Left Right symmetry, neutrinoless double beta and the LHC

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The Role of Heavy Fermions in Fundamental Physics
Portorož 2011

based on arXiv:1011.3522

Neutrino mass is an experimentally

confirmed evidence for particle physics

beyond the Standard Model.

Q: Dirac or Majorana?

Dirac vs. Majorana

Every fermion has an antiparticle.

$$\nu \neq \bar{\nu}$$

Dirac '28

Not true!

$$\nu = \bar{\nu}$$

Majorana '37

Neutrino-less double beta is a probe if $m_\nu \neq 0$

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

Racah '37, Furry '39

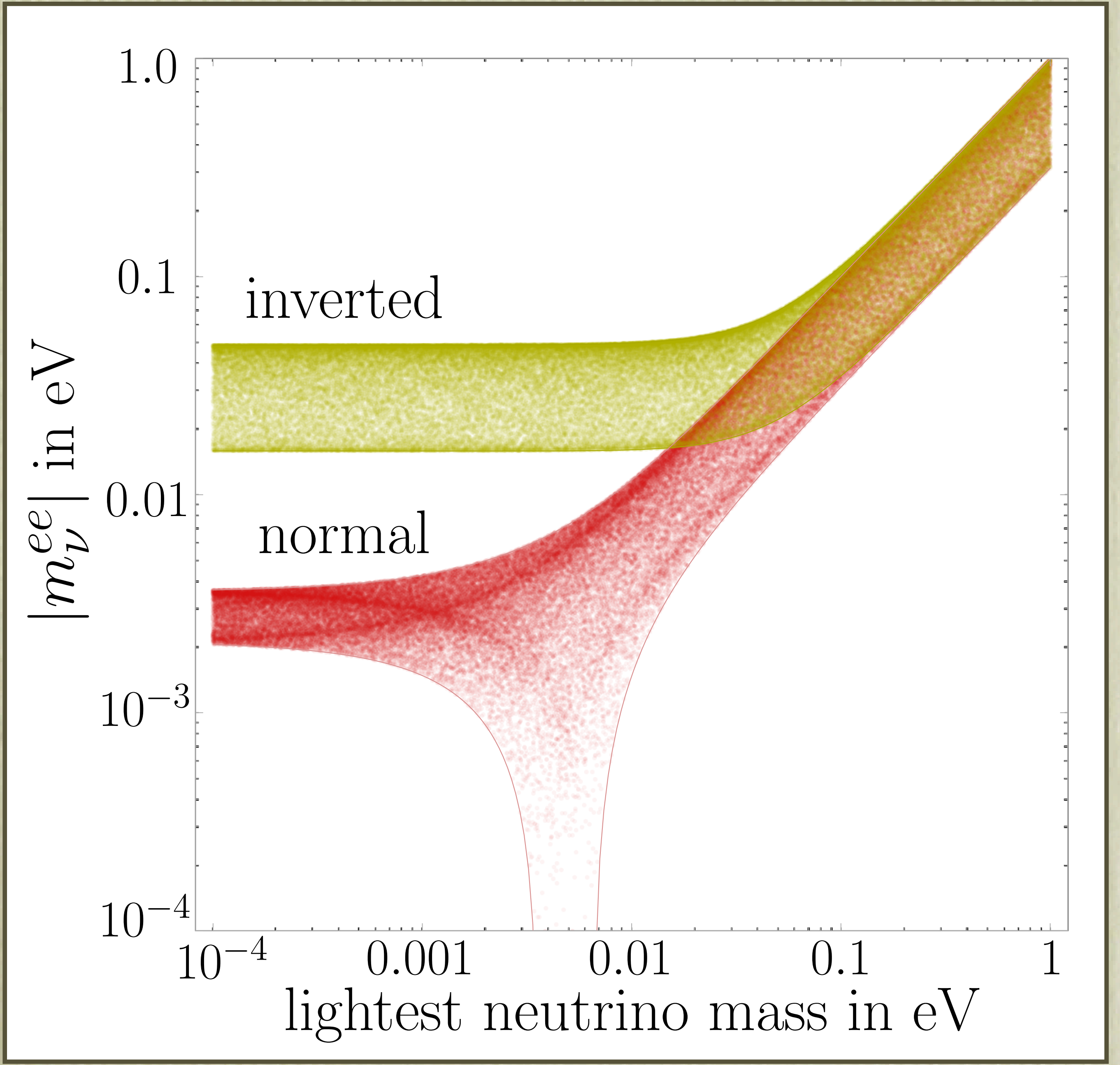
A test of lepton number conservation...

$0\nu2\beta$ and cosmology

- Neutrinos are massive → textbook source of $0\nu2\beta$

SuperKamiokande '98

Vissani '99



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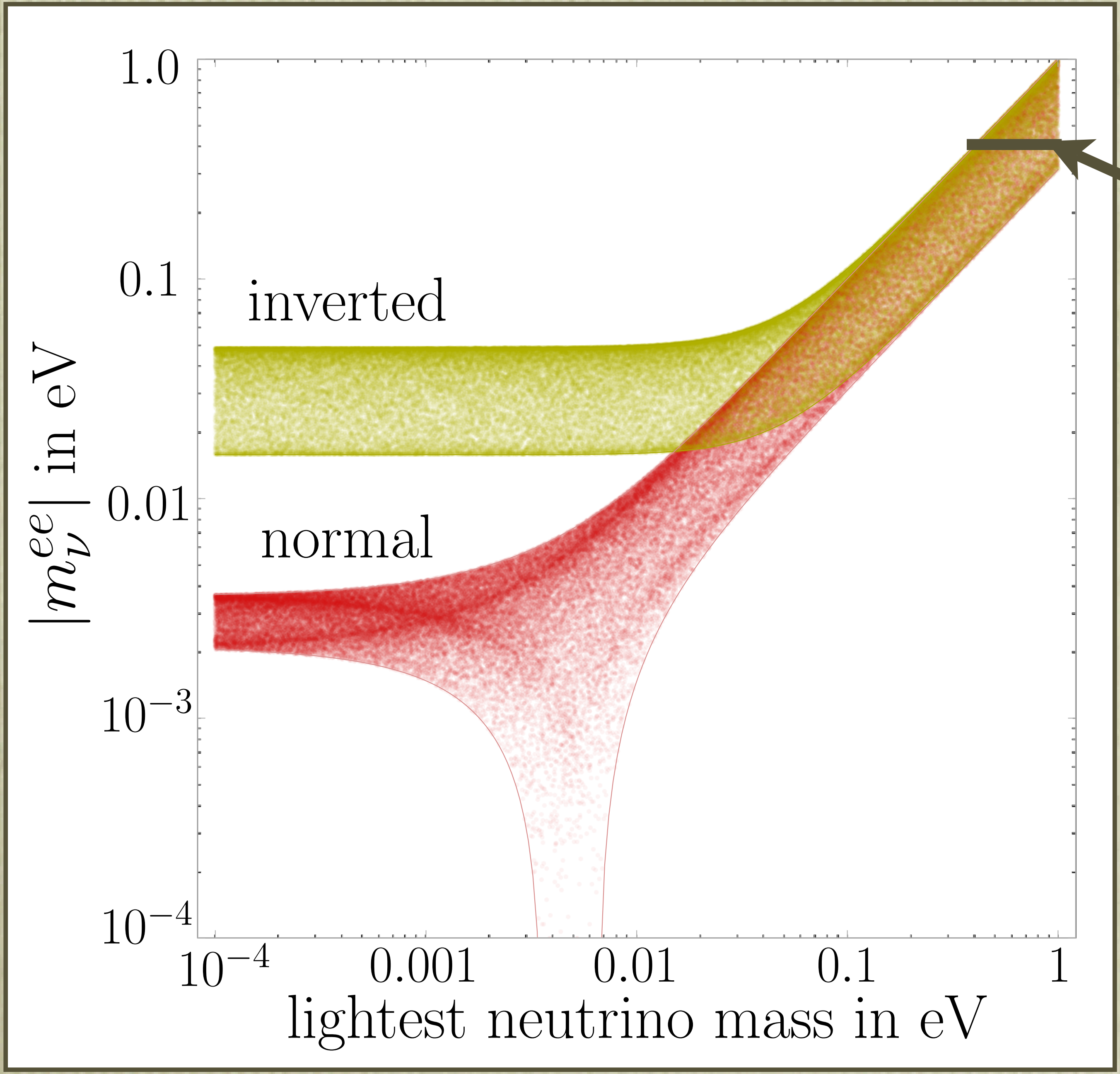

★ Claim of observation

Klapdor-Kleingrothaus '04 & '06

$|m_\nu^{ee}| \simeq 0.4$ eV

★ Upcoming experiments

GERDA, CUORE, NEMO3, SuperNEMO, etc.

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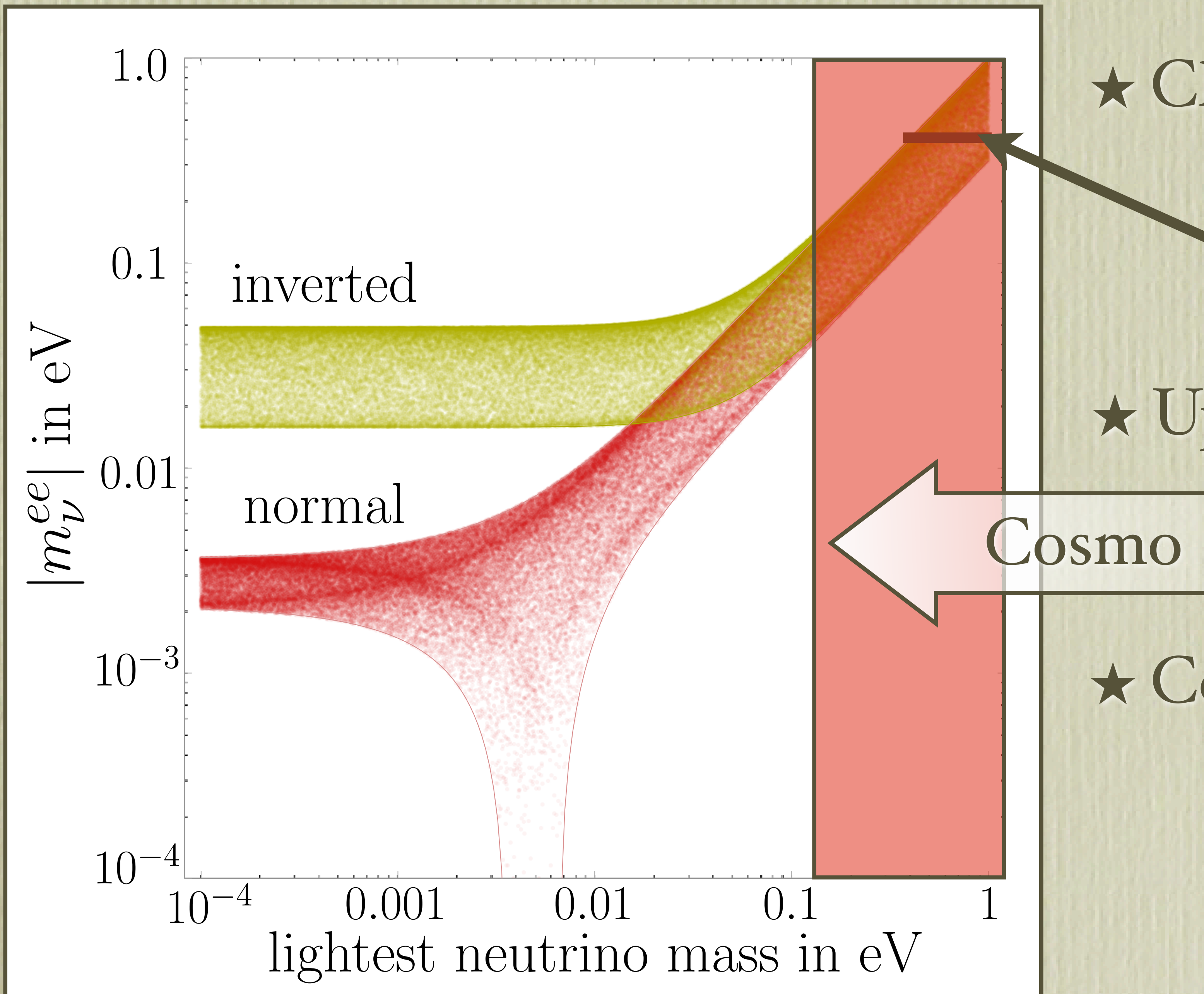

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$$|m_\nu^{ee}| \simeq 0.4 \text{ eV}$$

★ Upcoming experiments

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★ Cosmology limits

Fogli '08, Hannestad '10

$$m_\nu^{\min} < 0.15\,\text{eV}$$

also KATRIN and PLANCK

New physics and $0\nu 2\beta$

- Alternative mechanisms

Feinberg, Goldhaber '59, Pontecorvo '68

Neutrino mass mechanism

$$d = 5 : \mathcal{A}_\nu \propto G_F^2 \frac{m_\nu^{ee}}{p^2}$$

$$m_\nu \simeq 0.1 \text{ eV}$$
$$p \simeq 100 \text{ MeV}$$

New Physics

$$d = 9 : \mathcal{A}_{\text{NP}} \propto G_F^2 \frac{M_W^4}{\Lambda^5}$$

$$\Lambda \lesssim \mathcal{O}(\text{TeV})$$

★ Tailor-made for the LHC

- A theory of new physics behind $0\nu 2\beta$?
- Other phenomena, correlations, predictions?

Where is Majorana?

- There is a natural place for Majorana fermions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- Parity restored at high energies

Pati, Salam '74
Mohapatra, Pati '75
Mohapatra, Senjanović '75

- Broken spontaneously
  - gives neutrino mass

Minkowski '77
Senjanović '79
Senjanović Mohapatra '80

- Scale could be $\mathcal{O}(\text{TeV})$

See talk by Nesti

Bander, Beall, Soni '82, etc.
Most recent: Zhang et al. '07
Maiezza, MN, Nesti, Senjanović '10

Minimal Left Right Model

- Minimal Higgs sector $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$\Phi(2,2,0), \quad \Delta_L(3,1,2), \quad \Delta_R(1,3,2)$$

SM breaking — breaks L

$$\langle\Phi\rangle = \begin{pmatrix} v_1 & 0 \\ 0 & v_2\, e^{i\alpha} \end{pmatrix}, \quad \langle\Delta_L\rangle = 0, \quad \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

- Left-right parity taken to be C

More by Nesti

$$\mathcal{C}: f_L \leftrightarrow (f_R)^c, \quad \Phi \leftrightarrow \Phi^T, \quad \Delta_L \leftrightarrow \Delta_R^*$$

- Heavy gauge bosons and heavy Majorana fermions

$$M_{W_R} = g\, v_R, \quad m_N \propto v_R$$

New physics sources of $0\nu 2\beta$

Mohapatra, Senjanović '81

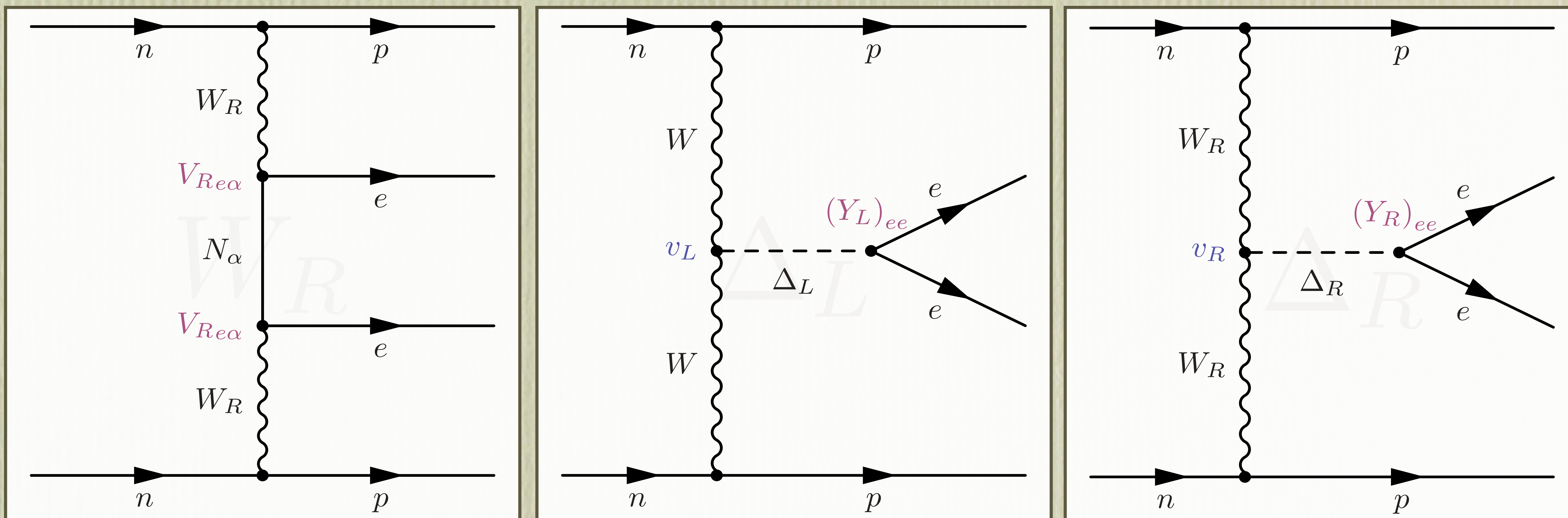
W_R

Δ_L

Δ_R

New physics sources of $0\nu2\beta$

Mohapatra, Senjanović '81



$\propto 1/m_N$ $\propto m_\nu$ $\propto m_N$

★ Large?

★ Tiny

★ Subdominant?

- Size of the NP contribution(s)?
- In accord with cosmology?

Mass spectra

- Yukawa couplings: Dirac and Majorana terms

$$\mathcal{L}_Y = \bar{\ell}_L (Y_\Phi \, \Phi + \tilde{Y}_\Phi \, \tilde{\Phi}) \ell_R + \ell_L^T \, Y_{\Delta_L} \Delta_L \ell_L + \ell_R^T \, Y_{\Delta_R} \Delta_R \ell_R + \text{h.c.}$$

★ Dirac masses

★ Two sources of seesaw

$$\begin{aligned} M_D &= v_1 \, Y_\Phi + v_2 \, \mathrm{e}^{-i\alpha} \, \tilde{Y}_\Phi, \quad & M_{\nu_R} &= v_R \, Y_{\Delta_R} \\ M_\ell &= v_2 \, \mathrm{e}^{i\alpha} \, Y_\Phi + v_1 \, \tilde{Y}_\Phi & M_{\nu_L} &= v_L \, Y_{\Delta_L} - M_D^T \, M_{\nu_R}^{-1} \, M_D \end{aligned}$$

$$\mathcal{C}: \quad Y_\Phi = {Y_\Phi}^T, \quad Y_{\Delta_{L,R}} = {Y_{\Delta_{R,L}}}^*$$

- Mass eigenstate basis

$$M_\ell = U_{\ell L} \, m_\ell \, U_{\ell R}^\dagger, \quad M_{\nu_L} = U_{\nu L}^* \, m_\nu \, U_{\nu L}^\dagger, \quad M_{\nu_R} = U_{\nu R}^* \, m_N \, U_{\nu R}^\dagger.$$

$$\mathcal{C}: U_{\ell L} = U_{\ell R}^*$$

Type II prevalence

- Several implications when Dirac mass term is negligible

$$M_{\nu_R} = v_R\, Y, \quad M_{\nu_L} = v_L\, Y^*, \quad v_L \propto \lambda\, v^2 / v_R$$

★ Masses

$$m_N \propto m_\nu$$

★ Mixings

$$U_{\nu R} = U^*_{\nu L} \Rightarrow V_R = V_L{}^*$$

$$V_{L,R} = U^\dagger_{\ell L,R} U_{\nu L,R}$$

$$\frac{m_{N_2}{}^2 - m_{N_1}{}^2}{m_{N_3}{}^2 - m_{N_1}{}^2} = \frac{m_{\nu_2}{}^2 - m_{\nu_1}{}^2}{m_{\nu_3}{}^2 - m_{\nu_1}{}^2} \simeq \pm 0.03$$

★ Hierarchy probe @ LHC

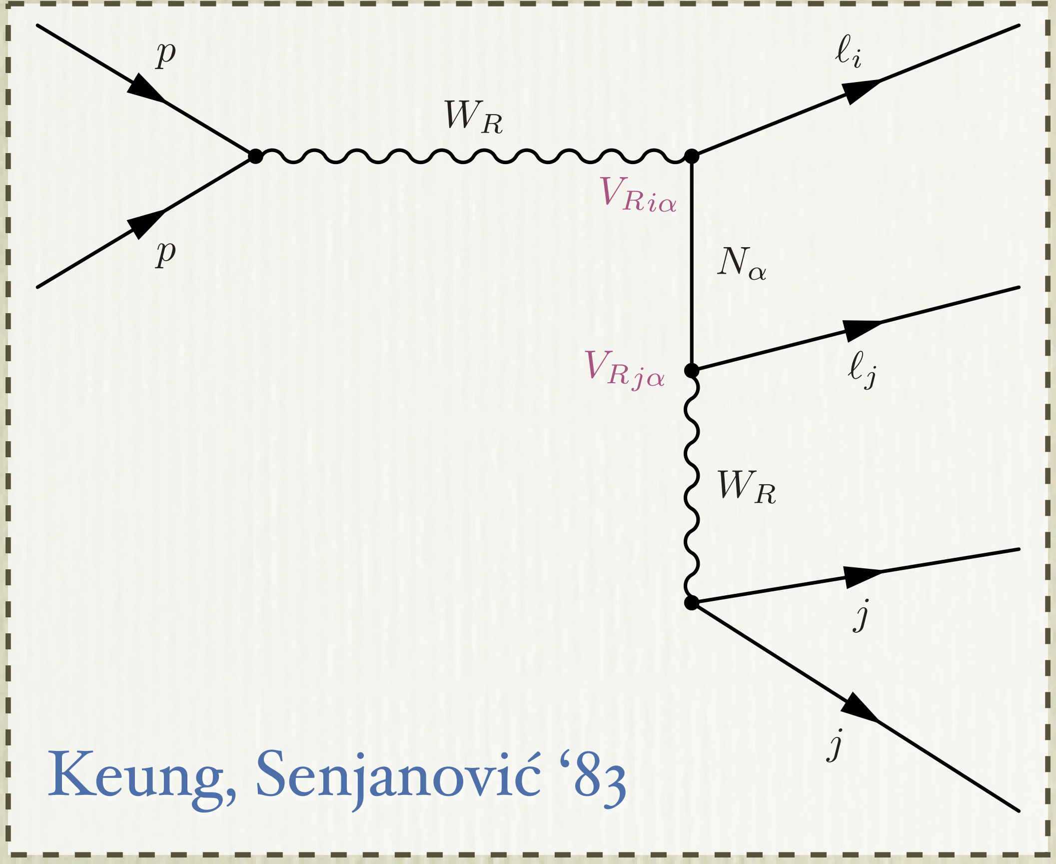
$$m_{\rm cosm} = \sqrt{\Delta m^2_A}\, \frac{\sum_i m_{N_i}}{\sqrt{|m_{N_3}{}^2 - m^2_{N_2}|}},$$

★ Cosmology-oscillations-LHC interplay

Interactions

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\nu}_L {V_L}^\dagger \not{W} \ell_L + \bar{\nu}_R {V_R}^\dagger \not{W}_R \ell_R \right)$$

- Flavour structure fixed: $V_R = {V_L}^* = V^*_{PMNS}$
- m_N and V_R measurable
  - ★ (Same)-sign di-leptons & 2 jets



- Doubly charged triplets

$$\mathcal{L}_{\Delta^{++}} = e_R^T \, Y \, \Delta_R^{++} \, e_R$$

$$Y = \frac{g}{M_{W_R}} {V_R}^* m_N {V_R}^\dagger$$

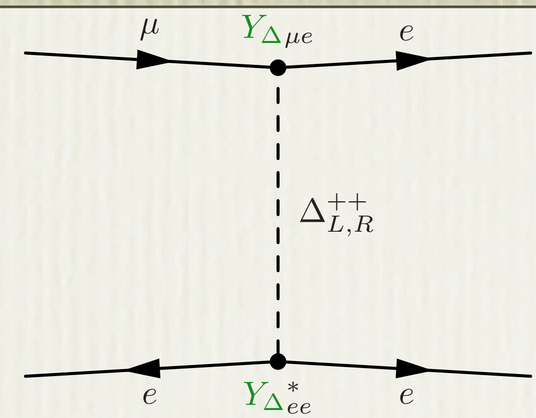
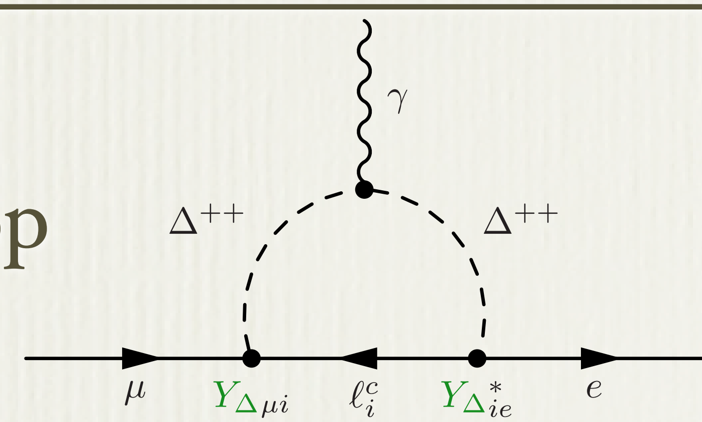
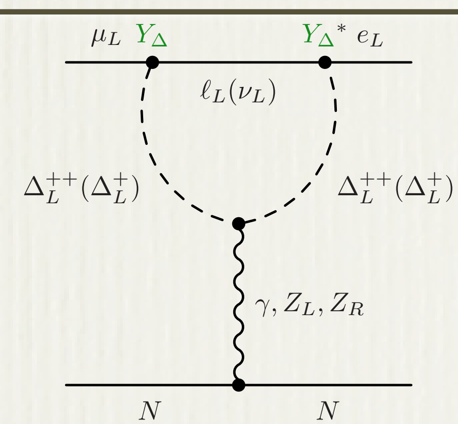
- Same flavour, all fixed in type II

★ Type II only an *example*! The interplay is general.

Lepton Flavor Violation

Cirigliano et al. '04

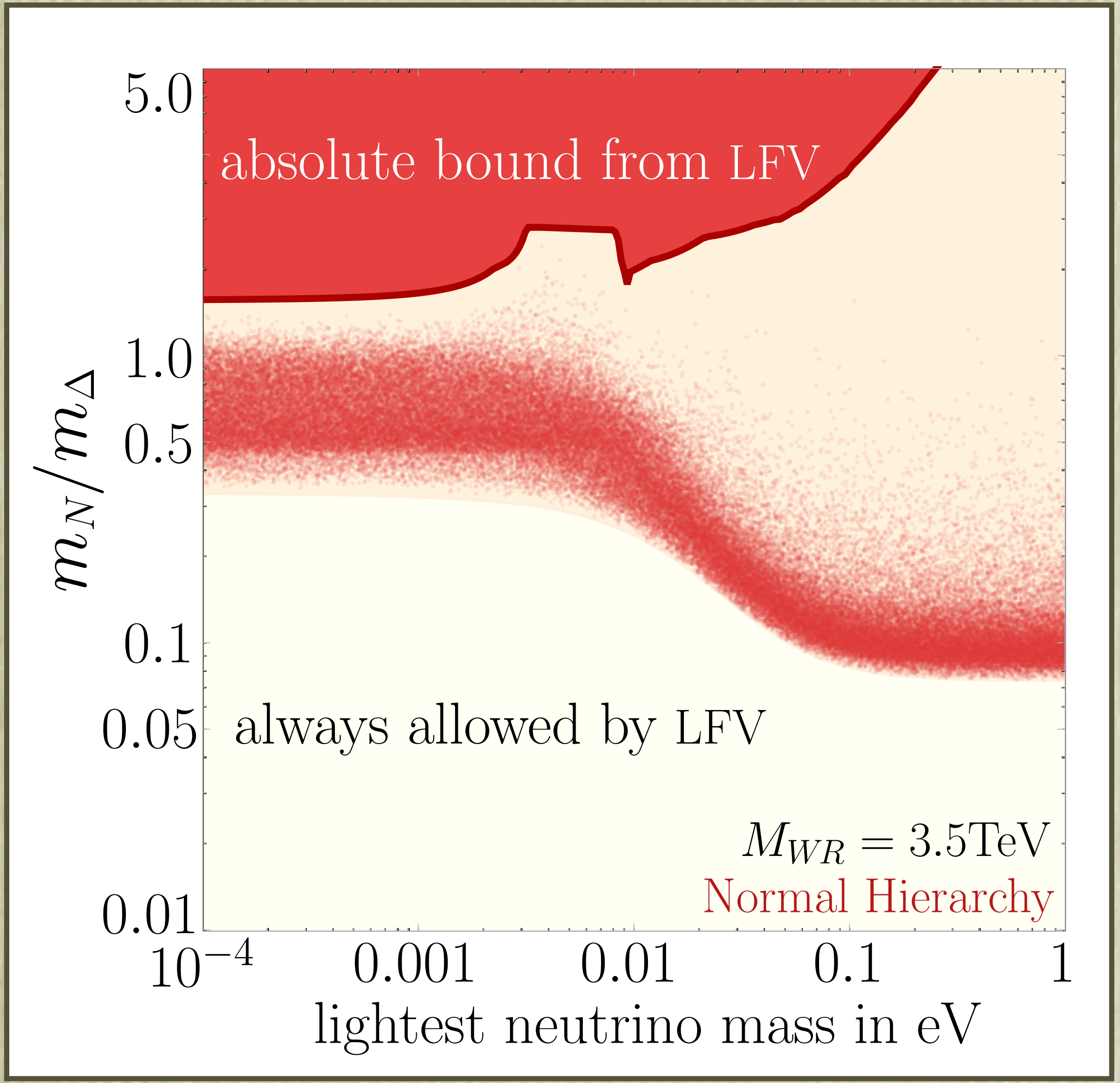
- μ channel: $\mu \to e\gamma,\ \mu \to 3e,\ \mu\,\mathrm{N} - e\,\mathrm{N}$ $\quad \mathrm{Br}^{\mathrm{exp}}_{\mu - e} \lesssim 10^{-11(-12)}$
- τ channel: $\tau \to \ell\,\gamma,\ \tau \to 3\,\ell$ $\quad \mathrm{Br}^{\mathrm{exp}}_{\tau - \ell} \lesssim 10^{-8}$

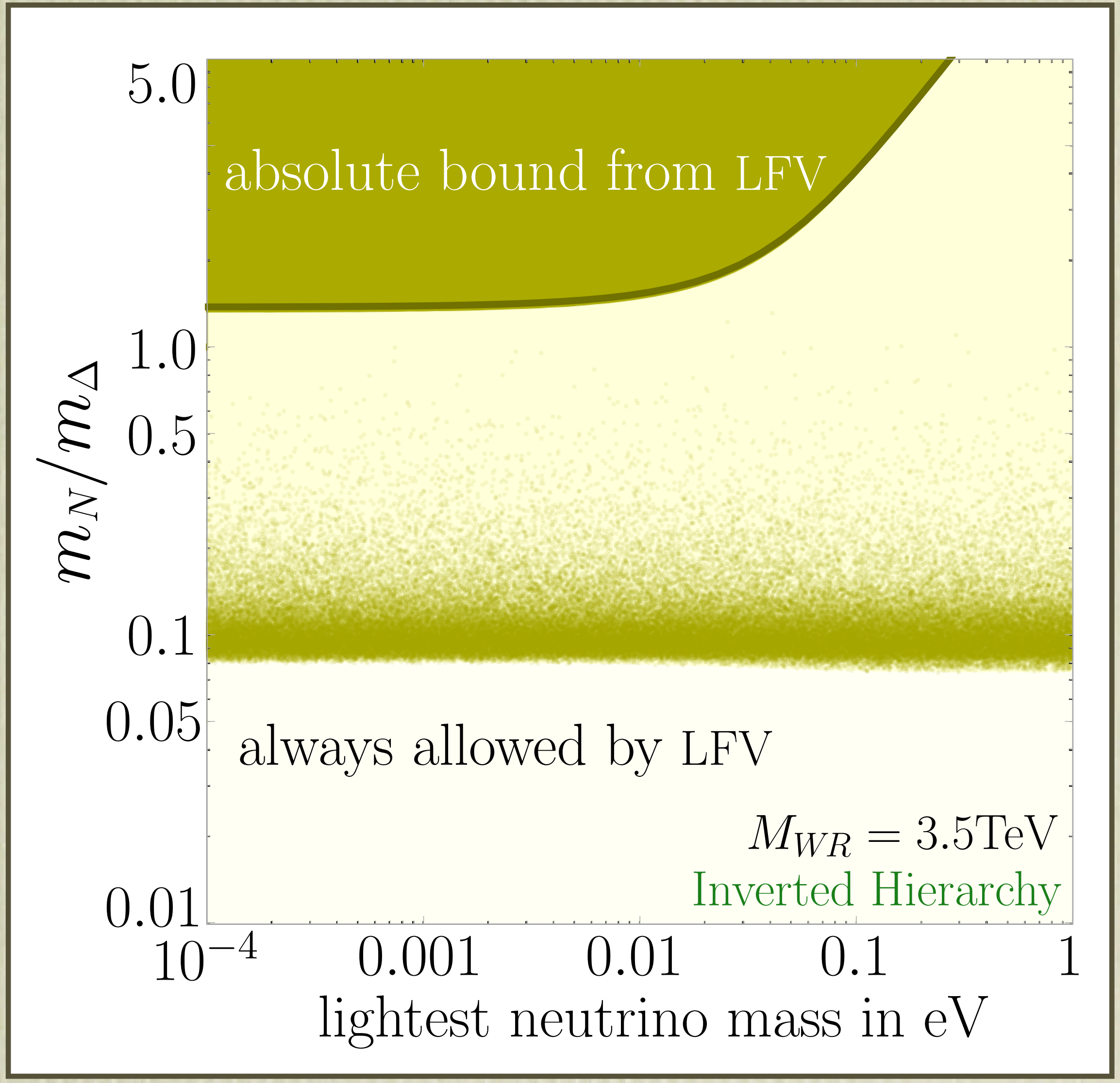
$\mu \to 3e$	tree 	$V_L\, m_N / m_\Delta\, V_L{}^T$
$\mu \to e\,\gamma$	loop 	$V_L\, m_N / m_\Delta\, V_L{}^\dagger$
$\mu\,\mathrm{N} \to e\,\mathrm{N}$	$\log \dfrac{m_\Delta^2}{m_\mu^2}$ 	$V_L\, m_N / m_\Delta\, V_L{}^\dagger$

LFV combined bound

$\mathrm{Br} \propto \left(V_L m_N / m_\Delta V_L{}^{T(\dagger)} \right)^4 < \mathrm{Br}^{\exp}$

- Vary $V_L = V_{PMNS}$, constrain $m_N/m_\Delta < \#$





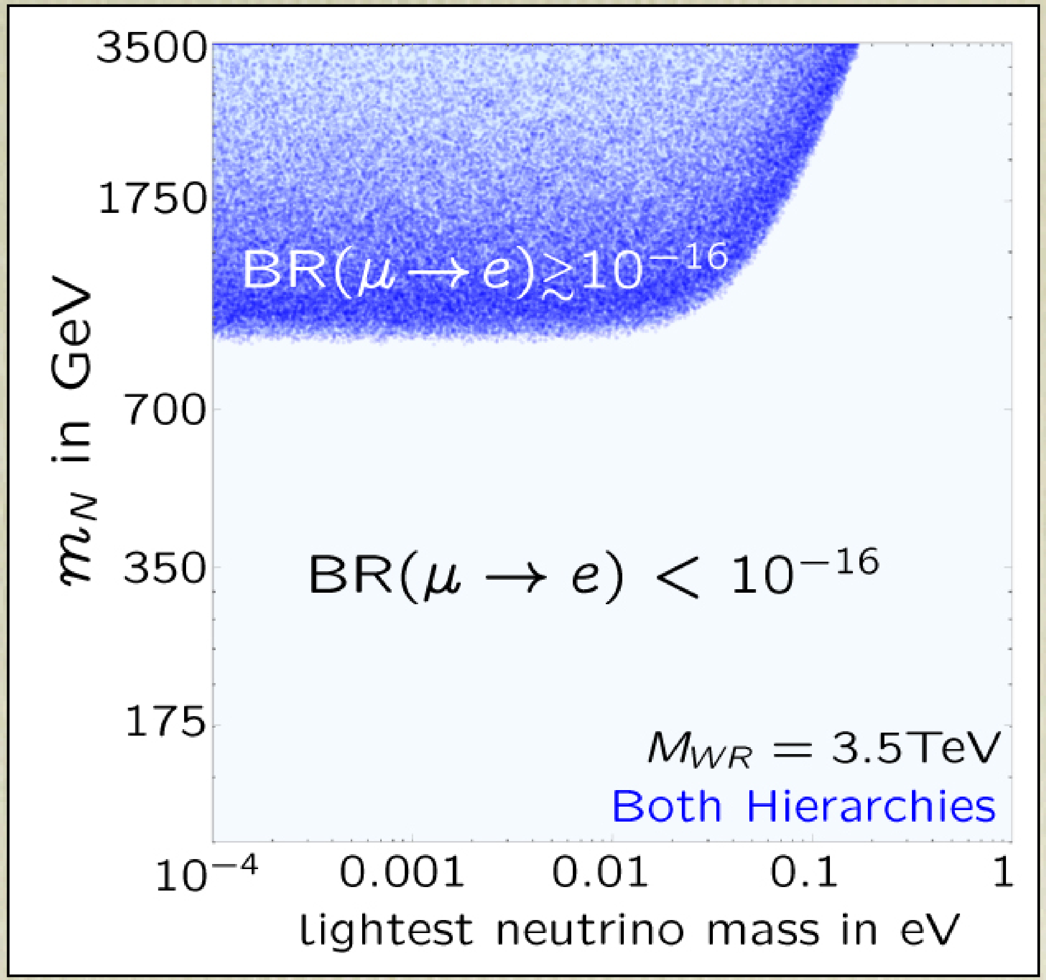
$\{\theta_{12}, \theta_{23}, \theta_{13}\} \in \{31^\circ - 39^\circ, 37^\circ - 53^\circ, 0^\circ\text{-}13^\circ\}$

$\phi_i \in \{0^\circ, 2\pi^\circ\}$

★ generically: $m_N/m_\Delta < 1$

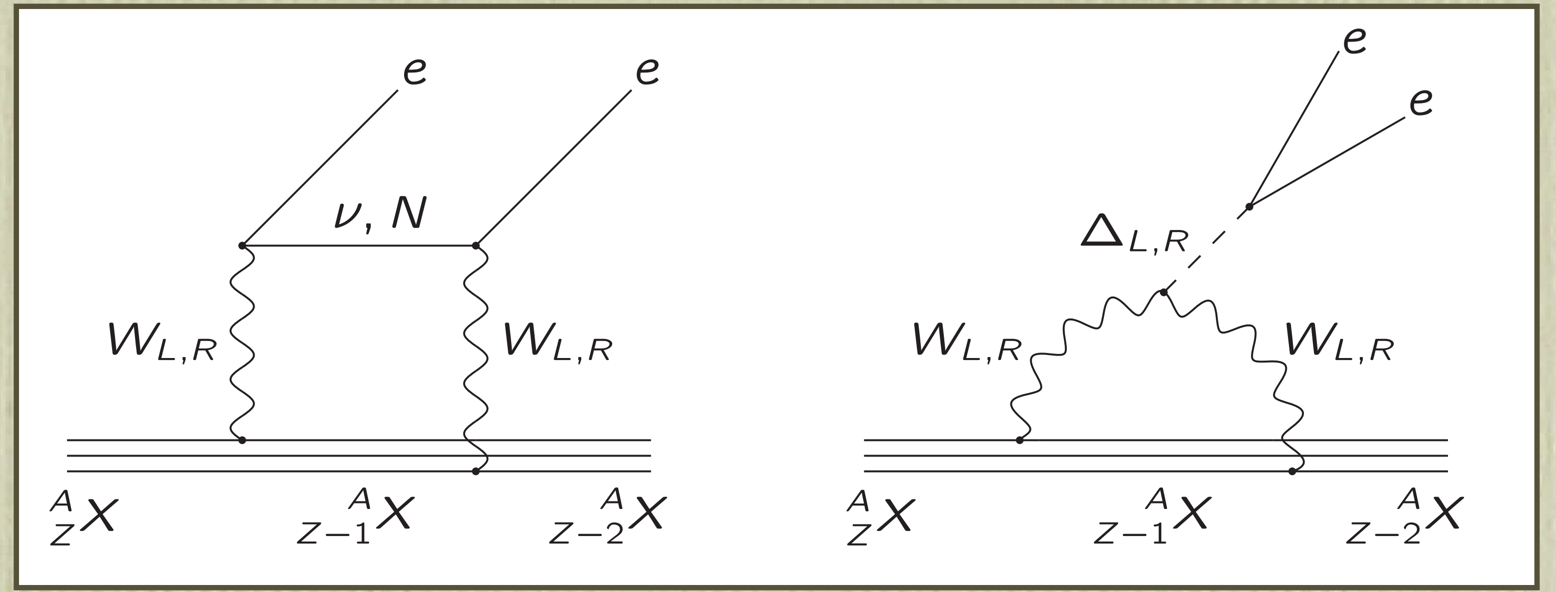
What about W_R?

- Less important for LFV
  - always loop suppressed
  - no log enhancement
  - always the same flavor structure



- Exciting future for mu-e conversion
  - COMET (J-Parc) & Mu2E (Fermilab) $\text{Br}^{\text{exp}}_{\mu-e} < 10^{-16}$
  - Discrimination of the mediator — Cirigliano, Kitano, Okada, Tuzon '09
  - A probe of CP phases — Bajc, MN, Senjanović '09

$0\nu2\beta$: the new contribution



- Tree-level W mixing

$$\sin\xi < 10^{-3}$$

- Dirac mass small

$$m_D \simeq 0$$

$$\mathcal{H}_{\rm NP} = G_F^2 {V_R}_{ej}^2 \left[\frac{1}{m_{N\,j}} + \frac{2\, m_{N\,j}}{m_\Delta^2}\right] \frac{M_W^4}{M_{W_R}^4} J_{R\mu} J_R^\mu \, \overline{e_R} e_R^c$$

- Δ_L contribution suppressed by m_ν / m_Δ^2
- LFV safety requires $m_N / m_\Delta < 1$
- In Type II: $V_R = {V_L}^* = V_{PMNS}^*$

Double beta rate

$$\frac{\Gamma_{0\nu\beta\beta}}{\ln 2} = G \cdot \left|\frac{\mathcal{M}_\nu}{m_e}\right|^2 \left(|m_\nu{}^{ee}|^2 + \left| p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_R{}^2_{ej}}{m_{N\,j}} \right|^2 \right)$$

$|m_\nu{}^{ee}| \simeq 0.1\,\mathrm{eV}$ ⟺ **comparable** ⟺ $M_{W_R} = 3.5\ \mathrm{TeV}$, $m_N = 100\,\mathrm{GeV}$

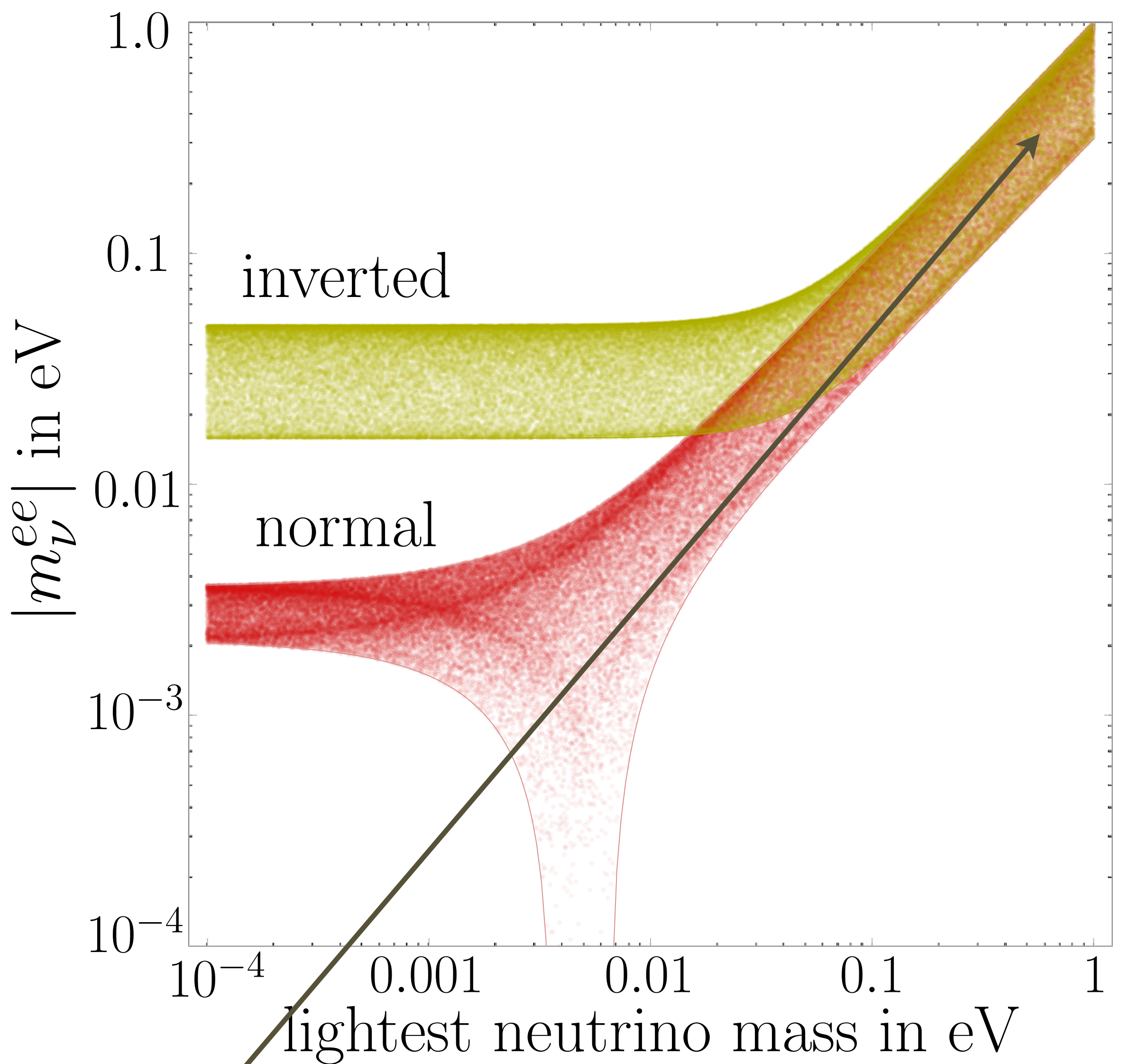
	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe	^{150}Nd
$G\lvert\mathcal{M}_\nu\rvert^2 \times 10^{13}\,\mathrm{yr}$	1.1	4.3	2.0	5.3	1.2	75.6
p MeV	190	186	189	180	280	210
$G\lvert\mathcal{M}_\nu\rvert^2 \times 10^{13}\,\mathrm{yr}$	2.7	–	15.2	12.2	–	–
p MeV	184	–	193	198	–	–

- Phase space factor G, nuclear matrix element $\mathcal{M}_\nu$
- p a measure of neutrino virtuality

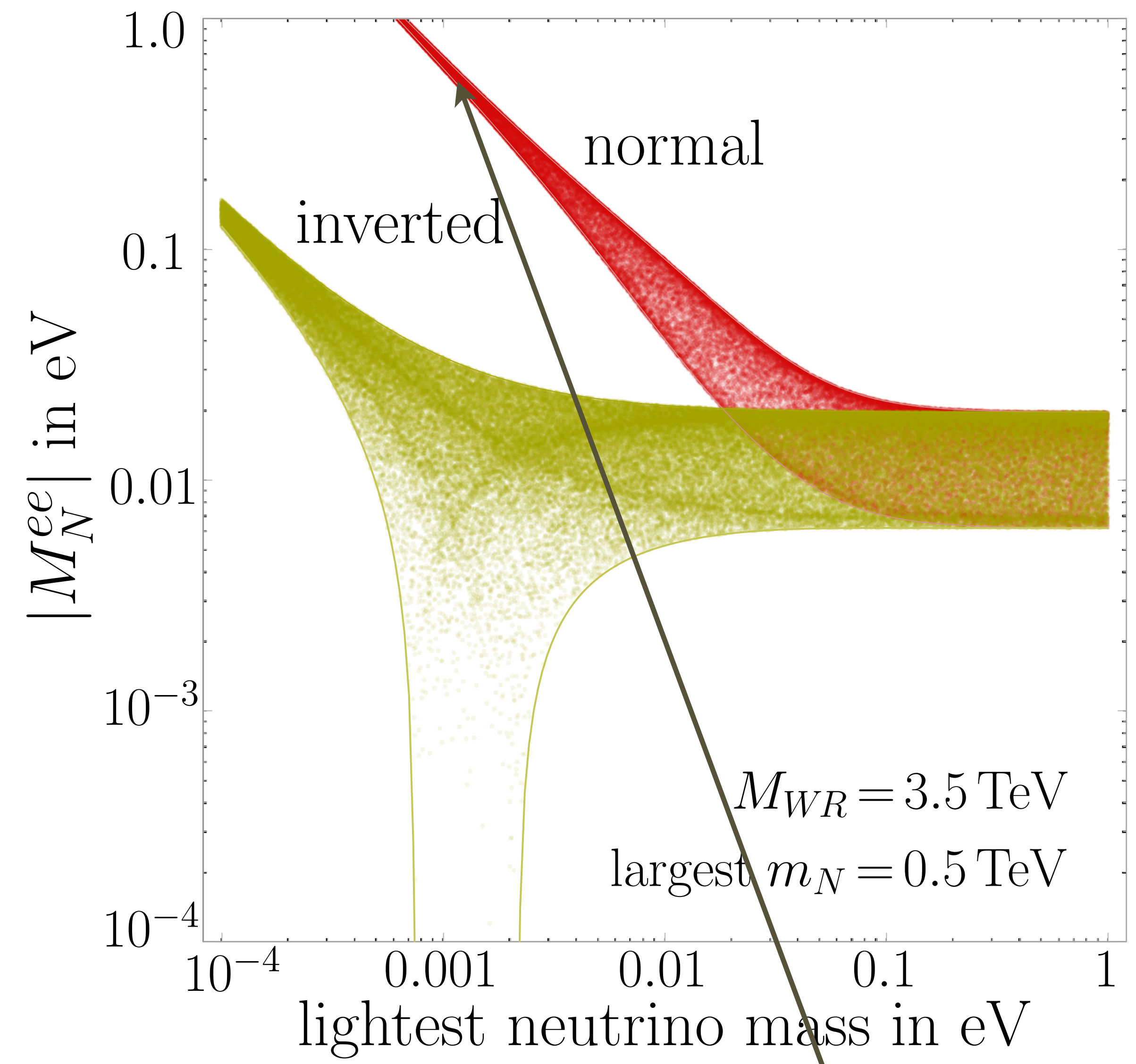
Hirsch et al. '96
Šimkovic et al. '10

Standard vs. New Physics

Neutrino mass mechanism



Left Right



$\propto m_\nu$

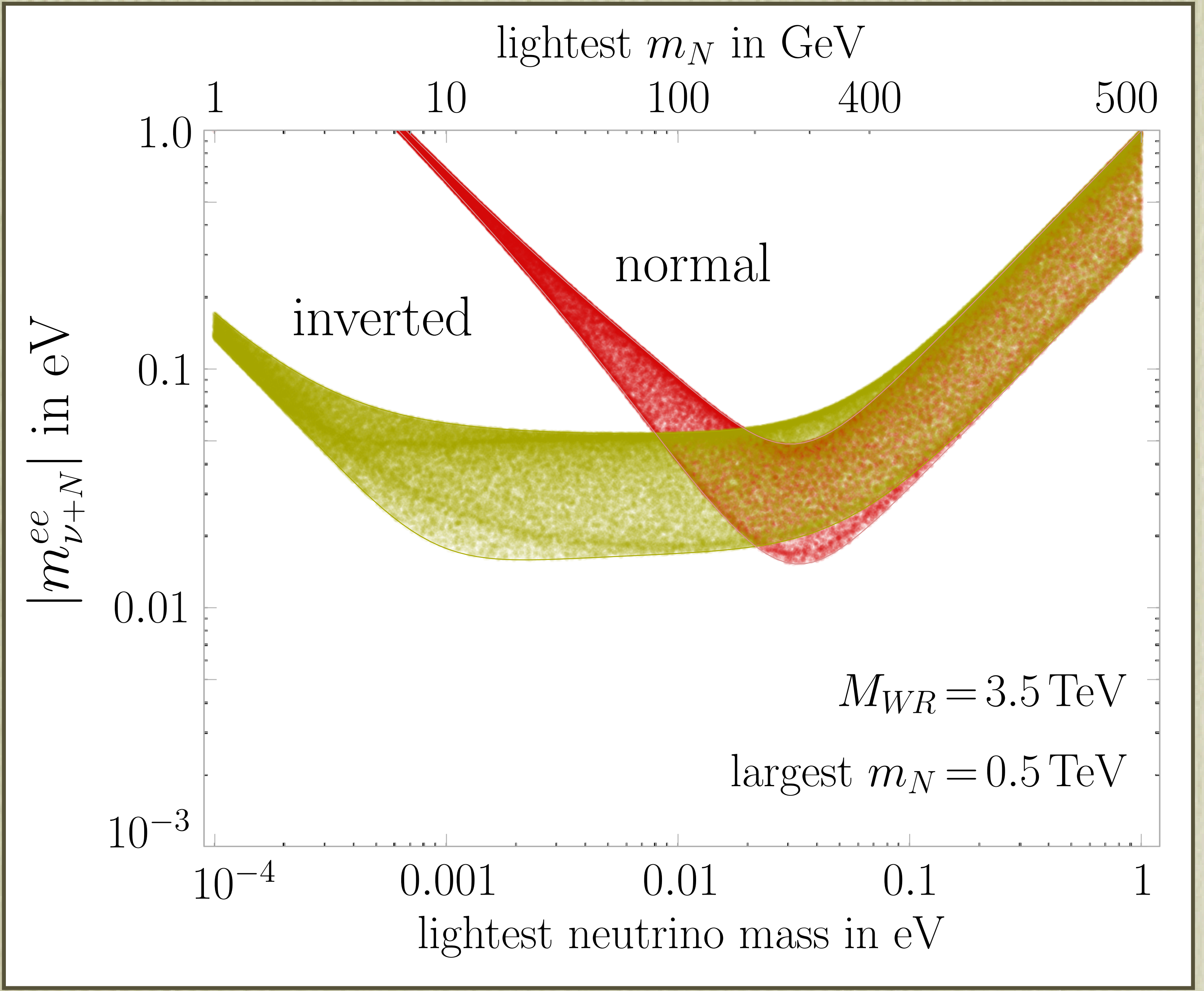
$$M_N{}^{ee} = p^2 \frac{M_W^4}{M_{W_R}^4} \frac{V_L{}^2_{ej}}{m_{Nj}}$$

$\propto 1/m_N$

Tello, MN, Nesti, Senjanović, Vissani '10

$0\nu 2\beta$: the total rate

★ LHC accessible regime



$$|m_{\nu+N}{}^{ee}|^2 \equiv |m_\nu{}^{ee}|^2 + |M_N{}^{ee}|^2$$

- Interference small
- Reversed role of hierarchies
- No tension with cosmology
- A light m_N

★ No cancellations (if type II)

A place for a heavy fermion

- Suppose NP is a must for $0\nu2\beta$. What does this imply for m_N ?
- For illustration $\theta_{13} \simeq 0$ and $\alpha \equiv 2(\varphi_2 - \varphi_1)$

$$|M_{\nu+N}{}^{ee}|^2 = |m_{\nu_1}\cos^2\theta_{12} + m_{\nu_2}e^{i\alpha}\sin^2\theta_{12}|^2 + \left|p^2\frac{M_W^4}{M_{W_R}^4}\left(\frac{1}{m_{N_1}}\cos^2\theta_{12} + \frac{1}{m_{N_2}}e^{i\alpha}\sin^2\theta_{12}\right)\right|^2$$

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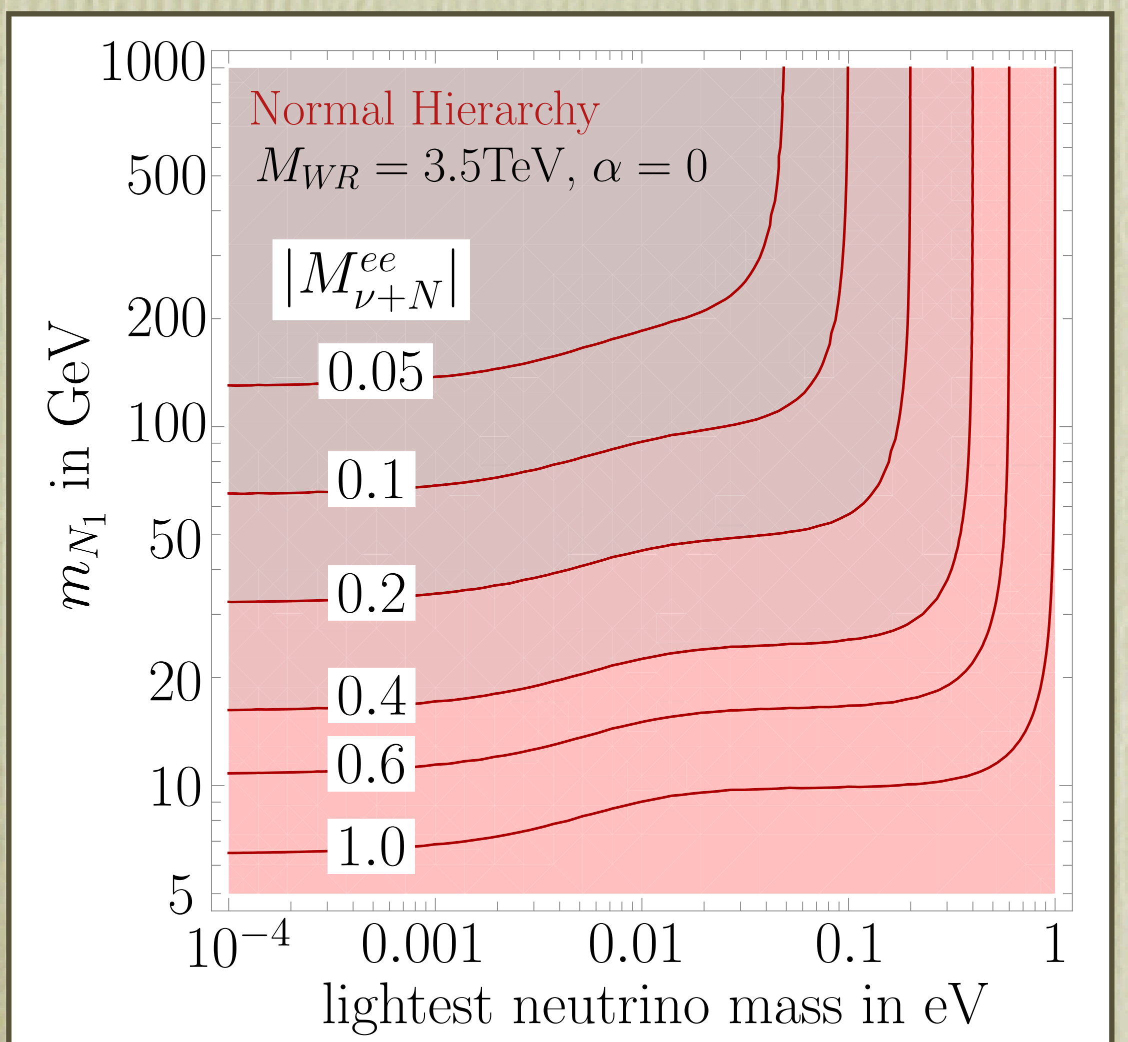

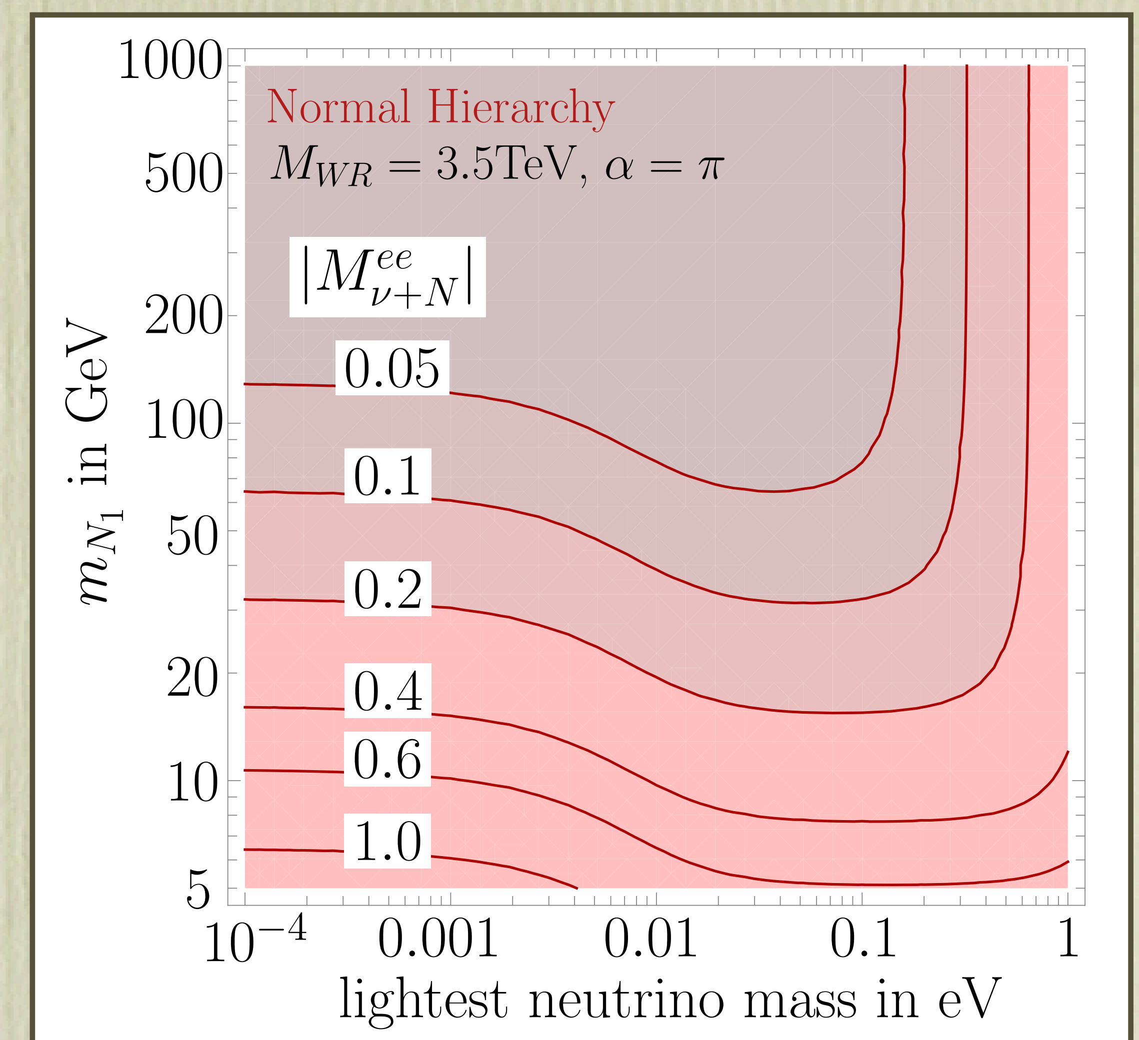

★ LHC range

$jj : m_N \gtrsim 50$ GeV

$j\ell : m_N \gtrsim 20$ GeV

$\not{j} : m_N \lesssim 20$ GeV

$\not{E} : m_N \lesssim 3 - 7$ GeV

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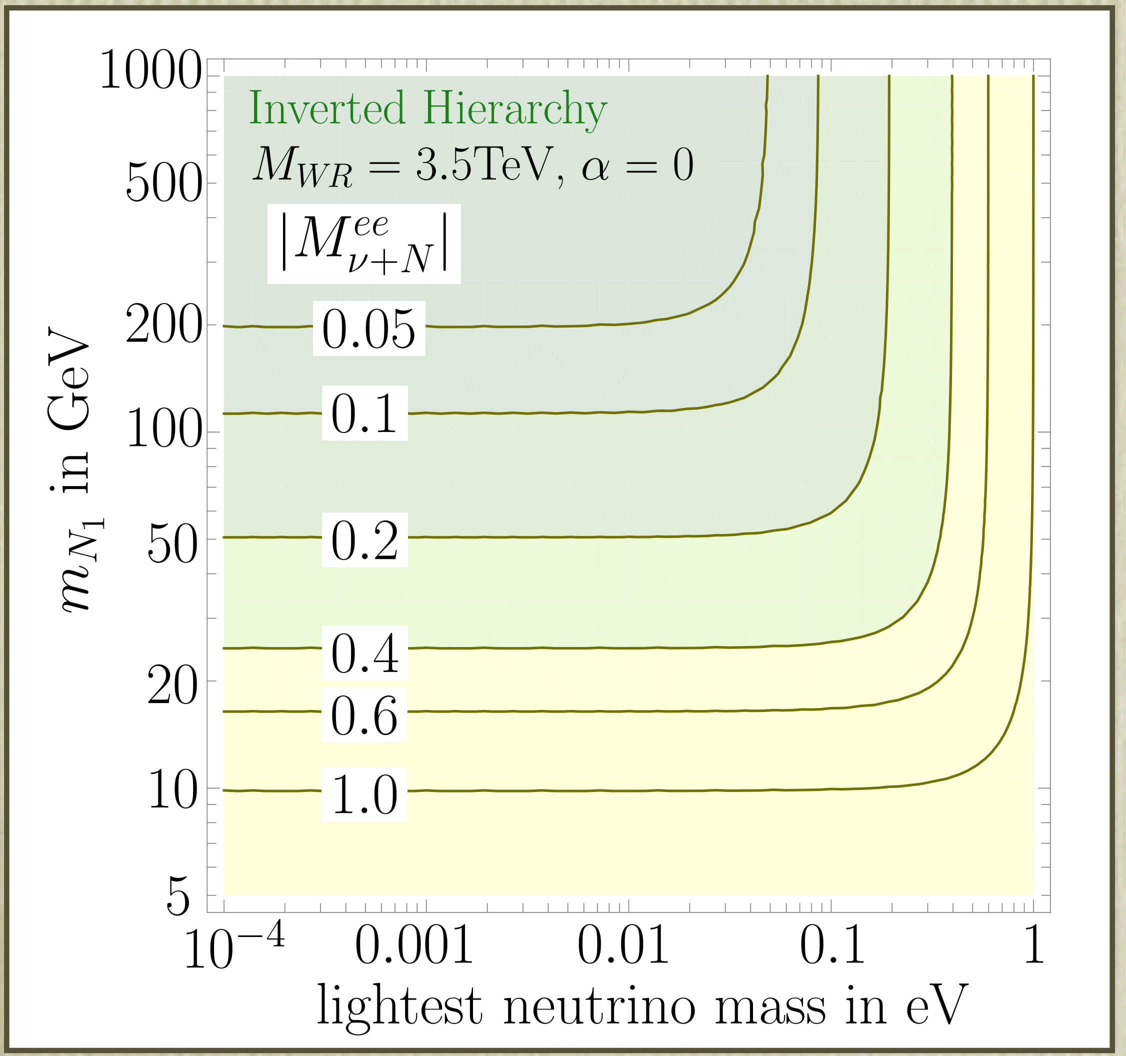

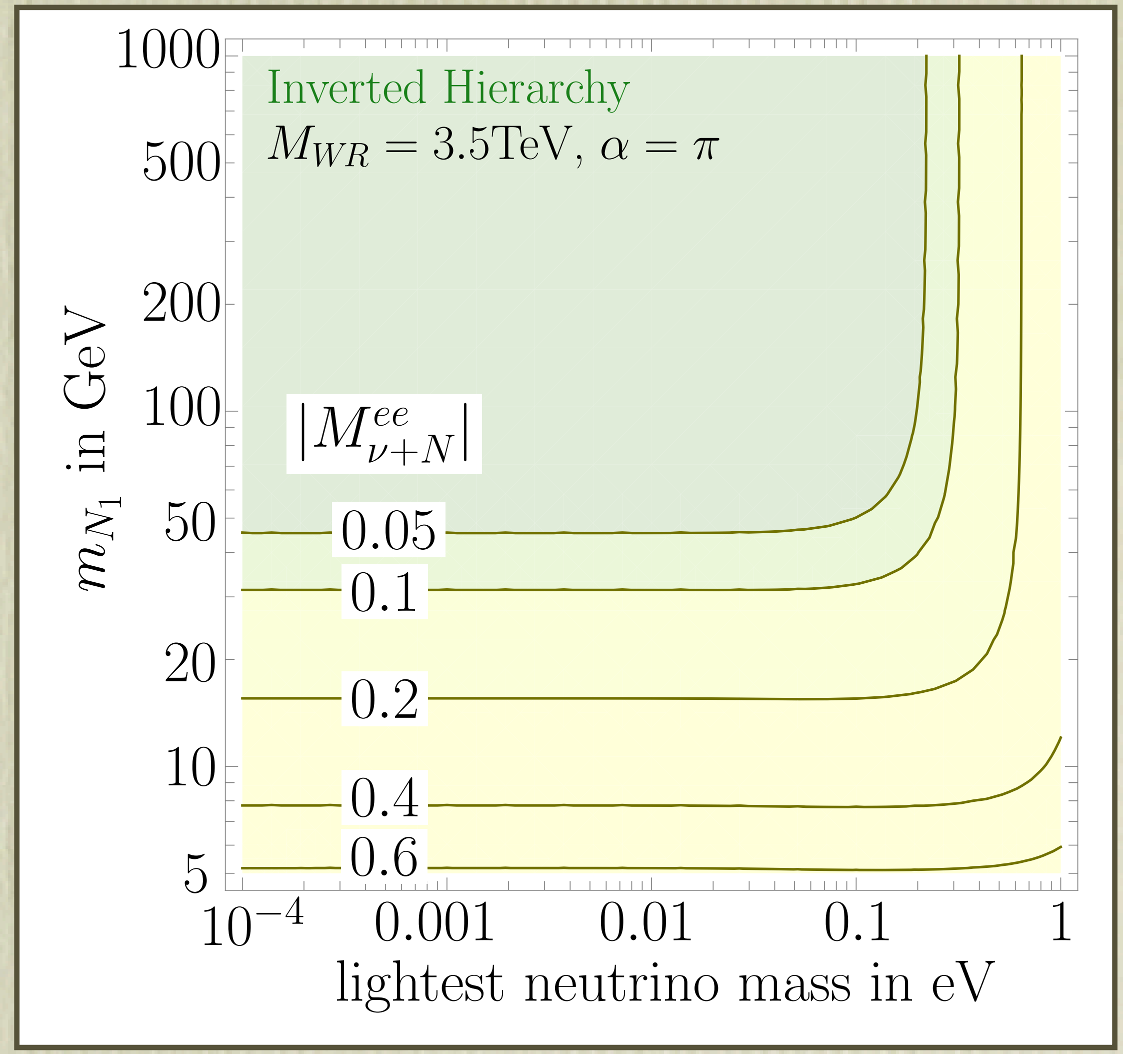

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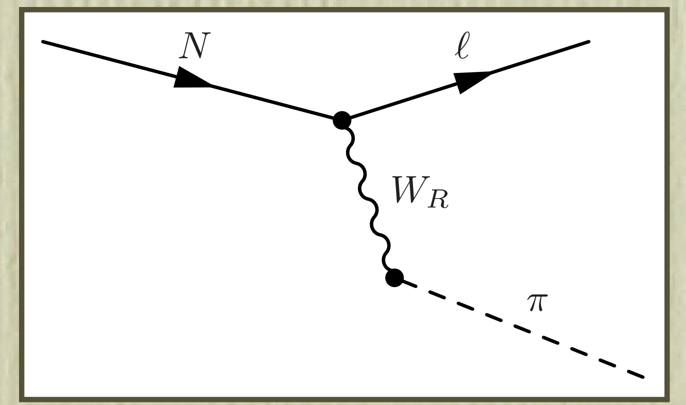
How light can N be?

- A light N decays quite fast



$$\Gamma_{N\to\ell\pi} \simeq 100 \left(\frac{M_W}{M_{W_R}}\right)^4 \frac{f_\pi^2 \, {m_N}^3}{m_\mu^5} |V_{L\,eN}|^2 \Gamma_\mu$$

$$\tau_N \ll \text{sec}$$

- $m_N < m_\pi$ problematic for BBN. A way out?

$$\Gamma_{N\to e\bar{e}\nu} = \Gamma_\mu \, (m_N/m_\mu)^5 \sin^2\xi$$

★ Too small

- What about $m_D \neq 0$? $U_{\nu N}^2 \simeq m_D^2/{m_N}^2 \simeq \dfrac{m_\nu}{m_N}$
  - All too small, unless fine-tuned
  - only a "contrived" scenario ${m_N}^{\text{lightest}} \simeq m_{\Delta_R^0} \simeq \text{eV}$

★ alternatively...

m_N and BBN

- A hint for light sterile neutrinos from BBN?

Hamann, Hannestad, Raffelt '10

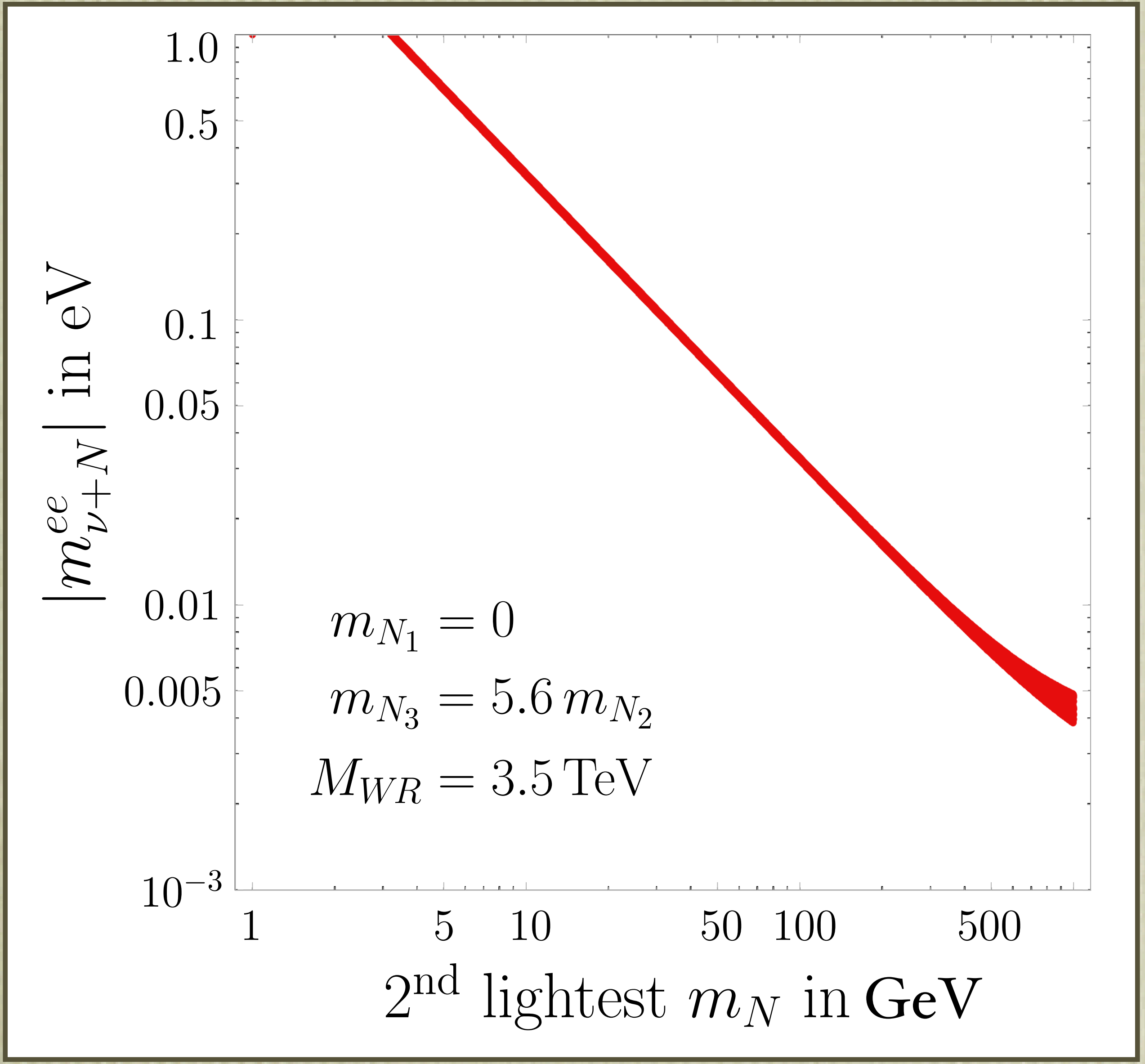
  - light ~eV states welcome during the BBN era
  - 3+1 better than 3+2 better than 3

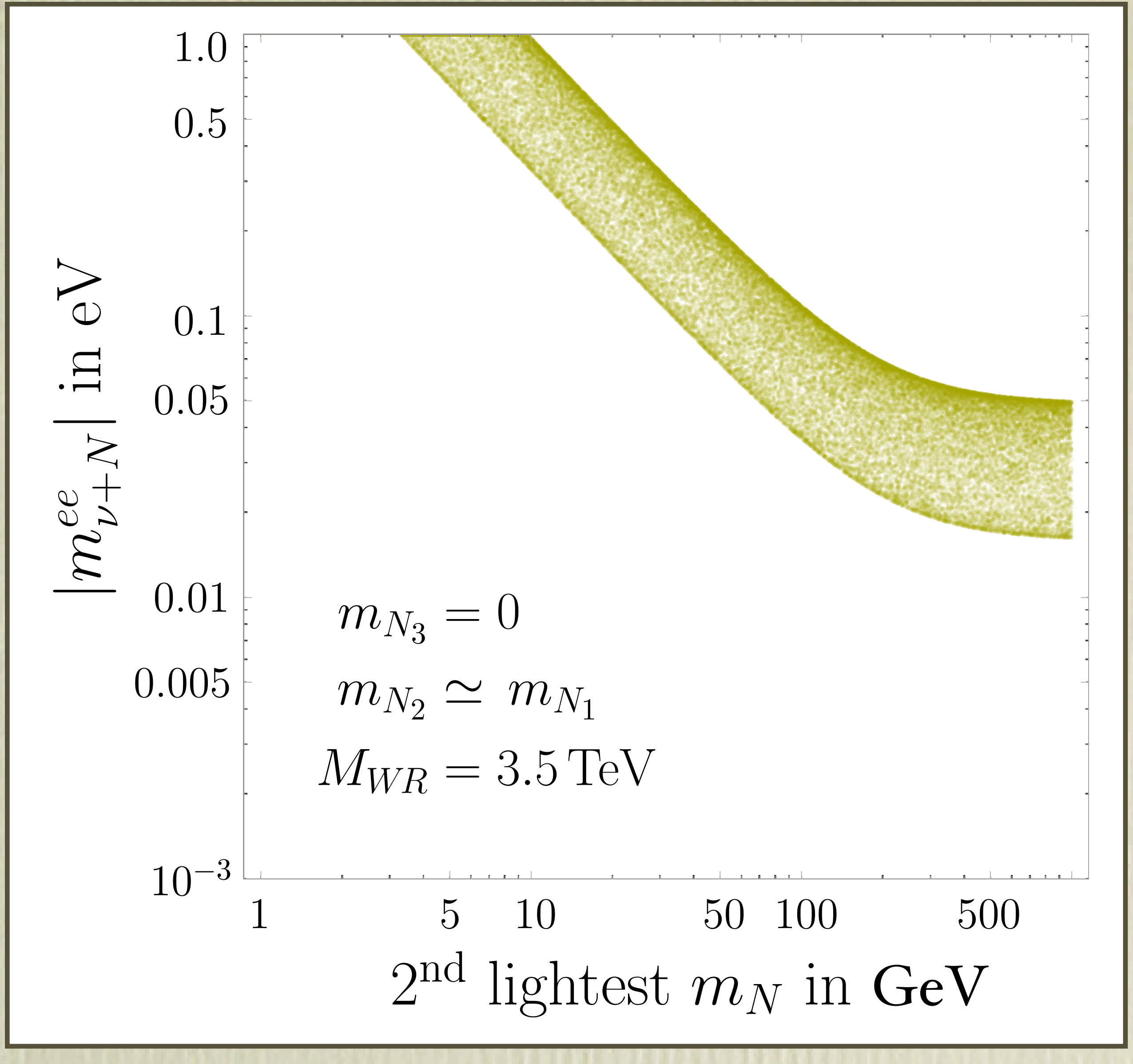
- Perfectly ok if $m_N \approx \text{eV}$ and stable. However...
  - Type II: $m_N \propto m_\nu$
    $m_N{}^{\text{min}} \simeq 0 \Rightarrow m_\nu{}^{\text{min}} \simeq 0$
  - only one light sterile neutrino!
  - the ratio between the others fixed!

NH(IH):
$m_N{}^{\text{max}}/m_N{}^{\text{min}} \simeq 6(1)$

★ Cross check at LHC

BBN and $0\nu2\beta$





★ A positive signal

$|{m_{\nu+N}}^{ee}| \approx 0.1 - 1\,\text{eV}$

★ LHC ballpark

${m_N}^{\text{mid}} \in 5 - 100\,\text{GeV}$

Conclusions

- A signal of $0\nu2\beta$ may require new physics at O(TeV)
- Left-right symmetry a natural candidate
  - explains the signal without tensions
  - provides additional cross-checks (LHC & LFV)
- Alternatively, the LHC is able to shed light on
  - the $0\nu2\beta$ rate
  - LFV transitions (remember also mu-e conversion)
- A light -sterile state may improve BBN

Outlook

- General case; Dirac mass and type I+II

hep-ph

- Right-handed triplet contribution
- A detailed LHC flavor study
- LHC data is already here

hep-ex

- Gerda, Cuore, etc. results
- A hint from LFV? (MEG, Mu2E, COMET)

Thank you

Neutrino Data

Figure 2.4: *Possible neutrino spectra: (a) normal (b) inverted.*

$\Delta m^2_{21} [10^{-5}\mathrm{eV}^2]$	7.6
$\vert\Delta m^2_{31}\vert [10^{-3}\mathrm{eV}^2]$	2.4
$\sin^2\theta_{12}$	0.32
$\sin^2\theta_{23}$	0.50
$\sin^2\theta_{13}$	0.007

Schwetz '09

Mass spectrum, type II