Minimal Extension of the Standard Model of Particle Physics

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Outline

1. Motivation: Phenomena Observed but Unexplained within the SM
2. The $\nu$MSM Model: Content and Lagrangian
3. The $\nu$MSM Model: Numbers in Sterile Neutrino Sector
4. Conclusions
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Motivation: Phenomena Observed but Unexplained within the SM

Neutrino Oscillations: Masses and Mixing

- $\Delta m^2$ [eV$^2$]
- $\tan^2 \theta$

Figure: Various experimental data points and theoretical predictions for neutrino oscillations, including Super-K, K2K, NOMAD, LSND, BNL E776, CHORUS, NOMAD, and CDHSW.
Baryons and Dark Matter in Astrophysics

Rotation curves

Gravitational lensing

“Bullet” cluster
Motivation: Phenomena Observed but Unexplained within the SM

Baryons and Dark Matter in Cosmology

Rotation curves

BBN

Gravitational lensing

Structures

CMB fluctuations

“Bullet” cluster

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Standard Model: Success and Problems

Gauge fields (interactions) – $\gamma, W^\pm, Z, g$

Three generations of matter: $L = (\nu_L, e_L), e_R; Q = (u_L, d_L), d_R, u_R$

- Describes
  - all experiments dealing with electroweak and strong interactions

- Does not describe
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$) — sterile neutrino as DM
  - Baryon asymmetry — leptogenesis via sterile neutrino oscillations

$\nu_{MSM}$ explains these but does not address those

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  - Dark energy ($\Omega_\Lambda$)
  - Inflation
  - Strong CP
  - Gauge hierarchy
  - Quantum gravity

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  - Dark energy ($\Omega_{\Lambda}$)
  - Inflation — $R^2, RH^\dagger H, \ldots$
  - Strong CP — changing topology, \ldots
  - Gauge hierarchy — No scales!
  - Quantum gravity

\textit{νMSM} explains these

explained by Plank-scale physics?
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νMSM Particle Content

36 quark states:

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

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9+3 leptonic states:

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

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

one Higgs doublet

Leptonic sector has similar structure as the quark sector
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Leptonic sector has similar structure as the quark sector
\( \nu \text{MSM Lagrangian} \)

- Let us try to use as little “new physics” as possible
- Require to get the correct neutrino oscillations
- Explain DM and baryon asymmetry of the Universe

\[ \mathcal{L}_{\nu \text{MSM}} = \mathcal{L}_{\text{MSM}} + \bar{N}_i i \partial \nu N_i - f_{i\alpha} H \bar{N}_i L_{\alpha} - \frac{M_i}{2} \bar{N}_i^c N_i + \text{h.c.} \]

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)

Asaka, Blanchet, Shaposhnikov, 2005

Asaka, Shaposhnikov, 2005
ν Masses and Mixings: “seesaw” from $f_l \alpha H N \frac{1}{L} \alpha$ 

$M_I \gg M^D = f v$ — says nothing about $M_I$! dangerous: $\delta m^2_h \propto M^2_I$ 

3 heavy neutrinos with masses $M_I$ similar to quark masses 

Light neutrino masses 

$$M^\nu = -(M^D)^T \frac{1}{M_I} M^D \propto f^2 \frac{v^2}{M_I}$$

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

Mixings: flavor state $\nu_\alpha = U_{\alpha i} \nu_i + \theta_{\alpha l} N^c_l$

Active-sterile mixings 

$$\theta_{\alpha l} = \frac{(M^D)_{\alpha l}^T}{M_I} \propto f \frac{v}{M_I} \ll 1$$
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The $\nu$MSM Model: Numbers in Sterile Neutrino Sector

Spectrum of $\nu$MSM

\[
\begin{array}{cccccc}
\text{eV} & 10^{10} & 10^6 & 10^2 & 10^{-2} & 10^{-6} \\
10^{-6} & t & c & b & \tau & \nu N_2 \\
10^{-2} & u & s & \mu & e & \nu N_2 \\
10^2 & d & \nu N_1 \\
10^6 & \nu N_1 & N_2 & N_3 \\
10^{10} & N_1 & N_2 & N_3 \\
\end{array}
\]

Dirac masses

Majorana masses

quarks

leptons

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DM – lightest sterile neutrino $N_1$

Phase-space density constraints

$\sin^2(2\theta_1)$ vs. $M_1$ [keV]

$\Omega_{N_1} > \Omega_{DM}$

$\Omega_{N_1} < \Omega_{DM}$

X-ray constraints

$\Omega_{N_1} > \Omega_{DM}$

$\Omega_{N_1} < \Omega_{DM}$

$L_6^{\text{max}} = 700$

BBN limit: $L_6^{\text{BBN}} = 2500$

$L_6 = 25$

$L_6 = 70$
BAU – heaviest sterile neutrinos $N_{2,3}$
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Conclusions

- \( \nu\text{MSM} \) — the simplest Standard Model extension with right handed neutrinos provides
  - active neutrino masses and mixing angles
  - 1-50 keV neutrino as DM
  - mechanism for baryon asymmetry generation

- Possible searches for Dark Matter keV sterile neutrino
  - X-ray observations — indirect evidence
  - \( 0\nu\beta\beta \) decay — very small rate, \( m_\nu \lesssim 10^{-5} \text{ eV} \)
  - Full kinematics measurement of beta decay in the laboratory?

- Possible searches for “heavy” sterile neutrinos responsible for baryogenesis
  - sterile neutrino from \( K, D, B, \tau \) decays with \( \text{Br} \approx 10^{-6} – 10^{-10} \)
  - sterile neutrino decays searches: CNGS, T2K, etc.

Model with \( M_N < M_K \) can be fully explored experimentally