Neutrinoless Double Beta Decay and Particle Physics

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MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

XII TH QUARK CONFINEMENT & THE HADRON SPECTRUM

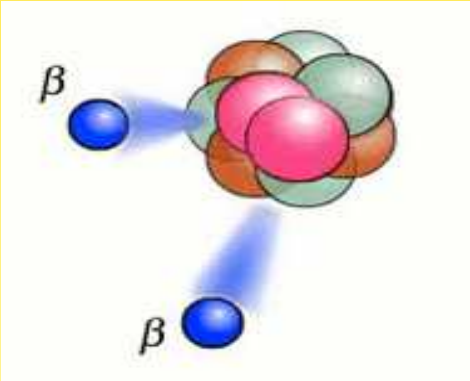
Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Neutrinoless Double Beta Decay

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

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



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

W.R., H. Päs, New J. Phys. 17, 115010 (2015)

Why should we probe Lepton Number Violation?

- 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 $J^B_\mu = \sum \overline{q_i}\,\gamma_\mu\,q_i$ and $J^L_\mu = \sum \overline{\ell_i}\,\gamma_\mu\,\ell_i$)

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

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

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	✓	–	–	–
CUPID	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
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	–	✓	–	–

Interpretation of Experiments

Master formula:

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

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

Interpretation of Experiments

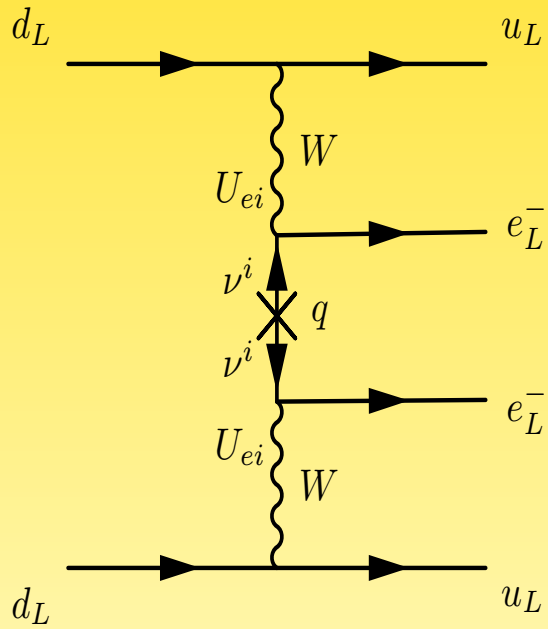
Master formula:

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

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

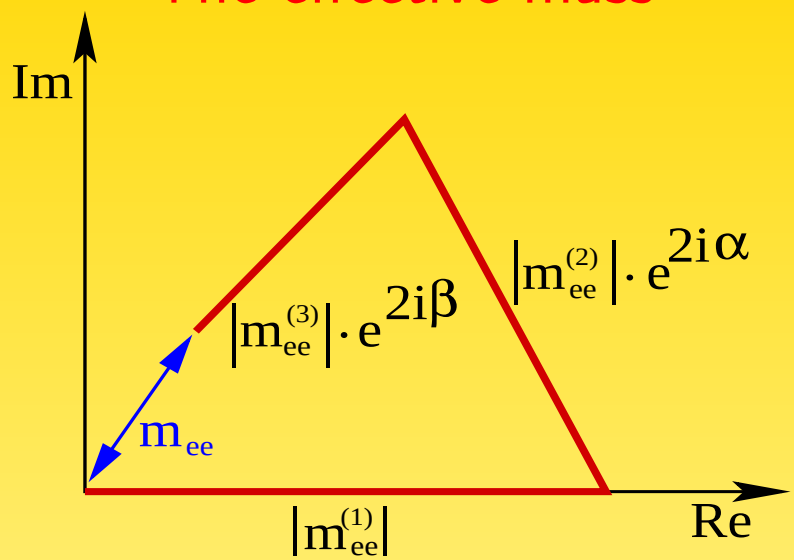
Standard Interpretation

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

The effective mass



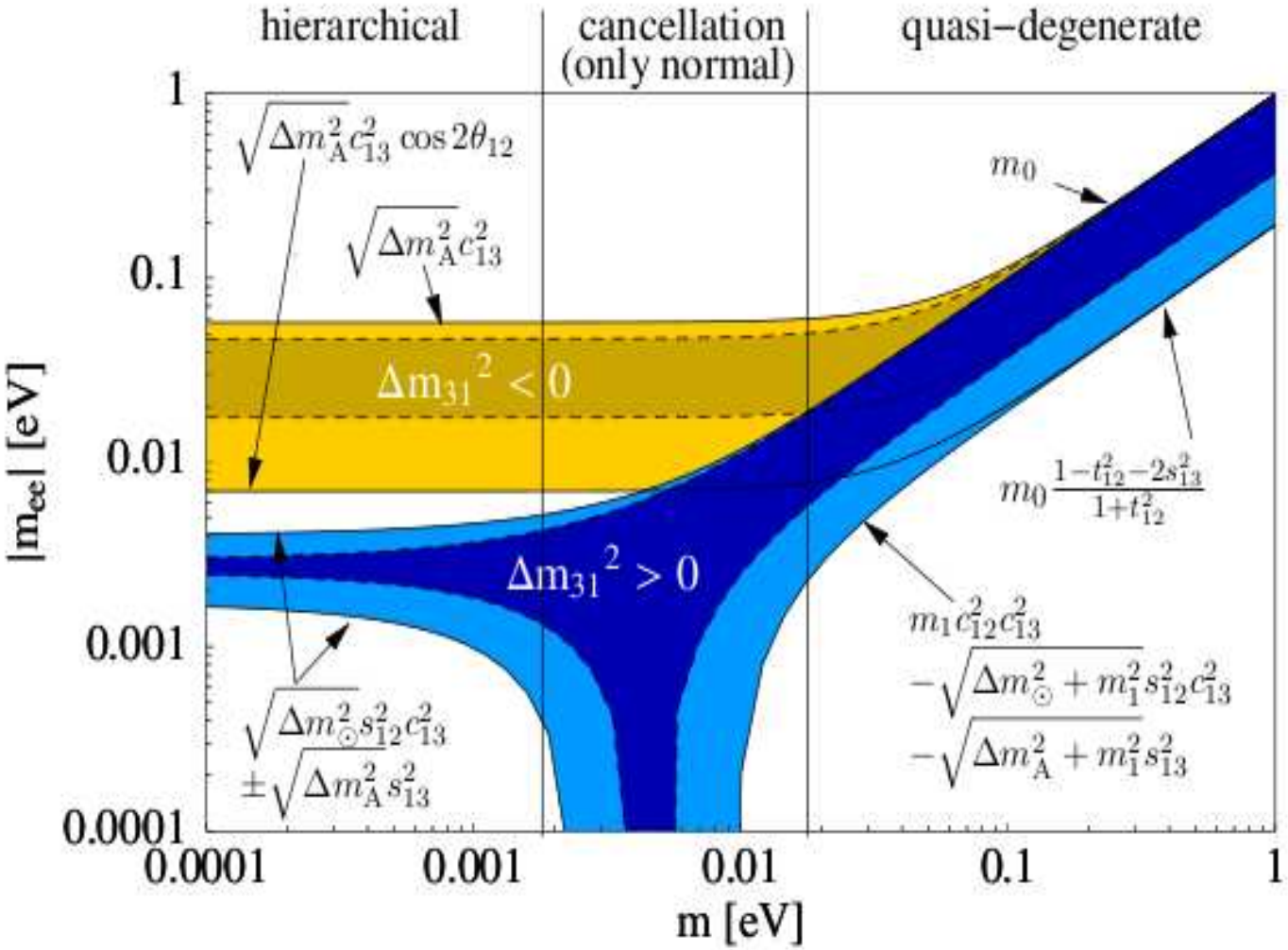
Amplitude proportional to coherent sum (“effective mass”):

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

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

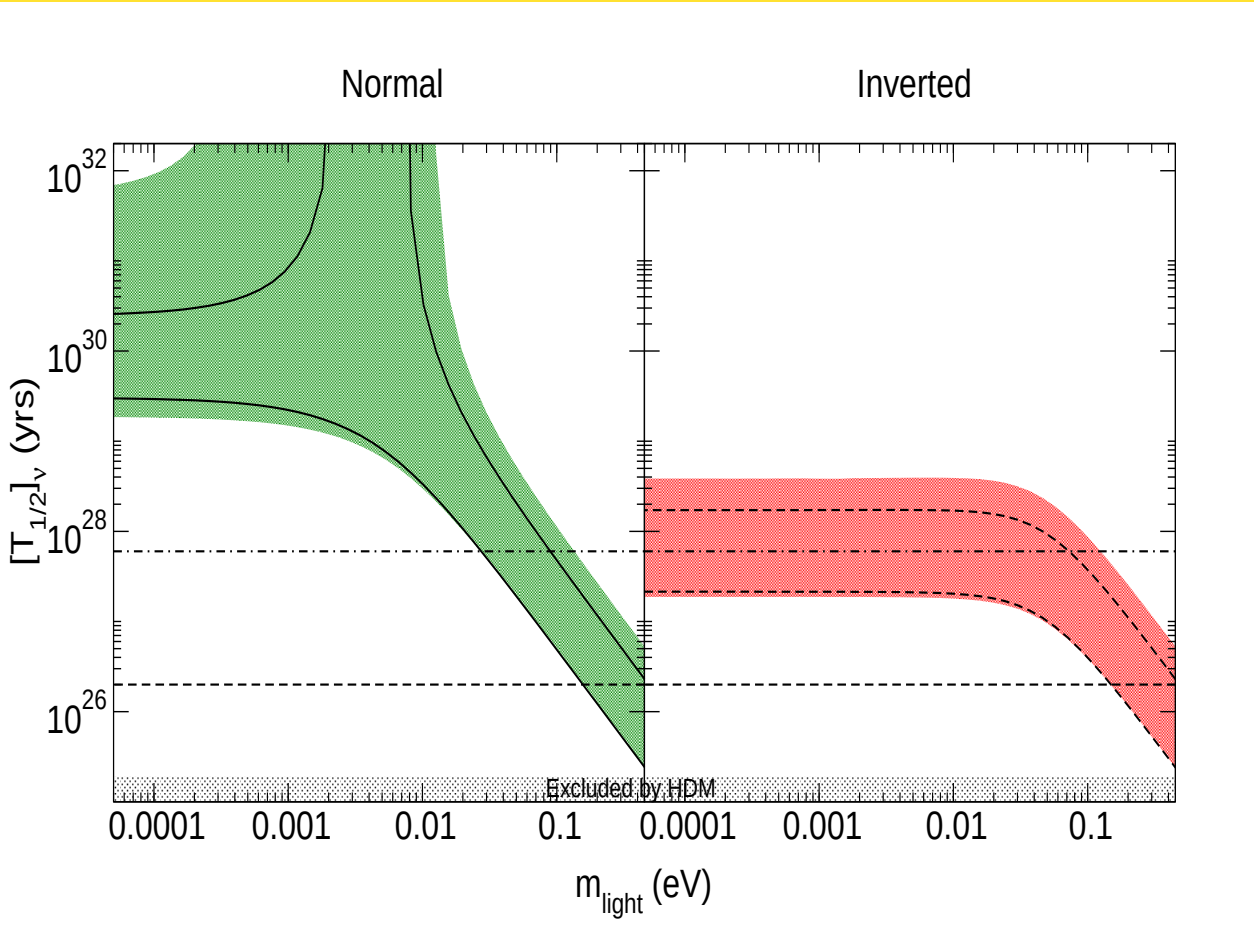
7 out of 9 parameters of neutrino physics!

The usual plot

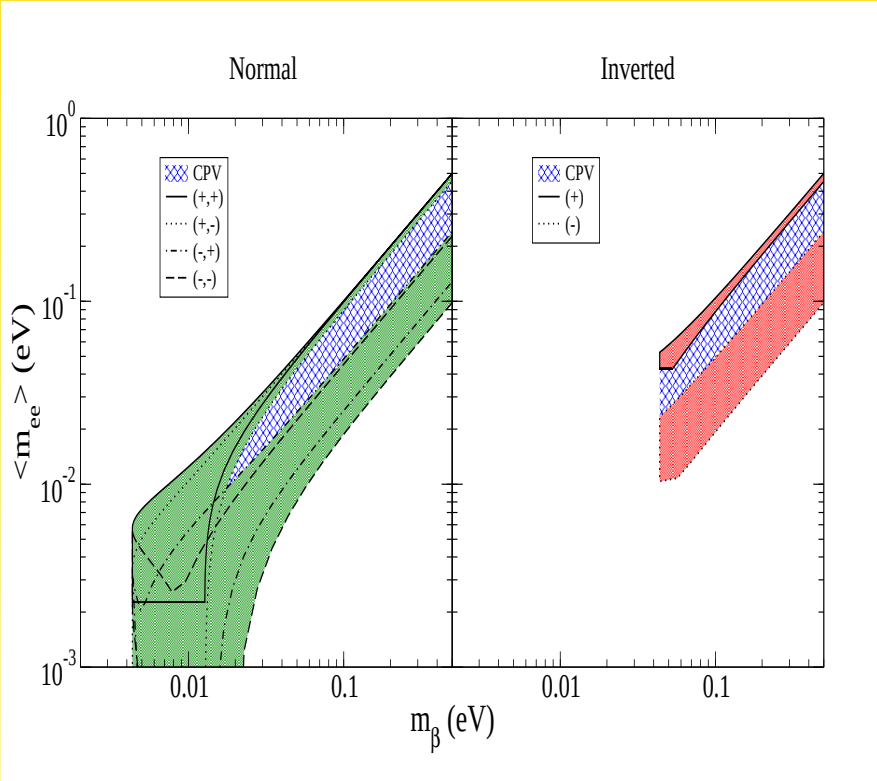


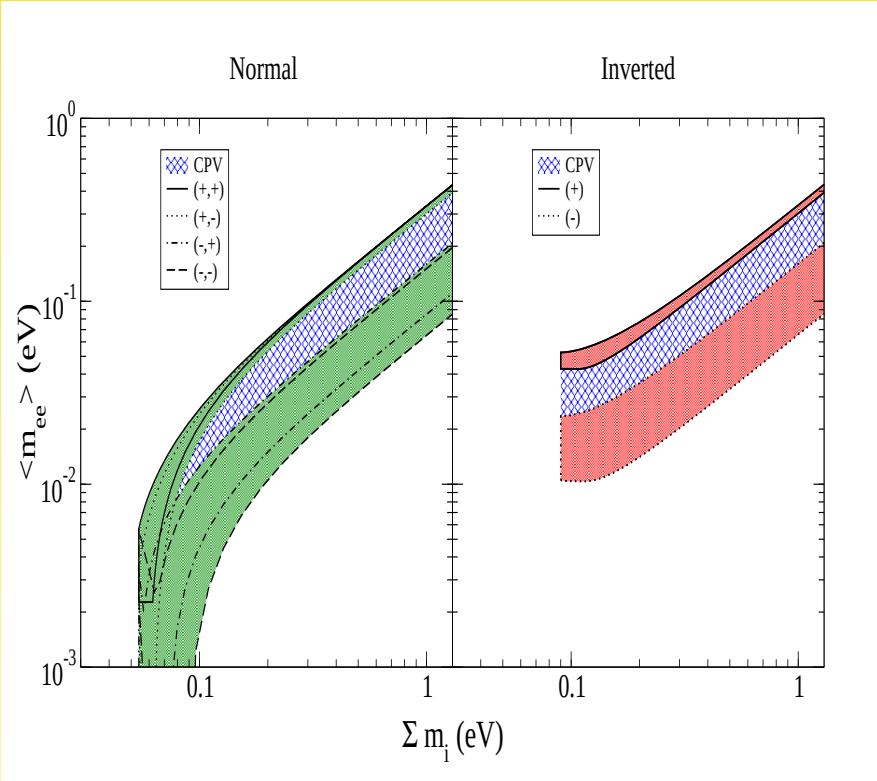
The usual plot

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



Plot against other observables





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

Neutrino Mass

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

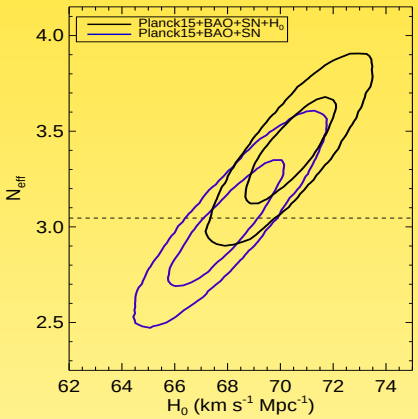
3 **complementary** methods to measure neutrino mass:

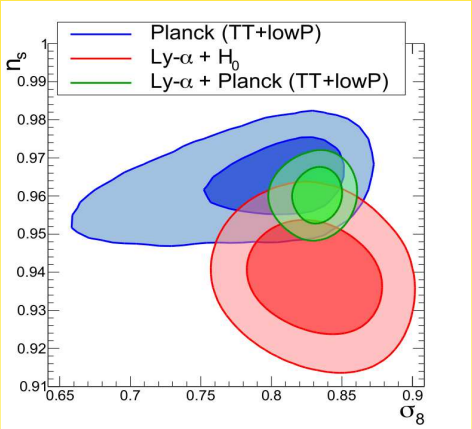
Method	observable	now [eV]	near [eV]	far [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 m_i^2}$	2.3	0.2	0.1	model-indep.; theo. clean	final?; worst
Cosmo.	$\sum m_i$	0.5	0.2	0.05	best; NH/IH	systemat.; model-dep.
$0\nu\beta\beta$	$\lvert\sum U_{ei}^2 m_i\rvert$	0.2	0.1	0.05	fundament.; NH/IH	model-dep.; theo. dirty

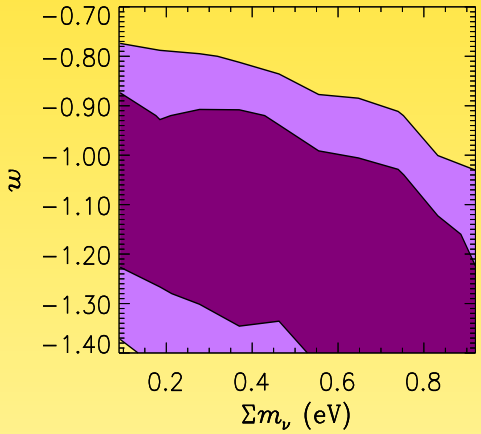
Cosmological Limits

stacking more and more data sets on top of each other, limits become stronger (needed to break degeneracies, but induces systematic issues)

including more and more parameters, limits become weaker







Riess *et al.*, 1604.01424

Palanque-Delabrouille *et al.*, 1506.05976

Hannestad, PRL **95**

(most extreme (1410.7244): at 1σ: $\Sigma m_\nu \leq 0.08$ eV, disfavors inverted ordering...)

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

- LSND/MiniBooNE/gallium/reactor anomalies, $\Delta m^2 \simeq 1$ eV^2, $U_{\alpha 4} \simeq 0.1$
- $|m_{ee}| = |\underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}^2| m_3 e^{2i\beta}}_{m_{ee}^{\rm act}} + \underbrace{|U_{e4}|^2 m_4 e^{2i\Phi_1}}_{m_{ee}^{\rm st}}|$
- sterile contribution to $0\nu\beta\beta$:

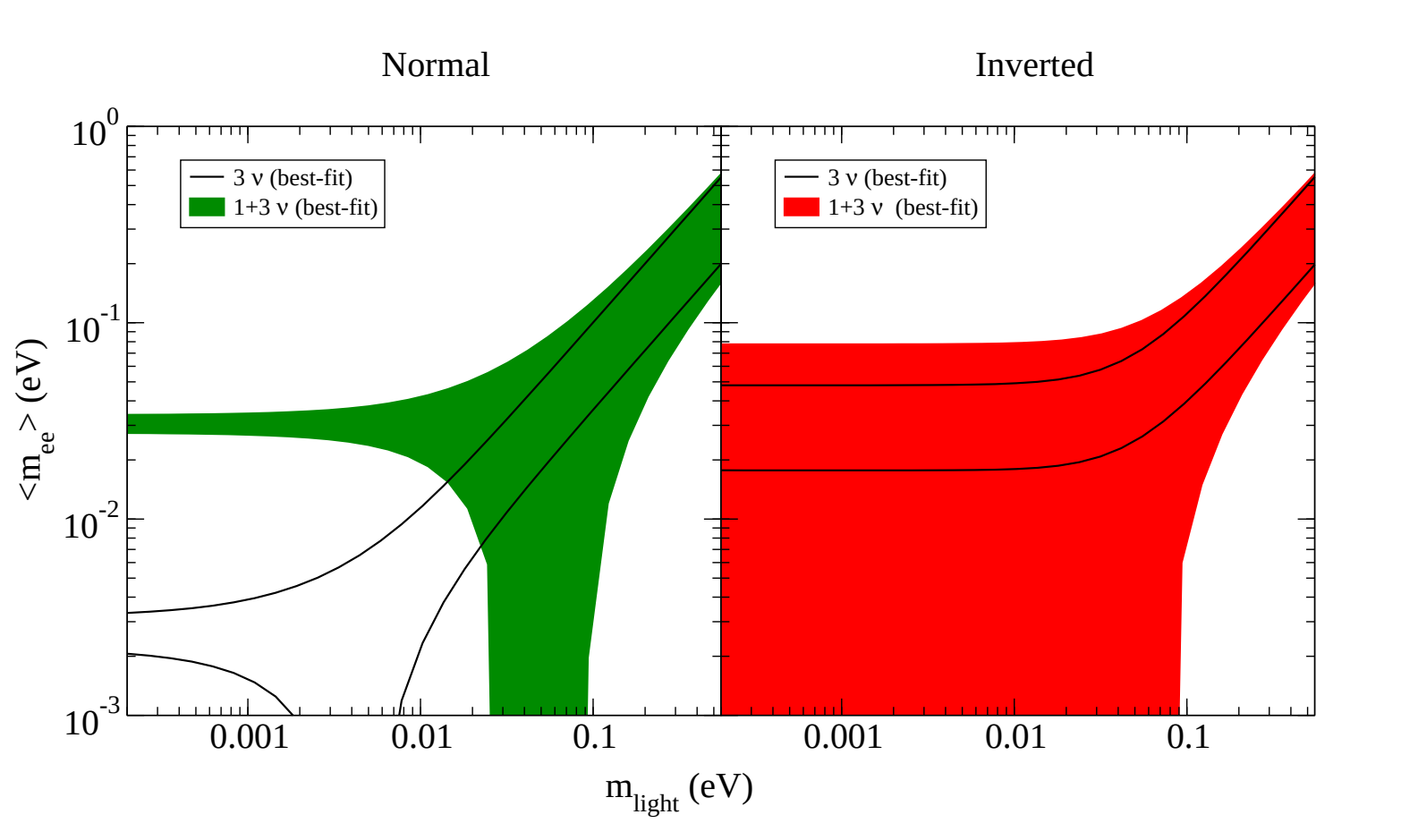
$$|m_{ee}|^{\rm st} \simeq \sqrt{\Delta m^2_{\rm st}}\, |U_{e4}|^2 \begin{cases} \gg |m_{ee}|^{\rm act}_{\rm NH} \\ \simeq |m_{ee}|^{\rm act}_{\rm IH} \end{cases}$$

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

$\Rightarrow$ usual phenomenology gets completely turned around!

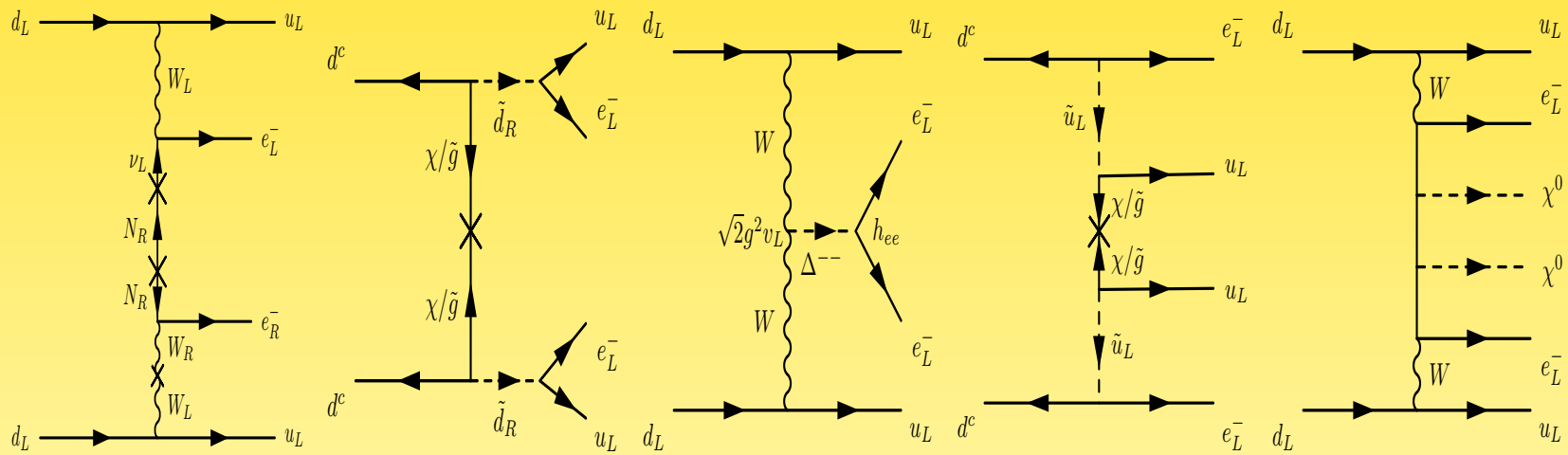
Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Petcov, Meroni, JHEP **1311**

Usual plot gets completely turned around!



Non-Standard Interpretations:

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



Clear experimental signature:

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

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

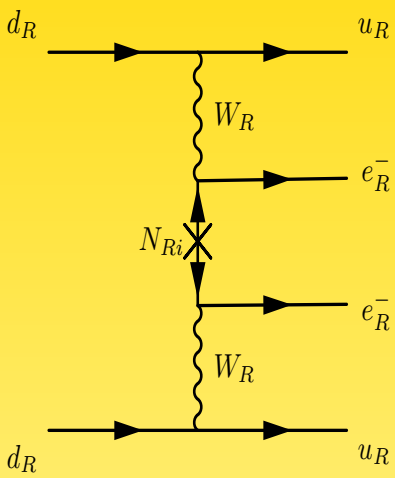
(cosmology limits decoupled from $0\nu\beta\beta$)

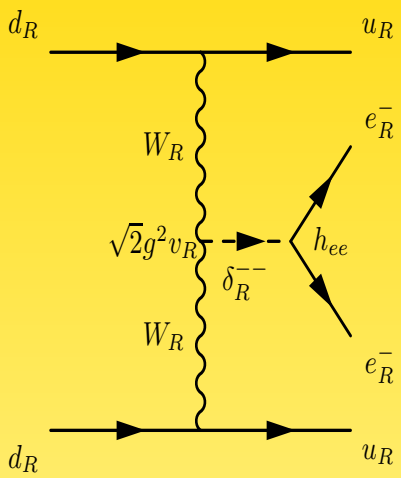
$$T^{0\nu}(1\ \mathrm{eV}) = T^{0\nu}(1\ \mathrm{TeV})$$

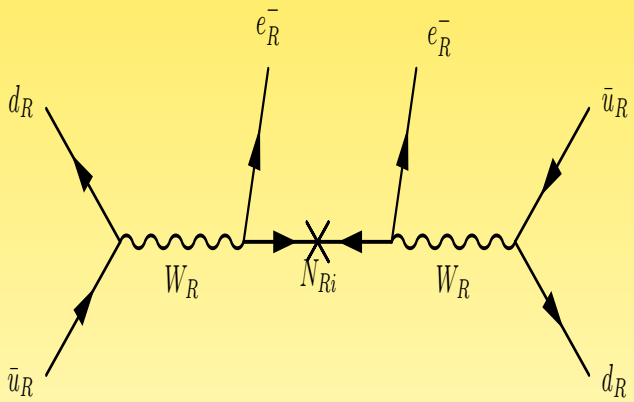
- RPV Supersymmetry
- left-right symmetry
- heavy neutrinos
- color octets
- leptoquarks
- effective operators
- extra dimensions
- ...

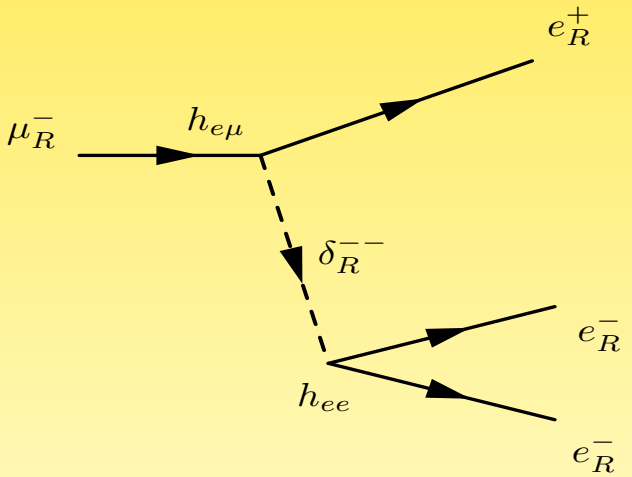
$\Rightarrow$ need to solve the inverse problem...

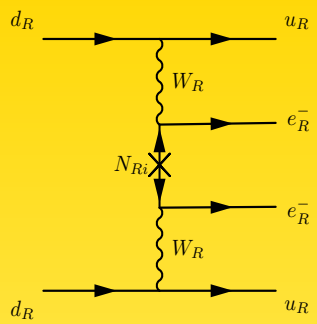
Example: Left-right symmetric theories

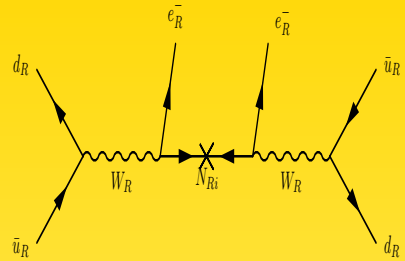


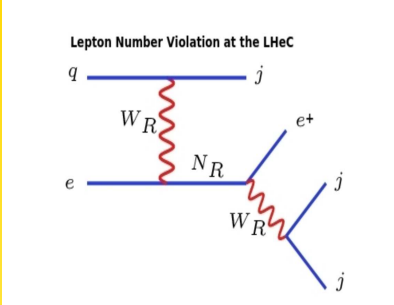


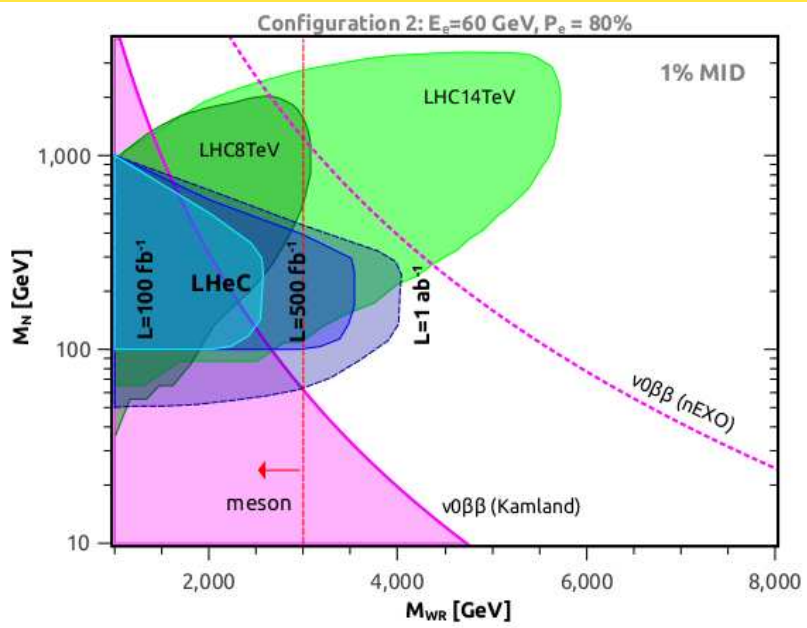


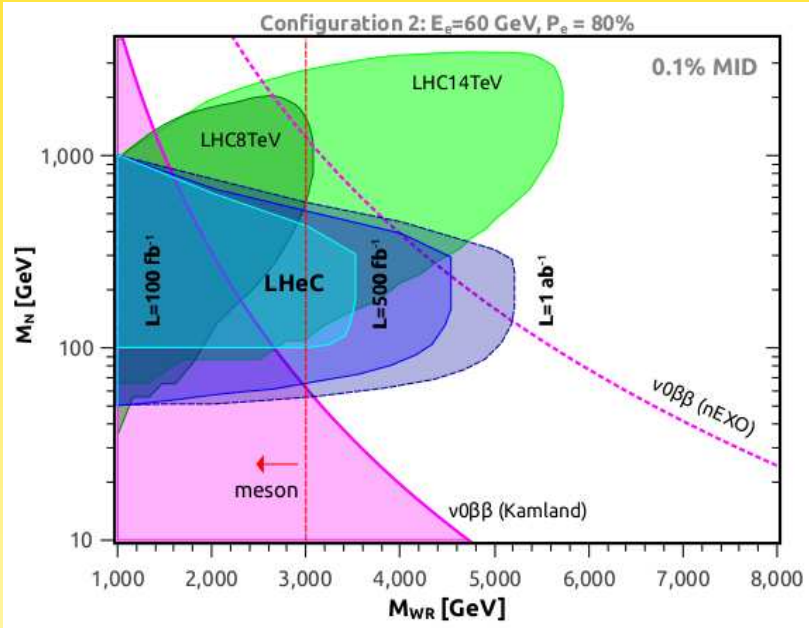








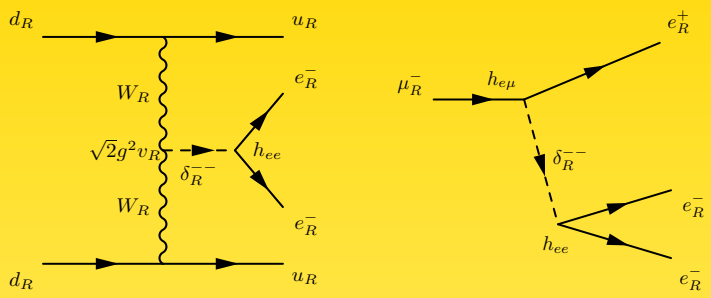


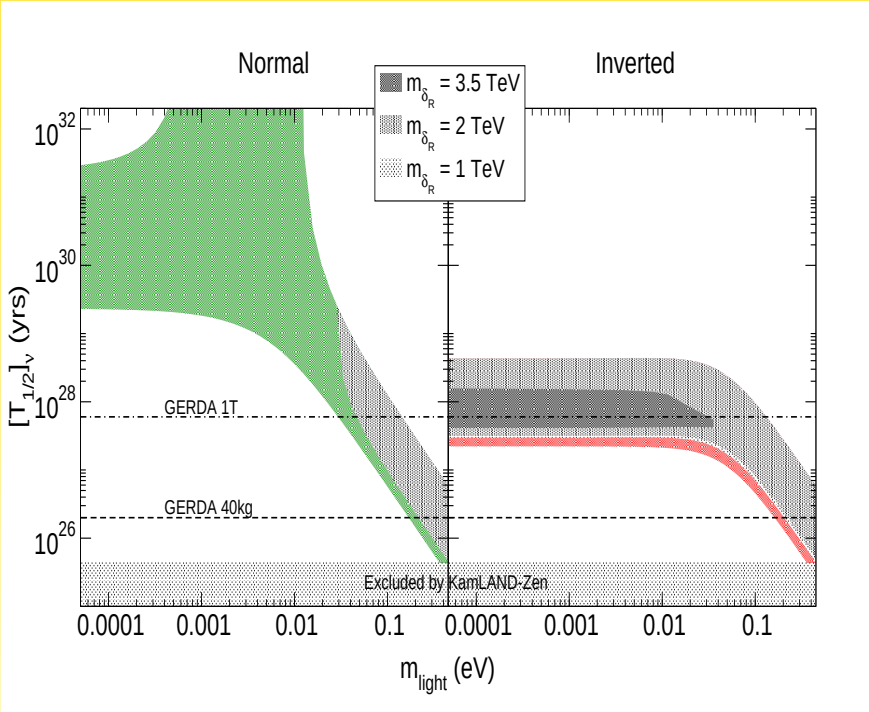


Lindner, Queiroz, W.R., Yaguna, JHEP **1606**

LHeC $\leftrightarrow$ polarization and complementarity

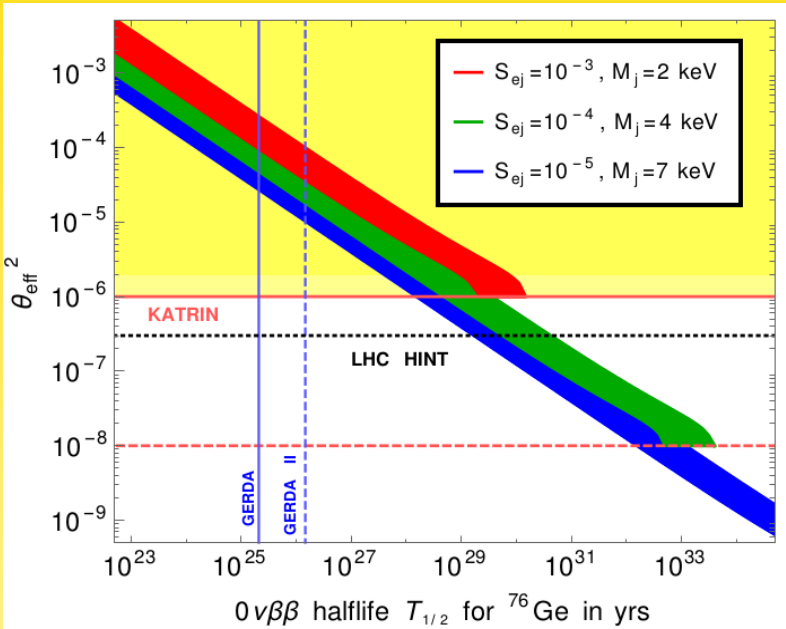
Constraints from Lepton Flavor Violation

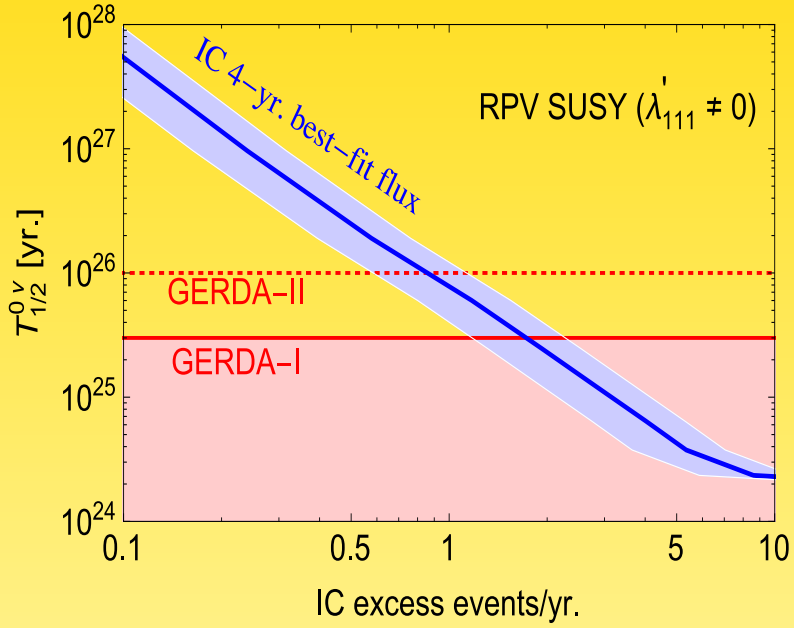




Barry, W.R., JHEP **1309**

Surprising correlations in alternative scenarios





keV-ν in KATRIN

(RH interaction)

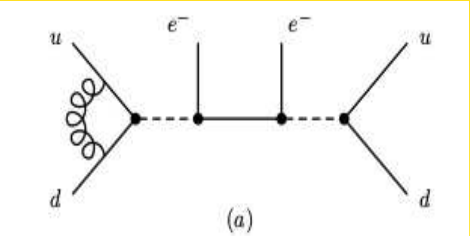
Barry, Heeck, W.R., JHEP **1407**

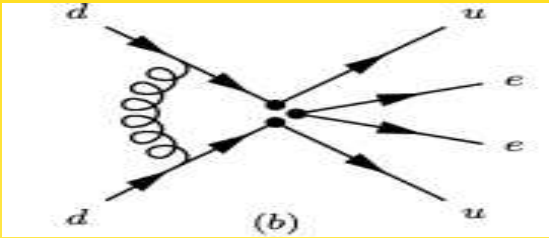
excess events in IceCube

(RPV SUSY)

Dev, Ghosh, W.R., 1605.09743

QCD corrections





- naive size $\alpha_s/(4\pi)\ln\frac{M_W^2}{(100\ \mathrm{MeV})^2} = 10\%$, true for standard interpretation
- but: creates in non $(V-A)\otimes(V-A)$ mechanisms color non-singlet operators, Fierz them and mix with new operators with different NMEs
- can give for alternative mechanisms large effect in either direction...
- (makes limit on right-handed diagrams slightly weaker)

Mahajan, PRL **112**; Gonzalez, Kovalenko, Hirsch, PRD **93**; Peng, Ramsey-Musolf, Winslow, PRD **93**

Do Dirac neutrinos mean there is no Lepton Number Violation?

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

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

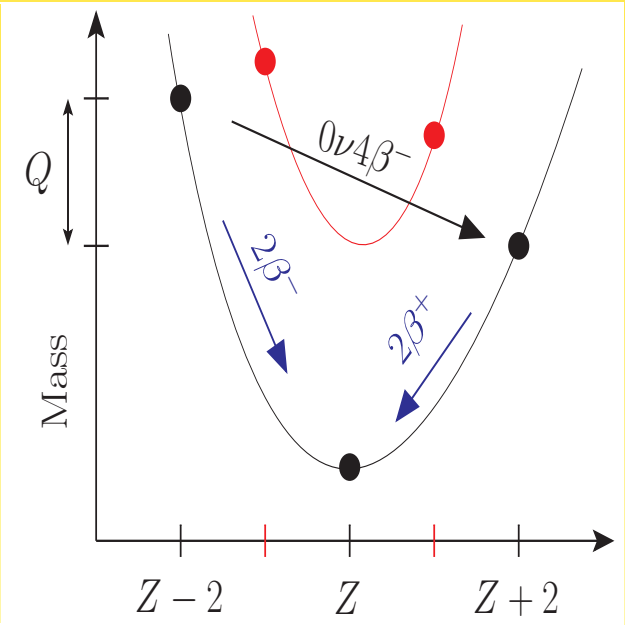
Heeck, W.R., EPL **103**

Do Dirac neutrinos mean there is no Lepton Number Violation?

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

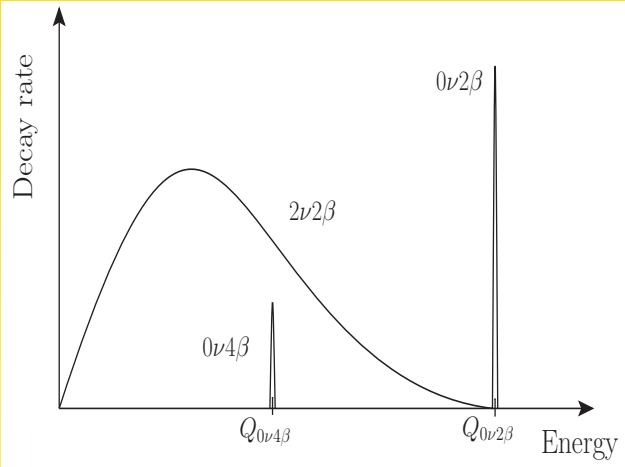
$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...

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



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

Candidates for neutrinoless quadruple beta decay



	$Q_{0\nu4\beta}$	Other decays	NA
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6

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

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.

Summary

- need to pursue all neutrino mass approaches
  - confirm 3 Majorana neutrino paradigm!
  - inconsistencies not unlikely
- LHC and $0\nu\beta\beta$ complementary
- distinguishing mechanisms necessary

Another extreme point of view: Quenching

$T^{0\nu}_{1/2} \propto g_A^{-4}$, where in $2\nu\beta\beta$-decay (Iachello)

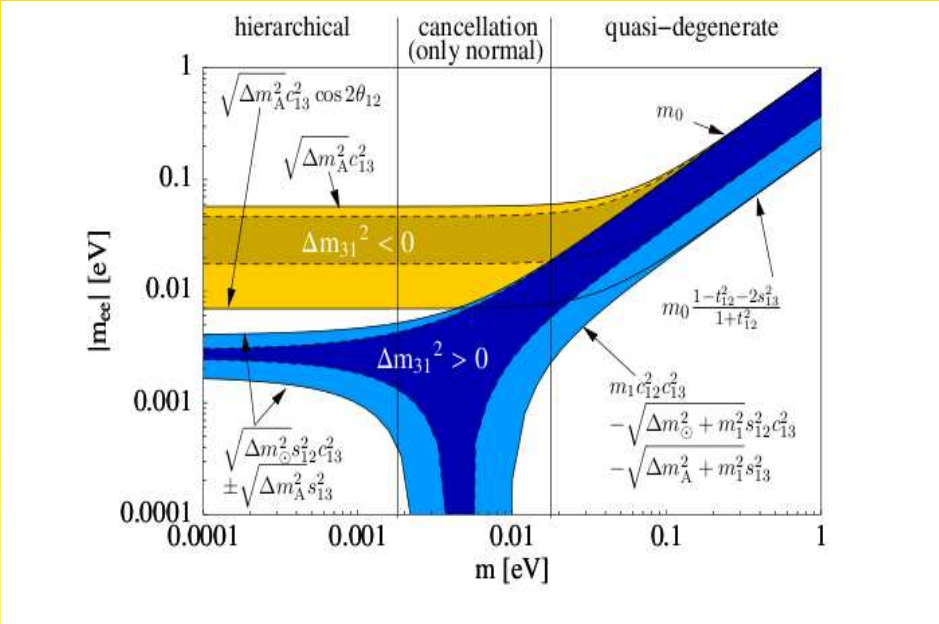
$$g_A^{\rm IBM} \simeq 1.27\, A^{-0.18} = \begin{cases} 0.58 & \text{Ge} \\ 0.53 & \text{Te} \\ 0.52 & \text{Xe} \end{cases}$$

would shift lifetimes an order of magnitude (in wrong direction...)

- model-space truncation (A-dep.)/omission of N^*, Δ (not A-dep.)
- energy scale (no quenching for muon capture)/many multipolarities in 0ν
- include 2 body currents (creation of 2p2h), weaker quenching in 0ν (Engel, Simkovic, Vogel, PRC**89**)

lots of nuclear theory work on the way, possibly no showstopper (20%?)

Inverted Ordering



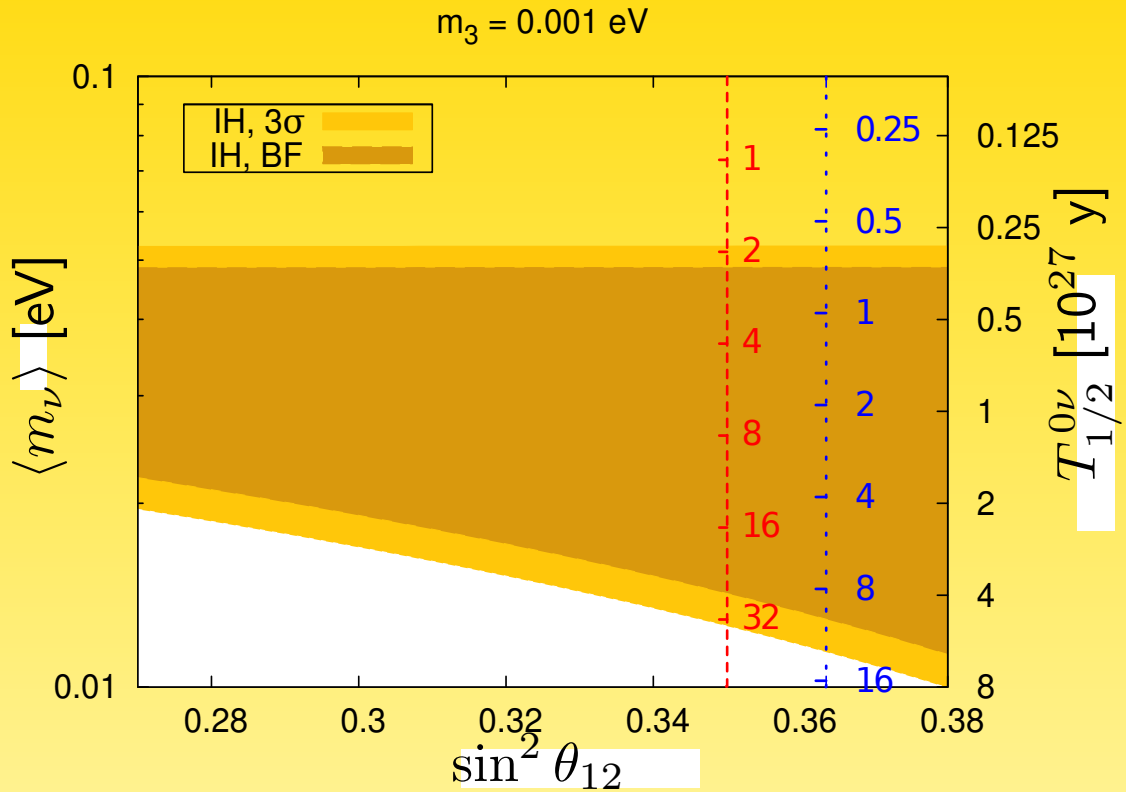
Nature provides 2 scales:

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

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

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

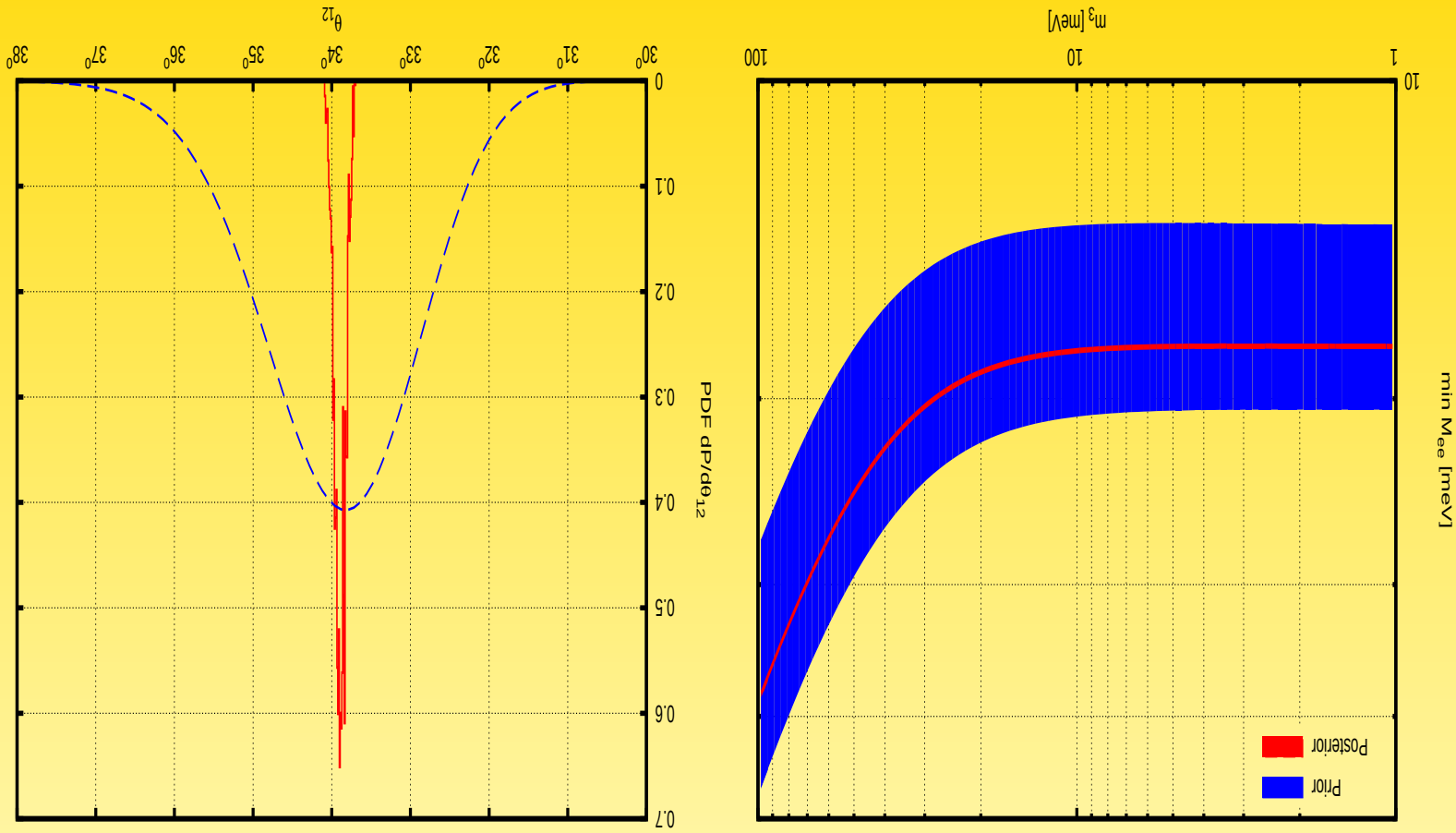
Inverted Hierarchy



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

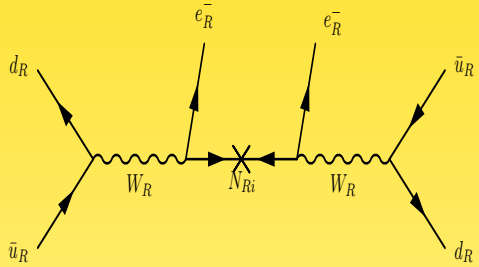
$(T^{0\nu}_{1/2})^{-1} \propto a\,\varepsilon\sqrt{\frac{M\,t}{B\,\Delta E}}$ $\Rightarrow$ need precision determination of θ_{12}! $\leftrightarrow$ JUNO

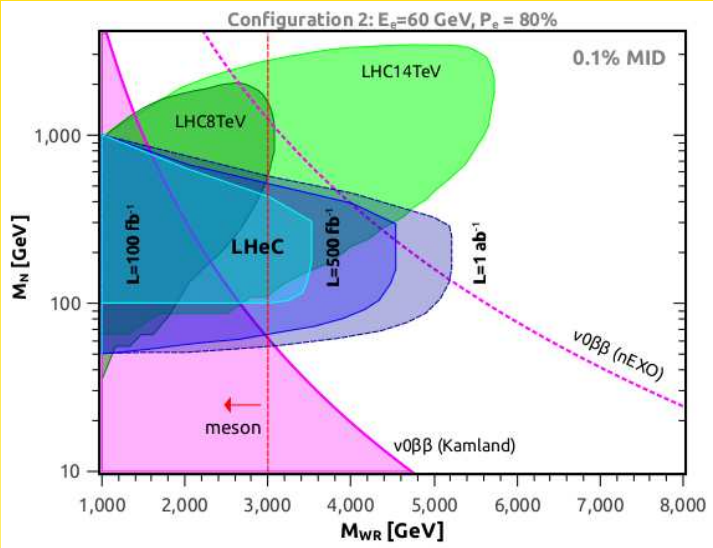
Dueck, W.R., Zuber, PRD **83**; Ge, W.R., PRD **92**



Ge, W.R., PRD **92**; http://nupro.hepforge.org

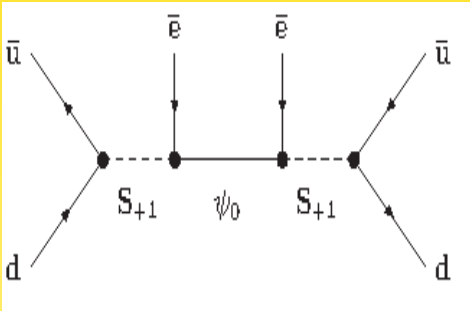
LHC vs. $0\nu\beta\beta$

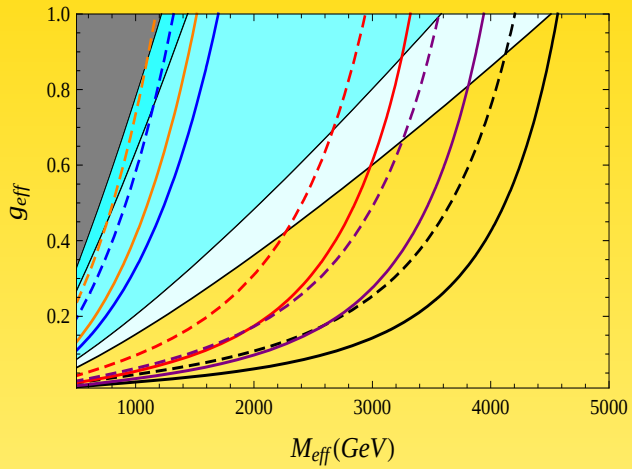




- LHC assumptions: $M_N < M_{W_R}$, BR$(M_N \to ee) = 1$, $g_R = g_L$
- cuts result in weak sensitivities for low M_N
- background processes?
- QCD corrections?
- (LNV at LHC and baryogenesis)

Background





Helo *et al.*, PRD **88**

one should include e.g.

- "jet fake" (high-p_T jet registered as electron)
- "charge flip" (e^- from opposite sign pair transfer p_T to e^+ via conversion)

Peng, Ramsey-Musolf, Winslow, 1508.04444

Background

one should include e.g.

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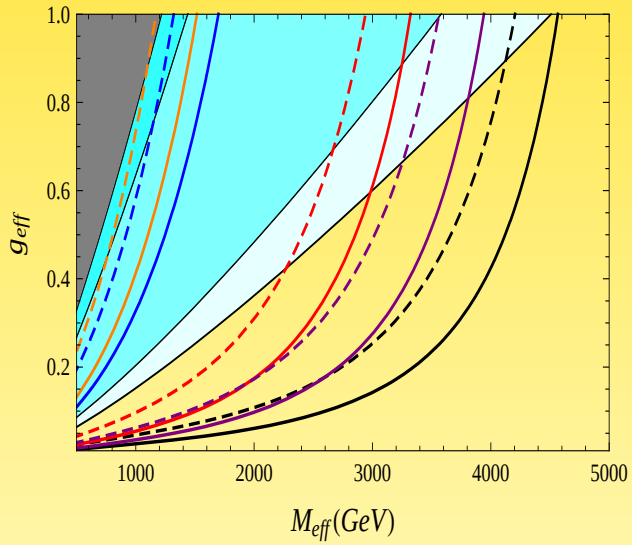
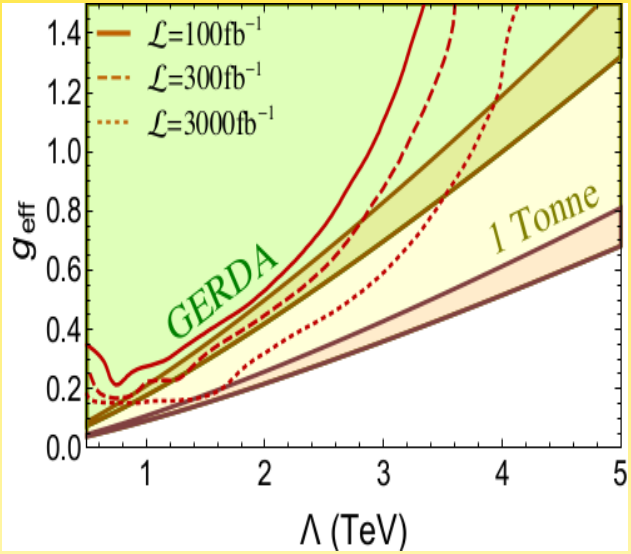




Peng, Ramsey-Musolf, Winslow, 1508.04444

Distinguishing Mechanisms

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

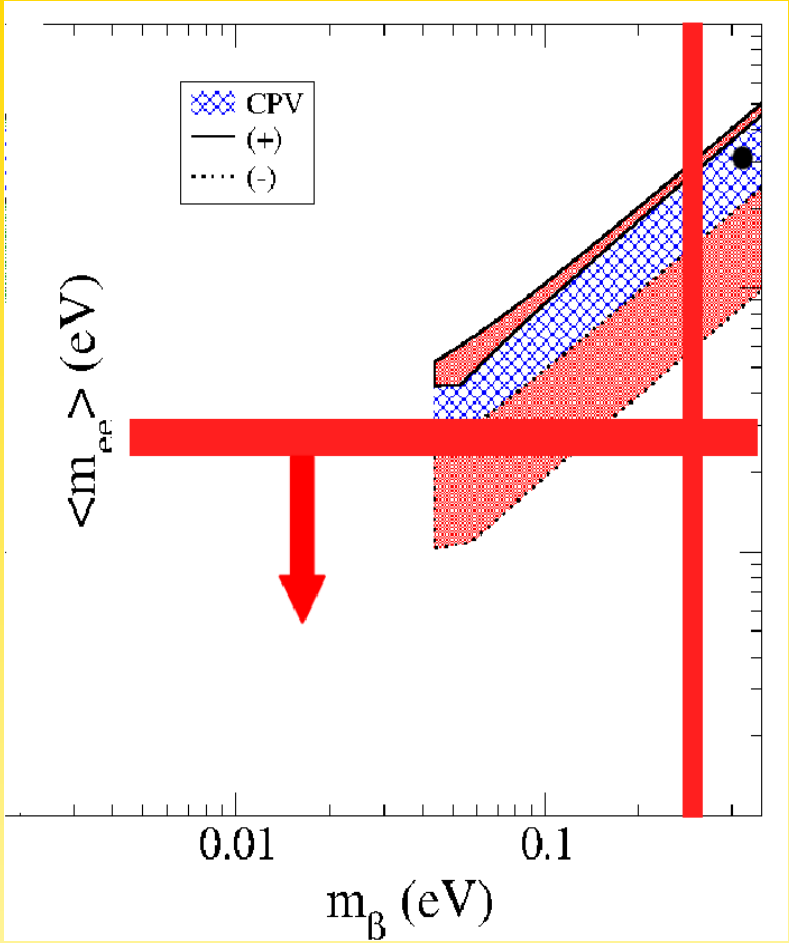
1.) Other observables (LHC, LFV, KATRIN, cosmology,...)

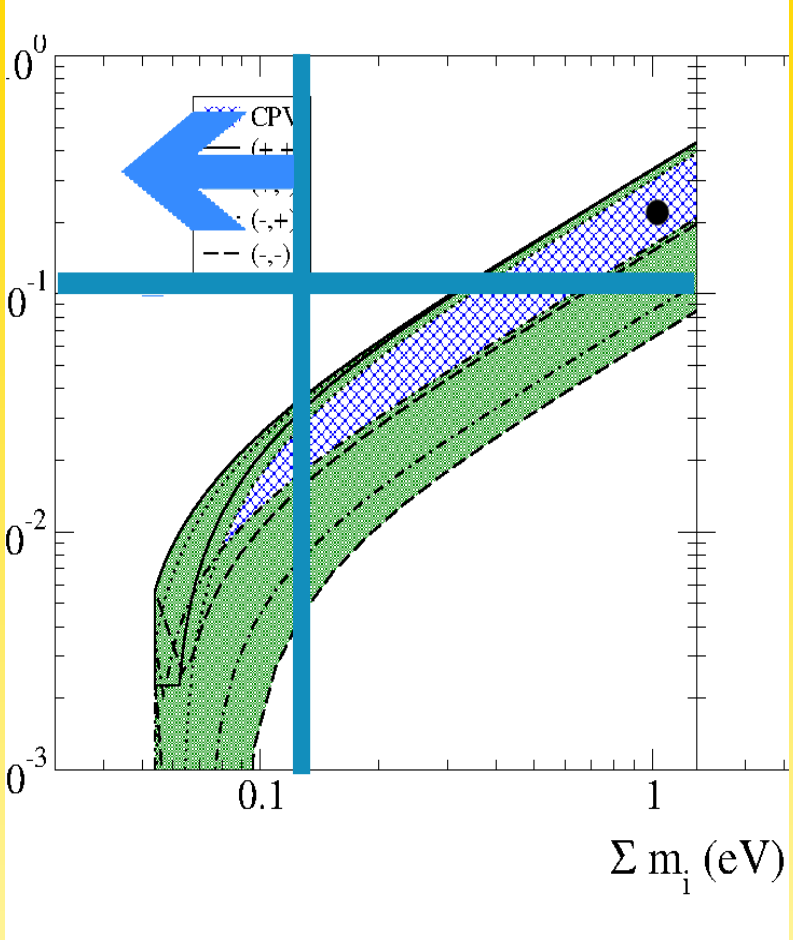
2.) Decay products (individual e^- energies, angular correlations, spectrum,...)
(SuperNEMO, EPJC **70**; Horoi, Neascu, 1511.00670)

3.) Nuclear physics (multi-isotope, 0νECEC, $0\nu\beta^+\beta^+$,...)
(Gehman, Elliott, JPG **34,35**)

Complementarity!

- are already in era of complementarity
  - cosmology limits rule out that light neutrinos saturate $0\nu\beta\beta$-limits
    - $*$ strictest limits start to disfavor inverted ordering
  - $0\nu\beta\beta$ limits rule out that light neutrinos saturate Mainz/Troitsk limit
- interesting possibilities in case inconsistencies arise...





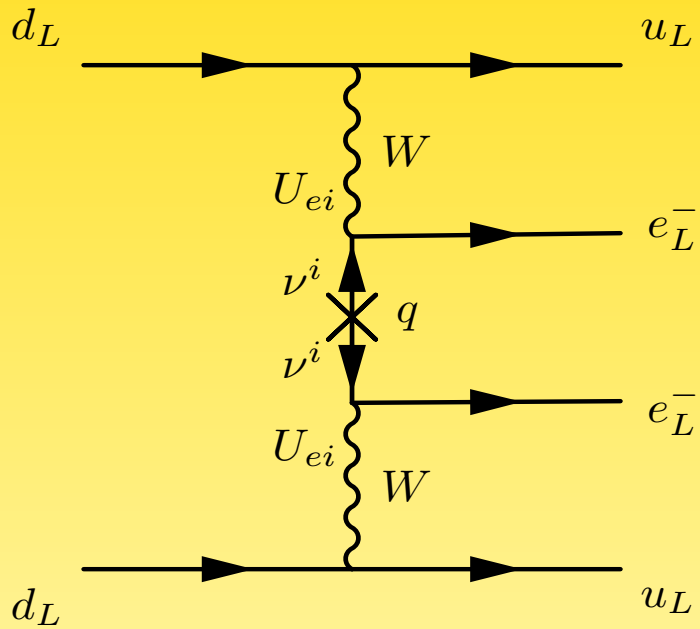
CP violation!

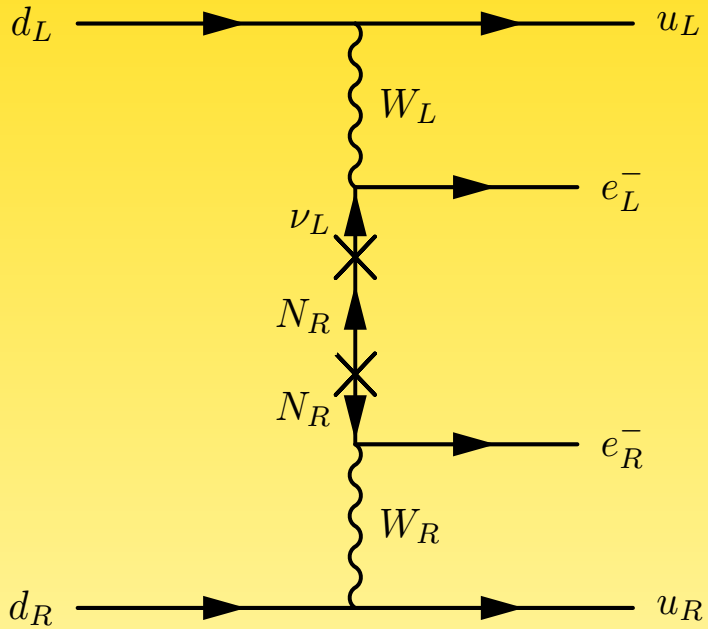
Dirac neutrinos!

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

Distinguishing via decay products

Consider standard plus λ-mechanism

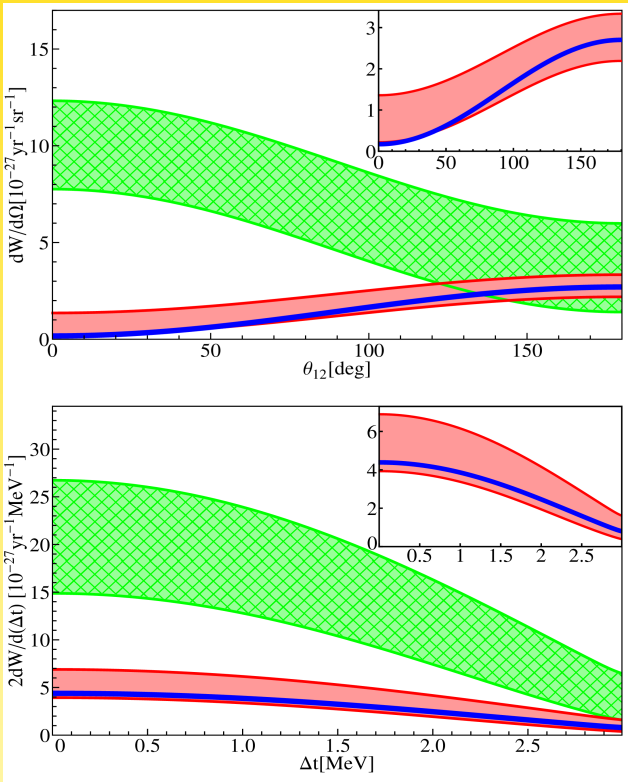




$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (1 - \beta_1\, \beta_2\, \cos\theta) \qquad \frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} \propto (E_1 - E_2)^2\, (1 + \beta_1\, \beta_2\, \cos\theta)$$

Arnold *et al.*, EPJC **70**

Distinguishing via decay products



$|m_{ee}| = 0.1$ eV and

$$\frac{U_{ei}S_{ei}}{M_{W_R}^2} = 0$$

$$\frac{U_{ei}S_{ei}}{M_{W_R}^2} = 8 \cdot 10^{-6}\,\mathrm{TeV}^{-2}$$

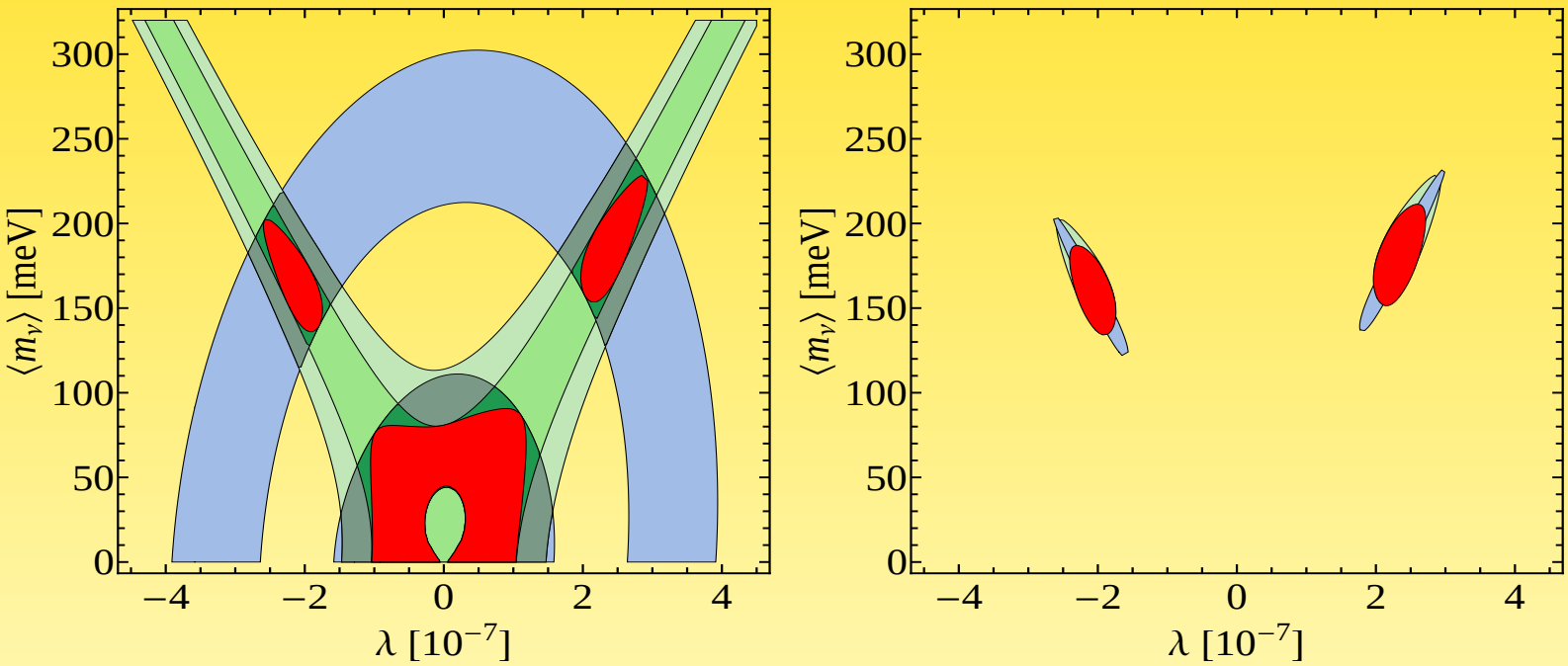
$$\frac{U_{ei}S_{ei}}{M_{W_R}^2} = 3 \cdot 10^{-5}\,\mathrm{TeV}^{-2}$$

Horoi, Neascu, 1511.00670

Distinguishing via decay products

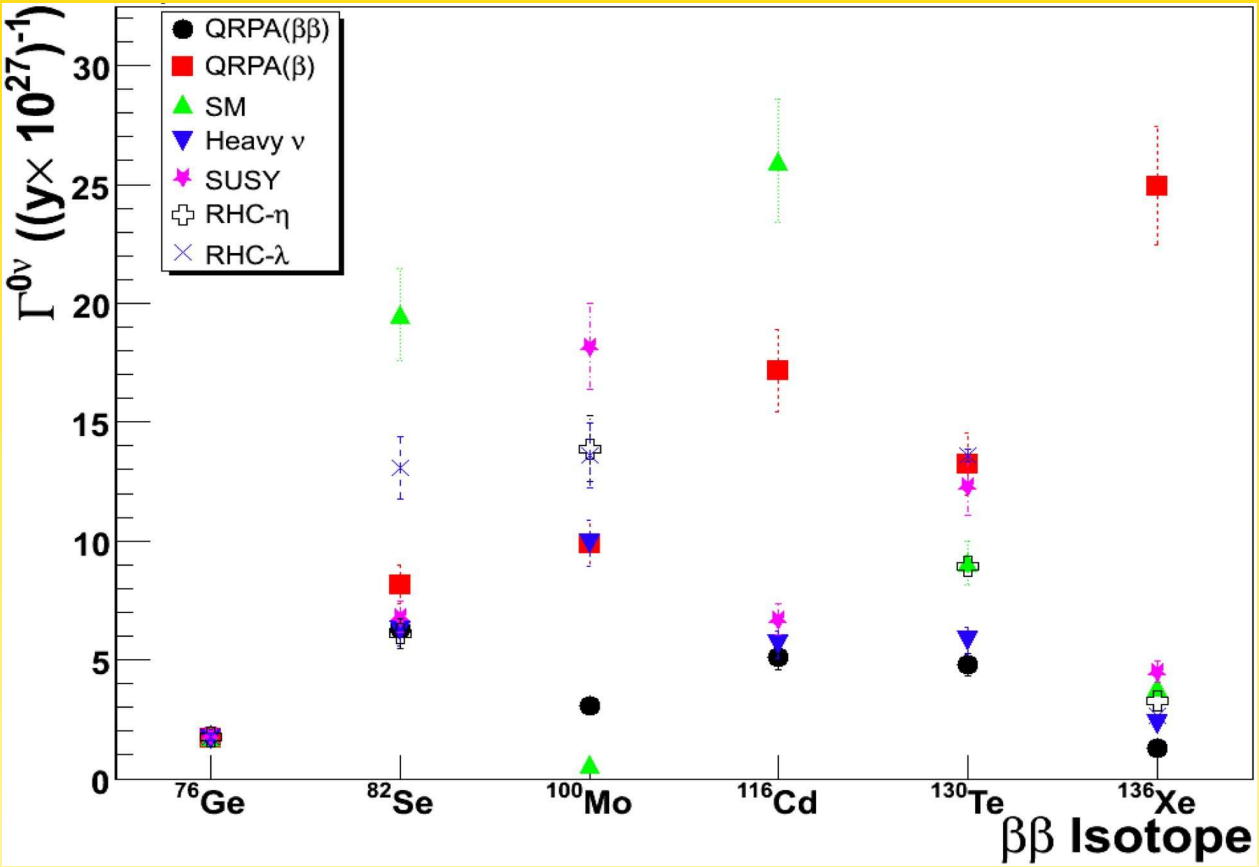
Defining asymmetries

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



Arnold *et al.*, EPJC **70**

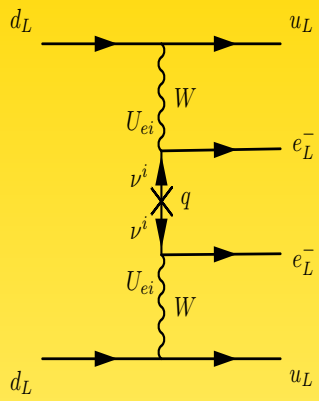
Distinguishing via nuclear physics



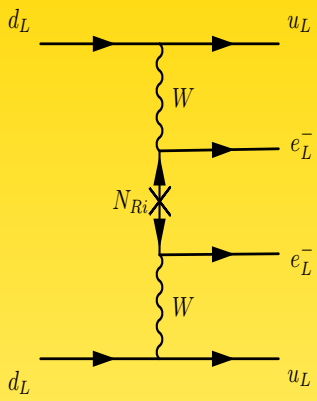
Gehman, Elliott, JPG **34,35**

3 to 4 isotopes necessary to disentangle mechanism

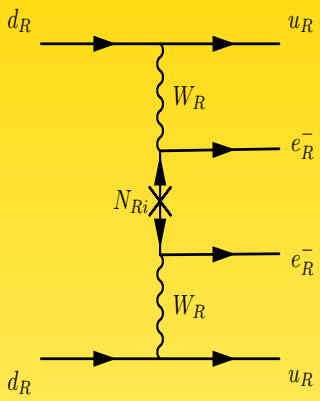
Left-right symmetry



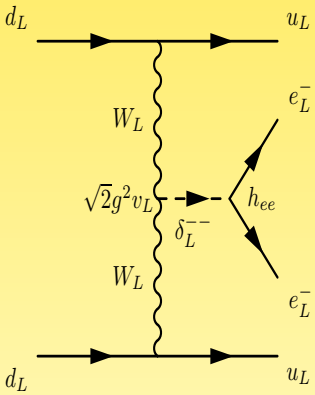
$$U_{ei}^2\, m_i$$



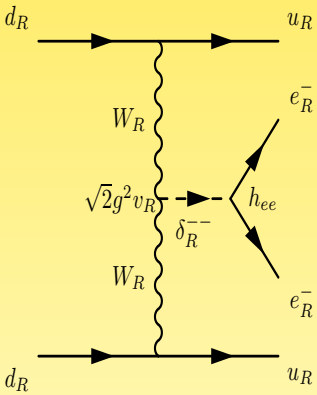
$$\frac{S_{ei}^2}{M_i}$$



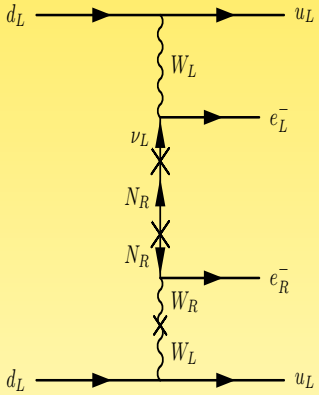
$$\frac{V_{ei}^2}{M_{W_R}^4\, M_i}$$



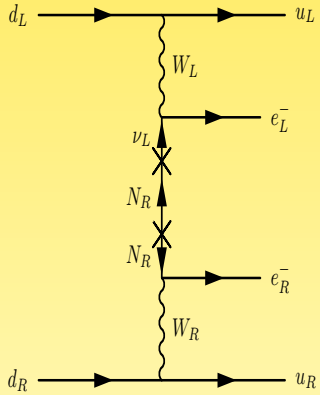
$$\frac{U_{ei}^2\, m_i}{M_{\Delta_L}^2}$$



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



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



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

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**

Recent Results

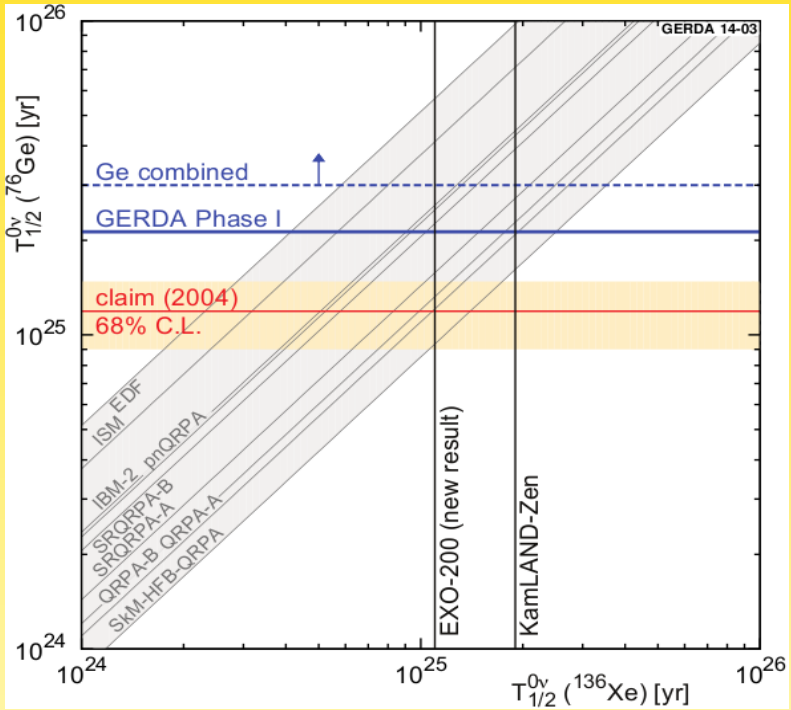
- ^{76}Ge:
  - GERDA: $T_{1/2} > 2.1 \times 10^{25}$ yrs
  - GERDA + IGEX + HDM: $T_{1/2} > 3.0 \times 10^{25}$ yrs
- ^{136}Xe:
  - EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yrs **(first run with less exposure: $T_{1/2} > 1.6 \times 10^{25}$ yrs. . .)**
  - KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$ yrs

Xe-limit is stronger than Ge-limit when:

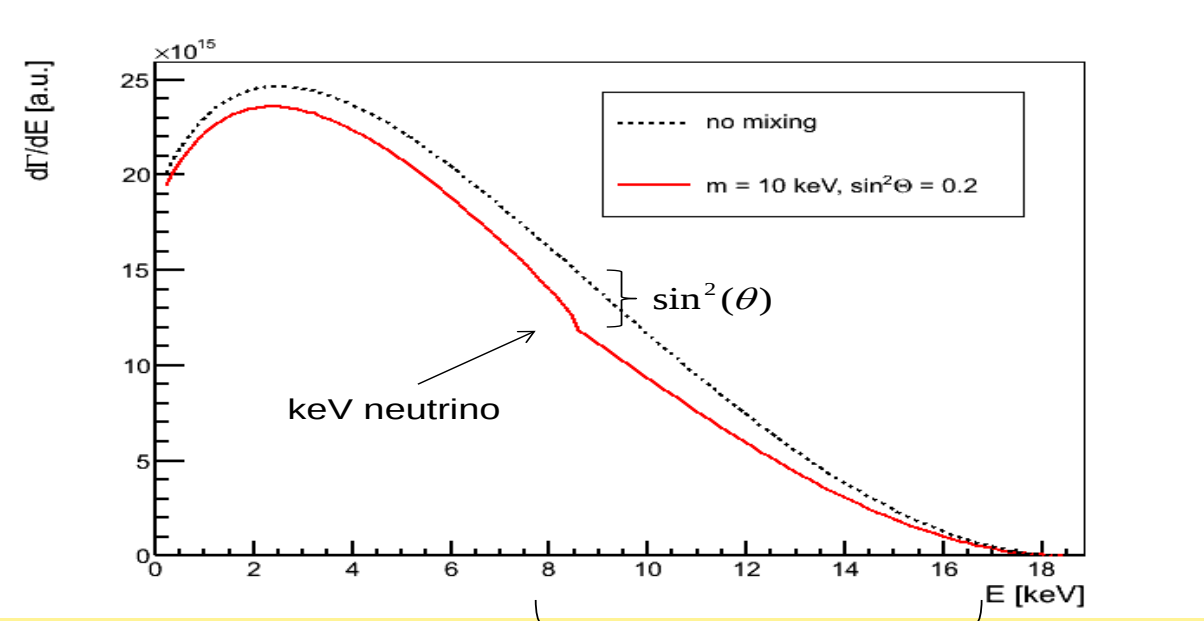
$$T_{\rm Xe} > T_{\rm Ge} \, \frac{G_{\rm Ge}}{G_{\rm Xe}} \left| \frac{\mathcal{M}_{\rm Ge}}{\mathcal{M}_{\rm Xe}} \right|^2 \text{ yrs}$$

Current new limits on $|m_{ee}|$ (post KamLAND-Zen)

NME	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	**0.32**	**0.27**	**0.06**	–
ISM(U)	**0.52**	**0.44**	**0.12**	–
IBM-2	**0.27**	**0.23**	**0.08**	–
pnQRPA(U)	**0.28**	**0.24**	**0.08**	–
SRQRPA-A	**0.31**	**0.26**	**0.11**	–
QRPA-A	**0.28**	**0.24**	**0.12**	–
SkM-HFB-QRPA	**0.29**	**0.24**	**0.15**	–

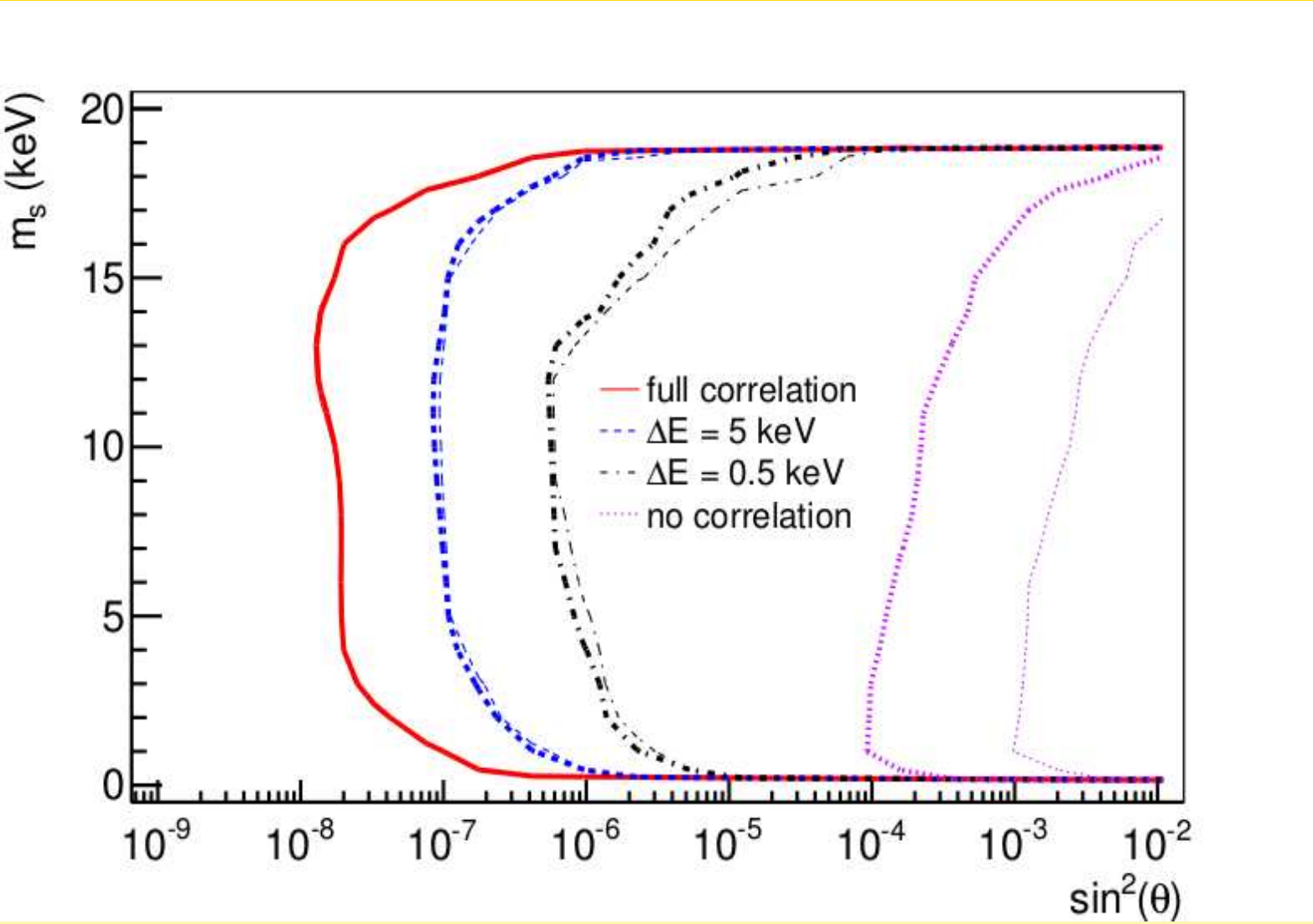


Imprint of keV neutrinos on ß-spectrum



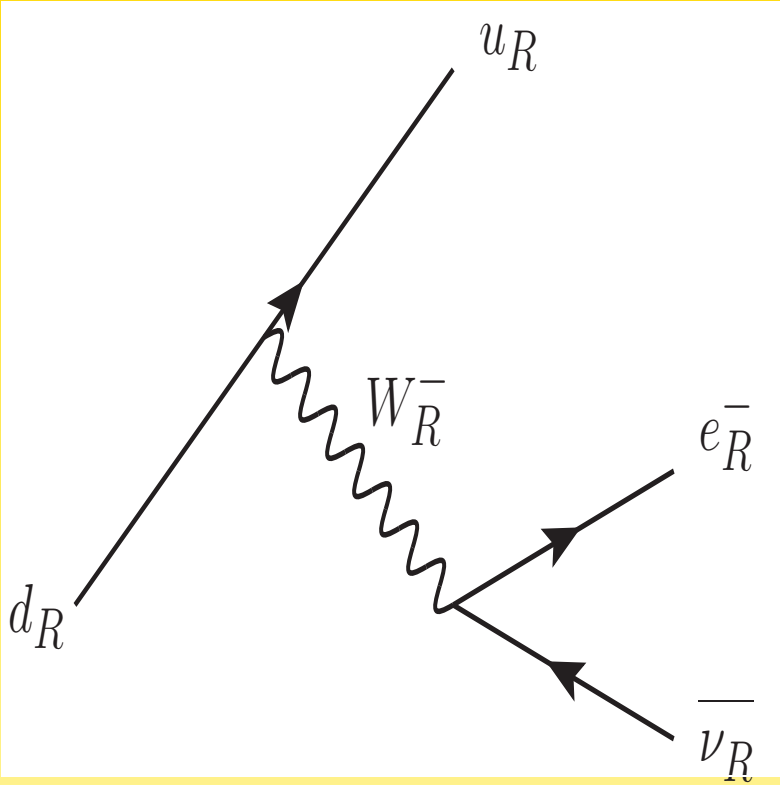
$m_{\nu_{heavy}}$

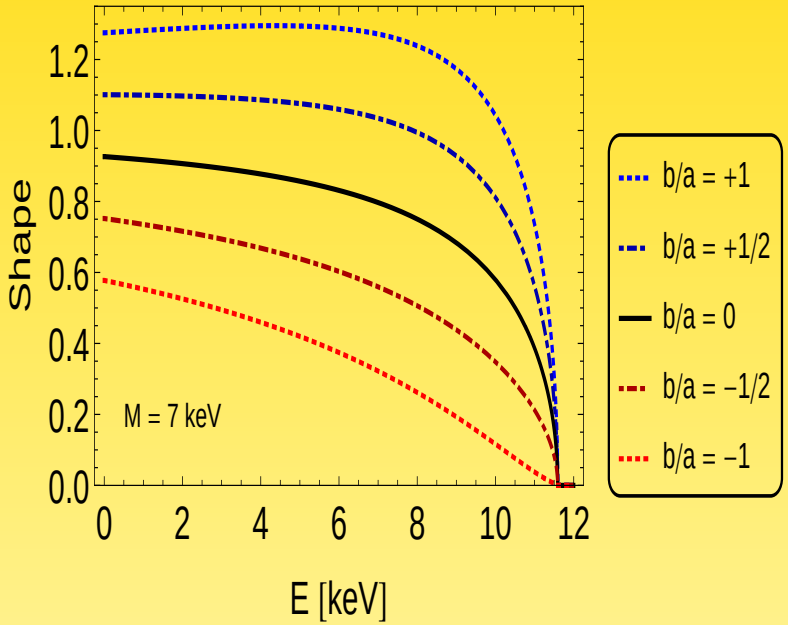
Mertens *et al.*, 1409.0920



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

Focus for simplicity on





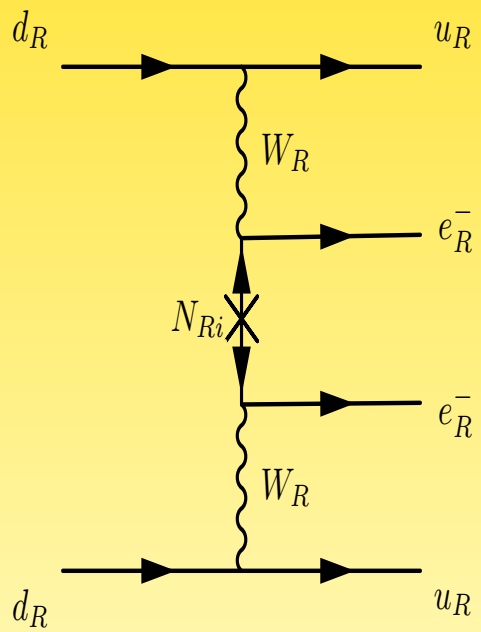
and assume keV neutrino with RH current

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

neglect interference term b:

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

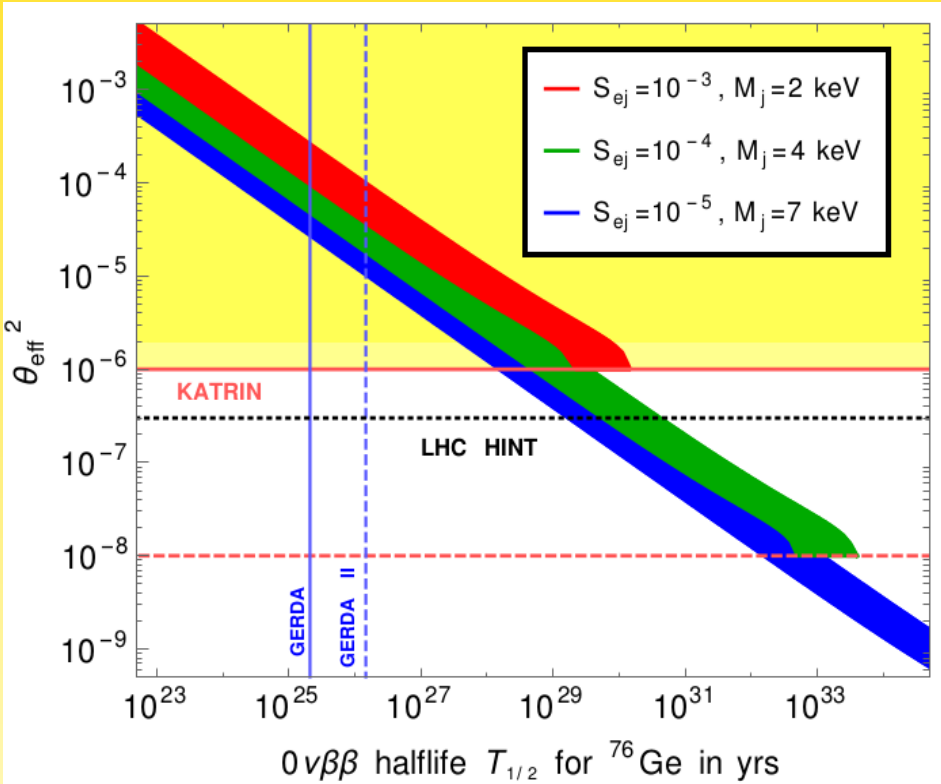
and note that M does $0\nu\beta\beta$ with amplitude $\propto |V_{ej}|^2\, (m_W/m_{W_R})^4\, M/q^2$



$\Rightarrow$ 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., 1404.5955

How the additional interactions save the day

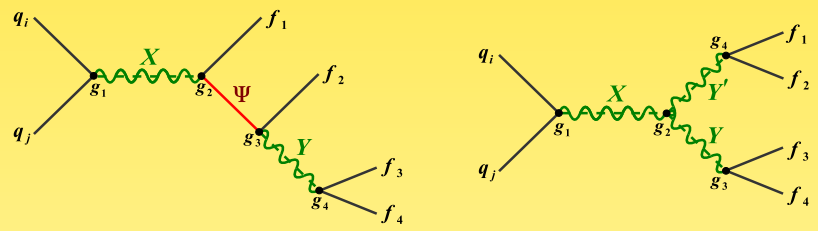
- double beta decay without RHC: $\theta^2 M = 7 \times 10^{-10}\,\mathrm{keV} = 70\,\mu\mathrm{eV}$
- double beta decay with RHC: $(m_{W_L}/m_{W_R})^4\,|V_{ei}|^2 M = 8\,\mathrm{meV}$
- decay: $\dfrac{\Gamma_{\mathrm{RHC}}(N_j \to \bar{\nu}\gamma)}{\Gamma_{\mathrm{SM}}(N_j \to \nu\gamma)} \simeq \dfrac{m_{W_L}^4\,|S_{ei}|^2}{m_{W_R}^4\,|T_{ei}|^2}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

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,...