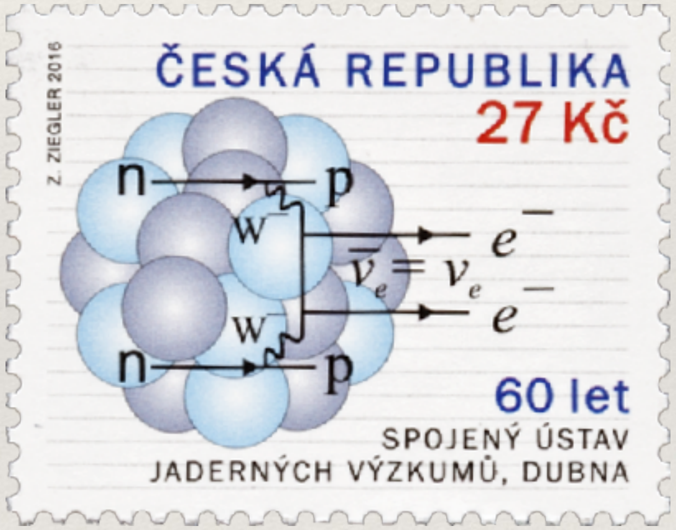
How to tell if a particle is its own antiparticle

Werner Rodejohann (MPIK)

26/01/22

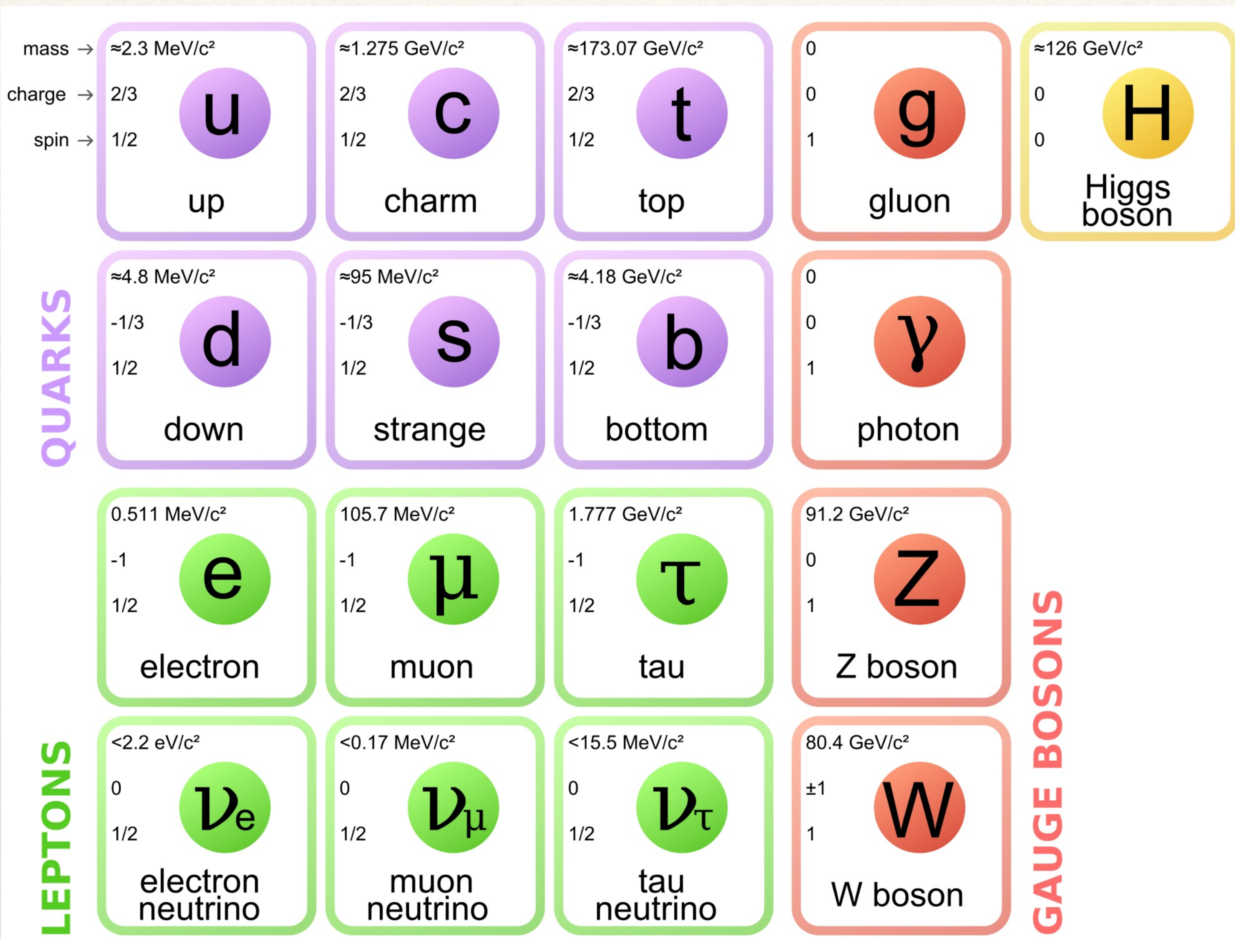
Outline

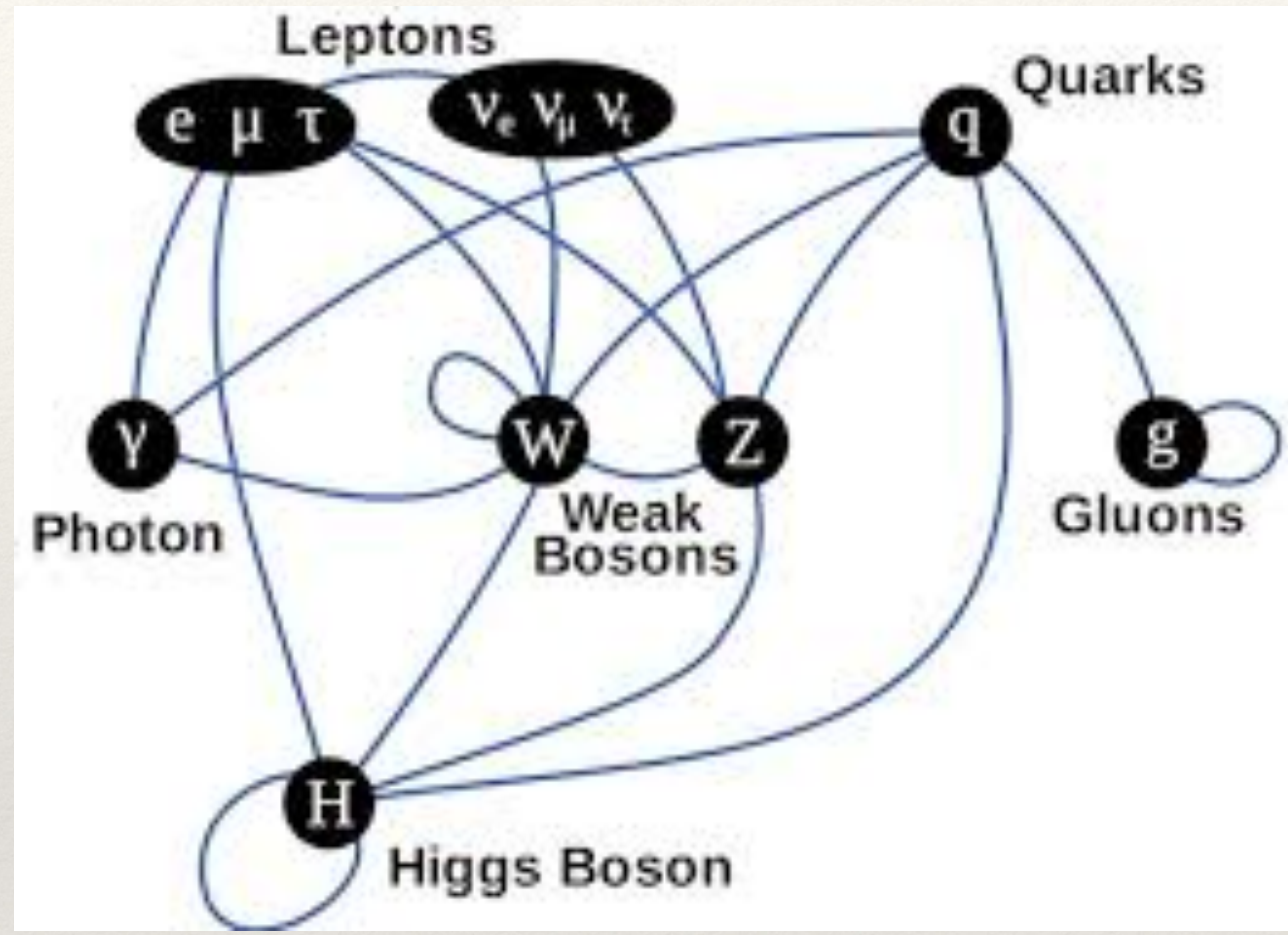
- Lepton Number Violation: Why look for it?
- Neutrinoless Double Beta Decay $(A,Z) \to (A,Z+2) + 2\,e^-$:
  - Standard Interpretation
  - Non-Standard Interpretations



- $\Delta L = 2$ versus $\Delta L = 4$
- Self-conjugacy of dark matter

The Standard Model

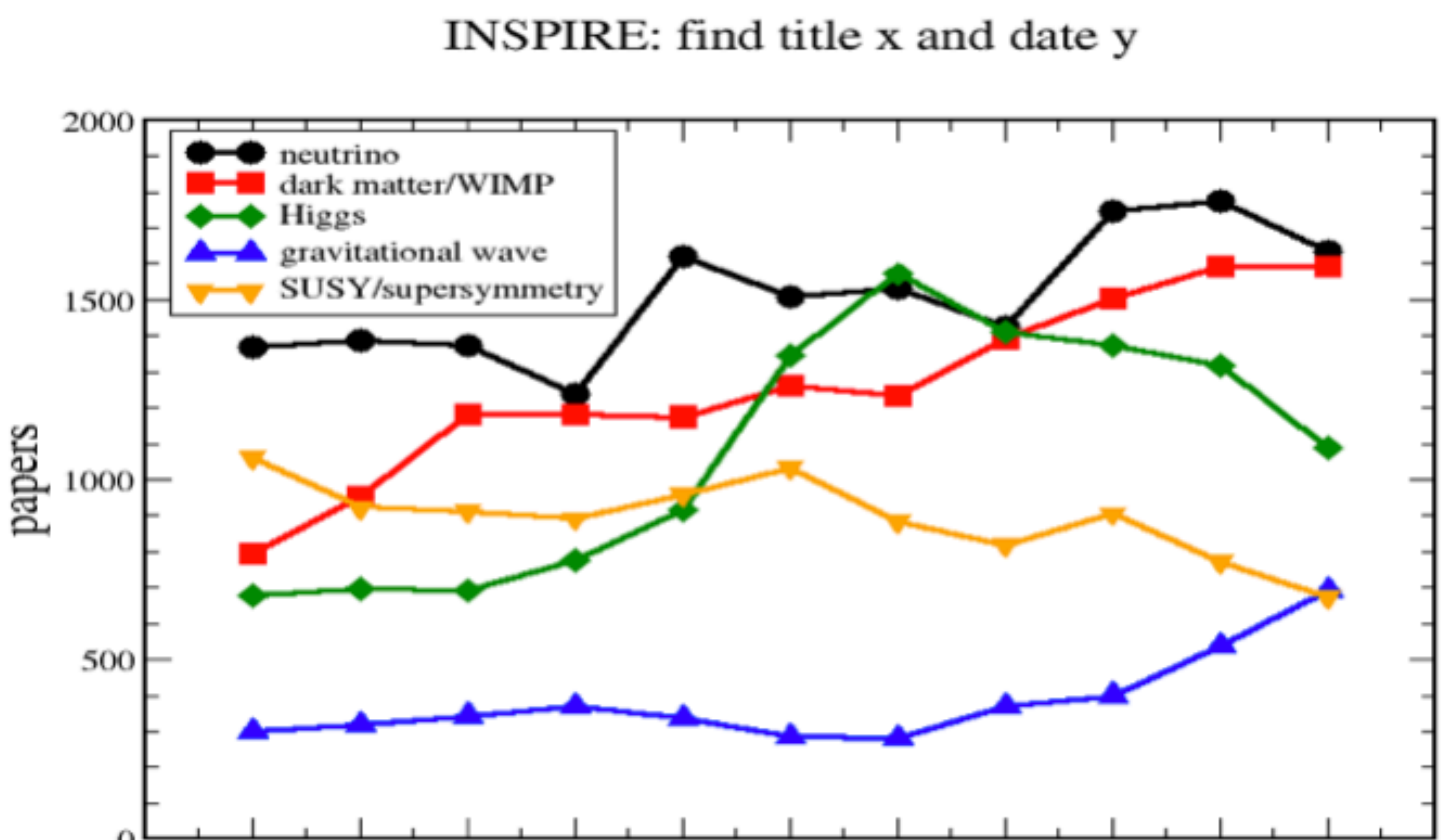




Single energy scale!
Interactions fixed by mathematical structure (gauge symmetry)
and symmetry breaking (Higgs): Confirmed!

Contains 19 free parameters, leaves unexplained many observational facts,…

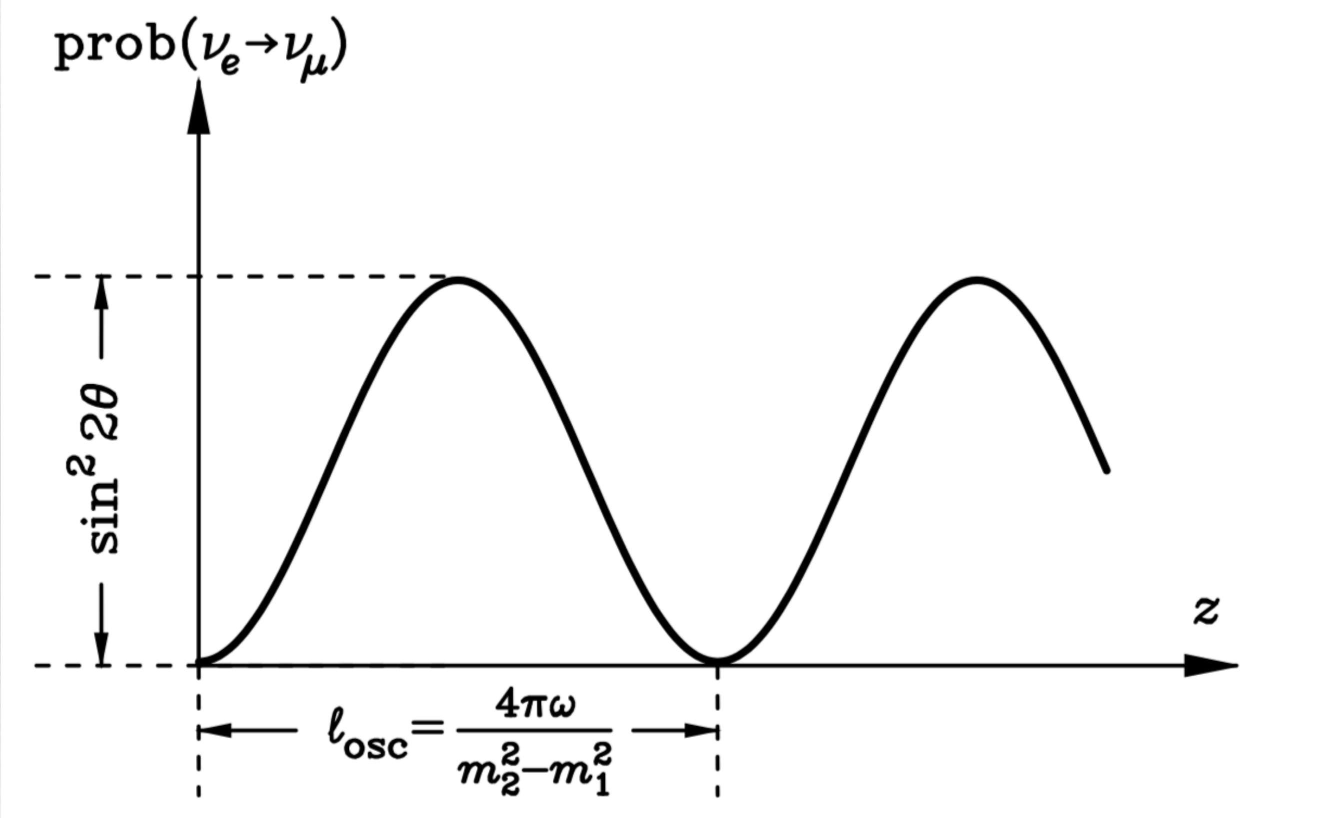
Neutrinos

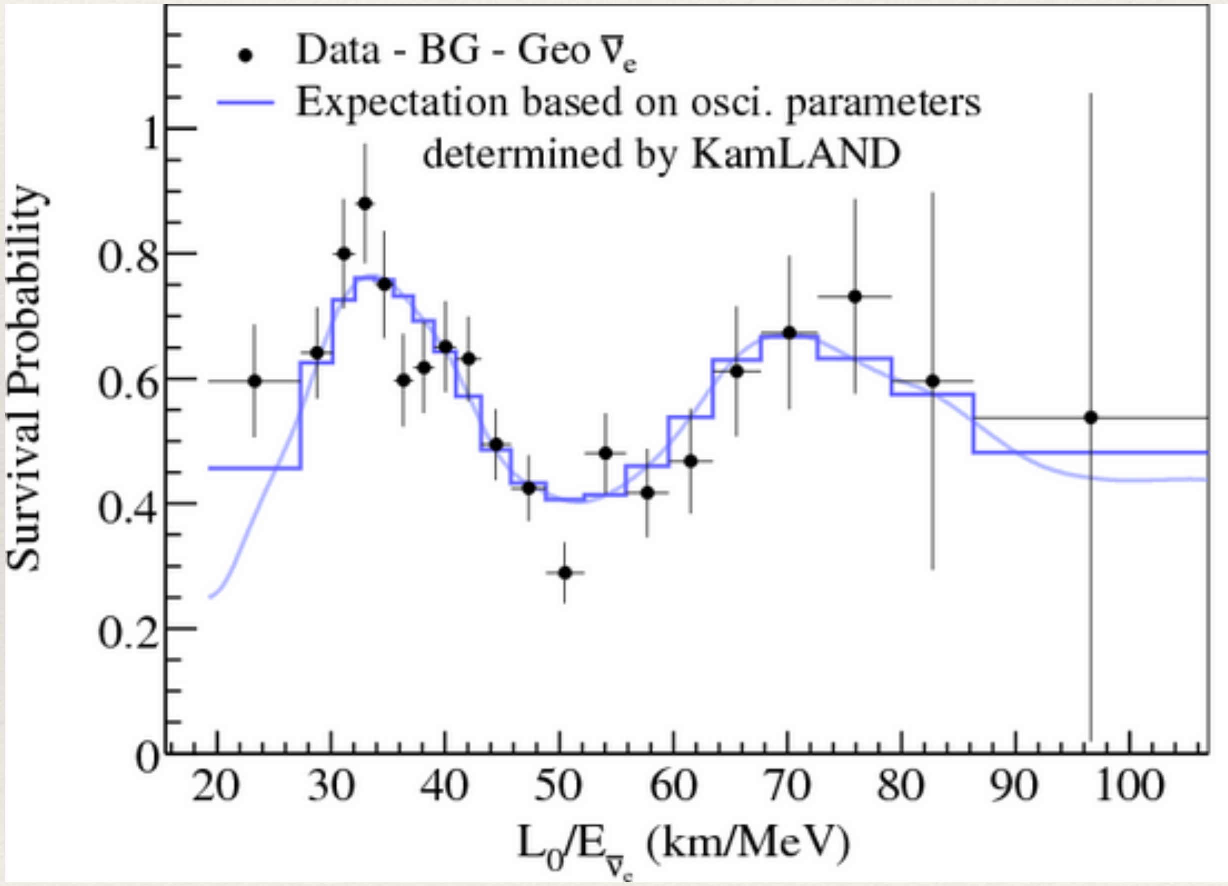


INSPIRE: find title x and date y
neutrino
dark matter/WIMP
Higgs
gravitational wave
SUSY/supersymmetry
papers
2000
1500
1000
500

Neutrinos do have mass!

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right).$$





Note: only mass (squared) differences can be measured!

Puzzles

- **neutrino mass much much smaller than all other masses**
- **lepton mixing completely different from quark mixing (CKM)**

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Origin of Neutrino Mass

- Most straightforward possibility: add N_R and obtain Dirac mass:

$$\overline{L}\, \Phi\, N_R \to m_D\, \overline{\nu_L}\, N_R$$

- Gauge invariance allows Majorana mass

$$M_R\, N_R\, N_R^c$$

- in total Majorana mass for SM neutrinos:

$$m_\nu\, \nu_L^c\, \nu_L \text{ with } m_\nu = m_D^2 / M_R = m_D\, \varepsilon \text{ with } \varepsilon = m_D / M_R = m_{SM} / M_R$$

violates lepton number by two units: $\Delta L=2$

m_ν inversely proportional to scale of origin!

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- mass term links LH and RH projection
- here RH projection is LH^c
- thus: nu = LH + RH = LH + LH^c
- and thus: nu^c = LH^c + LH = nu
- is its own antiparticle!

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  New concept: lepton number violation

violates lepton number by two units: $\Delta L=2$

m_ν inversely proportional to scale of origin!

Origin of Neutrino Mass

- *N_R could be TeV: colliders!*
- *N_R could be keV: dark matter!*
- *N_R could decay in early Universe: baryon asymmetry!*
- *N_R couples to Higgs: vacuum stability, hierarchy problem!*
- *N_R couples to lepton doublets: lepton flavor violation!*

==> Use this to distinguish the many (many!) mechanisms for neutrino mass

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…)

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  wi

Lepton Number as important as Baryon Number

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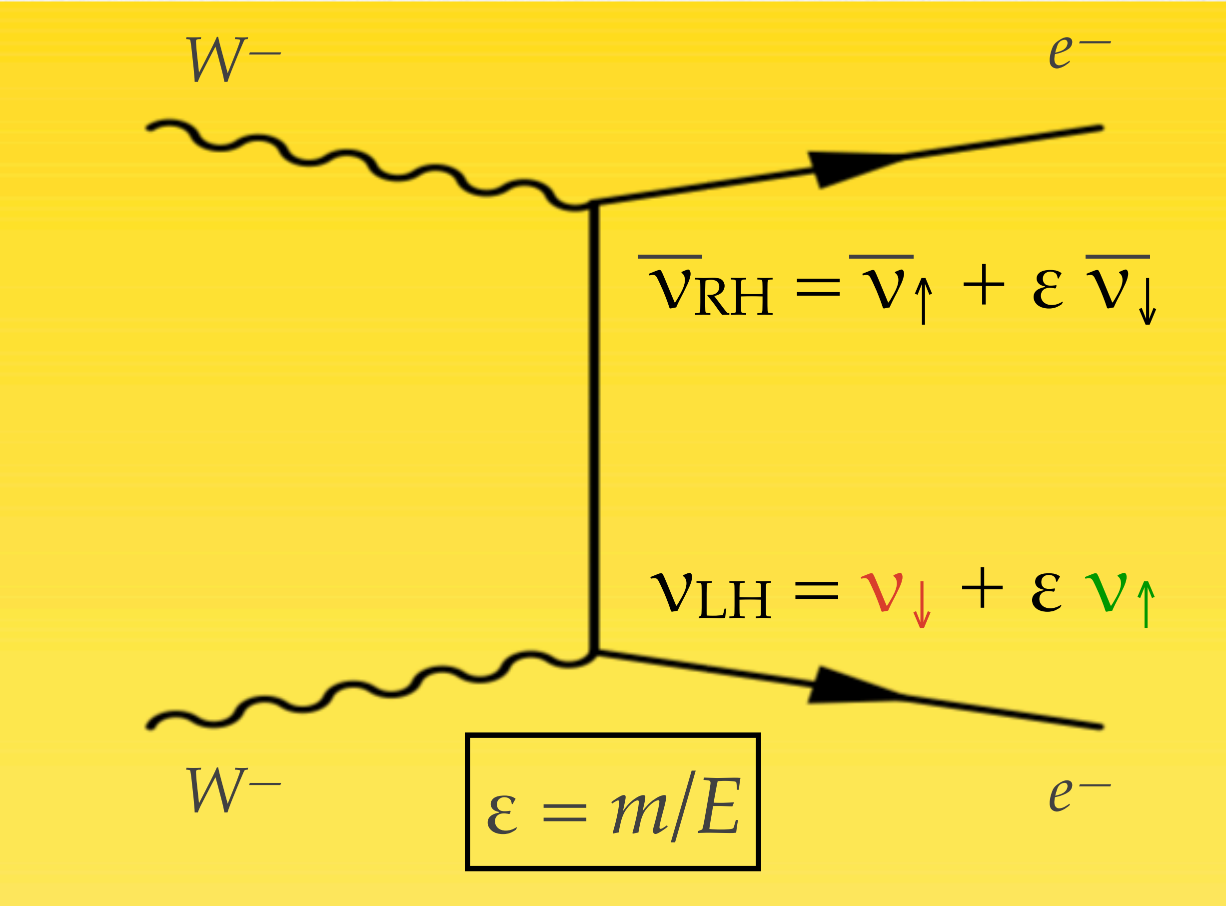
Lepton Number Conservation?

- accidental lepton number conservation difficult in BSM…
- need a symmetry to forbid $M_R N_R N_R$
  - *can apply flavor symmetries with* $(N_{R1}, N_{R2}, N_{R3}) \sim \underline{\mathbf{3}}$*, in groups that have no singlet in* $\underline{\mathbf{3x3}}$ *(e.g.* $\Delta(27)$*)*
  - *still need to explain smallness, e.g. wave-function overlap in ED, 2HDM with one vev of order eV,…*
- 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

Why so difficult to see $\Delta L = 2$?

- V-A makes things difficult: chirality vs. helicity
- $\nu_D = (\nu_\downarrow, \overline{\nu}_\downarrow, \nu_\uparrow, \overline{\nu}_\uparrow)$



- doesn't work

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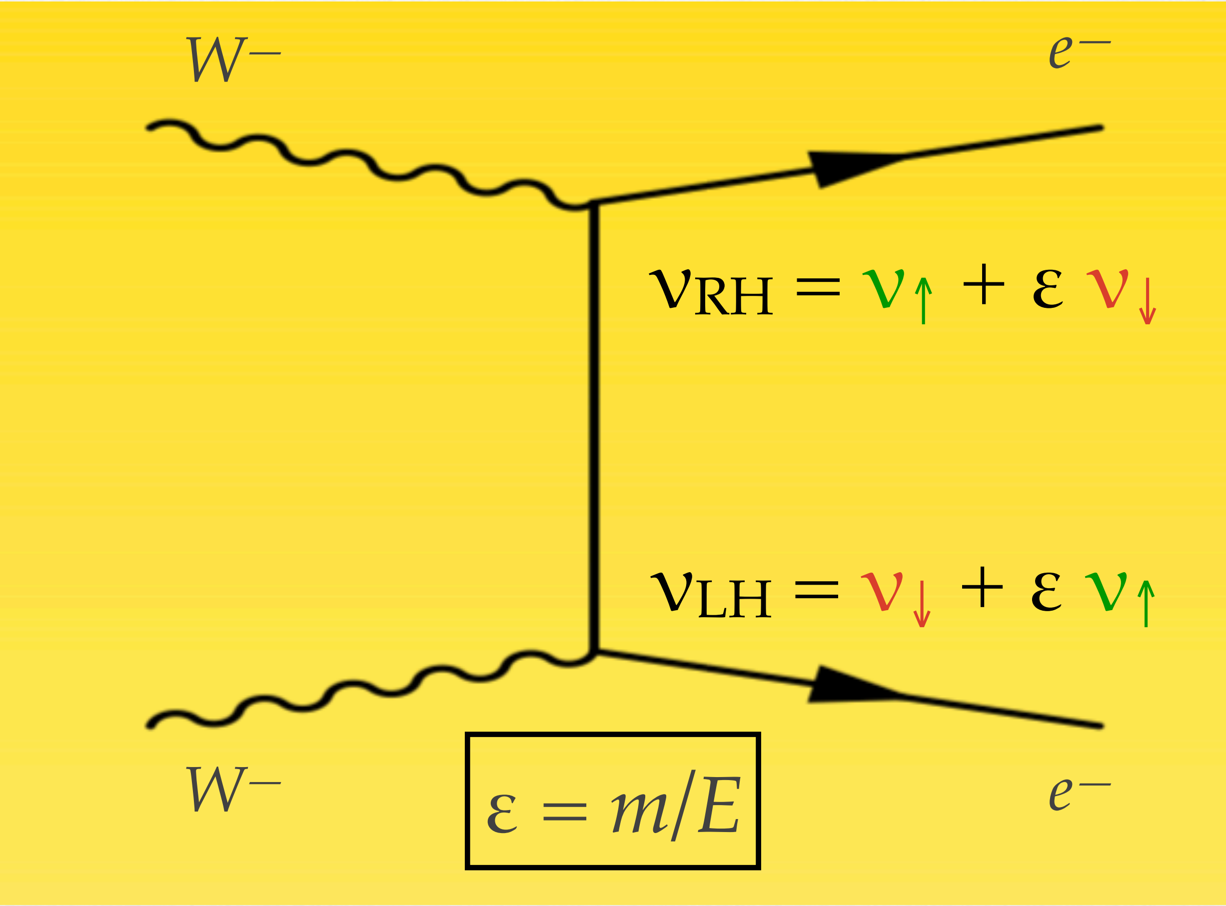

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  - $\Gamma(Z \to \nu_D \overline{\nu}_D)/\Gamma(Z \to \nu_M \nu_M) = 1 - 3\,(m_\nu/m_Z)^2$
  - $BR(K^+ \to \pi^- \, e^+ \, \mu^+) = \; 10^{-30} \, (< m_{e\mu} >/eV)^{\,2}$
  - $P(\nu_\alpha \to \overline{\nu}_\beta) = 1/E^2 \; | \, \Sigma \, U_{\alpha j} \, U_{\beta j} \, U_{\alpha i}^* \, U_{\beta i}^* \, m_i \, m_j \, e^{-i(E_i - E_j)\, t} \, |$
- Only way to beat m/E:

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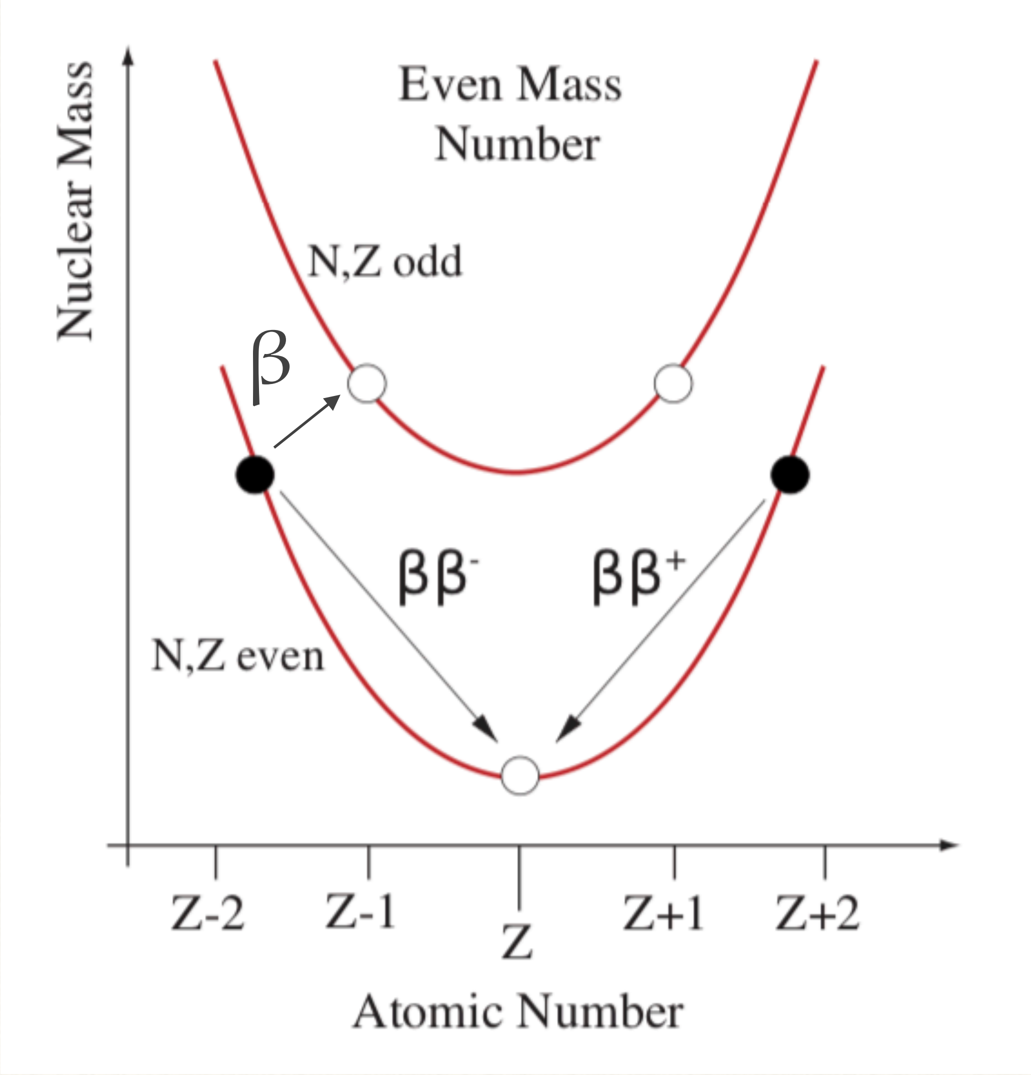
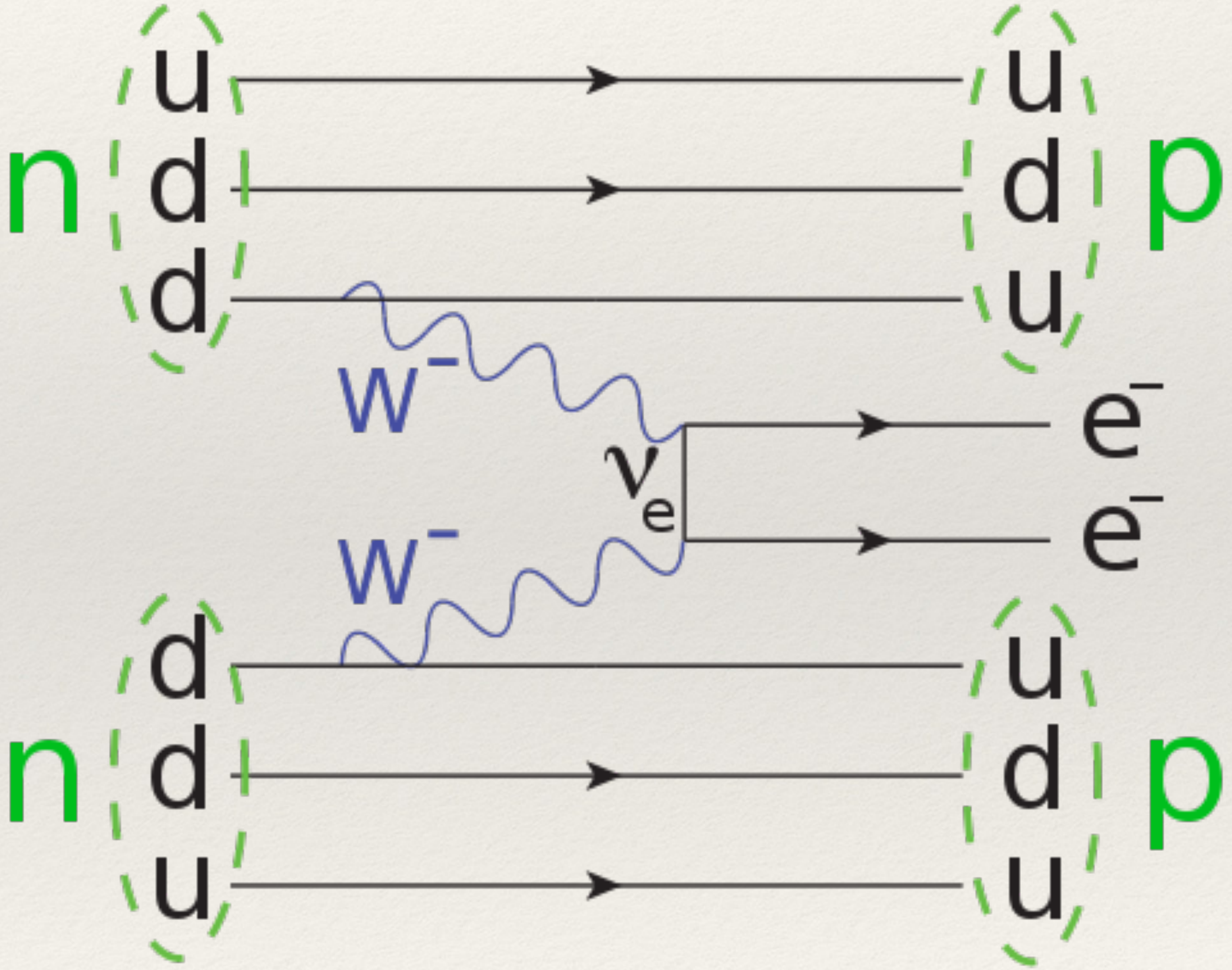
- Only way to beat m/E: Avogadro's number

Neutrinoless Double Beta Decay

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





need to forbid β-decay

„creates matter!"

Neutrinoless Double Beta Decay

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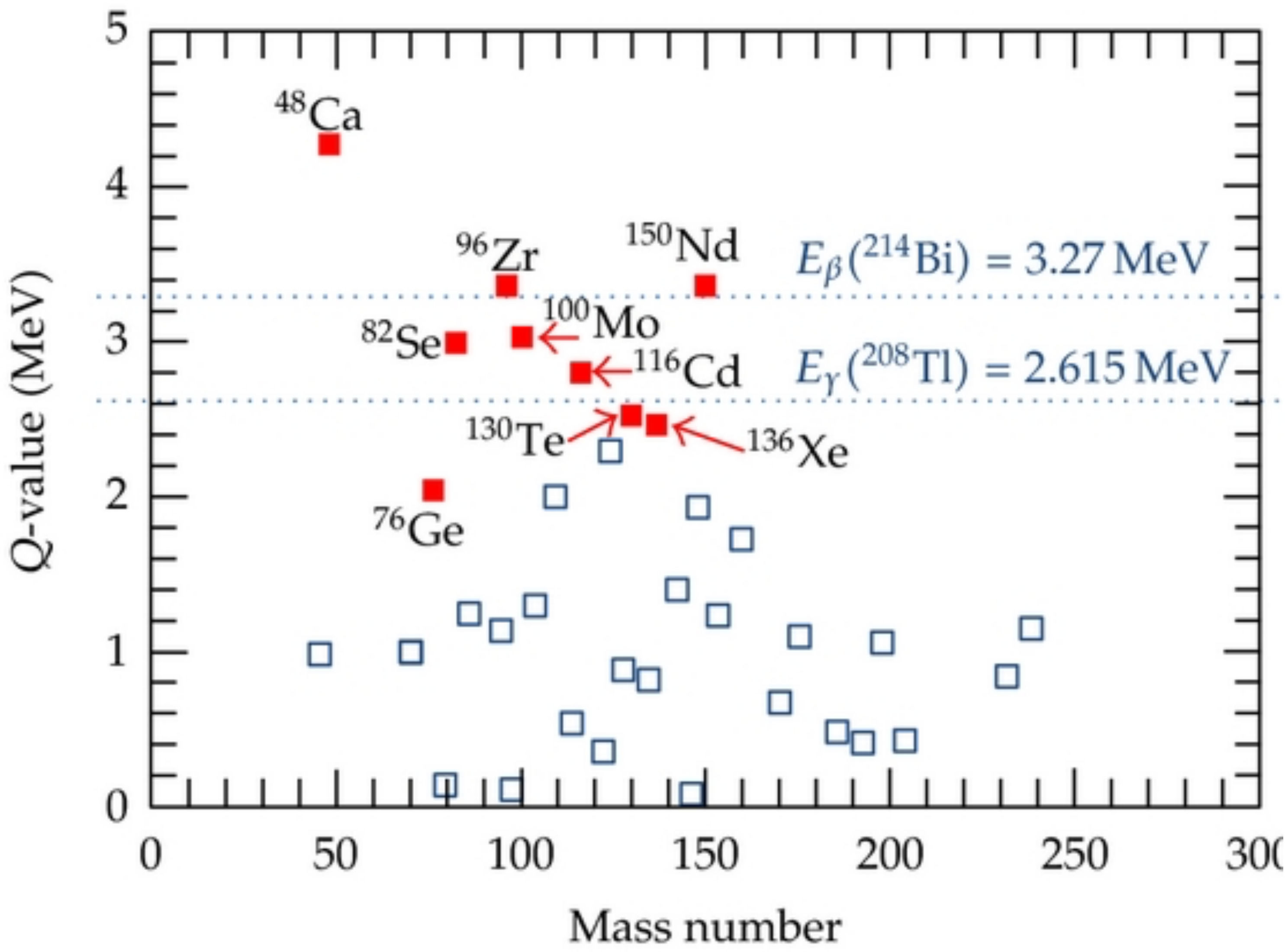

Isotope	G [10^{-14} yrs^{-1}]	Q [keV]	nat. abund. [%]
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

35 isotopes, 9 are useful

Current Limits

GERDA, 1909.02726

Experiment	Isotope	M_i (kmol)	FWHM (keV)	$\mathcal{L}(T_{1/2})$ (10^{25} yr)	$\mathcal{S}(T_{1/2})$ (10^{25} yr)	$m_{\beta\beta}$ (meV)
GERDA (this work)	^{76}Ge	0.41	3.3	9	11	104 - 228
Majorana [22]	^{76}Ge	0.34	2.5	2.7	4.8	157 - 346
CUPID-0 [23]	^{82}Se	0.063	23	0.24	0.23	394 - 810
CUORE [24]	^{130}Te	1.59	7.4	1.5	0.7	162 - 757
EXO-200 [25]	^{136}Xe	1.04	71	1.8	3.7	93 - 287
KamLAND-Zen [26]	^{136}Xe	2.52	270	10.7	5.6	76 - 234

reached 10^{26} years and 0.2 eV neutrino mass limits

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, $\propto Q^5$
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME)
  - η_x : particle physics parameter

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  - $G_x(Q,Z)$: phase space factor, $\propto Q^5$ calculable#
  - $\mathcal{M}_x(A,Z)$: Nuclear Matrix Element (NME) problematic*
  - η_x : particle physics parameter interesting

#ignore here

**ignore here even more*

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

WR, 1106.1334

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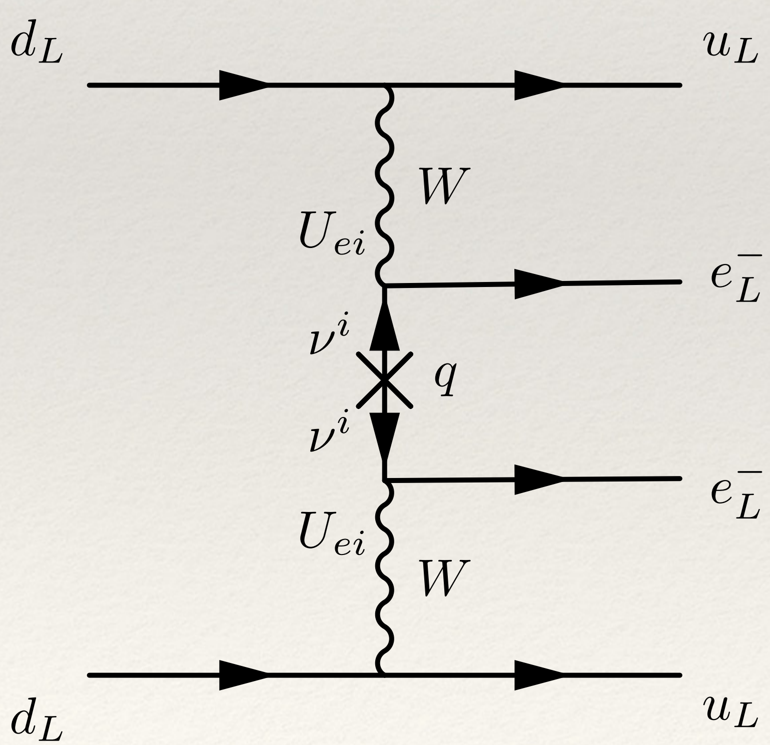
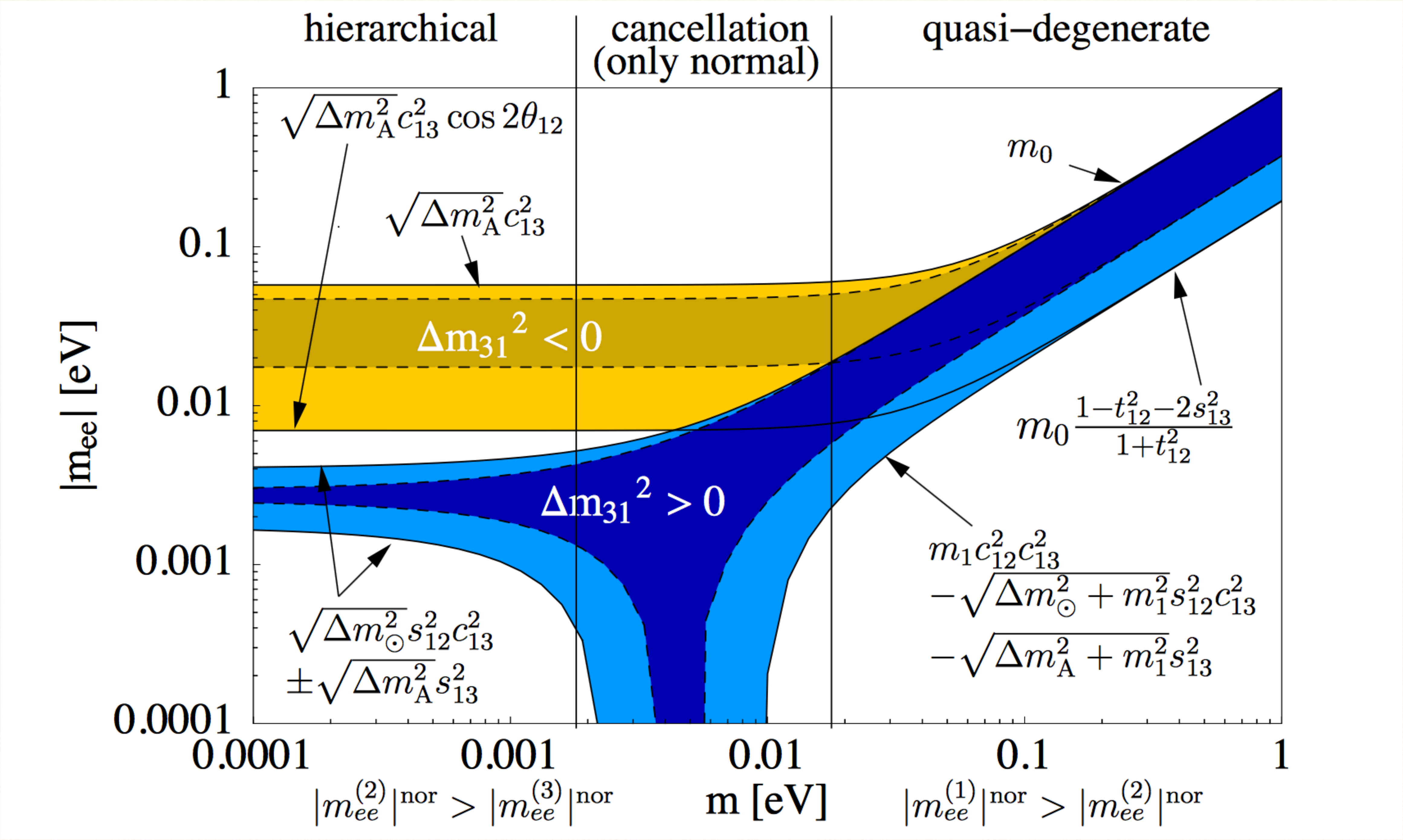


amplitude proportional to „effective mass“:

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

known limits unknown

The usual plot



Lindner, Merle, WR, PRD73

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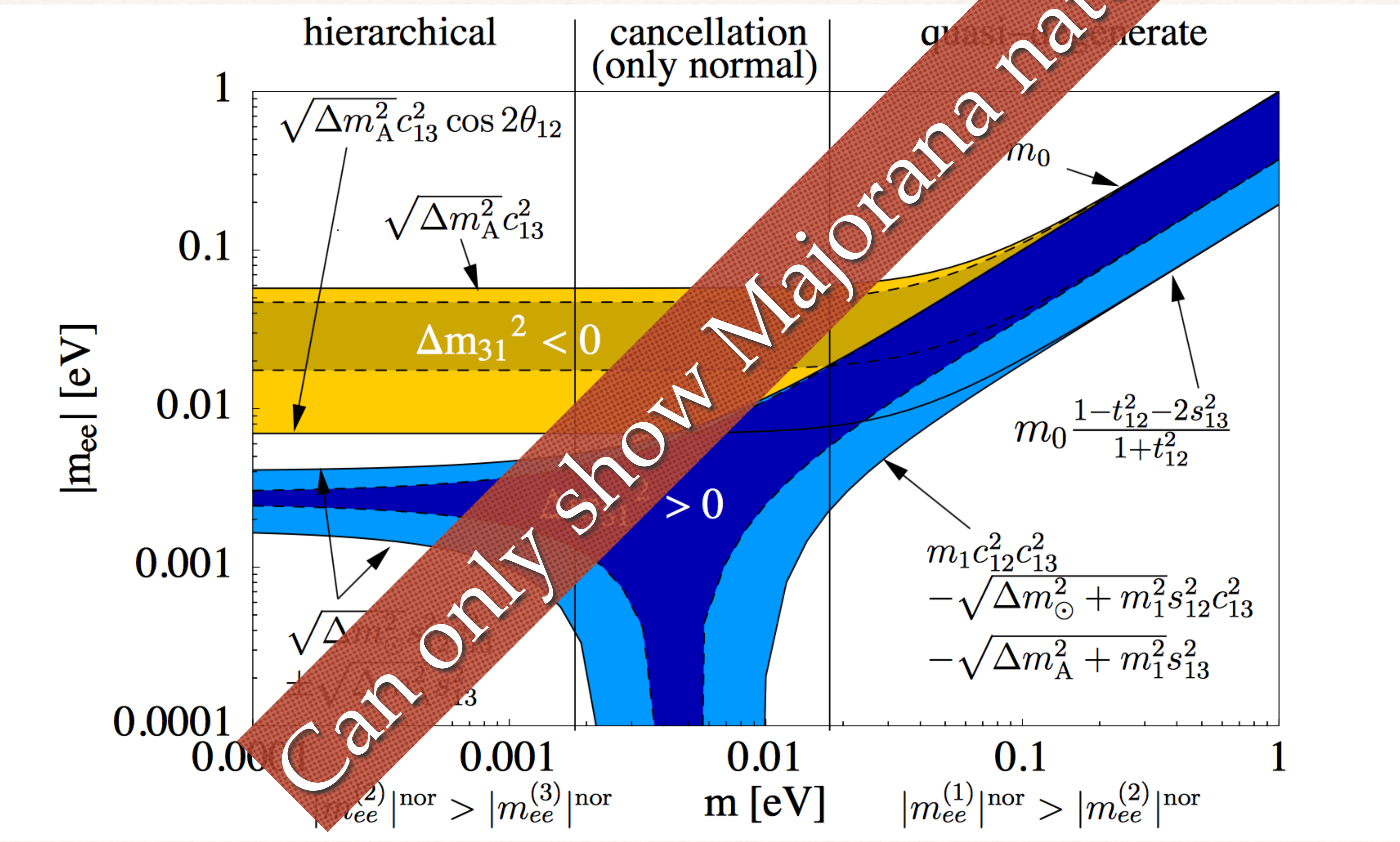

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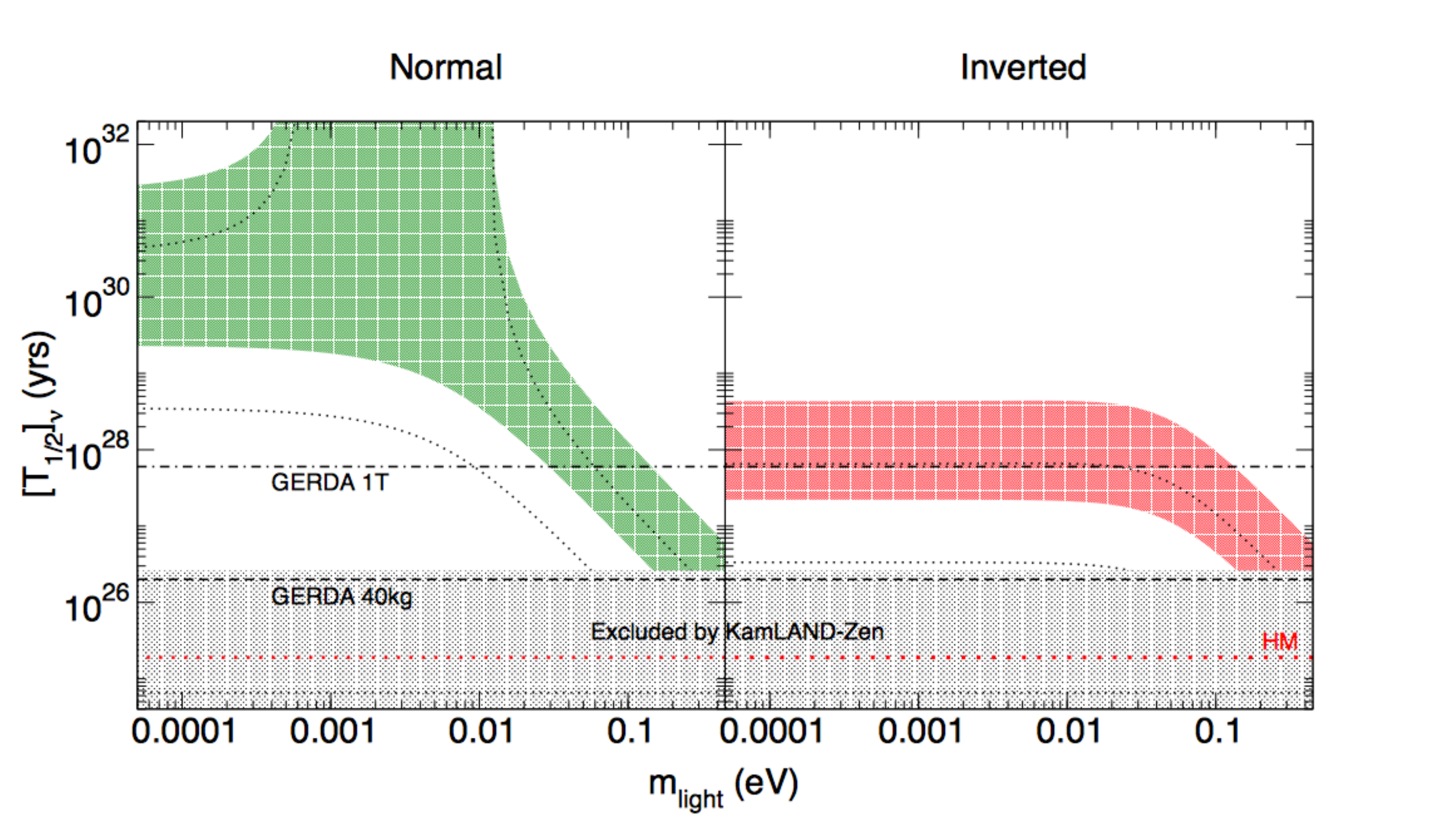
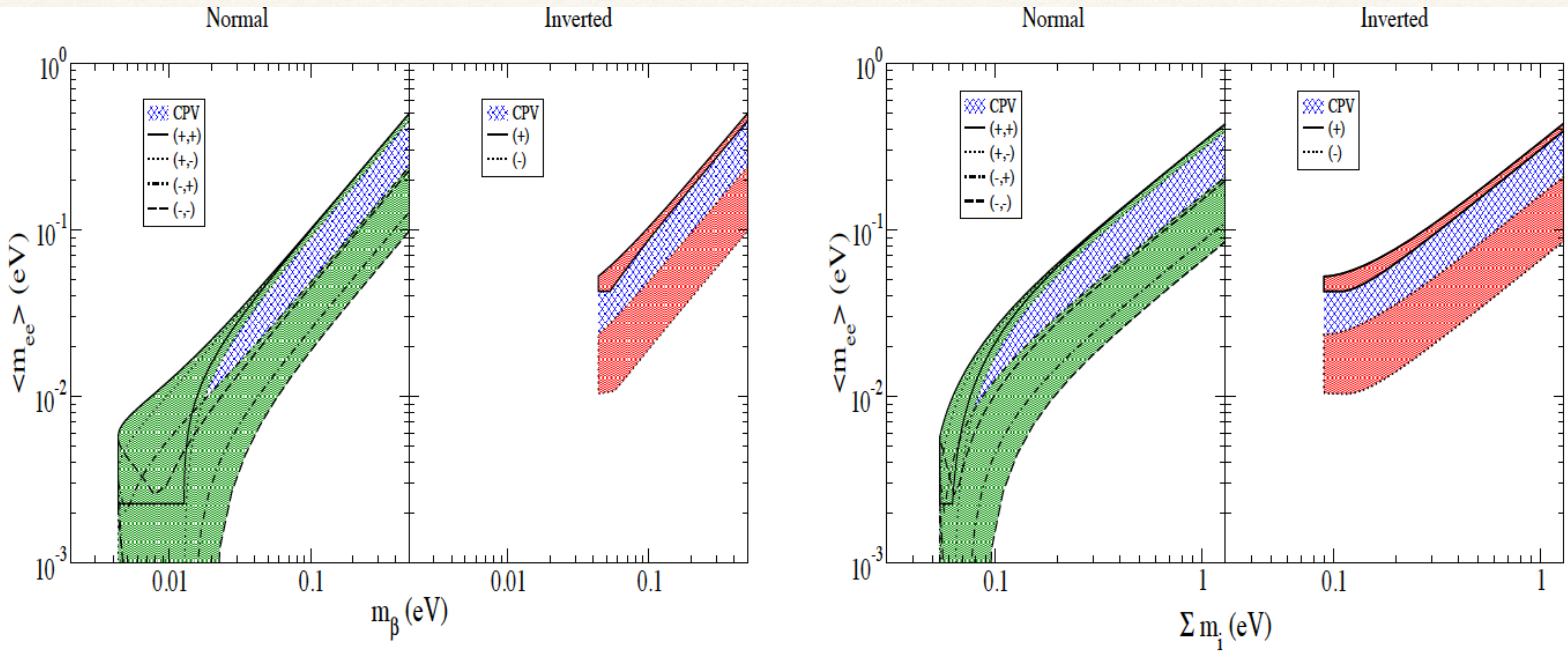


Neutrino Mass Observables

Method	Observable	current	near	far	pro	con
Kurie	$\sum \lvert U_{ei} \rvert^2 m_i^2$	0.8 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 KATRIN-limit
- $0\nu\beta\beta$ and conservative cosmology currently roughly same
- cosmology strongly disfavors a signal in KATRIN

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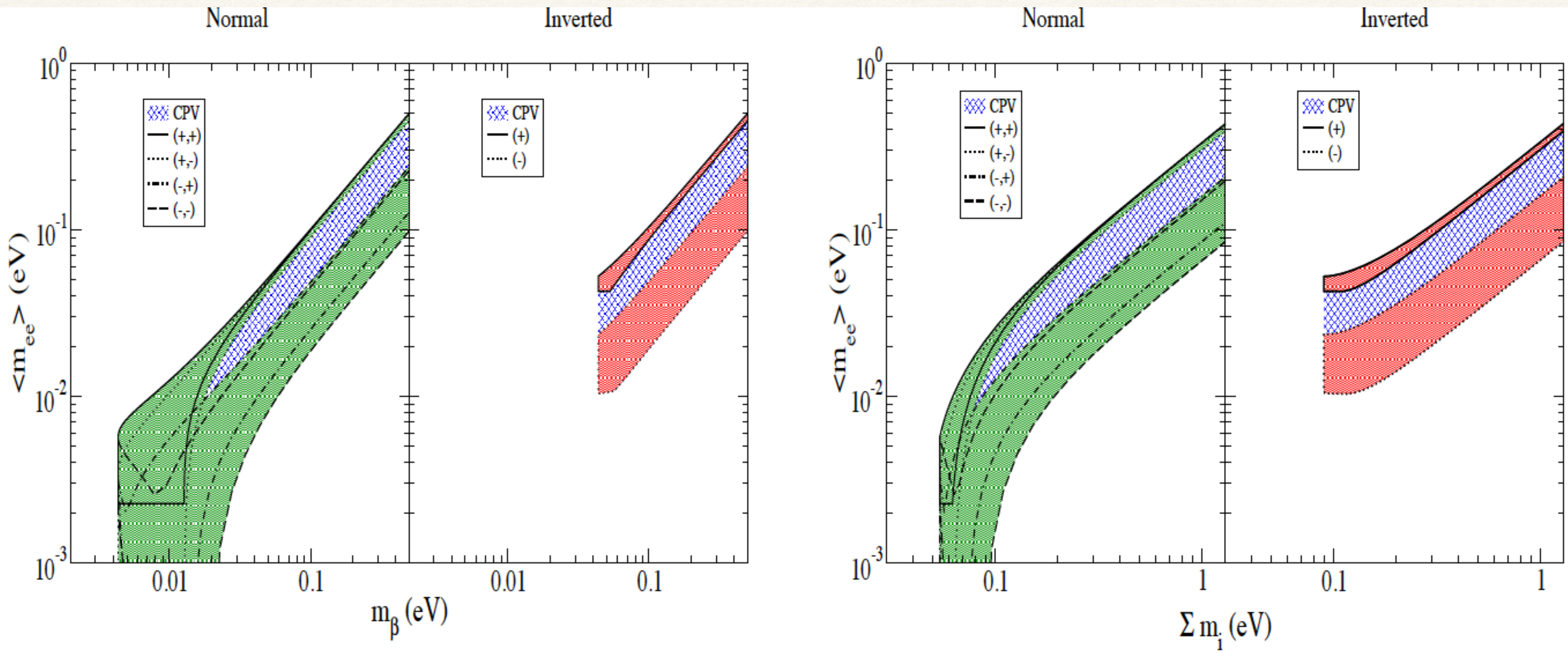

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All need to be pursued!

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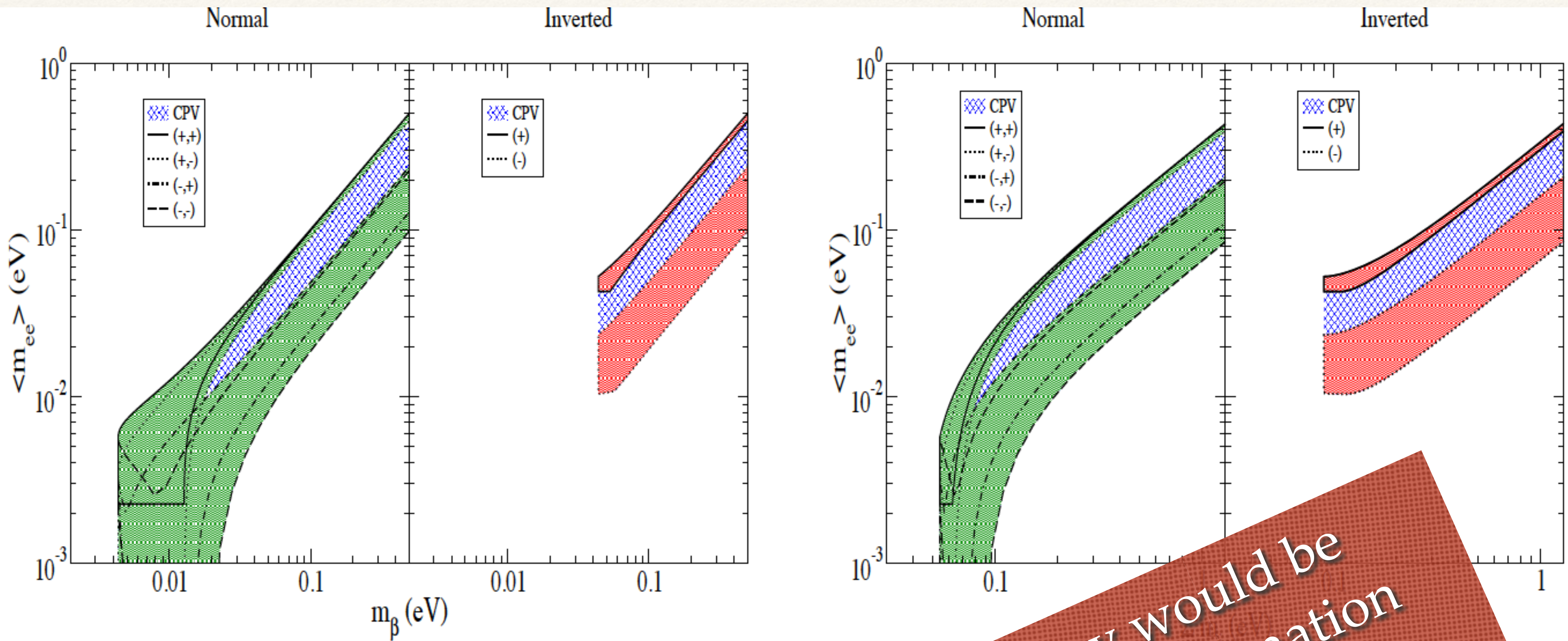

Consistency would be spectacular confirmation of 3 Majorana neutrino paradigm

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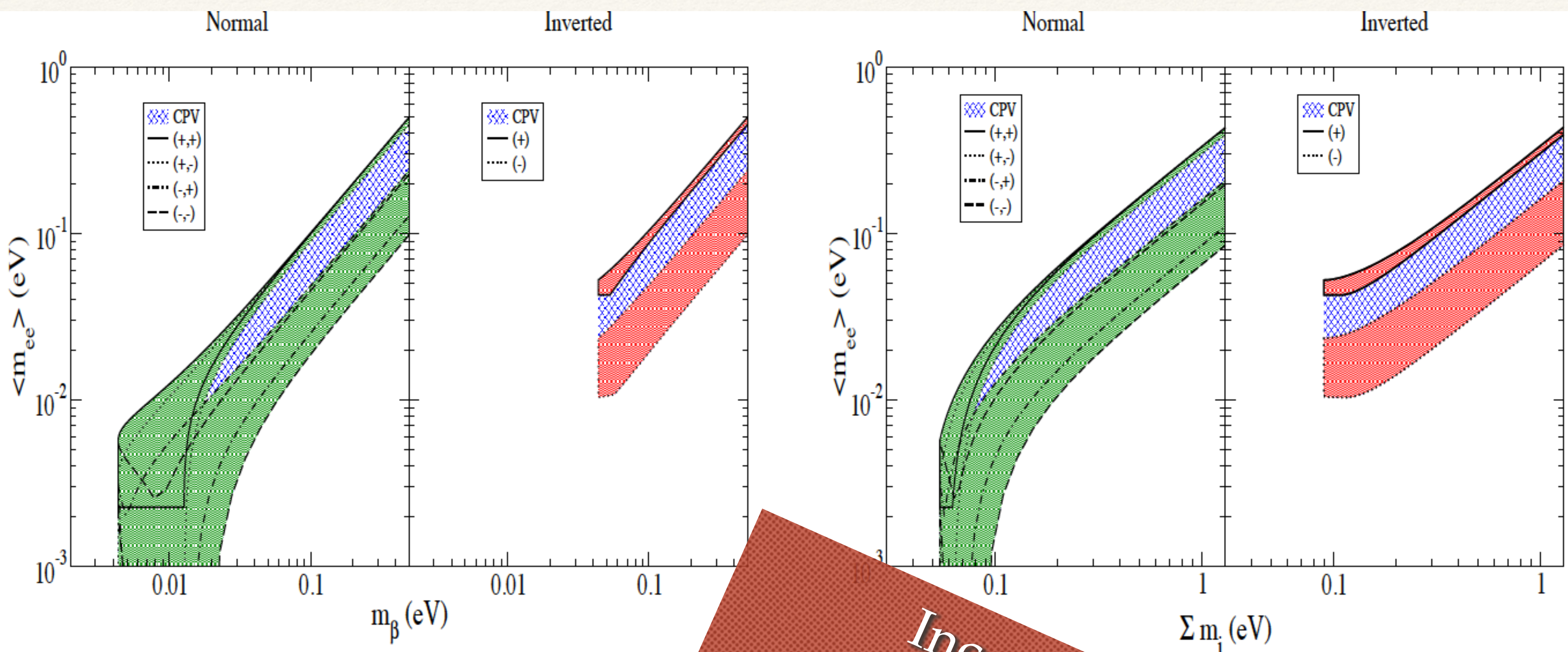

Inconsistencies would be major discovery!

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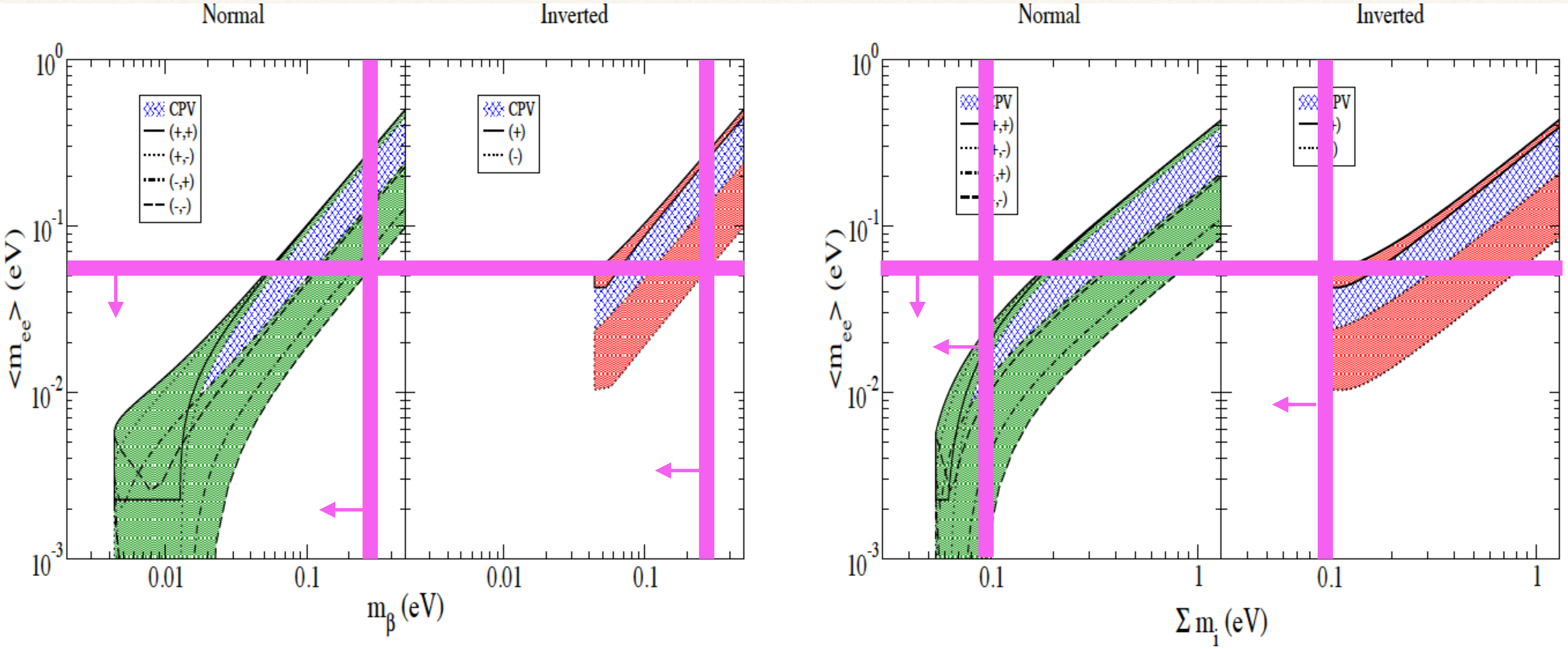
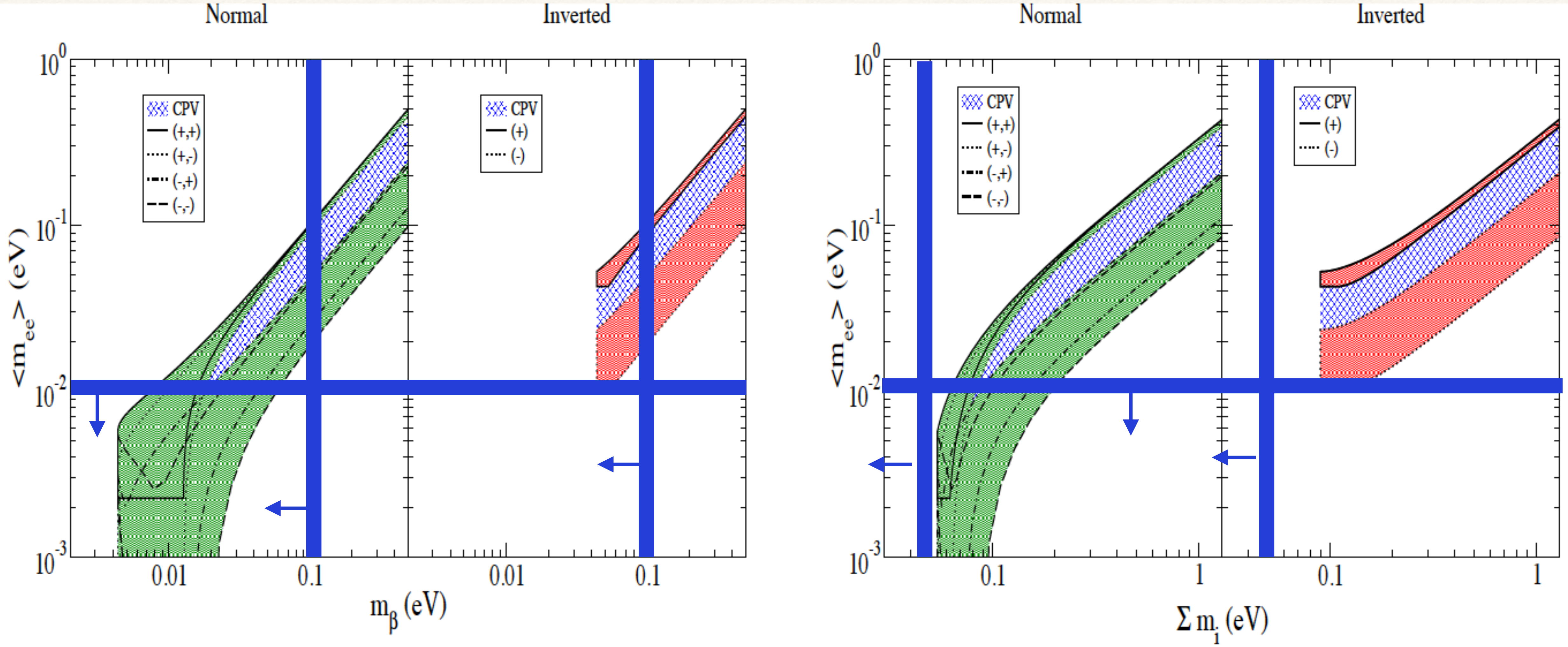


near future

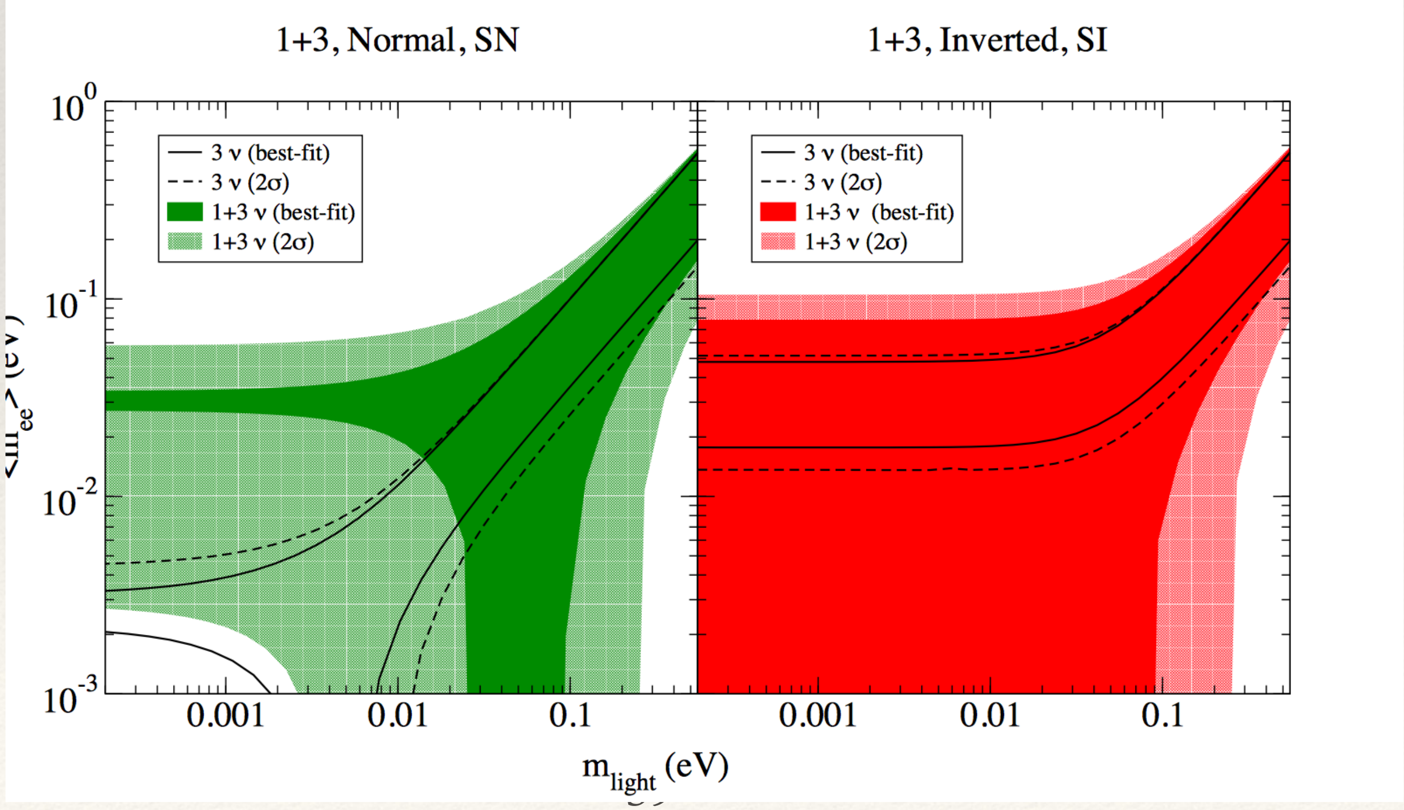
Neutrino Mass Observables



far future

Sterile Neutrinos

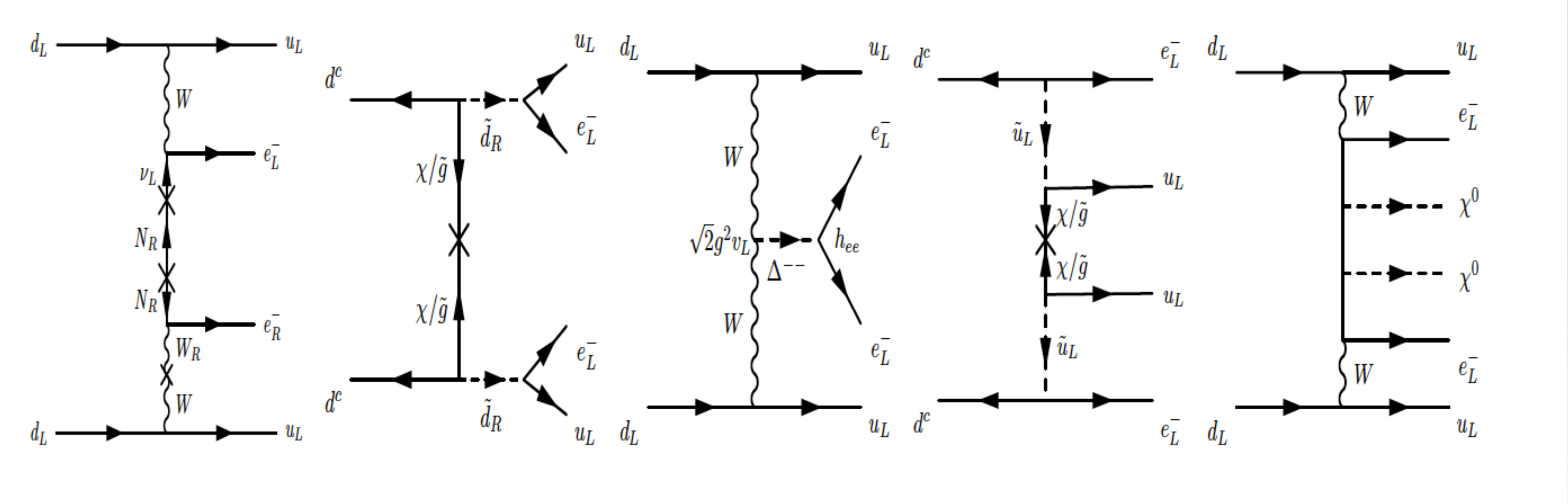
- are there sterile states (LSND / reactor / MiniBooNE, etc.) with mass $\Delta m^2 \simeq$ eV^2 and mixing $U_{e4} \simeq 0.1$?
- would make m_{ee} sum of 4 terms with sterile contribution $|U_{e4}|^2 \sqrt{\Delta m^2}$ that can cancel almost completely contribution of IH!
- usual pheno completely turned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



Barry, WR, Zhang, JHEP1107

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



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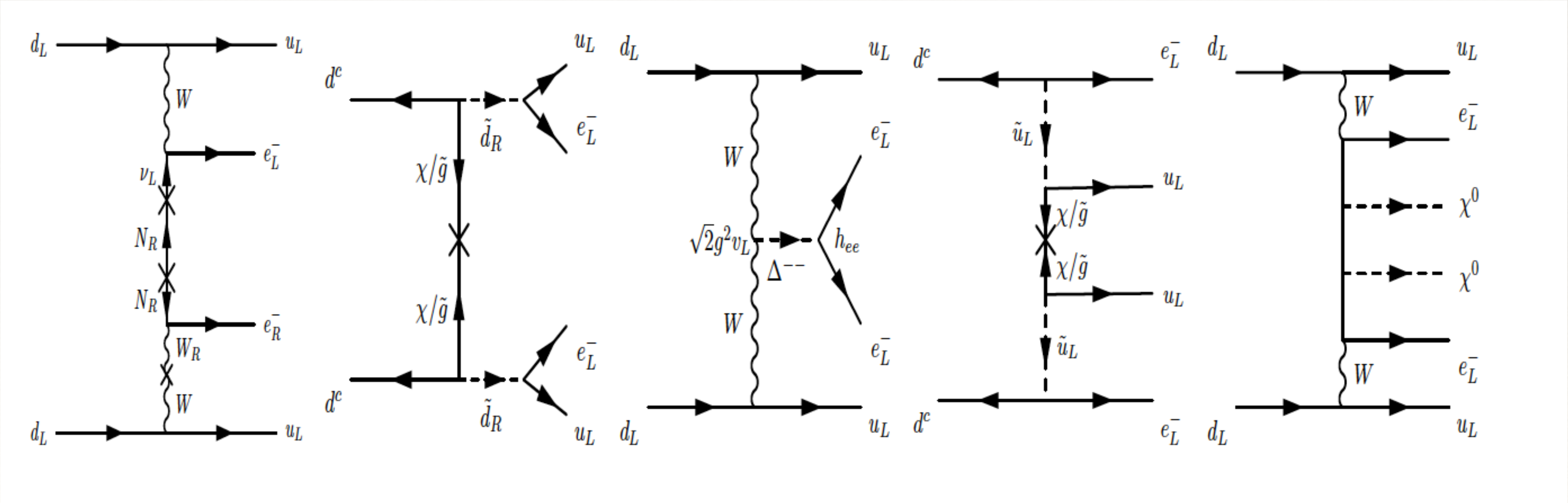

$\Rightarrow$ $0\nu\beta\beta$ is not a neutrino mass experiment!

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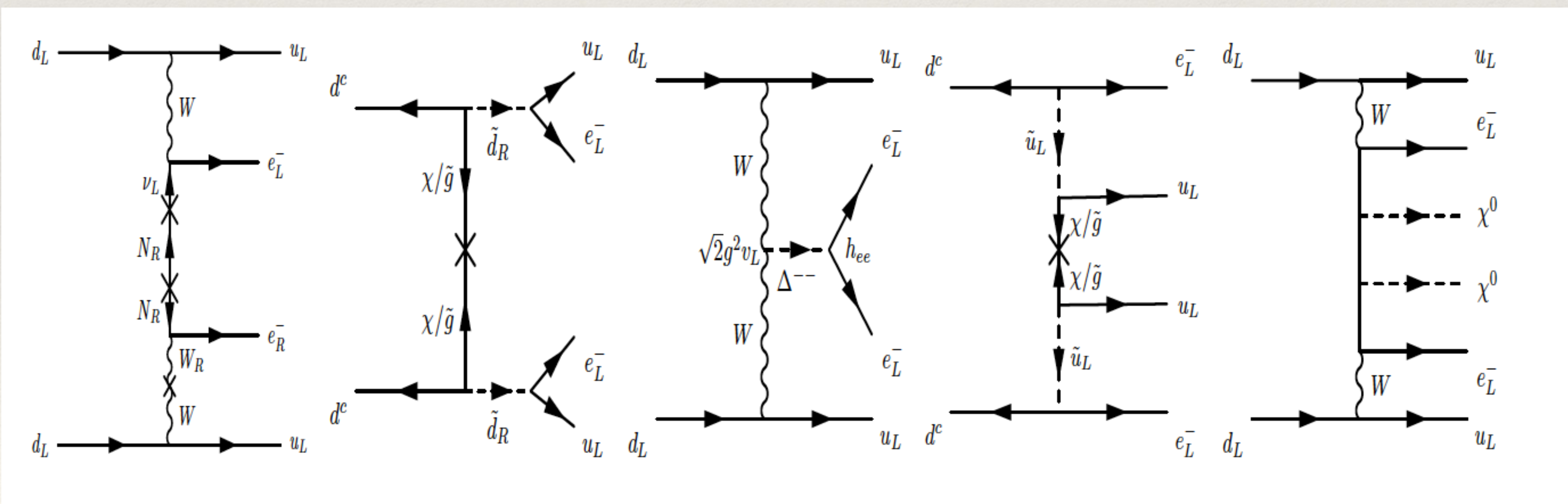

$\Rightarrow$ need to solve the „inverse problem“

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 $\not{R}$	$\frac{\|\lambda_{111}'^2\|}{\Lambda_{\rm SUSY}^5}$ $\Lambda_{\rm SUSY} = f(m_{\tilde{g}}, m_{\tilde{u}_L}, m_{\tilde{d}_R}, m_{\chi_i})$	7×10^{-18} GeV^{-5}	collider, flavor
long-range $\not{R}$	$\left\|\sin 2\theta^b \, \lambda_{131}' \lambda_{113}' \left(\frac{1}{m_{\tilde{b}_1}^2} - \frac{1}{m_{\tilde{b}_2}^2}\right)\right\|$ $\sim \frac{G_F}{q} m_b \frac{\|\lambda_{131}' \lambda_{113}'\|}{\Lambda_{\rm SUSY}^3}$	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

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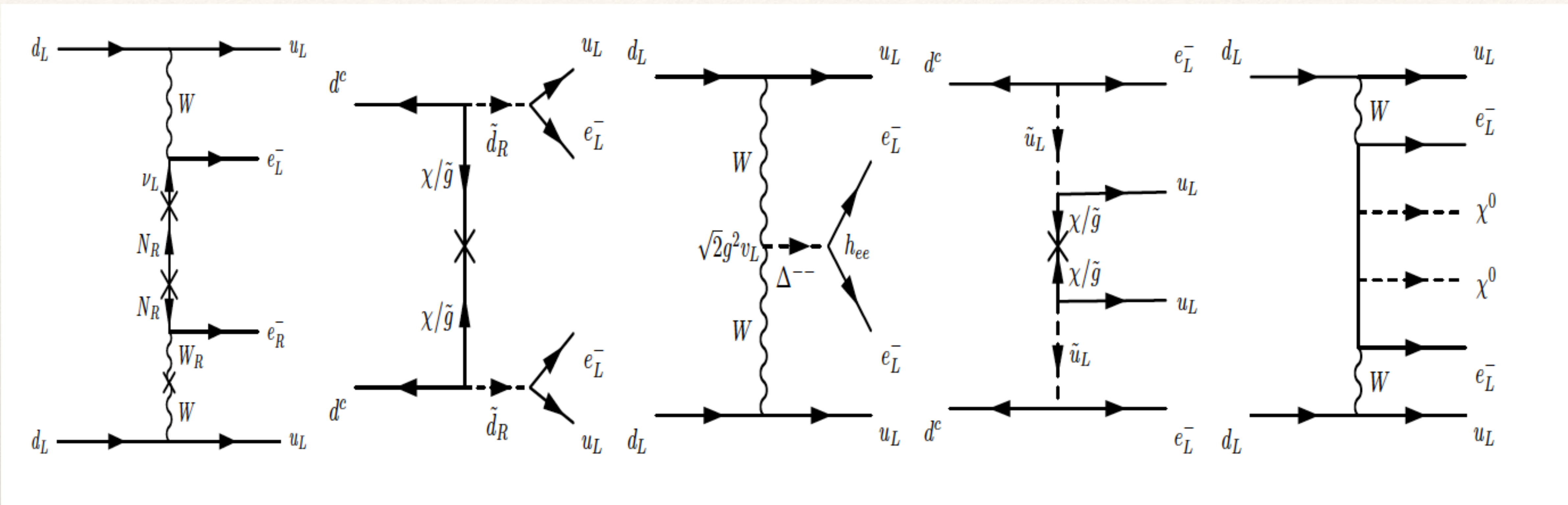
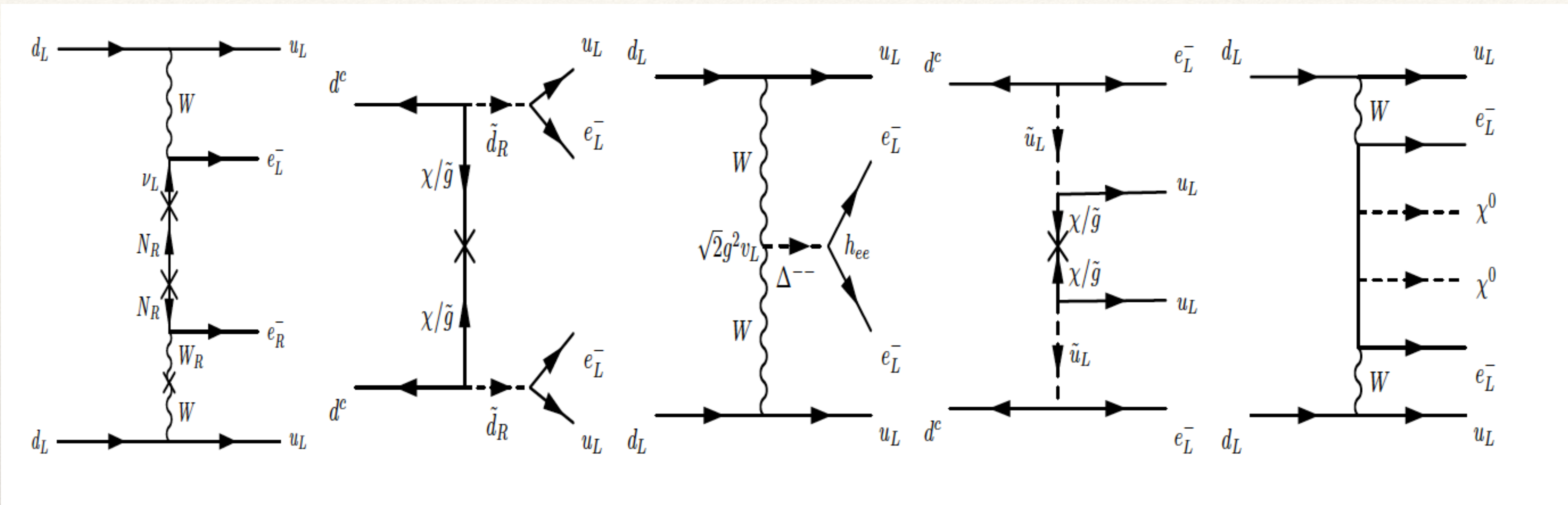


- decouples double beta decay from cosmology and KATRIN

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

Non-Standard Interpretations

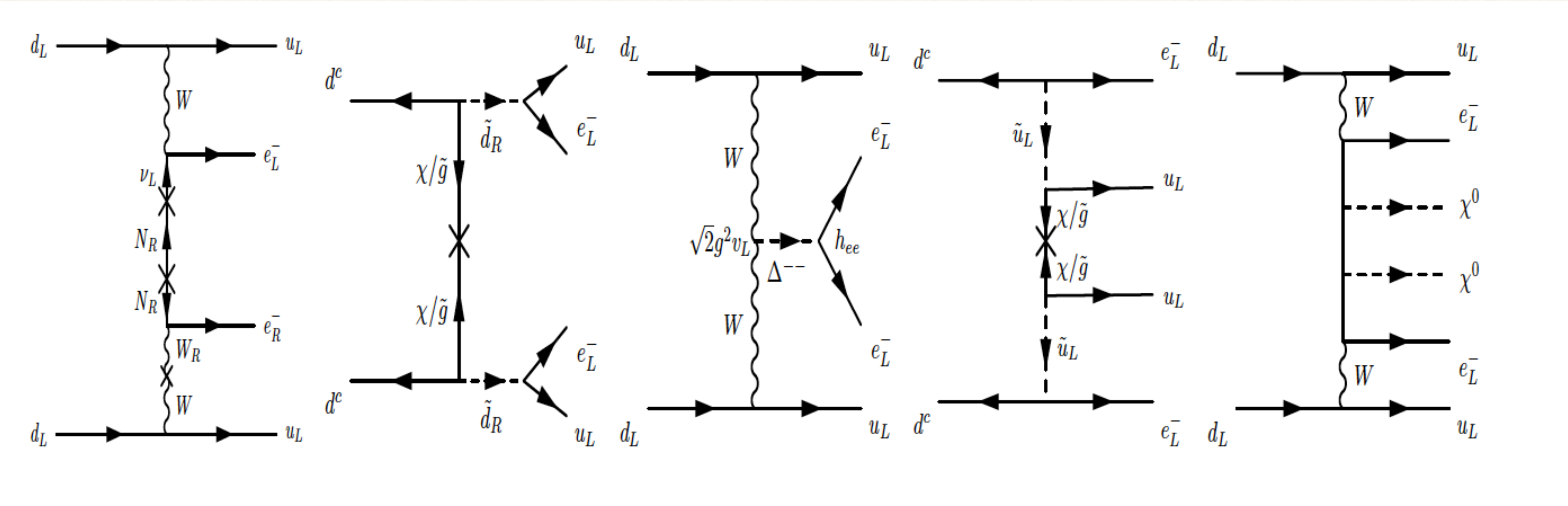


- decouples double beta decay from cosmology and KATRIN

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

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

Non-Standard Interpretations



- decouples double beta decay from cosmology and KATRIN

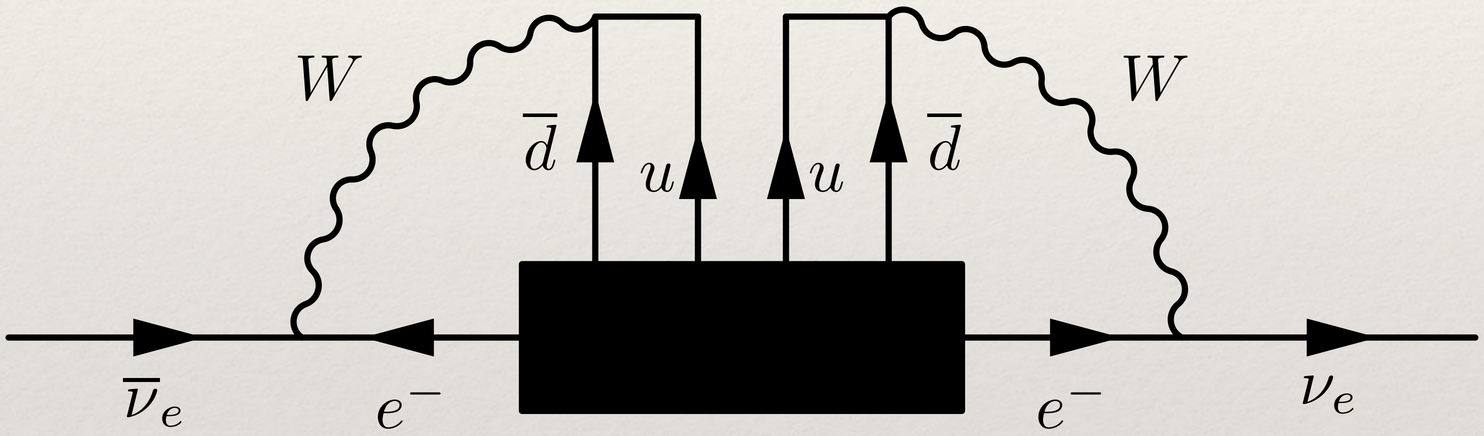
$$\mathcal{A}_{\rm Standard} = G_F^2 \frac{\langle m \rangle}{q^2} \text{ versus } \mathcal{A}_{\rm Non-Standard} = \frac{c}{M_X^5}$$

Therefore:
T(eV) = T(TeV)

⇒ Tests with LHC, LFV, etc.

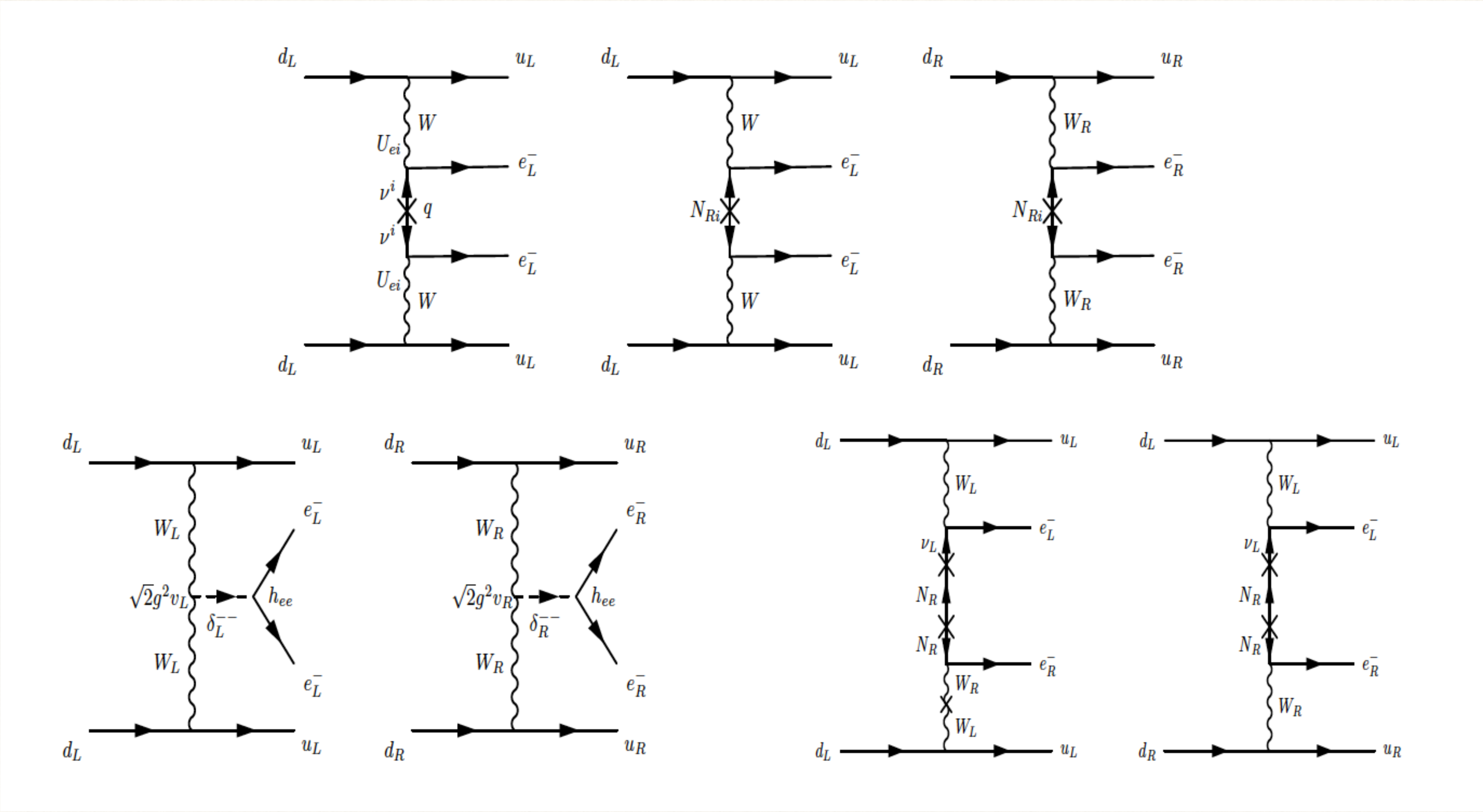
Black Box Theorem

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

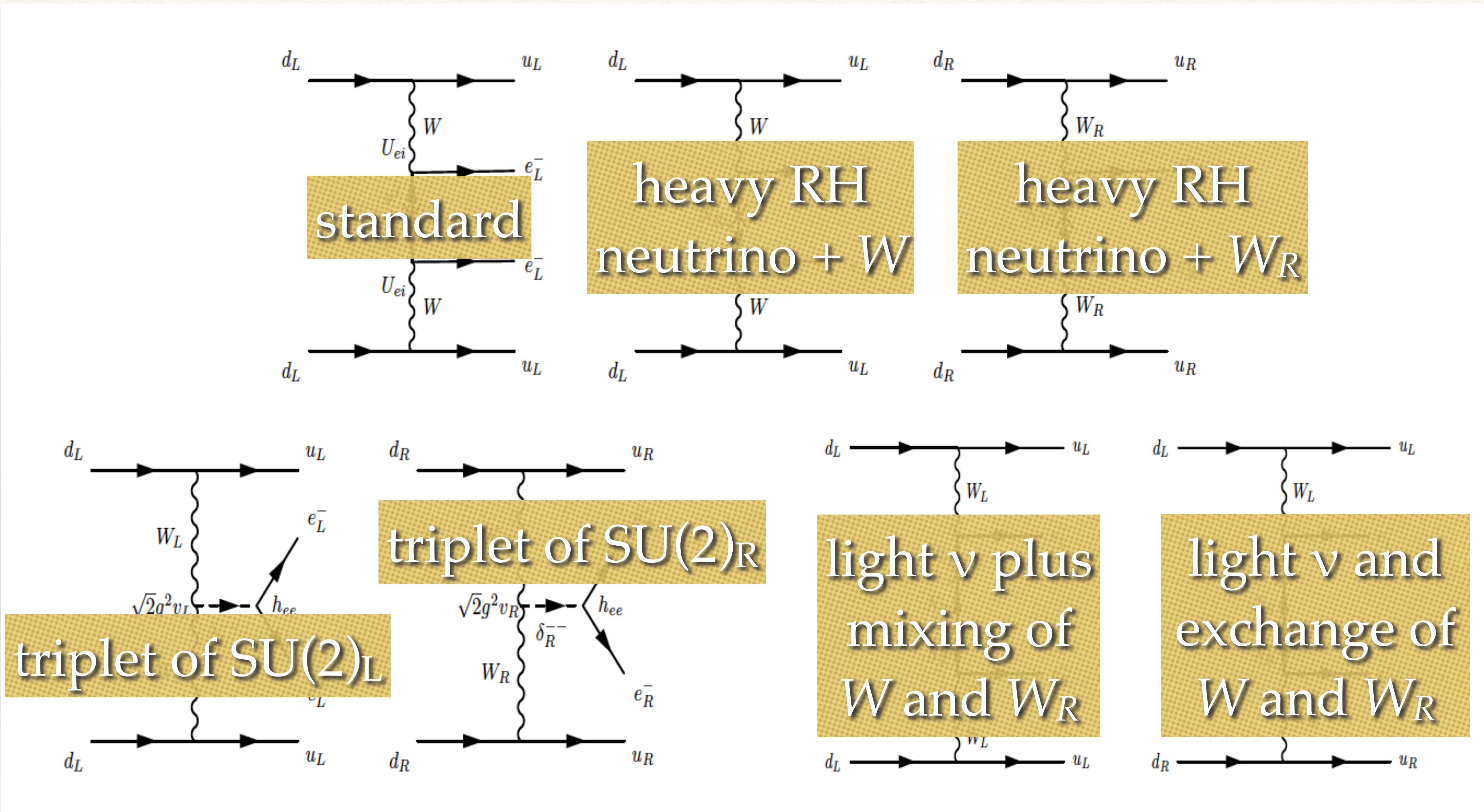


- is 4-loop diagram ⇒ tiny mass *(Dürr, Lindner, Merle, 1105.0901)*
- if you see *0νββ*: neutrinos are Majorana. If you don't, you can't tell…

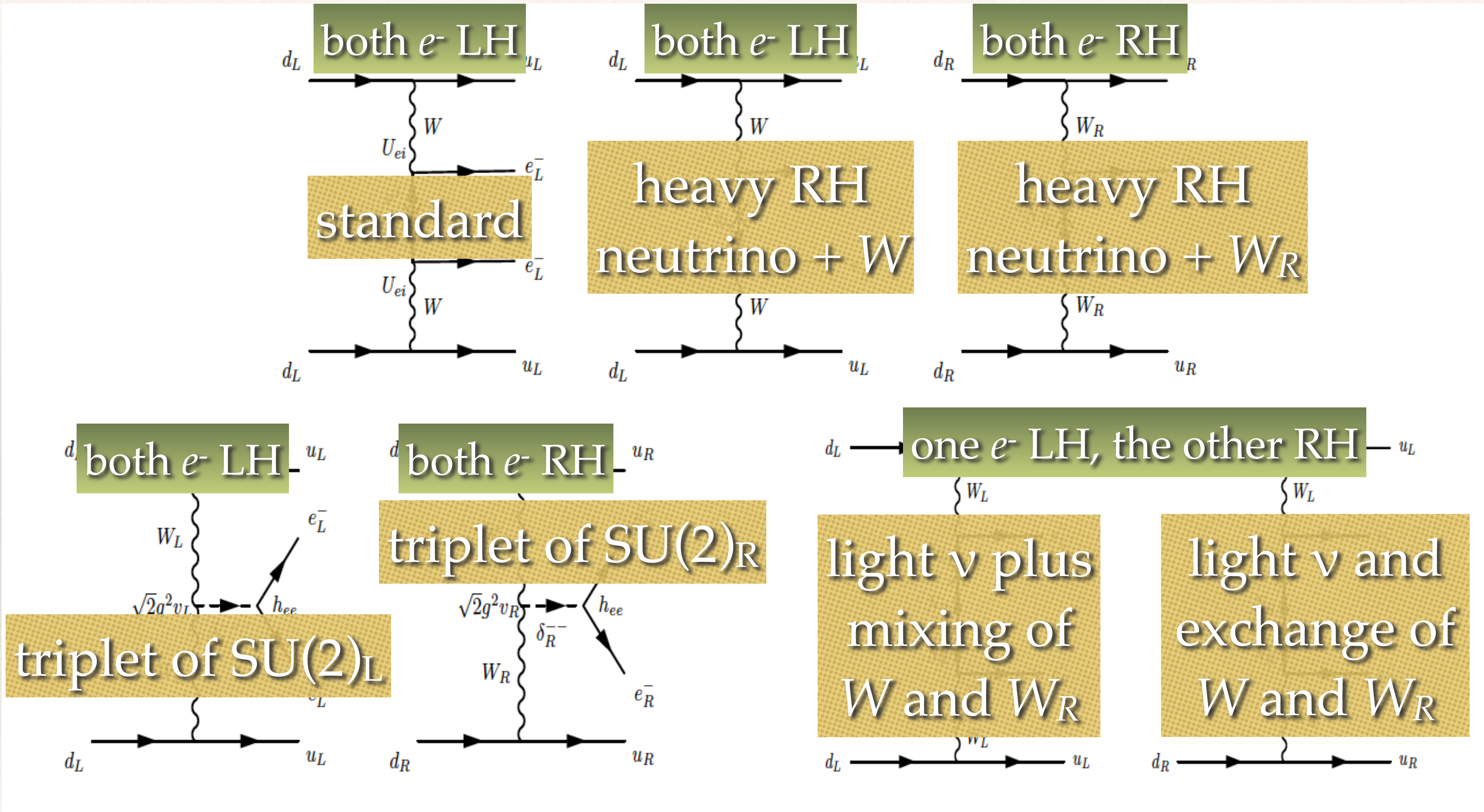
Double Beta Decay and LR-Symmetry



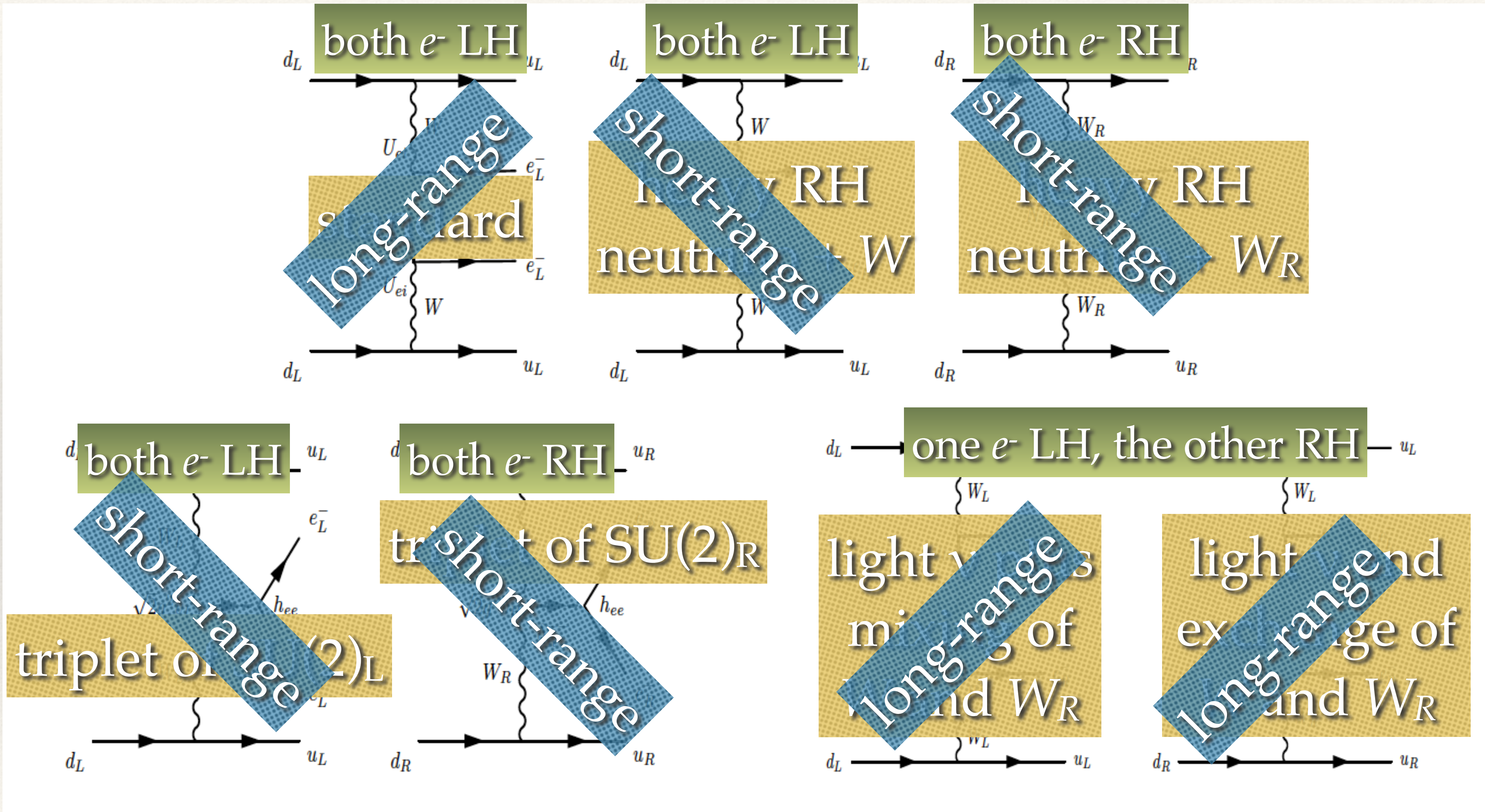
Double Beta Decay and LR-Symmetry



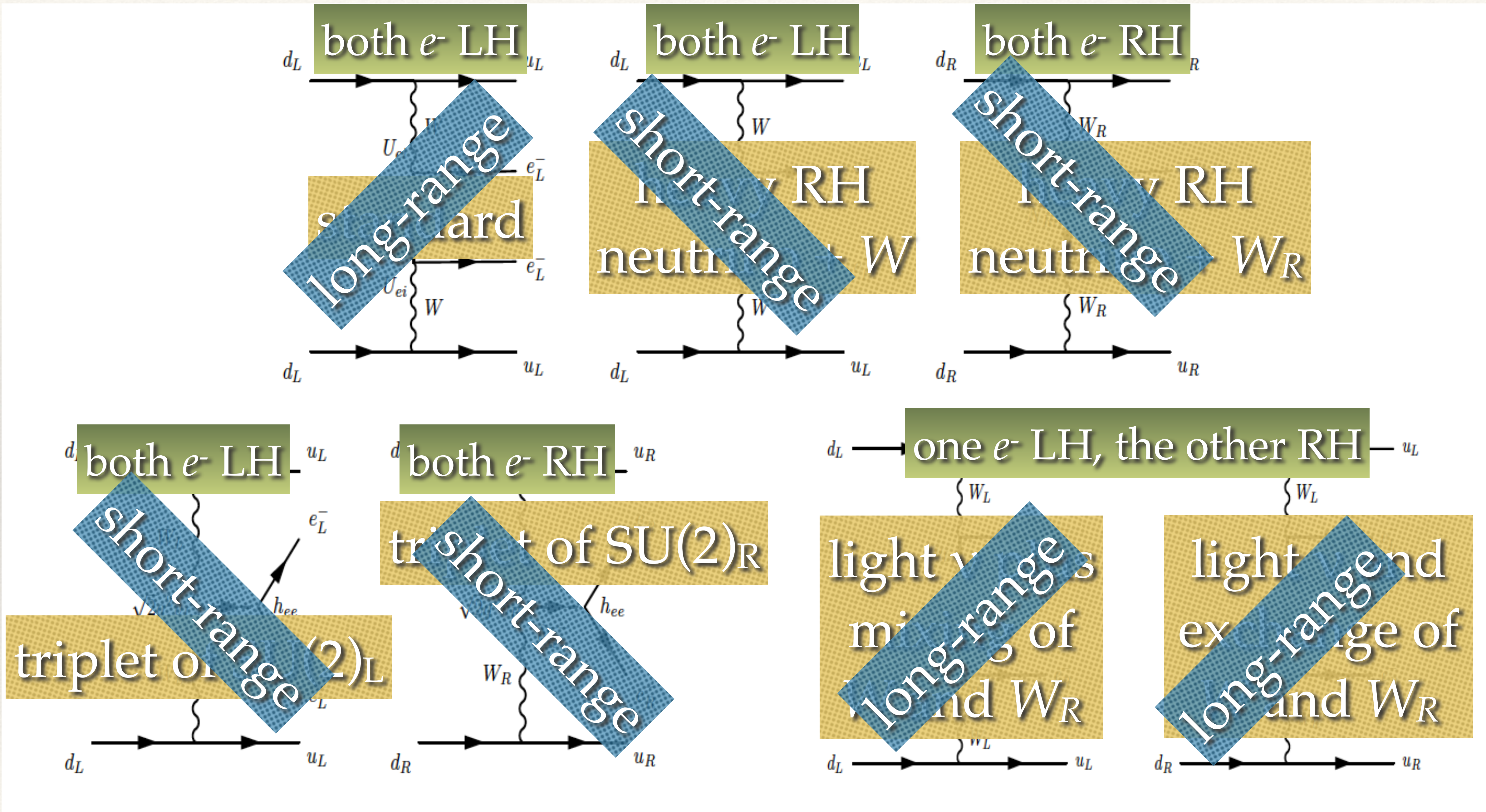
Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry



Double Beta Decay and LR-Symmetry

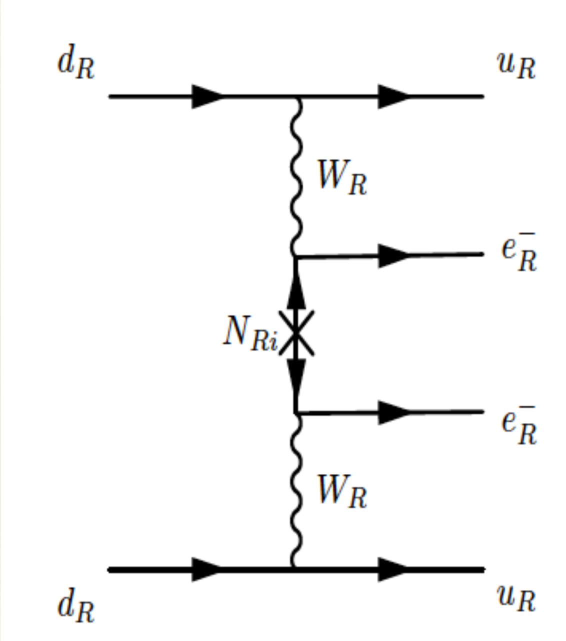


simultaneous presence / interference / …

Double Beta Decay and LR-Symmetry

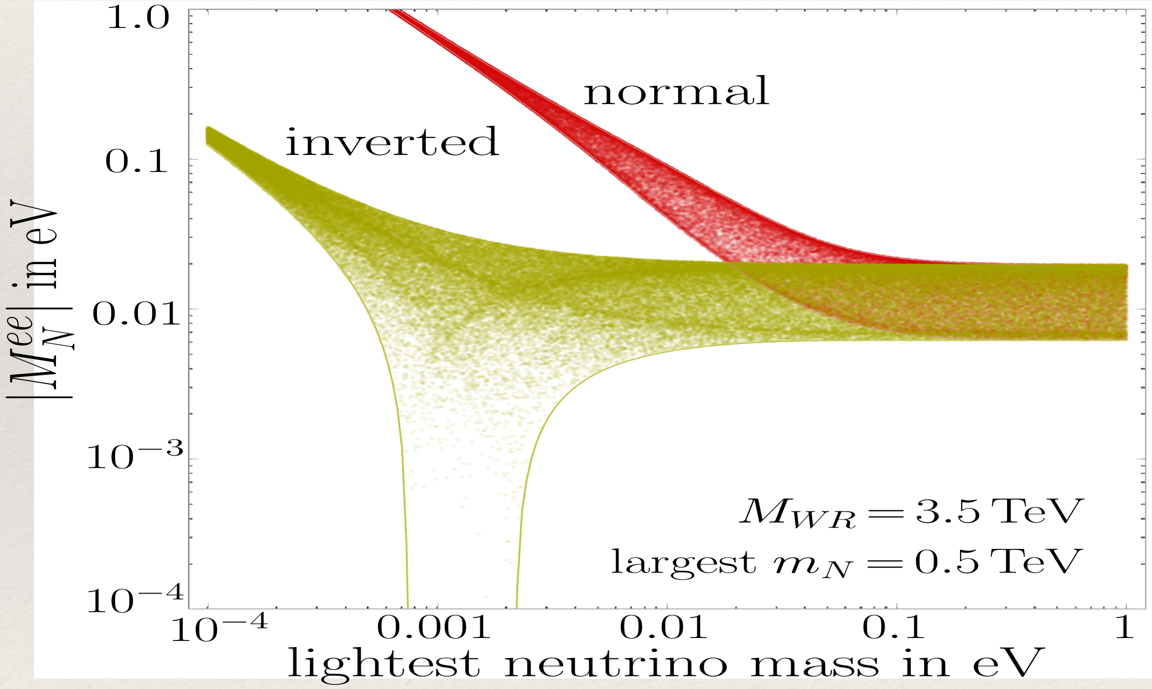
Type II dominance: $m_\nu = m_L - M_D^2/M_R \to m_L$ with $m_L \propto M_R$

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



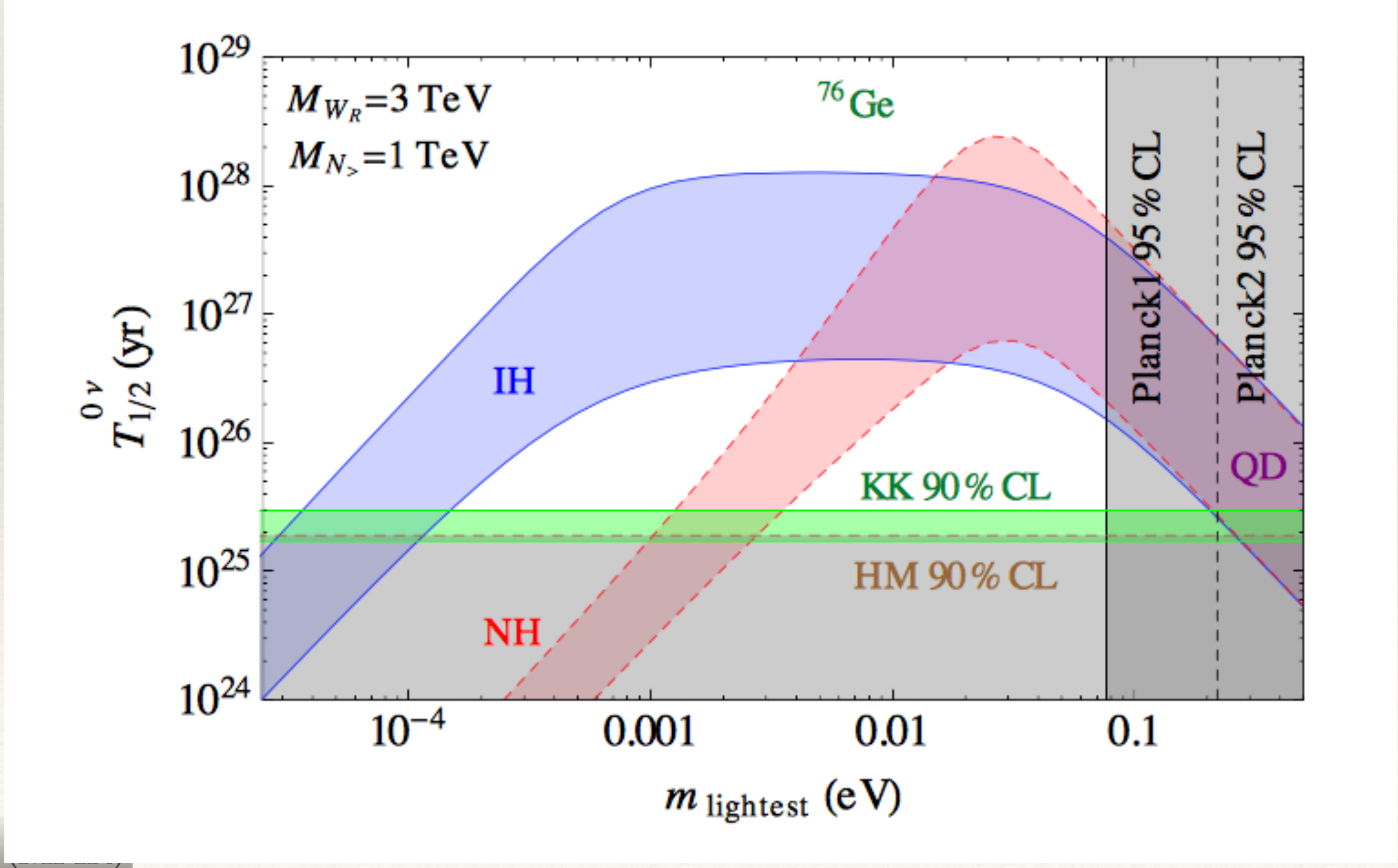
again, NH/IH turned around…

Senjanovic et al., 1011.3522

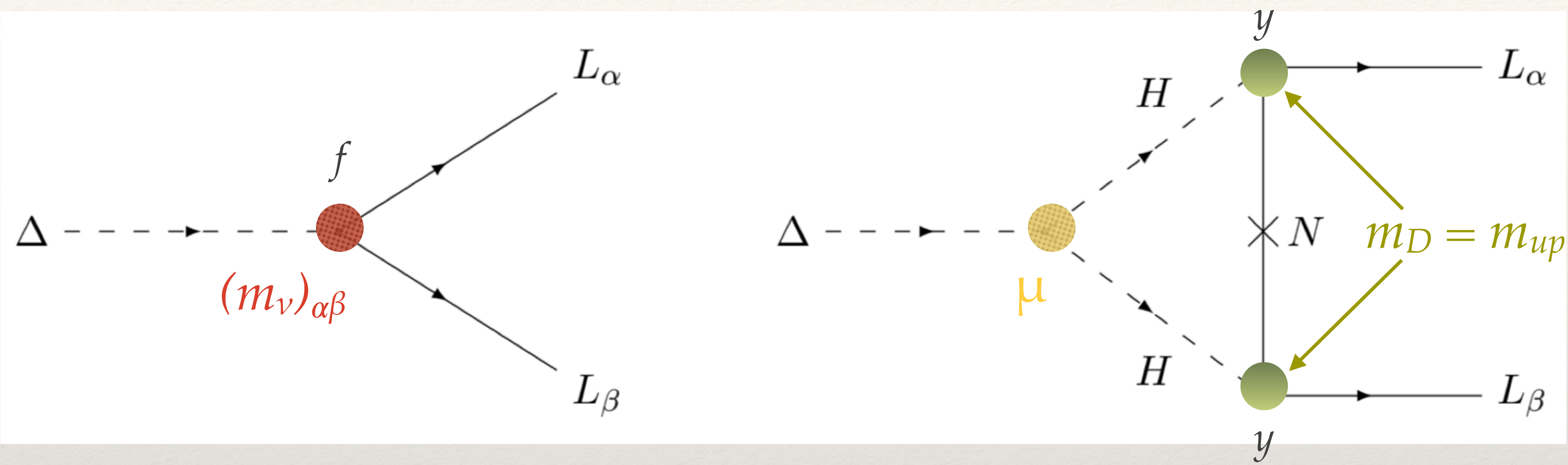
Double Beta Decay and LR-Symmetry

- 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

Barry, W.R., JHEP1309
Dev, Goswami, Mitra, WR, PRD88



Leptogenesis



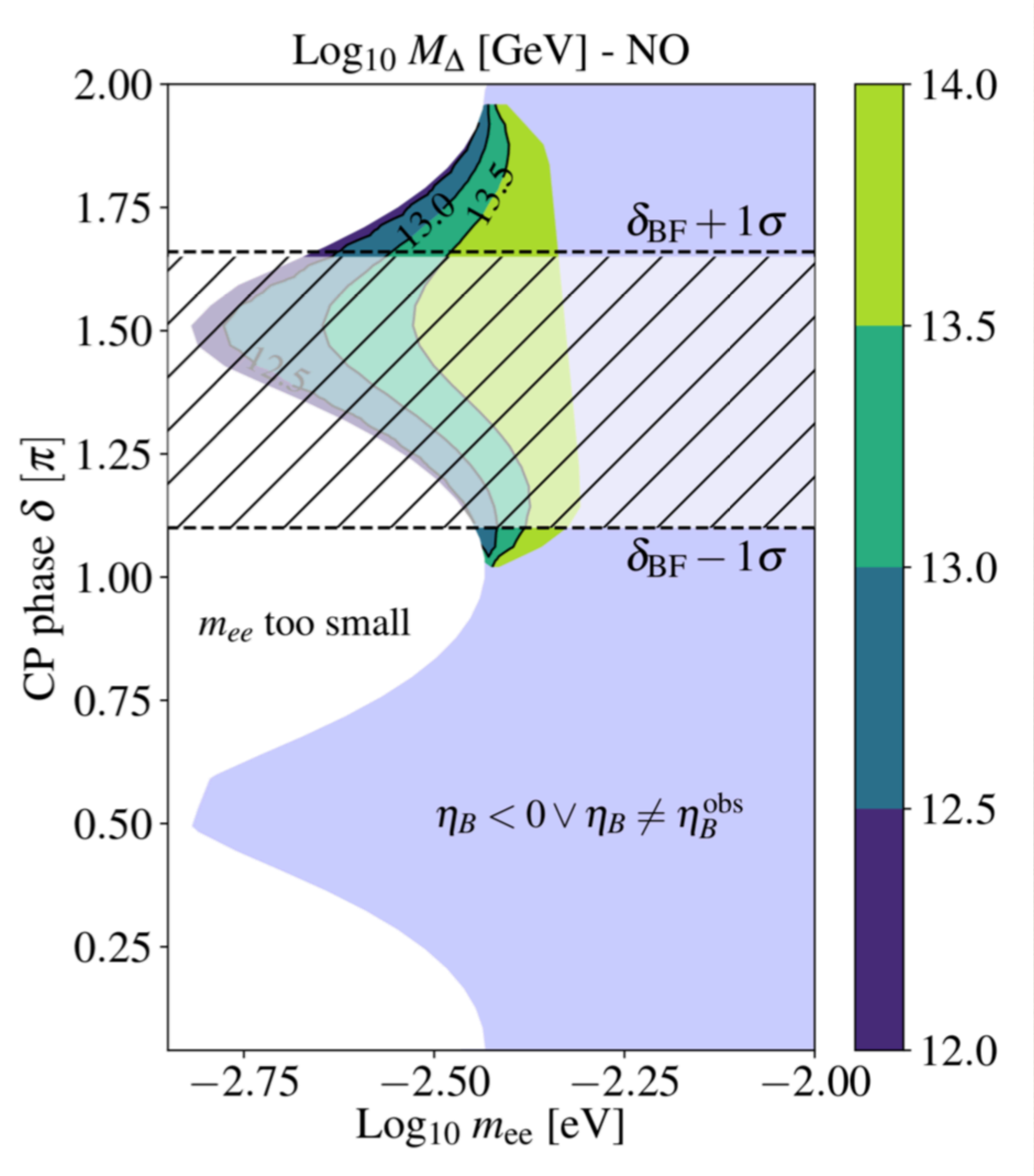
$$\epsilon_\Delta = -\frac{1}{8\pi}\sum_i M_i \frac{\mathrm{Im}\left[\mu\left(y^* f y^\dagger\right)_{ii}\right]}{M_\Delta^2 \mathrm{Tr}\left[f f^\dagger\right] + |\mu|^2} \ln\left(1 + \left(\frac{M_\Delta}{M_i}\right)^2\right)$$

becomes proportional to:

$$\sum_{i,j} \frac{m_i}{m_j} \mathrm{Im}\left[\left(U_{\tau i} U_{\tau j}^*\right)^2\right]$$

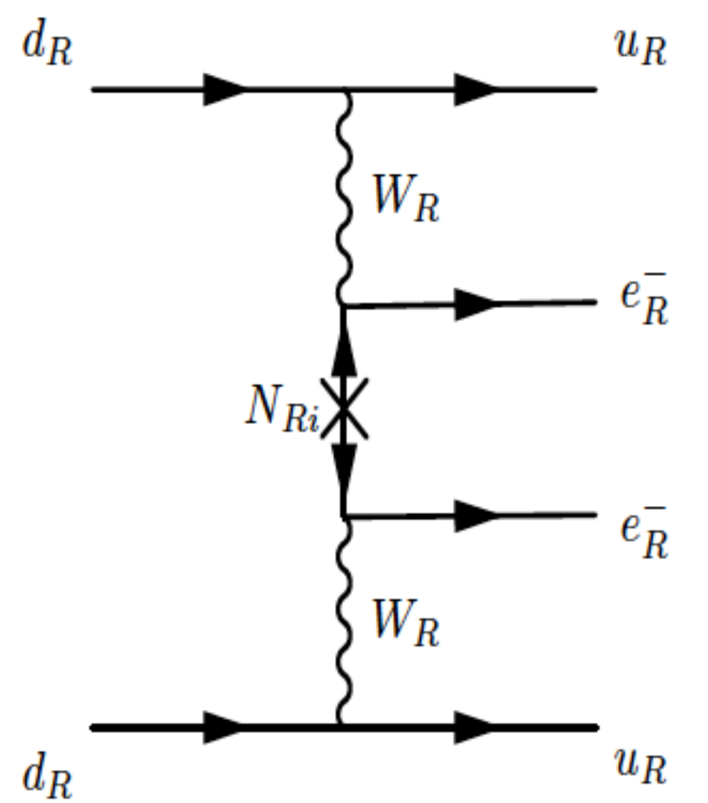
Rink, WR, Schmitz, NPB972

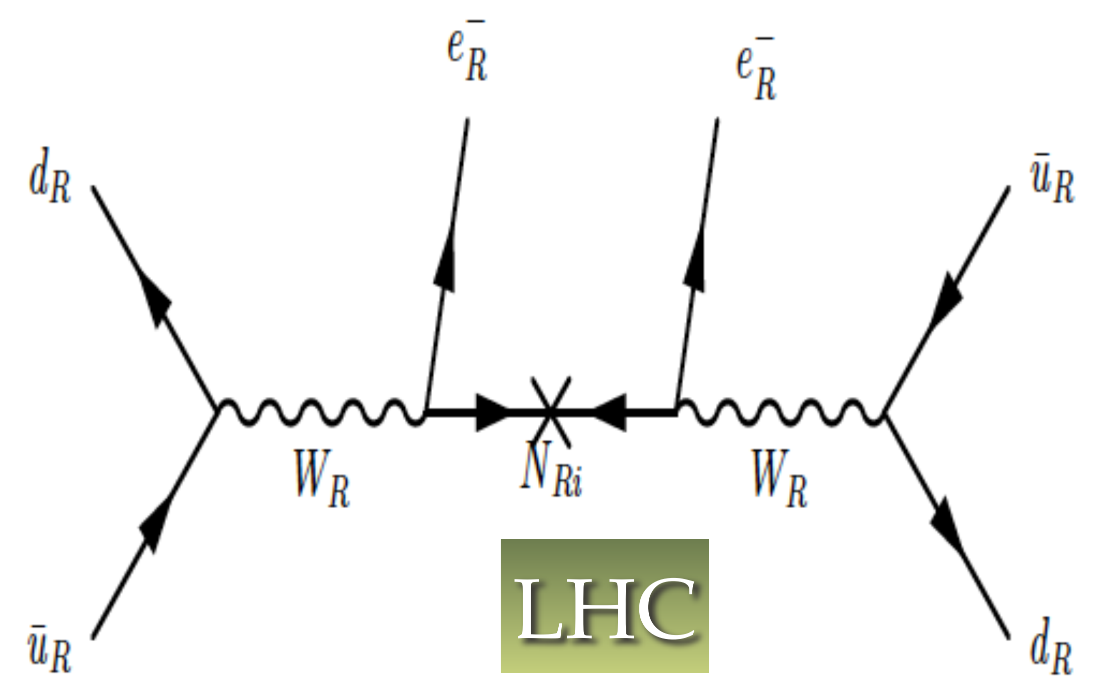
Leptogenesis

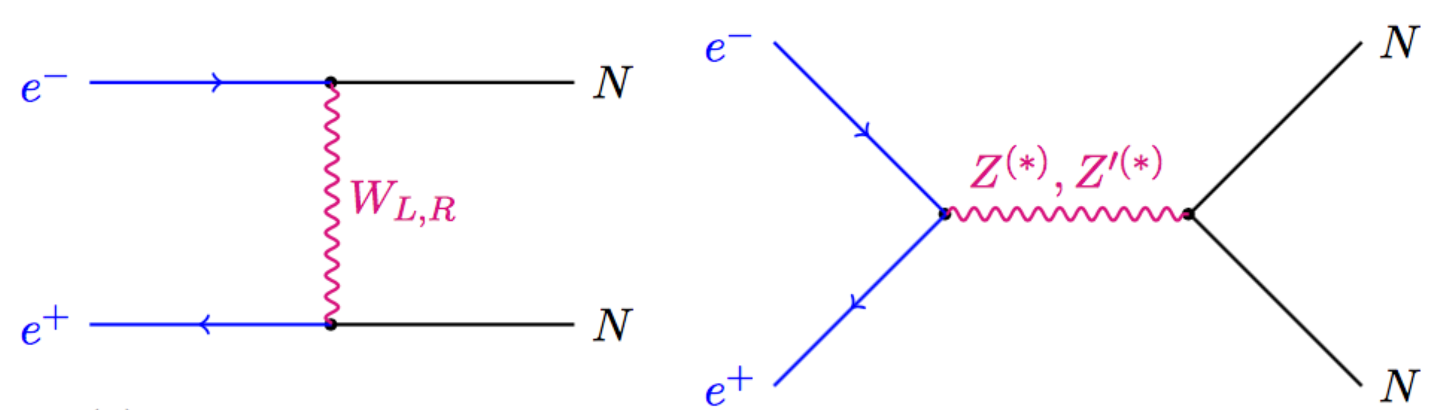


Rink, WR, Schmitz, NPB972

Colliders and Double Beta Decay



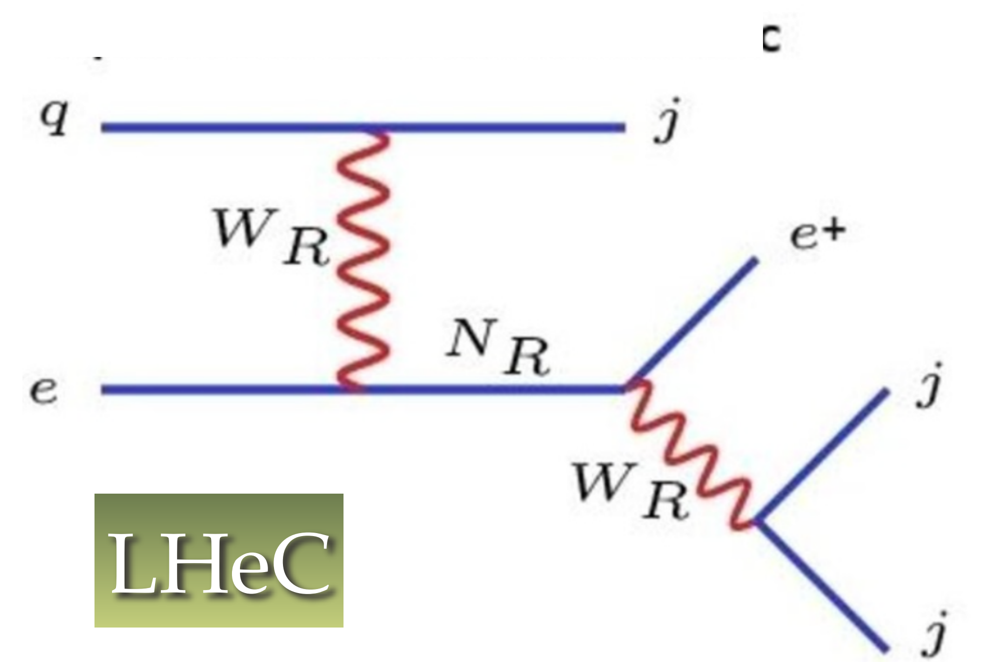




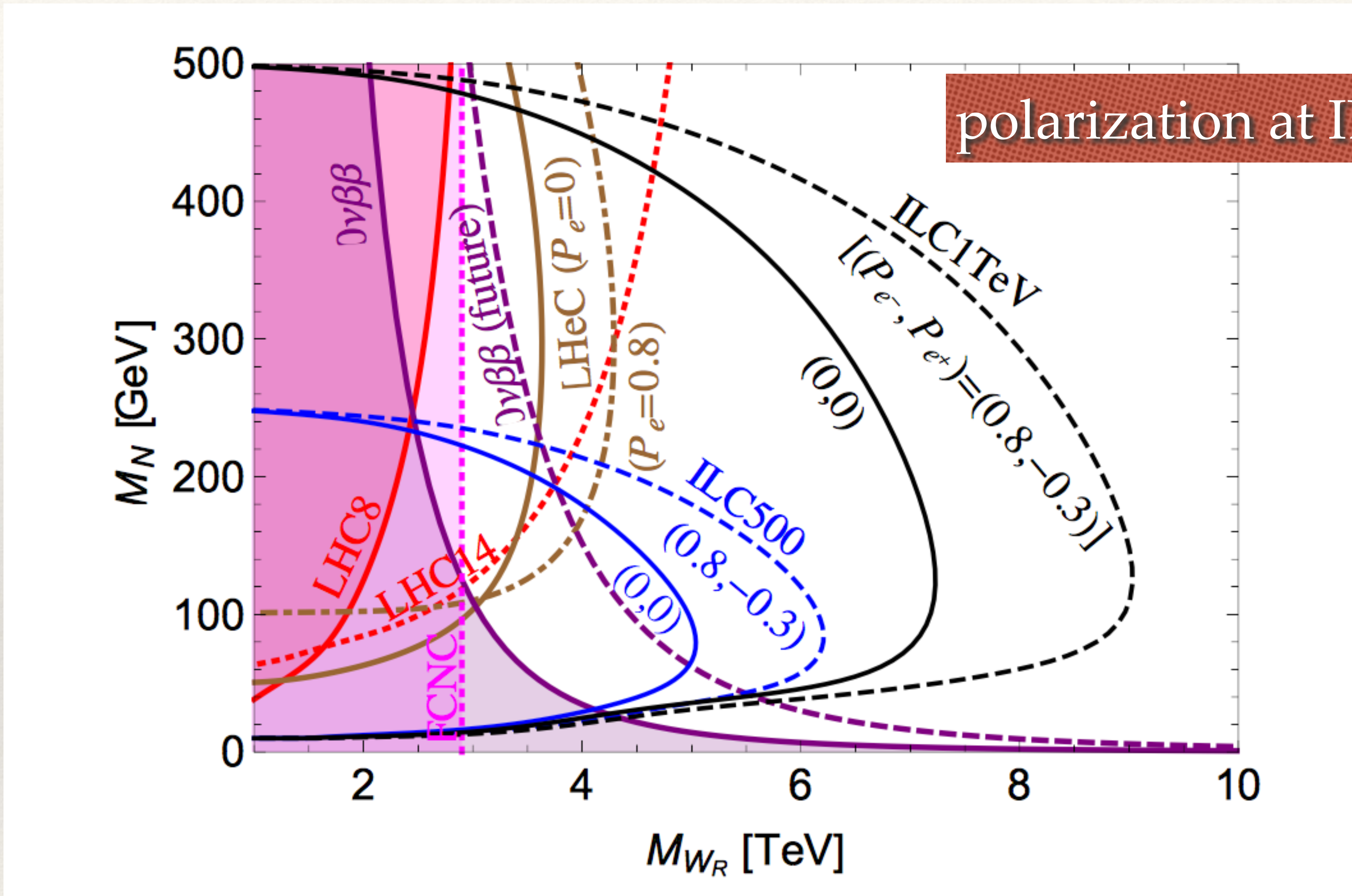
(a) t-channel production

(b) s-channel production

electron-positron



LHC and Double Beta Decay

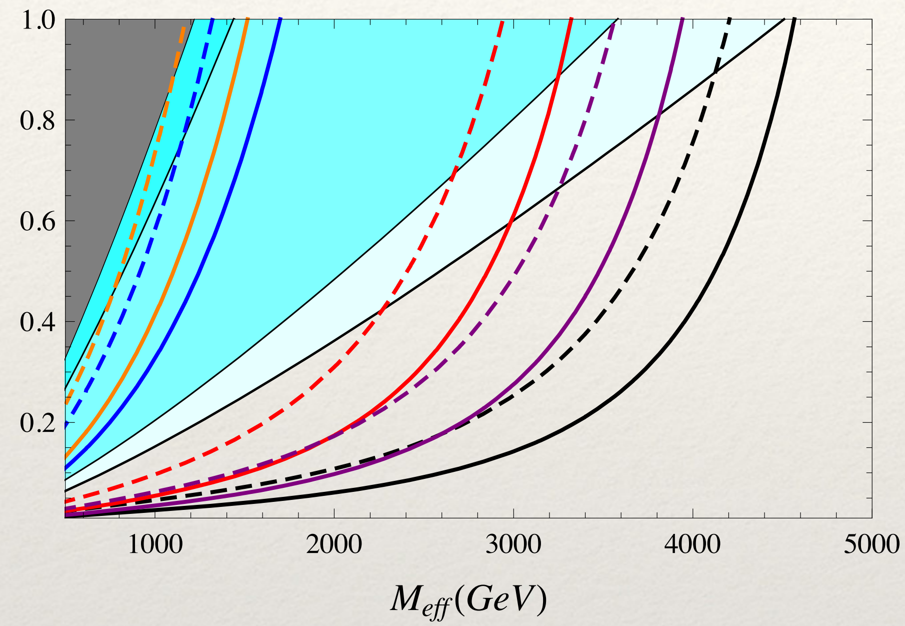


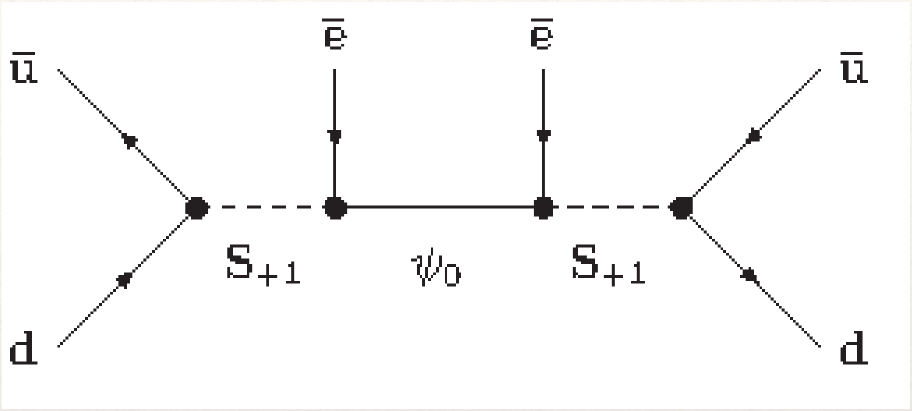
polarization at ILC and LHeC

Biwal, Bhupal Dev, 1701.08751
Lindner, Queiroz, WR, Yaguna, JHEP1606

Complementarity of LHC and 0νββ

Hirsch et al., 1511.03945

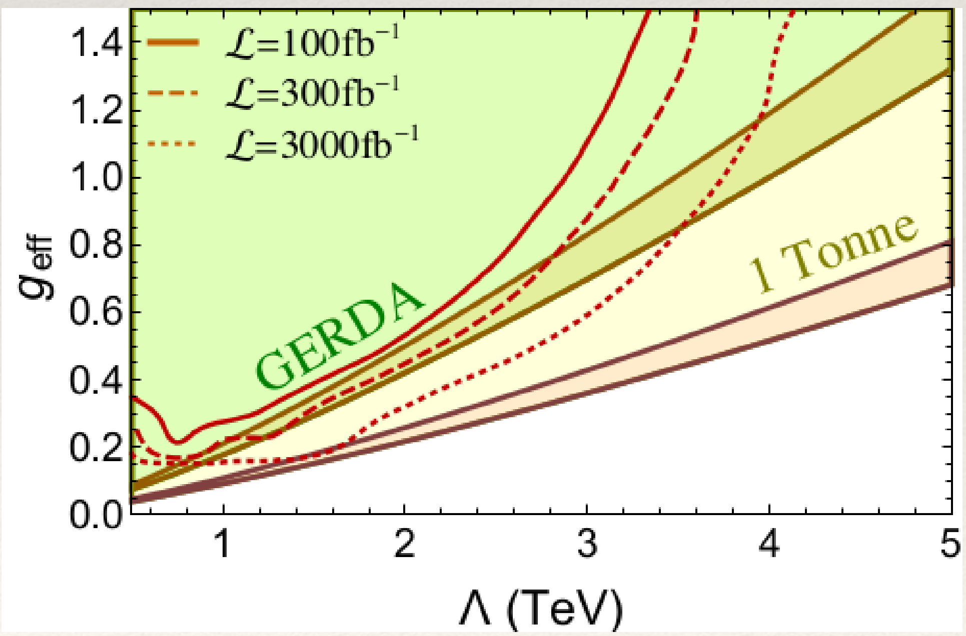




$S \sim (1,2)$

$\psi \sim (1,0)$

Ramsey-Musolf et al., 1508.04444

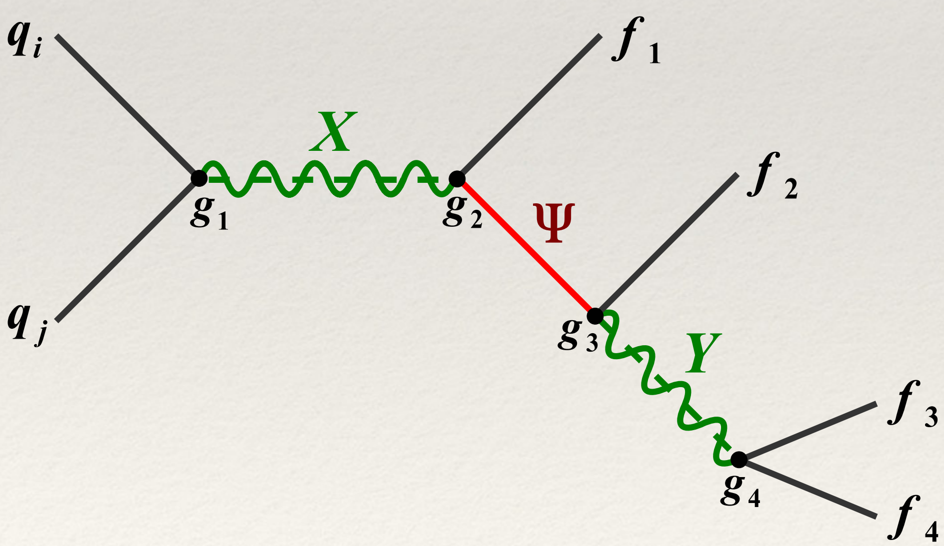


- LHC prefers $M_S > M_\psi$
- LHC has low sensitivity for small M_ψ
- include jet-fake rate, charge mis-ID, QCD corrections in 0νββ, etc.
- ⇒ complementary

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:

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

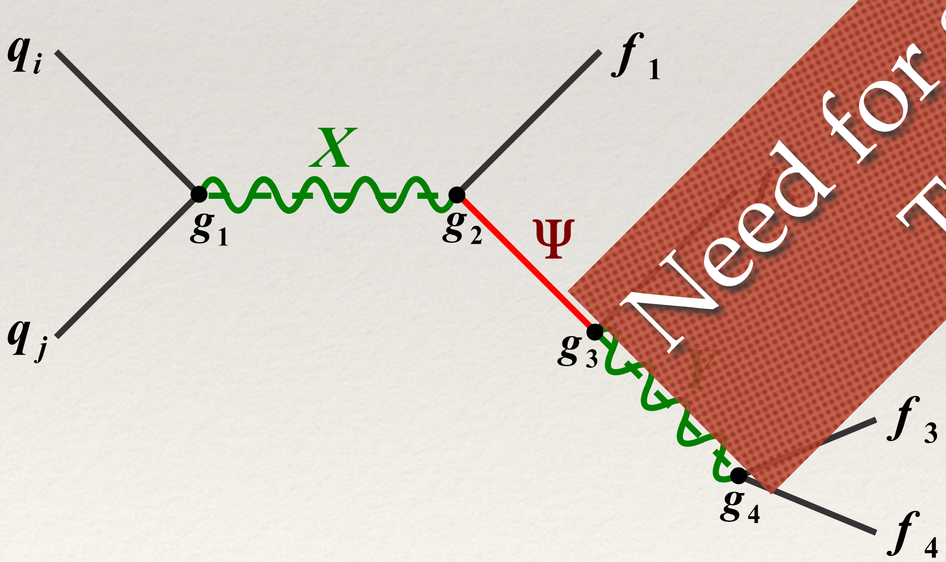
would need electroweak, resonant, ARS, post-sphaleron baryogenesis

TeV-scale LNV and Baryogenesis

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

- 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):



Washout:

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

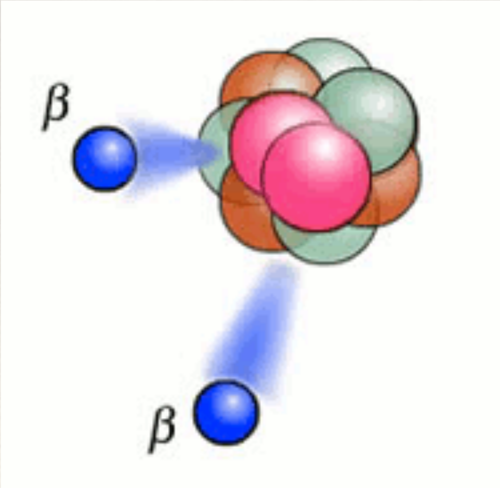
would need electroweak, resonant, ARS, post-sphaleron baryogenesis

Two Kinds of Double Beta Decay

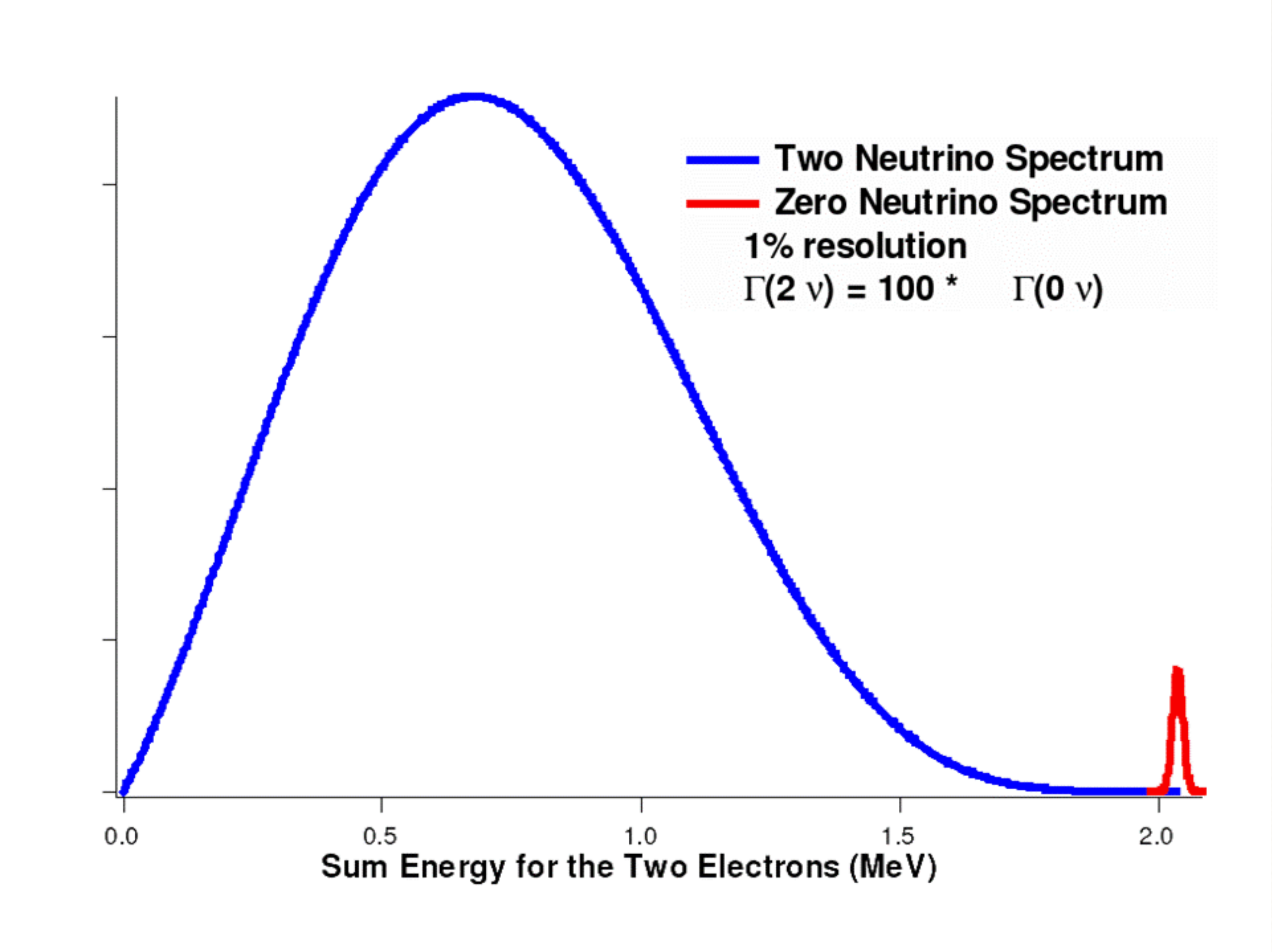
Inevitable Background

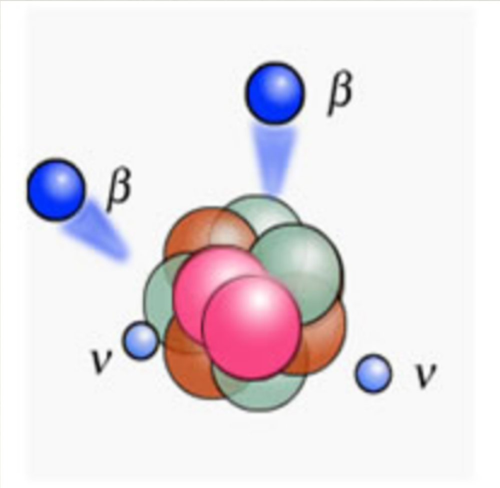
$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$

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



$\Delta L = 2$

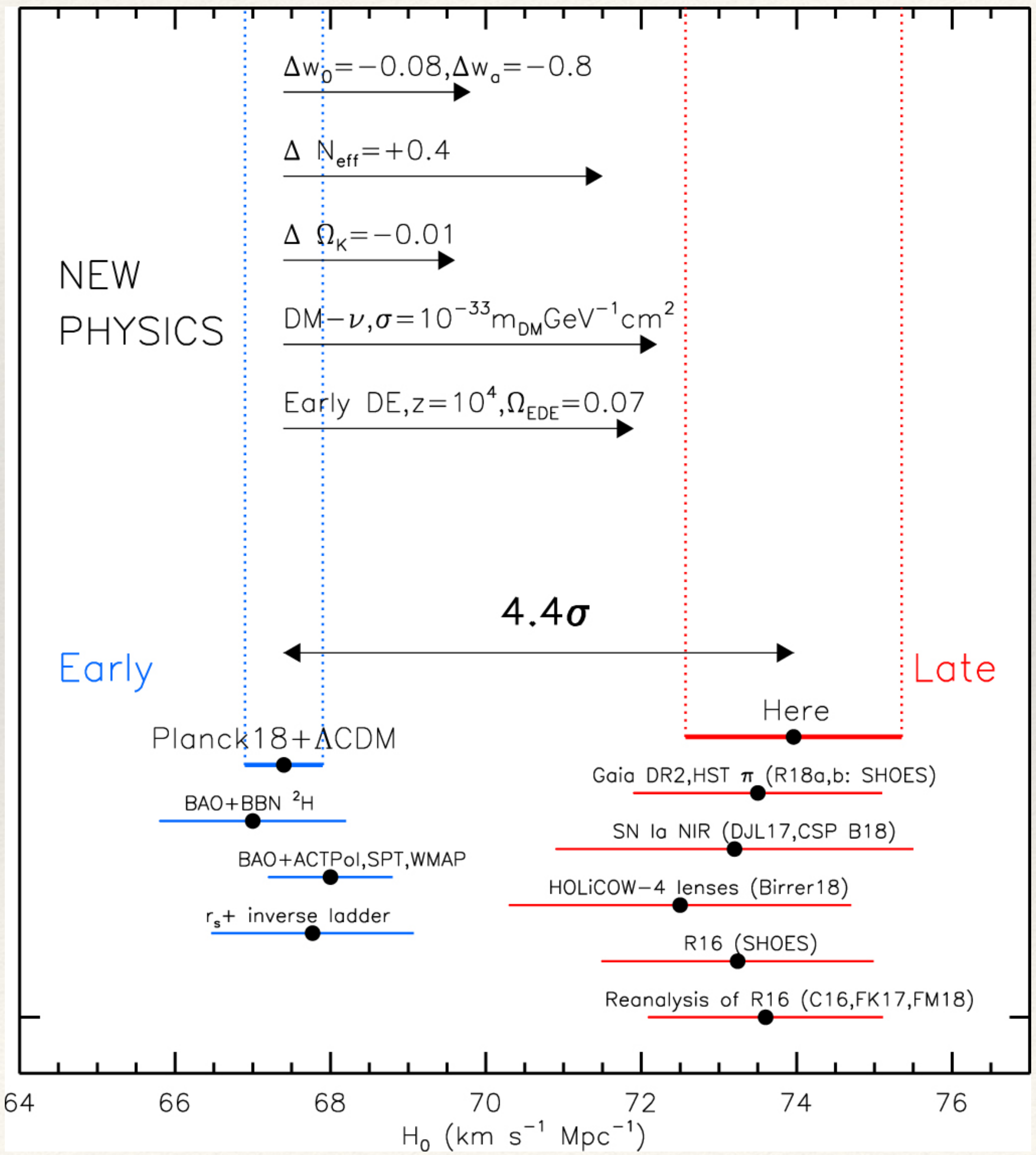




$\Delta L = 0$

New Physics with 2νββ

Hubble tension and new neutrino self-interactions



$$\mathcal{L}^{\rm LNC}_{\nu \rm SI} = G_S(\nu_e\nu_e)(\overline{\nu}_\alpha\overline{\nu}_\beta),$$
$$\mathcal{L}^{\rm LNV}_{\nu \rm SI} = G_S(\nu_e\nu_e)(\nu_\alpha\nu_\beta),$$

can resolve tension for strongly and „moderately" interacting ν:

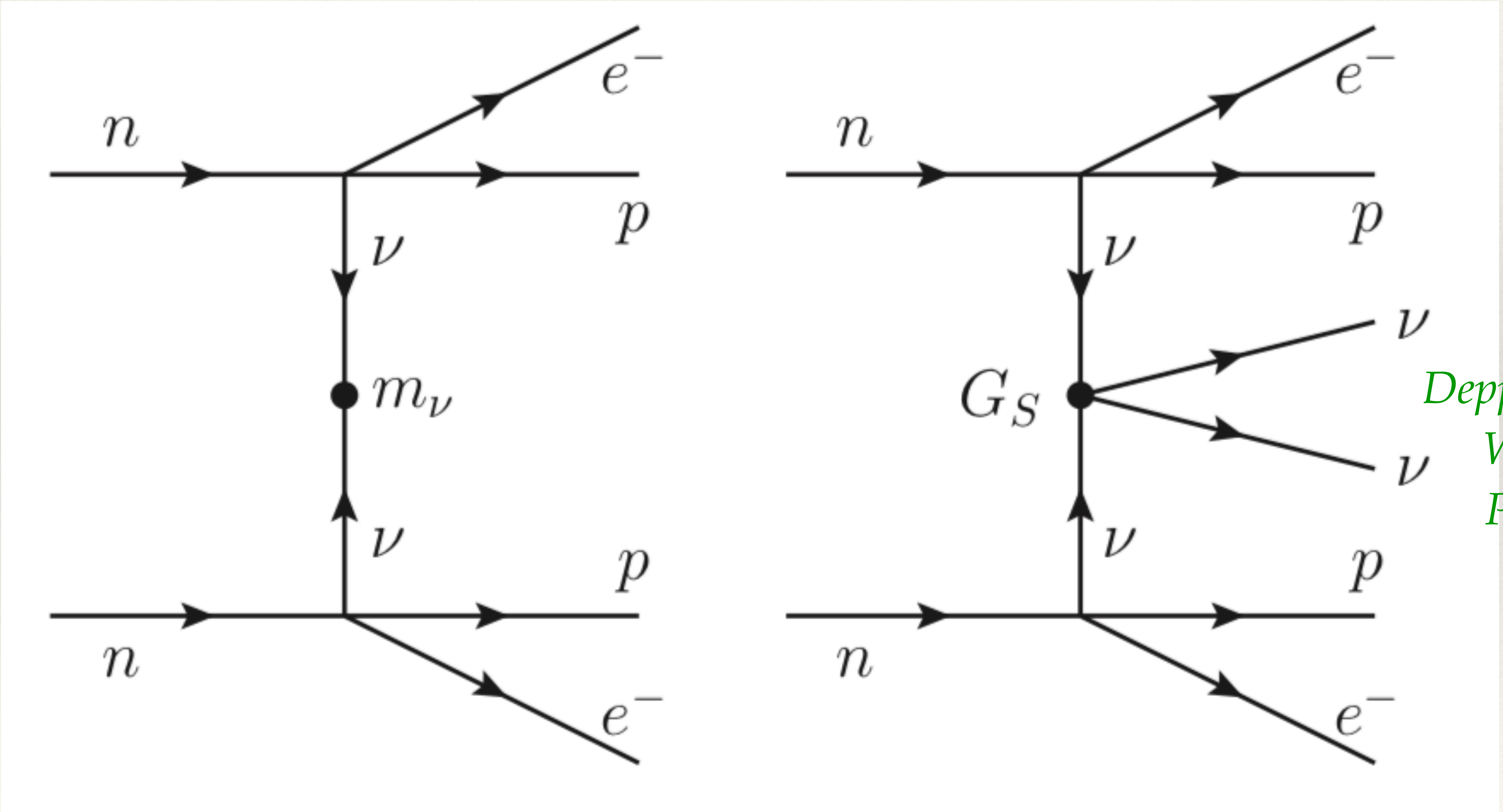
$$G_{\rm eff} = \begin{cases} (4.7^{+0.4}_{-0.6}\ {\rm MeV})^{-2} & ({\rm SI}\nu) \\ (89^{+171}_{-61}\ {\rm MeV})^{-2} & ({\rm MI}\nu) \end{cases}$$

Kreisch et al., 1902.00534

(extra radiation to modify *H*, delays matter-radiation equality, then νSI to compensate resulting CMB modifications)

New Physics with 2νββ

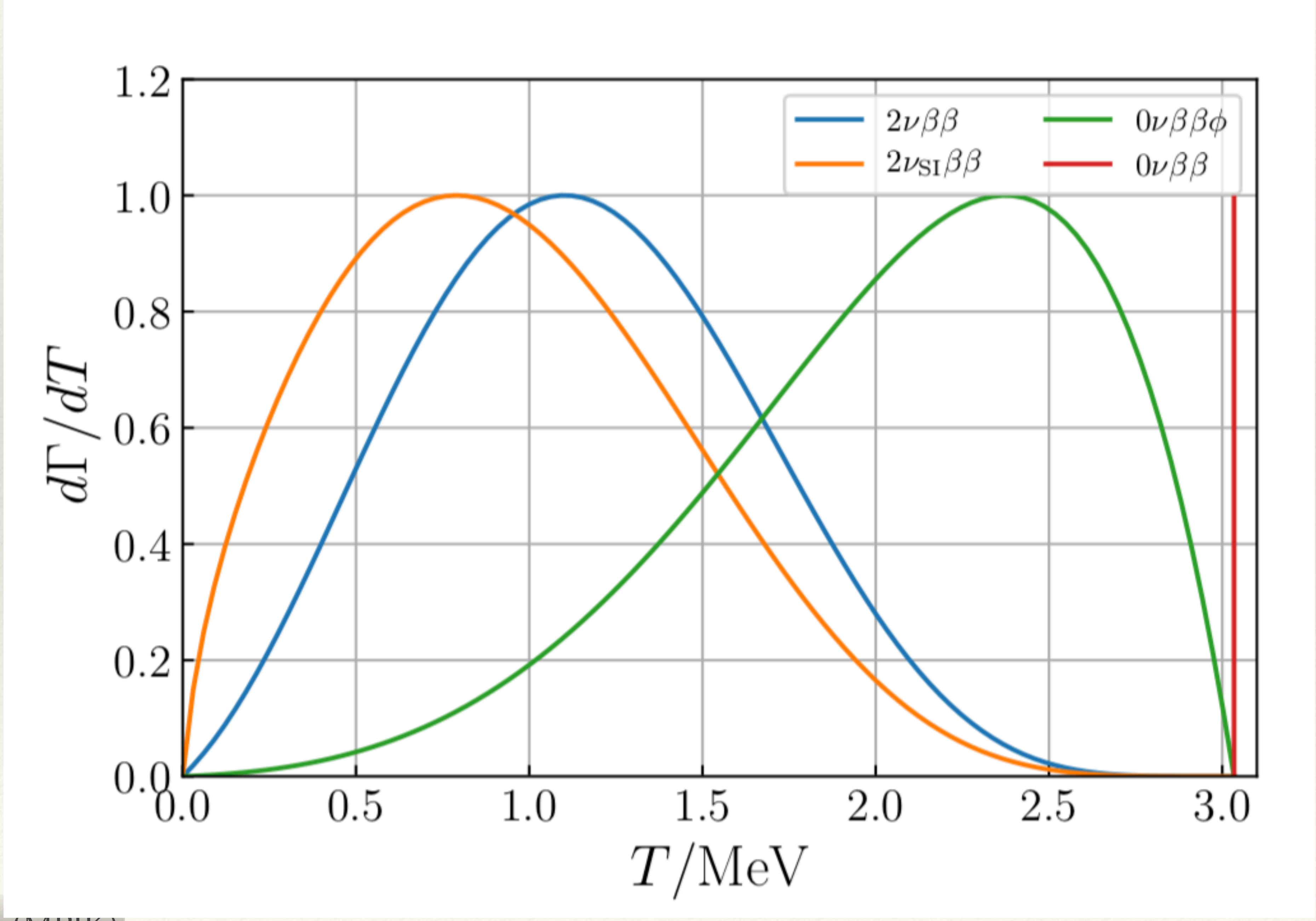
- 2-neutrino double beta decay only direct probe of 4-nu interactions:



Deppisch, Graf, WR, Xu, PRD102

New Physics with 2νββ

- Strong interactions ruled out by lab experiments, including double beta decay:



Deppisch, Graf, WR, Xu, PRD102

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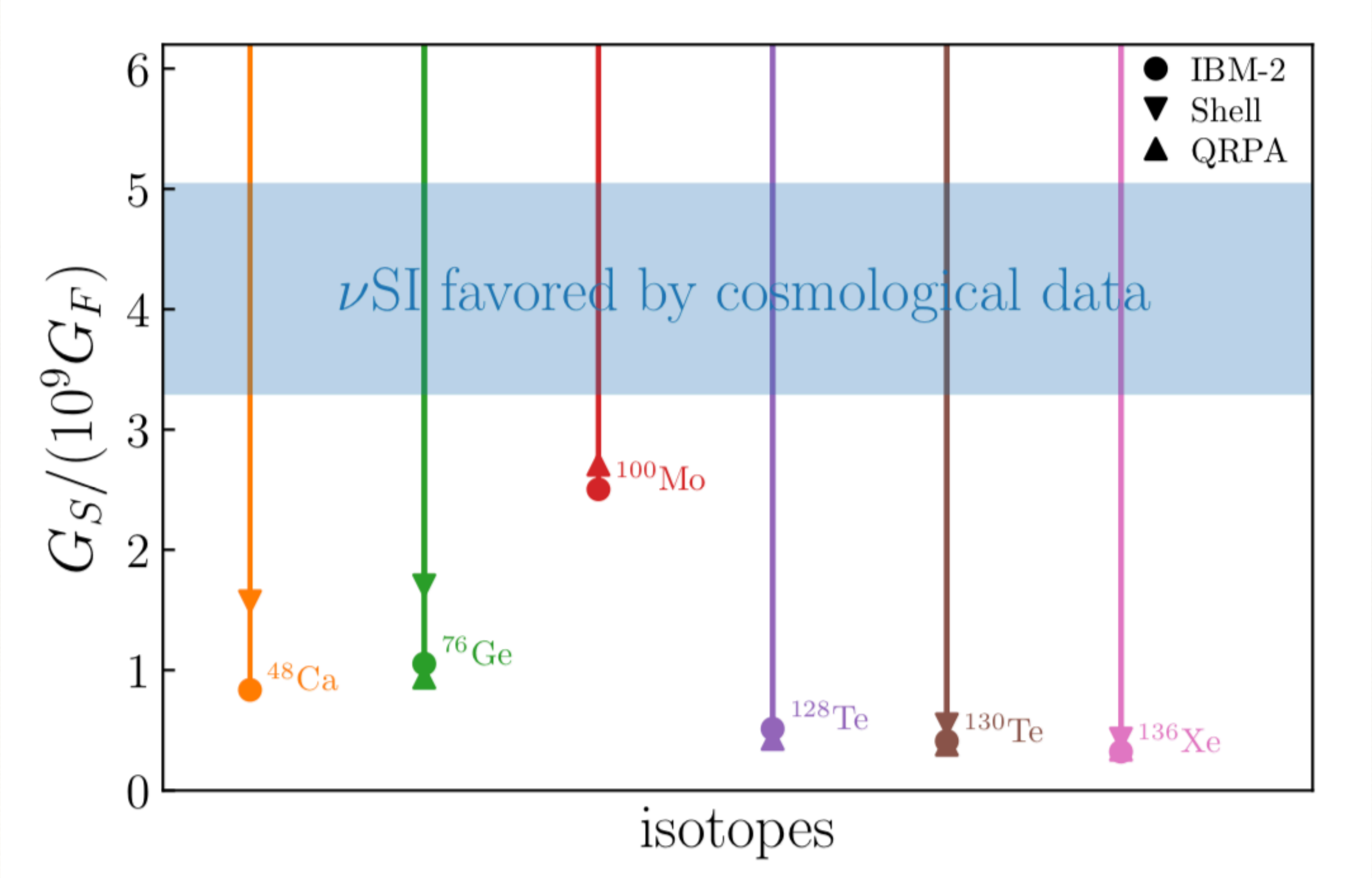
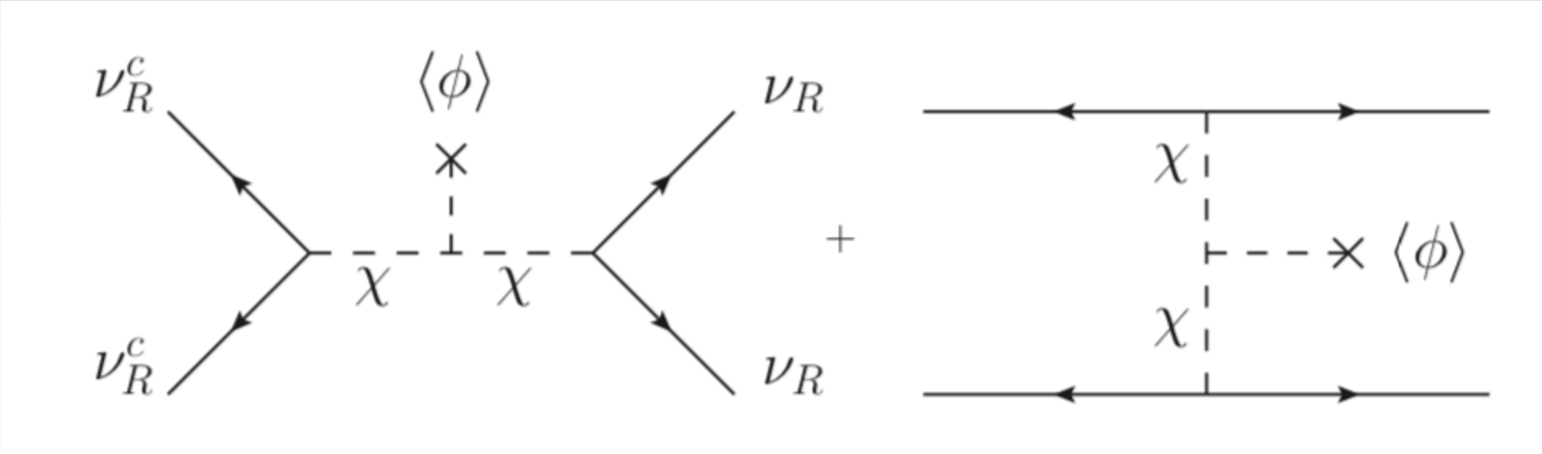


Deppisch, Graf, WR, Xu, PRD102

Lepton Number Violation with Dirac Neutrinos

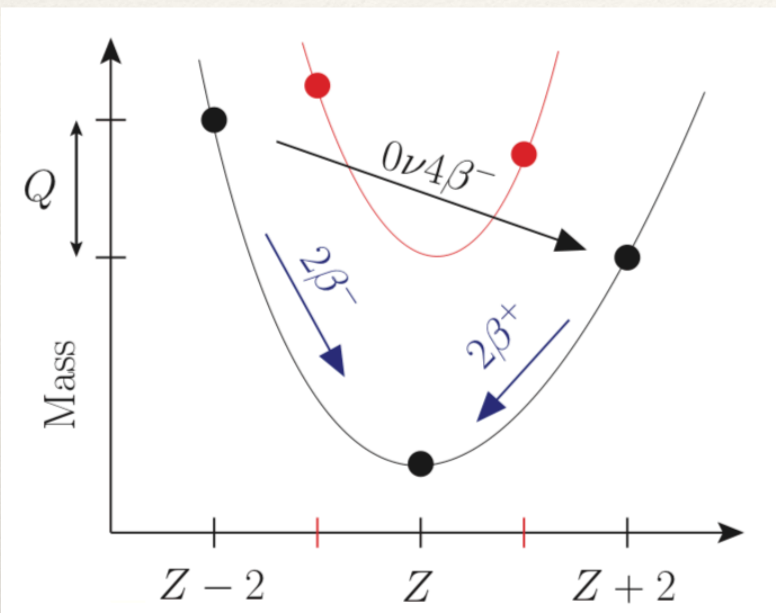
- Many models based on gauged B-L, broken by 2 units, hence Majorana masses and $\Delta L = 2$
- can break it also by 4 units, hence $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed!
- example: 3 RH nus with charge *-1*, an **<u>inert</u>** scalar χ with charge -2 and a scalar ϕ with charge +*4*



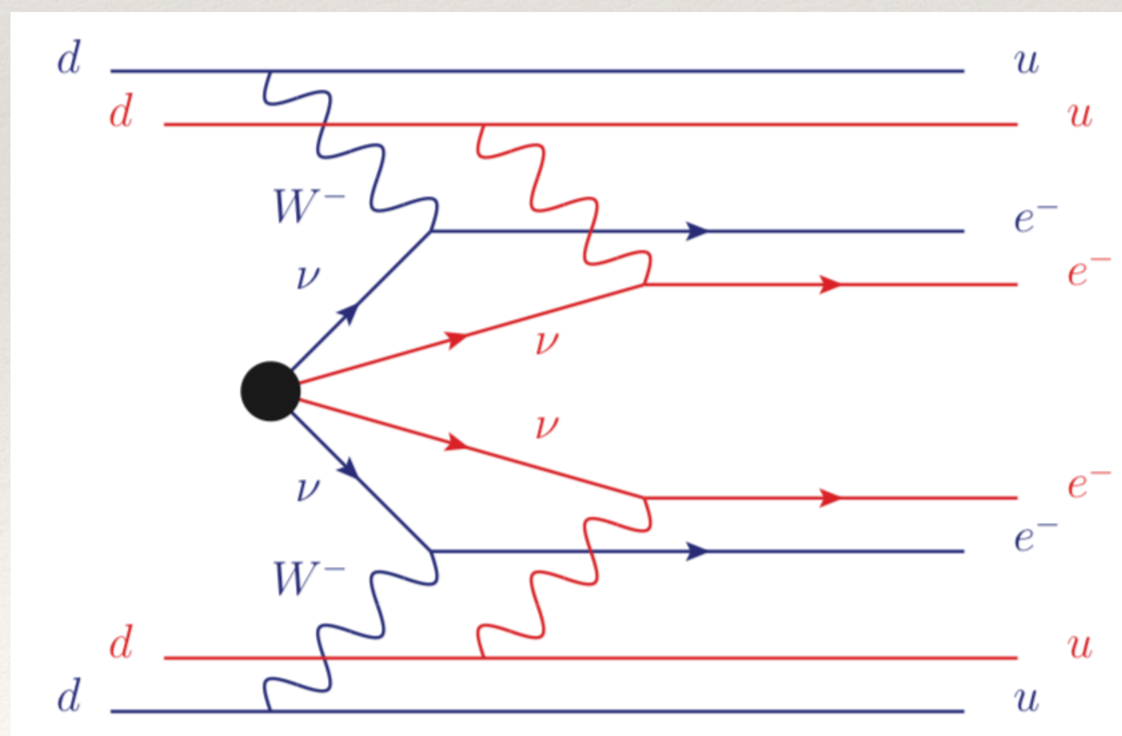
Heeck, WR, EPL103

Lepton Number Violation with Dirac Neutrinos

Phenomenology: Neutrinoless Quadruple Beta Decay 0νββββ



Candidates	$Q_{0\nu 4\beta}$	Other decays	NA
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6



Heeck, WR, EPL103

Lepton Number Violation with Dirac Neutrinos

PRL **119,** 041801 (2017) PHYSICAL REVIEW LETTERS week ending 28 JULY 2017

Search for Neutrinoless Quadruple-β Decay of ^{150}Nd with the NEMO-3 Detector

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NEMO-3 hunts for ultra-rare beta decay

30 Jun 2017

D vs. M with general interactions

- most general neutrino charged lepton interaction:

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

Rosen, PRL48

- with usual five possible terms:

$$\Gamma^a = \left\{ I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu} \equiv \tfrac{i}{2}[\gamma^\mu, \gamma^\nu] \right\}$$

- **<u>there can be sizable differences for Dirac and Majorana neutrinos!</u>**

D vs. M with general interactions

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

- in general, cross section for elastic neutrino electron scattering:

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

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

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

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: $C_V = D_V = C_T = D_T = 0$**

D vs. M with general interactions

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

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

- *Rosen* introduced a measurable ratio:

$$R_\rho \equiv \frac{2(A + 2B + C)}{A + C}$$

- differs for Dirac and Majorana neutrinos!

$$0 \le R_\rho \le 4\,(\text{Dirac}),$$
$$0 \le R_\rho \le 2\,(\text{Majorana})$$

($R_\rho = 2$ in SM)

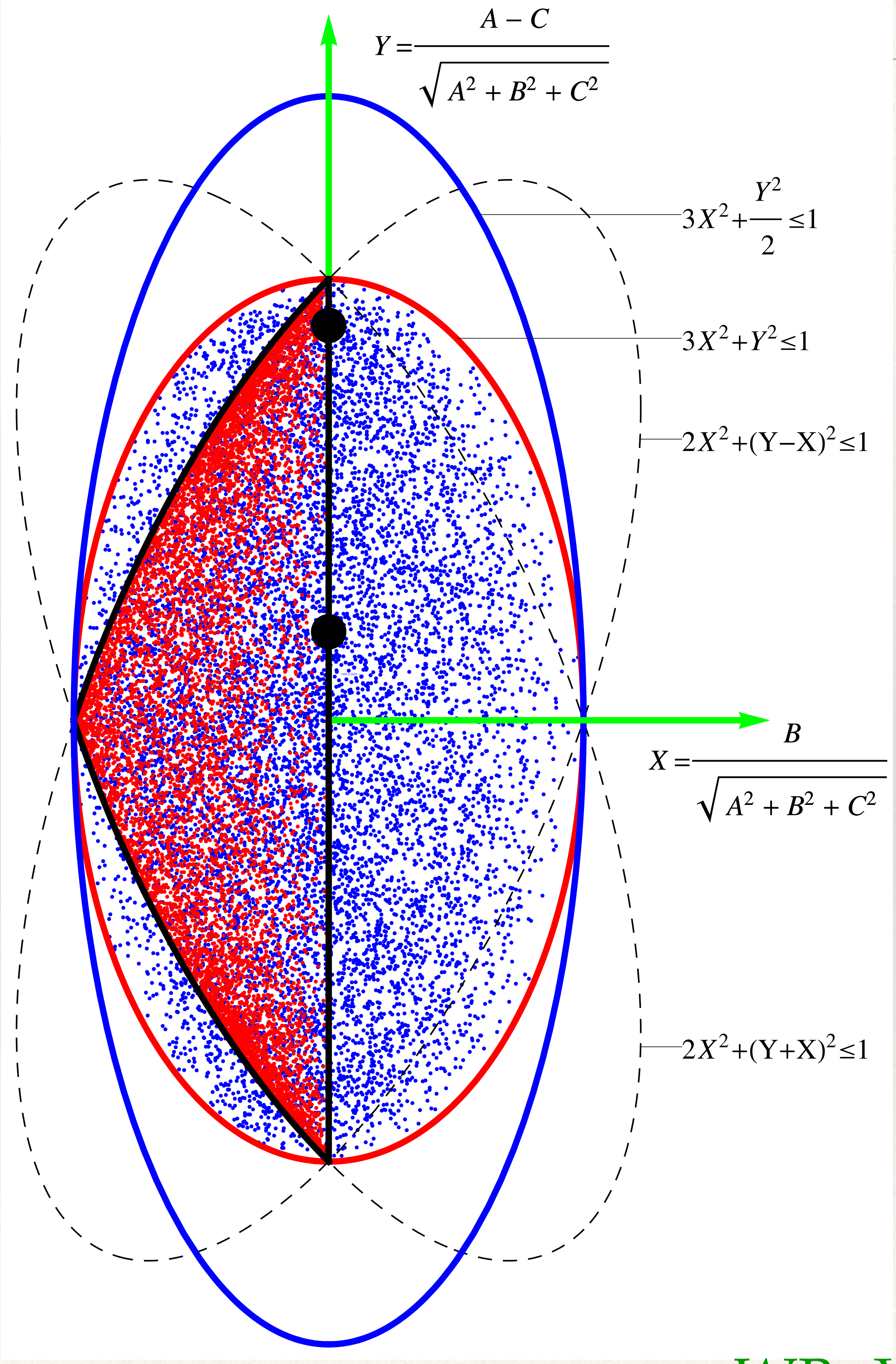
D vs. M with general interactions

$$0 \leq R_\rho \leq 4 \,(\text{Dirac}),$$
$$0 \leq R_\rho \leq 2 \,(\text{Majorana})$$

- measure between 0 and 2: can't tell
- measure between 2 and 4: Dirac!
- $\Rightarrow$ *can only show Dirac nature!*
- actually, slightly more complicated than just R_ρ

WR, Xu, Yaguna, JHEP1705

D vs. M with general interactions



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

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

Dirac:

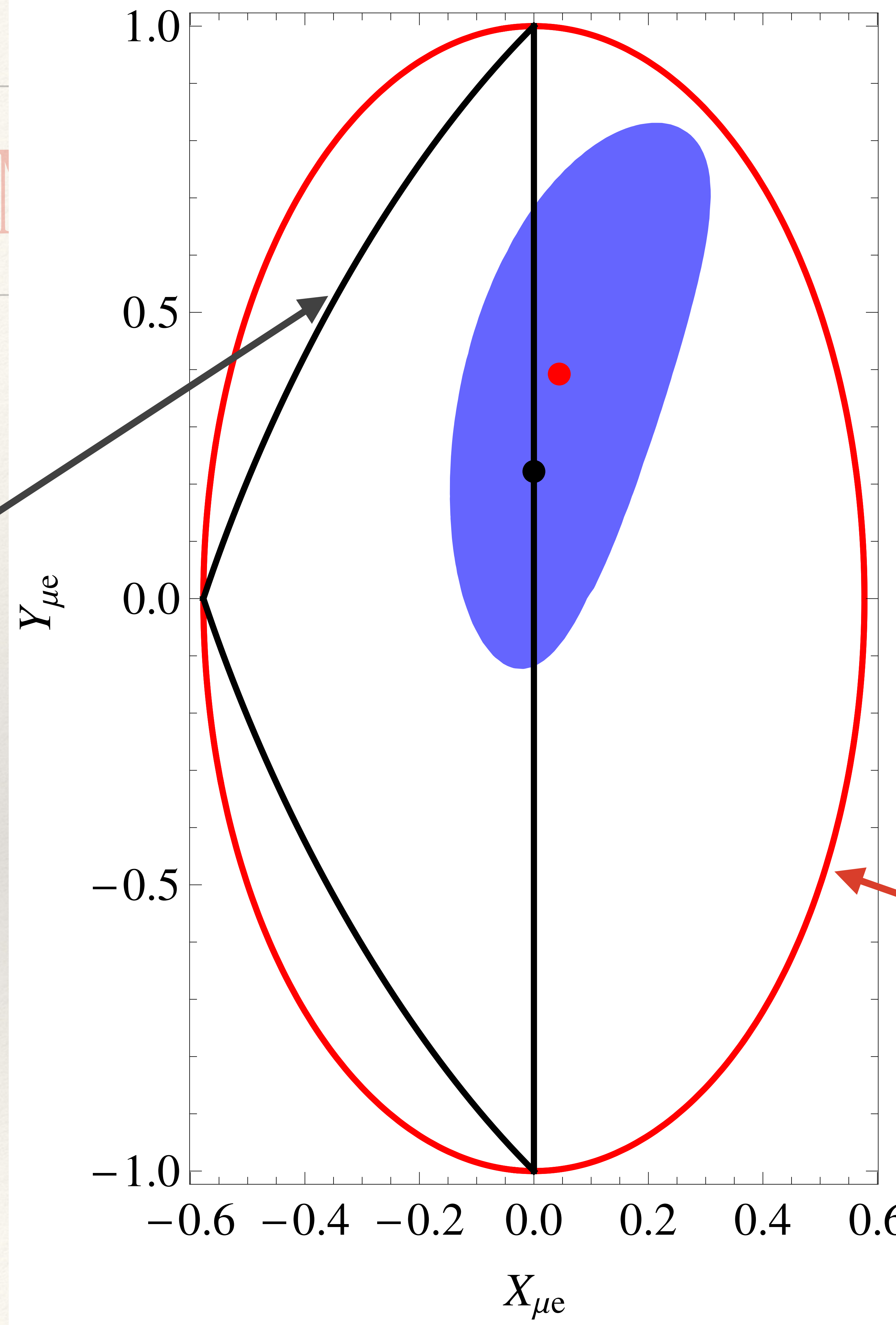
$$3X^2 + Y^2 \leq 1$$

Majorana:

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

WR, Xu, Yaguna, JHEP1705

D vs. actions



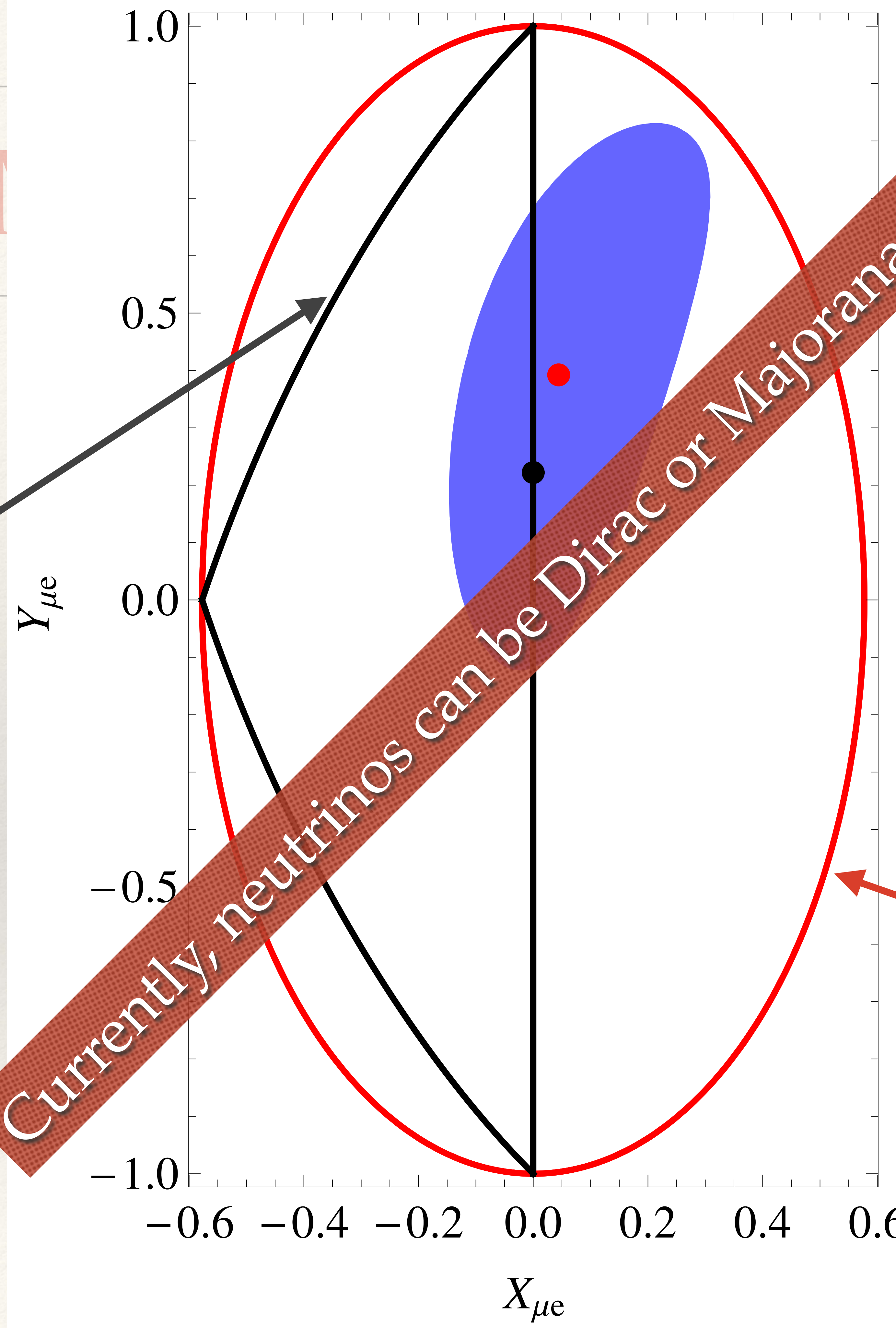
Majorana

CHARM-II data

Dirac

WR, Xu, Yaguna, JHEP1705

D vs. ctions

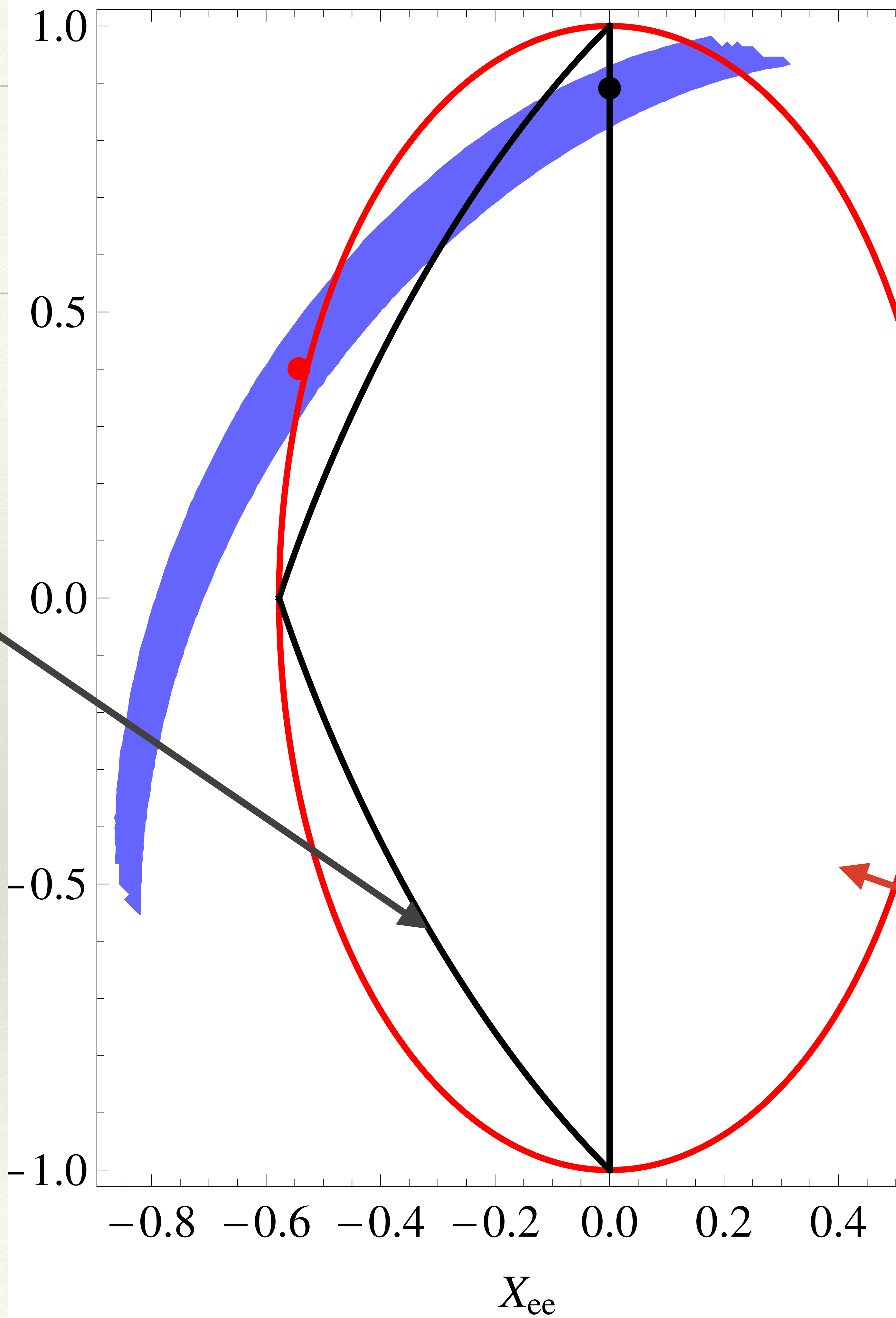


Majorana

CHARM-II data

Dirac

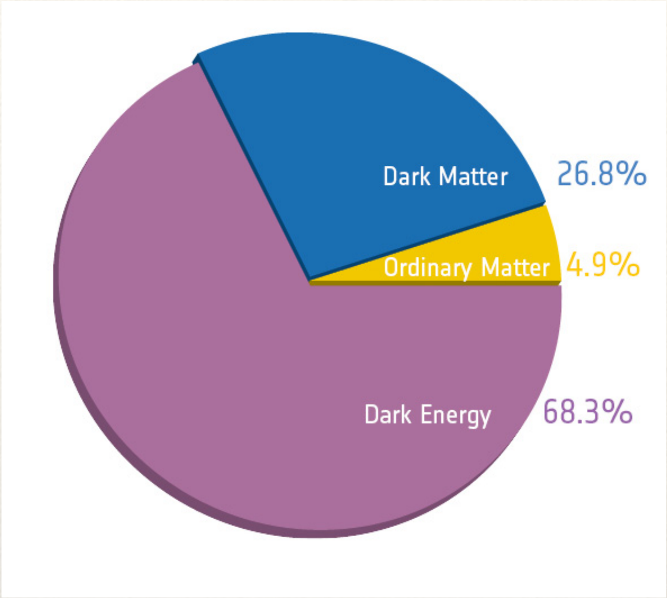
WR, Xu, Yaguna, JHEP1705

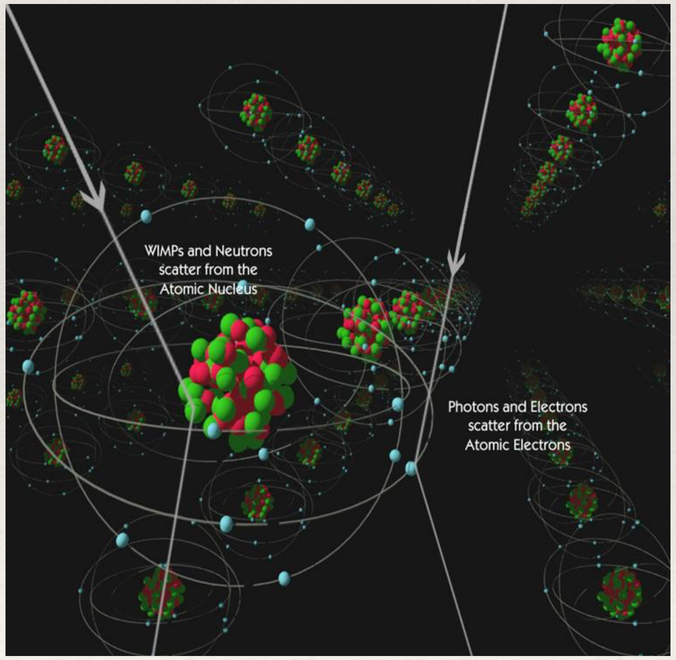


WR, Xu, Yaguna, JHEP1705


And now
for something
completely different...

Is Dark Matter its own Antiparticle?





- Dark Matter probably a particle
- natural, yet hardly asked question: *is it self-conjugate?*
- determining nature of DM particle turns out to be possible with direct detection only

(However, very difficult….)

Queiroz, WR, Yaguna, PRD95

Dirac versus Majorana DM

- difficult task, need:
  - isospin violating DM
  - non-zero coupling with *p* and *n* of DM particle and antiparticle
  - close density of DM particle and antiparticle
  - scalar **and** vector interactions
  - non-zero cross section with *p* and *n*
  - different ratio of (*p*,*n*)-coupling to DM particle and antiparticle

Queiroz, WR, Yaguna, PRD95

How it works:

- If χ is Dirac fermion: χ^D and anti-χ^D in principle both present $\Rightarrow$ <u>Dirac-DM has 4 possible interactions</u>:
    - χ^D talking to p, χ^D talking to n, anti-χ^D talking to p, anti-χ^D talking to n
- If χ is Majorana fermion: χ^M = anti-χ^M $\Rightarrow$ <u>Majorana-DM has 2 possible interactions</u>:
    - χ^M talking to p, χ^M talking to n
- $\Rightarrow$ Need to show that 4 interactions are present!
- $\Rightarrow$ ***can only show Dirac nature!***

Dirac versus Majorana DM

- most general SI interaction of fermion χ $(N = p,n)$:

$$\mathcal{L}^F_{SI} = \lambda_{N,e}\,\bar{\psi}_\chi\psi_\chi\,\bar{\psi}_N\psi_N + \lambda_{N,o}\,\bar{\psi}_\chi\gamma_\mu\psi_\chi\,\bar{\psi}_N\gamma^\mu\psi_N$$

- For Majorana: no vector interactions:

$$\sigma^M_{SI} = \frac{4\mu_\chi^2}{\pi}\left[\lambda_p^M\,Z + \lambda_n^M\,(A-Z)\right]^2$$

- For Dirac: particle and antiparticle:

$$\sigma^D_{SI} = \frac{4\mu_\chi^2}{\pi}\frac{1}{2}\left(\left[\lambda_p^D\,Z + \lambda_n^D\,(A-Z)\right]^2 + \left[\lambda_p^{\bar{D}}\,Z + \lambda_n^{\bar{D}}\,(A-Z)\right]^2\right)$$

$\lambda_N^D \equiv (\lambda_{N,e} + \lambda_{N,o})/2$ and $\lambda_N^{\bar{D}} \equiv (\lambda_{N,e} - \lambda_{N,o})/2$

Dirac versus Majorana DM

- suppose we have measured DM cross section with isotopes X and Y. Interpreted in terms of Majorana, we have:

$$\left[\lambda_p^M Z_X + \lambda_n^M (A_X - Z_X)\right]^2 = \frac{\pi \tilde{\sigma}_X}{4\mu_\chi^2},$$

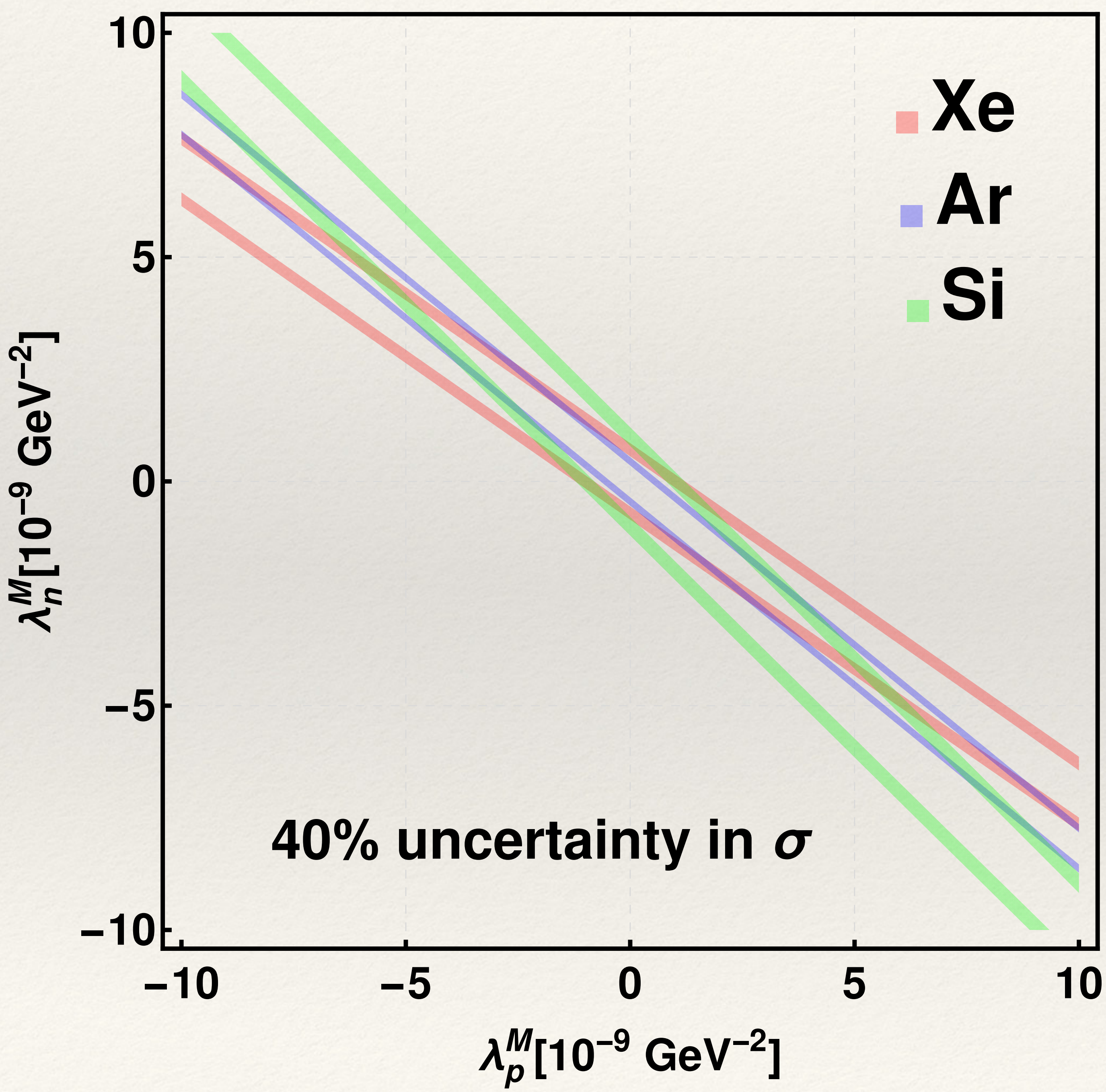
$$\left[\lambda_p^M Z_Y + \lambda_n^M (A_Y - Z_Y)\right]^2 = \frac{\pi \tilde{\sigma}_Y}{4\mu_\chi^2}.$$

extract $(\lambda_p{}^M, \lambda_n{}^M)$: two parallel lines each, with slopes $m_X = Z_X/(A_X - Z_X)$ and $m_Y = Z_Y/(A_Y - Z_Y)$

Dirac versus Majorana DM

- suppose we have measured DM cross section with isotopes X and Y. Interpreted in terms of Majorana, extract $(\lambda_p{}^M, \lambda_n{}^M)$: two parallel lines with slopes $m_X = Z_X/(A_X - Z_X)$ and $m_Y = Z_Y/(A_Y - Z_Y)$
- if $m_X \neq m_Y$: lines intersect at 4 different points
  $\Rightarrow$ always consistent with Majorana case!
  $\Rightarrow$ need third isotope V:
  - hit one of the crossing points of X and Y: can't tell Dirac from Majorana
  - miss all crossing points of X and Y: DM is Dirac particle!

Dirac versus Majorana DM



- red and blue lines for Xe and Ar: cross each other 4 times
- green line for Si: does not cross other lines in one point
  ⇒ Majorana interpretation does not work
  ⇒ DM must be Dirac particle

Experimental Aspects

- need isotopes with different Z and $N = A - Z$
- Z/N between 0.65 and 1 for stable nuclei
- Ar, Xe, Ge too close to each other
- Ar, Xe and Si or Ca or O would be nice…

isotope	Z	N	Z/N
Ar	18	22	0.82
Xe	54	77	0.70
Ge	32	40	0.80
Si	14	14	1.00
Na	11	12	0.92
F	9	10	0.90
Ca	20	20	1.00
O	8	8	1.00
W	74	110	0.67
I	53	74	0.72

Statistical Analysis

(do „realistic“ analysis with proper event numbers, experimental details, etc.)

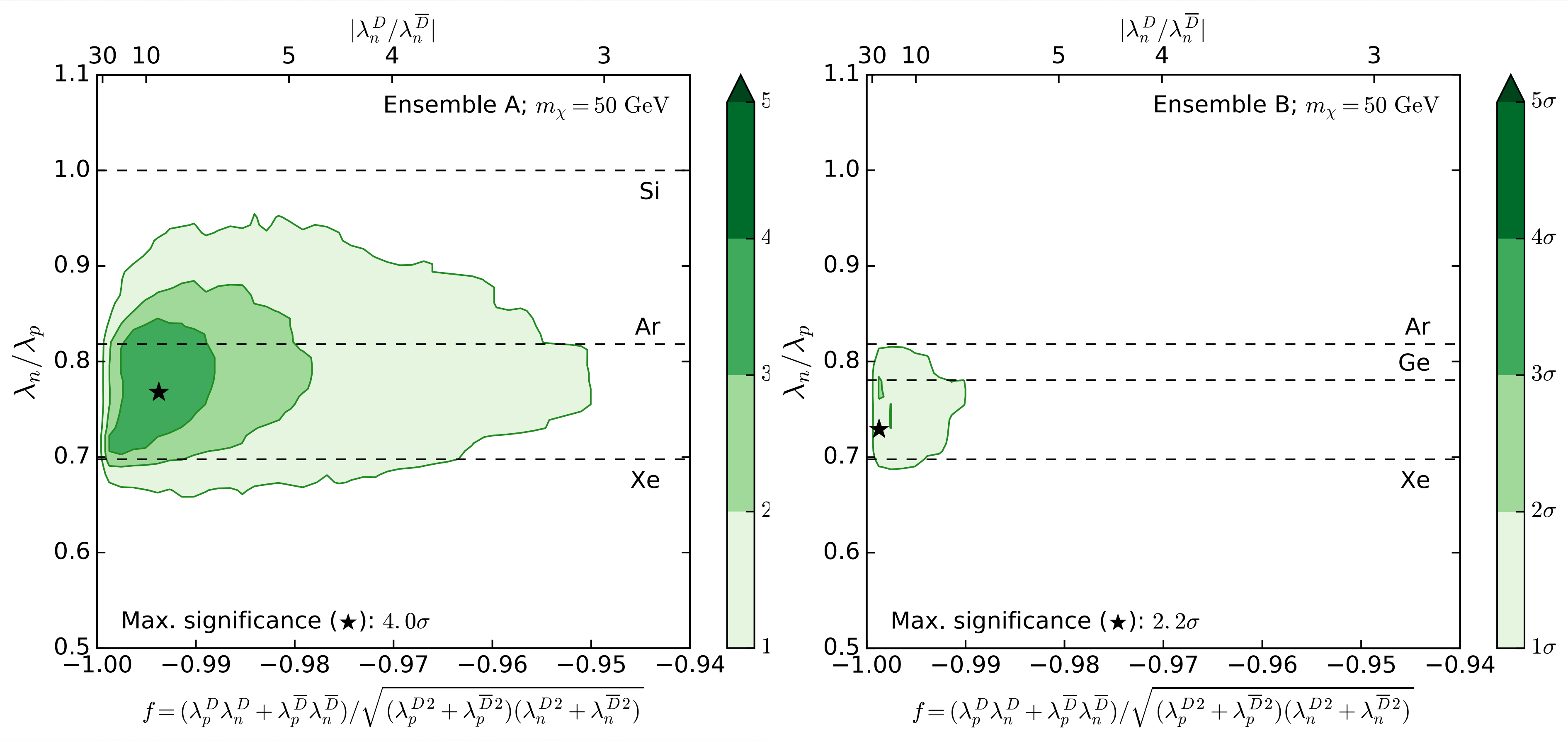
Target	$E_{\min}$ [keV]	$E_{\max}$ [keV]	Exposure [ton yr]
Xe	5	40	20
Ar	30	200	150
Si	7	100	3
Ge	5	100	3
$CaWO_4$	10	100	3

Ensemble A: Xe + Ar + Si

Ensemble B: Xe + Ar + Ge

Ensemble C: Xe + Ar + $CaWO_4$

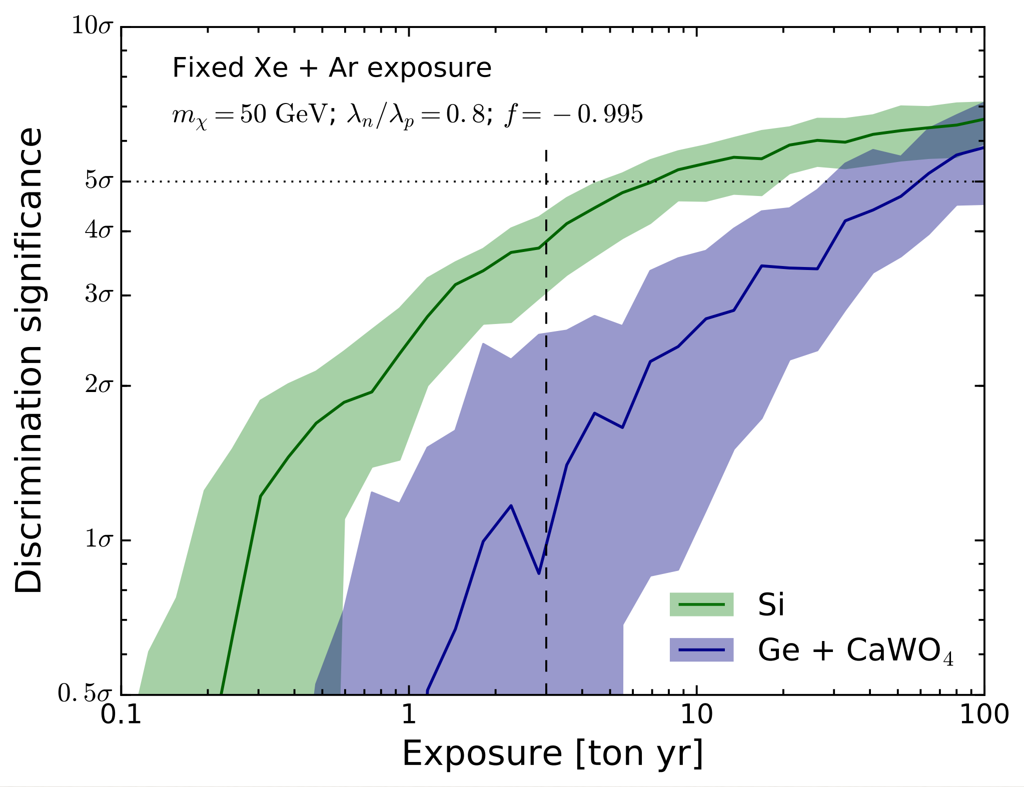
Ensemble D: Xe + Ar + 50% Ge + 50% $CaWO_4$



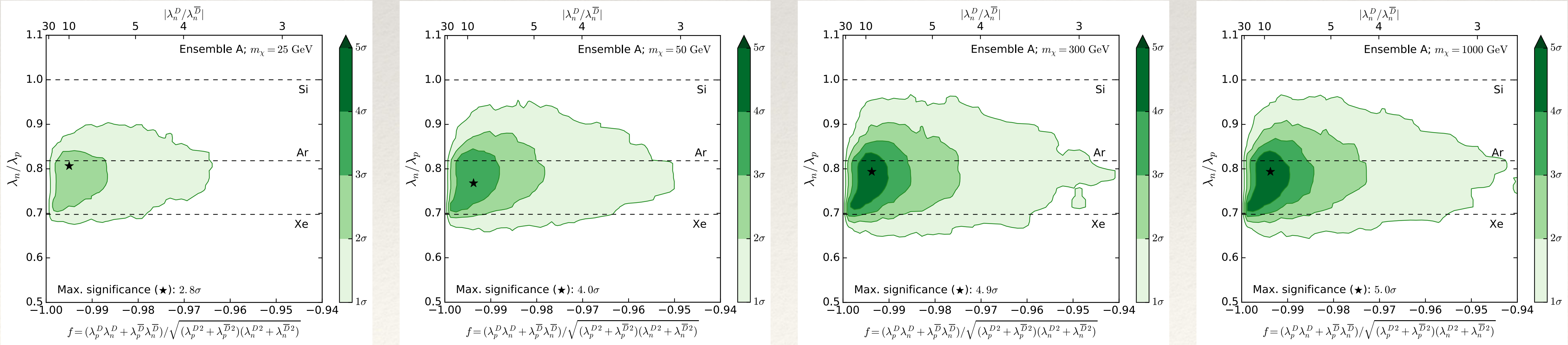
- fix event numbers for Xe
- at each mass, parameter ranges determined
- at each point, generate mock data
- fit under hypothesis D and M, respectively
- compare likelihoods

Kavanagh, Queiroz, WR, Yaguna, JHEP1710

Statistical Analysis



DM Mass [GeV]	25	50	300	1000
A (Xe+Ar+Si)	2.8σ	4.0σ	4.9σ	5.0σ
B (Xe+Ar+Ge)	1.7σ	2.2σ	2.7σ	2.8σ
C (Xe+Ar+CaWO$_4$)	2.0σ	2.4σ	3.0σ	2.9σ
D (Xe+Ar+Ge/CaWO$_4$)	3.2σ	2.6σ	2.9σ	3.2σ



Kavanagh, Queiroz, WR, Yaguna, JHEP1710

Scalar and Vector Dark Matter

- Scalar particle ϕ_χ also possible. If complex:

$$\mathscr{L}_{SI}^{S} = 2\lambda_{N,e} M_\chi \, \phi_\chi^\dagger \phi_\chi \, \bar{\psi}_N \psi_N + i\lambda_{N,o} \left[\phi_\chi^\dagger (\partial_\mu \phi_\chi) - (\partial_\mu \phi_\chi^\dagger)\, \phi_\chi\right] \bar{\psi}_N \gamma^\mu \psi_N$$

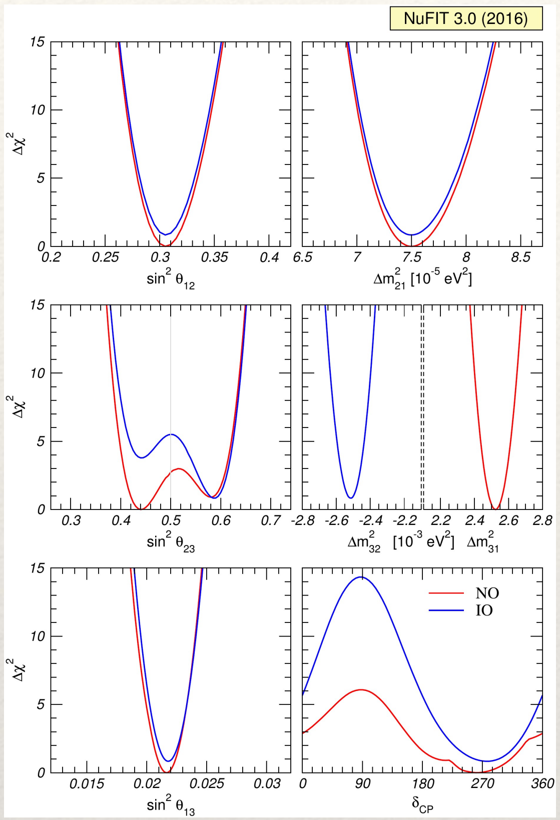
- if real: $\lambda_{N,o} = 0$
- Again, 4 parameters for complex DM, two for real
- Works similarly with vector DM

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.

Expectations of lifetimes

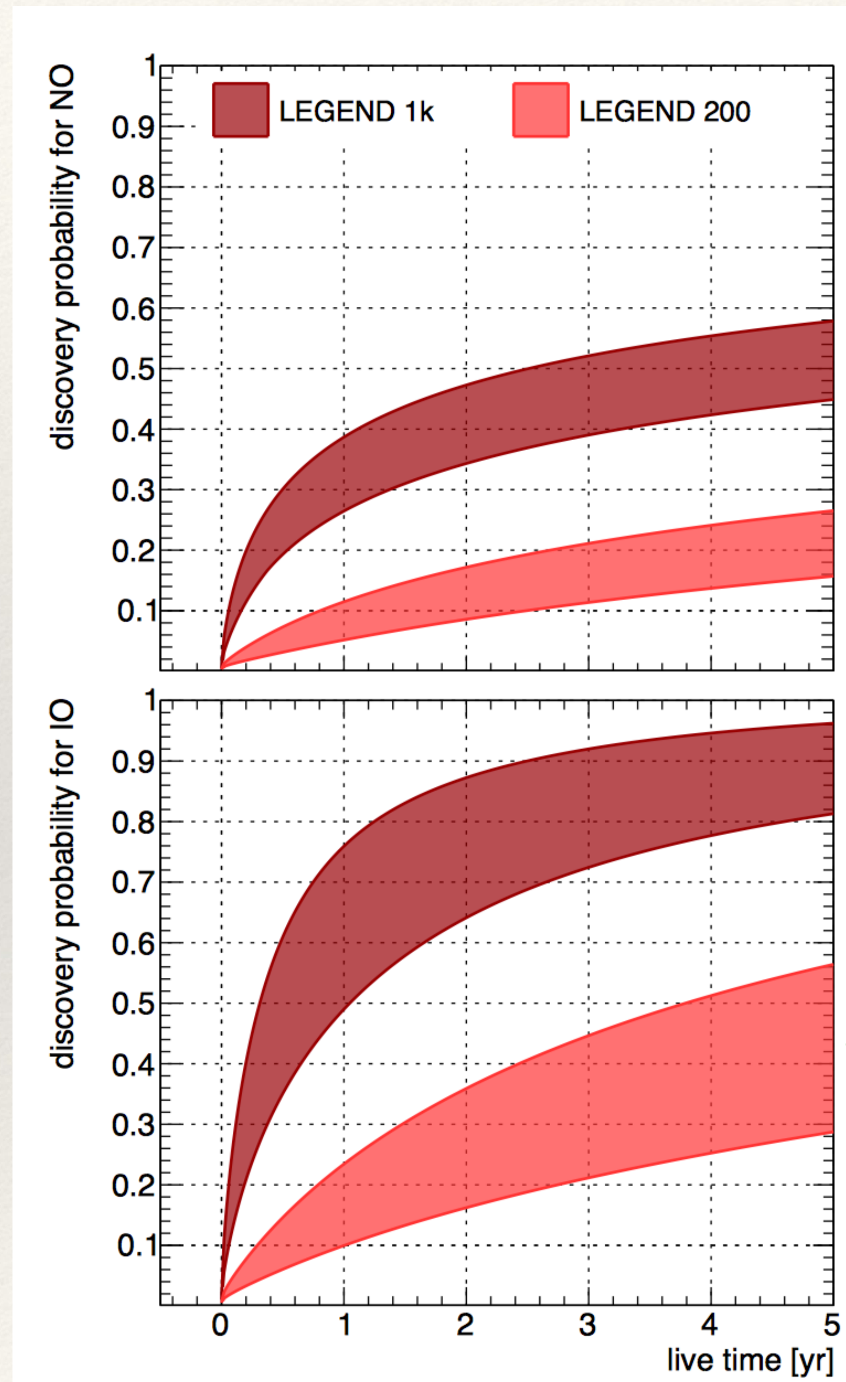


oscillation fits

+

expt. sensitiv.

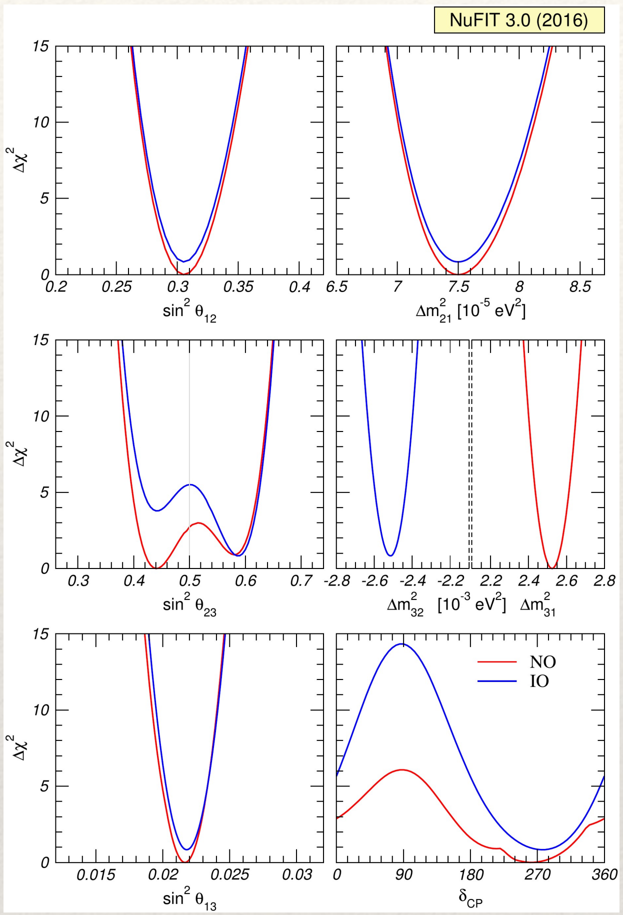
Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement Bkg	Required 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}

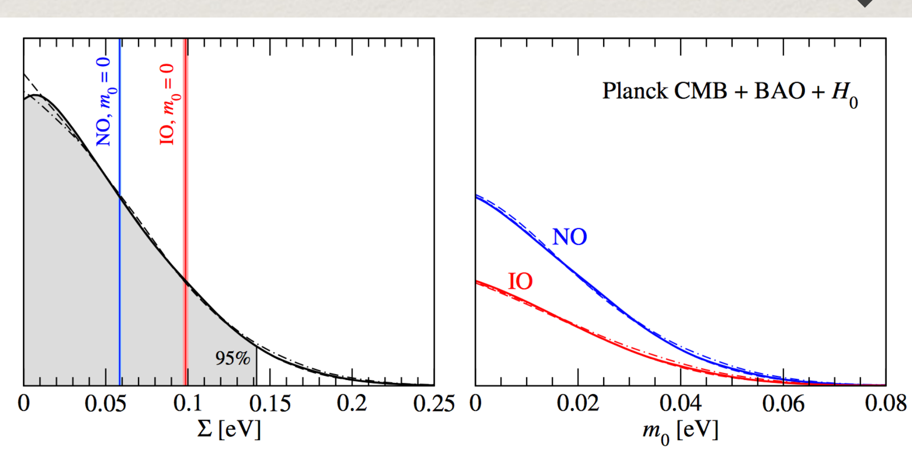
Agostini et al, 1705.02996;
also Caldwell et al., 1705.01945;
also Zhang, Zhou, 1508.05472

Expectations of lifetimes

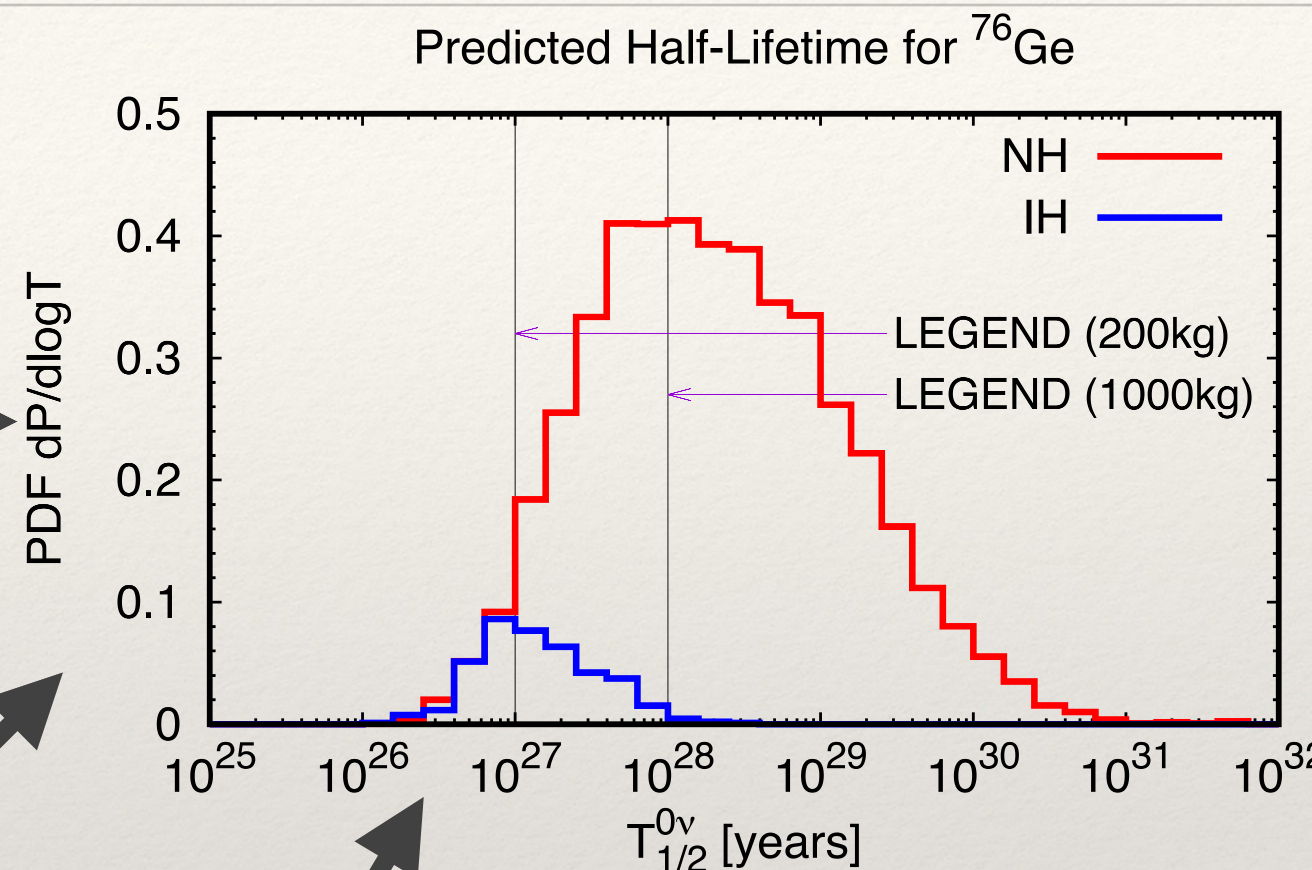


oscillation fits

+

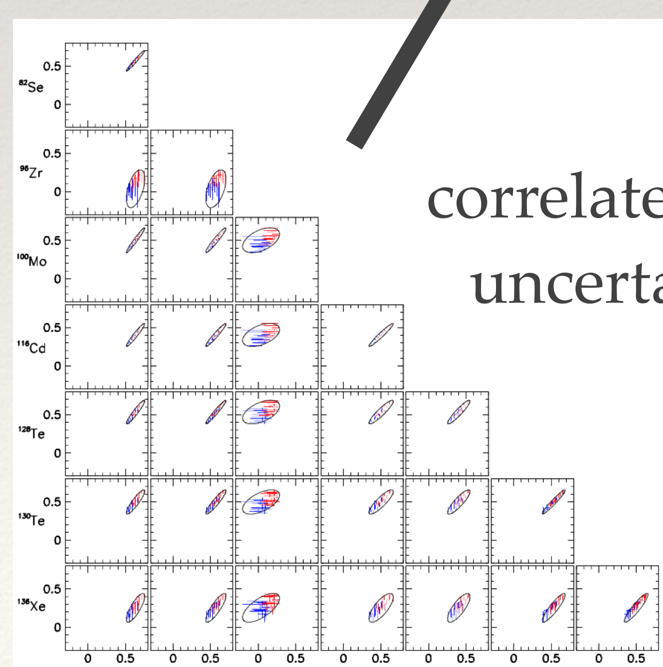


cosmology fit



Ge, WR, Zuber, PRD96

+

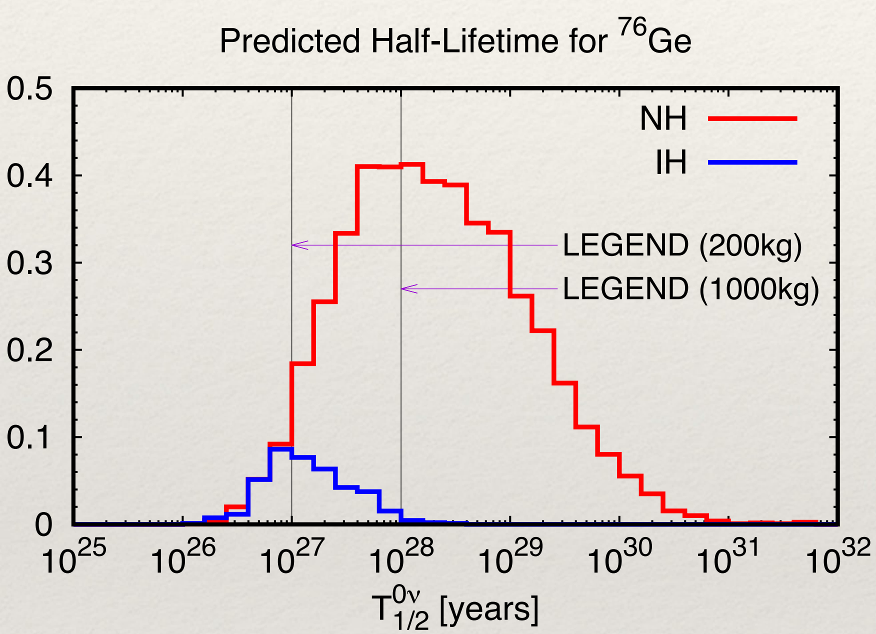


correlated NME uncertainties

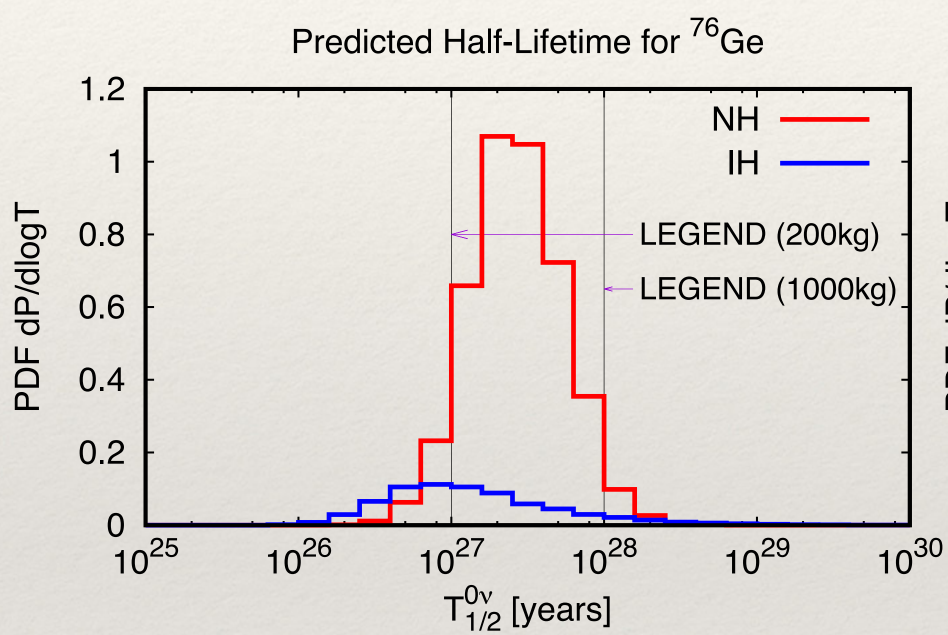
Faessler, Fogli et al., 0810.5733

Expectations for half-lifes

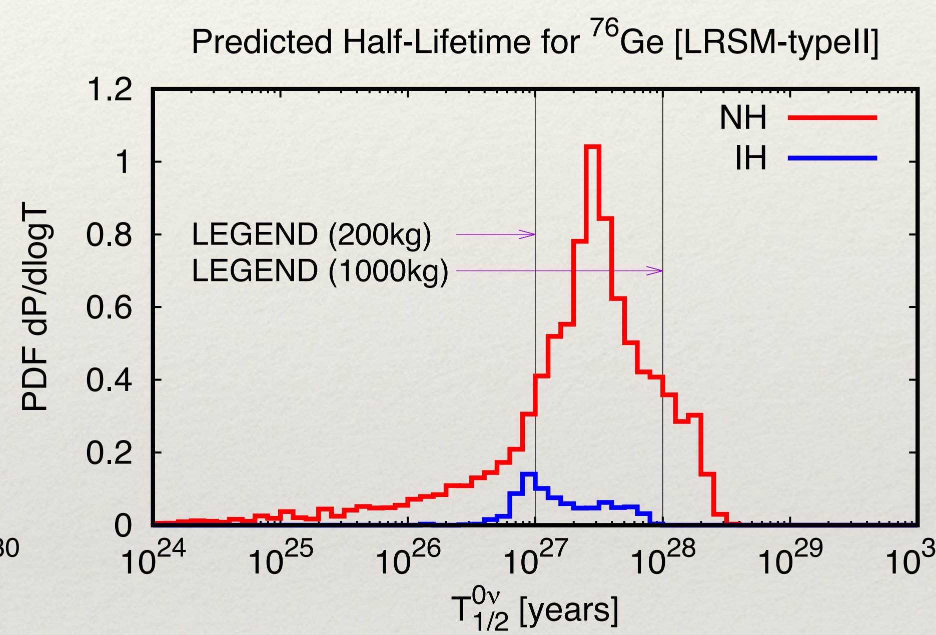
Standard



Sterile



Left-right



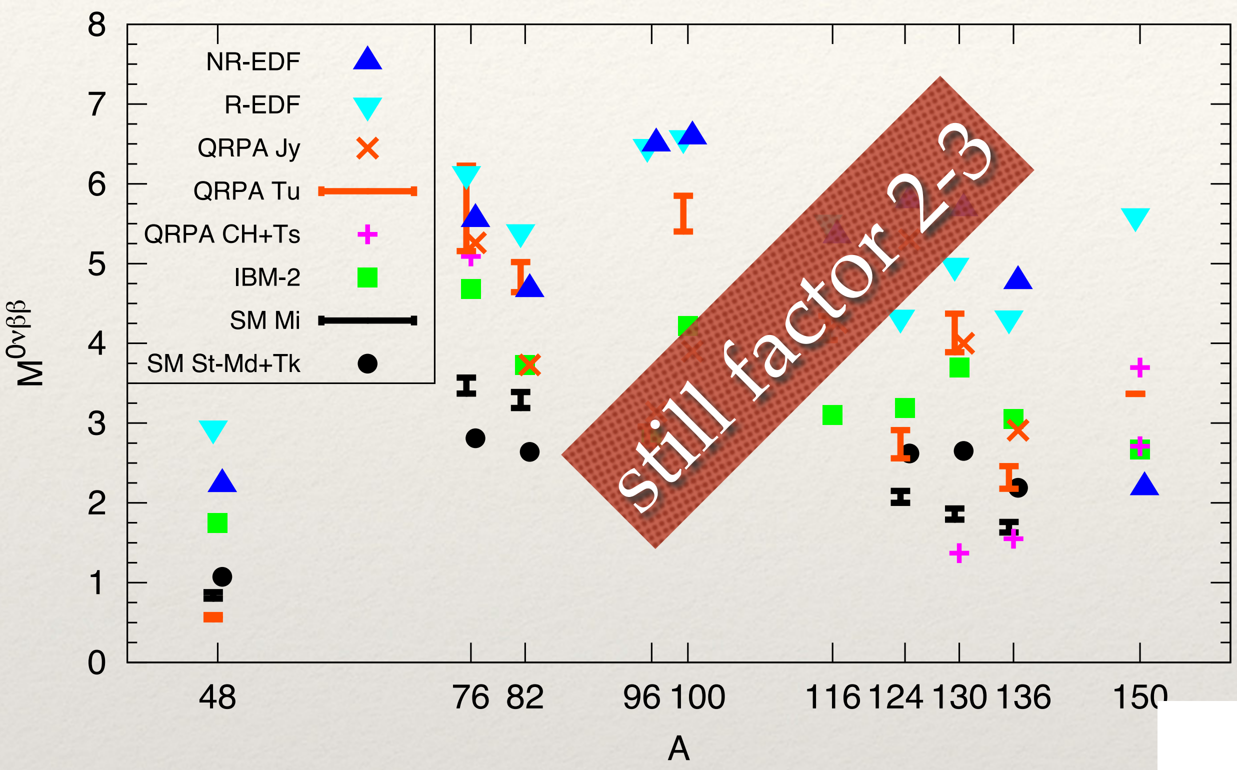
Ge, WR, Zuber, 1707.07904

However, most alternative mechanisms unrelated to neutrino parameters…

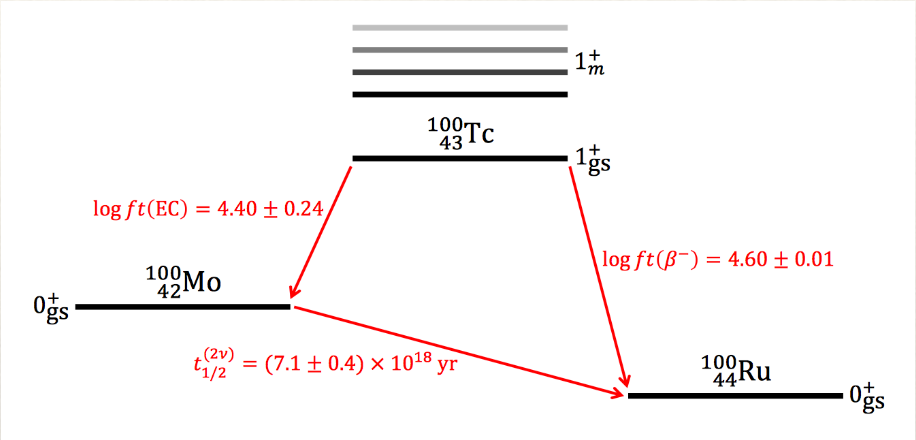
…thus decoupled from cosmology (and direct experiments)!

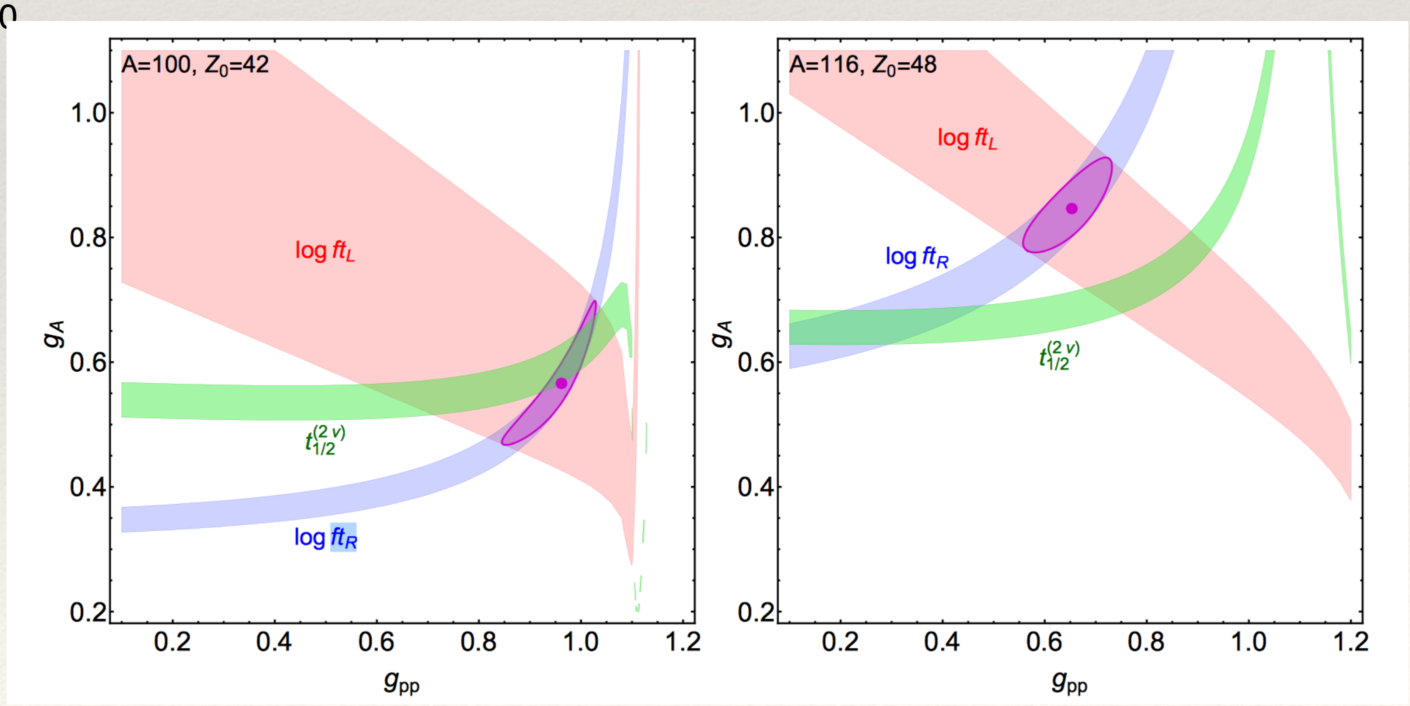
Nuclear Matrix Elements

Engel, Menendez, 1610.06548



How good are the models?
Example isobaric triplets
within QRPA



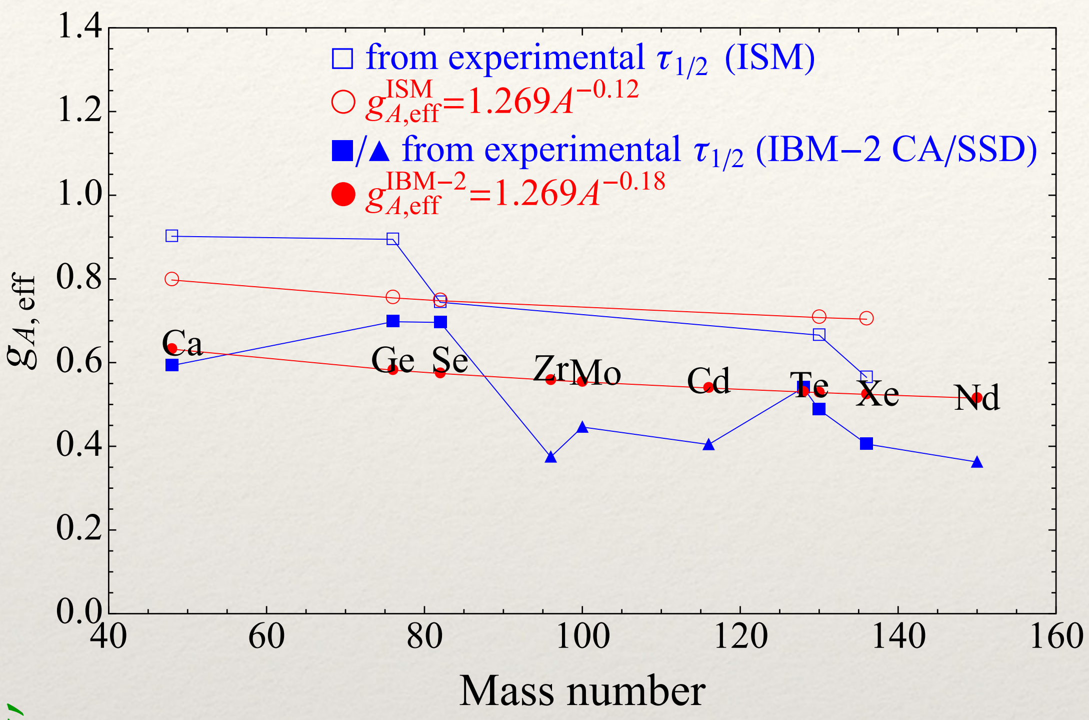


Deppisch, Suhonen, 1606.02908

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

Nuclear Matrix Elements

Iachello et al., 1506.08530

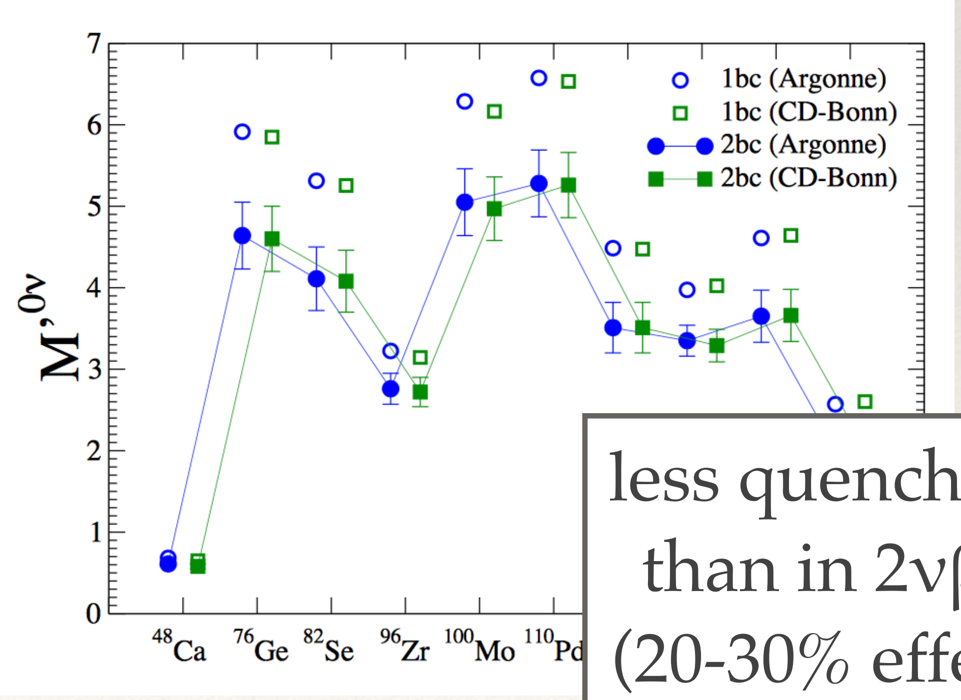


QUENCHING??

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

- 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

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

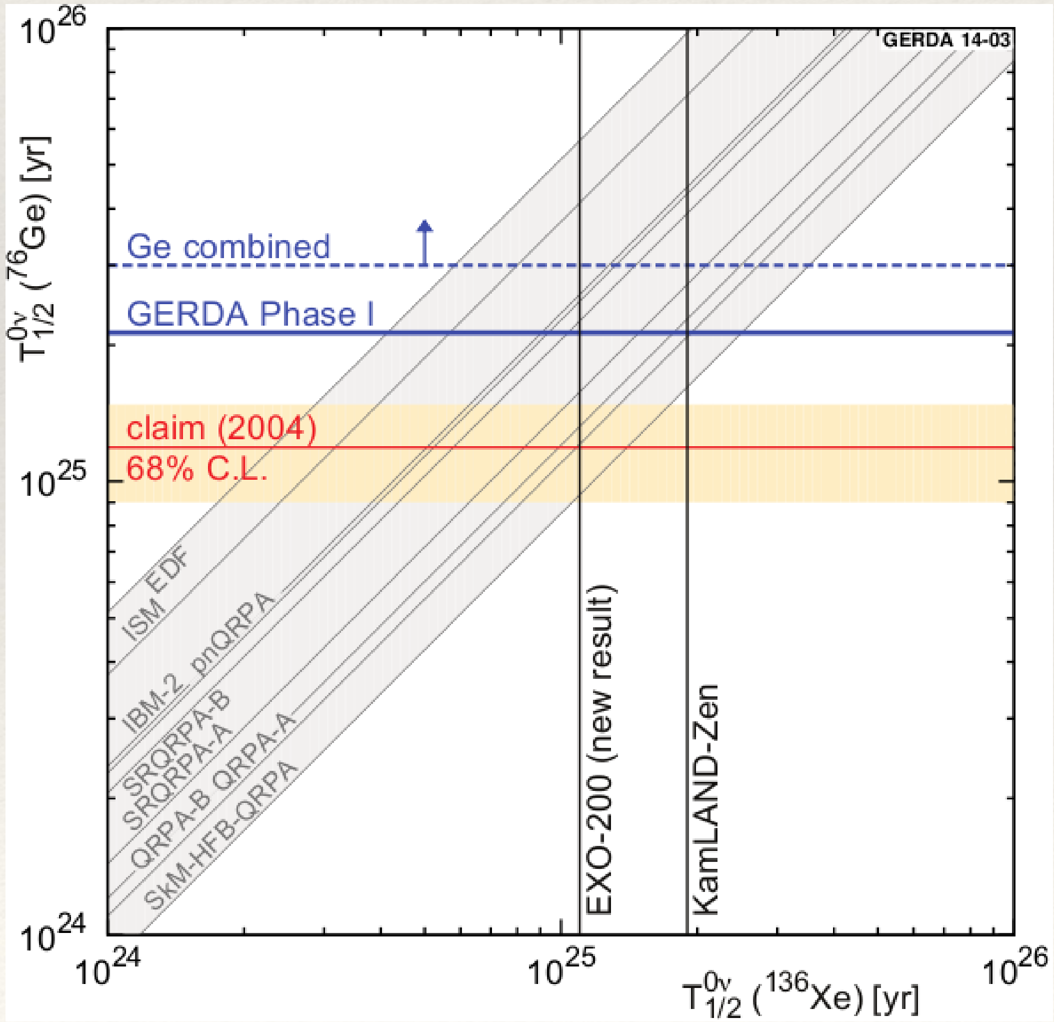


less quenching than in 2νββ (20-30% effect)

Comparison of Limits

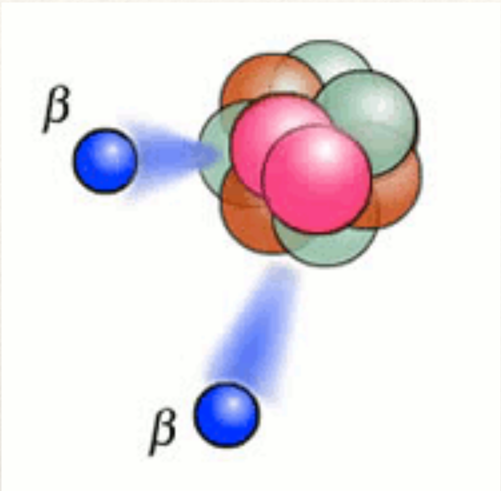
Limit from Xenon is better than limit from Germanium if:

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



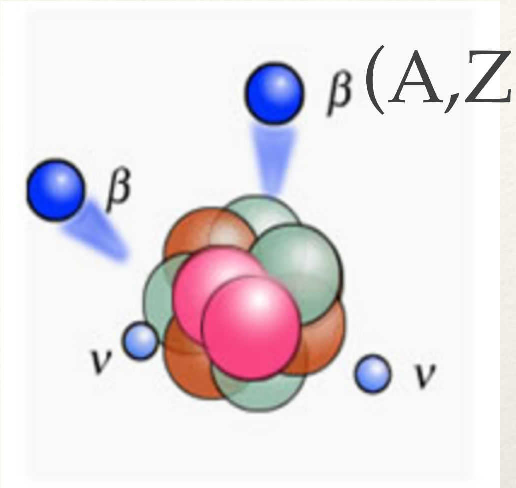
- depends on NMEs
- for most NMEs Xe better
- limit about $m_{ee} < 0.2$ eV
- means 0.2…0.6 eV for KATRIN
- means 0.6…1.8 eV for cosmo

Best chance: Neutrinoless Double Beta Decay



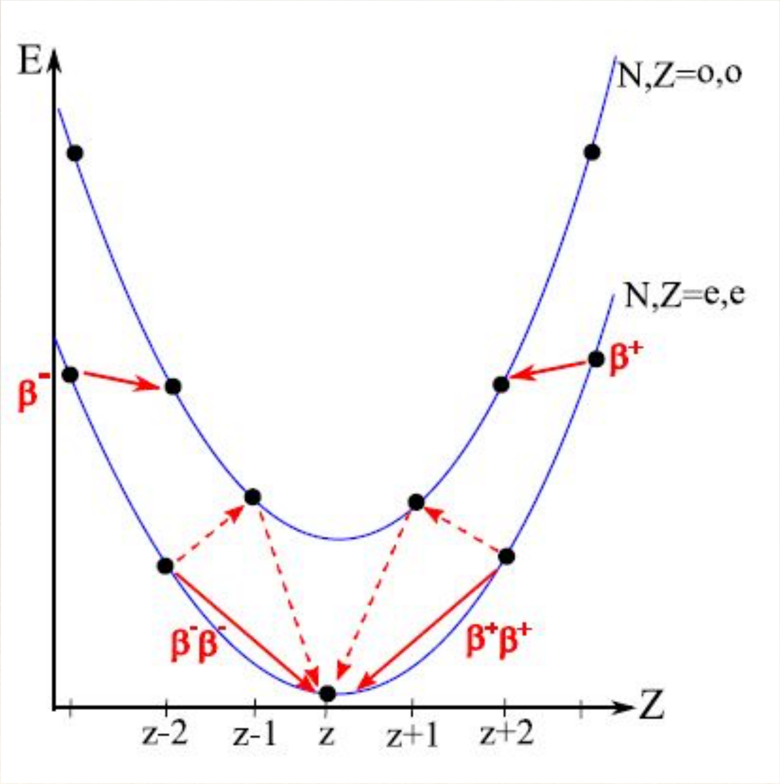
$(A,Z) \to (A,Z+2) + 2\,e^-$

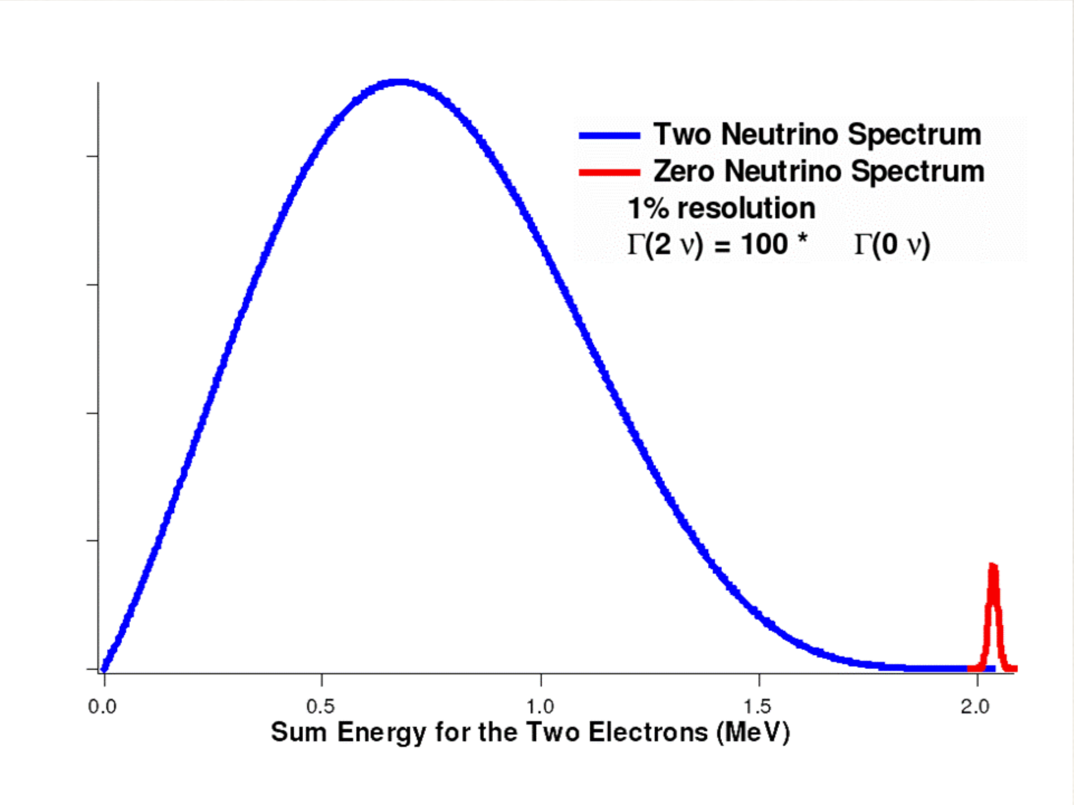
$\Delta L = 2$



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

$\Delta L = 0$

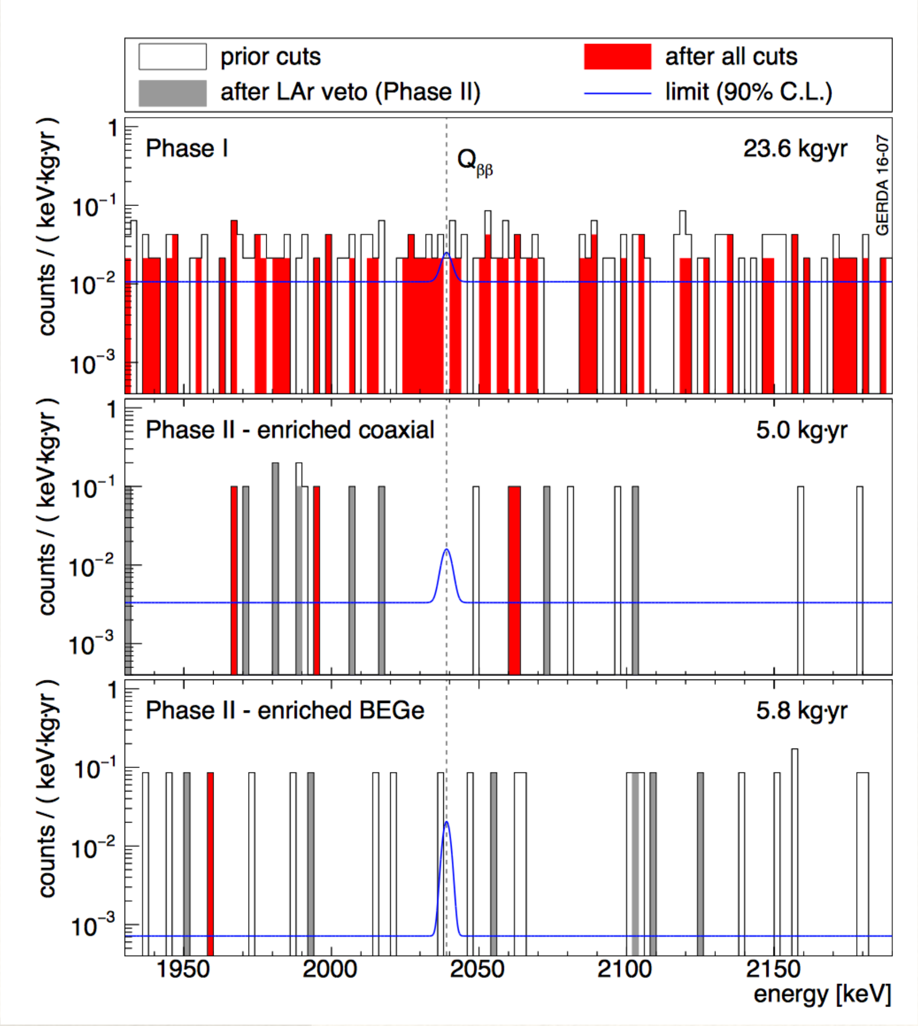




Neutrinoless Double Beta Decay

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

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

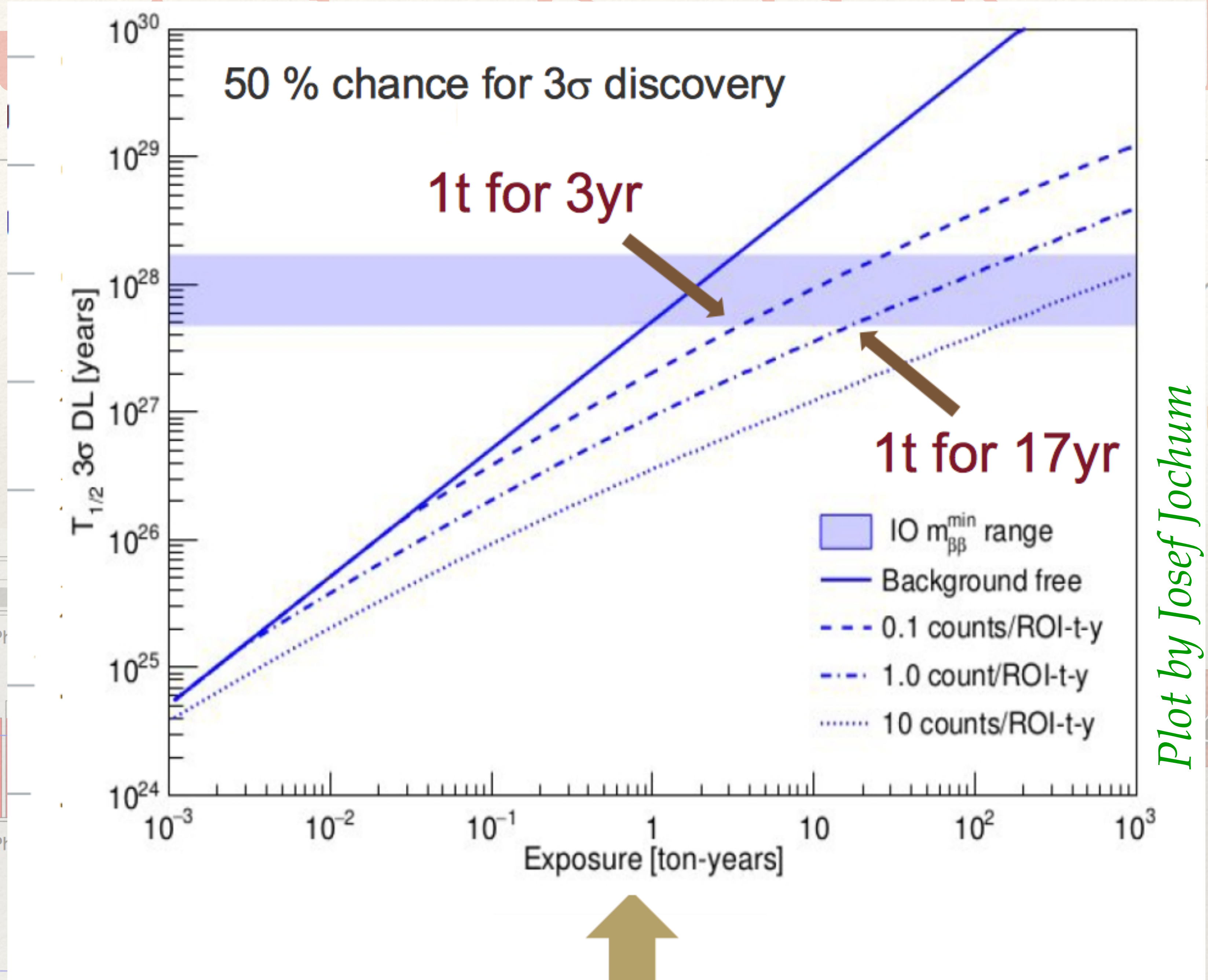
…round

…und

…ree result

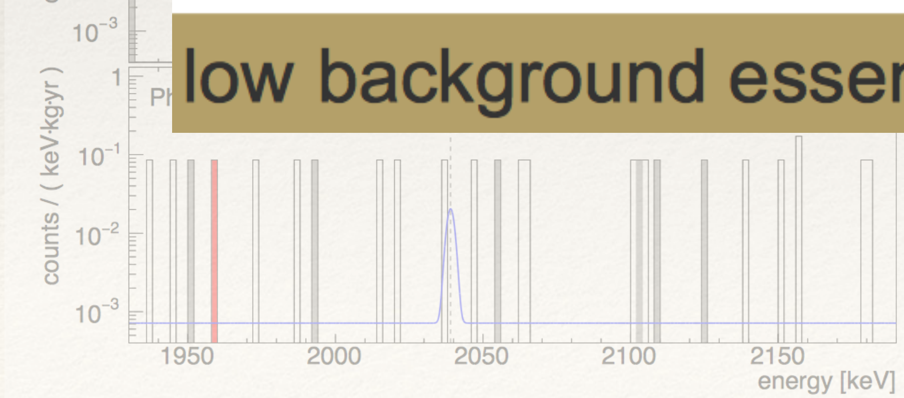
…10^{26} years

with exposure of about 100 kg · years



Plot by Josef Jochum

low background essential for discovery potential



GERDA, 1703.00570, Nature

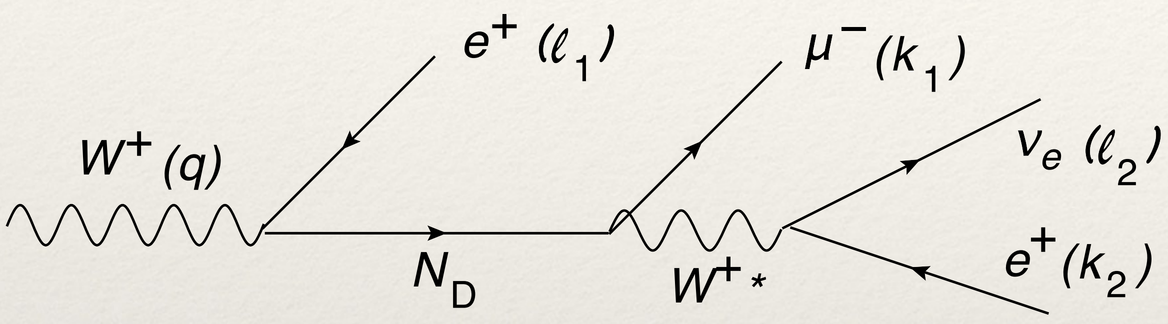
Neutrinoless Double Beta Decay

Table by Josef Jochum

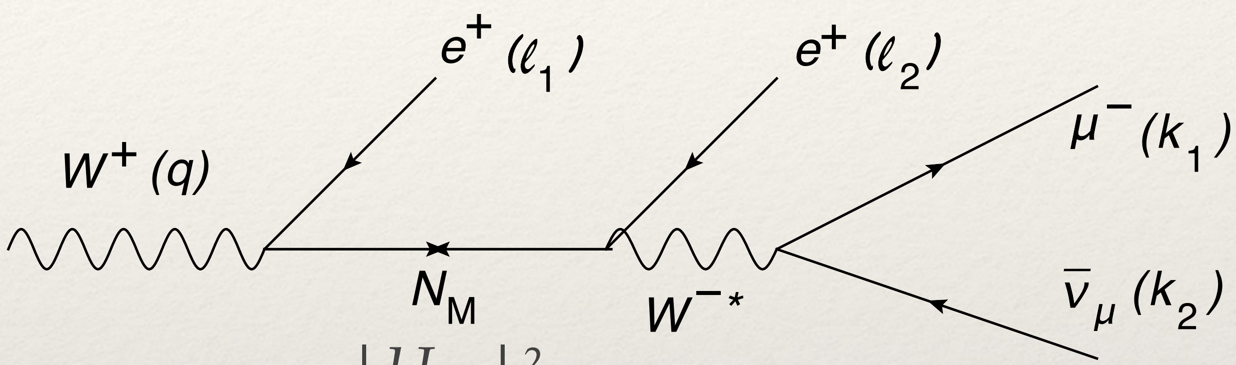
			isotope mass [kg] in FV	FWHM [keV]	background [(FWHM ε $t_{isotope}$ yr $)^{-1}$]	$T_{1/2}$ sensitivity after 4yr [10^{25} yr]	upper m_β limit [meV] (lowest NME
Ge detectors	GERDA	Ge	27	3	5	15	190
	Majorana-D	Ge	24	3	5	15	190
	LEGEND 200 kg	Ge	155	3	1	100	75
	LEGEND 1000 kg	Ge	780	3	0.2	1000	24
liquid 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

New Idea

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



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

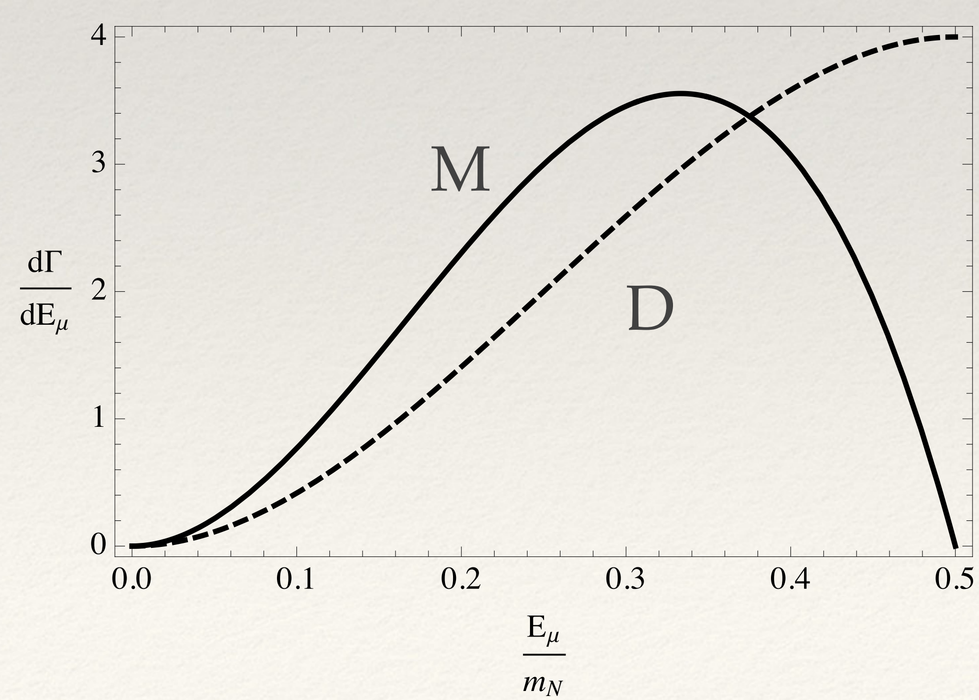


$|U_{Ne}|^2$

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

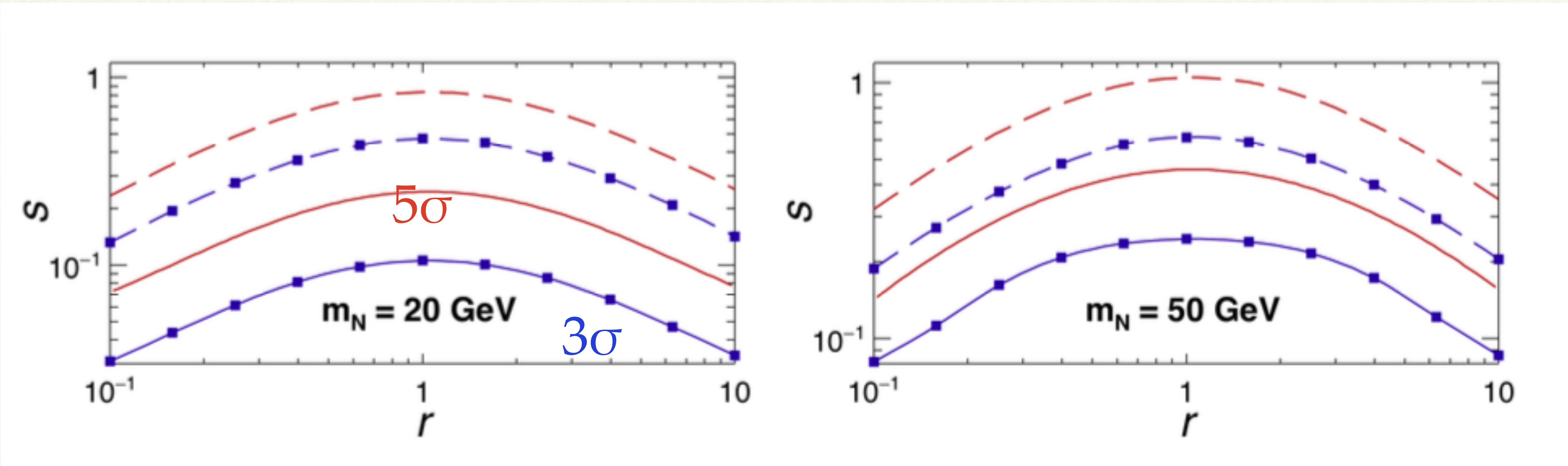
$W^+ \to e^+ \mu^- e^+$ **anti-ν_μ**

$\Delta L = 0$



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

New Idea



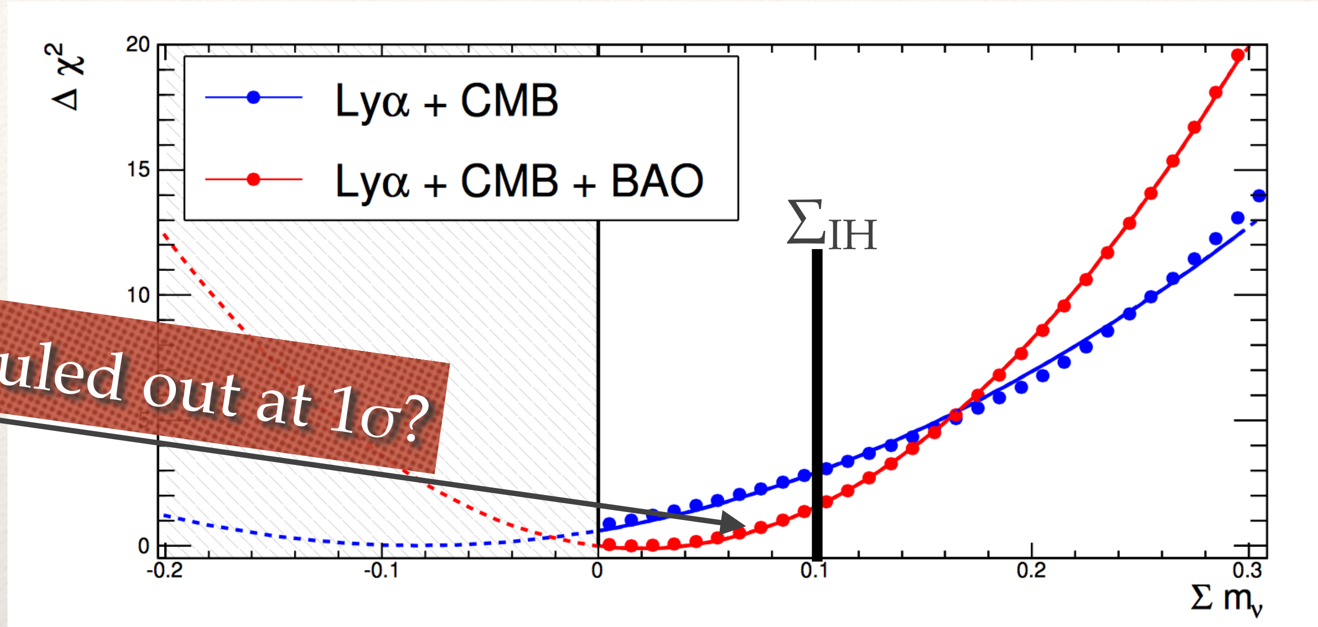
(solid is mult-variate; dashed is cut-and-count)

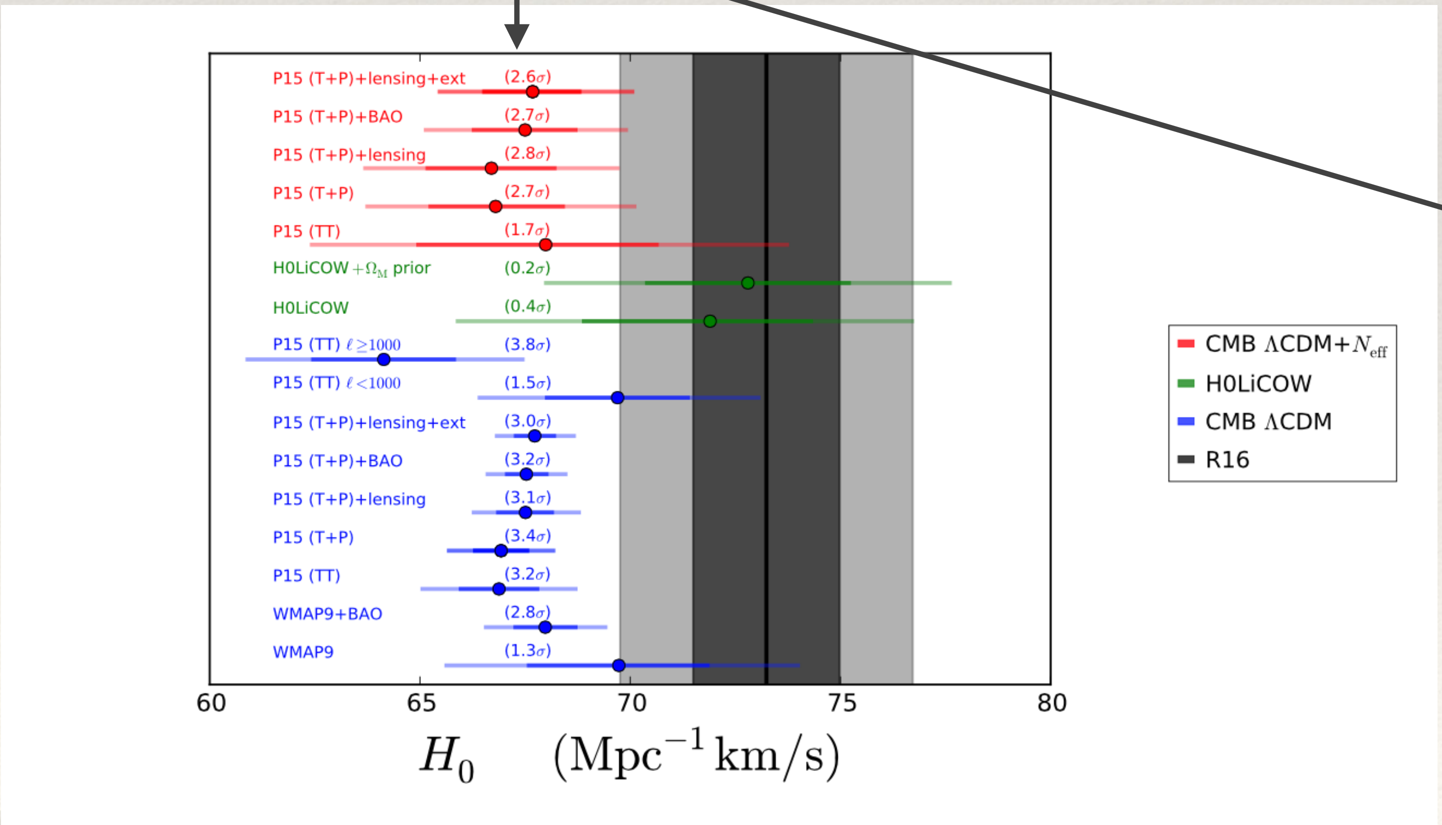
$$s \equiv 2 \times 10^6 \frac{|U_{Ne}U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}, \quad r \equiv \frac{|U_{Ne}|^2}{|U_{N\mu}|^2}.$$

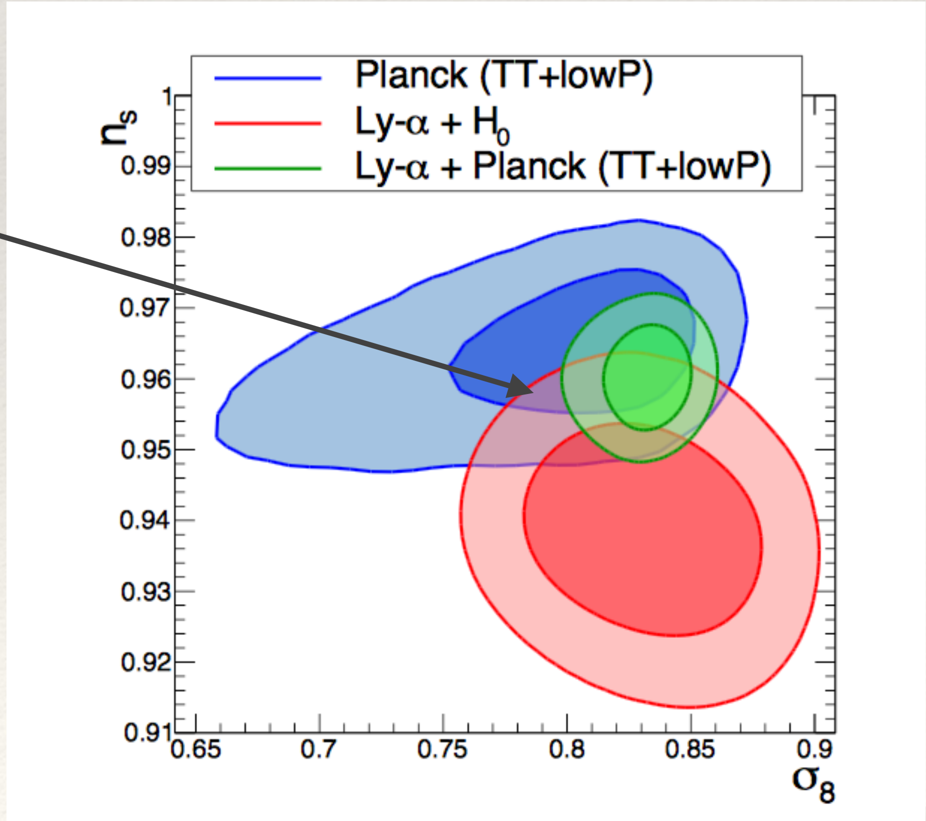
Dib, Kim, Wang, 1703.01936

Cosmological Mass Limits

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





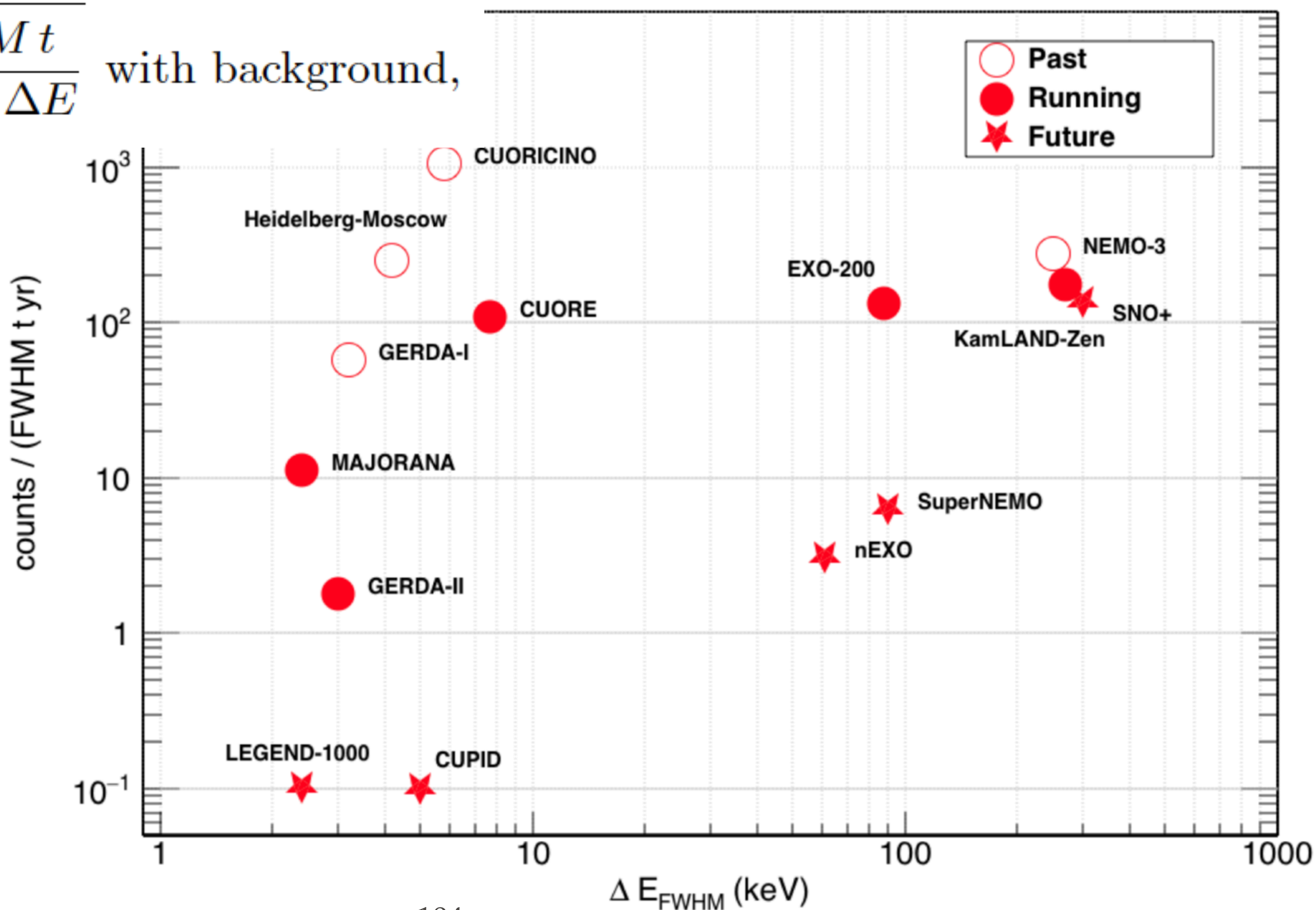


Bernal, Verde, Riess, 1607.05617

Palanque-Delabrouille et al., 1410.7244 + 1506.05976

Neutrinoless Double Beta Decay

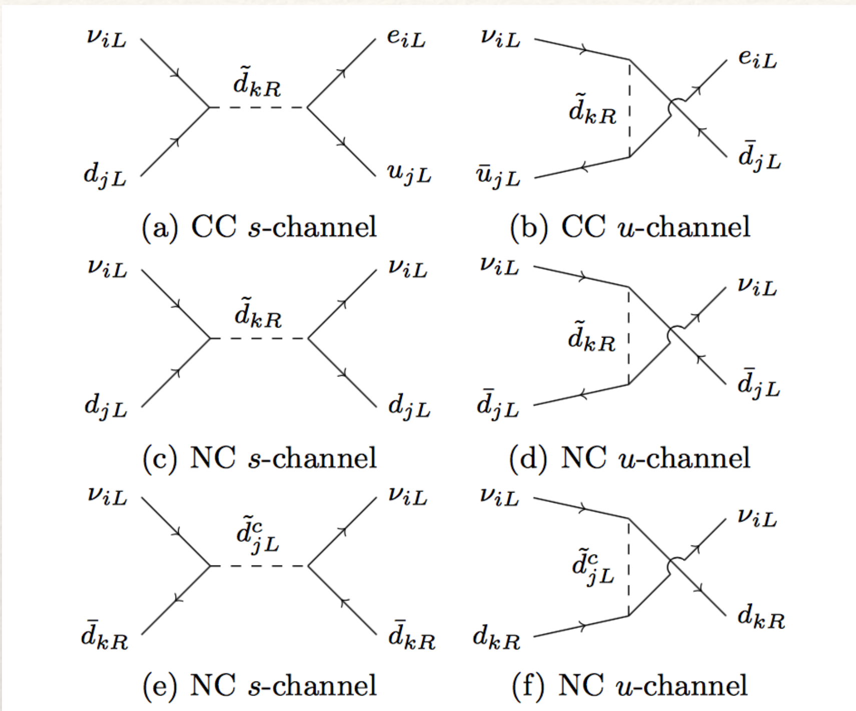
$$(T_{1/2}^{0\nu}) \propto \begin{cases} a\, M\, \varepsilon\, t & \text{background free,} \\ a\, \varepsilon \sqrt{\dfrac{M\, t}{B\, \Delta E}} & \text{with background,} \end{cases}$$



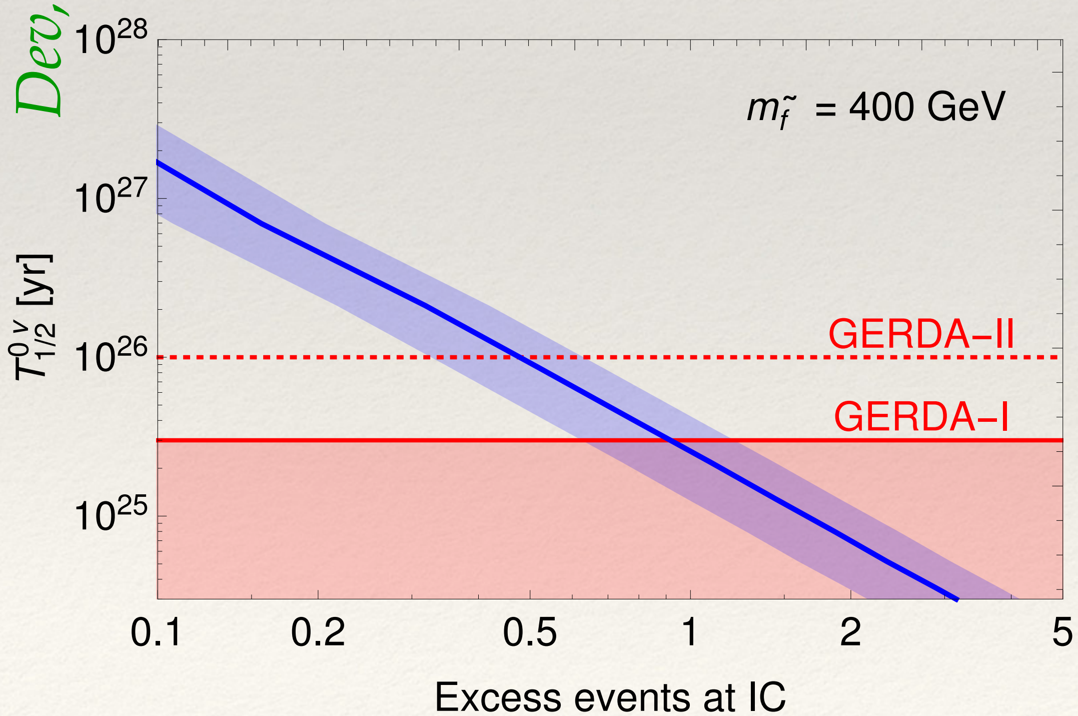
Dolinski, Poon, WR, 1902.04097

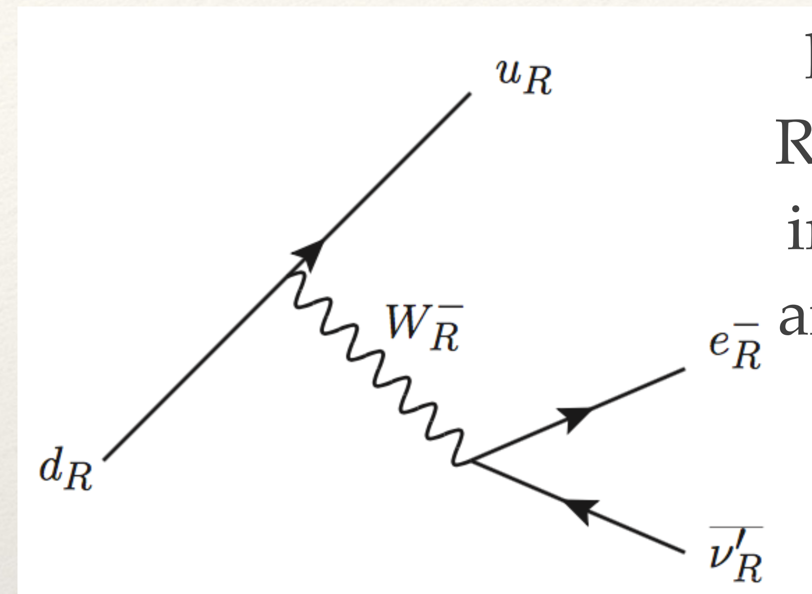
Unexpected Correlations with other Experiments

Dev, Ghosh, WR, 1605.09743

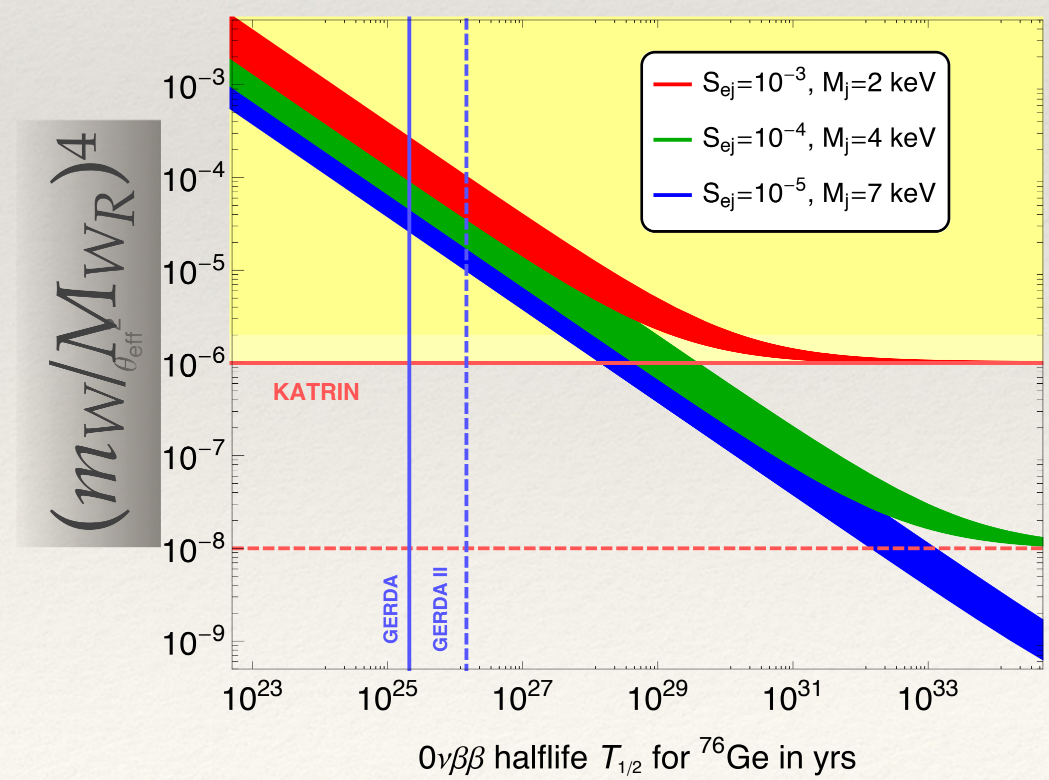


RPV SUSY
at IceCube
and in 0νββ





keV ν and
RH currents
in KATRIN
and in 0νββ



Barry, Heeck, WR, 1404.5955

D vs. M with general interactions

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

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

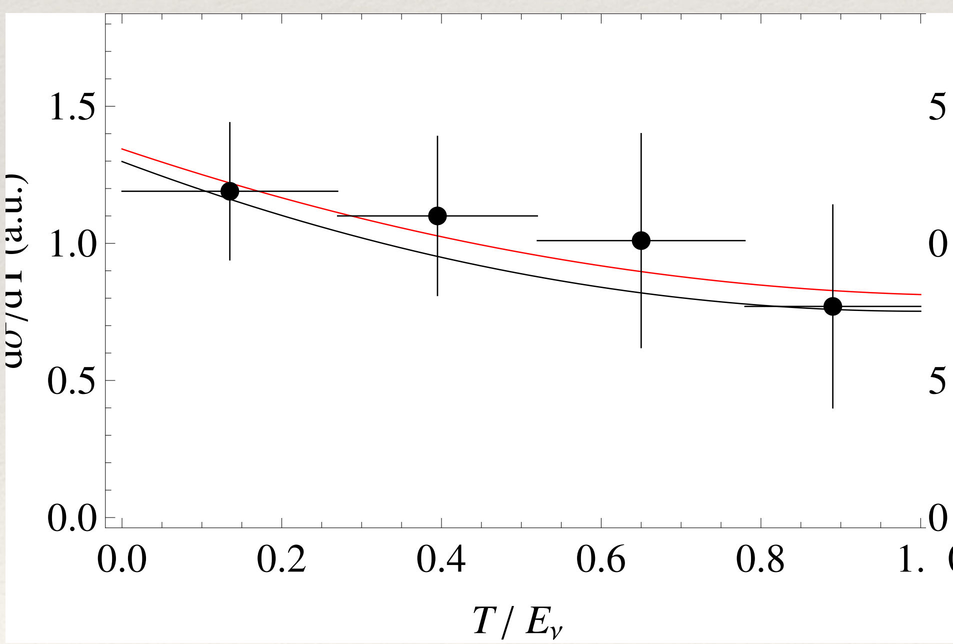
- SM: same cross sections for Dirac and Majorana

$$(A, B, C)^{\rm SM} = \left((1 + 2s_W^2)^2, 0, 4s_W^4\right) \; ({\rm NC + CC})$$

- not the same if other interactions are present!
- can extract *A*, *B*, *C* due to different *E*-dependence
- can also combine neutrino and antineutrino data

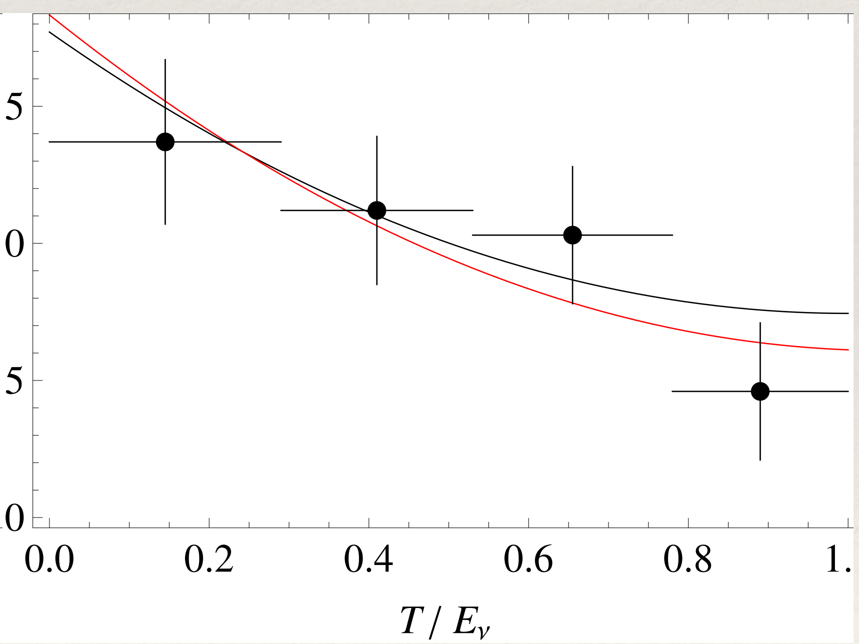
Experimental Constraints

- Data available from CHARM, CHARM-II, LAMPF, MINERνA, LSND, TEXONO,…
- take data from expt. with best measurement of $\sin^2 \theta_W$



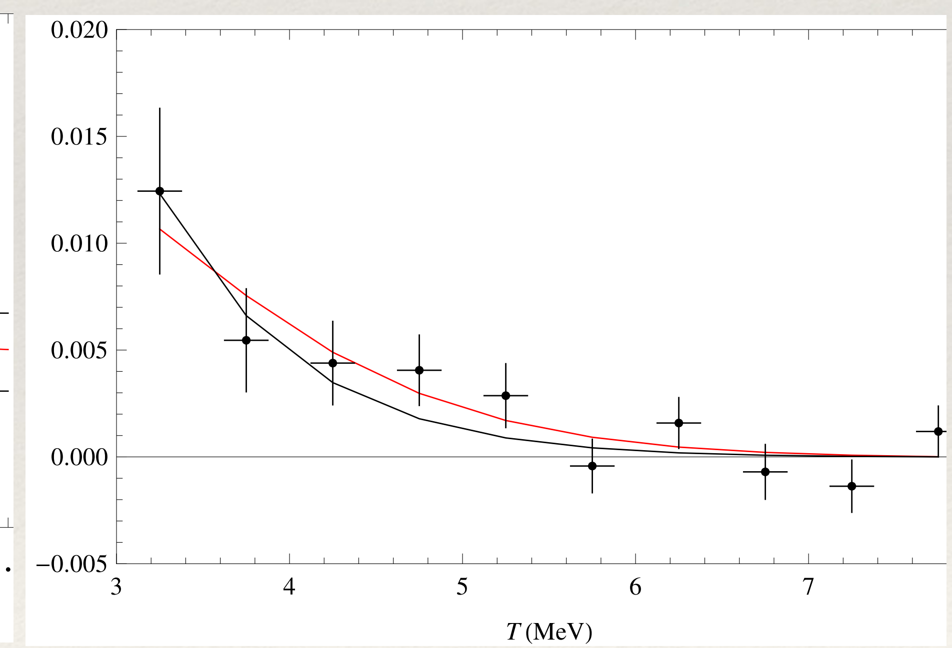
CHARM-II

ν_μ e scattering



CHARM-II

anti-ν_μ e scattering



TEXONO

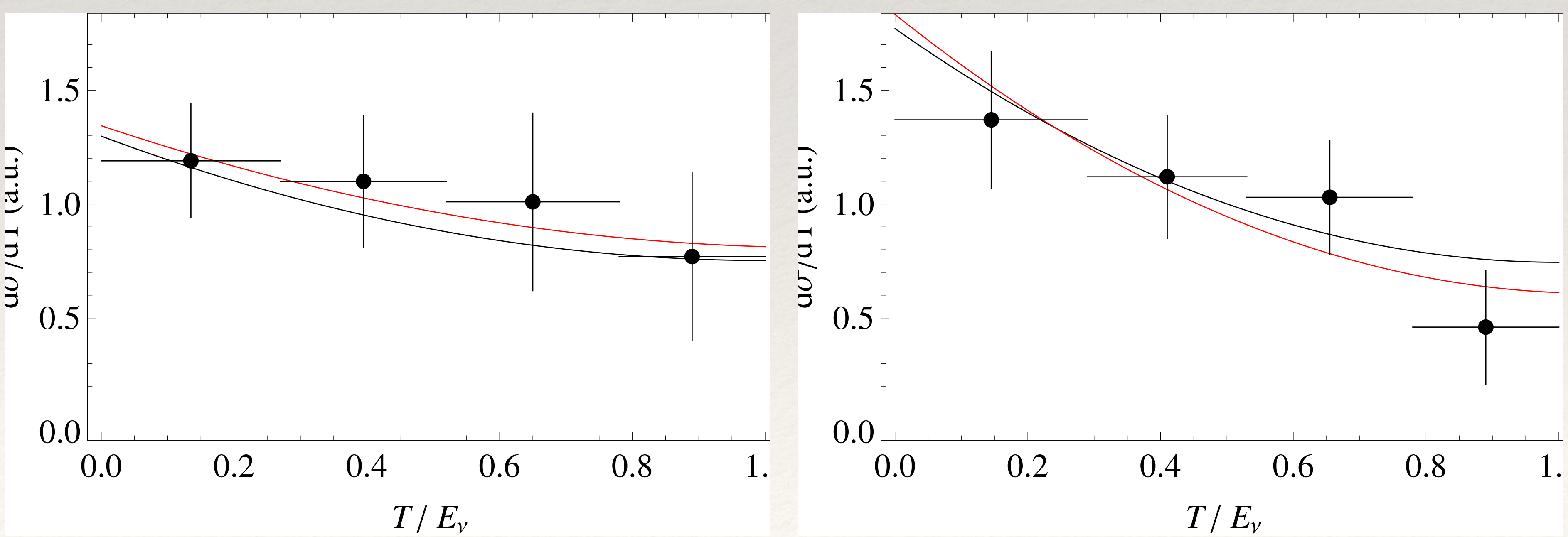
anti-ν_e e scattering

Experimental Constraints: CHARM-II

- CHARM-II: highly relativistic $E_\nu \simeq 20$ GeV and provide unfolded differential cross sections:

$$\chi^2(A_{\mu e}, B_{\mu e}, C_{\mu e}) = \sum_{i=T\,\text{bins}} \frac{\left[\left(\frac{d\sigma}{dT}\right)_i - s_i\right]^2}{\sigma_{s,i}^2} + (\nu_\mu \to \overline{\nu}_\mu)$$

- fit $A_{\mu e}$, $B_{\mu e}$, $C_{\mu e}$ and translate into $X_{\mu e}$, $Y_{\mu e}$ for normalization $R_{\mu e}$ fixed to SM-value



SM prediction vs. best-fit

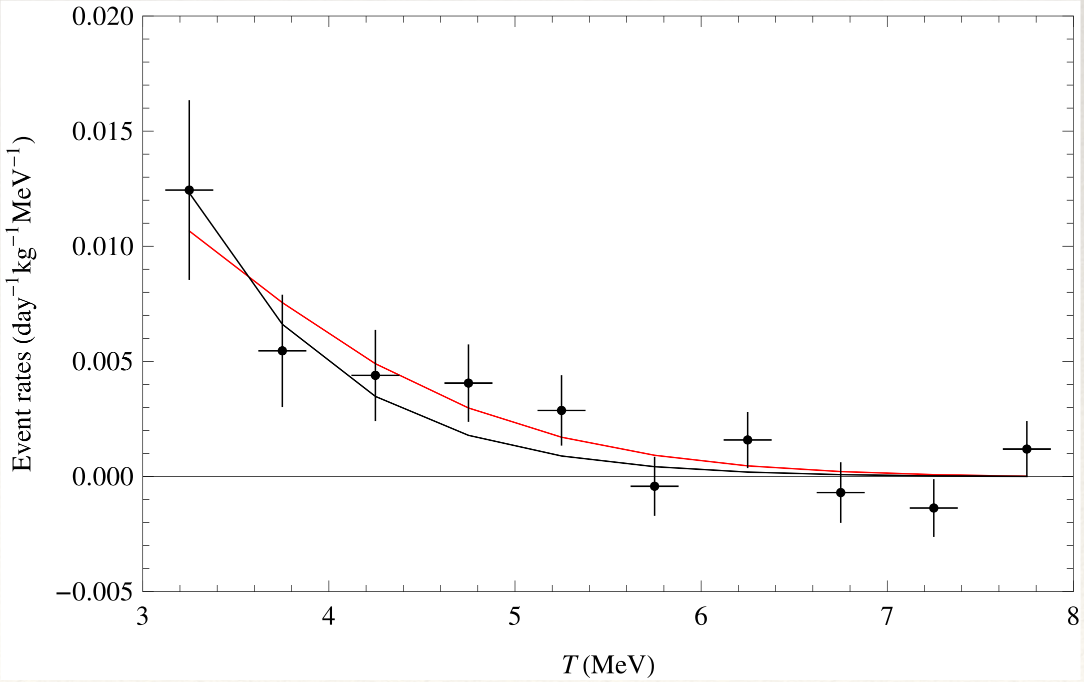
Experimental Constraints: TEXONO

- reactor neutrinos, thus non-relativistic
- provide event numbers:

$$N_i = \int_{T_i}^{T_i+\Delta T} dT \int_0^{8\,\text{MeV}} dE_\nu \Phi(E_\nu) \frac{d\sigma}{dT}(T, E_\nu)$$

$$\chi^2(A_{ee},\, B_{ee},\, C_{ee},\, D_{ee}) = \sum_{i=T\,\text{bins}} \frac{\left[N_i - N_i^0\right]^2}{\sigma_{N,i}^2}$$

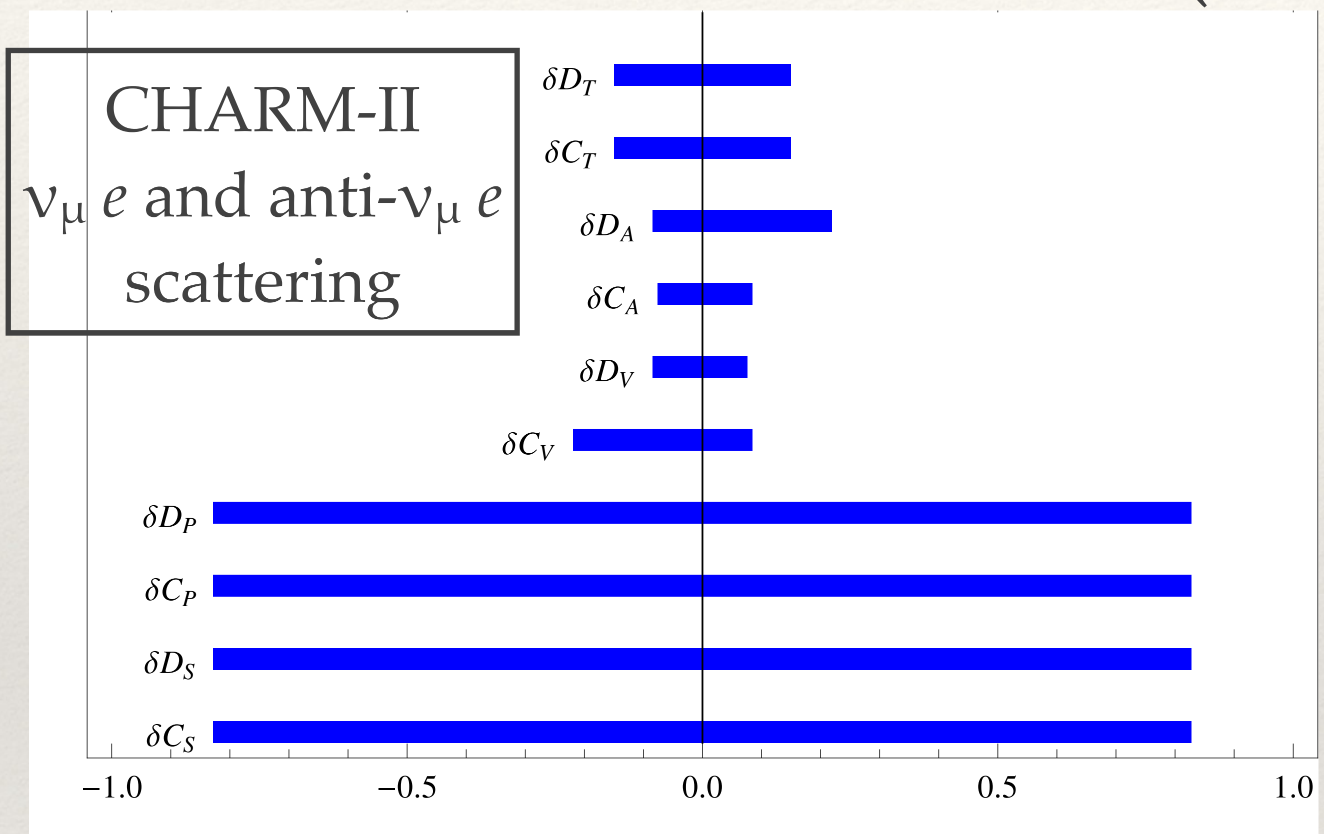
- fit A_{ee}, B_{ee} , C_{ee}, D_{ee} and translate into X_{ee} , Y_{ee} for normalization R_{ee} and D_{ee} fixed to SM-value

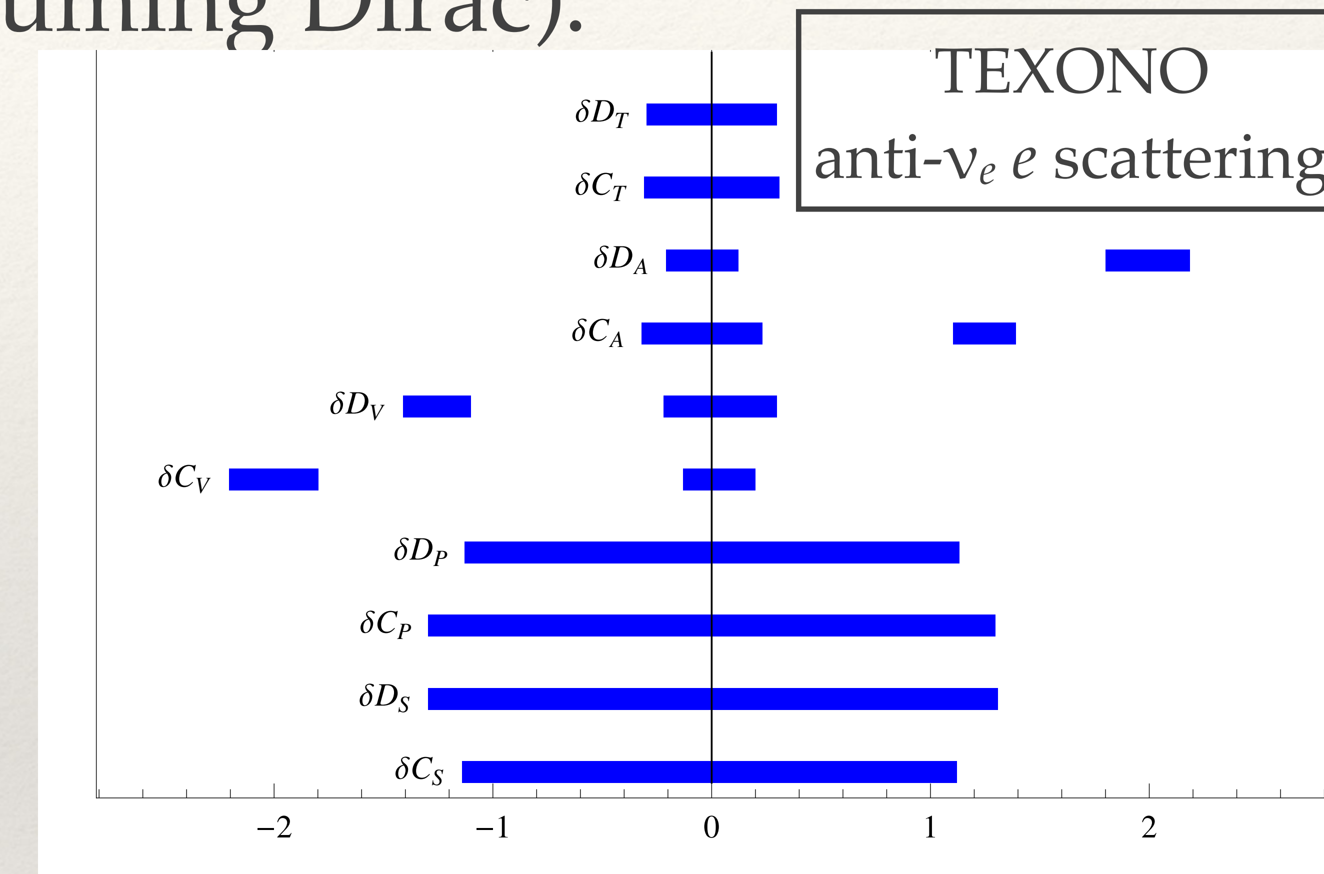


SM prediction
vs.
best-fit

Experimental Constraints

- Individual Parameters (assuming Dirac):





- weak limits on *P* and *S*

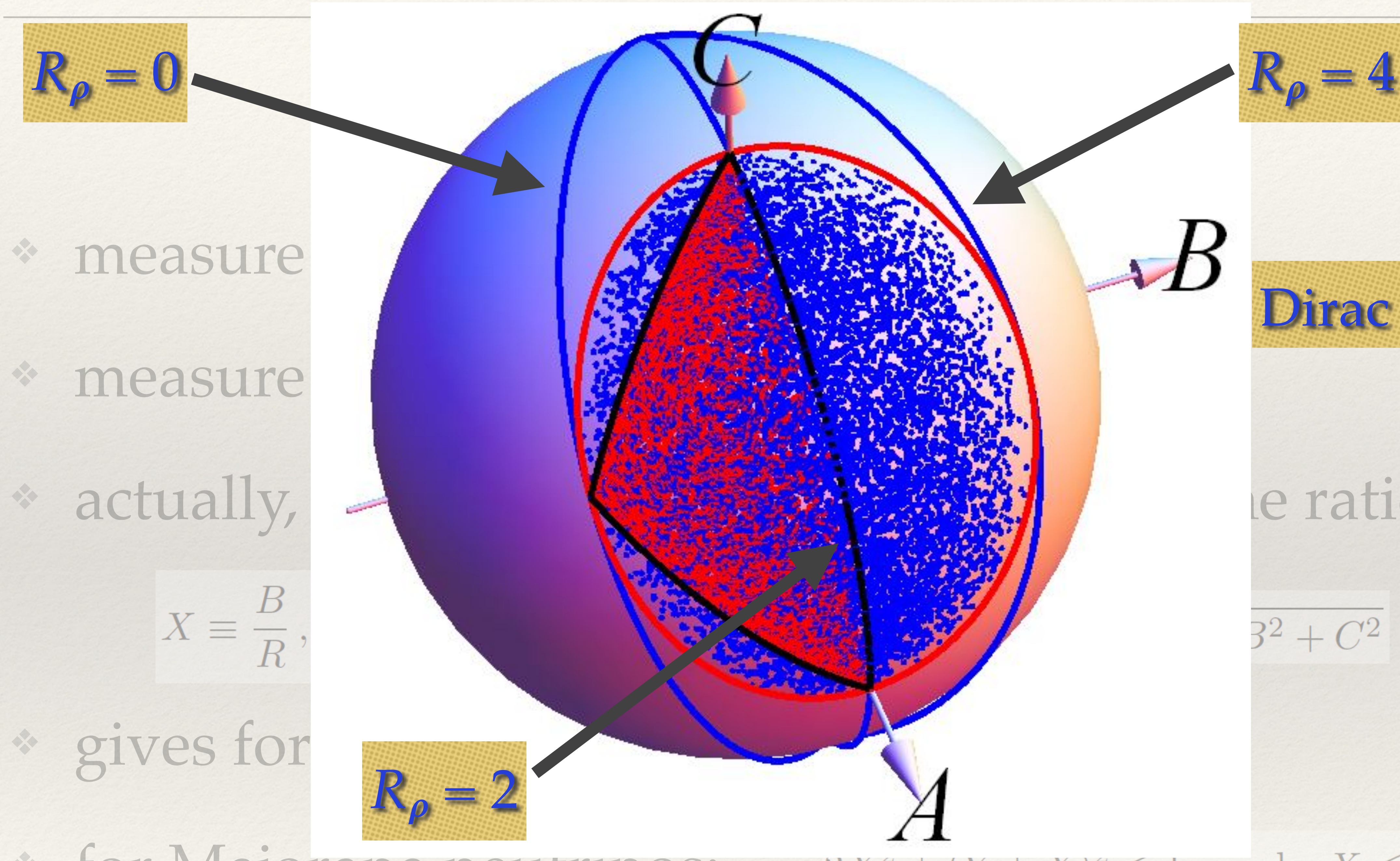
- *T*, *V* and *A* well constrained

D vs. M with general interactions

- measure
- measure
- actually, ... ne ratios

$$X \equiv \frac{B}{R}, \quad \ldots \quad B^2 + C^2$$

- gives for
- for Majorana neutrinos: $2X^2 + (Y \pm X)^2 \leq 1$ and $X \leq 0$

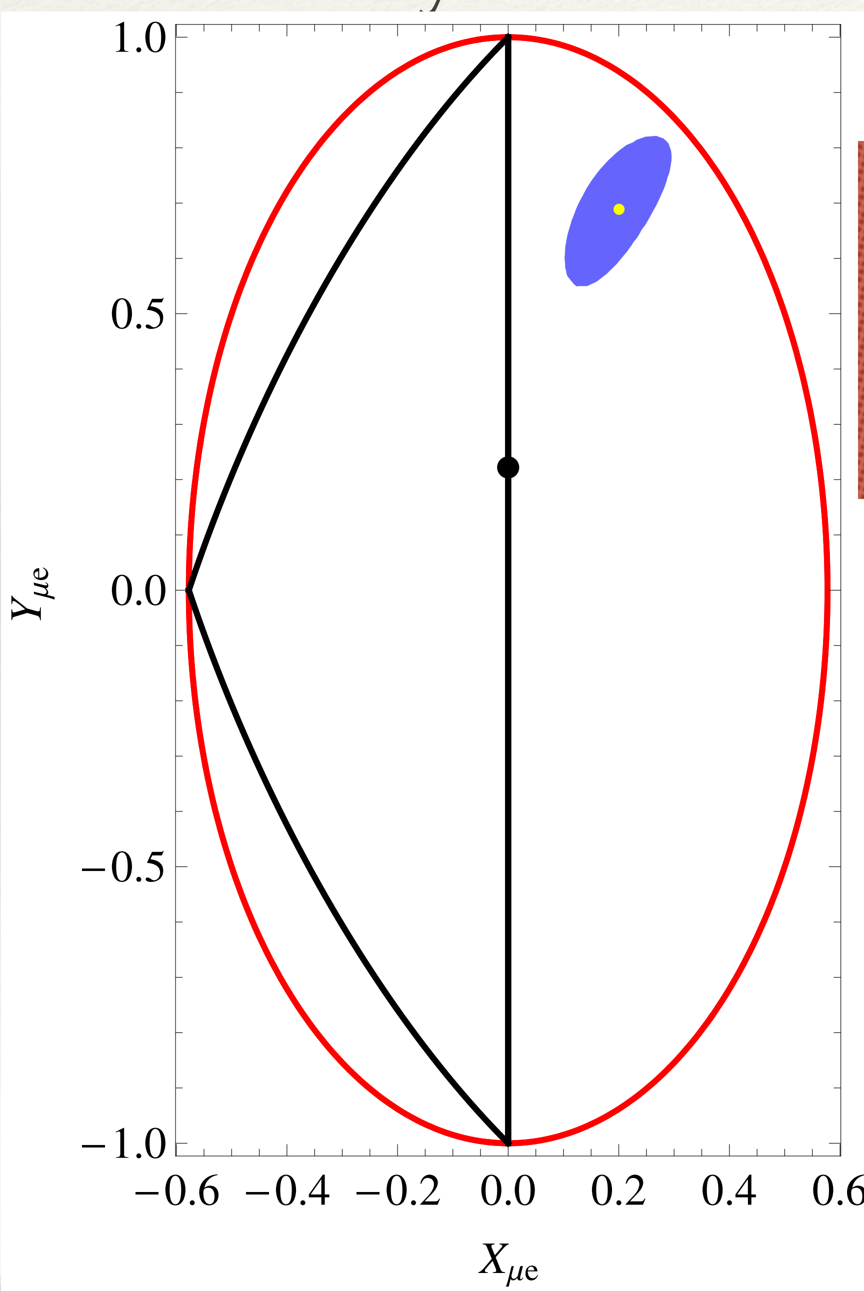


Dirac vs. Majorana

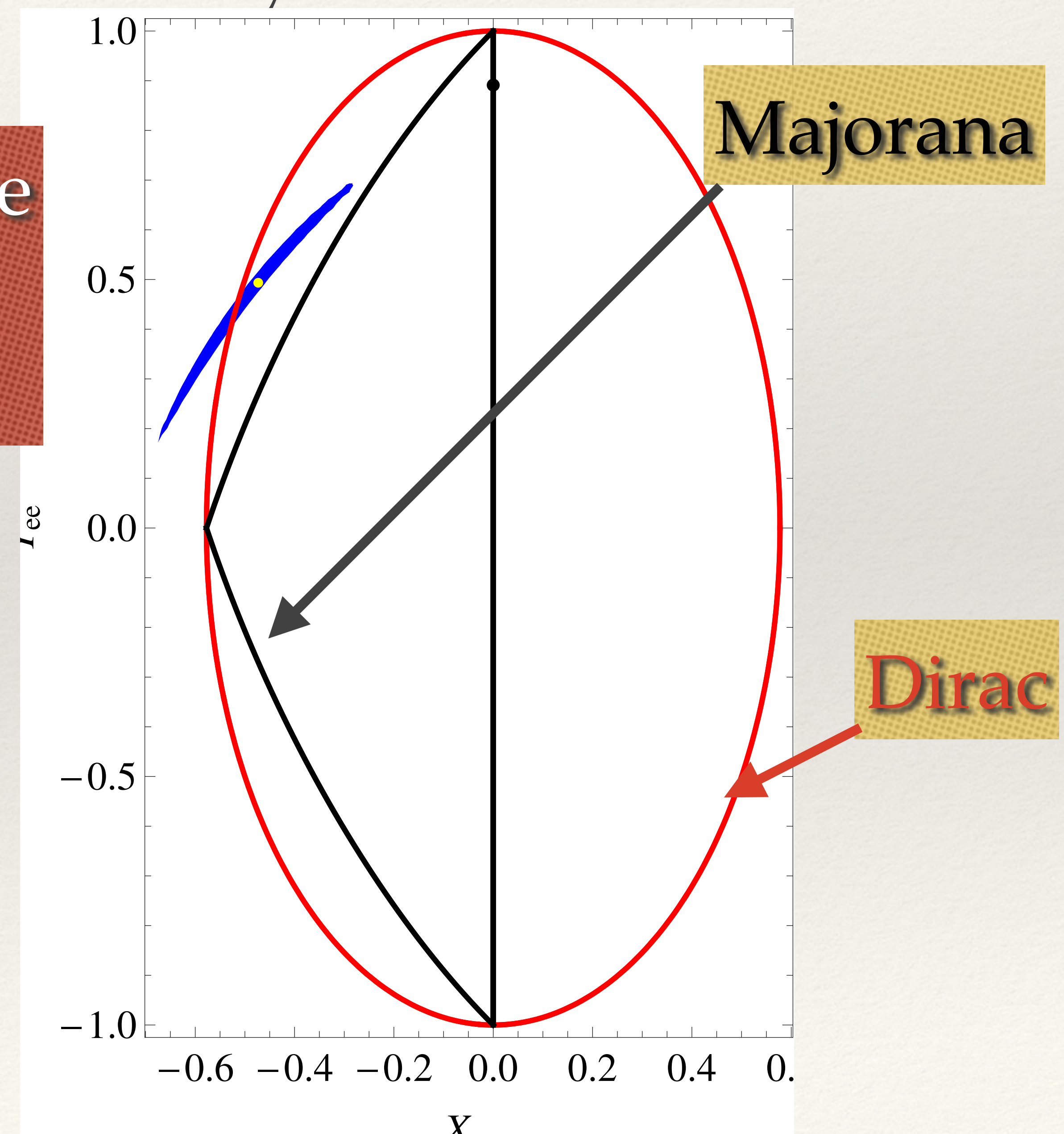
WR, Xu, Yaguna, 1702.05721

Future Constraints

- choose points in allowed 90% range, assume uncertainty reduced by factor 3 and 4, respectively:

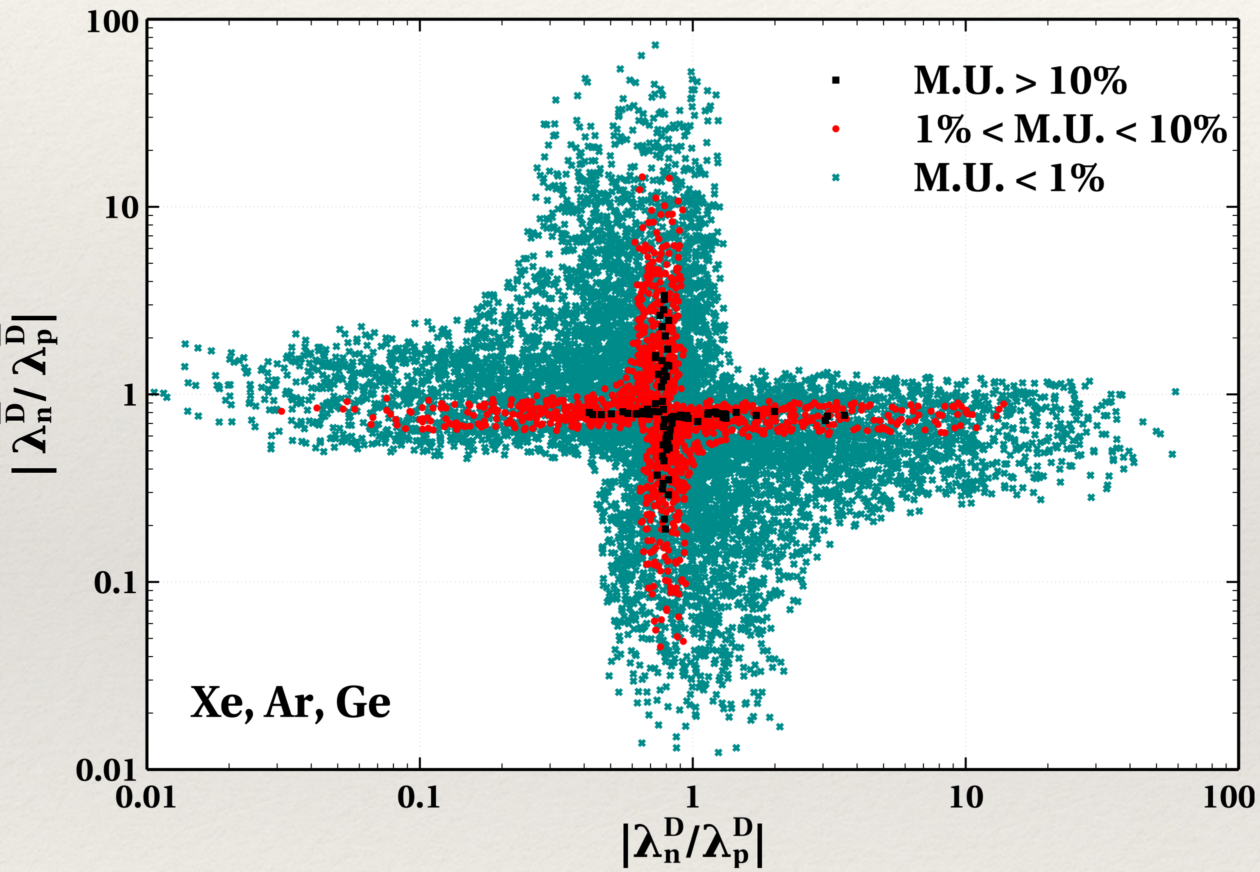


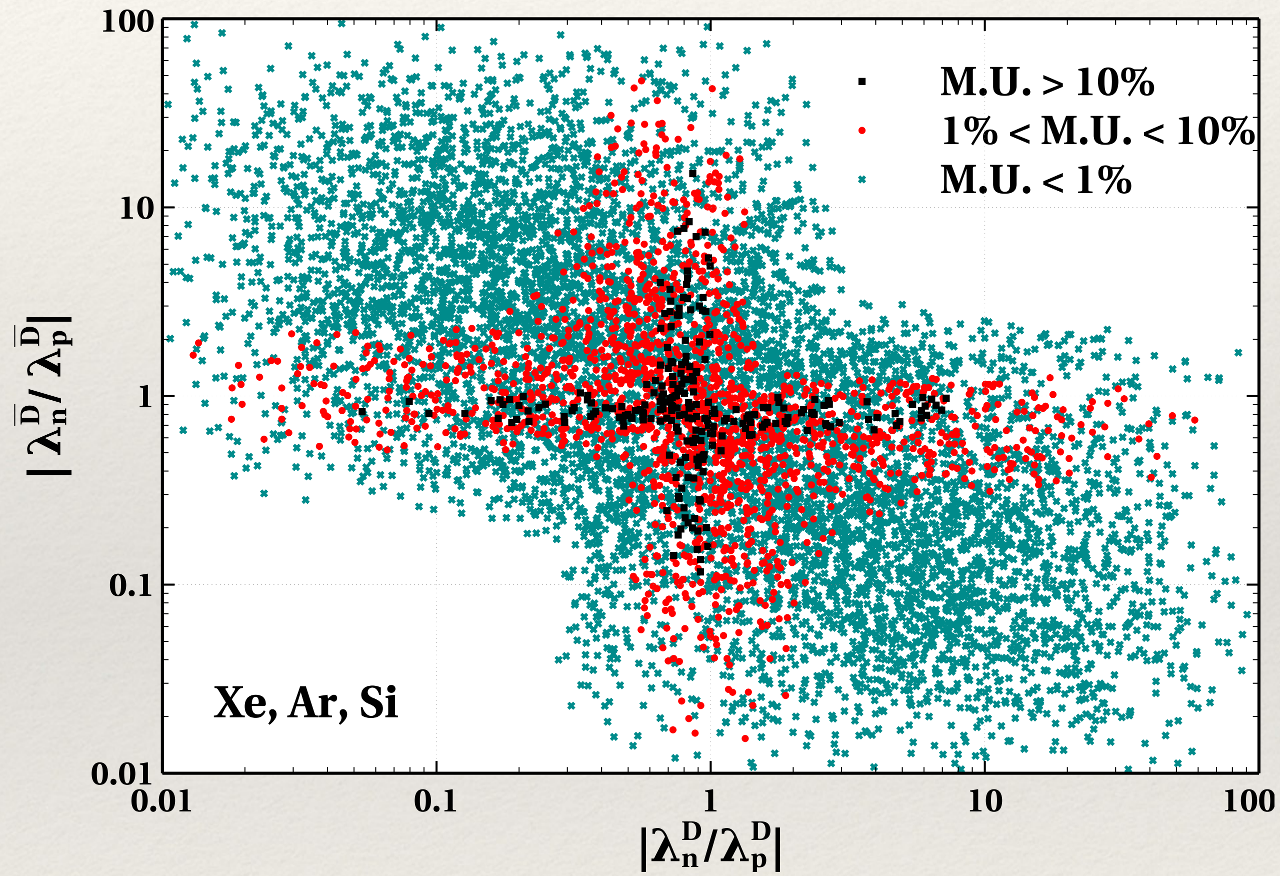
could prove Dirac nature!



Analysis

Assume Dirac DM and find values of the four interaction parameters such that data <u>can not</u> be explained in Majorana interpretation





Minimal **U**ncertainty to exclude Majorana particle:

larger than 10%

between 1% and 10%

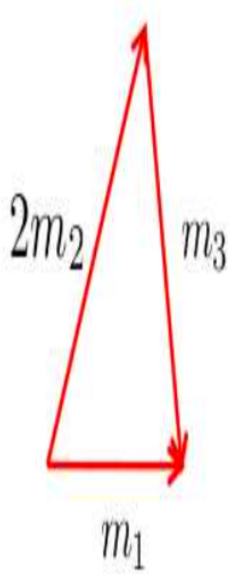
between 0.1% and 1%

$\lambda_n{}^D/\lambda_p{}^D < 0$

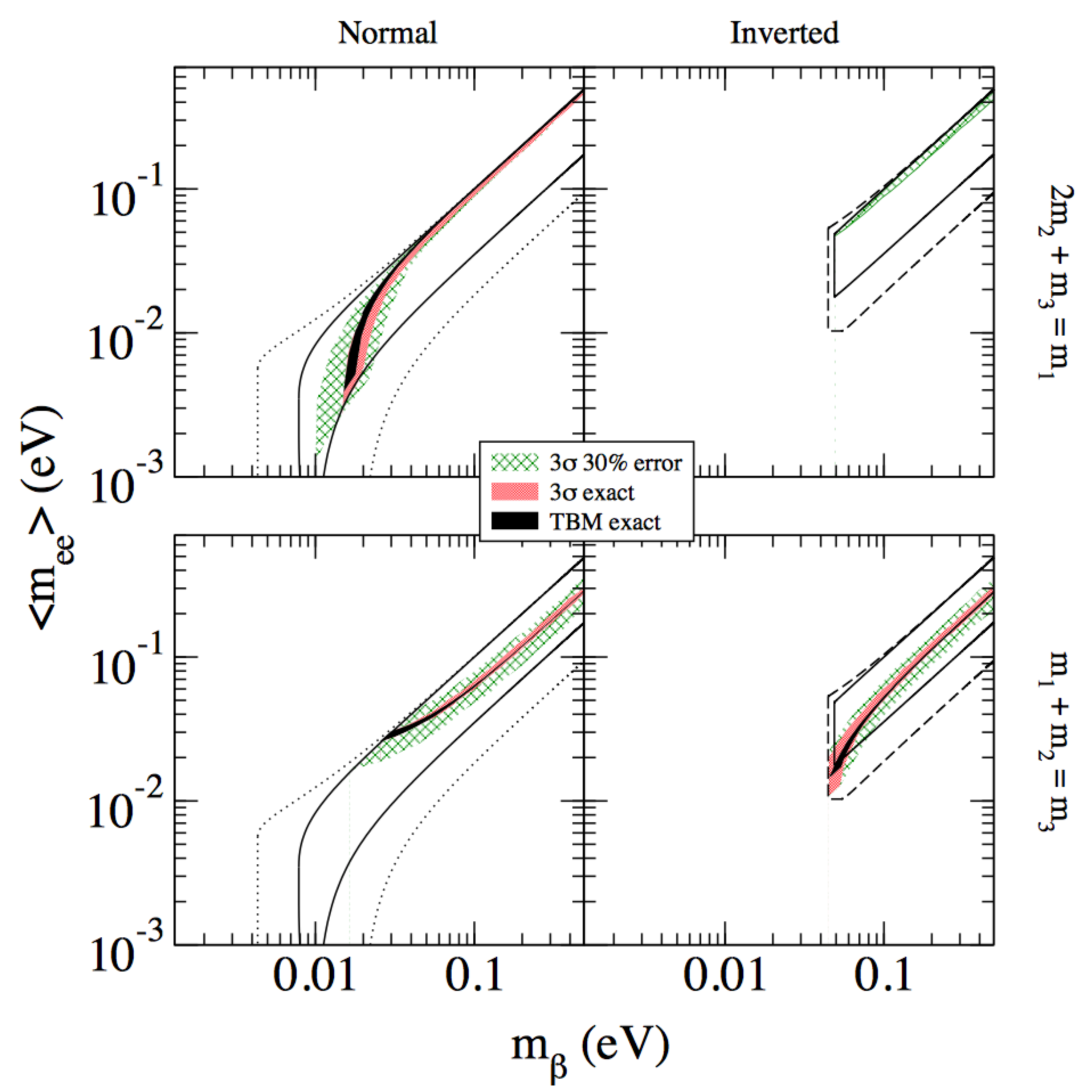
⇒ need partial cancellation between proton and neutron contributions to σ_{tot} of either particle or antiparticle

Predicting the effective mass

Flavor Symmetry models can not predict masses,
but relations between them:



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



Barry, WR, 1007.5217

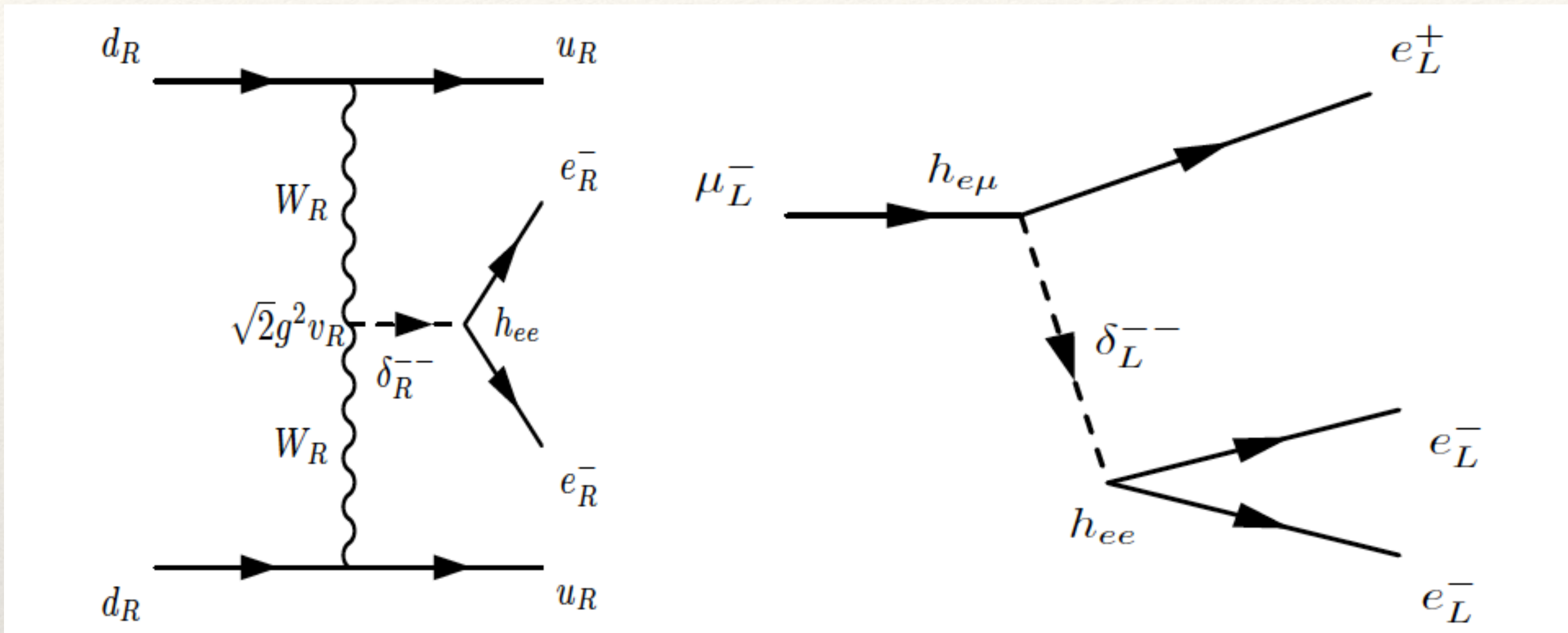
Scales

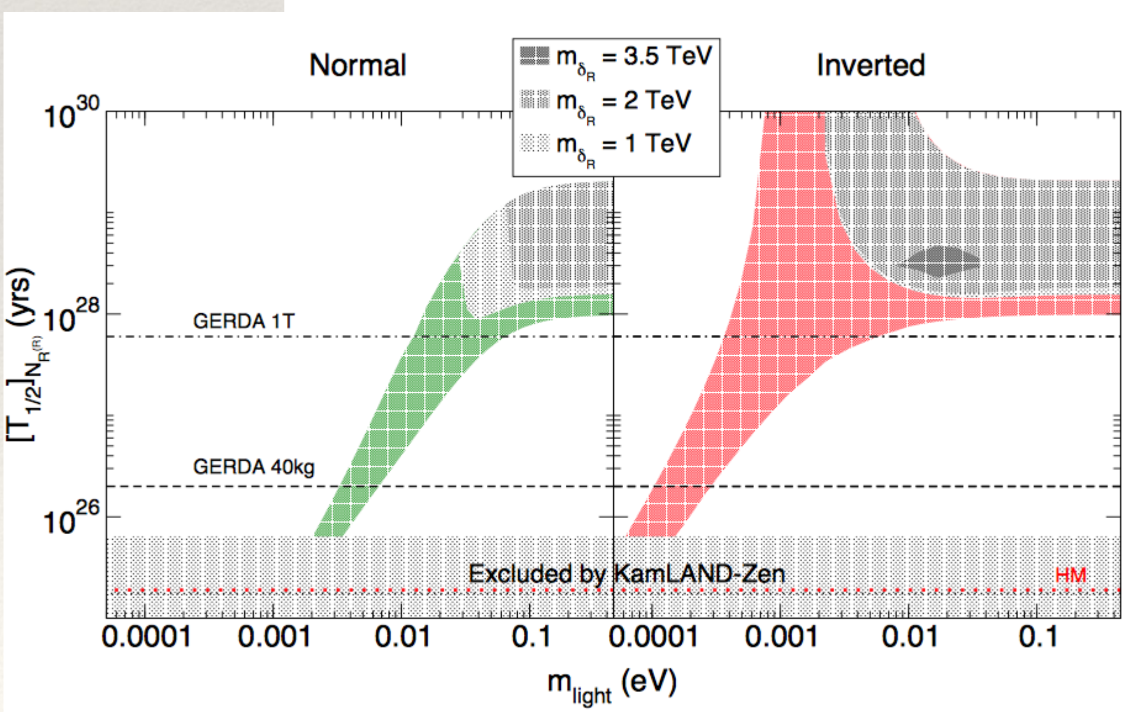
- $0\nu\beta\beta$ standard mechanism: $T_{½} \propto 1/(m_\nu^2)$
- $0\nu\beta\beta$ standard and Weinberg: $T_{½} \propto \Lambda^2$
- $0\nu\beta\beta$ and heavy Physics: $T_{½} \propto \Lambda^{10}$
- cf. to proton decay with $T_{½} \propto \Lambda^4$
- cf. to neutron-antineutron oscillation $P \propto \Lambda^{10}$

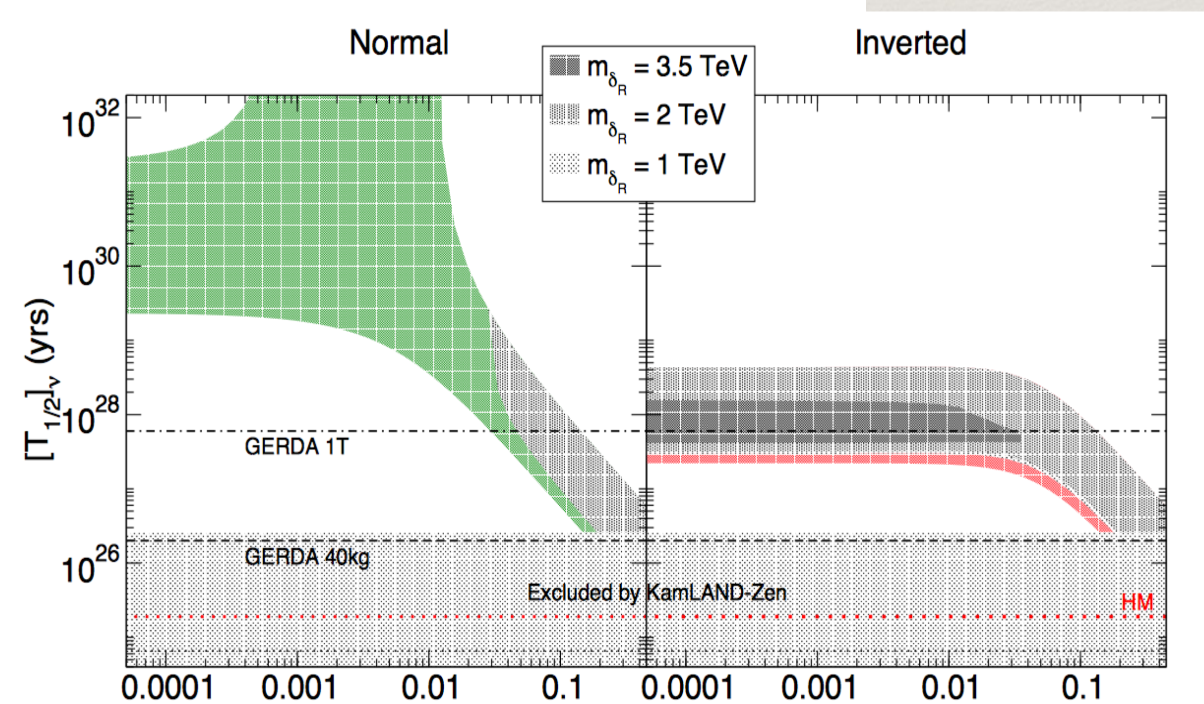
Scales

- $0\nu\beta\beta$ standard mechanism: $T_{1/2} \propto 1/(m_\nu^2)$
- $0\nu\beta\beta$ standard and Weinberg: $10^{4\text{-}14}$ 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 $P \propto$ 10^6 GeV

LFV and Double Beta Decay

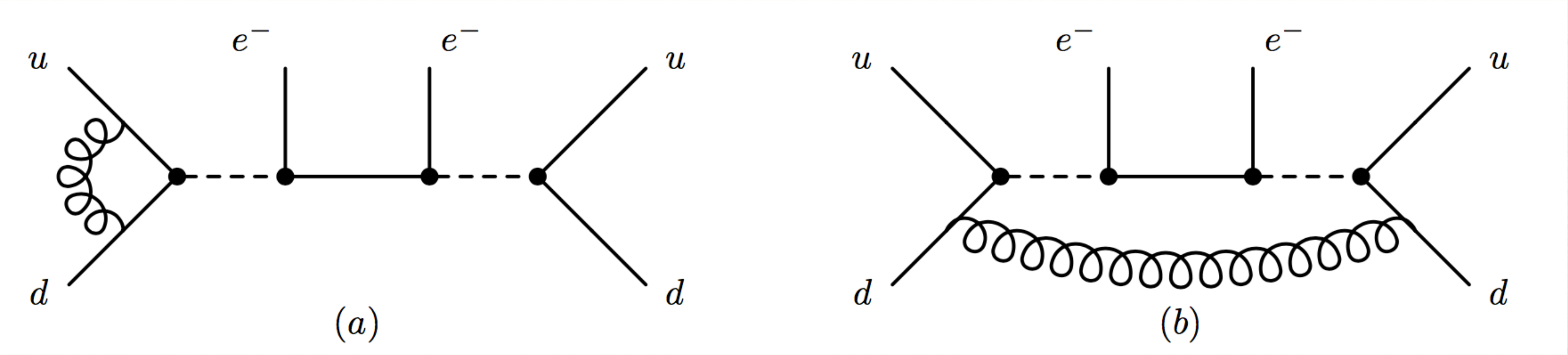






Barry, WR, 1303.6324

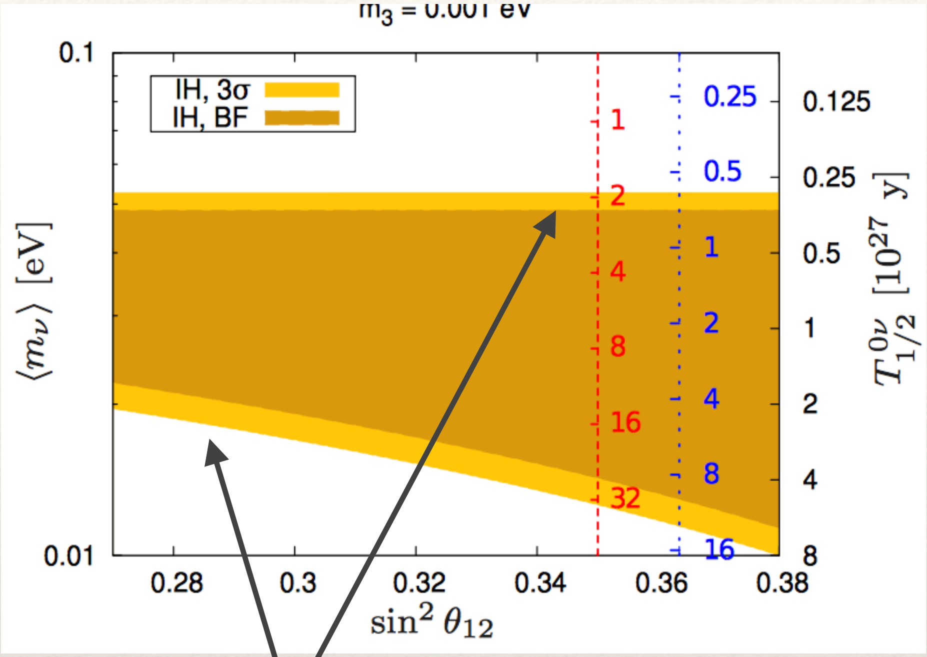
QCD Corrections



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

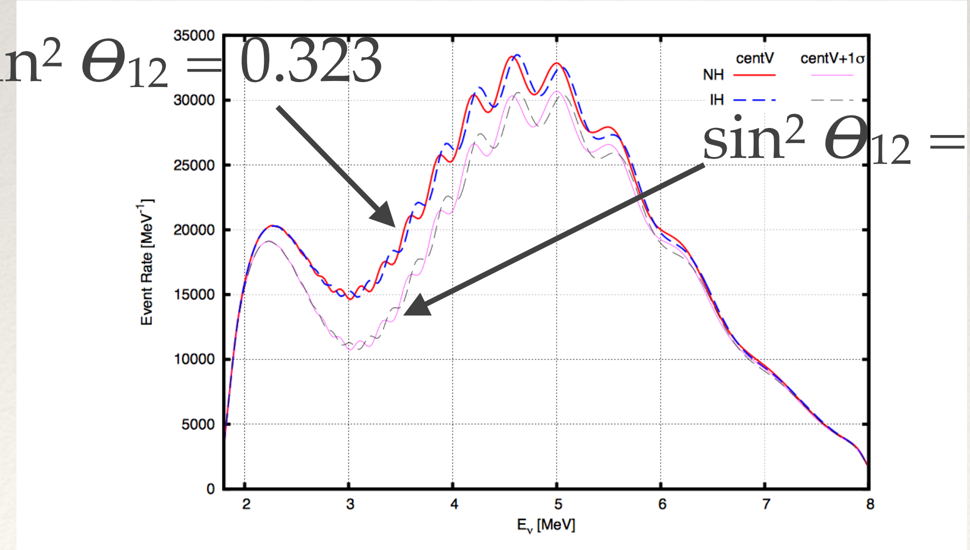
Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93; Peng, Ramsey-Musolf, Winslow, PRD 93

Connections to Oscillation Experiments



Nature gives us two scales

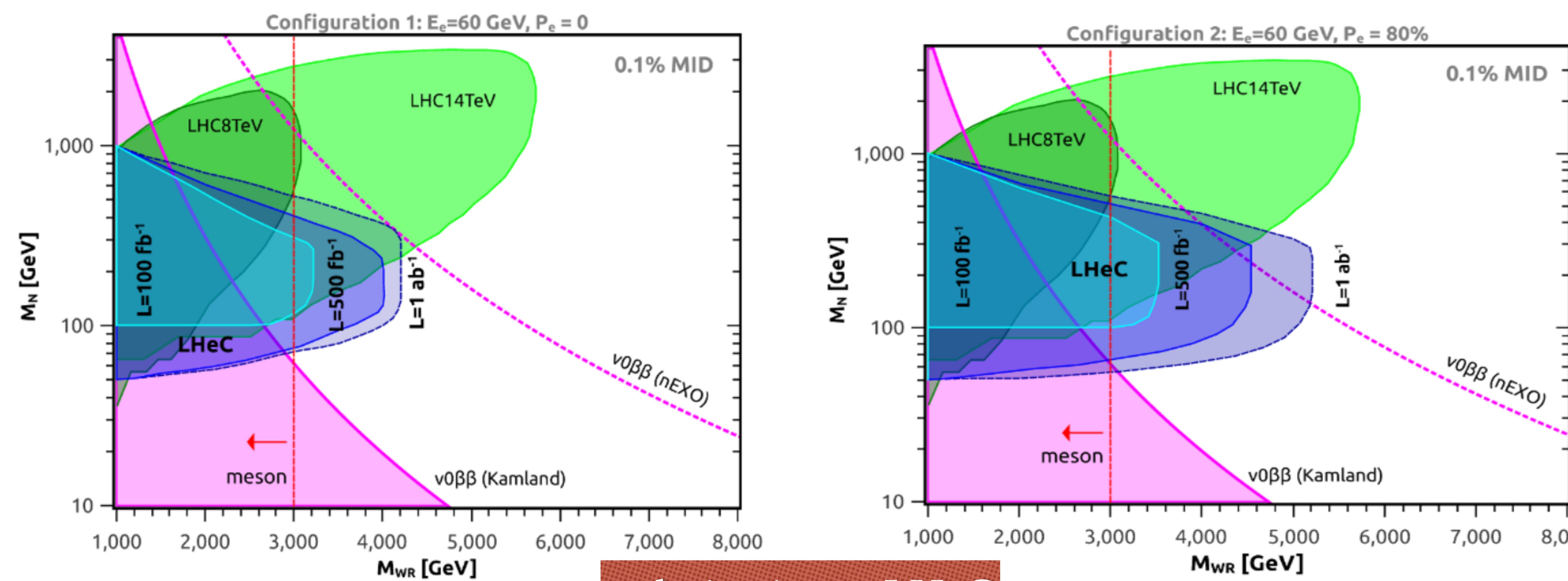
Factor 2 uncertainty of minimal m_{ee} in IH, mostly from Θ_{12}



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

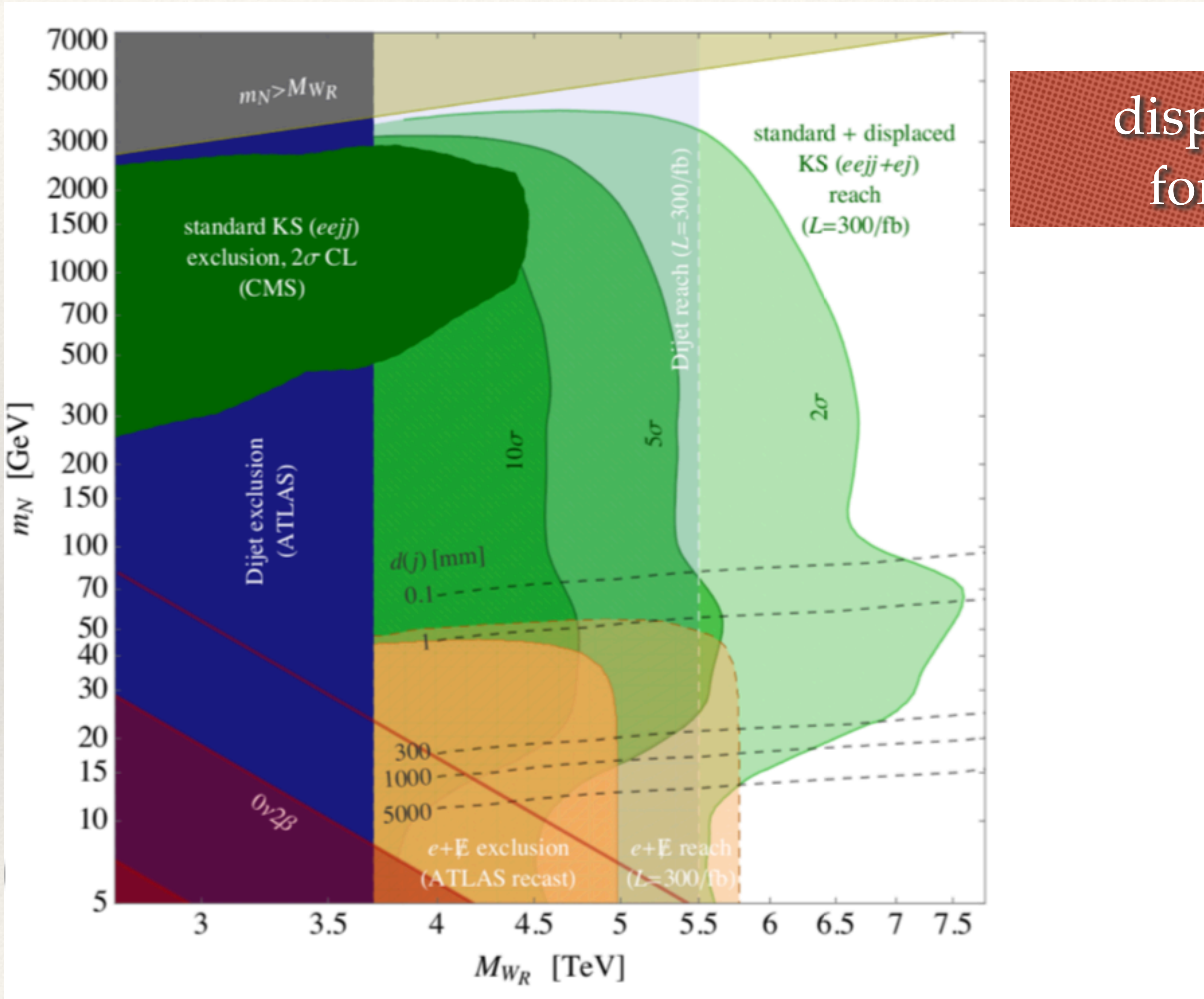
LHC and Double Beta Decay



polarization at LHeC

Lindner, Queiroz,
WR, Yaguna, JHEP1606

LHC and Double Beta Decay



displaced vertices for low masses

Nemevsek, Nesti, Popara, 1801.05813

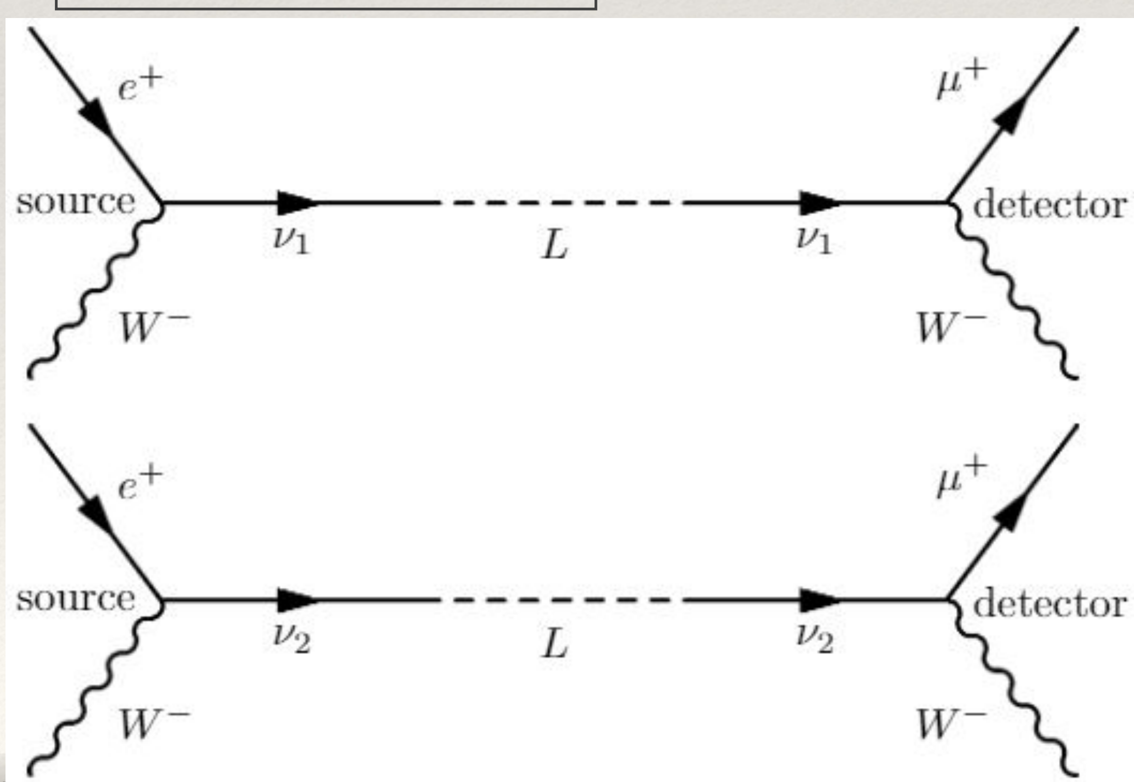
Neutrinos do have mass!

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavor states, produced in weak interaction

Mixing matrix PMNS

mass states, propagating



A_1

A_2

$$A_{\text{tot}} = A_1 + A_2$$

and

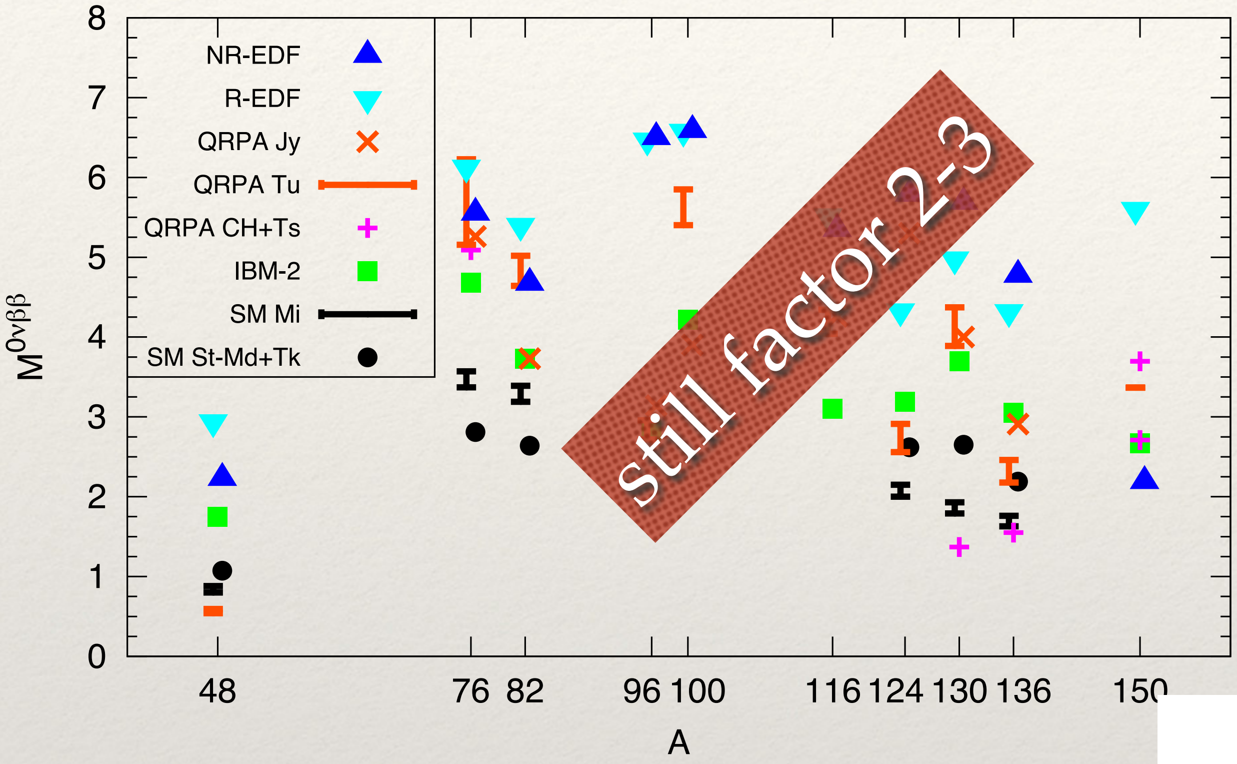
$$P = | A_1 + A_2 |^2$$

Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% c [10^{25} yr]
Past							
Cuoricino, [179]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [180]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [181]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [182, 183]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [167, 184]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [185]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [186]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [187, 188]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [189]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [174]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [190]	^{82}Se	bolometers	17 ($Zn^{82}Se$)	18	10	0.001	1.8
MAJORANA D., [191]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [192, 193]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [194]	^{100}Mo	bolometers	200 ($Ca^{enr}MoO_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [195]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [196]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [197]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [198, 199]	^{82}Se	tracker +	100 (^{82}Se)	500	120	0.01	10

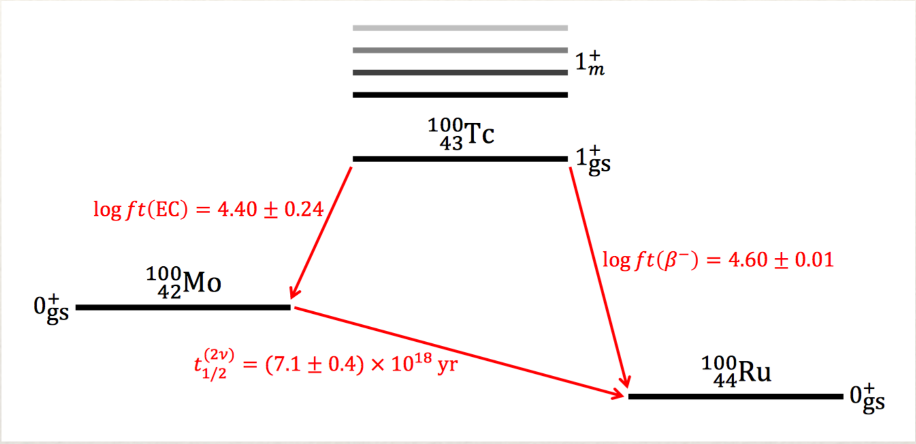
Dell'Oro et al., 1601.07512

Nuclear Matrix Elements

Engel, Menendez, 1610.06548

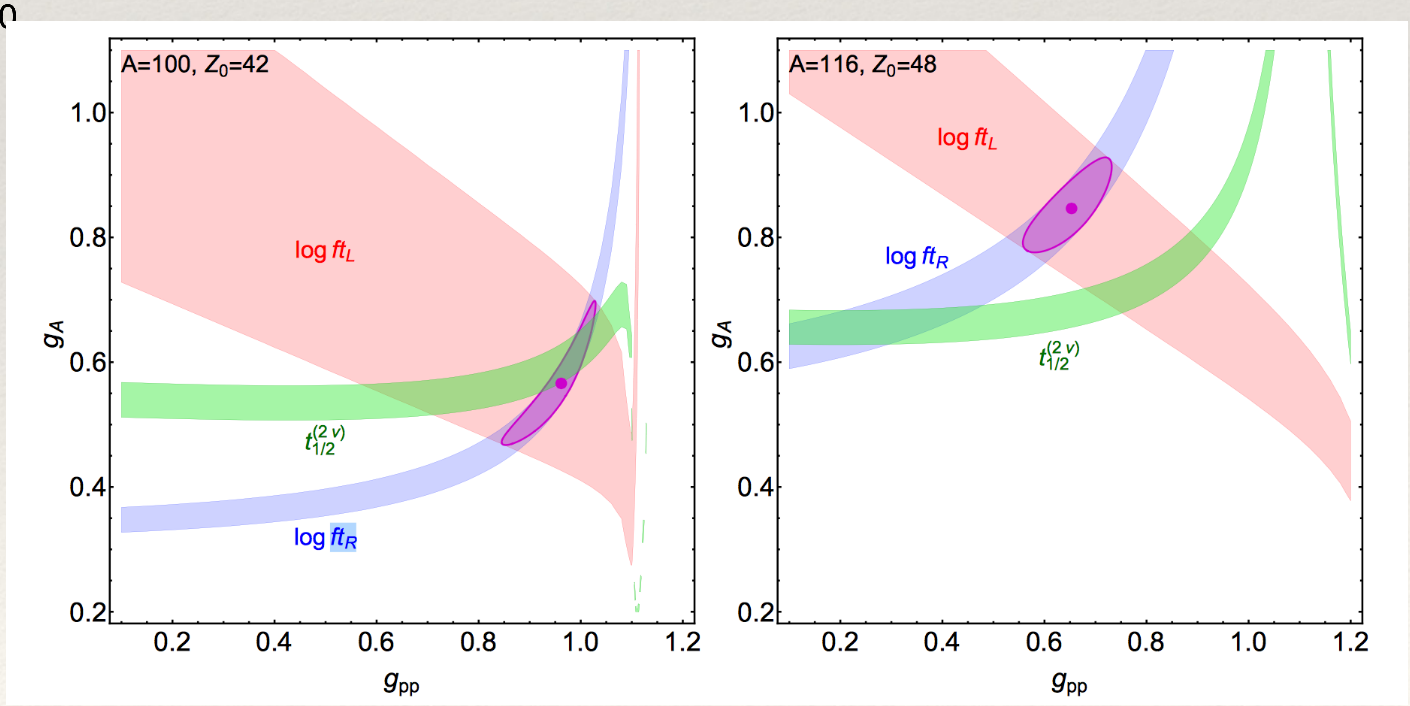


How good are the models?
Example isobaric triplets
within QRPA



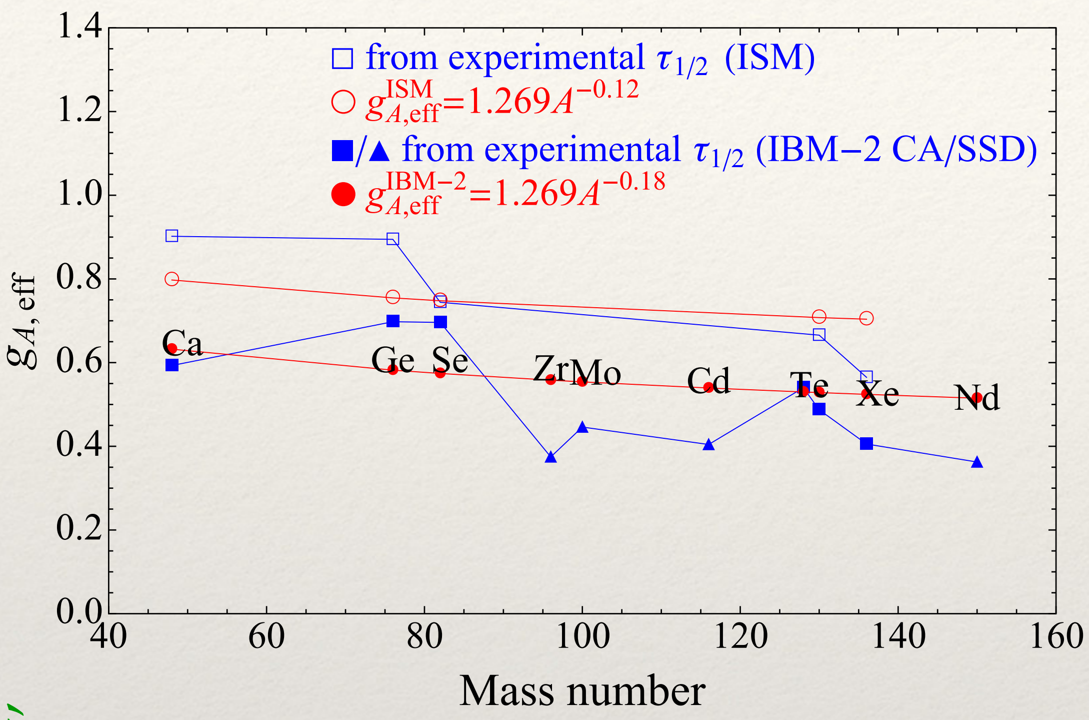
Deppisch, Suhonen, 1606.02908

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



Nuclear Matrix Elements

Iachello et al., 1506.08530

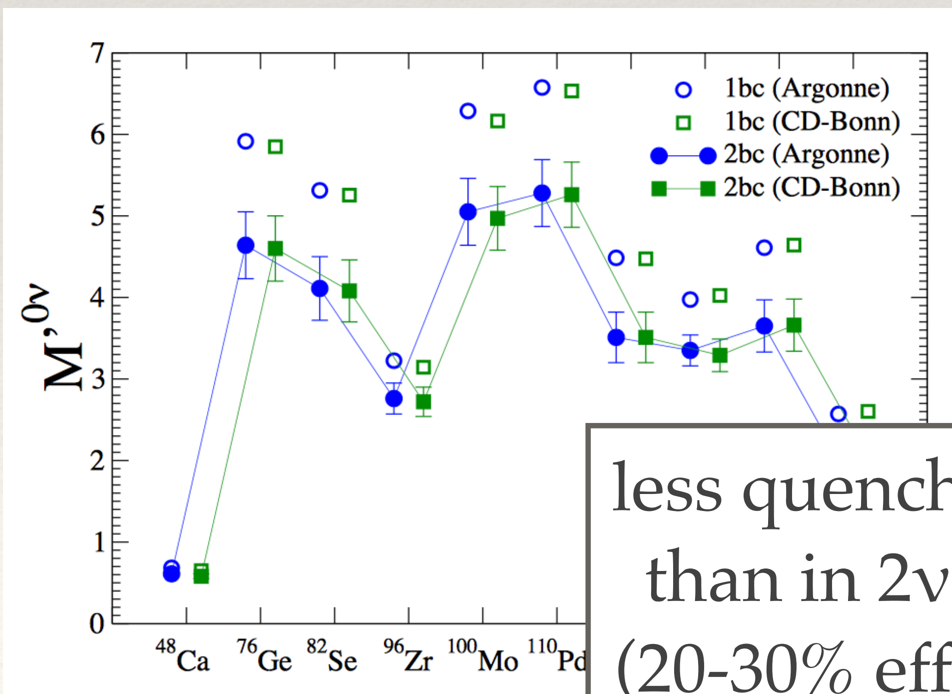


QUENCHING??

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

- 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

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

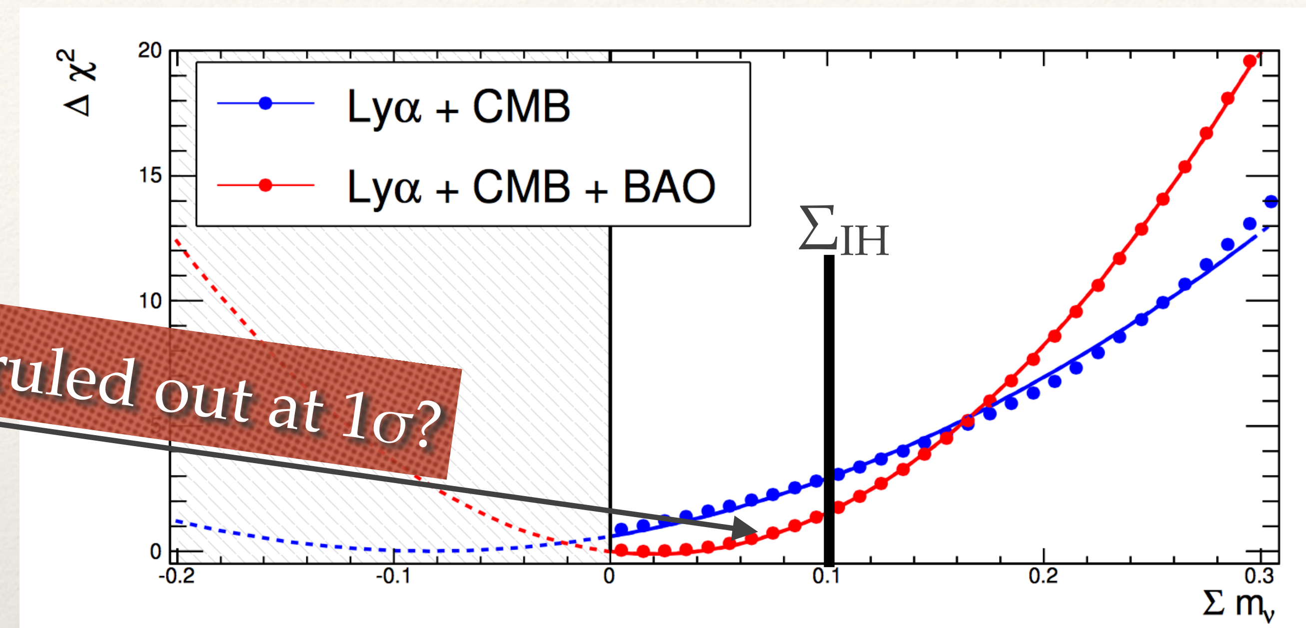


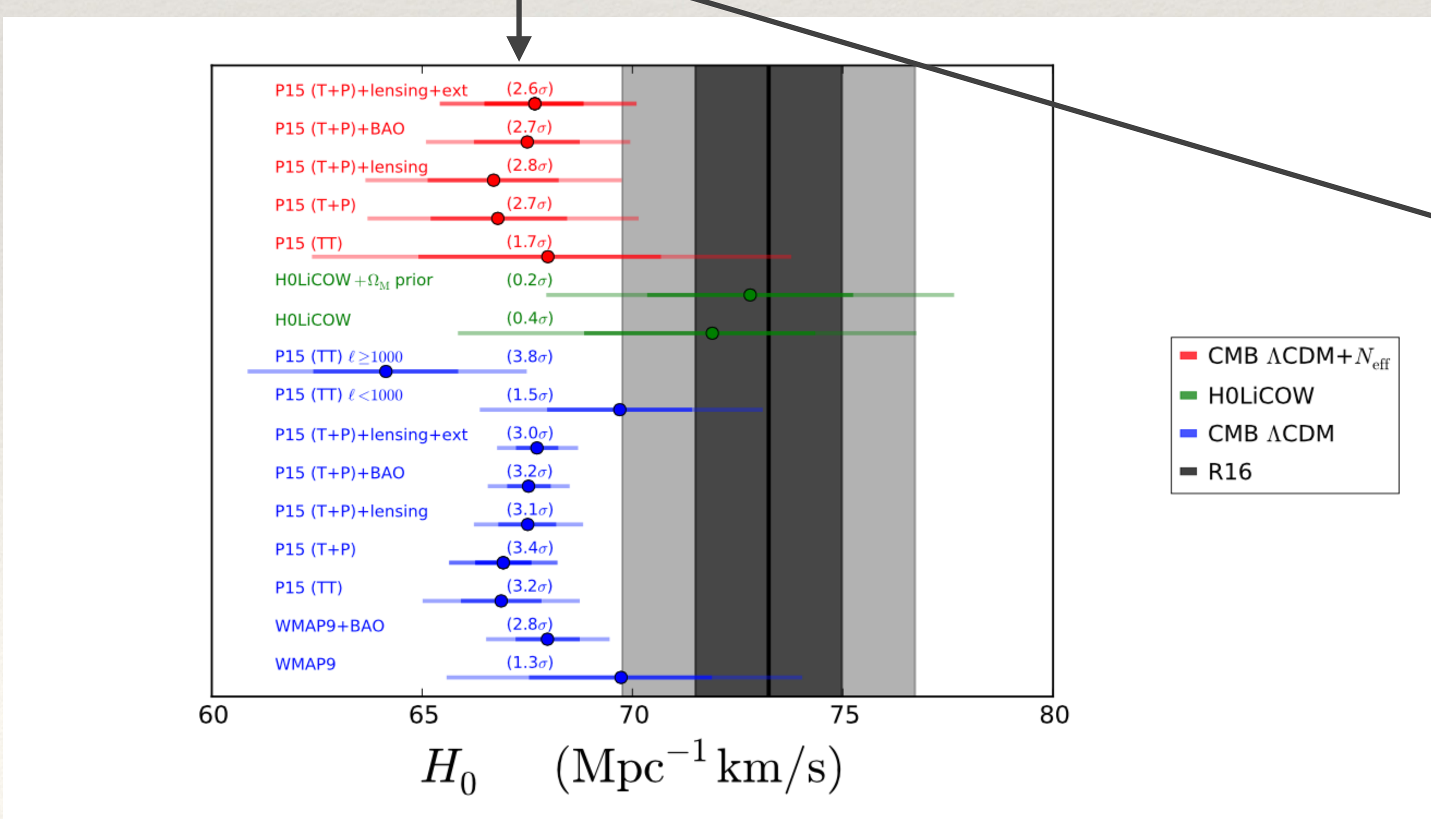
less quenching than in 2νββ (20-30% effect)

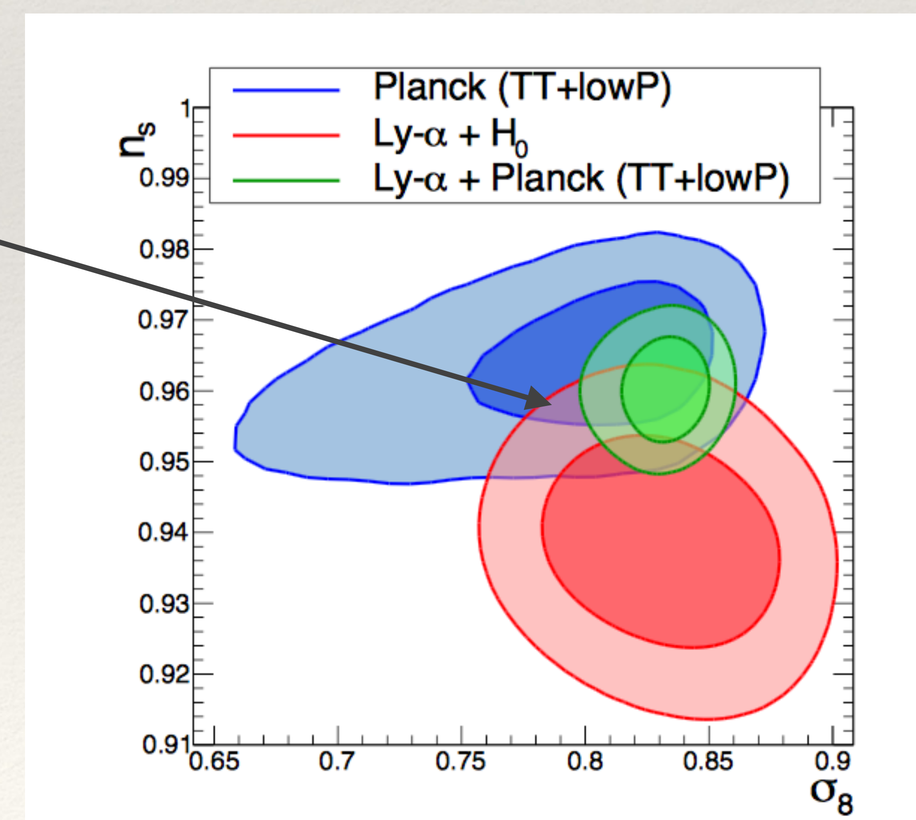
Cosmological Mass Limits

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

IH ruled out at 1σ?





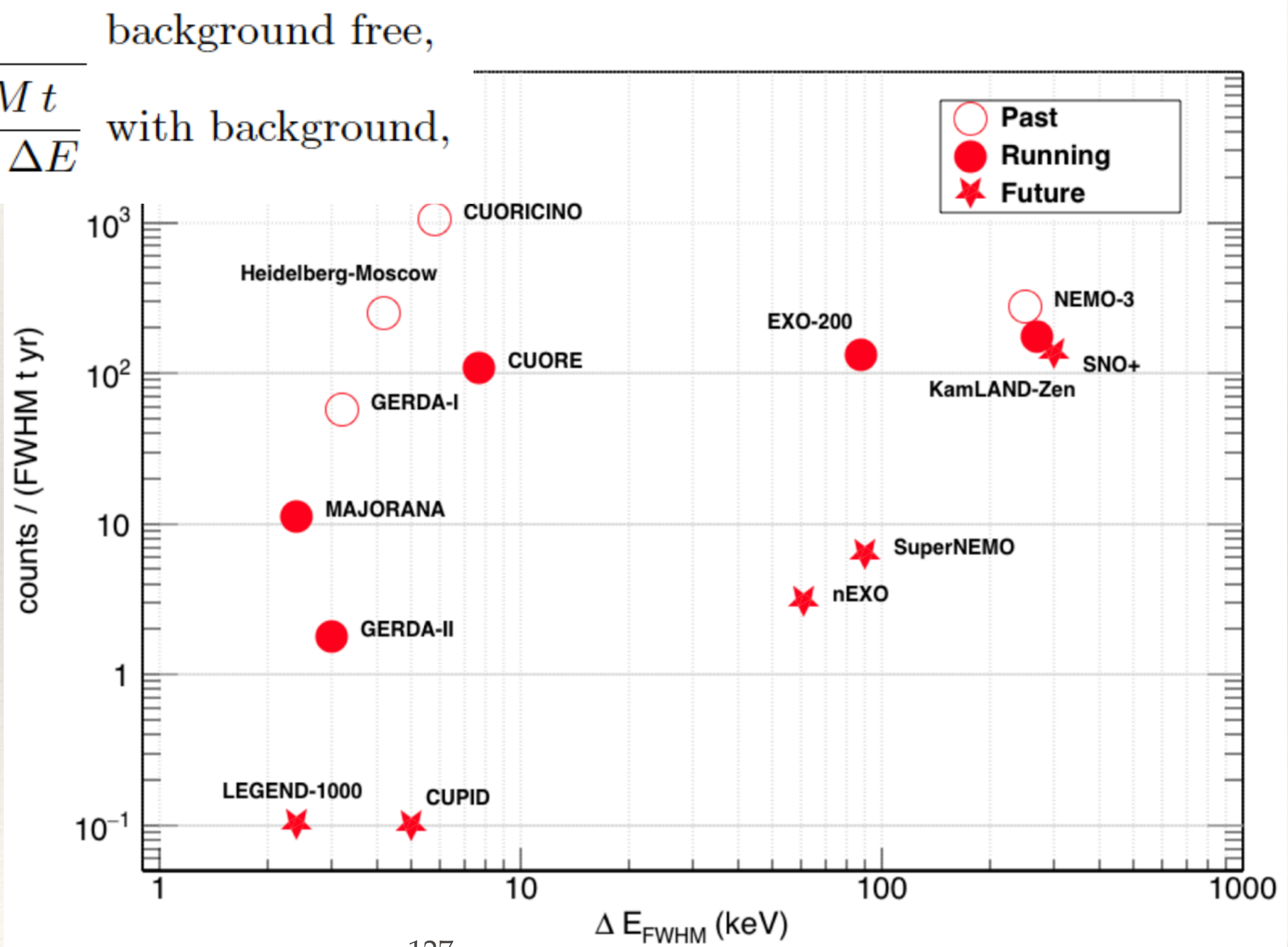


Bernal, Verde, Riess, 1607.05617

Palanque-Delabrouille et al., 1410.7244 + 1506.05976

Neutrinoless Double Beta Decay

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



Dolinski, Poon, WR, 1902.04097