The flavour violating Goldstone

Based on 2404.15415 & 2506.06449

In collaboration with Tim Herbermann, Antonio Herrero-Brocal and Avelino Vicente

Salvador Centelles Chuliá (IFIC/UV)

FLASY 2025, Rome
02/07/2025

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

IFIC INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA
CSIC

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN
GENERALITAT VALENCIANA Conselleria d'Educació, Cultura, Universitats i Ocupació
EXCELENCIA SEVERO OCHOA
ASTROPARTICLES Astroparticles and High Energy Physics Group

Table of contents

1. Introduction
2. Models and pheno overview
3. Flavour observables
4. Cosmological probes
5. Future directions and conclusions

Our understanding of particle physics is based on symmetries

The SM explains and predicts many subatomic phenomena.

- Interactions dictated by gauge symmetries $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- $U(1)_L$ and $U(1)_B$ prevent gauge-allowed phenomena, paradigmatically proton decay and neutrino masses.
- Fermion and gauge boson masses from SSB mechanism.
- Explicitly broken symmetries still shape our intuition: isospin, chiral, flavour, CP...
- Symmetries continue guiding our search for new physics.

Need for BSM physics

The SM has some well-known observational and theoretical shortcomings:

- Dark matter
- Matter-antimatter asymmetry
- **Neutrino masses**
- Strong CP problem
- Flavour puzzle
- Hierarchy problem (if new scales are added to the SM)
- Gravity
- ...

Neutrino masses

- Neutrino oscillations entering the precision ($<1\%$) era, see talk by Eligio Lisi. Simplest explanation for the L/E profile are massive neutrinos.
- For now, the neutrino mass mechanism is a mistery:
  - Tree level, radiative, extra dimensional...?
  - The scale(s) of relevant NP
  - Neutrino nature: Dirac or Majorana
  - Lepton number conservation/violation, for an exhaustive analysis of the $\Delta L = 2$ case see talk by Julia Harz
  - Why $0 < m_\nu \ll \Lambda_{EW}$ and big lepton mixing, part of the flavour puzzle
- Popular framework: **The seesaw mechanism**[1]

[1]Peter Minkowski. "$\mu \to e\gamma$ at a Rate of One Out of 10^9 Muon Decays?" In: *Phys.Lett.B* 67 (1977), pp. 421–428. DOI: 10.1016/0370-2693(77)90435-X, Tsutomu Yanagida. "Horizontal gauge symmetry and masses of neutrinos". In: *Conf. Proc. C* 7902131 (1979). Ed. by Osamu Sawada and Akio Sugamoto, pp. 95–99, Rabindra N. Mohapatra and Goran Senjanovic. "Neutrino Mass and Spontaneous Parity Nonconservation". In: *Phys. Rev. Lett.* 44 (1980), p. 912. DOI: 10.1103/PhysRevLett.44.912, Murray Gell-Mann, Pierre Ramond, and Richard Slansky. "Complex Spinors and Unified Theories". In: *Conf. Proc. C* 790927 (1979), pp. 315–321. arXiv: 1306.4669 [hep-th], J. Schechter and J. W. F. Valle. "Neutrino Masses in SU(2) x U(1) Theories". In: *Phys. Rev. D* 22 (1980), p. 2227. DOI: 10.1103/PhysRevD.22.2227.

Scales of the seesaw

- Seesaw mechanism: generates small m_ν via large scale suppression. In the Type-I:

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

- **High-scale seesaws:** Mixing proportional to m_ν, no realistically testable signatures
- **Low-scale seesaws:** m_ν suppressed by a symmetry-protected small parameter μ. Sizeable $N-\nu$ mixing even in the $m_\nu \to 0$ limit.[2]. Potentially testable, rich phenomenology.
  - Allows for: charged lepton flavour violation (cLFV), cosmological imprints, collider-accesible exotic particles, lepton non-unitarity...

[2]J. Bernabeu et al. "Lepton Flavor Nonconservation at High-Energies in a Superstring Inspired Standard Model". In: *Phys. Lett. B* 187 (1987), pp. 303–308. DOI: 10.1016/0370-2693(87)91100-2.

L breaking and Goldstone bosons

- Lepton number accidentally conserved in the SM. A choice has to be taken for neutrino masses[3]:
  - L conservation: Dirac neutrinos
  - $\Delta L = 2$: Majorana neutrinos
  - $\Delta L = 3$: Dirac neutrinos again
  - ...
- If broken spontneously, the Goldstone theorem: spontaneous breaking of a continuous global symmetry $\Rightarrow$ massless scalar[4]. Examples:
  - Pions (approximate chiral symmetry)
  - Axions (PQ symmetry)
  - Majoron, Diracon (lepton-number-like symmetries)
- In our models: Goldstone bosons arise naturally and play a key phenomenological role

[3]Martin Hirsch, Rahul Srivastava, and José W. F. Valle. "Can one ever prove that neutrinos are Dirac particles?" In: Phys. Lett. B 781 (2018), pp. 302–305. DOI: 10.1016/j.physletb.2018.03.073. arXiv: 1711.06181 [hep-ph].

[4]Yoichiro Nambu. "Quasiparticles and Gauge Invariance in the Theory of Superconductivity". In: Phys. Rev. 117 (1960). Ed. by J. C. Taylor, pp. 648–663. DOI: 10.1103/PhysRev.117.648, J. Goldstone. "Field Theories with

Model overview

- Known models (*Canonical* versions of IS & Type-I DS):
  - Spontaneous version of the inverse seesaw[5]
  - Type-I Dirac seesaw[6]
- New models (*Goldstone-Enhanced* versions of IS & Type-I DS):
  - Majoron-Enhanced Inverse Seesaw[7]
  - Diracon-Enhanced Type-I Dirac seesaw[8]

---

[5]M.C. Gonzalez-Garcia and J. W. F. Valle. "Fast Decaying Neutrinos and Observable Flavor Violation in a New Class of Majoron Models". In: *Phys.Lett.* B216 (1989), pp. 360–366. DOI: 10.1016/0370-2693(89)91131-3.

[6]Ernest Ma and Rahul Srivastava. "Dirac or inverse seesaw neutrino masses with $B - L$ gauge symmetry and S_3 flavor symmetry". In: *Phys. Lett. B* 741 (2015), pp. 217–222. DOI: 10.1016/j.physletb.2014.12.049. arXiv: 1411.5042 [hep-ph].

[7]Salvador Centelles Chuliá, Antonio Herrero-Brocal, and Avelino Vicente. "The Type-I Seesaw family". In: *JHEP* 07 (2024), p. 060. DOI: 10.1007/JHEP07(2024)060. arXiv: 2404.15415 [hep-ph].

[8]Salvador Centelles Chuliá et al. "Flavour and cosmological probes of Diracon models". In: (June 2025). arXiv: 2506.06449 [hep-ph].

The building blocks

- All of our models share a common structure. To the SM gauge and particle content we add:
  - One global $U(1)$ symmetry.
  - One complex scalar singlet σ breaking $U(1)$.
  - A set of gauge-singlet fermions with different $U(1)$ charges.
- Note that the direct Dirac analogue of the standard inverse seesaw is covered by the Type-I Dirac seesaw[9]

[9]Salvador Centelles Chuliá, Rahul Srivastava, and Avelino Vicente. "The inverse seesaw family: Dirac and Majorana". In: *JHEP* 03 (2021), p. 248. DOI: 10.1007/JHEP03(2021)248. arXiv: 2011.06609 [hep-ph].

Our guiding symmetry: a $U(1)$ with multiple roles

- Global $U(1)$ symmetry which plays several roles:
  - Determines the Dirac/Majorana nature of neutrinos.
  - Controls the Yukawa and seesaw structure.
  - Its breaking gives rise to a Goldstone boson (Majoron or Diracon) and controls its interactions.
  - The Dirac models are chiral.
  - If identified with $U(1)_{B-L}$ it is anomaly-free (except one model). Could be promoted to a gauge symmetry, see talk by Rahul Srivastava and[10]
  - Can stabilize a DM candidate (not studied here), see[11]
- This symmetry links the origin of neutrino mass to low-energy flavour and cosmological phenomenology

[10] Tim Herbermann and Manfred Lindner. "Improved cosmological limits on Z' models with light right-handed neutrinos". In: (May 2025). arXiv: 2505.04695 [hep-ph].

[11] Cesar Bonilla et al. "Dark matter stability and Dirac neutrinos using only Standard Model symmetries". In: Phys. Rev. D 101.3 (2020), p. 033011. DOI: 10.1103/PhysRevD.101.033011. arXiv: 1812.01599 [hep-ph], Salvador Centelles Chuliá et al. "Scotogenic dark symmetry as a residual subgroup of Standard Model symmetries". In: Chin. Phys. C 44.8 (2020), p. 083110. DOI: 10.1088/1674-1137/44/8/083110. arXiv: 1901.06402 [hep-ph].

Model overview: Inverse seesaw vs Type-I Dirac seesaw

		$U(1)$ **charges**			
		Majorana		**Dirac**	
Fields	$SU(2)_L \otimes U(1)_Y$	$\mathbf{IS^C}$	$\mathbf{IS}^J$	$\mathbf{T\text{-}I^C}$	$\mathbf{T\text{-}I}^{\mathcal{D}}$
H	$(\mathbf{2}, \frac{1}{2})$	0	0	0	0
σ	$(\mathbf{1}, 0)$	2	1	3	3
L	$(\mathbf{2}, -\frac{1}{2})$	-1	-1	-1	-1
ν_R	$(\mathbf{1}, 0)$	$\emptyset$	$\emptyset$	$(-4, -4, 5)$	2
N_L	$(\mathbf{1}, 0)$	-1	0	-1	2
N_R	$(\mathbf{1}, 0)$	-1	-1	-1	-1

$\mathbf{IS^C}$: Canonical Inverse Seesaw $\mathbf{IS}^J$: Majoron-enhanced Inverse Seesaw
$\mathbf{T\text{-}I^C}$: Canonical Type-I Dirac Seesaw $\mathbf{T\text{-}I}^{\mathcal{D}}$: $\mathcal{D}$-enhanced Type-I Dirac Seesaw

Phenomenological overview

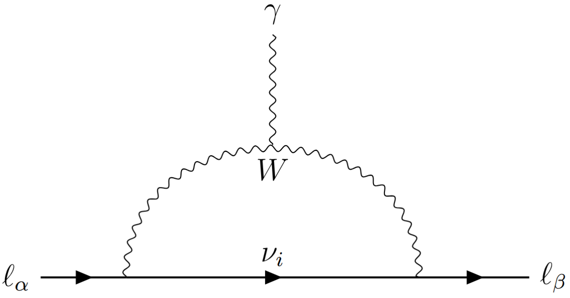
The $U(1)$ charges control the phenomenology!

Model	ν **nature**	cLFV	G-cLFV	ΔN_{eff}
Canonical IS	Majorana	🥇	❌	🥉
J-enhanced IS	Majorana	🥈	🥇	🥉
Canonical T-I DS	Dirac	🥈	❌	🥇
$\mathcal{D}$-enhanced T-I DS	Dirac	🥈	🥇	🥉

(IS = Inverse Seesaw, T-I DS = Type-I Dirac Seesaw,
J = Majoron, $\mathcal{D}$ = Diracon)

'Standard' cLFV: $\mu \to e\gamma$

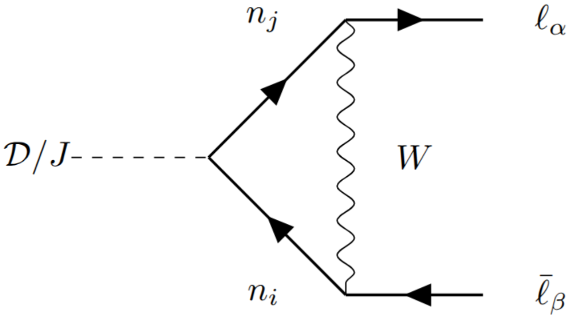
- All 4 models are low-scale seesaws, i.e. the $N - \nu$ mixing is not m_ν suppressed.
- cLFV discussed at length this week. Here we focus on the 'golden' decay $\mu \to e\gamma$



- $\text{BR}(\ell_\alpha \to \ell_\beta \gamma) \approx \frac{\alpha_W^3 s_W^2}{1024\pi^2} \left(\frac{m_{\ell_\alpha}}{m_W}\right)^4 \frac{m_{\ell_\alpha}}{\Gamma_{\ell_\alpha}} \left| \left(M_1 M_N^{-2} M_1^\dagger\right)_{\alpha\beta} \right|^2$

Flavour violating Goldstone: $\mu \to eG$

- Model-dependent. Completely general calculation in[12].
- It involves both the $N - \nu$ mixing and the structure of the $G\,\nu_i\nu_j$ coupling.



[12] Antonio Herrero-Brocal and Avelino Vicente. "The majoron coupling to charged leptons". In: *JHEP* 01 (2024), p. 078. DOI: 10.1007/JHEP01(2024)078. arXiv: 2311.10145 [hep-ph].

$\mu \to eG$, canonical models

In the canonical models, the Goldstone interaction with leptons is neutrino-mass suppressed.

Majorana Inverse Seesaw

$$\begin{pmatrix} \bar{\nu}_L \\ \bar{N}_R^c \\ \bar{S}_L \end{pmatrix}^T \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y & 0 \\ \frac{v}{\sqrt{2}} Y^T & 0 & M \\ 0 & M^T & \frac{v_\sigma}{\sqrt{2}} Y' \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \\ S_L^c \end{pmatrix}$$

$$m_\nu = \frac{v^2 v_\sigma}{2\sqrt{2}} Y M^{-1} Y' M^{-1} Y^T$$

Type-I Dirac Seesaw

$$\begin{pmatrix} \bar{\nu}_L \\ \bar{N}_L \end{pmatrix}^T \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y \\ \frac{v_\sigma}{\sqrt{2}} Y' & M \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

$$m_\nu = \frac{v\, v_\sigma}{2} Y M^{-1} Y'$$

The Yukawa structure and neutrino mass generation, completely fixed by the $U(1)$ charges, leads to $\mathcal{L}_{G\ell\ell} \propto m_\nu G \bar{\ell} \Gamma \ell$

$\mu \to eG$, enhanced models

In the enhanced models, the Goldstone interaction with leptons is **not suppressed** by neutrino masses.

Majoron-Enhanced Inverse Seesaw

$$\begin{pmatrix} \bar{\nu}_L \\ \bar{N}_R^c \\ \bar{S}_L \end{pmatrix}^T \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y & 0 \\ \frac{v}{\sqrt{2}} Y^T & 0 & \frac{v_\sigma}{\sqrt{2}} Y' \\ 0 & \frac{v_\sigma}{\sqrt{2}} Y'^T & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \\ S_L^c \end{pmatrix}$$

$$m_\nu = \frac{v^2}{v_\sigma^2} Y Y'^{-1} \mu Y'^{-1} Y^T$$

Diracon-Enhanced Type-I Seesaw

$$\begin{pmatrix} \bar{\nu}_L \\ \bar{N}_L \end{pmatrix}^T \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y \\ \mu & \frac{v_\sigma}{\sqrt{2}} Y' \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}$$

$$m_\nu = \frac{v}{v_\sigma} Y Y'^{-1} \mu$$

The Goldstone couplings are **not** responsible for the neutrino mass suppression!

$\mu \to eG$, enhanced models

In both cases:

$$\mathcal{L}_{\ell\ell G} = \frac{i\,G}{32\pi^2 v_\sigma}\bar{\ell}\left[M_\ell\,\text{Tr}(Y\,Y^\dagger)\,\gamma_5 + 2M_\ell\,Y\,Y^\dagger\,P_L - 2Y\,Y^\dagger\,M_\ell\,P_R\right]\ell$$

$$g_{G\ell\ell} \propto \frac{YY^\dagger}{v_\sigma} \text{ and } M_N = \frac{1}{\sqrt{2}}v_\sigma Y'$$

potentially sizeable even if $\mu \to 0$ leading to $m_\nu \to 0$

Comparison between cLFV decays

- $\mu \to eG$ is enhanced compared to $\mu \to e\gamma$. In the simplifying degenerate BSM limit ($Y' \to y' I_d$ and $\mu \to \mu I_d$):

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

- But experimental constraints are much stronger for $\mu \to e\gamma$:

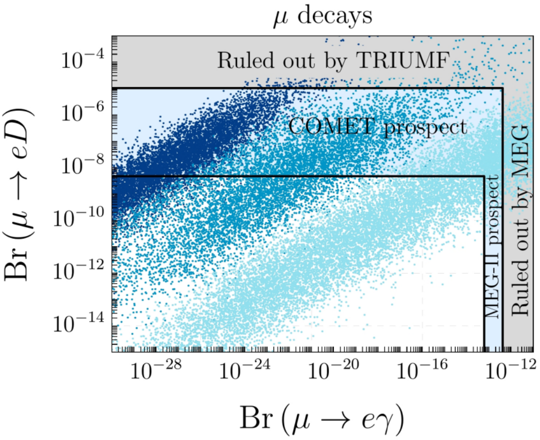
$\mathrm{BR}(\mu \to e\,\gamma) < 1.5 \times 10^{-13}$ (MEG-II)

$\mathrm{BR}(\mu \to e\,G) < 10^{-5}$ (TRIUMF)

- Both will be improved in the near future! See talk by Paolo Cattaneo.

Comparison between cLFV decays

- For sizeable Yukawas (darker blue), Goldstone decays dominate — even for high SSB scales ($v_\sigma \sim 10^4$ TeV).
- $\mu \to e\gamma$ becomes observable for smaller Yukawas (lighter blue).
- Models clearly plagued by the flavour problem!



Standard Neutrino Cosmology and ΔN_{eff}

- $T \gg 1$ MeV: active ν in thermal equilibrium with the plasma via weak interactions.
- ν decouple at $T \sim 1$ MeV, remaining as ultrarelativistic species. In the instantaneous decoupling approximation:

$$\rho_{\text{rad}} = \rho_\gamma + \rho_\nu = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \times 3\right]$$

- More generally:

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

- $N_{\text{eff}}^{\text{SM}} = 3.044$. BSM effects are parametrized as $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$
- Sensitive observable in BBN and CMB.
- See e.g.[13] for extended discussion

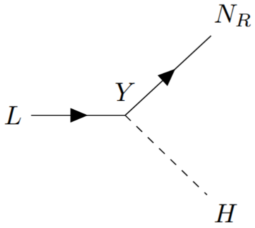
[13] Julien Lesgourgues et al. *Neutrino Cosmology*. Cambridge University Press, Feb. 2013. ISBN: 978-1-108-70501-1, 978-1-139-60341-6.

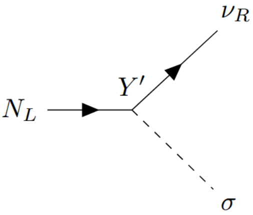
ΔN_{eff} in our models

- ρ_{BSM} can get contributions from
  - The massless Diracon/Majoron
  - Potentially light radial mode of σ
  - Extra light neutrino degrees of freedom in the Dirac models
- Scalar contributions to N_{eff} essentially dependent on $\lambda_{H\sigma}$. No constraints on neutrino physics.
- For Dirac models, contributions from ν_R can be very relevant! Produced by the decay of heavy N.

$\Delta N_{\rm eff}$ in the Canonical Dirac Type-I seesaw

$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_L \end{pmatrix} \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y \\ \frac{v_\sigma}{\sqrt{2}} Y' & M \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix}, \qquad m_\nu = \frac{v v_\sigma}{2} Y M^{-1} Y'$$

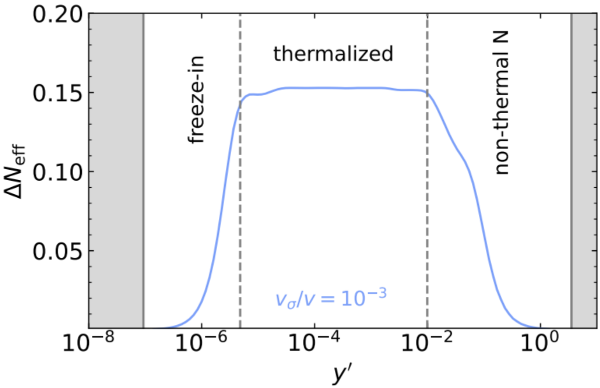




Production of N: controlled by Y Decay into ν_R: controlled by Y'

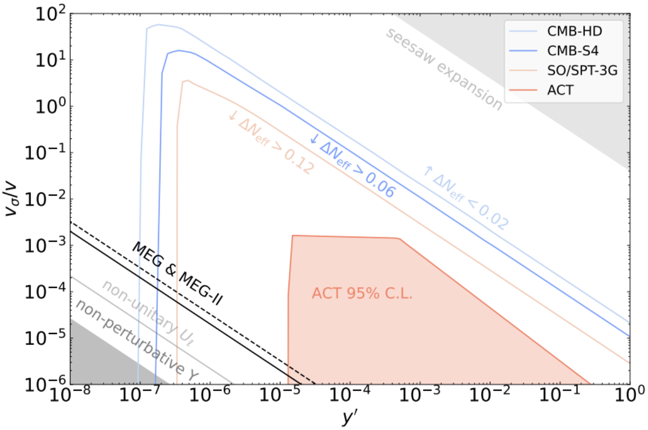
Both couplings (Y and Y') related to m_ν

$\Delta N_{\rm eff}$ in the Canonical Dirac Type-I seesaw



ν_R contribution to $\Delta N_{\rm eff}$ in terms of y' for a benchmark point $M_N = 1$ TeV in the degenerate BSM limit.

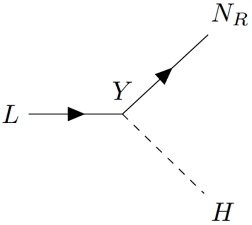
$\Delta N_{\rm eff}$ in the canonical Type-I seesaw



Combination of constraints for $M_N = 1$ TeV in the degenerate BSM limit.
Cosmology stronger than cLFV, but complementary!

ΔN_{eff} in the enhanced Diracon Type-I seesaw

$$\begin{pmatrix}\bar{\nu}_L & \bar{N}_L\end{pmatrix}\begin{pmatrix}0 & \frac{v}{\sqrt{2}}Y \\ \mu & \frac{v_\sigma}{\sqrt{2}}Y'\end{pmatrix}\begin{pmatrix}\nu_R \\ N_R\end{pmatrix}, \qquad m_\nu = \frac{v}{v_\sigma}YY'^{-1}\mu$$



Decay into ν_R: suppressed by mixing! In particular the $N - \nu_R$ Yukawas in the mass basis are proportional to

$$\mu/v_\sigma = Y'Y^{-1}m_\nu/v$$

Production of N: controlled by Y

Contribution of ν_R to ΔN_{eff} suppressed by m_ν

Potential future directions

- **Collider signatures:**
  - Production of exotic scalars or fermions.
  - Modified Higgs interactions.
- **Leptogenesis:**
  - Can the low(ish)-scale ($\sim 10^4$) TeV setup accommodate successful baryogenesis?
- **Extensions with flavour symmetries:**
  - Predictive frameworks for U_ℓ, LFV, CP phases and $\nu 0ee$ (for Majorana models).
- **Diracon/Majoron as dark matter candidates:**
  - If $U(1)$ is explicitly broken, the Goldstone boson acquires mass. Can be a good DM candidate.
  - Enhanced models will be more constrained than *canonical* models, already studied in the literature.

Conclusions and summary

- Low-scale seesaw models are theoretically motivated and phenomenologically rich.
- Similar field content and structure, phenomenology and neutrino nature controlled by $U(1)$ charges.
- Showcases the complementarity between 'standard' BSM cLFV searches, exotic lepton decays and cosmological probes.
- Goldstone bosons (Majoron, Diracon) are promising windows into the symmetry origin of neutrino masses.

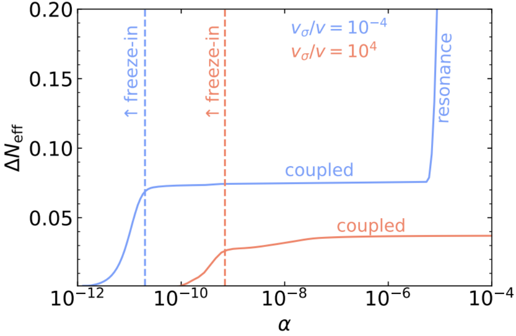
Conclusions and summary

Model	ν **nature**	cLFV	G-cLFV	ΔN_{eff}
Canonical IS	Majorana	🥇	❌	🥉
J-enhanced IS	Majorana	🥈	🥇	🥉
Canonical T-I DS	Dirac	🥈	❌	🥇
$\mathcal{D}$-enhanced T-I DS	Dirac	🥈	🥇	🥉

FLASY
ROME 2025
11TH WORKSHOP
Flavor Symmetries and Consequences in Accelerators and Cosmology

Thank you for your attention!

Scalar contributions to N_{eff}



For very small mixing angle α, the portal coupling at fixed v_σ is suppressed and production proceeds via freeze-in. At larger mixing, the extended scalar spectrum is tightly coupled to the SM. The difference between low and high-scale realizations comes from thermalization of the radial mode. If $v_\sigma \ll v$ Diracons can be resonantly produced.

Scalar contributions to N_{eff}

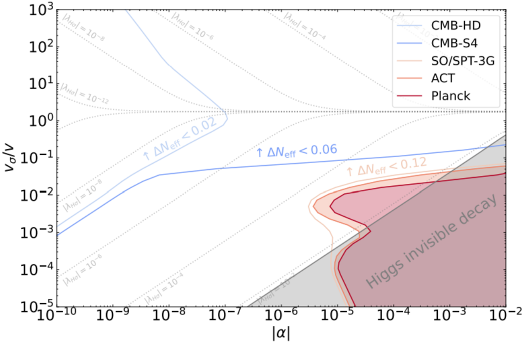


Figure 4: Limits on the scalar sector without considering contributions from the new heavy fermions. Current limits Planck and ACT are weaker than limits from Higgs invisible decay except for the resonant low-scale regime. Future experiments like CMB-S4 will put strong limits on low-scale variations, whereas futuristic proposals like CMB-HD have the potential to constrain the scalar sector on all scales. The scalar self coupling is fixed to $\lambda_\sigma = 0.1$, and we show contours of $|\lambda_{H\sigma}|$ for comparison.

445 solution

- The *445 solution* naturally leads to a Dirac seesaw with $\Delta L = 3$, as it forbids the tree level term $L H \nu_R$ but allows $L H \sigma \nu_R$
- It is anomaly free. From Ma, Srivastava 2014:

$U(1)_{B-L}$. Using the particle content of the standard model, all triangle gauge anomalies are zero except for

$$\sum U(1)^3_{B-L} = -3 \quad (1)$$

This is easily solved with the addition of three (right-handed) singlet neutrinos, which contribute $-3(-1)^3 = +3$. Note that the gauge-gravitational anomaly is also zero because $-3(-1) = +3$. Numerous studies have been made regarding this model of $U(1)_{B-L}$.

In this paper, we point out that there is another simple choice for three families [3–5]. Let $\nu_{Ri} \sim n_i$ under $B-L$, then $n_{1,2,3} = (+5, -4, -4)$ yields

$$-(+5)^3 - (-4)^3 - (-4)^3 = +3 \quad (2)$$