Flavour and Cosmological Probes of Diracon Models

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Motivation: Neutrino masses

SM does not explain neutrino masses

Natural explanation for the scale ⟹ **Seesaw Models**

High-scale seesaws: mixing (NP) proportional to m_ν . Example: type-I

$$m_\nu = \frac{y^2 v^2}{M}$$

Low-scale seesaws: m_ν suppressed by a symmetry-protected small parameter ⟹ **mixing (NP) unsuppressed. Typical NP signal:**

LFV, e.g. $\mu \to e\,\gamma$

Motivation: Neutrino masses. Dirac Type-I Seesaw

We define the Dirac Type-I seesaw as:

1) $$\mathcal{L}_{\text{mass}} = \begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & M_1 \\ M_2 & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix} + \text{h.c.}\,, \quad M_N \gg M_1,\, M_2$$

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Goldstone Theorem

Motivation: Goldstone LFV

Why is the Goldstone not observed?

Usually, Goldstone appears as a dynamical explanation for mass generation, as a DM-candidate or to fix some problem like axions

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Usually, Goldstone appears as a dynamical explanation for mass generation, as a DM-candidate or to fix some problem like axions

However, Goldstone phenomenology can be used to prove NP in LFV **[S. Centelles Chuliá et al. , 2404.15415]**

$$\ell_\beta \to \ell_\alpha\, G$$

Motivation: Goldstone LFV.

Qualitative argument: EFT

Let us work with SM + U(1) + a new scalar singlet, $\boldsymbol{\sigma}$, that breaks the U(1).

$$\sigma = \frac{1}{\sqrt{2}}\left(v_\sigma + \sigma^0 + iG\right)$$

When going to the EFT we have two possibilities depending on the VEV

U(1) is already violated

$$\mathcal{O}_5 = \begin{cases} c_5 \, G \, \dfrac{\bar{L}He_R}{\Lambda} \\ c_5 \, G \, \dfrac{\bar{L}\partial_\mu\gamma^\mu L}{\Lambda} \end{cases}$$

U(1) holds as a global symmetry

$$\mathcal{O}_6 = \begin{cases} c_6 \, \sigma \, \sigma^* \, \dfrac{\bar{L}He_R}{\Lambda^2} \\ c_6 \, \sigma \, \sigma^* \, \dfrac{\bar{L}\partial_\mu\gamma^\mu L}{\Lambda^2} \end{cases}$$

Motivation: Cosmology and N_{eff}

New light dofs are quite constrained: expansion rate in CMB, BBN, etc.

Using Boltzmann equations one can compute the energy density and translate into N_{eff}

$$\rho_{\rm rad} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right], \qquad N_{\rm eff} = \frac{\rho_\nu + \rho_{\rm BSM}}{\rho_\gamma}$$

⇓

$$\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM} < 0.163$$

Models

Remember: $\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & M_1 \\ M_2 & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$

Models

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Minimal scheme: $\mathrm{SM} + U(1) + \sigma + N_R + N_L + \nu_R$ ⟹ **two realizations**

		Canonical	Enhanced Diracon
Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_D$	$U(1)_D$
H	$(\mathbf{2}, \frac{1}{2})$	0	0
σ	$(\mathbf{1}, 0)$	3	3
L	$(\mathbf{2}, -\frac{1}{2})$	-1	-1
ν_R	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	2
N_L	$(\mathbf{1}, 0)$	-1	2
N_R	$(\mathbf{1}, 0)$	-1	-1

[E. Ma and R.

Models

Canonical

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ Y'\sigma & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

Enhanced

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ M_2 & Y'\sigma \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

Scalar sector is formally the same for both models: SM + singlet scalar

BUT

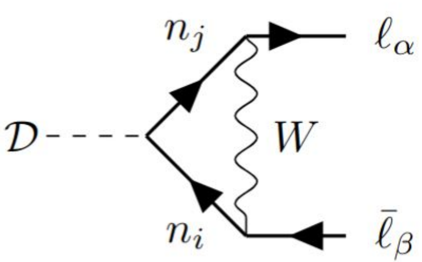
$v_\sigma \ll v$

$v_\sigma \gg v$

Models: LFV Phenomenology

Canonical

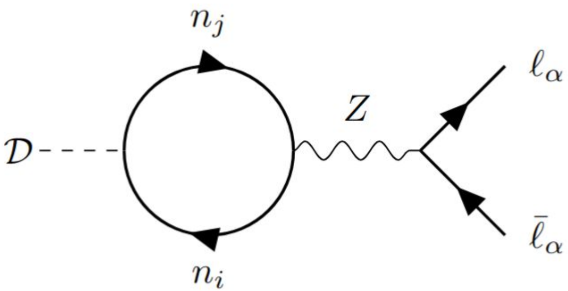
$$\begin{pmatrix}\bar{\nu}_L & \bar{N}_L\end{pmatrix}\begin{pmatrix}0 & YH \\ Y'\sigma & M_N\end{pmatrix}\begin{pmatrix}\nu_R \\ N_R\end{pmatrix}$$



$$\mathcal{L}_{J\ell\ell} \sim \frac{Y^2 Y'^2}{96\pi^2}\frac{M_\ell v_\sigma}{M_N^2}$$

Enhanced

$$\begin{pmatrix}\bar{\nu}_L & \bar{N}_L\end{pmatrix}\begin{pmatrix}0 & YH \\ M_2 & Y'\sigma\end{pmatrix}\begin{pmatrix}\nu_R \\ N_R\end{pmatrix}$$



General calculation:
[A.Herrero-Brocal and A. Vicente, 2311.10145]

$$\mathcal{L}_{J\ell\ell} \sim \frac{Y^2}{32\pi^2}\frac{M_\ell}{v_\sigma}$$

Models: LFV Phenomenology

Canonical | **Enhanced**

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ Y'\sigma & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ M_2 & Y'\sigma \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

In the simplifying BSM degenerate limit we find

$$\frac{\mathrm{BR}(\mu \to e\,\mathcal{D})}{\mathrm{BR}(\mu \to e\,\gamma)} \leq 1.02 \cdot 10^{-14}\, y'^2$$

$$\frac{\mathrm{BR}(\mu \to e\,\mathcal{D})}{\mathrm{BR}(\mu \to e\,\gamma)} \approx 2.3 \cdot 10^{8}\, y'^2 \left(\frac{m_N}{\mathrm{TeV}}\right)^2$$

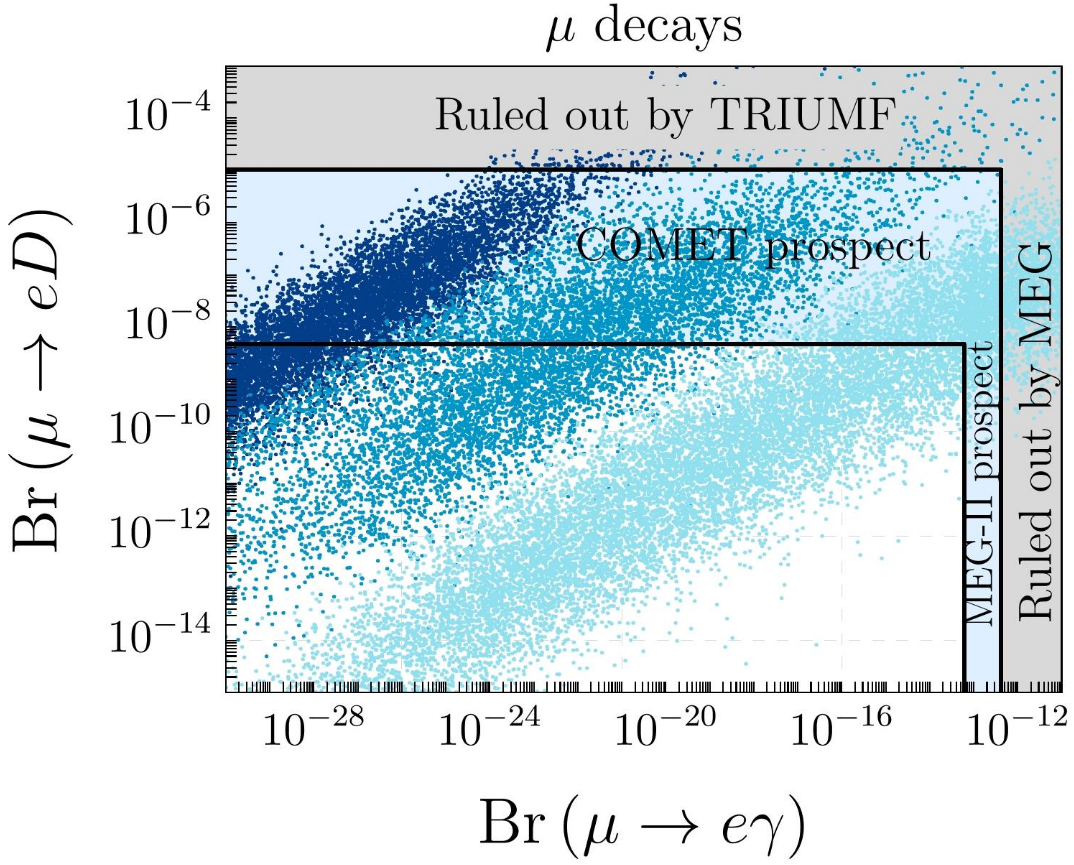
But experimental constraints:

$$\begin{cases} \mathrm{BR}\left(\mu \to e\,\gamma\right) < 4.2 \cdot 10^{-13} \\ \mathrm{BR}\left(\mu \to e\,\mathcal{D}\right) < 10^{-5} \end{cases}$$

Lepton Flavor Violation in the Enhanced model

- **For sizeable Yukawas (darker blue), the Diracon dominates, even for high SSB scales**

- $\mu \to e\gamma$ **becomes observable for smaller Yukawas (lighter blue)**



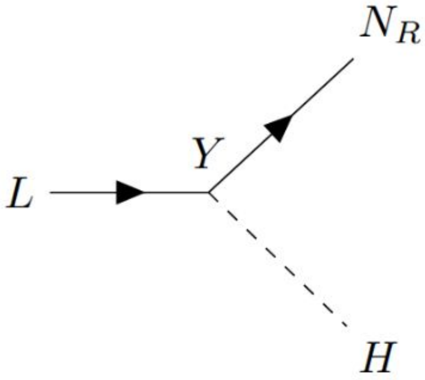
Models: ν_R and Diracon production

Canonical

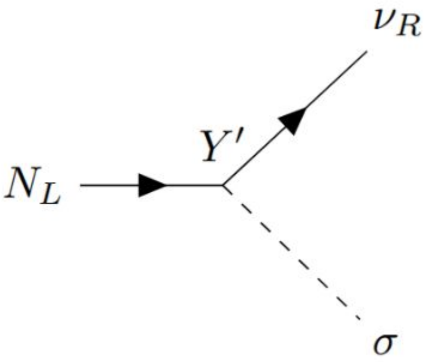
$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ Y'\sigma & M_N \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

Enhanced

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & YH \\ M_2 & Y'\sigma \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$



Production of N: controlled by Y

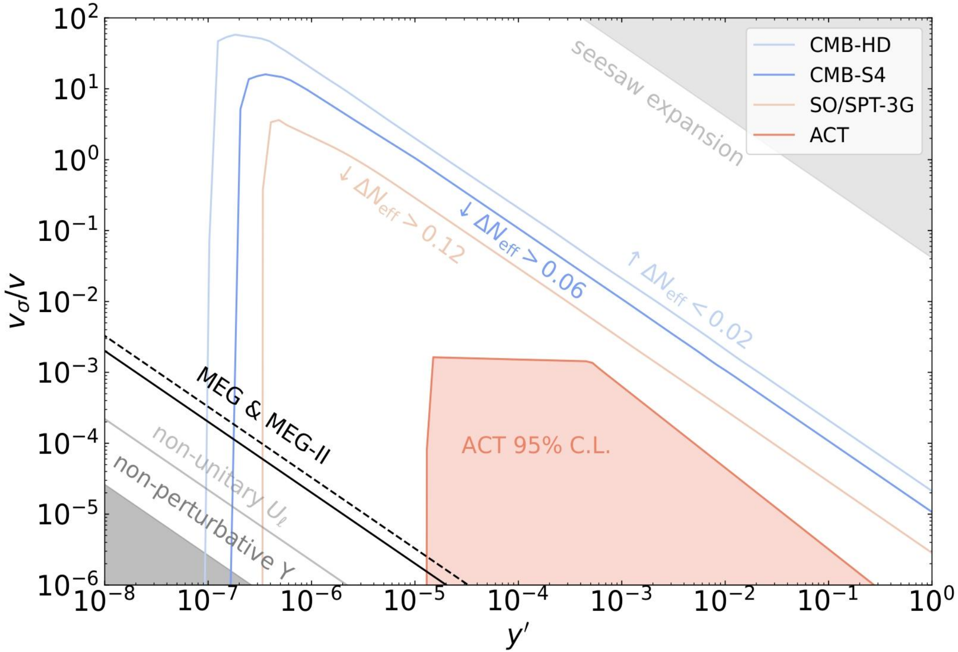


Decay into ν_R: controlled by Y'

Both couplings (Y and Y') related to m_ν

Cosmology and N_{eff} in the canonical model

$$M_N = 1\,\text{TeV}$$



Combination of constraints. Cosmology stronger than LFV

Conclusions

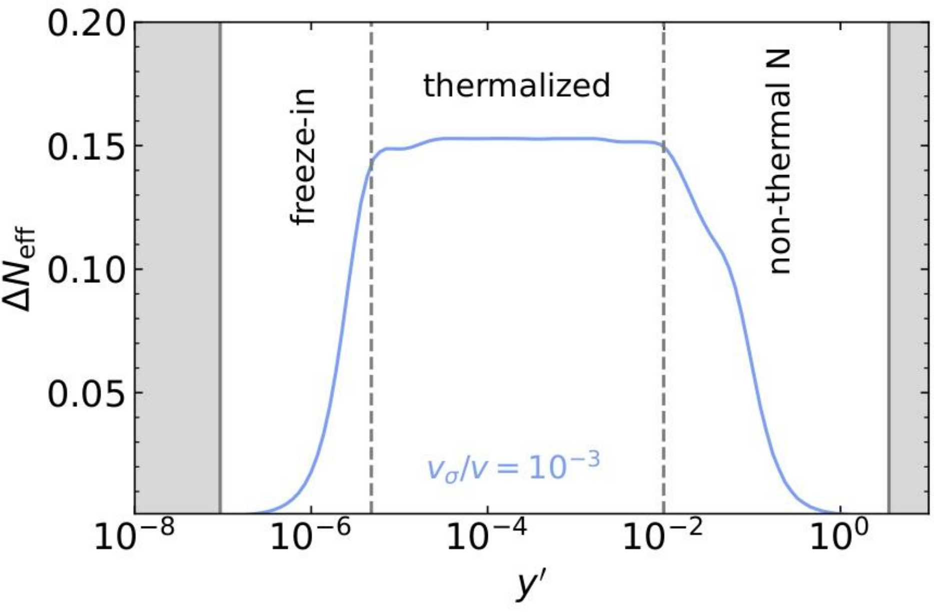
The Goldstone phenomenology in the Yukawa sector is completely determined by U(1) charges

Goldstone couplings give us a new window to explore models and test high scales

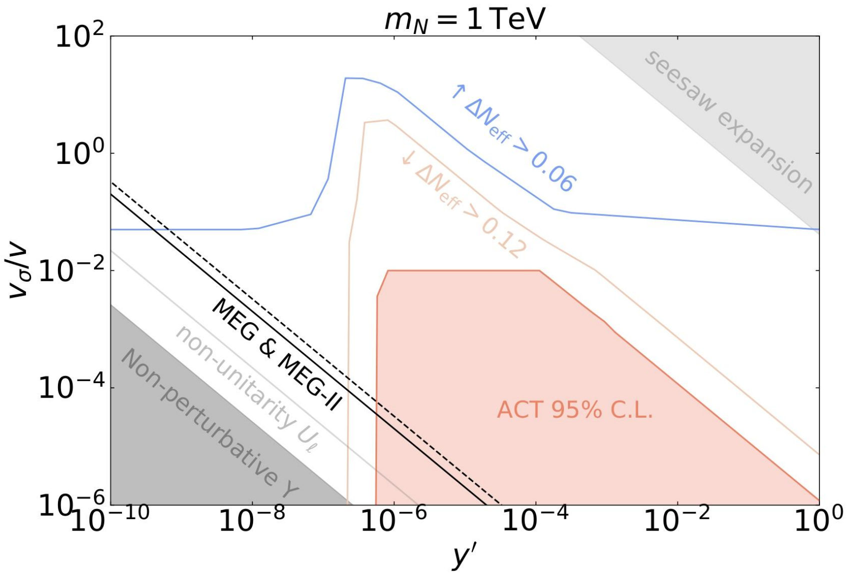
Dirac Type-I seesaw is a very promising mechanism because of complementarity: Flavor vs Cosmology

New directions to explore: enhanced Goldstone as DM-candidate, collider signatures, etc.

Backup: Cosmology and N_{eff} in the canonical model



ν_R contribution to N_{eff} in terms of y' for a benchmark point



Fermionic + scalar contribution to N_{eff}

Backup: Making the Goldstone a phenomenological actor. Inverse seesaw example

The key lies in the term that breaks the U(1):

Enhanced inverse seesaw

$$q_\nu = 1 \quad q_H = 0 \quad q_N = 1$$
$$q_S = 0 \quad q_\sigma = -1$$

⇓

$$\begin{pmatrix} \bar{\nu} & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & y_N H & 0 \\ y_N^T H & 0 & \lambda\sigma \\ 0 & \lambda^T \sigma & m_S \end{pmatrix} \begin{pmatrix} \nu^c \\ N \\ S \end{pmatrix}$$

⇓

$$\mathcal{L}_{J\ell\ell} \sim \frac{y_N^2}{16\pi^2} \frac{M_\ell}{v_\sigma}$$

Canonical inverse seesaw

$$q_\nu = 1 \quad q_H = 0 \quad q_N = 1$$
$$q_S = -1 \quad q_\sigma = -2$$

⇓

$$\begin{pmatrix} \bar{\nu} & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & y_N H & 0 \\ y_N^T H & \lambda_N \sigma & m_R \\ 0 & m_R^T & \lambda_S \sigma^* \end{pmatrix} \begin{pmatrix} \nu^c \\ N \\ S \end{pmatrix}$$

⇓

$$\mathcal{L}_{J\ell\ell} \sim \frac{y_N^2 \lambda_S^2}{96\pi^2} \frac{M_\ell v_\sigma}{m_R^2}$$