Erice09
Neutrinos in Cosmology

Neutrino mass models and dark matter

-- a possibility to relate neutrino mass to dark matter --

Daijiro Suematsu (Kanazawa Univ.)

J.Kubo, E.Ma, D.S, Phys. Lett. B642 (2006) 18
J.Kubo, D.S., Phys. Lett. B643 (2006) 336
D.S., Eur. Phys. J. C56 (2008) 379
D.A.Sierra, J.Kubo, D.Restrepo, D.S.,O.Zepata, Phys. Rev. D79 (2009) 013011
D.S, T.Toma, T.Yoshida, Phys. Rev. D79 (2009) 093004
H.Fukuoka, J.Kubo, D.S., Phys. Lett. B678 (2009) 401

Outline

- Motivation and basic idea
- A radiative seesaw model and its features
- Constraint on the model and solutions
- Relation to PAMELA/Fermi-LAT anomaly
- Summary

Motivation

- The standard model (SM) is a successful framework for physics up to weak scales, but it has been considered not to be satisfactory from a theoretical point of view.

  → supersymmetry, extra dimension, etc.

  DM LSP lightest K-K mode

- Several recent experimental results require to extend the SM.

  { the existence of neutrino masses
  the existence of dark matter

- It may be an important and promising way to consider the extension of the SM only on the basis of these experimental results. I follow this way in my talk.

Basic idea

Neutrino oscillation data suggest neutrino masses are small : $m_\nu \lesssim O(10^{-1})$ eV. ($\sum m_\nu < 1.3$ eV @WMAP5)

- If Dirac mass terms exist at tree level, right-handed neutrinos should be heavy enough. (depend on Dirac mass)

  ordinary seesaw mechanism

- If Dirac mass terms are forbidden at tree level by some symmetry, small neutrino masses may be induced radiatively even for rather light right-handed neutrinos.

  radiative seesaw mechanism

The same symmetry may guarantee the stability of some neutral particle (dark matter candidate).

origin of neutrino mass ⟺ origin of dark matter

A Radiative seesaw model

E. Ma

Z_2 is imposed to forbid Dirac neutrino masses at tree level.

- Field contents

	Z_2
SM fields	$+1$
η (SU(2) inert doublet)	-1
N_k (right handed neutrinos)	-1

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle \eta \rangle = 0$$

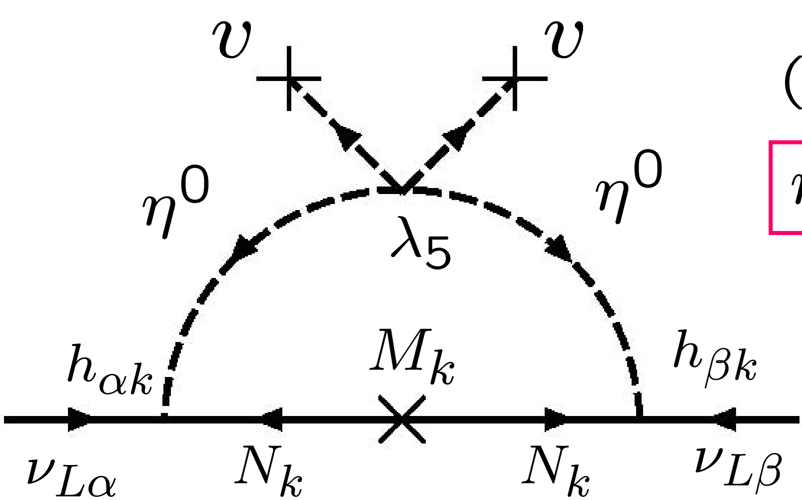
The lightest one is stable

- Z2 invariant interaction and potential

$$\mathcal{L}_N = h_{\alpha k} L_\alpha \eta N_k + \frac{1}{2} M_k N_k N_k + \text{h.c.}$$

$$\begin{aligned} V &= m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 \\ &+ \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_5}{2}[(H^\dagger \eta)^2 + \text{h.c.}] \end{aligned}$$

(1) Neutrino mass



$$I(x) = \frac{\lambda_5 v^2}{8\pi^2}\left(\frac{x}{1-x}\right)\left[1 + \frac{x \ln x}{1-x}\right]$$

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k \frac{h_{\alpha k} h_{\beta k} I(M_k^2/m_\eta^2)}{M_k}$$

$m_\eta \gg M_k$

$$\simeq \sum_k h_{\alpha k} h_{\beta k} \left(\frac{\lambda_5 v^2 M_k}{8\pi^2 m_\eta^2}\right)$$

Neutrino masses are proportional to right-handed neutrino masses.

$\lambda_5 \ll 1$

even if masses of N_k and η are $O(1)$ TeV

small neutrino masses are realized

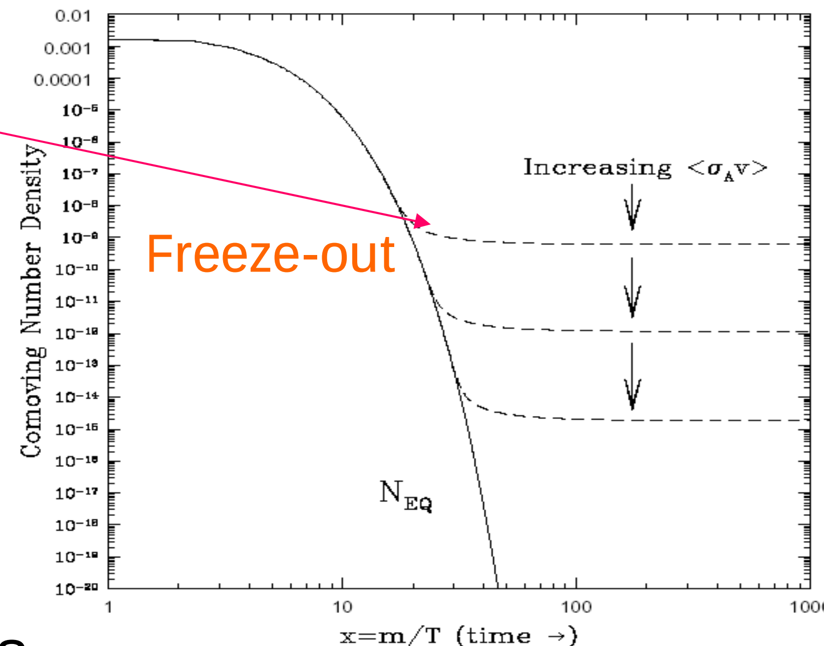
New physics is expected in lepton sector at TeV regions.

(2) Dark matter $N_k, \eta.$

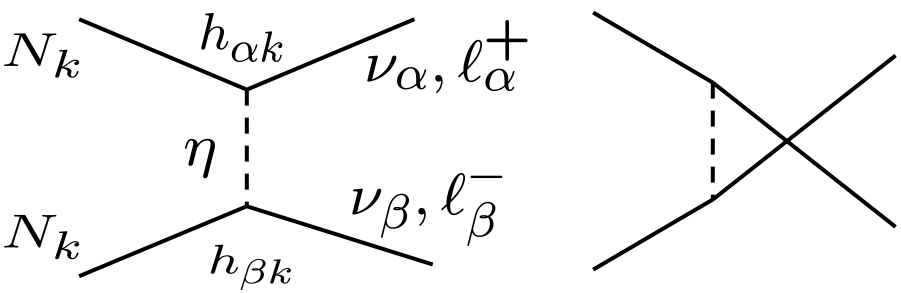
Relic abundance follows usual thermal relic scenario.

It is determined by the abundance at the freeze-out temperature as thermal relic.

$$\langle \sigma v \rangle_T \sim H(T)$$



Annihilation processes



- t-chanel η exchange processes
- final states consist of leptons only.

$$\frac{dn}{dt} = -3Hn - < \sigma v > \left[n^2 - n_{eq}^2\right]$$

(3) Constraints on this scenario

Neutrino mass

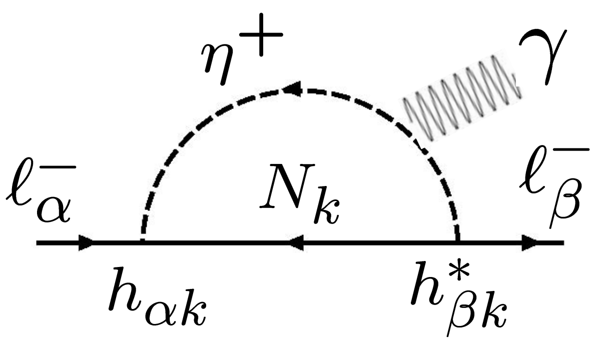
constraints

Neutrino Yukawa couplings $h_{\alpha k}$

New particle masses M_k, m_η

Dark matter abundance

Lepton flavor violating processes $\ell_\alpha \to \ell_\beta \gamma$



$$Br(\ell_\alpha \to \ell_\beta \gamma) = \frac{3\alpha}{64\pi (G_F m_\eta^2)^2} C_{\alpha\beta}^2$$

$$C_{\alpha\beta} = \left| \sum_k h_{\alpha k} h^*_{\beta k} F_2(M_k^2/m_\eta^2) \right|^{1/2}$$

Since there is no suppression due to λ_5, this contribution can be large.

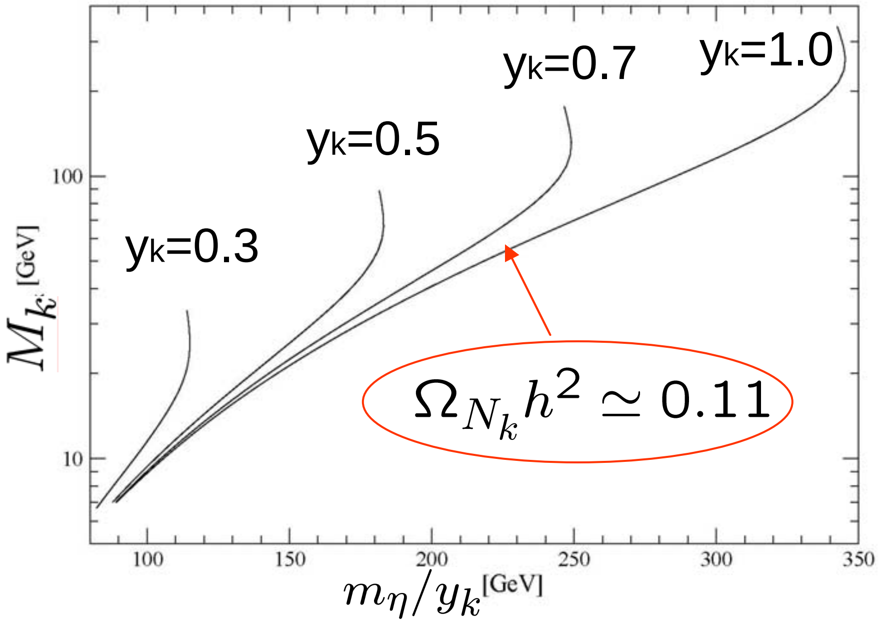
The original model

Kubo, Ma, D.S.

- No special assumption on flavor structure of $h_{\alpha k}$

<u>DM relic abundance</u>

$$y_k^4 = |\sum_{\alpha\beta} h_{\alpha k} h_{\beta k}^*|^2$$



$$m_\eta < 350 \text{ GeV for } y_k \lesssim 1$$

<u>$\mu \to e\gamma$ constraint</u>

$$Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$$

$$Br(\mu \to e\gamma) \simeq \left(\frac{30 \text{ GeV}}{m_\eta / C_{\mu e}}\right)^4$$

$$m_\eta \sim 350 \text{ GeV}$$

$$|\sum_k h_{\mu k} h_{ek}^*| \sim 1$$

$$Br(\mu \to e\gamma) \gtrsim 5 \times 10^{-7}$$

Serious contradiction is caused.
This seems a general fault of the model.

Several solutions for this problem

Key: How to suppress $\mu \to e\gamma$ without affecting the DM abundance for the same neutrino Yukawa couplings?

- To assume degeneracy among right-handed neutrinos
  - ⇒ cancellation in $C_{\mu e}$ — Kubo, Ma, D.S.
- To introduce Z' interaction — Kubo, D.S.
  - ⇒ enhancement of DM annihilation
- To assume a light right-handed neutrino N_1 — A.D.Sierra, et al.
  - ⇒ warm dark matter, smaller Yukawa couplings $h_{\alpha 1}$
- To assume special flavor structure of $h_{\alpha k}$
  - ⇒ suppression of $\mu \to e\gamma$ — D.S., Toma, Yoshida

A model with special flavor structure

To fix the flavor structure, we impose:

Neutrino mass matrix $\mathcal{M}_\nu$ is diagonalized by PMNS-matrix

$$U = \begin{pmatrix} \cos\theta_1 & \sin\theta_1 & 0 \\ -\frac{\sin\theta_1}{\sqrt{2}} & \frac{\cos\theta_1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta_1}{\sqrt{2}} & -\frac{\cos\theta_1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

tri-bi maximal mixing

$$\sin^2\theta_1 = \frac{1}{3}$$

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k h_{\alpha k} h_{\beta k} \Lambda_k$$

A solution

$$h_{ei} = 0, \quad h_{\mu i} = h_{\tau i} \quad (i = 1, 2);$$

$$h_{e3} \neq 0, \quad h_{\mu 3} = -h_{\tau 3}$$

Features on the lepton flavor

- The constraint from $\tau \to \mu\gamma$ may give a stronger condition than the constraint from $\mu \to e\gamma$ in certain parameter space.

$$M_1 \lesssim M_2 < M_3, m_\eta$$

$$h_{ei} = 0, \quad h_{\mu i} = h_{\tau i} \quad (i = 1, 2)$$ Relic abundance

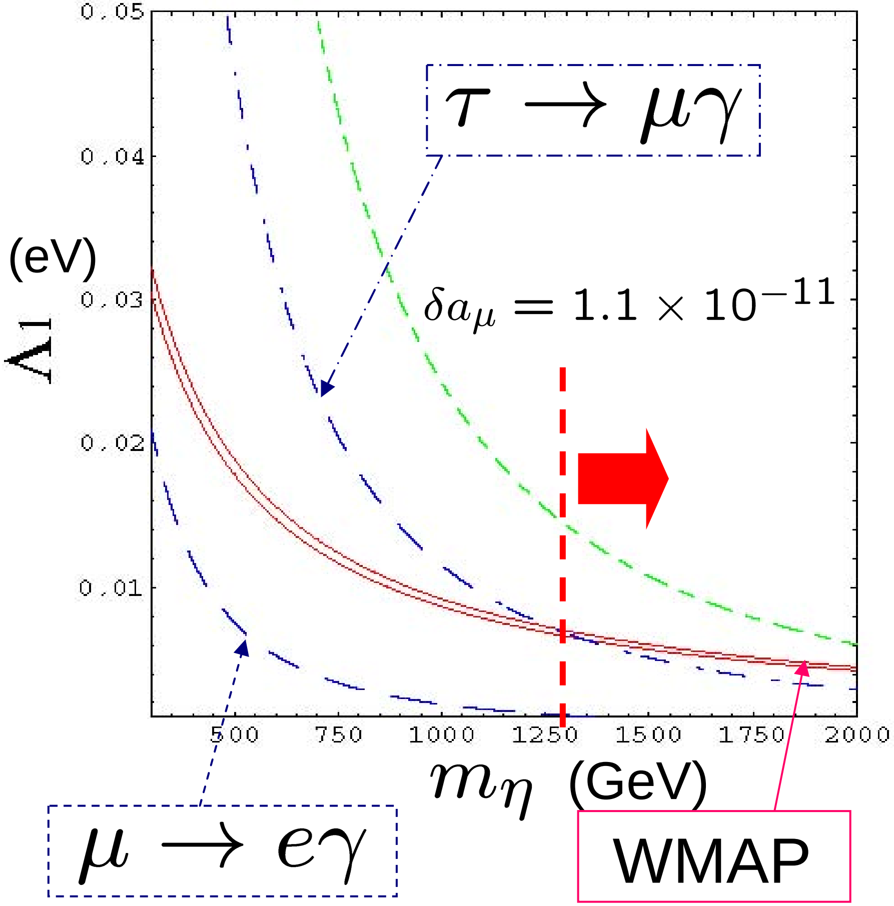
$$h_{e3} \neq 0, \quad h_{\mu 3} = -h_{\tau 3}$$ $\mu \to e\gamma$

Relevant Yukawa coupings for each process can be decoupled.

- The final states of N_1 annihilation contain $\mu^\pm$ and $\tau^\pm$ only, but $e^\pm$ are not included.

Allowed regions in a typical case

$M_1/m_\eta = 0.4,\ \ M_3/m_\eta = 10$



$$\Lambda_1 = \frac{\lambda_5 v^2 M_1}{8\pi^2 m_\eta^2}$$

- Neutrino oscillation data have been imposed in the figure.
- If $M_1 \gtrsim 1\mathrm{TeV}$ is satisfied, the model can realize the dark matter abundance successfully.
- Some additional contributions are necessary to explain $\delta a_\mu = (30.2 \pm 8,2) \times 10^{-10}$

Amonaly in PAMELA/Fermi-LAT

- Anomaly in cosmic rays

  PAMELA: excess of positron flux at 30 – 100 GeV region
  but no excess of antiproton

  Fermi-LAT: excess of (positron + electron) flux
  at 100 - 900 GeV energy region

- This may be explained by dark matter annihilation.

  required conditions

  -- final state includes no quarks

  -- annihilation cross section

  WMAP $\langle \sigma v \rangle_{T_F} \sim 10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{sec}$

  PAMELA $\langle \sigma v \rangle \sim 10^{-24}\ \mathrm{cm}^3 \cdot \mathrm{sec}$

- Model independent analyses for the amonaly suggest $\mu^+\mu^-$ and $\tau^+\tau^-$ are favored as the final states of annihilation, $M_{\mathrm{DM}} \gtrsim 1\mathrm{TeV}$

Explanation of PAMELA/Fermi-LAT

- Charged final states of the annihilation of this dark matter consist of leptons $(\mu^{\pm}, \tau^{\pm})$ only. $M_1 \gtrsim 1\text{TeV}$
- An extremely large enhancement $O(10^6)$ of cross section is required for the explanation of positron excess of PAMELA.

  If a singlet scalar is introduced, the Breit-Wigner enhancement may be applied to improve this fault.
- Other modification

  If the model is supersymmetrized, two types of dark matter candidates can appear. Since one of them may decay through anomaly induced interaction with extremely long life time, the positron excess may be explained.

Fukuoka, Kubo, D.S.

⇨ This model is potentially interesting for this anomaly.

A model with Z' interaction

- Discrete symmetry Z_2 is assumed as a remnant of $\mathrm{U}(1)'$.

● Field contents

	$\mathrm{U}(1)'$	Z_2
SM fields	$Q_L(2q), L_L(0), H(0)$	$+1$
η (SU(2) doublet)	$-q$	-1
N_2 (right handed neutrino)	0	$+1$
N_3 (right handed neutrino)	q	-1
ϕ (SM singlet)	$-2q$	$+1$

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \langle \eta \rangle = 0$$

$$\langle \phi \rangle \neq 0$$

☆ There are two types of right-handed netrino.
If a usual heavy right-handed neutrino like N_1 is additionally introduced, leptogenesis is also possible.

D.S.

● U(1)′ invariant interaction and potential

$$\mathcal{L}_N = h_{\alpha 1} L_\alpha H N_1 + h_{\alpha 2} L_\alpha \eta N_2 + \frac{1}{2} M_* N_1 N_1 + \frac{\lambda}{2} \phi N_2 N_2 + \text{h.c.}$$

$$\begin{aligned} V &= m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + m_\phi^2 \phi^\dagger \phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \frac{\lambda_3}{2}(\phi^\dagger \phi)^2 \\ &+ \lambda_4 (H^\dagger H)(\eta^\dagger \eta) + \lambda_5 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_6}{2M_*}[\phi(\eta^\dagger H)^2 + \text{h.c.}] \\ &+ \lambda_7 \phi^\dagger \phi H^\dagger H + \lambda_8 \phi^\dagger \phi \eta^\dagger \eta \end{aligned}$$

M_* Effective mass scale

After spontaneous breaking of $U(1)'$ due to $\langle\phi\rangle \ll M_*$

TeV scale

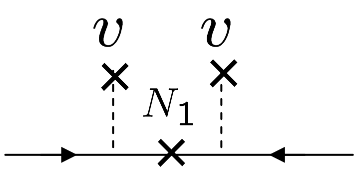
- $U(1)' \to Z_2$
- $\frac{\lambda_6}{2M_*}\langle\phi\rangle \ll O(1)$ ⇒ λ_5 in Z_2 model
- $M_{N_2} = \lambda\langle\phi\rangle$
- $M_{Z'} = 2\sqrt{2} g' q \langle\phi\rangle$

} Tev scale mass

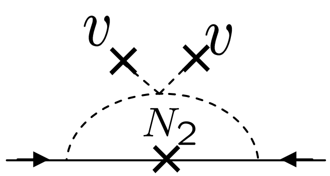
Neutrino mass and DM abundance

Neutrino mass

$$\mathcal{M}_\nu = \frac{v^2}{M_*}\left[\mu^{(1)} + \frac{\lambda_6 I(M_{N_2}^2/M_{\eta^0}^2)}{8\pi^2}\mu^{(2)}\right] \qquad \mu^{(a)} = \begin{pmatrix} h_{ea}^2 & h_{ea}h_{\mu a} & h_{ea}h_{\tau a} \\ h_{ea}h_{\mu a} & h_{\mu a}^2 & h_{\mu a}h_{\tau a} \\ h_{ea}h_{\tau a} & h_{\mu a}h_{\tau a} & h_{\tau a}^2 \end{pmatrix}$$



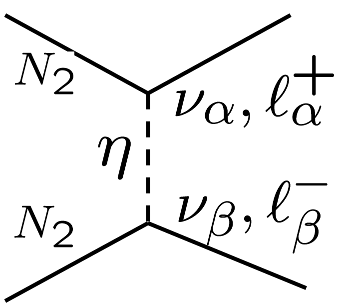
Seesaw mass



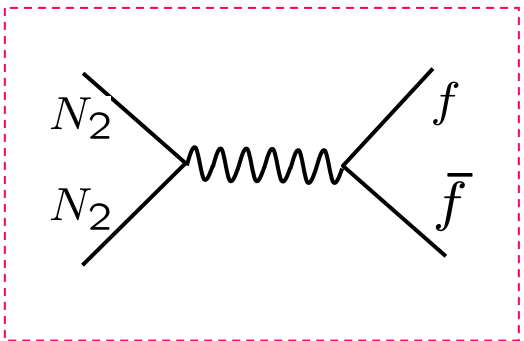
Radiative mass

Dark matter annihilation

η exchange



Z' exchange

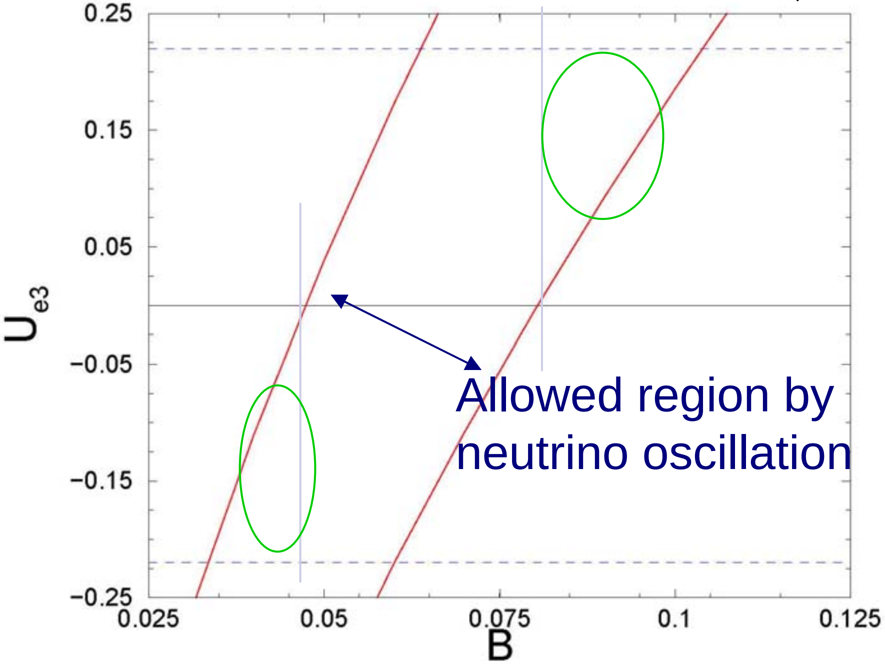


- Dominant contributions for the DM annihilation come from Z' exchange. The small neutrino couplings can be allowed.
- Quarks are included in the final states.

Predictions of the model

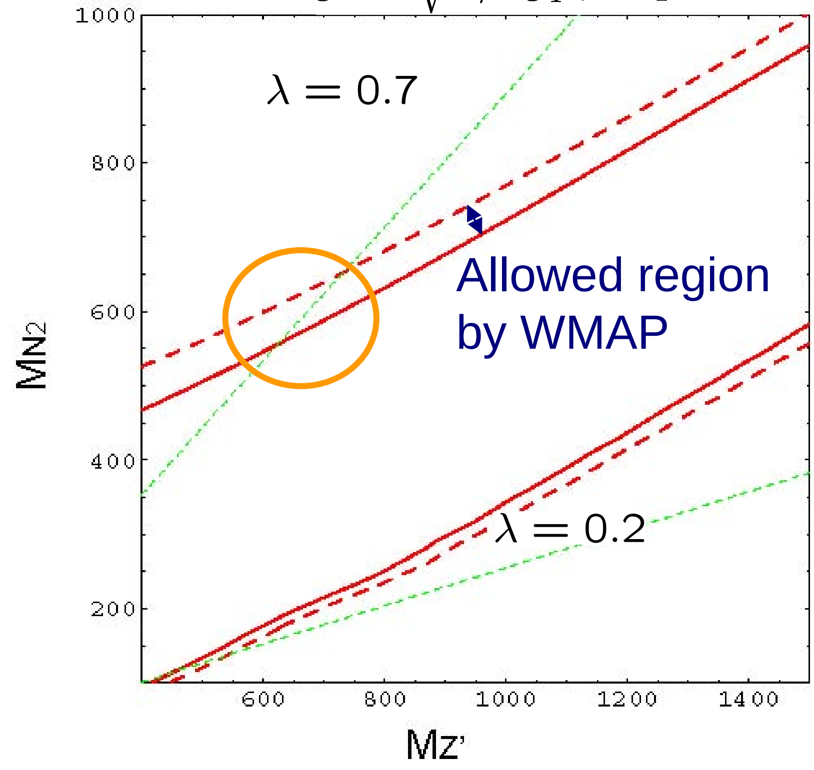
U_{e3}

$$B = \left(\frac{\lambda_6}{16\pi^2\lambda}\right)\left(\frac{h_{\tau 2}}{h_{\tau 1}}\right)^2 I\left(\frac{M_{N_2}^2}{M_{\eta^0}^2}\right)$$



$m_{Z'}$

$g' = \sqrt{5/3}g_Y, \quad q = 0.6$



Exsistence of $U_{e3} \neq 0$

$\langle m_{ee} \rangle \leq 6.3 \times 10^{-3}$eV

Consistent with WMAP

Summary

- Neutrino masses and dark matter can be strongly related each other. In that case the smallness of neutrino mass may give us some clues to explain the existence of dark matter.
- The radiative seesaw model gives a concrete example for such an idea.
- Lepton flavor violating processes give severe constraints on the model. How to overcome this problem is a key to construct a viable model.
- The model may be constrained and examined through experiments such as LHC, MEG and direct or indirect dark matter searches depending on the solution.