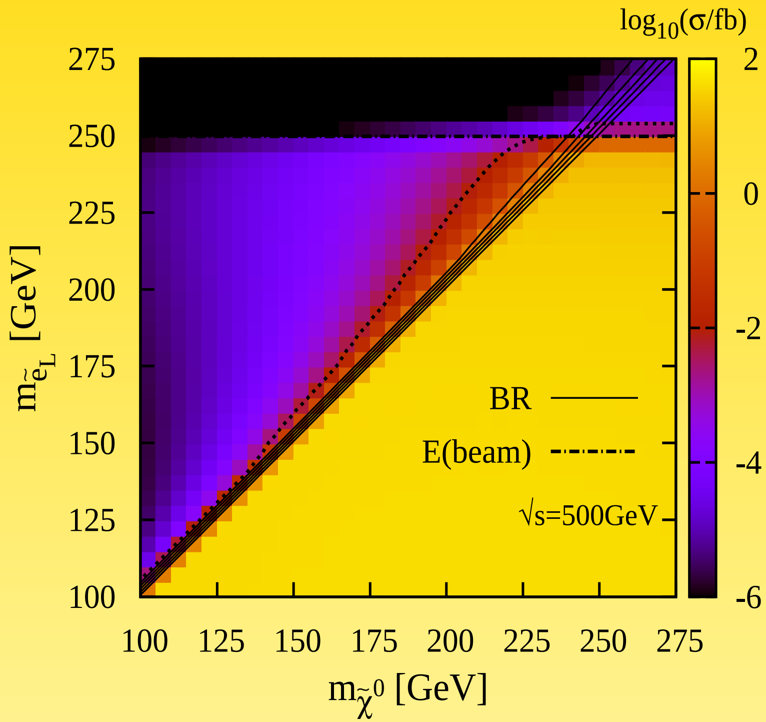
competing decays $\tilde{e}_L \to e\,\tilde{\chi}^0$ and $\tilde{e}_L \to jj$:

- $0\nu\beta\beta$-limit goes with $\Lambda^5_{\rm SUSY} \Rightarrow \lambda'_{111}$ can be $\mathcal{O}(1)$ and thus BR$(\tilde{e}_L \to jj) >$ BR$(\tilde{e}_L \to e\,\tilde{\chi}^0)$
- even for low masses, large BR$(\tilde{e}_L \to jj)$ possible for narrow band around $m_{\tilde{e}_L} - m_{\tilde{\chi}^0} \ll m_{\tilde{e}_L}$

reconstruction:

- mass and width of $\tilde{e}_L$: dijet invariant mass distribution
- BR$(\tilde{e}_L \to jj)$ and thus λ'_{111}: $\tilde{e}_L$ decays
- mass of $\tilde{\chi}^0$: rate of $e^-_L e^-_L \to \tilde{e}^-_L \tilde{e}^-_L$



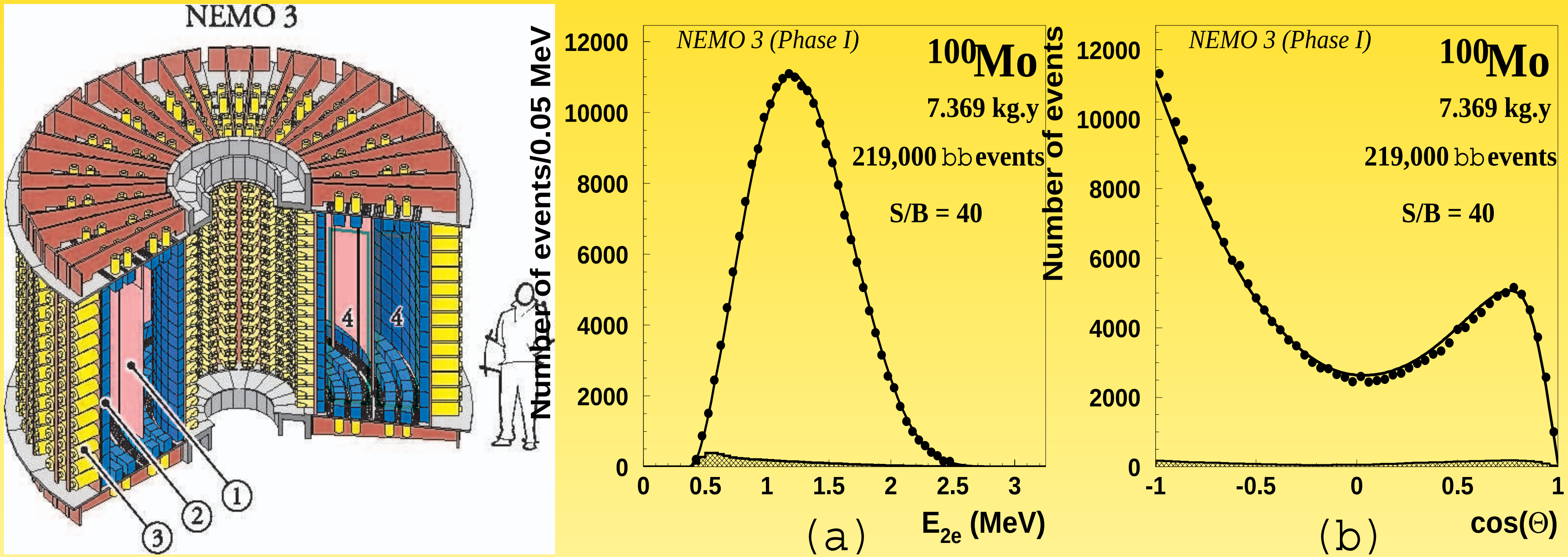


1.9×10^{25}yrs $\qquad$ 1.0×10^{27}yrs

Kom, W.R., 1110.3220

2.) Distinguishing via decay products

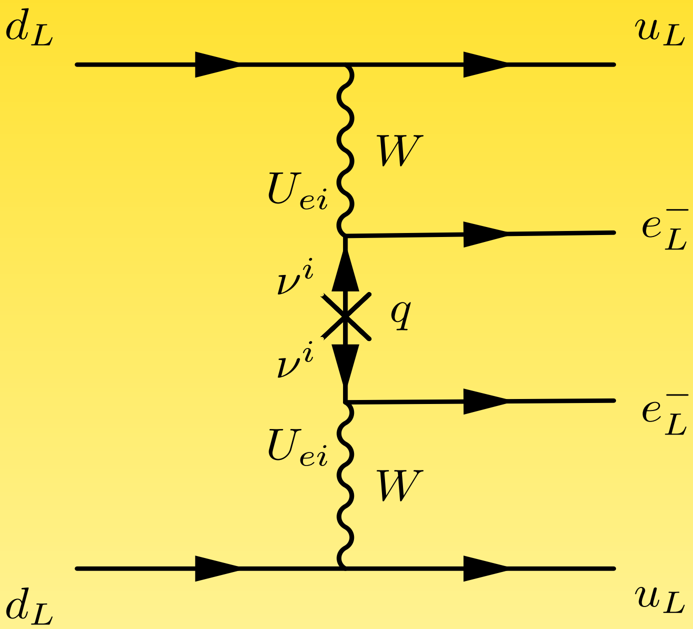
SuperNEMO

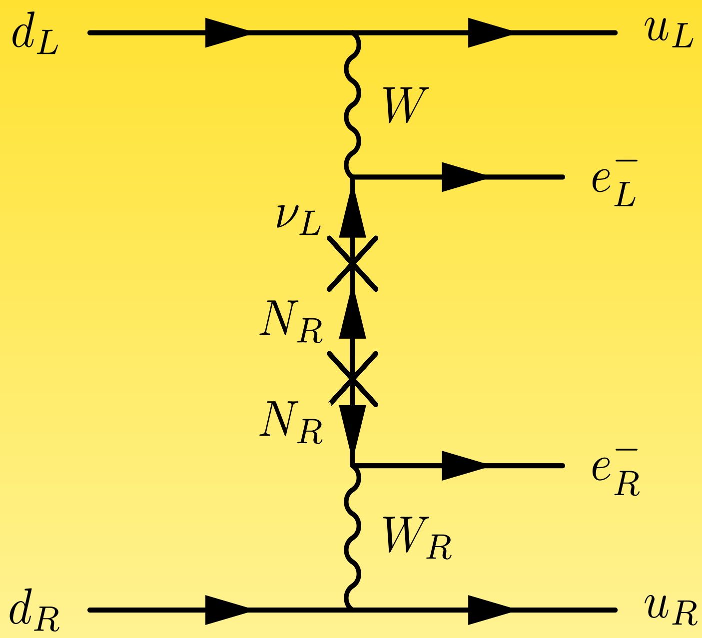


- source foils in between plastic scintillators
- individual electron energy, and their relative angle!

Distinguishing via decay products

Consider standard plus λ-mechanism





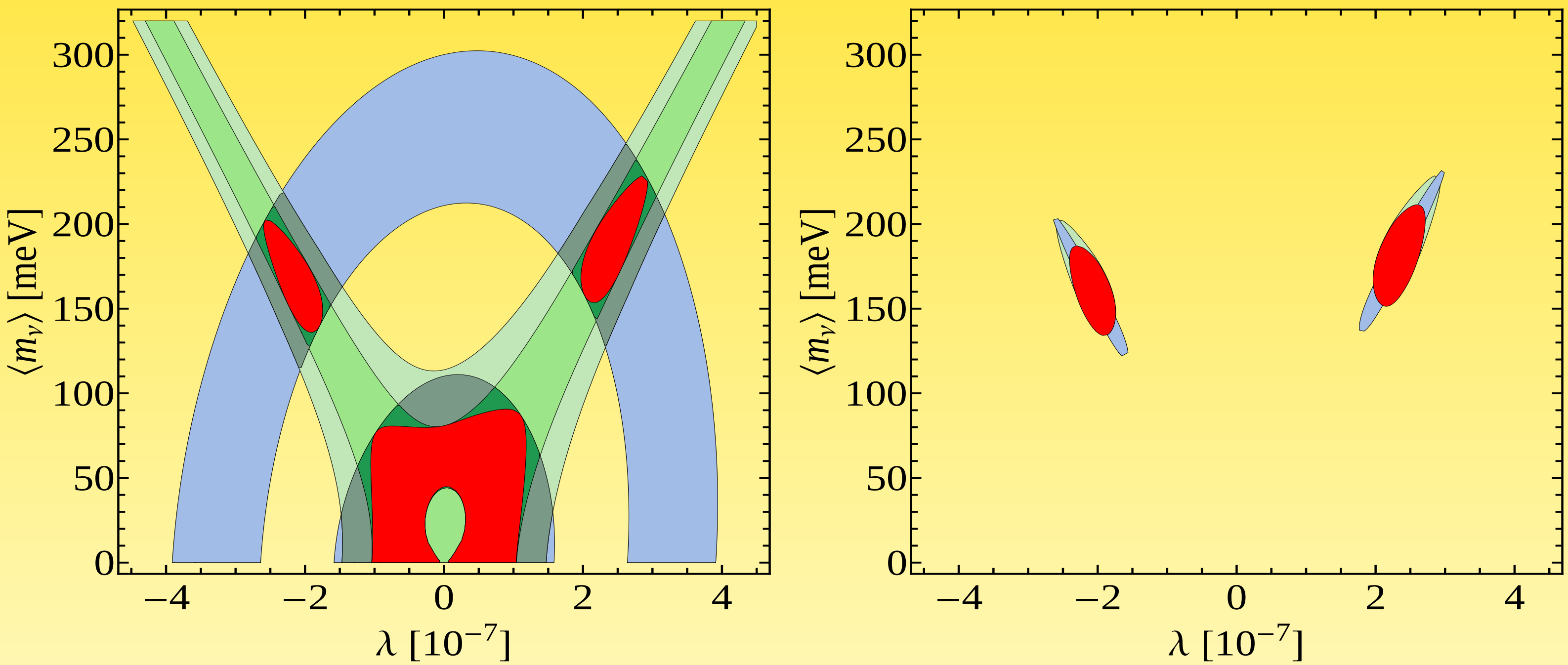
$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta) \qquad \frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$$

Arnold *et al.*, 1005.1241

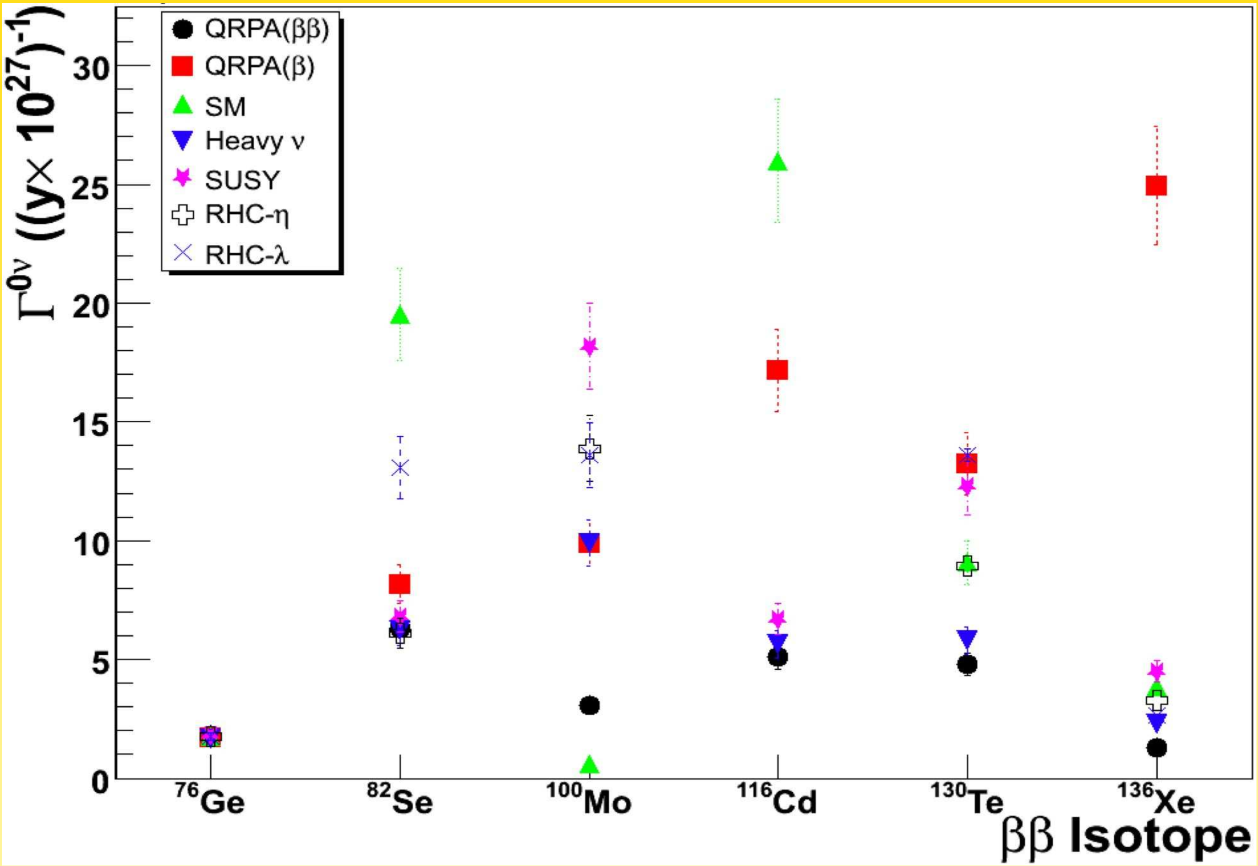
Distinguishing via decay products

Defining asymmetries

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



3.) Distinguishing via nuclear physics



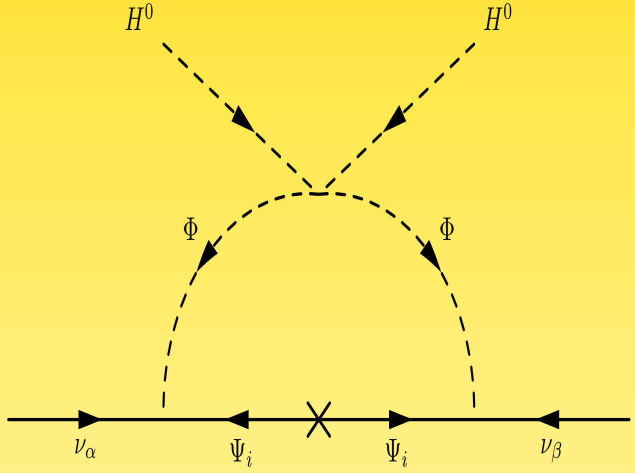
Gehman, Elliott, hep-ph/0701099

3 to 4 isotopes necessary to disentangle mechanism

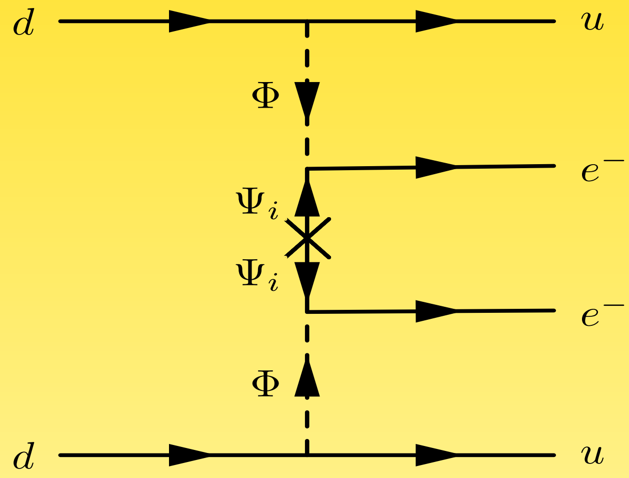
Direct vs. Indirect Contribution

Example: Color Octet Mechanism (Perez, Wise, PRD 80)

introduce $\rho_\alpha = (8,1,0)$ and $S = (8,2,\frac{1}{2})$



1-loop m_ν



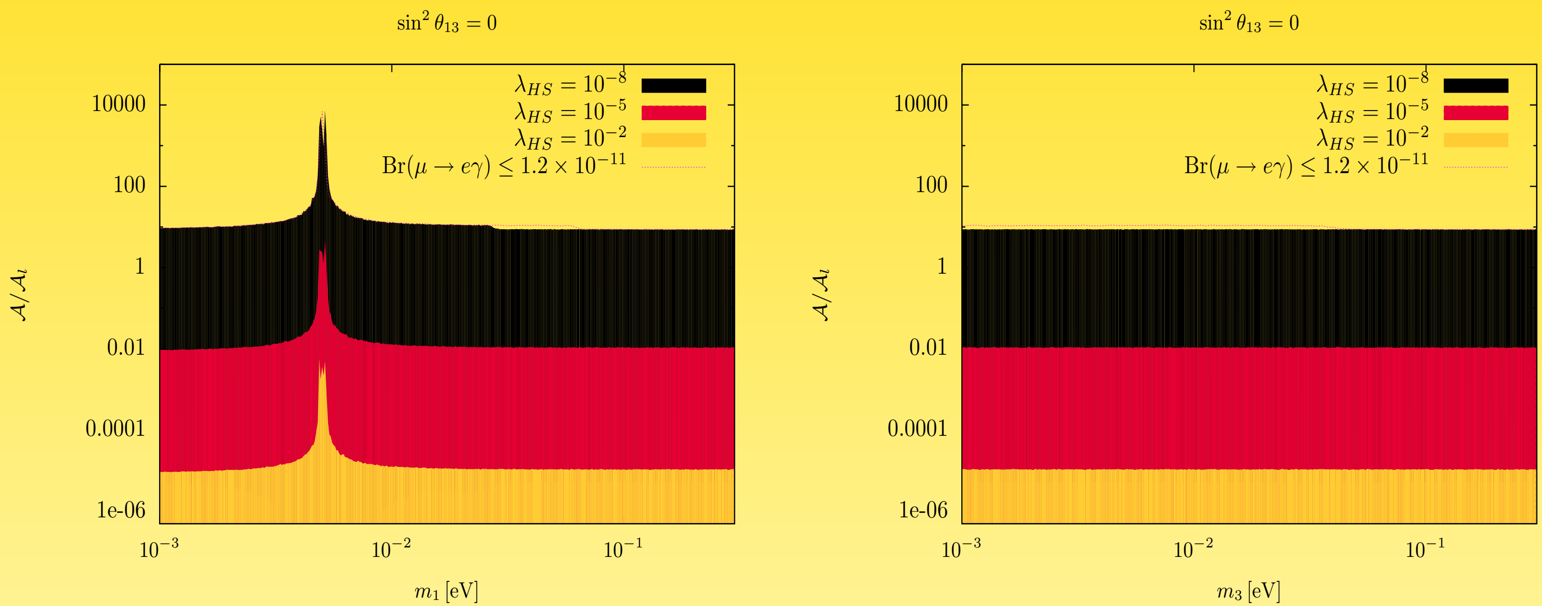
indirect contribution to $0\nu\beta\beta$:

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

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

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

Direct vs. Indirect Contribution



Choubey, Dürr, Mitra, W.R., in preparation

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.