Lepton Number Violation

from low to high scale

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Werner Rodejohann (MPIK)

01/06/17

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

29th Rencontres de Blois

May 28–June 2

BLOIS

PARTICLE PHYSICS AND COSMOLOGY 2017

Outline

- Lepton Number Violation: Why look for it?
- Neutrinoless Double Beta Decay $(A,Z) \to (A,Z+2) + 2\,e^-$:
  - Standard Interpretation
  - Non-Standard Interpretations
- Heavy Neutrinos

Why look for Lepton Number Violation?

- L and B accidentally conserved in SM
- $\mathcal{L} = \mathcal{L}_{SM} + 1/\Lambda\ \mathcal{L}_5 + 1/\Lambda^2\ \mathcal{L}_6 + \ldots$, with $\mathcal{L}_5 = L^c \phi\ \phi L \to m_\nu\, \nu_L{}^c\, \nu_L$
- Baryogenesis: B is violated
- B, L often connected in BSM, GUTs
- GUTs have seesaw and Majorana neutrinos
- (B and L non-perturbatively violated by 3 units in SM…)

Why look for Lepton Number Violation?

Lepton Number as important as Baryon Number

- L and B accidentally conserved in SM
- $\mathcal{L} = \mathcal{L}_{\rm SM} + 1/\Lambda\, \mathcal{L}_5 + 1/\Lambda^2\, \mathcal{L}_6 + \ldots$, with $\mathcal{L}_5 = L^c \Phi\, \Phi L \rightarrow m_\nu\, \nu_L{}^c\, \nu_L$
- Baryogenesis: B is violated
- B, L often connected in BSM, GUTs
- GUTs have seesaw and Majorana neutrinos
- (B and L non-perturbatively violated by 3 units in SM…)

Neutrinoless Double Beta Decay

best limit from 2002, improved since 2012 by one order of magnitude!

Name	Isotope	Source $=$ Detector; calorimetric with			Source $\neq$ Detector
		high ΔE	low ΔE	topology	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	–	✓	–	–
LEGEND	^{76}Ge	✓	–	–	–
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	–	✓	–	–

Talks by Wegmann, Marini

Neutrinoless Double Beta Decay

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

- Master Formula: $$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$
  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME)
  - η_x : particle physics parameter

Neutrinoless Double Beta Decay

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

- Master Formula: $$\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$$
  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$ calculable
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME) problematic
  - η_x : particle physics parameter interesting

Neutrinoless Double Beta Decay

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

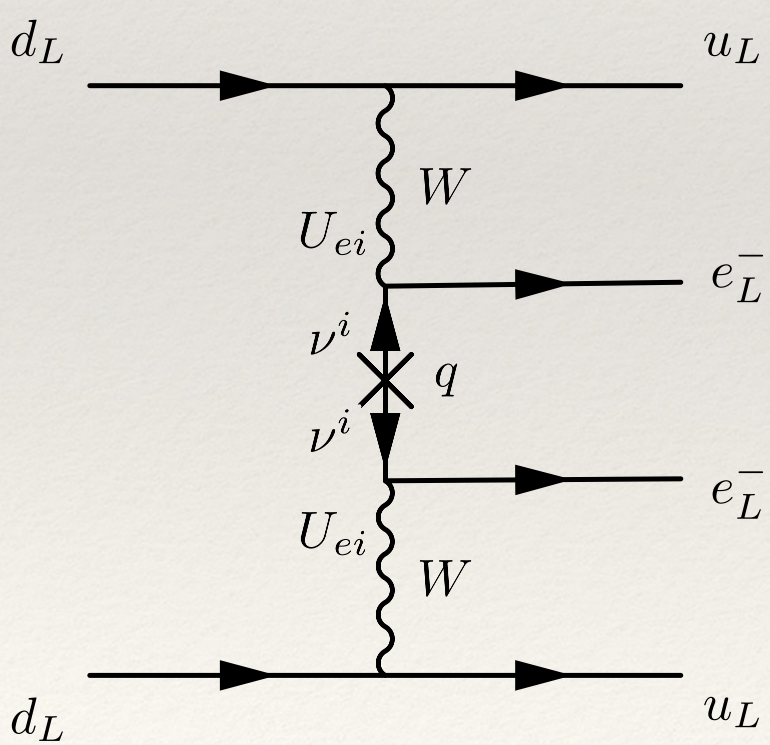
- Master Formula: $\Gamma^{0\nu} = G_x(Q,Z)\,|\mathcal{M}_x(A,Z)\,\eta_x|^2$
  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$ WIN!
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME) SAD!
  - η_x : particle physics parameter THINK!

Interpretations

- 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

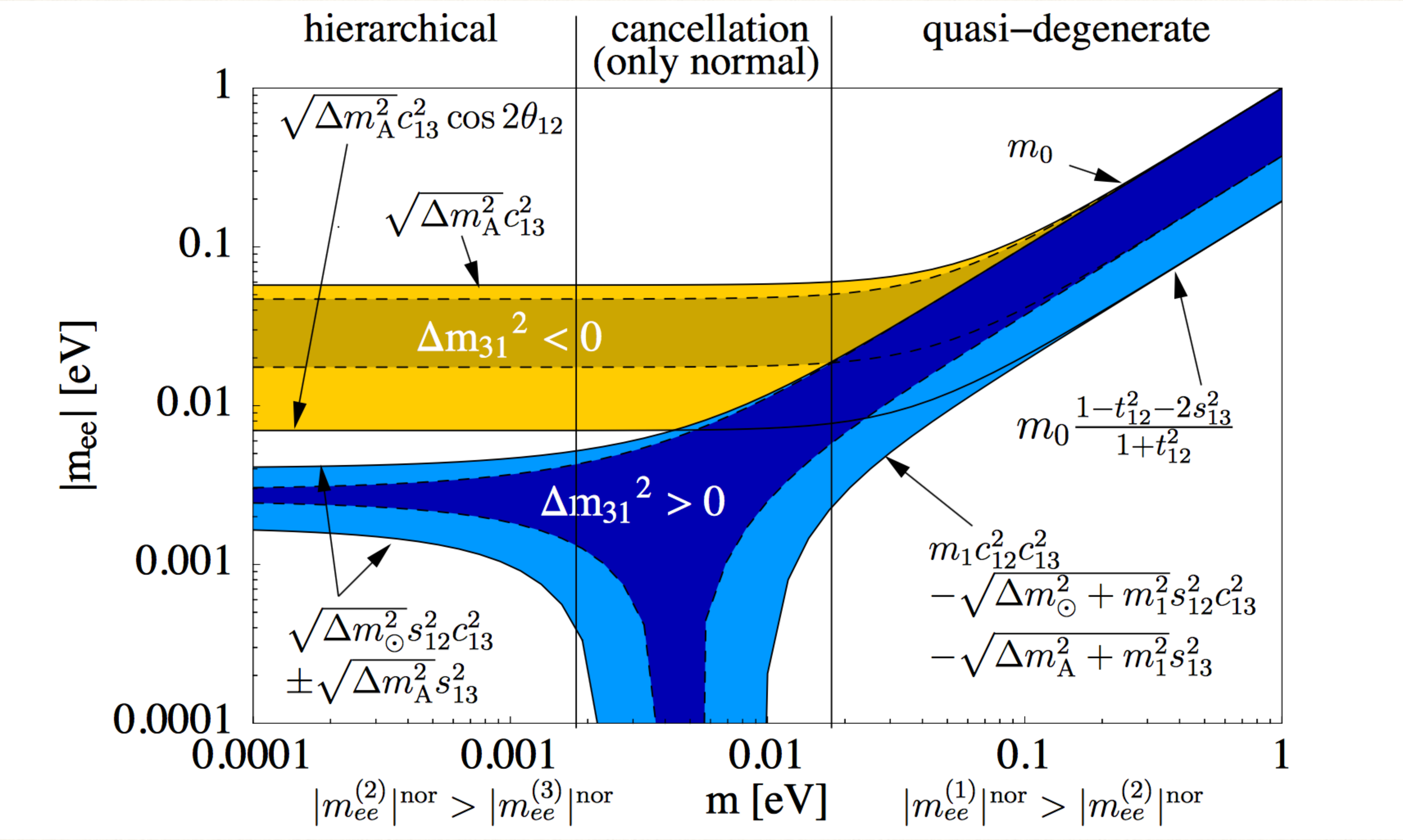
- Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to 0νββ give negligible or no contribution



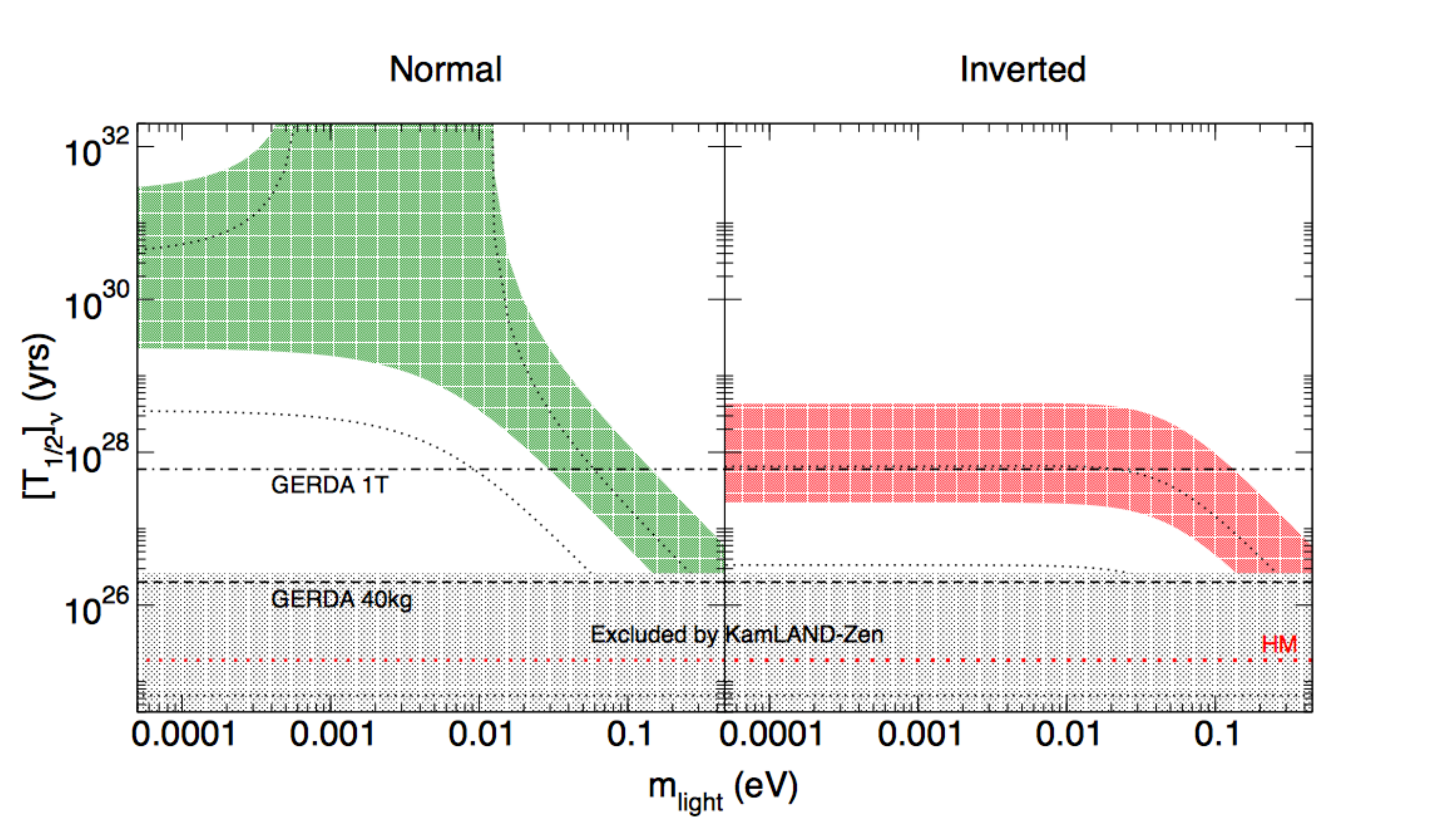
amplitude proportional to „effective mass“:

$$|m_{ee}| = |\sum U_{ei}^2 \, m_i| = |U_{e1}^2 \, m_1 + U_{e2}^2 \, m_2 e^{i\alpha} + U_{e3}^2 \, m_3 e^{i\beta}|$$
$$= f\left(\theta_{12}, |U_{e3}|, m_i, \text{sgn}(\Delta m_A^2), \alpha, \beta\right)$$

The usual plot



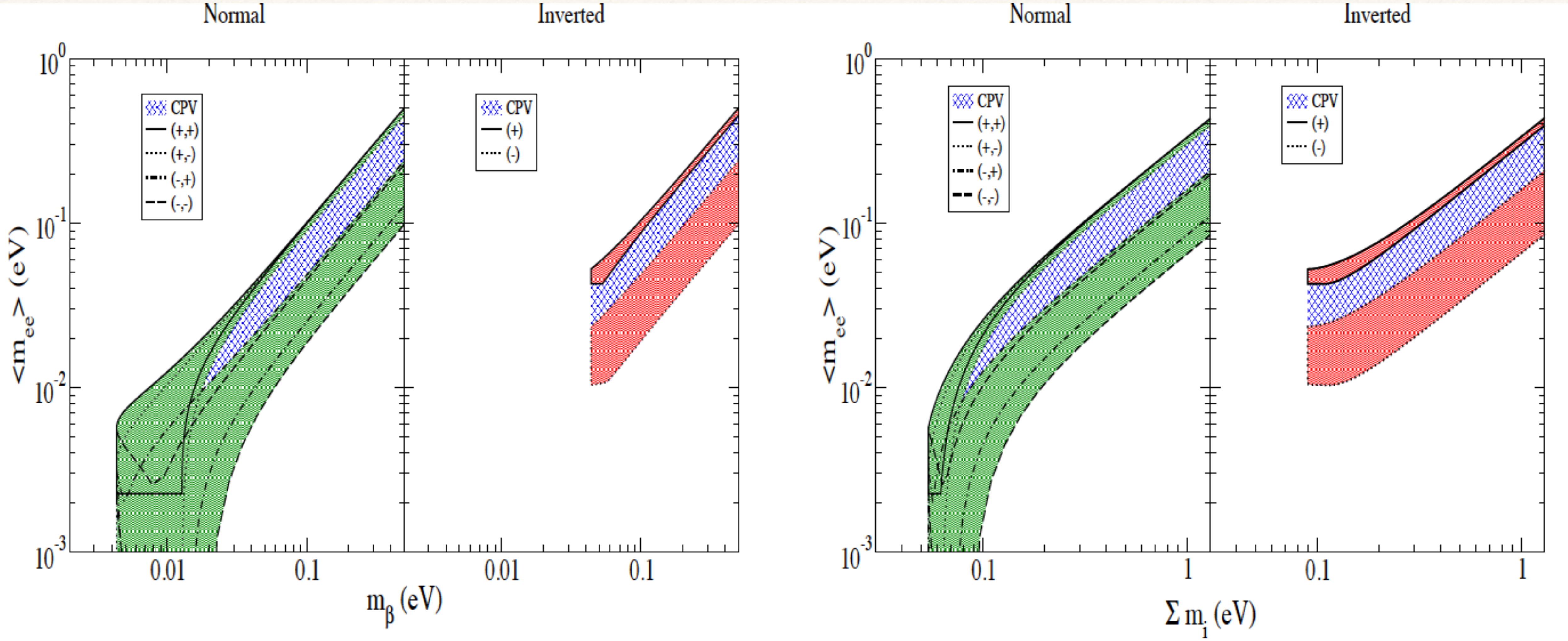
The usual plot



Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$\sum \lvert U_{ei} \rvert^2 m_i$	2.3 eV	0.3 eV	0.1 eV?	model-indep.; clean	final; weakest
cosmo	$\sum m_i$	0.5 eV	0.1 eV	0.05 eV?	best; NH/IH	model-dep.; systematics
$0\nu\beta\beta$	$\sum U_{ei}^2 m_i$	0.2 eV	0.05 eV	0.01 eV?	fundamental; NH/IH	model-dep.; NMEs

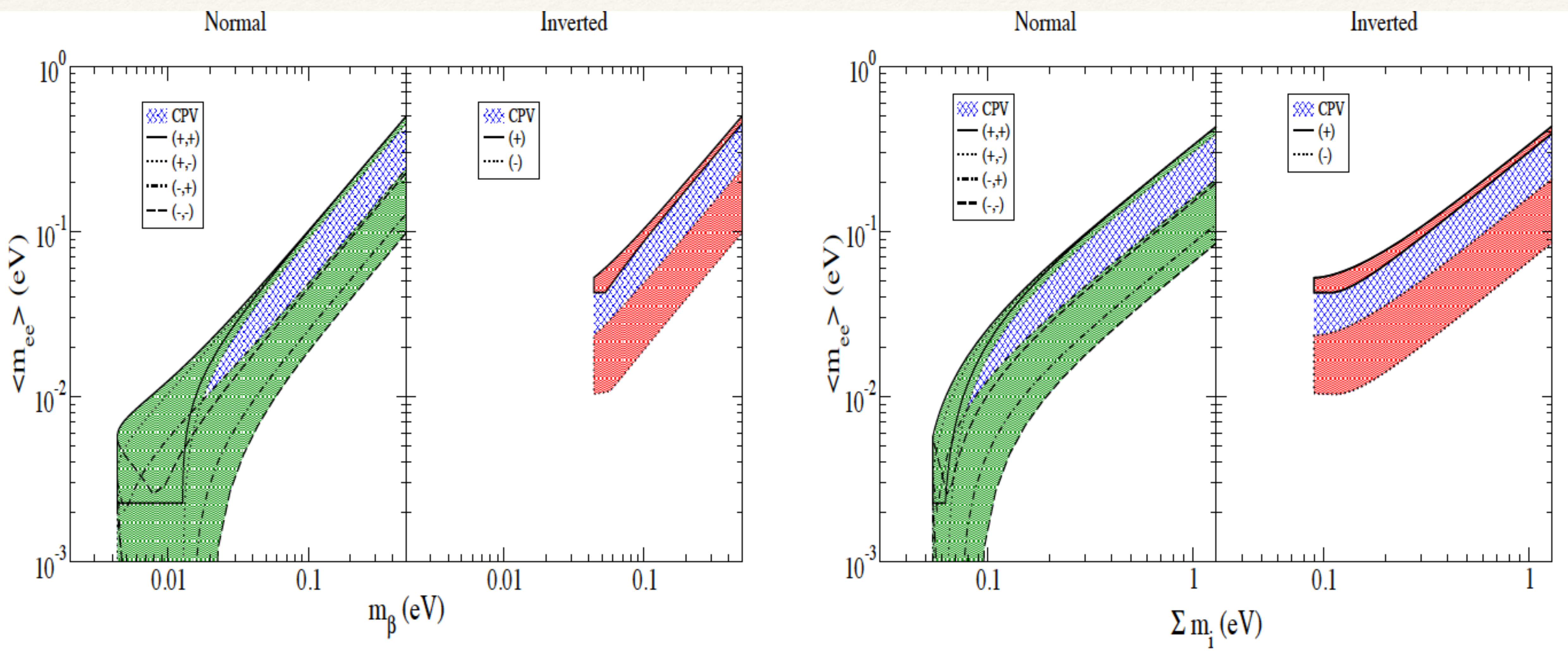
Neutrino Mass Observables



complete complementarity of observables

- $0\nu\beta\beta$ rules out that neutrinos saturate Mainz-limit
- $0\nu\beta\beta$ and cosmology currently roughly the same
- cosmology strongly disfavors a signal in KATRIN

Neutrino Mass Observables

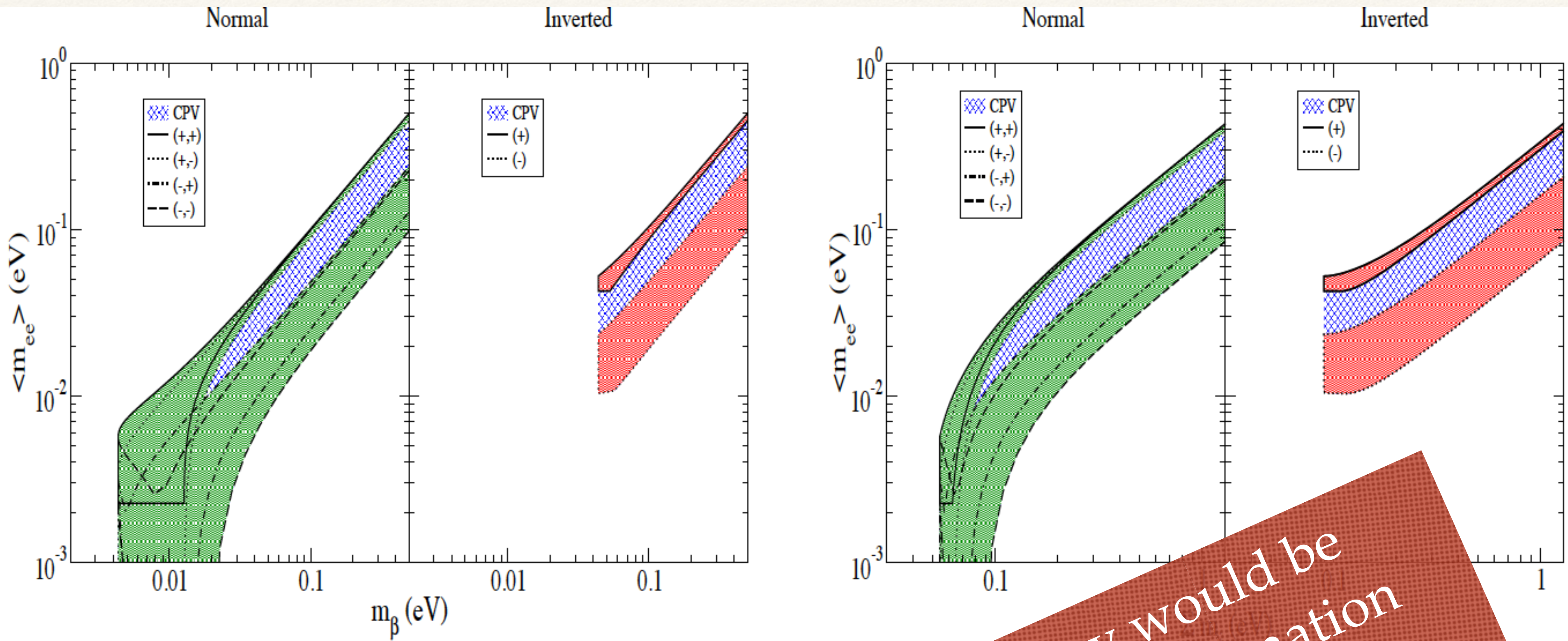


complete complementarity of observables

- 0νββ rules out that neutrin... e Mainz-limit
- 0νββ and cosm... ntly roughly the same
- cosmo... ngly disfavors a signal in KATRIN

All need to be pursued!

Neutrino Mass Observables

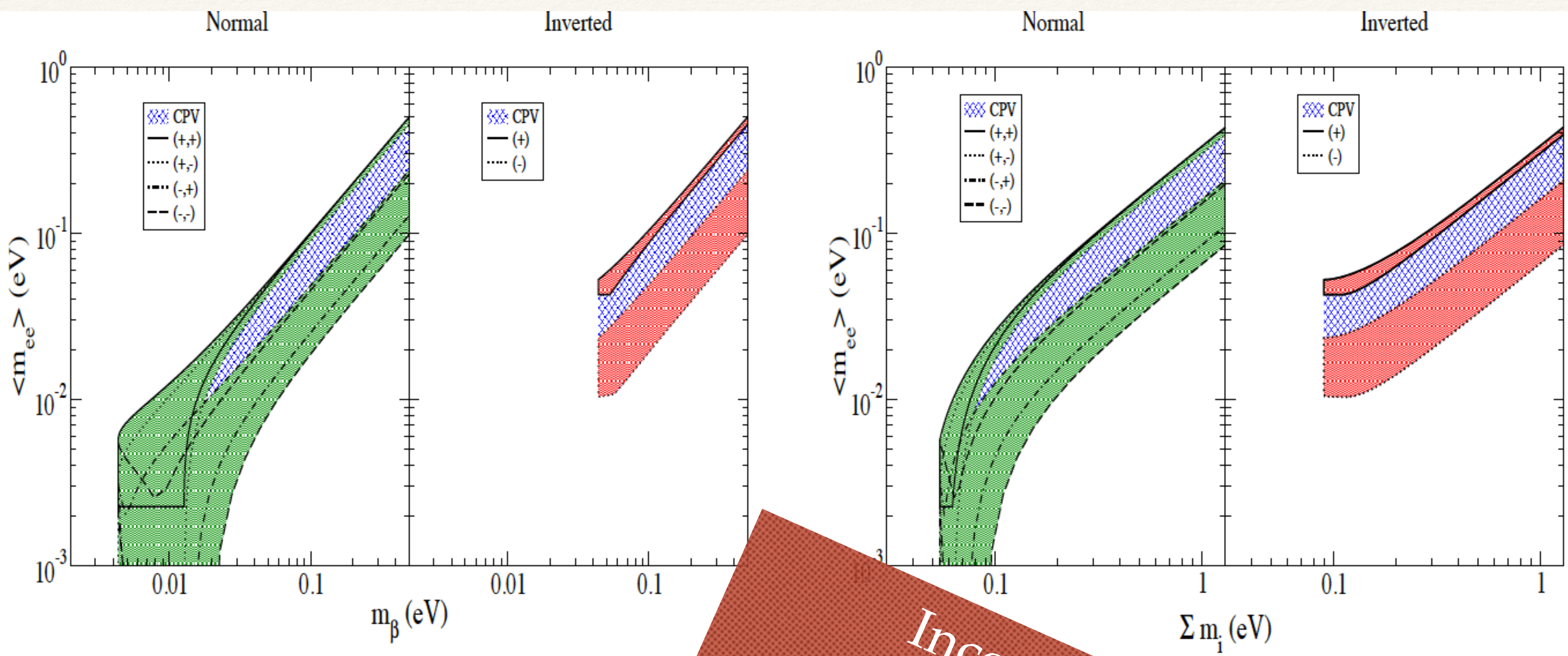


complete complementarity of observables

- 0νββ rules ... t
- 0νββ and ... the same
- cosmology ... rs a signal in KATRIN

Consistency would be spectacular confirmation of 3 Majorana neutrino paradigm

Neutrino Mass Observables



complete complementarity of observables

- 0νββ rules out that ... Mainz-limit
- 0νββ and cosmology ... roughly the same
- cosmology strongly disfavors a signal in KATRIN

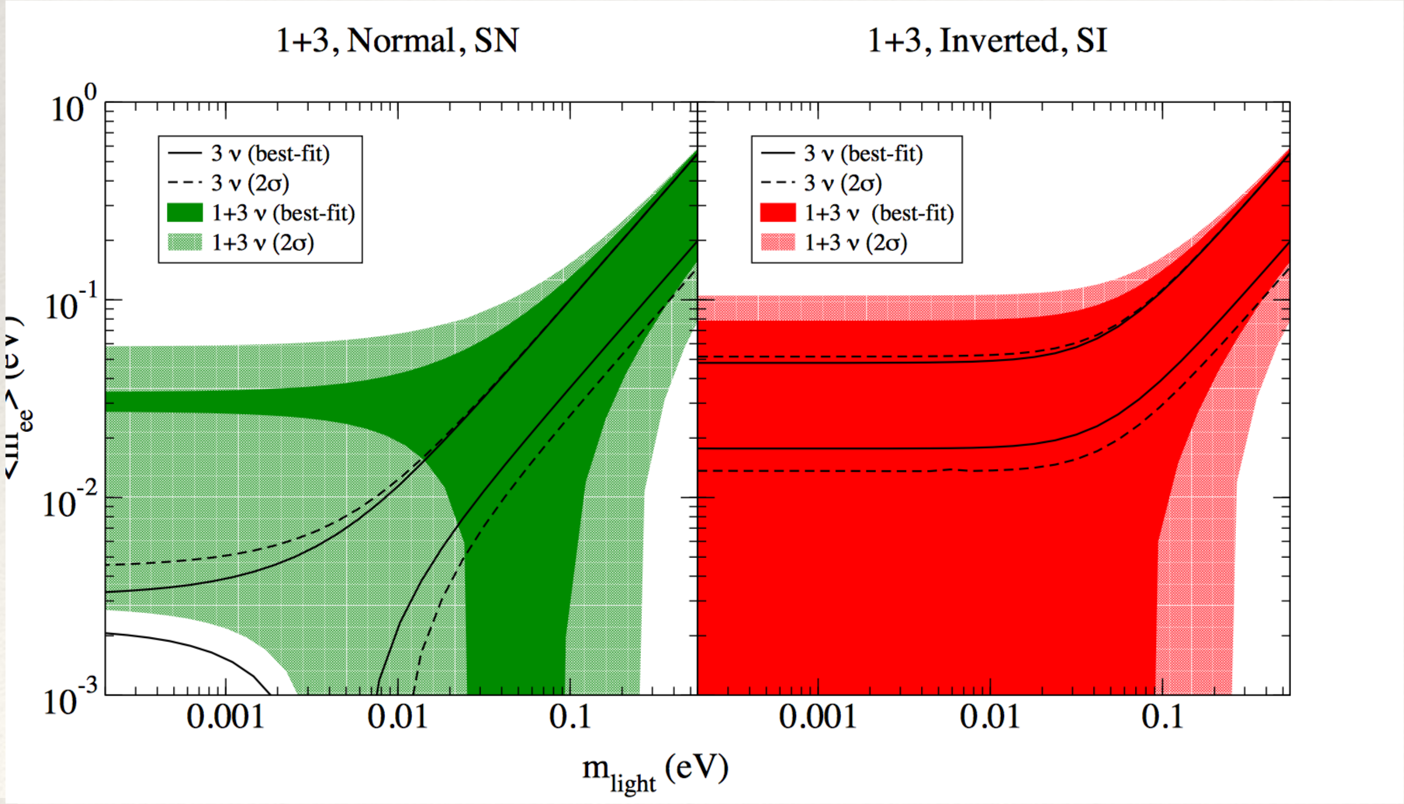
Inconsistencies would be major discovery!

Sterile Neutrinos

- are there sterile states (LSND / reactor / etc.) with mass $\Delta m^2 \simeq eV^2$ and mixing $U_{e4} \simeq 0.1$? *(Talk by Haser)*

- would make m_{ee} sum of 4 terms with sterile contribution $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel contribution of IH!

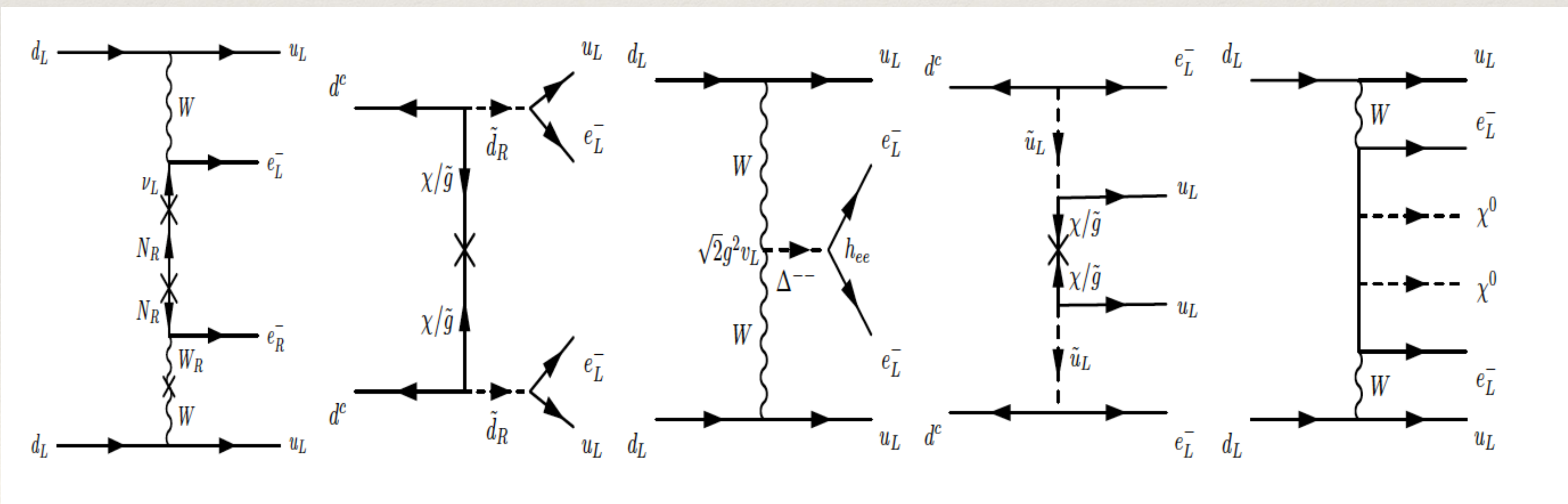
- usual pheno completely turned around!



Barry, WR, Zhang; Petcov et al., Giunti et al.

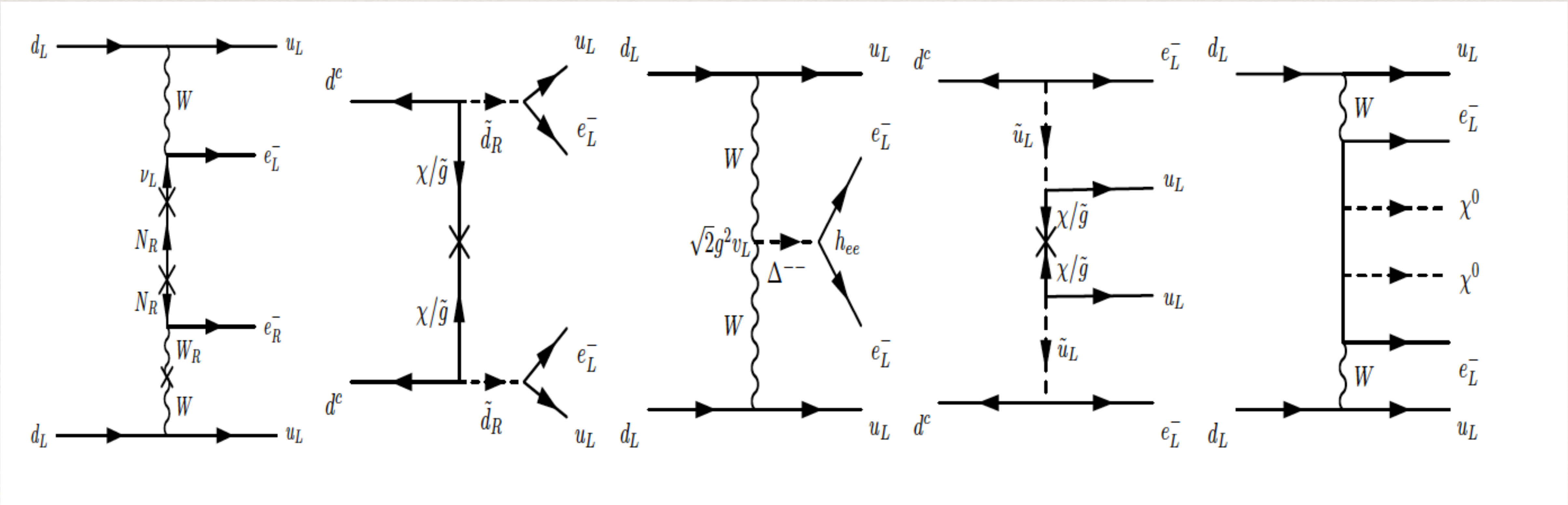
Non-Standard Interpretations

- 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



Non-Standard Interpretations

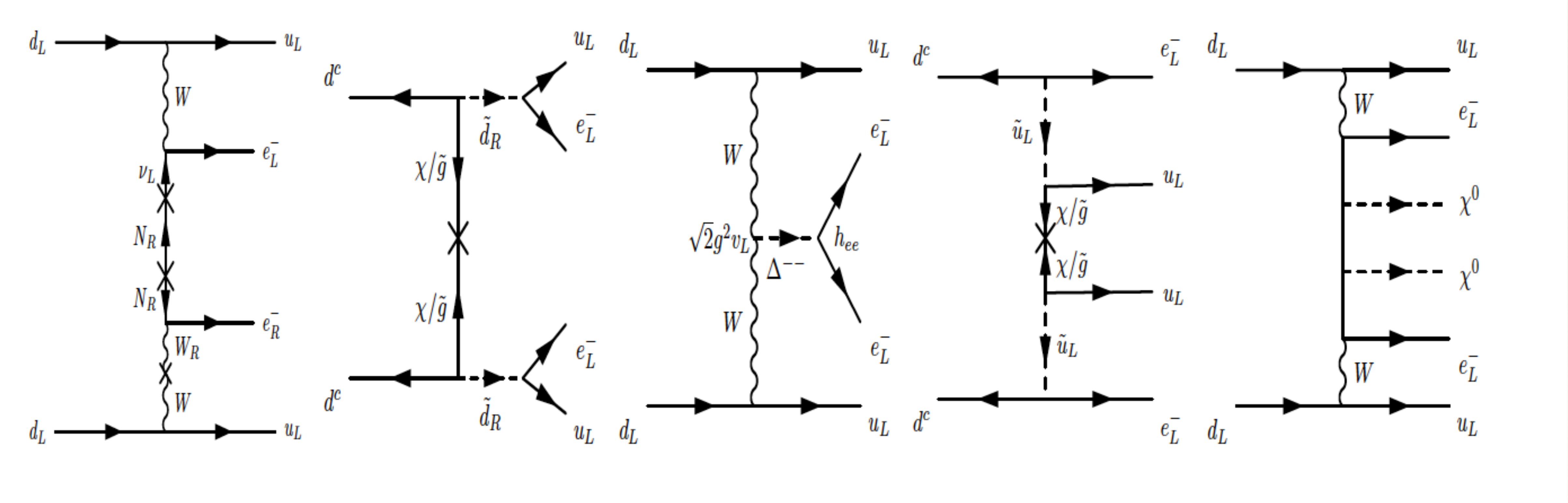
- There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism



$\Rightarrow$ $0\nu\beta\beta$ is not a neutrino mass experiment!

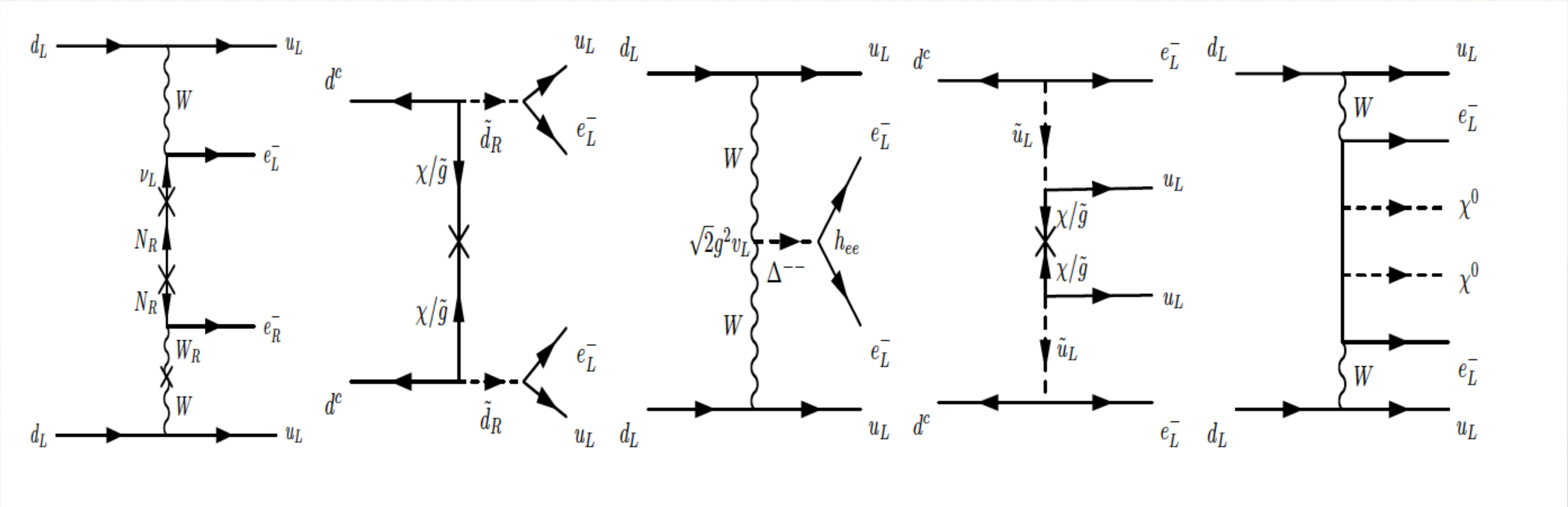
Non-Standard Interpretations

- 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



$\Rightarrow$ need to solve the „inverse problem“

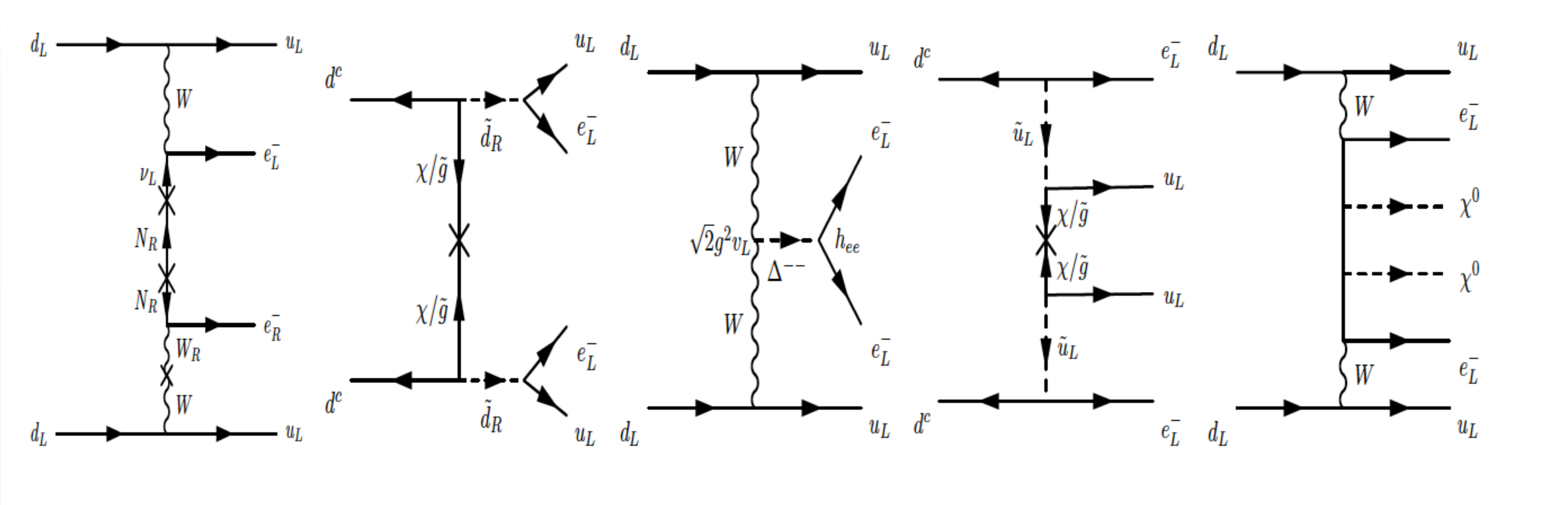
Non-Standard Interpretations



- decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \text{ versus } \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

Non-Standard Interpretations

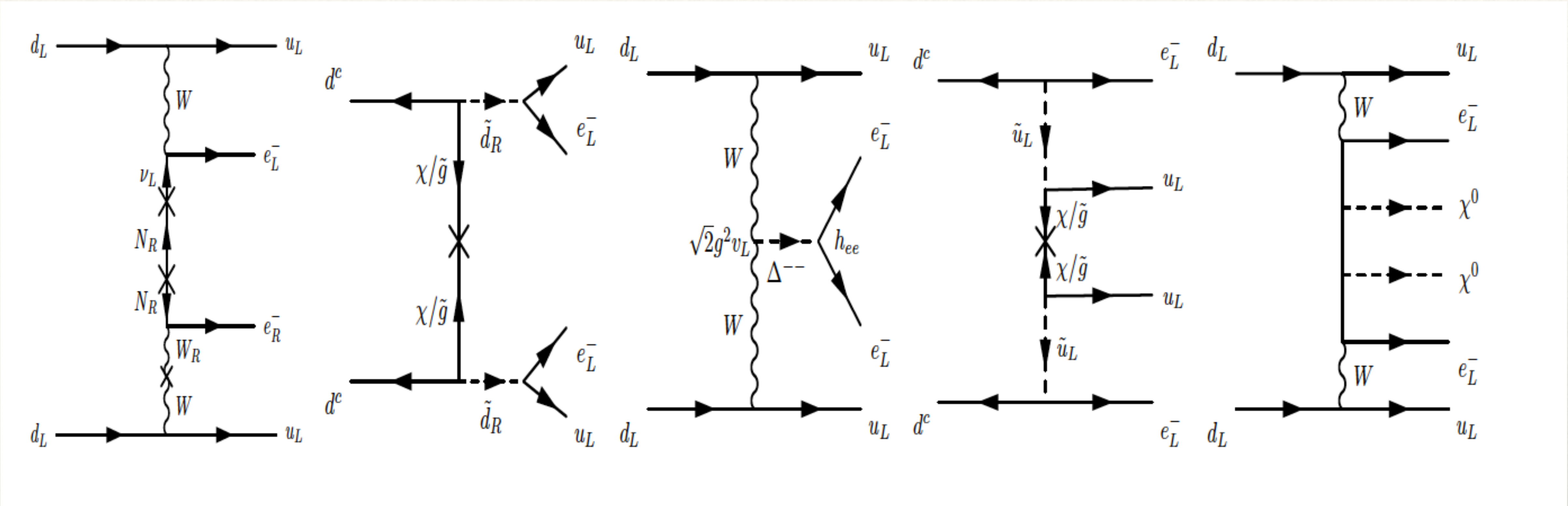


- decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \text{ versus } \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

Therefore:
T(eV) = T(TeV)

Non-Standard Interpretations



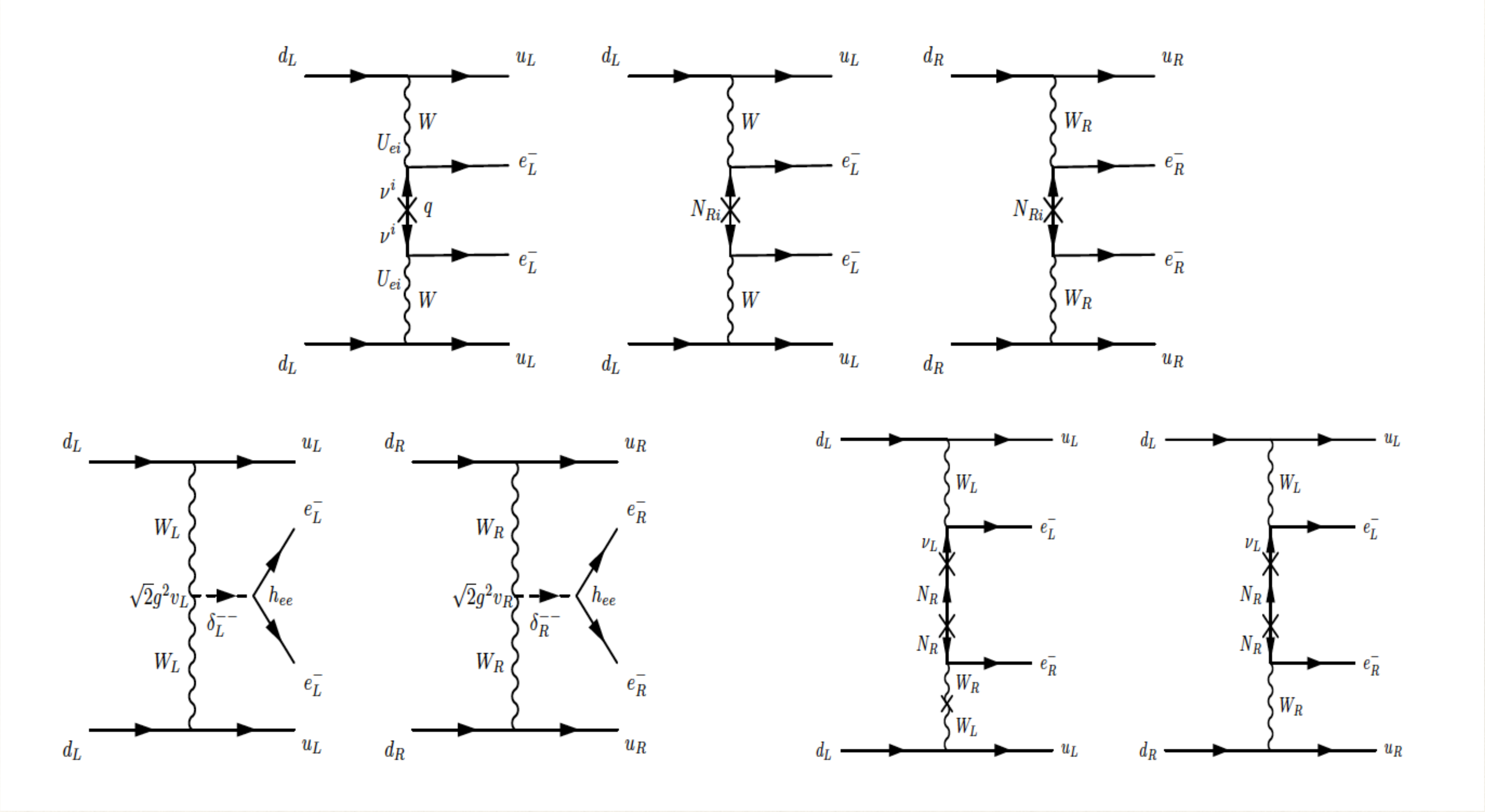
- decouples double beta decay from cosmology and KATRIN

$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \text{ versus } \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

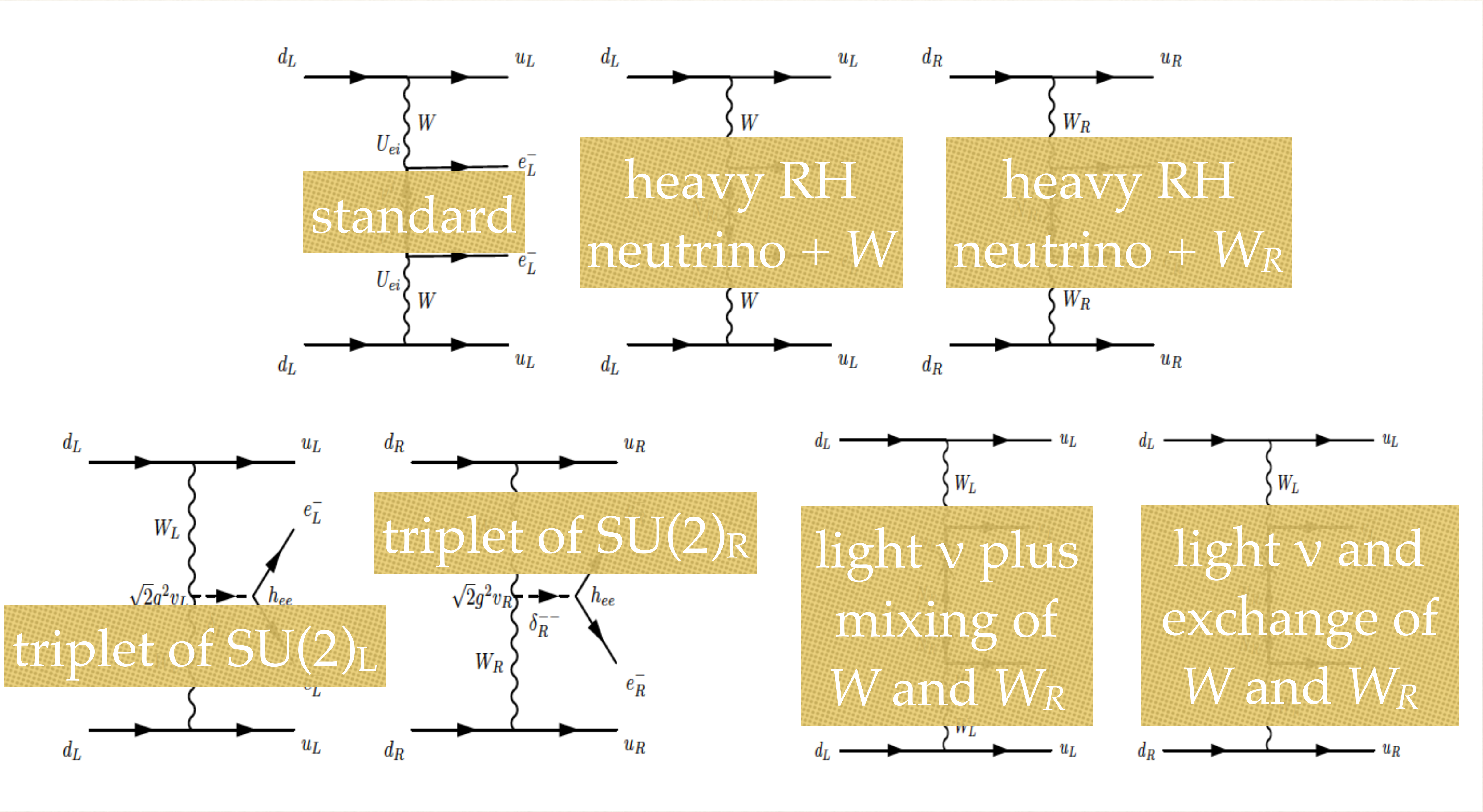
Therefore:
T(eV) = T(TeV)

$\Rightarrow$ Tests with LHC, LFV, etc.

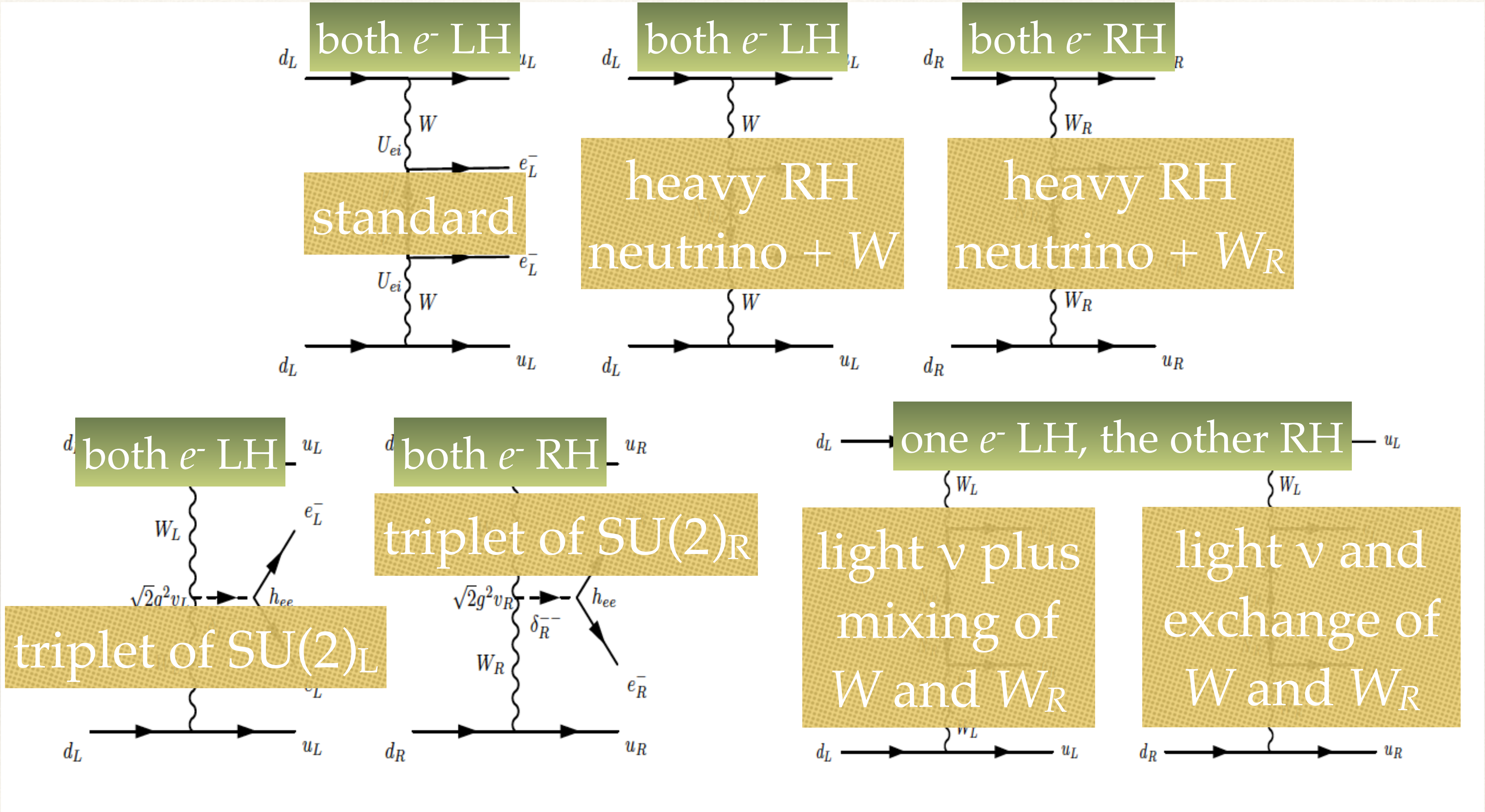
Double Beta Decay and LR-Symmetry



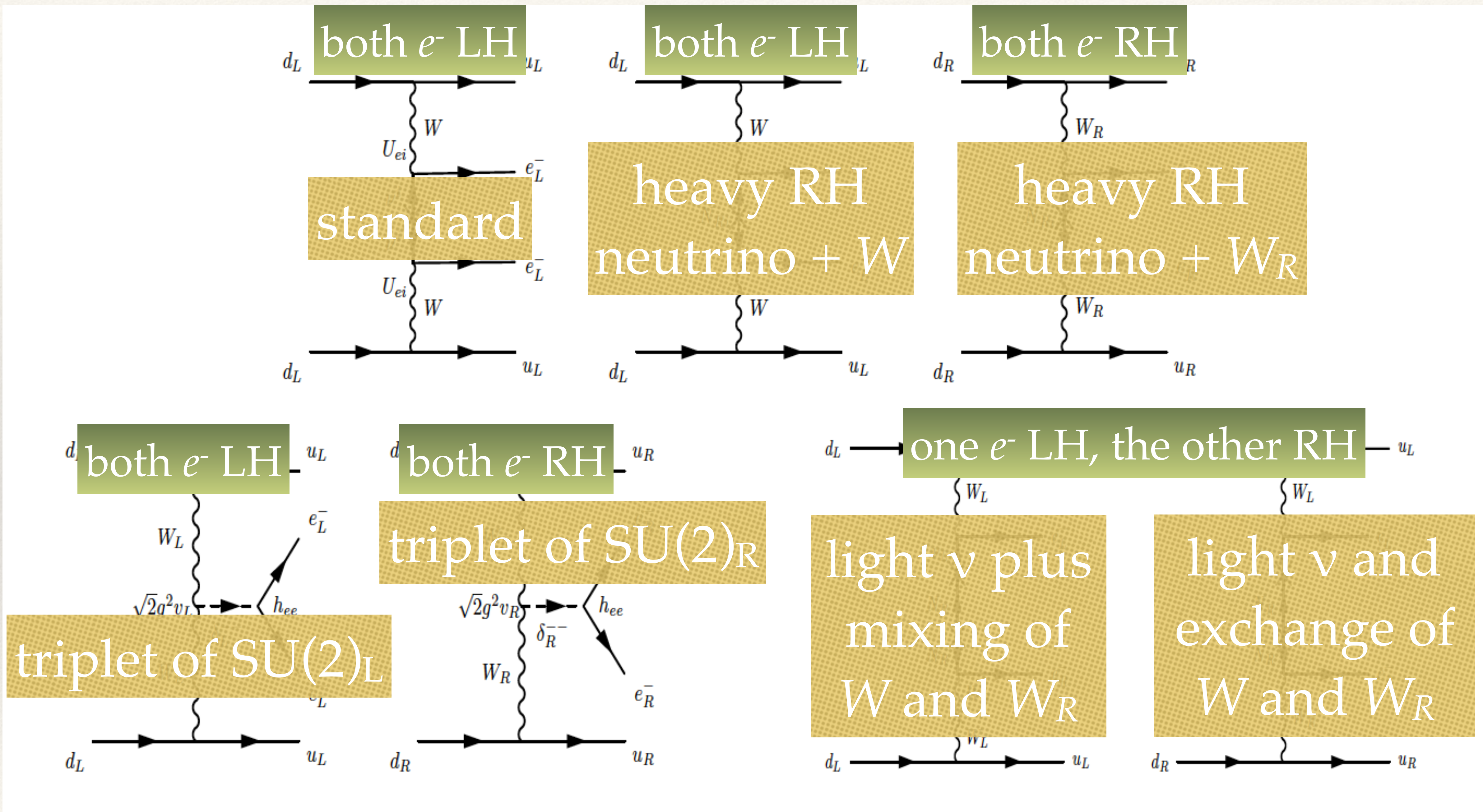
Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry

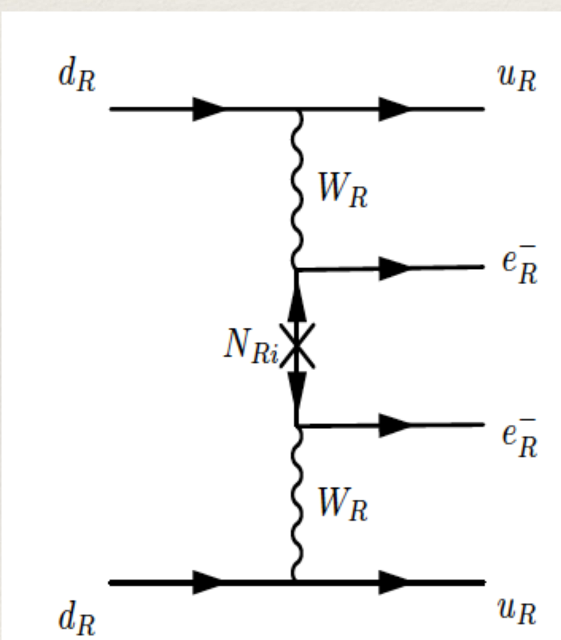


simultaneous presence / interference / …

Double Beta Decay and LR-Symmetry

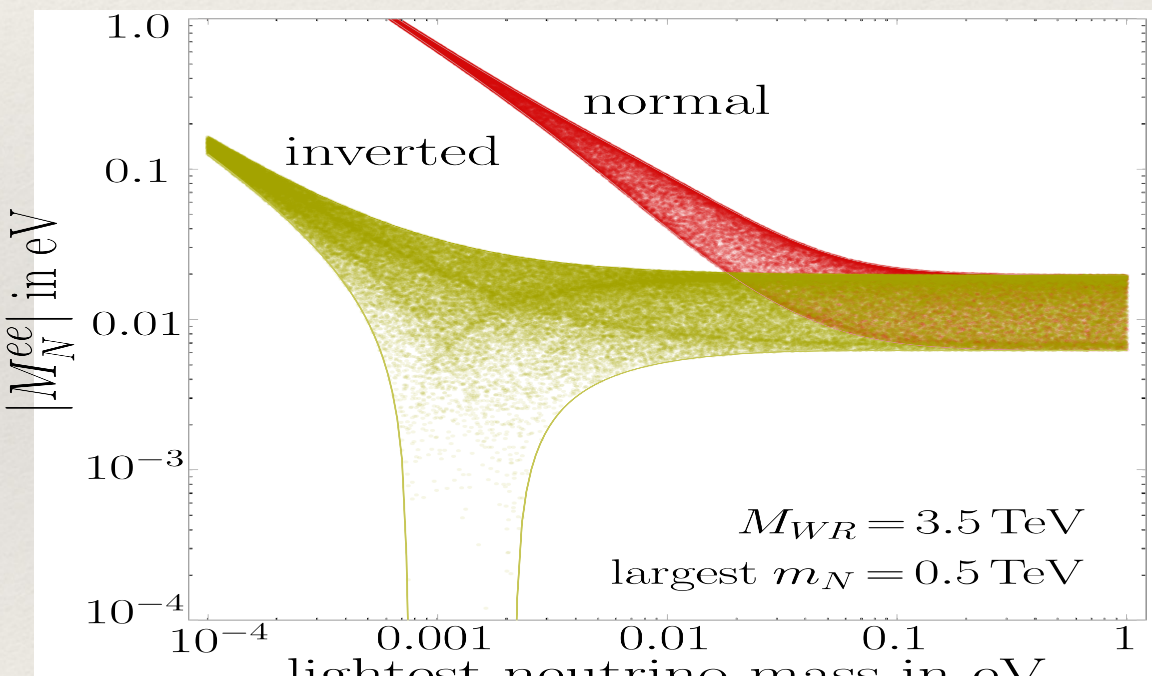
Type II dominance: $m_\nu = m_L - M_D^2/M_R \to m_L$ with $m_L \propto M_R$

$\Rightarrow$ right-handed neutrinos diagonalized by PMNS matrix!



$$\mathcal{A} \propto \frac{V_{ei}^2}{M_i} \propto \frac{U_{ei}^2}{m_i}$$

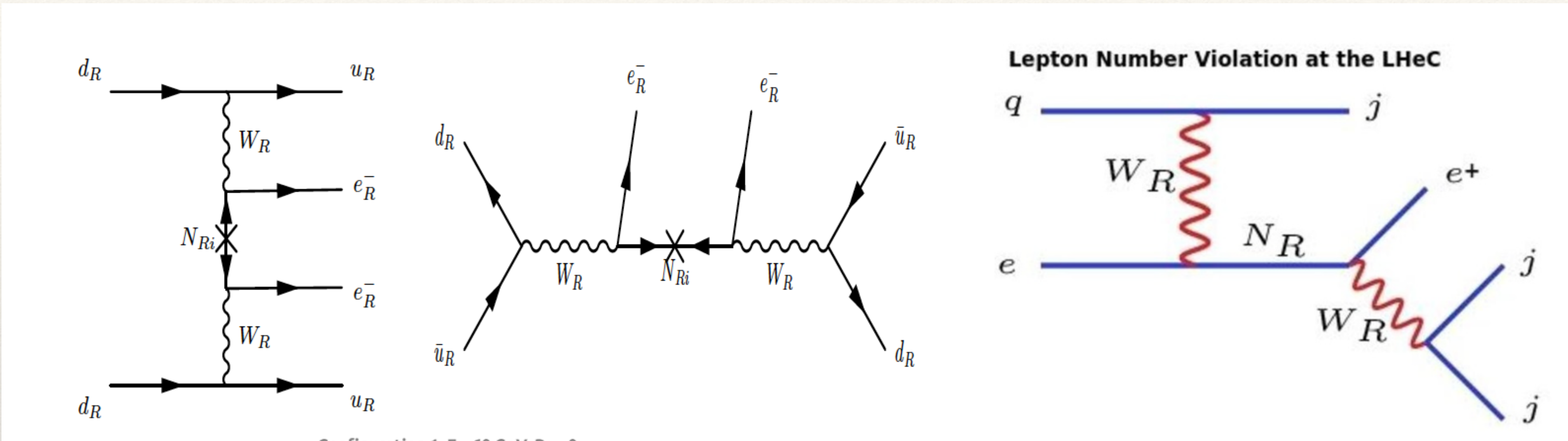
amplitude determined by PMNS, but $\propto 1/m_\nu$

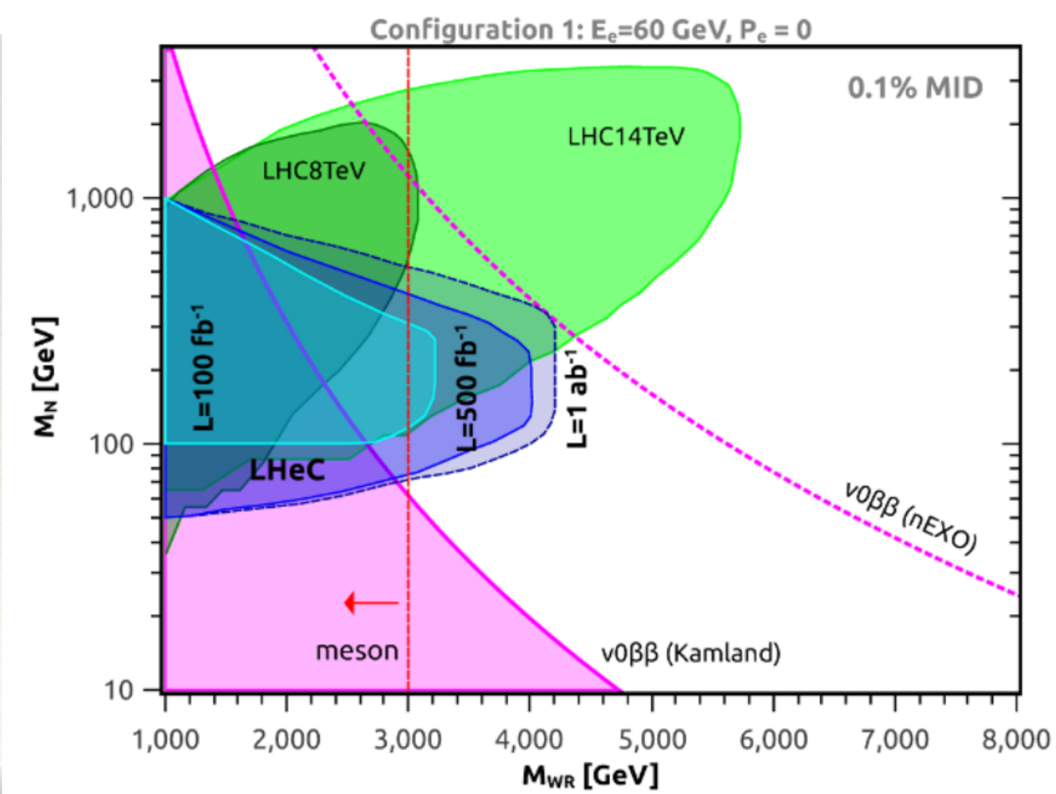


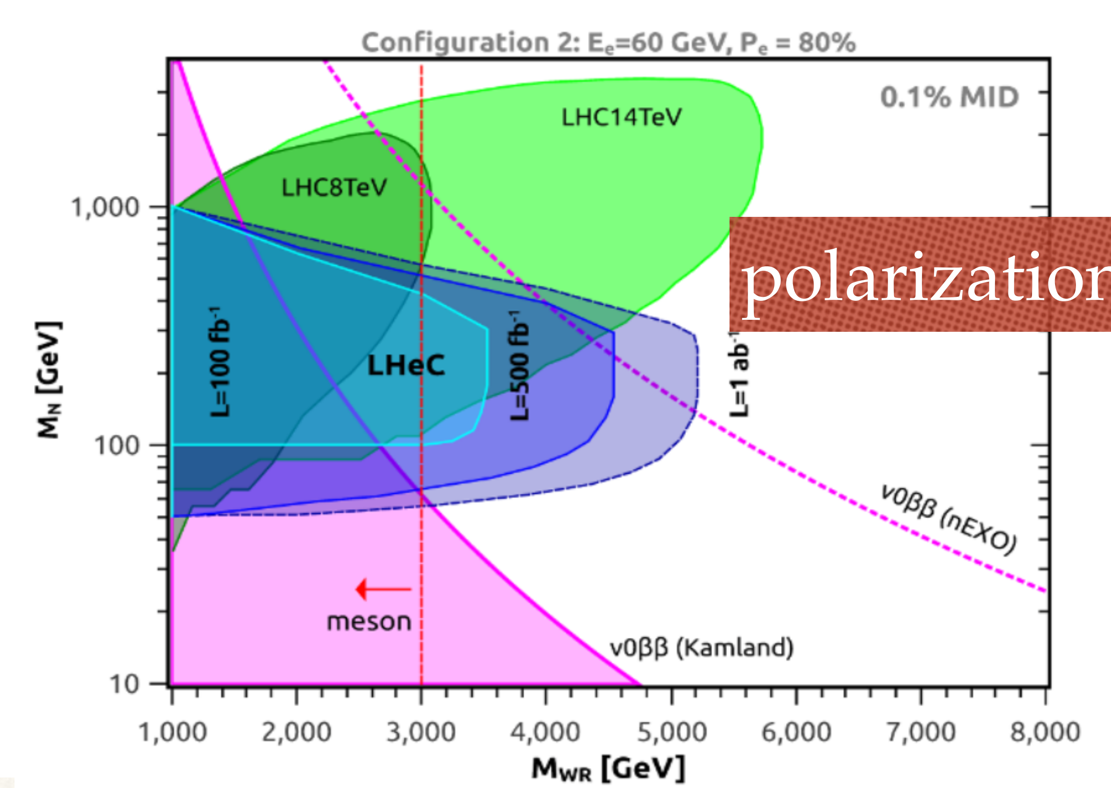
Senjanovic et al., 1011.3522

again, NH/IH turned around...

LHC and Double Beta Decay



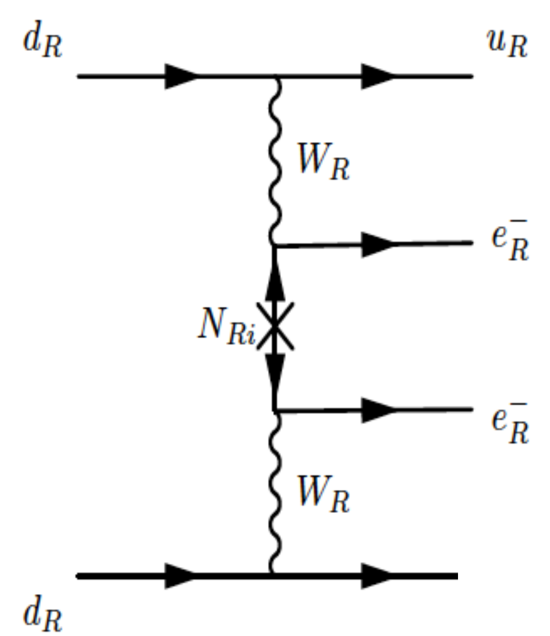


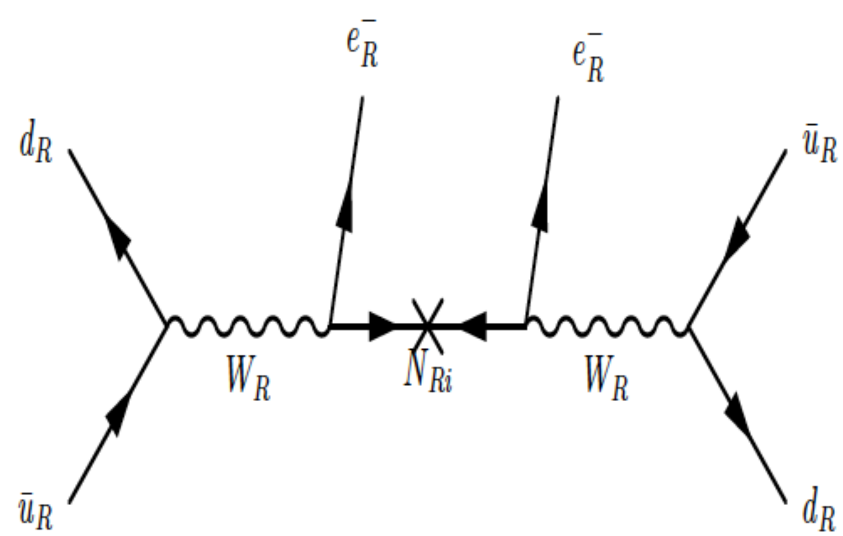


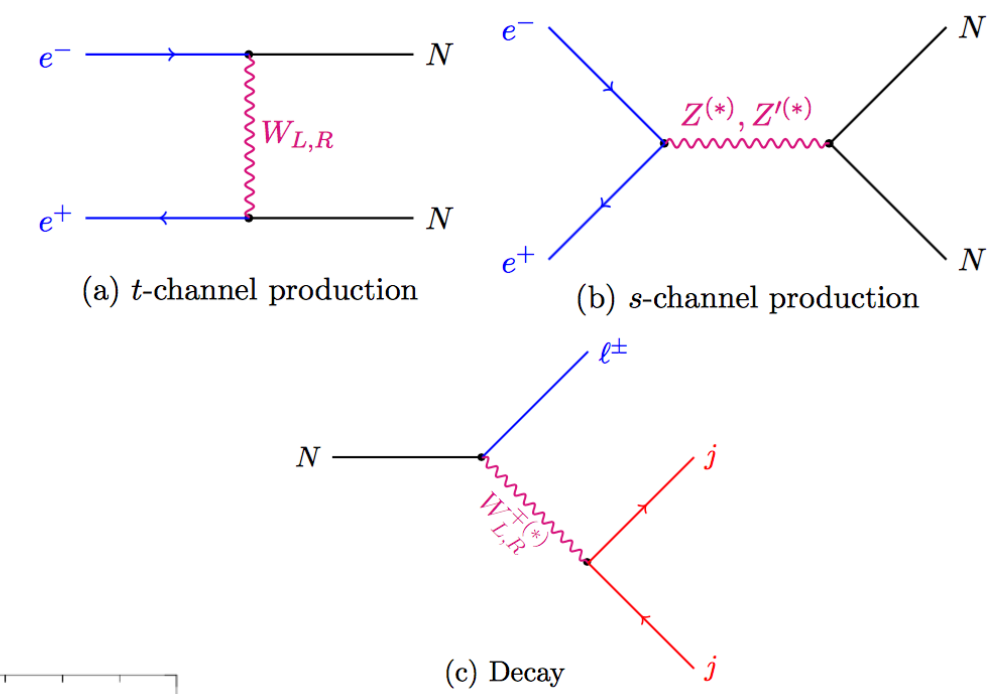
polarization at LHeC

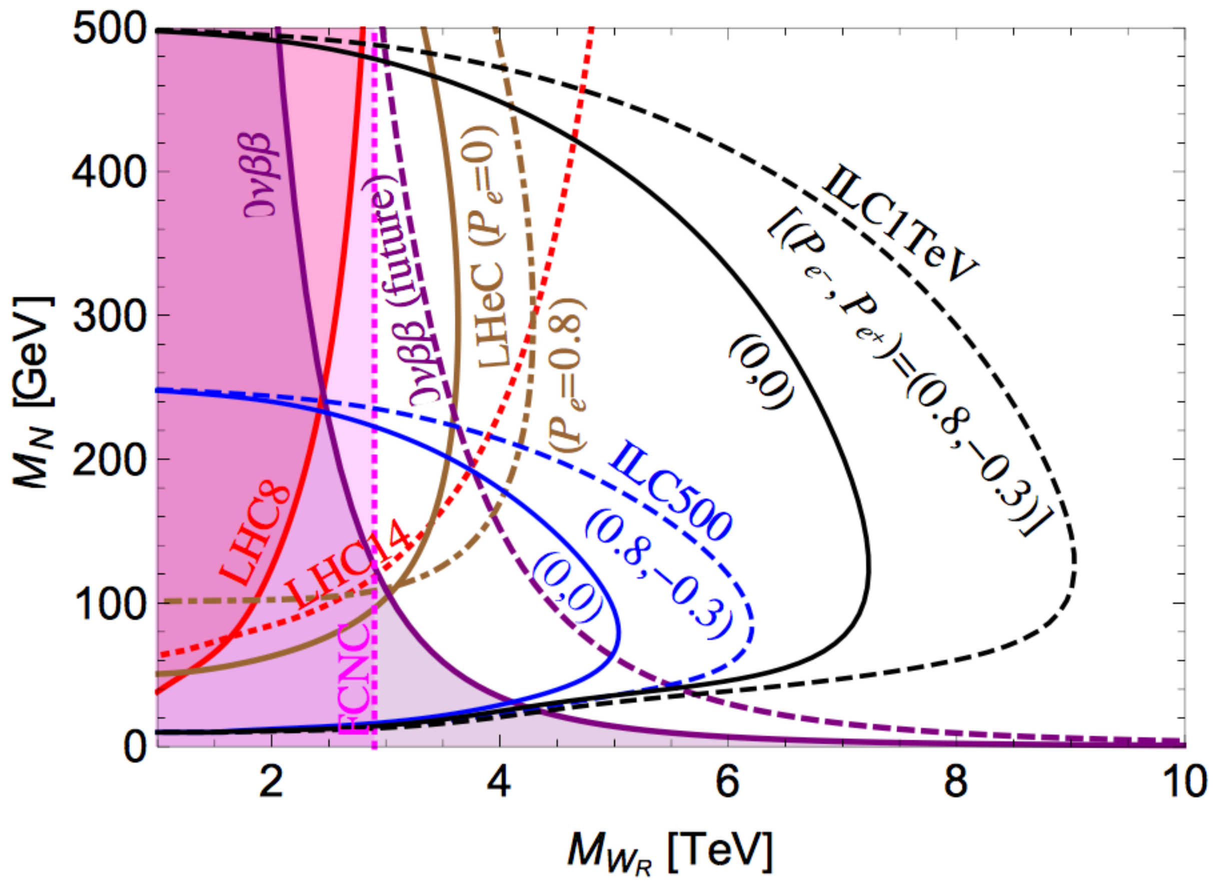
Lindner, Queiroz, WR, Yaguna, 1604.08596

LHC and Double Beta Decay





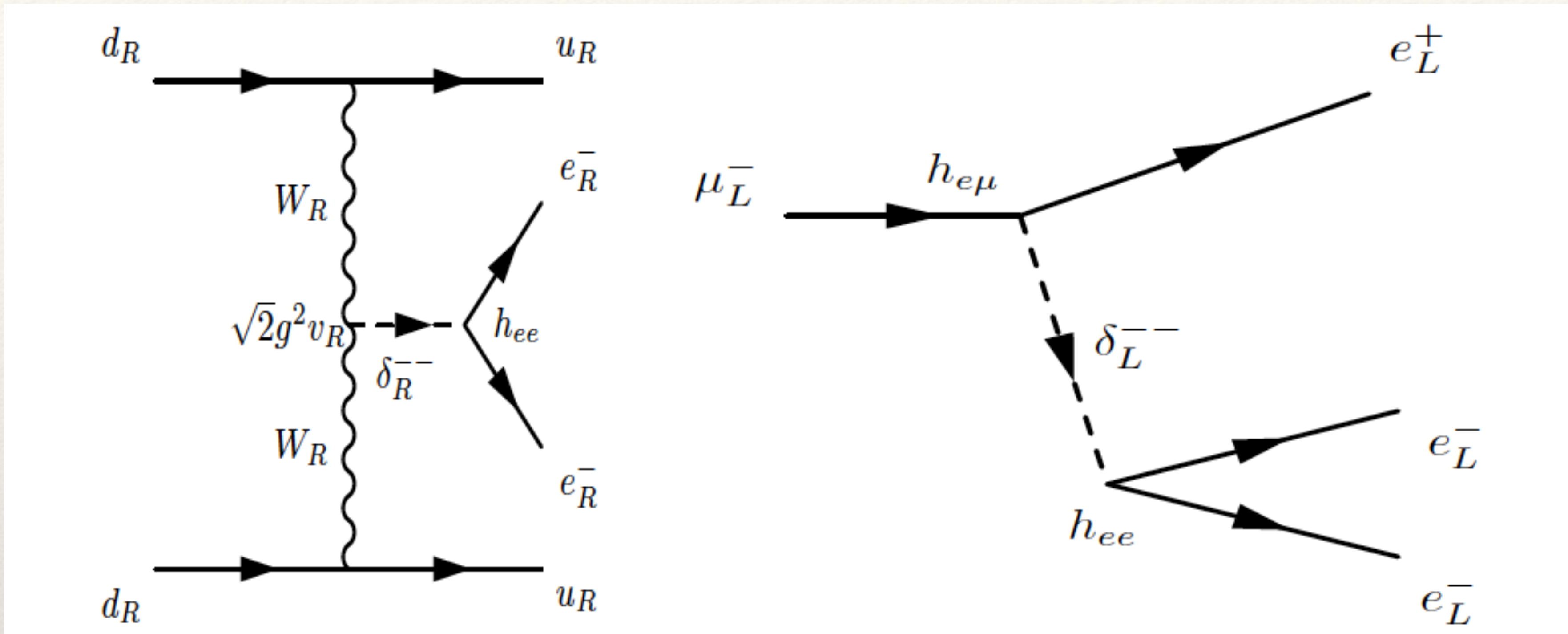


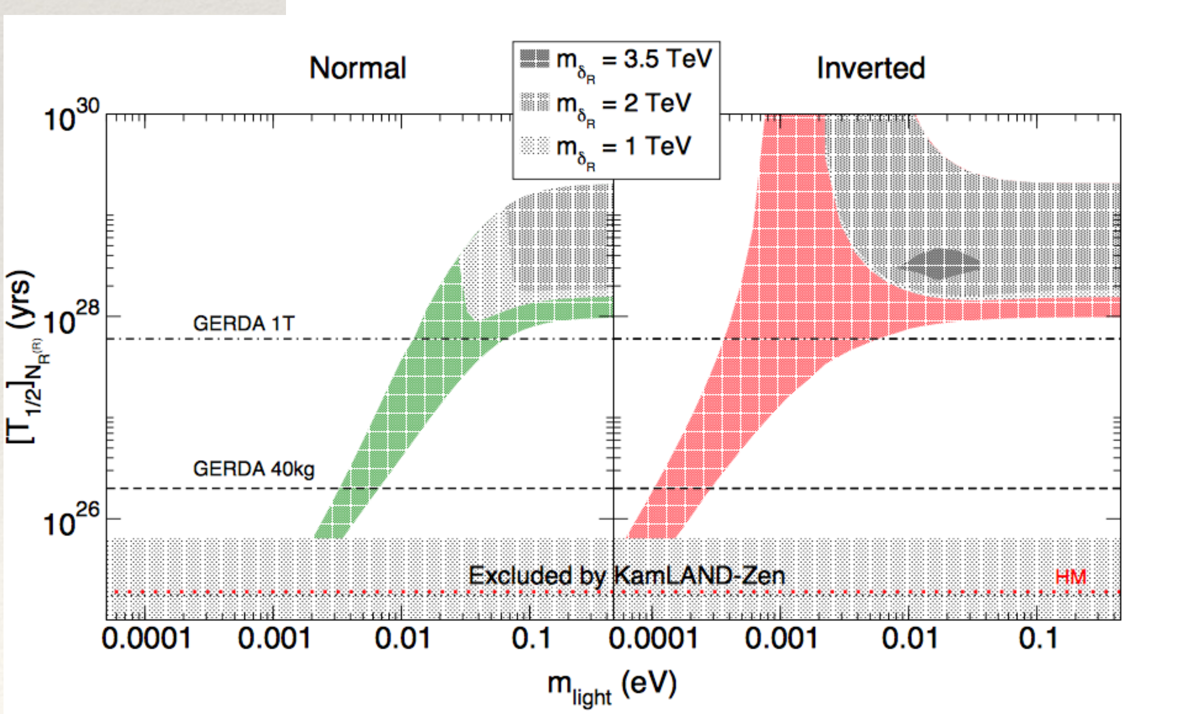


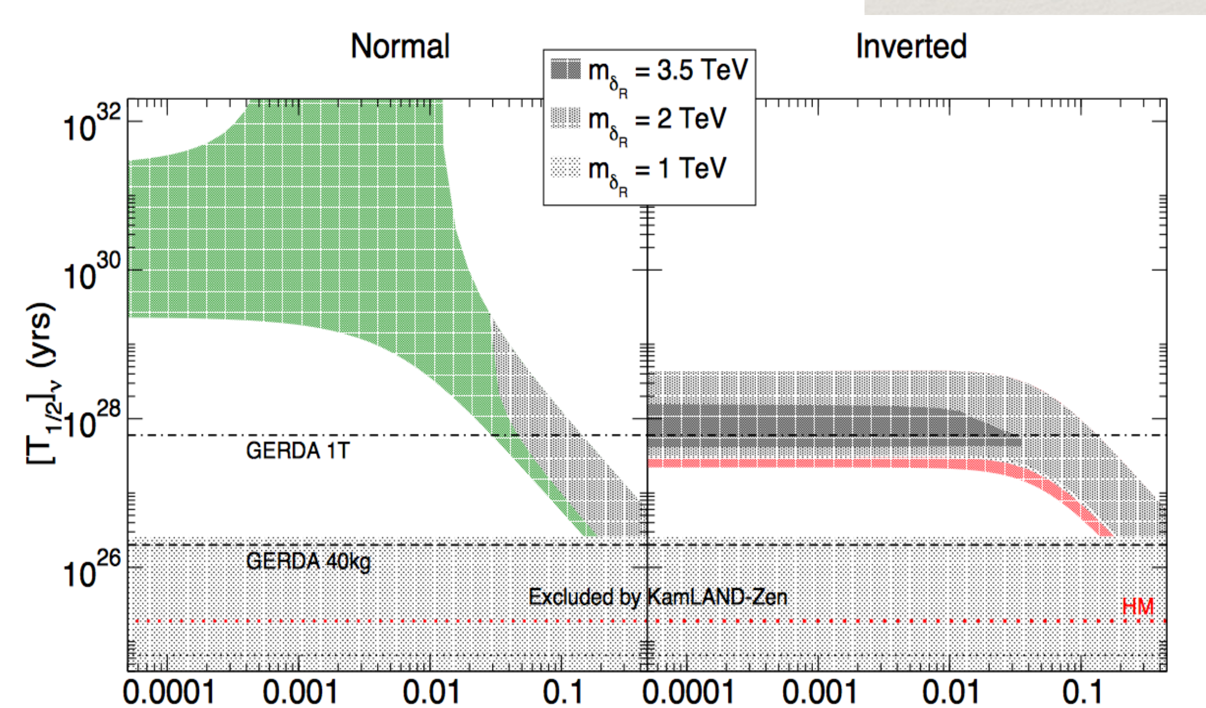
Biwal, Bhupal Dev, 1701.08751

polarization at ILC

LFV and Double Beta Decay



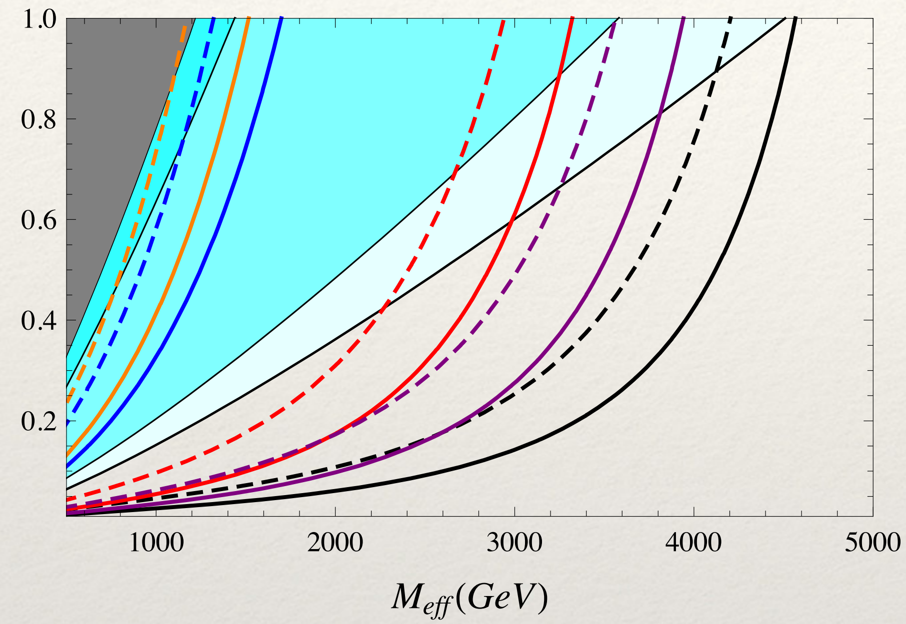




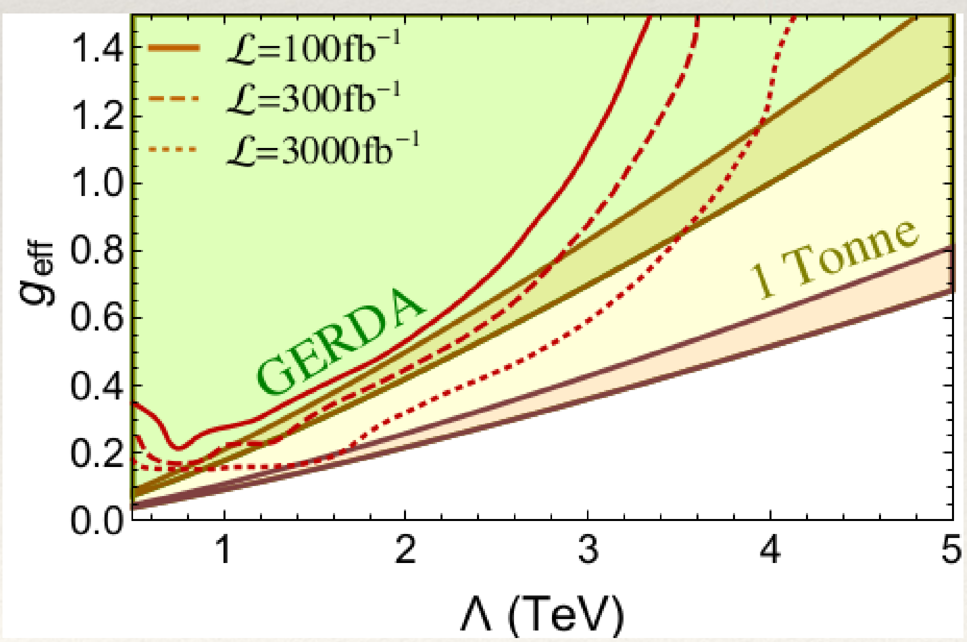
Barry, WR, 1303.6324

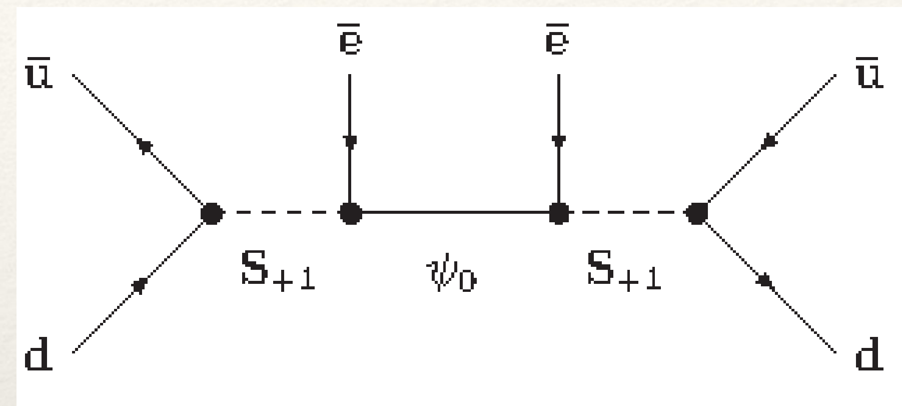
Complementarity of LHC and 0νββ

Hirsch et al., 1511.03945



Ramsey-Musolf et al., 1508.04444



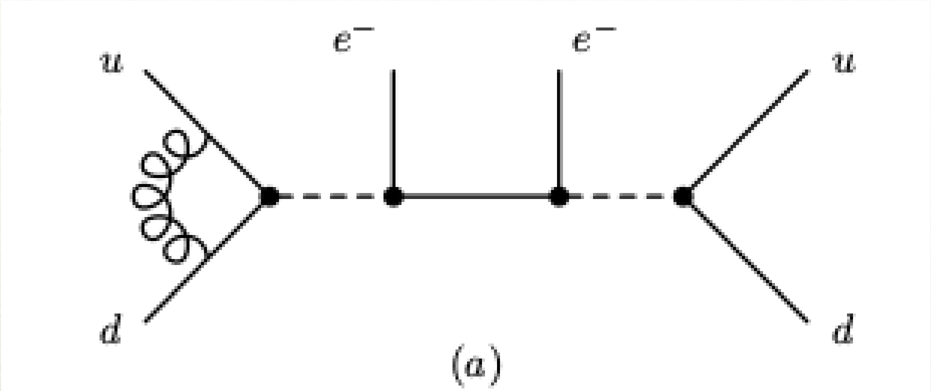


S~(1,2)

ψ~(1,0)

- LHC needs $M_S > M_\psi$
- LHC has low sensitivity for small M_ψ
- include jet-fake rate, charge mis-ID, QCD corrections in 0νββ, etc.
- ⇒ complementary

QCD Corrections



- naive size $(\alpha_s/4\pi) \ln (M_W/100 \text{ MeV})^2 \simeq 10\%$, true for standard diagram
- creates in non (V-A) $\otimes$ (V-A) mechanisms color non-singlets, Fierzing to singlets gives new operators with vastly different NMEs
- $\Rightarrow$ can give effect exceeding NME uncertainty…

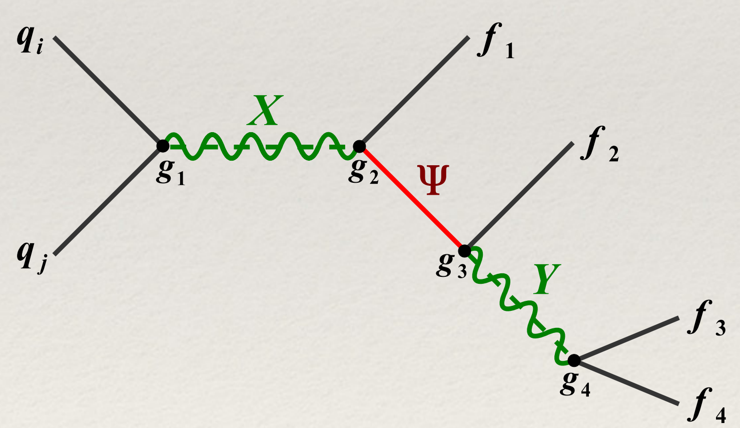
  Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93;

  Peng, Ramsey-Musolf, Winslow, PRD 93

TeV-scale LNV and Baryogenesis

- Example TeV-scale W_R: leads to washout in early Universe via $e_R\, e_R \leftrightarrow W_R\, W_R$ and $e_R\, W_R \leftrightarrow W_R\, e_R$; processes stay long in equilibrium *(Frere, Hambye, Vertongen; Bhupal Dev, Mohapatra; Sarkar et al.)*

- more model-independent *(Deppisch, Harz, Hirsch)*:



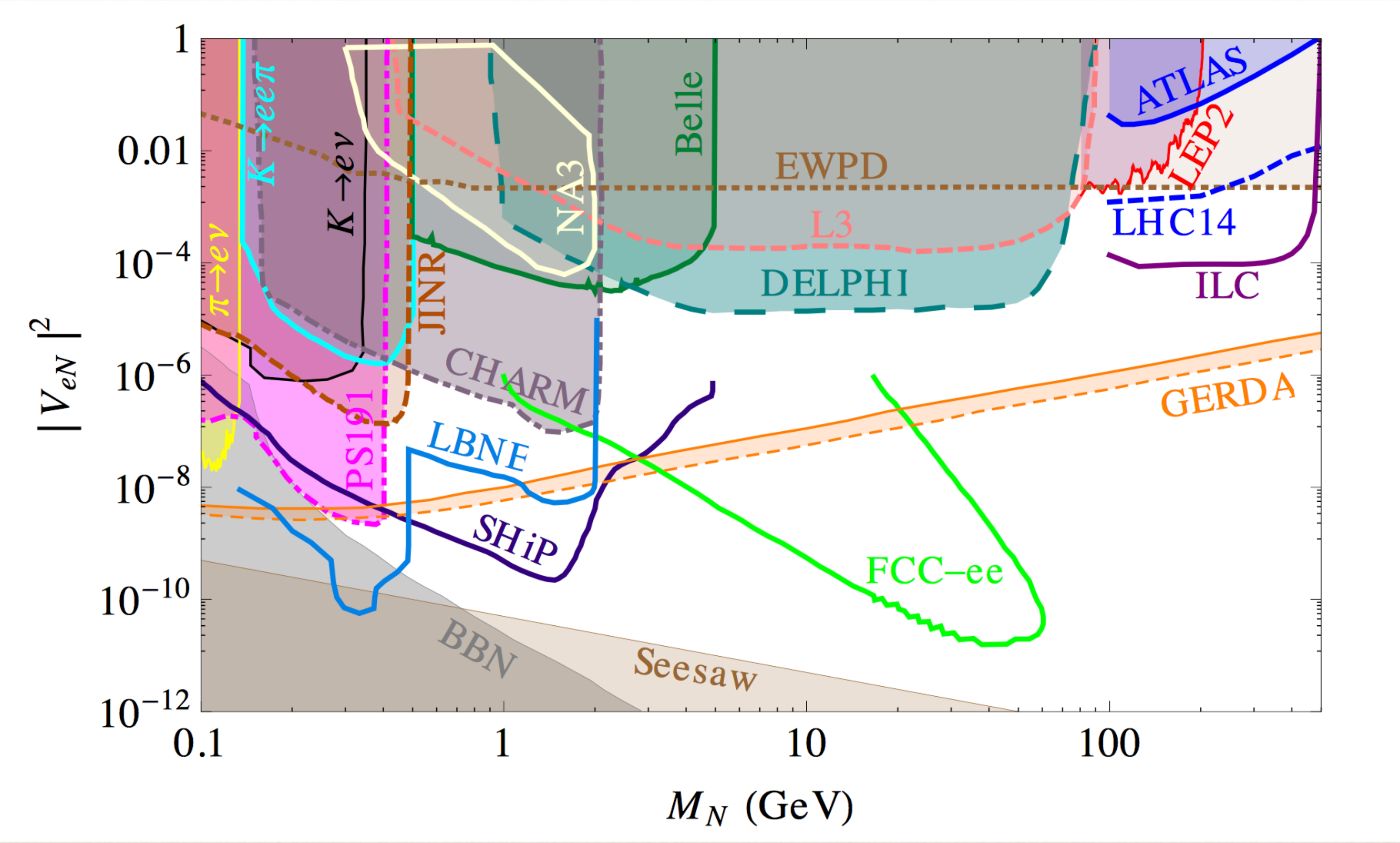
wash-out:

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

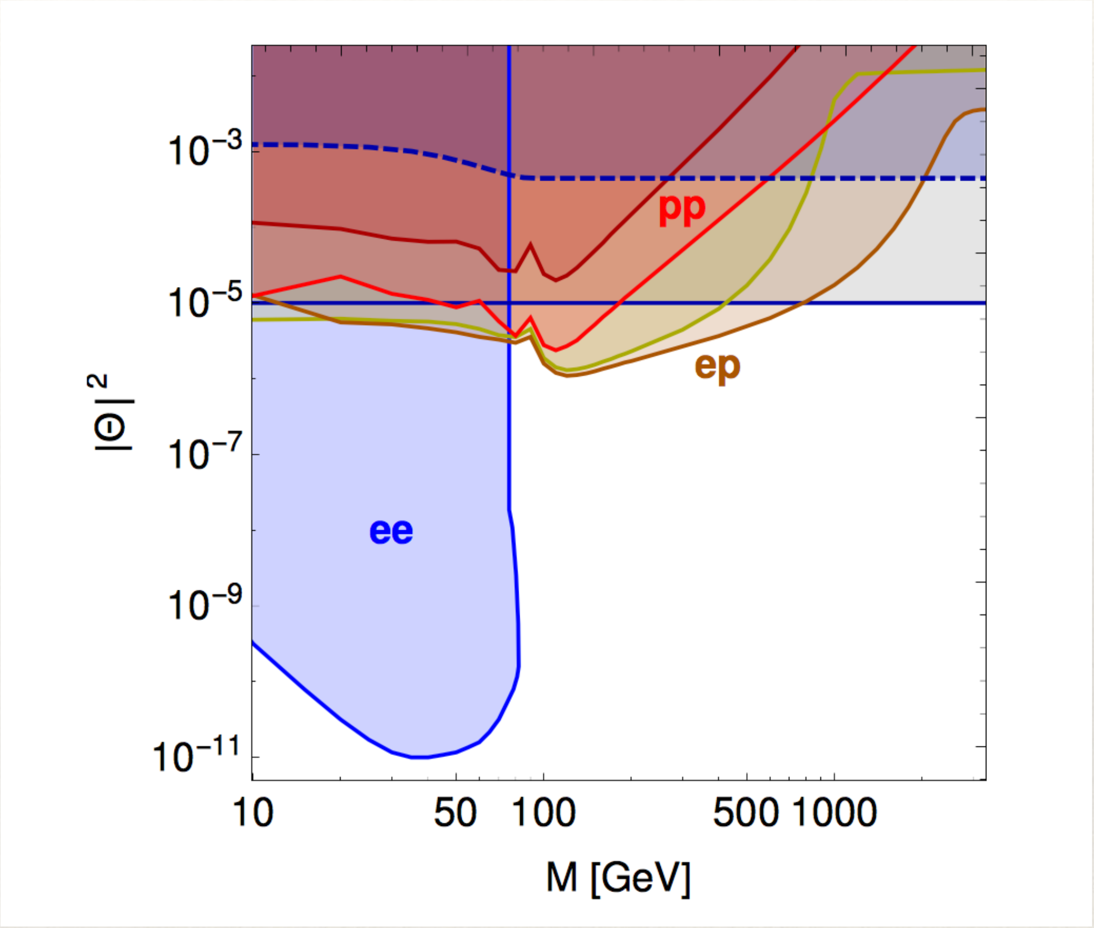
($\Leftrightarrow$ need for high-scale baryogengesis if TeV-scale LNV is present…?)

Limits on Heavy Neutrinos

$M(W_R) \leftrightarrow V_{\alpha N}$



Deppisch, Dev, Pilaftsis, 1502.06541



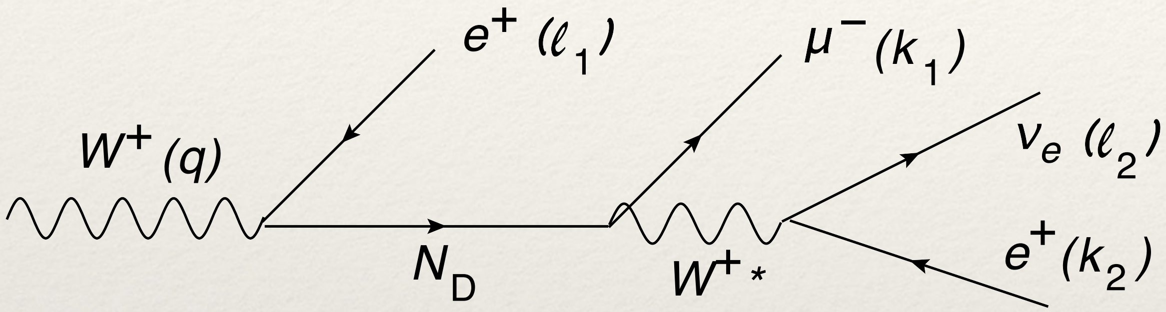
Antusch, Cazzato, Fischer, 1612.02728

peak searches, kink searches, LNV decays,…

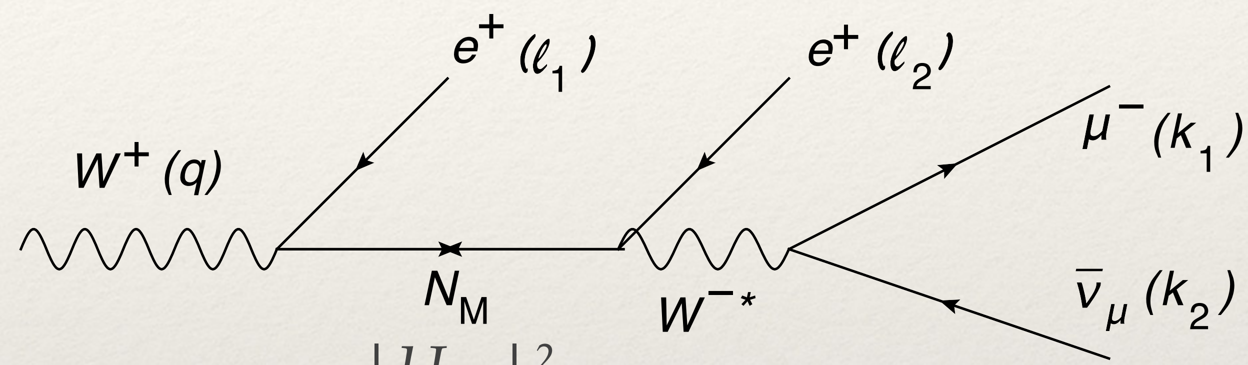
see also Atre et al., 0901.3589

New Idea

assume RH neutrinos with mass less than m_W *(Dib, Kim, 1509.05981)*:



$|U_{Ne}\, U_{N\mu}|^2$

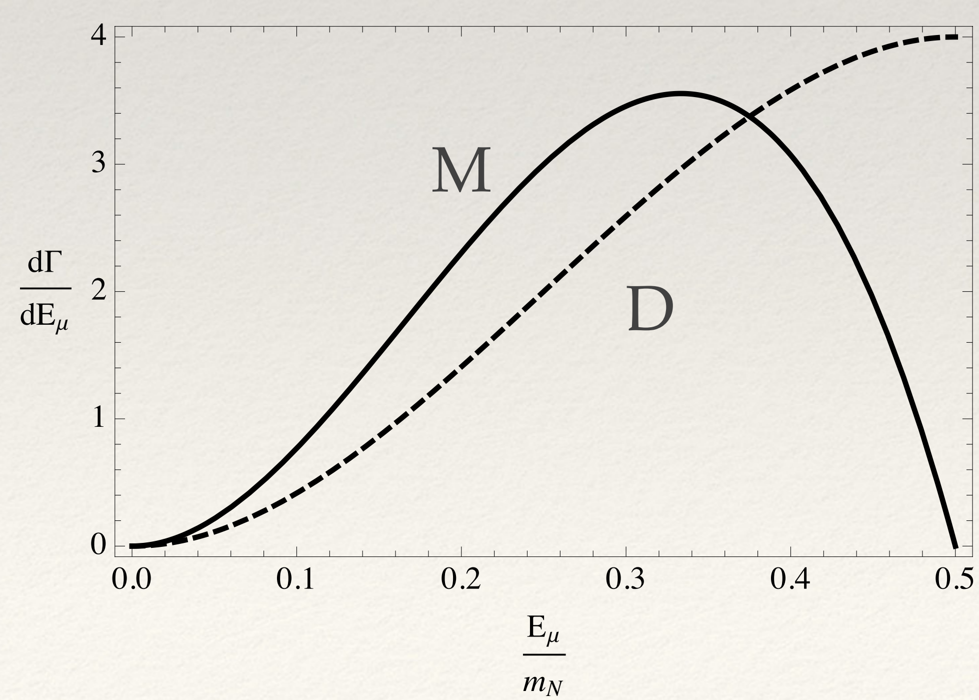


$|U_{Ne}|^2$

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

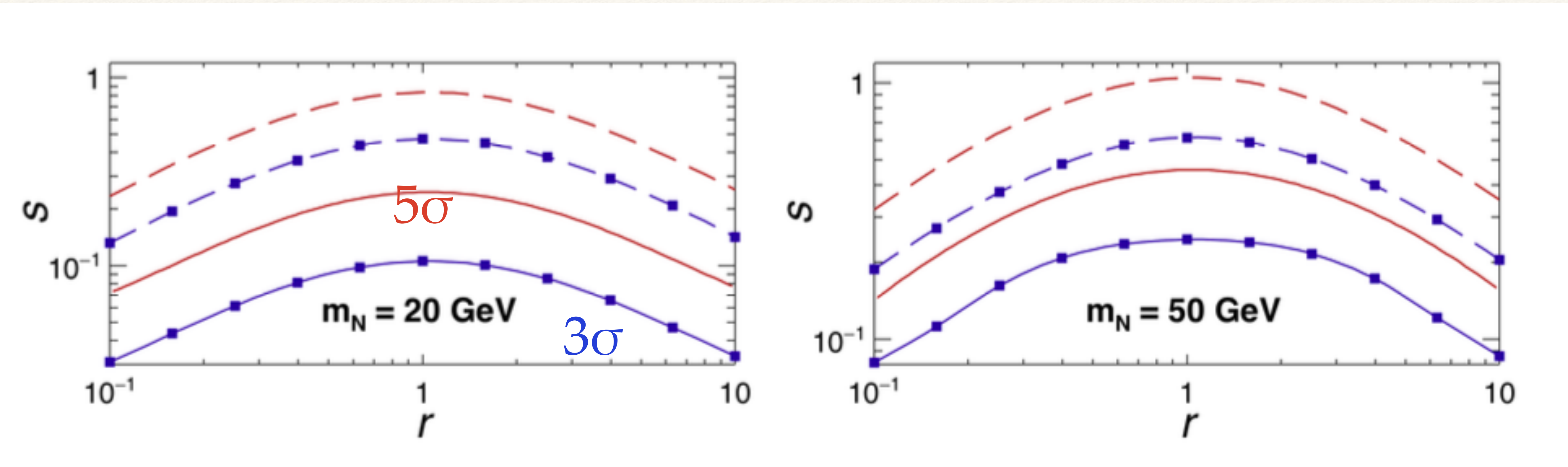
$W^+ \to e^+\ \mu^-\ e^+$ **anti-ν_μ**

$\Delta L = 0$



$\Delta L = 2$
hidden in ν…
but μ comes from different vertex!

New Idea



(solid is mult-variate; dashed is cut-and-count)

$$s \equiv 2 \times 10^6 \, \frac{|U_{Ne} U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}, \quad r \equiv \frac{|U_{Ne}|^2}{|U_{N\mu}|^2}.$$

Dib, Kim, Wang, 1703.01936

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.

„New“ Idea II

$$\mathcal{L} \supset \frac{G_F}{\sqrt{2}} \sum_a \overline{\nu}\Gamma^a \nu \left[\overline{\ell}\Gamma^a (C_a + \overline{D}_a i\gamma^5)\ell\right]$$

Rosen, PRL48 (1982)
WR, Xu, Yaguna, 1702.05721

- gives cross section for elastic neutrino electron scattering:

$$\frac{d\sigma}{dT}(\nu + \ell) = \frac{G_F^2 M}{2\pi}\left[A + 2B\left(1 - \frac{T}{E_\nu}\right) + C\left(1 - \frac{T}{E_\nu}\right)^2\right]$$

$$\frac{d\sigma}{dT}(\overline{\nu} + \ell) = \frac{G_F^2 M}{2\pi}\left[C + 2B\left(1 - \frac{T}{E_\nu}\right) + A\left(1 - \frac{T}{E_\nu}\right)^2\right]$$

$$T = \frac{2ME_\nu^2 c_\theta^2}{(M+E_\nu)^2 - E_\nu^2 c_\theta^2}$$

with:

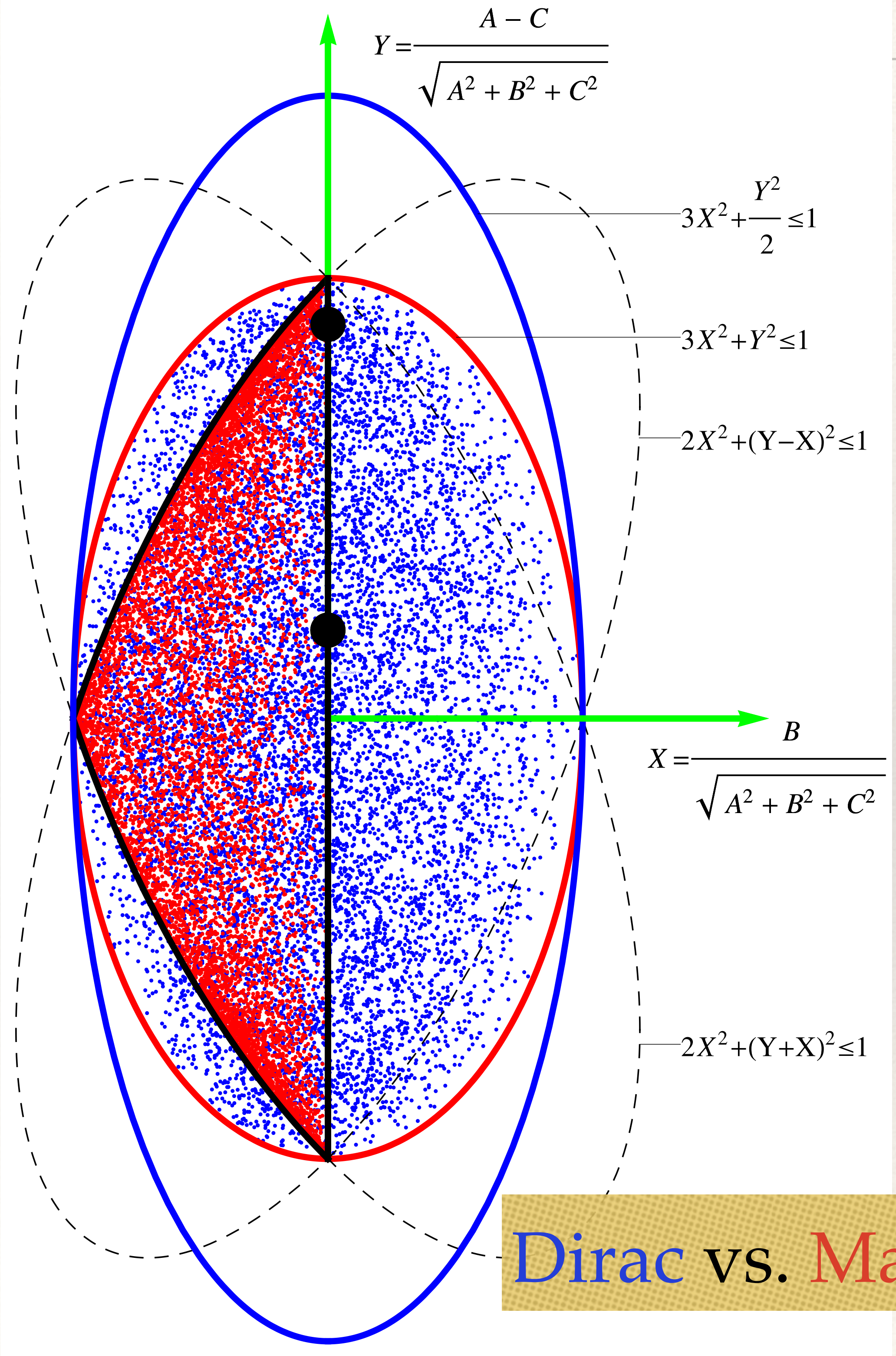
$$A \equiv \frac{1}{4}\left(C_A - D_A + C_V - D_V\right)^2 + \frac{1}{2}C_P C_T + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) - \frac{1}{2}C_S C_T + C_T^2 + \frac{1}{2}D_P D_T - \frac{1}{2}D_S D_T + D_T^2$$

$$B \equiv -\frac{1}{8}\left(C_P^2 + C_S^2 + D_P^2 + D_S^2\right) + C_T^2 + D_T^2\,,$$

$$C \equiv \frac{1}{4}\left(C_A + D_A - C_V - D_V\right)^2 - \frac{1}{2}C_P C_T + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) + \frac{1}{2}C_T C_S + C_T^2 - \frac{1}{2}D_P D_T + \frac{1}{2}D_S D_T + D_T^2$$

- **For Majorana neutrinos: $C_V = D_V = C_T = D_T = 0$**

New Idea II



Dirac vs. Majorana

can only demonstrate Dirac nature!

$$X \equiv \frac{B}{R}, \; Y \equiv \frac{A-C}{R}$$

$$R \equiv \sqrt{A^2+B^2+C^2}$$

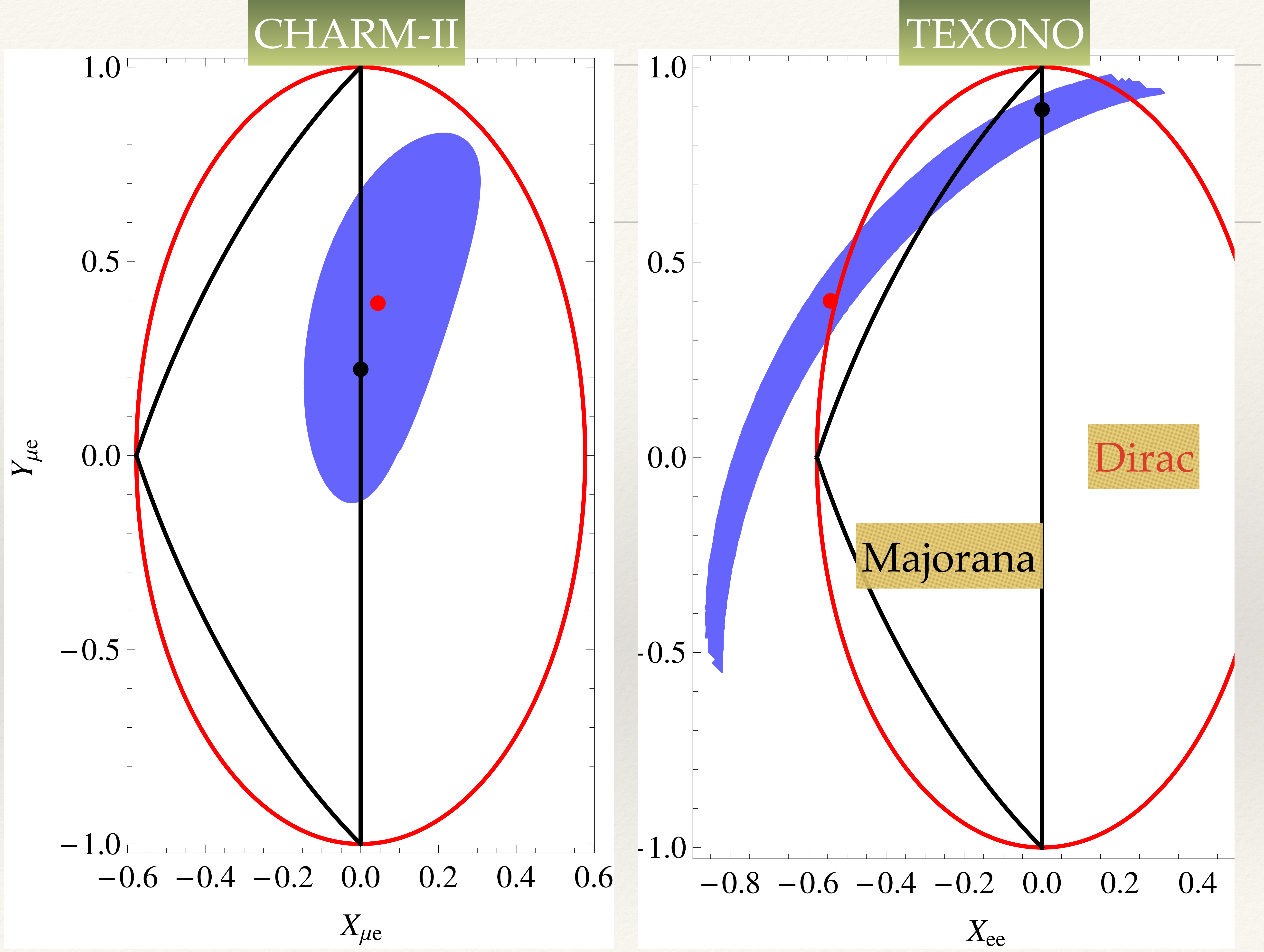
Dirac neutrinos:

$$3X^2 + Y^2 \le 1$$

Majorana neutrinos:

$$2X^2 + (Y \pm X)^2 \le 1 \quad \text{and} \quad X \le 0$$

WR, Xu, Yaguna, 1702.05721



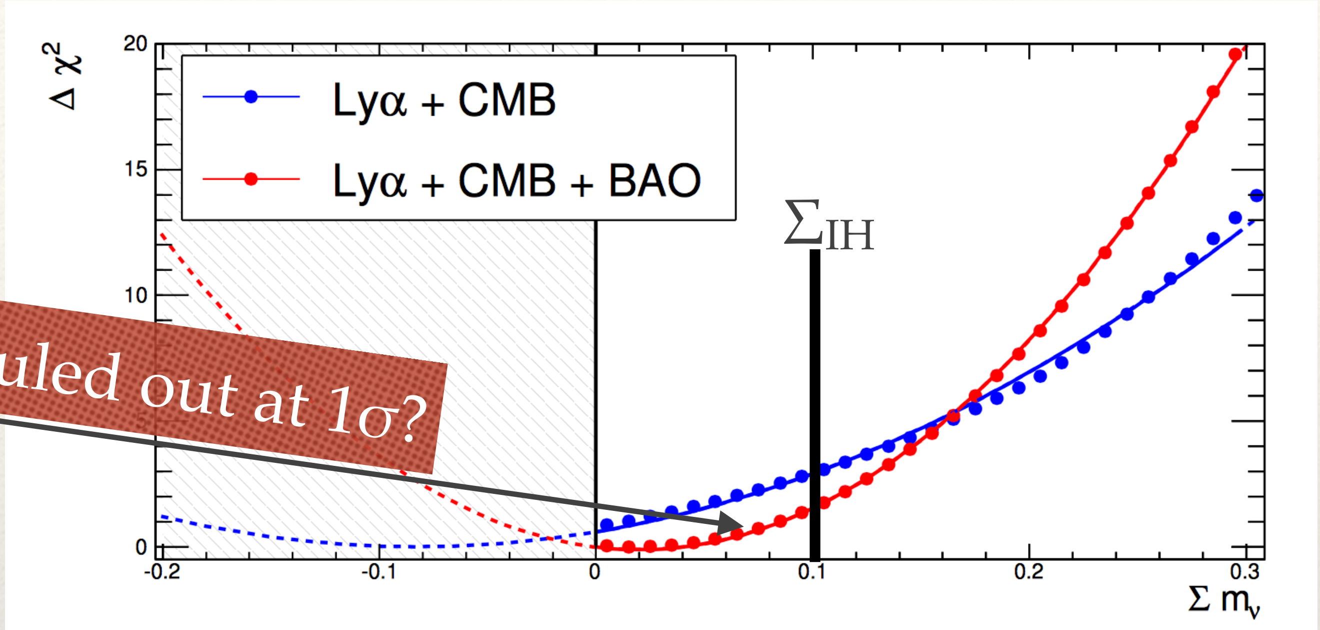
CHARM-II
TEXONO
1.0
0.5
0.0
−0.5
−1.0
$Y_{\mu e}$
−0.6 −0.4 −0.2 0.0 0.2 0.4 0.6
$X_{\mu e}$
−0.8 −0.6 −0.4 −0.2 0.0 0.2 0.4
X_{ee}
Dirac
Majorana

Cosmological Mass Limits

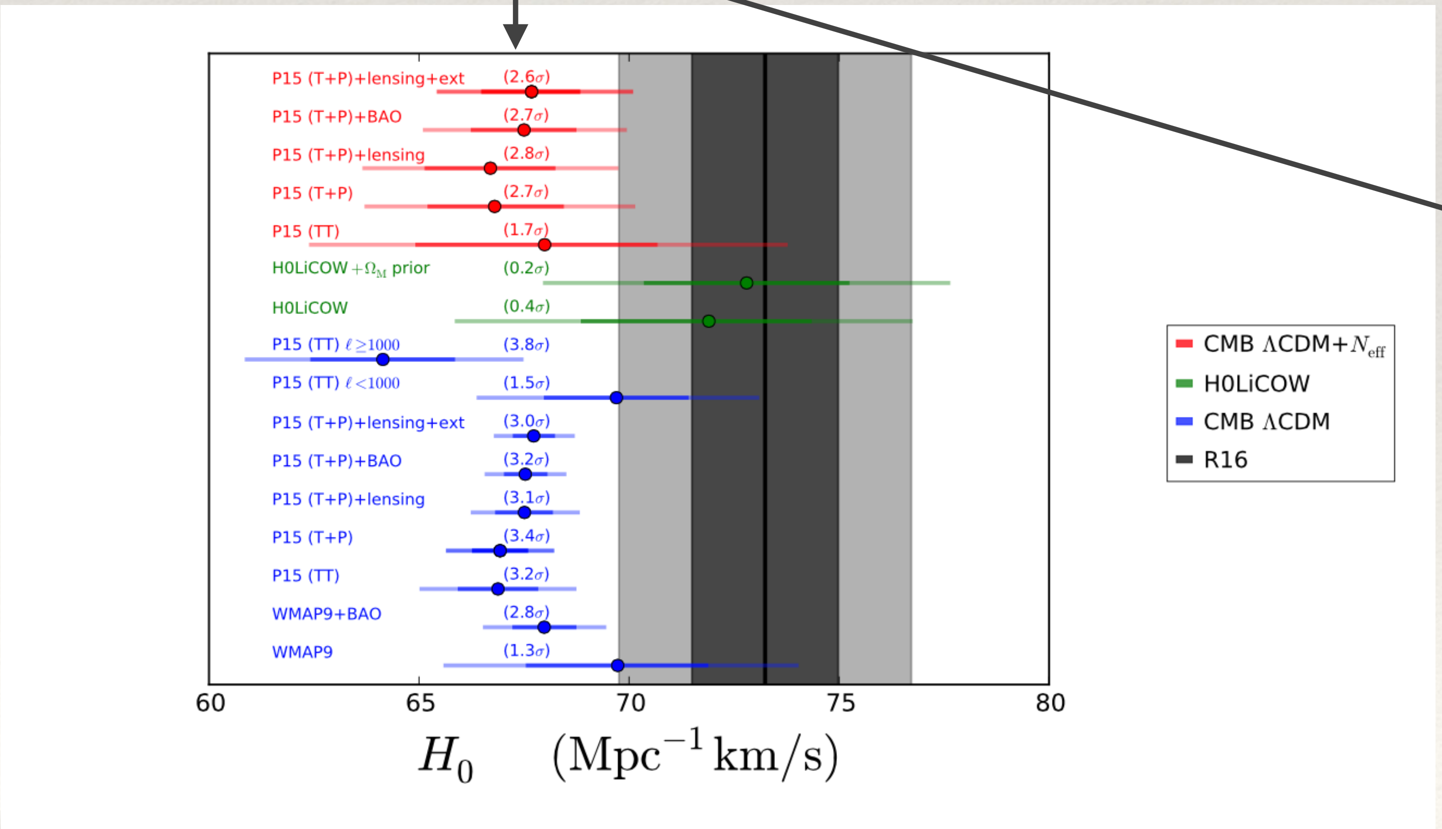
(Talk by Di Valentino)

- adding more and more data sets: breaks degeneracies and improves limits
- BUT: can introduce systematics?

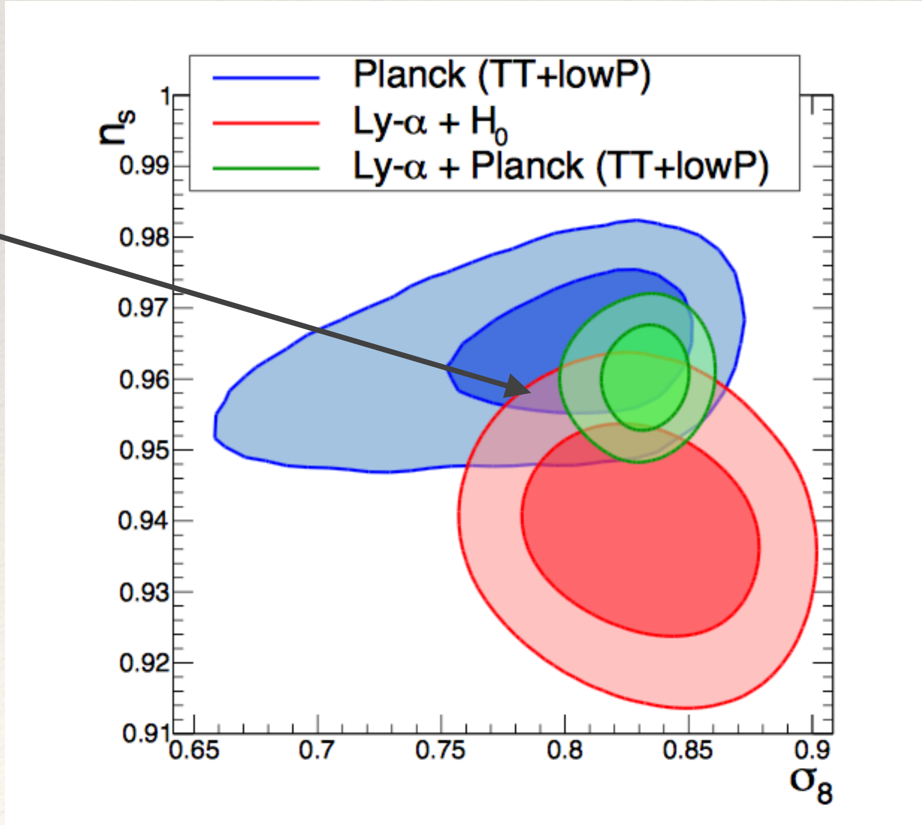
IH ruled out at 1σ?



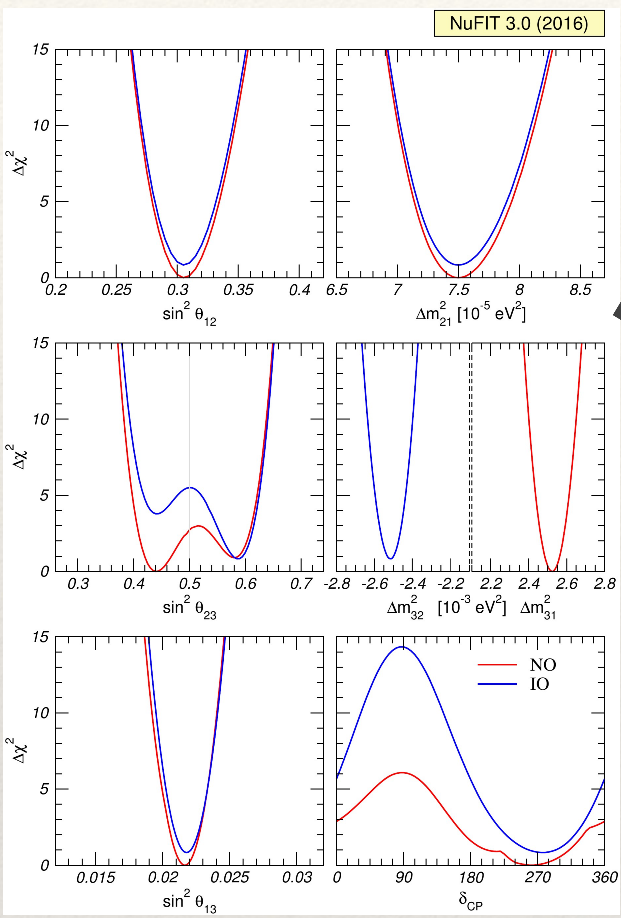
Palanque-Delabrouille et al., 1410.7244 + 1506.05976



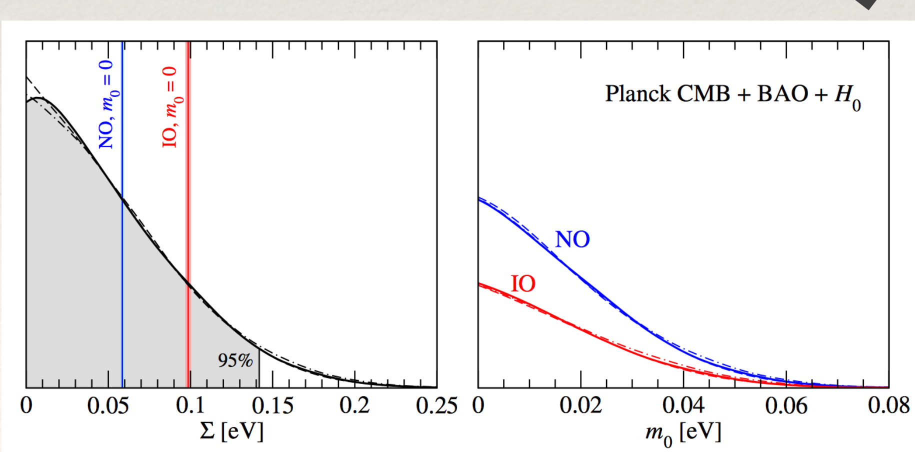
Bernal, Verde, Riess, 1607.05617

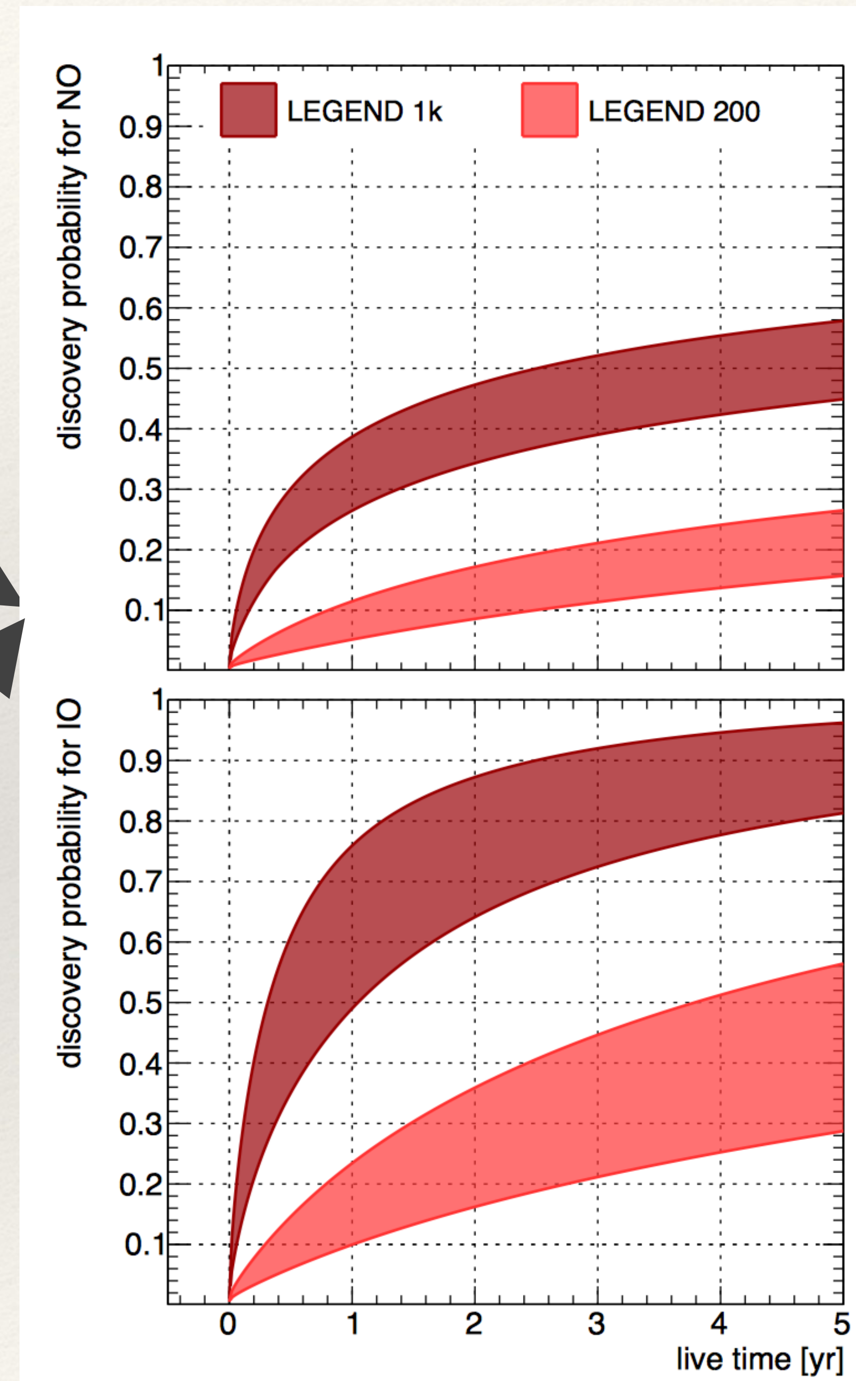


Expectations of lifetimes



+





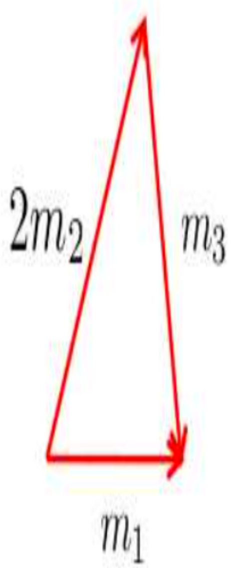
Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

Agostini et al, 1705.02996;
also Caldwell et al., 1705.01945

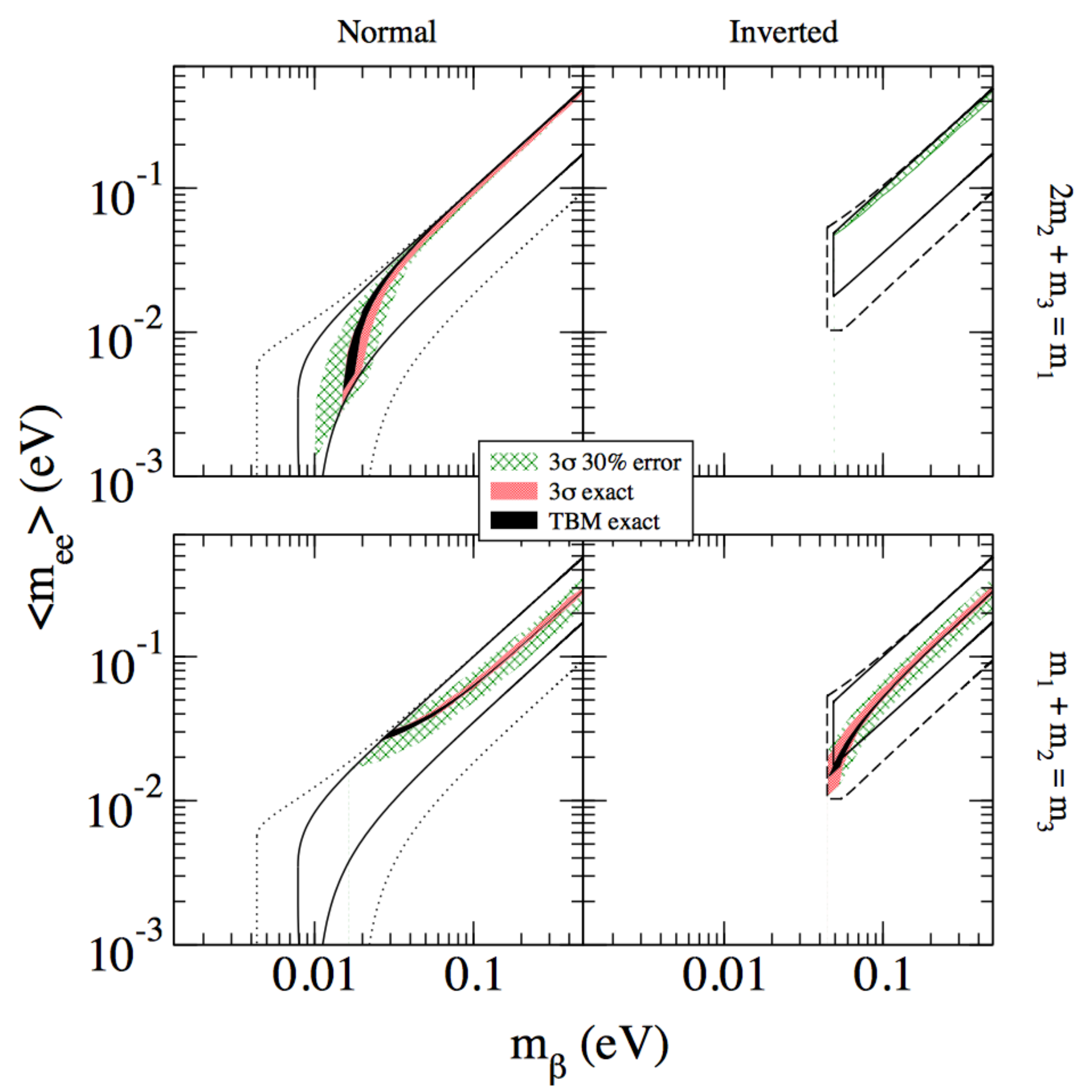
Neutrino Mass Sum-Rules

Flavor Symmetry models *(talk by Petcov)*
can not predict masses, but relations between them:

Barry, WR, 1007.5217

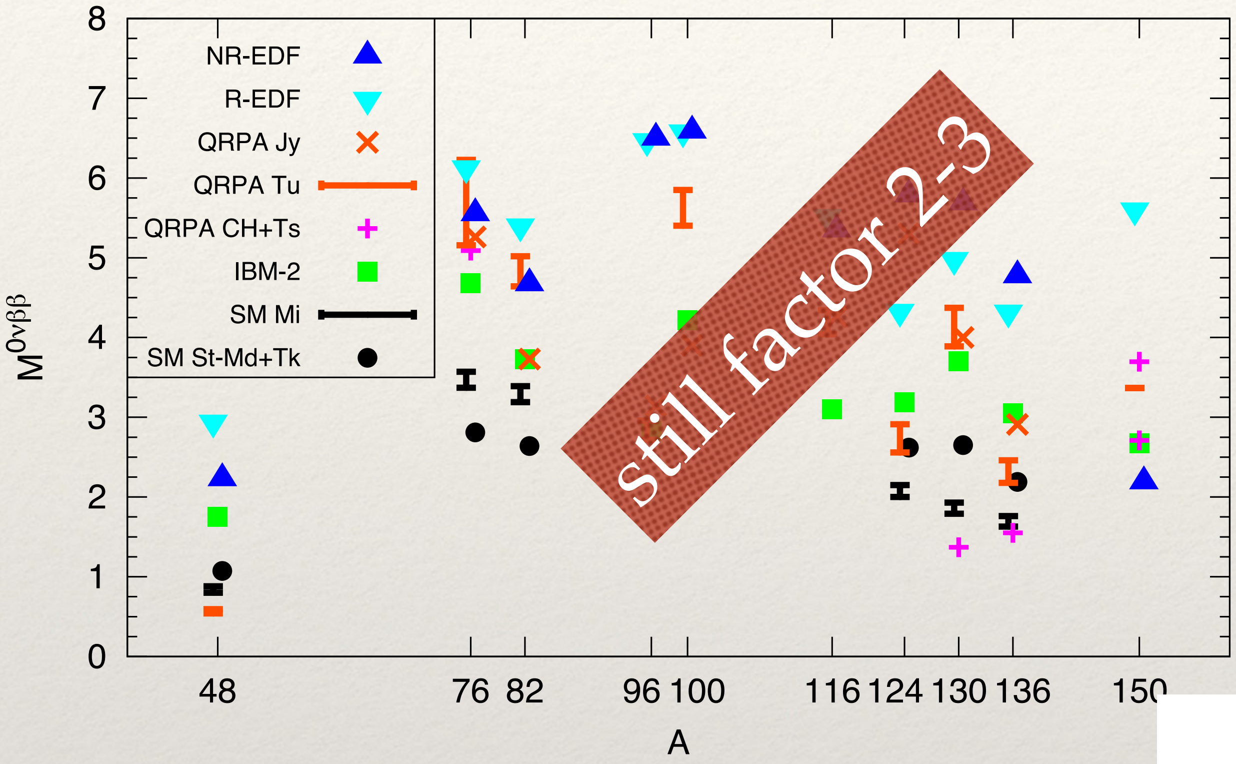


Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4

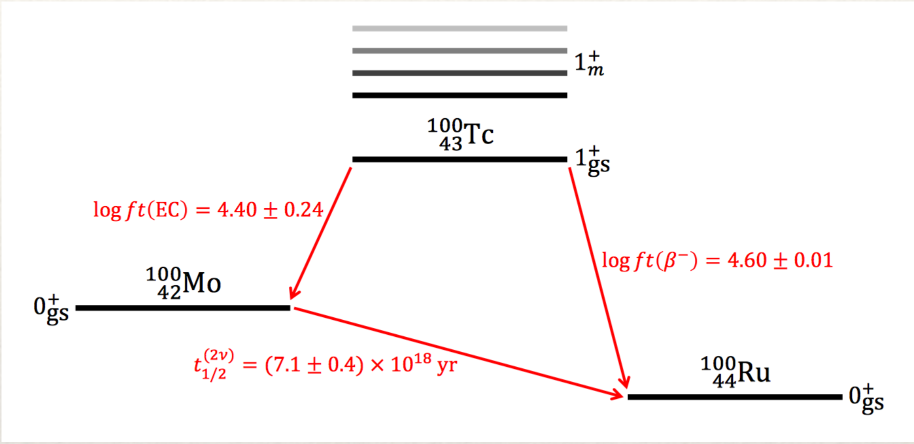


Nuclear Matrix Elements

Engel, Menendez, 1610.06548

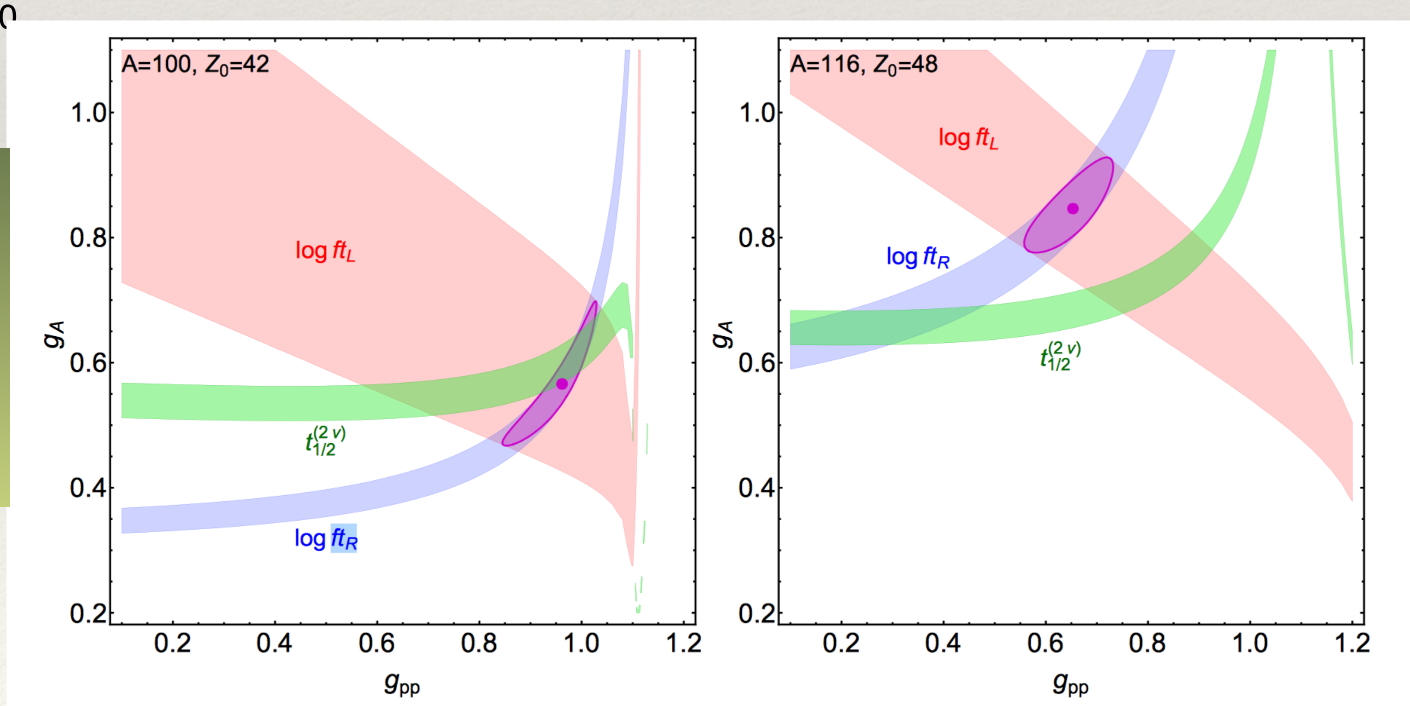


How good are the models?
Example isobaric triplets
within QRPA



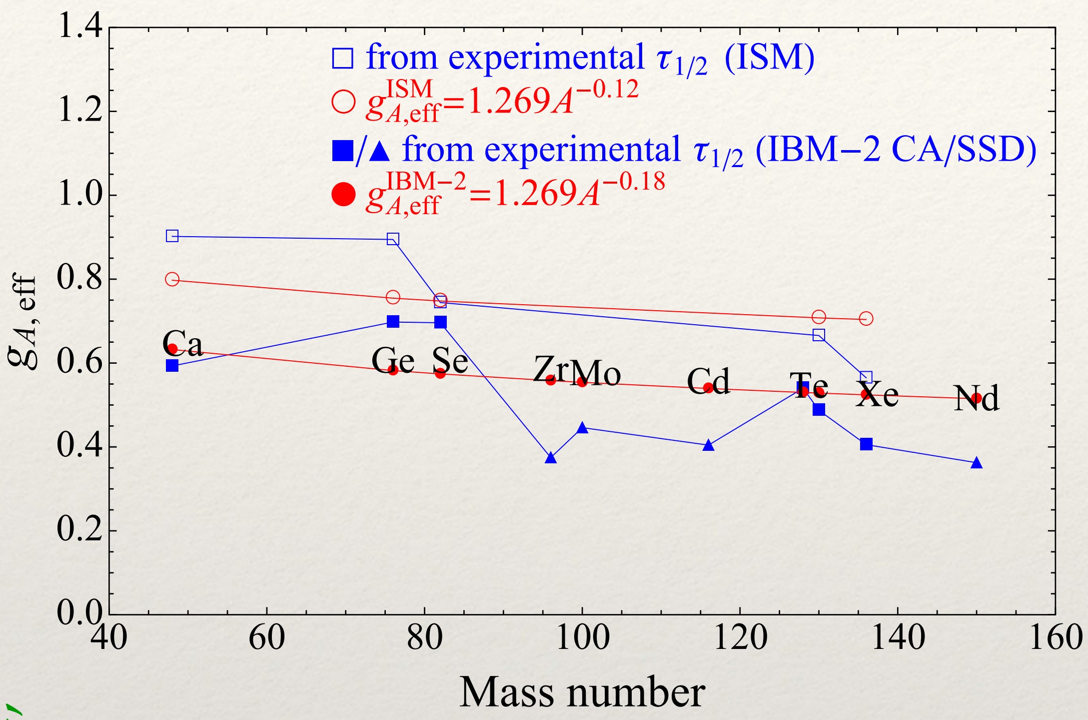
Deppisch, Suhonen, 1606.02908

⇒ Need as much experimental input (e.g. charge exchange) as possible…

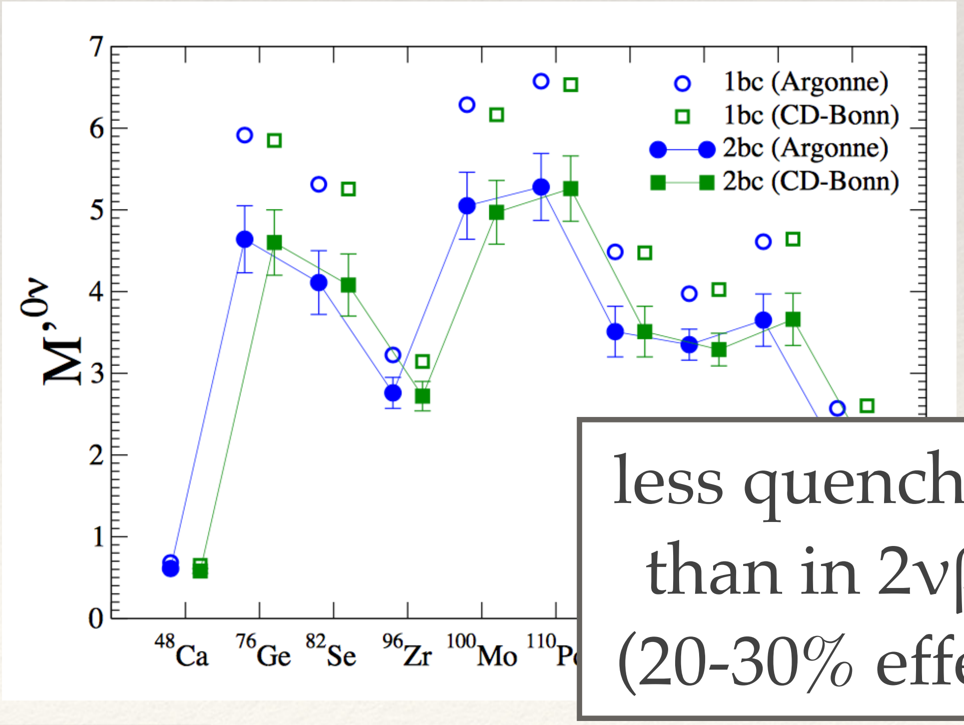


Nuclear Matrix Elements

Iachello et al., 1506.08530



Menendez, Gazit, Schwenk, 1103.3622; Engel, Simkovic, Vogel, 1403.7860



less quenching than in 2νββ (20-30% effect)

QUENCHING??

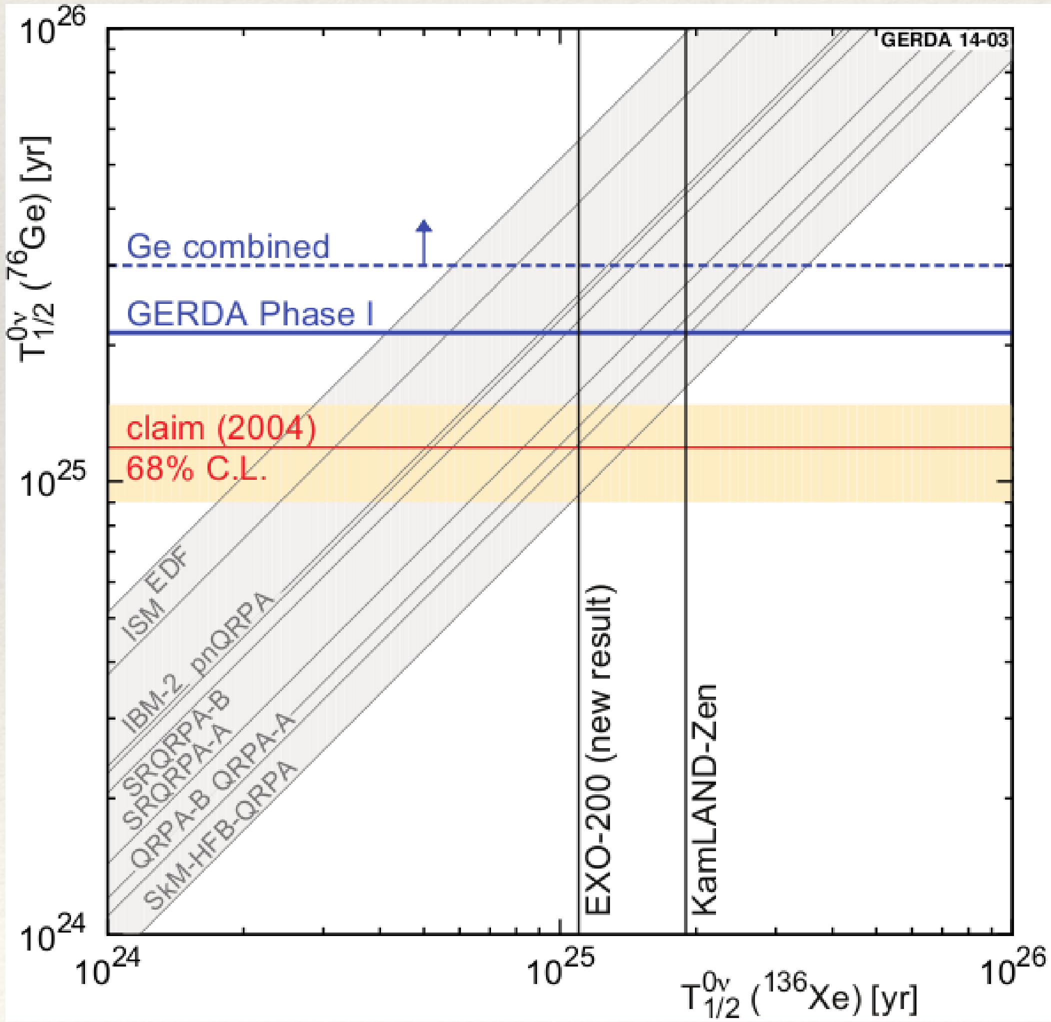
$$T_{\frac{1}{2}}^{0\nu} \propto g_A^{-4}$$

- fact in β and 2νββ
- truncation of model-space?
- also in 0νββ??
  - $q = 10^2$ vs. 10^0 MeV?
  - higher multipolarities?
  - two-body currents?
  - muon capture?
  - SM vs. QRPA

Comparison of Limits

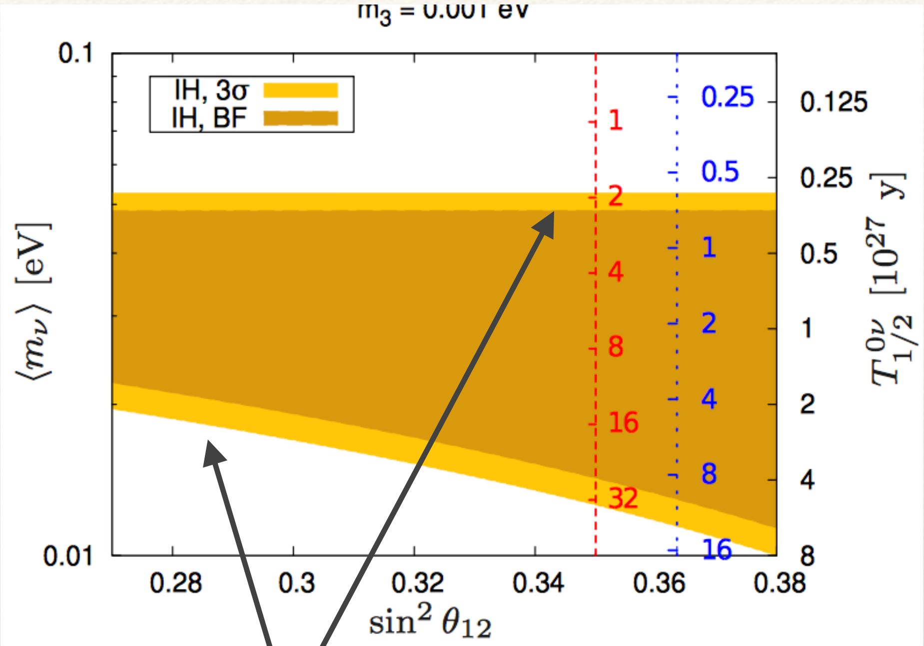
Limit from Xenon is better than limit from Germanium if:

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



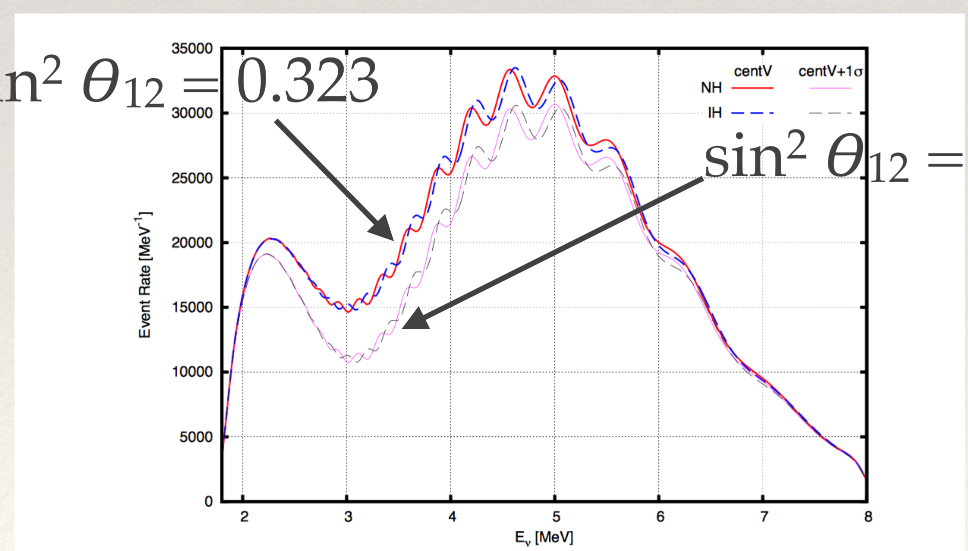
- depends on NMEs
- for most NMEs Xe better
- limit about $m_{ee} < 0.2$ eV
- means 0.2…0.6 eV for KATRIN
- means 0.6…1.8 eV for cosmo

Connections to Oscillation Experiments



Nature gives us two scales

$\sin^2\theta_{12} = 0.323$



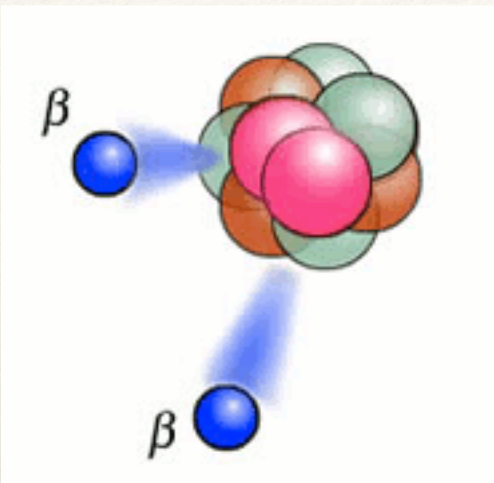
$\sin^2\theta_{12} = 0.339$

Factor 2 uncertainty of minimal m_{ee} in IH, mostly from θ_{12}

JUNO will fix θ_{12} and remove uncertainty in value of minimal m_{ee} in IH

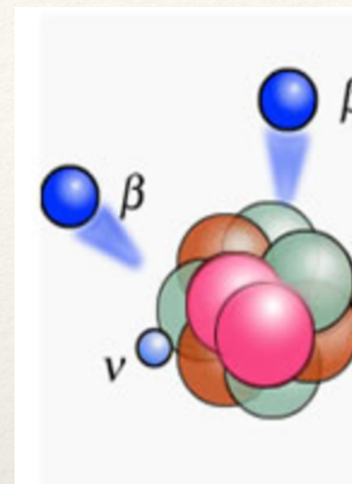
Dueck, WR, Zuber, 1103.4152; Ge, WR, 1507.05514

Best chance: Neutrinoless Double Beta Decay



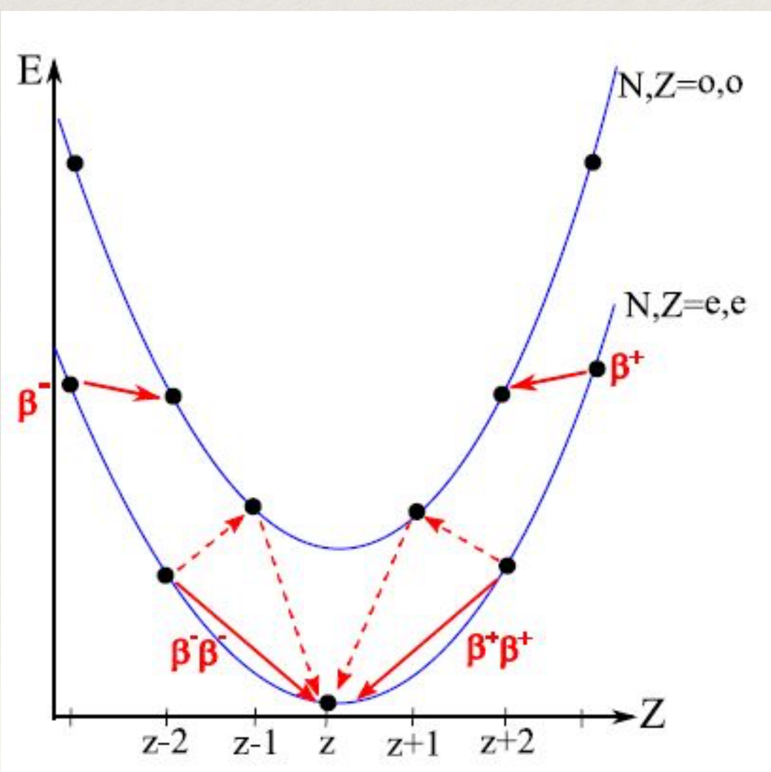
$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$

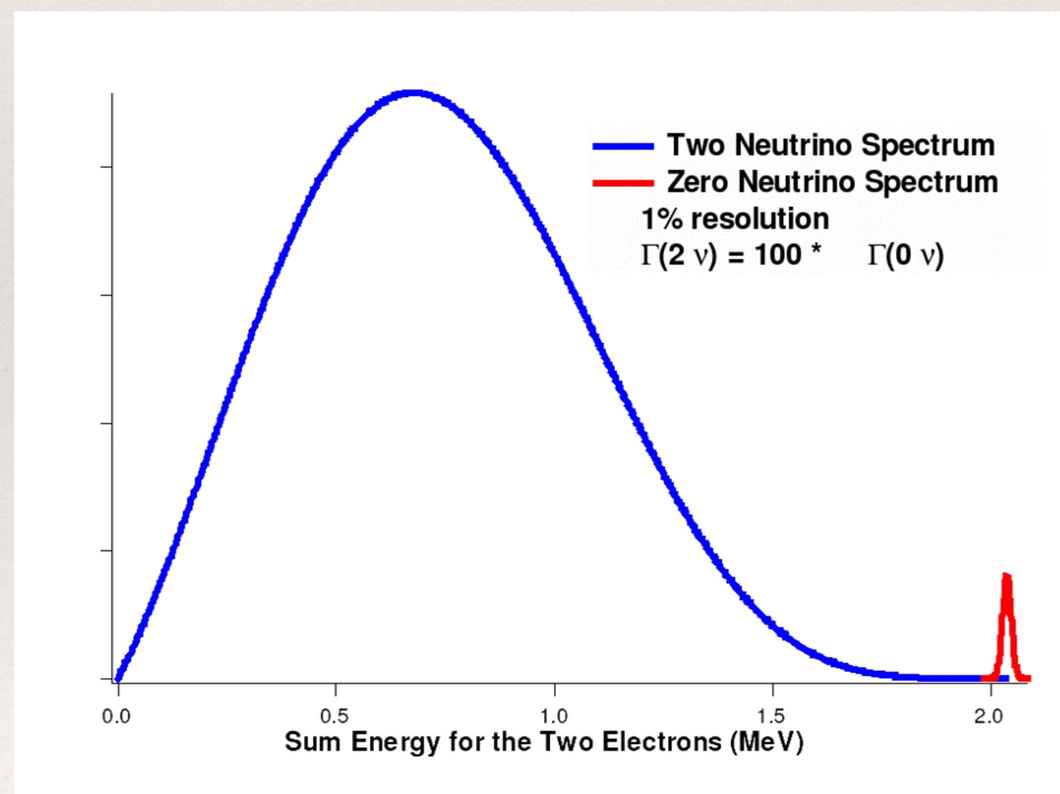
$\Delta L = 2$



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

$\Delta L = 0$

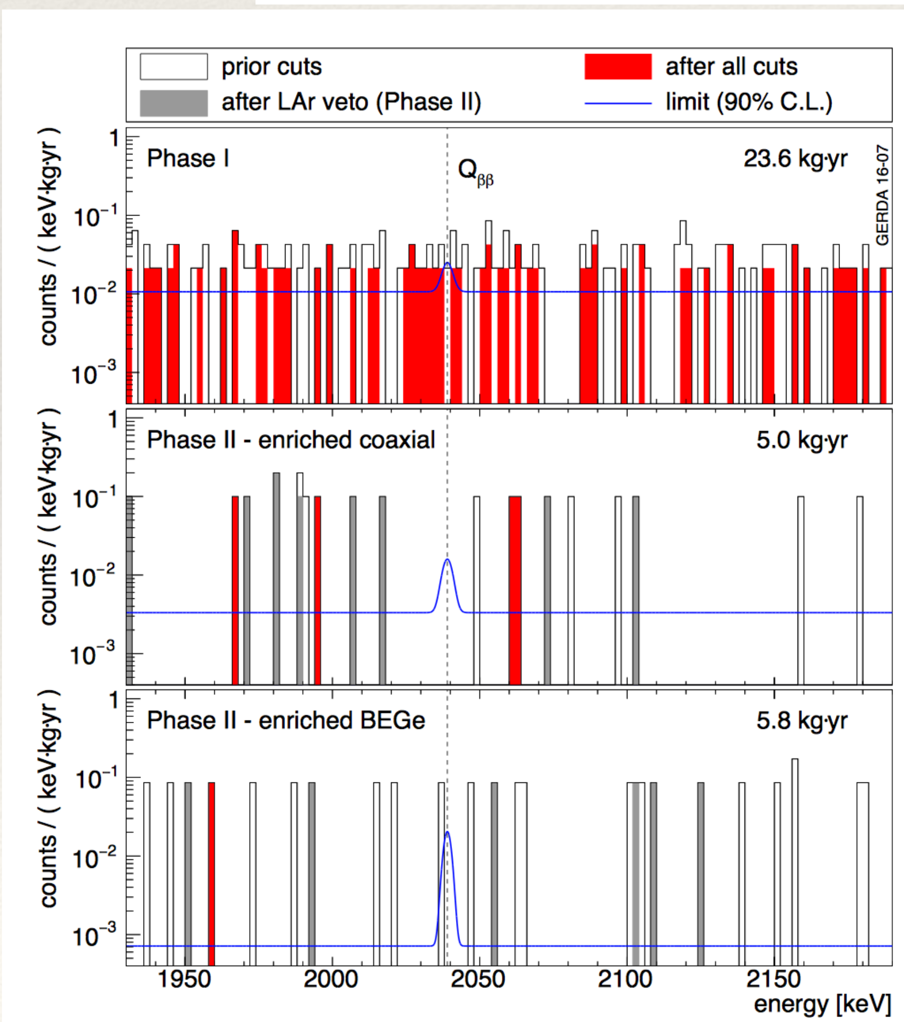




Neutrinoless Double Beta Decay

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

GERDA, 1703.00570, Nature

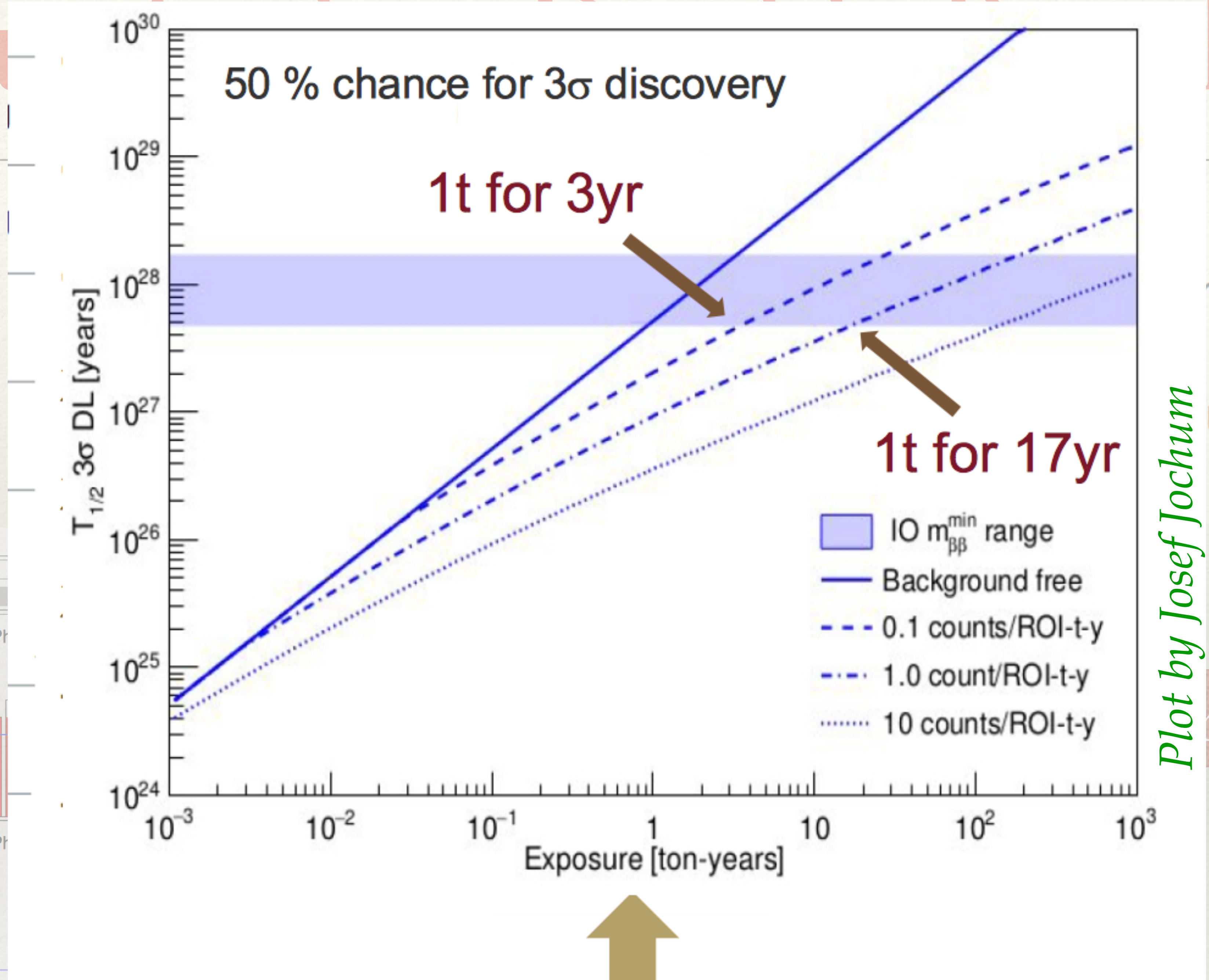


first background free result

see talk by Anne Wegmann

current limits: $T_{½} \gtrsim 10^{26}$ years
with exposure of about 100 kg • years

Ne Decay



Plot by Josef Jochum

low background essential for discovery potential

GERDA, 1703.00570, Nature

round

und

ree result

10^{26} years

100 kg · years

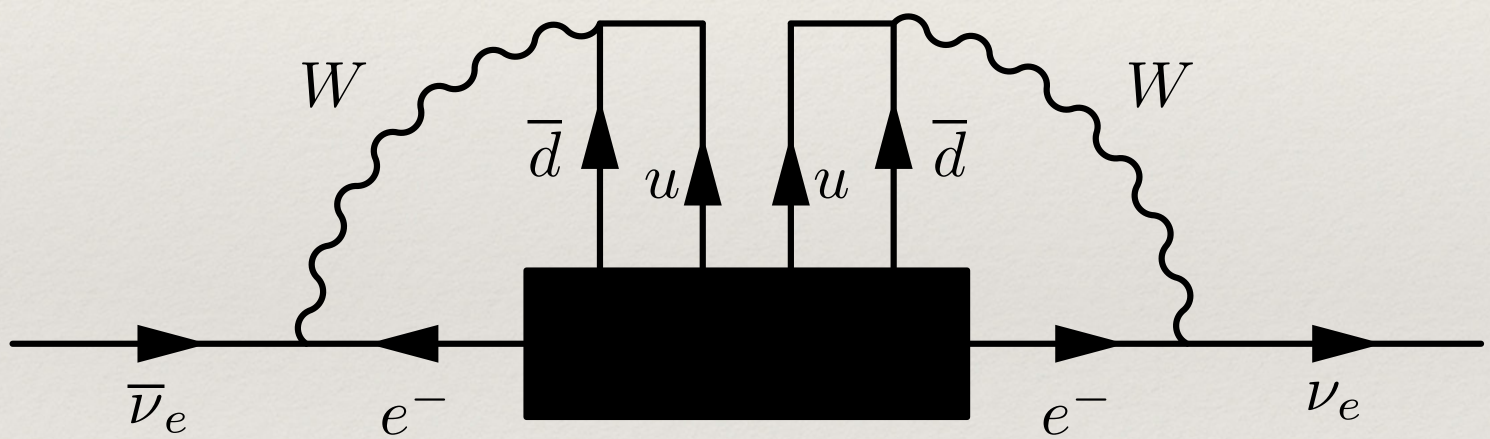
Neutrinoless Double Beta Decay

Table by Josef Jochum

			isotope mass [kg] in FV	FWHM [keV]	background [(FWHM ε $t_{isotope}$ yr $)^{-1}$]	$T_{1/2}$ sensitivity after 4yr [10^{25} yr]	upper m_β limit [meV] (lowest NME
Ge detectors	GERDA	Ge	27	3	5	15	190
	Majorana-D	Ge	24	3	5	15	190
	LEGEND 200 kg	Ge	155	3	1	100	75
	LEGEND 1000 kg	Ge	780	3	0.2	1000	24
liquid noble gas	EXO	Xe	80	88	220	6	240
	nEXO	Xe	4300	58	5	600	24
loaded liquid scintillator	KamLAND 400 kg	Xe	88	250	90	6	240
	KamLAND 800 kg	Xe	~180	250	~10	50	90
	SNO+	Te	260	190	60	17	160
cryo bolometers	CUORE	Te	206	5	180	9	210

Black Box Theorem

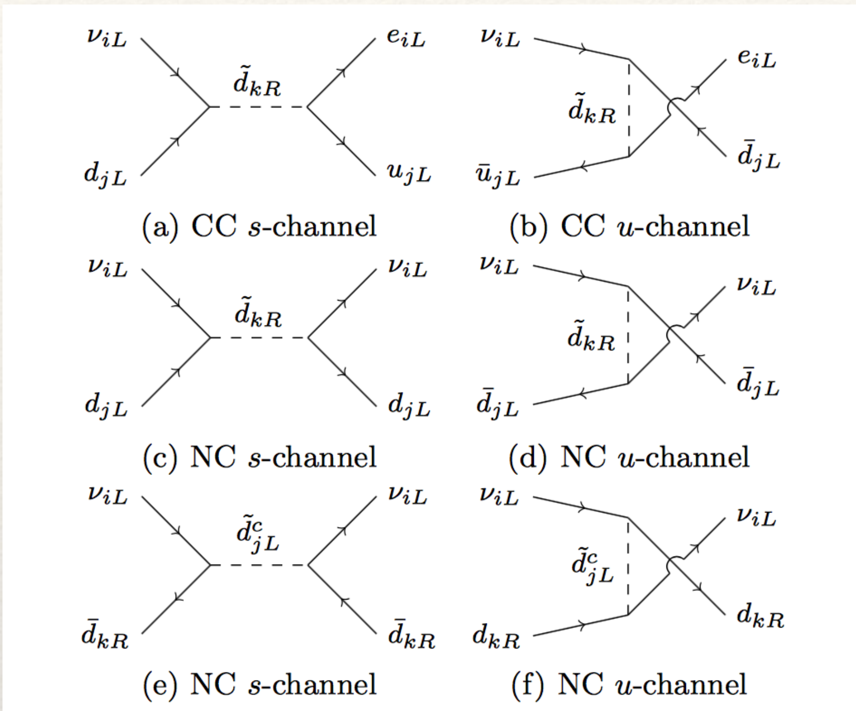
- Whatever the mechanism, observation of 0νββ implies Majorana neutrinos *(Schechter-Valle, '82)*



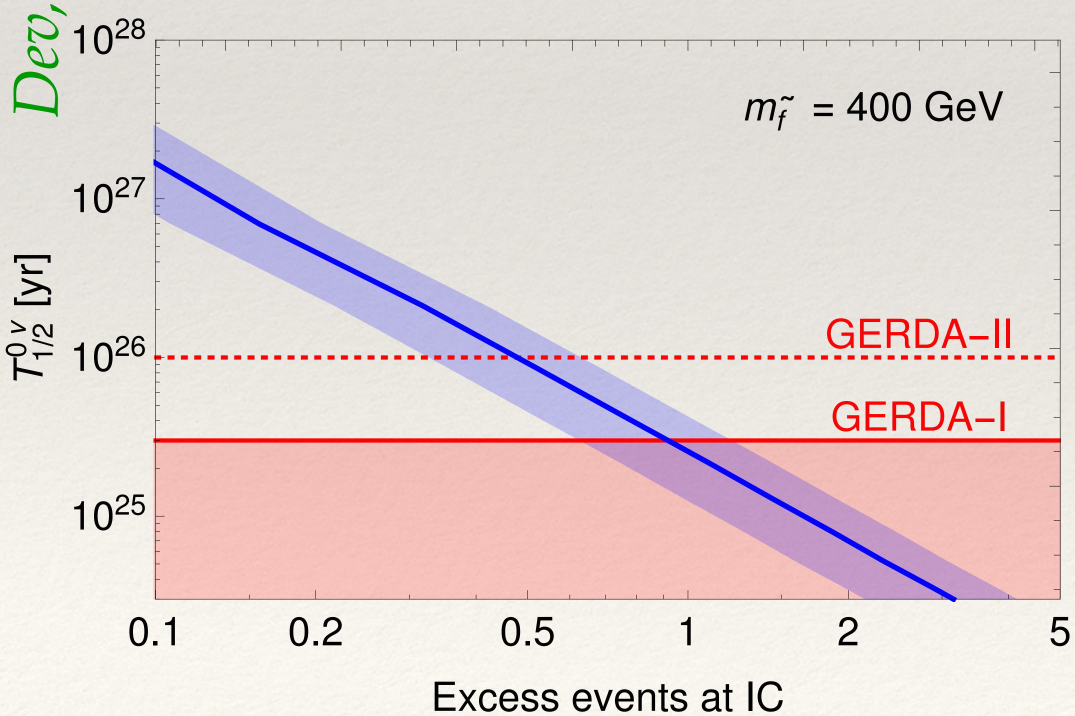
- is 4-loop diagram ⇒ tiny mass *(Dürr, Lindner, Merle, 1105.0901)*

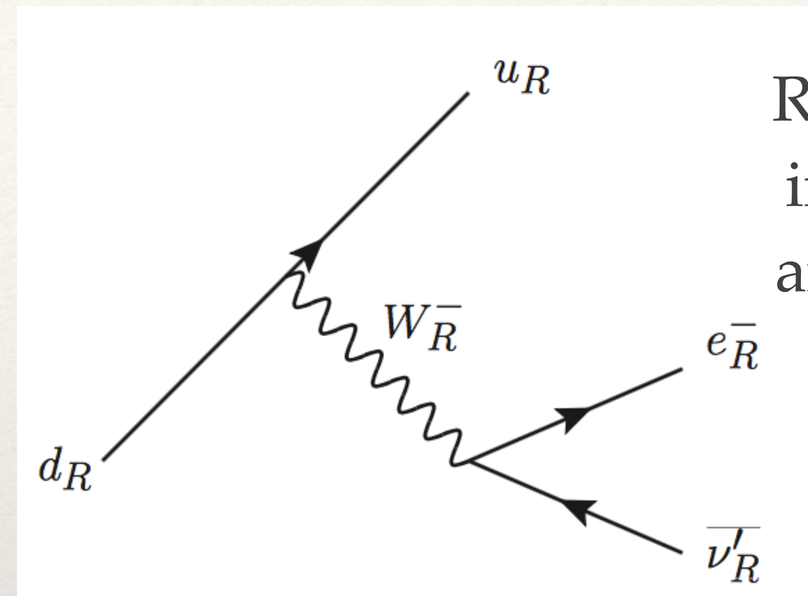
Unexpected Correlations with other Experiments

Dev, Ghosh, WR, 1605.09743

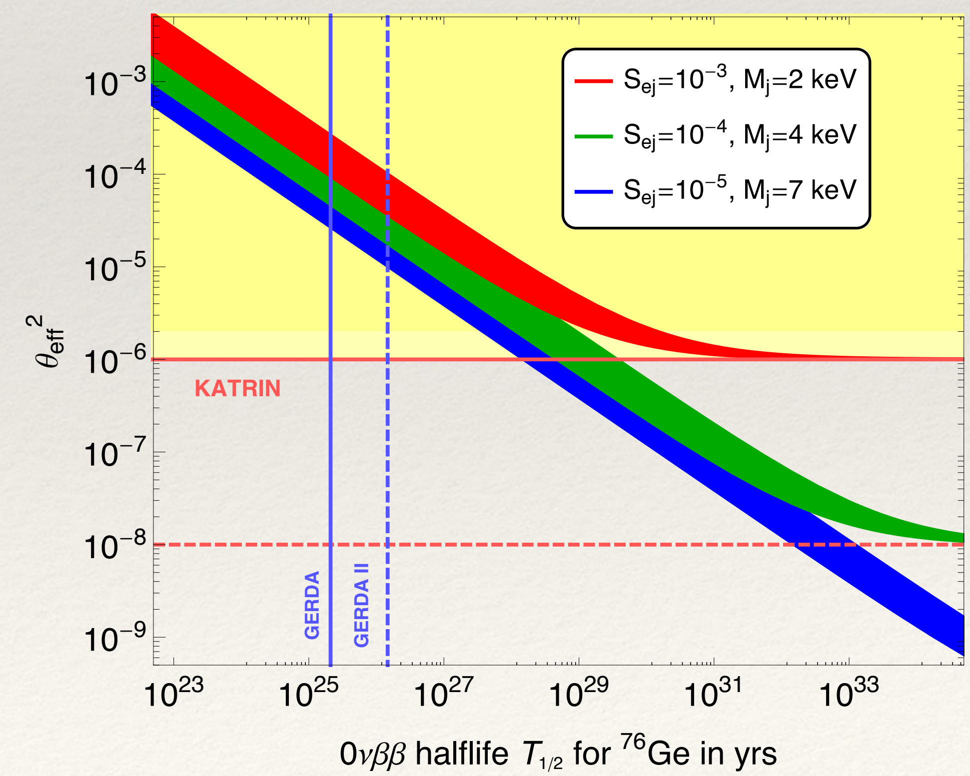


RPV SUSY at IceCube and in 0νββ





RH currents in KATRIN and in 0νββ



Barry, Heeck, WR, 1404.5955

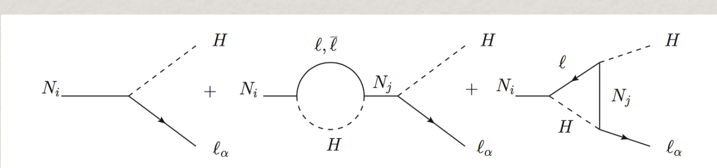
Type I Seesaw $m_\nu = m_D^2 / M_R$

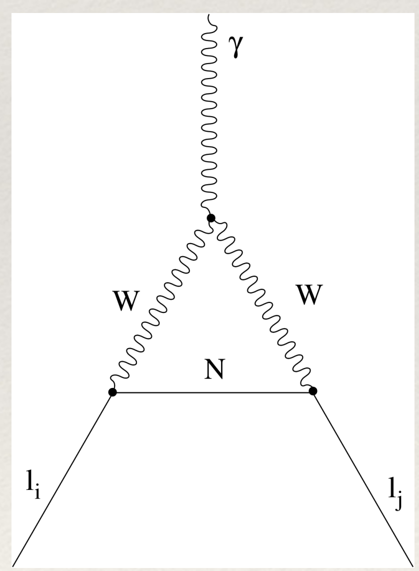
actually, does neither fix m_ν nor m_D nor M_R

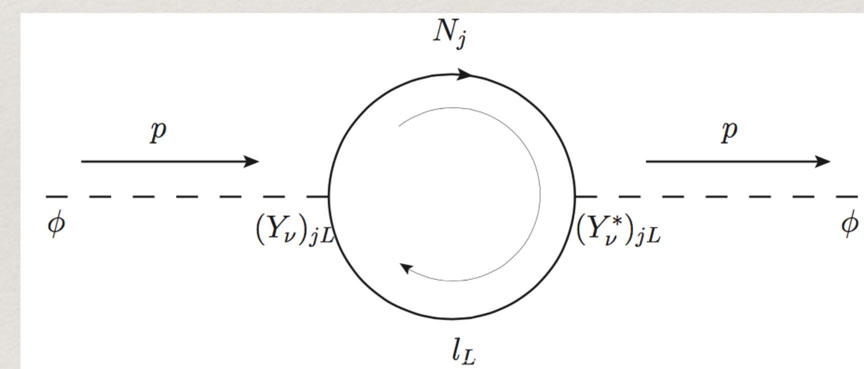
needs to be tested or has phenomenology via *„seesaw portal"*

Lepton-Higgs-Singlet Vertex: $L\,\Phi\,N_R$

$N_R \to L\,\Phi$ $\quad L_\alpha \to N_R\,\Phi \to L_\beta$ $\quad \Phi \to L\,N_R \to \Phi$







Leptogenesis

Lepton Flavor Violation

Vacuum stability, naturalness

Connections of ν to NP: talk by Kopp

Pathways to Neutrino Mass

similar discussion for all thinkable and unthinkable mass mechanisms

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	$N_R \sim (1,0)$	$h \overline{N_R} \Phi L + \overline{N_R} M_R N_R^c$	$\frac{(h v)^2}{M_R}$	$\Lambda = \frac{1}{h} M_R$
"indirect 2" (type III seesaw)	fermion triplets + LNV	$\Sigma \sim (3,0)$	$h \overline{\Sigma} \, L \Phi + \mathrm{Tr} \overline{\Sigma} M_\Sigma \Sigma$	$\frac{(h v)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h} M_\Sigma$

plus seesaw variants (linear, inverse, double, singular,…)

plus radiative mechanisms

plus higher dimensional operators

plus extra dimensional

plus plus plus

Lepton Number Conservation?

- accidental lepton number conservation difficult in BSM…
- need a symmetry to forbid $M_R N_R N_R$:
  - *can apply flavor symmetries with* $(L_e, L_\mu, L_\tau) \sim 3$ *and* $N_R \sim 3$*, and no singlet in 3x3 (e.g.* $\Delta(27)$*)*
  - *still need to explain smallness, e.g. wave-function overlap in ED, 2HDM with one vev of order eV,…*
  - can break $U(1)_{B-L}$ by scalars carrying charge $B\text{-}L = 3,4,\ldots$
- global $U(1)_L$ or $U(1)_{B-L}$ → expected to be broken by quantum gravity effects
- gauge $U(1)_L$ or $U(1)_{B-L}$ without breaking? → long range force, needs ultra-tiny charge