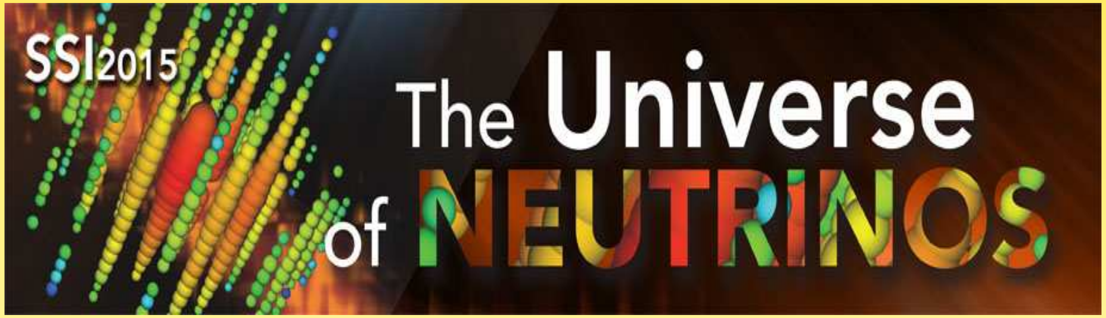
Neutrinoless Double Beta Decay: Theory

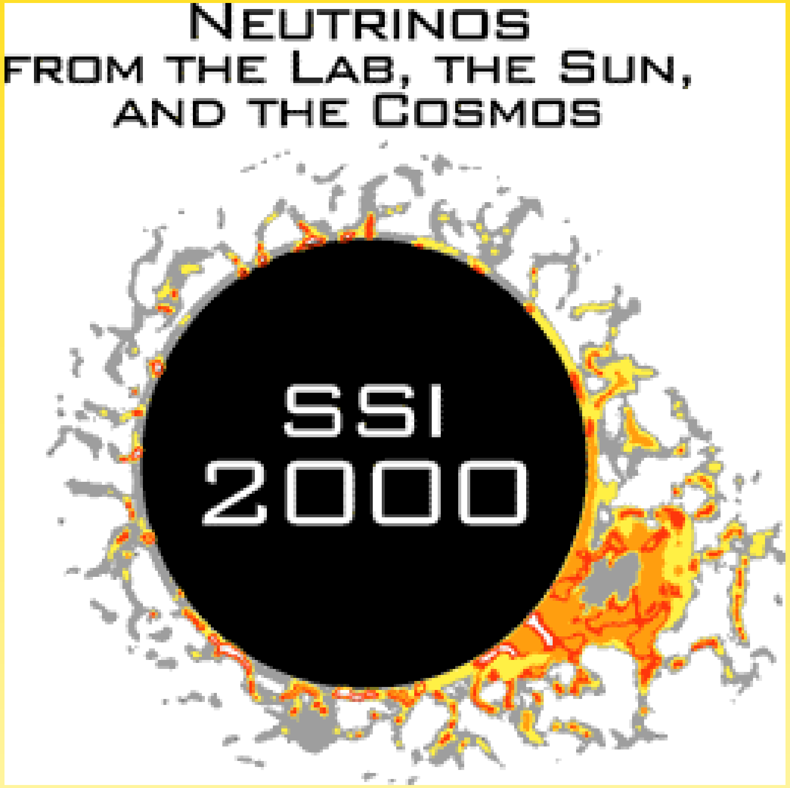
Werner Rodejohann

SSI 2015

17/08/15



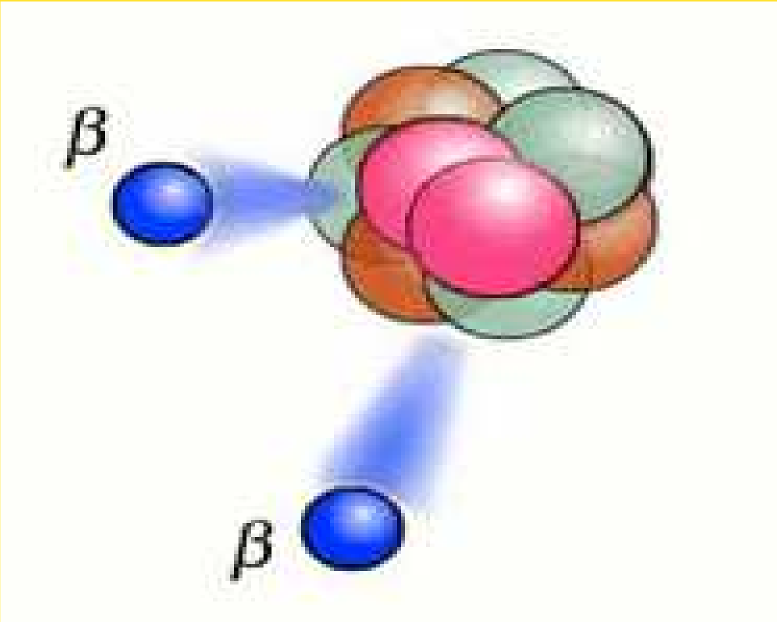
Neutrinos. . .

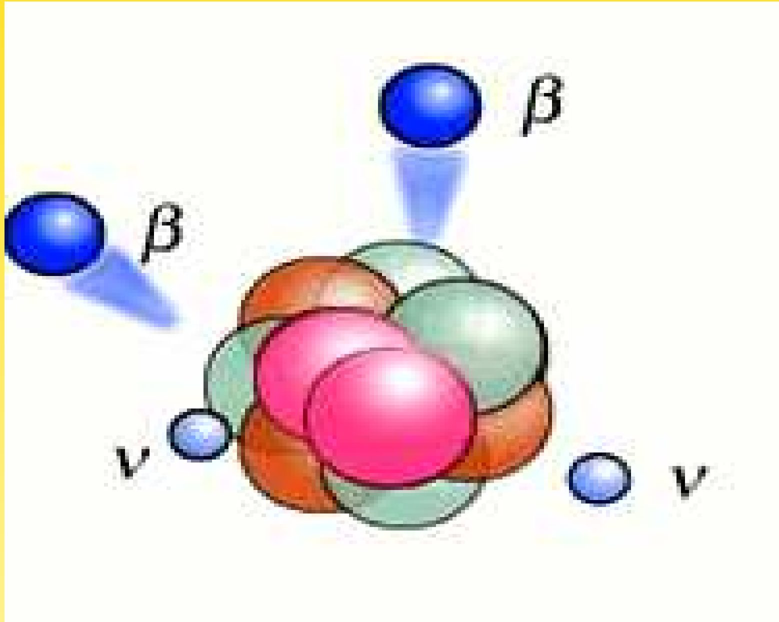


. . .still interesting. . .

What is Neutrinoless Double Beta Decay?

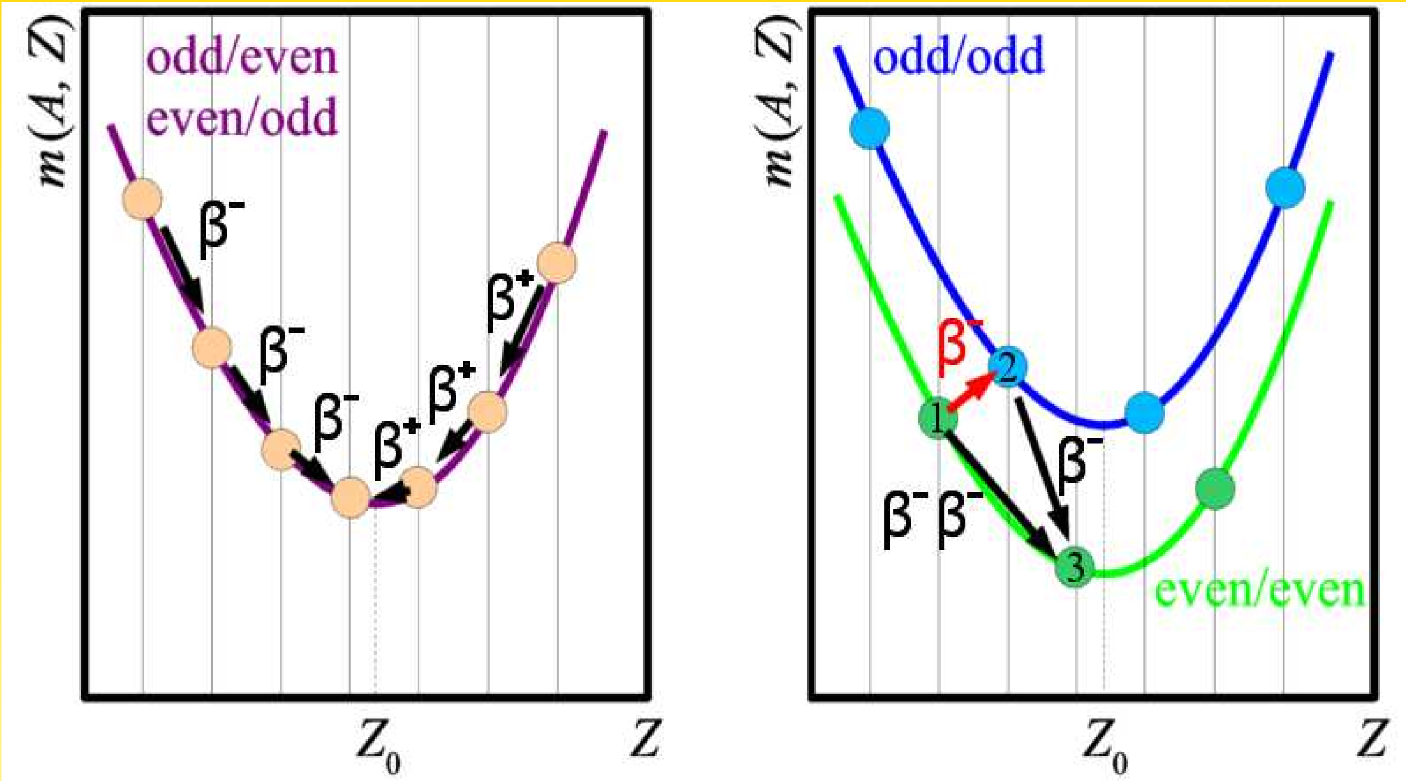
$$(A, Z) \to (A, Z+2) + 2\,e^- \quad (0\nu\beta\beta)$$





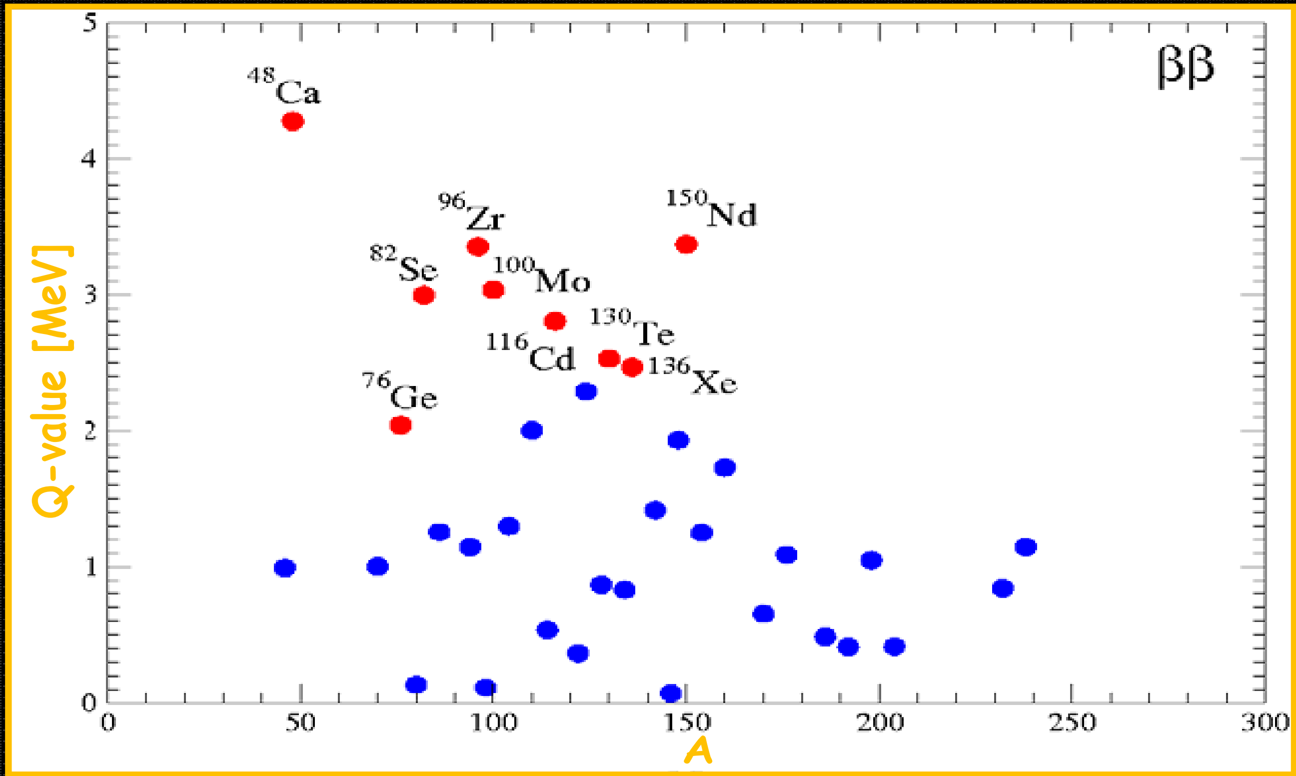
- second order in weak interaction, $\Gamma \propto G_F^4\, Q^5 \Rightarrow$ rare!
- not to be confused with $(A, Z) \to (A, Z+2) + 2\,e^- + 2\,\bar{\nu}_e \quad (2\nu\beta\beta)$ ($\Gamma \propto G_F^4\, Q^{11}$, but occurs more often. . .)

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 $\to$ even/even
- either direct ($0\nu\beta\beta$) or two simultaneous decays with virtual (energetically forbidden) intermediate state ($2\nu\beta\beta$)

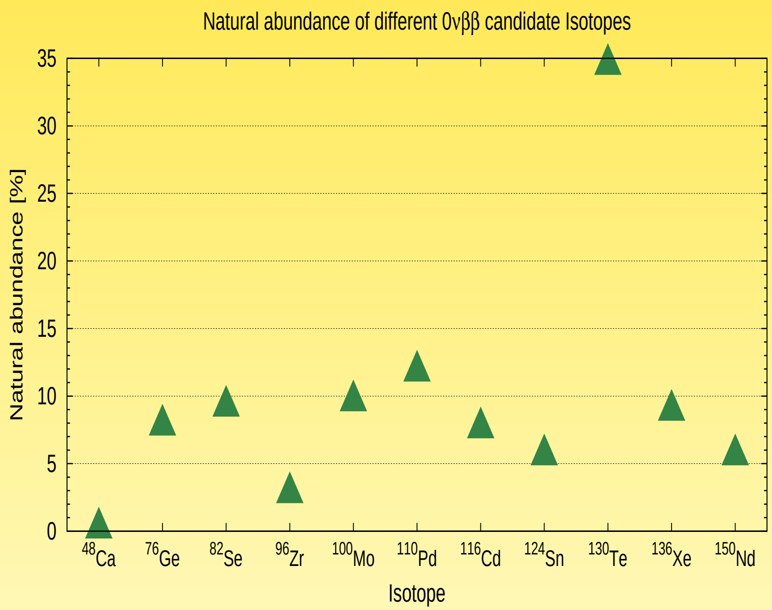
How many nuclei in this condition?



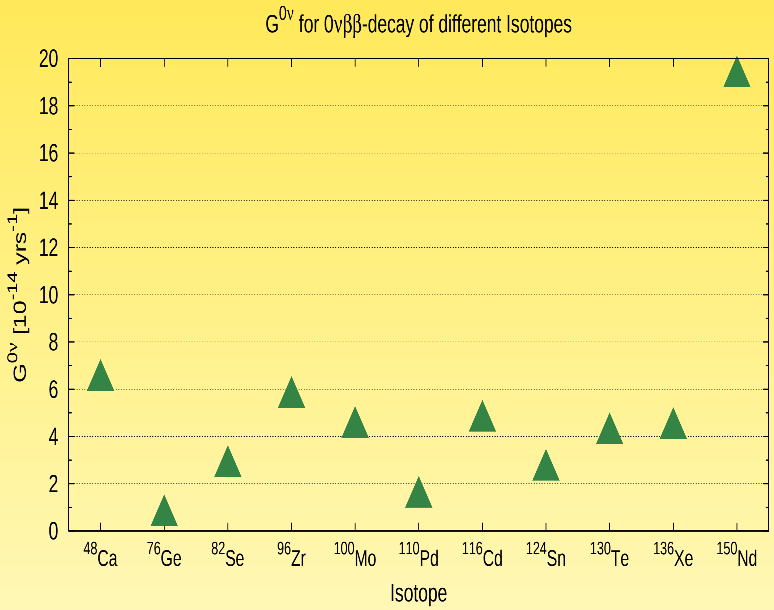
Slide by A. Giuliani, see lecture by Lisa Kaufman

- 35 candidate isotopes
- 10 are interesting: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, ^{150}Nd
- Q-value vs. natural abundance vs. reasonably priced enrichment vs. association with a well controlled experimental technique vs. . .

  $\Rightarrow$ no superisotope



$T^{0\nu}_{1/2} \propto 1/a$



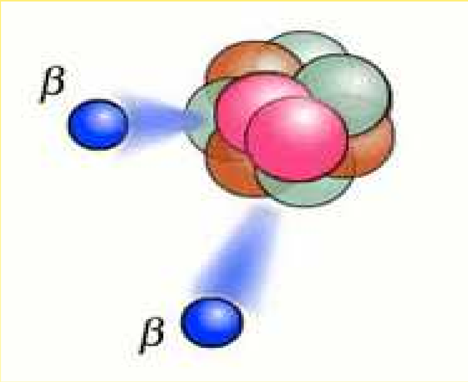
$T^{0\nu}_{1/2} \propto Q^{-5}$

Neutrinoless Double Beta Decay

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

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

Int. J. Mod. Phys. **E20**, 1833 (2011) [1106.1334]; J. Phys. **G39**, 124008 (2012) [1206.2560]; 1507.00170



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 $J_\mu^B = \sum \overline{q_i}\, \gamma_\mu\, q_i$ 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 **NOT** a neutrino mass experiment!!

Upcoming/running experiments: exciting time!!

best limit was from 2001, improved 2012

Name	Isotope	Source = Detector; calorimetric with high ΔE	low ΔE	topology	Source $\neq$ Detector topology
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA	^{116}Cd (and ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
CUPID	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LUCIFER	^{82}Se / ^{100}Mo / ^{130}Te	✓	–	–	–
LUMINEU	^{100}Mo	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se / ^{100}Mo / ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+	^{130}Te	–	✓	–	–
SuperNEMO	^{82}Se / ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

see lecture by Lisa Kaufman

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

Interpretation of Experiments

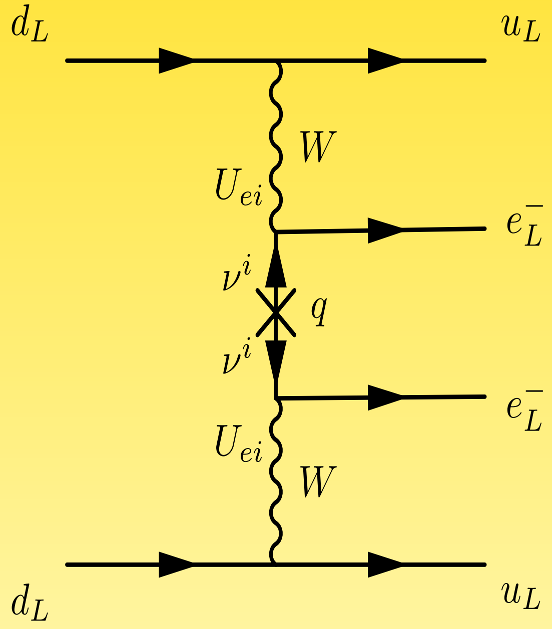
Master formula:

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

- $G_x(Q,Z)$: phase space factor, typically Q^5
- $\mathcal{M}_x(A,Z)$: nuclear physics; factor 2-3 uncertainty
- η_x: particle physics; many possibilities

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



prediction of $(100 - \epsilon)$ % of all neutrino mass mechanisms

(lecture by Andre De Gouvea)

Paths to Neutrino Mass

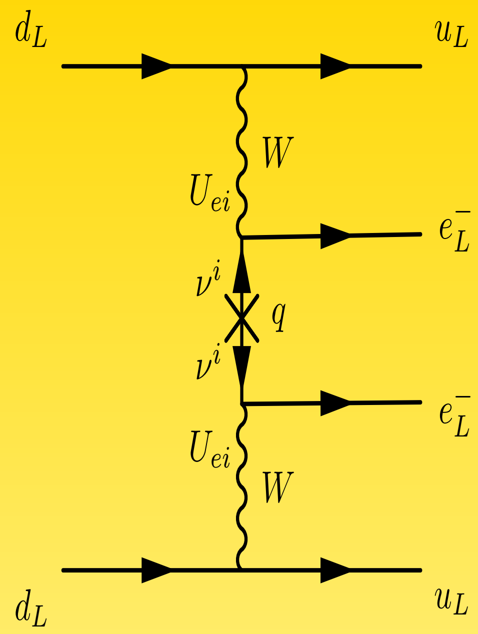
approach	ingredient	quantum number of messenger	$\mathcal{L}$	m_ν	scale
"SM" (Dirac mass)	**RH ν**	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L$	$h v$	$h = \mathcal{O}(10^{-12})$
"effective" (dim 5 operator)	**new scale + LNV**	–	$h \, \overline{L^c} \, \Phi \, \Phi \, L$	$\frac{h \, v^2}{\Lambda}$	$\Lambda = 10^{14}$ **GeV**
"direct" (type II seesaw)	**Higgs triplet + LNV**	$\Delta \sim (3,-2)$	$h \overline{L^c} \Delta L + \mu \Phi \Phi \Delta$	$h v_T$	$\Lambda = \frac{1}{h\mu} M_\Delta^2$
"indirect 1" (type I seesaw)	**RH ν + LNV**	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L + \overline{N_R} M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h} M_R$
"indirect 2" (type III seesaw)	**fermion triplets + LNV**	$\Sigma \sim (3,0)$	$h \overline{\Sigma} \, L \Phi + \mathrm{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

plus seesaw variants (linear, double, inverse,...)

plus radiative mechanisms

plus extra dimensions

plusplusplus



- U_{ei}^2 from charged current
- m_i/E_i from spin-flip and *if neutrinos are Majorana particles*

amplitude proportional to coherent sum **("effective mass")**

$$|m_{ee}| = \left|\sum U_{ei}^2\, m_i\right|$$

$m/E \simeq$ eV/100 MeV is tiny: only N_A can save the day!

Dirac vs. Majorana

in $V - A$ theories: observable difference **always** suppressed by $(m/E)^2$

- In terms of degrees of freedom (helicity and particle/antiparticle): $\nu_\mathrm{D} = (\nu_\uparrow, \nu_\downarrow, \bar{\nu}_\uparrow, \bar{\nu}_\downarrow)$ versus $\nu_\mathrm{M} = (\nu_\uparrow, \nu_\downarrow)$
- weak interactions act on chirality (left-/right-handed)
- chirality is not a good quantum number ("spin flip"): $L = \downarrow + \frac{m}{E} \uparrow$
- Dirac:
  - what we produce from a W^- is $\ell^-(\bar{\nu}_\uparrow + \frac{m}{E}\bar{\nu}_\downarrow)$
  - the $\bar{\nu}_\downarrow$ CANNOT interact with another W^- to generate another ℓ^-: $\Delta L = 0$
- Majorana:
  - what we produce from a W^- is $\ell^-(\nu_\uparrow + \frac{m}{E}\nu_\downarrow)$
  - the $\nu_\downarrow$ CAN interact with another W^- to generate another ℓ^-: $\Delta L = 2$

$\Rightarrow$ amplitude $\propto (m/E) \Rightarrow$ probability $\propto (m/E)^2$

Dirac vs. Majorana

- Z-decay:

$$\frac{\Gamma(Z \to \nu_{\rm D}\nu_{\rm D})}{\Gamma(Z \to \nu_{\rm M}\nu_{\rm M})} \simeq 1 - 3\frac{m_\nu^2}{m_Z^2}$$

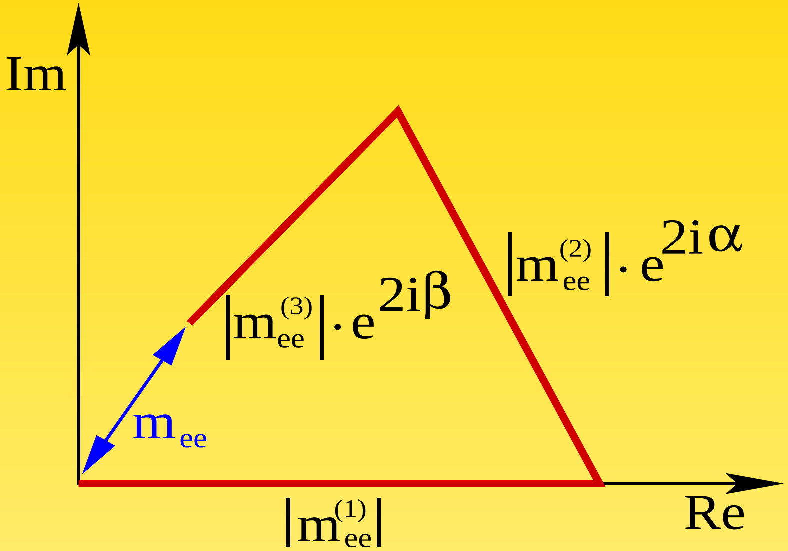
- Meson decays

$${\rm BR}(K^+ \to \pi^- \, e^+ \, \mu^+) \propto |m_{e\mu}|^2 = \left|\sum U_{ei} \, U_{\mu i} \, m_i\right|^2 \sim 10^{-30} \, \left(\frac{|m_{e\mu}|}{\rm eV}\right)^2$$

- neutrino-antineutrino oscillations

$$P(\nu_\alpha \to \bar{\nu}_\beta) = \frac{1}{E^2} \left| \sum_{i,j} U_{\alpha j} U_{\beta j} U_{\alpha i}^* U_{\beta i}^* \, m_i m_j \, \mathsf{e}^{-i(E_j - E_i)t} \right|$$

The effective mass



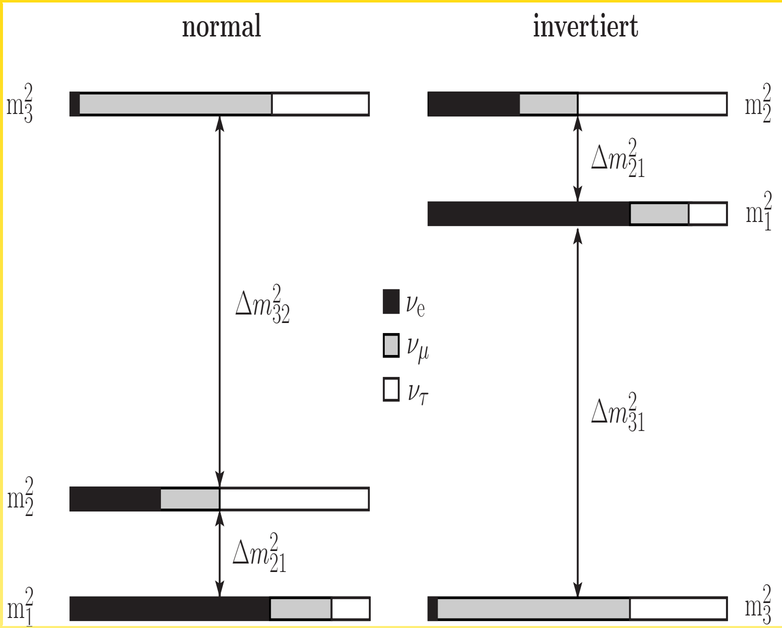
Amplitude proportional to coherent sum (<u>"effective mass"</u>):

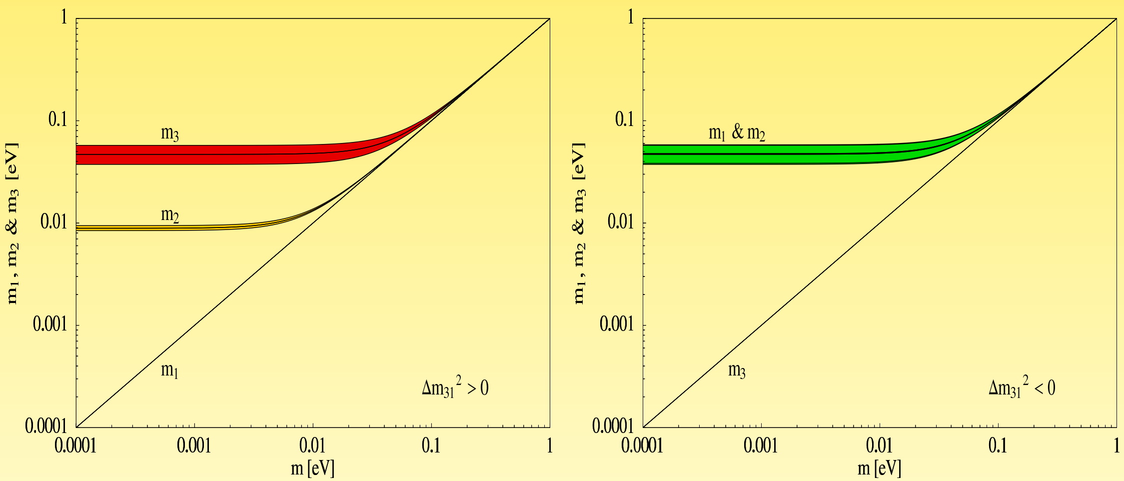
$$|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|$$

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

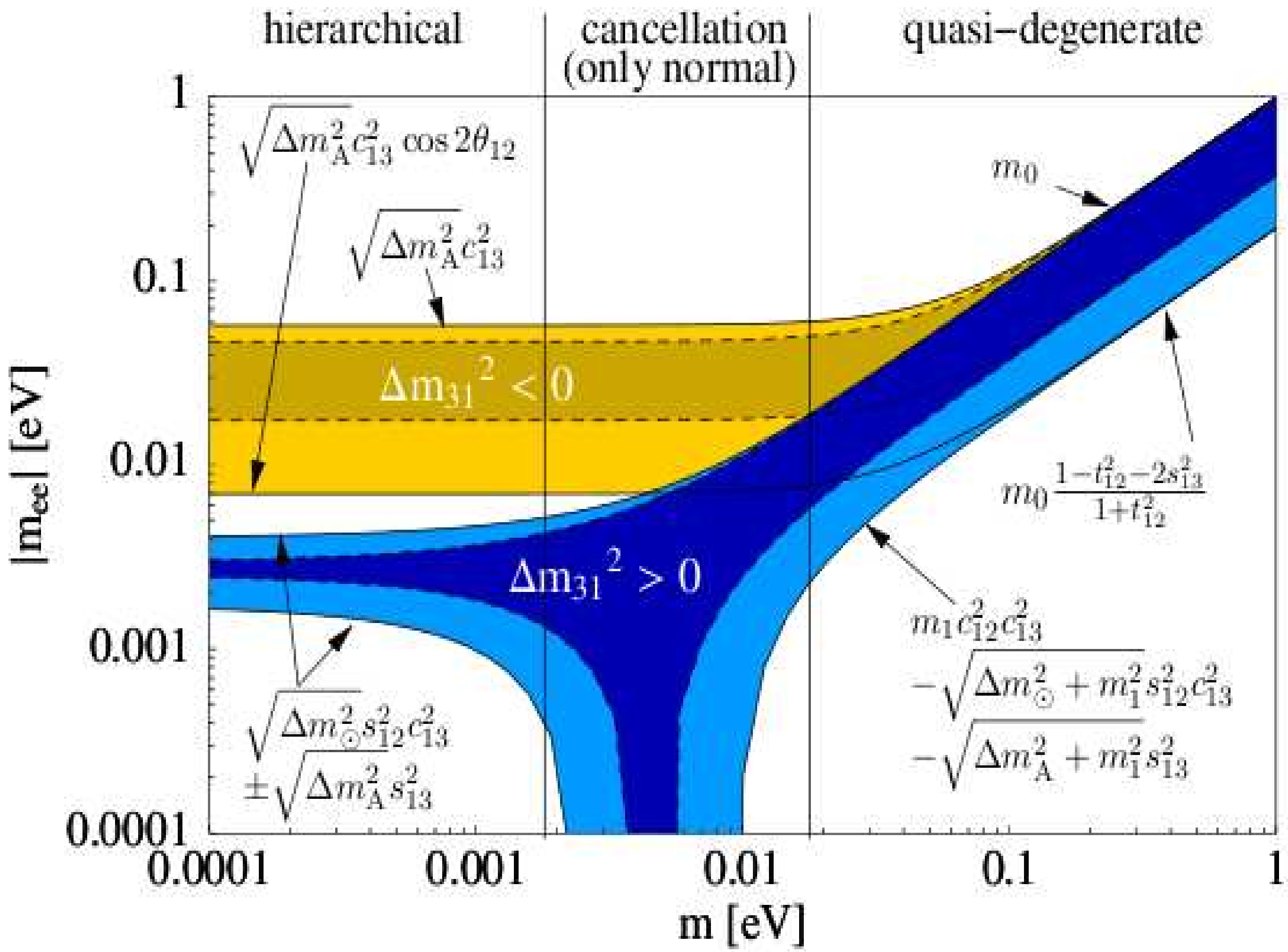
7 out of 9 parameters of neutrino physics!

Fix known things, vary unknown things. . .



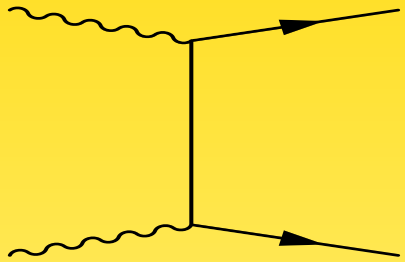


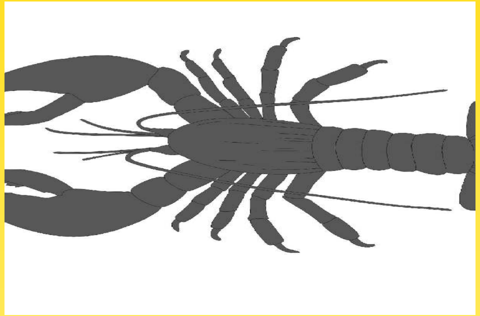
The usual plot



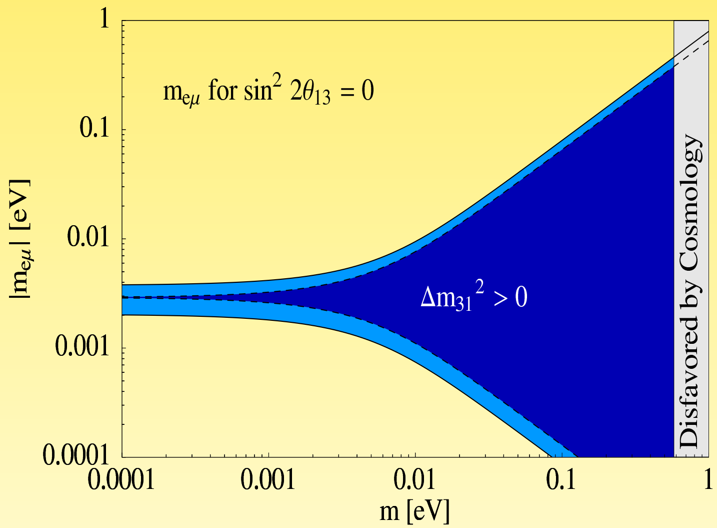
Alternative processes

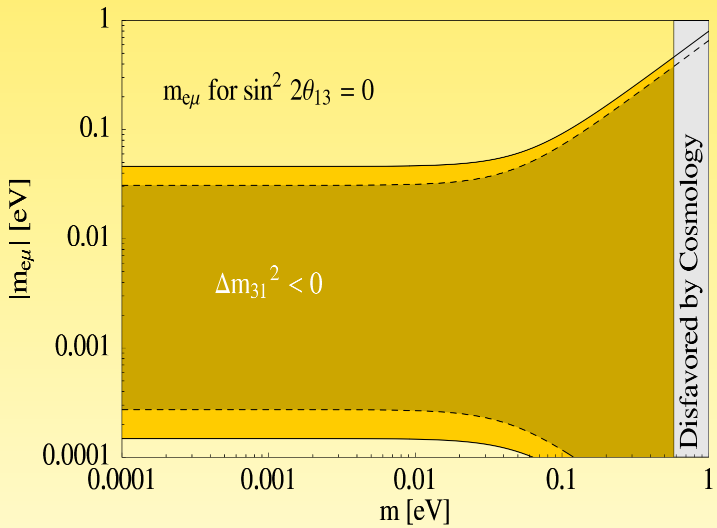
The lobster:





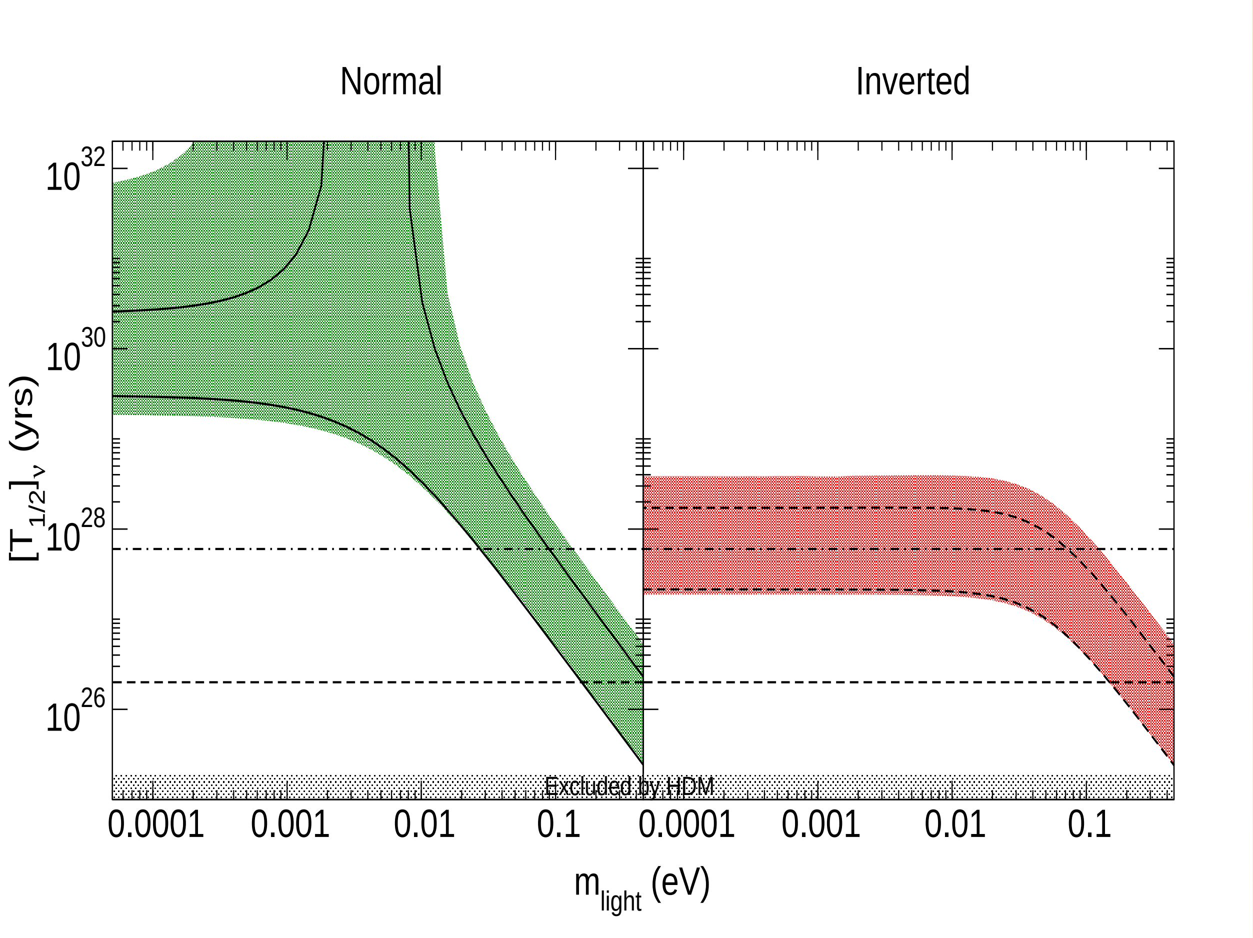
$$\mathrm{BR}(K^+ \to \pi^- \, e^+ \, \mu^+) \propto |m_{e\mu}|^2 = \left| \sum U_{ei} \, U_{\mu i} \, m_i \right|^2 \sim 10^{-30} \left(\frac{|m_{e\mu}|}{\mathrm{eV}} \right)^2$$





The usual plot

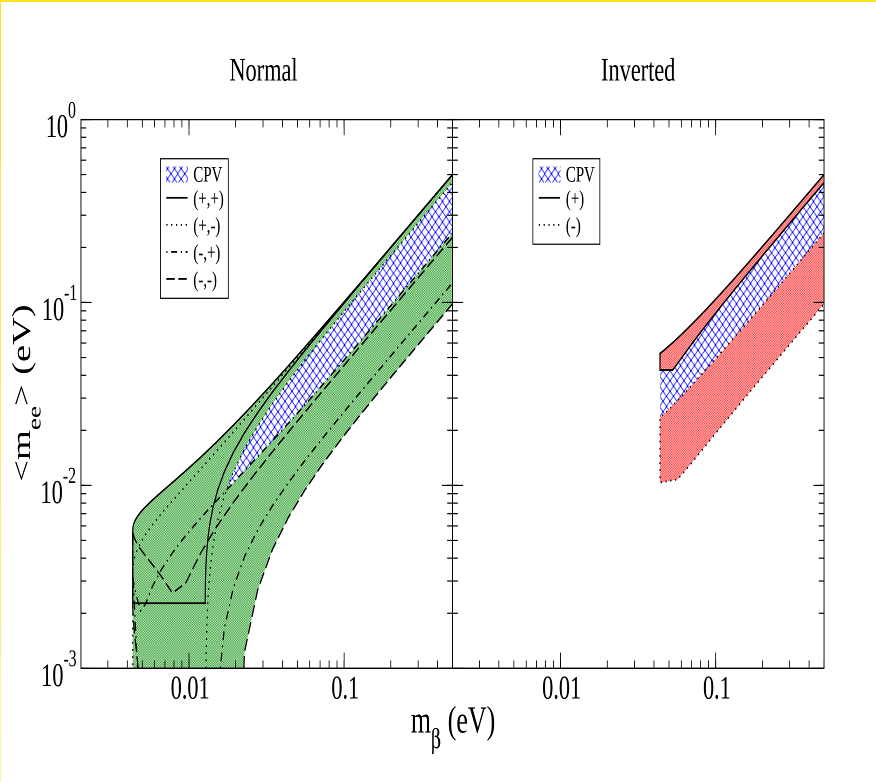
(life-time instead of $|m_{ee}|$)

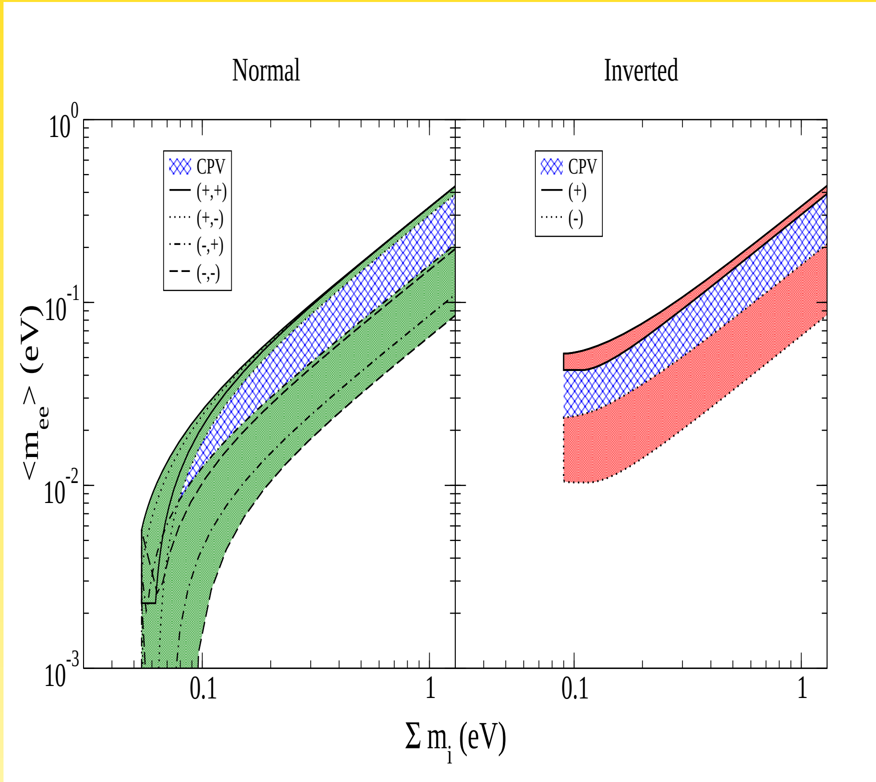


Which mass ordering with which life-time?

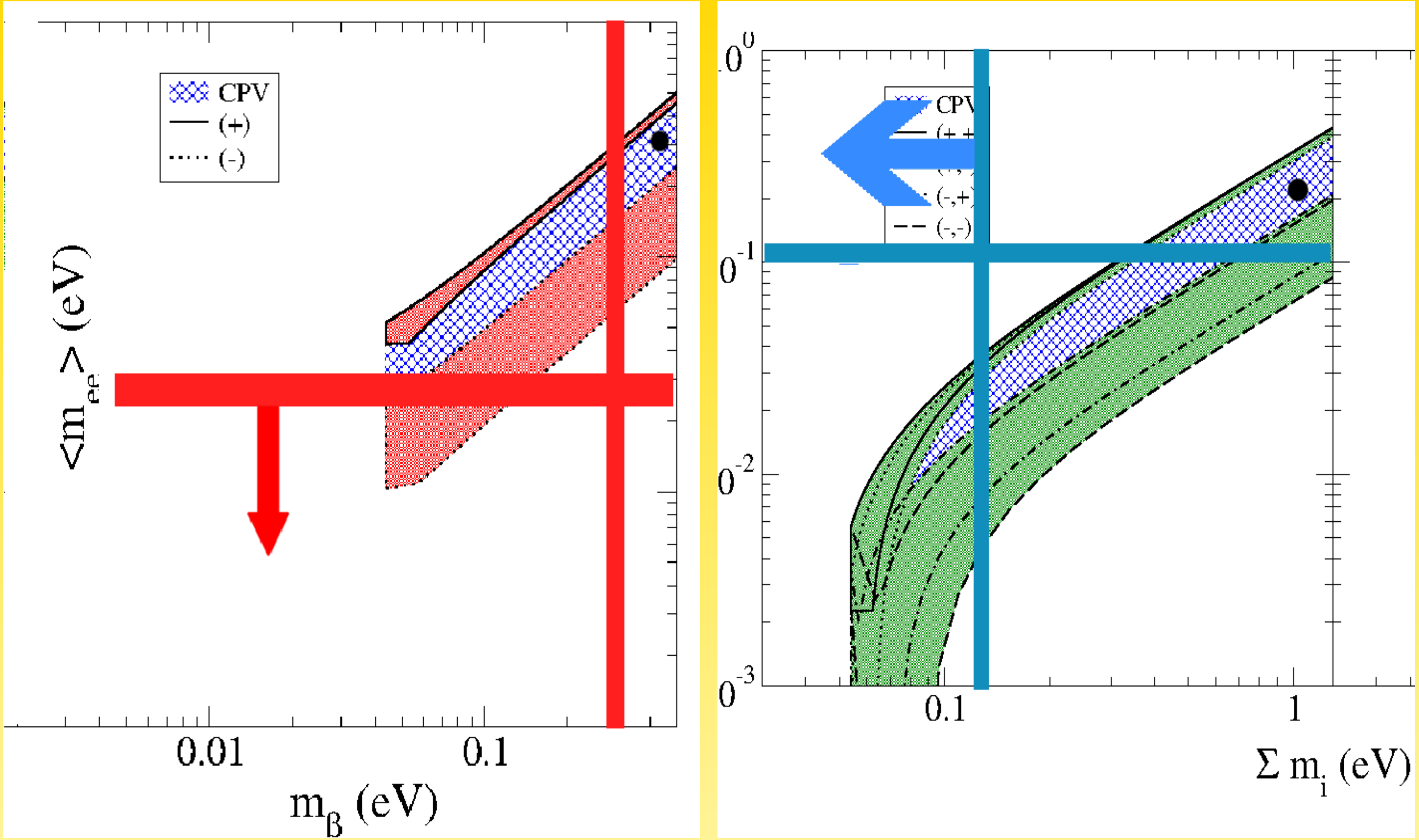
	Σ	m_β	$\lvert m_{ee}\rvert$
NH	$\sqrt{\Delta m_{\rm A}^2}$	$\sqrt{\Delta m_\odot^2 + \lvert U_{e3}\rvert^2 \Delta m_{\rm A}^2}$	$\left\lvert \sqrt{\Delta m_\odot^2} + \lvert U_{e3}\rvert^2 \sqrt{\Delta m_{\rm A}^2}\, e^{2i(\alpha-\beta)} \right\rvert$
	$\simeq 0.05$ eV	$\simeq 0.01$ eV	~ 0.003 eV $\Rightarrow T_{1/2}^{0\nu} \gtrsim 10^{28-29}$ 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

Plot against other observables





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



CP violation!

Dirac neutrinos!

something else does $0\nu\beta\beta$!

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	$\sqrt{\sum \|U_{ei}\|^2 m_i^2}$	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.
$0\nu\beta\beta$	$\|\sum U_{ei}^2 m_i\|$	0.3	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

see lectures by Alessandro Melchiorri and Joe Formaggio

Recent Results

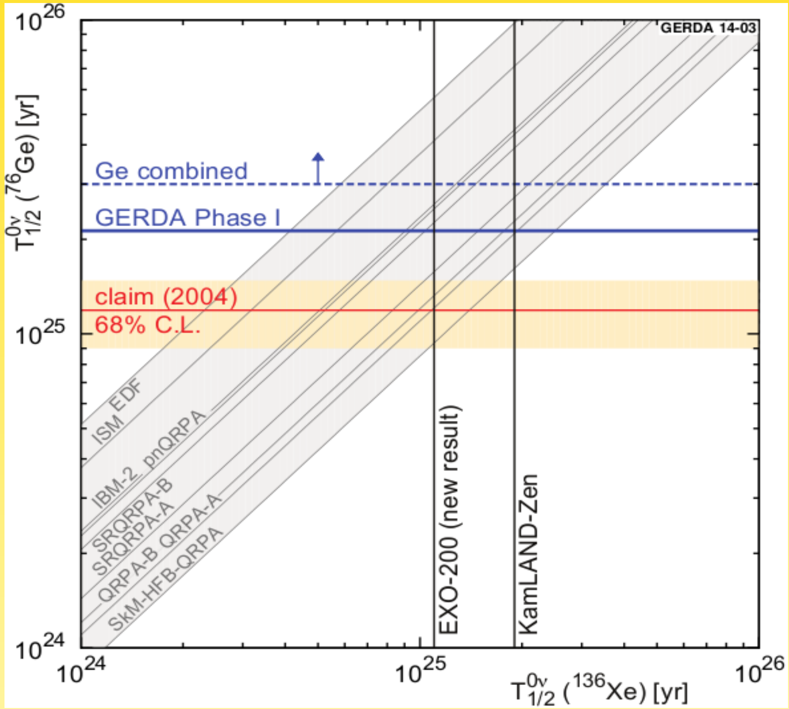
- ^{76}Ge:
  - GERDA: $T_{1/2} > 2.1 \times 10^{25}$ yrs
  - GERDA + IGEX + HDM: $T_{1/2} > 3.0 \times 10^{25}$ yrs
- ^{136}Xe:
  - EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yrs **(first run with less exposure:** $T_{1/2} > 1.6 \times 10^{25}$ **yrs. . .)**
  - KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$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

Xe-limit is stronger than Ge-limit when:

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

Current Limits on $|m_{ee}|$

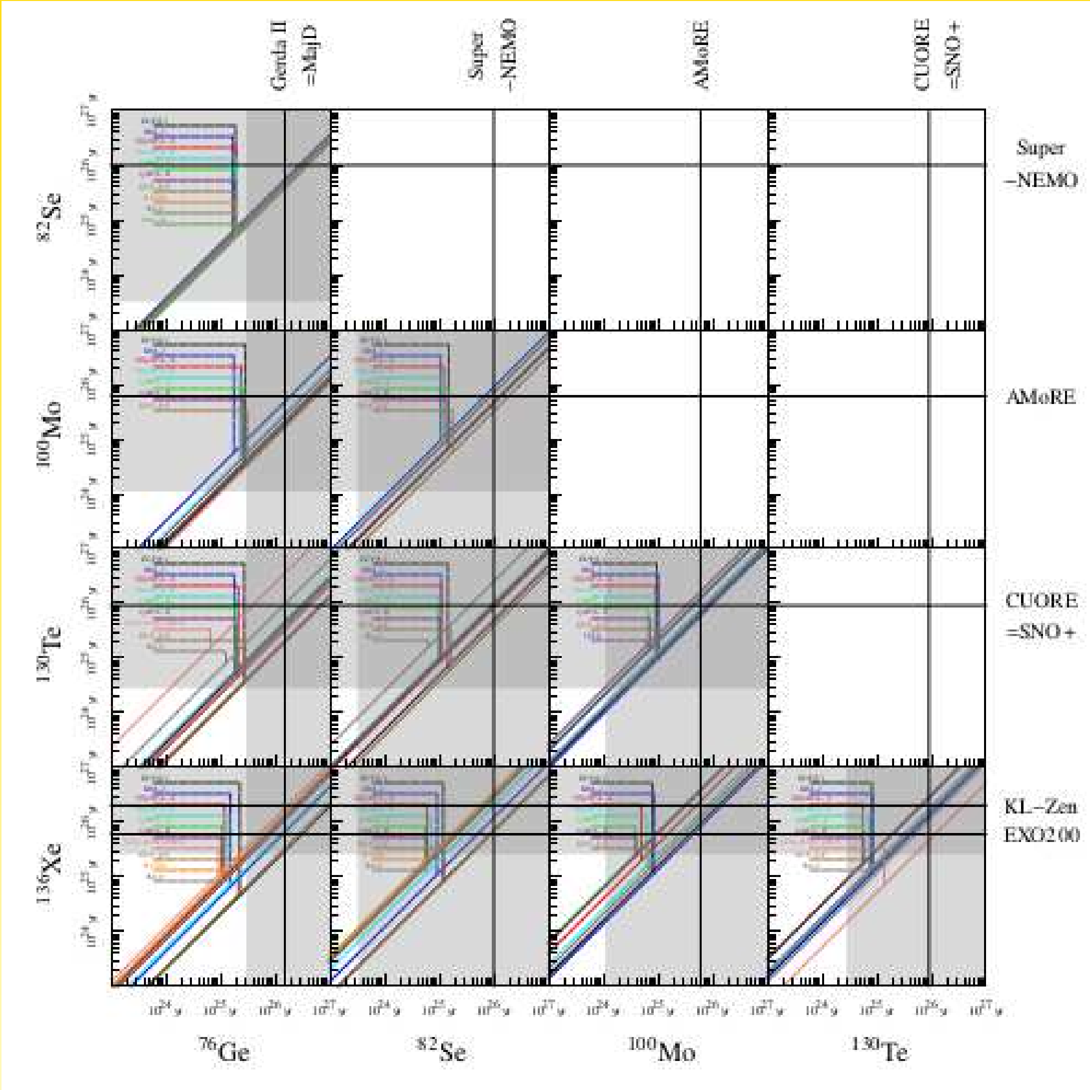
NME	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	**0.32**	**0.27**	**0.13**	–
ISM(U)	**0.52**	**0.44**	**0.24**	–
IBM-2	**0.27**	**0.23**	**0.16**	–
pnQRPA(U)	**0.28**	**0.24**	**0.17**	–
SRQRPA-A	**0.31**	**0.26**	**0.23**	–
QRPA-A	*0.28*	*0.24*	*0.25*	–
SkM-HFB-QRPA	*0.29*	*0.24*	*0.28*	–



GERDA

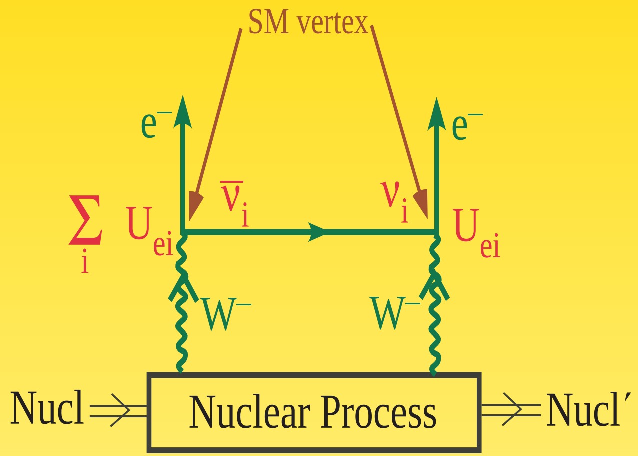
Bhupal Dev, Goswami, Mitra, W.R., Phys. Rev. **D88**

Generalization. . .



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 $q \simeq 1/r \simeq 0.1$ GeV
- NME $\leftrightarrow$ overlap of decaying nucleons...
- different approaches (QRPA, NSM, IBM, GCM, pHFB) imply uncertainty
- plus uncertainty due to model details

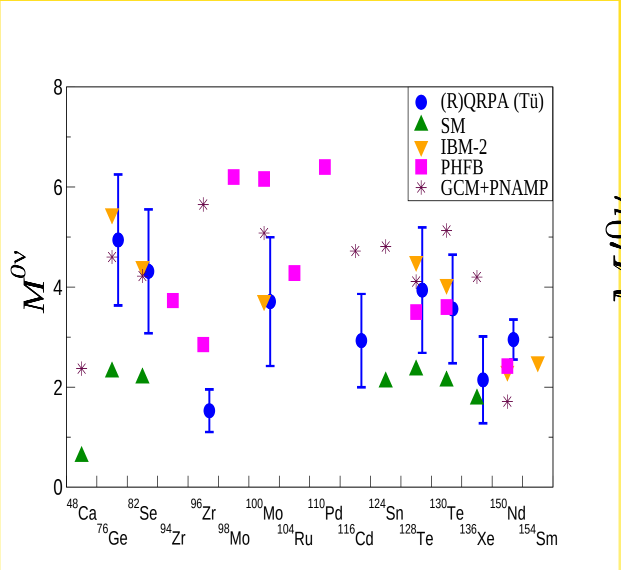
typical model for NME: set of single particle states with a number of possible wave function configurations; obtained by solving Dirac equation in a mean background field; interaction known, treatment of fields differs

- 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)**
- Generating Coordinate Method (GCM) **(many single particle states, few configurations)**
- projected Hartree-Fock-Bogoliubov model (pHFB)

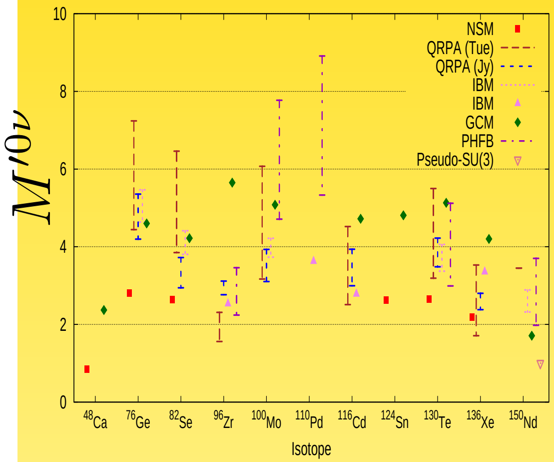
tends to overestimate NMEs

tends to underestimate NMEs

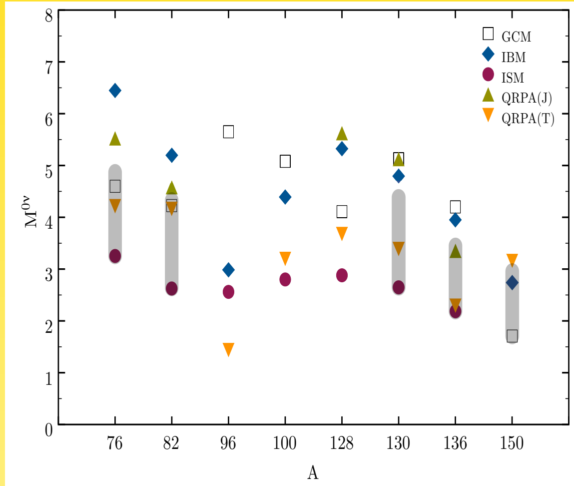
From life-time to particle physics: Nuclear Matrix Elements



Faessler, 1104.3700

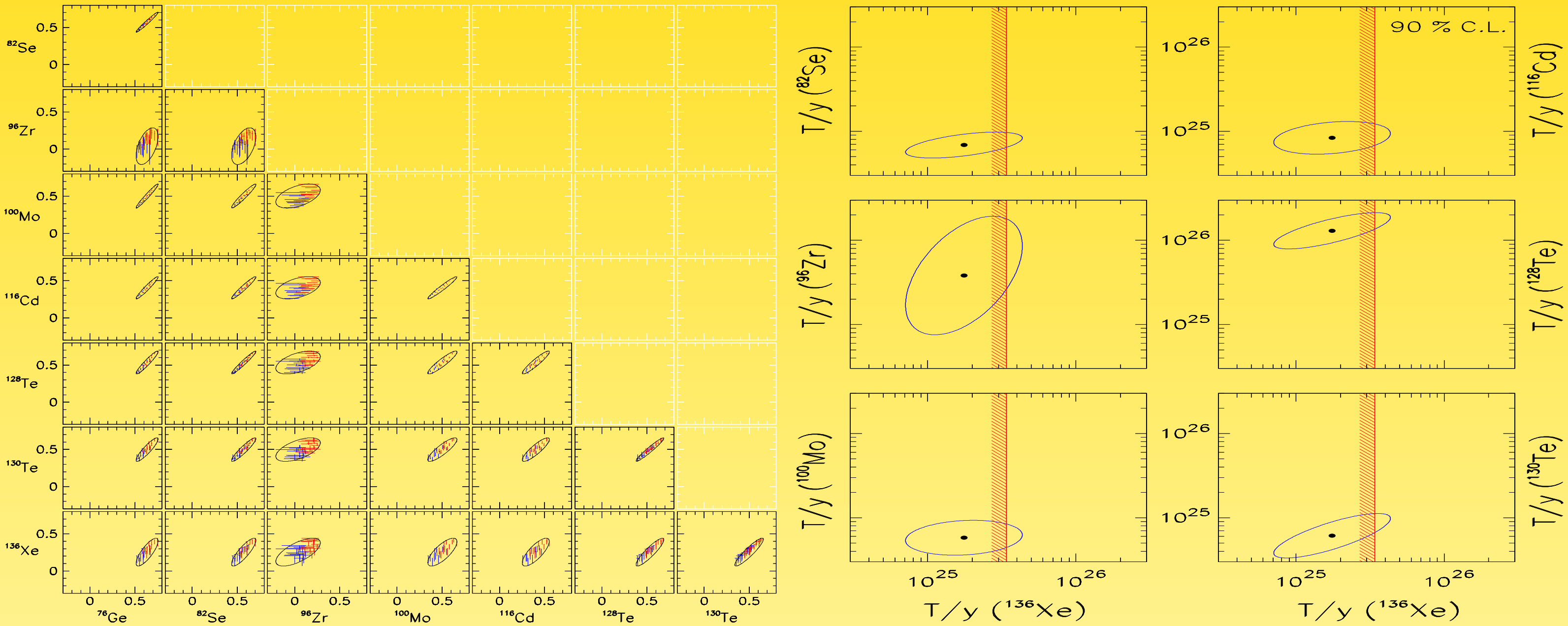


Dueck, W.R., Zuber, PRD **83**



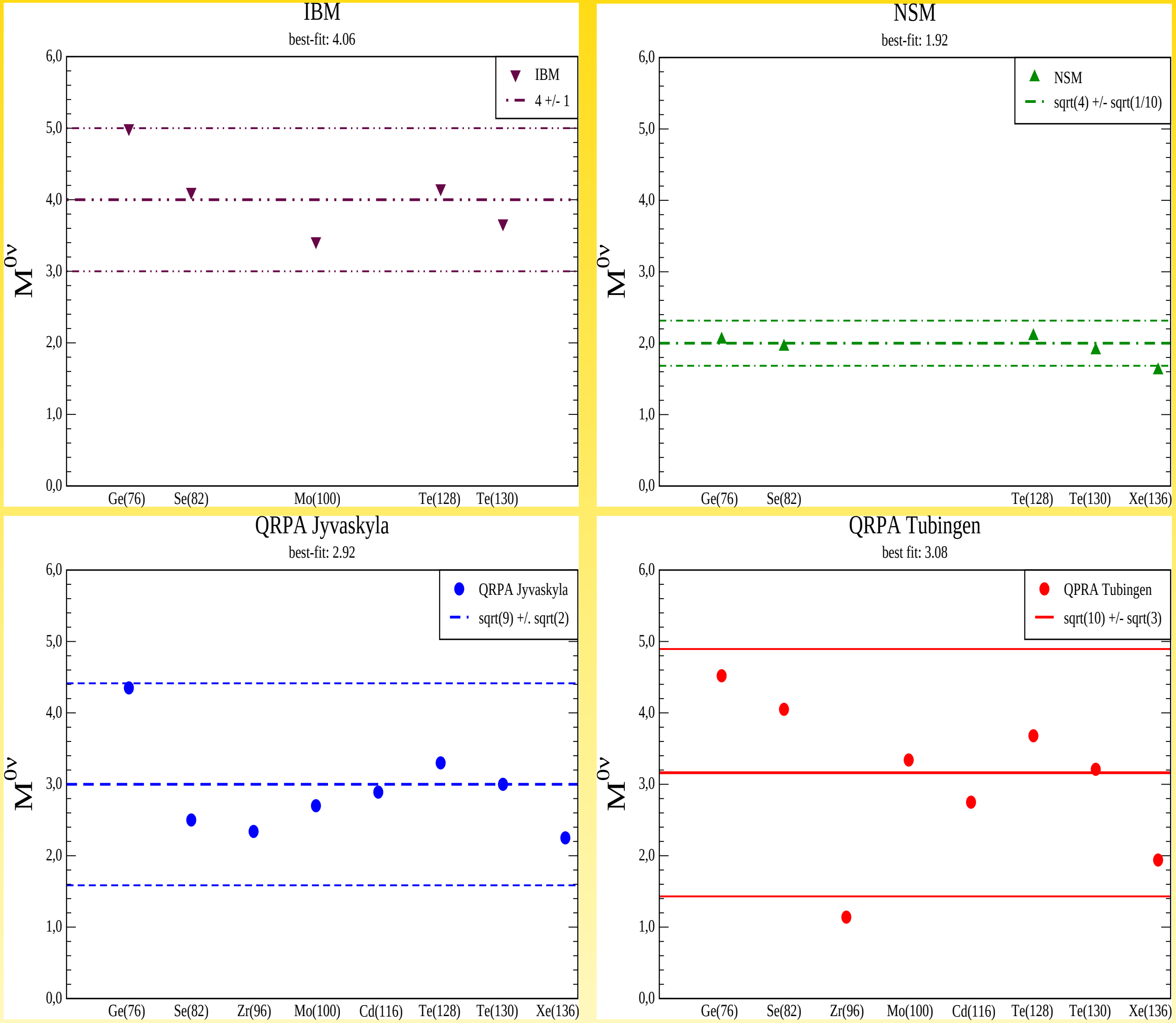
Gomez-Cadenas *et al.*, 1109.5515

to better estimate error range: correlations need to be understood



Faessler, Fogli *et al.*, PRD **79+87**

NMEs are order one numbers :-)



Experimental Aspect

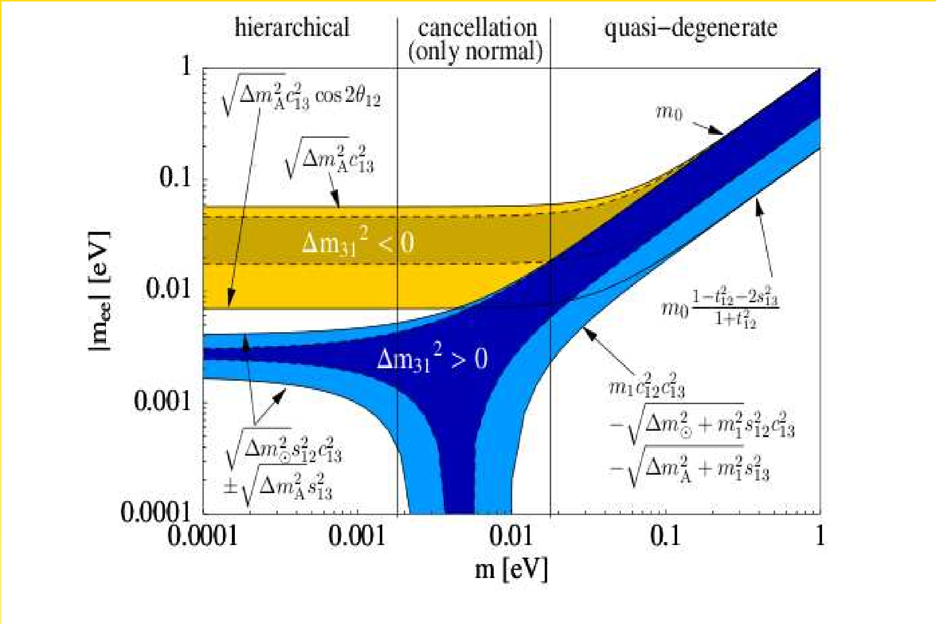
$$(T^{0\nu}_{1/2})^{-1} \propto \begin{cases} a\,M\,\varepsilon\,t & \text{without background} \\ a\,\varepsilon\,\sqrt{\dfrac{M\,t}{B\,\Delta E}} & \text{with background} \end{cases}$$

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 $M \times t \times B \times \Delta E$

Inverted Ordering



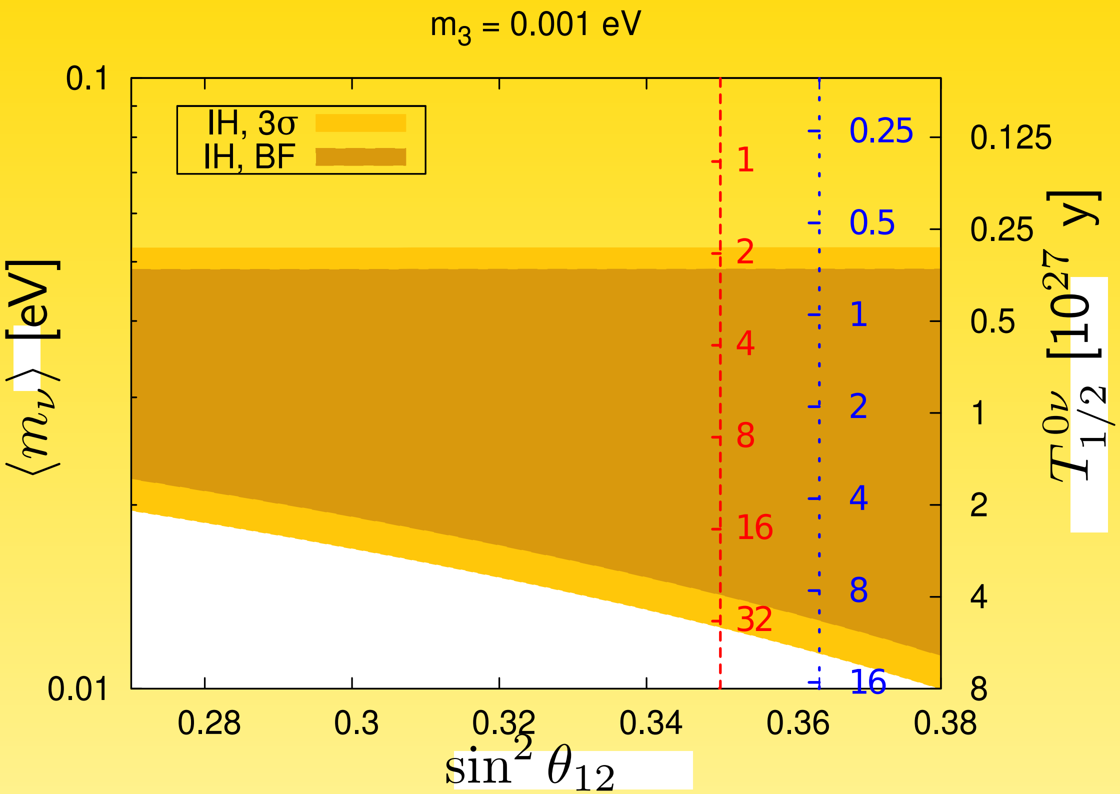
Nature provides 2 scales:

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

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

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

Inverted Hierarchy

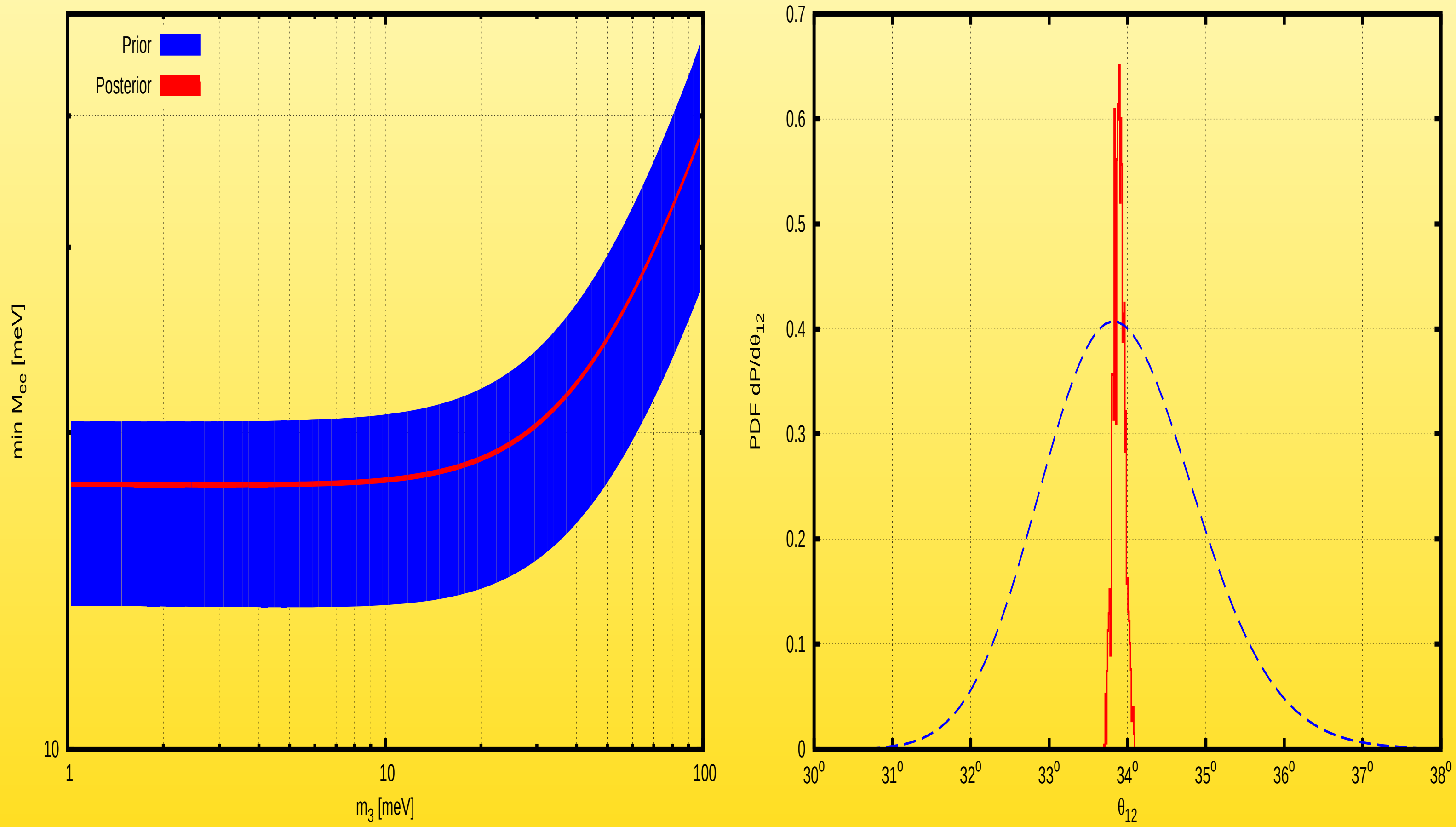


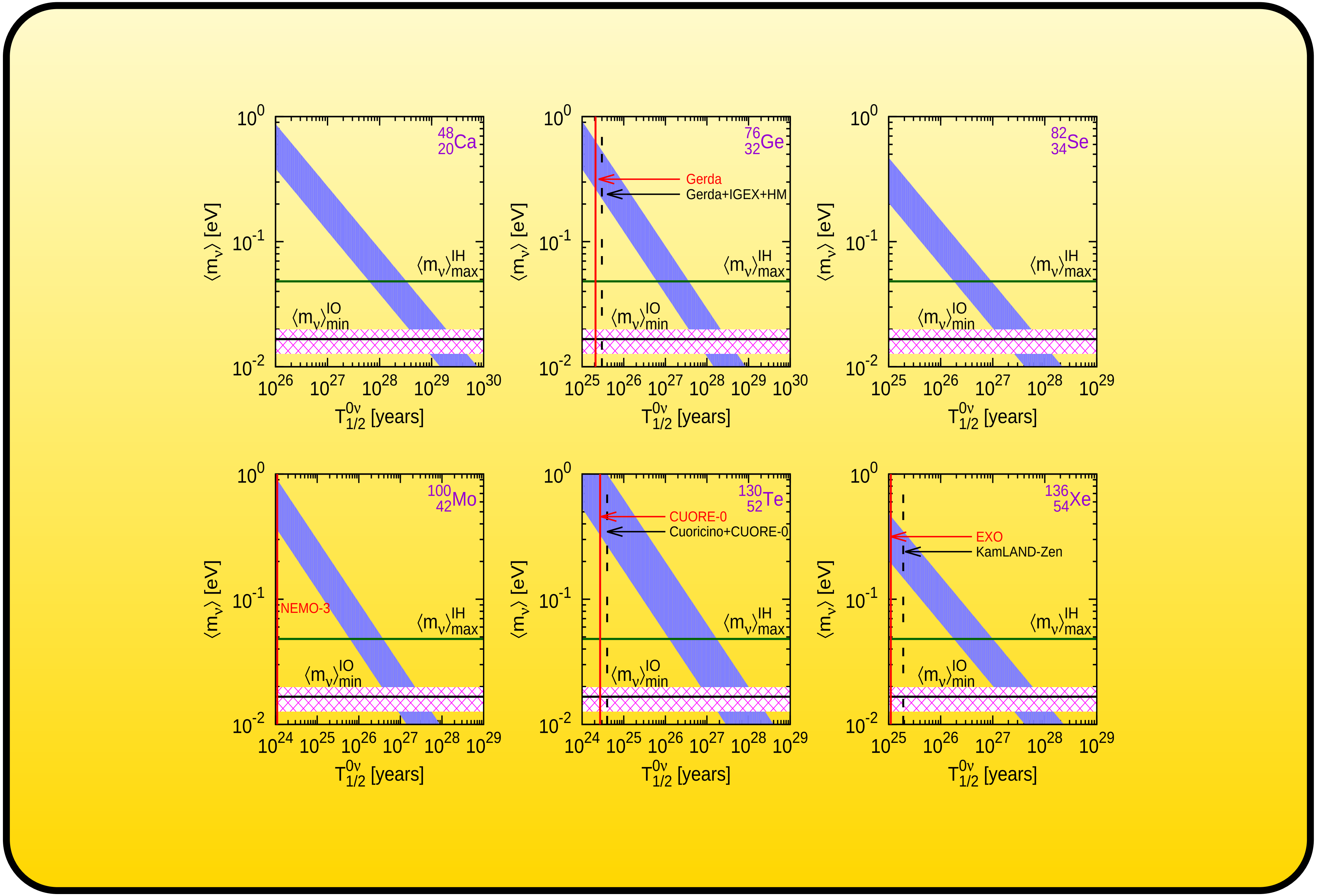
Current 3σ range of $\sin^2\theta_{12}$ gives factor of ~ 2 uncertainty for $|m_{ee}|^{\rm IH}_{\rm min}$

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

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

Dueck, W.R., Zuber, PRD **83**; Ge, W.R., 1507.05514


Prior
Posterior
min Mee [meV]
10
1
10
100
m3 [meV]
PDF dP/dθ12
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
30⁰
31⁰
32⁰
33⁰
34⁰
35⁰
36⁰
37⁰
38⁰
θ12



48 20 Ca
76 32 Ge
82 34 Se
100 42 Mo
130 52 Te
136 54 Xe
Gerda
Gerda+IGEX+HM
CUORE-0
Cuoricino+CUORE-0
EXO
KamLAND-Zen
NEMO-3
$\langle m_\nu \rangle^{IH}_{max}$
$\langle m_\nu \rangle^{IO}_{min}$
$\langle m_\nu \rangle$ [eV]
$T^{0\nu}_{1/2}$ [years]

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

- test lepton number violation
- test Majorana nature of neutrinos
- probe neutrino mass scale
- extract Majorana phase
- constrain inverted ordering

conceptually, it would increase our believe in

- GUTs
- seesaw mechanism
- leptogenesis

Sterile Neutrinos??

- LSND/MiniBooNE/gallium
- cosmology
- BBN
- r-process nucleosynthesis in Supernovae
- reactor anomaly

	$\Delta m^2_{41}[\mathrm{eV}^2]$	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\Delta m^2_{51}[\mathrm{eV}^2]$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$
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

see lectures by William Louis and Karsten Heeger

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):

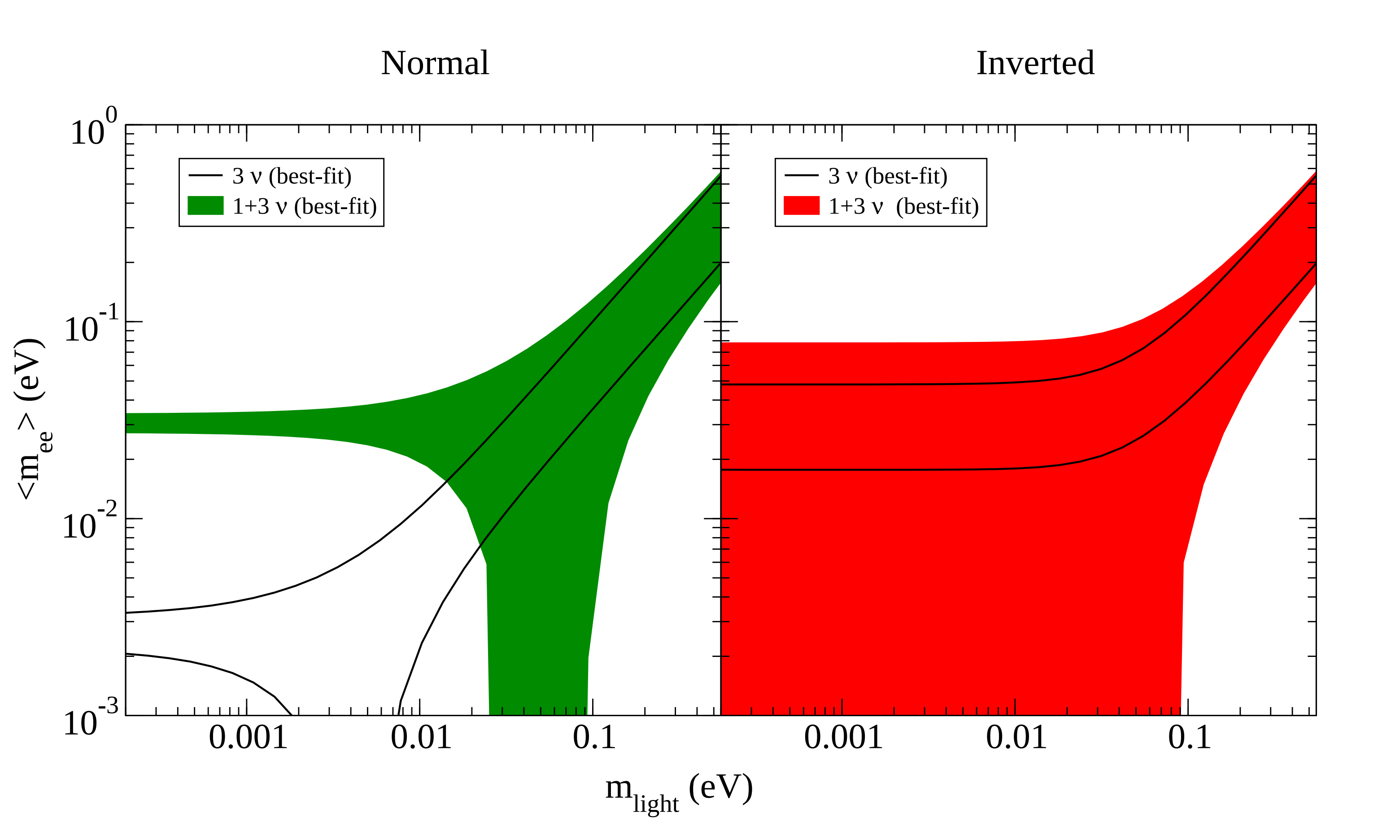
$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}} \, |U_{e4}|^2 \begin{cases} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{cases}$$

$\Rightarrow$ $|m_{ee}|_{\rm NH}$ 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, JHEP **1311**; Giunti, Zavanin, 1505.00978

Usual plot gets completely turned around!



Interpretation of Neutrino-less Double Beta Decay

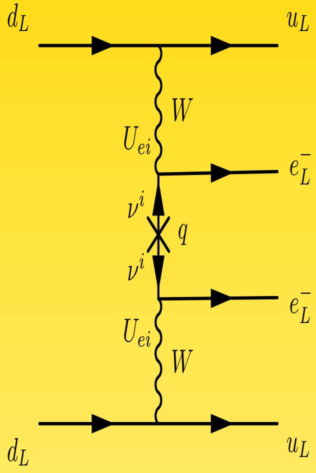
- **Standard Interpretation:**

  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

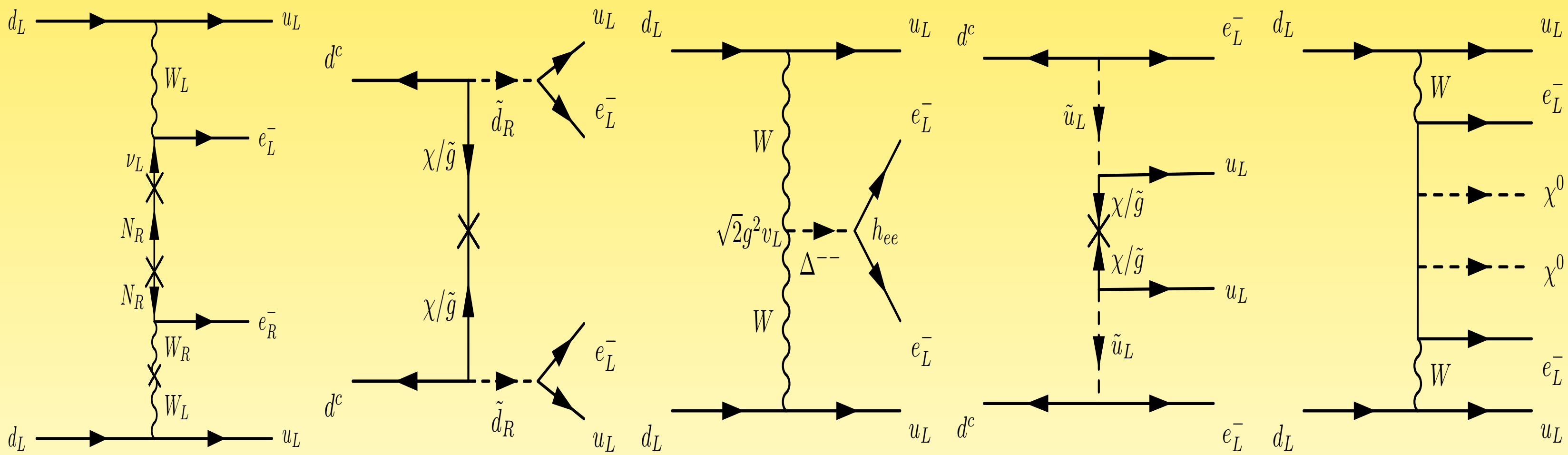
- **Non-Standard Interpretations:**

  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

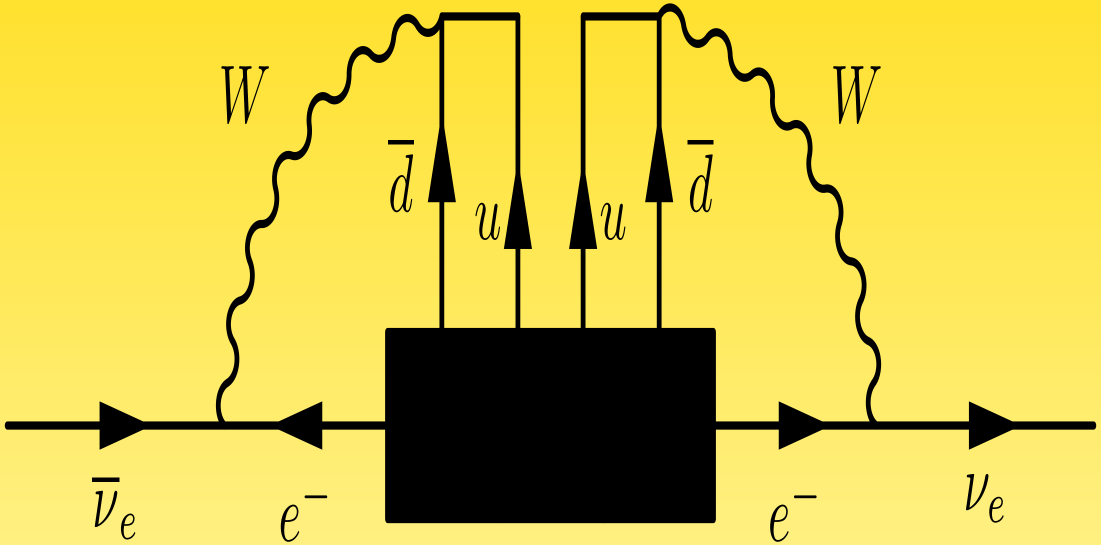
- **Standard Interpretation:**



- **Non-Standard Interpretations:**



Schechter-Valle theorem: observation of $0\nu\beta\beta$ implies Majorana neutrinos



is 4 loop diagram: $m_\nu^{\rm BB} \sim \dfrac{G_F^2}{(16\pi^2)^4}{\rm MeV}^5 \sim 10^{-25}\,{\rm eV}$

explicit calculation: Duerr, Lindner, Merle, 1105.0901

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left|U_{ei}^2\, m_i\right|$	0.5 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^{-1}	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 $\not{R}$	$\frac{\left|\lambda'^2_{111}\right|}{\Lambda^5_{SUSY}}$ $\Lambda_{SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left|\sin 2\theta^b\, \lambda'_{131}\, \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}}\right)\right|$ $\sim \frac{G_F}{q}\, m_b \frac{\left|\lambda'_{131}\, \lambda'_{113}\right|}{\Lambda^3_{SUSY}}$	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

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:

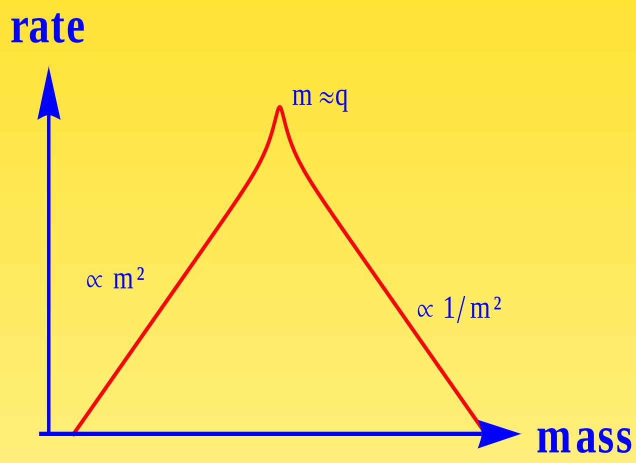
$$\boxed{1 \text{ eV} = 1 \text{ TeV}}$$

$\Rightarrow$ Phenomenology in colliders, LFV

Examples

- Fermions (and no RHC):

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

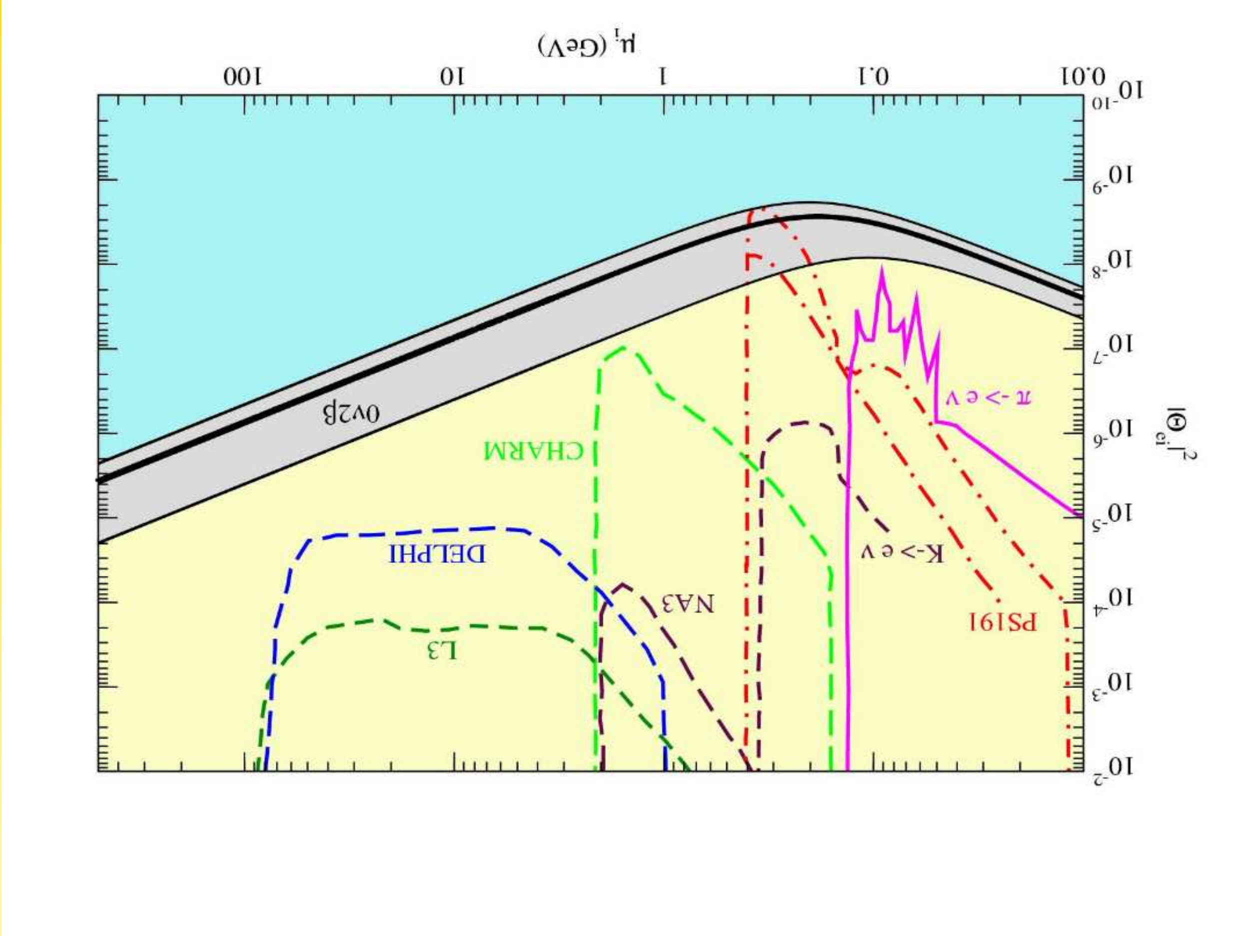


Note: maximum $\mathcal{A}$ corresponds to $m \simeq \langle q \rangle$: limits on $\mathcal{O}(m_K)$ Majorana neutrinos from $K^+ \to \pi^- \mu^+ e^+$

- heavy scalar/vector:

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

Heavy neutrinos



Mitra, Senjanovic, Vissani, 1108.0004

$$T^{0\nu}(1\ \mathrm{eV}) = T^{0\nu}(1\ \mathrm{TeV})$$

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

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

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.) Example Left-Right Symmetry

very simple extension of SM gauge group to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

usual particle content:

$$L_{Li} = \begin{pmatrix} \nu'_L \\ \ell_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, -\mathbf{1})\,, \quad L_{Ri} = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, -\mathbf{1})$$

$$Q_{Li} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \sim (\mathbf{2}, \mathbf{1}, \tfrac{\mathbf{1}}{\mathbf{3}})\,, \quad Q_{Ri} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i \sim (\mathbf{1}, \mathbf{2}, \tfrac{\mathbf{1}}{\mathbf{3}})$$

for symmetry breaking:

$$\Delta_L \equiv \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{3}, \mathbf{1}, \mathbf{2})\,, \quad \Delta_R \equiv \begin{pmatrix} \delta_R^+/\sqrt{2} & \delta_R^{++} \\ \delta_R^0 & -\delta_R^+/\sqrt{2} \end{pmatrix} \sim (\mathbf{1}, \mathbf{3}, \mathbf{2})$$

$$\phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (\mathbf{2}, \mathbf{2}, \mathbf{0})$$

Left-right Symmetry

- very rich Higgs sector (13 extra scalars)
- rich gauge boson sector ($Z', M_{W_R^\pm}$) with
  $M_{Z'} = \sqrt{\frac{2}{1-\tan^2\theta_W}} M_{W_R} \simeq 1.7\, M_{W_R} \gtrsim 4.3\,\mathrm{TeV}$
- 'sterile' neutrinos ν_R
- type I + type II seesaw for neutrino mass
- right-handed currents with strength $G_F \left(\frac{g_R}{g_L}\right)^2 \left(\frac{m_W}{M_{W_R}}\right)^2$
- $m_\nu \propto 1/M_{W_R}$: maximal parity violation $\leftrightarrow$ smallness of neutrino mass

(Note: in case of modified symmetry breaking $g_L \neq g_R$ and $M_{Z'} < M_{W_R}$ possible. . .)

Left-right Symmetry

6 neutrinos with flavor states n'_L and mass states $n_L = (\nu_L, N^c_R)^T$

$$n'_L = \begin{pmatrix} \nu'_L \\ {\nu_R}^c \end{pmatrix} = \begin{pmatrix} K_L \\ K_R \end{pmatrix} n_L = \begin{pmatrix} U & S \\ T & V \end{pmatrix} \begin{pmatrix} \nu_L \\ N^c_R \end{pmatrix}$$

Right-handed currents:

$$\mathcal{L}^{\rm lep}_{CC} = \frac{g}{\sqrt{2}} \left[\overline{\ell_L} \gamma^\mu K_L n_L (W^-_{1\mu} + \xi e^{i\alpha} W^-_{2\mu}) + \overline{\ell_R} \gamma^\mu K_R n^c_L (-\xi e^{-i\alpha} W^-_{1\mu} + W^-_{2\mu}) \right]$$

(K_L and K_R are 3×6 mixing matrices)

plus: gauge boson mixing

$$\begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi\, e^{i\alpha} \\ -\sin\xi\, e^{-i\alpha} & \cos\xi \end{pmatrix} \begin{pmatrix} W^\pm_1 \\ W^\pm_2 \end{pmatrix}$$

Connection to Neutrinos

Majorana mass matrices $M_L = f_L\, v_L$ from $\langle \Delta_L \rangle$ and $M_R = f_R\, v_R$ from $\langle \Delta_R \rangle$ (with $f_L = f_R = f$)

$$\mathcal{L}^{\nu}_{\rm mass} = -\tfrac{1}{2} \left(\overline{\nu'_L} \; \overline{\nu'_R}^{\,c} \right) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} {\nu'_L}^{c} \\ \nu'_R \end{pmatrix} \Rightarrow m_\nu = M_L - M_D\, M_R^{-1}\, M_D^T$$

useful special cases

(i) type I dominance: $m_\nu = M_D\, M_R^{-1}\, M_D^T = M_D\, f_R^{-1}/v_R\, M_D^T$

(ii) type II dominance: $m_\nu = f_L\, v_L$

for case (i): mixing of light neutrinos with heavy neutrinos of order

$$|S_{\alpha i}| \simeq |T^T_{\alpha i}| \simeq \sqrt{\frac{m_\nu}{M_i}} \lesssim 10^{-7} \left(\frac{\rm TeV}{M_i} \right)^{1/2}$$

small (or enhanced up to 10^{-2} by cancellations)

Right-handed Currents in Double Beta Decay

$$(A, Z) \to (A, Z+2) + 2e^-$$

$$\mathcal{L}_{CC}^{\text{lep}} = \frac{g}{\sqrt{2}} \sum_{i=1}^{3} \Big[\overline{e_L} \gamma^\mu (U_{ei} \nu_{Li} + S_{ei} N_{Ri}^c)(W_{1\mu}^- + \xi e^{i\alpha} W_{2\mu}^-)$$
$$+ \overline{e_R} \gamma^\mu (T_{ei}^* \nu_{Li}^c + V_{ei}^* N_{Ri})(-\xi e^{-i\alpha} W_{1\mu}^- + W_{2\mu}^-) \Big]$$

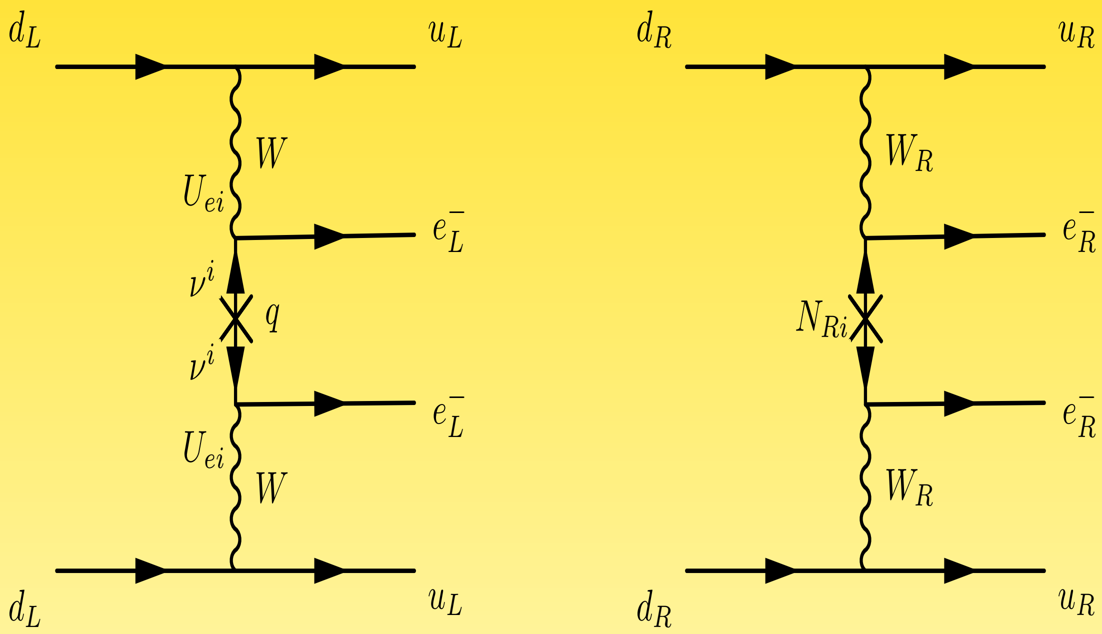
$$\mathcal{L}_Y^\ell = -\overline{L}_L'^c i \sigma_2 \Delta_L f_L L_L' - \overline{L}_R'^c i \sigma_2 \Delta_R f_R L_R'$$

classify diagrams:

- mass dependent diagrams (same helicity of electrons)
- triplet exchange diagrams (same helicity of electrons)
- momentum dependent diagrams (different helicity of electrons)

Mass Dependent Diagrams

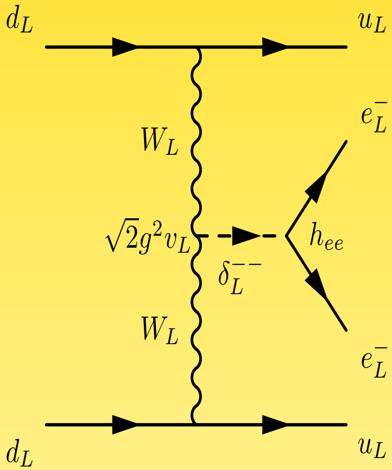
electrons either both left- or right-handed, leading diagrams:

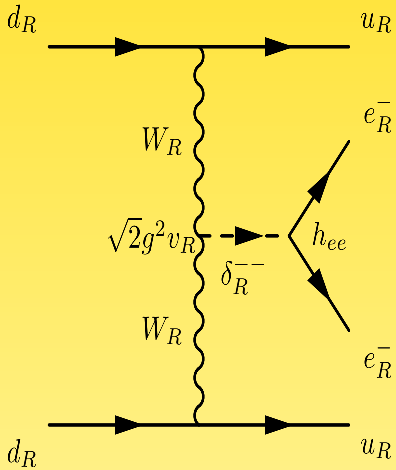


$\mathcal{A}_\nu \simeq G_F^2 \frac{m_{ee}}{q^2}$ $\qquad$ $\mathcal{A}_{N_R}^R \simeq G_F^2 \left(\frac{m_{W_L}}{m_{W_R}}\right)^4 \sum_i \frac{V_{ei}^{*\,2}}{M_i}$

Triplet Exchange Diagrams

leading diagrams:





$$\mathcal{A}_{\delta_L} \simeq G_F^2 \frac{h_{ee} v_L}{m^2_{\delta_L}} \qquad \mathcal{A}_{\delta_R} \simeq G_F^2 \left(\frac{m_{W_L}}{m_{W_R}}\right)^4 \sum_i \frac{V_{ei}^2 M_i}{m^2_{\delta_R}}$$

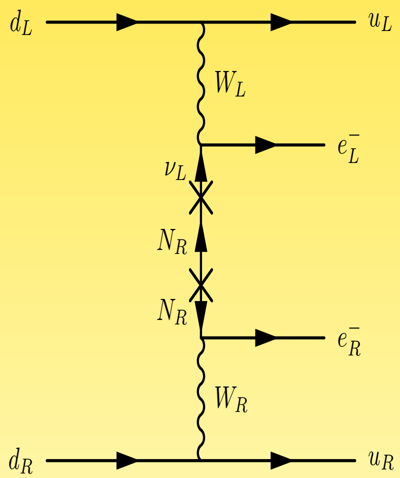
(negligible)

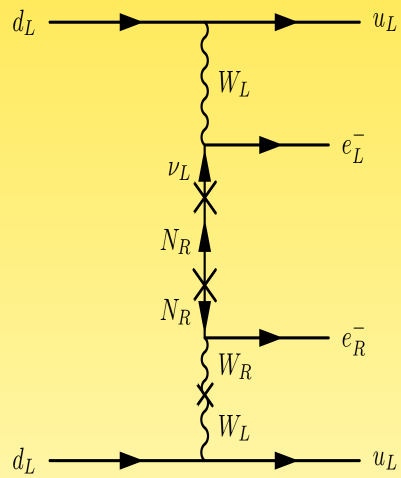
Momentum Dependent Diagrams

electrons with opposite helicity

$$\mathcal{A}_{LR} \simeq G_F^2 \left(\frac{m_{W_L}^2}{m_{W_R}^2} + \tan\xi \right) \sum_i \left(U_{ei} T_{ei}^* \frac{1}{q} - S_{ei} V_{ei}^* \frac{q}{M_i^2} \right)$$

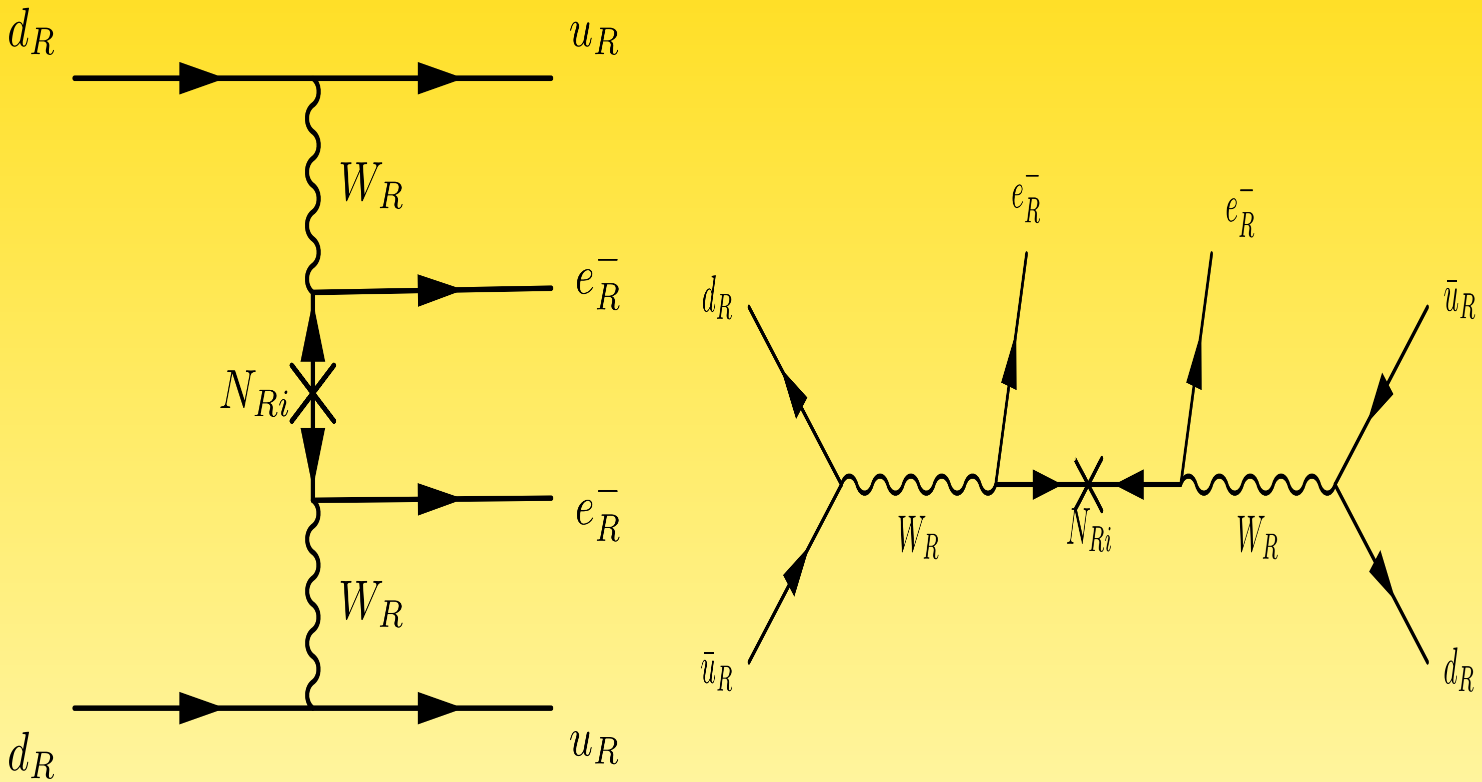
leading diagrams (long range):



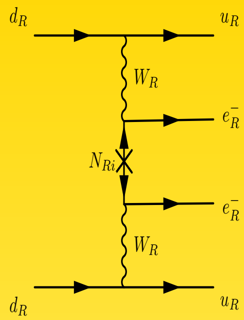


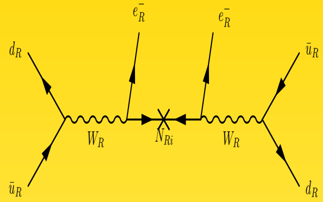
$$\mathcal{A}_\lambda \simeq G_F^2 \left(\frac{m_{W_L}}{m_{W_R}} \right)^2 \sum_i U_{ei} T_{ei}^* \frac{1}{q} \qquad \mathcal{A}_\eta \simeq G_F^2 \tan\xi \sum_i U_{ei} T_{ei}^* \frac{1}{q}$$

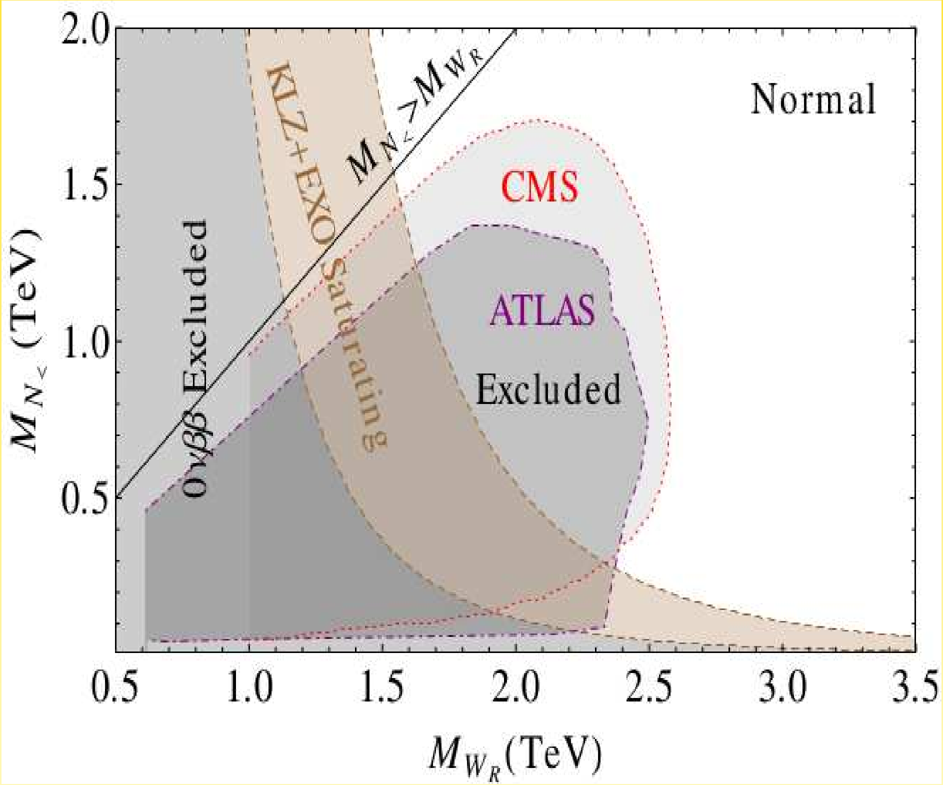
Left-right symmetry



`Senjanovic, Keung, 1983; Tello` *et al.*; `Nemevsek` *et al.*







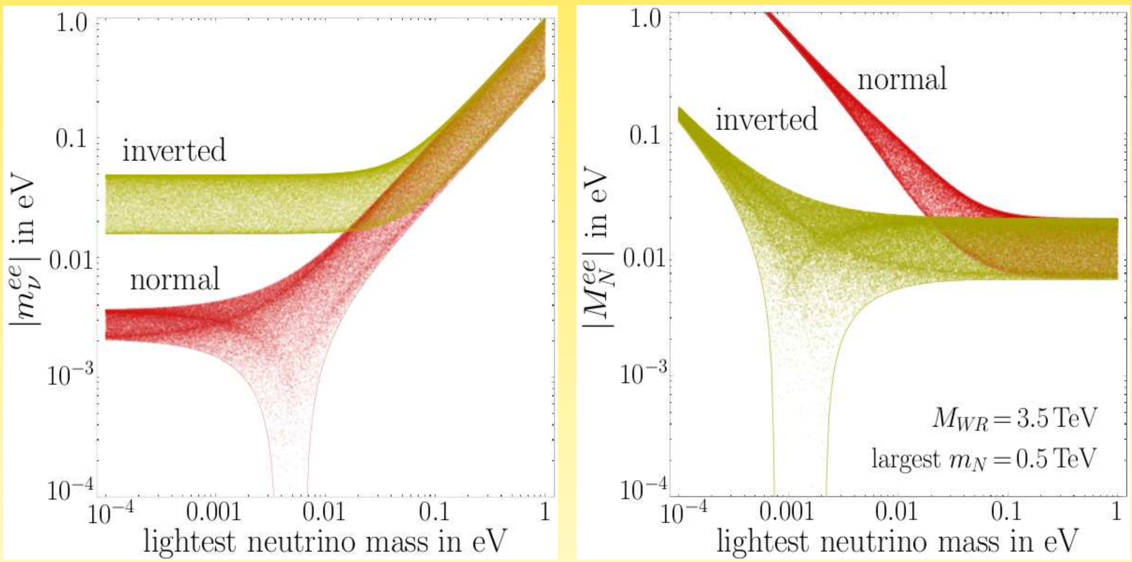
Bhupal Dev, Goswami, Mitra, W.R.

Type II dominance (Tello *et al.*, 1011.3522)

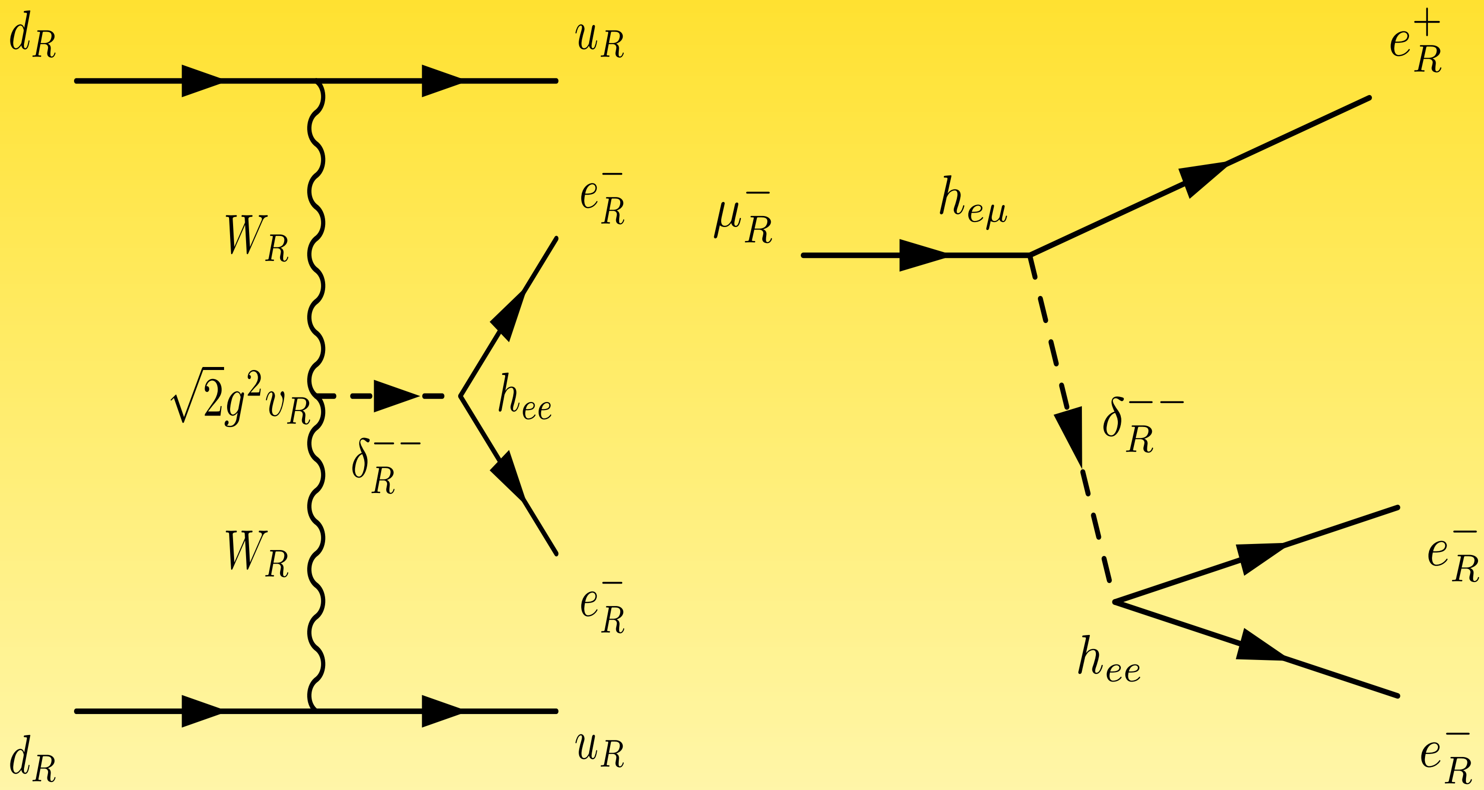
$$m_\nu = m_L - m_D\, M_R^{-1}\, m_D^T = v_L\, f - \frac{v^2}{v_R}\, Y_D\, f^{-1}\, Y_D^T \xrightarrow{\ *\ } v_L\, f$$

$\Rightarrow m_\nu$ fixes M_R and exchange of N_R with W_R fixed in terms of PMNS:

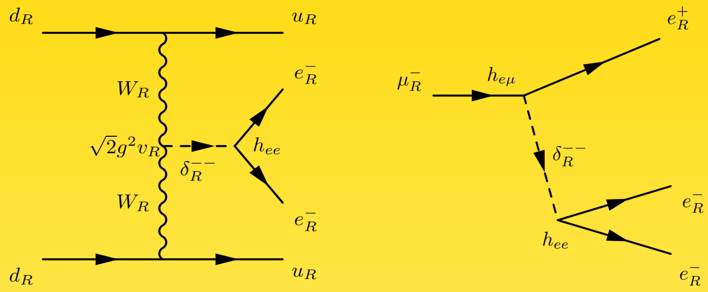
$$\Rightarrow \mathcal{A}_{N_R} \simeq G_F^2 \left(\frac{m_W}{M_{W_R}}\right)^4 \sum \frac{V_{ei}^2}{M_i} \propto \sum \frac{U_{ei}^2}{m_i}$$

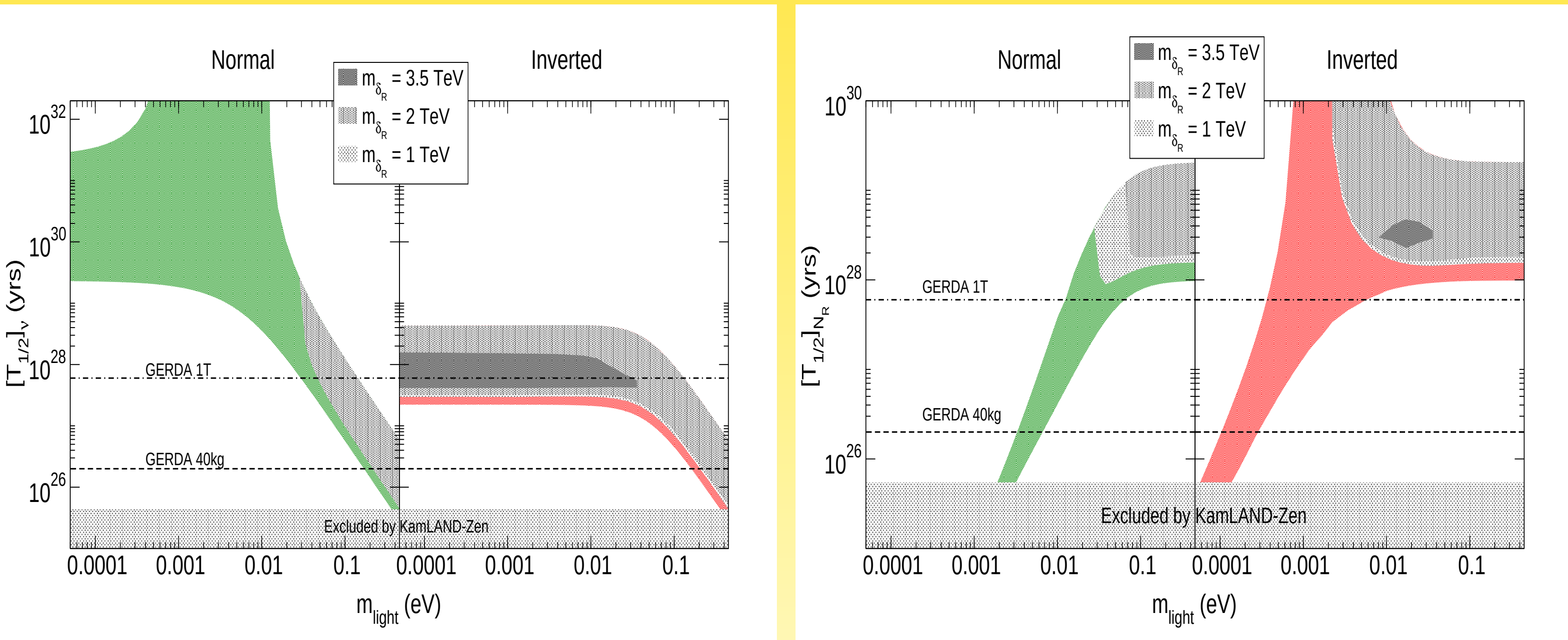


Constraints from Lepton Flavor Violation



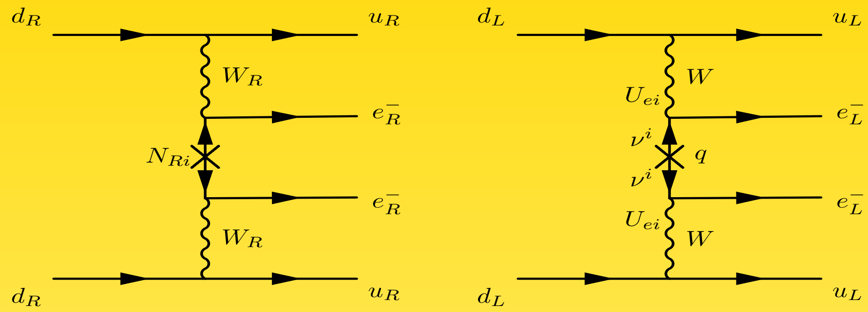
Constraints from Lepton Flavor Violation

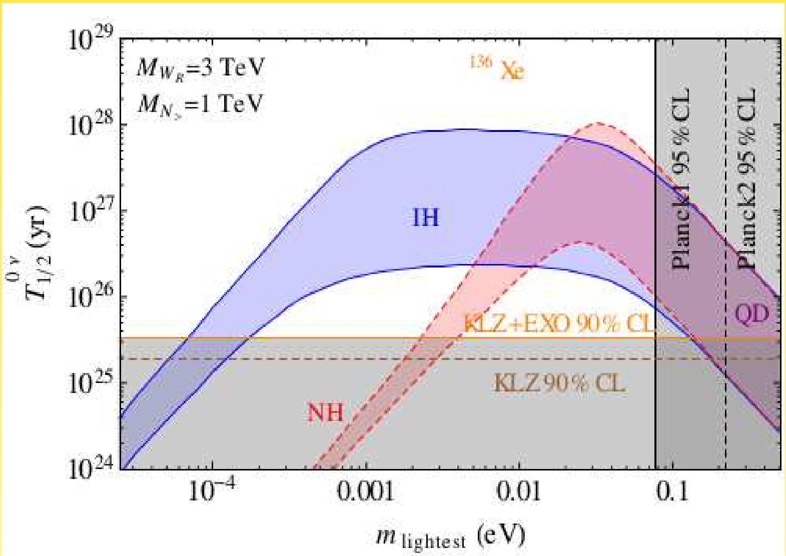




Barry, W.R., JHEP **1309**

Adding diagrams

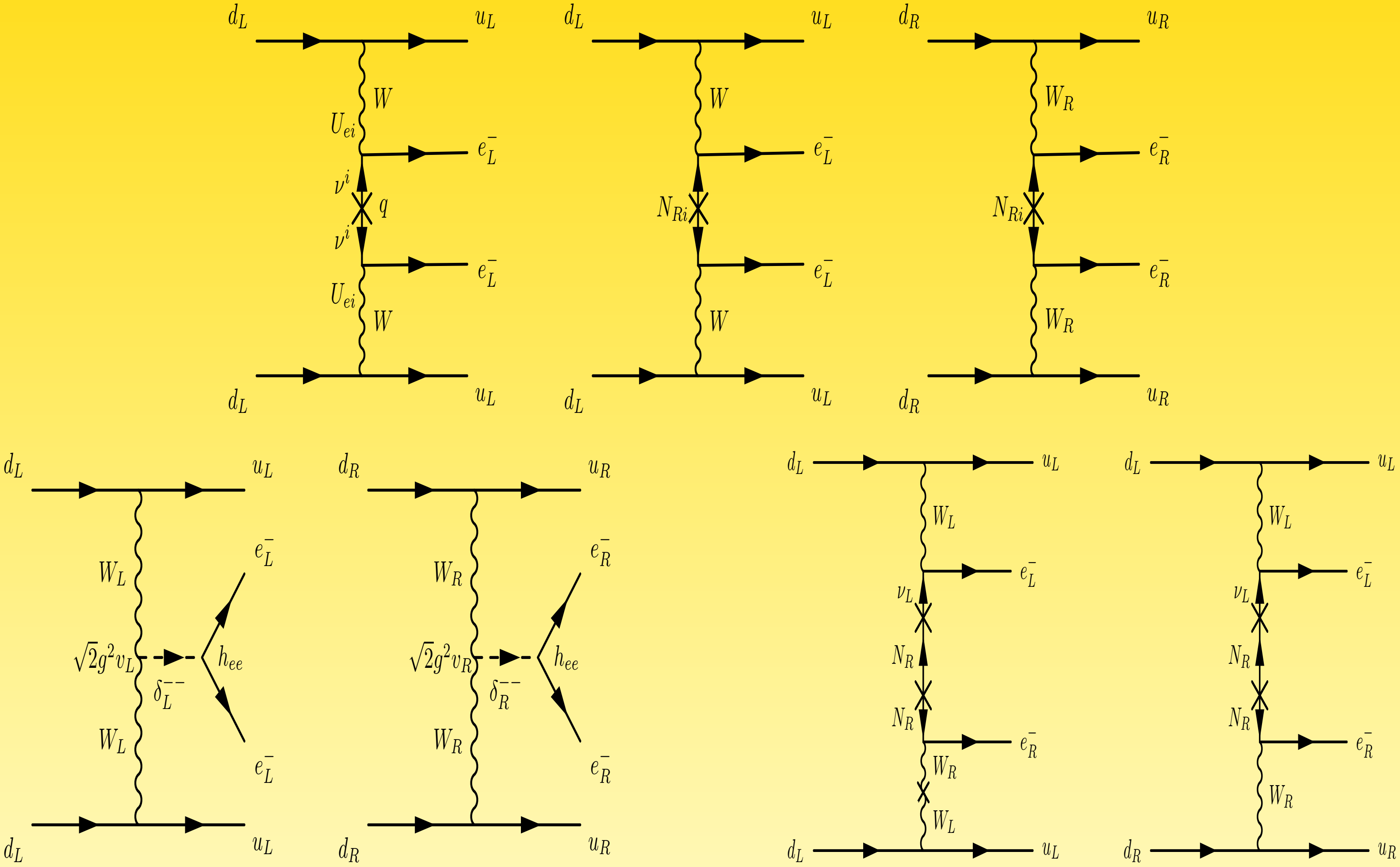




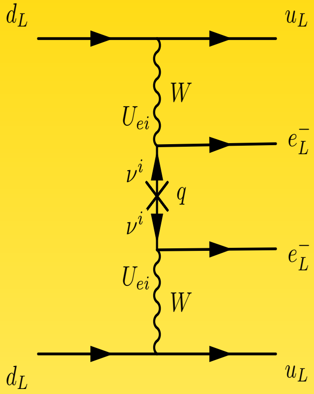
$\Rightarrow$ lower bound on $m(\text{lightest}) \gtrsim$ meV

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

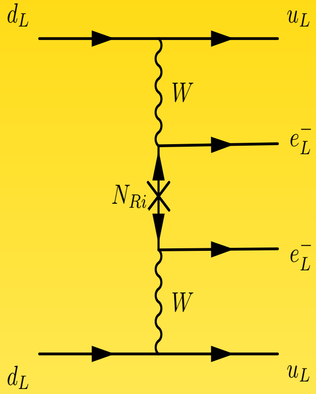
Left-right symmetry



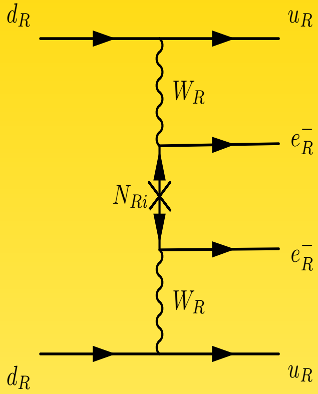
Left-right symmetry



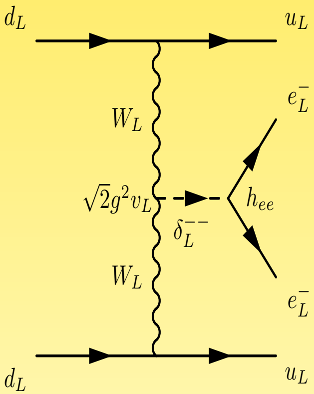
$$U_{ei}^2\, m_i$$



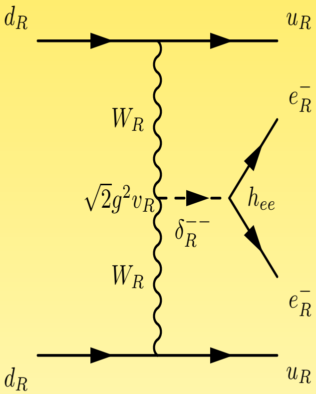
$$\frac{S_{ei}^2}{M_i}$$



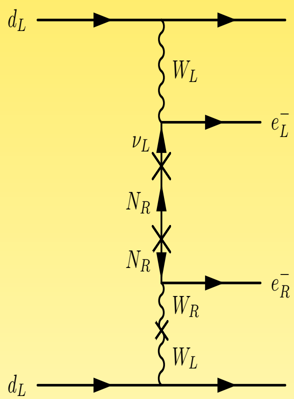
$$\frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



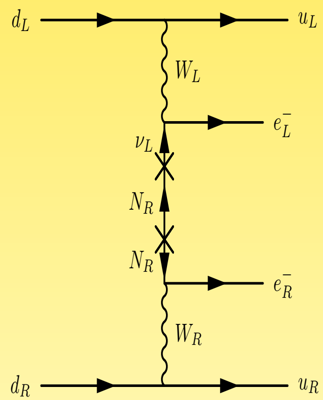
$$\frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$$



$$\frac{V_{ei}^2\, M_i}{M_{W_R}^4\, M_{\Delta_R}^2}$$

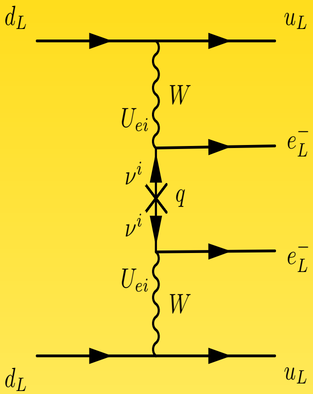


$$U_{ei}\, T_{ei}\, \tan\zeta$$

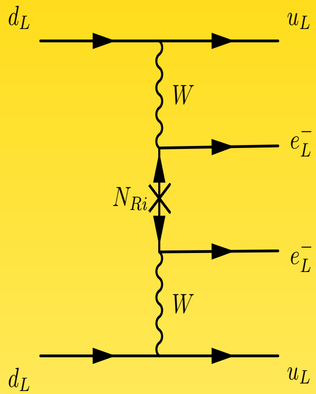


$$\frac{U_{ei}\, T_{ei}}{M_{W_R}^2}$$

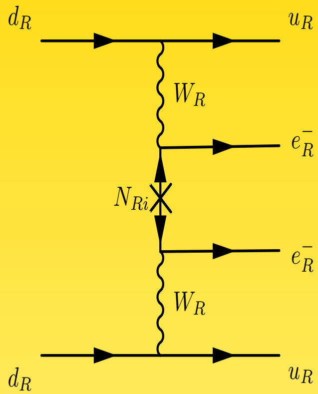
Left-right symmetry



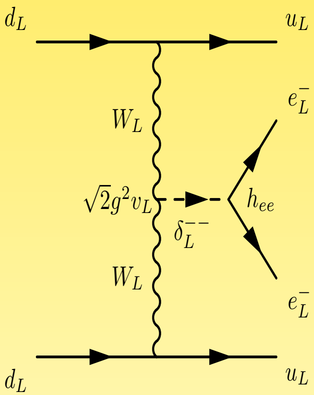
0.4 eV



2×10^{-8} GeV^{-1}



4×10^{-16} GeV^{-5}



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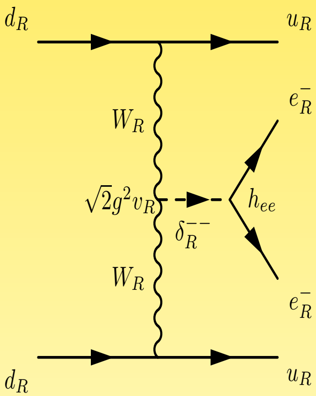
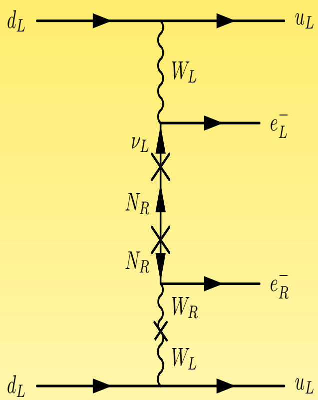
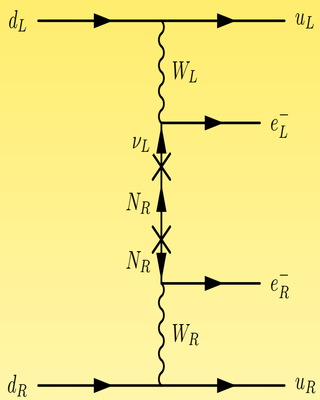


10^{-15} GeV^{-5}



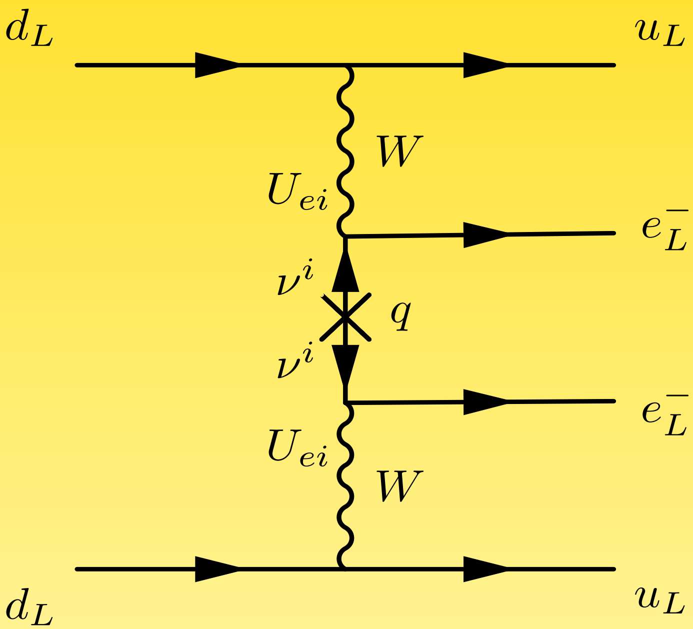
6×10^{-9}

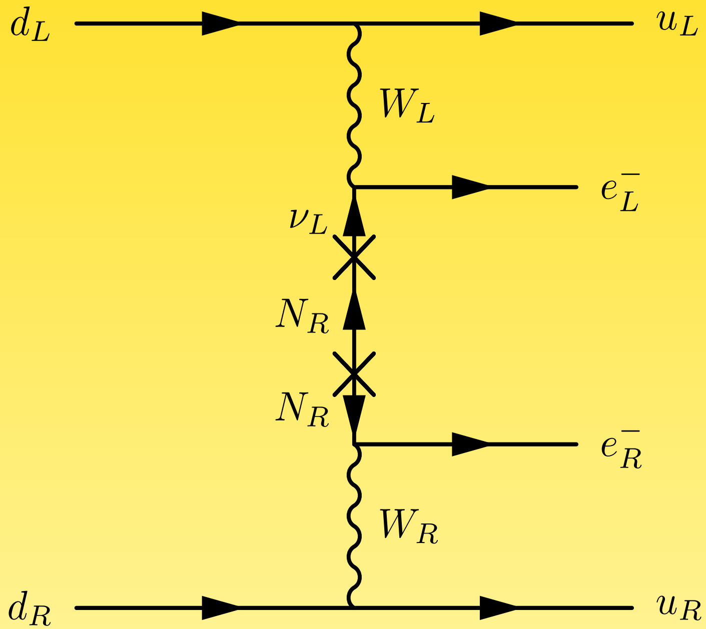


1.4×10^{-10} GeV^{-2}

2.) Distinguishing via decay products

Consider standard plus λ-mechanism





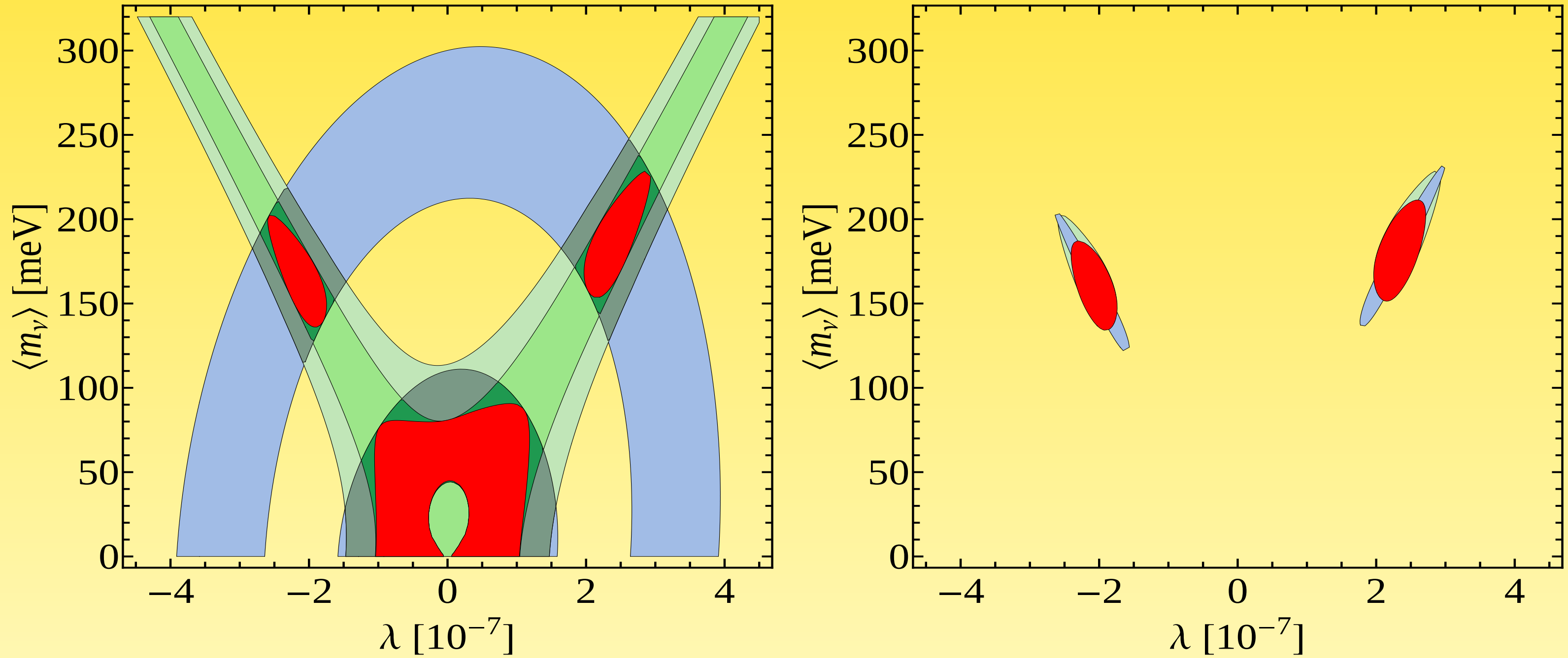
$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta) \qquad \frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$$

Arnold *et al.*, 1005.1241

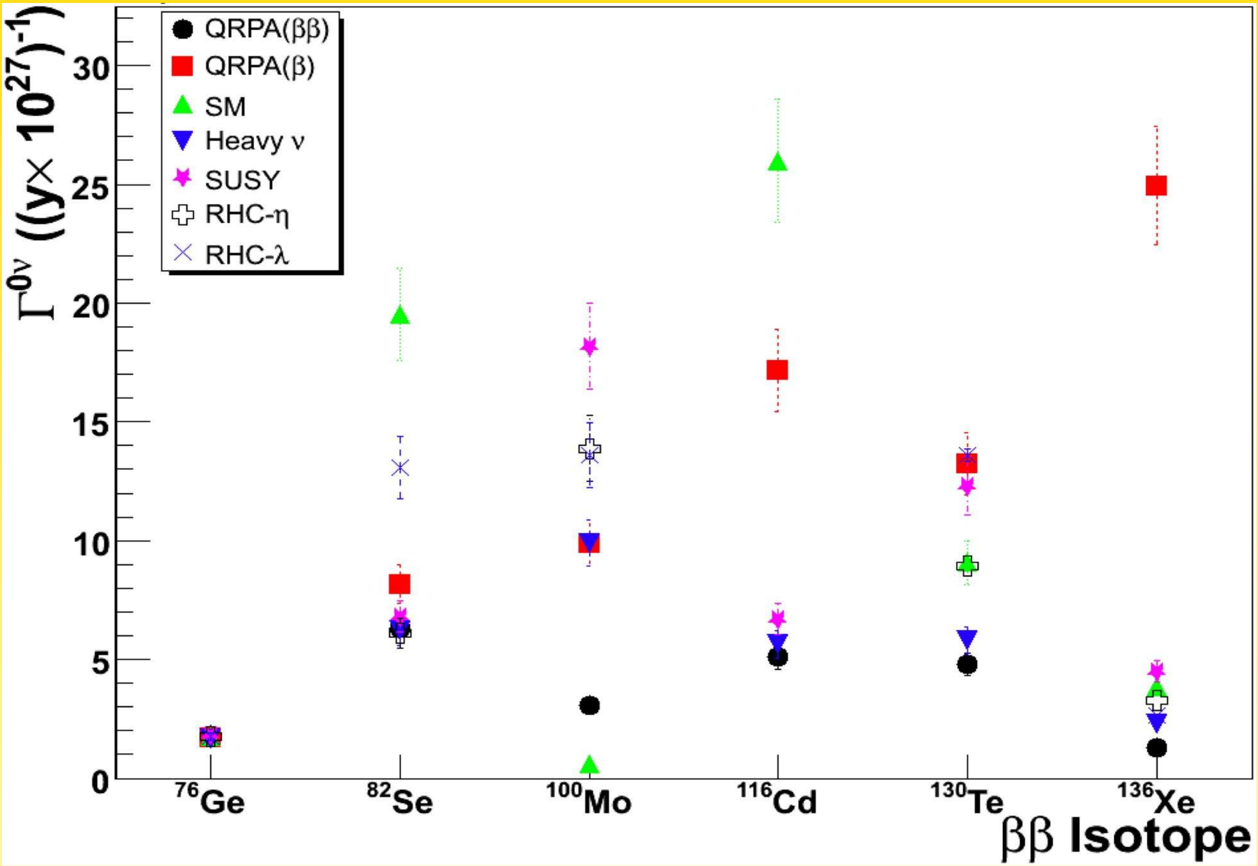
2.) Distinguishing via decay products

Defining asymmetries

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



3.) Distinguishing via nuclear physics

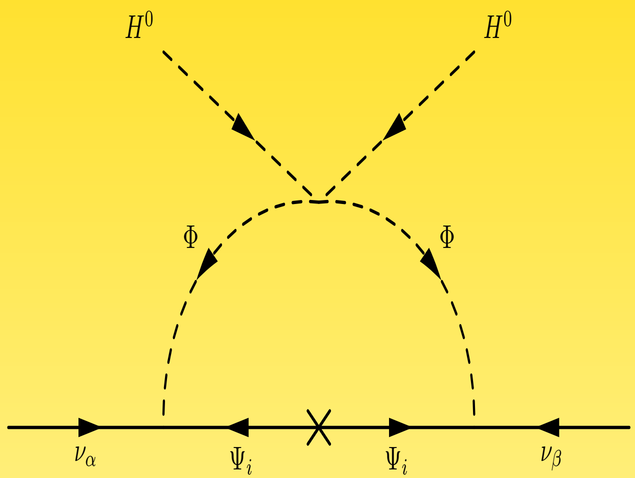


`Gehman, Elliott, hep-ph/0701099`

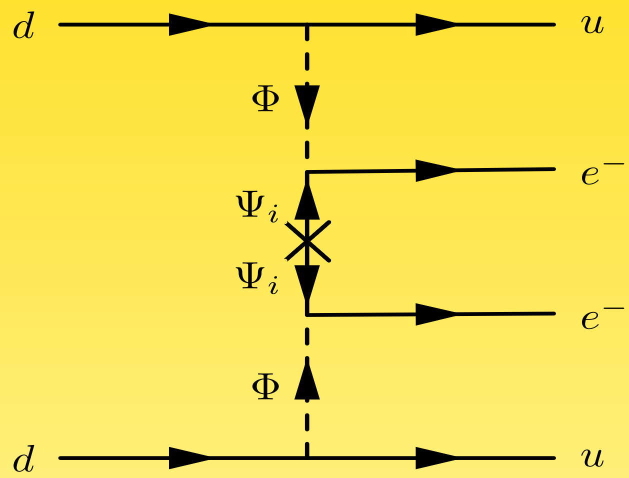
3 to 4 isotopes necessary to disentangle mechanism

Direct versus indirect contribution

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



1-loop m_ν



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

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

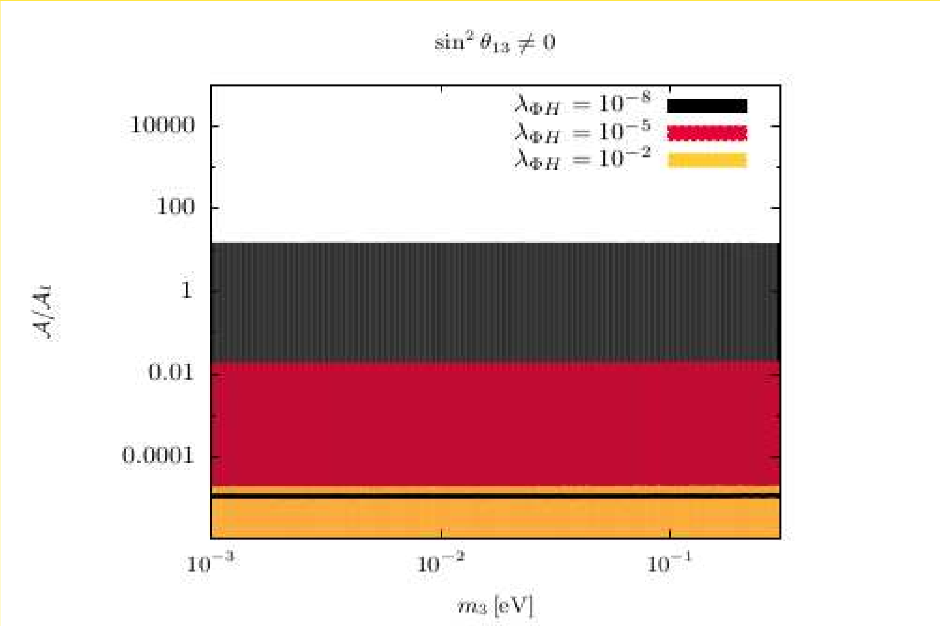
direct contribution to $0\nu\beta\beta$:

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

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

Direct versus indirect contribution

new contribution can dominate over standard one:



Do Dirac neutrinos imply that there is no Lepton Number Violation?

possible to construct $U(1)_{B-L}$ model with $\chi \sim -2$ and $\phi \sim 4$

$$\mathcal{L} = \left(y_{\alpha\beta} \overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta} \chi \, \overline{\nu}_{R,\alpha} \nu^c_{R,\beta} + h.c. \right) + \sum_{X=H,\phi,\chi} \left(\mu_X^2 |X|^2 + \lambda_X |X|^4 \right)$$

$$+ \lambda_{H\phi} |H|^2 |\phi|^2 + \lambda_{H\chi} |H|^2 |\chi|^2 + \lambda_{\chi\phi} |\chi|^2 |\phi|^2 \quad - \left(\mu \phi \chi^2 + h.c. \right)$$

break it by allowing only scalar ϕ to obtain VEV:

$\Rightarrow$ neutrinos are Dirac particles, and Lepton Number violated by 4 units!

$\Rightarrow$ neutrinoless double beta decay forbidden...

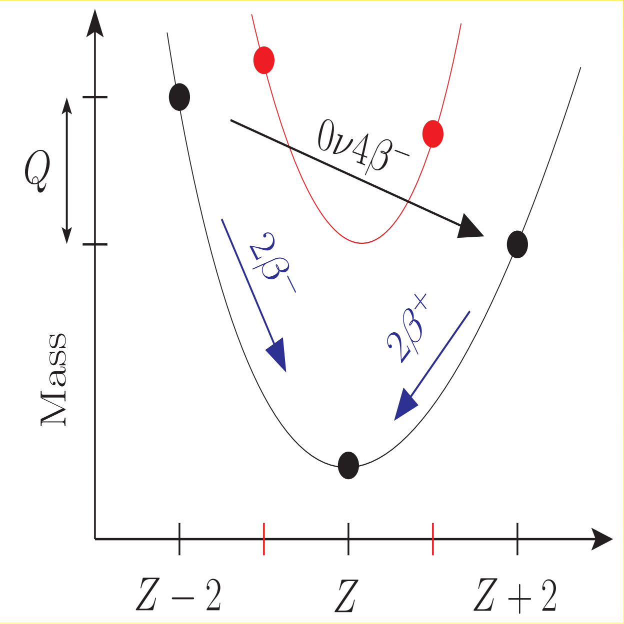
Heeck, W.R., EPL 103

Do Dirac neutrinos mean there is no Lepton Number Violation?

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

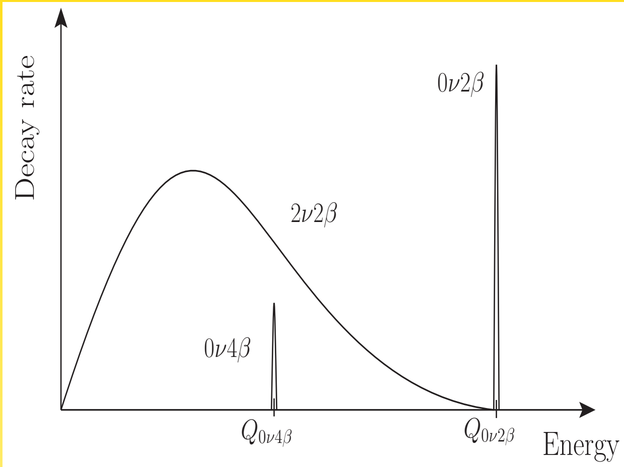
$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...

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



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

Candidates for neutrinoless quadruple beta decay



	$Q_{0\nu4\beta}$	Other decays	NA
$^{96}_{40}\text{Zr} \to ^{96}_{44}\text{Ru}$	0.629	$\tau_{1/2}^{2\nu2\beta} \simeq 2 \times 10^{19}$	2.8
$^{136}_{54}\text{Xe} \to ^{136}_{58}\text{Ce}$	0.044	$\tau_{1/2}^{2\nu2\beta} \simeq 2 \times 10^{21}$	8.9
$^{150}_{60}\text{Nd} \to ^{150}_{64}\text{Gd}$	2.079	$\tau_{1/2}^{2\nu2\beta} \simeq 7 \times 10^{18}$	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.

Mass terms

$$\mathcal{L} = m_\nu \, \overline{\nu_L} \, \nu_R + h.c. = m_\nu \, (\overline{\nu_L} \, \nu_R + \overline{\nu_R} \, \nu_L)$$

both chiralities a must for mass term!

Possibilities for $\overline{L}R$:

(i) ν_R independent of ν_L: **Dirac particle**

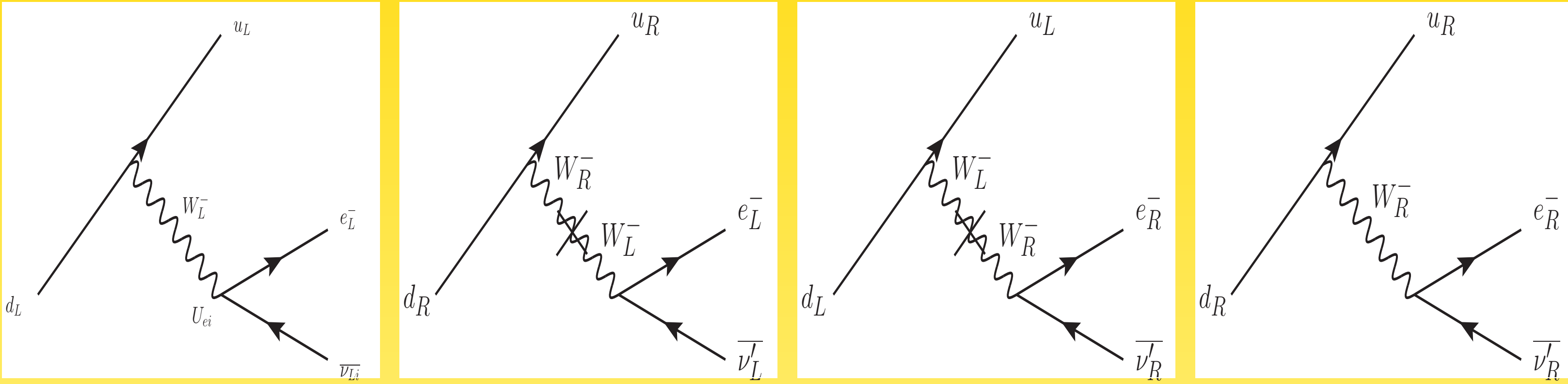
(ii) $\nu_R = (\nu_L)^c$: **Majorana particle**

$$\Rightarrow \nu^c = (\nu_L + \nu_R)^c = (\nu_L)^c + (\nu_R)^c = \nu_R + \nu_L = \nu : \boxed{\nu^c = \nu}$$

$\Rightarrow$ Majorana fermion is identical to its antiparticle, a truly neutral particle

$\Rightarrow$ all additive quantum numbers (Q, L, B,...) are zero

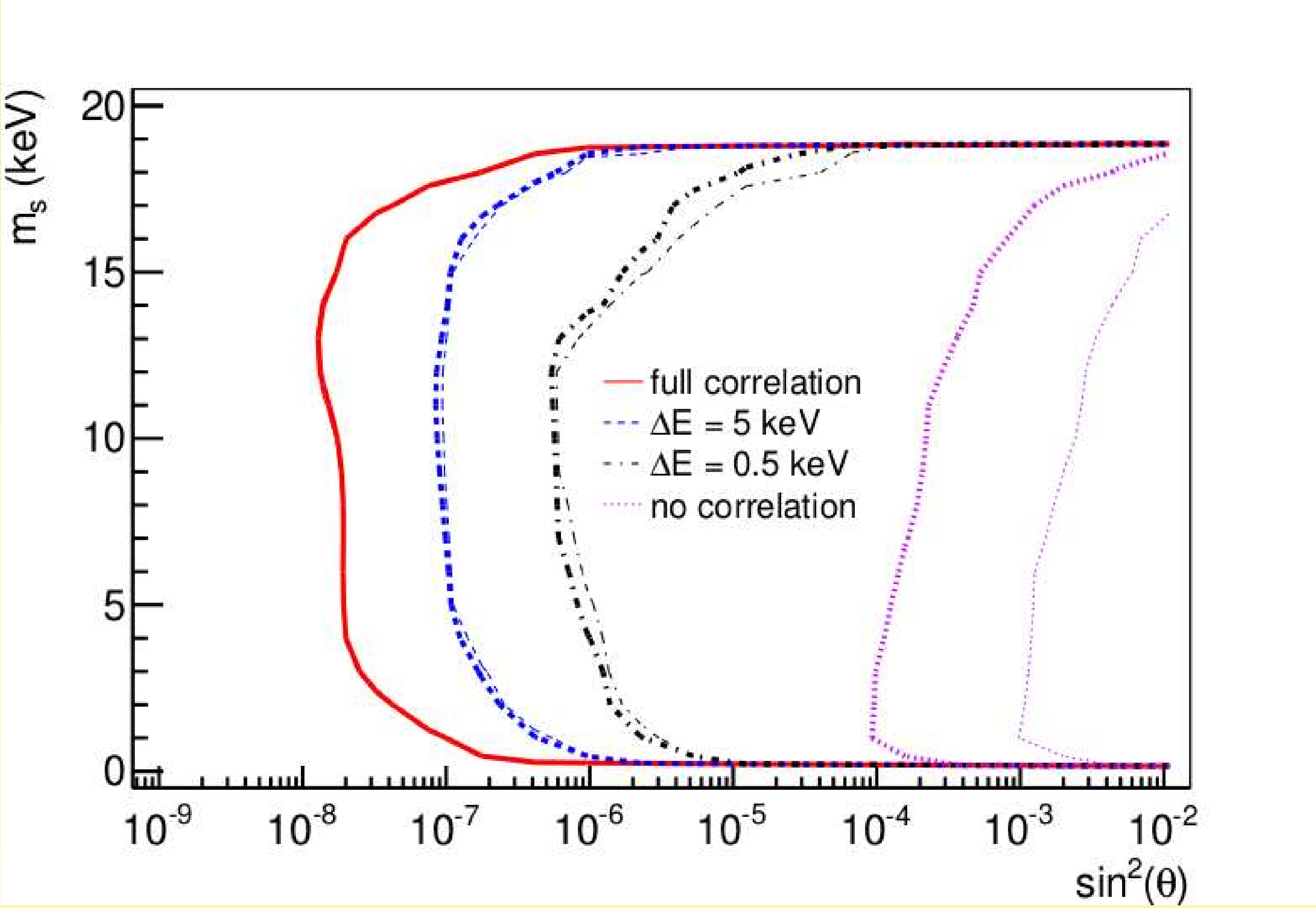
KATRIN and right-handed currents



- left-handed contribution
- right-handed contribution
- interference contribution

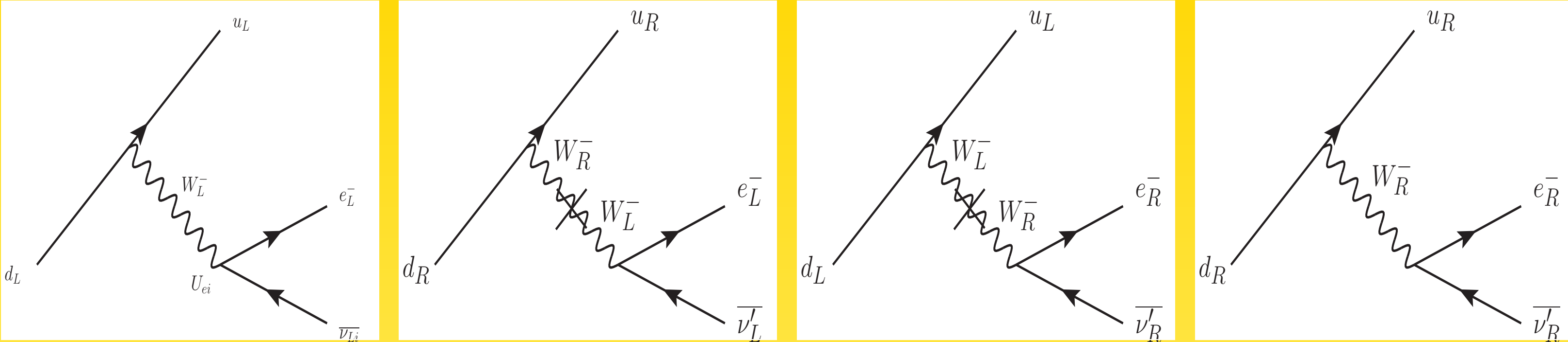
Neutrino masses up to $m = 18.6$ keV testable $\Leftrightarrow$ Warm Dark Matter!

(see lecture by Kevork Abazajian)



$\Rightarrow$ mixing down to 10^{-7} in reach!?

Mertens *et al.*, 1409.0920



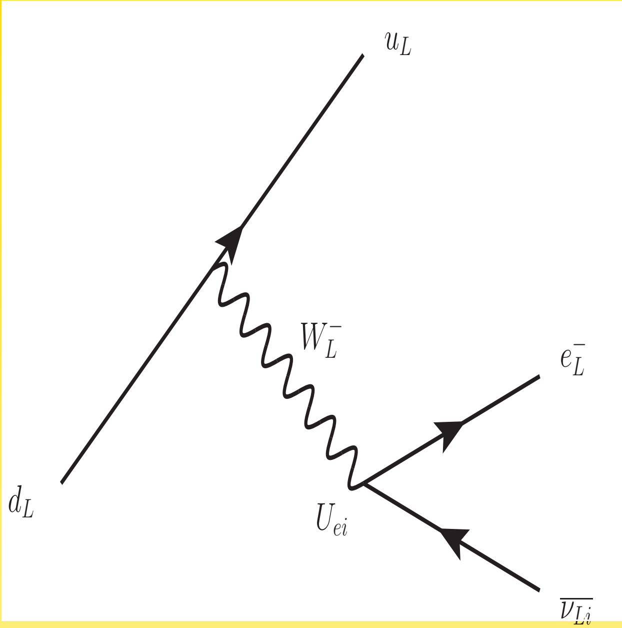
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} = K'(E+m_e)p_e X[1+2C\tan\xi]$$
$$\times\left[|U_{ei}|^2\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+|S_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]$$

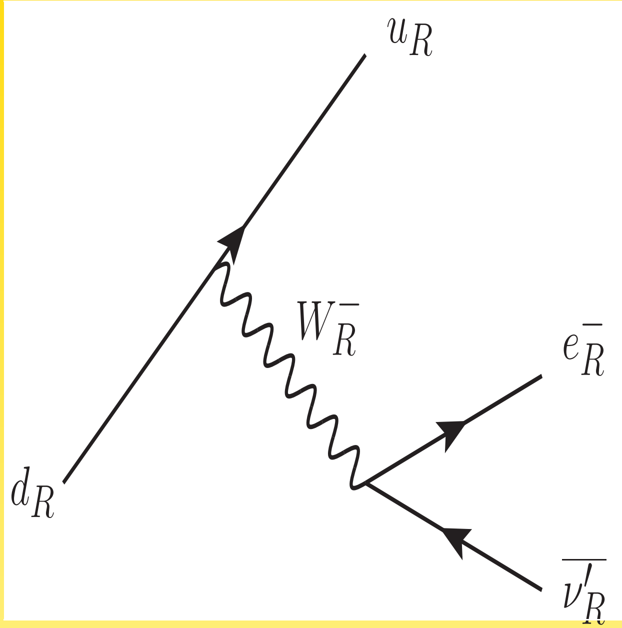
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} \simeq K'(E+m_e)p_e X\left[\frac{m_{W_L}^4}{m_{W_R}^4}+\tan^2\xi+2C\frac{m_{W_L}^2}{m_{W_R}^2}\tan\xi\right]$$
$$\times|V_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)$$

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

with $X = E_0 - E$

Focus for simplicity on





total contribution of keV neutrino with mass M to beta decay:

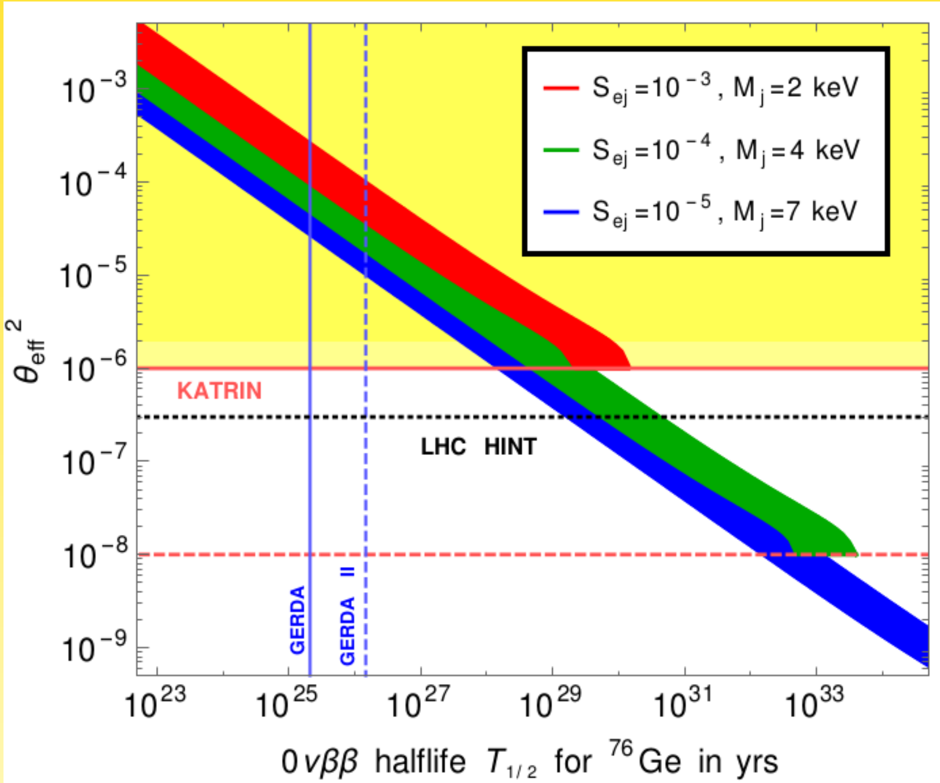
$$\theta_{\text{eff}}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6} \, |V_{ej}|^2 \left(\frac{2.5 \, \text{TeV}}{m_{W_R}} \right)^4$$

and note that M does $0\nu\beta\beta$ with amplitude $\propto |V_{ej}|^2 \, (m_W / m_{W_R})^4 \, M$

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

connection to $0\nu\beta\beta$ constraints:

$$\theta_{\rm eff}^2 = |S_{ej}|^2 + \frac{m_e}{M_j}\left[|\mathcal{M}_\nu^{0\nu}|^{-2}\left(G_{01}^{0\nu}\right)^{-1}\left(T_{1/2}^{0\nu}\right)^{-1} - |S_{ej}^2 M_j/m_e|^2\right]^{\frac{1}{2}}$$

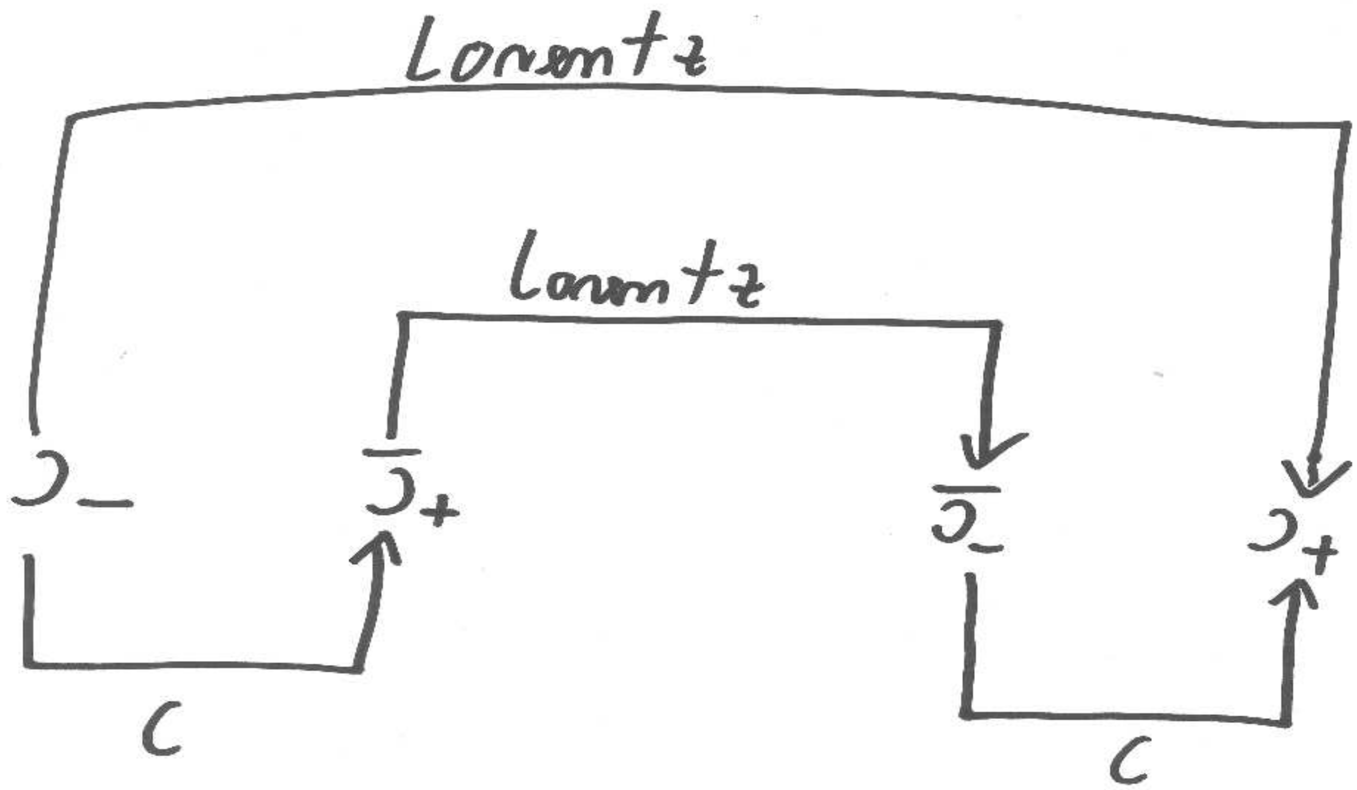


Barry, Heeck, W.R., JHEP **1407**

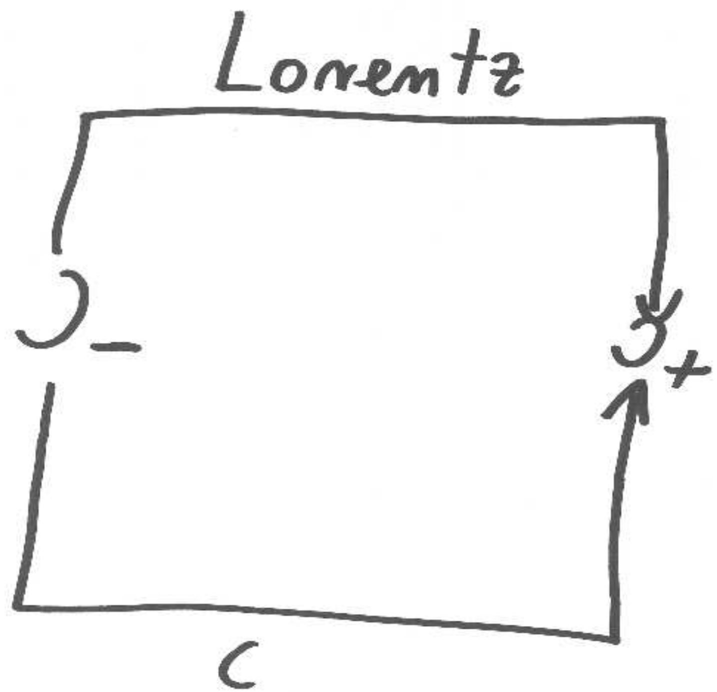
How the additional interactions save the day

- double beta decay without RHC: $\theta^2 M = 7 \times 10^{-10}\,\mathrm{keV} = 70\,\mu\mathrm{eV}$
- double beta decay with RHC: $(m_{W_L}/m_{W_R})^4\,|V_{ei}|^2 M = 8\,\mathrm{meV}$
- decay: $\dfrac{\Gamma_{\mathrm{RHC}}(N_j \to \bar{\nu}\gamma)}{\Gamma_{\mathrm{SM}}(N_j \to \nu\gamma)} \simeq \dfrac{m_{W_L}^4\,|S_{ei}|^2}{m_{W_R}^4\,|T_{ei}|^2} \simeq \dfrac{m_{W_L}^4}{m_{W_R}^4}$
- beta decay: $\theta_{\mathrm{eff}}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\,|V_{ej}|^2 \left(\frac{2.5\,\mathrm{TeV}}{m_{W_R}}\right)^4 > |S_{ej}|^2$

Dirac particles: $\nu \neq \nu^c$ helicity states $\pm$: 4 d.o.f.



Majorana particles: $\nu = \nu^c$ helicity states $\pm$: 2 d.o.f.



Mass term for Majorana particles:

$$\mathcal{L}_M = \frac{1}{2}\,\overline{\nu}\,m_\nu\,\nu = \frac{1}{2}\,\overline{\nu_L + (\nu_L)^c}\,m_\nu\,(\nu_L + (\nu_L)^c) = \tfrac{1}{2}\,\overline{\nu_L}\,m_\nu\,\nu_L^c + h.c.$$

- Majorana mass term
- $\mathcal{L}_M \propto \nu^\dagger\,\nu^* \Rightarrow$ NOT invariant under $\nu \to e^{i\alpha}\,\nu$
  $\Rightarrow$ breaks Lepton Number by 2 units

Dirac vs. Majorana

in $V-A$ theories: observable difference **always** suppressed by $(m/E)^2$

- suppose beam from π^+ decays: $\pi^+ \to \mu^+ \nu_\mu$ (left-handed)
- can we observe $\overline{\nu}_\mu + p \to n + \mu^+$? (right-handed)
- chirality is not a good quantum number: "spin flip"
- emitted ν_μ (negative helicity) is not purely left-handed:

$$u_\downarrow(p) = u_L^{(m=0)}(p) + \frac{m}{2E}\, u_R^{(m=0)}(-p)$$

- $P_R\, u_\downarrow \neq 0$ and μ^+ can be produced if $m \neq 0$ and "$u \propto v$" ($\leftrightarrow$ Majorana!)

$\Rightarrow$ amplitude $\propto (m/E) \Rightarrow$ probability $\propto (m/E)^2$

$\Rightarrow$ only N_A can save the day!

plus uncertainty due to model details:

- Short range correlations:
  - Jastrow function
  - Unitary Correlation Operator method
  - Coupled Cluster method
- model parameters
  - correlated: e.g., g_A, g_{pp}, SRC
  - uncorrelated: e.g., model space of single particle states
  - some include errors, some don't...

$$\mathcal{M}^{0\nu} = \left(\frac{g_A}{1.25}\right)^2 \left(\mathcal{M}^{0\nu}_{\rm GT} - \frac{g_V^2}{g_A^2}\mathcal{M}^{0\nu}_{\rm F}\right)$$

with

$$\mathcal{M}^{0\nu}_{\rm GT} = \langle f| \sum_{lk} \sigma_l\, \sigma_k\, \tau_l^-\, \tau_k^-\, H_{\rm GT}(r_{lk}, E_a)|i\rangle$$
$$\mathcal{M}^{0\nu}_{\rm F} = \langle f| \sum_{lk} \tau_l^-\, \tau_k^-\, H_{\rm F}(r_{lk}, E_a)|i\rangle$$

- $r_{lk} \simeq 1/p \simeq 1/(0.1\ \mathrm{GeV})$ distance between the two decaying neutrons
- E_a average energy
- *sum over all multipolarities!*
- 'neutrino potential' $H_{\rm GT,F}(r_{lk}, E_a)$ integrates over the virtual neutrino momenta
- (if heavy particles exchanged: nucleon structure: $g_A = g_A(0)/(1 - q^2/M_A^2)^2$)

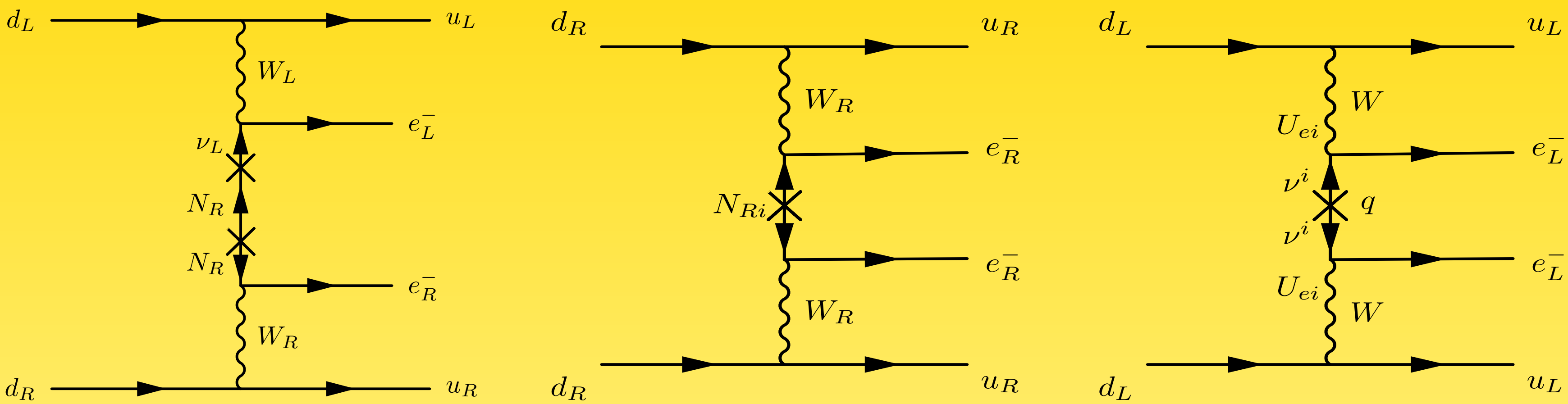
The $2\nu\beta\beta$ matrix elements can be written as

$$\mathcal{M}^{2\nu}_{\mathrm{GT}} = \sum_n \frac{\langle f|\sum_a \sigma_a \tau_a^- |n\rangle\langle n|\sum_b \sigma_b \tau_b^- |i\rangle}{E_n-(M_i-M_f)/2}$$

$$\mathcal{M}^{2\nu}_{\mathrm{F}} = \sum_n \frac{\langle f|\sum_a \tau_a^- |n\rangle\langle n|\sum_b \tau_b^- |i\rangle}{E_n-(M_i-M_f)/2}$$

- no direct connection to $0\nu\beta\beta\ldots$
- *sum over* 1^+ *states* (low momentum transfer)
- adjust some parameters to reproduce $2\nu\beta\beta$-rates
- $2\nu\beta\beta$ observed in ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo (plus exc. state), ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe ^{150}Nd (plus exc. state) with half-lives from 10^{18} to 10^{24} yrs
- can partly be tested with forward angle (= low momentum transfer) (p,n) charge exchange reactions

Mixed Diagrams can dominate



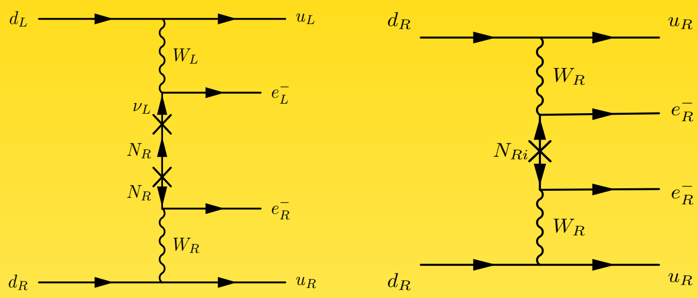
$$\mathcal{A}_\lambda \sim \left(\frac{m_W}{M_{W_R}}\right)^2 \frac{U\,T}{q} \qquad \mathcal{A}_{N_R} \sim \left(\frac{m_W}{M_{W_R}}\right)^4 \frac{V^2}{M_R} \qquad \mathcal{A}_\nu \sim U^2 \frac{m_i}{q^2}$$

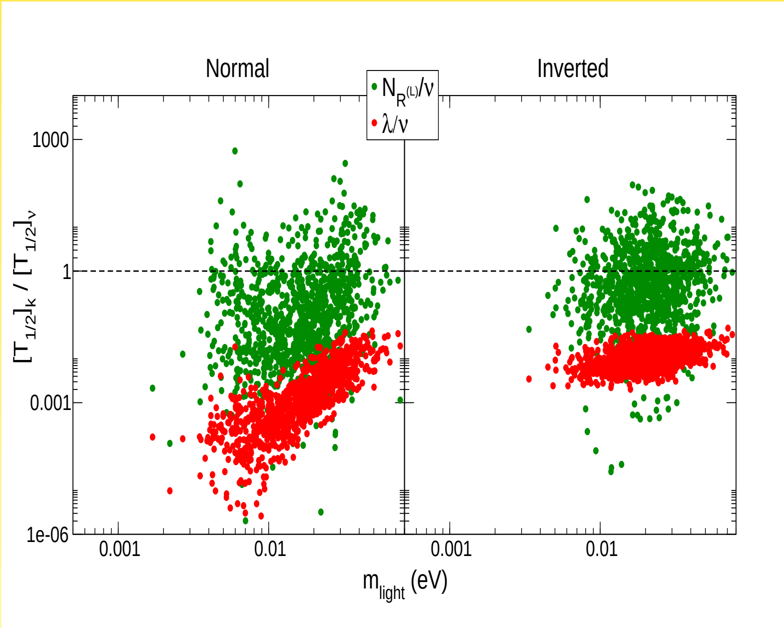
with $T \simeq \sqrt{\frac{m_\nu}{M_R}} \sim 10^{-7}$ (or huge enhancements up to 10^{-2})

$$\Rightarrow \frac{\mathcal{A}_\lambda}{\mathcal{A}_{N_R}} \simeq \frac{M_R}{q} \left(\frac{M_{W_R}}{m_W}\right)^2 T \simeq 10^5\, T$$

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

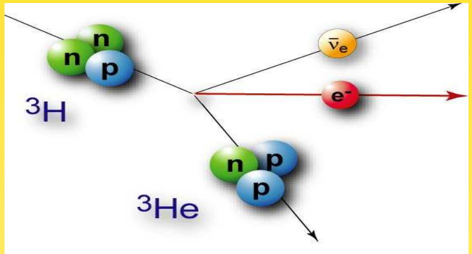
Mixed Diagrams can dominate





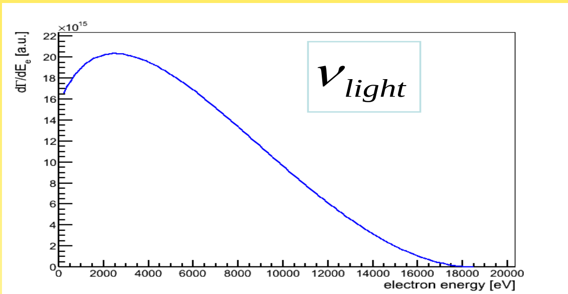
Barry, W.R., 1303.6324

Imprint of keV neutrinos on ß-spectrum

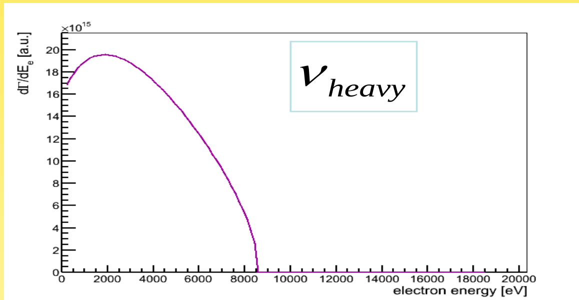


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

$\cos^2(\theta)$

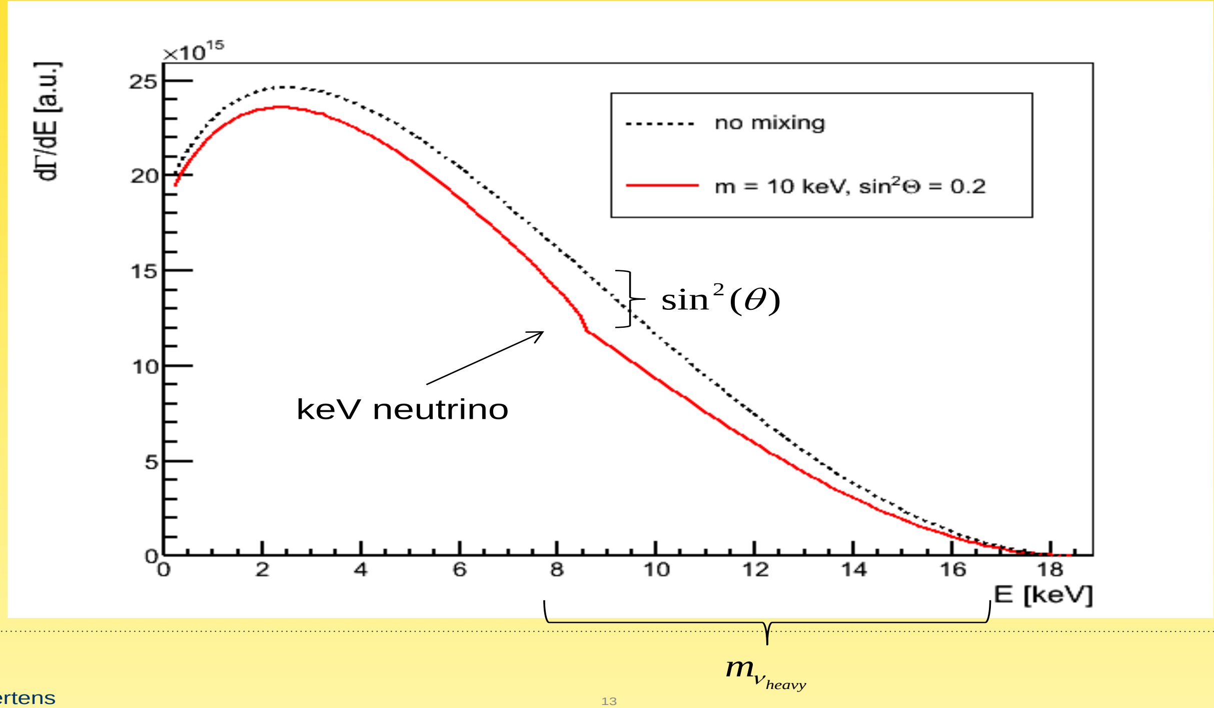


$+ \sin^2(\theta)$



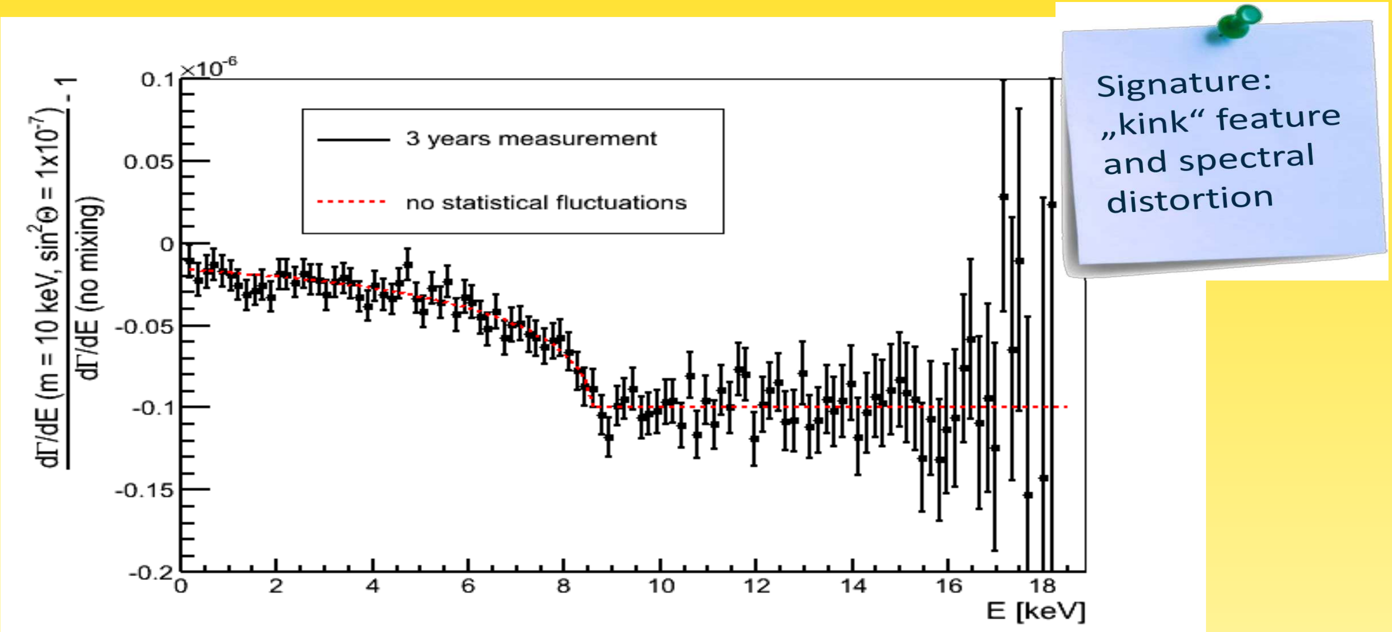
Mertens *et al.*, 1409.0920

Imprint of keV neutrinos on ß-spectrum



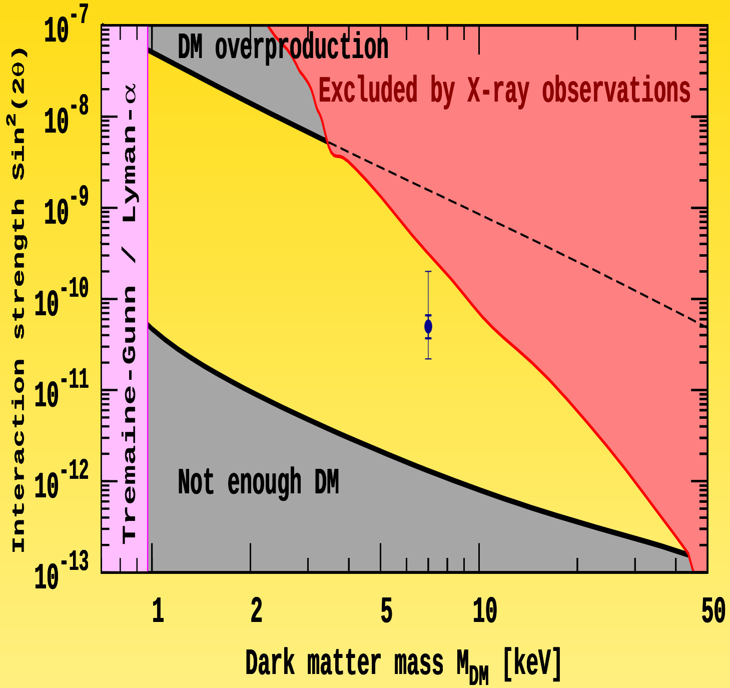
Mertens *et al.*, 1409.0920

Imprint of keV neutrinos on ß-spectrum



Susanne Mertens 15

Mertens *et al.*, 1409.0920

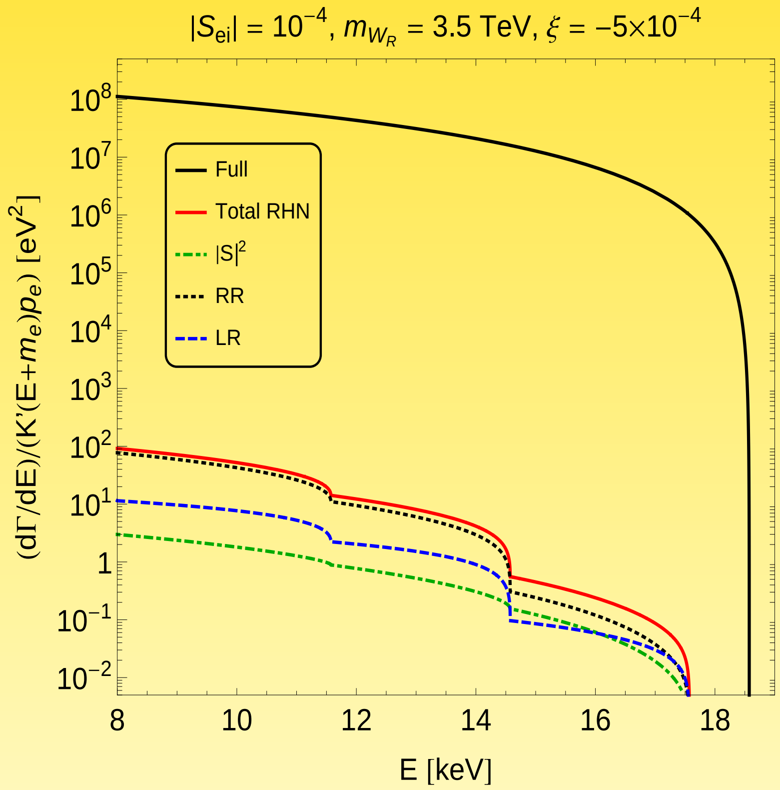


$\Rightarrow$ mixing down to 10^{-7} in reach!?

hard for KATRIN to see something. . .

. . .can increase signal with additional interactions, e.g. right-handed currents in total one has

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR}$$

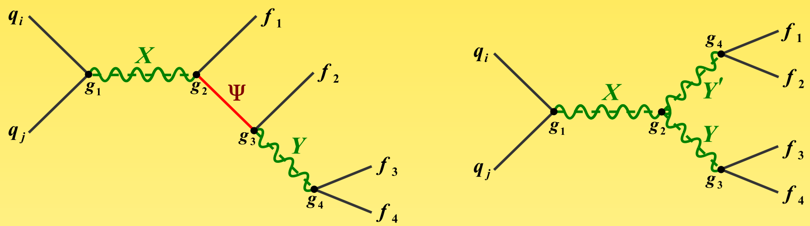


Observation of LNV at LHC implies washout effects in early Universe!

Example TeV-scale W_R: leading to washout $e_R^\pm e_R^\pm \to W_R^\pm W_R^\pm$ and $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$. Further, $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ stays long in equilibrium

(Frere, Hambye, Vertongen; Bhupal Dev, Lee, Mohapatra; U. Sarkar *et al.*)

More model-independent (Deppisch, Harz, Hirsch):

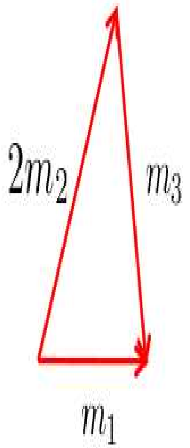


washout: $\log_{10} \dfrac{\Gamma_W(qq \to \ell^+\ell^+\, qq)}{H} \gtrsim 6.9 + 0.6 \left(\dfrac{M_X}{\text{TeV}} - 1\right) + \log_{10} \dfrac{\sigma_{\text{LHC}}}{\text{fb}}$

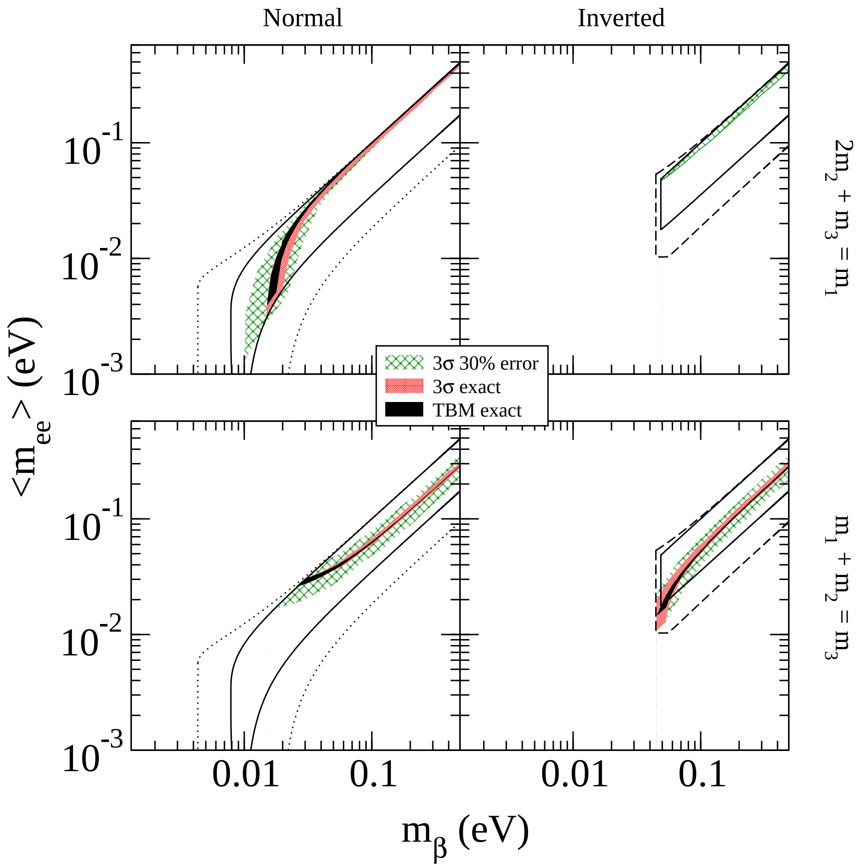
(TeV-$0\nu\beta\beta$, LFV and Y_B: Deppisch, Harz, Huang, Hirsch, Päs)

$\leftrightarrow$ post-Sphaleron mechanisms, τ flavor effects,...

Flavor Symmetry Models: 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



constraints on masses and Majorana phases

Barry, W.R., Nucl. Phys. **B842**

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	$\lvert m_{ee}\rvert$ [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**