Inflation, leptogenesis, neutrino masses and PeV neutrinos from right-handed neutrino dark matter

Ryosuke Sato（KEK）

"Neutrinoful Universe",Tetsutaro Higaki, Ryuichiro Kitano, RS,
[arXiv:1405.0013], JHEP 1407(2014)044

2014. 7. 29 @ PPP2014

Inflati eutrino masses
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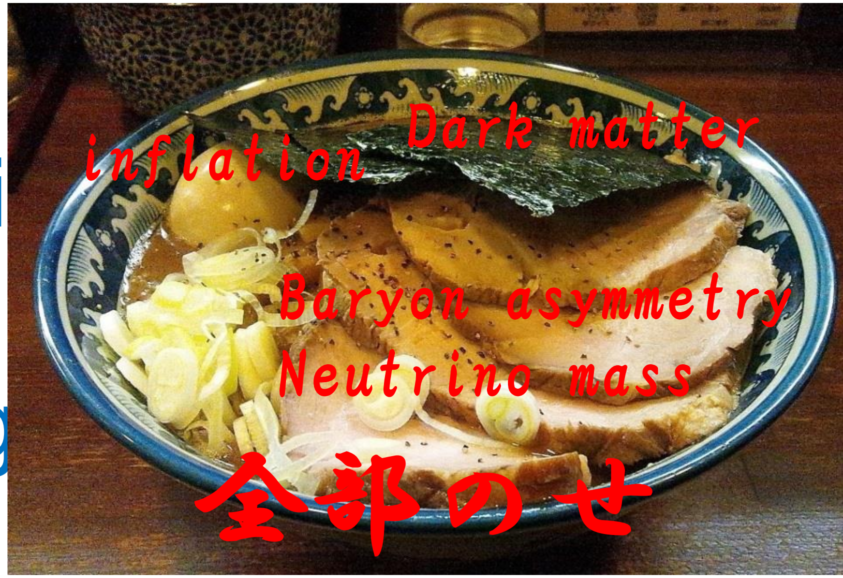

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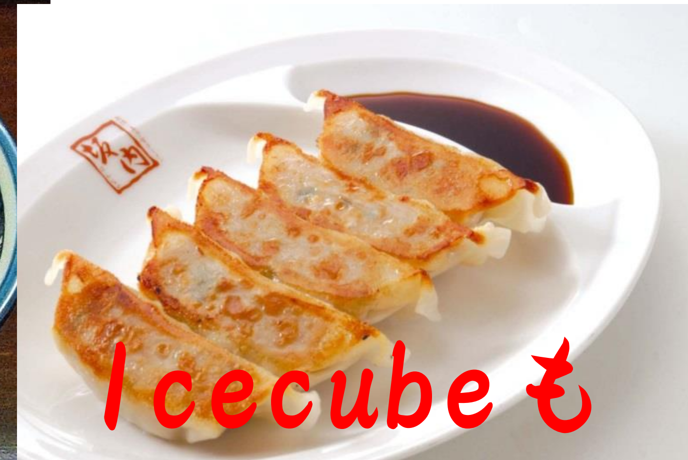

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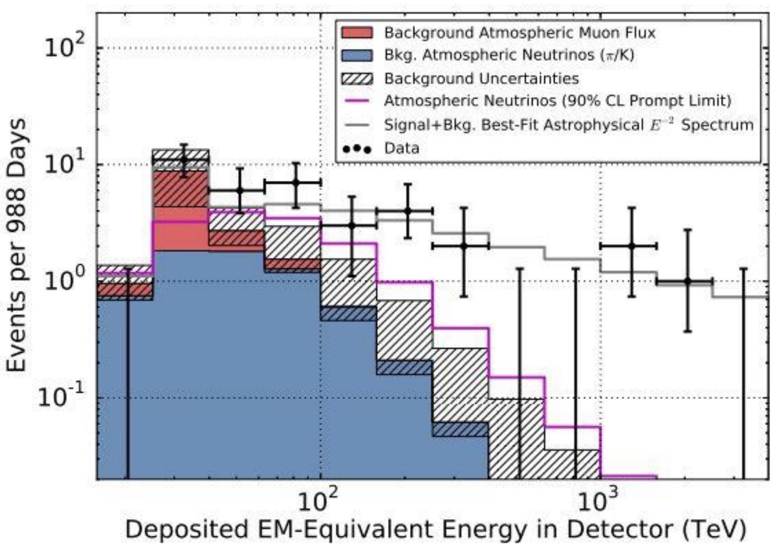
Mysteries in our universe

The standard model achieved a big success.
But, it might has to be extended to explain mysteries in our universe…

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



[IceCube collaborations, arXiv : 1405.5303]

We try to explain all of them!

1. Model
2. Inflation & Reheating
3. PeV neutrino signal

Our model

Standard model

+ 3 right-handed neutrinos w/ Majorana masses

+ $U(1)_{B\text{-}L}$ 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.

- Suppressed by Z_2 parity : $(N_1 \to -N_1)$ ⇨ N_1 is almost stable!

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

- N_2 and N_3 gives neutrino masses. [Frampton, Glashow, Yanagida (2002)]

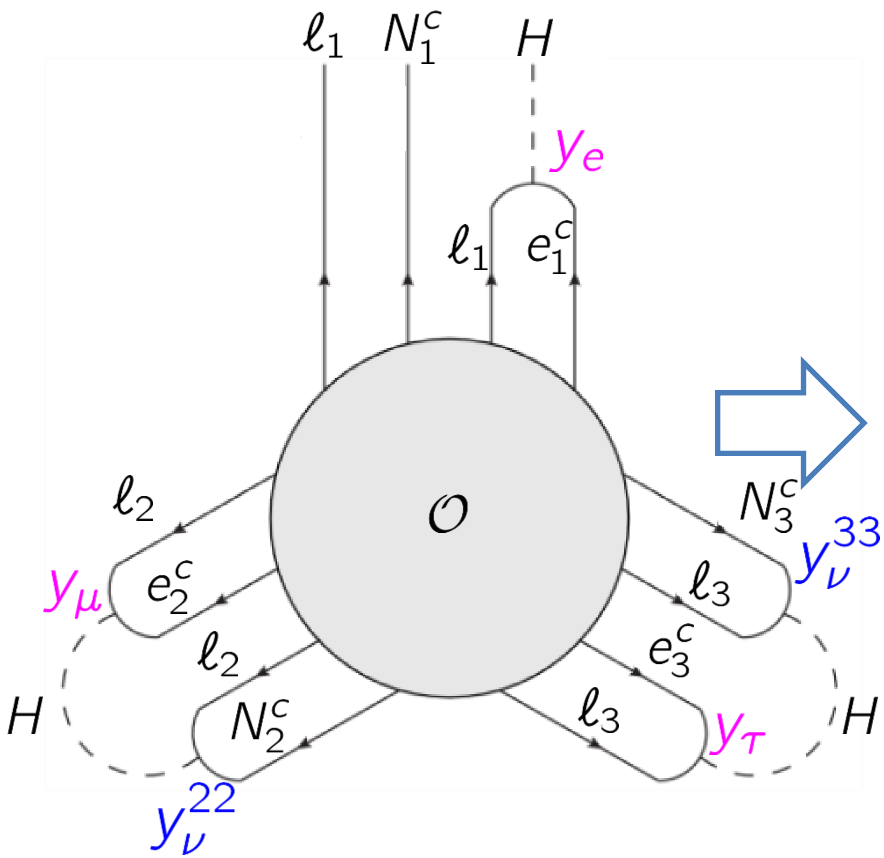
Lightest neutrino becomes massless.

y_{1i}

We have no reason to assume Z2 parity $(N_1 \to -N_1)$ is exact.

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

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



$y_\nu^{1k} \sim$ (very small number) $\times (\det y_e)\epsilon^{ijk} y_\nu^{2i} y_\nu^{3j}$

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

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

1. Model
2. Inflation & Reheating
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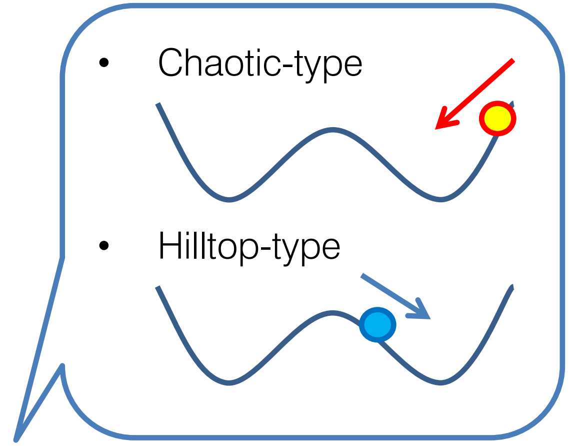
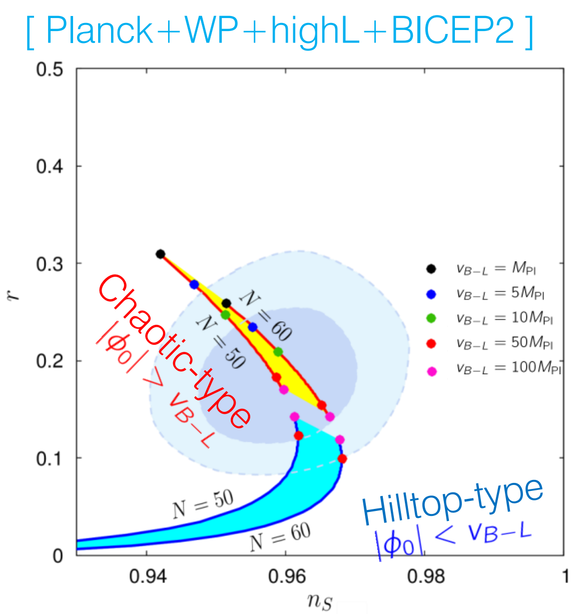
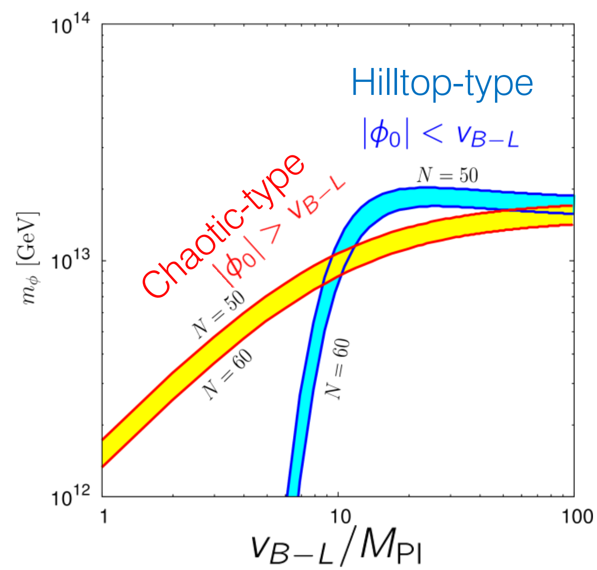
Inflation by B-L Higgs boson



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

[Okada, Shafi (2013)]





[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.

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

- 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

$$\frac{n_{N_2}}{s} \simeq \frac{3}{4}\frac{T_R}{m_\phi} \times 2$$

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

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

Spharelon factor

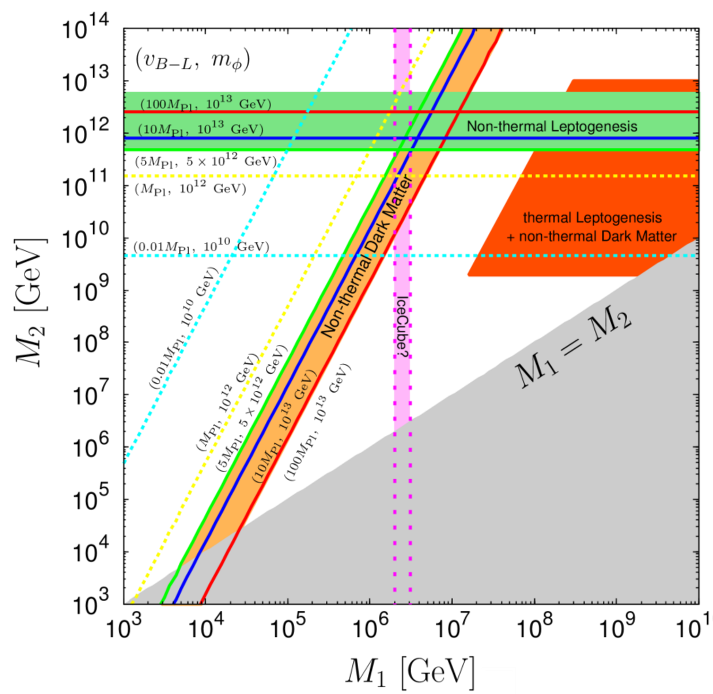
[Asasa, Hamaguchi, Kawasaki, Yanagida (1999)]

Viable region

$$\left\{ \begin{aligned} \Omega_{N_1} &\simeq 0.2 \times \left(\frac{M_1}{4\ \mathrm{PeV}}\right)^3 \left(\frac{M_2}{10^{12}\ \mathrm{GeV}}\right)^{-1} \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^{-1/2} \left(\frac{v_{B-L}}{5M_{\mathrm{Pl}}}\right)^{-1} \\ \left.\frac{n_B}{s}\right|_{\max} &\simeq \left(\frac{M_2}{10^{12}\ \mathrm{GeV}}\right)^2 \left(\frac{m_\phi}{10^{13}\ \mathrm{GeV}}\right)^{-1/2} \left(\frac{v_{B-L}}{5M_{\mathrm{Pl}}}\right)^{-1} \times \begin{cases} 1 \times 10^{-10} & \text{(Normal hierarchy)} \\ 2 \times 10^{-12} & \text{(Inverted hierarchy)} \end{cases} \end{aligned} \right.$$

(Upper bound on e depends on mass hierarchy)

PeV dark matter is attractive!



[Higaki, Kitano, RS (2014)]

1. Model

2. Inflation & Reheating

3. PeV neutrino signal

Decay of dark matter

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

- Lifetime

$$\tau_{N_1} \sim 10^{28}\ \mathrm{s} \left(\frac{M_1}{4\ \mathrm{PeV}}\right)^{-1} \left(\frac{\sqrt{\sum_i |y_{1i}|^2}}{10^{-29}}\right)^{-2}$$

- Decay modes and branching fractions

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

Decay of dark matter

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

- Lifetime

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- 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

$$\tau_{N_1} \sim 10^{28}\ \mathrm{s} \left(\frac{M_1}{4\ \mathrm{PeV}} \right)^{-1} \left(\frac{\sqrt{\sum_i |y_{1i}|^2}}{10^{-29}} \right)^{-2}$$

- Decay modes and branching fractions

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

Neutrino energy flux at the decay time

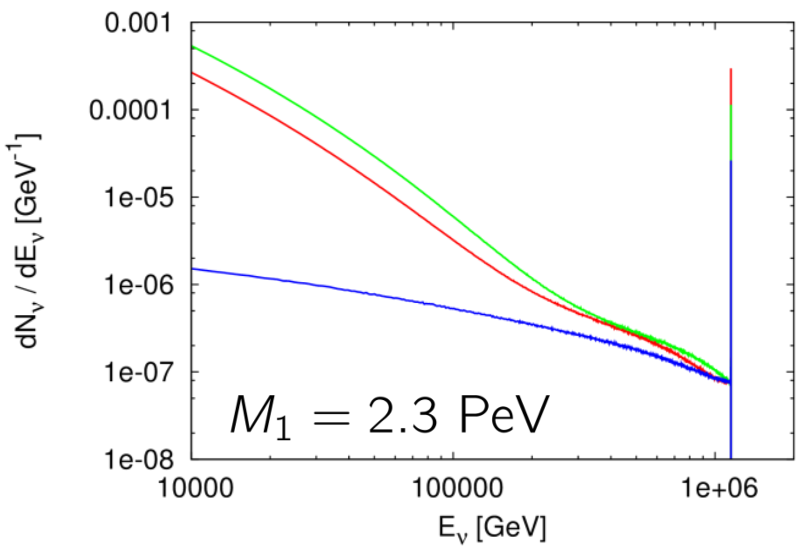
Energy spectrum at the decay time

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

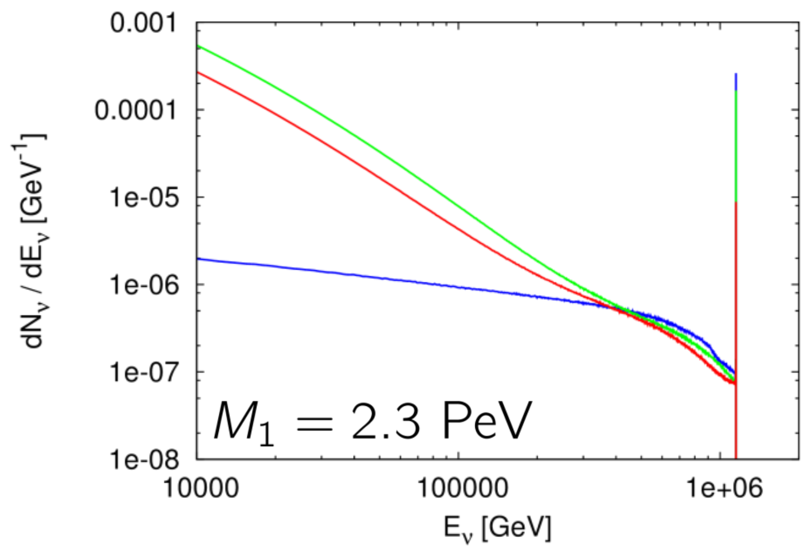
$\nu_\mu + \bar{\nu}_\mu$

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

Normal hierarchy



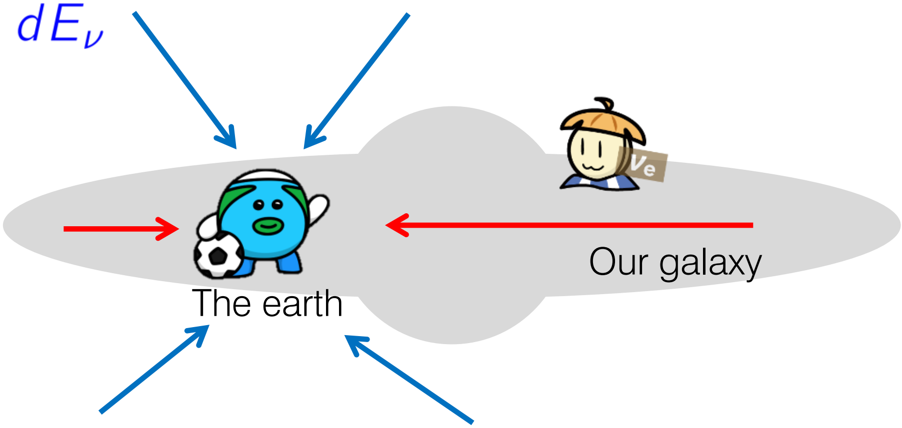
Inverted hierarchy



[Higaki, Kitano, RS (2014)]
(simulated by PYTHIA 8.1)

Neutrino energy flux at the Earth

$$\text{Neutrino flux at the Earth} = \frac{d\Phi_{\rm halo}}{dE_\nu} + \frac{d\Phi_{\rm eg}}{dE_\nu}$$



- Contribution from our galaxy

$$\frac{d\Phi_{\rm halo}}{dE_\nu} = D_{\rm halo}\frac{dN_\nu}{dE_\nu}$$

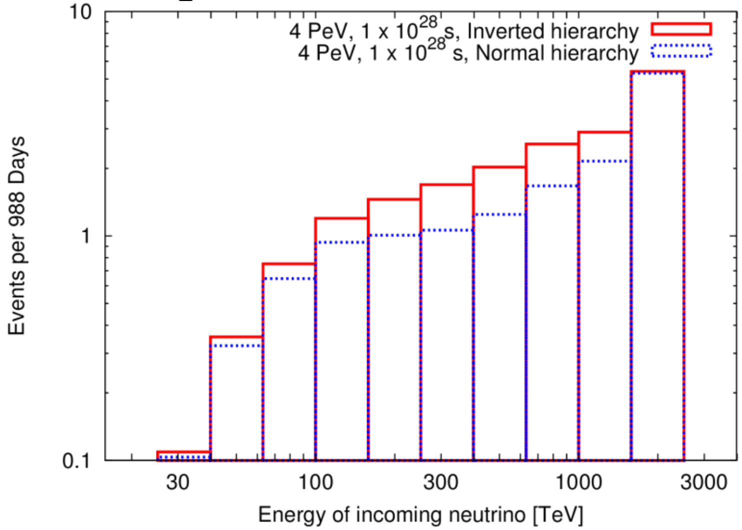
$$\begin{cases} D_{\rm halo} = \dfrac{1}{4\pi}\displaystyle\int_{-1}^{1} d\sin\theta \int_0^{2\pi}\left(\frac{1}{4\pi M_1 \tau_{N_1}}\int_0^\infty ds\,\rho_{\rm halo}(r(s,\theta,\phi))\right) \\ r(s,\theta,\phi) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot\cos\theta\cos\phi} \end{cases}$$

- Extra galactic contribution

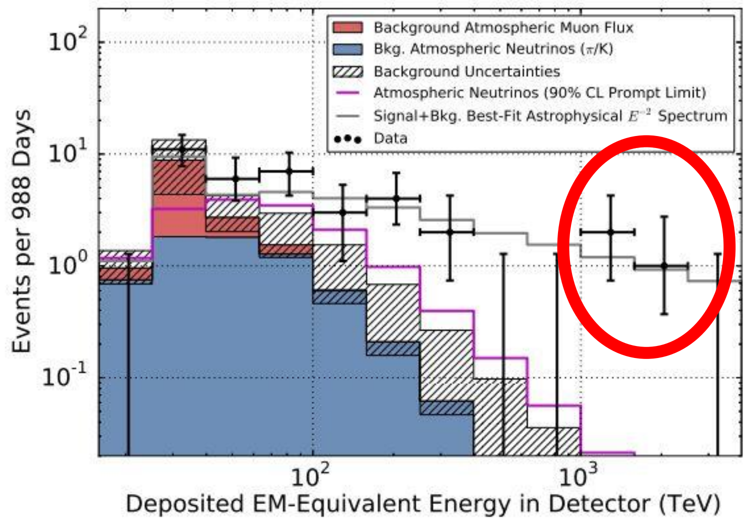
$$\frac{d\Phi_{\rm eg}}{dE_\nu} = \frac{\Omega_{\rm DM}\rho_c c}{4\pi M_1 \tau_{N_1}}\int_0^\infty \frac{dz}{H(z)} e^{-s(E_\nu,z)} \left.\frac{dN_\nu}{dE_\nu}\right|_{E=(1+z)E_\nu}$$

Number of events

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



[Higaki, Kitano, RS (2014)]



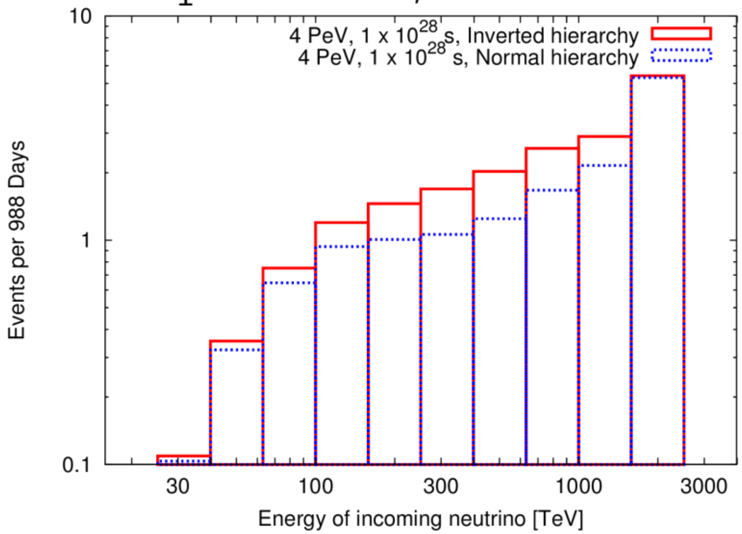
[arXiv : 1405.5303]

$$N_{\rm obs} = 4\pi \times 988{\rm days} \times \int dE \left(\sigma_{\rm eff}(E) \frac{d\Phi}{dE} \right)$$

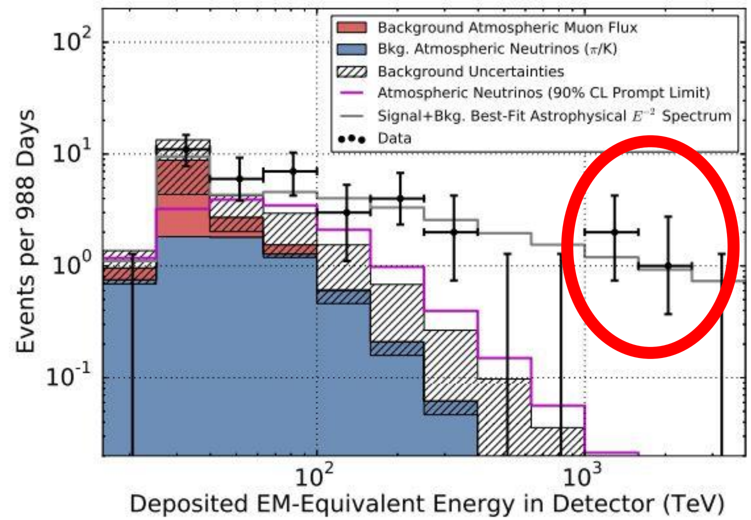
σ is effective area for neutrino energy E.

Number of events

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



[Higaki, Kitano, RS (2014)]



[arXiv : 1405.5303]

$N_{\rm obs}(E_\nu \geq 1\ \mathrm{PeV}) \Rightarrow$

$$3.0 \times \left(\frac{\tau_{N_1}}{1.6 \times 10^{28}\ \mathrm{s}} \right)^{-1} \quad \text{(Normal)}$$

$$3.0 \times \left(\frac{\tau_{N_1}}{1.9 \times 10^{28}\ \mathrm{s}} \right)^{-1} \quad \text{(Inverted)}$$

Summary

We consider a simple extension of the SM:

- Three right-handed neutrinos (N_1, N_2, N_3)
- B-L gauge symmetry and B-L Higgs boson ($\phi_{B\text{-}L}$)
- Z_2 parity for N_1 (tiny violation)

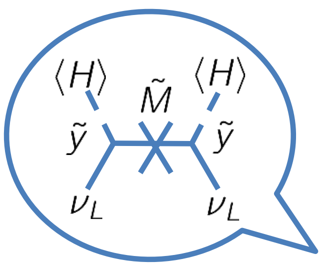
Our model explains,

- Inflation → Driven by B-L Higgs boson
- Dark matter → N_1 with $M_1 \sim O(\text{PeV})$
- Baryon asymmetry → Leptogenesis from N_2 decay
- Neutrino mass → Seesaw from N_2 and N_3
- IceCube excess → Decay of N_1 with $\tau \sim 10^{28}$s

Backup slides

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)]



$$y_\nu = \begin{pmatrix} \sim 0 & \sim 0 & \sim 0 \\ y_{\nu,21} & y_{\nu,22} & y_{\nu,23} \\ y_{\nu,31} & y_{\nu,32} & y_{\nu,33} \end{pmatrix} \quad \tilde{y} \qquad M = \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \quad \tilde{M}$$

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)

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

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

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

Flavor structure of y_{1i}

- Ibarra-Casas parametrization

$$\tilde{y} = \frac{1}{\langle H \rangle} \tilde{M}^{1/2} R m_\nu^{1/2} U^\dagger$$

U : PMNS matrix
z : a complex parameter

- Normal hierarchy

$$R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}$$

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

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

- Inverted hierarchy

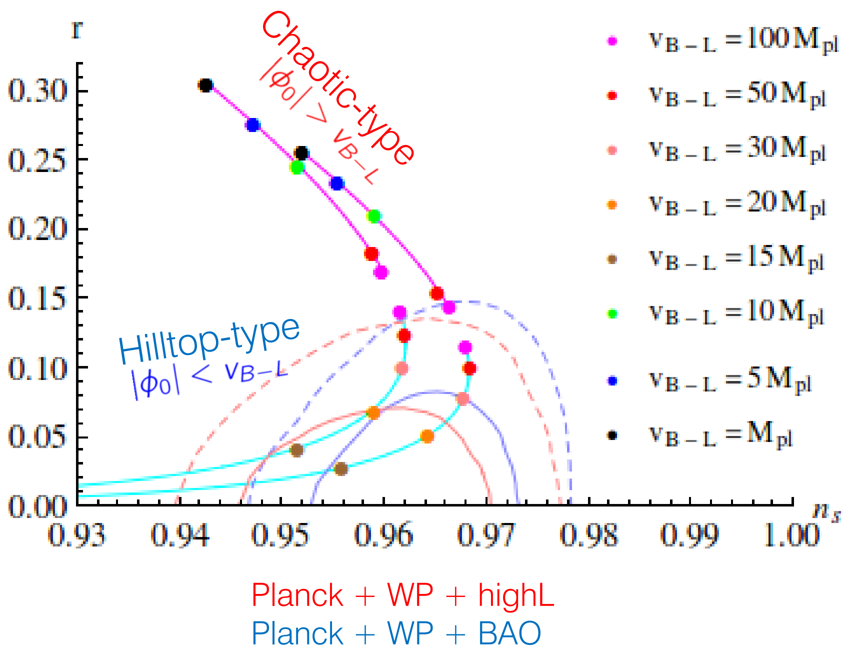
$$R = \begin{pmatrix} \cos z & \sin z & 0 \\ -\sin z & \cos z & 0 \end{pmatrix}$$

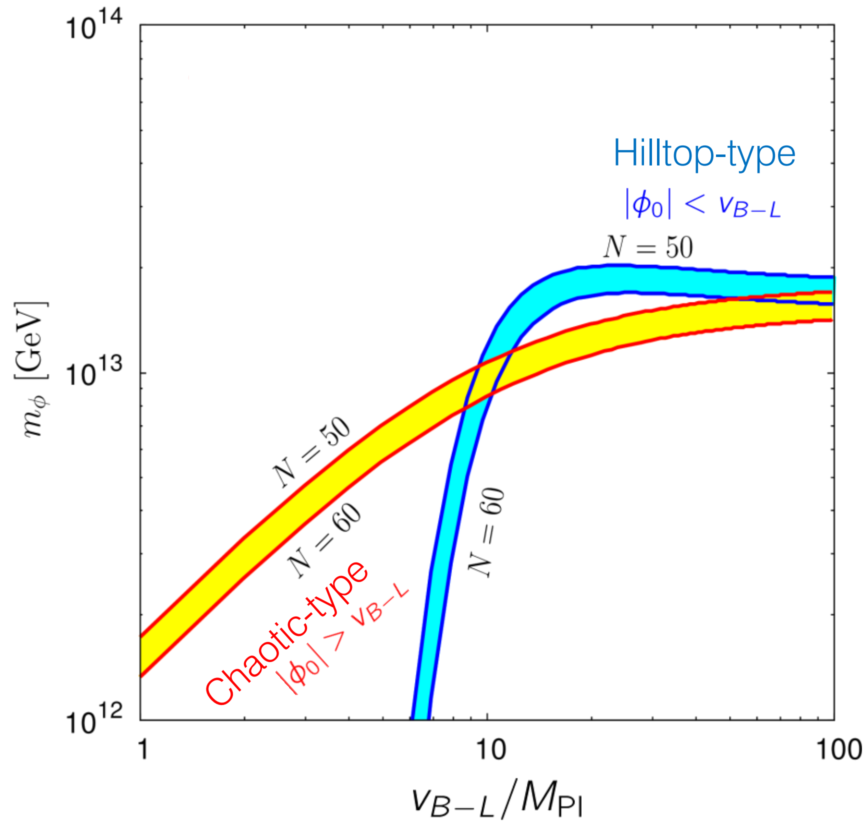
$$y_{2i} = \frac{\sqrt{M_2}}{\langle H \rangle}(\sqrt{m_2} U^*_{i1} \cos z - \sqrt{m_3} U^*_{i2} \sin z),$$
$$y_{3i} = \frac{\sqrt{M_3}}{\langle H \rangle}(\sqrt{m_2} U^*_{i1} \sin z + \sqrt{m_3} U^*_{i2} \cos z)$$

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

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.

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

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

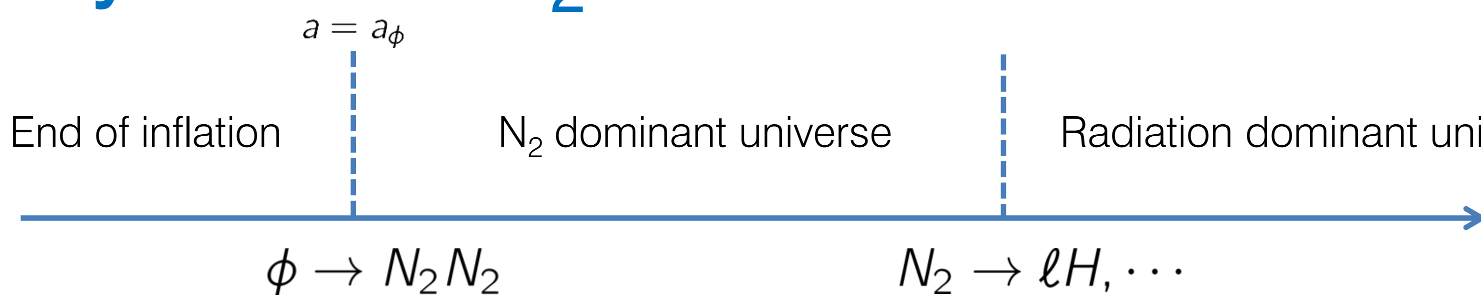
- Inverted hierarchy

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

[Harigaya, Ibe, Yanagida (2012)]

(z : a complex parameter)

Decay time of N_2



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.

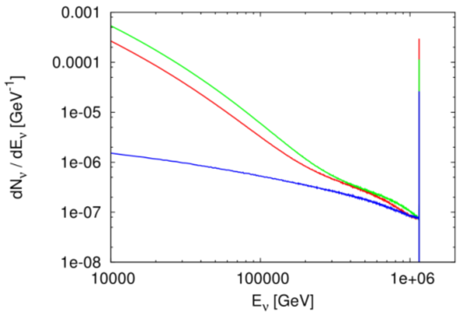
$$\frac{n_{N_2}}{s} \sim \frac{T_2}{M_2} \sim \frac{T_\phi}{m_\phi} \Delta \qquad \Delta = \Gamma_2 t_{\rm nonrela} = \frac{\Gamma_2}{\Gamma_\phi} \frac{m_\phi^2}{M_2^2} < 1$$

Everything is diluted by entropy production!

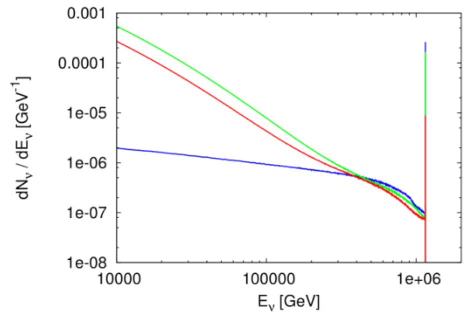
Effect of neutrino oscillation

Energy spectrum at the decay time (simulated by PYTHIA 8.1)

Normal hierarchy



Inverted hierarchy

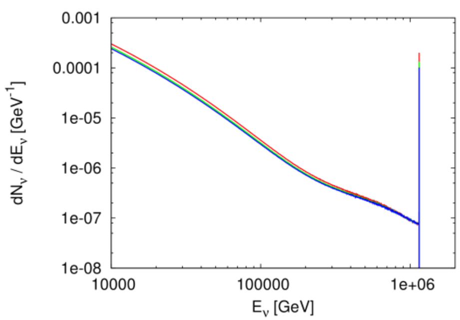


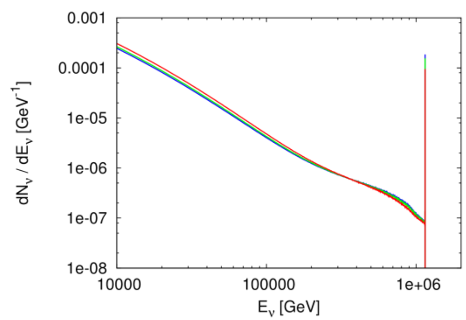
$\nu_e + \bar{\nu}_e$

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

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

$$P(\nu_\ell \to \nu_{\ell'}) \simeq \begin{pmatrix} 0.5 & 0.3 & 0.2 \\ 0.3 & 0.3 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$





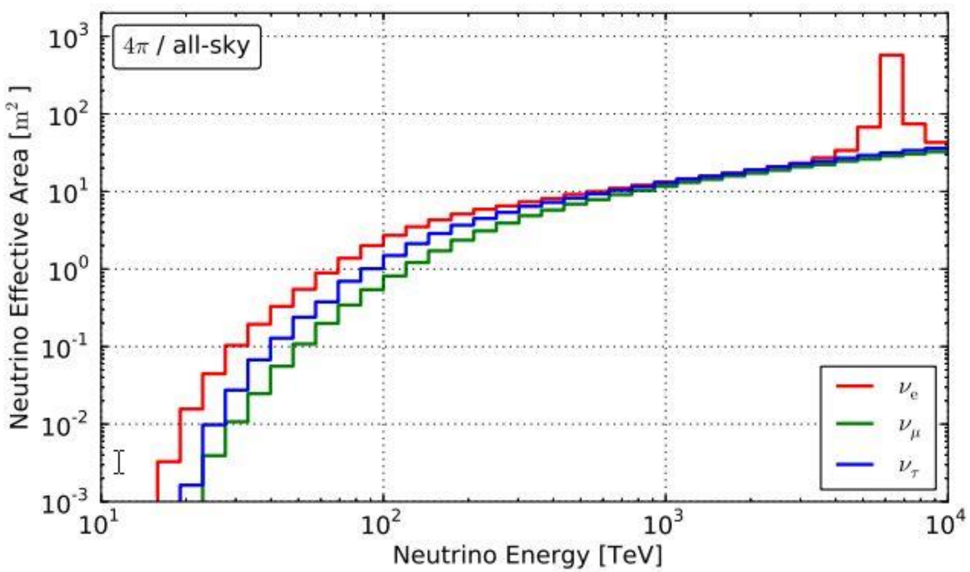
Effective area

Number of observed events can be calculated as,

$$N_{\rm obs} = 4\pi \times T \times \sum_{\ell=e,\mu,\tau} \int dE \times \sigma_{\rm eff}^{(\ell)} \left(\frac{d\Phi_{\nu_\ell}}{dE} + \frac{d\Phi_{\bar{\nu}_\ell}}{dE} \right)$$

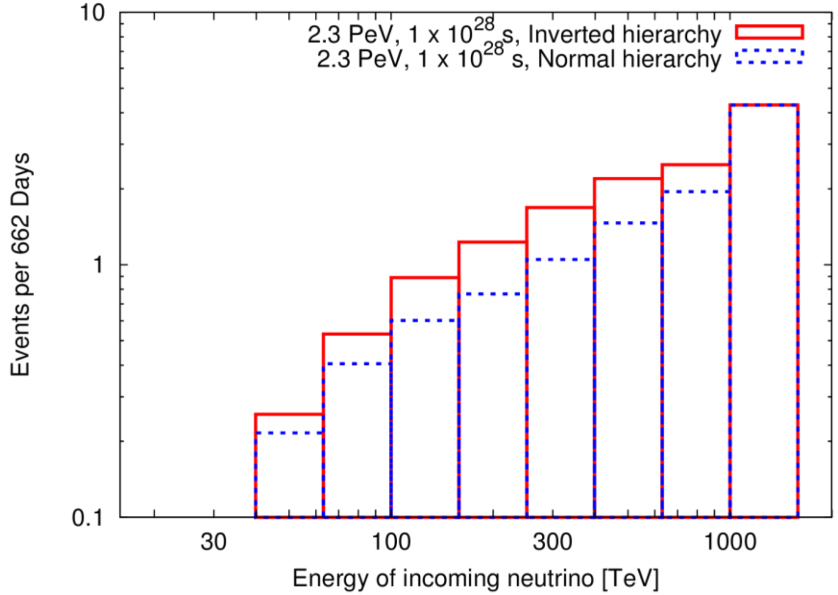
(T : the detector livetime)

Effective area



[IceCube collaboration arxiv:1311.5238]

Spectrum of number of events



$$M_1 = 2.3 \text{ PeV}, \quad \tau = 10^{28} \text{ s}$$

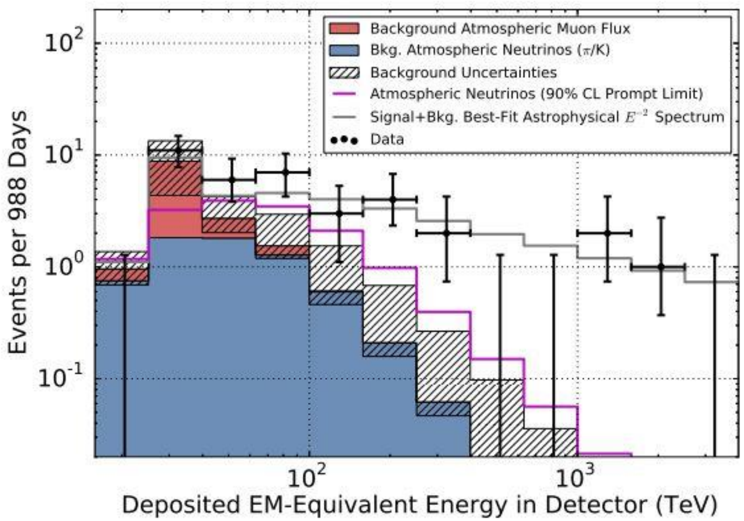
$$N(30 \text{ TeV} \leq E_\nu) = 6.5 \times \left(\frac{\tau_{N_1}}{10^{28} \text{ s}}\right)^{-1}$$

$$N(30 \text{ TeV} \leq E_\nu) = 9.4 \times \left(\frac{\tau_{N_1}}{10^{28} \text{ s}}\right)^{-1}$$

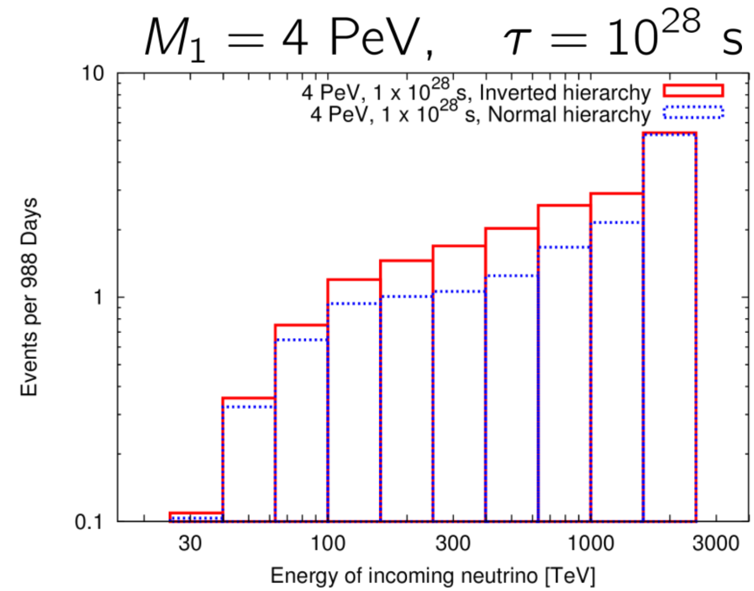
$$N(1 \text{ PeV} \leq E_\nu) = 4.3 \times \left(\frac{\tau_{N_1}}{10^{28} \text{ s}}\right)^{-1}$$

PeV dark matter with its lifetime to be around 10^{28} s
can explains the event excess at the IceCube experiment.

Number of events



[arXiv : 1405.5303]



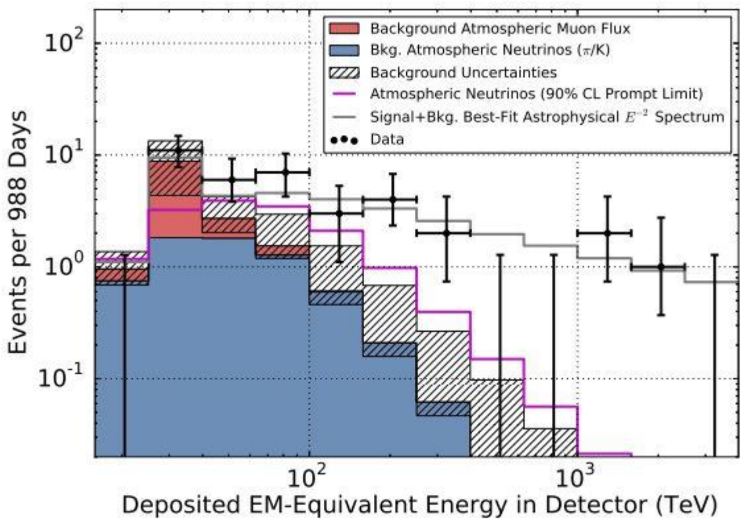
For Normal hierarchy,

$$N(30\ \text{TeV} \leq E_\nu) = 9.7 \times \left(\frac{\tau_{N_1}}{10^{28}\ \text{s}}\right)^{-1} = 22 \times \left(\frac{\tau_{N_1}}{0.44 \times 10^{28}\ \text{s}}\right)^{-1}$$

$$N(1\ \text{PeV} \leq E_\nu) = 5.0 \times \left(\frac{\tau_{N_1}}{10^{28}\ \text{s}}\right)^{-1} = 3.0 \times \left(\frac{\tau_{N_1}}{1.6 \times 10^{28}\ \text{s}}\right)^{-1}$$

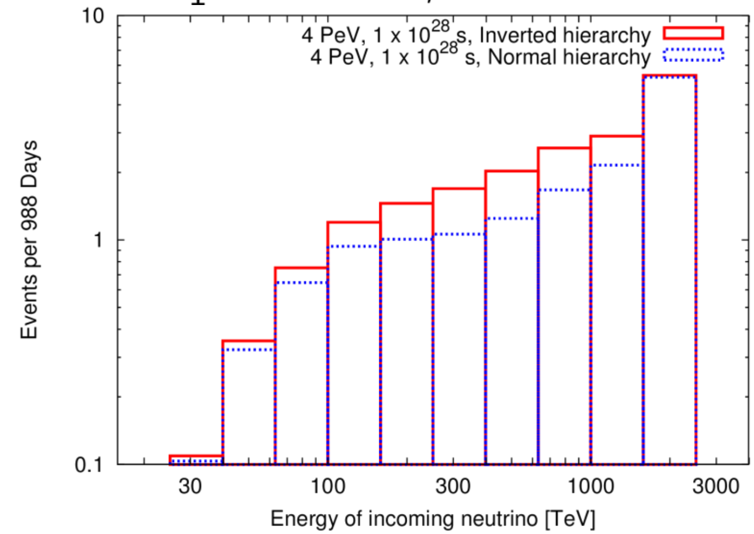
PeV dark matter with its lifetime to be around 10^{28} s
can explains the event excess at the IceCube experiment.

Number of events



[arXiv : 1405.5303]

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



For Inverted hierarchy,

$$N(30\ \mathrm{TeV} \le E_\nu) = 12.4 \times \left(\frac{\tau_{N_1}}{10^{28}\ \mathrm{s}}\right)^{-1} = 22 \times \left(\frac{\tau_{N_1}}{0.56 \times 10^{28}\ \mathrm{s}}\right)^{-1}$$

$$N(1\ \mathrm{PeV} \le E_\nu) = 5.6 \times \left(\frac{\tau_{N_1}}{10^{28}\ \mathrm{s}}\right)^{-1} = 3.0 \times \left(\frac{\tau_{N_1}}{1.9 \times 10^{28}\ \mathrm{s}}\right)^{-1}$$

PeV dark matter with its lifetime to be around 10^{28} s
can explains the event excess at the IceCube experiment.