Kaon physics within νMSM

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“ How to find neutral leptons of the νMSM?”

arXiv:0705.1729 [hep-ph]

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Outline

1. The νMSM Model
   - Motivation
   - Model content and Lagrangian
   - Properties
2. Constraints
   - Dark Matter constraints
   - Constraints from Baryon Asymmetry
3. Phenomenology of heavy neutrinos
   - Heavy neutrino sector
   - Constraints on heavy sterile neutrinos
   - Heavy sterile neutrinos in Kaon decays
   - Heavy sterile neutrinos from D, B, τ decays

Standard Model—Success and Problems

Gauge fields (interactions) – γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM}) — sterile neutrino as WDM
  - Baryon asymmetry — leptogenesis via sterile neutrino oscillations
  - Dark energy (Ω_Λ)
  - Inflation — new scalar
  - Strong CP
  - Gauge hierarchy
  - GUT
  - Quantum gravity

νMSM explains these but does not explain those

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νMSM particle content

36 quark states:

$(u,d)_L, \quad (c,s)_L, \quad (t,b)_L$ and $u_R, \ d_R, \ c_R, \ s_R, \ t_R, \ b_R$

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9+3 leptonic states:

$(\nu_e,e)_L, \quad (\nu_\mu,\mu)_L, \quad (\nu_\tau,\tau)_L$ and $N_1, \ e_R, \ N_2, \ \mu_R, \ N_3, \ \tau_R$

SU(3)×SU(2)×U(1) — 12 gauge bosons (8+3+1)

one Higgs doublet

Leptonic sector has similar structure as the quark sector

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$(u,d)_L$,	$(c,s)_L$,	$(t,b)_L$	and	u_R,	d_R,	c_R,	s_R,	t_R,	b_R
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νMSM Lagrangian

Most general renormalizable lagrangian

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{MSM} + i\bar{N}_I \partial\!\!\!/ N_I - F_{\alpha I}\bar{L}_\alpha \tilde{H} N_I - \frac{M_I}{2}\bar{N}_I^c N_I + \text{h.c.}$$

Extra coupling constants:

3 Majorana masses M_I

15 new Yukawa couplings
(Dirac mass matrix $M^D = F\langle H\rangle$ has 3 Dirac masses,
6 mixing angles and 6 CP-violating phases)

18 new parameters in total

T.Asaka, S.Blanchet, M.Shaposhnikov, PLB 631 (2005) 151; T.Asaka, M.Shaposhnikov, PLB 620 (2005) 17

ν masses and mixings

$M_I \gg M^D$ — "seesaw" mechanism is working:

3 heavy neutrinos with masses M_I

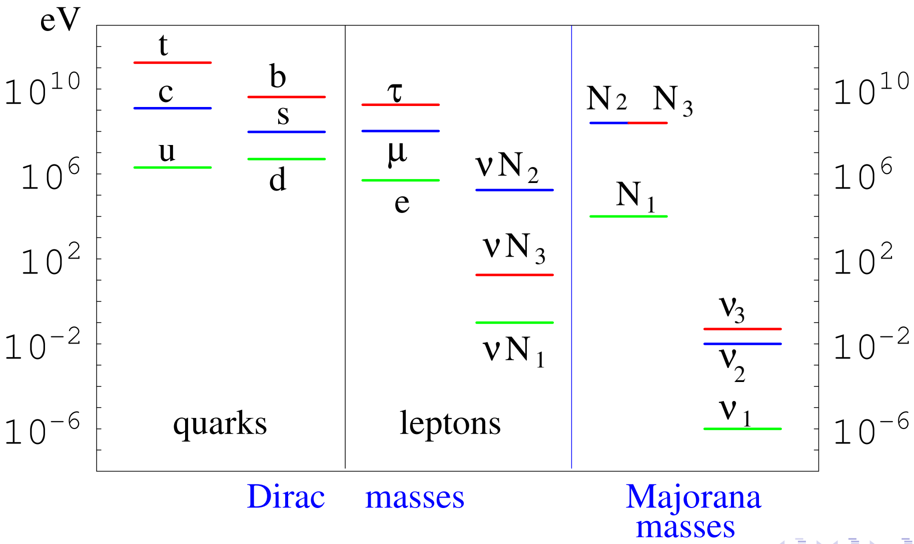
Light neutrino masses $M^\nu = -(M^D)^T \frac{1}{M_I} M^D$

$$V^T M^\nu V = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Mixing: flavor states $\nu_\alpha = V_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^c$

Active-sterile mixings $\Theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \ll 1$

The spectrum of νMSM



DM keV neutrino constraints

N_1 with the keV scale mass provides the Warm Dark Matter

Bounds on mass

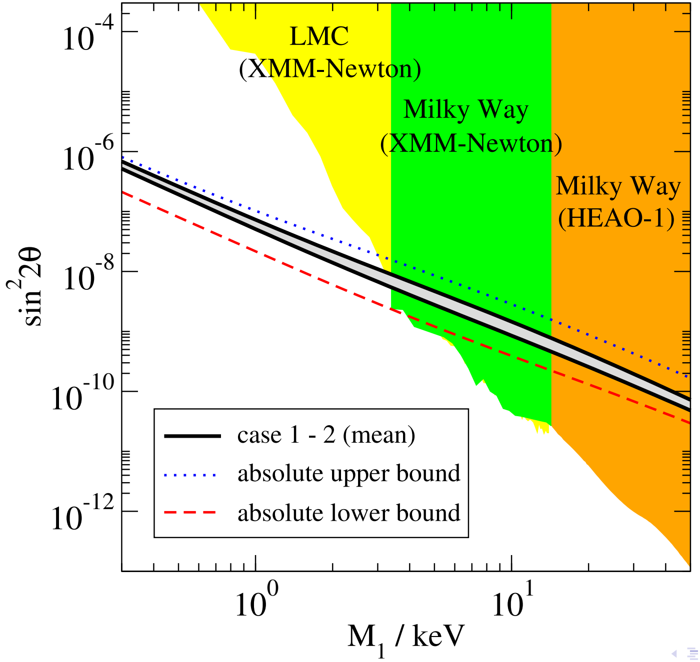
- Tremaine-Gunn bound $M_1 \gtrsim 0.3$ keV
- Lyman-α bound $M_1 \gtrsim 11.6$ keV or 8 keV

Bound on mass and mixing angle

- X-ray observation: $N_1 \to \nu + \gamma$

Production mechanism

- Dodelson-Widrow (thermal) scenario
- Primordial abundance: physics at higher energies
  - Entropy production
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.



LMC
(XMM-Newton)
Milky Way
(XMM-Newton)
Milky Way
(HEAO-1)
sin²2θ
10^-4
10^-6
10^-8
10^-10
10^-12
10^0
10^1
M_1 / keV
case 1 - 2 (mean)
absolute upper bound
absolute lower bound

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- X-ray observation: $N_1 \to \nu + \gamma$

Production mechanism

- Dodelson-Widrow (thermal) scenario is ruled out
- Primordial abundance: physics at higher energies
  - Entropy production
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.

Baryon Asymmetry

Baryogenesis via Leptogenesis (heavier sterile N_2 and N_3)

- Generation of lepton asymmetry in active neutrino sector via CP-violating neutrino oscillations
- LAU $\to$ BAU by sphaleron transformations, conserving $B+L$

$$M_{2,3} \lesssim 20\text{ GeV}$$

$$\frac{n_B}{s} = 2\times 10^{-10}\,\delta_{CP}\left(\frac{10^{-6}}{\Delta M_{32}^2/M_3^2}\right)^{\frac{2}{3}}\left(\frac{M_3}{10\text{ GeV}}\right)^{\frac{5}{3}}\,,$$

δ_{CP} describes CP in sterile sector; $\frac{n_B}{s} \simeq (0.9 \div 1.0)\times 10^{-10}$

- Should not thermalize before sphaleron processes stop:
  $\Theta_{2,3} < 2\kappa\times 10^{-8}\left(\frac{\text{GeV}}{M_{2,3}}\right)^2$
  ($\kappa \simeq 1(2)$ for normal(inverted) hierarchy)

T. Asaka, M. Shaposhnikov, PLB 620 (2005) 17

Heavy neutrino lagrangian

$$\mathcal{L}_N \simeq -\frac{1}{\sqrt{2}} f_\alpha \bar{L}_\alpha \tilde{H}(N_2 + N_3) - \frac{M_2}{2}\bar{N}_2^c N_2 - \frac{M_3}{2}\bar{N}_3^c N_3 + \mathrm{h.c.}\,,$$

active-sterile mixing: $U_\alpha \sim f_\alpha \cdot \frac{v}{2M}$

active neutrino mass-mixing patterns

$$\sum_\alpha |U_\alpha|^2 \equiv U^2 > 1.3\kappa \times 10^{-11} \left(\frac{\mathrm{GeV}}{M}\right)$$

Baryogenesis

- degeneracy: $\Delta M^2 = |M_2^2 - M_3^2| \lesssim 10^{-5} M^2$
- active-sterile mixing: $U^2 < 2\kappa \times 10^{-8} \left(\frac{\mathrm{GeV}}{M}\right)^2$

Heavy N mixing angle constraints

Upper limits (dashed):

Baryon asymmetry constraint:

$U^2 < 2\kappa \times 10^{-8} \left(\frac{\text{GeV}}{M_{2,3}}\right)^2$

CERN PS191 limits

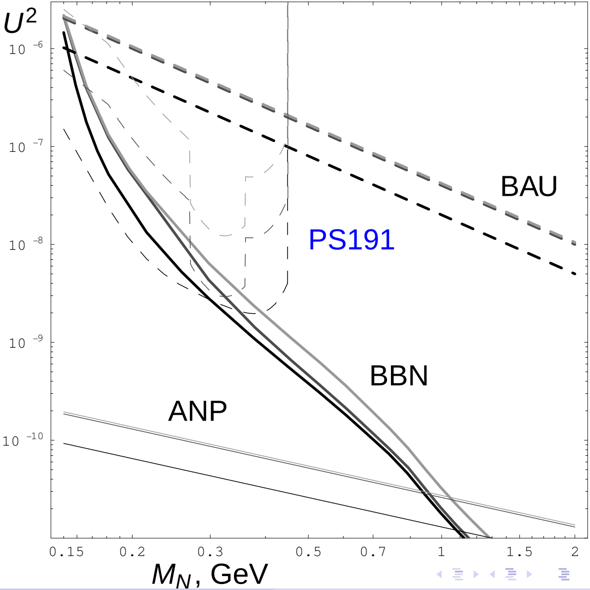
Lower limits (solid):

BBN bound ($N \to \nu\gamma$):

$\tau_{N_{2,3}} < 0.1$ s

Active neutrino patterns:

$U^2 > 1.3\kappa \times 10^{-11} \left(\frac{\text{GeV}}{M}\right)$



D.G., M.Shaposhnikov, arXiv:0705.1729

Heavy N lifetime constraints

Lower limits (dashed):

Baryon asymmetry constraint:

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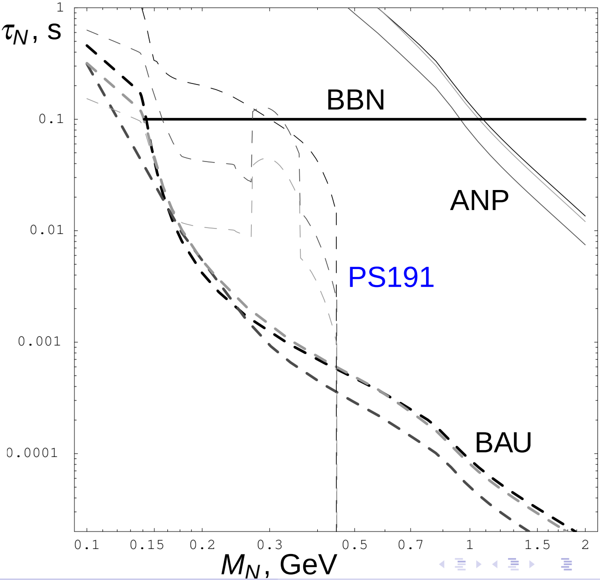

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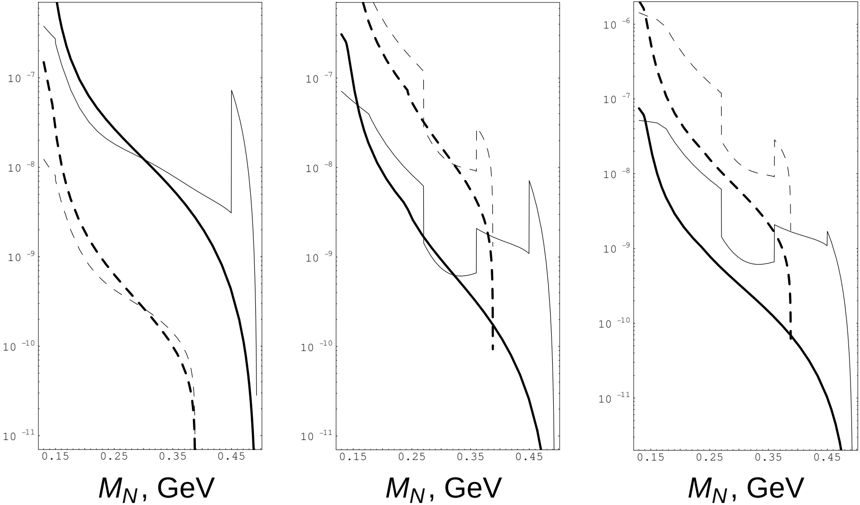
Kaon two-body decays

$Br(K \to eN_I)$ solid lines
$Br(K \to \mu N_I)$ dashed lines

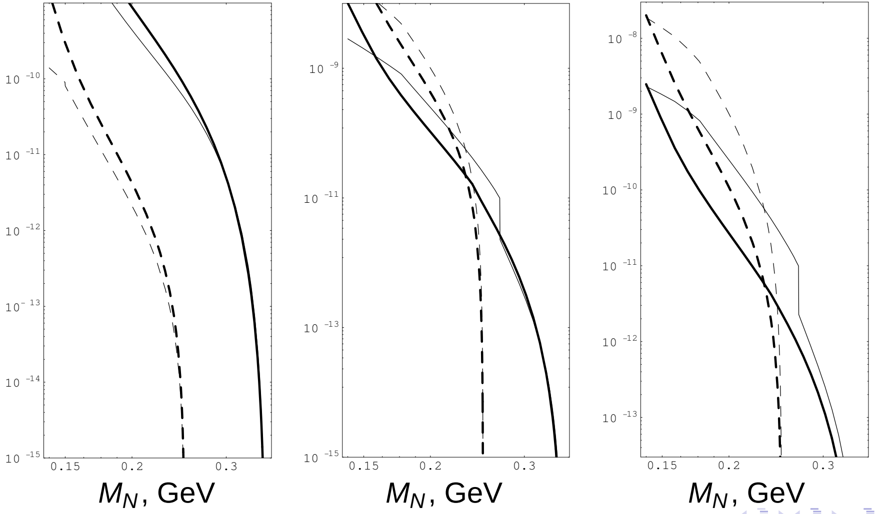
Upper limits — thin lines
Lower limits — thick lines



Kaon three-body decays

$Br(K \to \pi e N_I)$ solid lines
$Br(K \to \pi \mu N_I)$ dashed lines

Upper limits — thin lines
Lower limits — thick lines



Charmed and Beauty mesons, τ-lepton

Interesting branchings start from

$D \to l + N$	10^{-8}	$B \to l + N$	10^{-11}
$D_s \to l + N$	10^{-8}	$B_c \to l + N$	10^{-9}
$D \to P + l + N$	10^{-8}	$B \to D + l + N$	10^{-8}
$D \to V + l + N$	10^{-9}	$B_s \to D_s + l + N$	10^{-8}
$D_s \to P + l + N$	10^{-9}	$B_c \to \eta_c + l + N$	10^{-9}
$D_s \to V + l + N$	10^{-8}	$B \to D^* + l + N$	10^{-7}
$\tau \to P(V) + N$	10^{-8}	$B_s \to D_s^* + l + N$	10^{-7}
$\tau \to \nu + l + N$	10^{-8}	$B_c \to J/\psi + l + N$	10^{-8}

D.G., M.Shaposhnikov, arXiv:0705.1729 [hep-ph]

Conclusions

- νMSM — the simplest Standard Model extension with right handed neutrinos provides
  - active neutrino masses
  - keV neutrino as a WDM candidate
  - mechanism for baryon asymmetry generation
- Possible searches for Dark Matter keV sterile neutrino
  - X-ray observations — indirect evidence
  - $0\nu\beta\beta$ decay — may constraint the model
  - Full kinematics measurement of beta decay in the laboratory
- Possible searches for "heavy" sterile neutrinos responsible for baryogenesis
  - K, D, B, τ decays
  - sterile neutrino decays searches: CNGS, T2K, etc.

Model with $M_N < M_K$ can be fully explored experimentally