Relating the neutrino scale to the Planck scale

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Neutrino masses are very small

Why?

The seesaw mechanism

A simple and compelling explanation: add heavy right-handed neutrinos to the Standard Model particle content.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{i}{2}\overline{N_i^c}\partial\!\!\!/ N_i - Y_{ij}\bar{L}_i\widetilde{H}N_j - \frac{1}{2}M_{ij}\overline{N_i^c}N_j + \text{h.c.}$$

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$$\boxed{\mathcal{M}_\nu = YM^{-1}Y^T\langle H^0\rangle^2}$$

The seesaw mechanism

Neutrino masses are yet unknown. However,

$$\Delta m^2_{31} \simeq 2.5 \times 10^{-3}\,\mathrm{eV} \quad \text{(global fits)}$$

$$\Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\mathrm{eV} \quad \text{(global fits)}$$

$$\mathcal{M}_{ee} \leq 0.060 - 0.161\,\mathrm{eV} \quad \text{(KamLAND-ZEN)}$$

$$m_{\nu_e} \leq 2.2\,\mathrm{eV} \quad \text{(Mainz)}$$

$$\sum m_\nu \lesssim 0.16\,\mathrm{eV} \quad \text{(BOSS)}$$

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$$\boxed{\text{Data suggest } m_\nu = \mathcal{O}(0.1\,\mathrm{eV})}$$

Can the seesaw mechanism accommodate $m_\nu = \mathcal{O}(0.1\,\mathrm{eV})$

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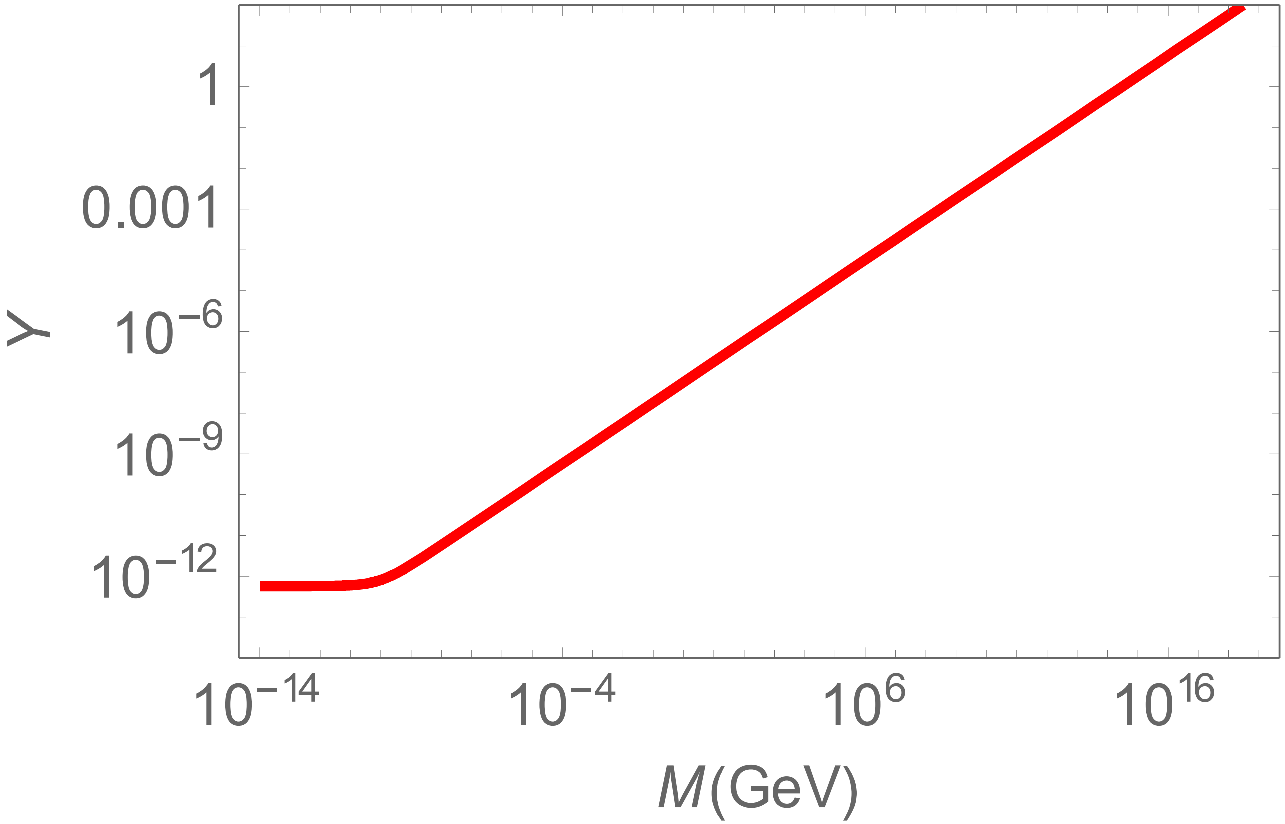
Clearly yes. Many free parameters.

The seesaw mechanism

$$\frac{Y^2}{M}\langle H^0\rangle^2 \sim 0.1\,\mathrm{eV}$$



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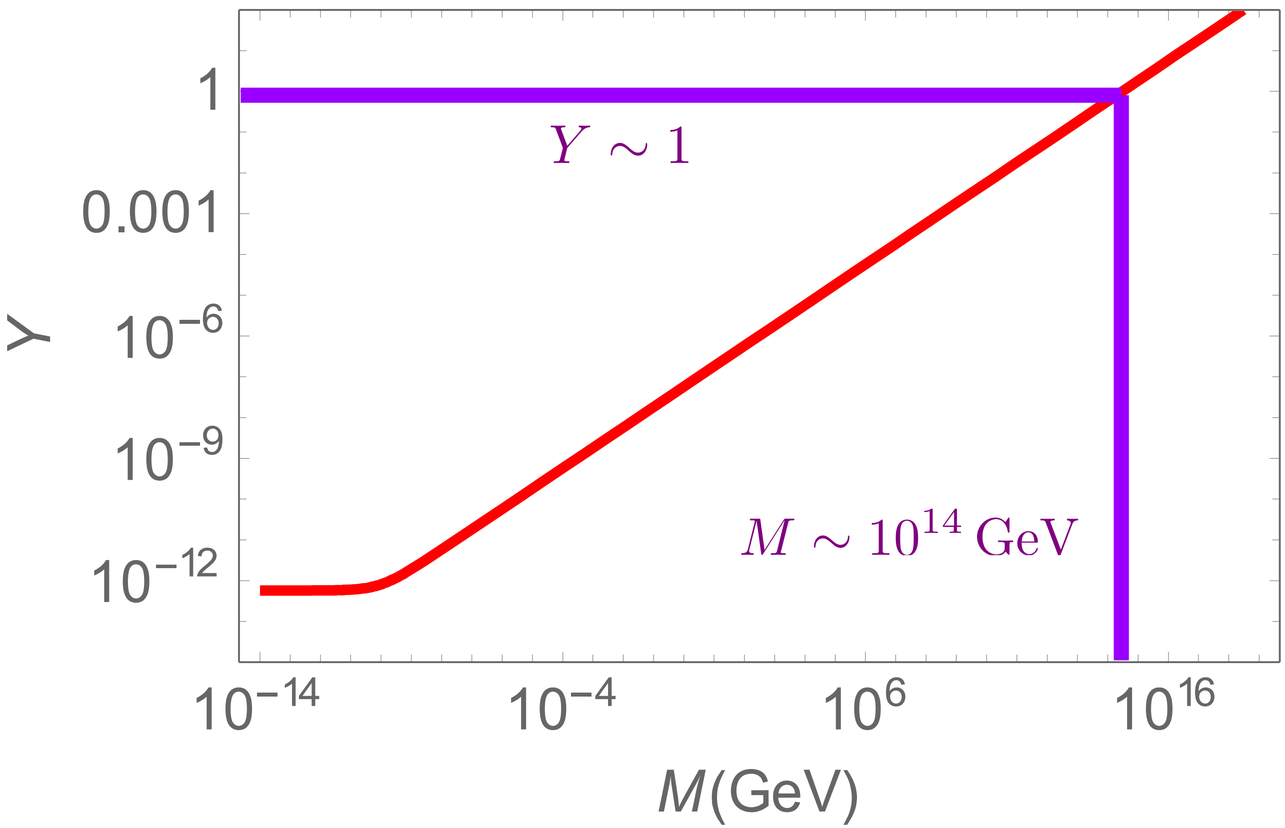

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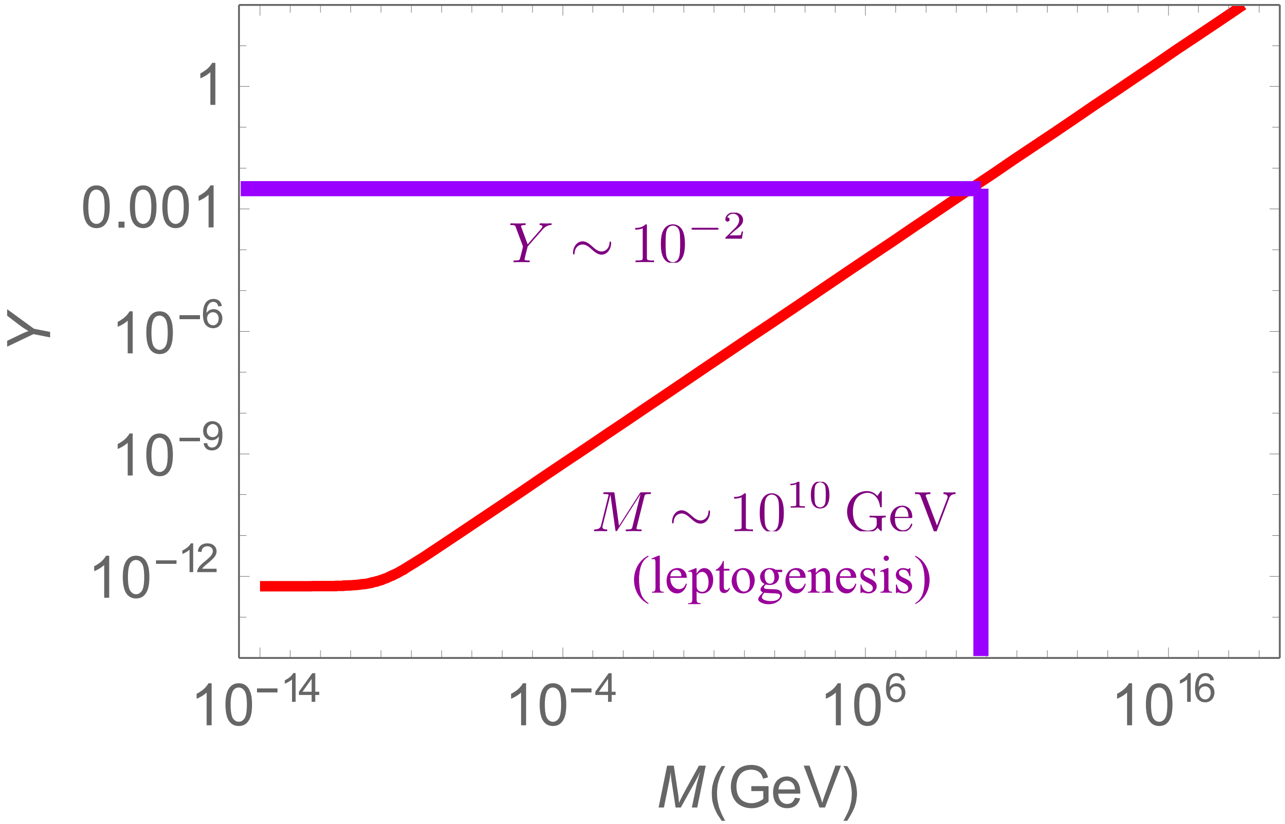

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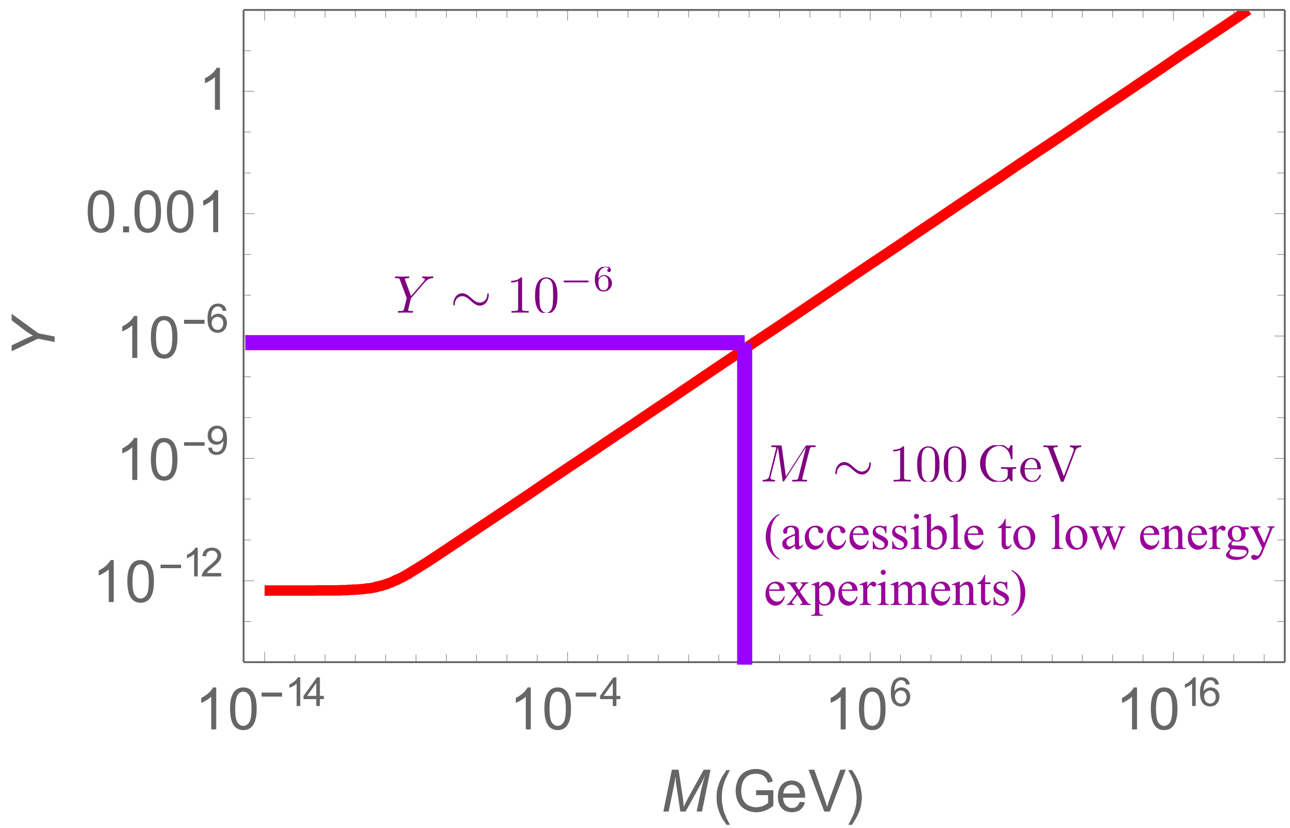

The seesaw can accommodate $m_\nu = \mathcal{O}(0.1\,\mathrm{eV})$

However, the framework is not fully satisfactory: a new mass scale has to be introduced in order to reproduce the observed neutrino mass scale

Is it possible to explain $m_\nu = \mathcal{O}(0.1\,\mathrm{eV})$

without introducing new mass scales?

(and for reasonable Yukawas)

Explaining the neutrino mass scale

Mass scales in the Standard Model

- Higgs vacuum expectation value $\langle H^0 \rangle = 174\,\mathrm{GeV}$

  (or Higgs mass parameter or Z-boson mass)

Explaining the neutrino mass scale

Mass scales in the Standard Model (extended with gravity)

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- Planck mass $M_\mathrm{P} = 1.2 \times 10^{19}\,\mathrm{GeV}$

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Note:

1) RH Majorana masses break lepton number
2) Electroweak symmetry does not break lepton number
3) Gravity effects are expected to break global symmetries

Natural values for the Majorana mass: $\sim M_\mathrm{P}$ *or zero*

Explaining the neutrino mass scale

Simplest possibilities (assume one generation of lepton doublets)

$\text{1RHN}, \; M = 0$

$$-\mathcal{L} \supset Y \bar{L} \widetilde{H} N + \text{h.c.}$$

$$m_{a_1, a_2} = \pm Y \langle H^0 \rangle$$

Excluded, unless the Yukawa is conspicuously small

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$1\text{RHN},\ M \sim M_{\text{P}}$

$$-\mathcal{L} \supset Y \bar{L} \widetilde{H} N + \frac{1}{2} M \overline{N^c} N + \text{h.c.}$$

$$m_s \sim M_{\text{P}}$$

$$m_a \sim \frac{Y^2 \langle H^0 \rangle^2}{M_{\text{P}}} \lesssim 10^{-6}\,\text{eV}$$

Too small to explain oscillation experiments

Explaining the neutrino mass scale

$2\text{RHN}, M_1 = 0, M_2 = 0$

$$-\mathcal{L} \supset Y_1 \bar{L}\widetilde{H}N_1 + Y_2 \bar{L}\widetilde{H}N_2 + \text{h.c.}$$

$$m_s = 0$$

$$m_{a_1,a_2} = \pm\sqrt{Y_1^2 + Y_2^2}\langle H^0\rangle$$

Excluded, unless the Yukawa is conspicuously small

$2\text{RHN}, M_1 \sim M_\text{P}, M_2 \sim M_\text{P}$

$$-\mathcal{L} \supset Y_1 \bar{L}\widetilde{H}N_1 + Y_2 \bar{L}\widetilde{H}N_2 + \frac{1}{2}M_1\overline{N_1^c}N_1 + \frac{1}{2}M_2\overline{N_2^c}N_2 + \text{h.c.}$$

$$m_{s_1} \sim M_\text{P}$$

$$m_{s_2} \sim M_\text{P}$$

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$$m_s \sim M_{\mathrm{P}}$$

$$m_{a_1,a_2} \sim \underbrace{\pm Y_1 \langle H^0 \rangle}_{\text{too large}} - \underbrace{\frac{Y_2^2}{2M_2} \langle H^0 \rangle^2}_{\text{too small}}$$

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We argue that:

1) This calculation is too simplistic, and leads to wrong conclusions

2) The scenario with $M_1 = 0, M_2 \sim M_{\rm P}$ leads, under reasonable assumptions, to $m_\nu = \mathcal{O}(0.1\,\text{eV})$

Symmetries in the seesaw Lagrangian

Kinetic part of the seesaw Lagrangian

$$\mathcal{L}_{\rm kin} = i\bar{L}\not{D}L + \frac{i}{2}\overline{N_j^c}\not{\partial}N_j$$

Invariant under the global symmetries

$$U(1)_L: \quad L \to e^{i\alpha}L$$

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Key observation: non-vanishing values for Y_1, Y_2, M_2 already break the global symmetry completely. No symmetry protects M_1 and will be generated by quantum effects, proportional to M_2

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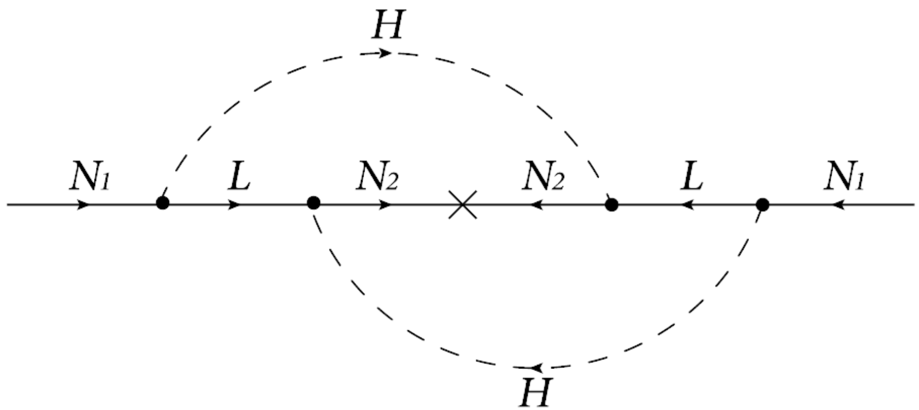
$$U(1)_L \times U(2)_N \xrightarrow[Y_2,\, M_2]{} U(1)_{N_1}$$

If Y_1 or Y_2 vanish, there is a residual U(1) global symmetry $N_1 \to e^{i\beta} N_1$ that protects M_1 against quantum effects.

Quantum effects on RH neutrino masses

Assume that the conditions $M_1 = 0, M_2 \sim M_\mathrm{P}$ hold at a cut-off scale $\Lambda = M_\mathrm{P}$

Two loop effects induce a mass for M_1



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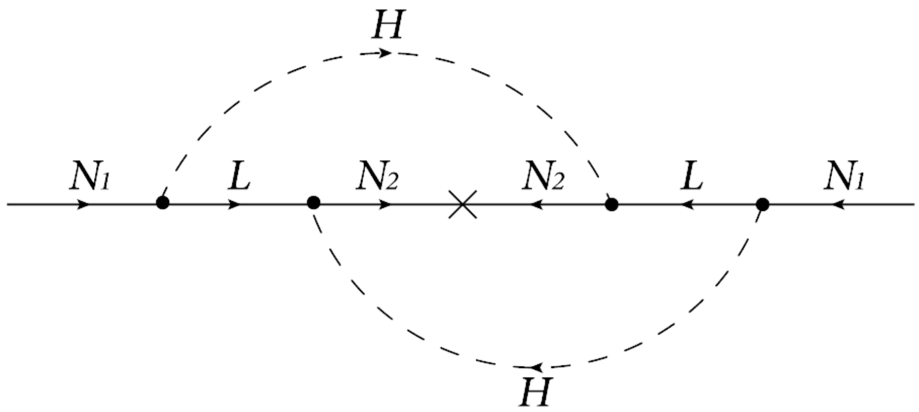


Physical RH neutrino masses

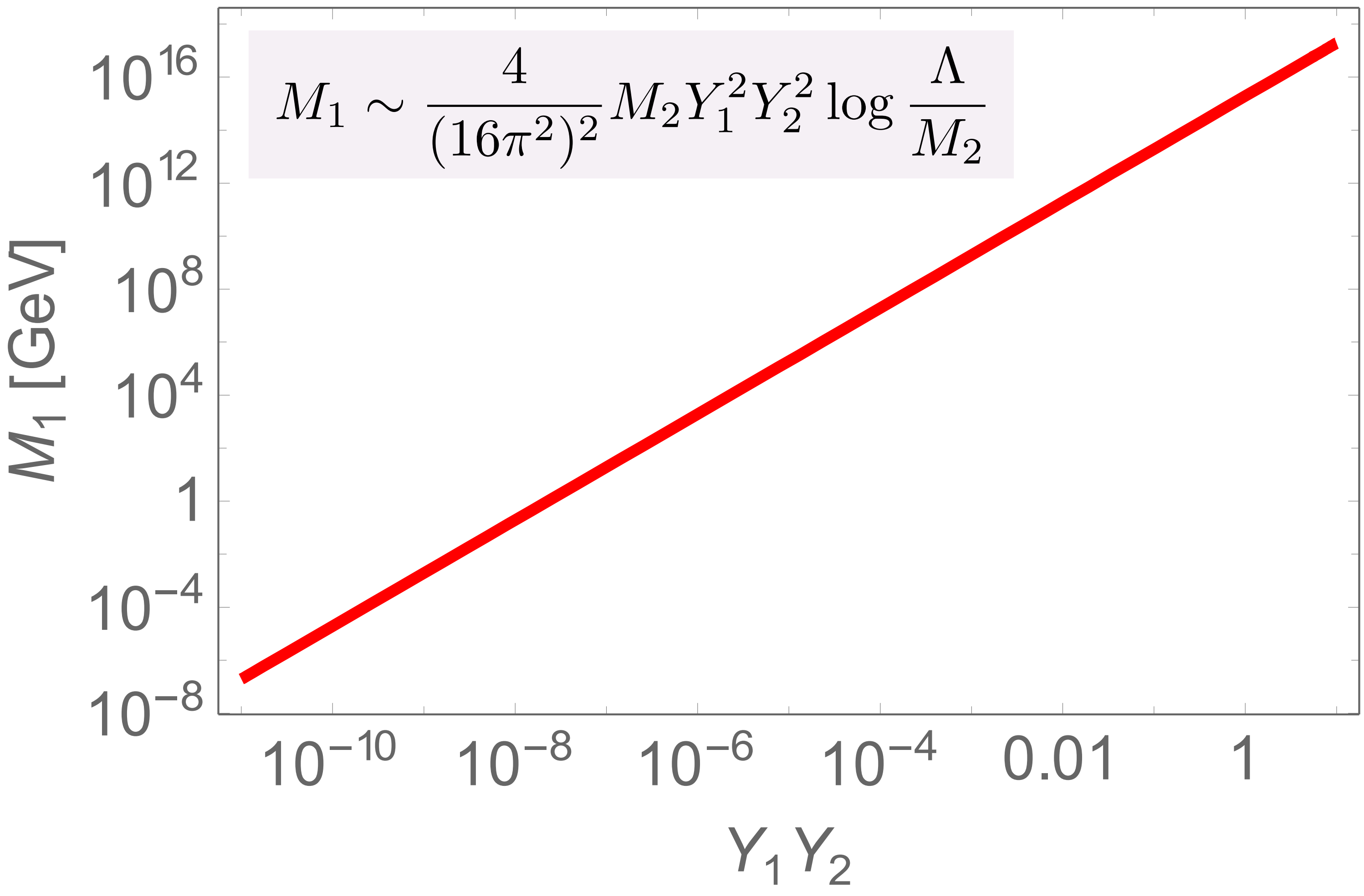
$$M_2\Big|_{\mu=M_2} \sim M_\mathrm{P}$$

$$M_1\Big|_{\mu=M_1} \sim \frac{4}{(16\pi^2)^2} M_2 Y_1^2 Y_2^2 \log\frac{\Lambda}{M_2}$$

Quantum effects on RH neutrino masses

Implications

1- A non-zero Majorana mass for the lightest RH neutrino is generated via quantum effects



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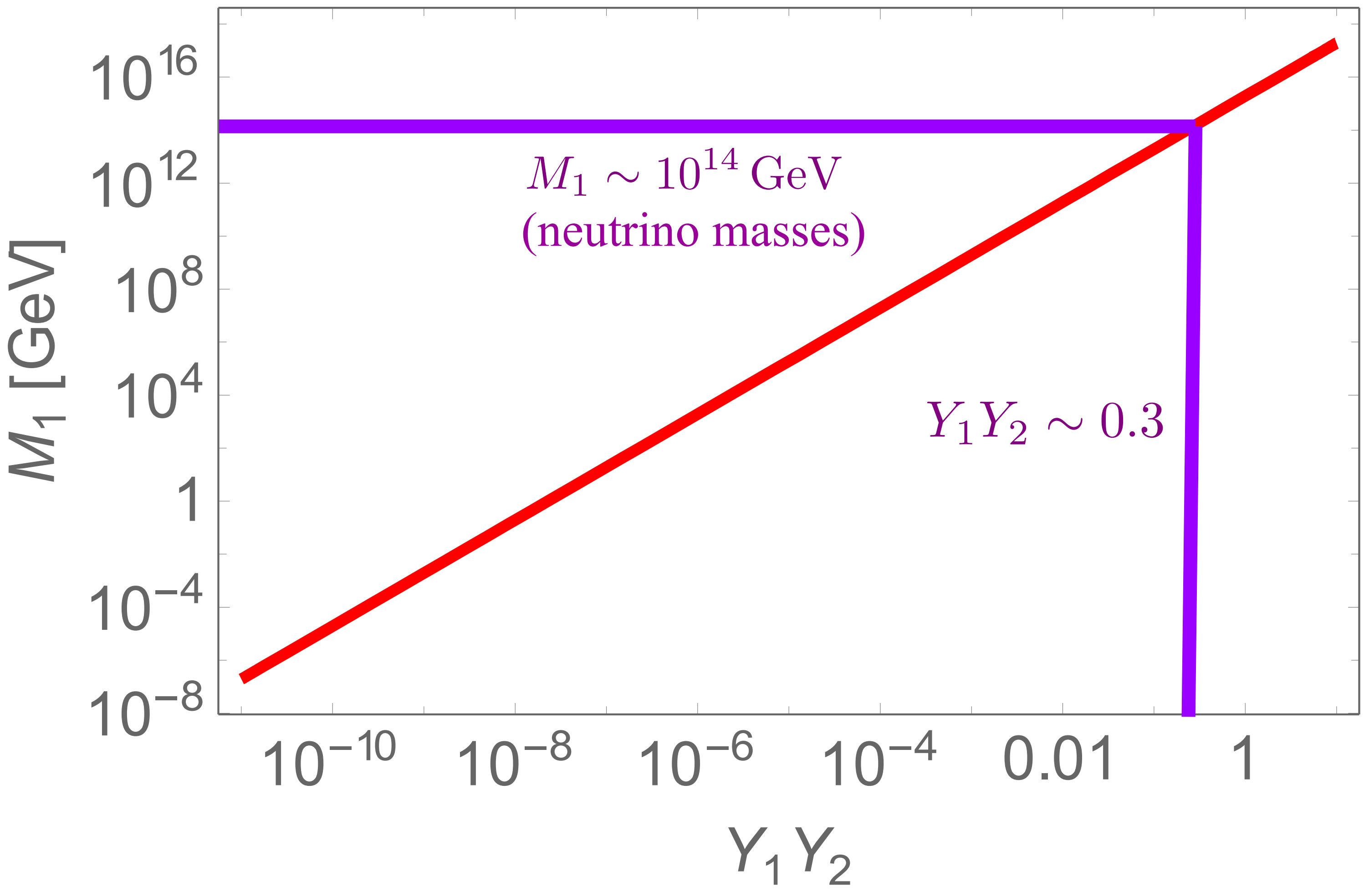

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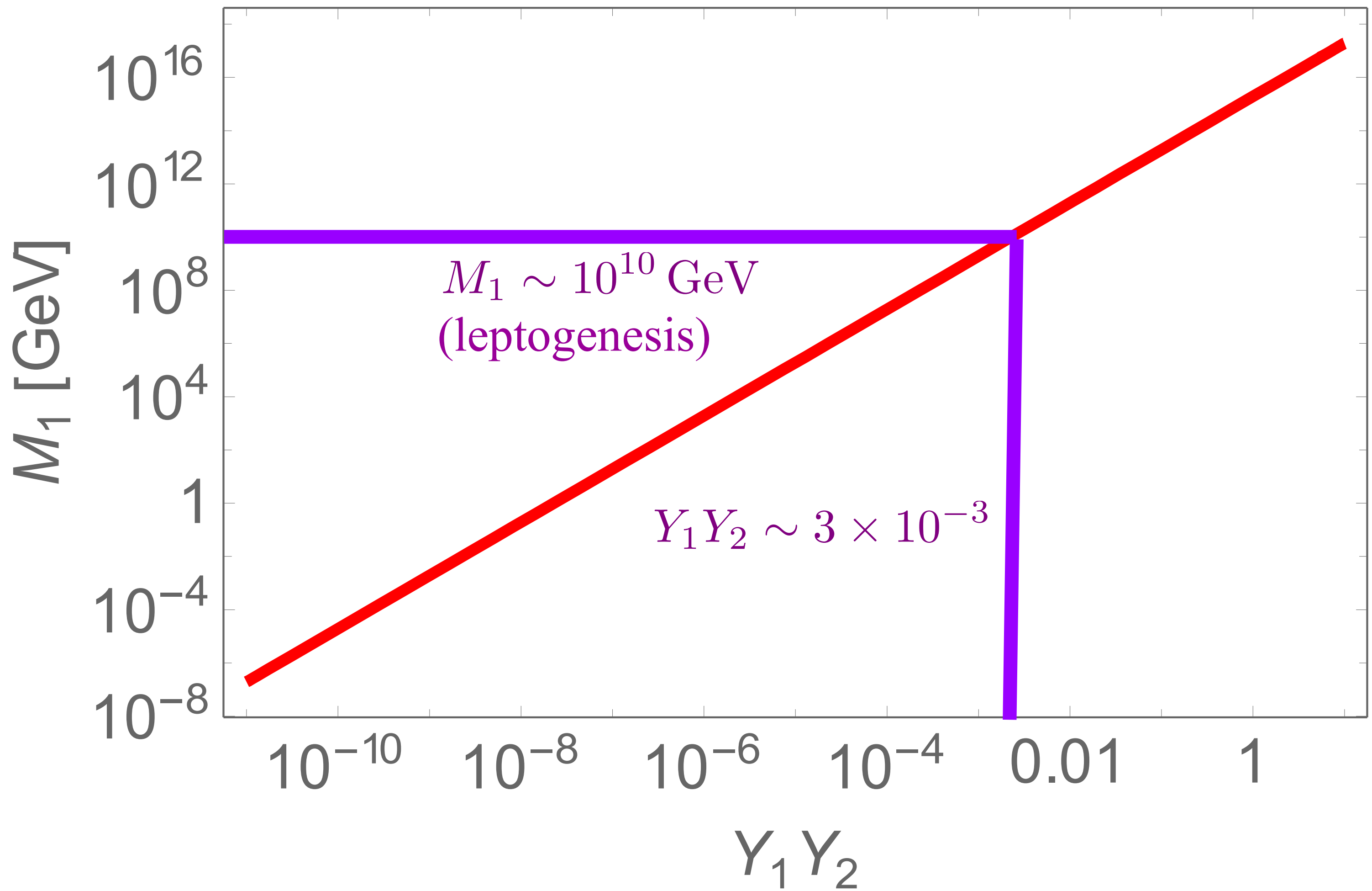

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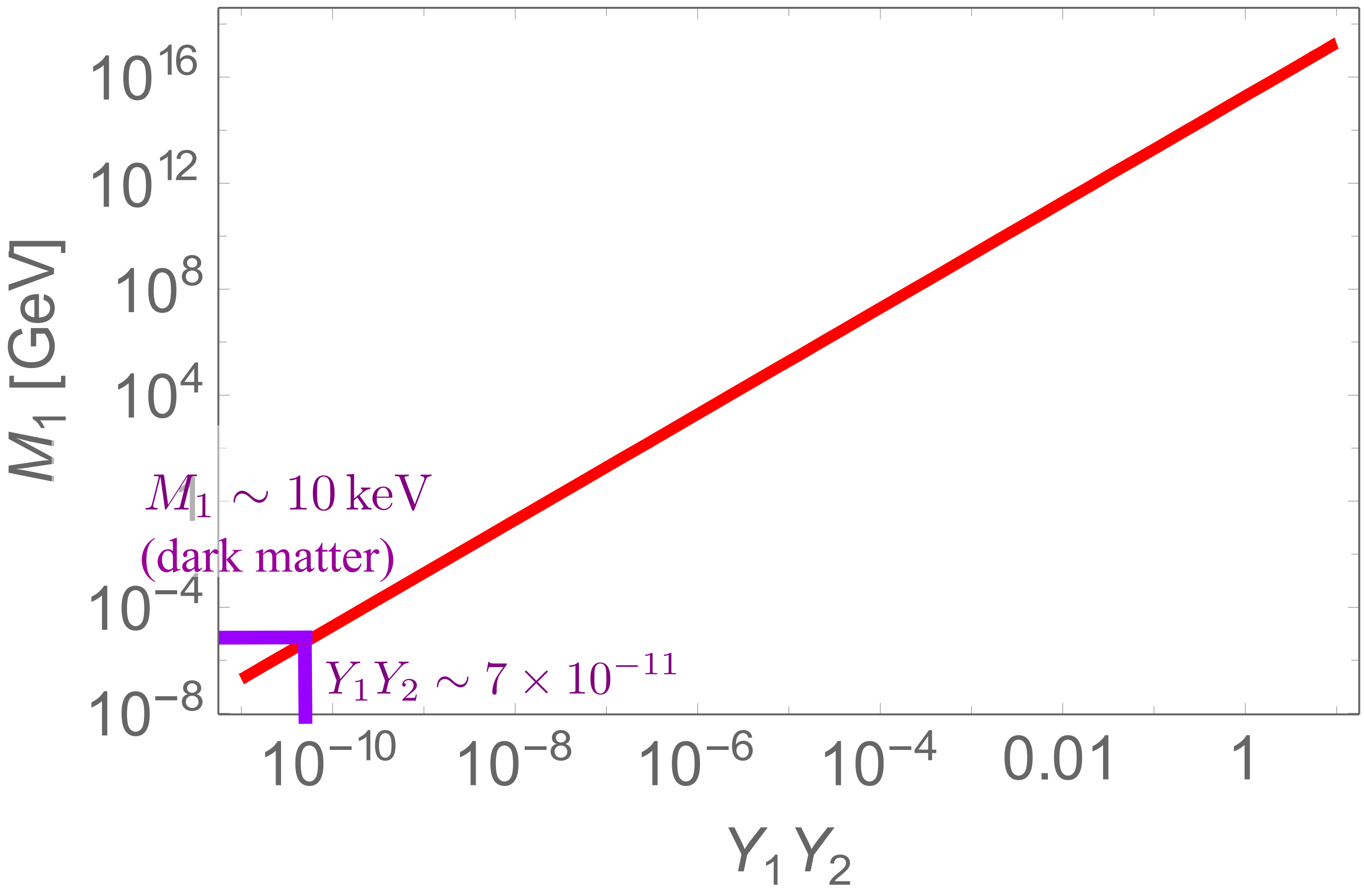

Quantum effects of RH neutrino masses

Implications

2- The number of free parameters is reduced

The seesaw model with two right-handed neutrinos and one lepton doublet contains 5 parameters

$$Y_1, \quad Y_2, \quad |M_1|e^{i\alpha}, \quad |M_2|$$

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If $M_1(\Lambda) = 0$
only 3 parameters

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Enhanced predictivity.

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Same conclusion also when $M_1(\Lambda) \neq 0$, if the quantum contribution dominates over the tree level value.

$$M_1(M_1) = M_1(\Lambda) + \underbrace{\delta M_1}_{\substack{\text{prop. to } M_2 \\ \text{possibly larger than } M_1(\Lambda)}}$$

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Enhanced predictivity.

Implications for sterile neutrino dark matter?
For leptogenesis?
For collider searches?
...
For the neutrino mass spectrum?

Quantum effects of RH neutrino masses

Implications

3- The neutrino spectrum is significantly modified with respect to the naïve (tree-level) calculation

Tree level result

$$m_s \sim M_{\mathrm{P}}$$

$$m_{a_1,a_2} \sim \pm Y_1 \langle H^0 \rangle - \frac{Y_2^2}{M_2} \langle H^0 \rangle^2$$

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Wrong

$$m_{s_2} \sim M_2\Big|_{\mu=M_2} \sim M_\mathrm{P}$$

$$m_{s_1} \sim M_1\Big|_{\mu=M_1} \sim \frac{4}{(16\pi^2)^2} M_2 Y_1^2 Y_2^2 \log\frac{\Lambda}{M_2}$$

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$$m_a \sim 0.05\,\mathrm{eV} \left(\frac{Y_2}{0.6} \right)^{-2} \left(\frac{M_2}{1.2 \times 10^{19}\,\mathrm{GeV}} \right)^{-1}$$

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This relation arises naturally if:

- The Standard Model is extended by right-handed neutrinos.
- Lepton number is broken at ~ M_P
- The heaviest RH neutrino couples to the lepton doublet with an O(1) Yukawa coupling.
- One of the right-handed neutrinos is very light at the cut-off scale, such that its mass is dominated by quantum effects induced by the Higgs boson.

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No new scales, no new symmetries, no new particles (other than the right-handed neutrinos)

The realistic case with 3 lepton doublets and 3 right-handed neutrinos

Kinetic part of the seesaw Lagrangian

$$\mathcal{L}_{\text{kin}} = i\bar{L}_j \not{D} L_j + \frac{i}{2}\overline{N_j^c}\not{\partial} N_j$$

Invariant under the global symmetries

$$U(3)_L : \quad L \to U\,L \qquad\qquad \text{with } N = \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}, \quad L = \begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix}$$

$$U(3)_N : \quad N \to U\,N$$

The Yukawa couplings and RH masses break the global symmetry

$$U(3)_L \times U(3)_N \xrightarrow[Y_{ij}, M_1, M_2, M_3]{} \text{nothing}$$

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No symmetry protects M_1 and will be generated by quantum effects, proportional to M_2, M_3

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The realistic case with 3 lepton doublets and 3 right-handed neutrinos

Assume that the conditions $M_3 \sim M_{\rm P},\ M_2 \ll M_3,\ M_1 = 0$ hold at some cut-off scale Λ, close to the Planck mass. The physical masses are:

$$M_3 \sim M_{\rm P}$$

$$M_2 \sim -\frac{1}{(16\pi^2)^2} M_3 y_3^4 \sin^4\zeta \times O(1)\ \text{factors}$$

$$M_1 \sim M_2 \frac{\sin^4\xi}{\sin^4\zeta} \times O(1)\ \text{factors}$$

The realistic case with 3 lepton doublets and 3 right-handed neutrinos

Assume that the conditions $M_3 \sim M_{\rm P},\ M_2 \ll M_3,\ M_1 = 0$ hold at some cut-off scale Λ, close to the Planck mass. The physical masses are:

$$M_3 \sim M_{\rm P}$$

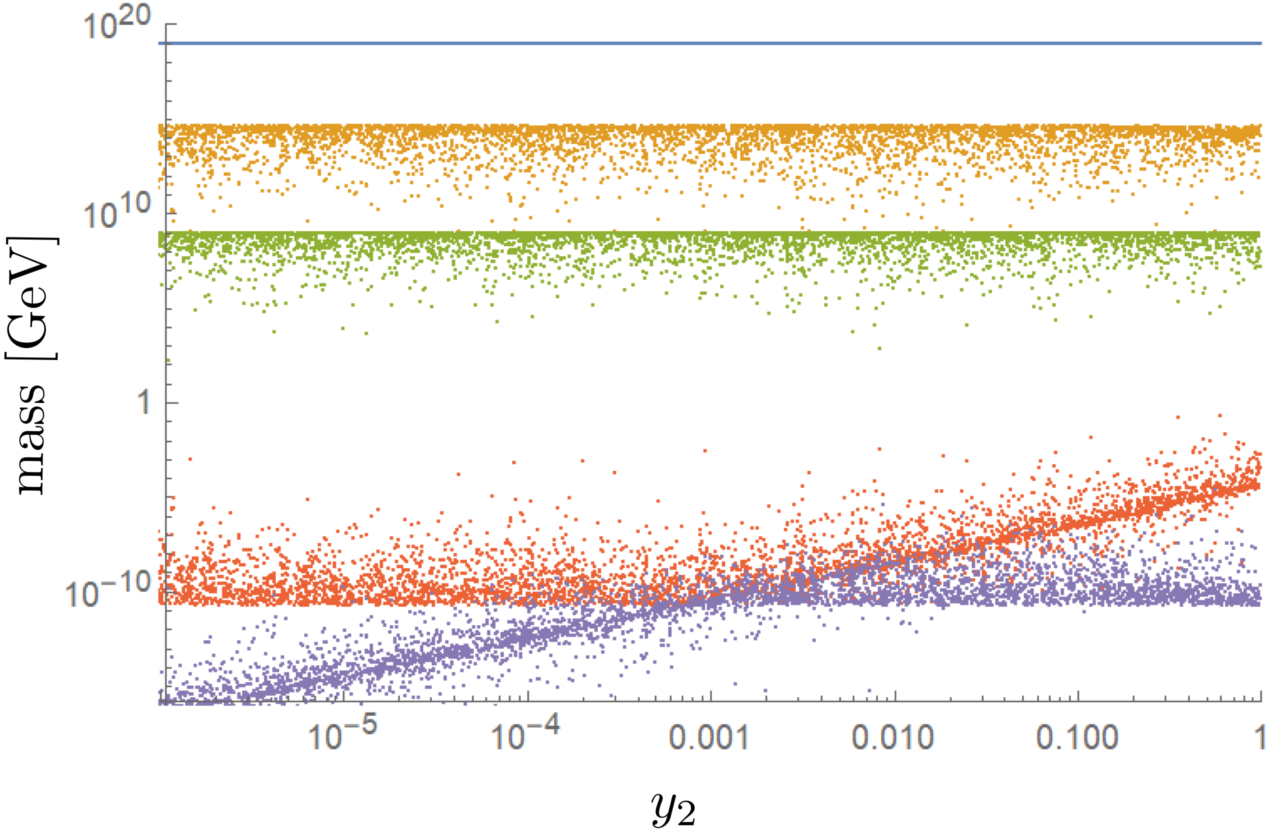
$$M_2 \sim -\frac{1}{(16\pi^2)^2} M_3 y_3^4 \sin^4\zeta \times O(1)\ \text{factors}$$

$$M_1 \sim M_2 \frac{\sin^4\xi}{\sin^4\zeta} \times O(1)\ \text{factors}$$

y_3 : largest Yukawa eigenvalue

$\sin\zeta$: combination of mixing angles in the RH sector

The realistic case with 3 lepton doublets and 3 right-handed neutrinos



Values at the cut-off

$M_3 = 10^{19}$ GeV

$M_2 = 10^{9}$ GeV

$M_1 = 0$

$y_3 = 1$

$y_2 =$ free

$y_1 = 0$

- One of the active neutrino masses lies in the ballpark of the experimental values.
- Possible to obtain the correct mass hierarchy.

- The seesaw scenario with Planck scale lepton number breaking generically leads to one active neutrino mass O(0.1) eV.
But, the other active neutrino mass has to be adjusted.

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• The seesaw scenario with two Higgs doublets generically leads to a mild neutrino mass hierarchy.
But the overall neutrino mass has to be adjusted. Ibarra, Simonetto
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- The seesaw scenario with two Higgs doublets generically leads to a mild neutrino mass hierarchy.
But the overall neutrino mass has to be adjusted.

Ibarra, Simonetto
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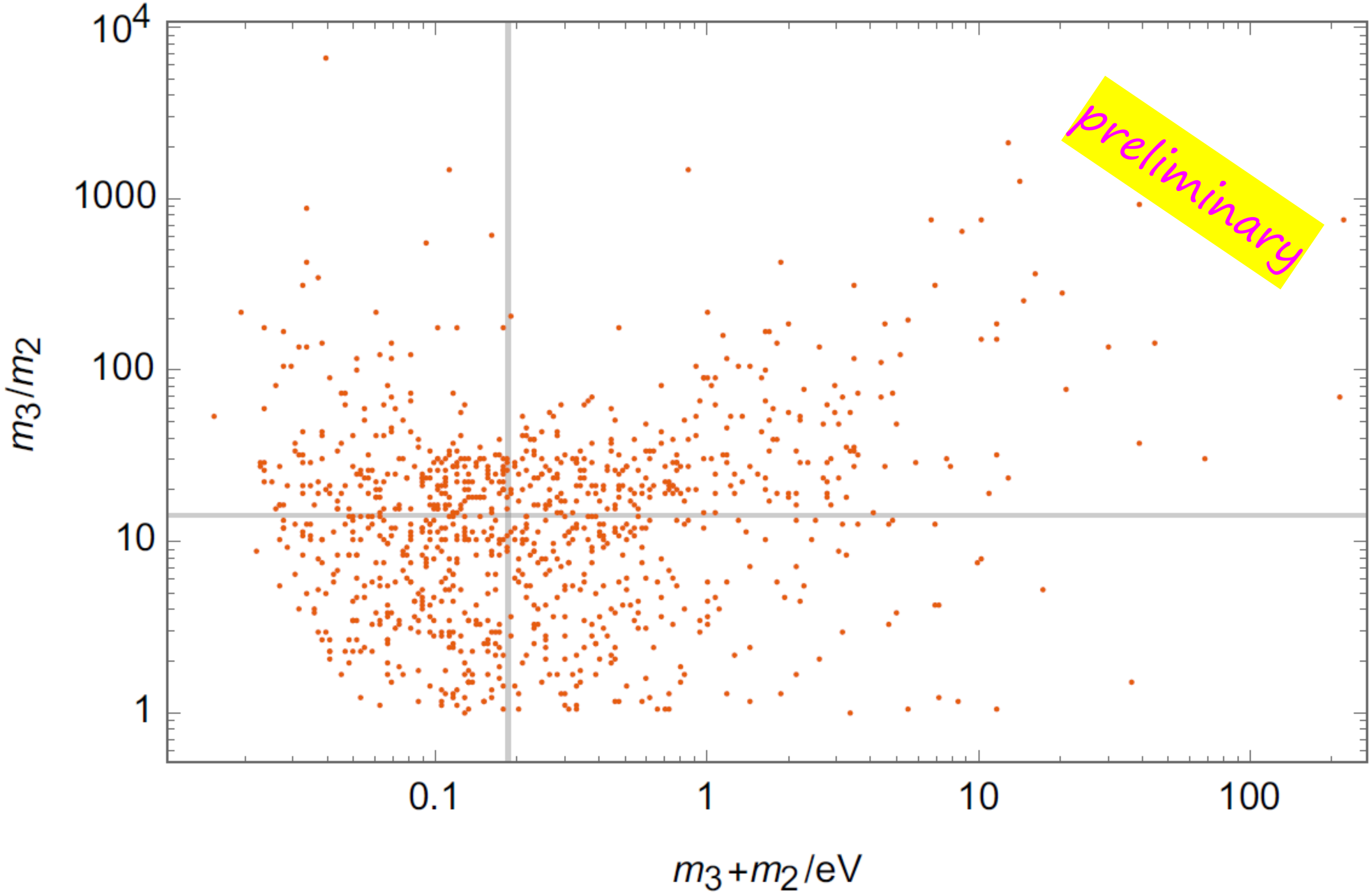
Combine both frameworks

A mild mass hierarchy from an extended scalar sector



Conclusions

• We have studied a seesaw scenario where the right-handed neutrino mass matrix has very hierarchical eigenvalues at the cut-off scale. We have shown that the lighter RH neutrino masses receive sizeable (possibly dominant) contributions from quantum effects.

• If the lepton number breaking occurs at $\sim M_{\rm P}$, and for reasonable Yukawas, this scenario leads quite generically to an active neutrino mass O(0.1) eV. No additional particles nor new symmetries are needed.

$$(16\pi^2)^2 \frac{\langle H^0 \rangle^2}{M_{\rm P}} \sim m_\nu$$

• A mild neutrino mass hierarchy is not predicted, but can be accommodated. An extension of the model by one scalar doublet leads, under reasonable assumptions, also to a neutrino mass hierarchy in the ballpark of the experimental values.

• This scenario contains less free parameters than the general seesaw mechanism. Predictions and other applications are under investigation.