PeV neutrinos
from right-handed neutrino dark matter

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“Neutrinoful Universe”,Tetsutaro Higaki, Ryuichiro Kitano, RS,
[arXiv:1405.0013], JHEP1407(2014)044

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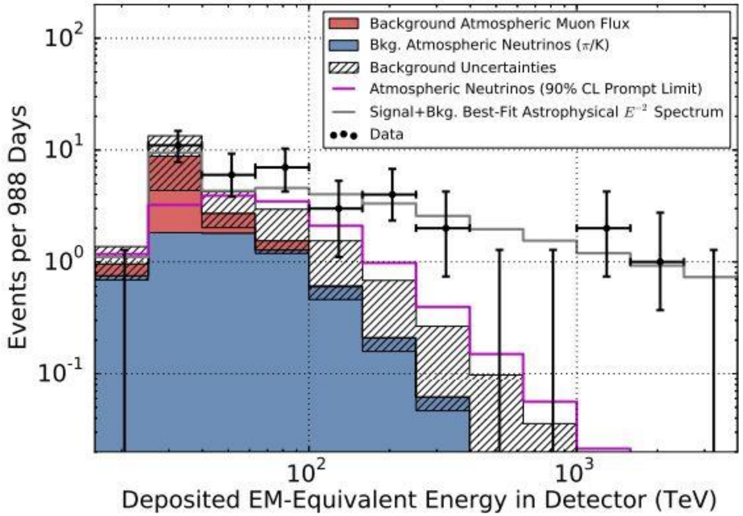
Hints of beyond the standard model

- Neutrino mass
- Dark matter
- Inflation
- Baryon asymmetry
- IceCube??

5.7 sigma excess!!



[IceCube : 1405.5303]

We try to explain all of them!

Our model

Standard model

+ 3 right-handed neutrinos w/ Majorana masses

+ $U(1)_{B-L}$ gauge symmetry & B-L Higgs boson

$$M_i = \frac{\lambda_i v_{B-L}}{\sqrt{2}}$$

$$\mathcal{L} = \mathcal{L}_{SM} - y_{\nu,ij} H N_i \ell_j - \frac{\lambda_i}{2} \phi_{B-L} N_i^2 - \kappa \left(|\phi_{B-L}|^2 - \frac{v_{B-L}^2}{2} \right)^2$$

We assume y_{1i}'s are extremely small. (approximate Z_2 parity : $N_1 \rightarrow -N_1$)

- N_1 (decaying) dark matter
- N_2, N_3 } Leptogenesis & seesaw mechanism
- ϕ_{B-L} Inflaton. It decays into RH neutrinos at reheating.

Thermal history of the universe

$$\mathrm{Br}(\phi \to N_1 N_1) : \mathrm{Br}(\phi \to N_2 N_2) \;=\; M_1^2 : M_2^2$$

1. $\phi_{B\text{-}L}$ drives inflation
2. $\phi_{B\text{-}L}$ decays into RH neutrinos via ϕNN interaction (reheating)
3. Decay of N_2 generates lepton number asymmetry (leptogenesis)
4. N_1 remains as a dark matter

$$\Omega_{N_1} \simeq 0.2 \times \left(\frac{M_1}{4\ \mathrm{PeV}}\right)^3 \left(\frac{M_2}{10^{12}\ \mathrm{GeV}}\right)^{-1} \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^{-1/2} \left(\frac{v_{B-L}}{5M_{\mathrm{Pl}}}\right)^{-1}$$

$$\left.\frac{n_B}{s}\right|_{\mathrm{max}} \simeq \left(\frac{M_2}{10^{12}\ \mathrm{GeV}}\right)^2 \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^{-1/2} \left(\frac{v_{B-L}}{5M_{\mathrm{Pl}}}\right)^{-1} \times \begin{cases} 1 \times 10^{-10} & \text{(Normal hierarchy)} \\ 2 \times 10^{-12} & \text{(Inverted hierarchy)} \end{cases}$$

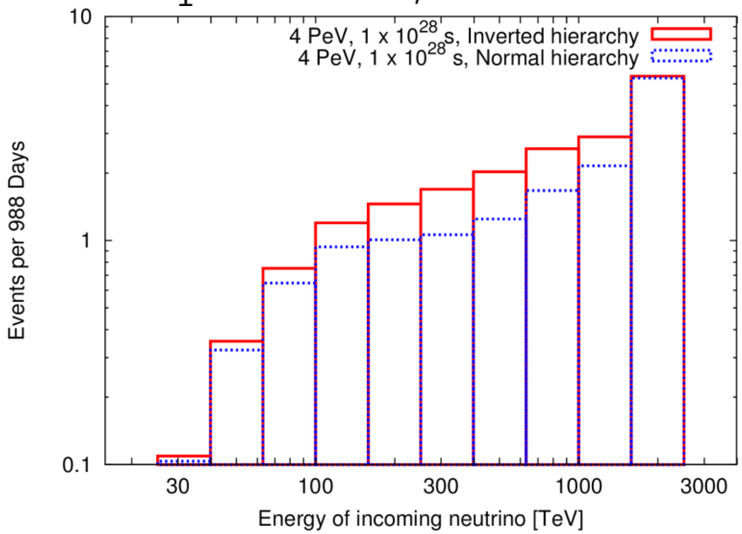
(Upper bound on e depends on mass hierarchy)

Our model predicts PeV dark matter!

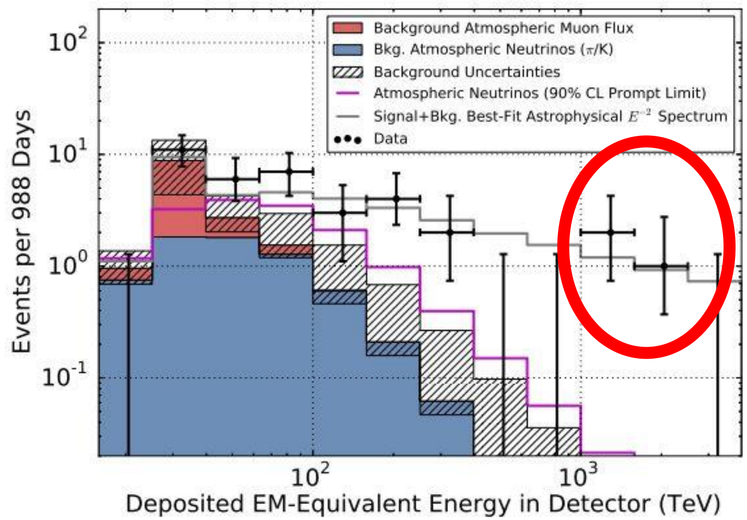
Events at IceCube experiment

Main decay mode : $N_1 \to \ell^{\pm} W^{\mp},\ \nu Z,\ \nu h$

$M_1 = 4\ \mathrm{PeV}, \quad \tau = 10^{28}\ \mathrm{s}$



[Higaki, Kitano, RS (2014)]



[IceCube : 1405.5303]

$$N_{\mathrm{obs}}(E_\nu \geq 1\ \mathrm{PeV}) \sim 3 \times \left(\frac{\tau_{N_1}}{2 \times 10^{28}\ \mathrm{s}}\right)^{-1} \Longleftrightarrow y_{1i} \sim 10^{-29}$$

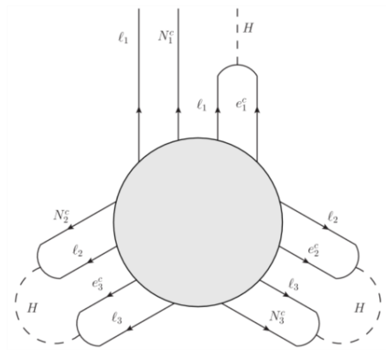
Backup slides

Tiny y_{1i}

We have no reason to assume Z_2 parity $(N_1 \to -N_1)$ is exact.

e.g., we can write, $\dfrac{1}{\Lambda^{14}}(\ell_1\ell_2)(\ell_2\ell_3)(\ell_3\ell_1)e_1^c e_2^c e_3^c N_1^c N_2^c N_3^c$

(such a operator may be generated by some non-perturbative effect.)



$$y_\nu^{1k} \propto (\det y_e)\epsilon^{ijk} y_\nu^{2i} y_\nu^{3j}$$

Our assumption : $y_\nu^{1k} = c\epsilon^{ijk} y_\nu^{2i} y_\nu^{3j}$

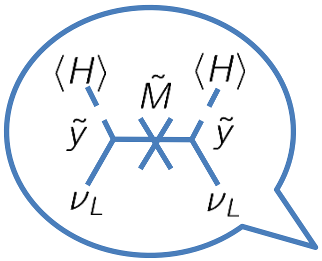
(c is a very small number.)

Normal hierarchy $\rightarrow$ $y_\nu^{1k} \propto U_{k1}$

Inverted hierarchy $\rightarrow$ $y_\nu^{1k} \propto U_{k3}$

Neutrino mass

Neutrino mass is generated by seesaw mechanism.
RH neutrino sector in our model is essentially two RH neutrino model.
[Frampton, Glashow, Yanagida (2002)]



$$y_\nu = \begin{pmatrix} \sim 0 & \sim 0 & \sim 0 \\ y_{\nu,21} & y_{\nu,22} & y_{\nu,23} \\ y_{\nu,31} & y_{\nu,32} & y_{\nu,33} \end{pmatrix} \quad \tilde{y}$$

$$M = \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \quad \tilde{M}$$

Neutrino mass matrix:

$$m_\nu = \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} = (U^T \tilde{y}^T \tilde{M}^{-1} \tilde{y} U) \langle H \rangle^2 \longrightarrow$$

Rank 2 matrix
Lightest neutrino is massless!

(U : Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix)

$$\Delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{31}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$$ [Particle Data Group]

a) Normal hierarchy $\xrightarrow[m_1<m_2<m_3]{}$ $m_1 = 0$ eV, $m_2 \simeq 0.0087$ eV, $m_3 \simeq 0.048$ eV

b) Inverted hierarchy $\xrightarrow[m_3<m_1<m_2]{}$ $m_1 \simeq 0.048$ eV, $m_2 \simeq 0.049$ eV, $m_3 = 0$ eV

Flavor structure of y_{1i} (Normal hierarchy)

- Ibarra-Casas parametrization

$$\tilde{y} = \frac{1}{\langle H \rangle} \tilde{M}^{1/2} R m_\nu U^\dagger, \qquad R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}$$

U : PMNS matrix
z : a complex parameter

$$\Downarrow$$

$$\begin{aligned} y_{2i} &= \frac{\sqrt{M_2}}{\langle H \rangle}(\sqrt{m_2} U_{i2}^* \cos z - \sqrt{m_3} U_{i3}^* \sin z), \\ y_{3i} &= \frac{\sqrt{M_3}}{\langle H \rangle}(\sqrt{m_2} U_{i2}^* \sin z + \sqrt{m_3} U_{i3}^* \cos z) \end{aligned}$$

$$\Downarrow$$

$$\begin{aligned} y_{1k} &= c\epsilon^{ijk} y_{2i} y_{3j} \\ &= \frac{c\sqrt{M_2 M_3 m_2 m_3}}{\langle H \rangle^2} \times U_{k1} \end{aligned}$$

Flavor structure of y1k is determined by PMNS matrix and mass hierarchy.

Flavor structure of y_{1i} (Inverted hierarchy)

- Ibarra-Casas parametrization

$$\tilde{y} = \frac{1}{\langle H \rangle} \tilde{M}^{1/2} R m_\nu U^\dagger, \qquad R = \begin{pmatrix} \cos z & \sin z & 0 \\ -\sin z & \cos z & 0 \end{pmatrix}$$

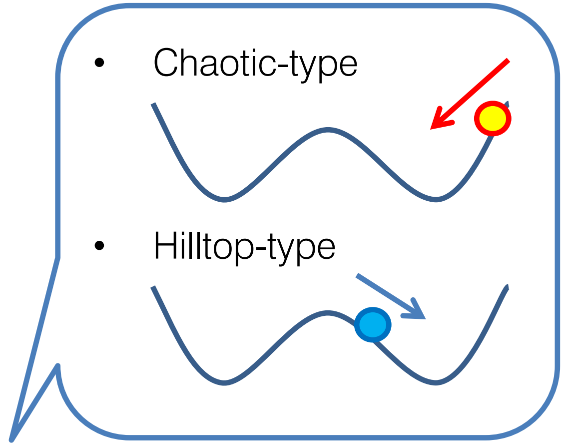
U : PMNS matrix
z : a complex parameter

$$\begin{aligned} y_{2i} &= \frac{\sqrt{M_2}}{\langle H \rangle} (\sqrt{m_2} U^*_{i1} \cos z - \sqrt{m_3} U^*_{i2} \sin z), \\ y_{3i} &= \frac{\sqrt{M_3}}{\langle H \rangle} (\sqrt{m_2} U^*_{i1} \sin z + \sqrt{m_3} U^*_{i2} \cos z) \end{aligned}$$

$$\begin{aligned} y_{1k} &= c \epsilon^{ijk} y_{2i} y_{3j} \\ &= \frac{c\sqrt{M_2 M_3 m_2 m_3}}{\langle H \rangle^2} \times U_{k3} \end{aligned}$$

Flavor structure of y1k is determined by PMNS matrix and mass hierarchy.

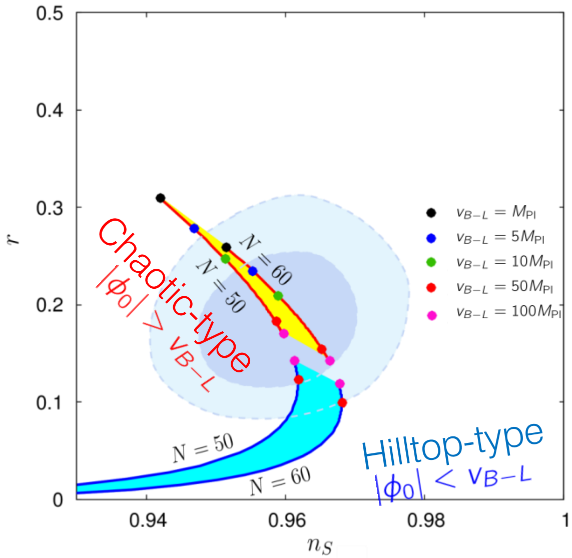
Inflation by B-L Higgs boson

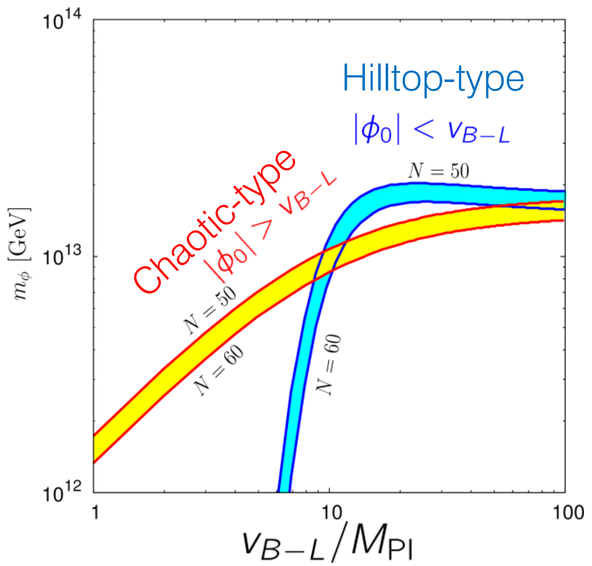


$$V(\phi) = \frac{\kappa}{4}\left(\phi^2 - v_{B-L}^2\right)^2 \qquad \left(\phi_{B-L} = \frac{1}{\sqrt{2}}(\phi + iG)\right)$$

[Okada, Shafi (2013)]

[Planck+WP+highL+BICEP2]





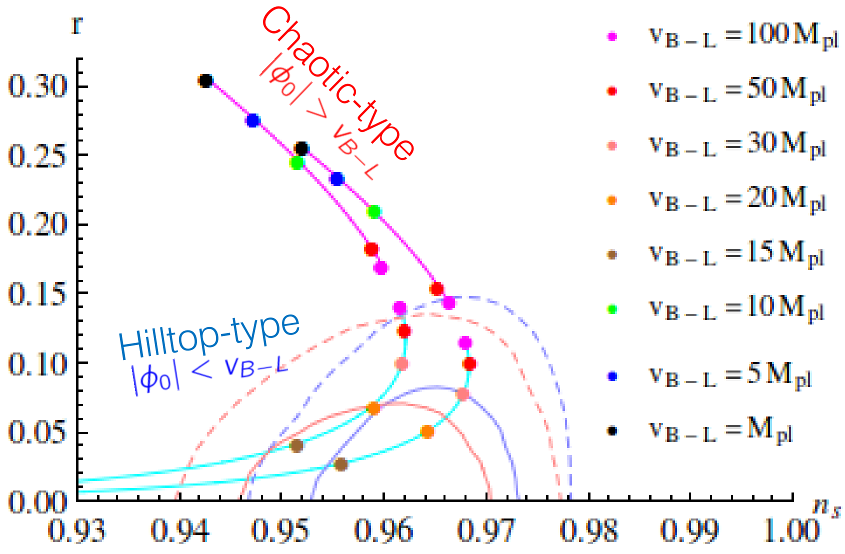
[Higaki, Kitano, RS (2014)]

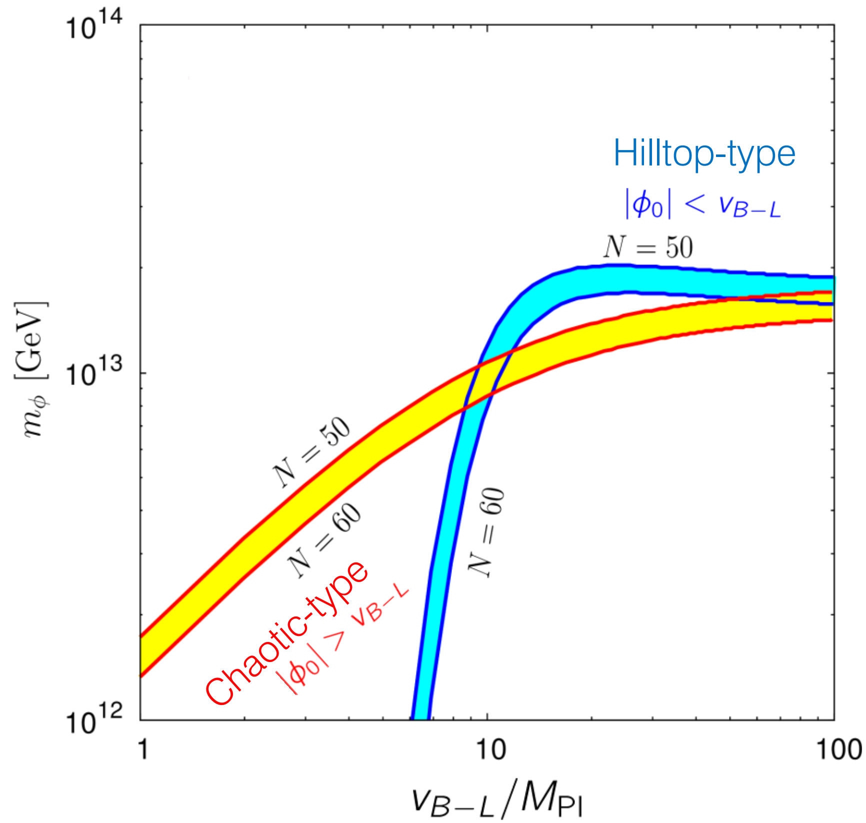
CMB observation suggests $m_\phi \sim 10^{13}$ GeV

Chaotic type initial condition with $v_{B\text{-}L} / M_{Pl} > 5$ is consistent with BICEP2 data.

Inflation without BICEP2

$$V(\phi) = \frac{\kappa}{4}\left(\phi^2 - v_{B-L}^2\right)^2$$





[Higaki, Kitano, RS (2014)]

CMB observation suggests $m_\phi \sim 10^{13}$ GeV

Hilltop type initial condition with $v_{B-L} / M_{Pl} = 15\text{-}30$ is consistent with Planck data.

Reheating

$$\mathcal{L} \ni -\frac{M_i}{2v_{B-L}}\phi N_i N_i$$

Inflaton decays into a pair of RH neutrinos : $\phi \to N_i N_i$

$$\frac{n_\phi}{s} = \frac{\rho_\phi/m_\phi}{s} = \frac{3}{4}\frac{T_R}{m_\phi}$$: Number of ϕ per entropy at the time of reheating.

We assume $M_1 \ll M_2 < m_\phi < M_3$ $\Rightarrow$ $\begin{cases} \mathrm{Br}(\phi \to N_1 N_1) & \simeq M_1^2/M_2^2 \\ \mathrm{Br}(\phi \to N_2 N_2) & \simeq 1 \end{cases}$

- N_1 from inflaton decay → dark matter production

$$\frac{n_{N_1}}{s} \simeq \frac{3}{4}\frac{T_R}{m_\phi} \times 2 \times \mathrm{Br}(\phi \to N_1 N_1)$$

- N_2 from inflaton decay → leptogenesis

$$\frac{n_{N_2}}{s} \simeq \frac{3}{4}\frac{T_R}{m_\phi} \times 2 \longrightarrow \frac{n_B}{s} \simeq \frac{3}{4}\frac{T_R}{m_\phi} \times 2 \times \epsilon \times \left(-\frac{28}{79}\right)$$

$$\epsilon = \frac{\Gamma(N_2 \to \ell H) - \Gamma(N_2 \to \bar{\ell} H^\dagger)}{\Gamma(N_2 \to \ell H) + \Gamma(N_2 \to \bar{\ell} H^\dagger)}$$

Spharelon factor

[Asasa, Hamaguchi, Kawasaki, Yanagida (1999)]

Decay time of N_2

$a = a_\phi$

End of inflation | N_2 dominant universe | Radiation dominant universe

$\phi \to N_2 N_2$ $\qquad$ $N_2 \to \ell H, \cdots$

For N_2 dominant era,

$$H = \Gamma_\phi \left(\frac{a}{a_\phi} \right)^{-2} \xrightarrow{a_{\rm nonrela}/a_\phi \sim m_\phi/M_2} t_{\rm nonrela}^{-1} \sim \Gamma_\phi \left(\frac{m_\phi}{M_2} \right)^{-2}$$

The time when N_2 becomes non-relativistic.

a) $t_{\rm nonrela} > \Gamma_2^{-1}$: N_2 decays when N_2 is relativistic.

$$\frac{n_{N_2}}{s} \sim \frac{T_\phi}{m_\phi}$$

b) $t_{\rm nonrela} < \Gamma_2^{-1}$: N_2 decays when N_2 is non-relativistic.

$$\frac{n_{N_2}}{s} \sim \frac{T_2}{M_2} \sim \frac{T_\phi}{m_\phi}\Delta \qquad \Delta = \Gamma_2 t_{\rm nonrela} = \frac{\Gamma_2}{\Gamma_\phi}\frac{m_\phi^2}{M_2^2} < 1$$

Everything is diluted by entropy production!

Upper bound on ε

$y_{1i} \simeq 0, \;\; M_2 \ll M_3$

$$\epsilon \;=\; \frac{\Gamma(N_2 \to \ell H) - \Gamma(N_2 \to \bar{\ell} H^\dagger)}{\Gamma(N_2 \to \ell H) + \Gamma(N_2 \to \bar{\ell} H^\dagger)} \;\simeq\; -\frac{3}{16\pi} \frac{\mathrm{Im}(y_\nu y_\nu^\dagger)_{23}^2}{(y_\nu y_\nu^\dagger)_{22}} \frac{M_2}{M_3}$$

[Covi, Roulet, Vissani (1996)]

- Normal hierarchy

$$\epsilon \simeq -\frac{3}{16\pi} \frac{M_2}{v^2} \frac{\mathrm{Im}[m_2^2 \cos^2 z + m_3^2 \sin^2 z]}{m_2 |\cos z|^2 + m_3 |\sin z|^2} \quad \Rightarrow \quad |\epsilon| < \frac{3 M_2}{16\pi v^2}(m_3 - m_2)$$

- Inverted hierarchy

$$\epsilon \simeq -\frac{3}{16\pi} \frac{M_2}{v^2} \frac{\mathrm{Im}[m_1^2 \cos^2 z + m_2^2 \sin^2 z]}{m_1 |\cos z|^2 + m_2 |\sin z|^2} \quad \Rightarrow \quad |\epsilon| < \frac{3 M_2}{16\pi v^2}(m_2 - m_1)$$

[Harigaya, Ibe, Yanagida (2012)]

(z : a complex parameter)

Decay of dark matter

$$\mathcal{L} \ni \; - y_{\nu,1j} H N_1 \ell_j - \frac{M_1}{2} N_1^2$$

- Lifetime

$$\tau_{N_1} \sim 10^{29}\ \mathrm{s} \left(\frac{M_1}{1\ \mathrm{PeV}}\right) \left(\frac{\sqrt{\sum_i |y_{1i}|^2}}{10^{-29}}\right)^{-2}$$

- Decay modes and branching fractions

$e^{\pm}W^{\mp}$	$\nu_e Z, \bar{\nu}_e Z$	$\nu_e h, \bar{\nu}_e h$
$\mu^{\pm}W^{\mp}$	$\nu_\mu Z, \bar{\nu}_\mu Z$	$\nu_\mu h, \bar{\nu}_\mu h$
$\tau^{\pm}W^{\mp}$	$\nu_\tau Z, \bar{\nu}_\tau Z$	$\nu_\tau h, \bar{\nu}_\tau h$

0.50 : 0.25 : 0.25

c.f.) goldstone boson equivalence theorem

Decay of dark matter

$$\mathcal{L} \ni \; - y_{\nu,1j} H N_1 \ell_j - \frac{M_1}{2} N_1^2$$

- Lifetime

$$\tau_{N_1} \sim 10^{29}\ \mathrm{s} \left(\frac{M_1}{1\ \mathrm{PeV}}\right) \left(\frac{\sqrt{\sum_i |y_{1i}|^2}}{10^{-29}}\right)^{-2}$$

- Decay modes and branching fractions

			Normal hierarchy: $y_\nu^{1k} \propto U_{k1}$	Inverted hierarchy: $y_\nu^{1k} \propto U_{k3}$
$e^\pm W^\mp$	$\nu_e Z, \bar{\nu}_e Z$	$\nu_e h, \bar{\nu}_e h$	**0.68**	**0.02**
$\mu^\pm W^\mp$	$\nu_\mu Z, \bar{\nu}_\mu Z$	$\nu_\mu h, \bar{\nu}_\mu h$	**0.24+0.02 cosδ**	**0.38**
$\tau^\pm W^\mp$	$\nu_\tau Z, \bar{\nu}_\tau Z$	$\nu_\tau h, \bar{\nu}_\tau h$	**0.08-0.02 cosδ**	**0.60**

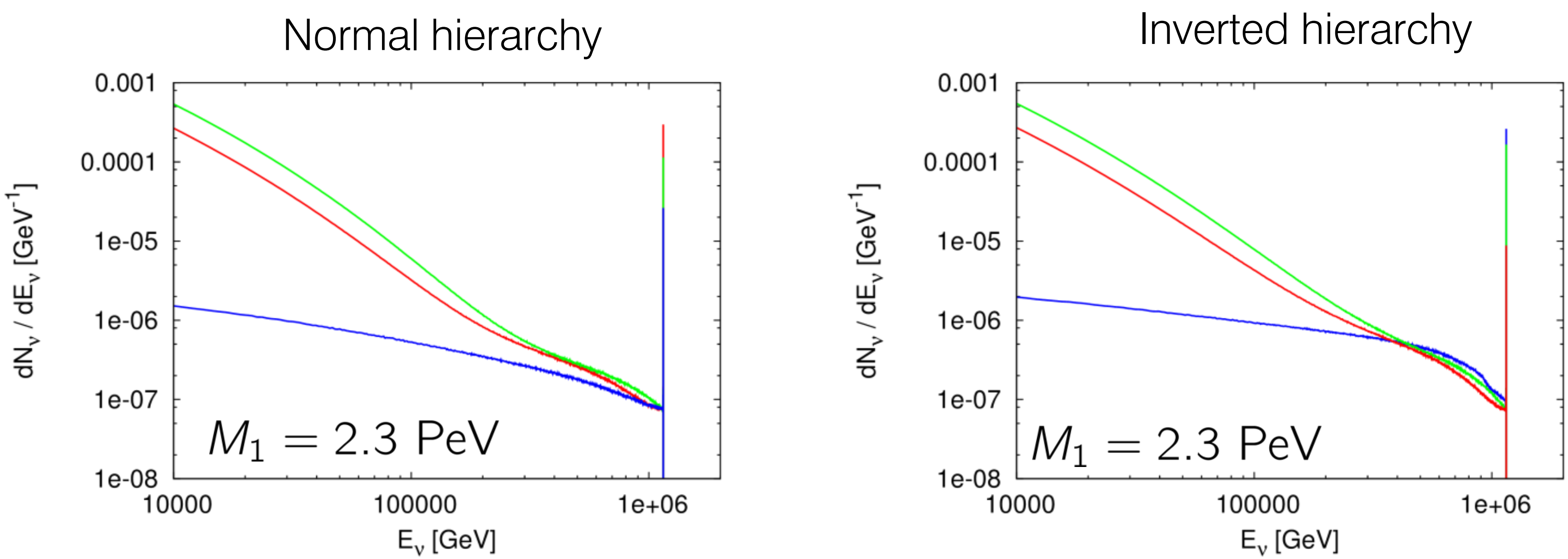
Neutrino energy flux at the decay time

Energy spectrum at the decay time

$\nu_e + \bar{\nu}_e$

$\nu_\mu + \bar{\nu}_\mu$

$\nu_\tau + \bar{\nu}_\tau$



[Higaki, Kitano, RS (2014)]

(simulated by PYTHIA 8.1)