

Neutrinos and Physics beyond the Standard Model



Frank Deppisch
f.deppisch@ucl.ac.uk

University College London

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Overview

- **Neutrinos**
 - Oscillations
 - Absolute Mass
- **$0\nu\beta\beta$ Decay**
- **Lepton Flavour Violation**
- **Neutrino Mass Generation**
 - Seesaw Mechanism
 - SUSY Seesaw
 - Left-Right Symmetry
- **Conclusion**

Neutrino Oscillations

- **Neutrino interaction states different from mass eigenstates**

Neutrino flavour can change through propagation

$$\nu_i = \sum_{\alpha} U_{i\alpha} \nu_{\alpha}, \quad \nu_i(t) = e^{-i(E_i t - p_i x)} \nu_i$$
$$\Rightarrow P_{\alpha \rightarrow \beta} = \sin^2(2\theta) \sin^2 \left(1.27 \frac{\Delta m^2}{\text{eV}^2} \frac{L/\text{km}}{E/\text{GeV}} \right)$$

- **Solar neutrino oscillations**

Large mixing

- **Atmospheric oscillations**

≈ Maximal mixing

- **Reactor and accelerator neutrinos**

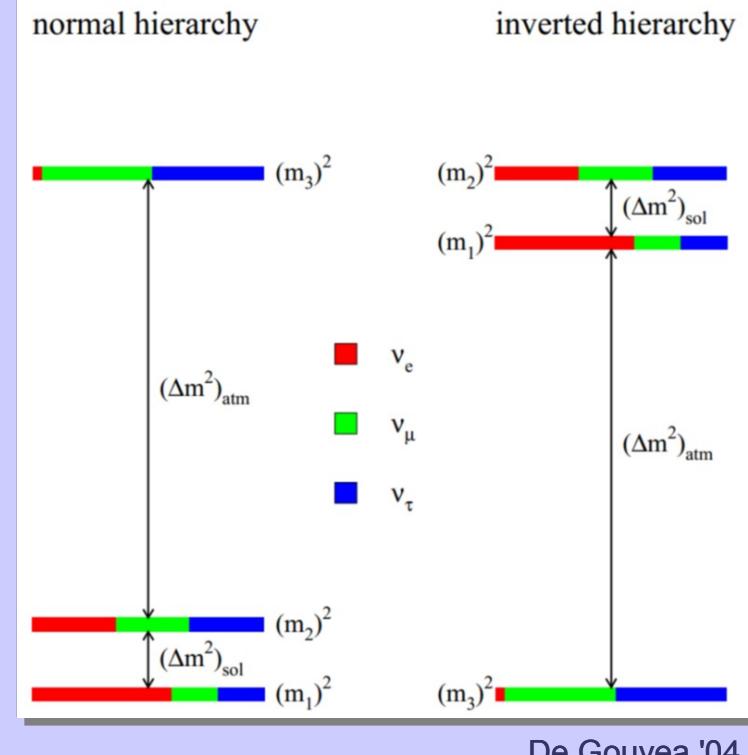
Antineutrino disappearance at Daya Bay

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.021$$

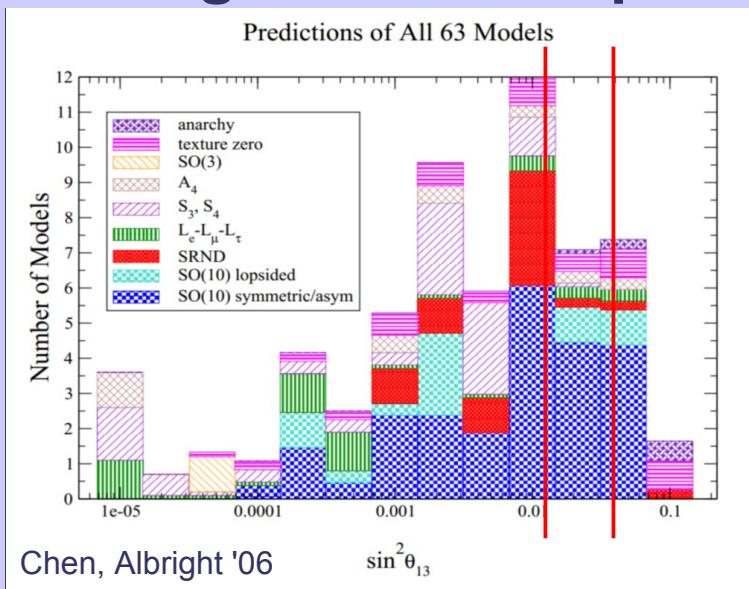
Neutrino Oscillations

- Neutrino mixing matrix and mass differences

$$U \approx \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0.15 e^{i\delta} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} \times \begin{pmatrix} e^{i\phi} & 0 & 0 \\ 0 & e^{i\theta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Constraining the model space



- Experimental unknowns and anomalies

CP violation?, Sign of Δm_{23} ?, Sterile Neutrinos?

Neutrinos and BSM Physics

Absolute Neutrino Mass

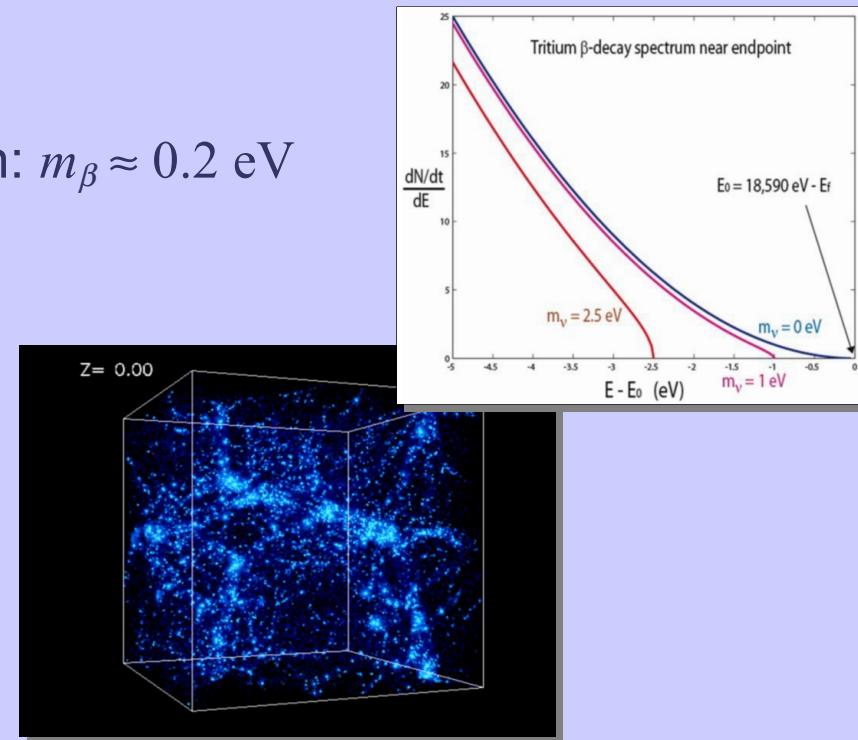
- Energy endpoint in Beta decay

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 < (2.2 \text{ eV})^2$$

Katrin: $m_\beta \approx 0.2 \text{ eV}$

- Impact on Large Scale Structure

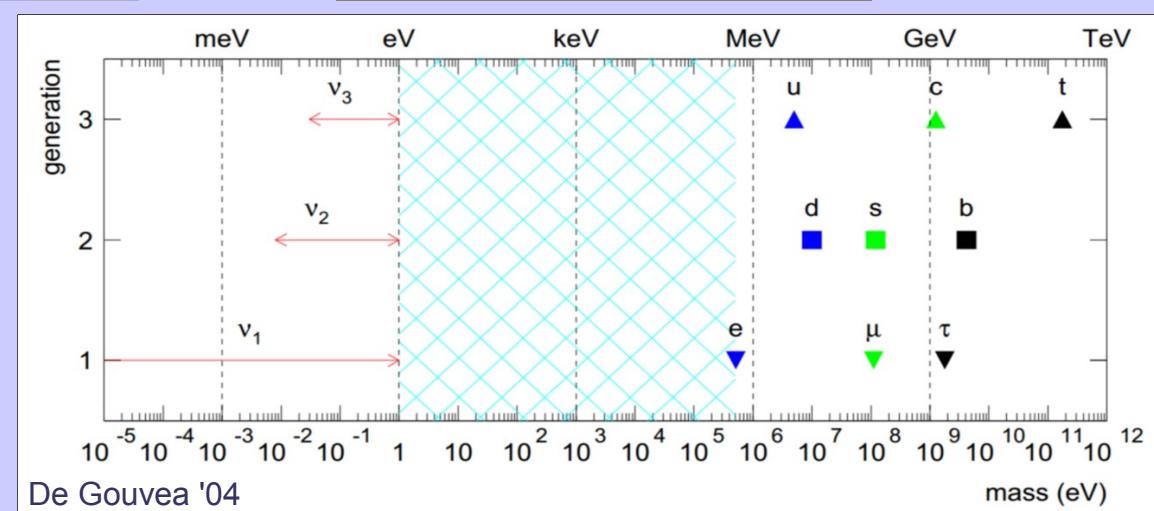
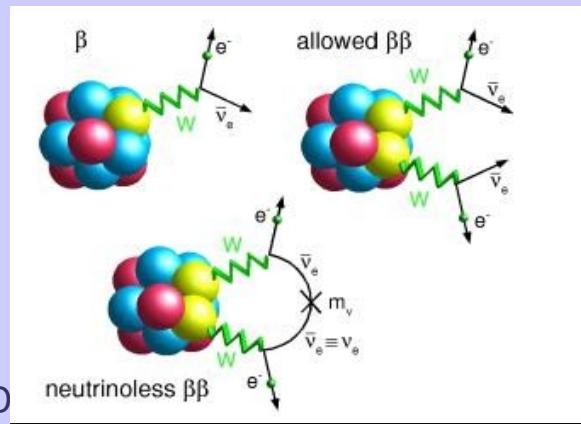
$$\Sigma = \sum_i m_i < 0.4 - 1 \text{ eV}$$



- Neutrinoless Double Beta Decay

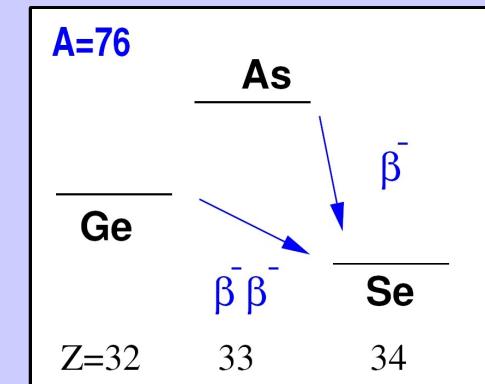
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| < 0.2 - 2.0 \text{ eV}$$

Future Experiments:
 $m_{\beta\beta} \approx 0.01 \text{ eV}$



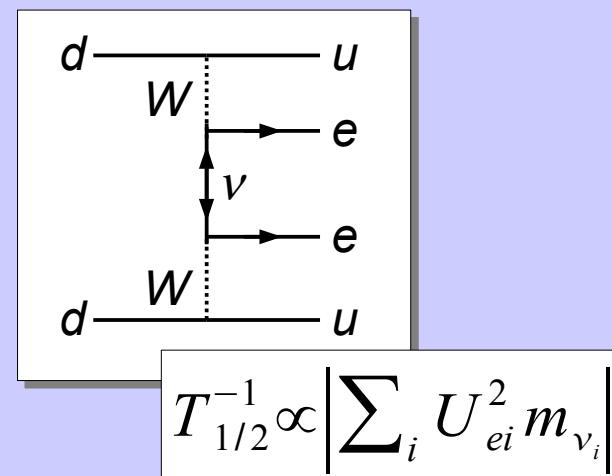
Neutrinoless Double Beta Decay

- **Process:** $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- **Uncontroversial detection of $0\nu\beta\beta$ of utmost importance**
 - Prove lepton number to be broken
 - Prove neutrinos to be Majorana particles (Schechter, Valle '82)
- **Which mechanism triggers the decay?**

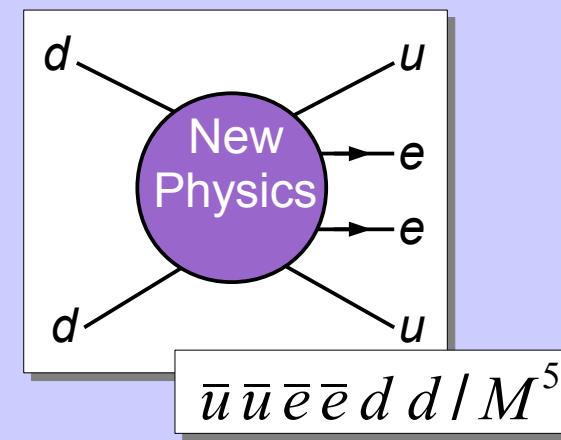


Heidelberg-Moscow
 $T_{1/2}(^{76}\text{Ge}) \approx 1.9 \cdot 10^{25} \text{ y}$
 $\langle m_\nu \rangle \approx (0.3 - 0.6) \text{ eV}$

Light Neutrino Exchange
(LH Current, Mass Mechanism)



General Effective Operator



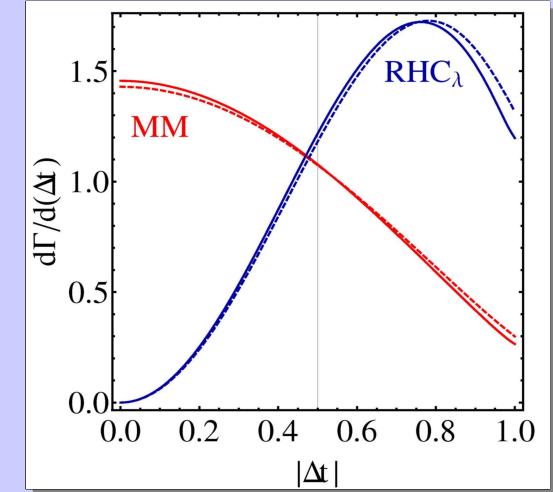
Disentangling New Physics Scenarios

- **Angular and Energy distribution of emitted electrons**

(Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

$$\frac{d\Gamma}{dE_1 dE_2 d\cos\theta} = \frac{\Gamma}{2} (1 - k(E_1, E_2) \cos\theta) \quad -1 < k < 1$$

- Linear in $\cos\theta$
- $k(E_1, E_2)$ depends on $0\nu\beta\beta$ mechanism



- **Comparison of $0\nu\beta\beta$ in multiple isotopes**

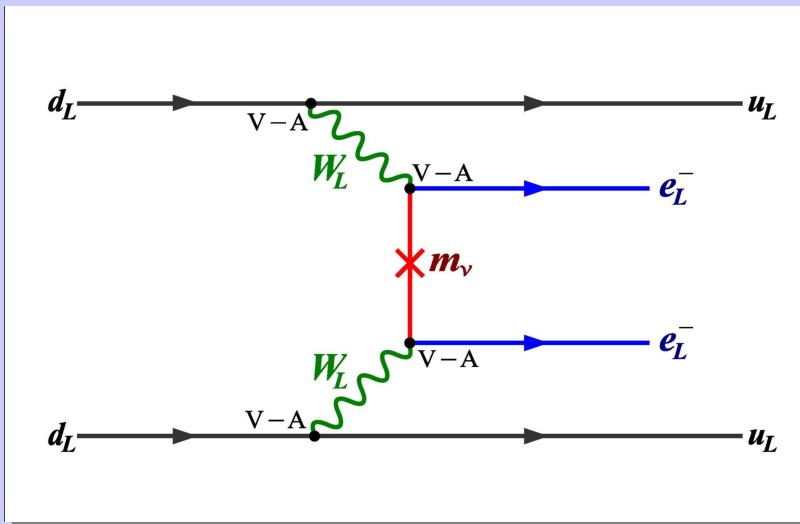
(FFD, Päs PRL 2007)

$$\frac{T_{1/2}(^AX)}{T_{1/2}(^BY)} = \frac{G(^BY) |M(^BY)|^2}{G(^AX) |M(^AX)|^2}$$

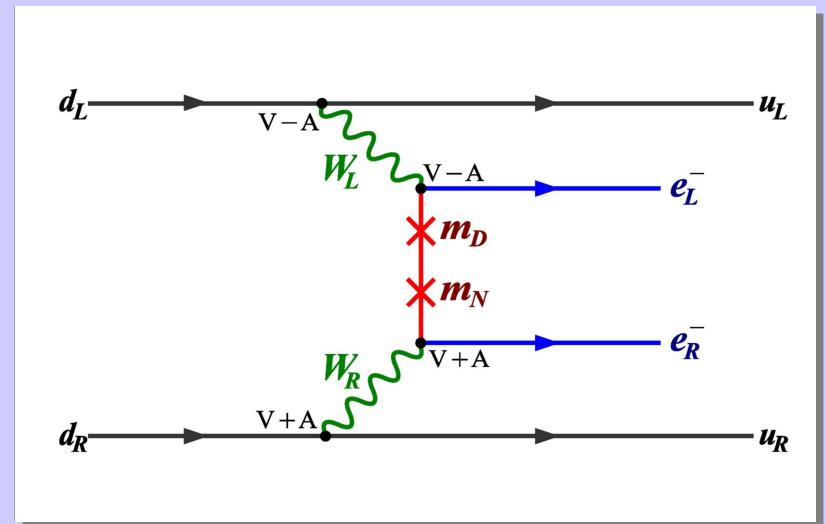
- Depends on $0\nu\beta\beta$ mechanism
- Independent of details of new physics
(if one mechanism dominates)

Left-Right Symmetric Model

- Left-Right symmetric models predict heavy $SU(2)_R$ gauge bosons and heavy right-handed neutrinos
- Subset of contributions



LH hadronic and leptonic current
(Mass Mechanism, MM)



RH hadronic and leptonic current
(Right-Handed Current, RHC $_\lambda$)

- New Physics Parameters

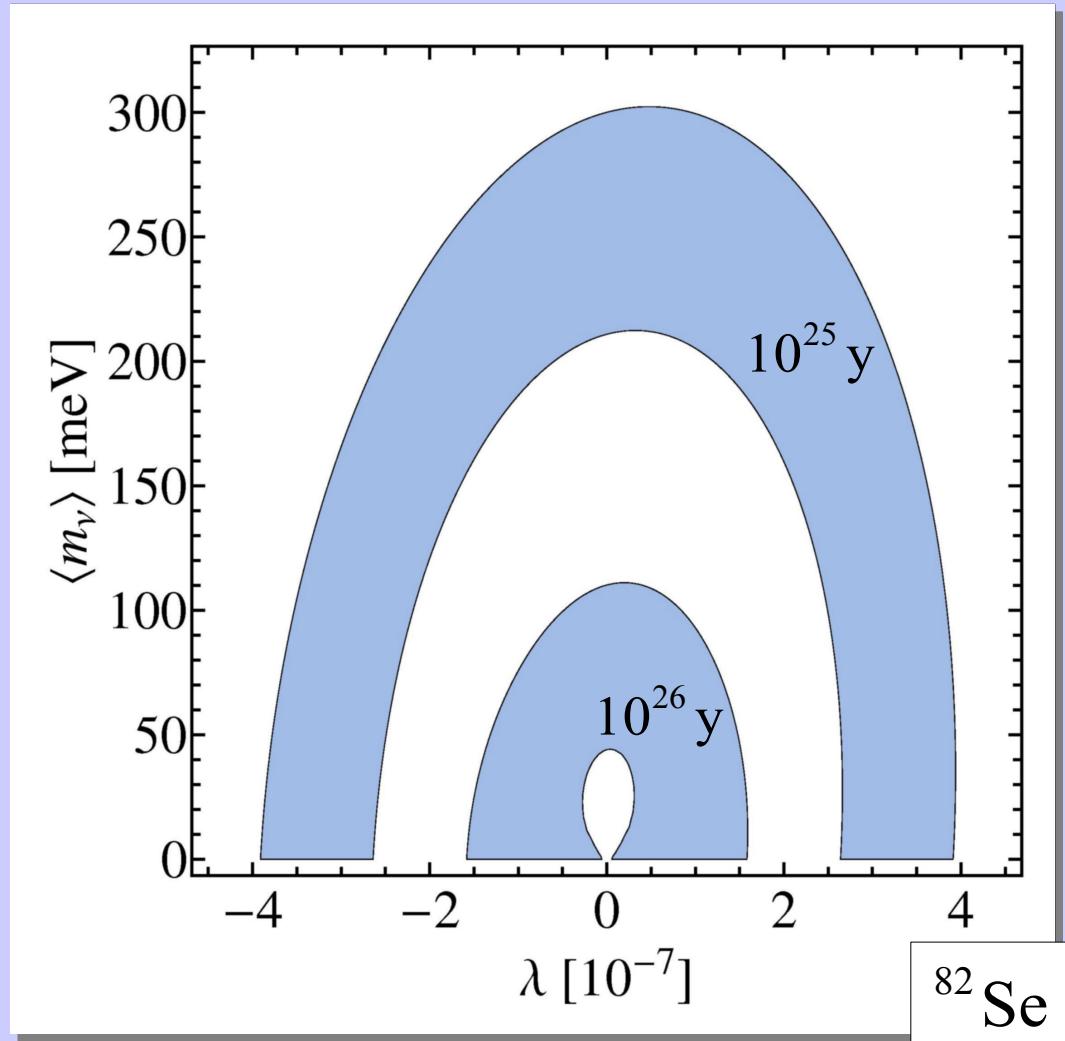
$$\mu = m_e^{-1} \sum_i (U_{ei}^{\text{LL}})^2 m_{\nu_i} = \frac{\langle m_\nu \rangle}{m_e}$$

$$\lambda = \left(\frac{M_{W_L}}{M_{W_R}} \right)^2 \sum_i U_{ei}^{\text{LL}} U_{ei}^{\text{LR}} \approx \left(\frac{M_{W_L}}{M_{W_R}} \right)^2 \sqrt{\frac{m_\nu}{M_N}}$$

Angular and Energy Correlations

- Constraints on the parameter space
 - Half-life measurement

- Statistical uncertainties from simulation
- Theoretical nuclear matrix element uncertainty: 30%

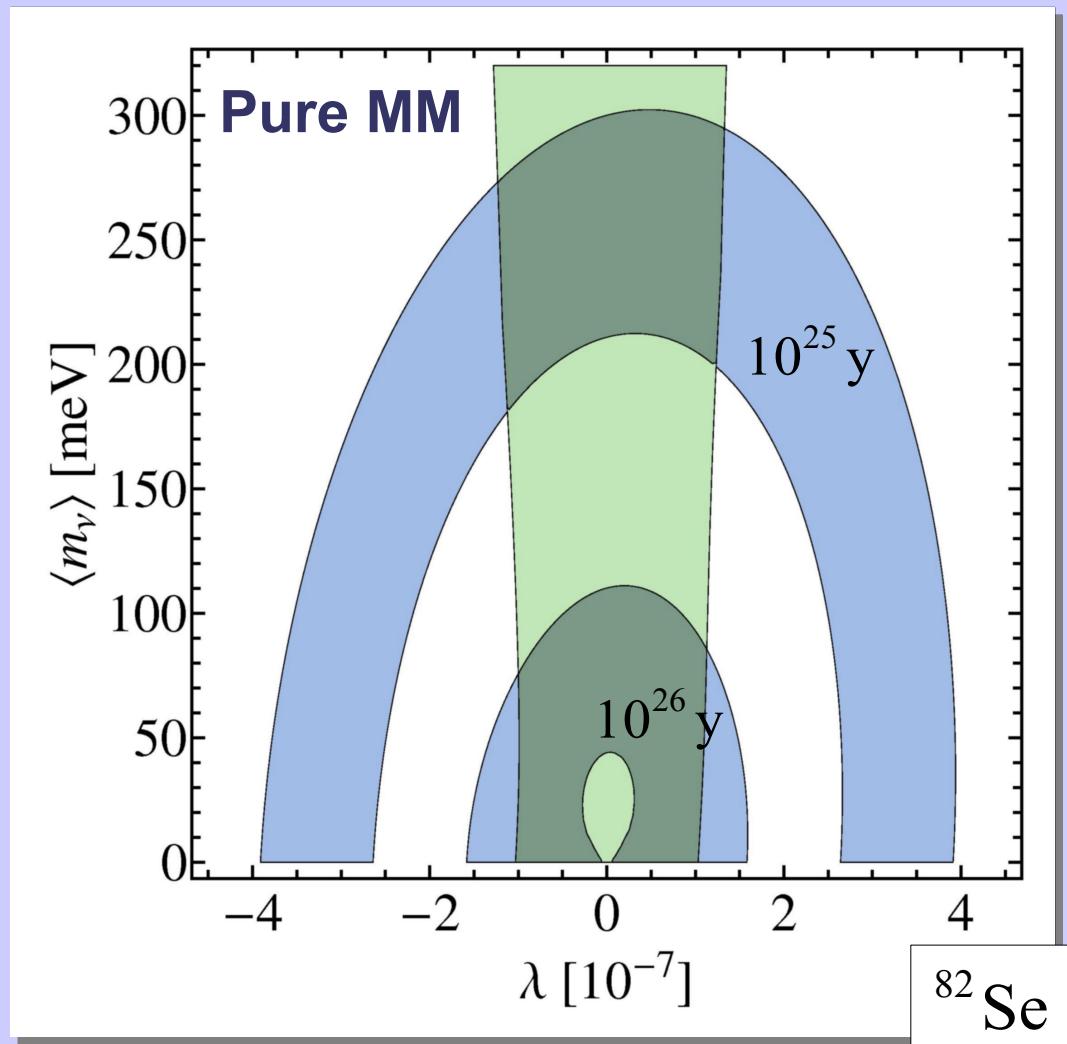


Arnold et al. arXiv:1005.1241

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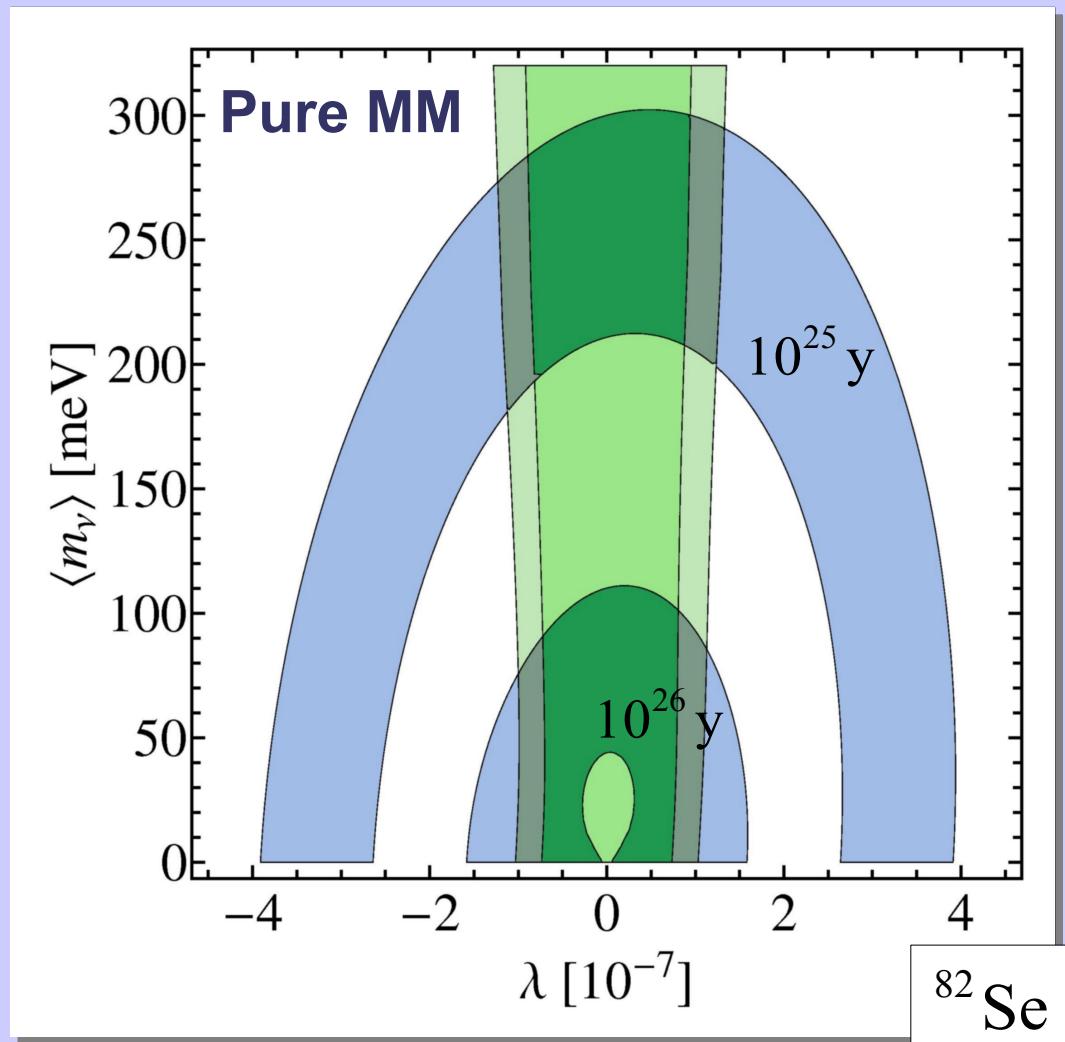
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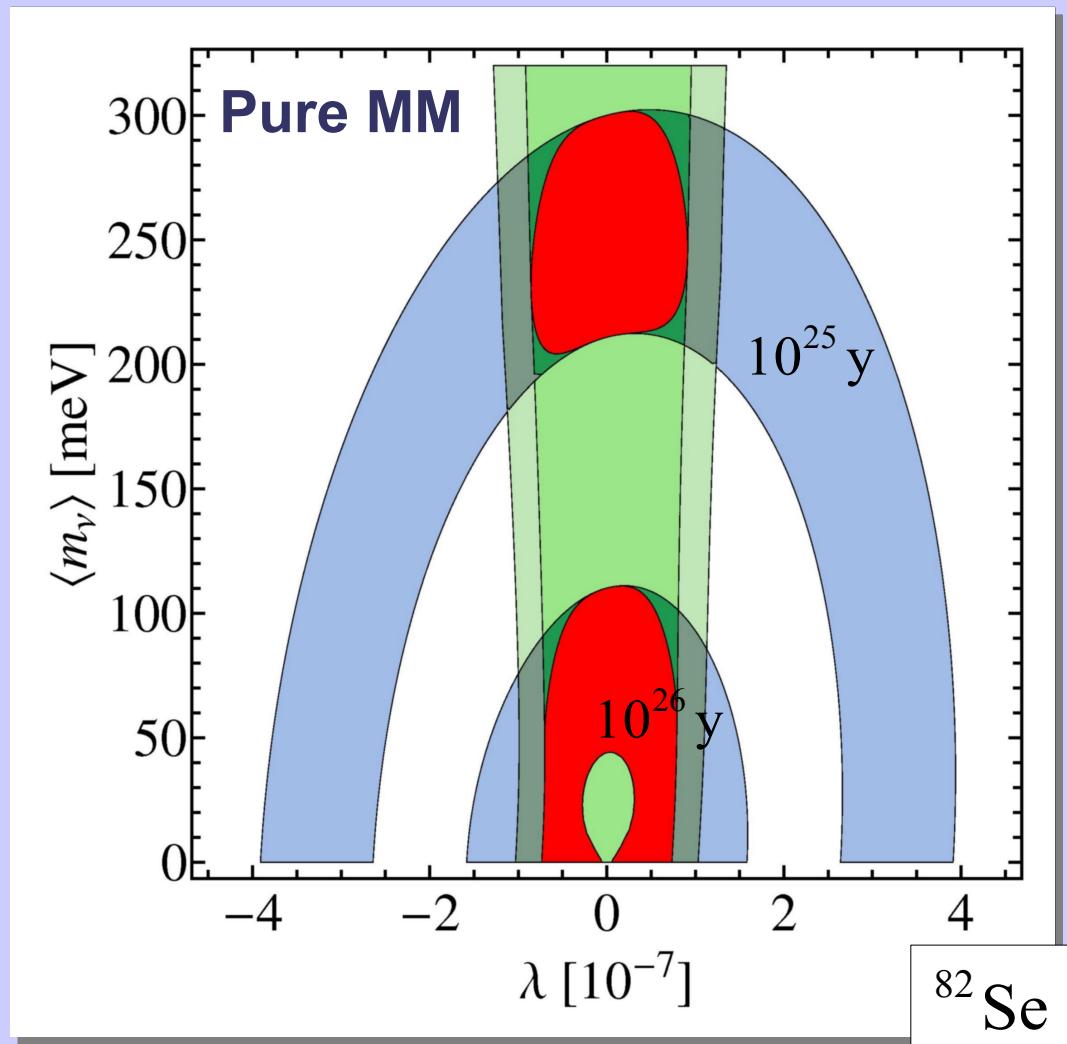
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Angular and Energy Correlations

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 - Combined 1σ area

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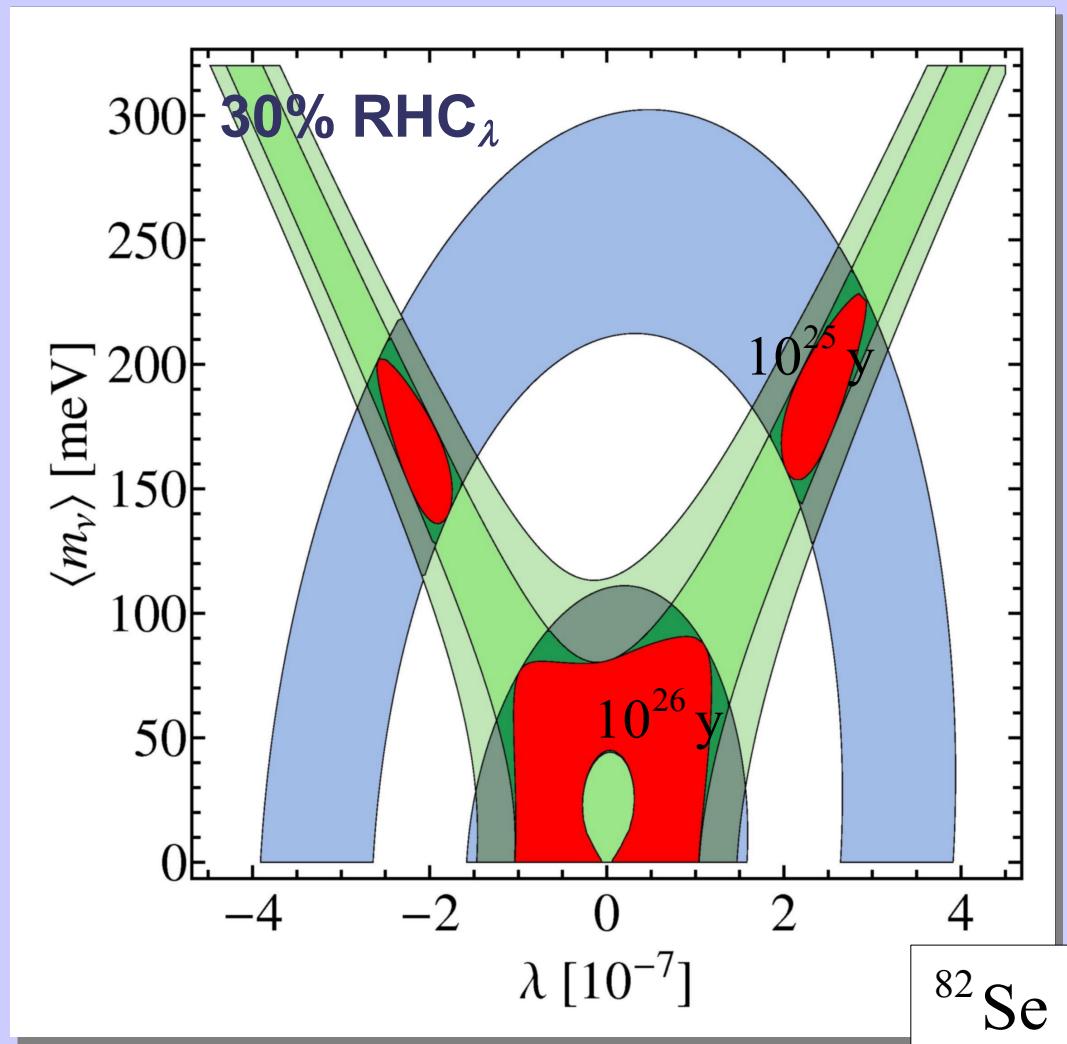
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Charged Lepton Flavour Violation

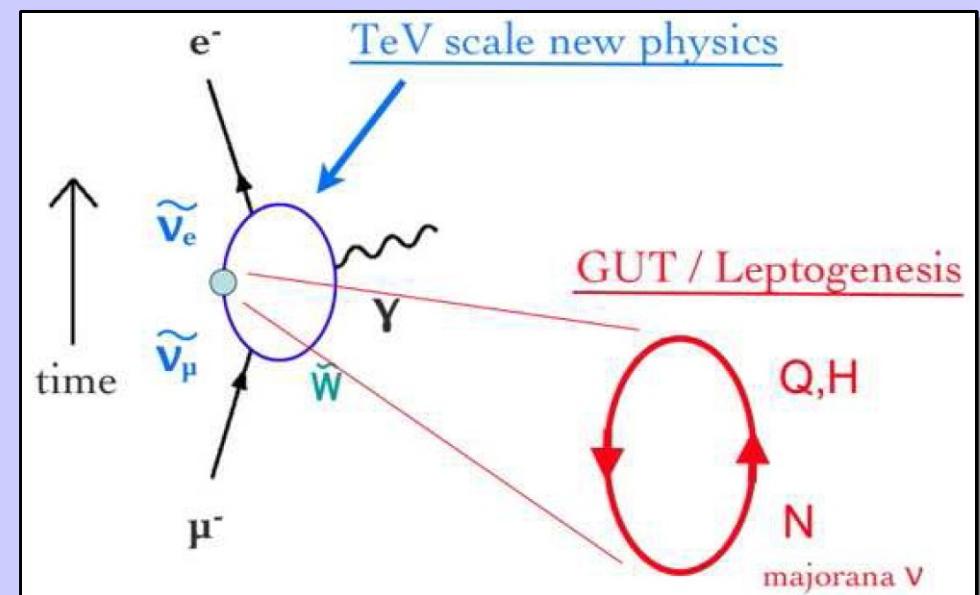
- Lepton flavour practically conserved in the Standard Model

$$Br(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{e i} \frac{\Delta m_{1i}^2}{m_W^2} \right|^2 \approx 10^{-56}$$

LFV is clear sign for BSM physics

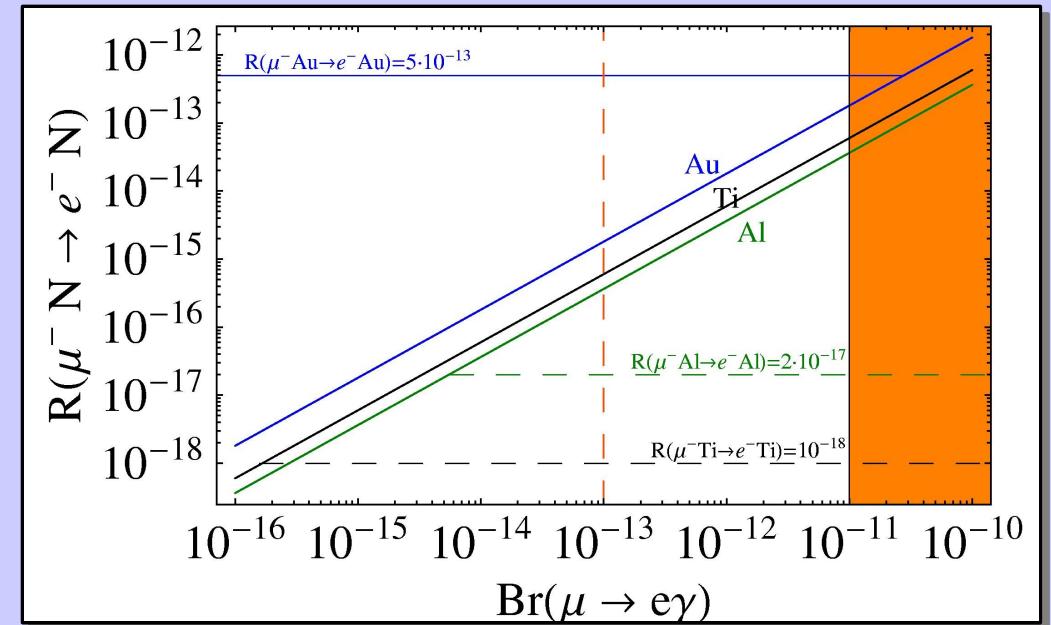
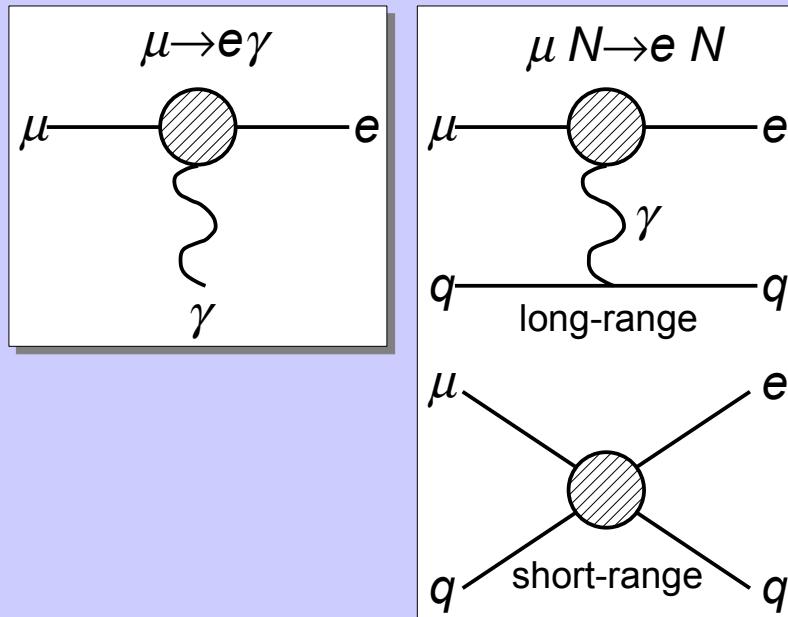
- Flavour violation in quark and neutrino sector
Strong case to look for charged LFV

- LFV can shed light on
 - Grand Unification models
 - Flavour symmetries
 - Origin of flavour



Rare LFV Processes

- Current bounds and future sensitivities
 - $\text{Br}(\mu \rightarrow e\gamma) < 1.2 \cdot 10^{-11}$ (MEGA) 10^{-13} (MEG, 2009)
 - $\text{Br}(\tau \rightarrow \mu\gamma) < 6.8 \cdot 10^{-8}$ (Belle) 10^{-8} (Super-B Factory, LHC?)
 - $\text{Br}(\tau \rightarrow e\gamma) < 3.7 \cdot 10^{-7}$ (BaBar) 10^{-8} (Super-B Factory)
 - $R(\mu N \rightarrow e N) < 7 \cdot 10^{-13}$ (Sindrum) 10^{-16} (COMET), $\mu \rightarrow e$ conversion in nuclei
 - $\mu \rightarrow 3e$, $\tau \rightarrow 3\mu$ (LHC), etc.
- Correlation between processes of same flavour transition



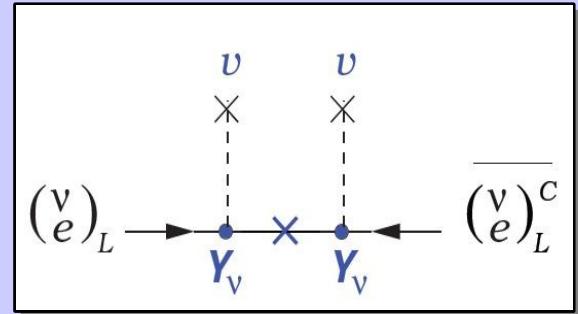
Seesaw Mechanism

- Add right-handed neutrinos to (MS)SM
particle content, $M_R \approx 10^{14}$ GeV

$$W = W_{\text{MSSM}} - \frac{1}{2} \hat{\nu}_R^{cT} M_R \hat{\nu}_R^c + \hat{\nu}_R^{cT} Y_\nu \hat{L} \cdot \hat{H}_u$$

- Integrate out heavy right-handed neutrinos

$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}^T \quad \text{with} \quad m_D = Y_\nu \langle H_u^0 \rangle \ll M_R$$



- Effective light neutrino mass matrix at low energies

$$m_\nu = m_D^T M^{-1} m_D \quad \text{for } m_D \ll M_R \quad m_\nu \approx 0.1 \text{ eV} \left(\frac{m_D}{100 \text{ GeV}} \right)^2 \left(\frac{M_R}{10^{14} \text{ GeV}} \right)^{-1}$$

Seesaw Mechanisms

Seesaw I

$$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c$$

Seesaw II

$$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c$$

Inverse Seesaw

$$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c, S_i$$

$$\begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix}$$

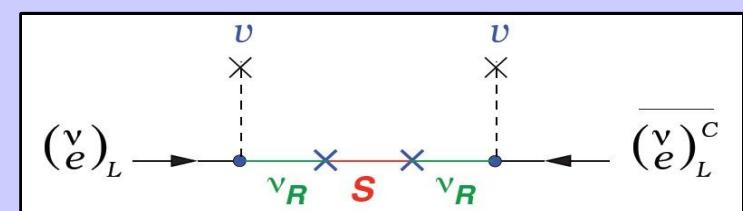
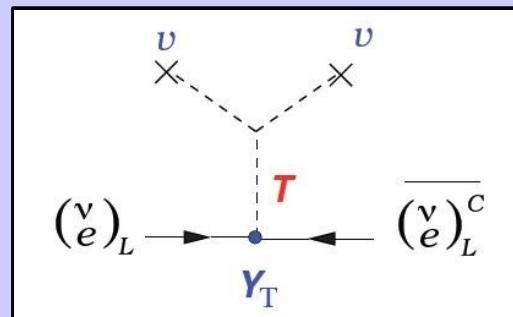
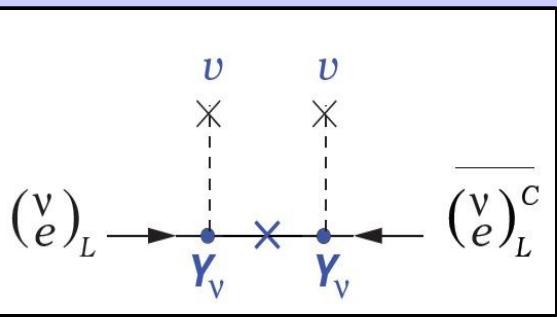
$$\begin{pmatrix} m_{LL} & m_D^T \\ m_D & M_R \end{pmatrix}$$

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix}$$

$$m_D \ll M_R \Rightarrow \\ m_\nu = m_D^T M^{-1} m_D$$

$$m_D \ll M_R \Rightarrow \\ m_\nu = m_{LL} - m_D^T M^{-1} m_D$$

$$\mu, m_D \ll M_R \Rightarrow \\ m_\nu = m_D^T M_R^{T-1} \mu M_R^{-1} m_D$$

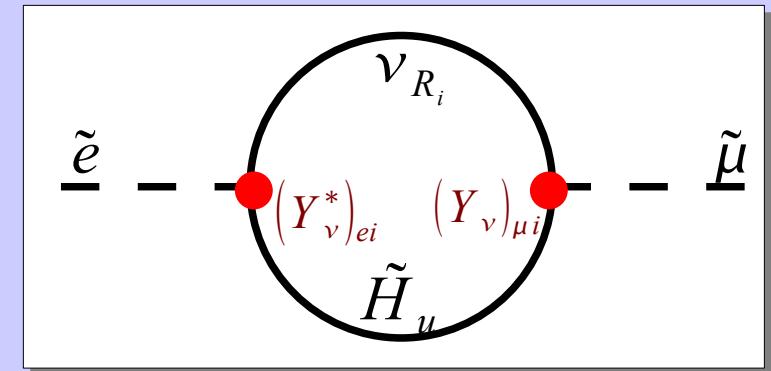


SUSY Seesaw



Achieve testability via impact on sleptons

- Neutrino flavour mixing radiatively induces slepton flavour mixing (Masiero, Borzumati)
- Correlation between slepton and neutrino flavour mixing



$$(\delta m_L^2)_{ij} = \begin{pmatrix} \delta_{11} & \delta_{12} & \delta_{13} \\ \delta_{12}^* & \delta_{22} & \delta_{23} \\ \delta_{13}^* & \delta_{23}^* & \delta_{33} \end{pmatrix} \propto Y_\nu^+ \cdot Y_\nu \log(M_{\text{GUT}}/M_R)$$

$\Im(\delta_{ij}) \Rightarrow \text{EDMs } d_e, d_\mu$

Slepton mass differences (Colliders)

⇒ 9 potential observables

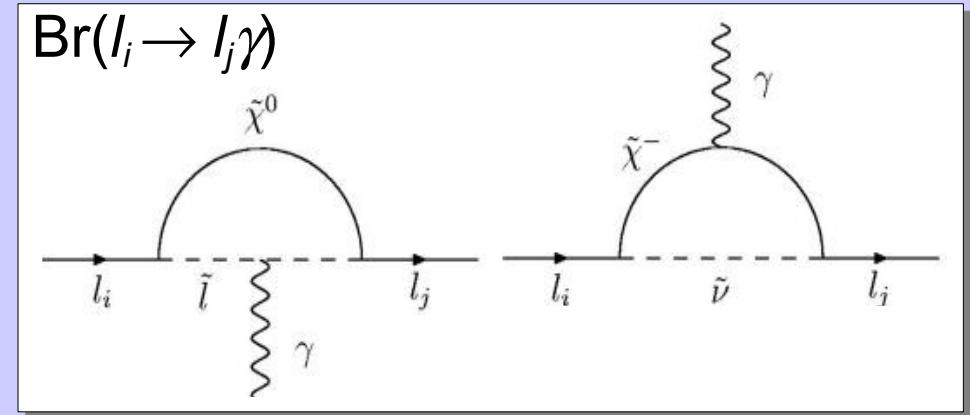
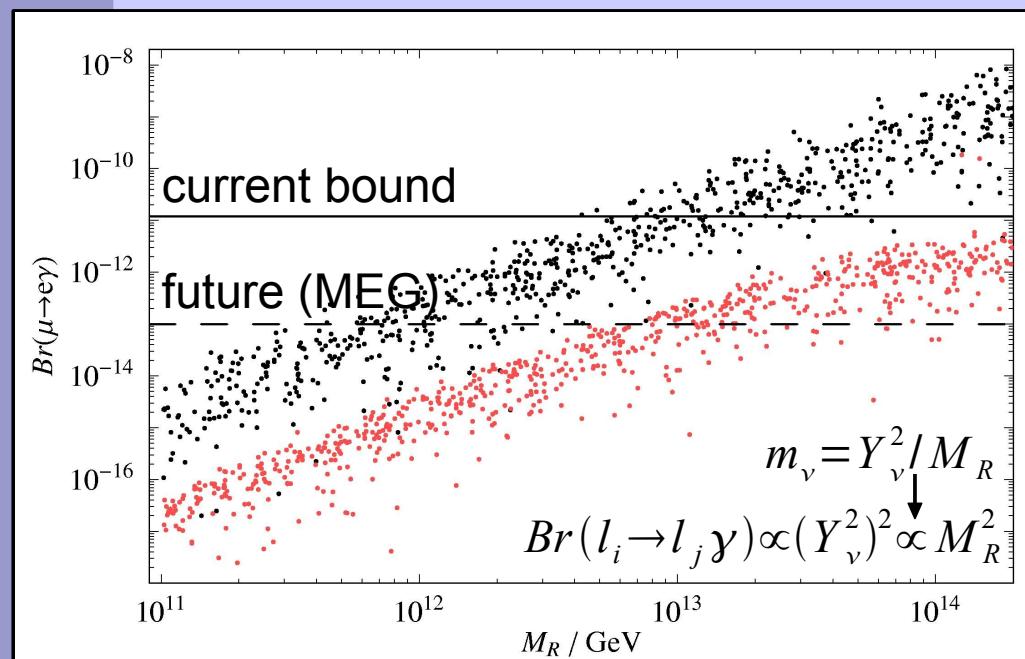
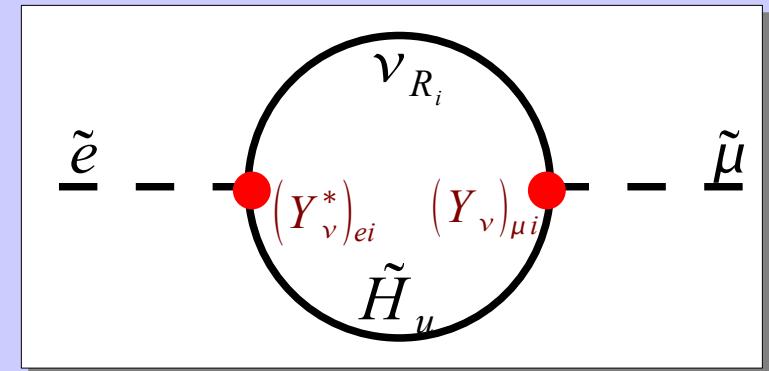
⇒ SUSY Seesaw testable (in principle)

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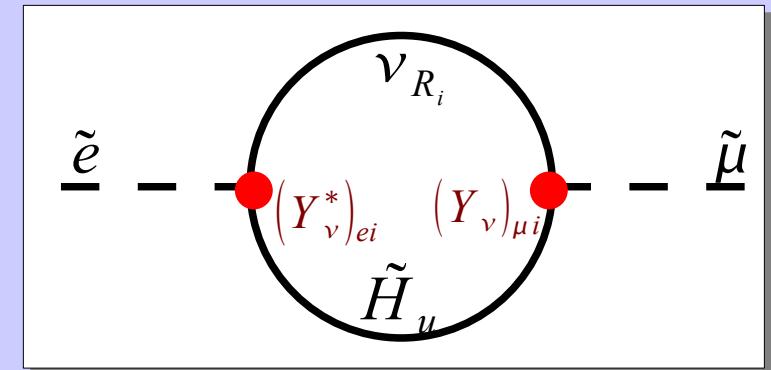
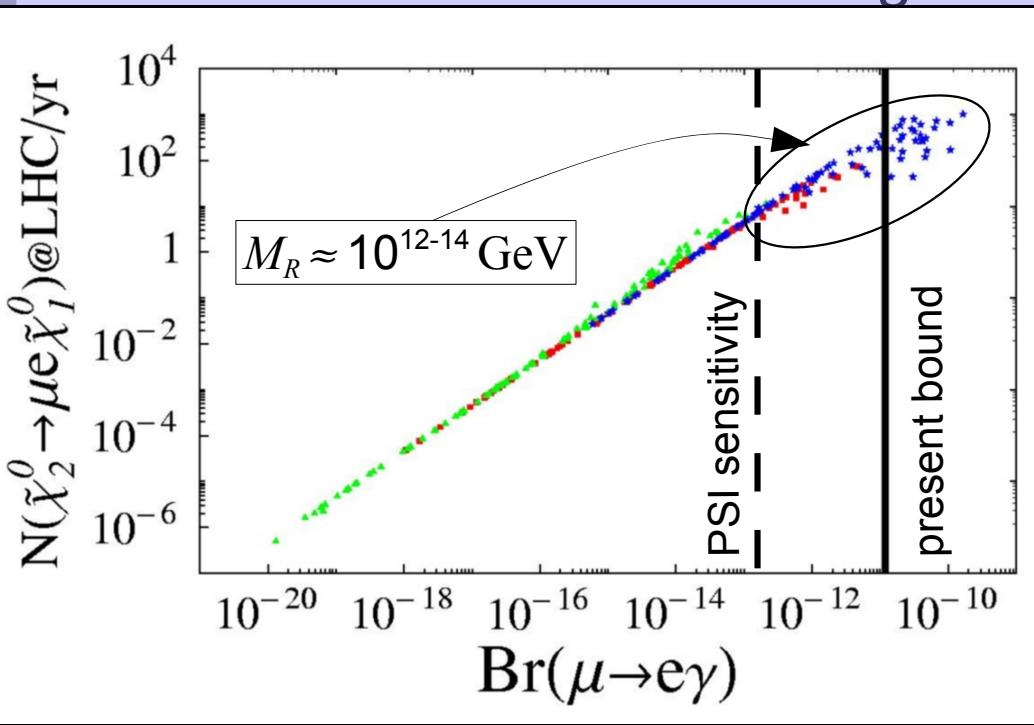


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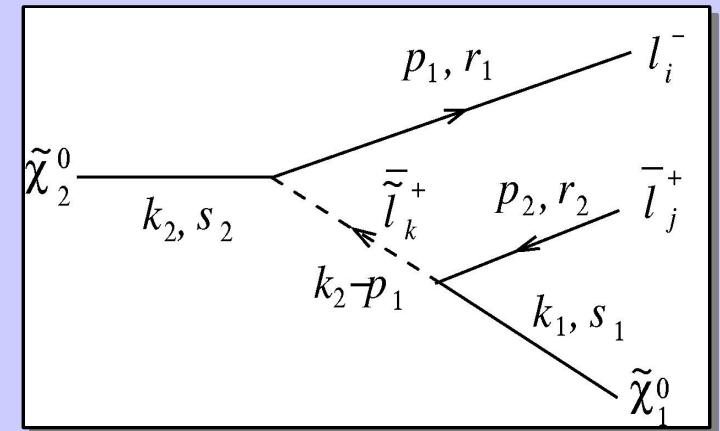


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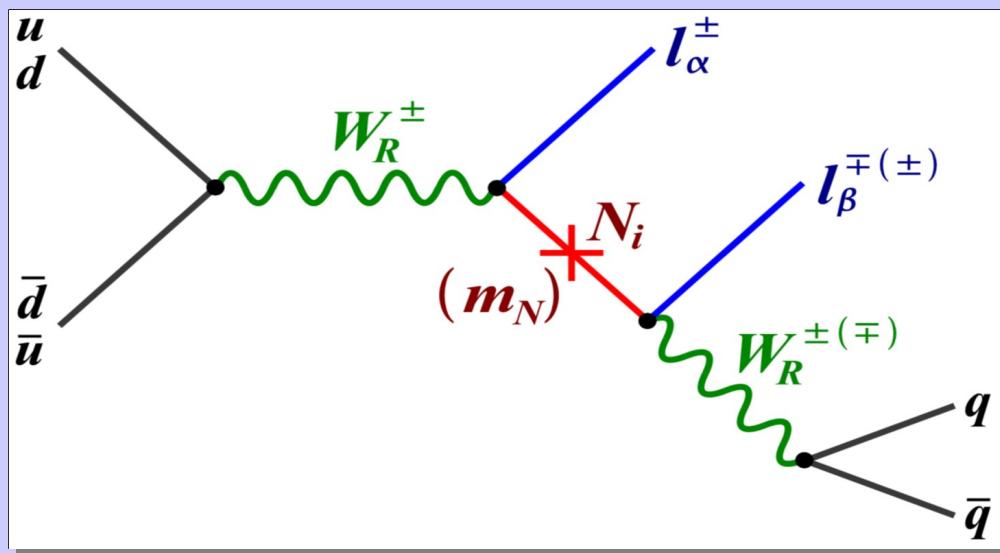
- Cascade LFV decays of second lightest neutralino



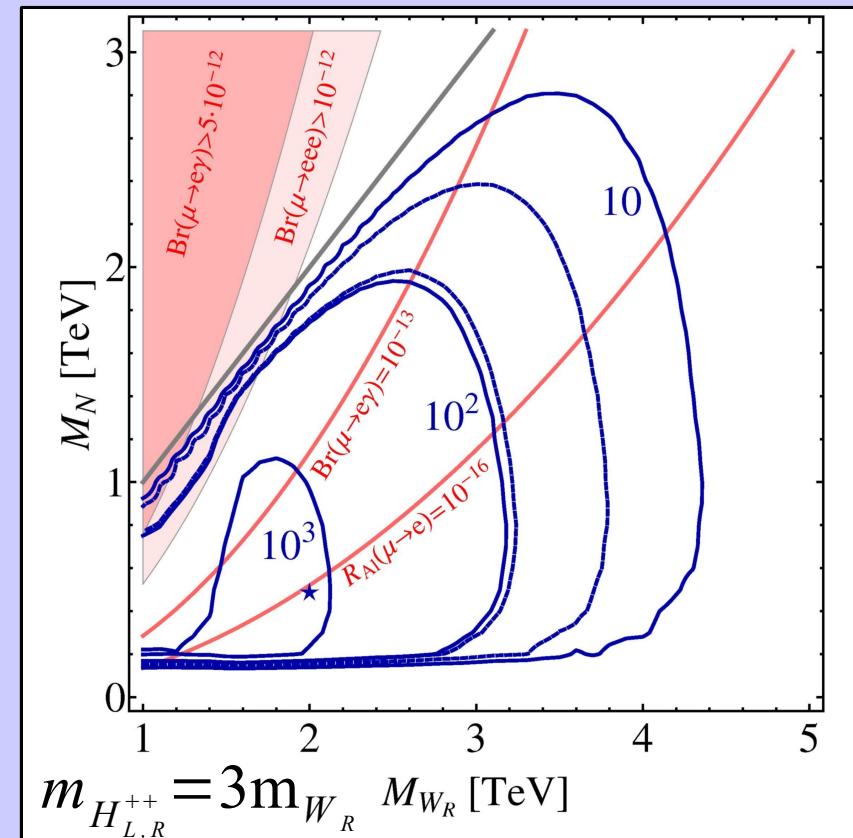
Light Right-Handed Neutrinos



- Inverse Seesaw mechanism
- “Anti”-Seesaw mechanism
- Left-Right symmetric models
Right-handed neutrinos couple with gauge strength to charged leptons



Probing right-handed neutrino mixing,
Large LFV and LNV rates at LHC

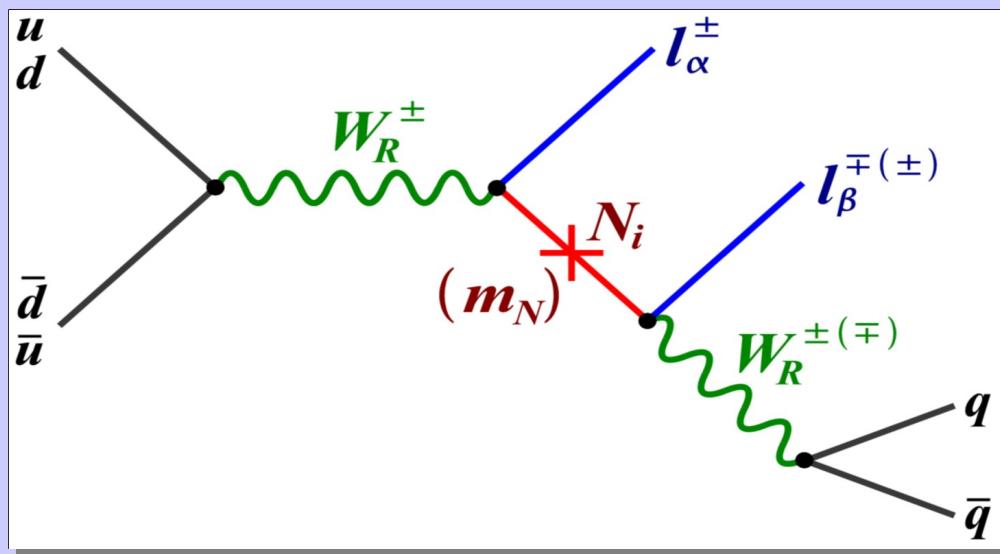


Aguila, Aguilar-Saavedra, Das, FFD,
Kittel, Valle, work in progress

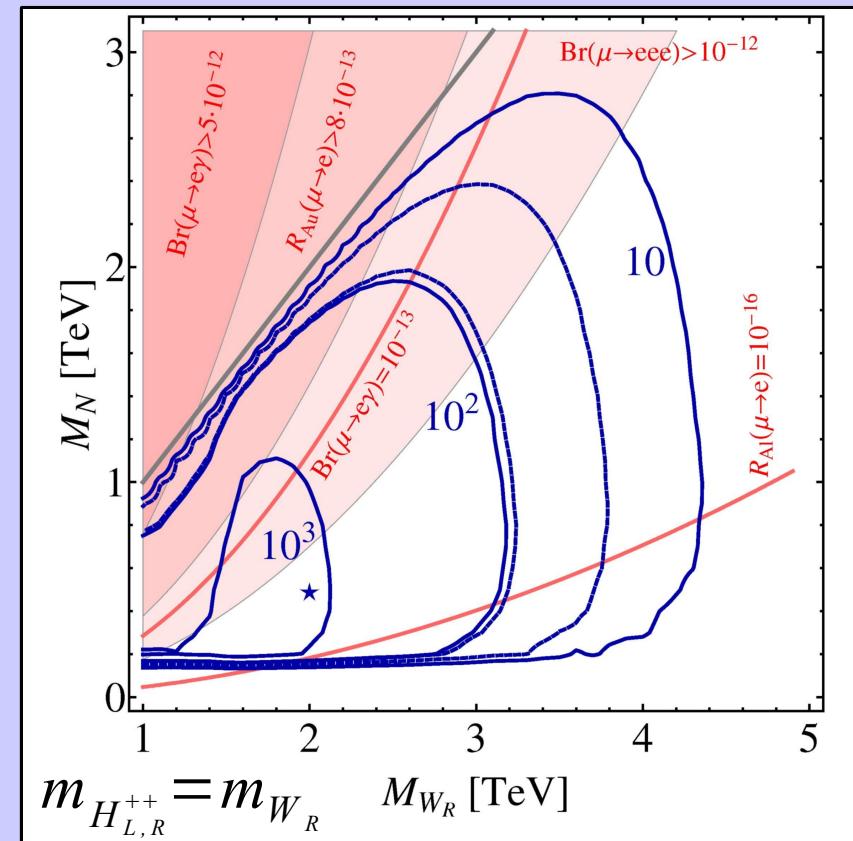
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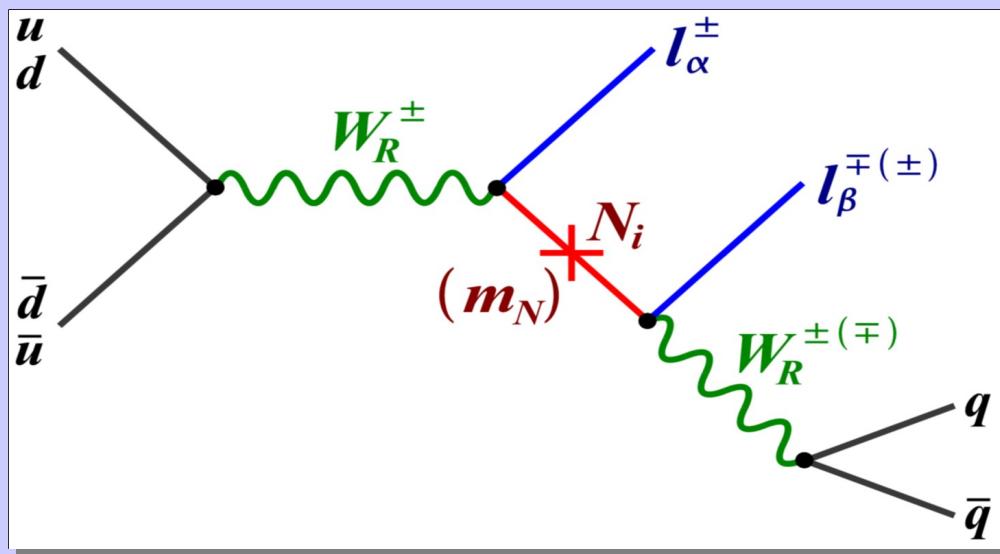


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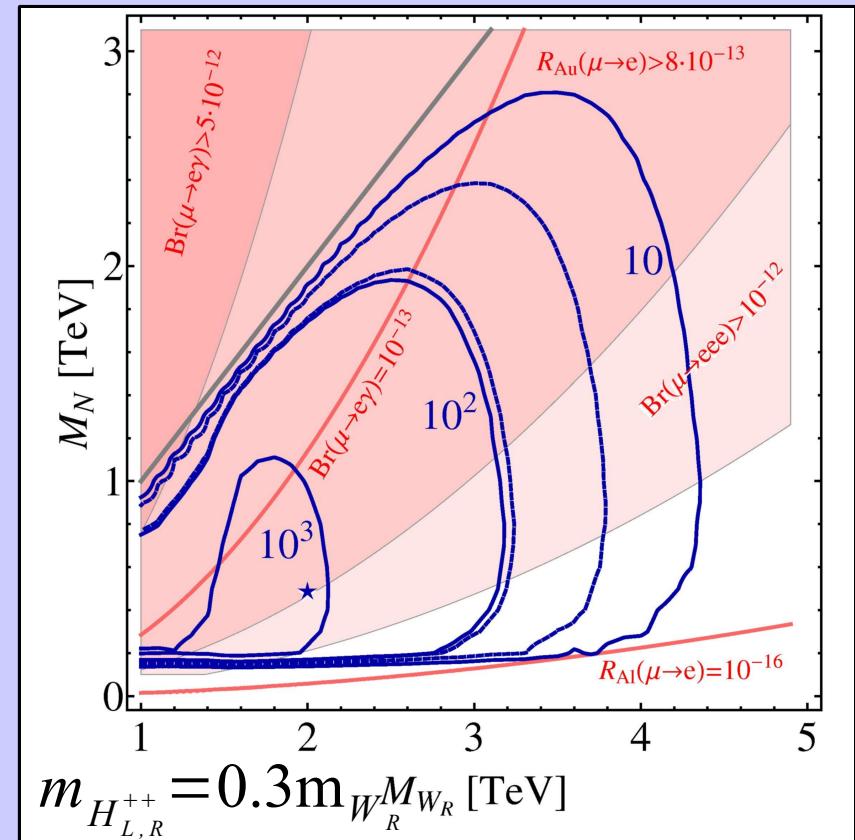
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Conclusion

- **Neutrinos much lighter than other fermions**
Strong experimental program to probe absolute mass
Mechanism of mass generation?
- **Neutrino flavour oscillations**
Nearly bi-maximal mixing \neq quark mixing
Flavour symmetry? CP Violation?
- **Neutrinos are the only neutral fermions**
Dirac or Majorana? Lepton number violation?
- **Neutrino impact on cosmology**
Baryogenesis via Leptogenesis?
- **Rich phenomenology in models of neutrino mass generation**
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 - LFV and LNV processes at the LHC

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- **Neutrinos faster than light?**
Maybe not...

