

# 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...

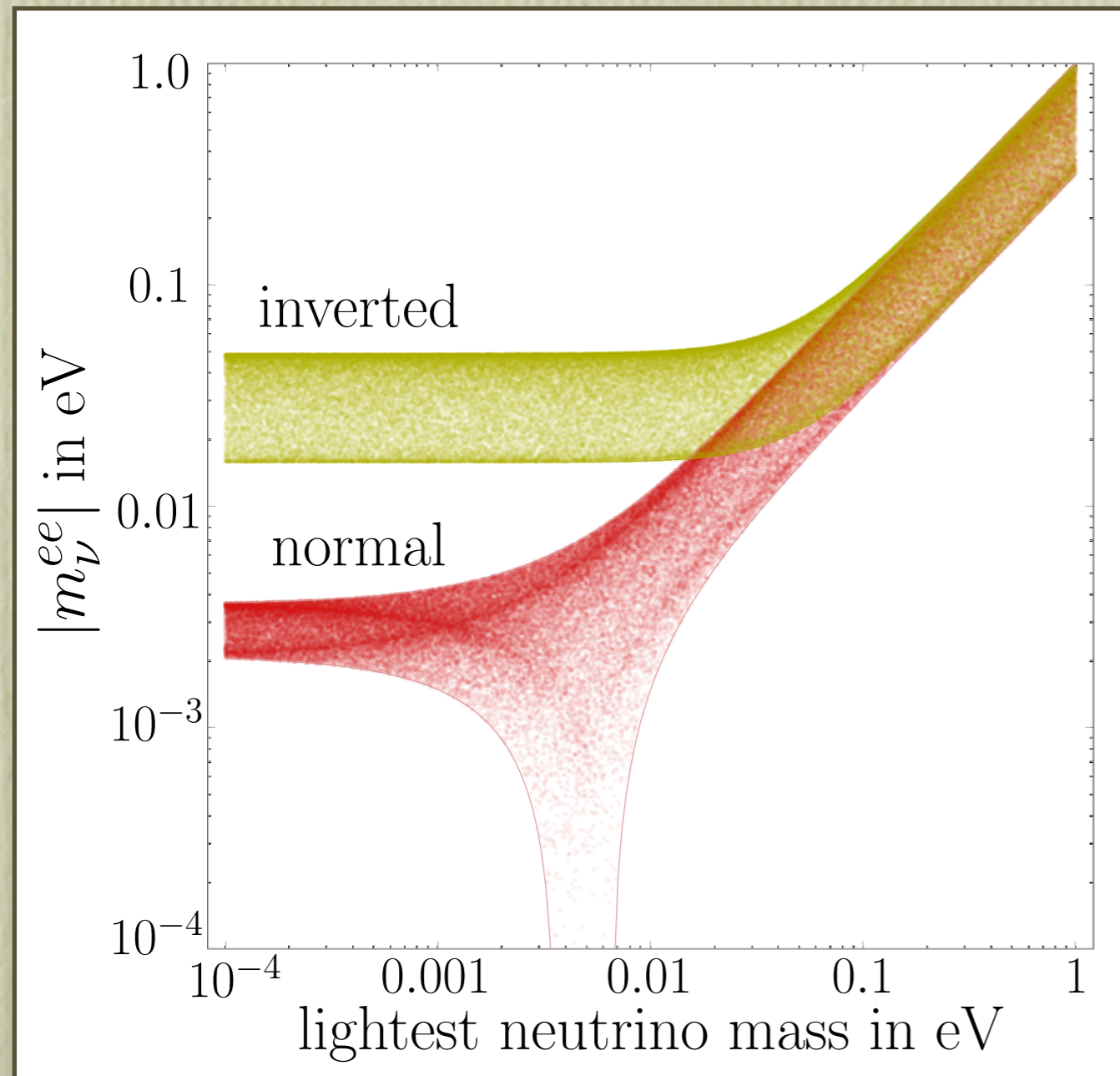
# $0\nu 2\beta$ and cosmology

- Neutrinos are massive

SuperKamiokande '98

textbook source of  $0\nu 2\beta$

Vissani '99



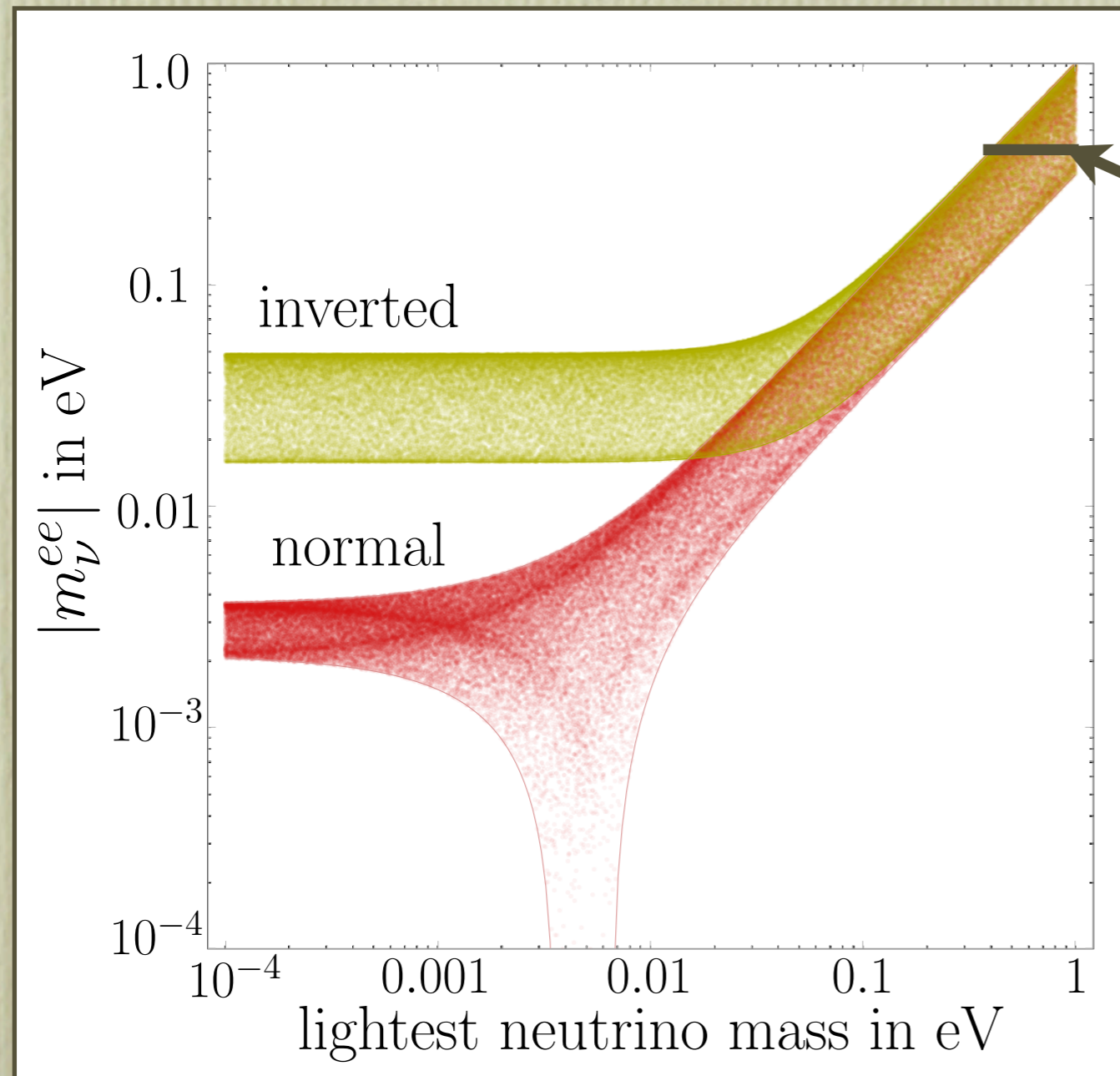
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- ★ Claim of observation

Klapdor-Kleingrothaus '04 & '06

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

- ★ Upcoming experiments

GERDA, CUORE,  
NEMO<sub>3</sub>, SuperNEMO, etc.

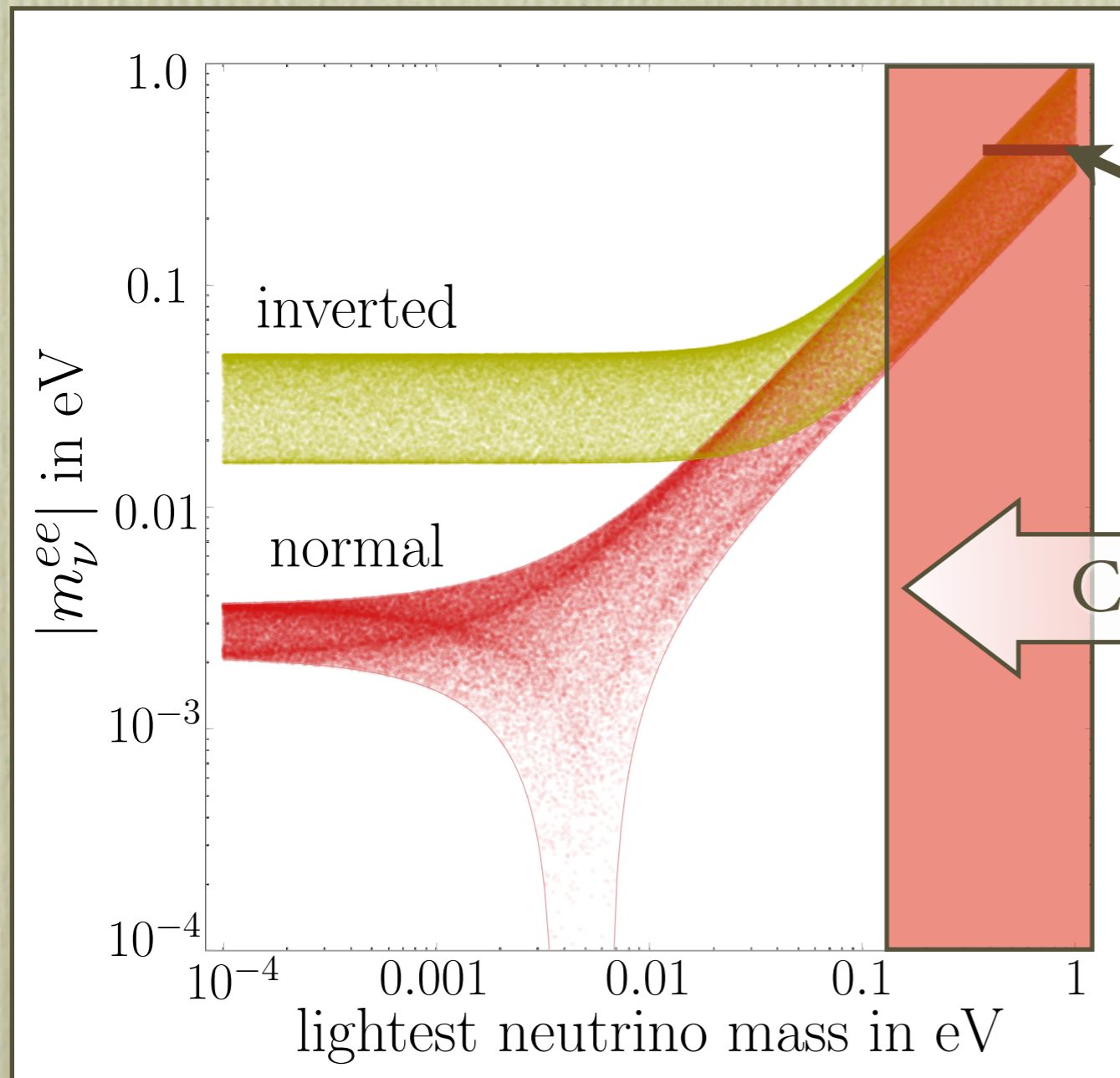
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$$|m_{\nu}^{ee}| \simeq 0.4 \text{ eV}$$

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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

Minkowski '77  
Senjanović '79  
Senjanović Mohapatra '80

- gives neutrino mass

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

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

See talk by [Nesti](#)



# 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

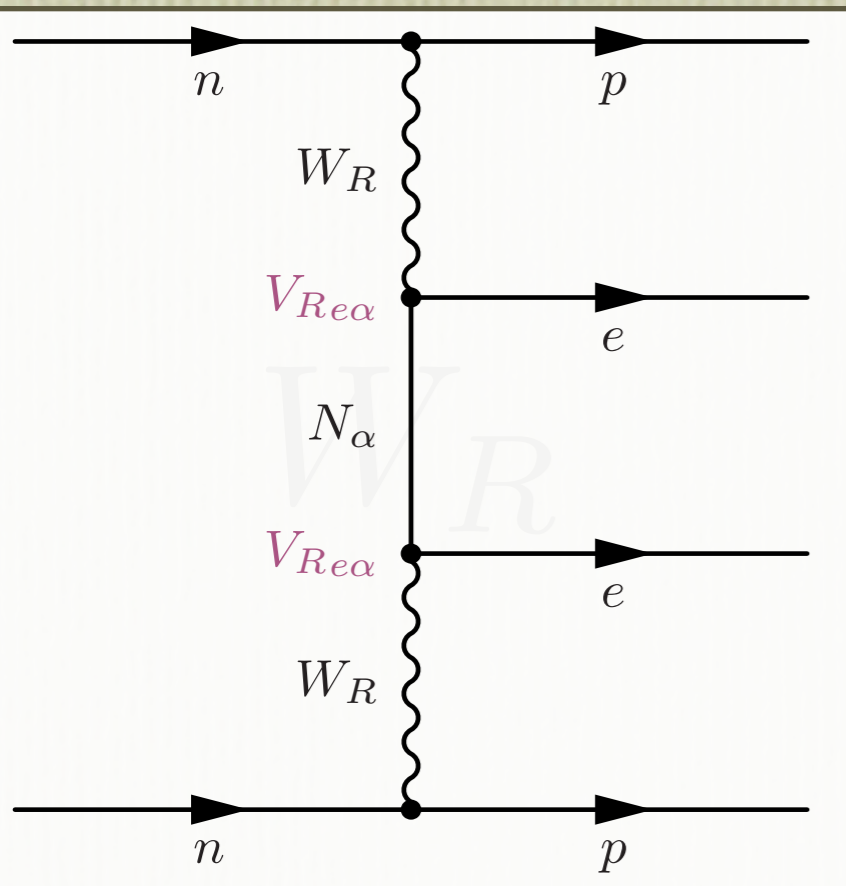
$$W_R$$

$$\Delta_L$$

$$\Delta_R$$

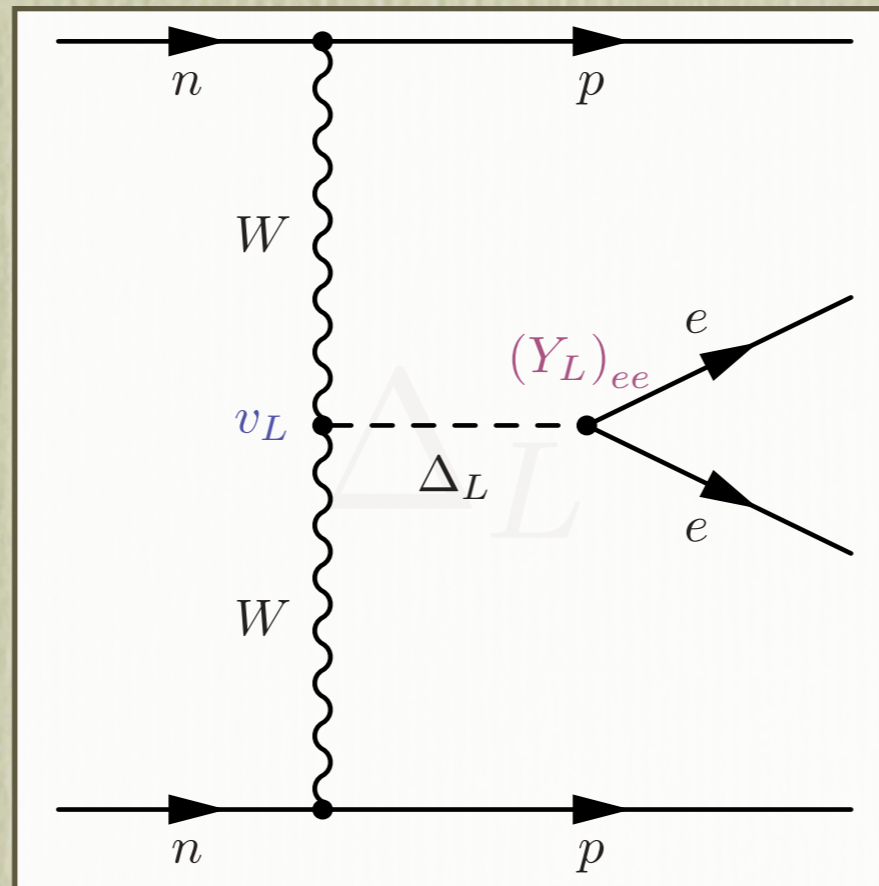
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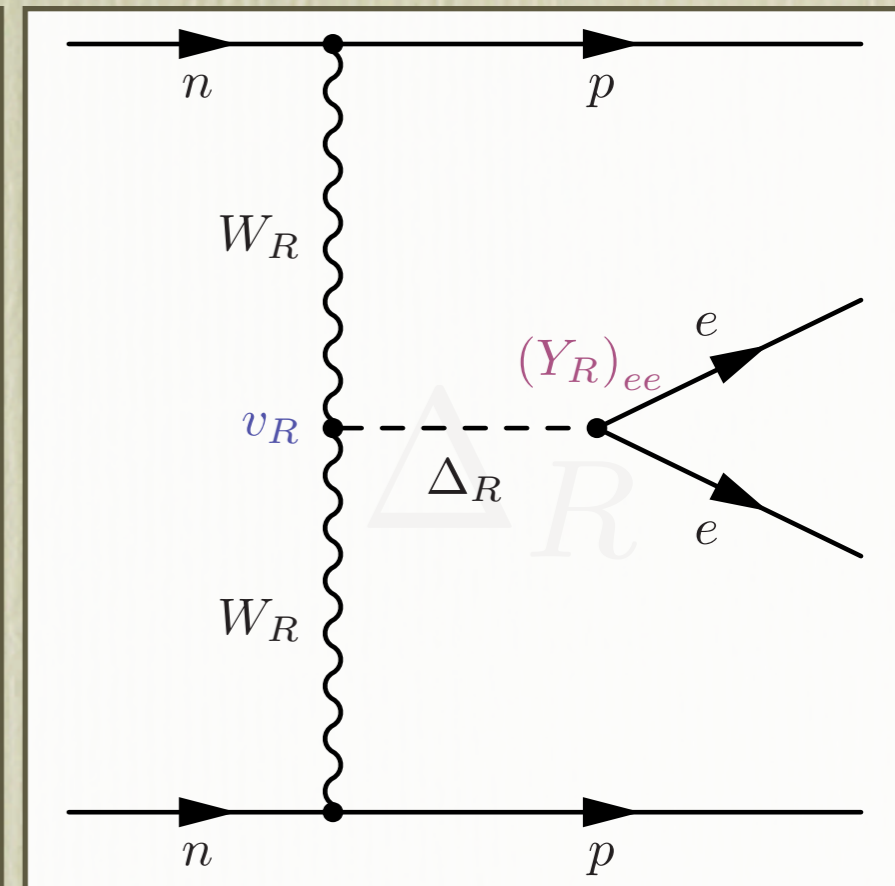
$$\propto 1/m_N$$

★ Large?



$$\propto m_\nu$$

★ Tiny



$$\propto m_N$$

★ Subdominant?

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

# Mass spectra

- Yukawa couplings: **Dirac** and **Majorana** terms

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

★ Dirac masses

★ Two sources of seesaw

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

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

- 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

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

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

$$\frac{m_{N_2}^2 - m_{N_1}^2}{m_{N_3}^2 - m_{N_1}^2} = \frac{m_{\nu_2}^2 - m_{\nu_1}^2}{m_{\nu_3}^2 - m_{\nu_1}^2} \simeq \pm 0.03 \quad \star \text{Hierarchy probe @ LHC}$$

$$m_{\text{cosm}} = \sqrt{\Delta m_A^2} \frac{\sum_i m_{N_i}}{\sqrt{|m_{N_3}^2 - m_{N_2}^2|}},$$

★ Cosmology-oscillations-  
LHC interplay

# Interactions

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} (\bar{\nu}_L V_L^\dagger W \ell_L + \bar{\nu}_R V_R^\dagger W_R \ell_R)$$

- Flavour structure fixed:  $V_R = V_L^* = V_{PMNS}^*$

- $m_N$  and  $V_R$  measurable

★ (Same)-sign di-leptons & 2 jets

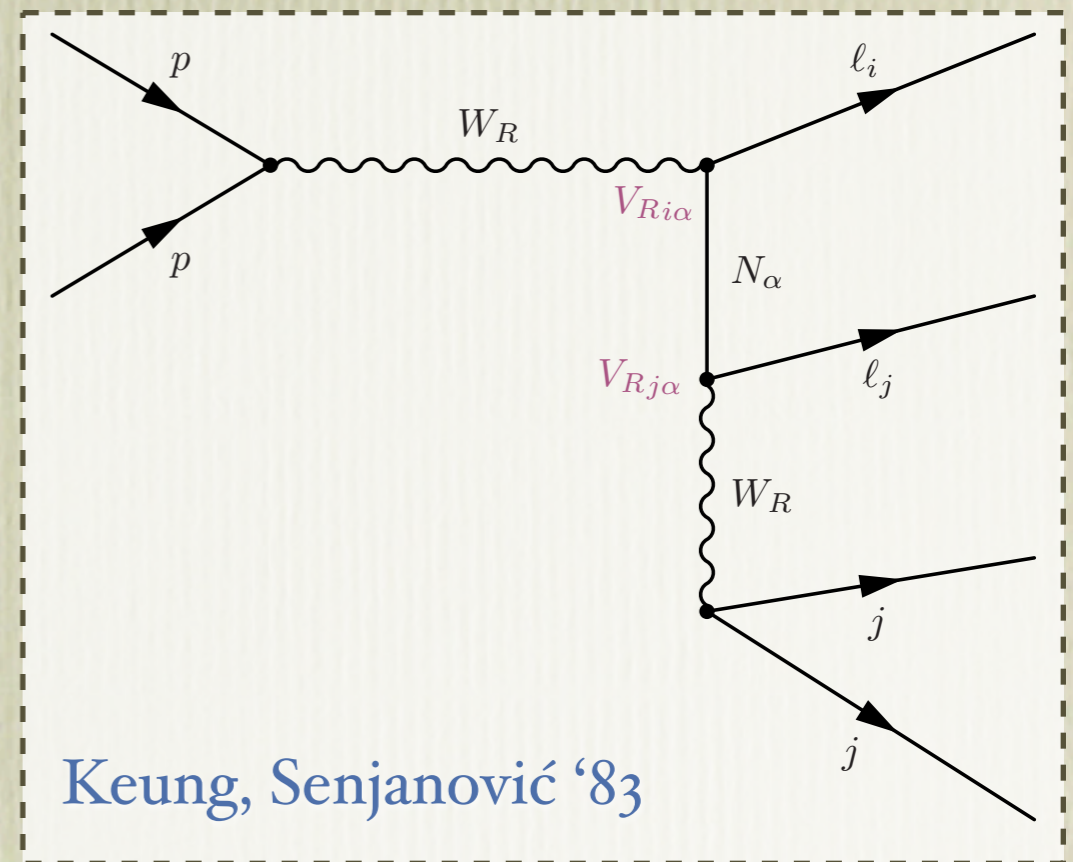
- Doubly charged triplets

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

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

- Same flavour, all fixed in type II

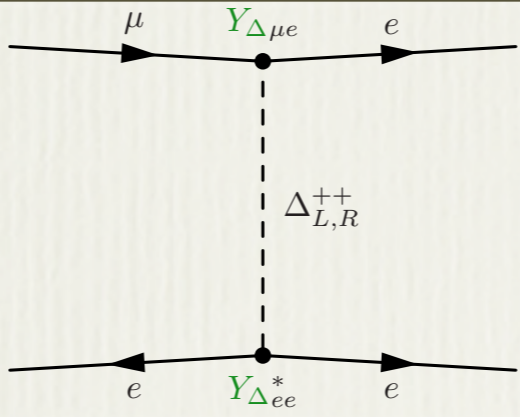
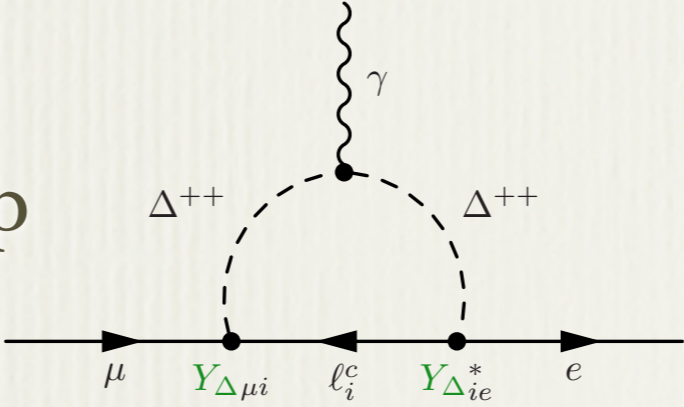
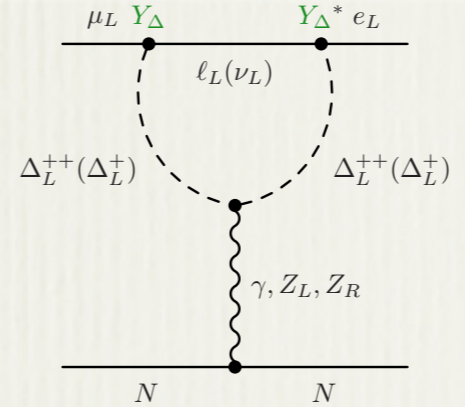
★ Type II only an *example*! The interplay is general.



# Lepton Flavor Violation

Cirigliano et al. '04

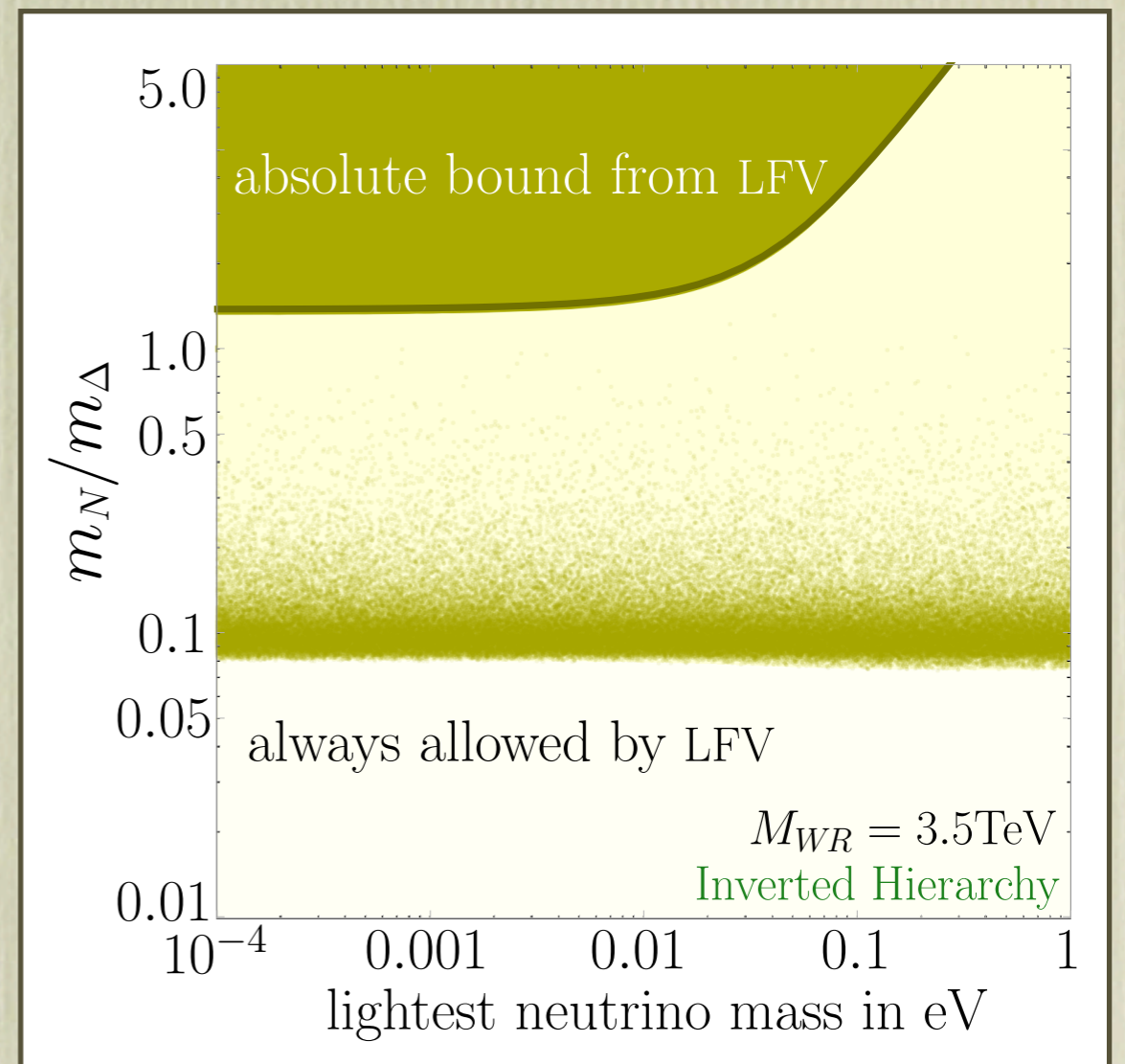
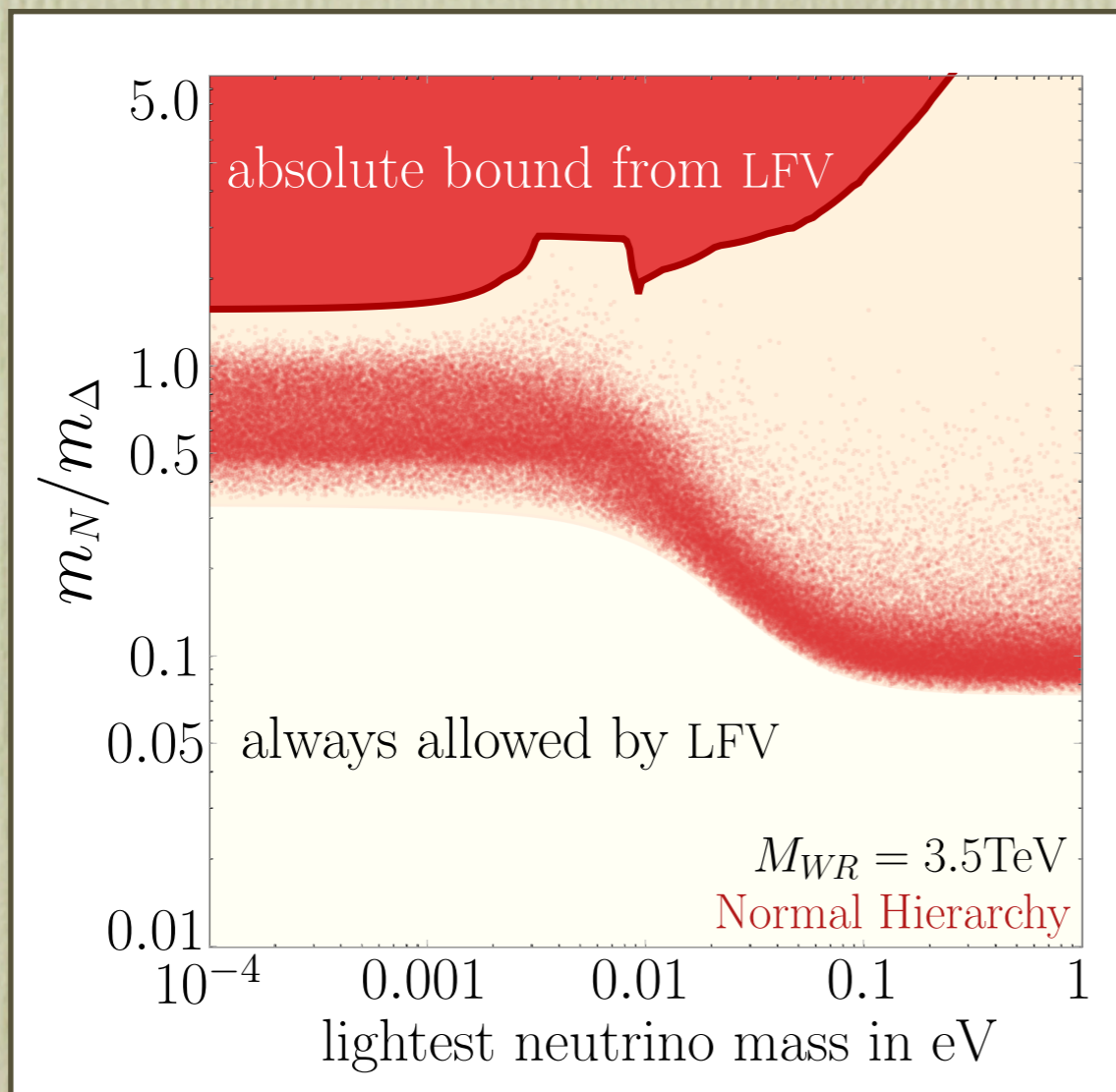
- $\mu$  channel:  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow 3e$ ,  $\mu N - e N$   $\text{Br}_{\mu \rightarrow e}^{\text{exp}} \lesssim 10^{-11}(-12)$
- $\tau$  channel:  $\tau \rightarrow \ell\gamma$ ,  $\tau \rightarrow 3\ell$   $\text{Br}_{\tau \rightarrow \ell}^{\text{exp}} \lesssim 10^{-8}$

$\mu \rightarrow 3e$	<p>tree</p> 	$V_L m_N / m_\Delta V_L^T$
$\mu \rightarrow e\gamma$	<p>loop</p> 	$V_L m_N / m_\Delta V_L^\dagger$
$\mu N \rightarrow e N$	<p><math>\log \frac{m_\Delta^2}{m_\mu^2}</math></p> 	$V_L m_N / m_\Delta V_L^\dagger$

# LFV combined bound

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

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



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

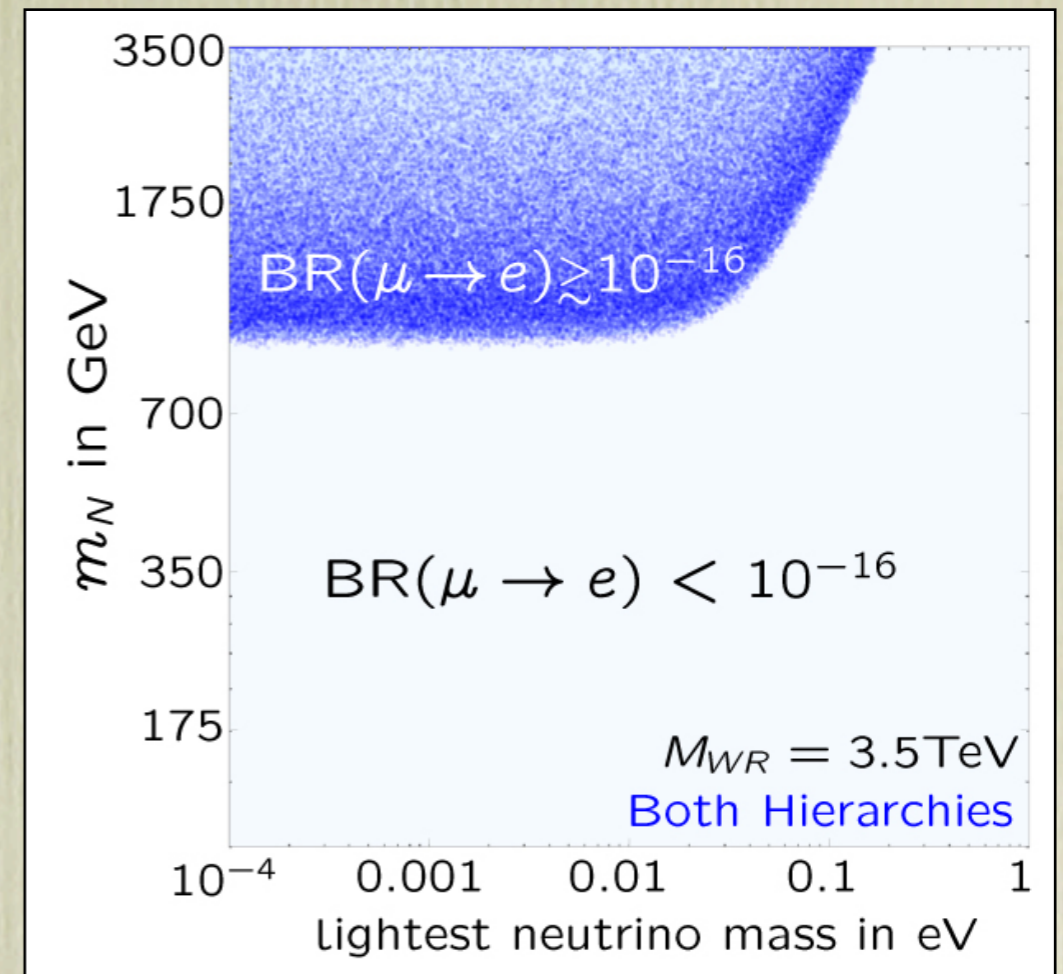
$$\phi_i \in \{0^\circ, 2\pi^\circ\}$$

★ 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)

$$Br_{\mu-e}^{\text{exp}} < 10^{-16}$$

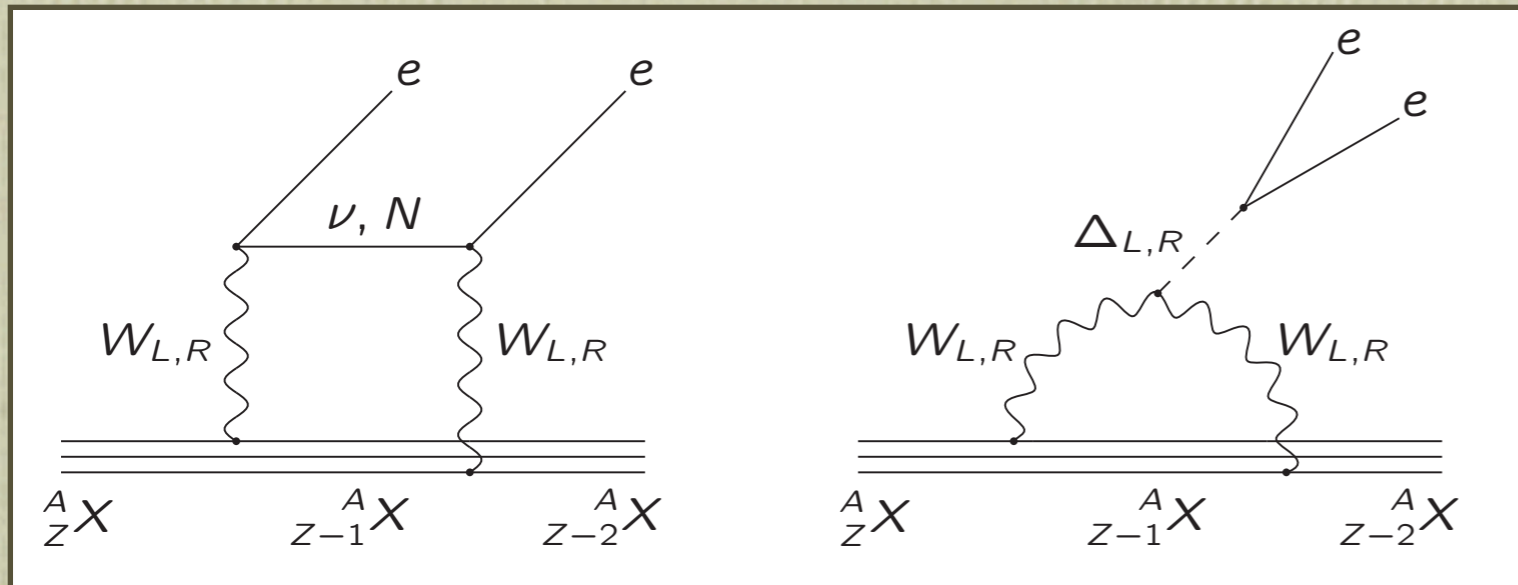
- Discrimination of the mediator

Cirigliano, Kitano, Okada, Tuzon '09

- A probe of CP phases

Bajc, MN, Senjanović '09

# $0\nu 2\beta$ : the new contribution



- Tree-level W mixing

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

- Dirac mass small

$$m_D \simeq 0$$

$$\mathcal{H}_{\text{NP}} = G_F^2 V_R^2 \left[ \frac{1}{m_{Nj}} + \frac{2 m_{Nj}}{m_\Delta^2} \right] \frac{M_W^4}{M_{W_R}^4} J_{R\mu} J_R^\mu \bar{e}_R e_R^c$$

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

# Double beta rate

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

$$|m_\nu^{ee}| \simeq 0.1 \text{ eV}$$



$$M_{W_R} = 3.5 \text{ TeV}$$

$$m_N = 100 \text{ GeV}$$

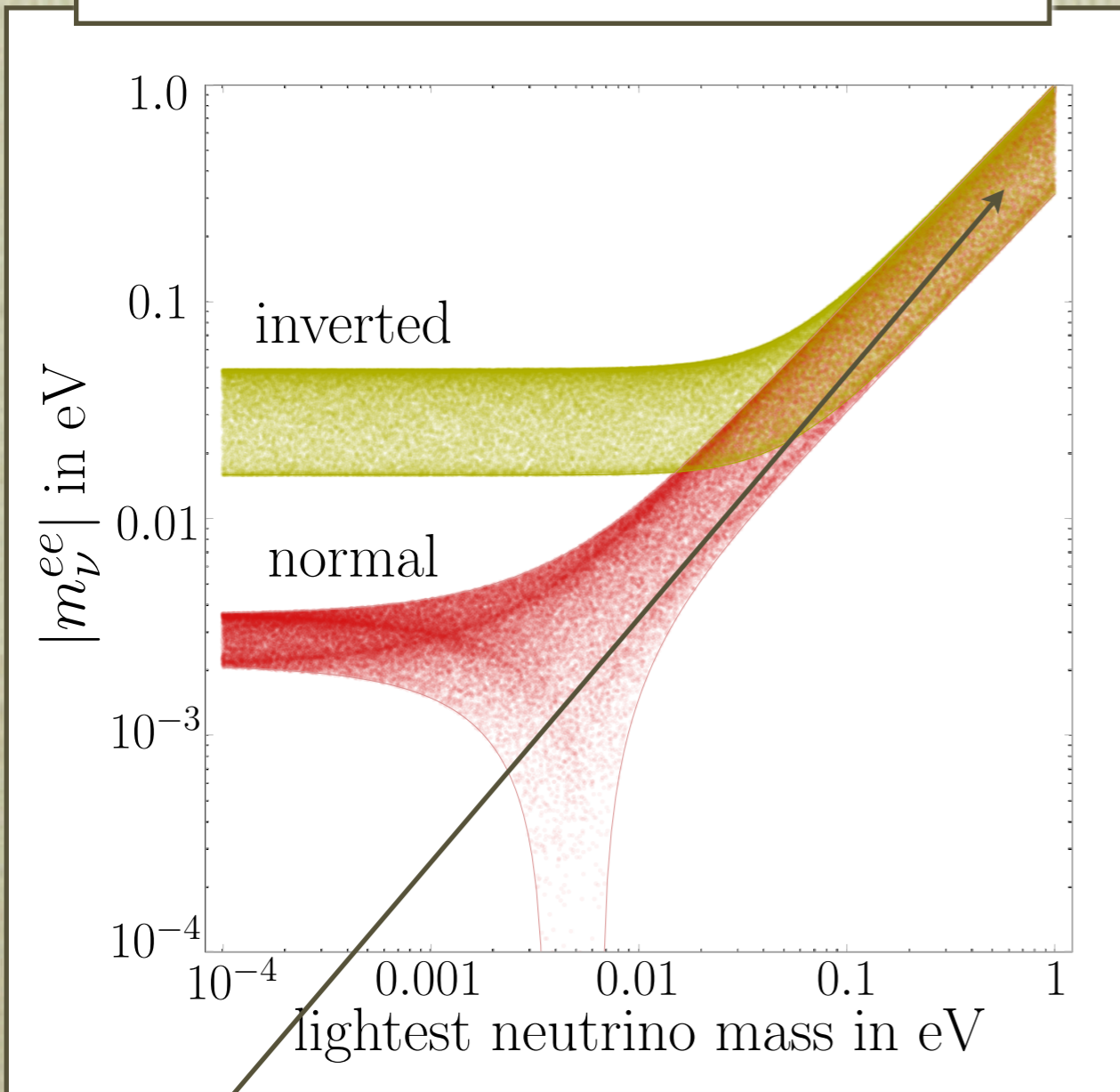
	<sup>76</sup> Ge	<sup>82</sup> Se	<sup>100</sup> Mo	<sup>130</sup> Te	<sup>136</sup> Xe	<sup>150</sup> Nd
$G \mathcal{M}_\nu ^2 \times 10^{13} \text{ yr}$	1.1	4.3	2.0	5.3	1.2	75.6
$p \text{ MeV}$	190	186	189	180	280	210
$G \mathcal{M}_\nu ^2 \times 10^{13} \text{ yr}$	2.7	—	15.2	12.2	—	—
$p \text{ MeV}$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

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

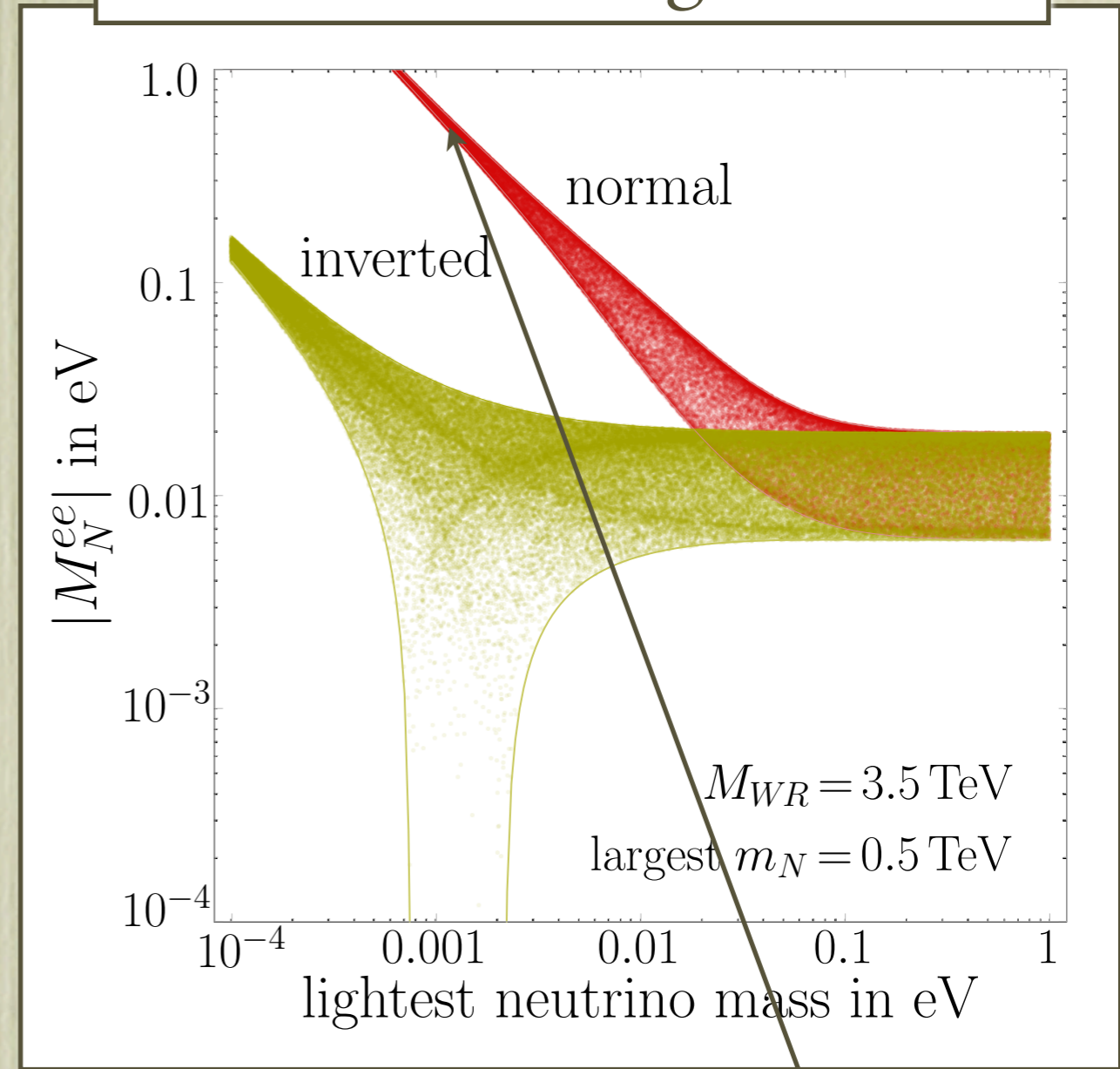
Hirsch et al. '96  
Šimkovic et al. '10

# Standard vs. New Physics

Neutrino mass mechanism



Left Right



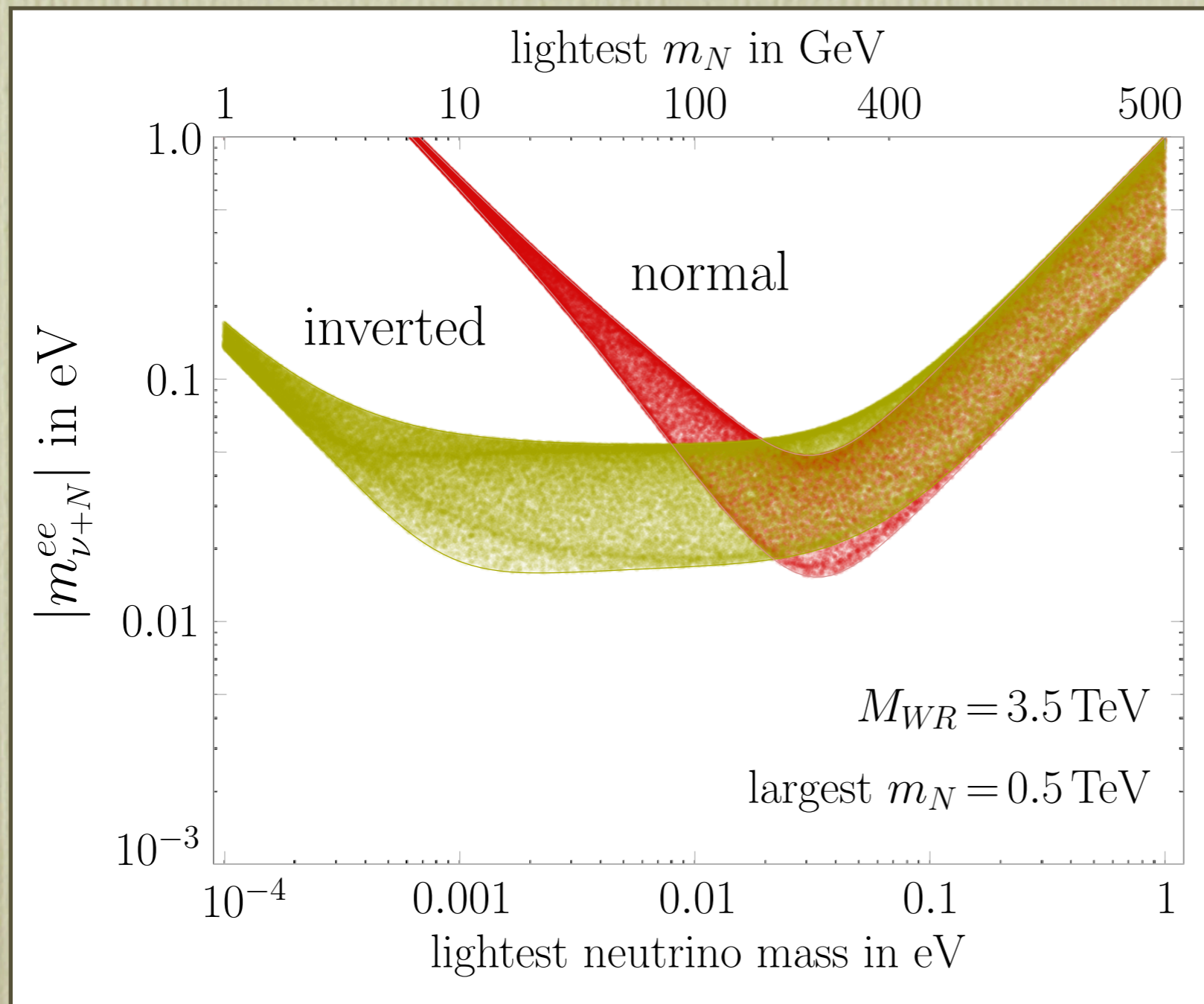
$$\propto m_\nu$$

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

$$\propto 1/m_N$$

# $0\nu 2\beta$ : 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)

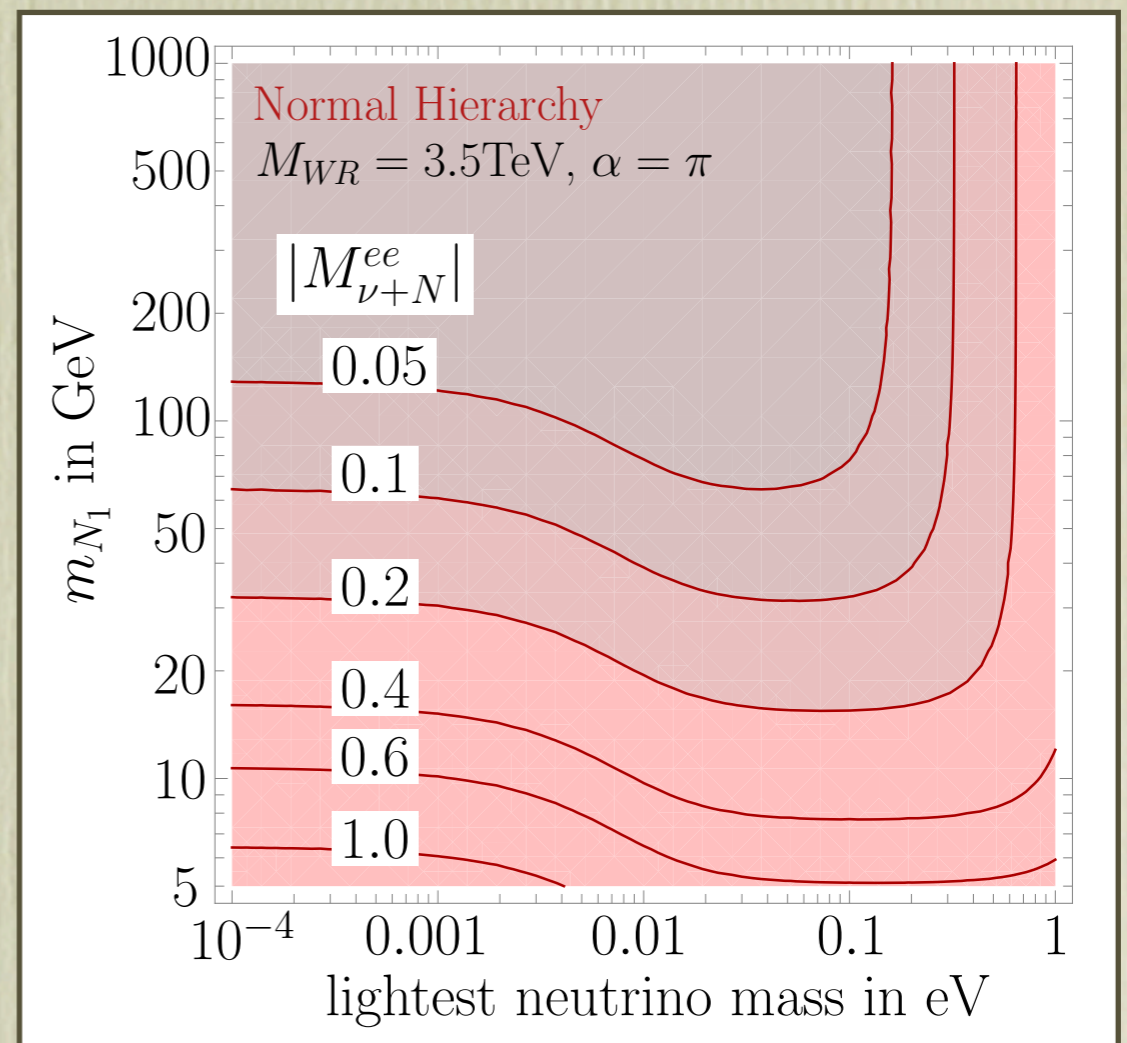
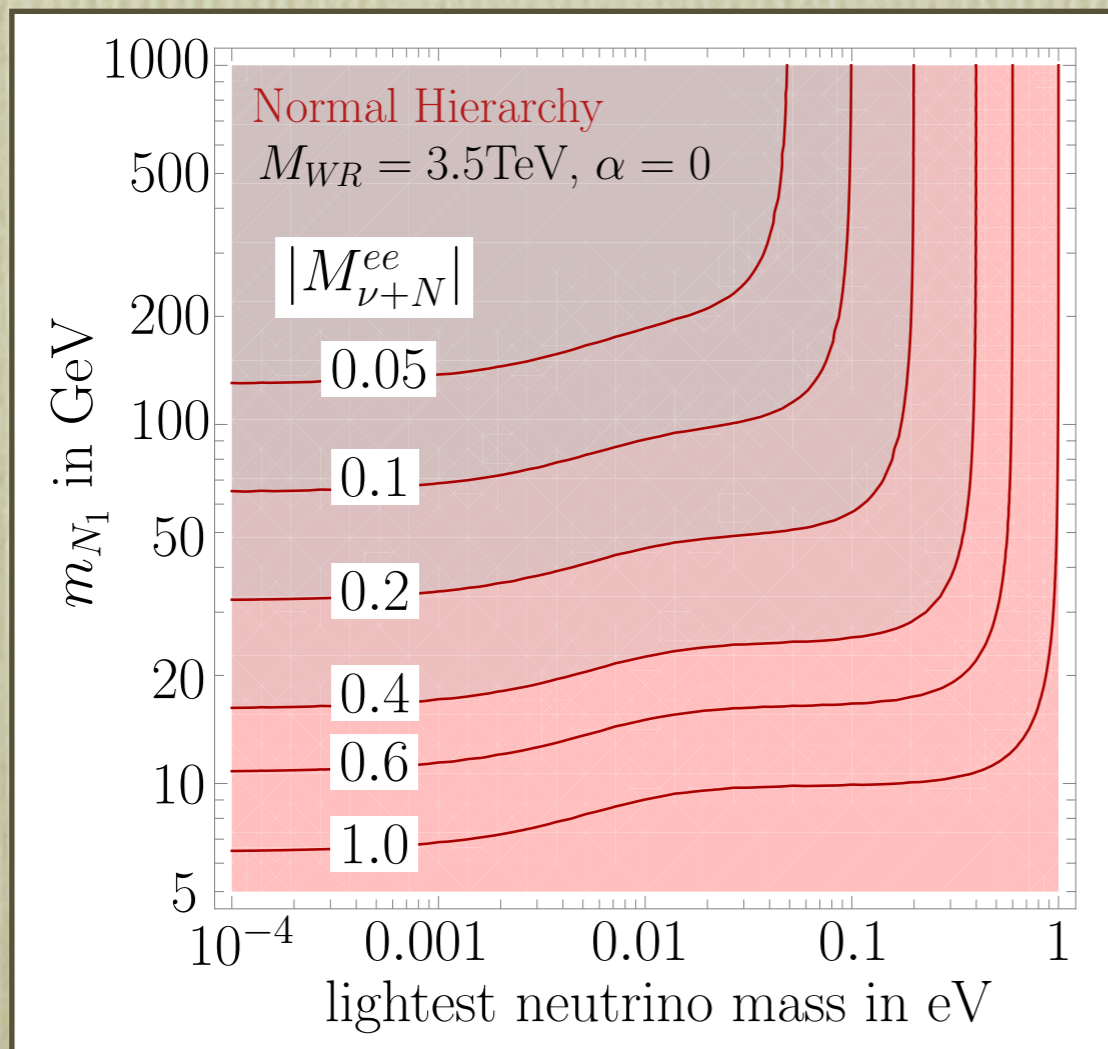
# A place for a heavy fermion

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

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

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★ LHC range

$jj : m_N \gtrsim 50 \text{ GeV}$

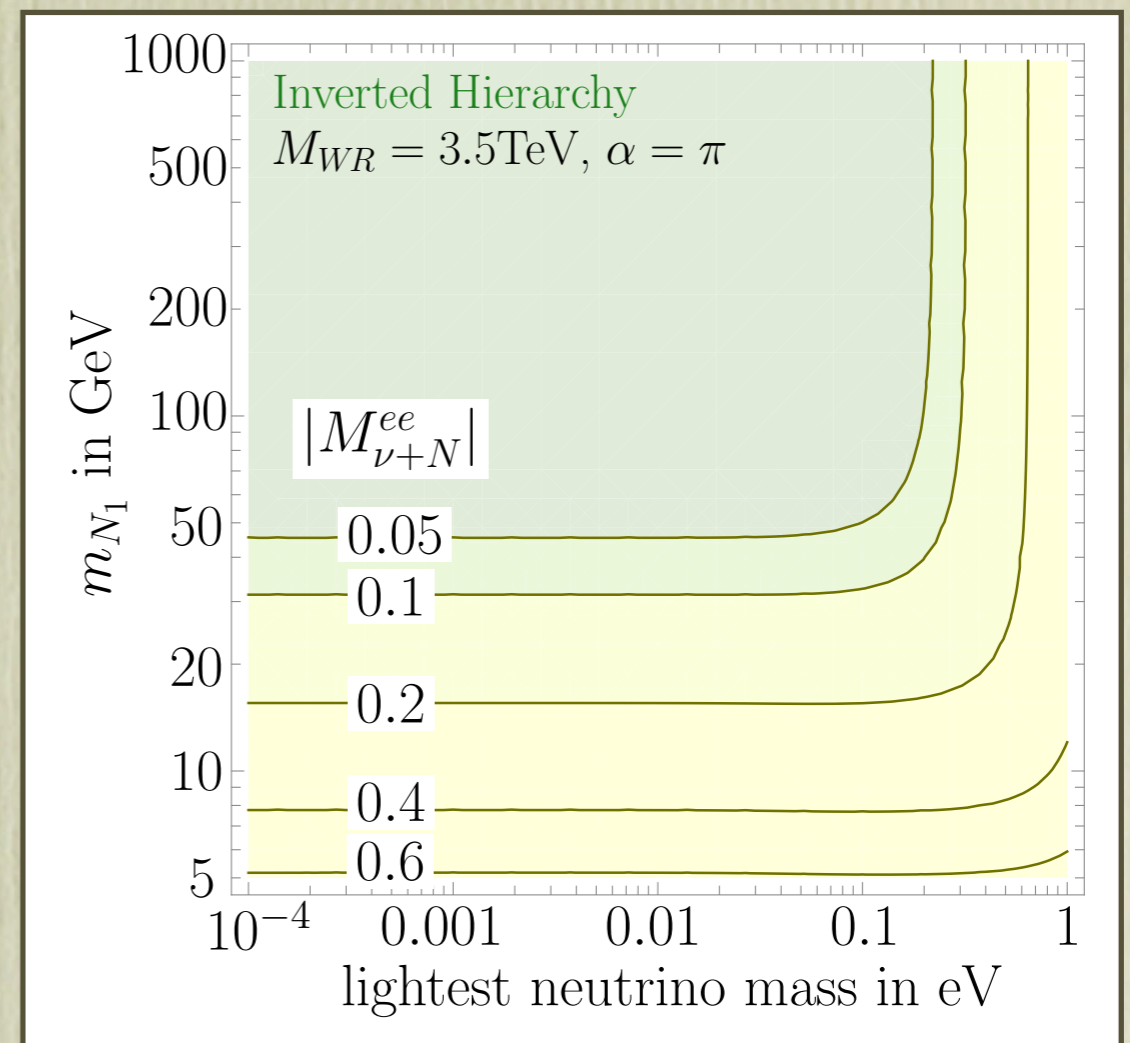
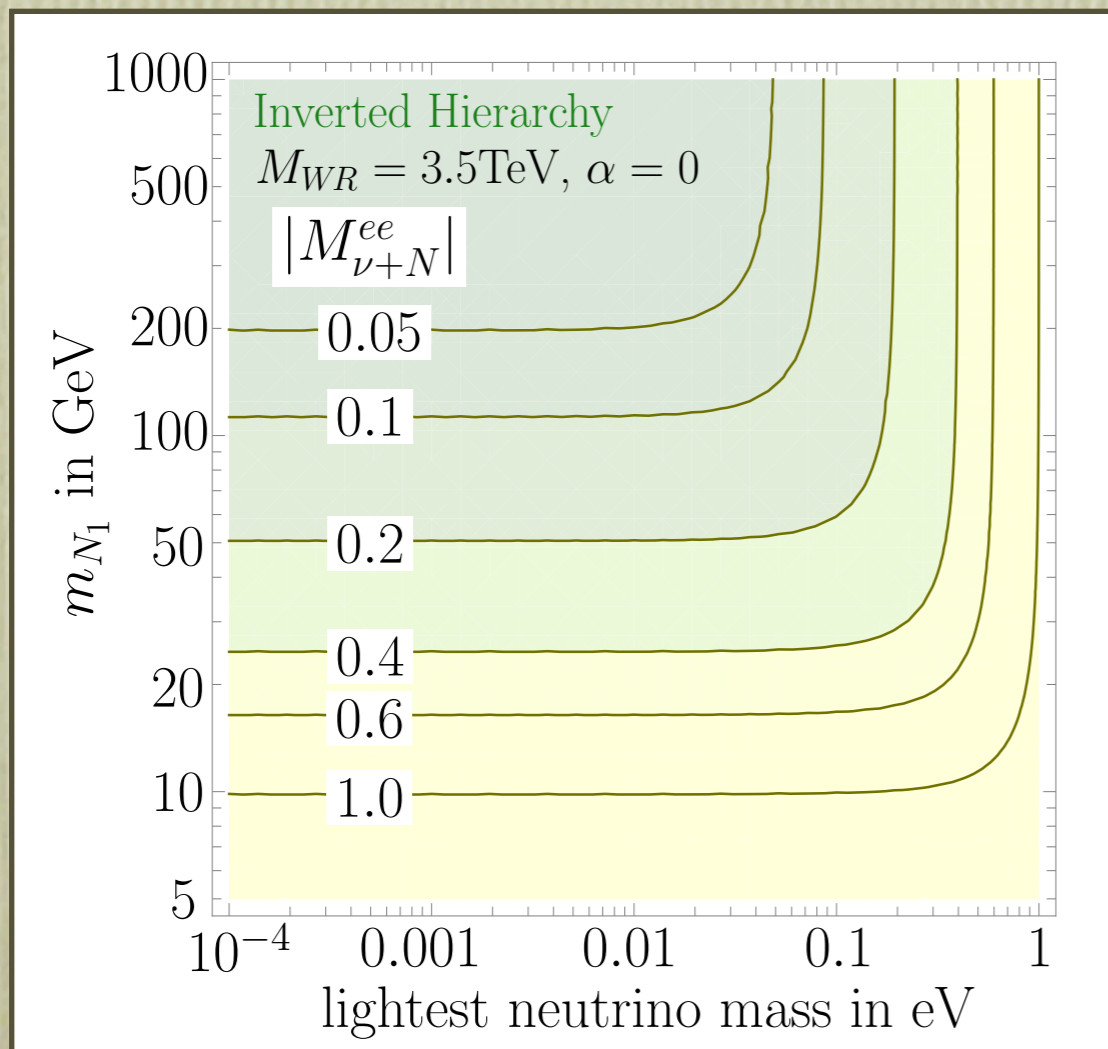
$j\ell : m_N \gtrsim 20 \text{ GeV}$

$\psi : m_N \lesssim 20 \text{ GeV}$

$\cancel{E} : m_N \lesssim 3 - 7 \text{ GeV}$

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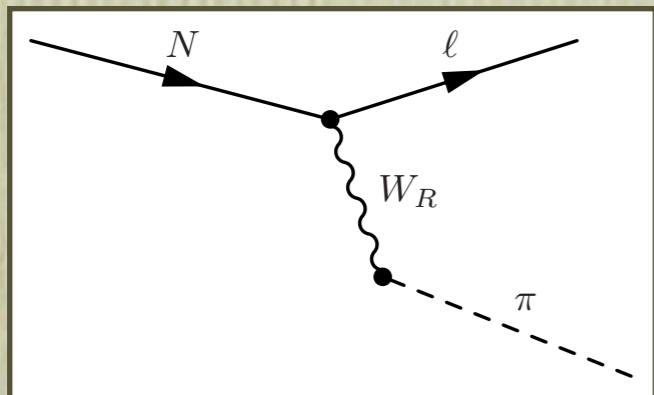


- ★ LHC range
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- $j\ell : m_N \gtrsim 20 \text{ GeV}$        $\cancel{E} : m_N \lesssim 3 - 7 \text{ GeV}$



# How light can N be?

- A light N decays quite fast



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

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

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

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

★ Too small

- What about  $m_D \neq 0$ ?  $U_{\nu N}^2 \simeq m_D^2 / m_N^2 \simeq \frac{m_\nu}{m_N}$

- 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  $\sim eV$  states welcome during the BBN era
- 3+2 better than 3+1 better than 3
- Perfectly ok if  $m_N \approx eV$  and stable. However...

- Type II:  $m_N \propto m_\nu$   
 $m_N^{\min} \simeq 0 \Rightarrow m_\nu^{\min} \simeq 0$

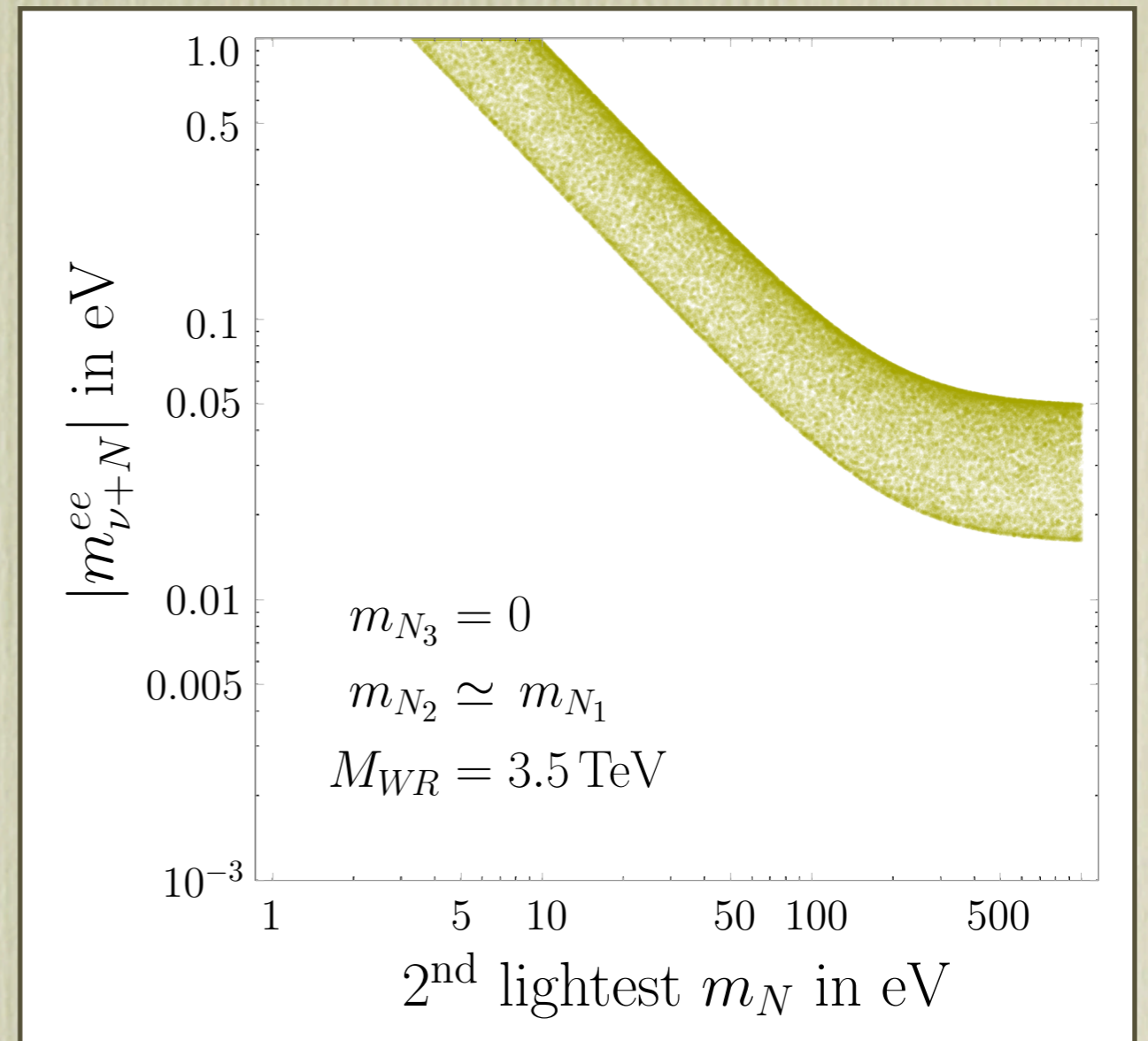
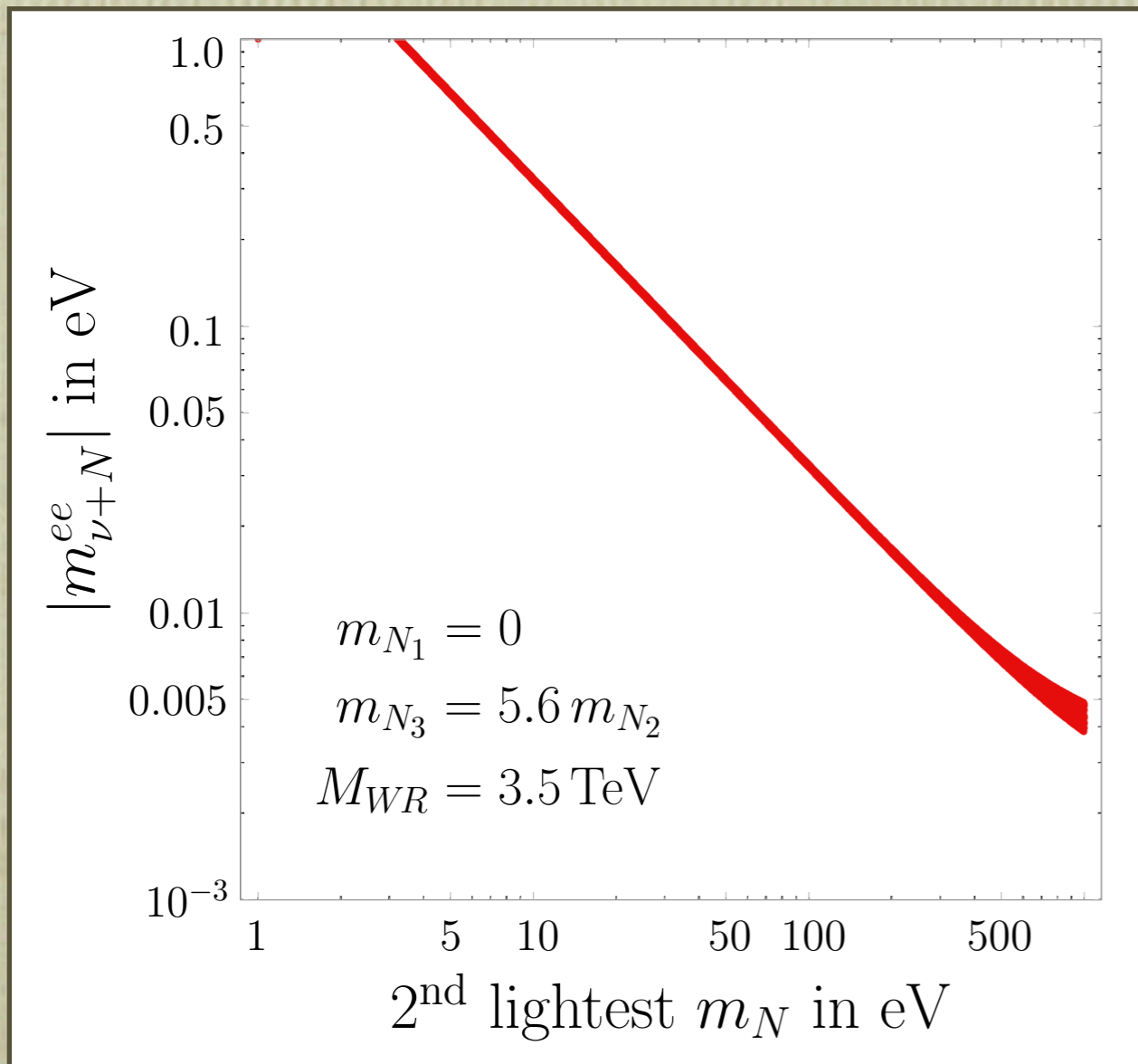
- only one light sterile neutrino!
- the ratio between the others fixed!

NH(IH):

$$m_N^{\max} / m_N^{\min} \simeq 6(1)$$

★ Cross check at LHC

# BBN and $0\nu 2\beta$



★ 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  $0\nu 2\beta$  may require new physics at  $O(\text{TeV})$
- 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  $0\nu 2\beta$  rate
  - LFV transitions (remember also  $\mu$ -e conversion)
- A light  $\tilde{\nu}$ -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

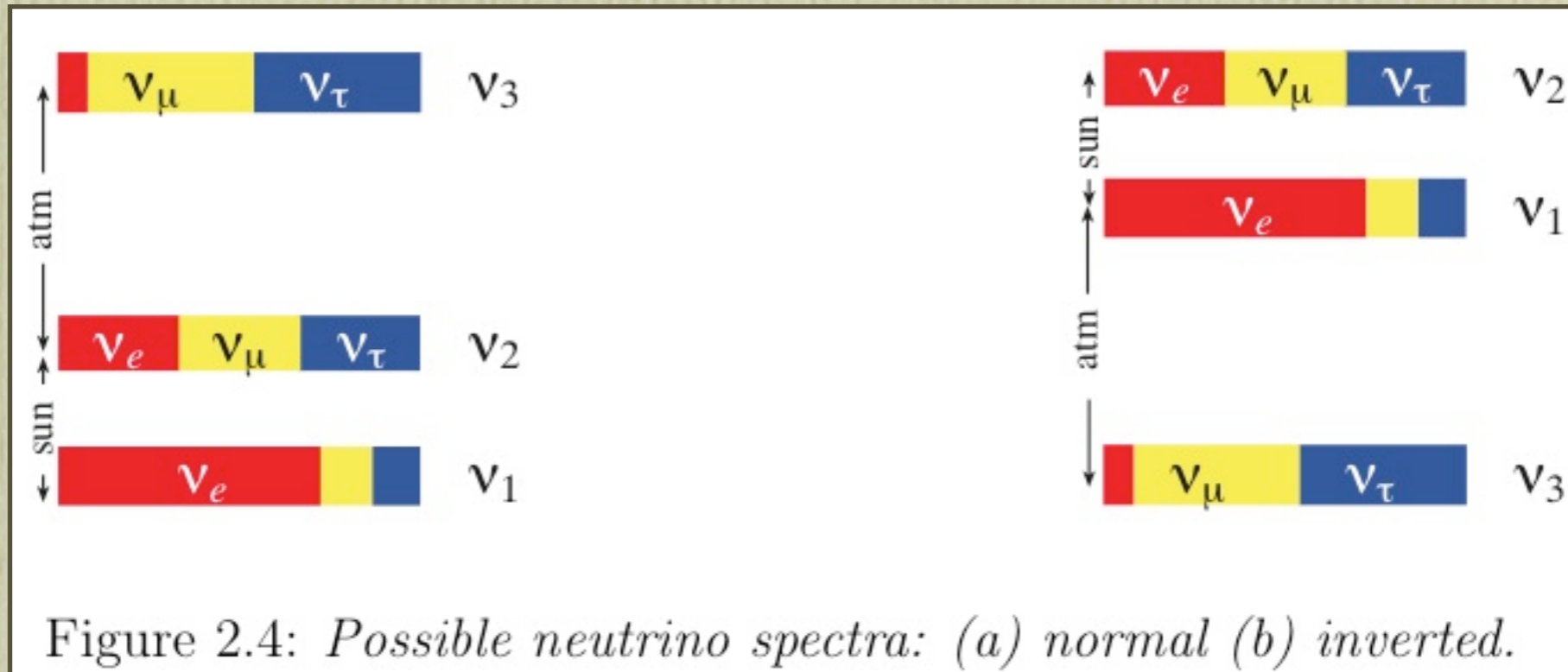
hep-ex

- Gerda, Cuore, etc. results

- A hint from LFV? (MEG,  $\text{Mu}2\text{E}$ , COMET)

Thank you

# Neutrino Data



$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	7.6
$ \Delta m_{31}^2  [10^{-3} \text{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

