Majorana Fermion Dark Matter from Flavor Symmetry

-- Revisiting right handed neutrinos as dark matter --

Fumihiro Takayama (Yukawa Institute for Theoretical Physics, Kyoto Univ.)

29th July 2016: DSU2016 at Bergen

Based on JHEP1410(2014)183
JHEP1510(2015)042

Collaboration with Y.Hamada, T.Kobayashi, Y.Omura, A.Ogasahara, D.Yasuhara

Flavor symmetry

Three generation structure in Standard Model is flavor blind for gauge interaction but it's non-universal for yukawa interaction.

Yukawa structure in SM would carry a lot of information and it can be a clue to identify the origin of generations (= more fundamental description of SM).

Flavor symmetry might exist behind the observed masses and mixings of leptons and quarks.
The flavor structure of elementary particles would arise after the symmetry breaking.

Quark flavor: masses/mixings are hierarchical → Abelian?

Lepton flavor: neutrino masses....degenerate or hierarchical??
mixings....Large angles → Non-Abelian? (Tri-bimaximal, Bi-maximal....)

Underlying flavor symmetry might be working differently on lepton and quark sector.

The GUT embedding is non-trivial.

Flavor symmetry

Three generation structure in Standard Model is flavor blind for gauge interaction but it's non-universal for yukawa interaction.

Yukawa structure in SM would carry a lot of information and it can be a clue to identify the origin of generations (= more fundamental description of SM).

Flavor symmetry might exist behind the observed masses and mixings of leptons and quarks.
The flavor structure of elementary particles would arise after the symmetry breaking.

Quark flavor: masses/mixings are hierarchical → Abelian?

Lepton flavor: neutrino masses....degenerate or hierarchical??
mixings....Large angles → Non-Abelian? (Tri-bimaximal, Bi-maximal....)

Underlying flavor symmetry might be working differently on lepton and quark sector.

The GUT embedding is non-trivial.

The hidden (flavor) symmetry would predict the partner particles for known SM particles.

Flavor symmetry

Three generation structure in Standard Model is flavor blind for gauge interaction but it's non-universal for yukawa interaction.

Yukawa structure in SM would carry a lot of information and it can be a clue to identify the origin of generations (= more fundamental description of SM).

Flavor symmetry might exist behind the observed masses and mixings of leptons and quarks.
The flavor structure of elementary particles would arise after the symmetry breaking.

Quark flavor: masses/mixings are hierarchical → Abelian?

Lepton flavor: neutrino masses....degenerate or hierarchical??
mixings....Large angles → Non-Abelian? (Tri-bimaximal, Bi-maximal....)

Underlying flavor symmetry might be working differently on lepton and quark sector.

The GUT embedding is non-trivial.

The hidden (flavor) symmetry would predict the partner particles for known SM particles.

Lepton Flavor Symmetry introduces leptophilic partners.

(Leptophilic) Dark Matter from (Lepton) Flavor symmetry

The extended particle spectrum beyond SM may contain species of dark matter.
Candidates: right handed neutrinos and flavor scalars.

These particles can be charged under Flavor symmetry.

Neutrino masses and Dark Matter through Flavor Symmetry breaking

(Leptophilic) Dark Matter from (Lepton) Flavor symmetry

The extended particle spectrum beyond SM may contain species of dark matter.
Candidates: right handed neutrinos and flavor scalars.

These particles can be charged under Flavor symmetry.

Neutrino masses and Dark Matter through Flavor Symmetry breaking

Dark matter stability can be explained by a residual symmetry after the Flavor Symmetry breaking.

e.g Z_2 symmetry

(Leptophilic) Dark Matter from (Lepton) Flavor symmetry

The extended particle spectrum beyond SM may contain species of dark matter.
Candidates: right handed neutrinos and flavor scalars.

These particles can be charged under Flavor symmetry.

Neutrino masses and Dark Matter through Flavor Symmetry breaking

Dark matter stability can be explained by a residual symmetry after the Flavor Symmetry breaking.

e.g Z_2 symmetry

Dark Matter interaction with SM particles could be controlled by flavor symmetry.

Lepton flavor symmetry → leptophilic nature

Tiny neutrino masses

The Leading information of flavor symmetry breaking

Right handed neutrino SeeSaw (similar discussion is possible for triplet higgs case)

Three possibilities with right handed neutrino(s) to realize tiny neutrino masses

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$$y_l \bar{L} H e_R + \mathrm{h.c}$$

$$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \mathrm{h.c}$$

$1. M_R \sim M_{\mathrm{pl}} \gg m_{\mathrm{EW}} \qquad \eta = H \qquad y_\nu \sim O(1)$

$2. y_\nu \ll 1 \qquad \eta = H \qquad M_R < O(\mathrm{TeV})$

$3. v_\eta \ll m_{\mathrm{EW}}$ TeV scale ν_R and $y_\nu \sim O(1)$

leptophilic new $SU(2)_L$ doublet bosons required!

VEV of flavored scalar bosons could be the origin of both neutrino masses and Flavor symmetry breaking

↓

Small VEV (and residual symmetry Z2) TeV scale right handed neutrinos

↓

Very small Flavor symmetry breaking $\frac{v_\eta}{M_R}, \frac{v_\eta}{m_\eta} \sim O(10^{-6})$

Tiny neutrino masses

The Leading information of flavor symmetry breaking

Right handed neutrino SeeSaw (similar discussion is possible for triplet higgs case)

Three possibilities with right handed neutrino(s) to realize tiny neutrino masses

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$y_l \bar{L} H e_R + \mathrm{h.c}$

$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \mathrm{h.c}$

1.$M_R \sim M_{\mathrm{pl}} \gg m_{\mathrm{EW}}$ $\quad \eta = H \quad y_\nu \sim O(1)$

2.$y_\nu \ll 1 \quad \eta = H \quad M_R < O(\mathrm{TeV})$

3.$v_\eta \ll m_{\mathrm{EW}}$ $\quad$ TeV scale ν_R and $y_\nu \sim O(1)$

leptophilic new $SU(2)_L$ doublet bosons required!

VEV of flavored scalar bosons could be the origin of both neutrino masses and Flavor symmetry breaking

↓

Small VEV (and residual symmetry Z2) $\qquad$ TeV scale right handed neutrinos

↓

Very small Flavor symmetry breaking $\quad \frac{v_\eta}{M_R}, \frac{v_\eta}{m_\eta} \sim O(10^{-6})$

Neutrino mass structure: only the place that flavor symmetry breaking effects are relevant.

Tiny neutrino masses

The Leading information of flavor symmetry breaking

Right handed neutrino SeeSaw (similar discussion is possible for triplet higgs case)

Three possibilities with right handed neutrino(s) to realize tiny neutrino masses

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$$y_l \bar{L} H e_R + \text{h.c}$$

$$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \text{h.c}$$

$1. M_R \sim M_{\text{pl}} \gg m_{\text{EW}} \quad \eta = H \quad y_\nu \sim O(1)$

$2. y_\nu \ll 1 \quad \eta = H \quad M_R < O(\text{TeV})$

$3. v_\eta \ll m_{\text{EW}}$ TeV scale ν_R and $y_\nu \sim O(1)$

leptophilic new $SU(2)_L$ doublet bosons required!

VEV of flavored scalar bosons could be the origin of both neutrino masses and Flavor symmetry breaking

↓

Small VEV (and residual symmetry Z2) TeV scale right handed neutrinos

↓

Very small Flavor symmetry breaking $\frac{v_\eta}{M_R}, \frac{v_\eta}{m_\eta} \sim O(10^{-6})$

Neutrino mass structure: only the place that flavor symmetry breaking effects are relevant.

The full flavor symmetry can be a good approximate symmetry in Low energy observables.

Tiny neutrino masses

The Leading information of flavor symmetry breaking

Right handed neutrino SeeSaw (similar discussion is possible for triplet higgs case)

Three possibilities with right handed neutrino(s) to realize tiny neutrino masses

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$$y_l \bar{L} H e_R + \mathrm{h.c}$$

$$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \mathrm{h.c}$$

$1. M_R \sim M_{\mathrm{pl}} \gg m_{\mathrm{EW}} \quad \eta = H \quad y_\nu \sim O(1)$

$2. y_\nu \ll 1 \quad \eta = H \quad M_R < O(\mathrm{TeV})$

$3. v_\eta \ll m_{\mathrm{EW}}$ TeV scale ν_R and $y_\nu \sim O(1)$

leptophilic new $SU(2)_L$ doublet bosons required!

TeV scale ν_R DM ←→ Flavor symmetry symmetric LFV

VEV of flav ... y breaking

Small VEV (and residual symmetry Z_2) TeV scale right handed neutrinos

Very small Flavor symmetry breaking $\frac{v_\eta}{M_R}, \frac{v_\eta}{m_\eta} \sim O(10^{-6})$

Neutrino mass structure: only the place that flavor symmetry breaking effects are relevant.

The full flavor symmetry can be a good approximate symmetry in Low energy observables.

Tiny neutrino masses

The Leading information of flavor symmetry breaking

Right handed neutrino SeeSaw (similar discussion is possible for triplet higgs case)

Three possibilities with right handed neutrino(s) to realize tiny neutrino masses

$$m_\nu = y_\nu^2 \frac{v_\eta^2}{M_R}$$

$$y_l \bar{L} H e_R + \mathrm{h.c}$$

$$y_\nu \bar{L} \eta \nu_R + M_R \overline{\nu_R^c} \nu_R + \mathrm{h.c}$$

$1. M_R \sim M_{\mathrm{pl}} \gg m_{\mathrm{EW}} \quad \eta = H \quad y_\nu \sim O(1)$

$2. y_\nu \ll 1 \quad \eta = H \quad M_R < O(\mathrm{TeV})$

$3. v_\eta \ll m_{\mathrm{EW}}$ TeV scale ν_R and $y_\nu \sim O(1)$

leptophilic new $SU(2)_L$ doublet bosons required!

TeV scale ν_R DM ←→ Flavor symmetry symmetric LFV

VEV of flav ... y breaking

↓

Small VEV (and residual symmetry Z2) TeV scale right handed neutrinos

↓

Very small Flavor symmetry breaking $\frac{v_\eta}{M_R}, \frac{v_\eta}{m_\eta} \sim O(10^{-6})$

Neutrino mass structure: only the place that flavor symmetry breaking effects are relevant.

The full flavor symmetry can be a good approximate symmetry in Low energy observables.

For multi-Higgs vs FCNC : flavor symmetry symmetric solution?

A Concrete Model

Based on discrete DM model by M.Hirsch(2011)

$A_4 \to Z_2$: odd states(ν_{R2}, ν_{R3}) can be dark matter.

Along with this line, let's consider the following model.

Lepton flavor symmetry=Non-Abelian discrete symmetry

	L_e	L_μ	L_τ	e_R	μ_R	τ_R	$\nu_R = (\nu_R^1, \nu_R^2, \nu_R^3)$	N_4	h	$\eta = (\eta_1, \eta_2, \eta_3)$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
A_4	$\mathbf{1}$	$\mathbf{1}'$	$\mathbf{1}''$	$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$

Scalar DM: M.Hirsch et al (2011)

Right handed neutrino DM: Our work (2014)

Z3 symmetry in charged lepton sector

$$\mathcal{L}_{\rm Yukawa} = y_e \overline{L}_e e_R h + y_\mu \overline{L}_\mu \mu_R h + y_\tau \overline{L}_\tau \tau_R h$$
$$+ y_\nu^e \overline{L}_e (\nu_R \tilde{\eta})_1 + y_\nu^\mu \overline{L}_\mu (\nu_R \tilde{\eta})_{1''} + y_\nu^\tau \overline{L}_\tau (\nu_R \tilde{\eta})_{1'}$$
$$+ Y_4 \overline{L}_e N_4 \tilde{h} + M_N \overline{\nu_R^c} \nu_R + M_4 \overline{N_4^c} N_4 + \text{h.c.}.$$

$$(ab)_{\mathbf{1}} = a_1 b_1 + a_2 b_2 + a_3 b_3,$$
$$(ab)_{\mathbf{1}'} = a_1 b_1 + \omega a_2 b_2 + \omega^2 a_3 b_3,$$
$$(ab)_{\mathbf{1}''} = a_1 b_1 + \omega^2 a_2 b_2 + \omega a_3 b_3,$$
$$(ab)_{\mathbf{3}_1} = \begin{pmatrix} a_2 b_3 \\ a_3 b_1 \\ a_1 b_2 \end{pmatrix}, \quad (ab)_{\mathbf{3}_2} = \begin{pmatrix} a_3 b_2 \\ a_1 b_3 \\ a_2 b_1 \end{pmatrix}.$$

$$\begin{aligned} V(h,\eta) = {} & m_\eta^2 \eta^\dagger \eta + m_h^2 h^\dagger h - m_{h\eta_1}^2 \eta_1^\dagger h + \text{h.c.}, \\ & + \lambda_1 (h^\dagger h)^2 + \lambda_2 [\eta^\dagger \eta]_1^2 + \lambda_3 [\eta^\dagger \eta]_{1'} [\eta^\dagger \eta]_{1''} \\ & + \lambda_4 ([\eta^\dagger \eta^\dagger]_{1'} [\eta\eta]_{1''} + [\eta^\dagger \eta^\dagger]_{1''} [\eta\eta]_{1'}) + \lambda_5 [\eta^\dagger \eta^\dagger]_1 [\eta\eta]_1 \\ & + \lambda_6 ([\eta^\dagger \eta]_{3_1} [\eta^\dagger \eta]_{3_1} + [\eta^\dagger \eta]_{3_2} [\eta^\dagger \eta]_{3_2}) + \lambda_7 [\eta^\dagger \eta]_{3_1} [\eta^\dagger \eta]_{3_2} + \lambda_8 [\eta^\dagger \eta^\dagger]_{3_1} [\eta\eta]_{3_1} \\ & + \lambda_9 [\eta^\dagger \eta]_1 (h^\dagger h) + \lambda_{10} [\eta^\dagger h]_3 [h^\dagger \eta]_3 + \lambda_{11} ([\eta^\dagger \eta^\dagger]_1 hh + h^\dagger h^\dagger [\eta\eta]_1) \\ & + \lambda_{12} ([\eta^\dagger \eta^\dagger]_{3_1} [\eta h]_3 + [h^\dagger \eta^\dagger]_3 [\eta\eta]_{3_2}) + \lambda_{13} ([\eta^\dagger \eta^\dagger]_{3_2} [\eta h]_3 + [h^\dagger \eta^\dagger]_3 [\eta\eta]_{3_1}) \\ & + \lambda_{14} ([\eta^\dagger \eta]_{3_1} [\eta^\dagger h]_3 + [h^\dagger \eta]_3 [\eta^\dagger \eta]_{3_2}) + \lambda_{15} ([\eta^\dagger \eta]_{3_2} [\eta^\dagger h]_3 + [h^\dagger \eta]_3 [\eta^\dagger \eta]_{3_1}). \end{aligned}$$

$$\mathbf{1}' \otimes \mathbf{1}' = \mathbf{1}'', \quad \mathbf{1}'' \otimes \mathbf{1}'' = \mathbf{1}', \quad \mathbf{1}' \otimes \mathbf{1}'' = \mathbf{1},$$
$$\mathbf{3} \otimes \mathbf{3} = \mathbf{3}_1 \oplus \mathbf{3}_2 \oplus \mathbf{1} \oplus \mathbf{1}' \oplus \mathbf{1}''.$$

Thermal freeze out and ν_R Dark Matter relic abundance

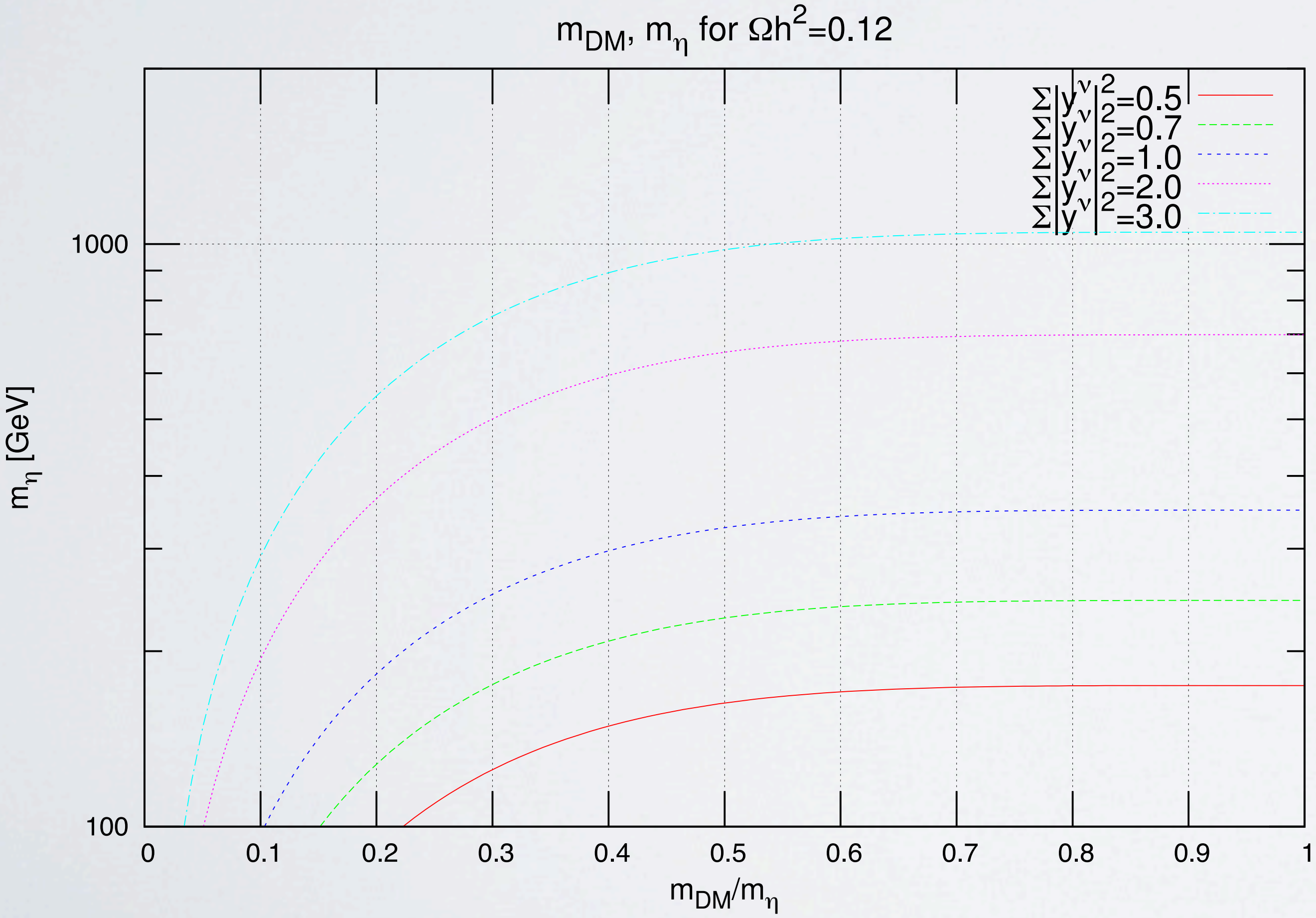
Another clue of new scales beyond SM

$$
\begin{aligned}
\sigma_{\rm ann} v_{\rm rel} &\simeq \frac{y_\nu^2}{16\pi}\frac{1}{m_N^2}\frac{1+(m_\eta/m_N)^4}{(1+(m_\eta/m_N)^2)^4}v_{\rm rel}^2, \\
&\sim 2.4\text{pb}\left(\frac{v_{\rm rel}^2}{0.3}\right)\left(\frac{y_\nu^2}{1.0}\right)^2\left(\frac{350\text{GeV}}{m_N}\right)^2\left(\frac{(1+(\frac{m_\eta}{m_N})^4)/(1+(\frac{m_\eta}{m_N})^2)^4}{1/8}\right)
\end{aligned}
$$

$y_\nu^2 = \sum_{i=e,\mu,\tau}(y_\nu^i)^2$

(*) High degeneracy → two to three/coannihilation processes have to be taken into account.

$m_\eta - m_N \sim E_\gamma \ll m_\eta$



The large regions are accessible at LHC.

However, the region of mass degeneracy would be hard to be probed at LHC.

If the dilution happen after the freeze out, the preferred mass range could be shifted to ν_R heavier mass.

Neutrino masses/PMNS mixing matrix

We take CP inv mulit-higgs potential here,
but we could introduce CP phase in this model.

In this model, the degree of freedom in neutrino mass matrix is 5 (+relative signs).

$$m_\nu = \begin{pmatrix} a^2 + X_A & ab & ac \\ ab & b^2 & bc + X_B \\ ac & bc + X_B & c^2 \end{pmatrix}. \qquad \frac{(m_\nu)_{12}^2}{(m_\nu)_{22}} = \frac{(m_\nu)_{13}^2}{(m_\nu)_{33}}.$$

Radiative correction included.

Physical degree of freedom of neutrino mass matrix=3(masses)+3(mixing)+1(CP)+2(Majorana Phase)

Experiments have fixed 5 observables in neutrino mass matrix(+1(CP)+mee).

Parameter	3σ range	best fit value
Δm_{21}^2 ($10^{-5}\mathrm{eV}^2$)	$6.99 - 8.18$	7.54
$\lvert\Delta m^2\rvert$ ($10^{-3}\mathrm{eV}^2$)	$2.19 - 2.62(2.17 - 2.61)$	$2.43(2.42)$
$\sin^2\theta_{12}$	$0.259 - 0.359$	0.307
$\sin^2\theta_{23}$	$0.331 - 0.637(0.335 - 0.663)$	$0.386(0.392)$
$\sin^2\theta_{13}$	$0.0169 - 0.0313(0.0171 - 0.0315)$	$0.0241(0.0244)$

Neutrino masses/PMNS mixing matrix

We take CP inv mulit-higgs potential here, but we could introduce CP phase in this model.

In this model, the degree of freedom in neutrino mass matrix is 5 (+relative signs).

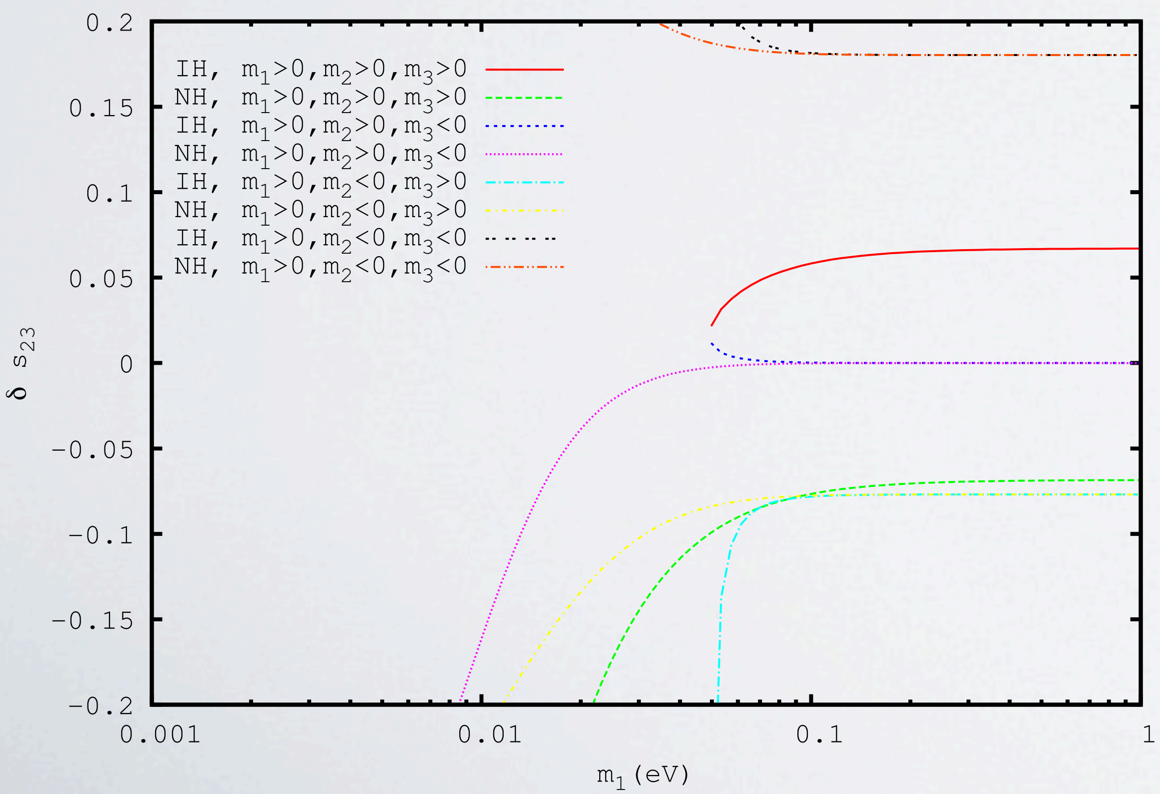
$$m_\nu = \begin{pmatrix} a^2 + X_A & ab & ac \\ ab & b^2 & bc + X_B \\ ac & bc + X_B & c^2 \end{pmatrix}. \qquad \frac{(m_\nu)_{12}^2}{(m_\nu)_{22}} = \frac{(m_\nu)_{13}^2}{(m_\nu)_{33}}.$$

Radiative correction included.

Physical degree of freedom of neutrino mass matrix=3(masses)+3(mixing)+1(CP)+2(Majorana Phase)

Experiments have fixed 5 observables in neutrino mass matrix(+1(CP)+mee).

Parameter	3σ range	best fit value
Δm^2_{21} $(10^{-5}\mathrm{eV}^2)$	$6.99 - 8.18$	7.54
$\lvert\Delta m^2\rvert$ $(10^{-3}\mathrm{eV}^2)$	$2.19 - 2.62(2.17 - 2.61)$	$2.43(2.42)$
$\sin^2\theta_{12}$	$0.259 - 0.359$	0.307
$\sin^2\theta_{23}$	$0.331 - 0.637(0.335 - 0.663)$	$0.386(0.392)$
$\sin^2\theta_{13}$	$0.0169 - 0.0313(0.0171 - 0.0315)$	$0.0241(0.0244)$



Neutrino masses/PMNS mixing matrix

We take CP inv mulit-higgs potential here,
but we could introduce CP phase in this model.

In this model, the degree of freedom in neutrino mass matrix is 5 (+relative signs).

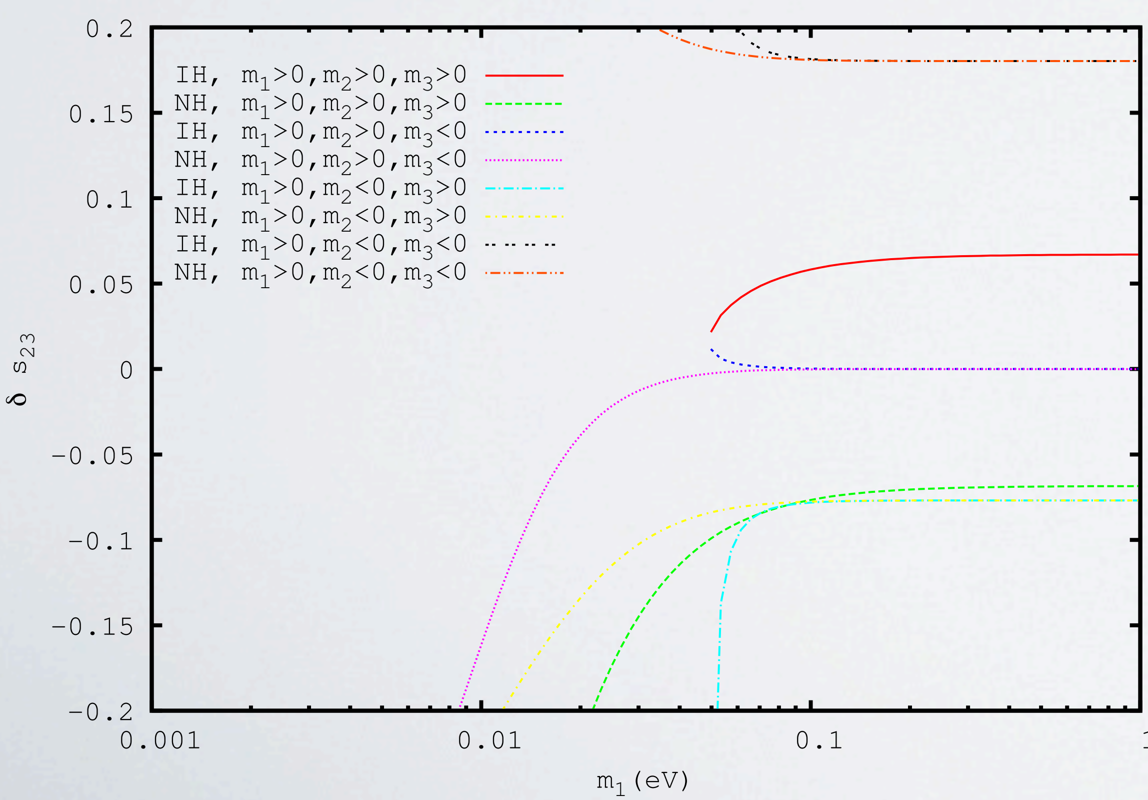
$$m_\nu = \begin{pmatrix} a^2 + X_A & ab & ac \\ ab & b^2 & bc + X_B \\ ac & bc + X_B & c^2 \end{pmatrix}. \qquad \frac{(m_\nu)_{12}^2}{(m_\nu)_{22}} = \frac{(m_\nu)_{13}^2}{(m_\nu)_{33}}.$$

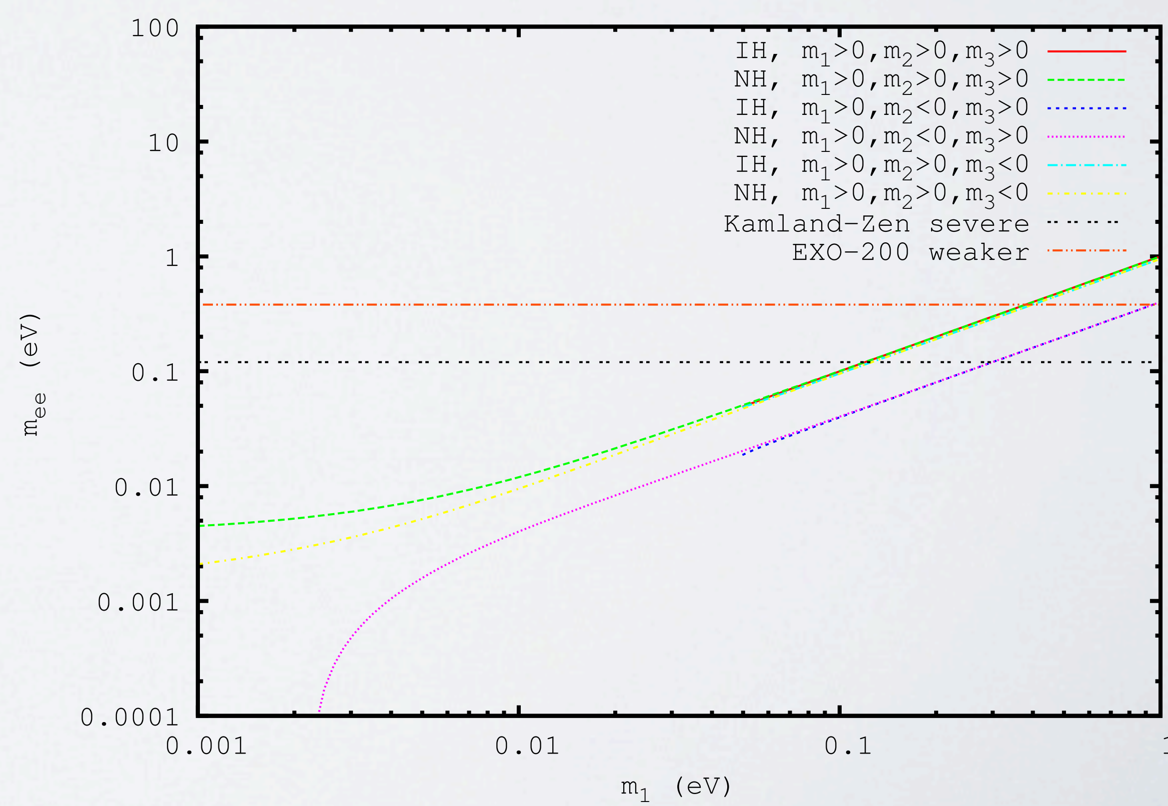
Radiative correction included.

Physical degree of freedom of neutrino mass matrix=3(masses)+3(mixing)+1(CP)+2(Majorana Phase)

Experiments have fixed 5 observables in neutrino mass matrix(+1(CP)+mee).

Parameter	3σ range	best fit value
Δm^2_{21} $(10^{-5}\mathrm{eV}^2)$	$6.99 - 8.18$	7.54
$\lvert\Delta m^2\rvert$ $(10^{-3}\mathrm{eV}^2)$	$2.19 - 2.62(2.17 - 2.61)$	$2.43(2.42)$
$\sin^2\theta_{12}$	$0.259 - 0.359$	0.307
$\sin^2\theta_{23}$	$0.331 - 0.637(0.335 - 0.663)$	$0.386(0.392)$
$\sin^2\theta_{13}$	$0.0169 - 0.0313(0.0171 - 0.0315)$	$0.0241(0.0244)$





Charged Lepton Flavor violation(LFV) and Flavor symmetry

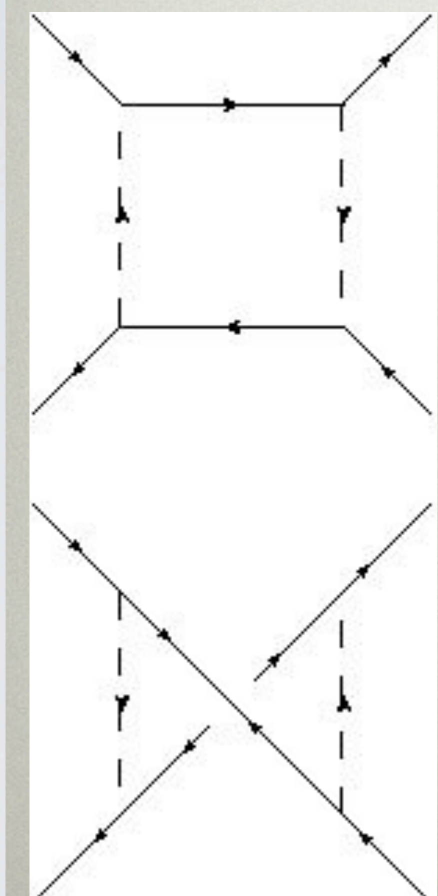
Tests of Flavor symmetry symmetric structure in LFV processes

Lepton non-universality/EW precision

Flavor symmetric structure: The role of Z3 (of A4) in charged lepton sector

Flavor symmetry breaking coupling $\sim v_\eta / v_h \sim O(10^{-6})$

$\rightarrow$ Flavor symmetry control LFV!
Flavor symmetry is a good symmetry in low energy processes.



A. Flavor symmetry violating processes are highly suppressed.

Flavor symmetry prohibit $\mu \to e\gamma$, $\mu \to e$ conversion due to Z_3 of A_4,

$$L_{LFV} \sim \frac{c_{ij}}{\Lambda}^2 \overline{L_i} H \sigma_{\mu\nu} (e_R)_j F^{\mu\nu}$$

B. Flavor symmetric processes are unsuppressed.

$$L_{\rm LFV} \sim \frac{c_{ijkl}}{\Lambda^2} (\overline{L_i} \gamma_\mu L_j)(\overline{L_k} \gamma^\mu L_l)$$

$$\Lambda \sim \frac{3}{4} \frac{1}{(4\pi)^2} \frac{1}{m_\eta^2}, \quad c_{ijkl} = y_\nu^i y_\nu^j y_\nu^k y_\nu^l$$

EWPT, lepton rare decay $\rightarrow$ $m_\eta >$ a few 100GeV $\times \left(\frac{y_\nu^2}{1.0}\right)$

Neutrino interaction can also be modified but obtain weaker constraints.

Neutrino mass information can fix all neutrino yukawa which results predictions to LFV

Charged Lepton Flavor violation(LFV) and Flavor symmetry

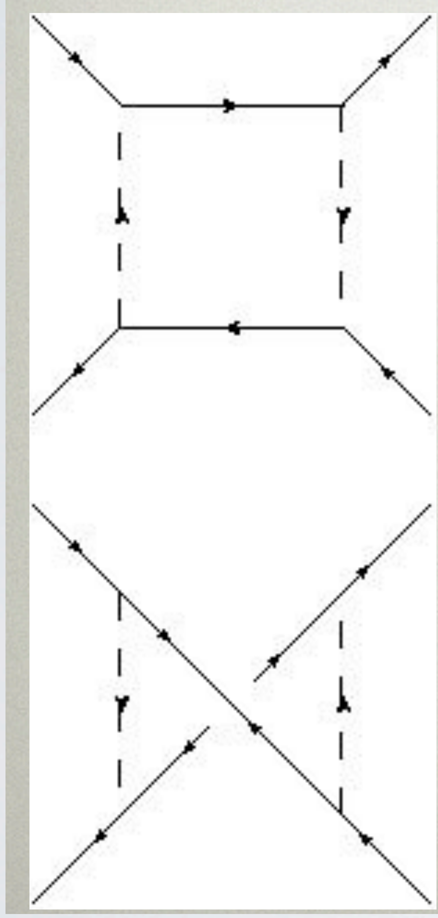
Tests of Flavor symmetry symmetric structure in LFV processes

Lepton non-universality/EW precision

Flavor symmetric structure: The role of Z3 (of A4) in charged lepton sector

$$\text{Flavor symmetry breaking coupling} \sim v_\eta/v_h \sim O(10^{-6})$$

→ Flavor symmetry control LFV!
Flavor symmetry is a good symmetry in low energy processes.



A. Flavor symmetry violating processes are highly suppressed.

Flavor symmetry prohibit $\mu \to e\gamma$, $\mu \to e$ conversion due to Z_3 of A_4,

$$L_{LFV} \sim \frac{c_{ij}}{\Lambda}^2 \overline{L_i} H \sigma_{\mu\nu} (e_R)_j F^{\mu\nu}$$

B. Flavor symmetric processes are unsuppressed.

$$L_{\rm LFV} \sim \frac{c_{ijkl}}{\Lambda^2} (\overline{L_i}\gamma_\mu L_j)(\overline{L_k}\gamma^\mu L_l)$$

$$\Lambda \sim \frac{3}{4}\frac{1}{(4\pi)^2}\frac{1}{m_\eta^2}, \quad c_{ijkl} = y_\nu^i y_\nu^j y_\nu^k y_\nu^l$$

EWPT, lepton rare decay → $m_\eta >$ a few 100GeV $\times\, (\frac{y_\nu^2}{1.0})$

Neutrino interaction can also be modified but obtain weaker constraints.

Neutrino mass information can fix all neutrino yukawa which results predictions to LFV

For the other models, e.g $L = Y_{ij}^k \bar{L}_i H_k e_R^j$ (Direct LFV source in charged lepton sector)

The Z3 structure could work well in similar way.

F.Takayama et al JHEP1510(2015)042

Charged Lepton Flavor violation(LFV) and Flavor symmetry

Tests of Flavor symmetry symmetric structure in LFV processes

Lepton non-universality/EW precision

Flavor symmetric structure:The role of Z3 (of A4) in charged lepton sector

Table 13: Best published limits on lepton-flavour-violating decays [523–533].

$\mathrm{Br}(\mu^- \to \mathrm{X}^-) \cdot 10^{12}$	(90% CL)								
$e^-\gamma$	0.57	$e^-2\gamma$	72	$e^-e^-e^+$	1.0				
$\mathrm{Br}(\tau^- \to \mathrm{X}^-) \cdot 10^{8}$	(90% CL)								
$e^-\gamma$	3.3	$e^-e^+e^-$	2.7	$e^-\mu^+\mu^-$	2.7	$e^-e^-\mu^+$	1.5	$e^-\pi^0$	8.0
$\mu^-\gamma$	4.4	$\mu^-e^+e^-$	1.8	$\mu^-\mu^+\mu^-$	2.1	$\mu^-\mu^-e^+$	1.7	$\mu^-\pi^0$	11
$e^-\eta$	9.2	$e^-\eta'$	16	$e^-\rho^0$	1.8	$e^-\omega$	4.8	$e^-\phi$	3.1
$\mu^-\eta$	6.5	$\mu^-\eta'$	13	$\mu^-\rho^0$	1.2	$\mu^-\omega$	4.7	$\mu^-\phi$	8.4
e^-K_S	2.6	e^-K^{*0}	3.2	$e^-\bar{K}^{*0}$	3.4	$e^-K^+\pi^-$	3.1	$e^-\pi^+K^-$	3.7
μ^-K_S	2.3	μ^-K^{*0}	5.9	$\mu^-\bar{K}^{*0}$	7.0	$\mu^-K^+\pi^-$	4.5	$\mu^-\pi^+K^-$	8.6
$e^-K_SK_S$	7.1	$e^-K^+K^-$	3.4	$e^-\pi^+\pi^-$	2.3				
$\mu^-K_SK_S$	8.0	$\mu^-K^+K^-$	4.4	$\mu^-\pi^+\pi^-$	2.1				
$e^-f_0(980) \to e^-\pi^+\pi^-$			3.2	$\mu^-f_0(980) \to \mu^-\pi^+\pi^-$			3.4		
$\mathrm{Br}(\mathrm{Z} \to \mathrm{X}^0) \cdot 10^{6}$	(95% CL)								
$e^\pm\mu^\mp$	1.7	$e^\pm\tau^\mp$	9.8	$\mu^\pm\tau^\mp$	12				
$\mathrm{Br}(\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{X}^0) \cdot 10^{8}$	(95% CL)								
$B^0 \to e^\pm\mu^\mp$	0.37	$B^0_s \to e^\pm\mu^\mp$	1.4						
$\mathrm{Br}(\mu^- + \mathrm{N} \to \mathrm{e}^- + \mathrm{N}) \cdot 10^{12}$	(90% CL)								
Au	0.7	Ti	4.3	Pb	46				

$0^{-6})$

processes.

y suppressed.

version due to Z_3 of A_4,

$\sim \frac{c_{ij}}{\Lambda}^2 \overline{L_i} H \sigma_{\mu\nu}(e_R)_j F^{\mu\nu}$

$\frac{1}{\eta^2}$, $c_{ijkl} = y_\nu^i y_\nu^j y_\nu^k y_\nu^l$

$100\mathrm{GeV} \times (\frac{y_\nu^2}{1.0})$

t obtain weaker constraints.

results predictions to LFV

For the other models, e.g $L = Y_{ij}^k \bar{L}_i H_k e_R^j$ (Direct LFV source in charged lepton sector)

The Z3 structure could work well in similar way.

F.Takayama et al JHEP1510(2015)042

Flavor ν_R Dark Matter signatures

neutrino line search give factor a few stronger constraint.

Dark Matter accumulation in Sun(SuperK/ANTARES/IceCube)

$$\sigma \sim \frac{1}{\pi}\frac{m_e^2}{(m_\eta^2 - m_\chi^2)^2}$$

$$\sigma_{\chi e}^0 \equiv \frac{G^2 m_e^2}{\pi} = \frac{m_e^2}{\pi\Lambda^4} \approx 3.1\times 10^{-39}\,\mathrm{cm}^2 \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^{-4}$$

neutrino-DM scattering can also be large.

Dark Matter direct searches

Basic discussions based on J.Kopp et al (2009,2014)

For anapole mode, P.Gondolo et al , K.Kopp et al

Loop induced DM couplings with Weak bosons are negligible.

Majorana nature forbids flavor diagonal vector and tensor coupling with vector bosons.

$$\overline{\nu_R}\gamma_\mu\nu_R V_\mu + \mathrm{h.c},\ \overline{\nu_R}\sigma_{\mu\nu}\nu_R F^{\mu\nu}_{(V)} + \mathrm{h.c} \to 0$$

Pseudo-vector couplings are allowed but it's suppressed by multiple cutoff scale and loop factor.

$$\frac{c_A}{\Lambda^2}(\overline{\nu_R}\gamma_5\gamma_\mu\nu_R)\times i(H^\dagger D_\mu H) \qquad c_A \sim O(1)\times\frac{\lambda}{16\pi^2}y_\nu^2$$

$$\boxed{\sigma_p^{\mathrm{SI}} \sim 10^{-47}\mathrm{cm}^2 \times \left(\frac{100\mathrm{GeV}}{m_{\nu_R}}\right)^4 \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{\sigma_{\mathrm{ann}} v}{1\mathrm{pb}}\right),\ v^2 \sim 3\frac{T_f}{m_{\nu_R}} \sim 0.1}$$

The flavor changing couplings are highly suppressed due to small flavor violation. $\frac{v_\eta}{v_h} \sim 10^{-6}$

$$\frac{c_V}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\gamma_\mu\nu_R]_3]_1 V_\mu + \mathrm{h.c},\ \frac{c_T}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\sigma_{\mu\nu}\nu_R]_3]_1 F^{\mu\nu}_{(V)} + \mathrm{h.c}$$

Flavor ν_R Dark Matter signatures

neutrino line search give factor a few stronger constraint.

Dark Matter accumulation in Sun(SuperK/ANTARES/IceCube)

$$\sigma \sim \frac{1}{\pi} \frac{m_e^2}{(m_\eta^2 - m_\chi^2)^2}$$

$$\sigma_{\chi e}^0 \equiv \frac{G^2 m_e^2}{\pi} = \frac{m_e^2}{\pi \Lambda^4} \approx 3.1 \times 10^{-39}\,\mathrm{cm}^2 \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^{-4}$$

neutrino-DM scattering can also be large.

Dark Matter direct searches

Basic discussions based on J.Kopp et al (2009,2014)

For anapole mode, P.Gondolo et al , K.Kopp et al

Loop induced DM couplings with Weak bosons are negligible.

Majorana nature forbids flavor diagonal vector and tensor coupling with vector bosons.

$$\overline{\nu_R}\gamma_\mu \nu_R V_\mu + \mathrm{h.c},\ \overline{\nu_R}\sigma_{\mu\nu}\nu_R F^{\mu\nu}_{(V)} + \mathrm{h.c} \to 0$$

Pseudo-vector couplings are allowed but it's suppressed by multiple cutoff scale and loop factor.

$$\frac{c_A}{\Lambda^2}(\overline{\nu_R}\gamma_5\gamma_\mu\nu_R) \times i(H^\dagger D_\mu H) \qquad c_A \sim O(1) \times \frac{\lambda}{16\pi^2} y_\nu^2$$

$$\boxed{\sigma_p^{\mathrm{SI}} \sim 10^{-47}\mathrm{cm}^2 \times \left(\frac{100\mathrm{GeV}}{m_{\nu_R}}\right)^4 \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{\sigma_{\mathrm{ann}} v}{1\mathrm{pb}}\right),\ v^2 \sim 3\frac{T_f}{m_{\nu_R}} \sim 0.1}$$

The flavor changing couplings are highly suppressed due to small flavor violation. $\frac{v_\eta}{v_h} \sim 10^{-6}$

$$\frac{c_V}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\gamma_\mu\nu_R]_3]_1 V_\mu + \mathrm{h.c},\ \frac{c_T}{\Lambda^2}[(H^\dagger\eta)_3[\overline{\nu_R}\sigma_{\mu\nu}\nu_R]_3]_1 F^{\mu\nu}_{(V)} + \mathrm{h.c}$$

At dim 5 if CP is violated,

$$\frac{c_{\mathrm{CPV}}}{\Lambda}\overline{\nu_R}\gamma_5\sigma_{\mu\nu}\nu_R F^{\mu\nu}$$

At dim 6 if CP is well-conserved,

$$\frac{c_{\mathrm{CP}}}{\Lambda^2}\overline{\nu_R}\gamma_5\gamma_\mu\nu_R\partial_\nu F^{\mu\nu}$$

This again can contribute to SI process in DM direct search.

neutrino line search give factor a few stronger constraint.
Dark Matter accumulation in Sun(SuperK/ANTARES/IceCube)

Flavor ν_R Dark Matter signatures

$$\sigma \sim \frac{1}{\pi}\frac{m_e^2}{(m_\eta^2 - m_\chi^2)^2}$$

Dark Matter direct searches

Basic discussions based on J.Kopp et al (2009,2014)
For anapole mode, P.Gondolo et al , K.Kopp et al

$$\sigma^0_{\chi e} \equiv \frac{G^2 m_e^2}{\pi} = \frac{m_e^2}{\pi \Lambda^4} \approx 3.1\times 10^{-39}\,\mathrm{cm}^2 \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^{-4}$$

neutrino-DM scattering can also be large.

Loop induced DM couplings with Weak bosons are negligible.

Majorana nature forbids flavor diagonal vector and tensor coupling with vector bosons.

$$\overline{\nu_R}\gamma_\mu \nu_R V_\mu + \mathrm{h.c}, \;\; \overline{\nu_R}\sigma_{\mu\nu}\nu_R F^{\mu\nu}_{(V)} + \mathrm{h.c} \to 0$$

Pseudo-vector couplings are allowed but it's suppressed by multiple cutoff scale and loop factor.

$$\frac{c_A}{\Lambda^2}(\overline{\nu_R}\gamma_5\gamma_\mu\nu_R)\times i(H^\dagger D_\mu H) \qquad c_A \sim O(1)\times\frac{\lambda}{16\pi^2}y_\nu^2$$

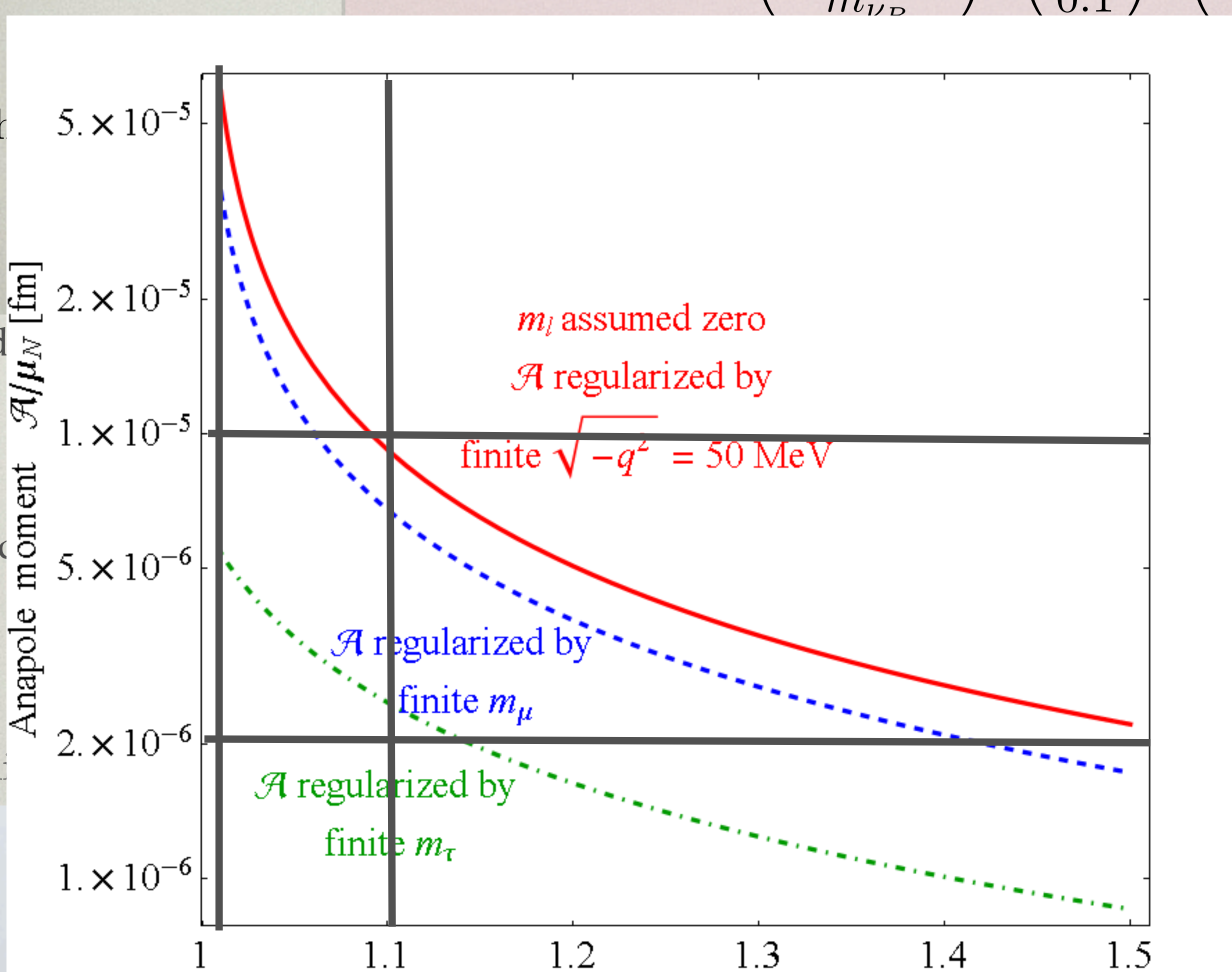
$$\sigma_p^{\mathrm{SI}} \sim 10^{-47}\mathrm{cm}^2 \times \left(\frac{100\mathrm{GeV}}{m_{\nu_R}}\right)^4 \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{\sigma_{\mathrm{ann}} v}{\cdots}\right) \cdots$$

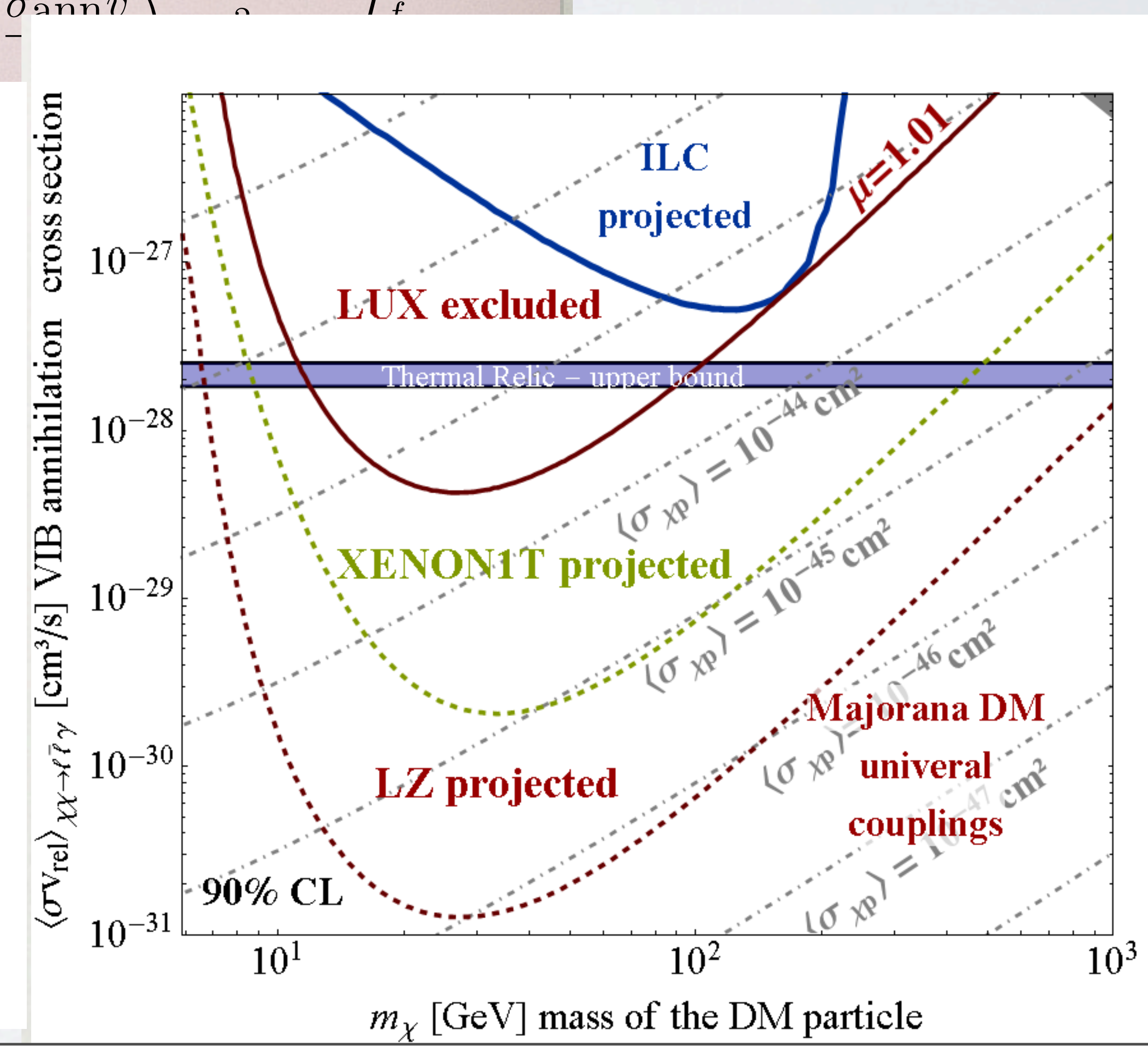
Th

At d

At c

Thi





Flavor ν_R Dark Matter signatures

neutrino line search give factor a few stronger constraint.
Dark Matter accumulation in Sun(SuperK/ANTARES/IceCube)

$$\sigma \sim \frac{1}{\pi}\frac{m_e^2}{(m_\eta^2 - m_\chi^2)^2}$$

$$\sigma^0_{\chi e} \equiv \frac{G^2 m_e^2}{\pi} = \frac{m_e^2}{\pi\Lambda^4} \approx 3.1\times 10^{-39}\,\mathrm{cm}^2 \left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^{-4}$$

neutrino-DM scattering can also be large.

Dark Matter direct searches

Basic discussions based on J.Kopp et al (2009,2014)

For anapole mode, P.Gondolo et al , K.Kopp et al

Loop induced DM couplings with Weak bosons are negligible.

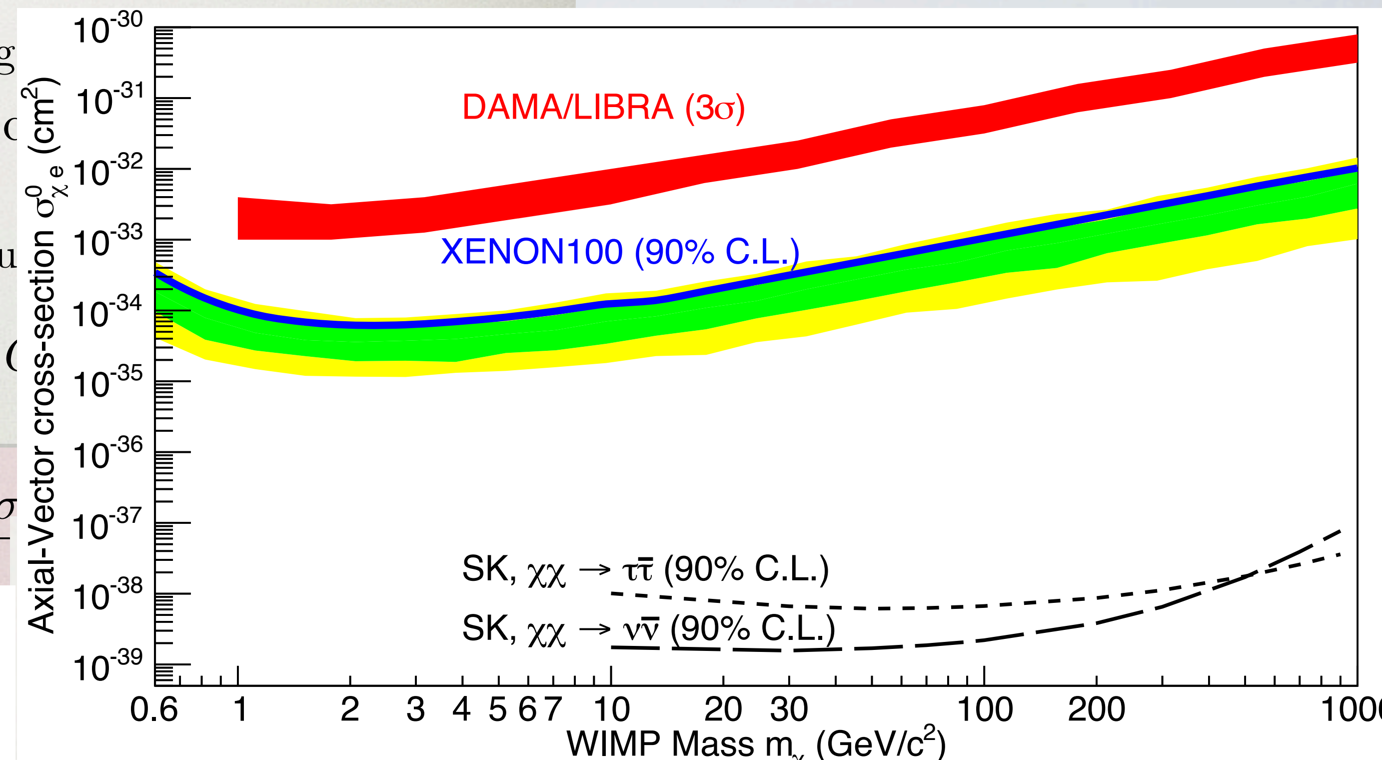
Majorana nature forbids flavor diagonal vector and tensor coupling

$$\overline{\nu_R}\gamma_\mu\nu_R V_\mu + \mathrm{h.c},\ \overline{\nu_R}\sigma_{\mu\nu}\nu_R F^{\mu\nu}_{(V)} + \mathrm{h.c}$$

Pseudo-vector couplings are allowed but it's suppressed by multiple cu

$$\frac{c_A}{\Lambda^2}(\overline{\nu_R}\gamma_5\gamma_\mu\nu_R)\times i(H^\dagger D_\mu H) \qquad c_A \sim ($$

$$\sigma_p^{\mathrm{SI}} \sim 10^{-47}\mathrm{cm}^2 \times \left(\frac{100\mathrm{GeV}}{m_{\nu_R}}\right)^4 \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{\sigma}{}\right.$$

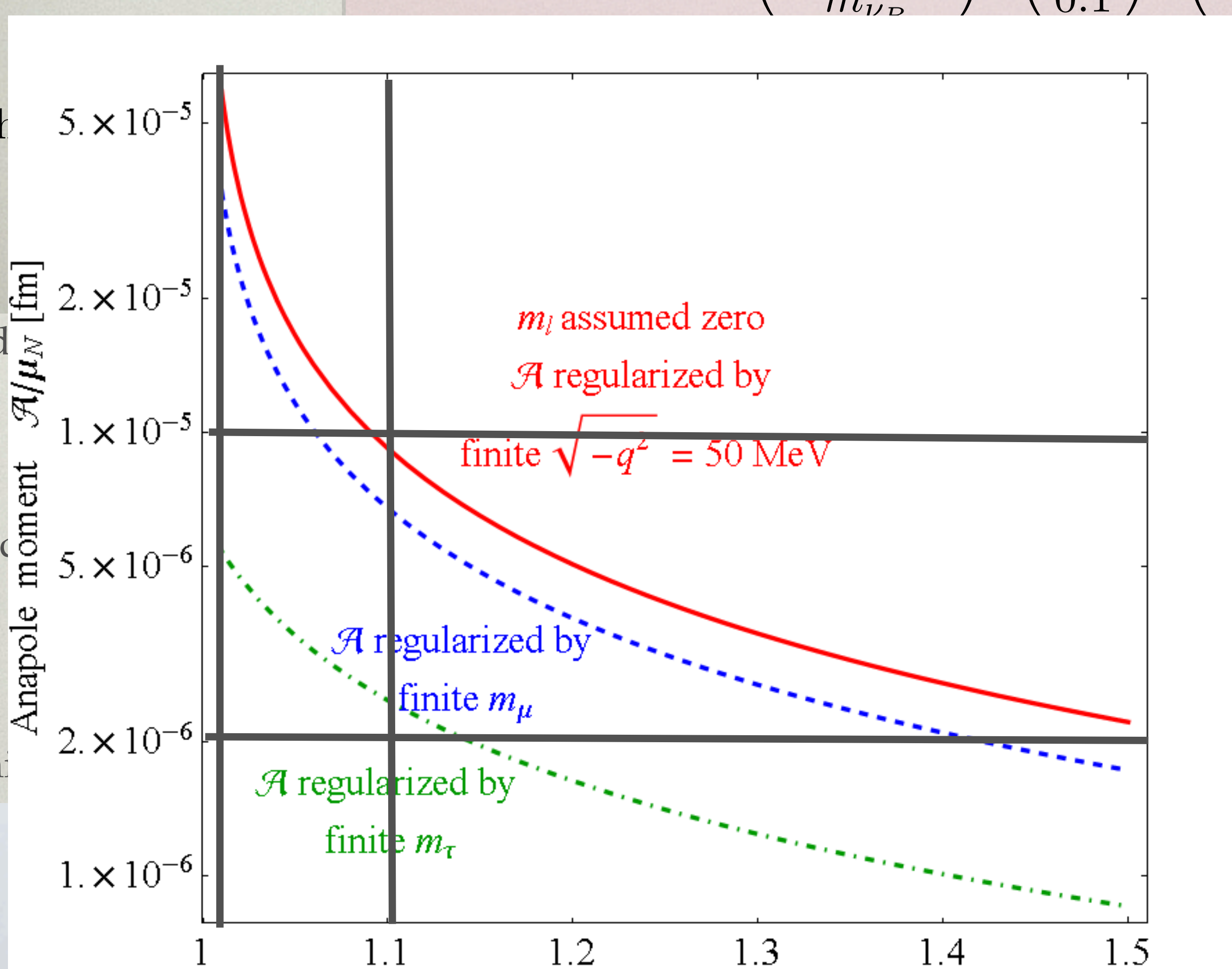


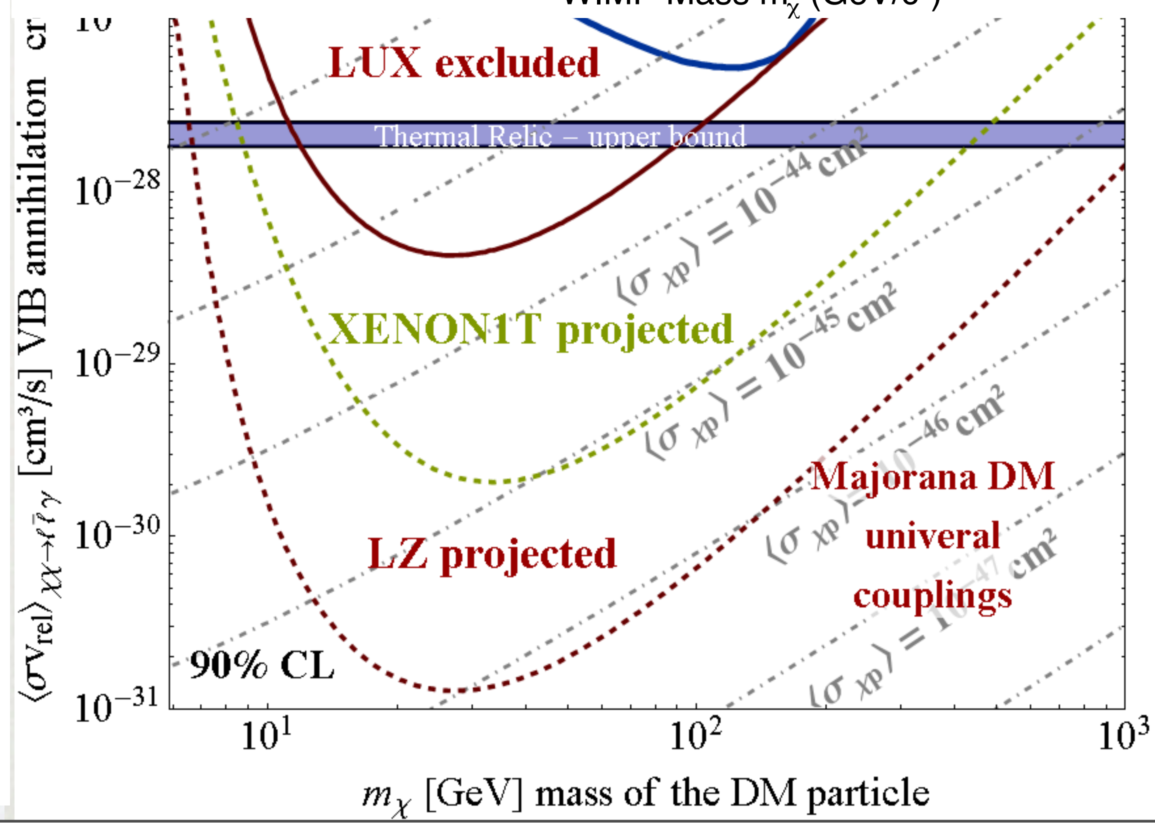
Th

At d

At c

Thi





Dark Matter indirect detections

Internal bremsstrahlung and gamma ray/electron/positron signatures

Torsten Bringmann, L.Bergstrom and J.Edsjo (2007) .....

W/Z internal bremsstrahlung: constraints from anti-proton flux

N.Bell, J.Dent, A.Galea, T.Jacques, L.Krauss and T.Weiler(2011), M.Garmy, W.Ibarra, S.Vogl (2011)....

Collider search: EW vector boson fusion into a flavored higgs boson pair

Summary

Flavor symmetry might be a clue to find DM family in beyond SM spectrum.

If neutrino tiny masses are given by the tiny flavor symmetry breaking, low energy LFV processes may be flavor symmetry symmetric.

Lepton flavor symmetry may obtain leptophilic dark matter and the distinct dark matter signature can be tested in near future through direct/indirect/collider/LFV/precision...

A lot of observables in current/future experiments will tell us how to fix the shape of models.