Phenomenological implications of sterile neutrinos in the $\mu\nu$SSM

Paulina Knees

Instituto de Física de Buenos Aires UBA & CONICET, Departamento de Física, Facultad de Ciencia Exactas y Naturales, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina

Introduction

We analyse the sterile neutrino as dark matter in the context of the μ-from-ν supersymmetric standard model, $\mu\nu$SSM. We adopt a minimalistic approach, reproducing neutrino masses and mixing angle at tree-level using two right-handed neutrinos as part of the see-saw mechanism. A third right-handed neutrino don't contribute significantly to the mass of the three active ones. As we show in this work this right-handed neutrino behaves as a sterile neutrino that can be a good dark matter candidate.(Work in progress with my PhD advisor and collaborators).

Neutrino physics: actual state

▶ Experimental evidence of neutrino oscillations: transitions between the different flavour neutrinos, caused by nonzero neutrino masses and neutrino mixing.
▶ Actual state of neutrino physics measurements is the following (source: PDG)

Parameter	Best fit	3σ
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	7.37	6.93-7.96
$\Delta m_{31(23)}^2 [10^{-3} \text{eV}^2]$	2.56 (2.54)	2.45-2.69 (2.42-2.66)
$\sin^2 \theta_{21}$	0.297	0.250-0.354
$\sin^2 \theta_{23}, \Delta m_{31(31)}^2 > 0$	0.425	0.381-0.615
$\sin^2 \theta_{23}, \Delta m_{32(31)}^2 < 0$	0.589	0.384-0.636
$\sin^2 \theta_{13}, \Delta m_{31(32)}^2 > 0$	0.0215	0.0190-0.0240
$\sin^2 \theta_{13}, \Delta m_{32(31)}^2 > 0$	0.0216	0.0190-0.0242
δ/π	1.38 (1.31)	$2\sigma : (1.0 - 1.9)$ $(2\sigma : (0.92 - 1.88))$

The $\mu\nu$ Supersymmetric Standard Model

▶ The $\mu\nu$SSM was proposed in [1,2] and arises naturally as a supersymmetric model with minimal content of particles adding neutrino right extra fields, without the μ problem.
▶ R-parity breaking makes the $\mu\nu$SSM phenomenology very different from the MSSM and the NMSSM.

The superpotential of this model is given by

$$W = \epsilon_{ab} \left(Y_u^{ij} \hat{H}_u^b \hat{Q}_i^a \hat{u}_j^c + Y_d^{ij} \hat{H}_d^a \hat{Q}_i^b \hat{d}_j^c + Y_e^{ij} \hat{H}_d^a \hat{L}_i^b \hat{e}_j^c \right) +$$
$$+ \epsilon_{ab} (\underbrace{Y_\nu^{ij} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c}_{\text{Dirac Yukawa coupling for neutrinos}} - \underbrace{\lambda^i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b}_{\text{generates the effective } \mu \text{ term after EWSB}}) + \underbrace{\frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c}_{\text{generates Majorana masses}} \quad (1)$$

The effective μ term is given by $\mu = \frac{\lambda v_R}{\sqrt{2}}$, whereas the Majorana masses are $\mathcal{M}_{ij} = 2\kappa_{ijk} \frac{v_{kR}}{\sqrt{2}}$.

▶ These last three terms are also the responsible of breaking explicitly R-parity, harmless to the proton decay.
▶ Neutrino Yukawa couplings Y_ν are the parameters that controls the amount of R_p in the $\mu\nu$ SSM.

[1] D.E López-Fogliani and C. Muñoz, *Proposal for a Supersymmetric Standard Model*, Phys. Rev. Lett., 97:041801, 2006.
[2] D.E. López-Fogliani and C. Muñoz, "Searching for Supersymmetry: The $\mu\nu$SSM" (review), *Eur. Phys. J. ST* **229** no. 21, (2020) 3263–3301, arXiv:2009.01380 [hep-ph]

Neutrino Sector

▶ As a consequence of R-partiry violation, the MSSM neutralinos mix with the left and right-handed neutrinos. The neutral fermions have the flavor composition $\chi^0 = (\nu_i, \hat{B}, \hat{W}, \hat{H}_d, \hat{H}_u, \nu_{iR})$ and thus neutrino masses arise naturally from the generalized see-saw mechanism. The neutralino 10×10 mass matrix in the flavour basis is given by [2]

$$m_{\chi^0} = \begin{pmatrix} 0_{3\times 3} & m^T \\ m & \mathcal{M}_{7\times 7} \end{pmatrix}$$

▶ At tree level, we can write the effective active-neutrino mixing mass matrix

$$m_{eff} = -m^T \mathcal{M}^{-1} m \underset{\text{diagonalization}}{\Longrightarrow} U_{MNS}^T m_{eff} U_{MNS} = (m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

▶ Independent parameters of neutrino sector
$$v_{iL}, v_{iR}, Y_{\nu_{ij}}, \kappa_{ijk}, \lambda_i, \tan\beta, M_1, M_2$$

Sterile neutrinos

Sterile neutrinos are right-handed fermions that are singlets under Standard Model gauge group, in consequence they are totally neutral.
Our purpose is to propose one of the three right-handed neutrinos as a light sterile one, using only two RH-neutrinos in the see-saw mechanism. We are interested one **serile state in the keV scale**.

✓ Decouple one right-handed neutrino from the see-saw mechanism $\Longrightarrow$ $Y_{\nu_i} \sim 10^{-13}$.
✓ Achieve the mass scale wanted $\Longrightarrow$ $\kappa \sim 10^{-9}$.

Numerical analysis

To find a sterile state that reproduces neutrino physics data, we did a numerical analysis using the SPheno code for $\mu\nu$SSM, generated by SARAH *Mathematica Package*.
▶ Low Yukawa coupling needed to generate the sterile state.
▶ Low κ in order to achieve the mass scale wanted.
▶ Low λ coupling in order to avoid tachyonic states in the scalar and pseudoscalar sector.
▶ Non-diagonal terms in the Yukawa matrix to obtain the correct neutrino mixing angles.

We perform the analysis for sterile neutrino mass in the range $2keV \leq m_s \leq 90keV$.
Parameter space that reproduces neutrino physics and is in agreement with the constraints on the active-sterile mixing angle.

ν_{1L} (GeV)	ν_{2L} (GeV)	ν_{3L} (GeV)	ν_{1R} (GeV)	ν_{2R} (GeV)	ν_{3R} (GeV)	M_1
1×10^{-4}	4.45×10^{-4}	3.8×10^{-4}	2.4×10^3	1.5×10^3	1.4×10^3	360

λ_1	λ_2	λ_3	κ_1	κ_2	κ_3	M_2
4×10^{-4}	2×10^{-7}	1.5×10^{-1}	1×10^{-1}	$(1.1 \times 10^{-9}; 4.25 \times 10^{-8})$	4.5×10^{-1}	1600

$$Y_\nu = \begin{pmatrix} 8 \times 10^{-8} & 0 & 1.7 \times 10^{-8} \\ -2.8 \times 10^{-7} & 4 \times 10^{-13} & -8.6 \times 10^{-8} \\ 0 & 0 & 5.5 \times 10^{-8} \end{pmatrix}$$

We found for this parameter space that the active-sterile mixing $|U_s|^2$ is in the range $5.8 \times 10^{-10} \leq |U_s|^2 \leq 3.13 \times 10^{-15}$.

Decay width and lifetime

The dominant decay mode is given by $\nu_s \rightarrow \nu\nu\nu$
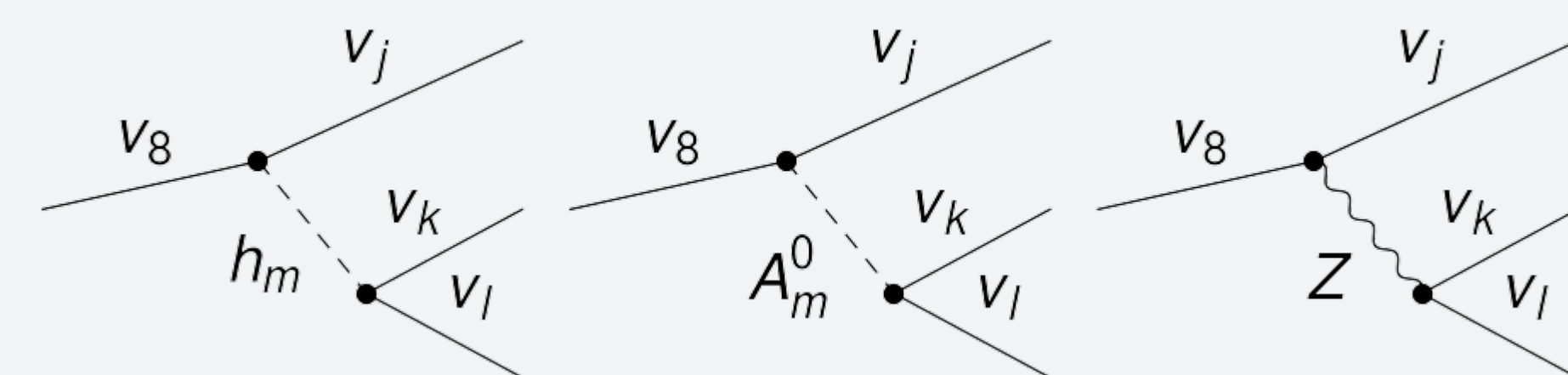
The first two diagrams are suppressed respect to the Z contribution. The suppression arises from the Yukawa coupling responsible and the mixing between the scalar Higgs/pseudoscalar with sneutrinos of order $\sim 10^{-8}$. Considering only the third diagram we obtained

$$\Gamma(\nu_s \rightarrow \nu_i \nu_j \nu_k) = \frac{G_F^2 m_s^5}{6\pi^3} O_{si}^2 O_{jk}^2 \underset{\text{SM} + \nu_R \text{ limit}}{\longrightarrow} \frac{G_F^2 m_s^5}{96\pi^3} |U_{si}^V|^2$$

Where the O factors are given by

$$O_{lm} = -\frac{1}{2} U_{l6}^V U_{m6}^{V*} + \frac{1}{2} U_{l7}^V U_{m7}^{V*} - \frac{1}{2} \sum_{q=1}^3 U_{lq}^V U_{mq}^{V*}$$

Thus we obtained for $m_s \sim \mathcal{O}(keV)$ that the lifetime is $\tau \sim 10^{23}$ s> $\tau_{universe}$.

Detection and exclusion limits

▶ The radiative decay $\nu_s \rightarrow \nu\gamma$ is $\sim 10^2$ orders of magitud smaller than the main channel.
▶ The resulting photons with energy $E = \frac{m_s}{2}$ can be observed in X-ray signals. There are several constraints to the sterile-active mixing angle that come from X-ray observations and Lymann-α forests.

The relevant diagrams in the $\mu\nu$SSM that contribute to the radiative decay are
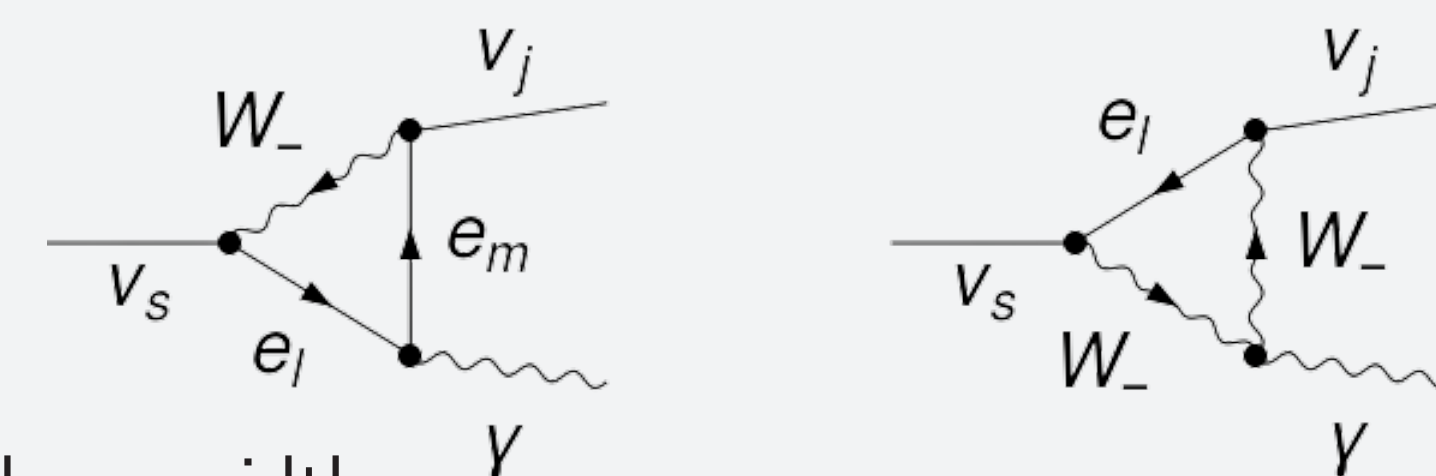
We obtained the folowing decay width

$$\Gamma(\nu_s \rightarrow \nu_j \gamma) = \frac{m_s}{512\pi} \left[\frac{m_s^2 e^2 g^4}{64\pi^4} \left(\frac{3m_s}{4m_W^2} \left(O_{jl}^{''L} O_{sl}^{''L} - O_{jl}^{''R} O_{sl}^{''R} \right) - \frac{2m_e}{m_W^2} \left(O_{jl}^{''L} O_{sl}^{''R} - O_{jl}^{''R} O_{sl}^{''L} \right) \right)^2 \right]$$

$$\underset{\text{SM} + \nu_R \text{ limit}}{\longrightarrow} \frac{9 G_F^2 \alpha m_s^5 |U_s^V|^2}{1024\pi^4}$$

The $O^{''R,L}$ factors are

$$O_{ij}^{''R} = U_{i4}^{e,L} U_{j5}^V + \frac{1}{\sqrt{2}} \sum_{a=1}^3 U_{ia}^{e,L} U_{ja}^V + \frac{1}{\sqrt{2}} U_{i5}^{e,L} U_{j6}^V \qquad O_{ij}^{''L} = U_{i4}^{e,R} U_{j5}^V - \frac{1}{\sqrt{2}} U_{i5}^{e,R} U_{j7}^V$$

We found that our results are in agreement with the actual constraints on $|U_s|^2$ [3]. In the case $m_s = 7$ keV we obtained an active-sterile mixing element $|U_s|^2 \sim 5 \times 10^{-11}$, which wolud be in agreement with the experimental evidence of the 3.5keV line excess in X-ray observations (with the correct reliq density). With all the analysis done, we can conclude that the **sterile neutrino can be a viable Dark Matter candidate within the $\mu\nu$SSM**.

[3] R. Adhikari, M. Agostini, N. Anh Ky, *et al.*, "White paper on kev sterile neutrinodark matterâ, *Journal of Cosmology and Astroparticle Physics* **2017** no.1