νMSM: predictions for neutrino mass and $0\nu\beta\beta$-decay

hep-ph/0505247

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Outline

Standard Model—Success and Problems

γ, $W^{\pm}$, Z, g

three matter generations: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry
  - Dark energy (Ω_Λ)

    Inflation

    Gravity

νMSM explains this and does not explain this

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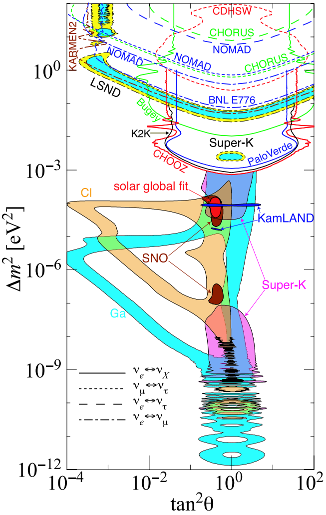
Neutrino oscillations

Δm^2_{21}	$7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2 Solar ν [SNO,KamLAND]
$\tan^2\theta_{12}$	$0.40^{+0.10}_{-0.07}$ For $\theta_{13} = 0$
$\lvert\Delta m^2_{32}\rvert$	$2.0^{+0.6}_{-0.4} \times 10^{-3}$ eV^2 Atmospheric ν [SuperK]
$\sin^2 2\theta_{23}$	> 0.95 For $\theta_{13} = 0$ [SuperK]
$\sin^2\theta_{13}$	< 0.016



http://hitoshi.berkeley.edu/neutrino

Dark Matter

- Universe is flat ($\Omega_{\text{tot}} = 1$) and contains now
  - $\Omega_\Lambda \sim 0.73$
  - $\Omega_{DM} \sim 0.22$ — sterile neutrino from νMSM as WDM
  - $\Omega_b \sim 0.05$
- ν as "Warm" Dark Matter:
  - 2 keV $< m <$ 5 keV
  - Weak coupling — never in thermal equilibrium
  - Nearly stable – $T_{\text{life}} > T_{\text{Universe}}$

Dolgov, Hansen 2000; Hansen et.al 2001; Shi, Fuller 1998; Abazajian, Fuller, Patel 2001

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Baryon Asymmetry

- There are matter in the Universe and no antimatter
- Ratio of number of baryons to entropy (or to photon number $s = 7.04 n_\gamma$)
$$\frac{n_B}{s} \simeq (8.8 \div 9.8) \times 10^{-11}$$
- Needed process
  - not in thermal equilibrium
  - CP violating
  - baryon number violating

νMSM

Standard Model with addition of $\mathcal{N}$ right-handed SU(2)×U(1) singlet neutrinos N_I ($I = 1, \ldots, \mathcal{N}$) ($\mathcal{N} = 3$ in most cases)

$$\mathscr{L} = \overline{N}_I i\partial\!\!\!/ N_I - f_{I\alpha} H \overline{N}_I L_\alpha - \frac{M_I}{2} \overline{N}_I^c N_I + h.c.$$

Dirac mass ($M^D = f\langle H\rangle$)   Majorana mass

H — Higgs doublet
L_α — left lepton doublet, $\alpha = e, \mu, \tau$

Gauge-invariant and renormalizable

hep-ph/0503065, T.Asaka, S.Blanchet, M.Shaposhnikov

Model parameters

In addition to the Standard Model

$\mathscr{N} = 3$ sterile neutrinos — 18 parameters

- 3 Majorana masses M_I
- 3 Dirac masses
- 6 mixing angles
- 6 CP-phases

$\left.\begin{array}{l}\text{3 Dirac masses}\\ \text{6 mixing angles}\\ \text{6 CP-phases}\end{array}\right\} M^D$

ν masses and mixings

$M_I \gg M^D$ — seesaw mechanism:
3 heavy neutrinos M_I
Light neutrino mass matrix:

$$M^\nu = (M^D)^T M_I^{-1} M^D$$

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

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$

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

Dark Matter constraints on νMSM

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}}\right)\left(\frac{M_I}{1\text{ keV}}\right)^2 \text{ should be } \sim 0.12$$

$$\Downarrow$$

$$\sum_I \sum_{\alpha=e,\mu,\tau} |M^D_{I\alpha}|^2 = m_0^2 \sim (0.1\text{ eV})^2$$

and dark matter neutrinos has masses in the range

$$2\text{ keV} \lesssim M_I \lesssim 5\text{ keV}$$

Stable within the Universe age

$$\tau_{N_1} = 5\times 10^{26}\text{sec}\left(\frac{M_1}{1\text{ keV}}\right)^{-5}\left(\frac{\Theta^2}{10^{-8}}\right)^{-1}$$

Two sterile neutrinos ($\mathscr{N} = 2$)—Example

Lightest active neutrino is massless $m_1 = 0$.

- Both N_1 and N_2 are dark matter

$$
\begin{aligned}
m_2 + m_3 &= \sum_{i=1}^{3} \left[\frac{((M^D U)_{1i})^2}{M_1} + \frac{((M^D U)_{2i})^2}{M_2} \right] \\
&\le \sum_{i=1}^{3} \left[\frac{|M^D_{1i}|^2}{M_1} + \frac{|M^D_{2i}|^2}{M_2} \right] \le \frac{m_0^2}{1 \text{ keV}} \le 10^{-5} \text{ eV}
\end{aligned}
$$

Contradicts with $m_3 > 5 \times 10^{-2}$ eV from oscillations

Three sterile neutrinos – one DM

- Only one sterile N_1 is dark matter

$$
\begin{aligned}
m_1 &= \frac{((M^D U)_{11})^2}{M_1} + \frac{m_1}{m_2}\frac{((M^D U)_{12})^2}{M_1} + \frac{m_1}{m_3}\frac{((M^D U)_{13})^2}{M_1} \\
&\leq \sum_{i=1}^{3} \frac{|(M^D)_{1i}|^2}{M_1} \leq \frac{m_0^2}{1\ \mathrm{keV}} \sim 10^{-5}\ \mathrm{eV}
\end{aligned}
$$

No constraints on the masses m_2, m_3 and mixings U from dark matter in this case.

Baryon Asymmetry

Baryogenesis via Leptogenesis

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

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

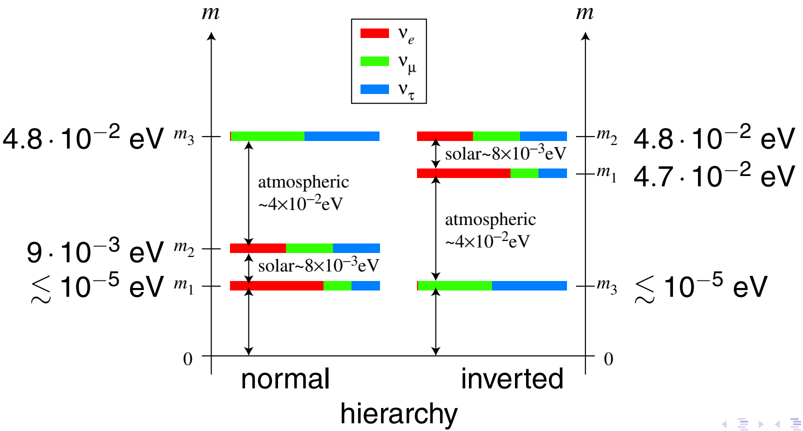
and $M_{2,3} \sim 10$ GeV. δ_{CP} describes CP in sterile sector.
In Universe: $\frac{n_B}{s} \simeq (8.8 \div 9.8) \times 10^{-11}$

hep-ph/0505013, T.Asaka, M.Shaposhnikov

Active neutrino masses — prediction!

The mass of the lightest active neutrino:

$$m_{\text{lightest}} \lesssim 10^{-5}\ \text{eV}$$



$0\nu\beta\beta$ decay

$$m_{\beta\beta} = |\sum_{i=1}^{3} m_i U_{ei}^2 + M_1 \Theta_{e1}^2|$$

Usual (active neutrino) contribution

Sterile DM neutrino contribution

Dark matter constraints: $M_1 \sim 3$ keV

$$|\Theta_{e1}|^2 = \left|\frac{(M^D)_{1e}}{M_1}\right|^2 \leq \frac{m_0^2}{M_1^2} \sim 10^{-8}$$

$$\Downarrow$$

$$|M_1 \Theta_{e1}^2| \leq 10^{-5} \text{ eV}$$

Negligible

$m_{\beta\beta}$ prediction

So, $m_{\text{lightest}} \sim 0$ is small

- Normal hierarchy

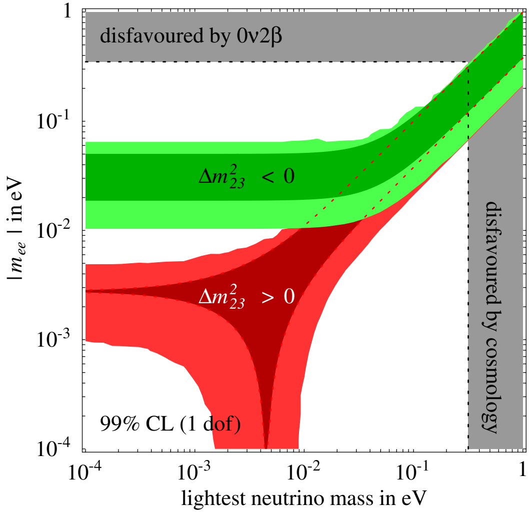
$$m_{\beta\beta}^{NH} = \left| \sqrt{\Delta m_{21}^2} \sin^2\theta_{12} \cos^2\theta_{13} + \sqrt{|\Delta m_{31}^2|} \sin^2\theta_{13} e^{-i\alpha_2} \right| .$$

- Inverted hierarchy

$$m_{\beta\beta}^{IH} = \sqrt{|\Delta m_{31}^2|} \cos^2\theta_{13} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \frac{\alpha_2 - \alpha_1}{2}} .$$

Here α_1, α_2 – Majorana phases

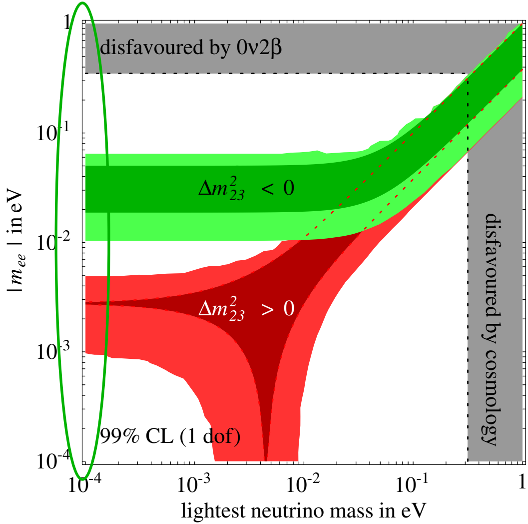
$0\nu\beta\beta$ effective Majorana mass



$0\nu\beta\beta$ effective Majorana mass

$$13 \text{ meV} < m^{IH}_{\beta\beta} < 50 \text{ meV}$$

$$1.3 \text{ meV} < m^{NH}_{\beta\beta} < 3.4 \text{ meV}$$



Light Sterile Neutrino Properties

- 2 keV $< m <$ 5 keV
- Lifetime $\tau_{N_1} = 5 \times 10^{26}\text{sec} \left(\frac{M_1}{1\ \text{keV}}\right)^{-5} \left(\frac{\Theta^2}{10^{-8}}\right)^{-1}$
- Mixing with active (electron) neutrinos
  $|\Theta_{e1}|^2 = \left|\frac{(M^D)_{1e}}{M_1}\right|^2 \leq \frac{m_0^2}{M_1^2} \sim 10^{-8}$
- Decay modes
  - $3\nu_{\text{active}}$
  - $\gamma\nu_{\text{active}}$
- Possible (or not) ways of detection
  - monochromatic X-ray (at 1–2.5 keV) from dark halos
  - threshold feature in β decay at 2–5 keV from end of electron spectrum, 10^{-8} magnitude
  - additional peak in μ energy in $\pi \to \mu\nu$ decay, 10^{-8} magnitude, 2–5 keV energy difference

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Conclusions

- νMSM — simplest renormalizable extension of the Standard Model with right-handed neutrinos
- Neutrino oscillation explanation
- All Dark Matter provided by one sterile neutrino

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  - The mass of the lightest neutrino is predicted $m_1 \lesssim 10^{-5}$ eV
  - Majorana mass determined in $0\nu\beta\beta$ decay is predicted $1.3 \times 10^{-3}\ \text{eV} < m_{\beta\beta} < 3.4 \times 10^{-3}\ \text{eV}$ for normal and $1.3 \times 10^{-2}\ \text{eV} < m_{\beta\beta} < 5 \times 10^{-2}\ \text{eV}$ for inverse hierarchy.
- Baryon asymmetry also explained

Let us hope that inverse hierarchy is realized in Nature

And probably more predictions to follow!

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Nucleosynthesis constraints

- DM neutrino not in the thermal equilibrium
- $N_{2,3}$ are in the thermal equilibrium
- they should decay before BBN

$$M_{2,3} > 1\ \text{GeV}$$

This with DM constraint leads to bounds on some mixing angles.

LSND anomaly

- It is impossible to have simultaneously dark matter, BAU, correct neutrino oscillations and LSND neutrino in νMSM.
- However, possible
  - dark matter, correct neutrino oscillations and LSND neutrino. In this case the masses of sterile neutrinos are: 1 eV (LSND), $2 \div 5$ keV (Dark Matter), $\simeq 1$ GeV

    or
  - BAU, correct neutrino oscillations and LSND neutrino. In this case the masses of sterile neutrinos are: 1 eV (LSND) and 2 degenerate neutrinos with mass $\simeq 1$ GeV (BAU generation).