The νMSM

-- Neutrino Masses, Dark Matter and
Baryon Asymmetry of the Universe --

Takehiko Asaka (Tohoku University)

@ ICFP2005, Chungli, Taiwan, 3-8 October 2005

TA, M.Shaposhnikov [PLB 620 (05) 17, hep-ph/0505013]
Outline

- What is the νMSM?
- Dark Matter in the νMSM
- Baryon Asymmetry in the νMSM
- Conclusions
Neutrino oscillations

- The Minimal Standard Model (MSM) of particle physics conflicts with ν oscillation experiments!!
  - Solar, atmospheric, reactor and accelerator experiments
  - Neutrino mass scales:
    \[ \Delta m^2_{\text{atm}} \approx 2 \times 10^{-3} \text{ eV}^2 \quad \Delta m^2_{\text{sol}} \approx 8 \times 10^{-5} \text{ eV}^2 \]

- A simplest extension including neutrino masses is

  **The νMSM**
I. What is the νMSM?
What is the $\nu$MSM?

- The MSM + Three right-handed neutrinos $N_I$ ($I = 1, 2, 3$)

$$\delta L = i \bar{N}_I \bar{\partial}_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \Phi - \frac{M_I}{2} \bar{N}_I N_I^c + \text{h.c.}$$

*Not new!*

- 18 new parameters
  - 3 Majorana masses $M_I$ of $N_I$
  - 15 parameters in the Dirac Yukawa matrix $F$
    (3 Dirac masses, 6 mixing angles, 6 CP phases)
In this talk

- We show that the $\nu$MSM can explain simultaneously
  - Neutrino oscillations
  - Dark matter
  - Baryon asymmetry

- The point:
  
  Majorana masses are $M_I \leq O(100)$GeV

  - No new energy scale is introduced
  - Seesaw mechanism still works if $M_I \gg M_D = F \langle \Phi \rangle$
Scale of the \( \nu \text{MSM} \)

\[
M_\nu = -M_D^T \frac{1}{M_M} M_D \quad \Rightarrow \quad M_M = M_D^2 / M_\nu = F^2 \langle \Phi \rangle^2 / M_\nu
\]

\[M_\nu = \sqrt{\Delta m_{atm}^2}\]

Very small Yukawa couplings!
II. Dark Matter in the νMSM

Dark Matter

\[ \Omega_{dm} \sim 23\% \]

Baryon

\[ \Omega_b \sim 4\% \]

Dark Energy

\[ \Omega_\Lambda \sim 73\% \]
Dark matter in the $\nu$MSM

- The unique particle physics candidate for DM:

  Long-lived sterile (right-handed) neutrino(s)

  Peebles '82, Olive, Turner '82
  Dodelson, Widrow '94, Shi, Fuller '99
  Dolgov, Hansen '00, Abazajian, Fuller, Patel '01

  • Hot dark matter of massive active neutrinos is excluded
    by the LSS and CMBR $\sum \Omega_\nu h^2 < 4.5 \times 10^{-3}$
    U. Seljak et al '04

- We discuss the sterile neutrino DM in the $\nu$MSM
  – Constraints and implications
When Yukawa couplings are very small, sterile neutrinos can be very long-lived!!

Main decay channel: $N_I \rightarrow 3\nu$

$$\tau \approx 5 \times 10^{26} \text{ sec} \left(\frac{1 \text{ keV}}{M_I}\right)^5 \left(\frac{10^{-8}}{|\Theta|^2}\right)$$

Barger, Phillips, Sarkar '95

Lifetime can exceed the age of universe $\sim 10^{17}$ sec
Production of sterile neutrinos

- When Yukawa couplings are very small, sterile neutrinos are not thermalized.

- Main production is due to the scatterings at $T \sim 100\text{MeV} \left(\frac{M_I}{1\text{keV}}\right)^{1/3}$

$$
\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left( \frac{\Theta_{\alpha I}}{10^{-8}} \right) \left( \frac{M_I}{1\text{keV}} \right)^2
$$

Dolgov, Hansen ’00, Abazajian, Fuller, Patel ‘01

- Dirac masses (couplings) are determined!

$$
\sum_I \sum_{\alpha=e,\mu,\tau} |(M_D)_{\alpha I}|^2 = m_0^2, \quad m_0 = O(0.1)\text{eV}
$$

TA, Blanchet, Shaposhnikov ‘05
Cosmological constraints

- Radiative decays of DM sterile neutrinos are limited by X-ray observations
  \[ M_I \leq 5 \text{keV} \]  
  Abazajian, Fuller, Tucker '01

- Warm dark matter is limited by structure formation
  - WMAP + Matter power spectrum inferred from Ly-\(\alpha\) forest
  \[ M_I \geq 2 \text{keV} \]  
  Viel, Lesgourgues, Haehnelt, Matarrese, Riotto '05

- Only a small window is left!
  \[ 2 \text{keV} \leq M_I \leq 5 \text{keV} \]
Implications of sterile neutrino DM

- Dark matter constraints:

\[ 2\text{keV} \leq M_I \leq 5\text{keV}, \quad \sum_I |(M_D)_{\alpha I}|^2 = m_0^2 = [O(0.1)\text{eV}]^2 \]

- Consistency with \( \nu \) oscillation experiments leads to

- The minimal number of sterile neutrinos is “three”
- Only ”one” sterile neutrino can be dark matter
- The lightest active neutrino mass is \( m_1 < O(10^{-5})\text{eV} \)

TA, Blanchet, Shaposhnikov ‘05
We can determine the absolute values of active $\nu$ masses

$$m_1 \leq O(10^{-5})\text{eV} \implies m_2, m_3$$
Test for sterile neutrino DM

- Radiative decays of DM sterile neutrinos may be seen in X-ray observations!!

- The current status
  \[ 2\text{keV} \leq M_I \leq 5\text{keV} \]
  
  CMBR+Ly-α ↗  X-ray

- The future experiments, e.g. the Constellation X, will detect or exclude the sterile neutrino dark matter.

  Abazajian, Fuller, Tucker ‘01
III. Baryon Asymmetry in the νMSM

Baryon Asymmetry

Baryon

\[ \Omega_b \sim 4\% \]

Dark Matter

\[ \Omega_{dm} \sim 23\% \]

Dark Energy

\[ \Omega_\Lambda \sim 73\% \]
Baryogenesis conditions

- **C and CP violations**
  - 1 CKM phase in quark sector
  - and 6 phases in lepton sector

- **B and L violations**
  - L violation in Majorana masses can be neglected for \( T > T_{EW} \)
    \( \Rightarrow \) Leptogenesis does not work!
  - EW sphaleron is active for \( T > T_{EW} \)

- **Out of equilibrium**
  - No strong 1st order EW phase transition
  - **Sterile neutrinos are not equilibrated for** \( T > T_{EW} \)
    \( \Rightarrow f_\nu \leq 2 \times 10^{-7} \quad \Rightarrow M_\nu \leq 17 \text{GeV (atm)} \)
Baryogenesis via neutrino oscillations

Akhmedov, Rubakov, Smirnov ‘98

Idea: Sterile neutrino oscillation is a source of BAU

- Sterile neutrinos are created and oscillate with CPV
- The total lepton number is zero but is distributed between active and sterile neutrinos
- The asymmetry of active left-handed neutrinos is transferred into baryon asymmetry by sphaleron effects
Baryogenesis in the νMSM

TA, Shaposhnikov ‘05

- Impose the dark matter constraints
  - ARS formula gives too small BAU, since DM constraints remove CPV in $\begin{array}{c} N \end{array} \begin{array}{c} L \end{array} \begin{array}{c} N \end{array}$

- Find another parameter space for successful baryogenesis
  - Communication between sterile neutrinos and active sector (=active neutrinos+charged leptons)
  - Dynamical generations of both asymmetries
Kinetic equations

- **Sterile neutrinos:**
  \[
  i \frac{d \rho_{NN}}{dt} = [H_{NN}, \rho_{NN}] - \frac{i}{2} \{ \Gamma_{NN}^d, \rho_{NN} - \rho_{NN}^{eq} \} \\
  + \frac{i \sin \phi}{4} T \cdot F^\dagger (\rho_{LL} - \rho_{LL}^{eq})F
  \]

- **Active neutrinos:**
  \[
  i \frac{d \rho_{LL}}{dt} = [H_{LL}, \rho_{LL}] - \frac{i}{2} \{ \Gamma_{LL}^d, \rho_{LL} - \rho_{LL}^{eq} \} \\
  + \frac{i \sin \phi}{4} T \cdot F (\rho_{NN} - \rho_{NN}^{eq})F^\dagger
  \]

We can solve these equations numerically and analytically by using the perturbation in \( F \).
Sterile neutrinos are created and oscillate in a CP invariant way due to the DM constraints.

CP violations in LL sector generate flavor asymmetries of active neutrinos and charged leptons.

The flavor asymmetries evolve differently, leading to the total asymmetries in L and N.

\[ \Delta L = \Delta L_e + \Delta L_\mu + \Delta L_\tau \neq 0 \]
\[ \Delta N = \Delta N_1 + \Delta N_2 + \Delta N_3 \neq 0 \]

but \( \Delta L + \Delta N = 0 \)
Evolution of asymmetries

**Active sector**

\[ \Delta L_\tau [10^{-6}] \]

\[ \Delta L_e [10^{-6}] \]

\[ \Delta L_\mu [10^{-6}] \]

**Sterile sector**

\[ \Delta N_3 [10^{-9}] \]

\[ \Delta N_2 [10^{-9}] \]

\[ \Delta N_1 [10^{-19}] \]

\[ T_L \sim 10^4 \text{ GeV} \]

3-8 October 2005
Total asymmetries in active and sterile sectors

\[ \Delta N = \Delta N_1 + \Delta N_2 + \Delta N_3 \]

- We can generate \( \Delta N \neq 0, \Delta L \neq 0 \)
  but \( \Delta N + \Delta L = 0 \)

- Production starts
  \[ T_L \sim 10^4 \text{GeV} \]

Shaleron converts \( \Delta L \) partially into baryon asymmetry

\[ \Delta B = -\frac{28}{79} \Delta L \neq 0 \]

Kuzmin, Rubakov, Shaposhnikov
Baryon asymmetry of the universe

\[
\frac{n_B}{s} \approx 2 \times 10^{-10} \delta_{CP} \left( \frac{10^{-5}}{\Delta M_{32}^2 / M_3^2} \right)^{2/3} \left( \frac{M_3}{10 \text{GeV}} \right)^{5/3}
\]

in NH \( m_3 \approx \sqrt{\Delta m_{\text{atm}}^2} \), \( m_2 \approx \sqrt{\Delta m_{\text{sol}}^2} \)

- The effective CP violation parameter

\[
\delta_{CP} = 4 s_{R23} c_{R23} \left[ s_{L12} s_{L13} c_{L13} \left( c_{L23}^4 + s_{L23}^4 \right) c_{L13}^2 - s_{L13}^2 \right] \cdot \sin(\delta_L + \alpha_2) \\
+ c_{L12} c_{L13}^2 s_{L23} c_{L23} \left( c_{L23}^2 - s_{L23}^2 \right) \cdot \sin \alpha_2
\]

\( \delta_{CP} \sim 1 \) may be possible

- Heavier sterile neutrinos should be degenerate in mass

\( M_2, M_3 \sim 10 \text{GeV} \quad M_3 - M_2 \sim \text{keV} \sim M_1 \)
Conclusions

We can solve experimental and observational problems --\(\nu\) oscillations, dark matter and baryon asymmetry-- in the MSM.
Conclusions

vMSM
Thank you very much!
Dirac Yukawa Couplings

\[ F = K_L \cdot P_\alpha \cdot F_d \cdot K_R^\dagger \cdot P_\beta \]

\[ F_d = \text{diag}(f_1, f_2, f_3) \]

\[ P_\alpha = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1), \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1) \]

\[
K_L = \begin{pmatrix}
1 & c_{L13} & s_{L13} e^{-i\delta_L} \\
-c_{L23} & s_{L23} & 1 \\
-s_{L23} & c_{L23} & s_{L13} e^{i\delta_L}
\end{pmatrix}
\begin{pmatrix}
c_{L12} & s_{L12} \\
-s_{L12} & c_{L12}
\end{pmatrix}
\]

\[
K_R = \begin{pmatrix}
1 & c_{R13} & s_{R13} e^{-i\delta_R} \\
-c_{R23} & s_{R23} & 1 \\
-s_{R23} & c_{R23} & s_{R13} e^{i\delta_R}
\end{pmatrix}
\begin{pmatrix}
c_{R12} & s_{R12} \\
-s_{R12} & c_{R12}
\end{pmatrix}
\]
Kinetic equations (2)

\[
H_{NN} = H_{NN}^0 + V_{NN} \quad H_{LL} = H_{LL}^0 + V_{LL}
\]

\[
H_{NN}^0 = \frac{1}{2k} \text{diag}(M_1^2, M_2^2, M_3^2)
\]

\[
V_{NN} = \frac{T^2}{8k} F^\dagger F \quad \Gamma_{NN}^d = 2 \sin \phi \cdot V_{NN}
\]

\[
H_{LL}^0 = \frac{T^2}{k} \left[ \frac{3g_W^2 + g_Y^2}{32} \text{diag}(1,1,1) + \frac{1}{8} \text{diag}(h_e^2, h_\mu^2, h_\tau^2) \right]
\]

\[
V_{LL} = \frac{T^2}{8k} FF^\dagger \quad \Gamma_{LL}^d = 2 \sin \phi \cdot V_{LL}
\]
• **Flavor eigenstates:**

  Left-handed neutrinos

  \[ \nu_e, \nu_\mu, \nu_\tau \]

  Right-handed neutrinos

  \[ N_1, N_2, N_3 \]

• **Mass eigenstates:**

  Active neutrinos

  \[ \nu_1, \nu_2, \nu_3 \]

  \[ m_1 \leq m_2 \leq m_3 \]

  \[ M_\nu = -M_D^T M^{-1}_I M_D \]

  Sterile neutrinos

  \[ N_1, N_2, N_3 \]

  \[ M_1 \leq M_2 \leq M_3 \]

  \[ \nu \text{ oscillations} \]
Sterile (right-handed) neutrinos

- The lightest sterile neutrino
  \[ M_1 = 2 - 5 \text{keV}, \quad f_1 \approx 6 \times 10^{-13} \]
  - The long-lived dark matter

- The second and third sterile neutrinos
  \[ M_2 = O(10)\text{GeV}, \quad f_2 \approx 5 \times 10^{-8} \quad [\text{Solar osc.}] \]
  \[ M_3 = O(10)\text{GeV}, \quad f_3 \approx 1 \times 10^{-7} \quad [\text{Atmospheric osc.}] \]
  - Explain neutrino oscillation experiments
  - \( M_{2,3} = O(10)\text{GeV} \) for successful baryogenesis
  - Decay before BBN