On Perturbative Completions to the Neutrino Option: No-Go Constraints

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[2009.11813]

[2010.15428]

w/ I Brivio & M. Trott

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Outline

The Neutrino Option and its phenomenology

UV completions & global symmetries

No-go constraints

The Neutrino Option: Type-I seesaw

- The Type-I seesaw model (Minkowski '77, et al.) is perhaps the most popular mechanism for generating light neutrino masses:

$$\mathcal{L}_N = \frac{1}{2}\left(\bar{N}_p i\partial\!\!\!/ N_p - \bar{N}_p M_{pr} N_r\right) - \left[\bar{N}_p\, \omega_{p\beta}\, \tilde{H}^\dagger l_\beta + \mathrm{h.c.}\right] \qquad N_p = e^{i\theta_p/2} N_{R,p} + e^{-i\theta_p/2} (N_{R,p})^c$$

- Upon integrating out heavy sterile neutrinos N, one induces a contribution to the (Weinberg '79) operator of the dim-5 SM-EFT:

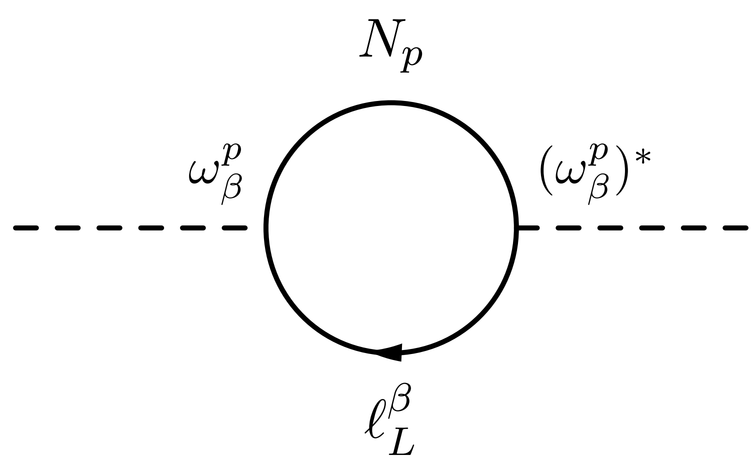
$$\mathcal{L}^{(5)} = \frac{c^{(5)}_{\alpha\beta}}{2}\left(l^T_\alpha \tilde{H}^*\right) C \left(\tilde{H}^\dagger l_\beta\right) + \mathrm{h.c.} \qquad c^{(5)}_{\alpha\beta} = \left(\omega^T M^{-1} \omega\right)_{\alpha\beta}$$

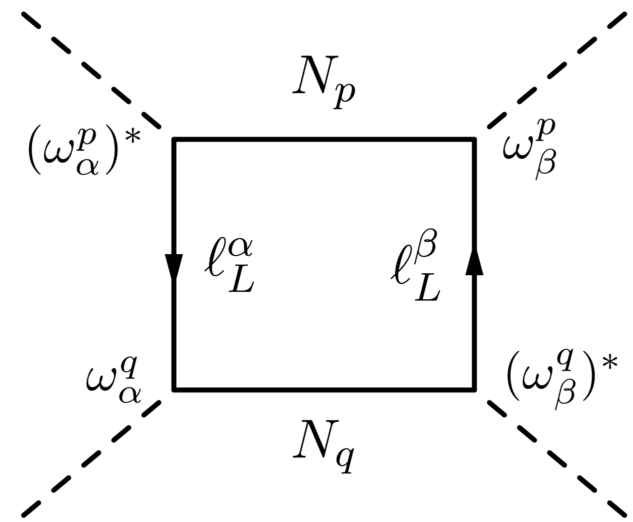
- Upon EWSB, this then describes light, LH Majorana neutrinos in accord with data:

$$\mathcal{L}^{(5)} \supset -\frac{m_{\nu,k}}{2}\, \overline{\nu_L^{\prime c,k}}\, \nu_L^{\prime k} + \mathrm{h.c.} \qquad m_{\nu,k} = -\frac{v^2}{2} (U^T)_{k\alpha}\, c_{5,\alpha\beta}\, U_{\beta k}$$

The Neutrino Option: basic idea

- But integrating out heavy N does more than just induce light neutrinos…





$$V(H) = -\frac{m_{h0}^2 + \Delta m_h^2}{2} H^\dagger H + (\lambda_0 + \Delta\lambda)(H^\dagger H)^2 \longrightarrow \Delta m_{\rm h}^2 = M_p^2 \frac{|\omega_p|^2}{8\pi^2}$$

- This is either **(A)** a direct *manifestation* of the EW hierarchy problem (*Vissani 1998*),
- or **(B)** a route to a minimal *solution* of the EW hierarchy problem (*Brivio, Trott 2017*)! This scenario is the so-called **Neutrino Option.**

$$m_\nu \sim \frac{\omega_p^2 \bar{v}_T^2}{M_p}, \quad m_h \sim \frac{\omega_p M_p}{4\pi}, \quad \bar{v}_T \sim \frac{\omega_p M_p}{4\sqrt{2}\pi\sqrt{\lambda}}$$

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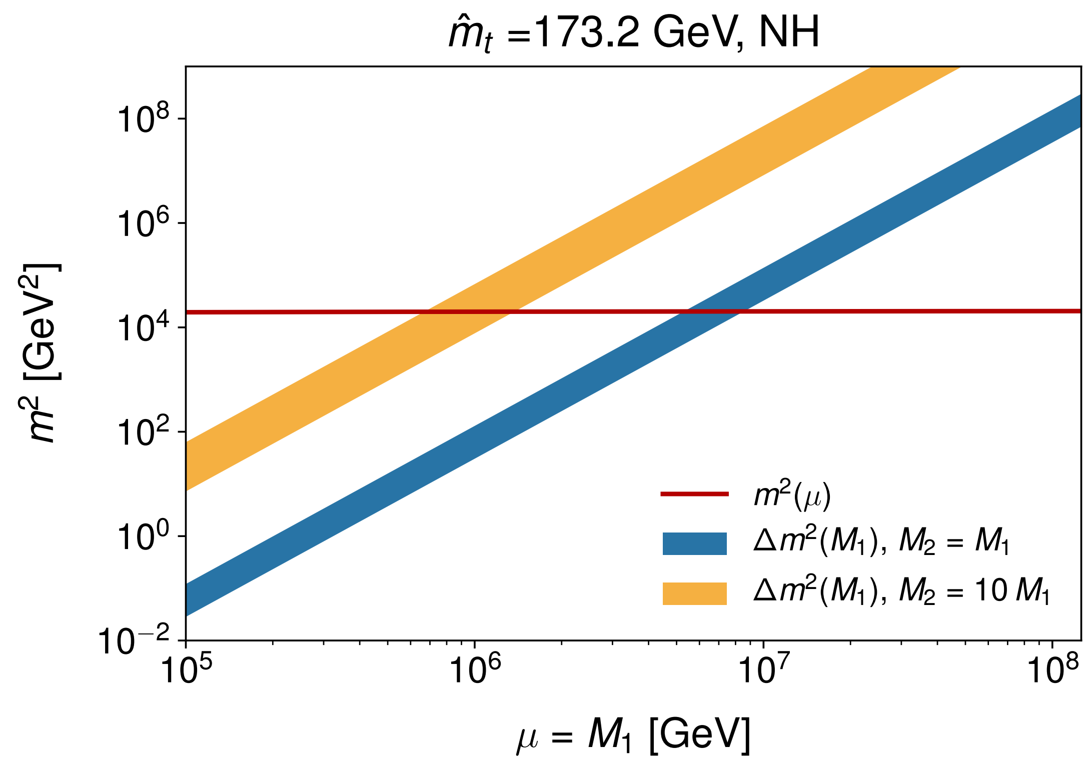
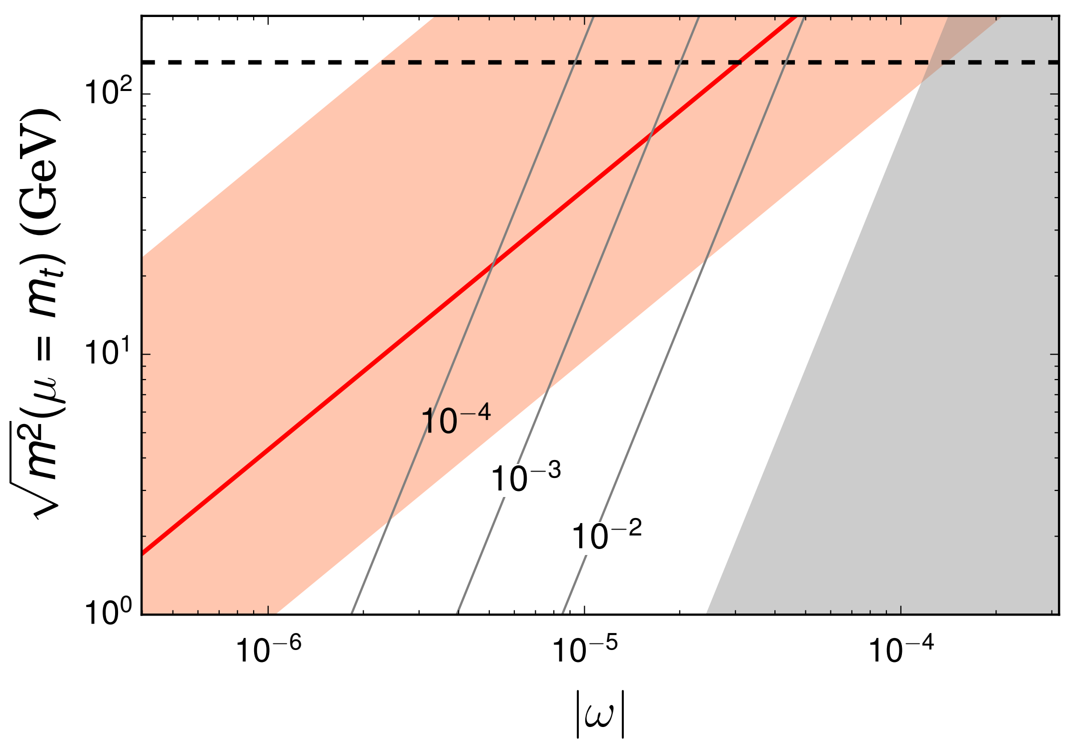
[1809.03450]

The Neutrino Option: phenomenology





[1703.10924]
[1809.03450]
[1905.12642]
[1905.12634]

Higgs Mass

125.10±0.14

(2020 PDG Average)

+

Neutrino Masses

$$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2} \qquad \frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$$

$$7.42^{+0.21}_{-0.20} \qquad 2.514^{+0.028}_{-0.027}$$

(2020 NuFIT)

+

Other precision inputs (e.g. top mass) & RGE

=

$$M \lesssim 10^4\,\mathrm{TeV} \simeq 10\,\mathrm{PeV}\,. \qquad |\omega| \simeq \frac{\mathrm{TeV}}{M}$$

\+ Leptogenesis

$$M \gtrsim 1\,\mathrm{PeV}$$

What about the Majorana scale?!

Hierarchy Problem ———————- ✔

Neutrino Masses ——————— ✔

CP Violation / Leptogenesis - ✔

Dark Matter ——————————- ✔?

Flavour Problem ——————— - ✔?

…

K.Steegmans

- The Neutrino Option is consistent with a number of the outstanding issues of BSM physics!
- **BUT**, an explanation for the required PeV scale Majorana neutrinos is needed…

What are the minimal options for UV-completing the Neutrino Option?

UV completions: the minimal requirements

In general, a successful UV completion to the Neutrino Option will

1. generate at least two non-zero sterile neutrino masses.
2. not introduce additional large threshold corrections to the Higgs mass, from beyond the Majorana mass sector.
3. not generate unsuppressed EFT terms proportional to $(\bar{N}N)(H^\dagger H)$.
4. not spoil the RGE of Higgs and neutrino parameters via new states.
5. not introduce fine-tuning of parameter space.

Generic symmetric perturbations

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- Consider a minimal scenario where a single UV Majorana scale is given by GUT or Plankian dynamics. E.G. :

UV mechanism plausibly flavor-blind, see e.g. [9205230]

$$M = \frac{M_{UV}}{3}\begin{pmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{pmatrix} \longrightarrow M = \begin{pmatrix}0 & & \\ & 0 & \\ & & M_{UV}\end{pmatrix}$$

- Consider generic perturbations about symmetric matrix elements:

$$U_0^f = \begin{pmatrix} a & a & a\\ a & a & a\\ a & a & a\end{pmatrix} \longrightarrow U_0 + U = U_0 + \sum_k \alpha_k \cdot \chi^k$$

$$\lambda_{U_0^f} \in \{3a, 0, 0\}$$

Induced by some perturbative UV mechanism…

$$\chi^{(1,2,3)}|_{3D} \in \left\{\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, \begin{pmatrix}0&0&0\\0&1&0\\0&0&0\end{pmatrix}, \begin{pmatrix}0&0&0\\0&0&0\\0&0&1\end{pmatrix}\right\}$$

$$\chi^{(4,5,6)}|_{3D} \in \left\{\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}, \begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}, \begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}\right\}.$$

- Both diagonal and off-diagonal perturbations can generate additional non-zero eigenvalues:

$$U_0^f + \alpha_k \chi^k|_{k=1,2,3} \implies \lambda_{U_1^f} \in \left\{0, \frac{1}{2}\left(3a + \alpha_k \pm \sqrt{9a^2 - 2a\alpha_k + \alpha_k^2}\right)\right\}$$

$$U_0^f + \alpha_k \chi^k|_{k=4,5,6} \implies \lambda_{U_1^f} \in \left\{-\alpha_k, \frac{1}{2}\left(3a + \alpha_k \pm \sqrt{9a^2 + 2a\alpha_k + \alpha_k^2}\right)\right\}.$$

- **GOAL**: identity physical mechanism for generating perturbations to M(UV).
- **BUT**: we must simultaneously **DE**-couple M_{UV} from Higgs threshold corrections…

Global symmetries of the Type-I seesaw

[2010.15428]

- Before looking into these, let's return to the Type-I seesaw Lagrangian:

$$\mathcal{L}_N = \frac{1}{2}\left(\bar{N}_p i\partial\!\!\!/ N_p - \bar{N}_p M_{pr} N_r\right) - \left[\bar{N}_p\, \omega_{p\beta}\, \tilde{H}^\dagger l_\beta + \text{h.c.}\right]$$

- This exhibits a number of global (continuous & discrete) symmetries, depending on the number of sterile N generations (n):

Kinetic Terms		Mass Term			Yukawa Terms
$\mathrm{U(1)_{N,3} \times SU(3)_N}$		$U(1)_{N,2} \times SU(2)_N \times \mathbb{Z}_2$	$(n=1)$		
	$\longrightarrow$	$U(1)_N \times \mathbb{Z}_2 \times \mathbb{Z}_2$	$(n=2)$	$\longrightarrow$	$\mathrm{U(1)_{l+N} \supset U(1)_{l,3} \times U(1)_{N,3}}$
$\mathrm{U(1)_{l,3} \times SU(3)_l}$		$\mathbb{Z}_2 \times \mathbb{Z}_2$	$(n=3)$		
		[Lam 2007]			

- Augment the (a priori) *accidental* Z_2 symmetry to a UV fixed-point *natural* symmetry of the UV Lagrangian:

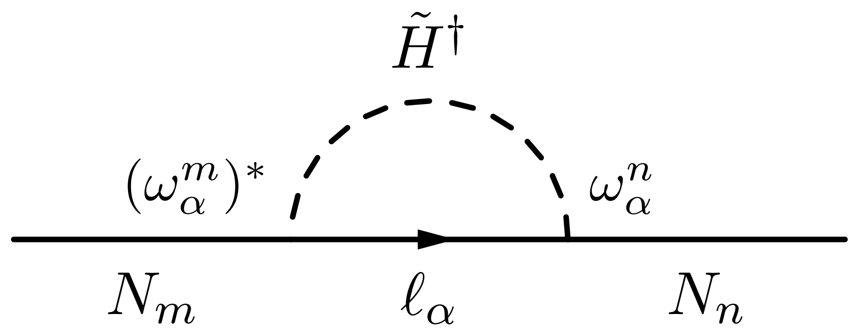
$$N_p \longrightarrow T_{pr}\, N_r\,, \quad \text{with} \quad T_{pr} = \text{diag}\,(1, 1, -1)$$

$$\bar{N}\,\omega\,\tilde{H}^\dagger\, l \overset{!}{=} \bar{N}\,T^\dagger\,\omega\,\tilde{H}^\dagger\, l$$
$$\Rightarrow\ T^\dagger\,\omega = \omega \ \Rightarrow\ \omega_{3\beta} \equiv 0$$

- Finally, recall that non-zero M eigenvalues correspond to $\Delta L = 2$ violation.

One-loop perturbative corrections

- The relevant one-loop diagram to consider in the Type-I seesaw is given by:



???

$$\delta_M^{(1)} = \frac{|\omega|^2}{16\pi^2} M_{UV}$$

$$\delta_M^{(1)} \simeq \text{PeV} \quad \text{for} \quad \begin{cases} |\omega| \simeq 10^{-4}\,, & (M_{UV} \simeq M_{GUT}) \\ |\omega| \simeq 10^{-5.5}\,. & (M_{UV} \simeq M_{Pl}) \end{cases}$$

- Unfortunately, neither **threshold corrections** nor **RGE** can induce non-zero masses from initially massless N at one-loop, in minimal setup:

$$\Delta L = 2$$ ✗

- **Option (1)**: consider n = 2 UV mass scales. Then corrections go as $\omega\omega^\dagger$.

$$\mathbb{Z}_2 \times \mathbb{Z}_2$$ ✗

- Allowing for soft Z_2 breaking, the RGE at one-loop reads:

$$16\pi^2 \mu \frac{dM}{d\mu} = \left(\omega\omega^\dagger\right) M + M \left(\omega\omega^\dagger\right)^T \equiv \mathcal{R} \longrightarrow \begin{array}{c} M_p(\mu) = \gamma_p(\mu,\mu_0) M_p(\mu_0)\,, \\ \gamma_p(\mu,\mu_0) \sim 1 + \frac{\omega^2}{16\pi^2} \ln\left[\frac{\mu}{\mu_0}\right] \end{array} \longrightarrow \gamma_p(\text{PeV}, M_{UV}) = \epsilon \simeq \frac{\text{PeV}}{M_{UV}} \sim 10^{-10} - 10^{-13}$$

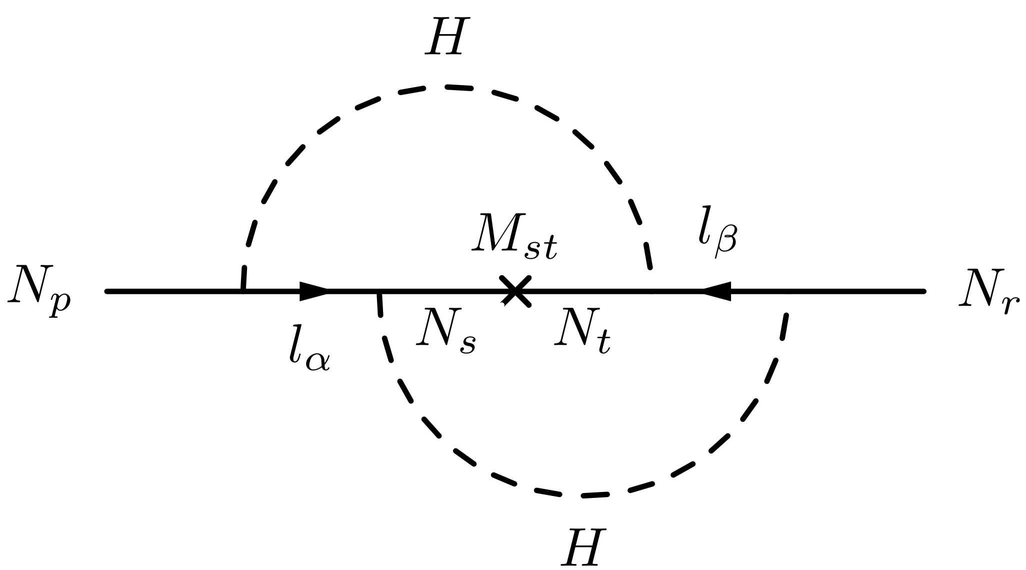
Extreme fine-tuning required! ✗

Multi-loop corrections?

[1802.09997]
[2006.13584]
[2010.15428]

- **Option (2)**: consider two/multi-loop perturbative generation with n=1:

Multi-loop corrections?



$$\delta^{(2)}_{M,pr} \sim \frac{(\omega\omega^\dagger)_{p3}(\omega\omega^\dagger)_{r3}}{256\pi^4} M_{UV}$$

$$\delta^{(2)}_M \neq 0 \text{ only if } \omega_{3\beta} \neq 0$$

Higgs mass unprotected! ✗

$$\omega\omega^\dagger M\,, \quad \omega\omega^\dagger M(\omega\omega^\dagger)^T\,, \quad (\omega\omega^\dagger)(\omega\omega^\dagger)M$$

$\mathbb{Z}_2$ ✗

- Even if we allow for soft Z_2 breaking, the desired mass scales are too low for the PeV scales required. ✗
- Such scales may be interesting, however, for light sterile neutrino phenomenology…
- Multi-loop corrections with new states may also be interesting…

New BSM states?

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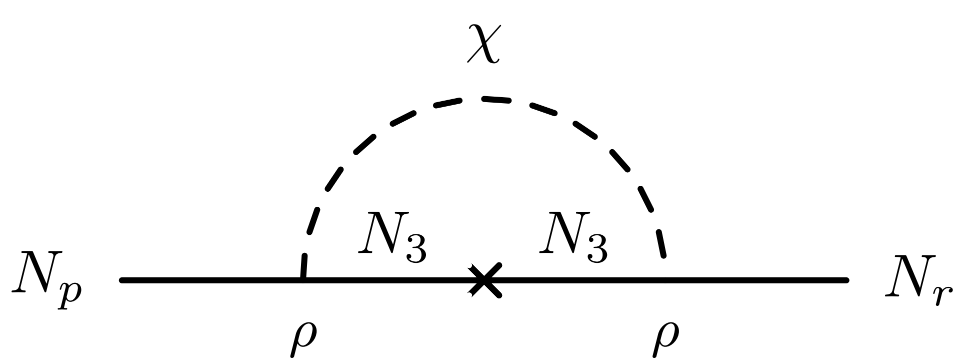
- Allow a generic new boson (vector or scalar) in a minimal extension to the seesaw.

New boson?



$$\frac{1}{2}\bar{N}\left[\rho_S\,\chi_S + i\rho_P\,\gamma_5\chi_P\right]N$$

$$\frac{1}{2\Lambda^2}\bar{N}\left[\rho_V\,\gamma_\mu\gamma_5\right]N\partial_\nu\chi_V^{\nu\mu}$$

$\rightarrow$

$$\frac{(\rho_S^2+\rho_P^2)\,M_{33}}{64\pi^2}\left[1+\frac{1}{M_{33}^2-m_\chi^2}\left(M_{33}^2\log\frac{\mu^2}{M_{33}^2}-m_\chi^2\log\frac{\mu^2}{m_\chi^2}\right)\right]$$

$$\frac{3\,\rho_V^2\,M_{33}^5}{16\pi^2\,\Lambda^4}\left[1+\log\frac{\mu^2}{M_{33}^2}\right]$$

↓

ΔL and Z2 safe, but…

χχHH

χNN

↓

Scalar masses unprotected! ❌

- For states with non-trivial SM gauge #s, things are no less complicated. MSSM ?? yields no new L violation and leptoquarks, e.g., only induce N masses at two-loops!
- Others (Brdar et al.) have considered adding new states, in realizing a **conformal NO**. Strong dynamics, dark matter, and gravity waves explored.

[1006.1092]
[1603.04993]
[1807.11490]
[1905.12634]
[1810.12306]
[2007.04367]
[2006.02960]

Achieving simple perturbations to M(UV) is not so easy, while realizing the Neutrino Option!

Non-perturbative speculations

[0609213]
[0609191]
[0703028]
[0704.1079]
[2009.11813]

- What if the Majorana scale is not generated perturbatively, or through a new scalar VEV? What if it is instead ***non-perturbative***?

$$m_s \, e^{-U} \, \overline{N} N$$

m_s: fundamental (UV) scale

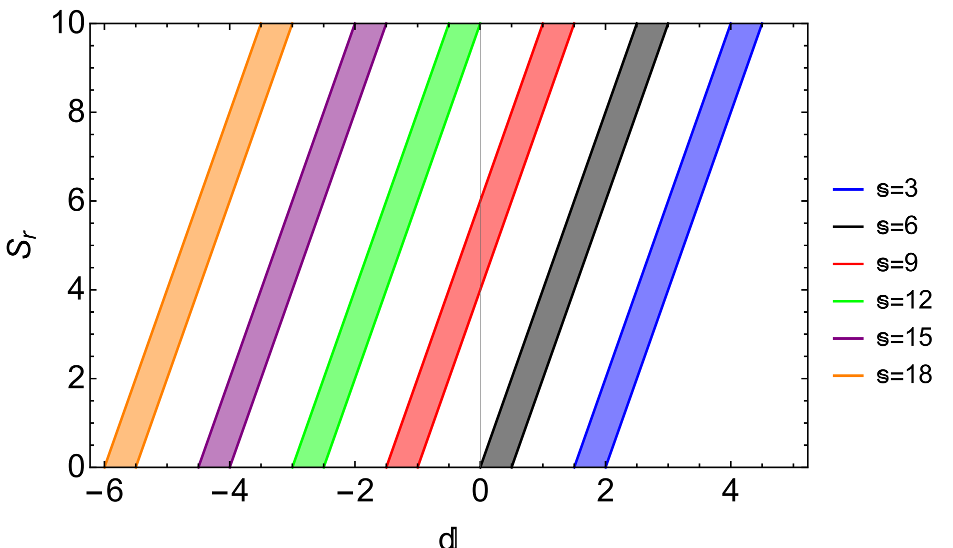
U: suppression factor associated to non-perturbative dynamics

- Such a scenario exists in certain stringy orientifold compactifications:

$$M = 2m_s \sum_r e^{-S_r} \mathrm{diag}\left(d_1^{(r)}, d_2^{(r)}, d_3^{(r)}\right) \cdot \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \cdot \mathrm{diag}\left(d_1^{(r)}, d_2^{(r)}, d_3^{(r)}\right)$$

$$\mathbb{s} \equiv \log_{10} m_s, \quad \mathbb{d} \equiv \log_{10} d_a^{(r)}, \quad \mathbb{p} \equiv \log_{10} M_p$$

$$\mathbb{s} + 2\mathbb{d} - \left(\frac{1}{2} S_r + \mathbb{p}\right) \approx 0$$



- **<u>However</u>**, this scenario is not yet predictive, nor am I aware of a fully consistent string theory that can generate the N mass term without additional excitations that destabilize the Higgs mass…???
- Other scenarios might exist, e.g. through gravitational condensation (see e.g. Barenboim et al.) ???

Summary and outlook

- The **Neutrino Option** represents an elegant and minimal approach to solving the EW hierarchy problem alongside the neutrino mass (and potentially more) problem(s)!
- However, **minimal perturbative explanations** for the origin of the Majorana mass scale required for Neutrino Option phenomenology seem **limited** due to **global (discrete) symmetries** (Lepton Number x Z_2 Mass).
- Other, less-minimal frameworks which introduce **new states** may be viable, e.g. the Conformal Neutrino Option of Brdar et al..
- **Non-perturbative** mechanisms explaining the origin of the Majorana scale may exist! Further formal analysis is required here.
- Neutrino-Option-inspired **phenomenology** of sterile neutrinos possible — cf. ongoing work with Michael Trott (not discussed in this talk)**…**

THANK YOU!