Neutrinoless Double Beta Decay and particle physics: an overview

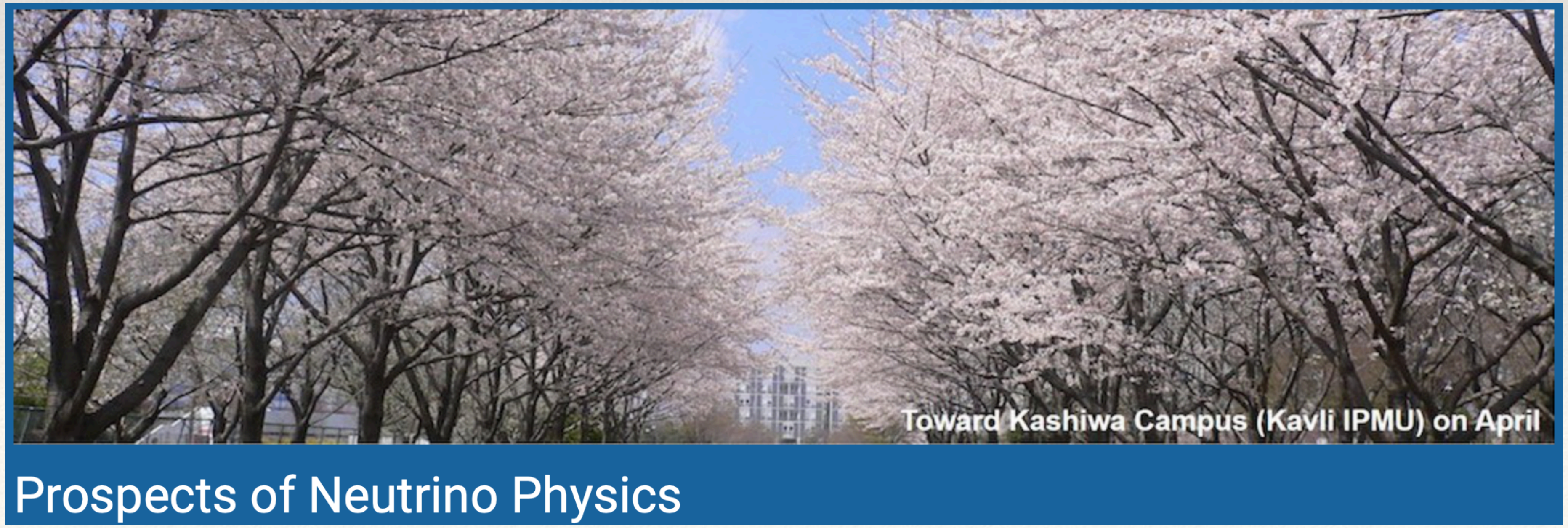
Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Werner Rodejohann (MPIK)

10/04/19

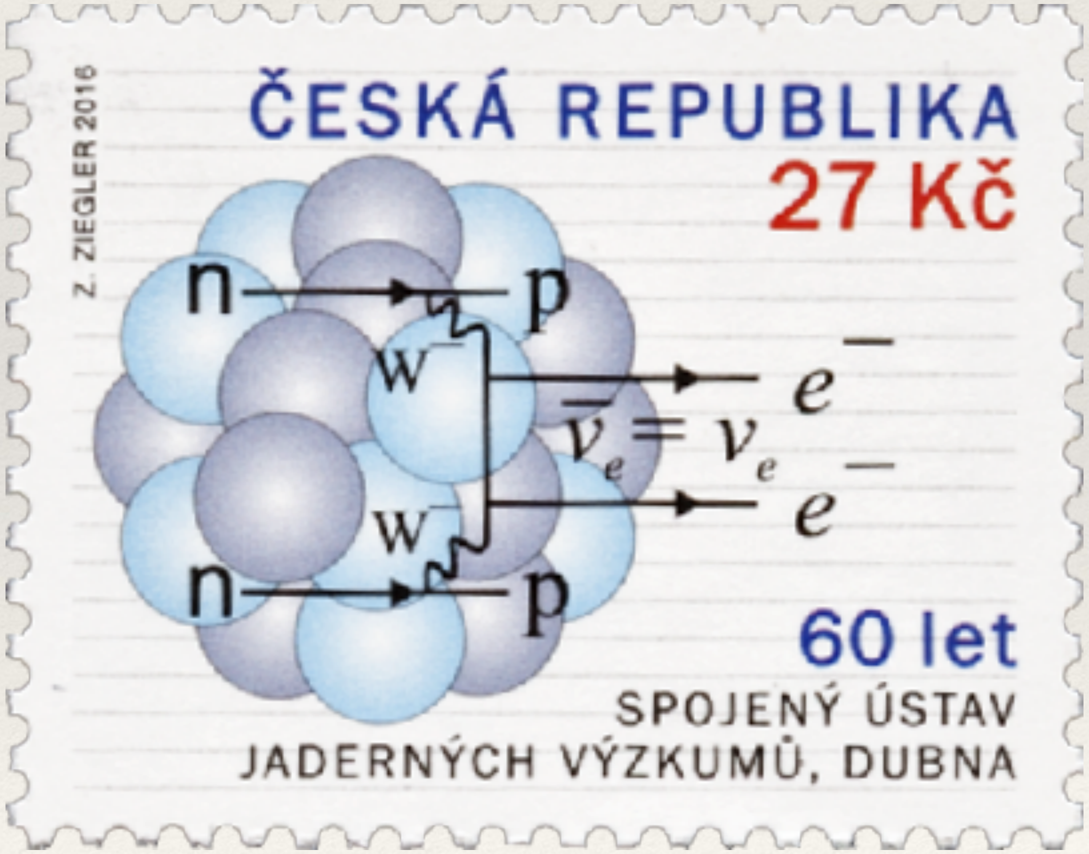
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK



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



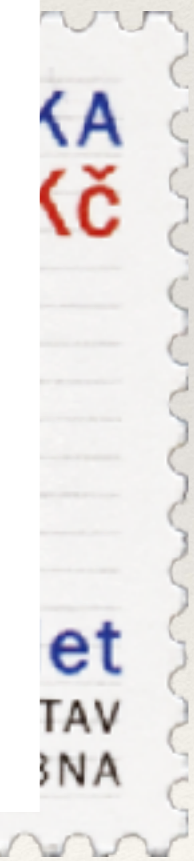
Outline

Neutrinoless Double-Beta Decay: Status and Prospects

Michelle J. Dolinski,[1] Alan W. P. Poon,[2] and Werner Rodejohann[3]

[1]Department of Physics, Drexel University, Philadelphia, Pennsylvania 19104, USA; email: dolinski@drexel.edu
[2]Institute for Nuclear and Particle Astrophysics, Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA; email: awpoon@lbl.gov
[3]Max-Planck-Institut für Kernphysik, Postfach 10 39 80, 69029 Heidelberg, Germany; email: werner.rodejohann@mpi-hd.mpg.de

arXiv:1902.04097v1 [nucl-ex] 11 Feb 2019



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?

- *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 $\mathcal{L}_5 = L^c \phi\, \phi L \to m_\nu\, \nu_L{}^c\, \nu_L$
- Ba

Lepton Number as important as Baryon Number

- *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?

- *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 $\mathcal{L}_5 = L^c\phi\, \phi L \to m_\nu\, \nu_L{}^c\, \nu_L$
- Bary

0νββ is not just a neutrino mass experiment!

- *B*, *L* often connected in BSM, GUTs
- GUTs have seesaw and Majorana neutrinos
- (*B* and *L* non-perturbatively violated by 3 units in SM…)

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 (N_{R1}, N_{R2}, N_{R3}) ~ **3**, in groups that have 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-L=3,4,…)
- 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

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	–	✓	–	–

Talk by Inoue

Neutrinoless Double Beta Decay

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

Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA
	> 1.9	$< 0.24 - 0.52$	MAJORANA DEMONSTRATOR
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3
^{128}Te	$> 1.1 \times 10^{-2}$	—	—
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-Zen
	> 1.8	$< 0.15 - 0.40$	EXO-200
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3

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

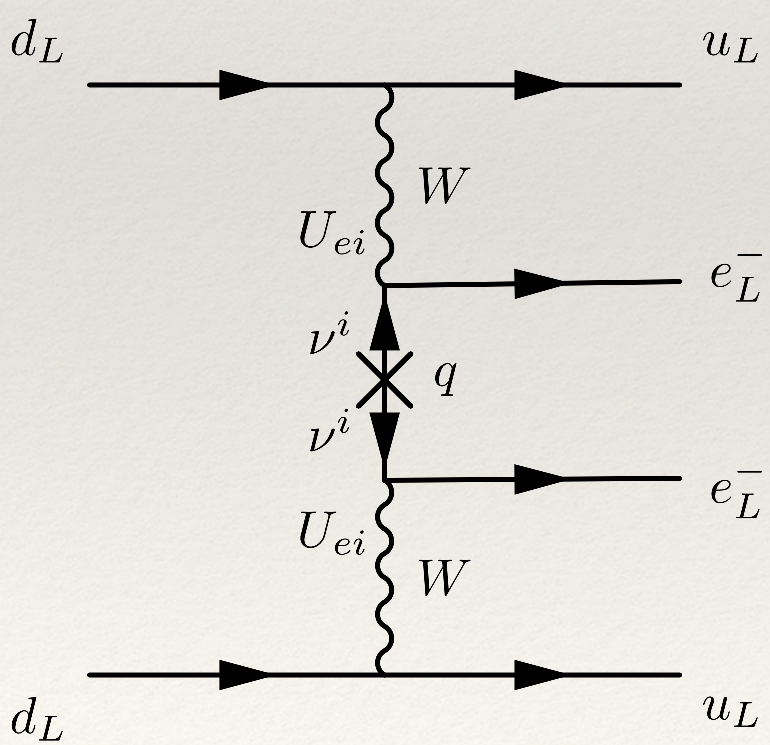
**NME talk by Suhonen*

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

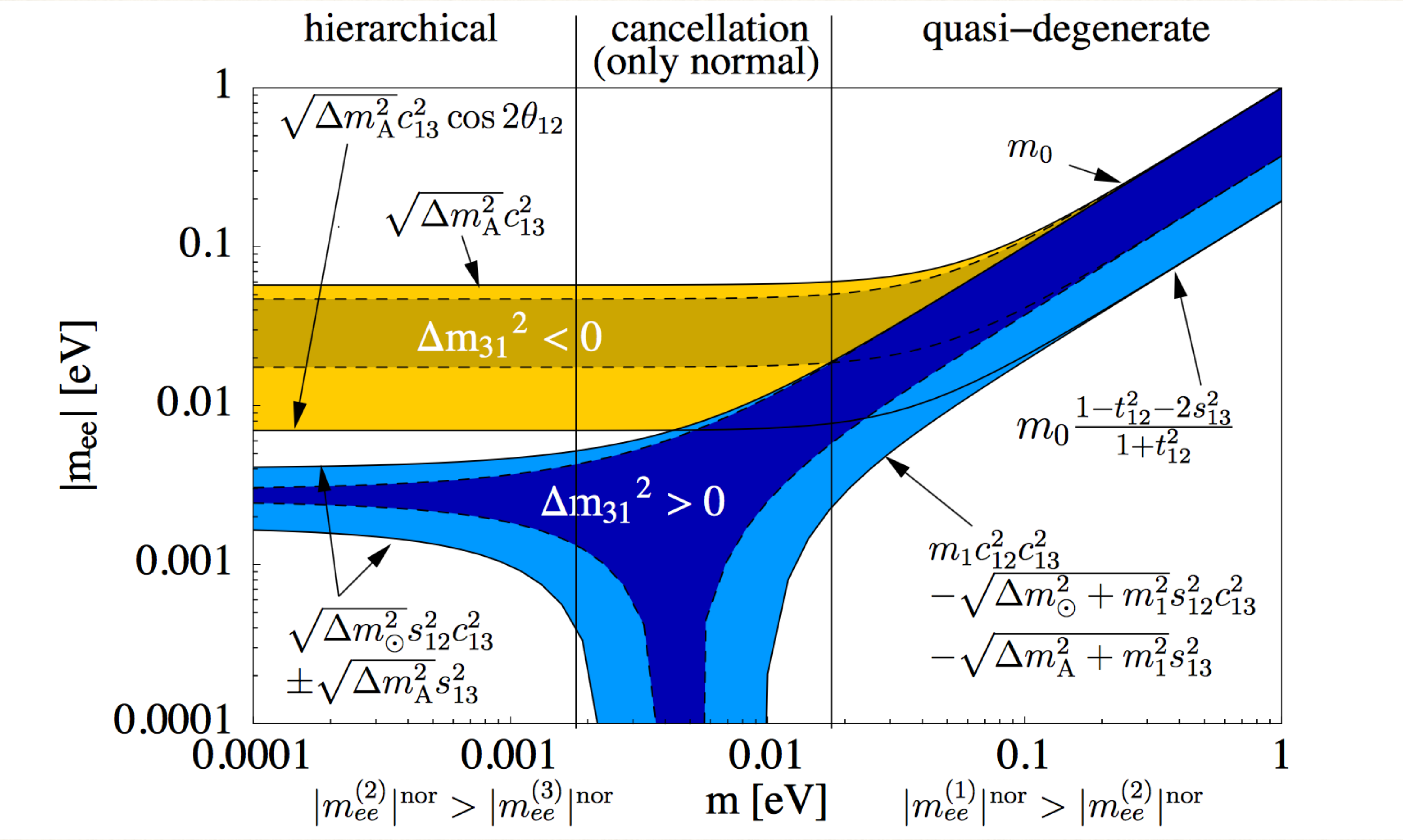


amplitude proportional to „effective mass“:

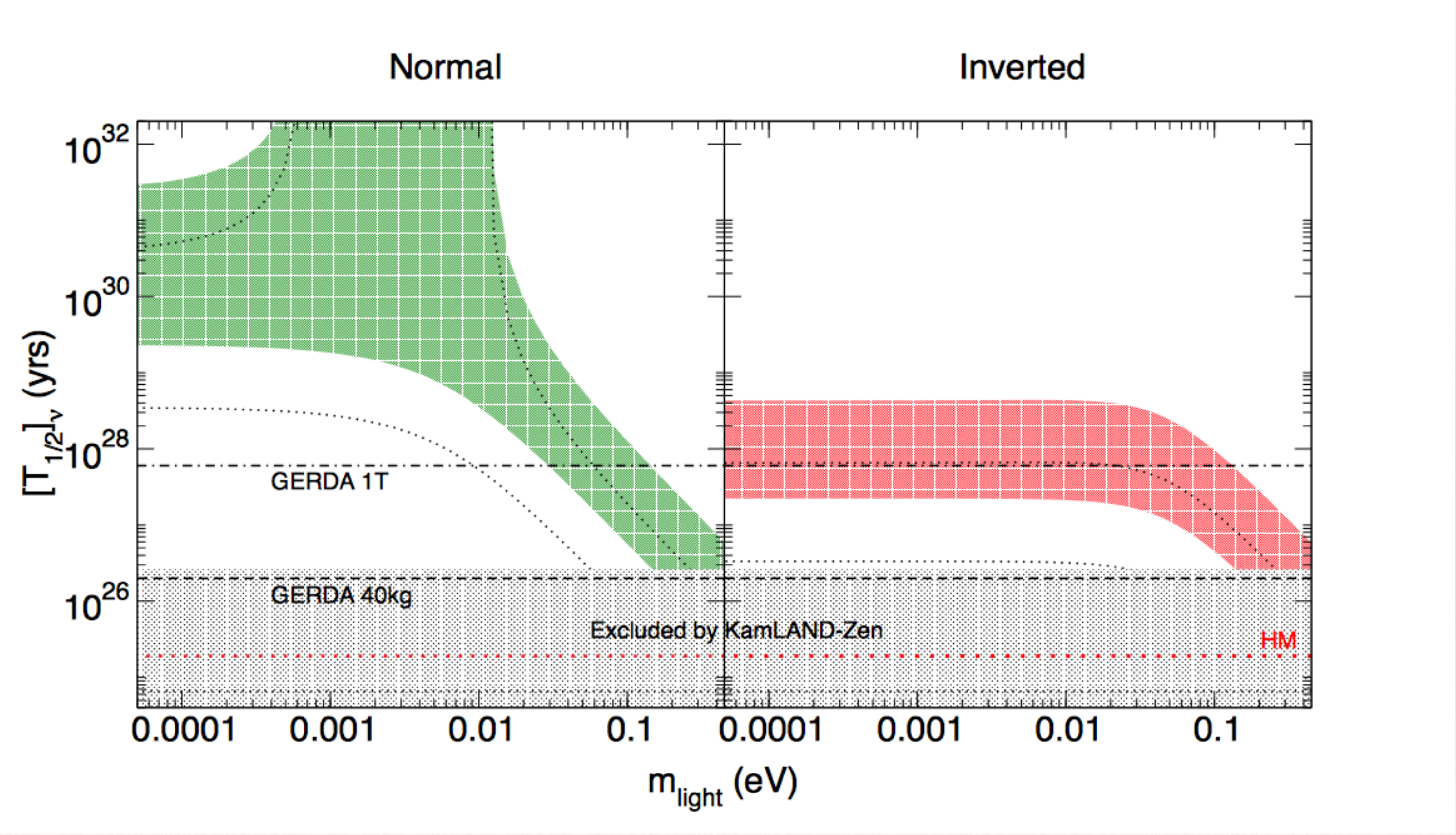
$$|m_{ee}| = |\sum U_{ei}^2\, m_i| = |U_{e1}^2\, m_1 + U_{e2}^2\, m_2 e^{i\alpha} + U_{e3}^2\, m_3 e^{i\beta}|$$
$$= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m^2_{\mathrm{A}}), \alpha, \beta\right)$$

known — $\theta_{12}, |U_{e3}|$; limits — m_i; unknown — $\mathrm{sgn}(\Delta m^2_{\mathrm{A}}), \alpha, \beta$

The usual plot



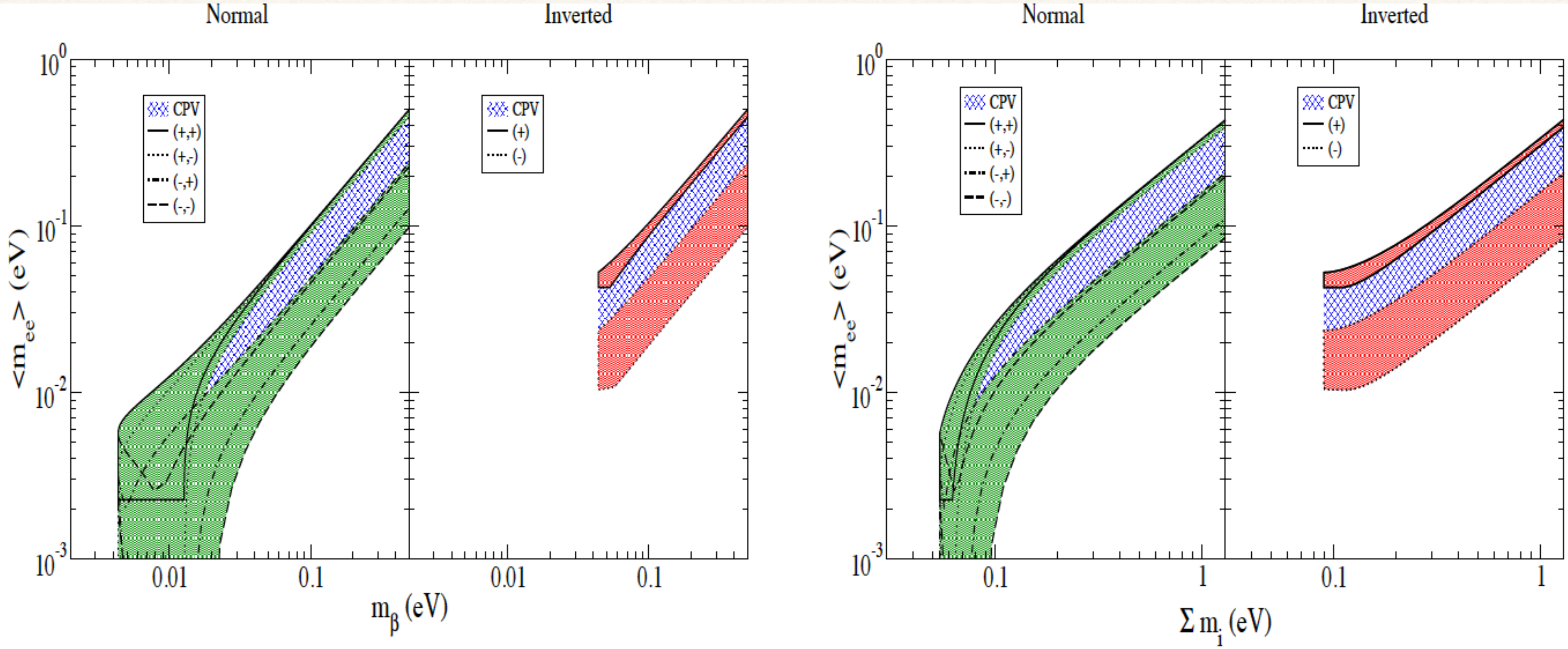
The usual plot



Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$\sum \lvert U_{ei} \rvert^2 m_i^2$	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

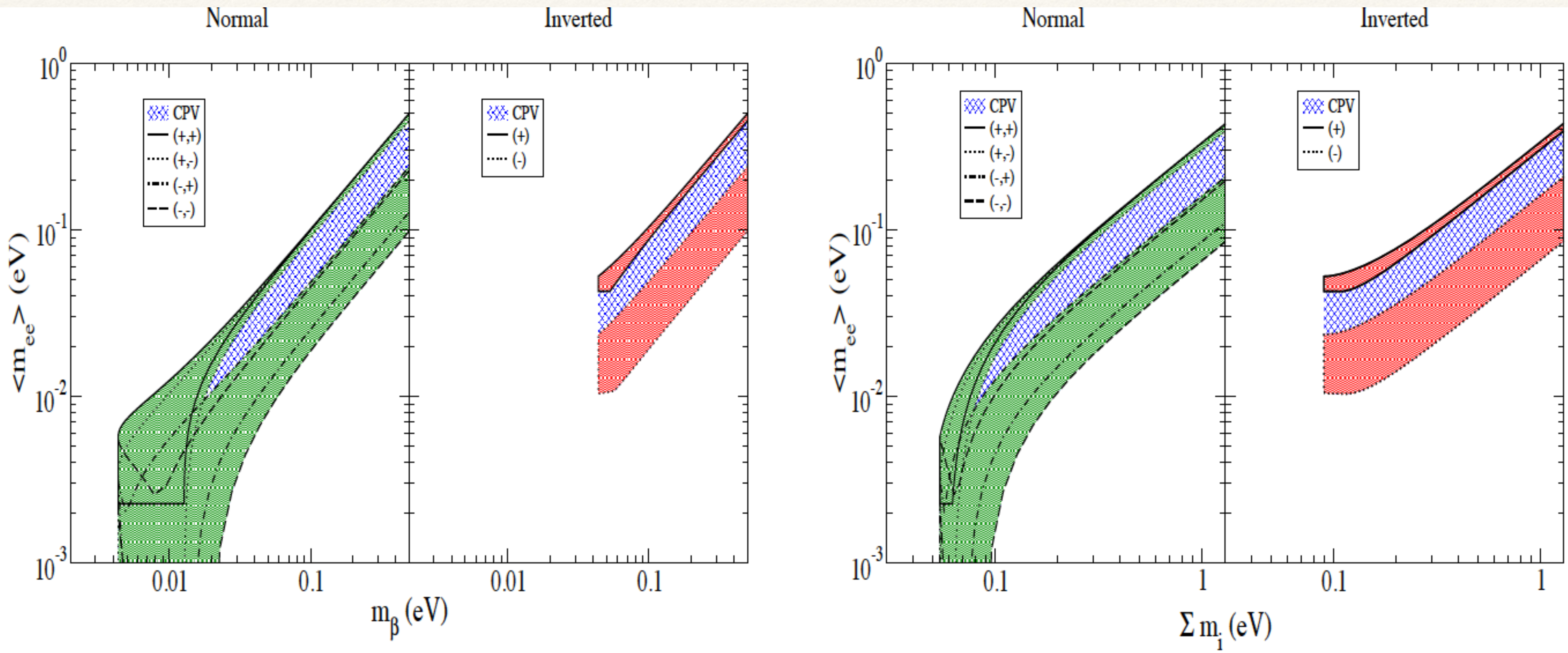
Neutrino Mass Observables



complete complementarity of observables

- 0νββ rules out that neutrinos saturate Mainz-limit
- 0νββ and reasonable cosmology currently roughly same
- cosmology strongly disfavors a signal in KATRIN

Neutrino Mass Observables

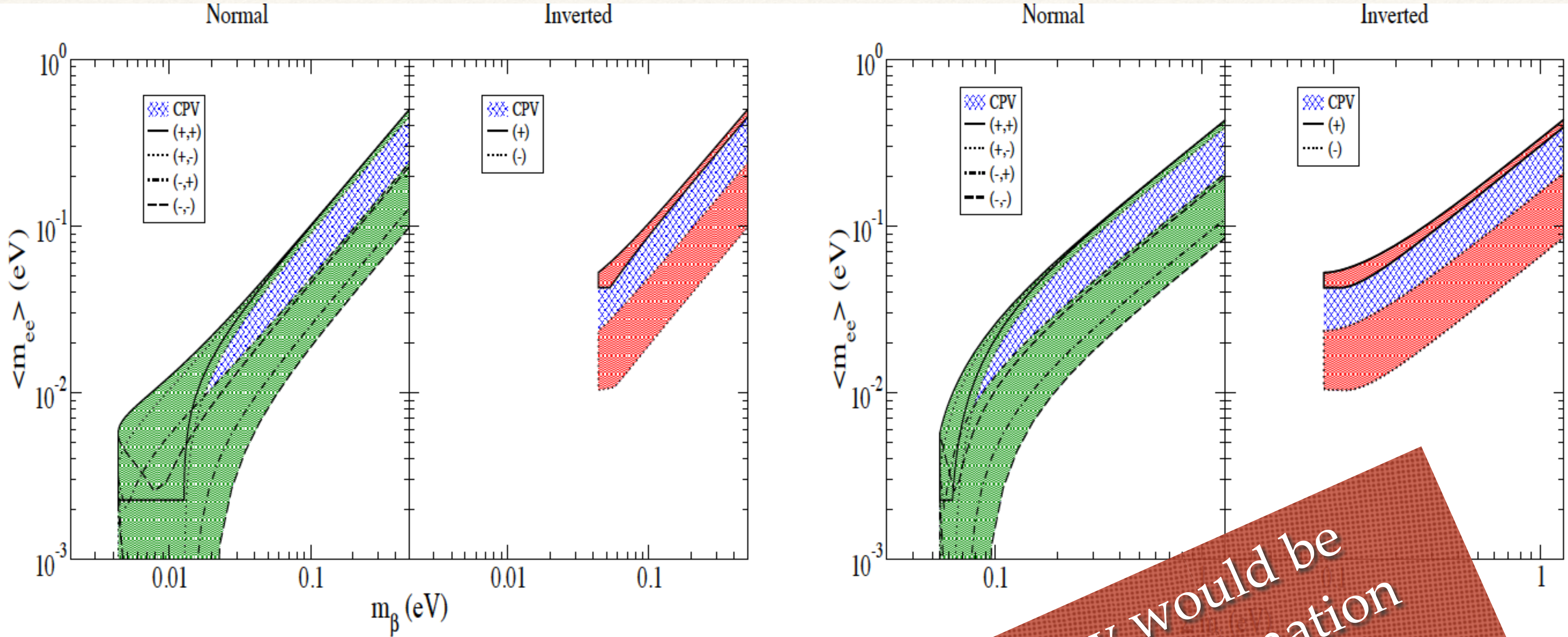


complete complementarity of observables

- 0νββ rules out that neutrin… …e Mainz-limit
- 0νββ and reaso… …ology currently roughly same
- cosmo… …ngly disfavors a signal in KATRIN

All need to be pursued!

Neutrino Mass Observables

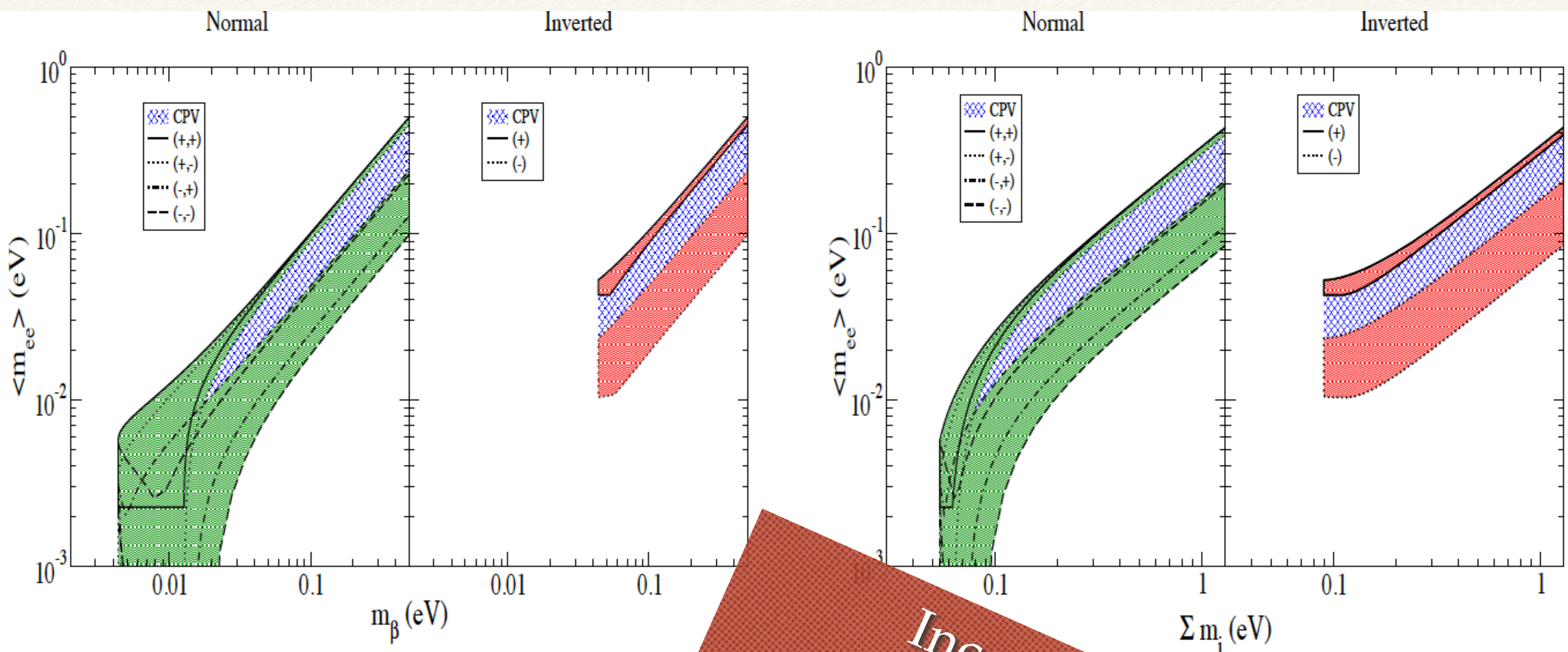


complete complementarity of observables

- $0\nu\beta\beta$ rules …
- $0\nu\beta\beta$ and … ntly roughly same
- cosmology … rs a signal in KATRIN

Consistency would be spectacular confirmation of <u>3 Majorana neutrino paradigm</u>

Neutrino Mass Observables

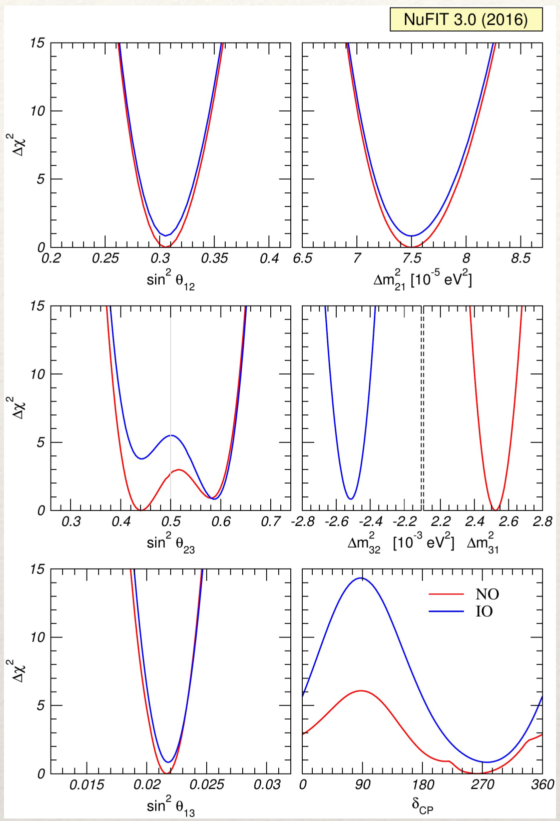


Inconsistencies would be major discovery!

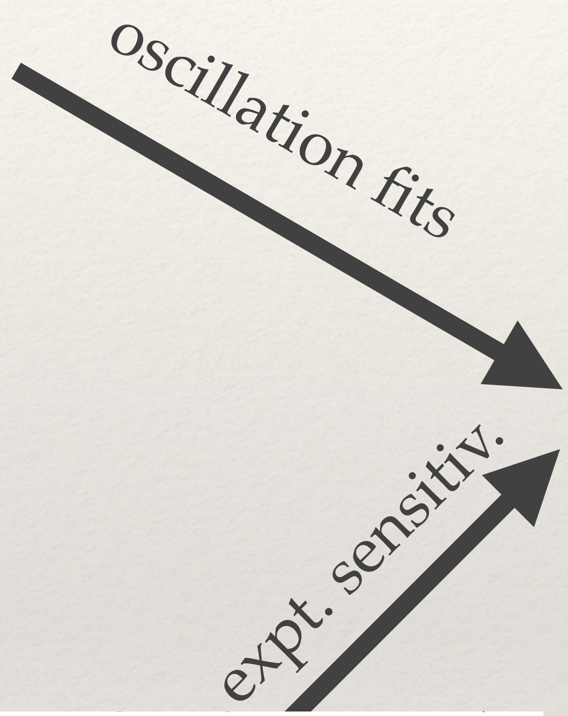
complete complementarity of observables

- 0νββ ru… Mainz-limit
- 0νββ and reasonab… …ghly same
- cosmology strongly disfavors a signal in KATRIN

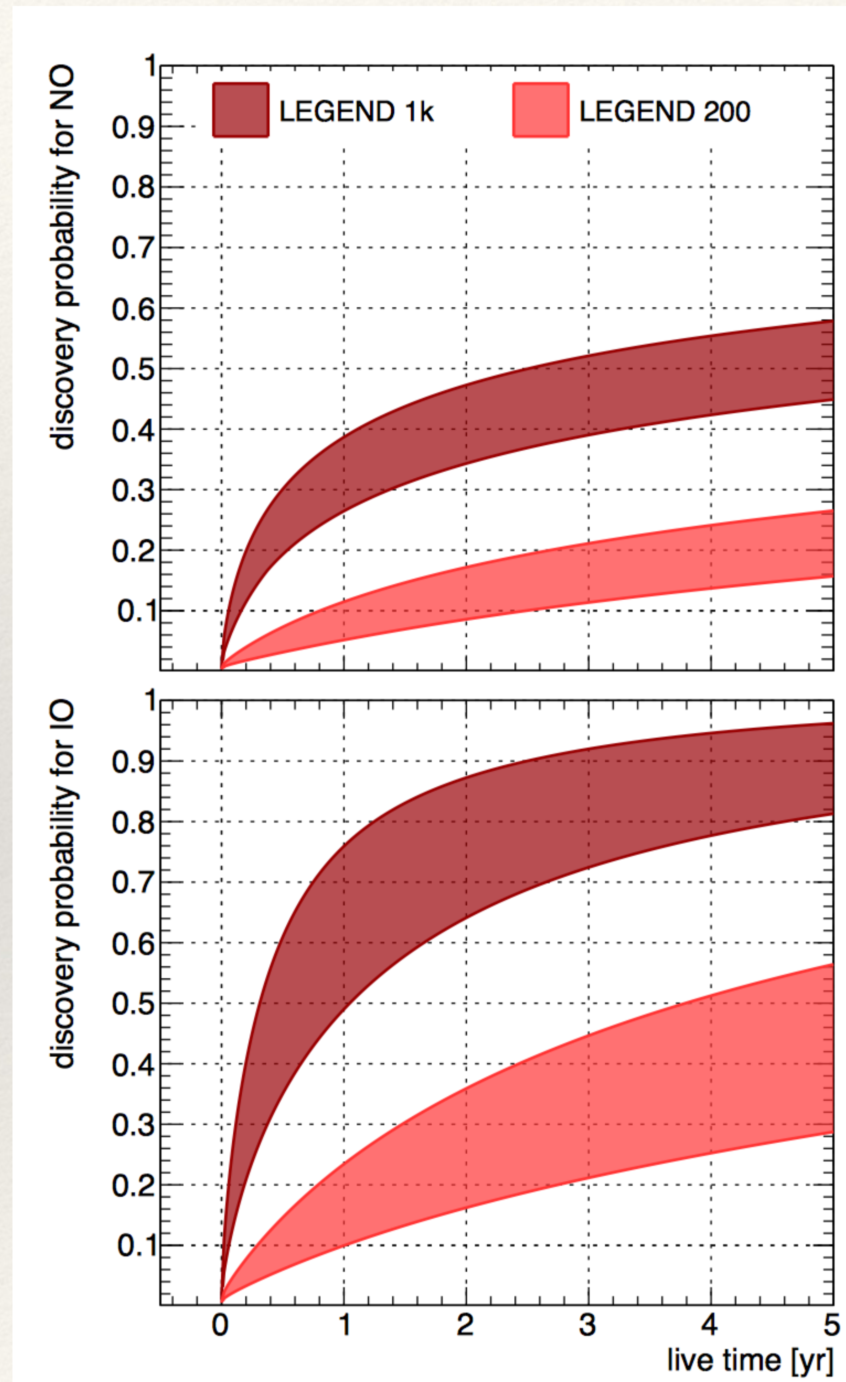
Expectations of lifetimes



+



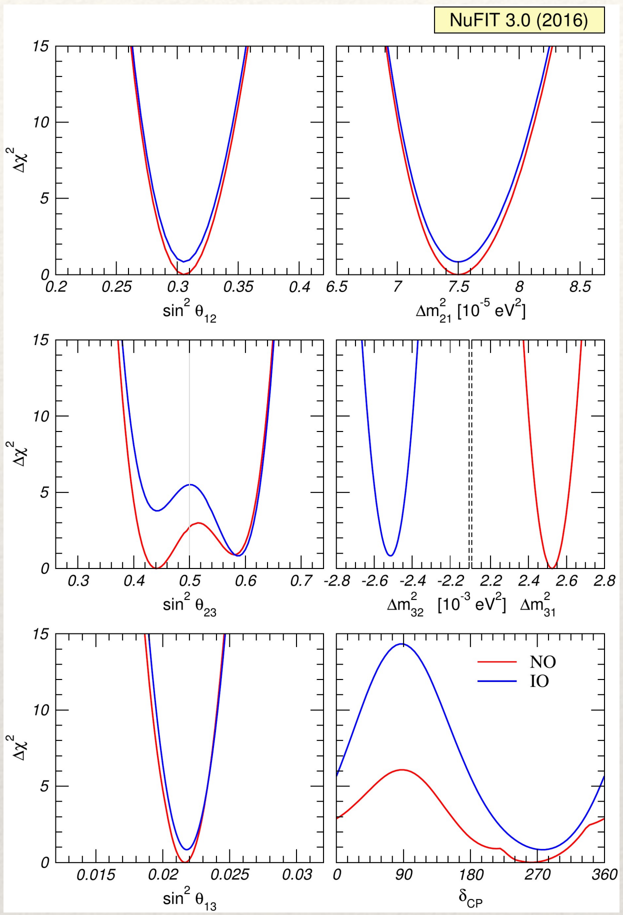
Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required Improvement σ	Required Improvement Iso. Mass
LEGEND 200 [61, 62]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [61, 62]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [68, 69]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [58, 59, 70]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [52, 53]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [58, 59, 70]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [66, 71]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [67]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [60]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [60]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [72]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [64, 73]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [74]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [65]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [65]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a



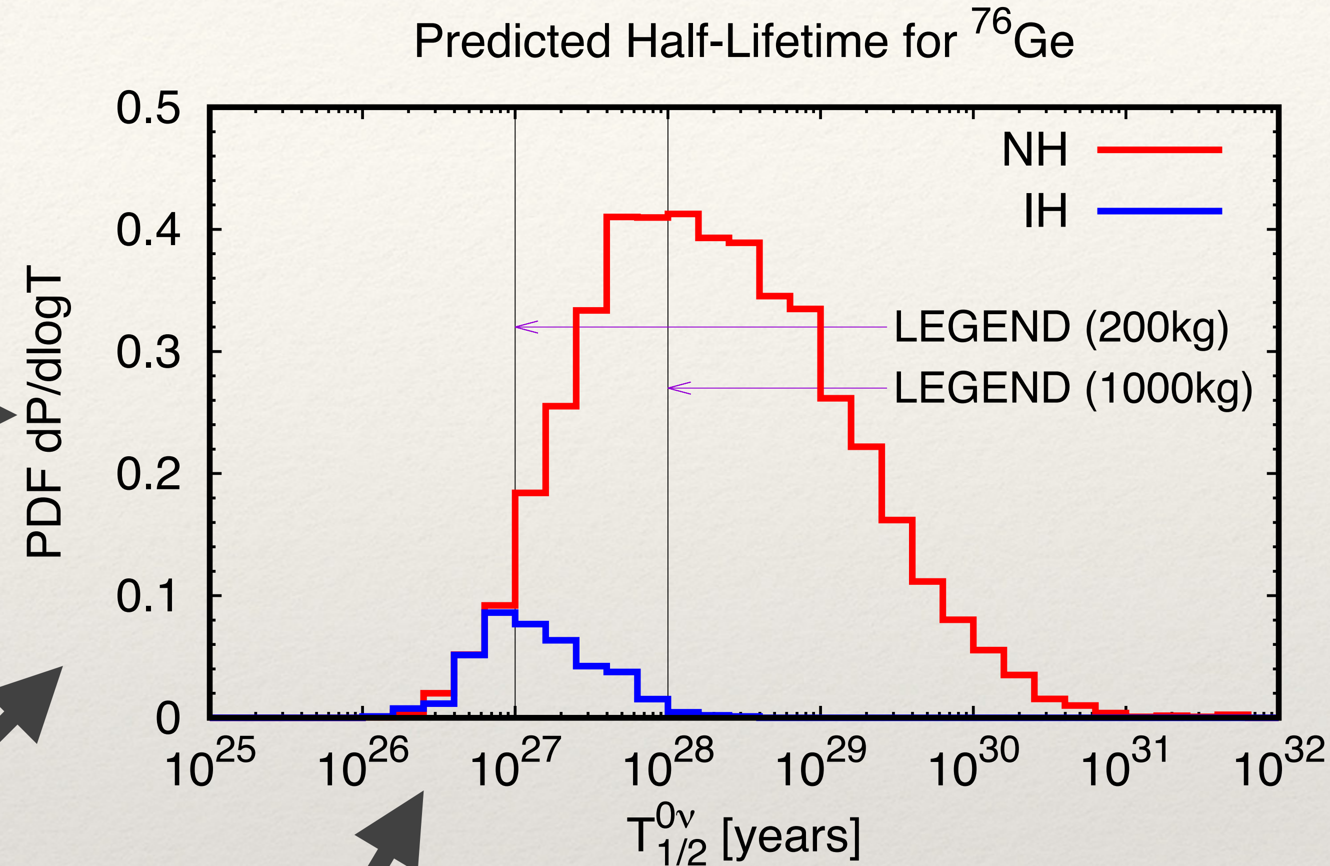
Bayesian discovery probability: discovery sensitivity (value of m_{ee} for which expt. has 50% chance to see it at 3σ) folded with probability distribution of m_{ee}

Agostini et al, 1705.02996; also Caldwell et al., 1705.01945; also Zhang, Zhou, 1508.05472

Expectations of lifetimes



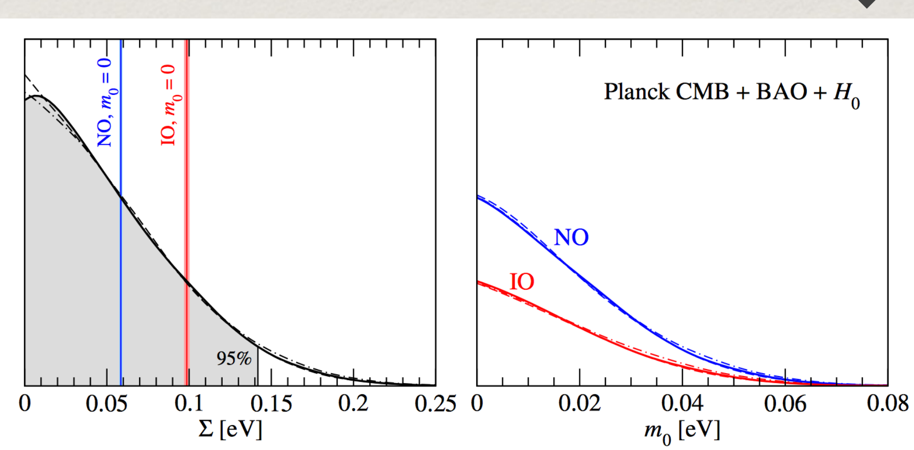
oscillation fits



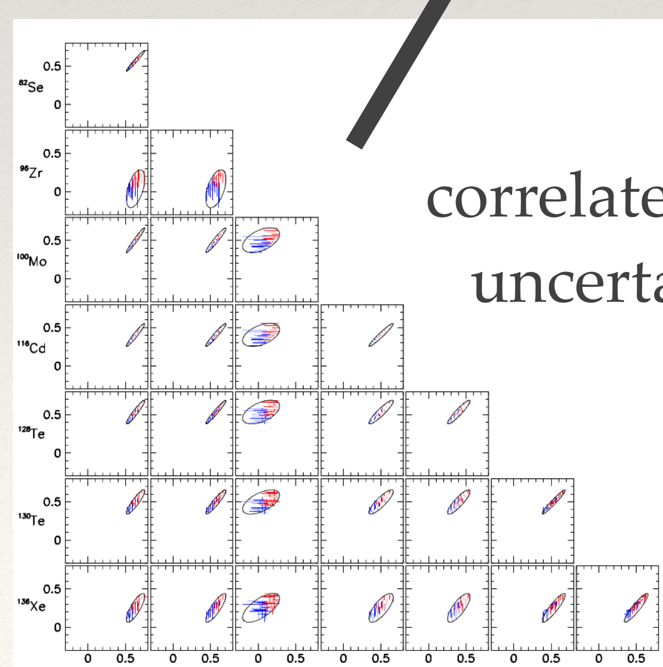
Ge, WR, Zuber, 1707.07904

+

cosmology fit



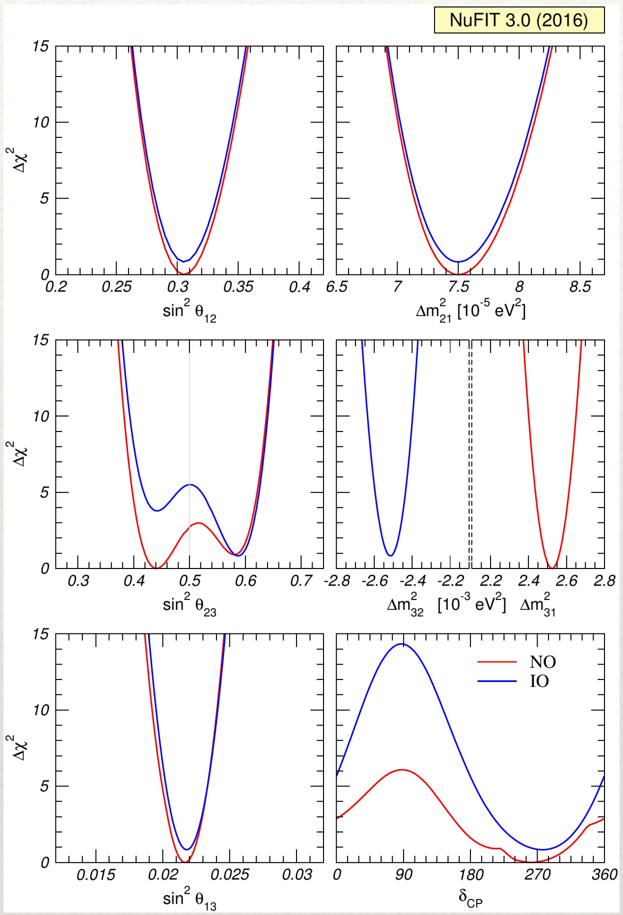
+



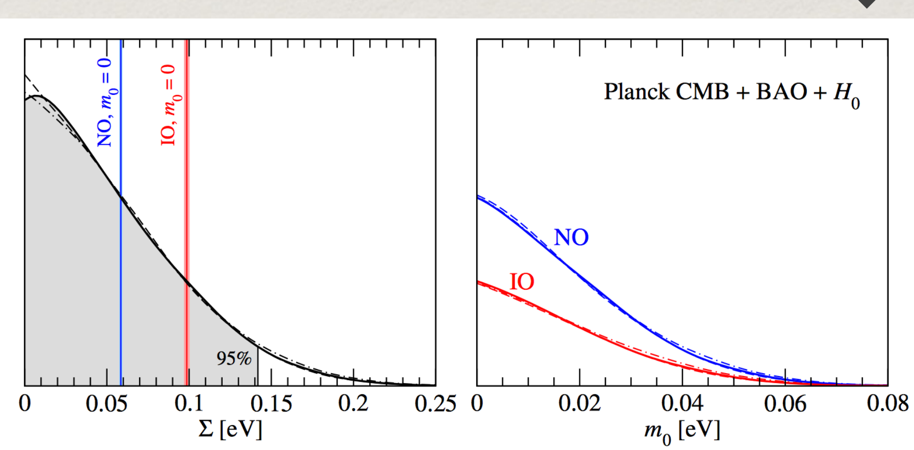
correlated NME uncertainties

Faessler, Fogli et al., 0810.5733

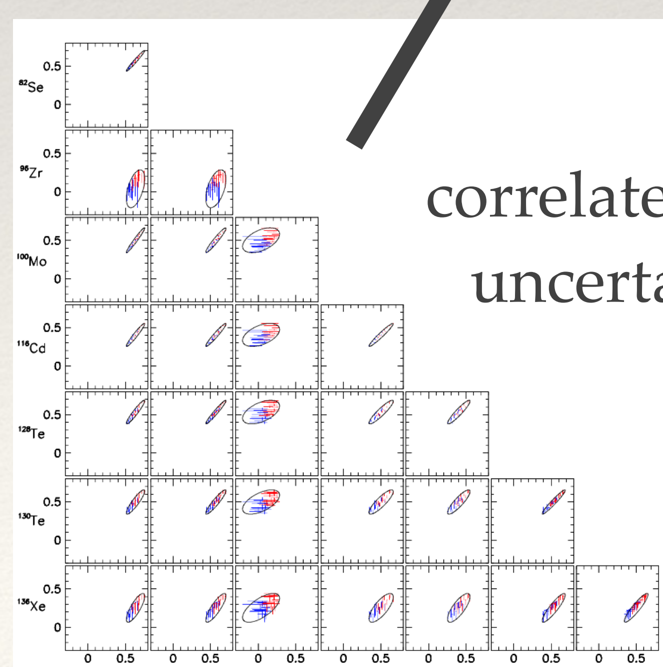
Expectations of lifetimes



+



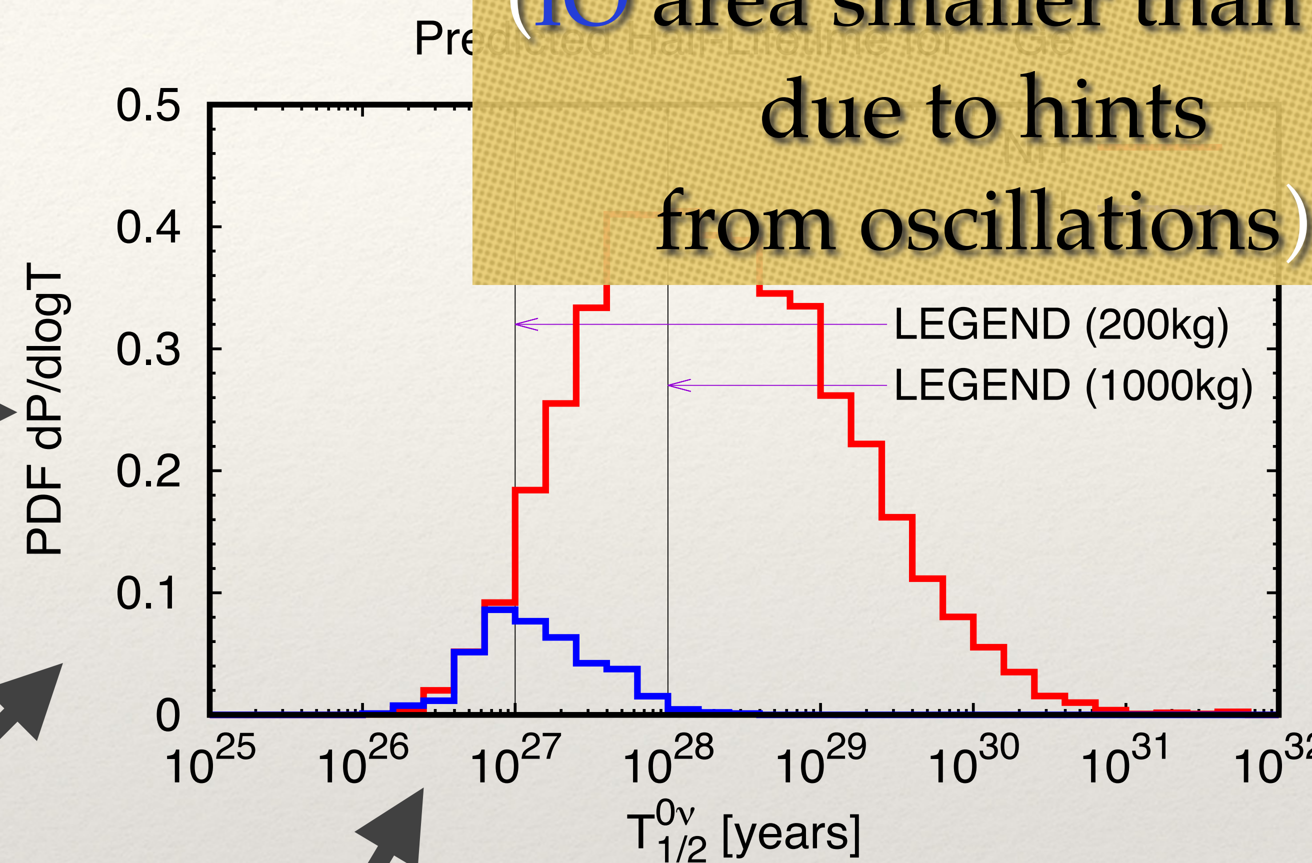
+



oscillation fits

cosmology fit

correlated NME uncertainties



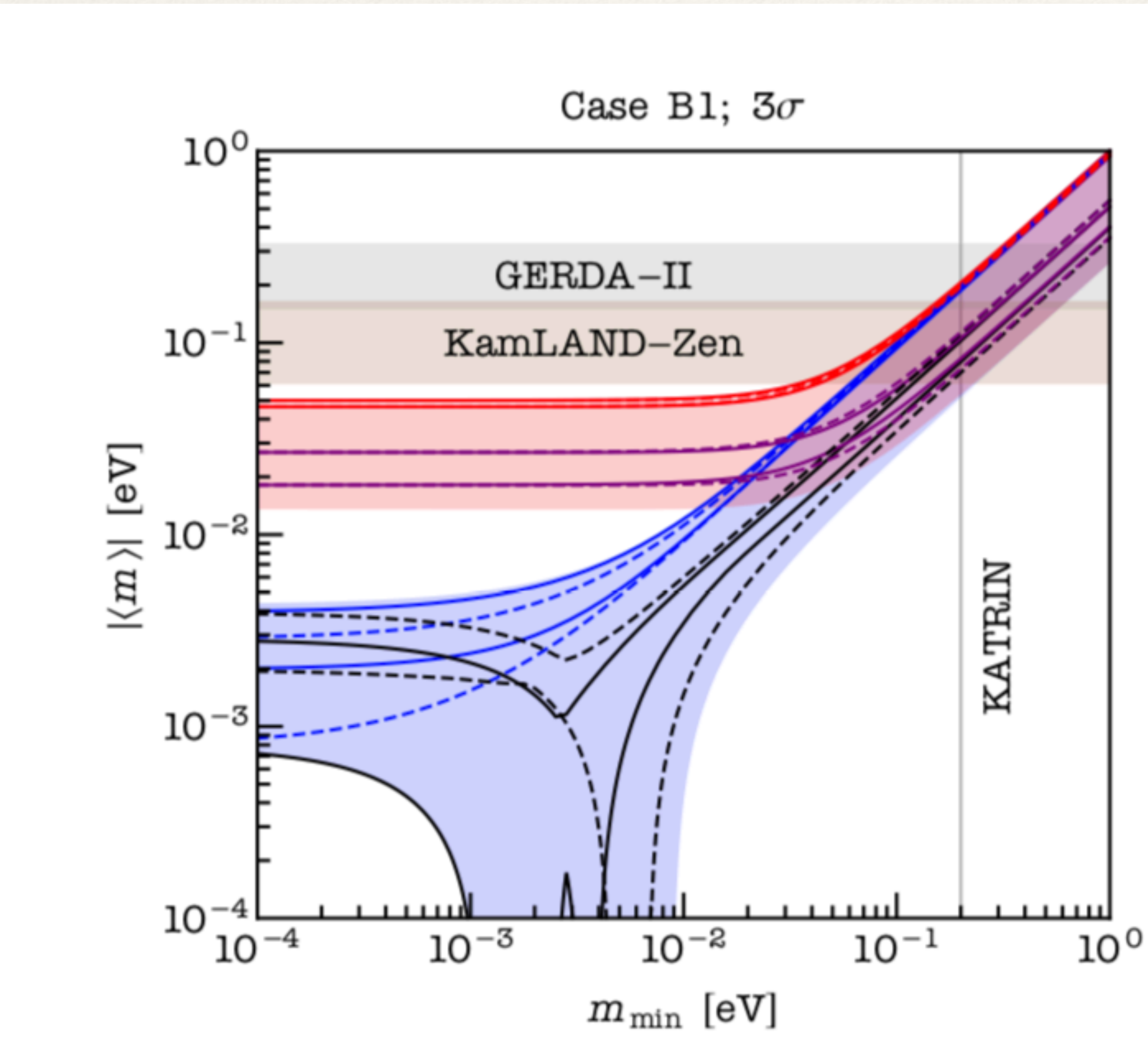
(IO area smaller than NO due to hints from oscillations)

Ge, WR, Zuber, 1707.07904

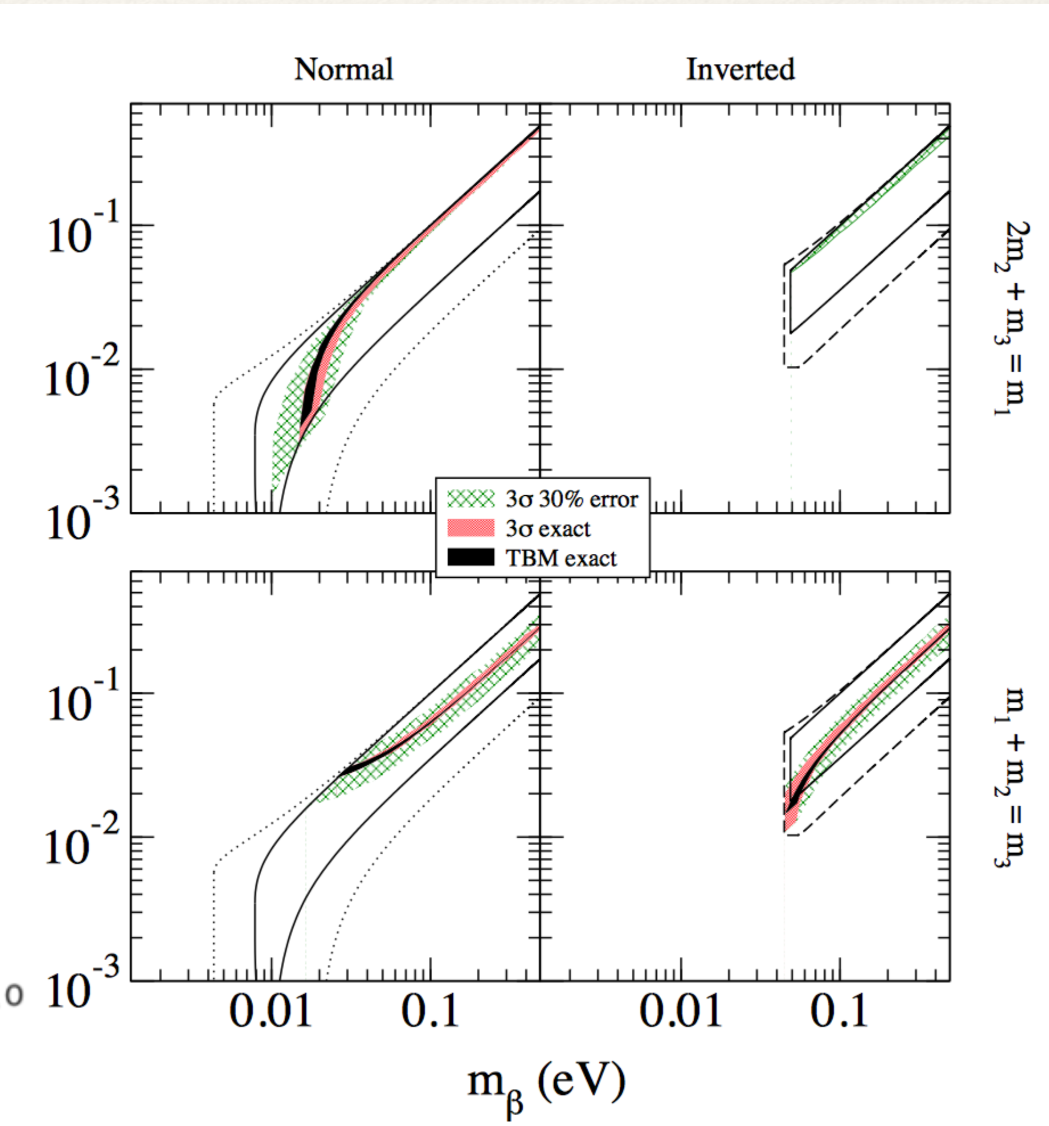
Faessler, Fogli et al., 0810.5733

Predicting the effective mass

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



Penedo, Petcov, Titov, 1705.00309

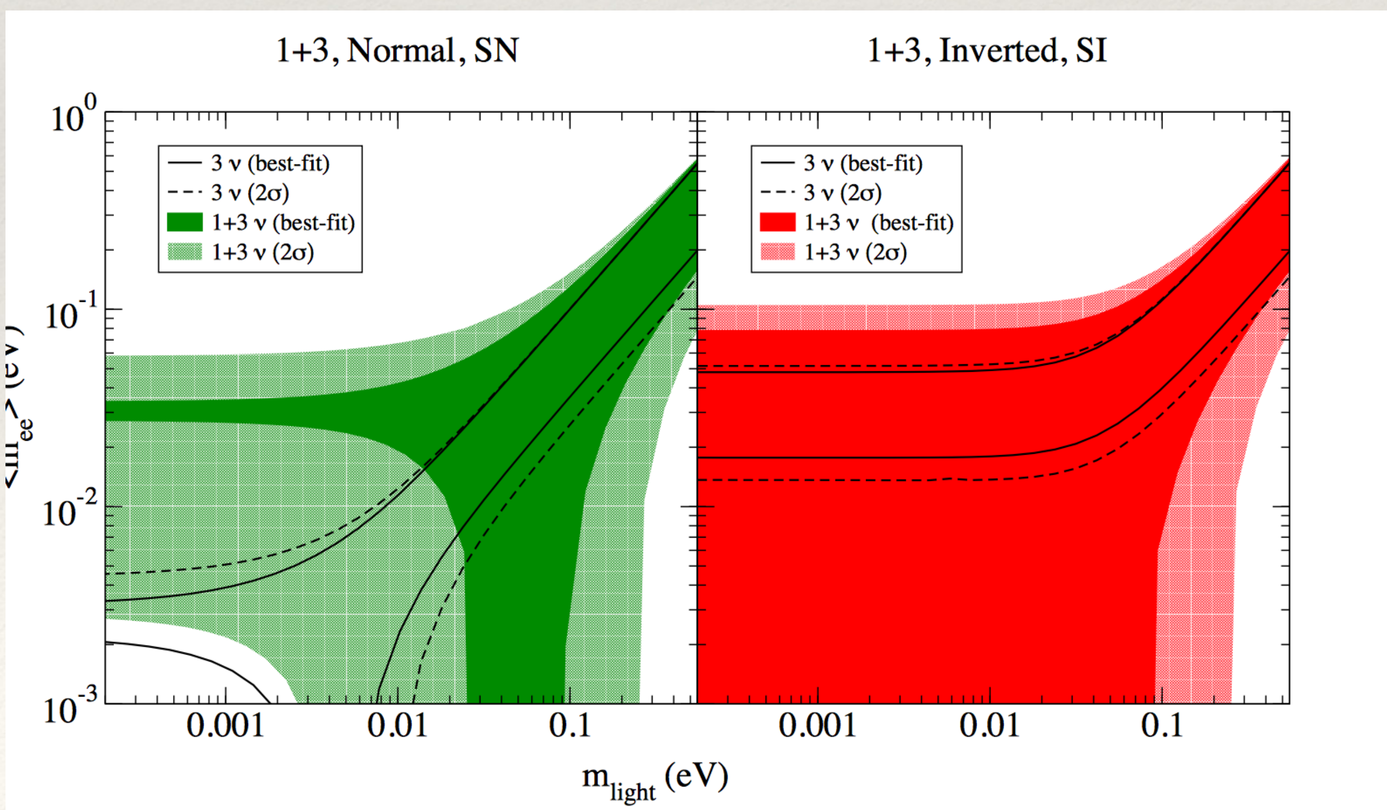


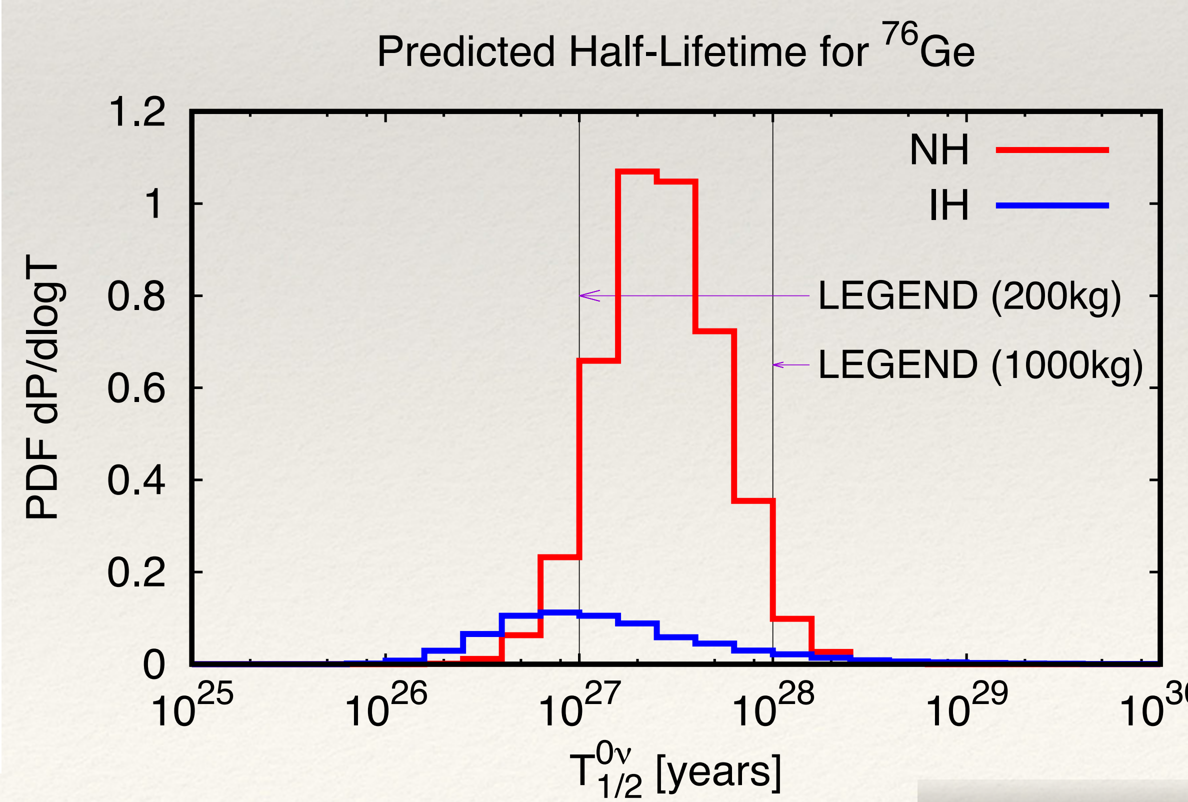
Barry, WR, 1007.5217

Sterile Neutrinos

Talk by Martinez-Soler

- are there sterile states (LSND / reactor / etc.) with mass $\Delta m^2 \simeq$ eV^2 and mixing $U_{e4} \simeq 0.1$?
- would make m_{ee} sum of 4 terms with sterile contribution
  $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel almost completely contribution of IH!
- usual pheno completely turned around!



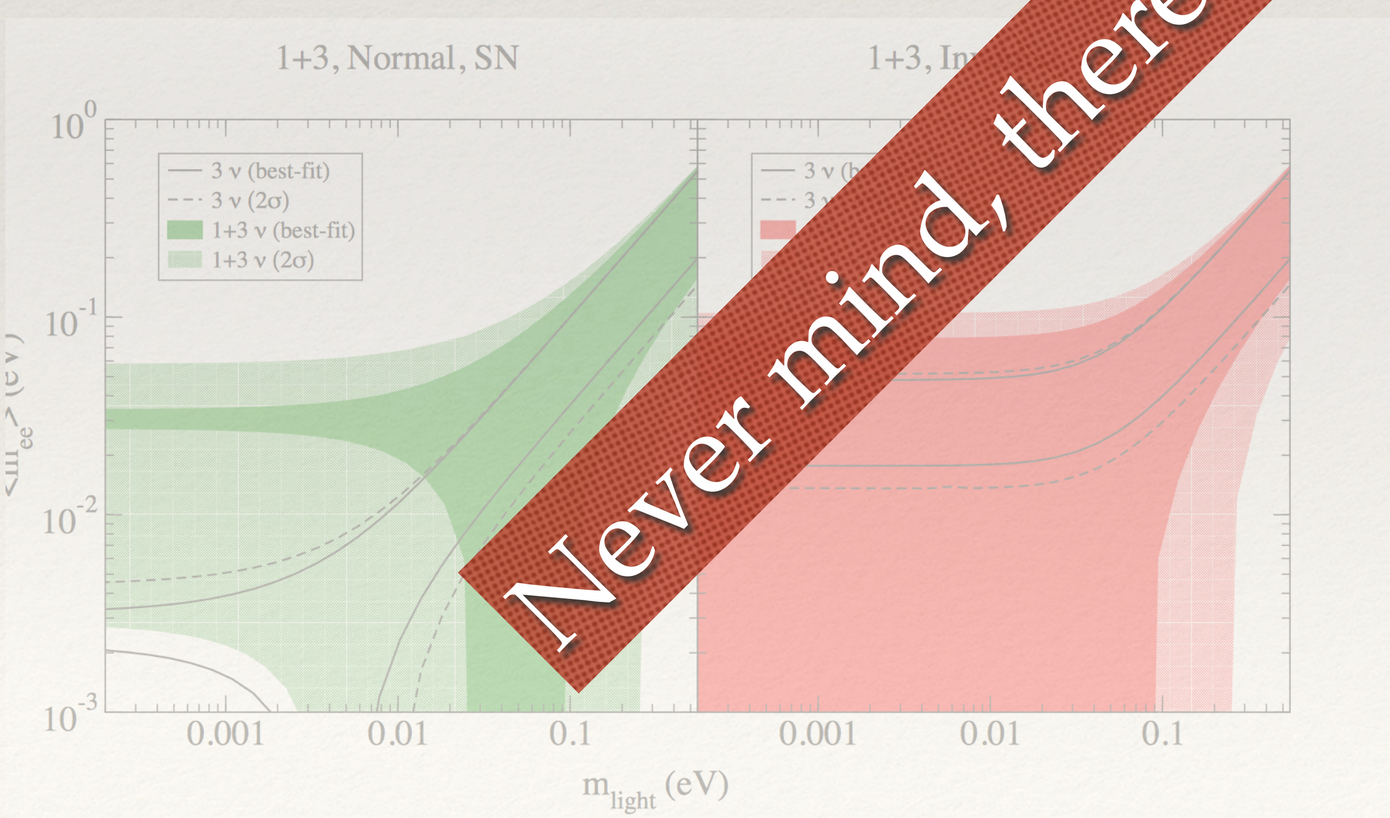


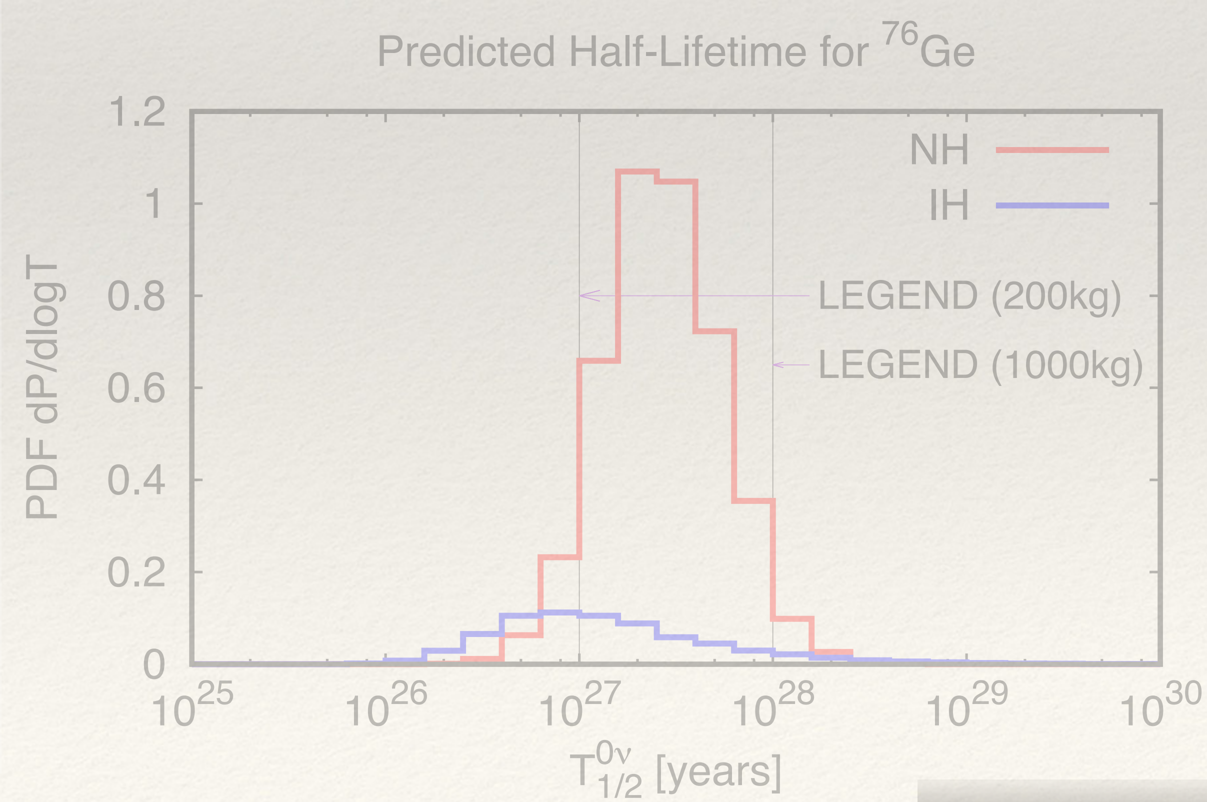
Sterile Neutrinos

Talk by Martinez-Soler

- are there sterile states (LSND / reactor / etc.) mass $\Delta m^2 \simeq \text{eV}^2$ and mixing $U_{e4} \simeq 0.1$?
- would make m_{ee} sum of 4 terms wi le contribution $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel al mpletely contribution of IH!
- usual pheno completely tu ound!

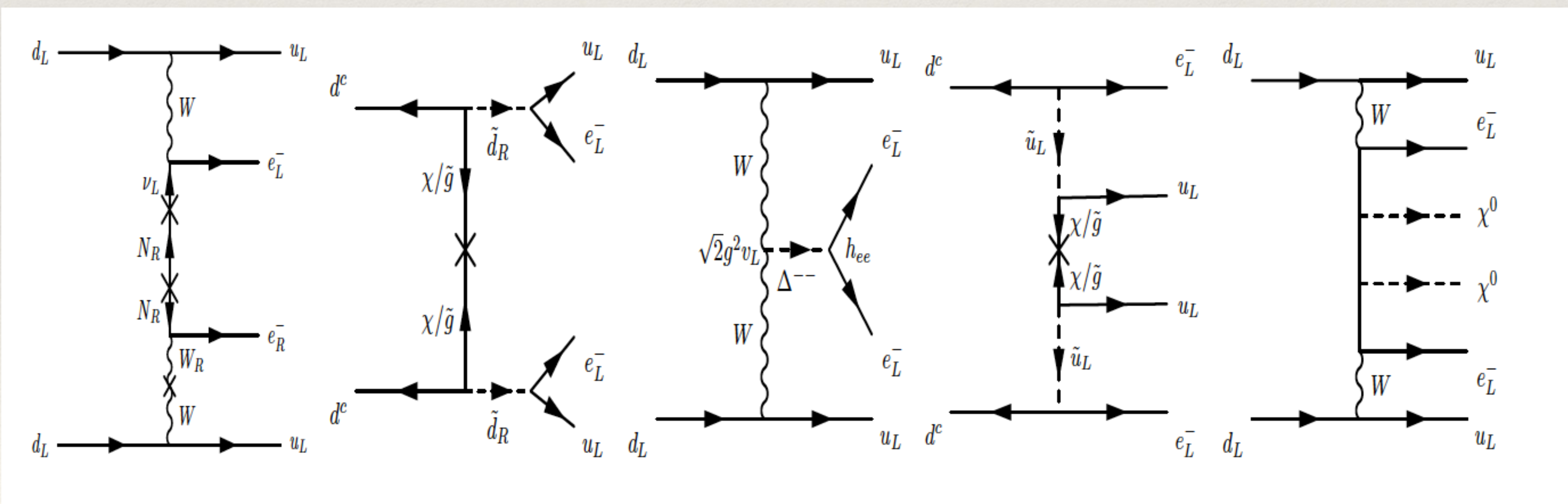
Never mind, there are no sterile neutrinos





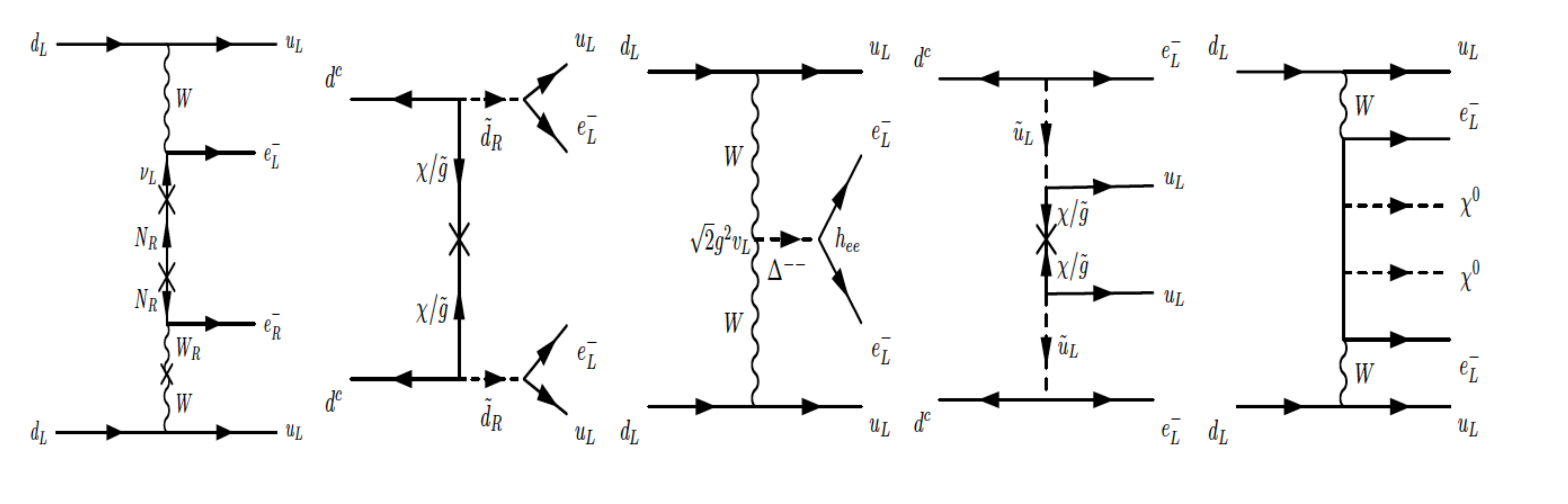
Non-Standard Interpretations

- 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

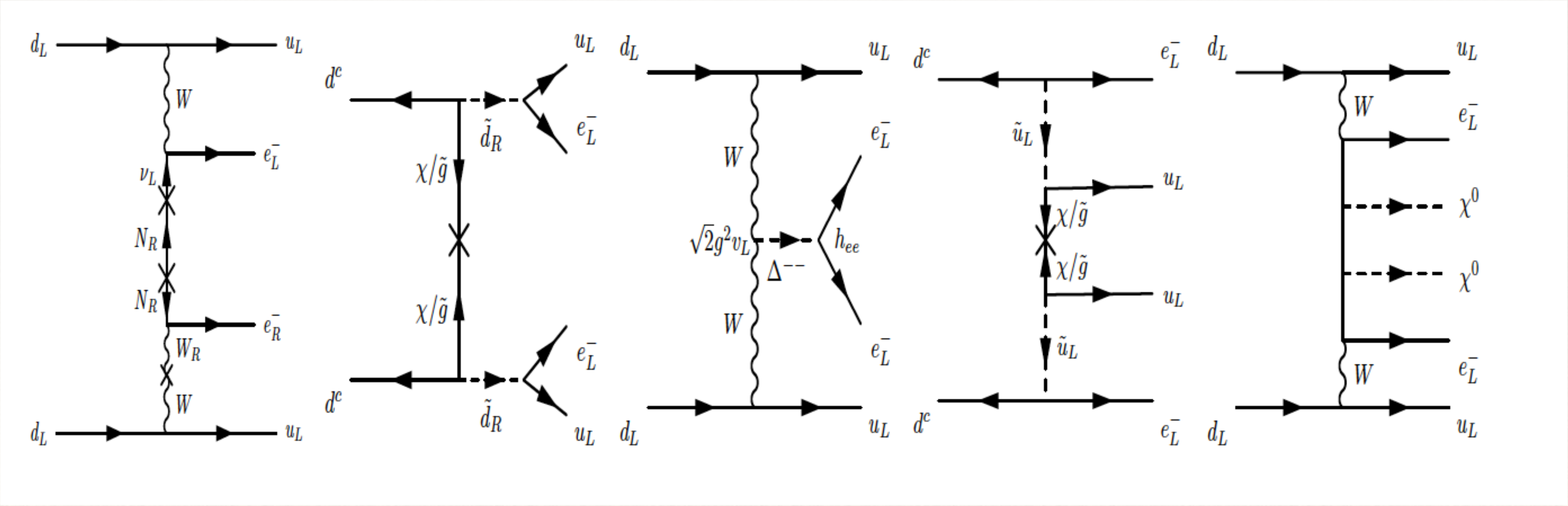
- There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism



$\Rightarrow$ $0\nu\beta\beta$ 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

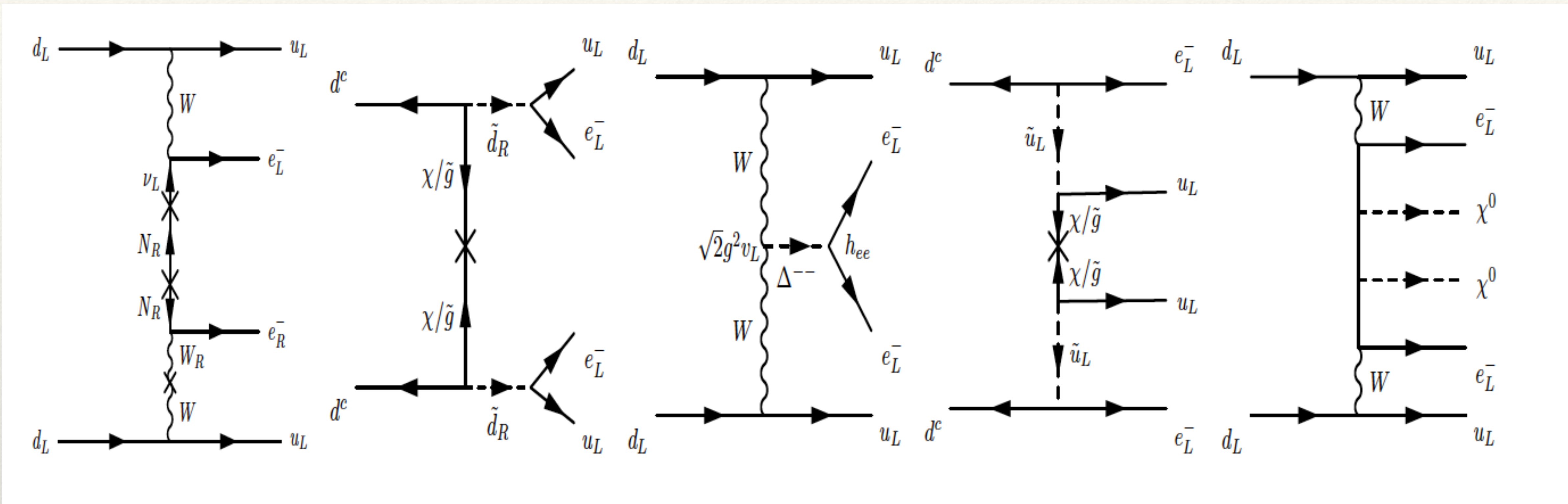


⇒ need to solve the „inverse problem“

Non-Standard Interpretations

mechanism	physics parameter	current limit	test
light neutrino exchange	$\left\|U_{ei}^2 m_i\right\|$	0.2 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 $\not{R}$	$\frac{\|\lambda'^2_{111}\|}{\Lambda^5_{\rm SUSY}}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\|\sin 2\theta^b \lambda'_{131} \lambda'_{113} \left(\frac{1}{m^2_{\tilde{b}_1}} - \frac{1}{m^2_{\tilde{b}_2}}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda'_{131} \lambda'_{113}\|}{\Lambda^3_{\rm SUSY}}$	2×10^{-13} GeV^{-2} 1×10^{-14} GeV^{-3}	flavor, collider
Majorons	$\|\langle g_\chi \rangle\|$ or $\|\langle g_\chi \rangle\|^2$	$10^{-4} \ldots 1$	spectrum, cosmology

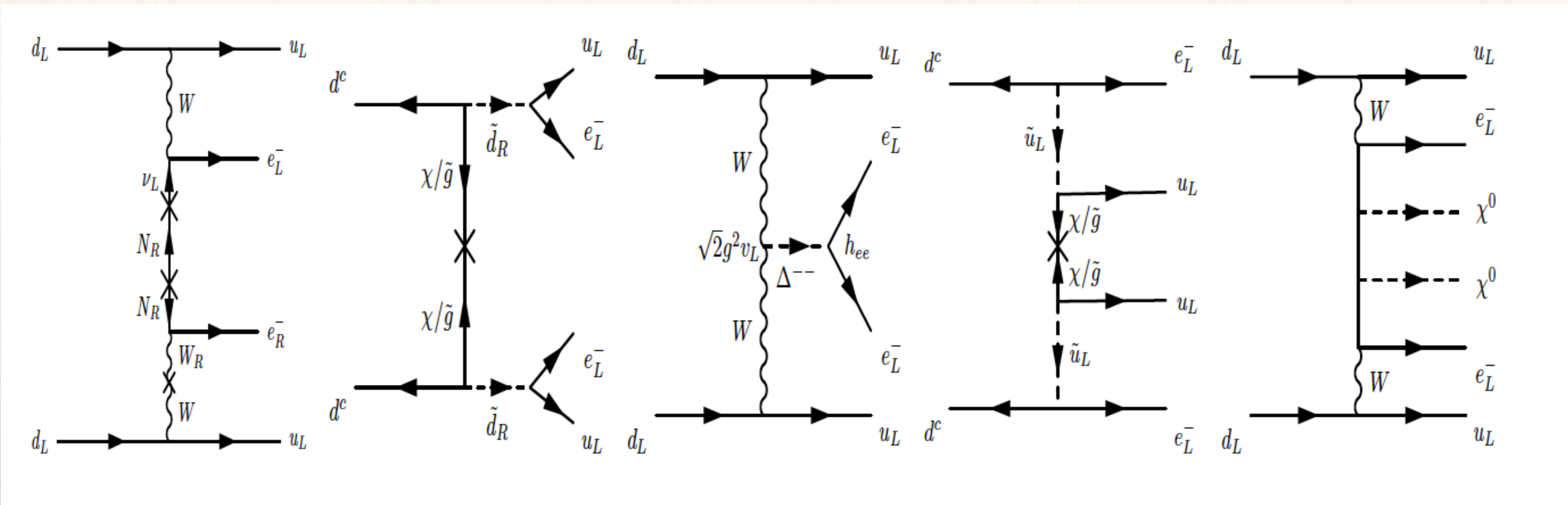
Non-Standard Interpretations



- 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

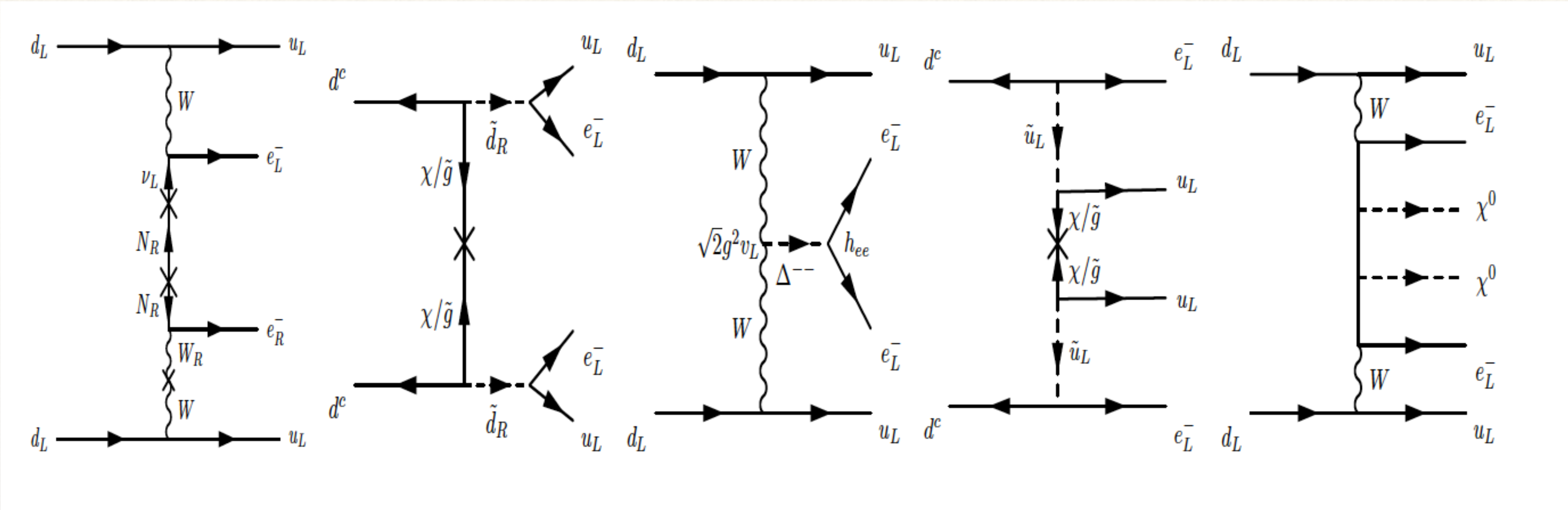


- decouples double beta decay from cosmology and KATRIN

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

Therefore:
$T(\text{eV}) = T(\text{TeV})$

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:
$T(\text{eV}) = T(\text{TeV})$

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

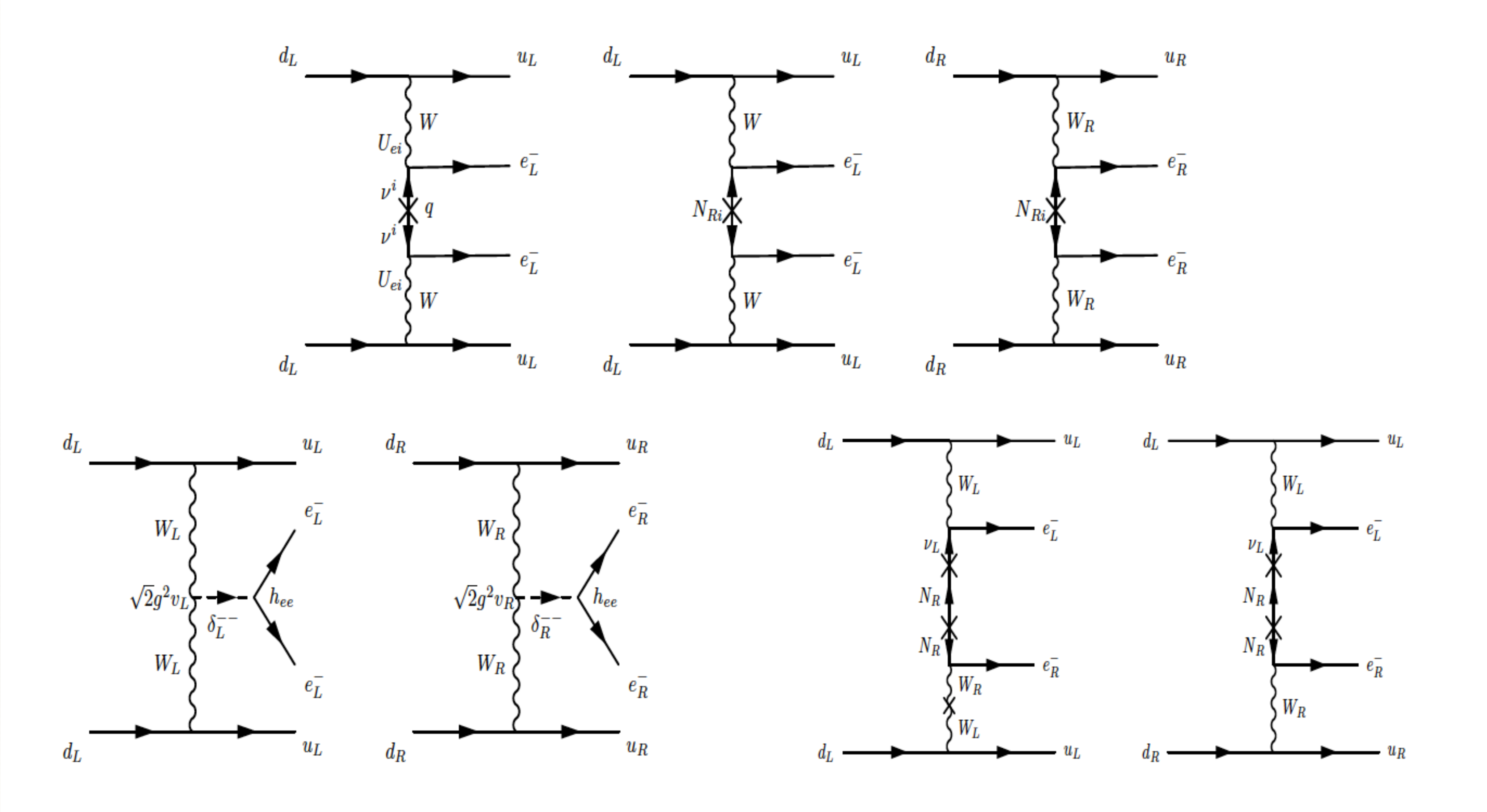
Scales

- $0\nu\beta\beta$ standard mechanism: $T_{1/2} \propto 1/(m_\nu^2)$
- $0\nu\beta\beta$ standard and Weinberg: $m_\nu \propto 1/\Lambda \Rightarrow T_{1/2} \propto \Lambda^2$
- $0\nu\beta\beta$ and heavy Physics: $T_{1/2} \propto \Lambda^{10}$
- cf. to proton decay with $T_{1/2} \propto \Lambda^4$
- cf. to neutron-antineutron oscillation $P \propto \Lambda^{10}$

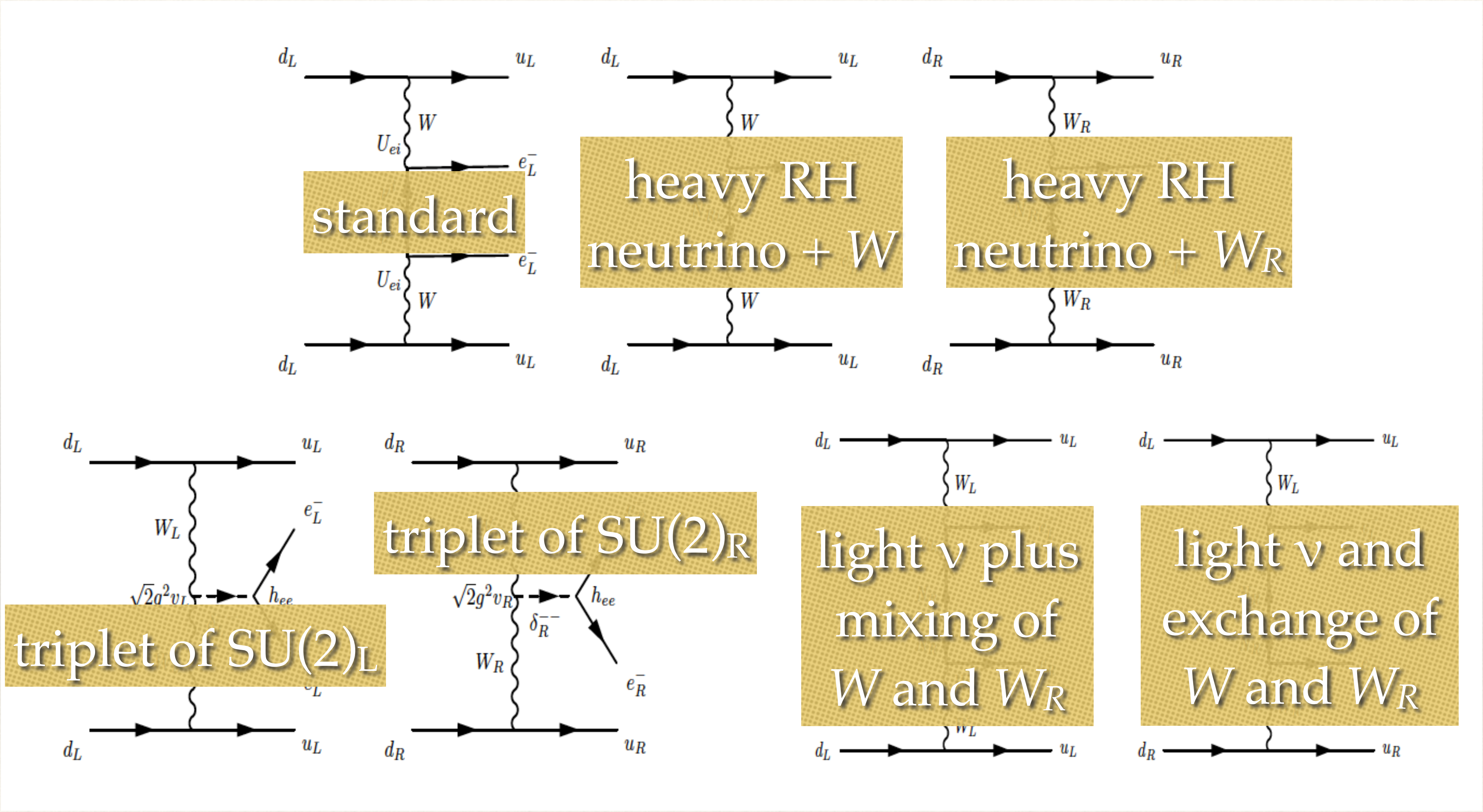
Scales

- $0\nu\beta\beta$ standard mechanism: $T_{1/2} \propto 1/(m_\nu^2)$
- $0\nu\beta\beta$ standard and Weinberg: $m_\nu \propto 1/\Lambda \Rightarrow$ $10^{4\text{-}14}$ GeV
- $0\nu\beta\beta$ and heavy Physics: $T_{1/2} \propto \Lambda^{10}$ 10^3 GeV
- cf. to proton decay with $T_{1/2} \propto \Lambda^4$ 10^{16} GeV
- cf. to neutron-antineutron oscillation P ∝ 10^6 GeV

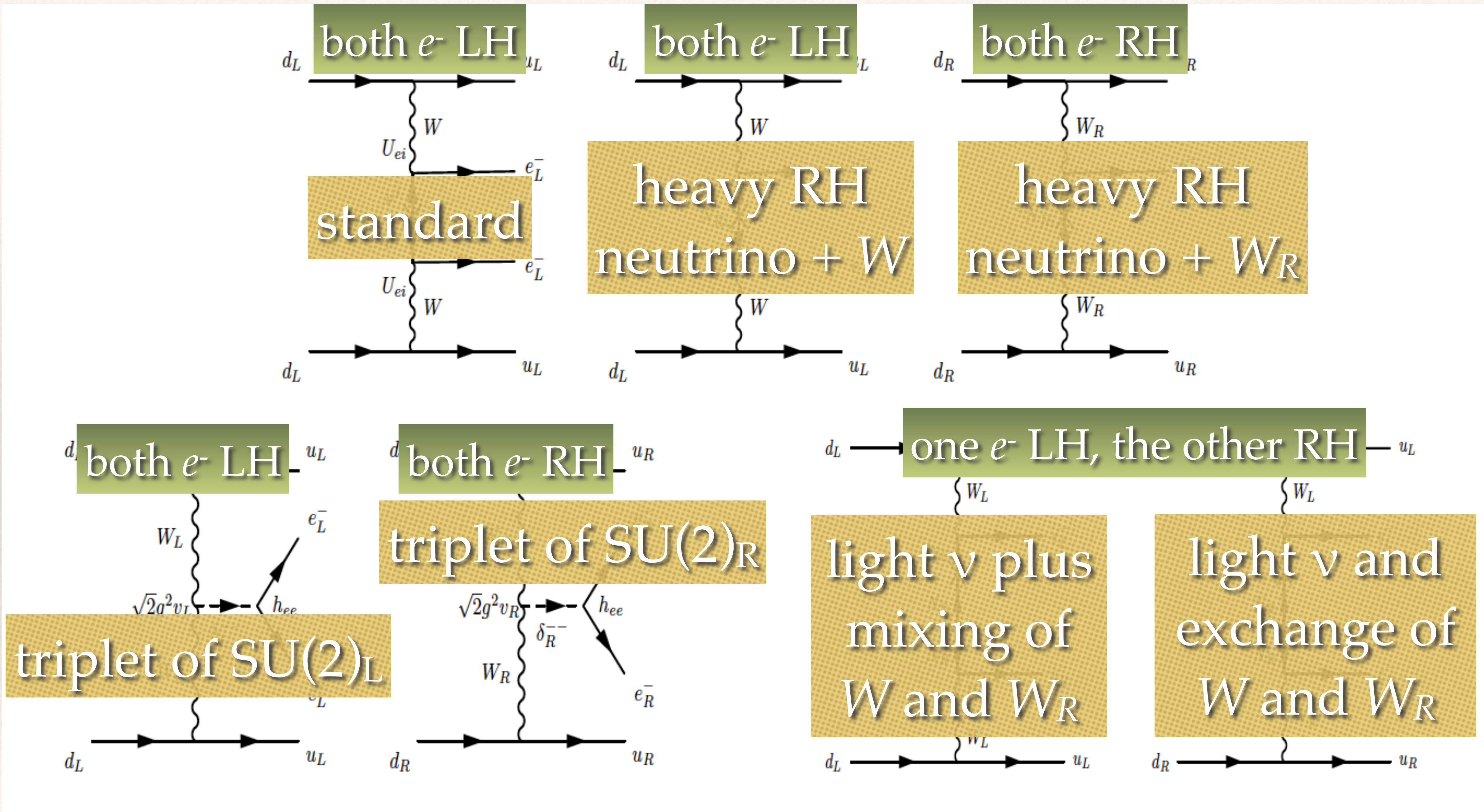
Double Beta Decay and LR-Symmetry



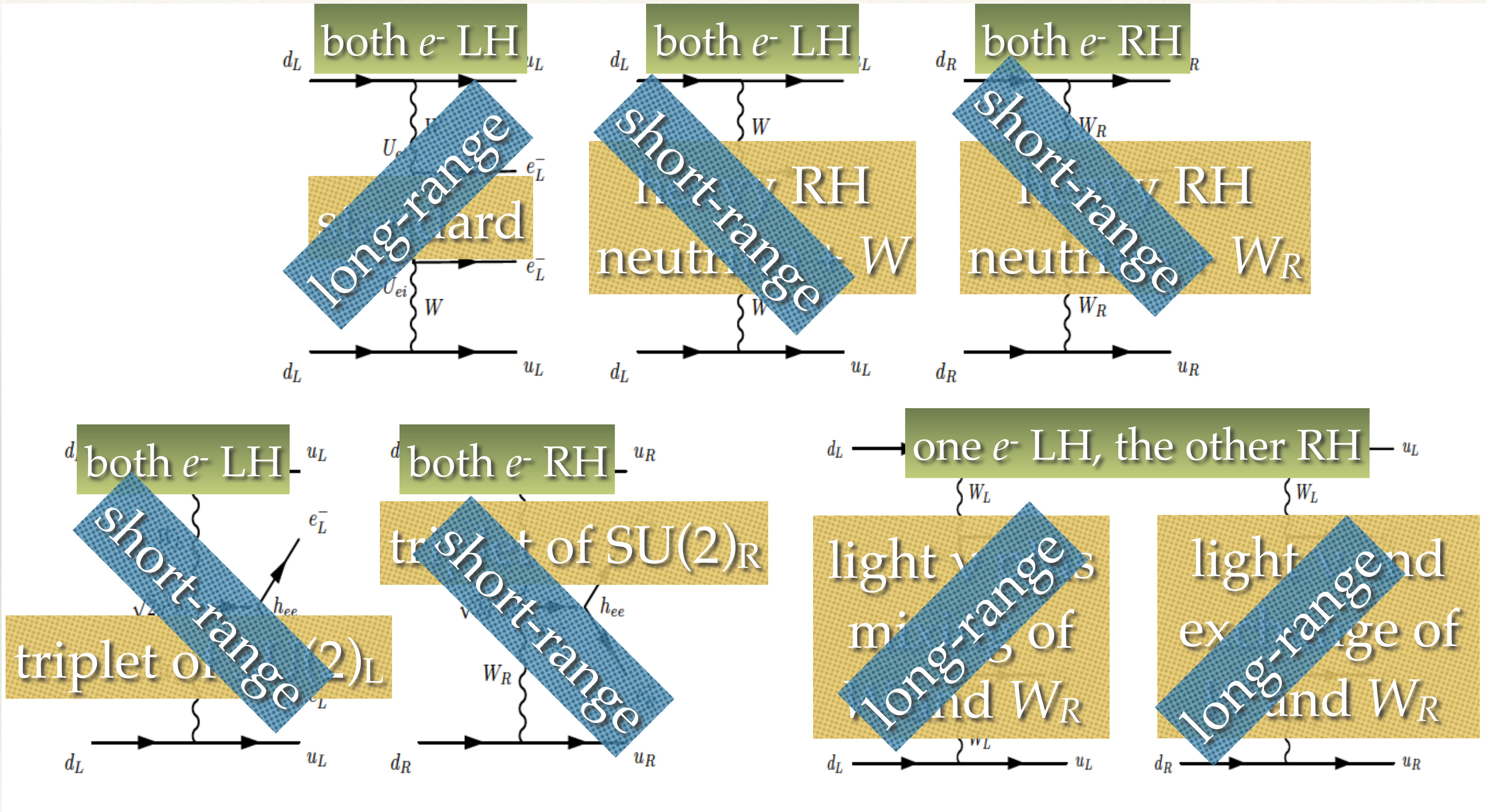
Double Beta Decay and LR-Symmetry



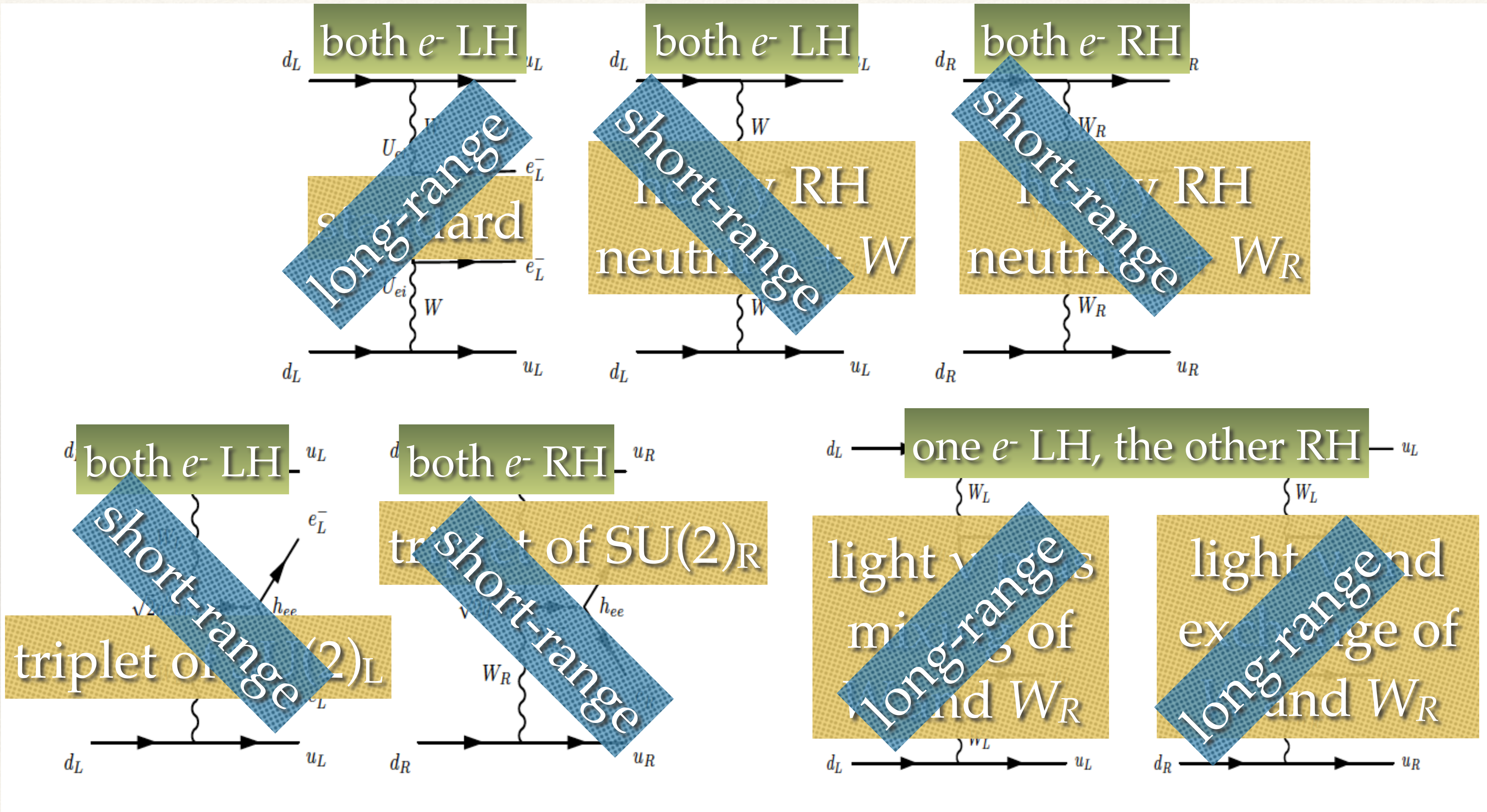
Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry

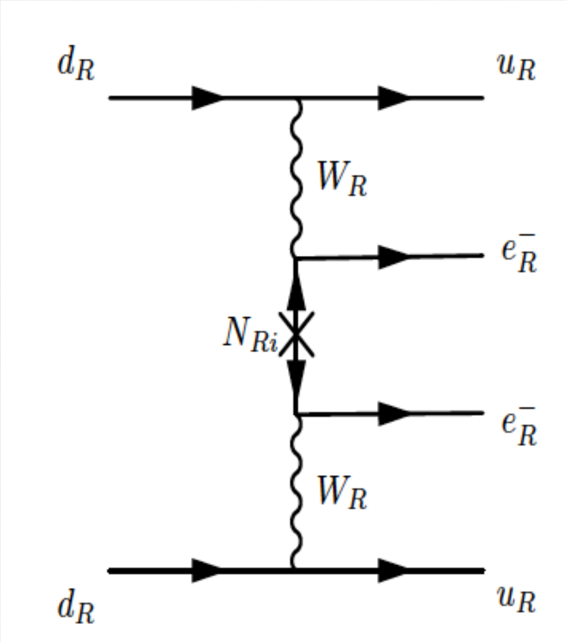


simultaneous presence / interference / …

Double Beta Decay and LR-Symmetry

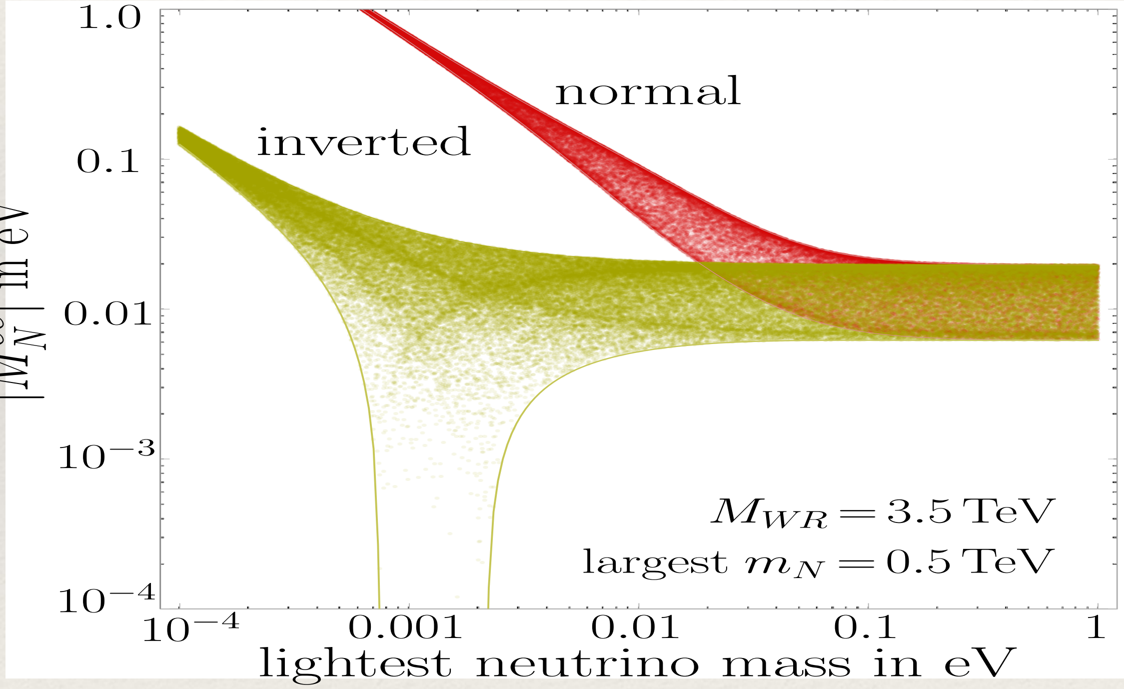
Type II dominance: $m_\nu = m_L - M_D^2/M_R \to m_L$ with $m_L \propto M_R$

$\Rightarrow$ 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 $\propto 1/m_\nu$

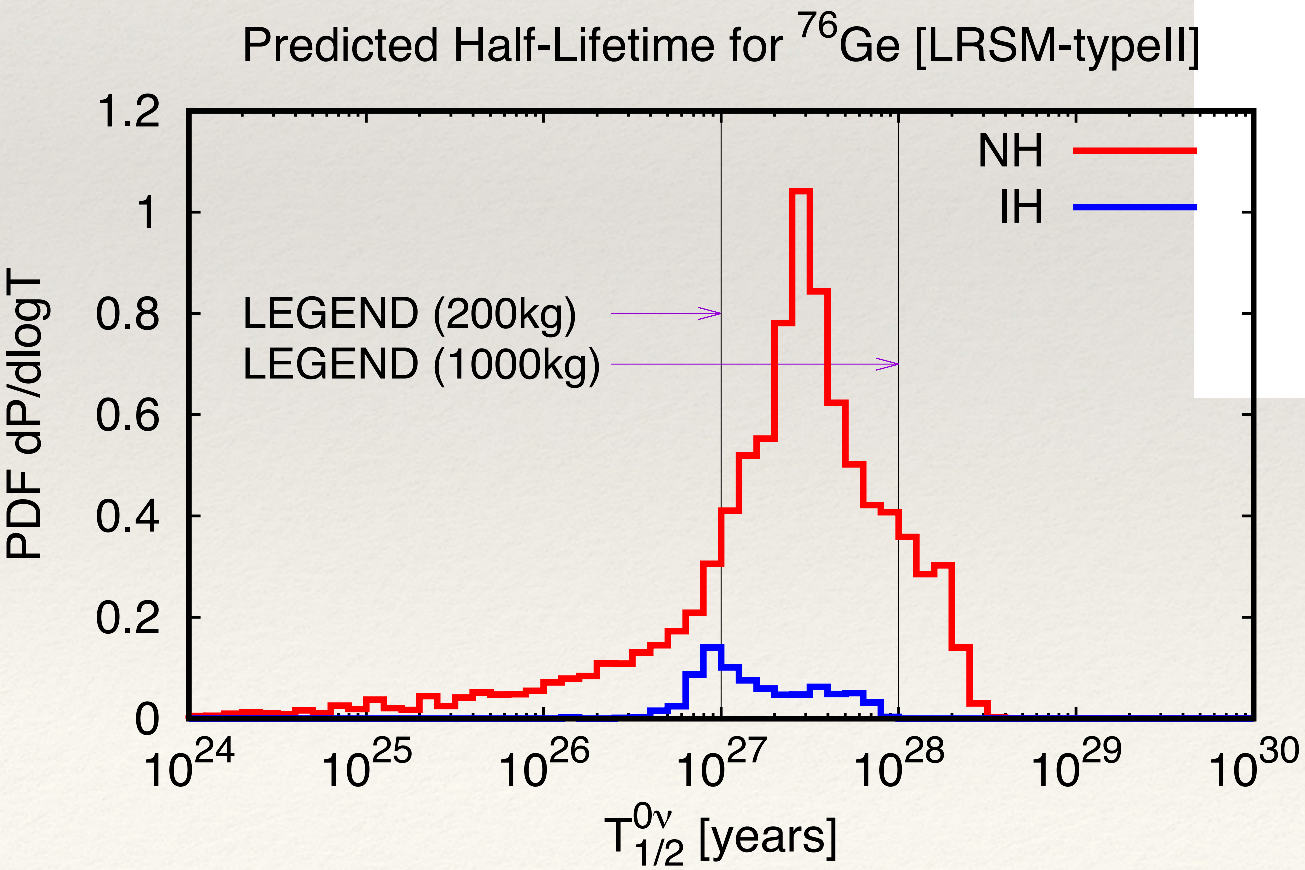


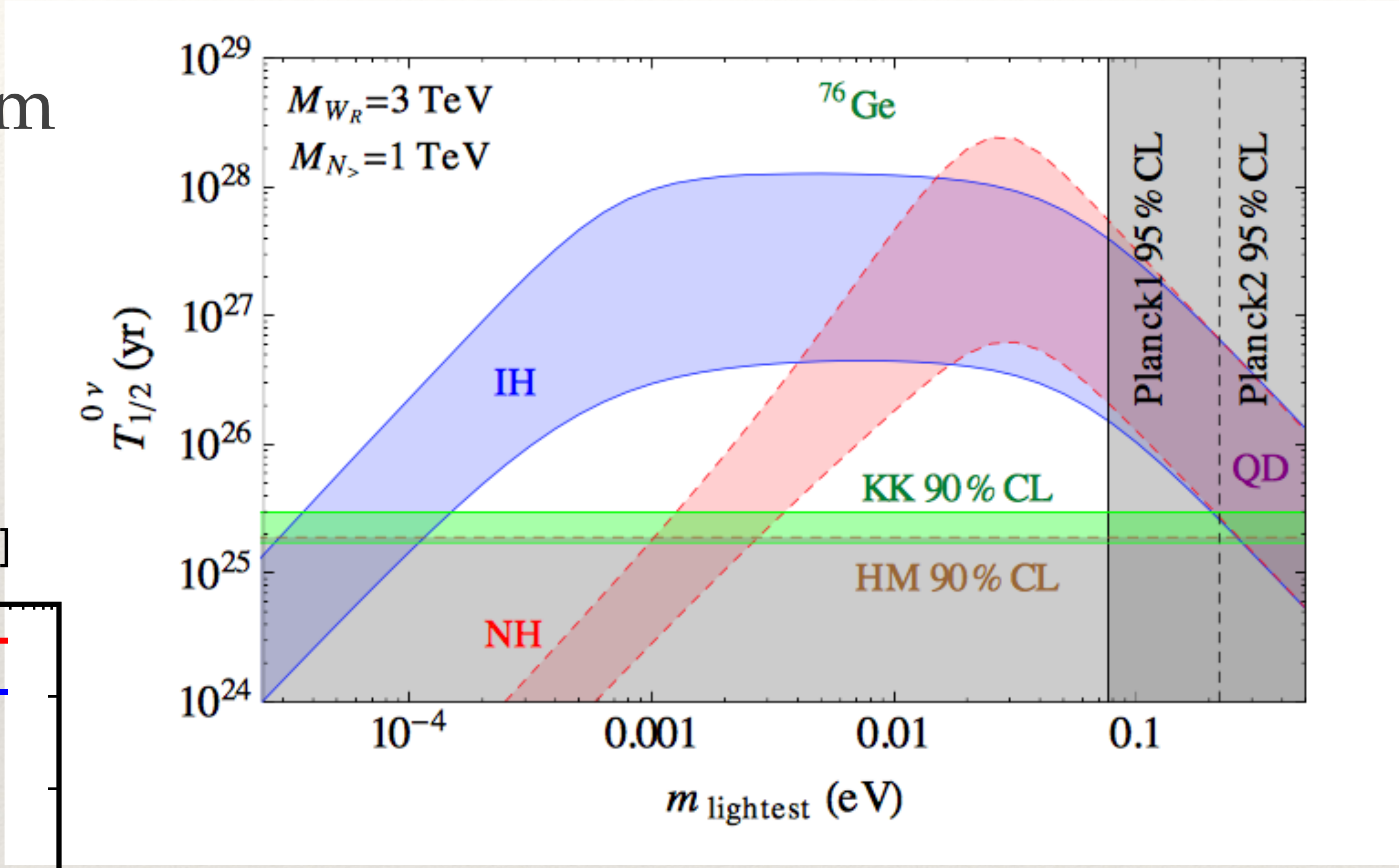
again, NH/IH turned around…

Senjanovic et al., 1011.3522

Double Beta Decay and LR-Symmetry

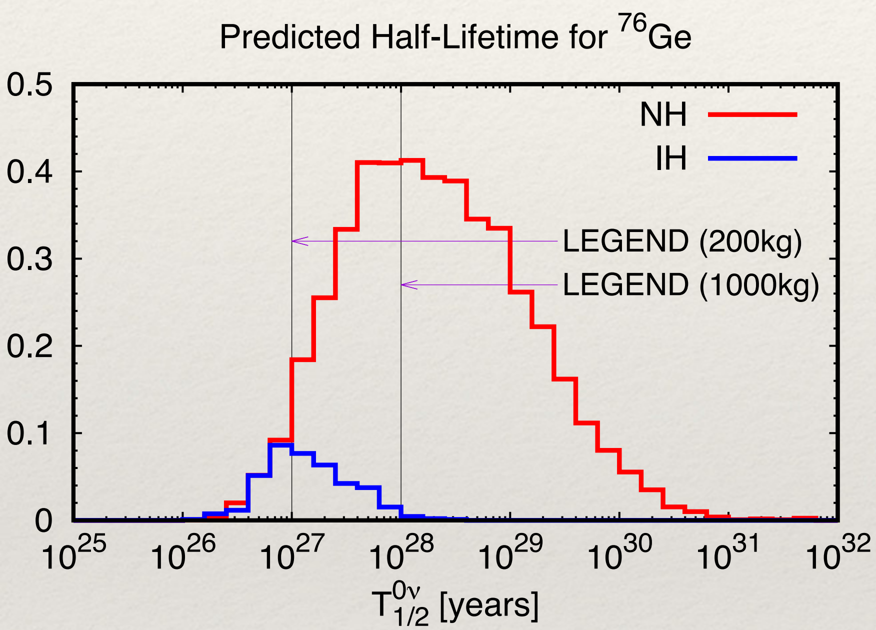
- add Standard and LR-diagram
- $T_{St} \propto 1/m_\nu^2$ and $T_{LR} \propto m_\nu^2$
- gives ***lower limit*** on m_ν



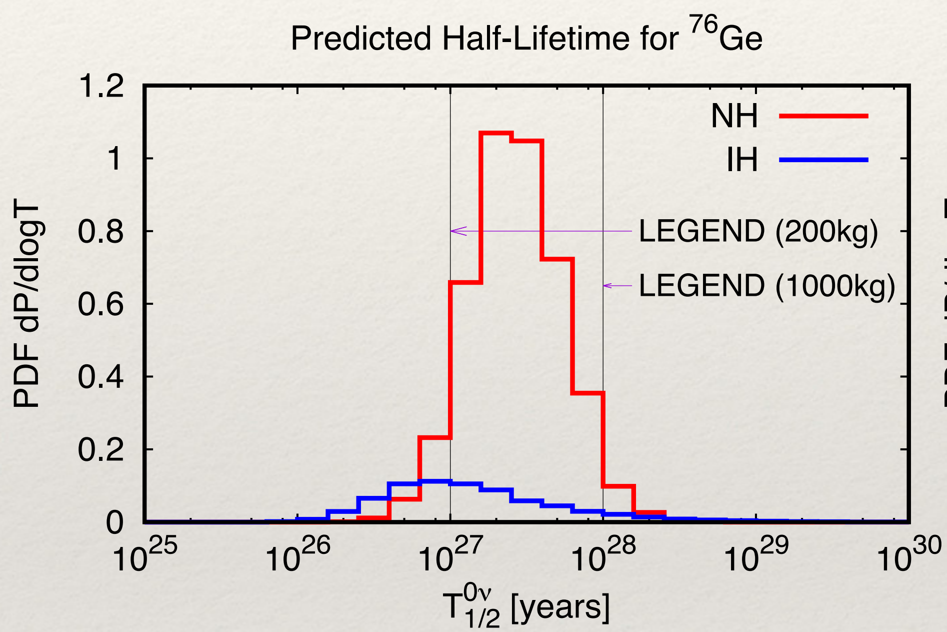


Expectations for half-lifes

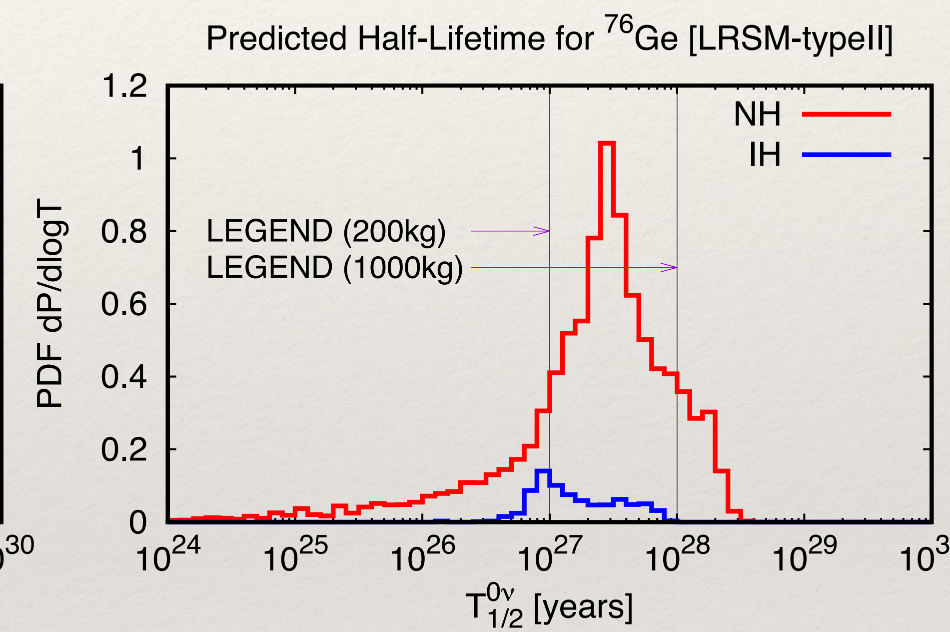
Standard



Sterile



Left-right



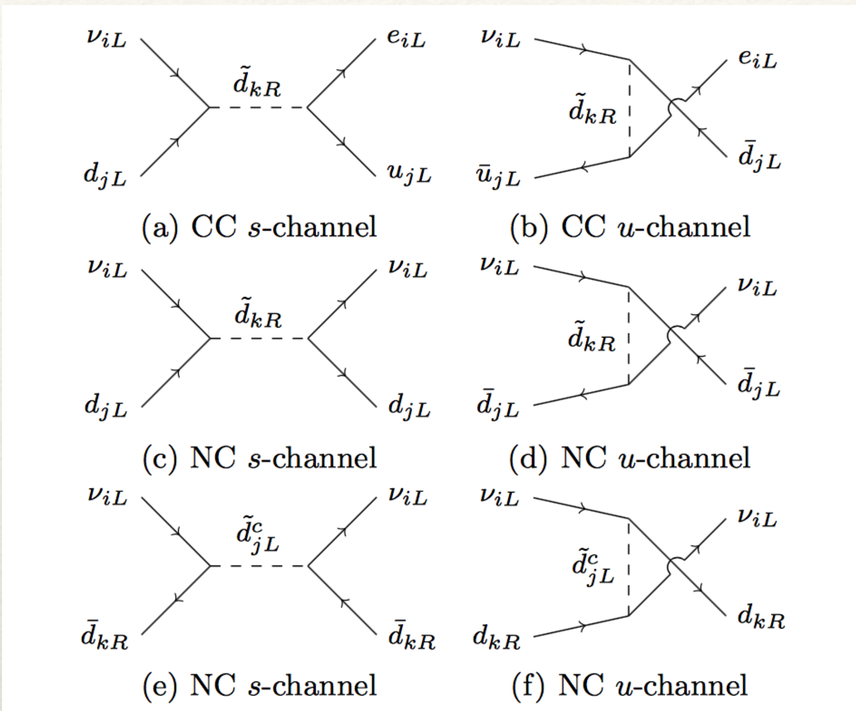
Ge, WR, Zuber, 1707.07904

However, most alternative mechanisms unrelated to neutrino parameters…

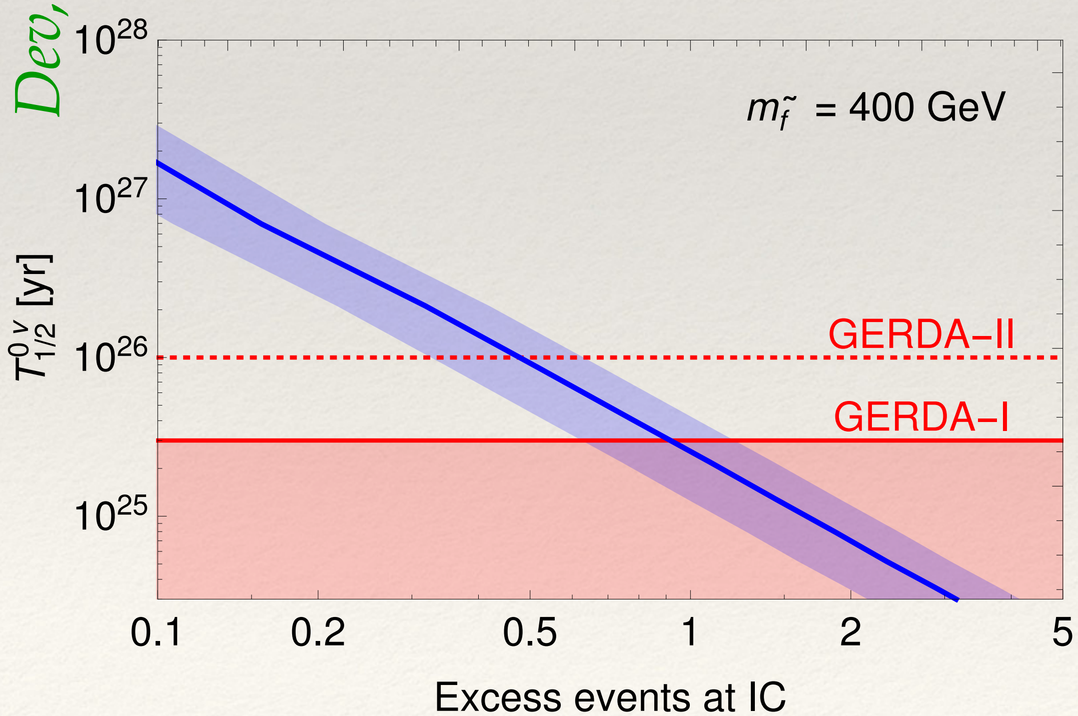
…thus decoupled from cosmology (and direct experiments)!

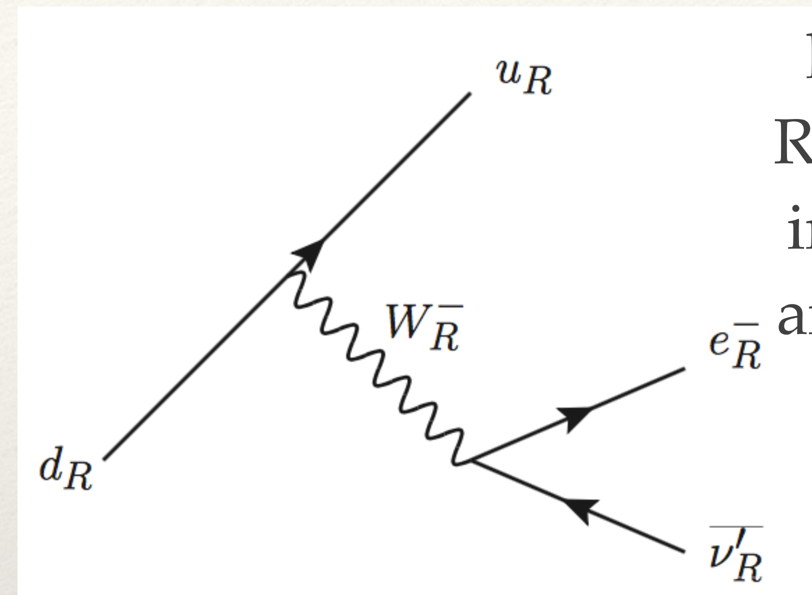
Unexpected Correlations with other Experiments

Dev, Ghosh, WR, 1605.09743

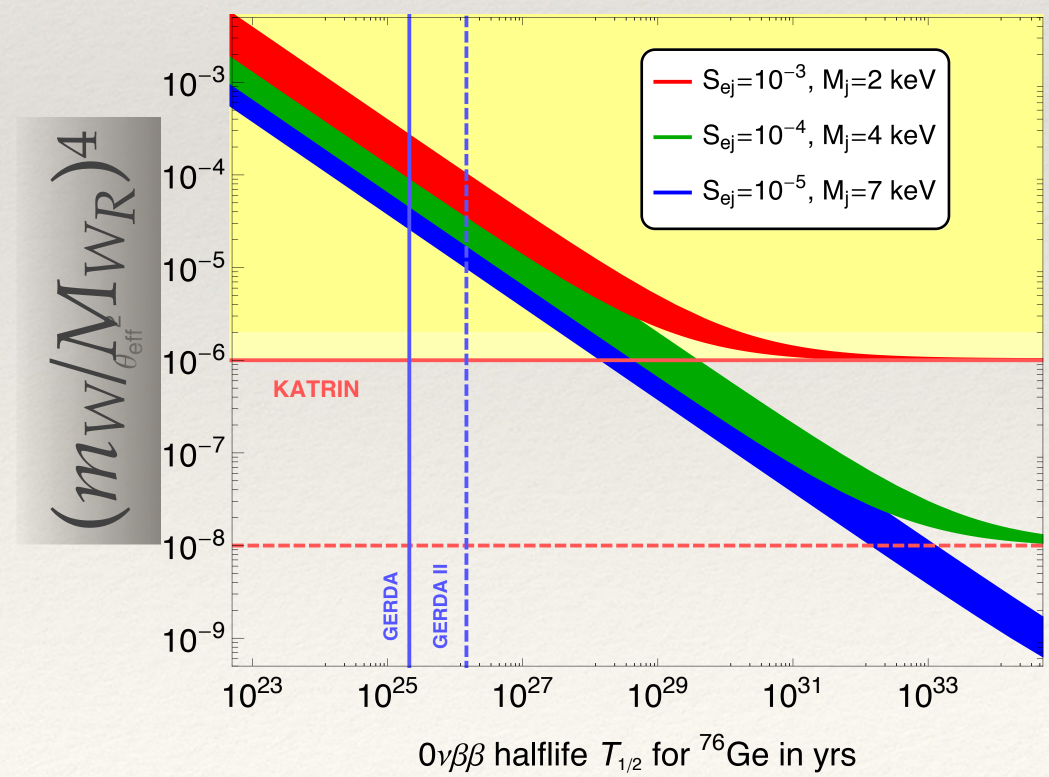


RPV SUSY at IceCube and in 0νββ



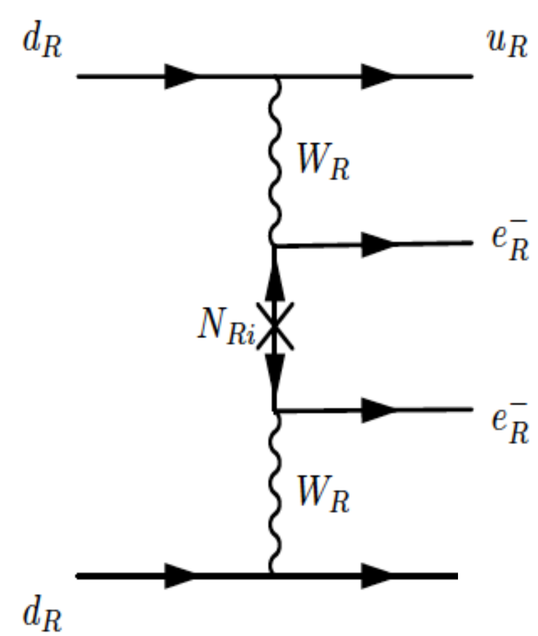


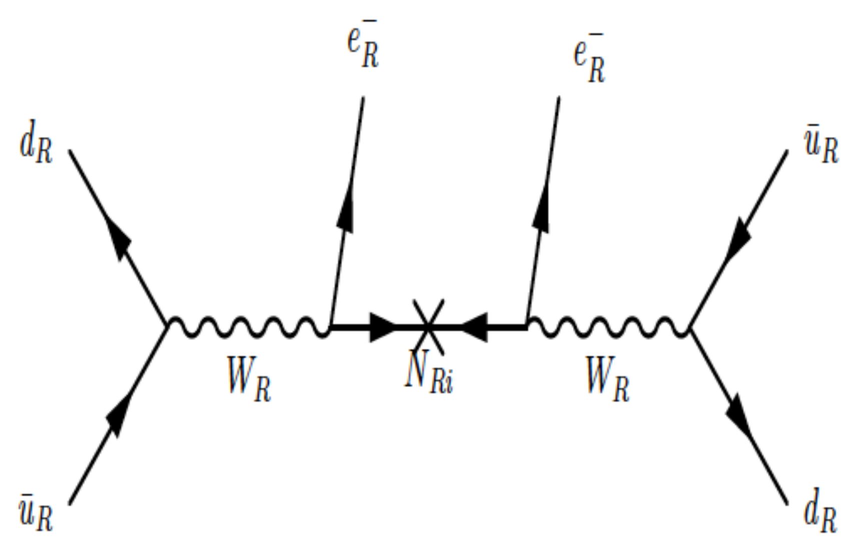
keV ν and RH currents in KATRIN and in 0νββ

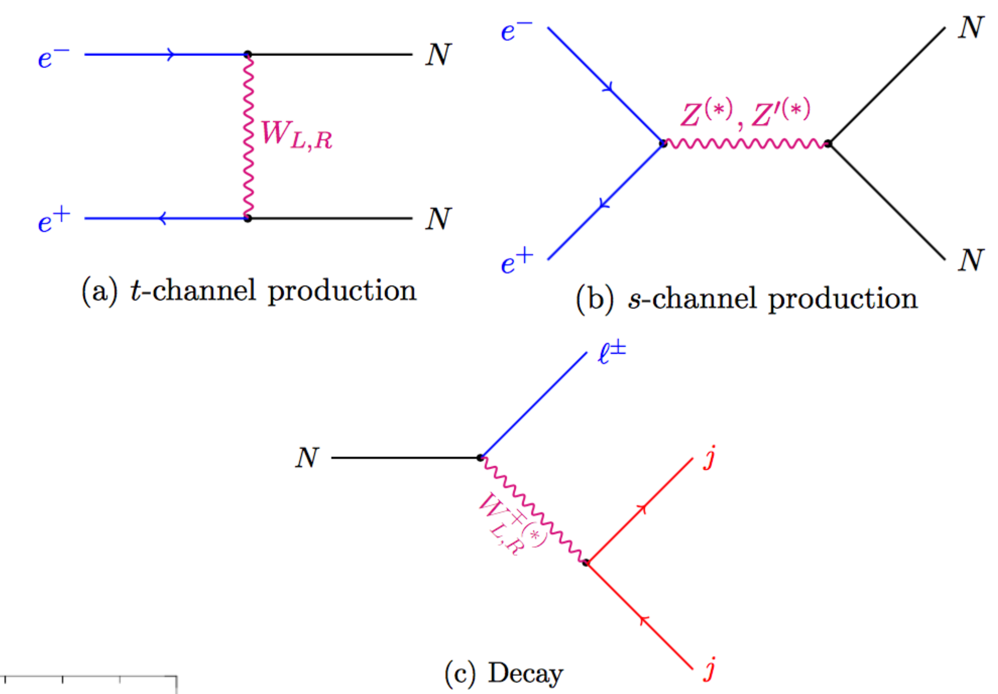


Barry, Heeck, WR, 1404.5955

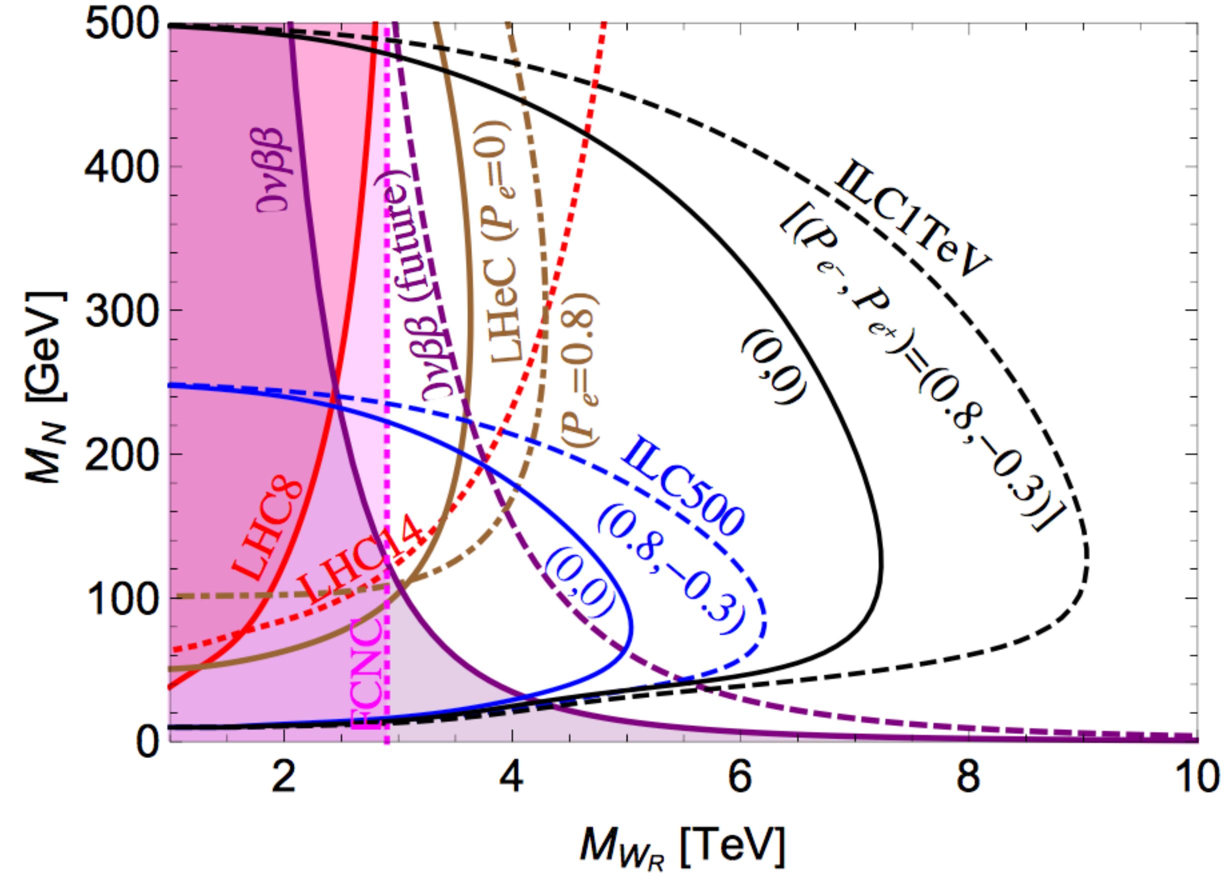
LHC and Double Beta Decay





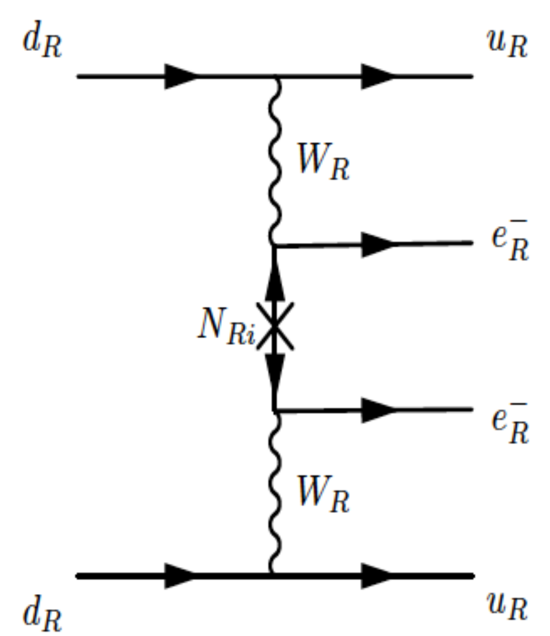


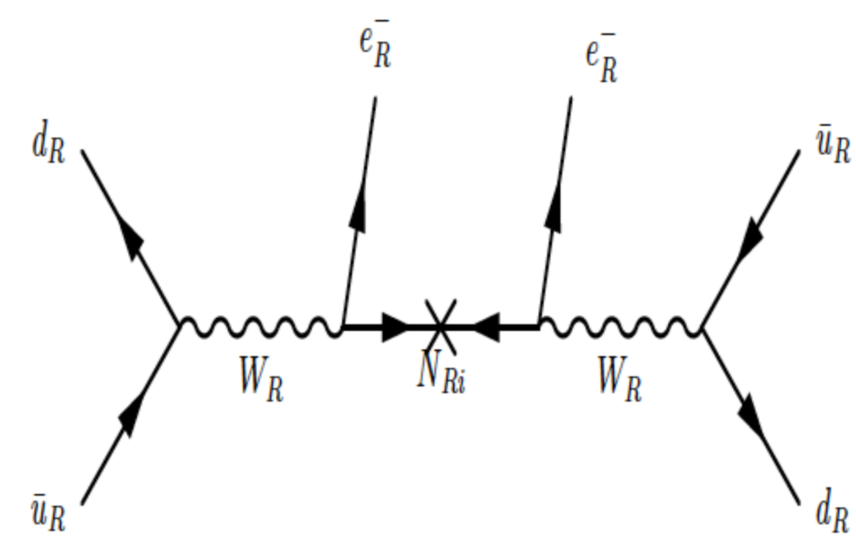
Biwal, Bhupal Dev,
1701.08751

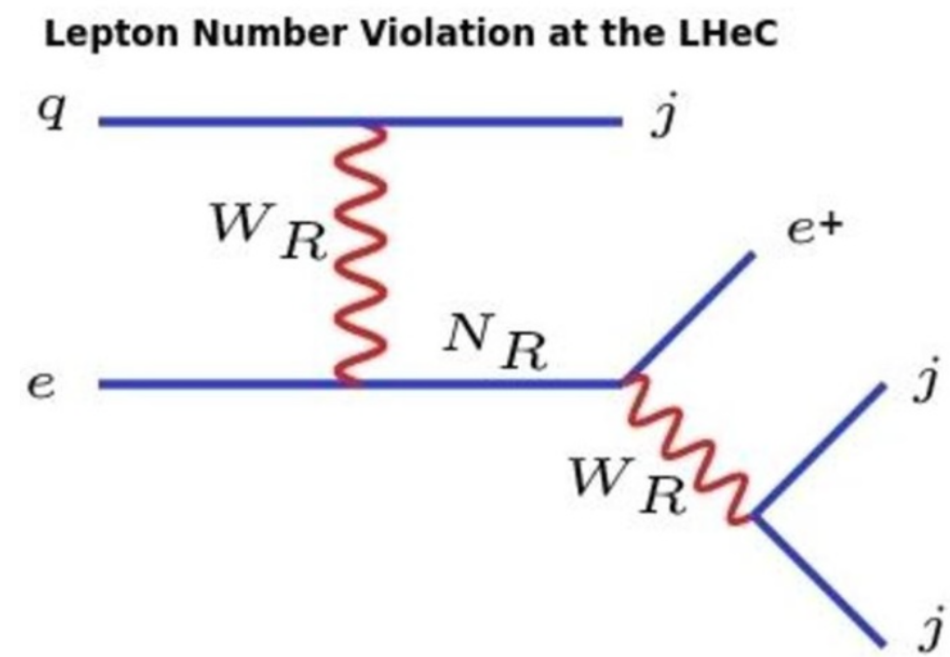


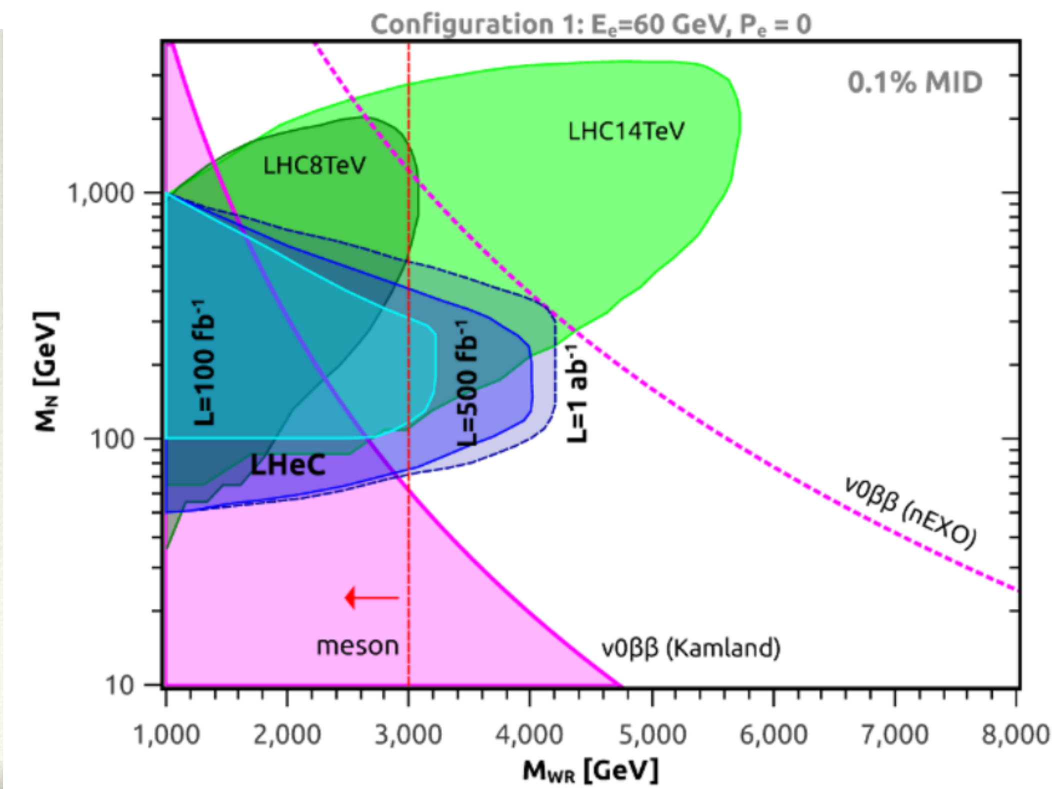
polarization at ILC

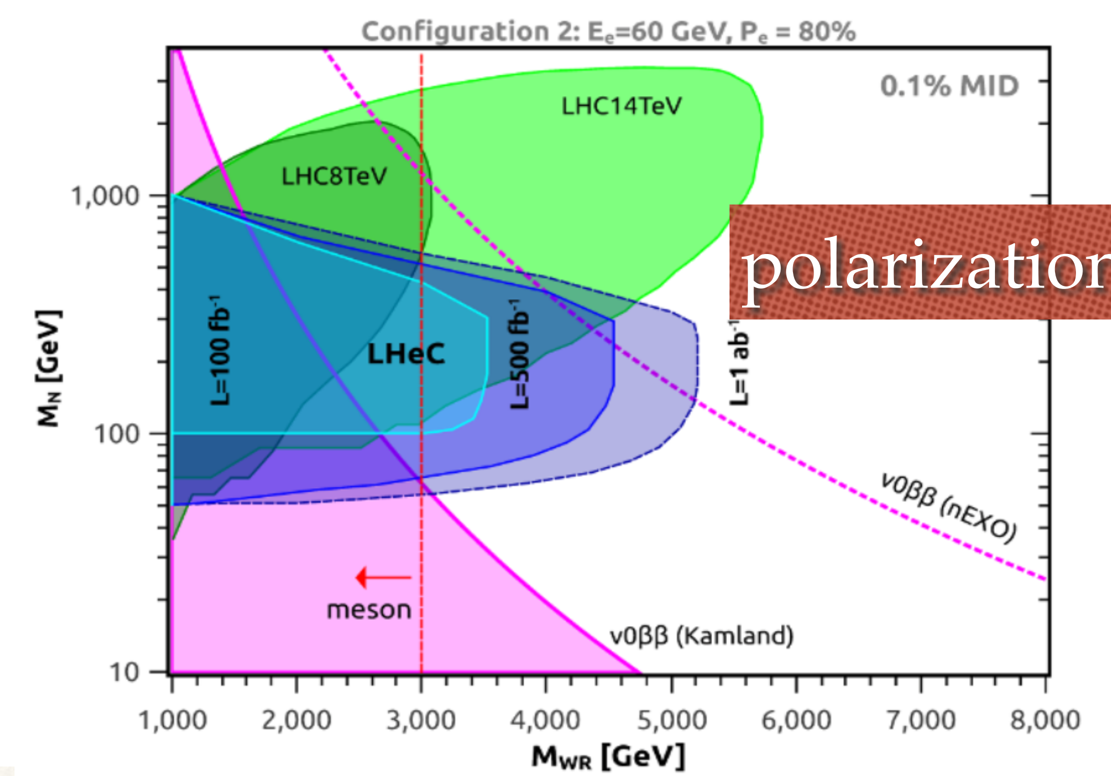
LHC and Double Beta Decay







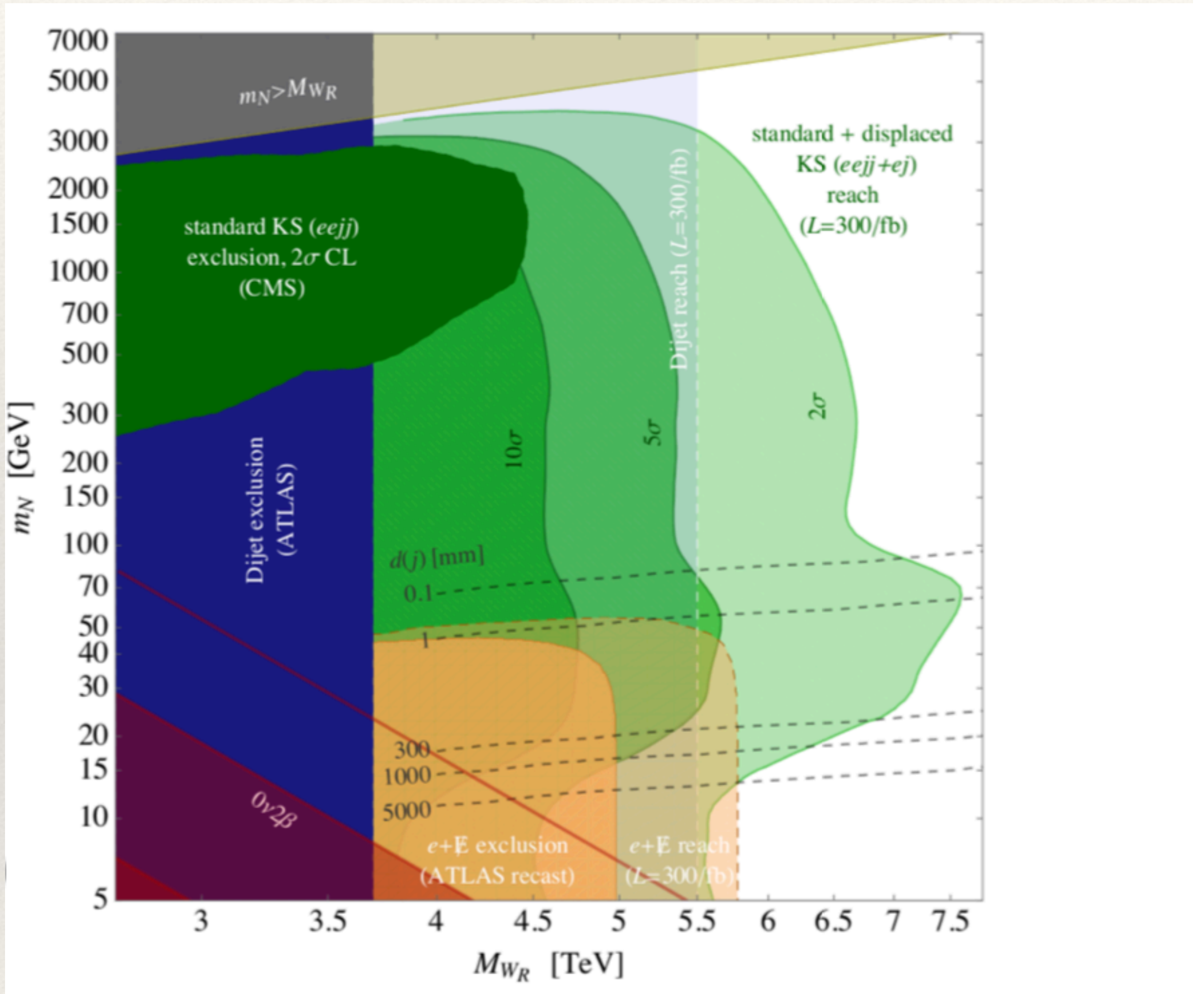




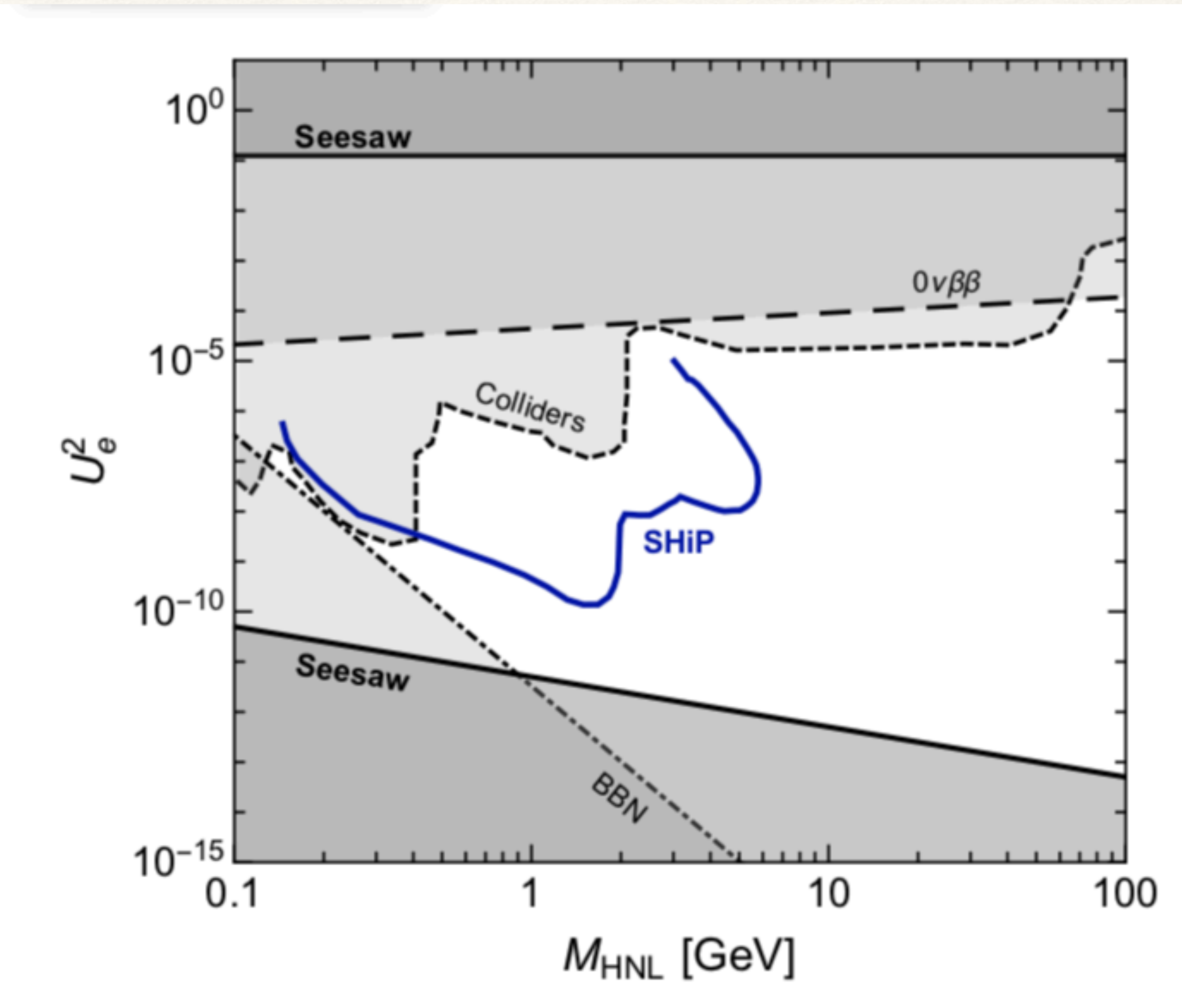
polarization at LHeC

Lindner, Queiroz, WR, Yaguna, 1604.08596

LHC and Double Beta Decay



Nemevsek, Nesti, Popara, 1801.05813

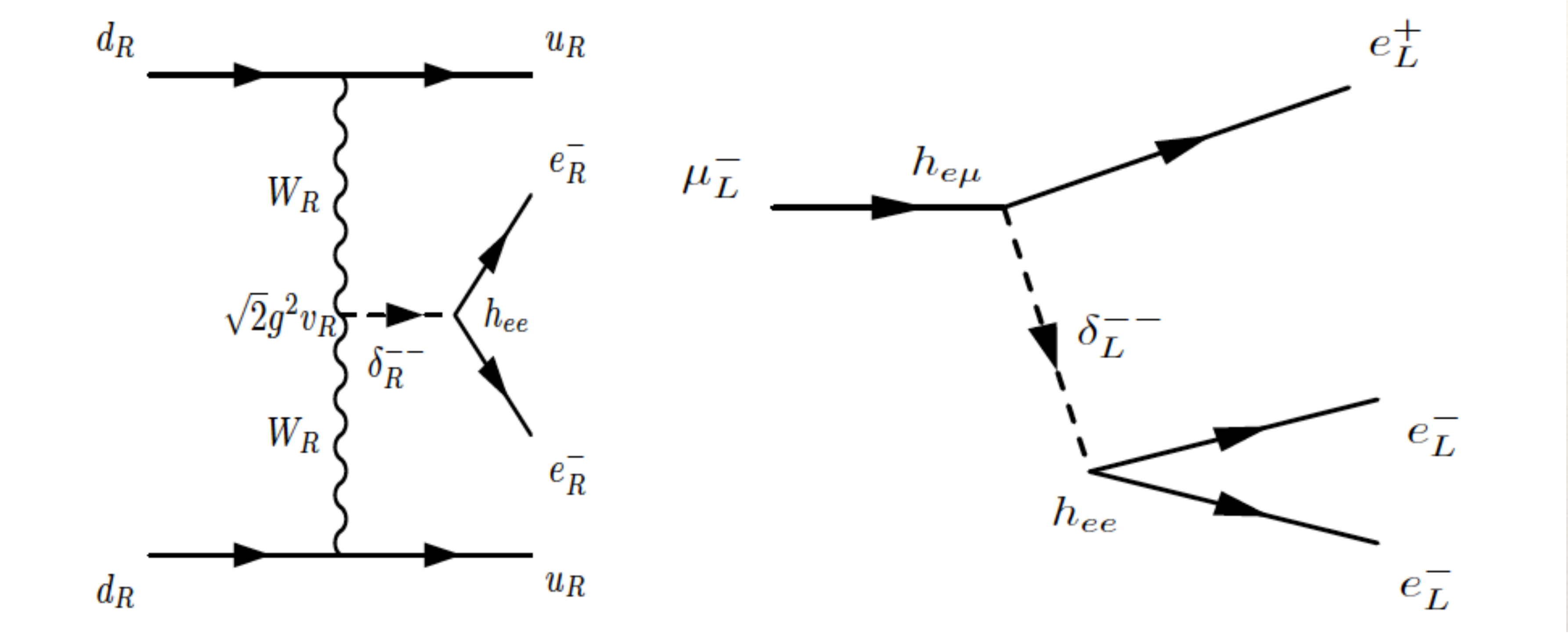


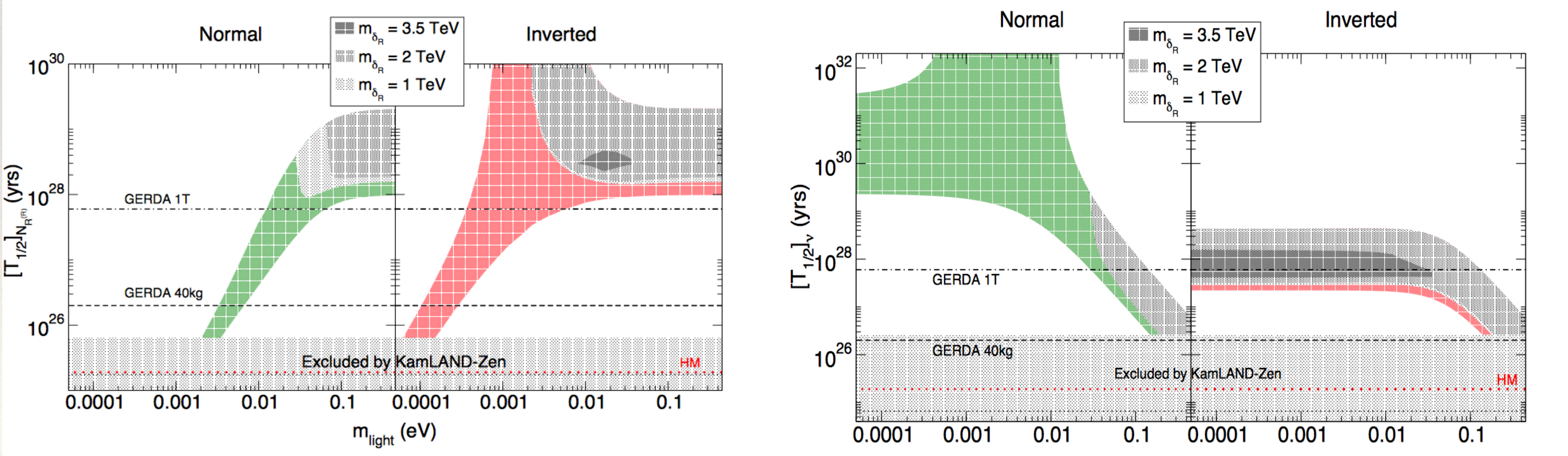
Chianese et al., 1812.01994

displaced vertices for low masses

low mass neutrinos better constrained by other expts.

LFV and Double Beta Decay

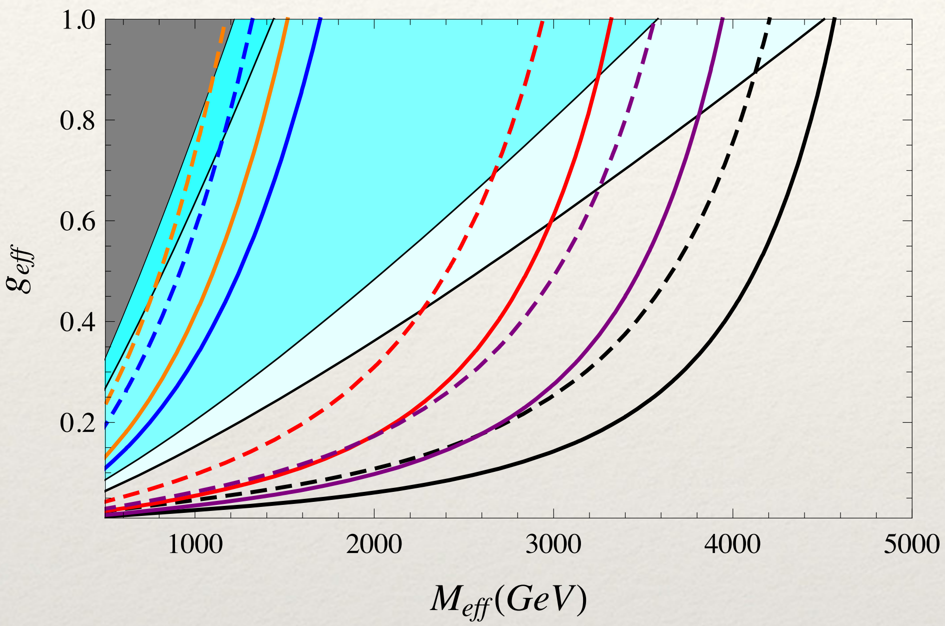




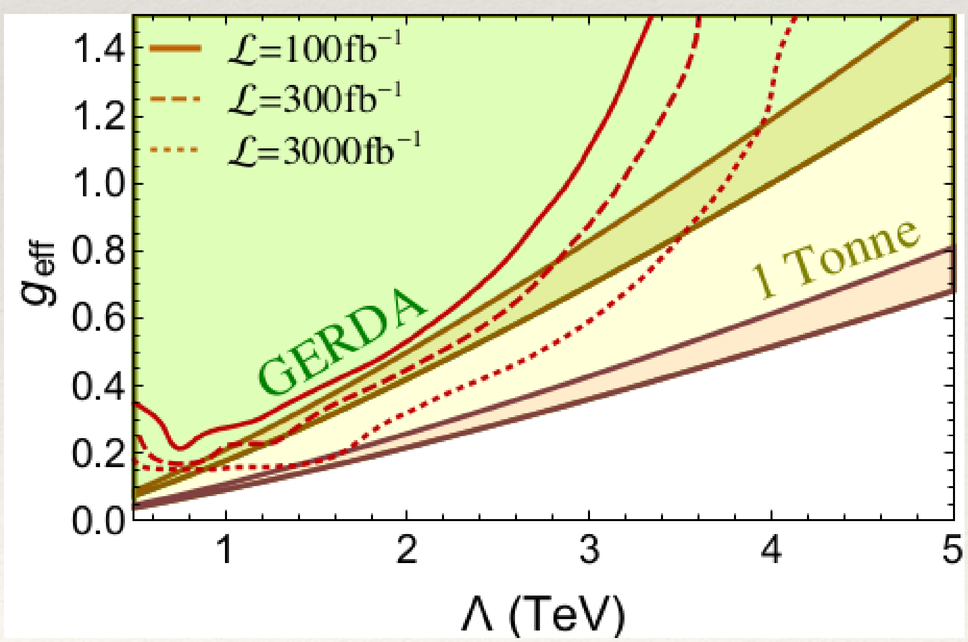
Barry, WR, 1303.6324

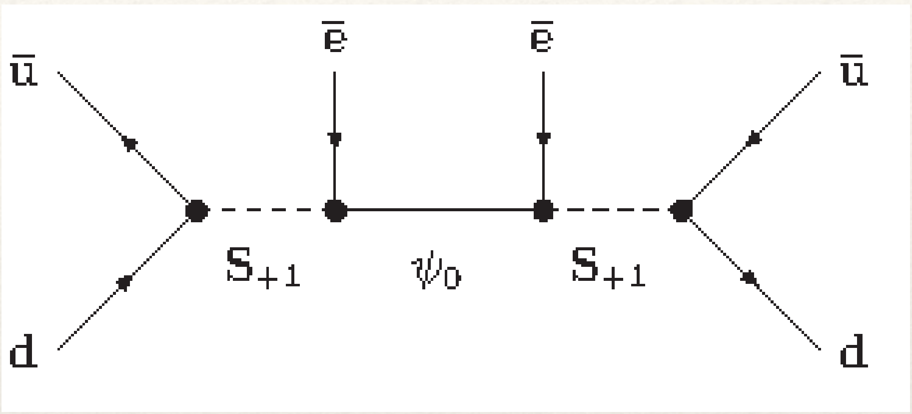
Complementarity of LHC and 0νββ

Hirsch et al., 1511.03945



Ramsey-Musolf et al., 1508.04444



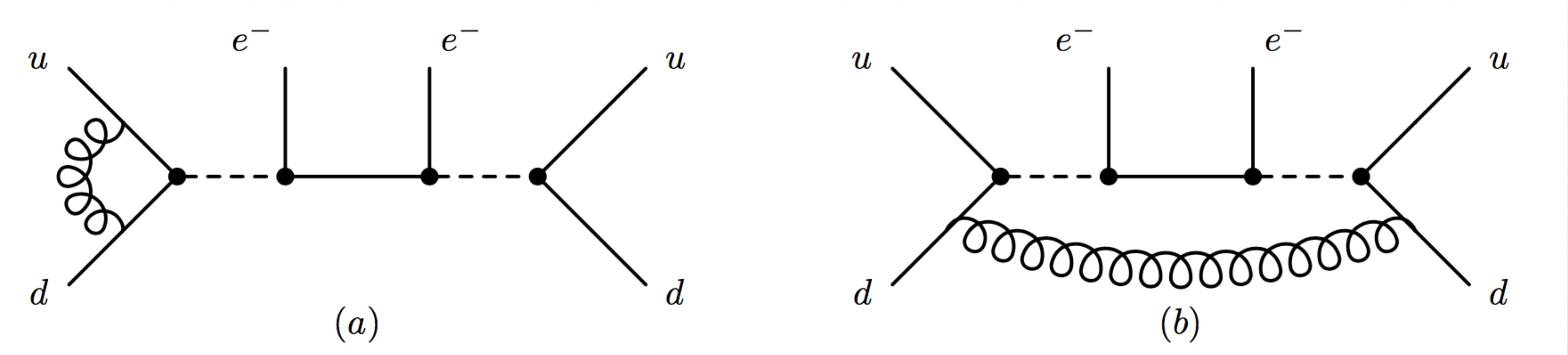


S~(1,2)

ψ~(1,0)

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

QCD Corrections

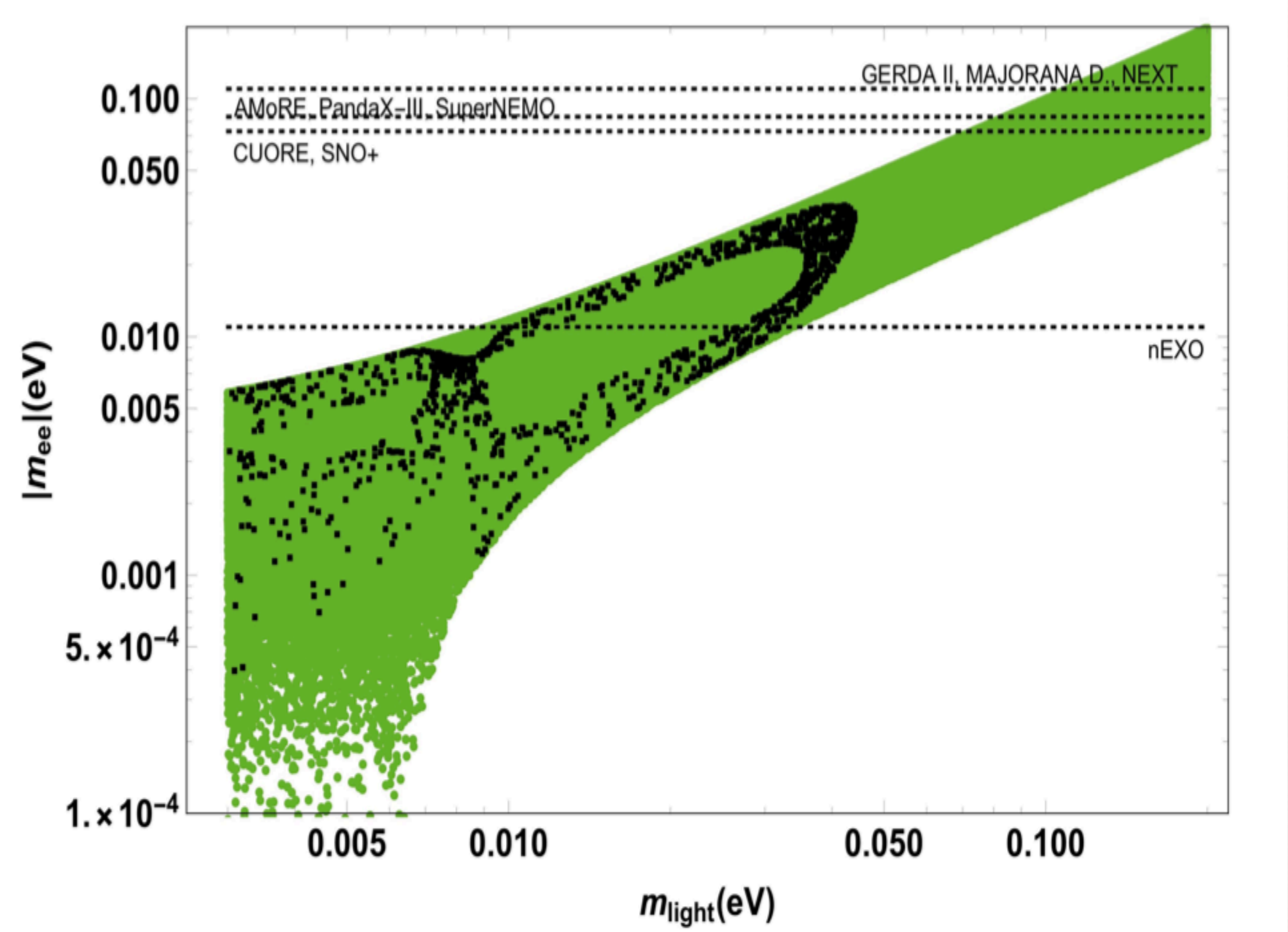


- naive size $(\alpha_s/4\pi)\ln(M_W/100\text{ MeV})^2 \simeq 10\%$, true for standard diagram
- creates in non (V-A) $\otimes$ (V-A) short-range mechanisms color non-singlets, Fierzing to singlets gives different operators with vastly different NMEs
- $\Rightarrow$ can give effect exceeding NME uncertainty…

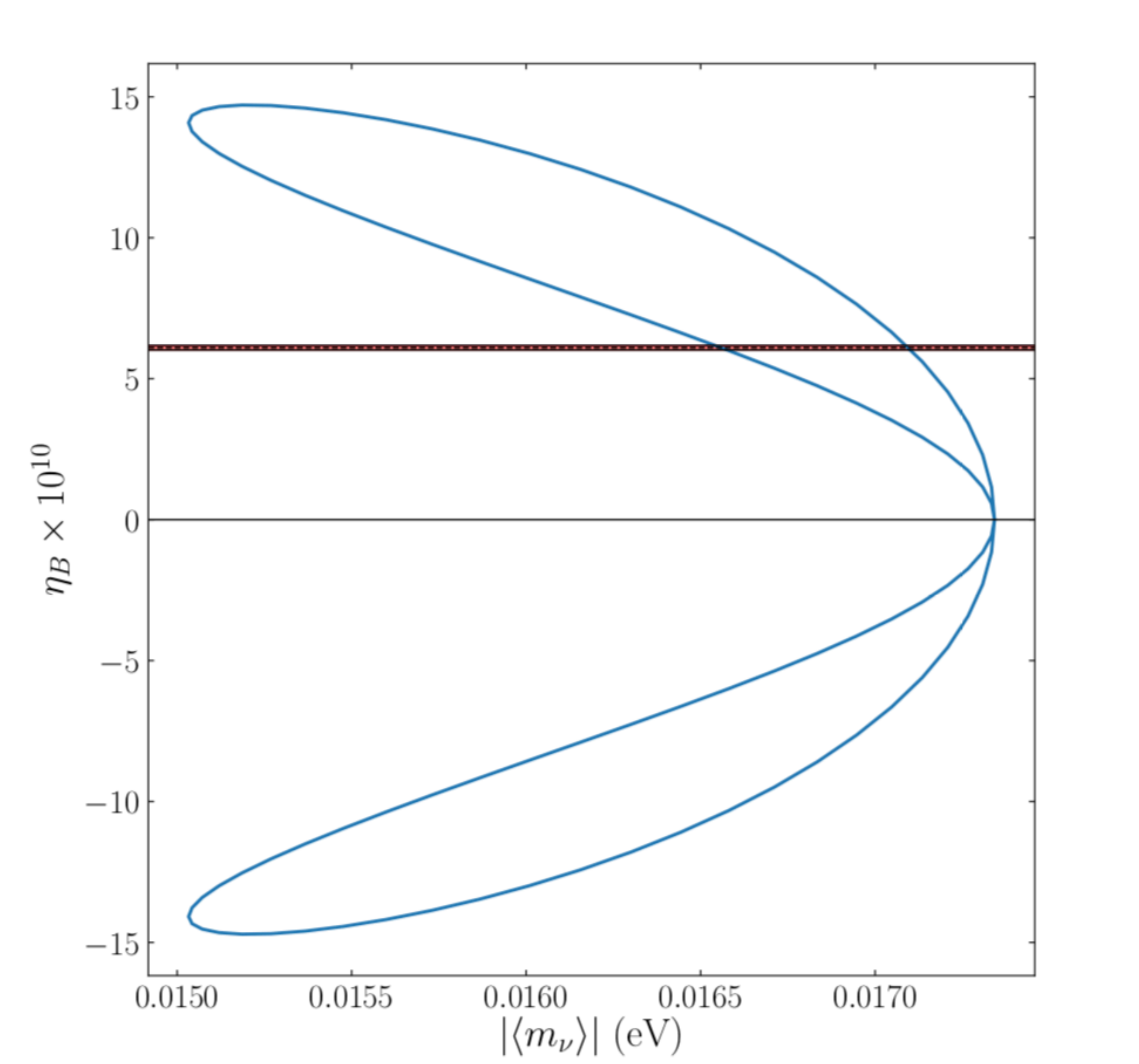
Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93; Peng, Ramsey-Musolf, Winslow, PRD 93

Leptogenesis

Many connections to 0νββ possible, just some examples…



a) $|m_{ee}|$ *vs* $m_{\rm light}$ for the NO case

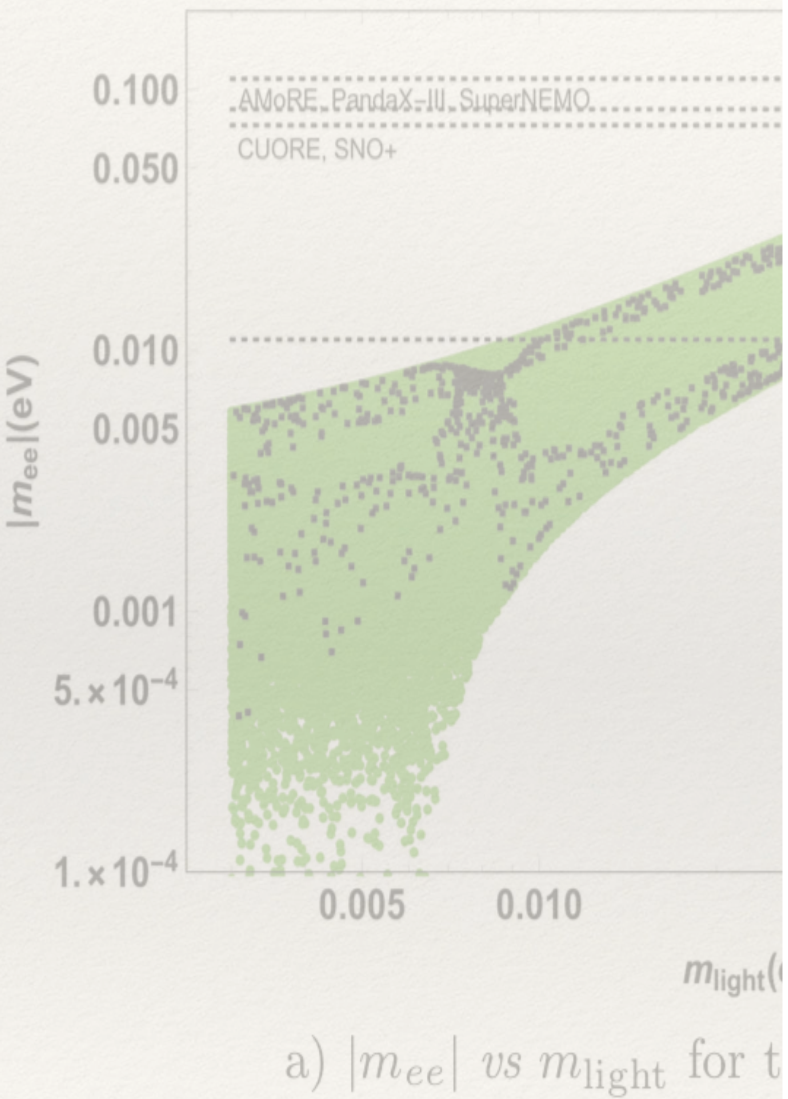


Merlo, Rosauro-Alcaraz, 1801.03937

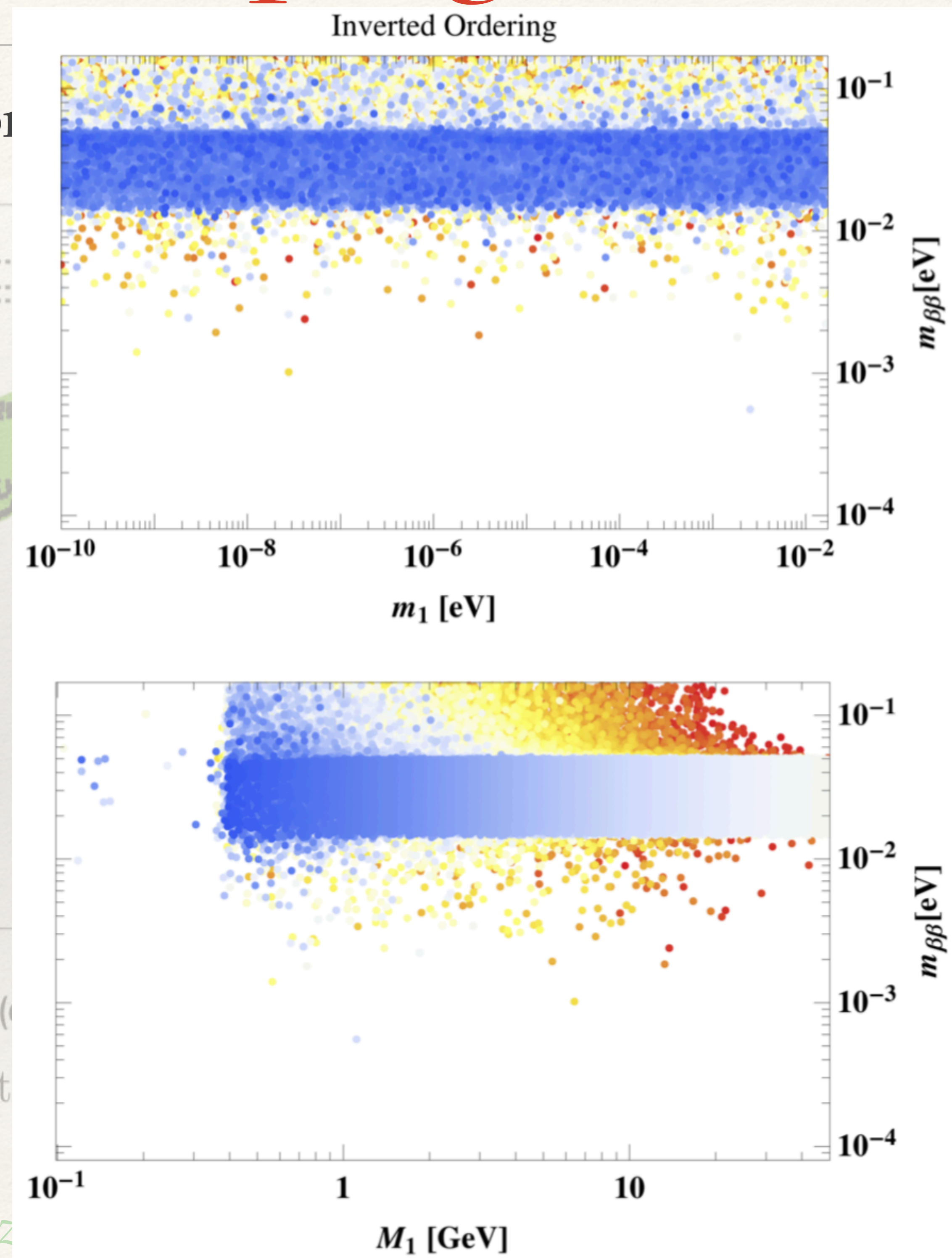
Moffat, Pascoli, Petcov, Turner, 1809.08251

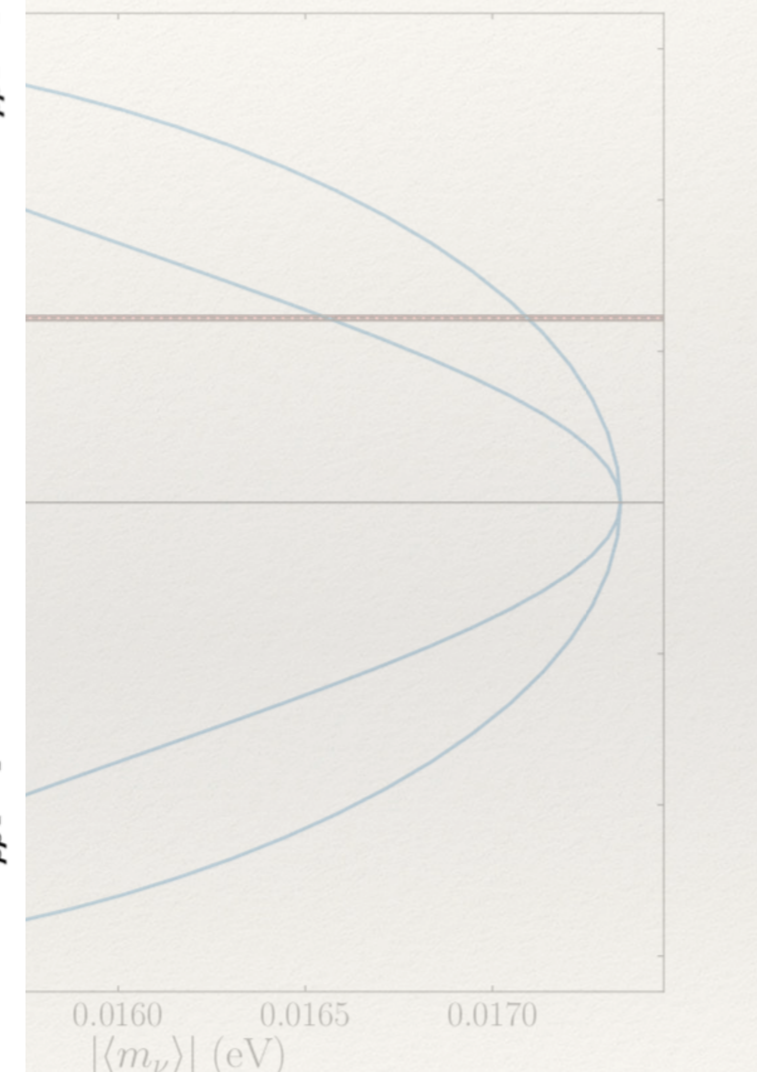
Leptogenesis

Many co … amples…



a) $|m_{ee}|$ vs $m_{\rm light}$ for t



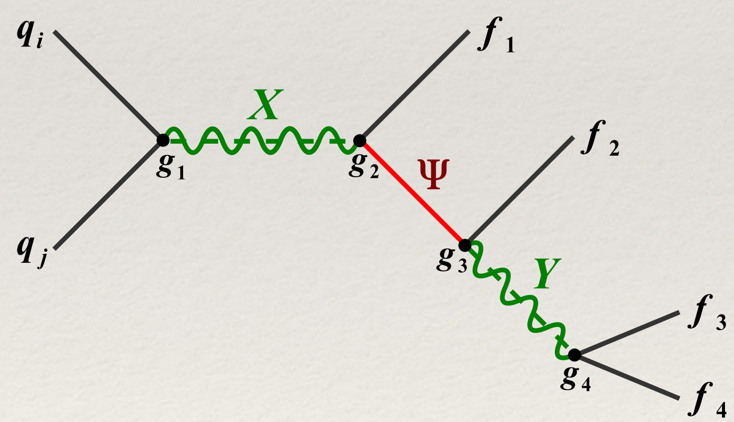


Merlo, Rosauro-Alcaraz … *Petcov, Turner, 1809.08251*

Arcadi et al., 1810.12463

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; Dev, Mohapatra; Sarkar et al.)*
- more model-independent *(Deppisch, Harz, Hirsch)*:



wash-out:

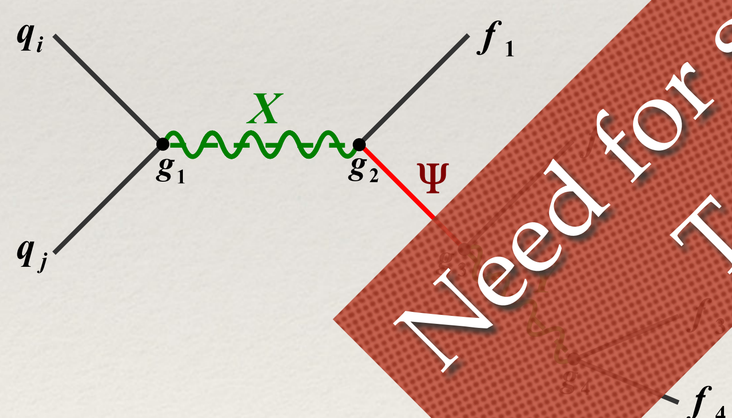
$$\log_{10} \frac{\Gamma_W(qq \to \ell^+ \ell^+ qq)}{H} \gtrsim 6.9 + 0.6 \left(\frac{M_X}{\text{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}$$

would need electroweak, resonant, ARS, post-sphaleron baryogenesis

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 ... $\leftrightarrow W_R\, e_R$; processes stay long in equilibrium (...ere, Hambye, *Vertongen; Dev, Mohapatra; ... al.)*

- more model-independent (*...ppisch, Harz, Hirsch*):



...ut:

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

Need for standard leptogenesis when TeV-scale LNV is present?

would need electroweak, resonant, ARS, post-sphaleron baryogenesis

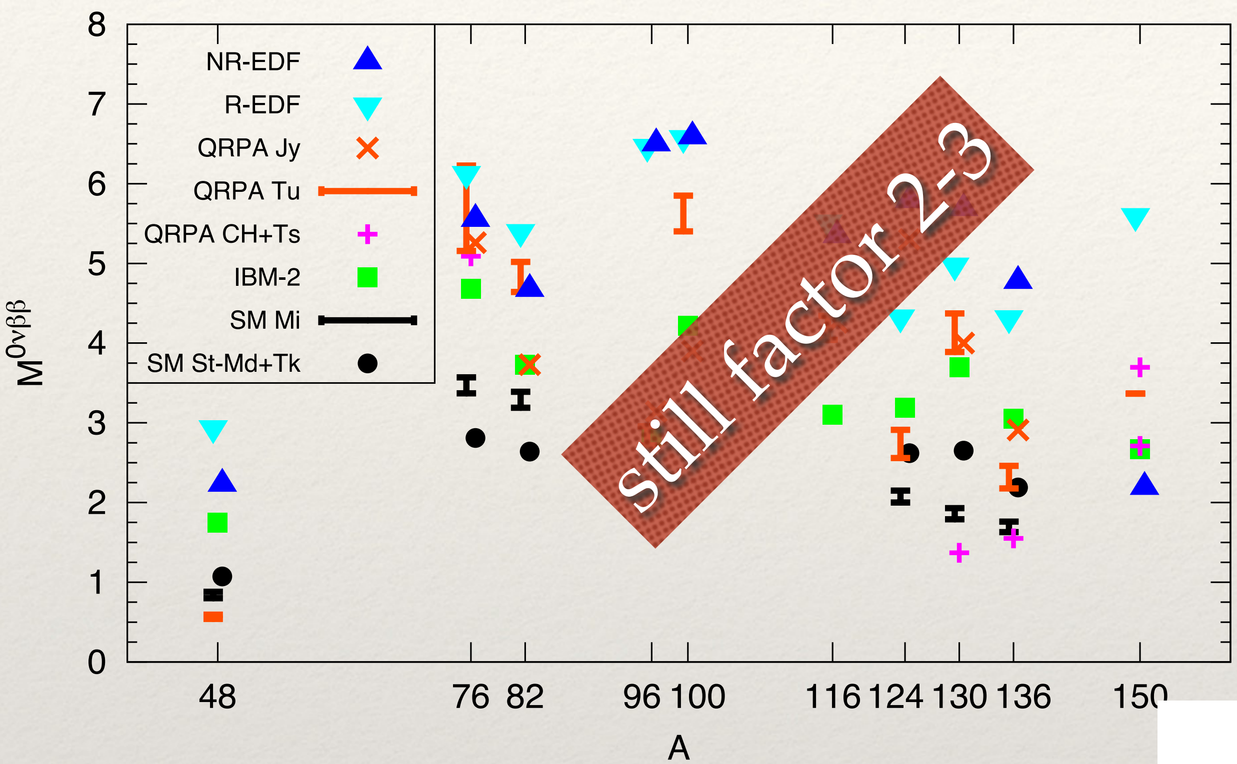
Summary

Chi l'ha visto?

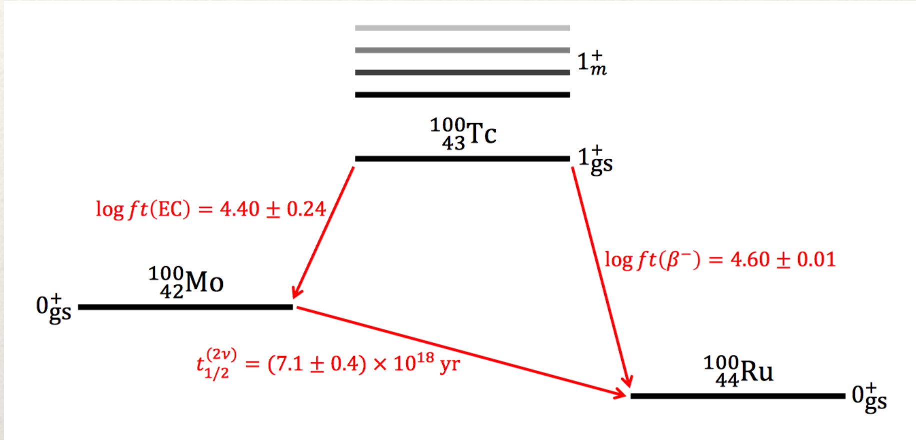
Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Nuclear Matrix Elements

Engel, Menendez, 1610.06548

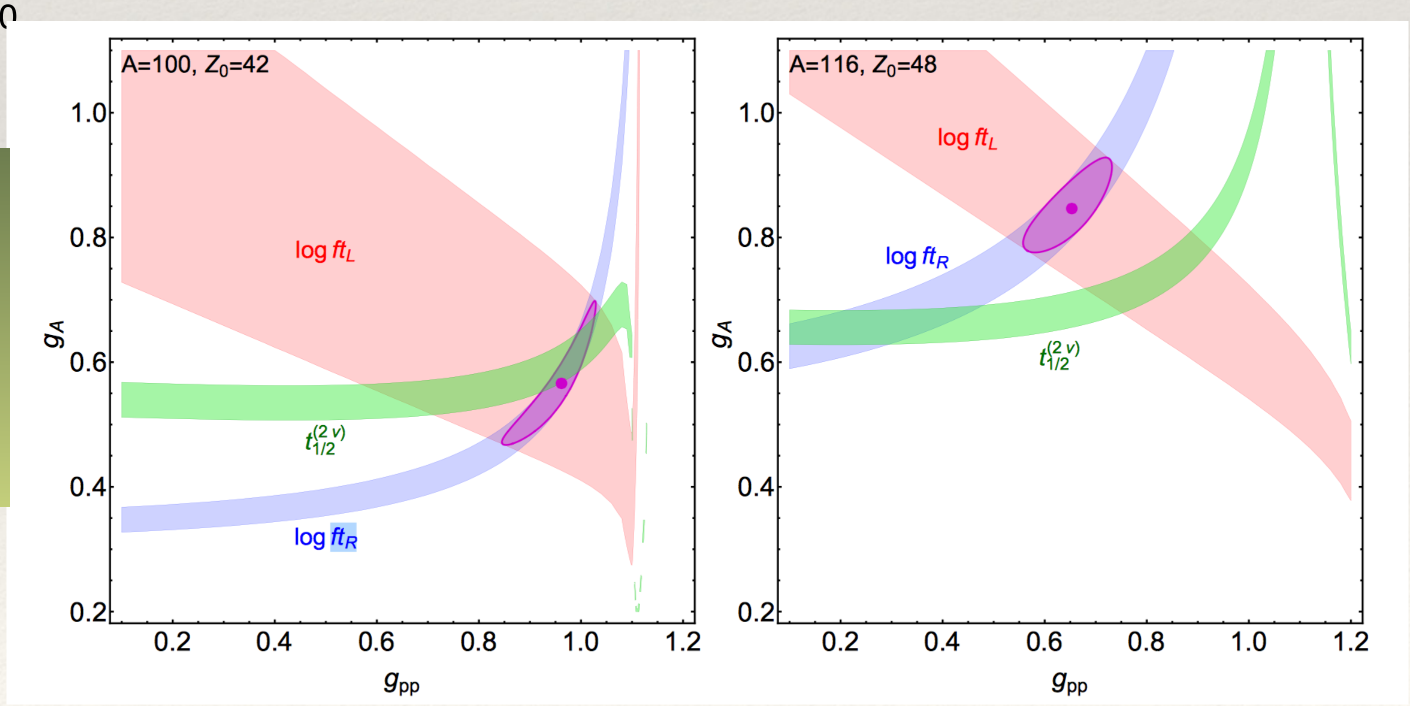


How good are the models?
Example isobaric triplets
within QRPA



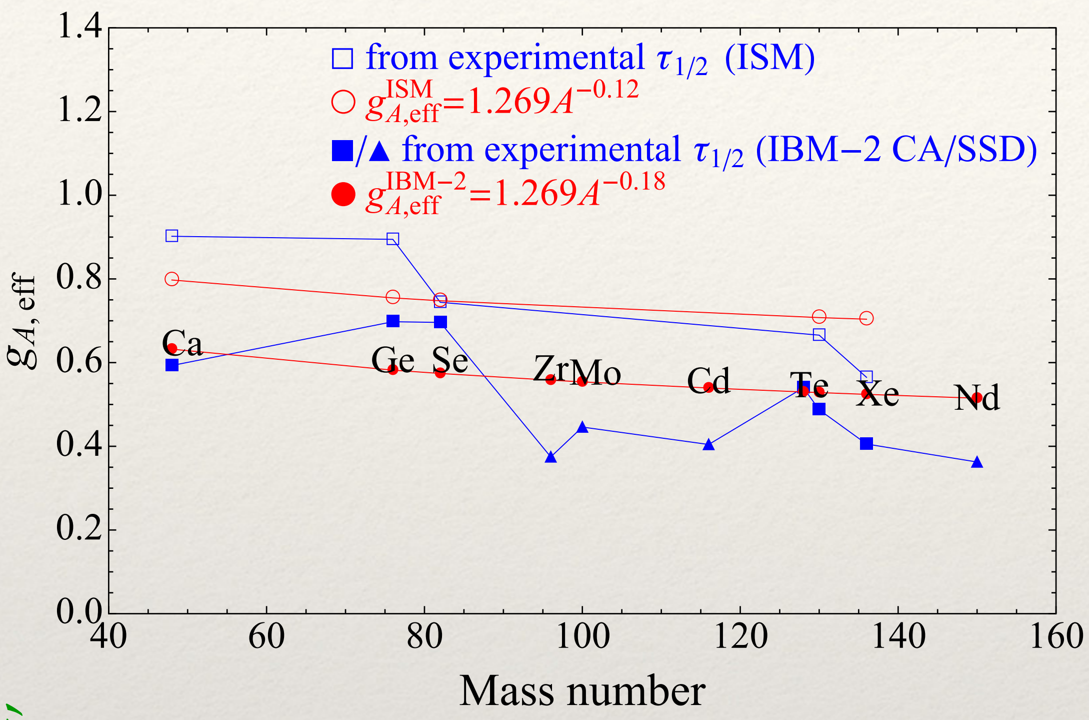
Deppisch, Suhonen, 1606.02908

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

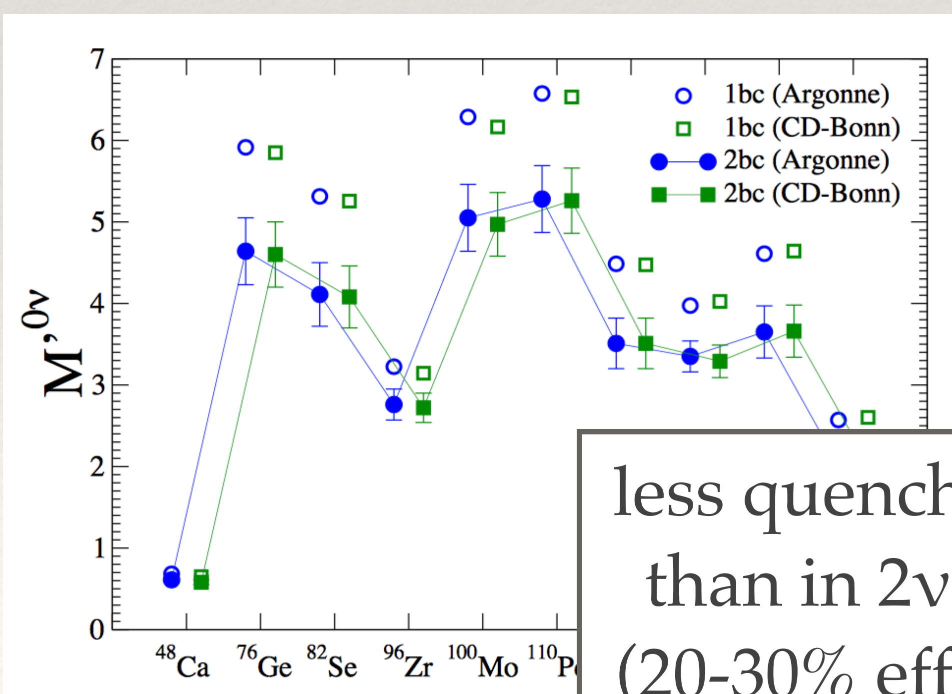


Nuclear Matrix Elements

Iachello et al., 1506.08530



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



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

QUENCHING??

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

- 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

Dirac vs. Majorana beyond *V-A*

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

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:

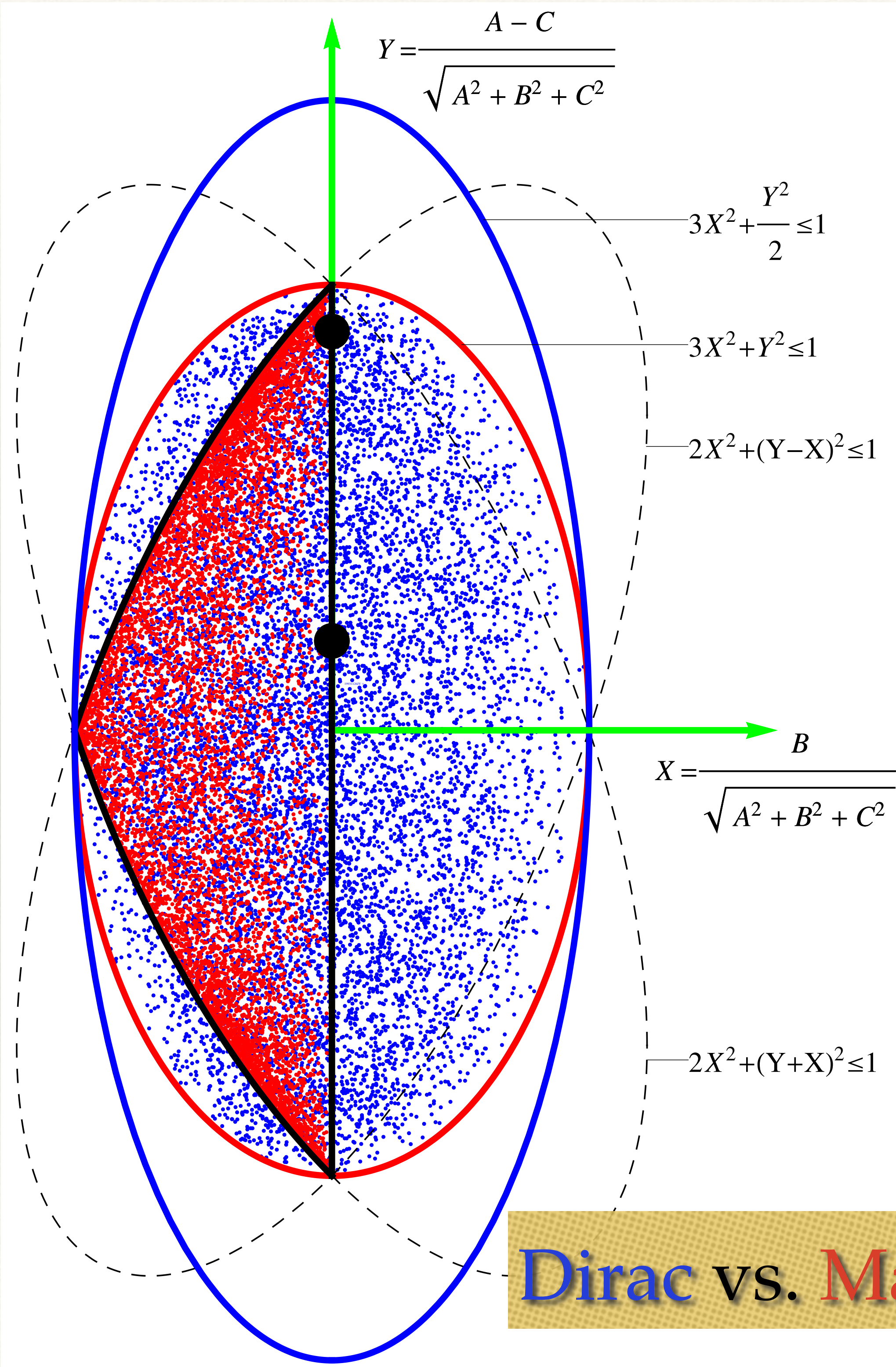
$$A \equiv \frac{1}{4}(C_A - D_A + C_V - D_V)^2 + \frac{1}{2}C_P C_T + \frac{1}{8}(C_P^2 + C_S^2 + D_P^2 + D_S^2) - \frac{1}{2}C_S C_T + C_T^2 + \frac{1}{2}D_P D_T - \frac{1}{2}D_S D_T + D_T^2$$

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

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

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

Dirac vs. Majorana beyond *V-A*



Dirac vs. Majorana

can only demonstrate Dirac nature!

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

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

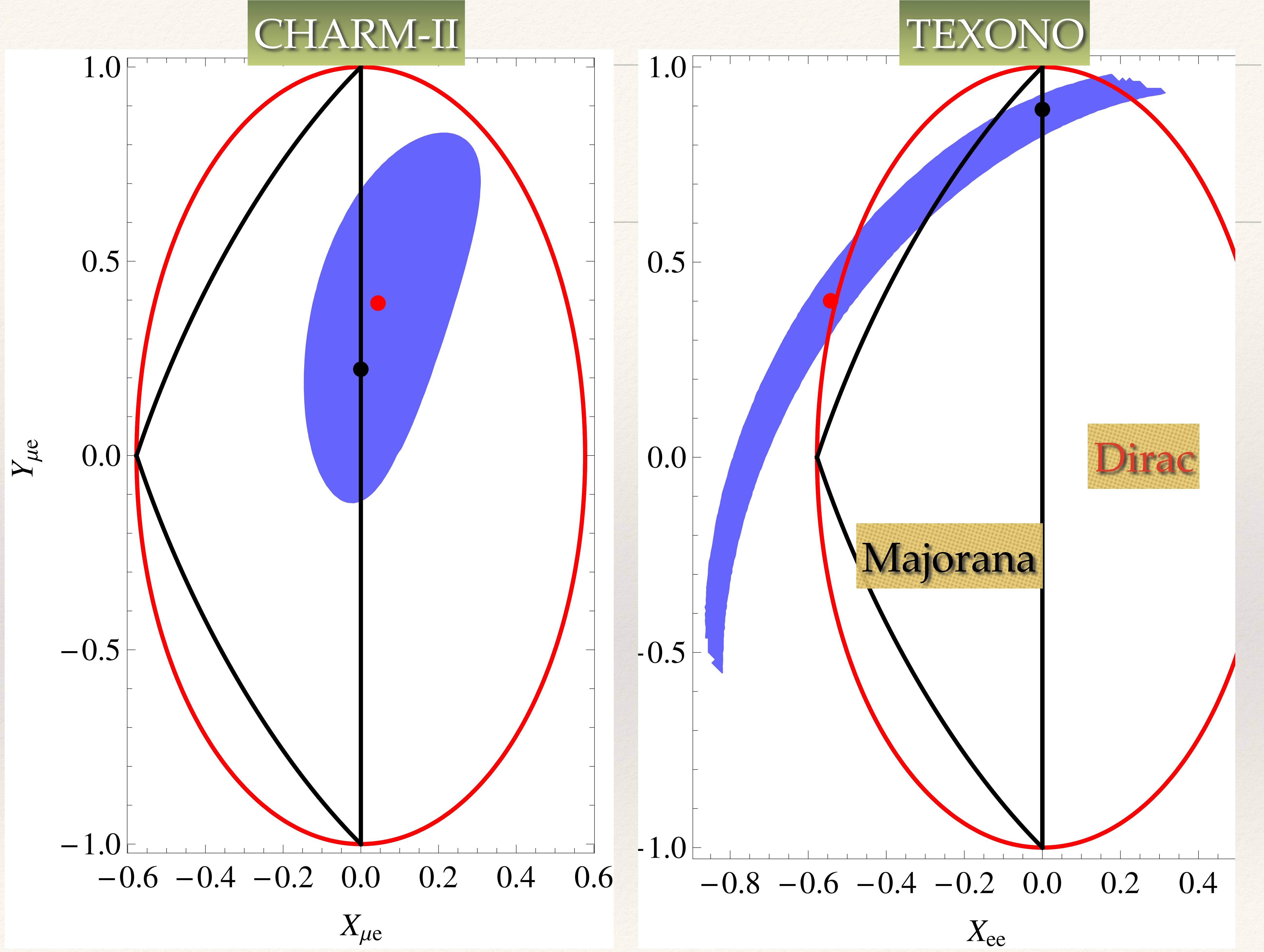
Dirac neutrinos:

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

Majorana neutrinos:

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

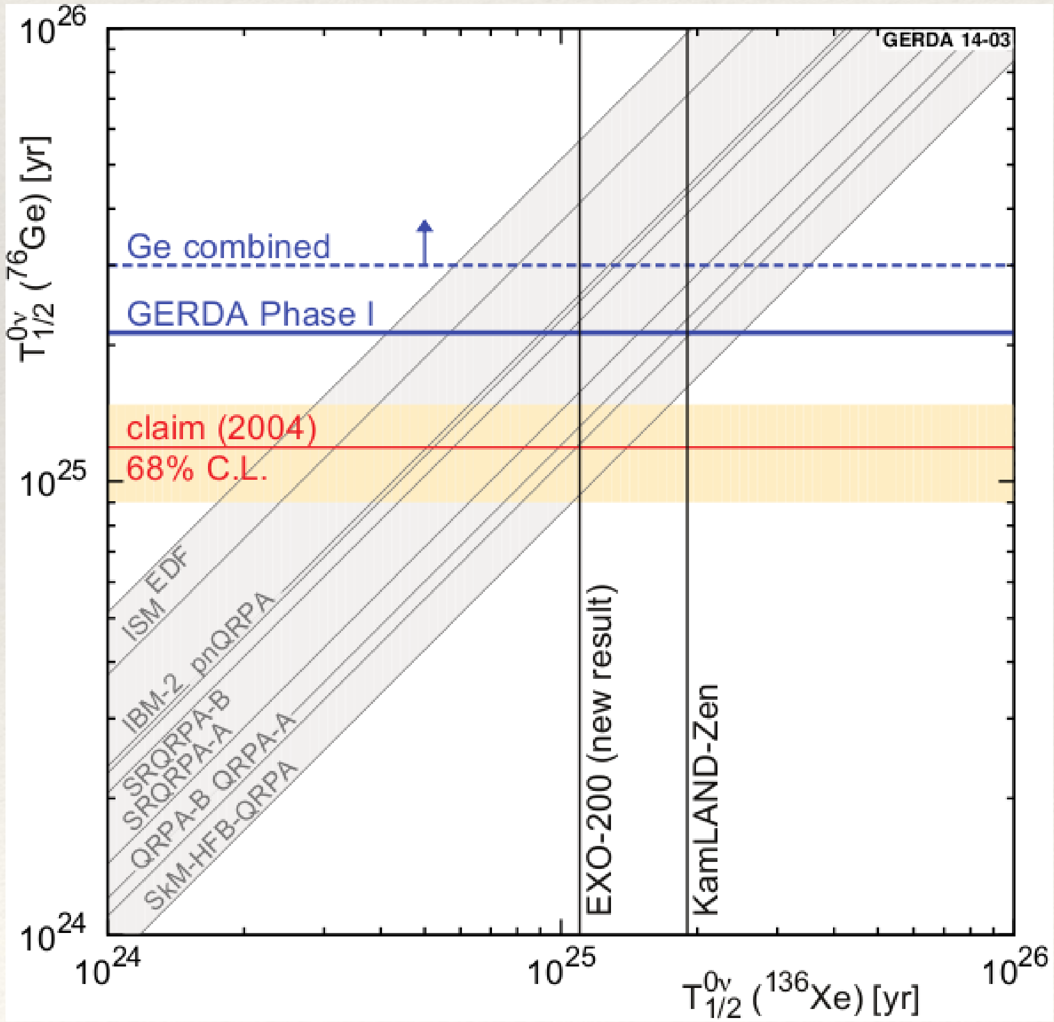
WR, Xu, Yaguna, 1702.05721


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
$X_{\mu e}$
-0.5
-1.0
−0.8
X_{ee}
Dirac
Majorana

Comparison of Limits

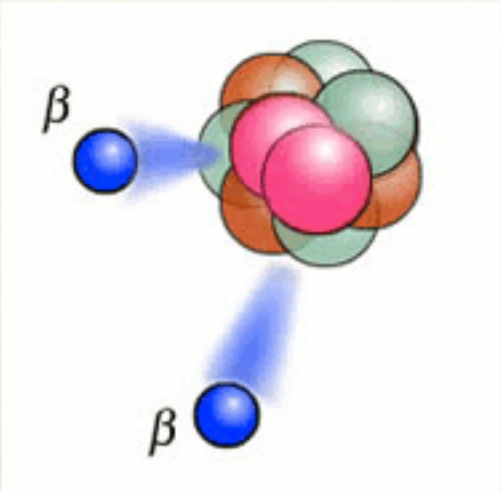
Limit from Xenon is better than limit from Germanium if:

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



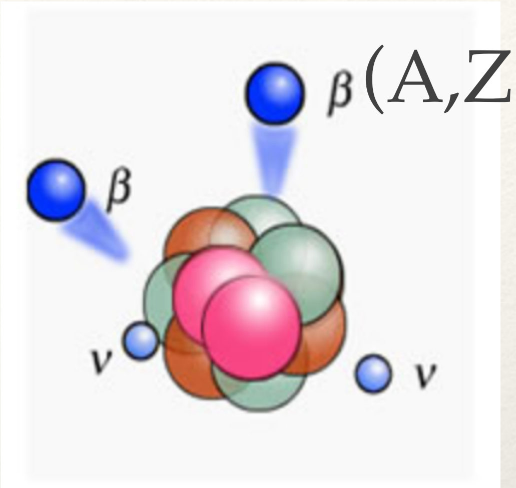
- depends on NMEs
- for most NMEs Xe better
- limit about $m_{ee} < 0.2$ eV
- means 0.2…0.6 eV for KATRIN
- means 0.6…1.8 eV for cosmo

Best chance: Neutrinoless Double Beta Decay



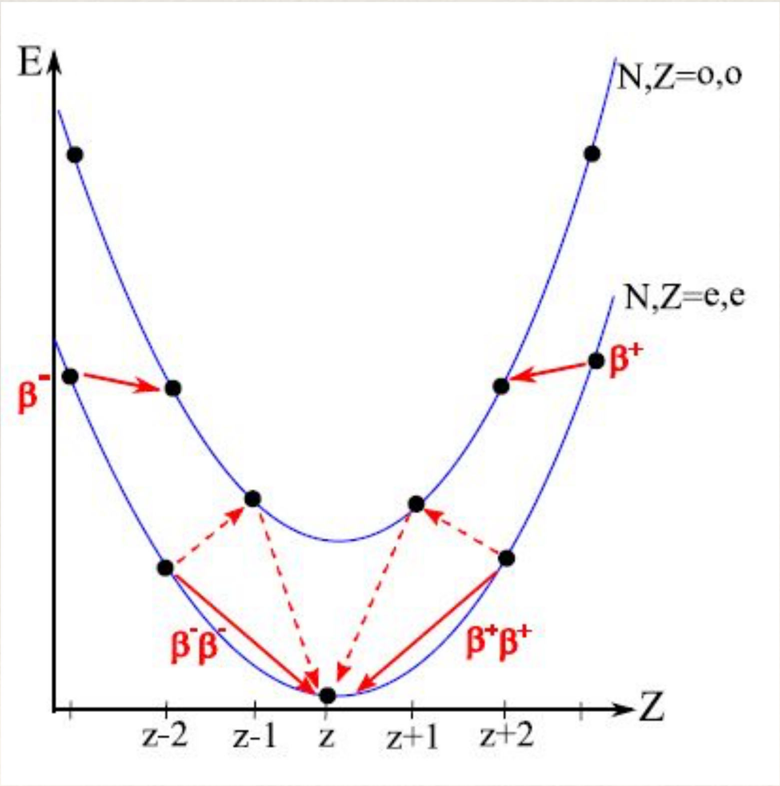
$(A,Z) \to (A,Z+2) + 2\,e^-$

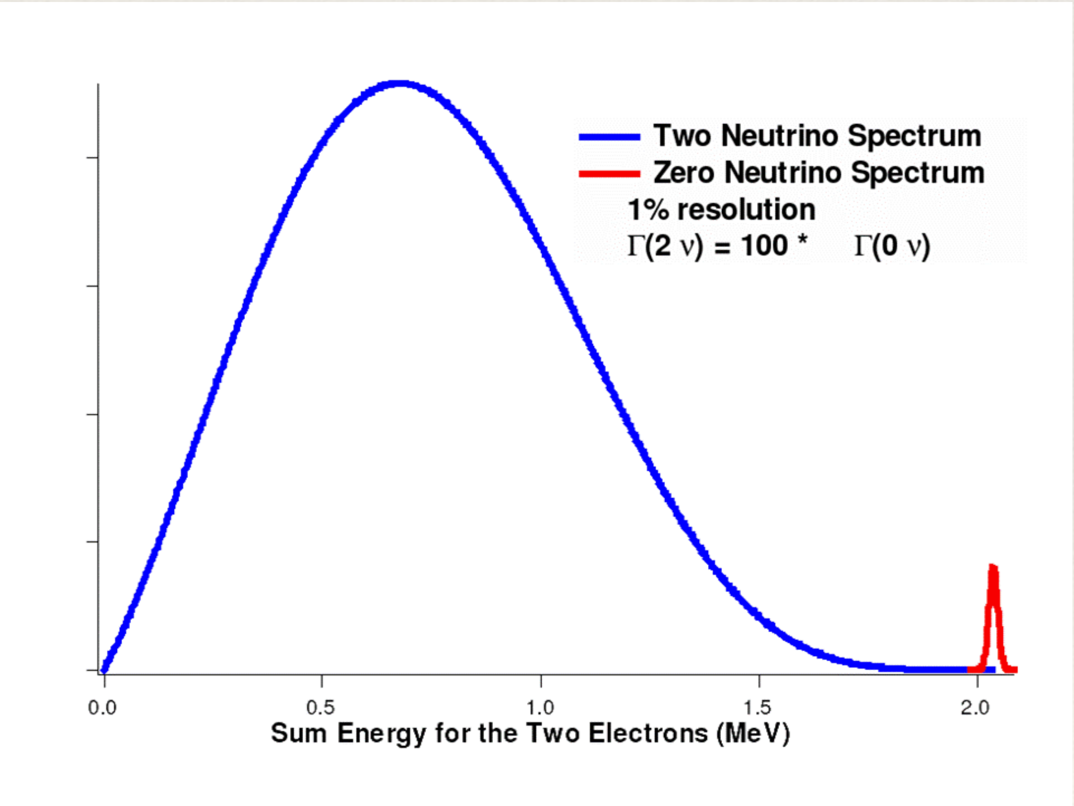
$\Delta L = 2$



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

$\Delta L = 0$

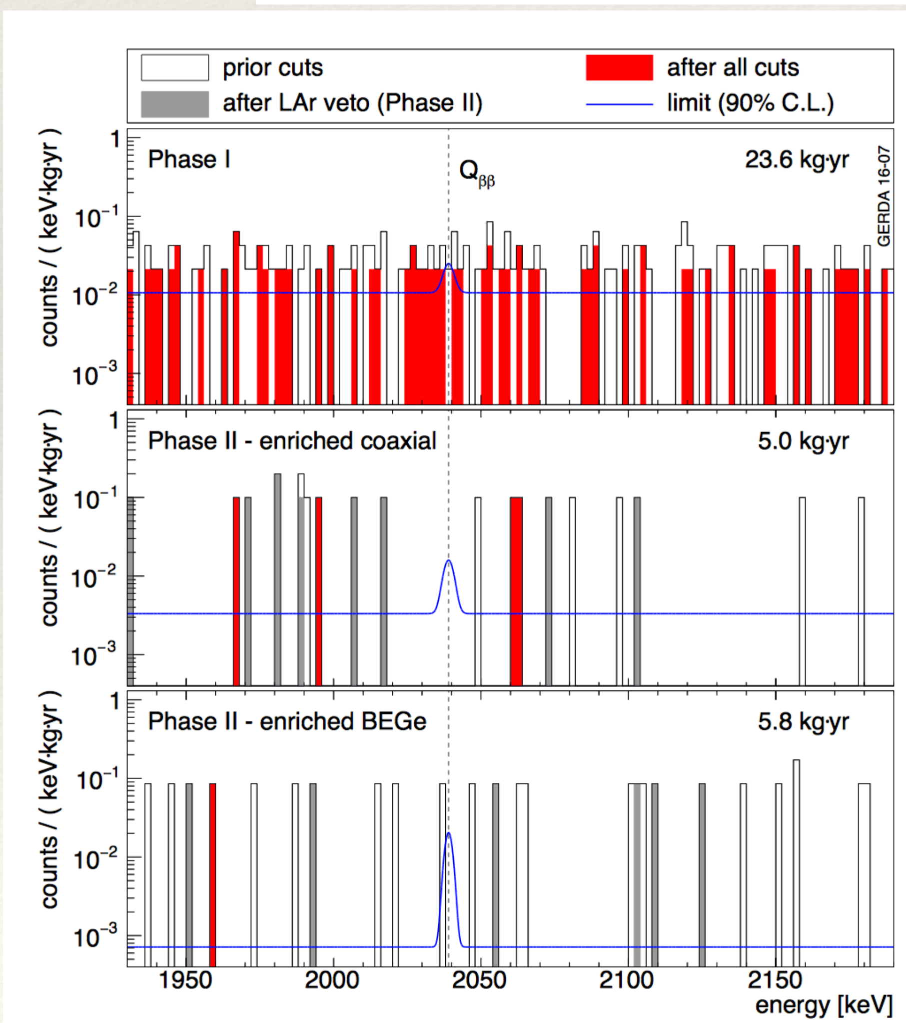




Neutrinoless Double Beta Decay

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

GERDA, 1703.00570, Nature



first background free result

current limits: $T_{1/2} \gtrsim 10^{26}$ years
with exposure of about 100 kg • years

Ne… Decay

…ound

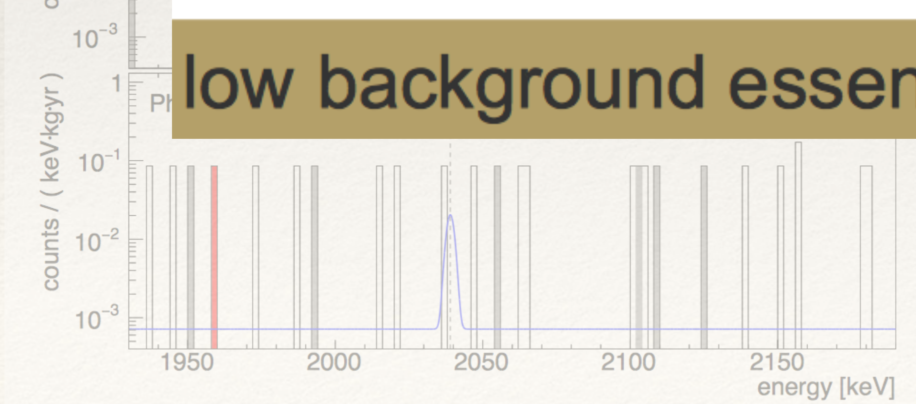
…und

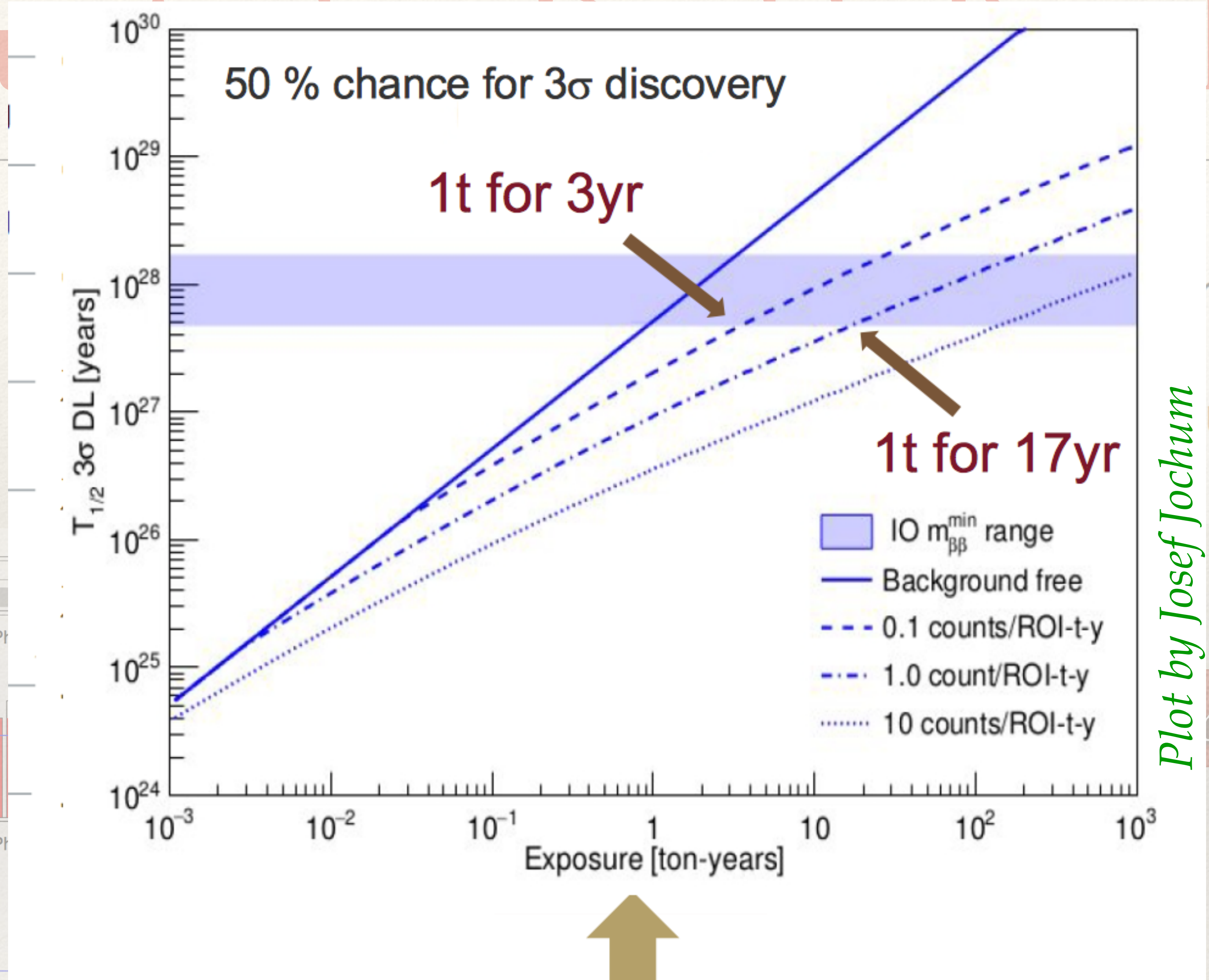
…ree result

… 10^{26} years

… 100 kg · years

GERDA, 1703.00570, Nature





Plot by Josef Jochum

low background essential for discovery potential

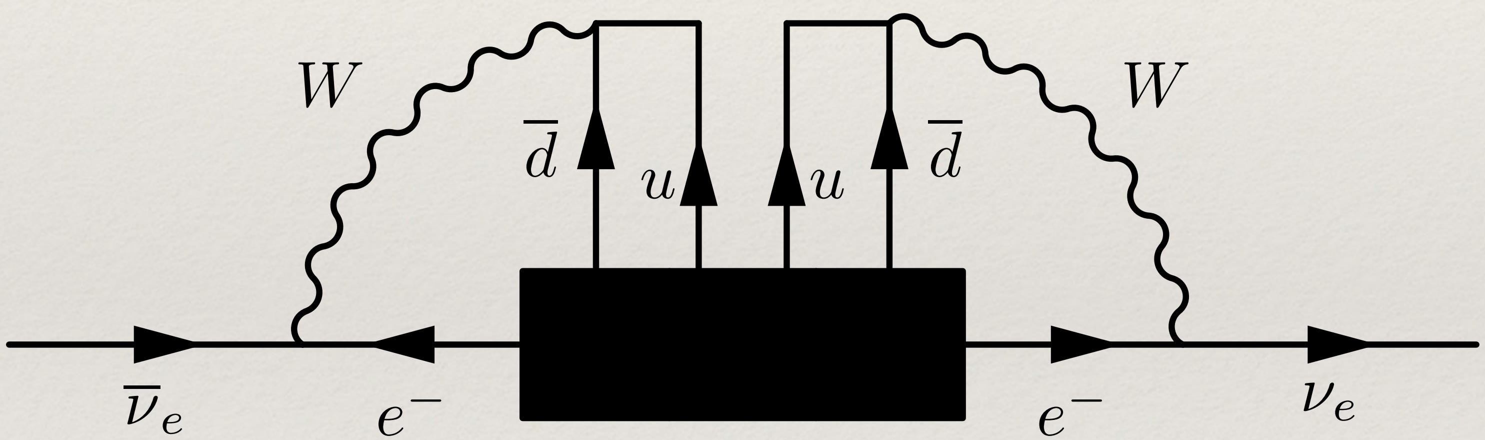
Neutrinoless Double Beta Decay

Table by Josef Jochum

			isotope	isotope mass [kg] in FV	FWHM [keV]	background [(FWHM $\varepsilon\, t_{isotope}$ 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

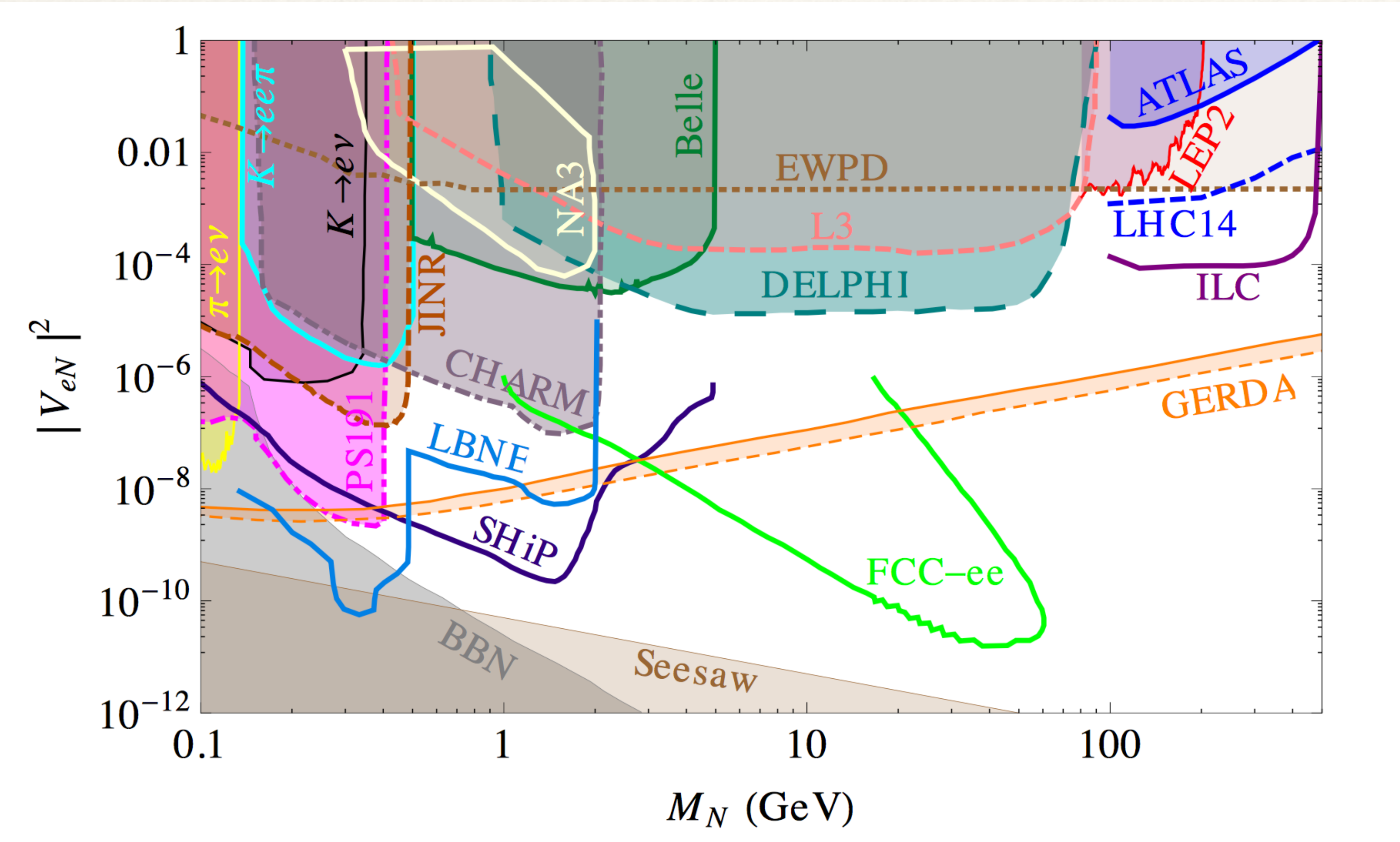
- Whatever the mechanism, observation of 0νββ implies Majorana neutrinos *(Schechter-Valle, '82)*

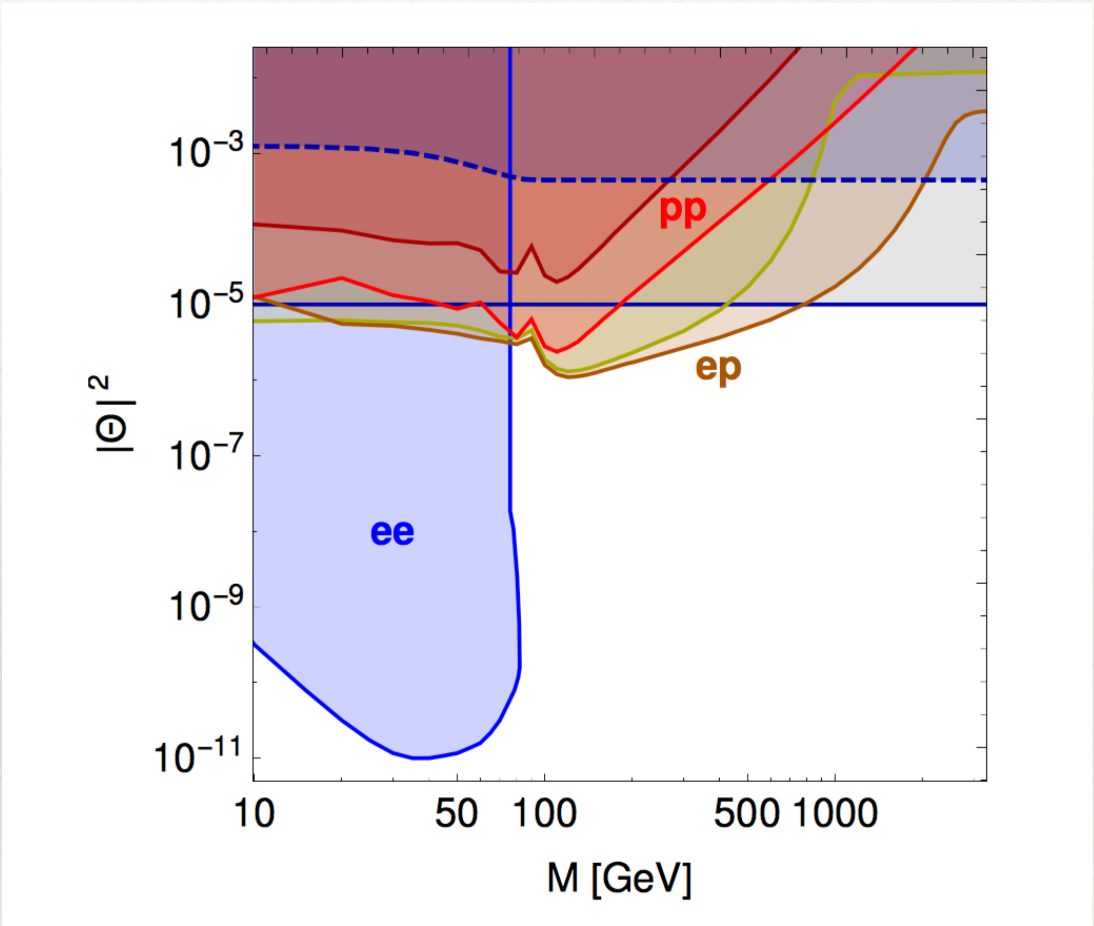


- is 4-loop diagram ⇒ tiny mass *(Dürr, Lindner, Merle, 1105.0901)*

Limits on Heavy Neutrinos

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





Deppisch, Dev, Pilaftsis, 1502.06541

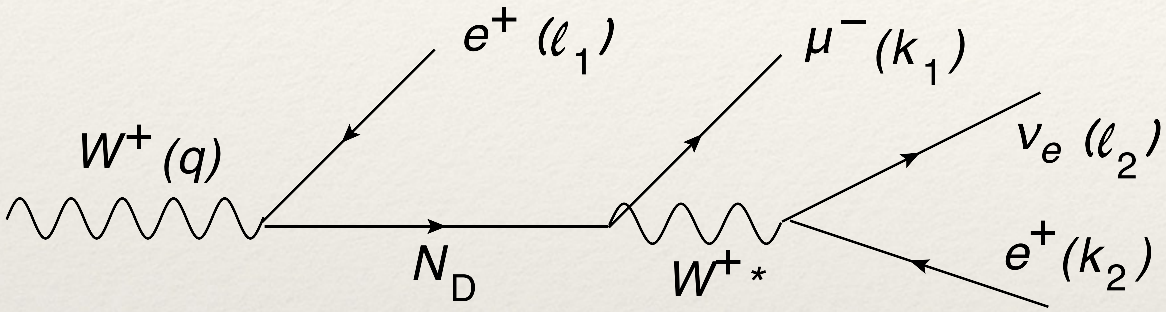
Antusch, Cazzato, Fischer, 1612.02728

peak searches, kink searches, LNV decays,…

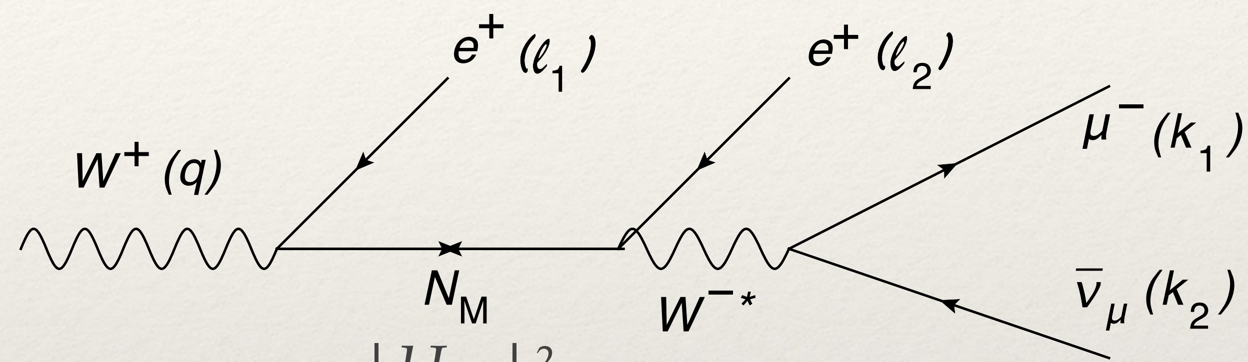
see also Atre et al., 0901.3589

New Idea

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



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

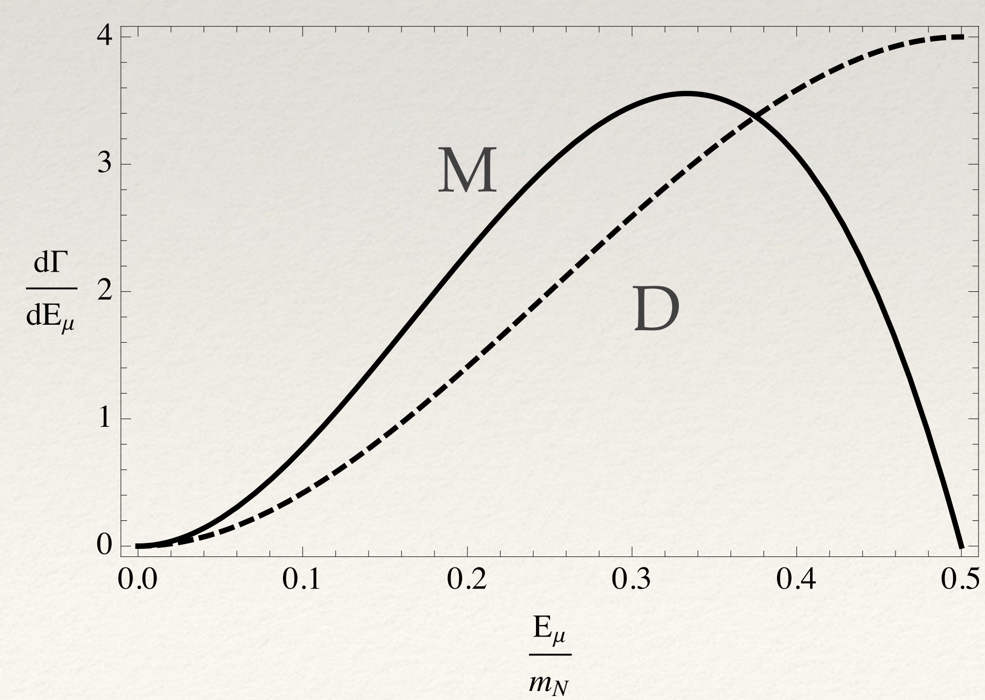


$|U_{Ne}|^2$

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

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

$\Delta L = 0$

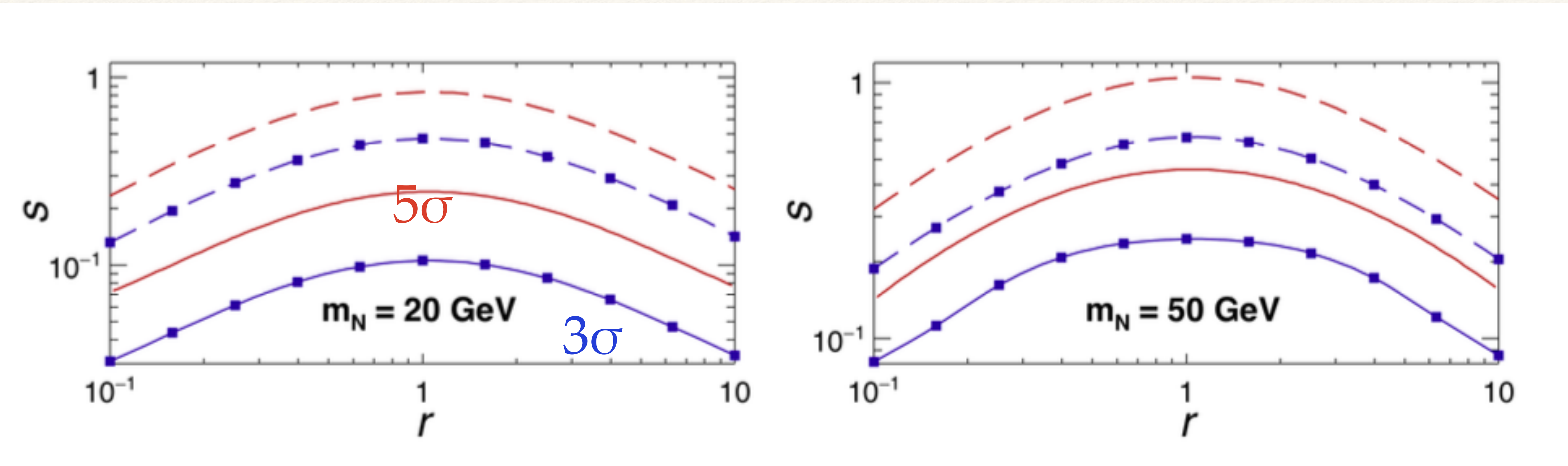


$\Delta L = 2$

hidden in ν…

but μ comes from different vertex!

New Idea

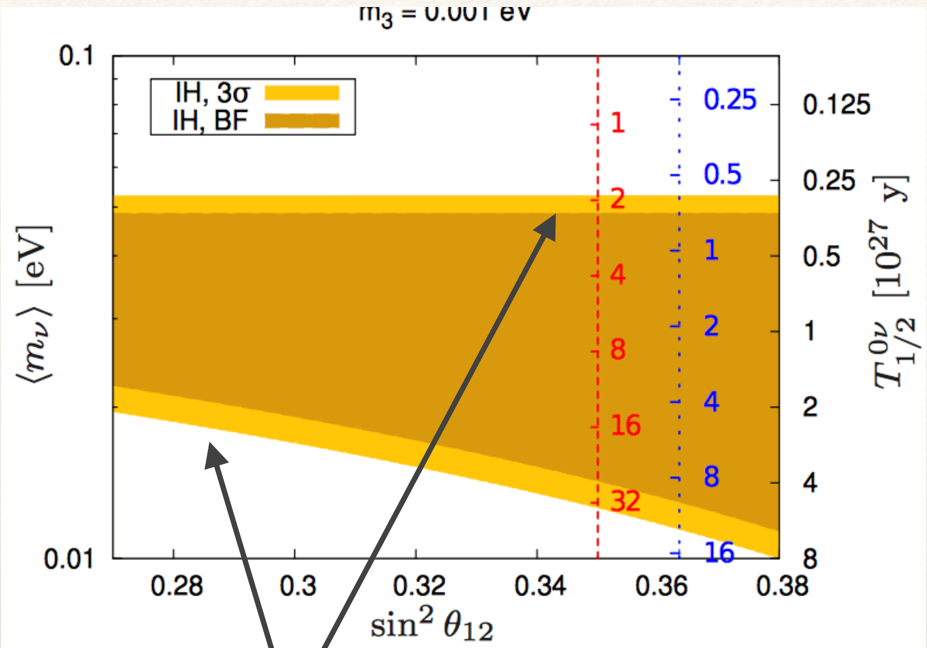


(solid is mult-variate; dashed is cut-and-count)

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

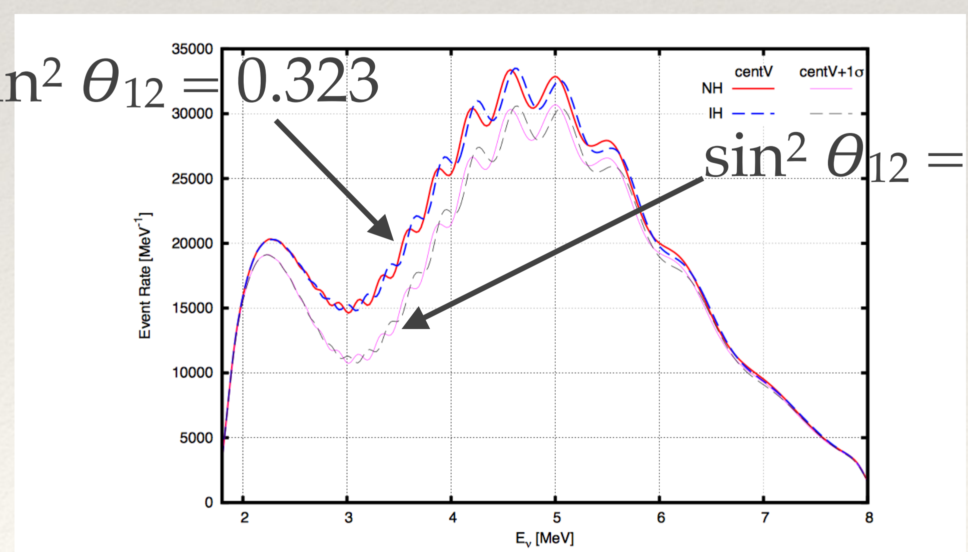
Dib, Kim, Wang, 1703.01936

Connections to Oscillation Experiments



Nature gives us two scales

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



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

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

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

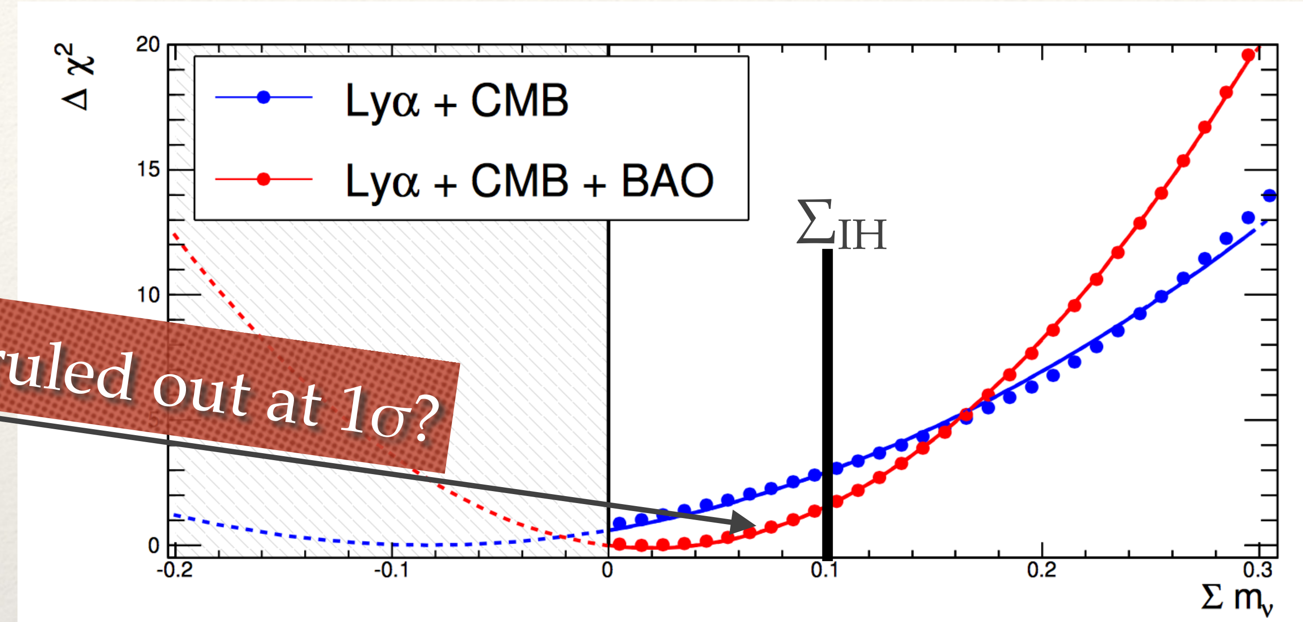
Dueck, WR, Zuber, 1103.4152; Ge, WR, 1507.05514

Cosmological Mass Limits

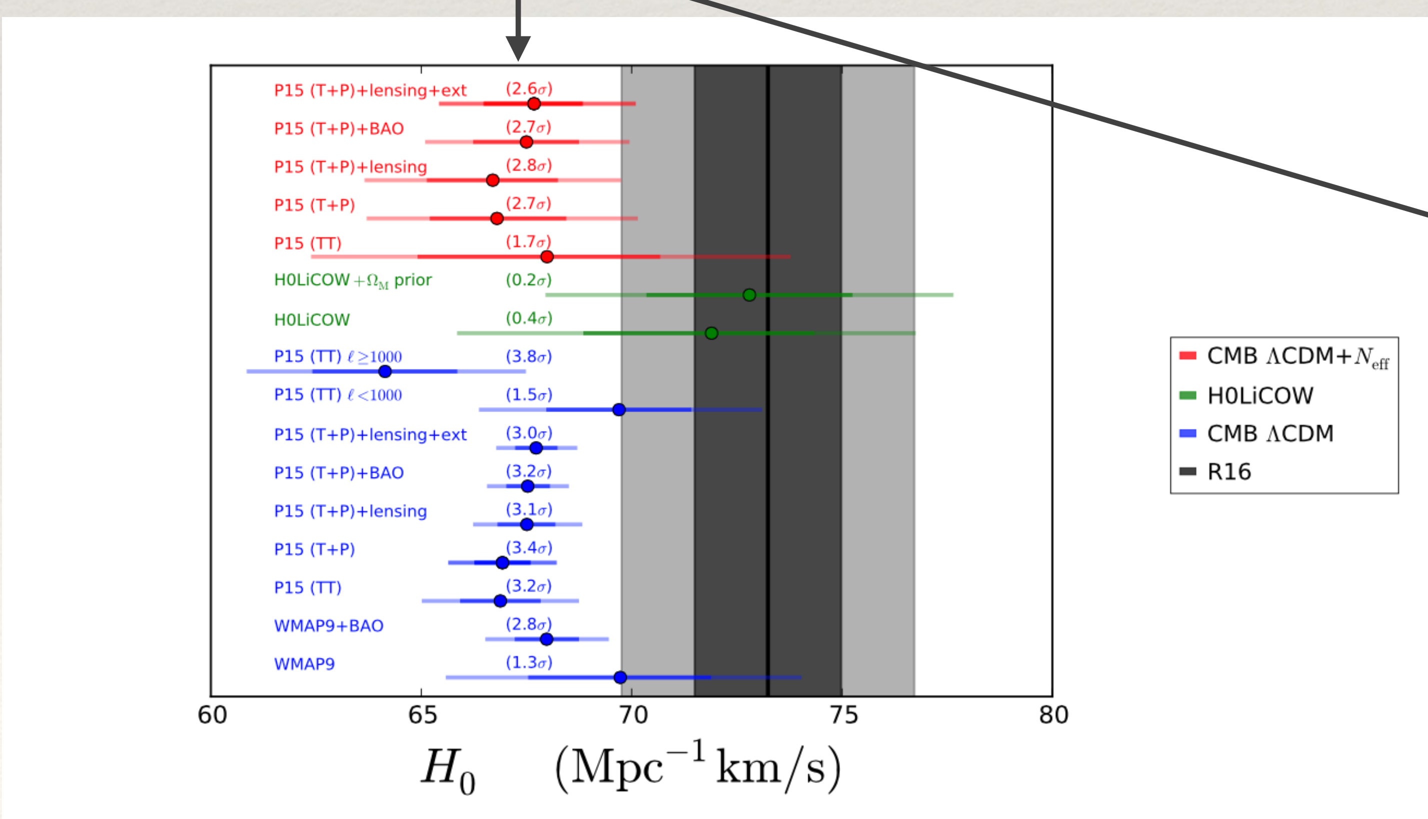
talk by Takada

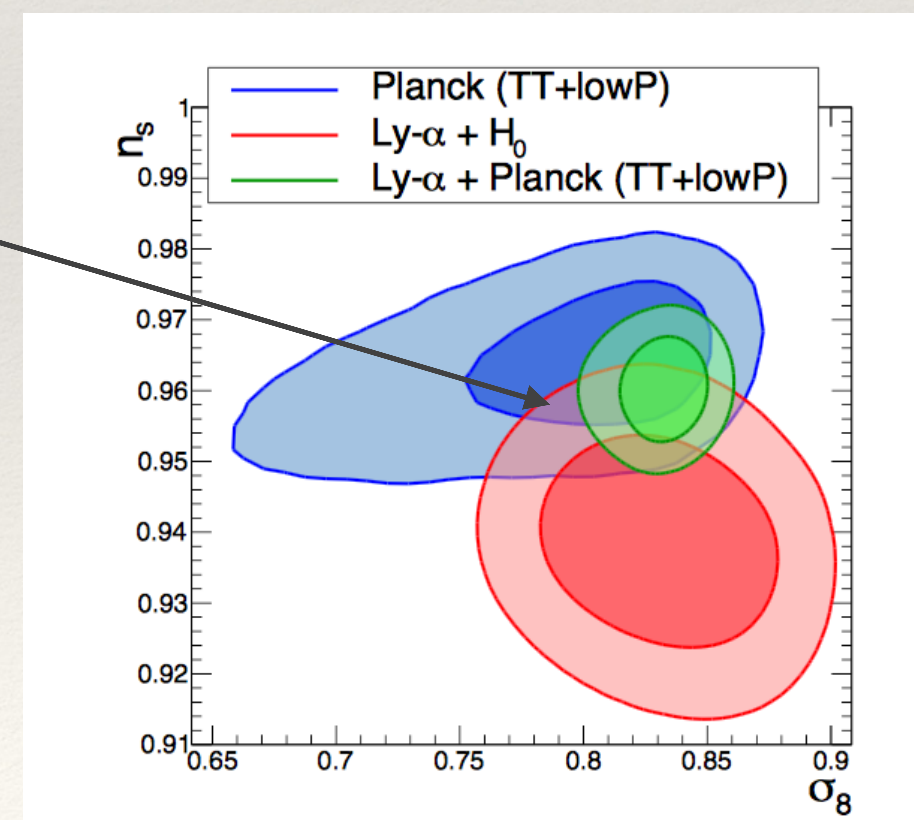
- adding more and more data sets: breaks degeneracies and improves limits
- BUT: can introduce systematics?

IH ruled out at 1σ?



Palanque-Delabrouille et al., 1410.7244 + 1506.05976

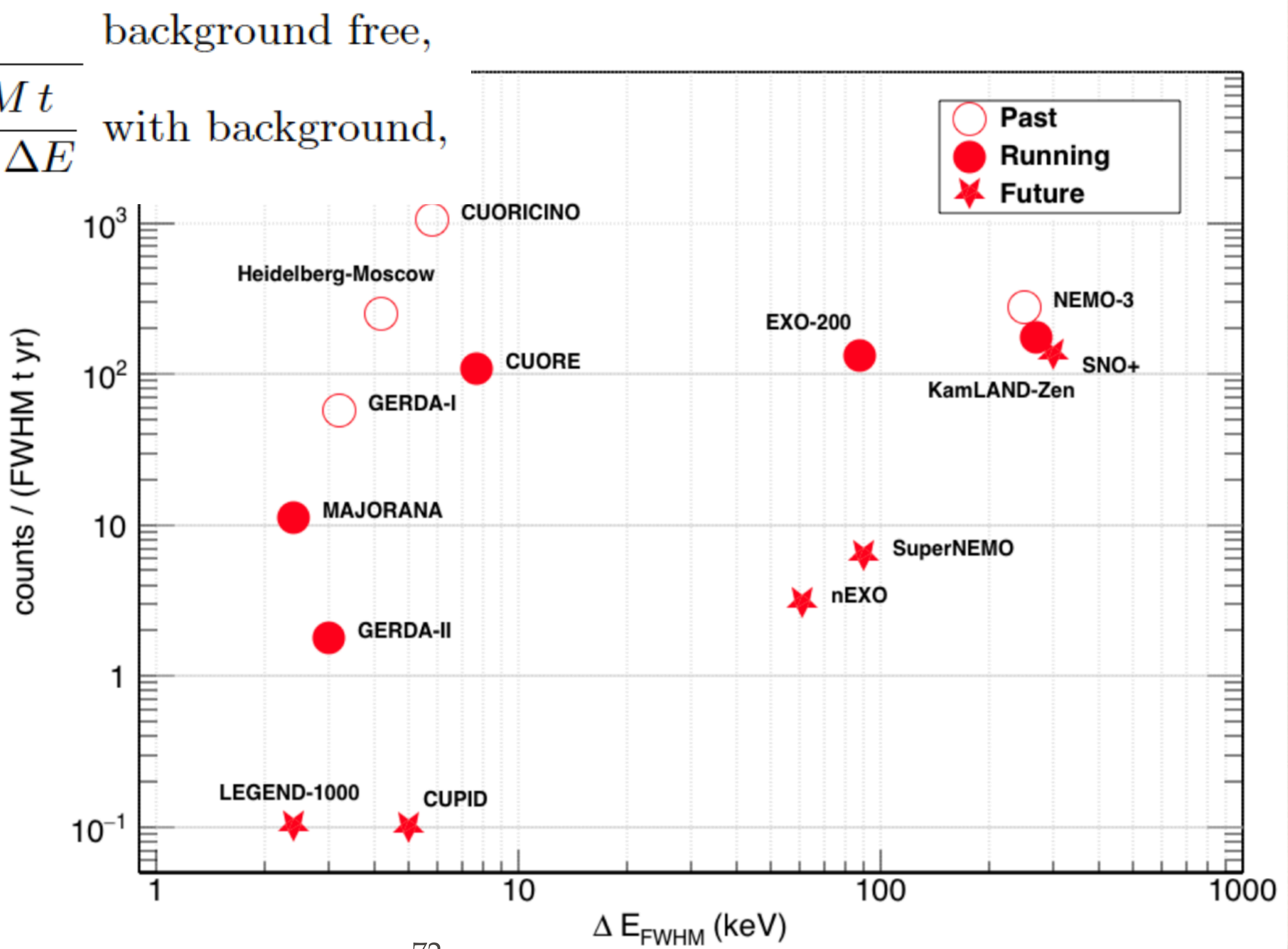




Bernal, Verde, Riess, 1607.05617

Neutrinoless Double Beta Decay

$$(T_{1/2}^{0\nu}) \propto \begin{cases} a\, M\, \varepsilon\, t & \text{background free,} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background,} \end{cases}$$



Dolinski, Poon, WR, 1902.04097