

Cosmic-Ray Neutrinos
from the Decay of Long-Lived Particle
– Implication to the IceCube Results –

Takeo Moroi (Tokyo)

Refs:

Ema, Jinno & TM, PLB 733 ('14) 120 [arXiv:1312.3501]

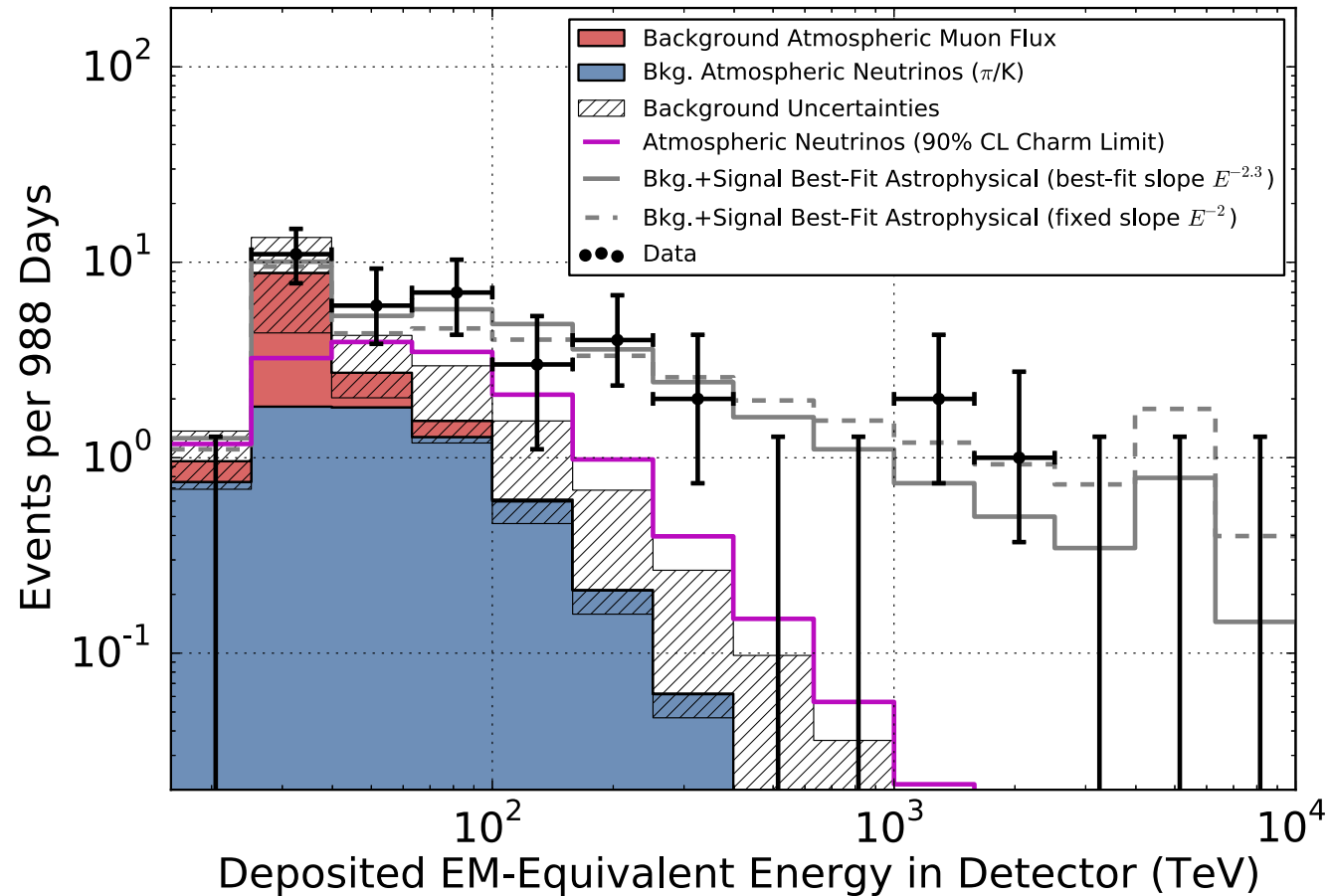
Ema, Jinno & TM, JHEP (to appear) [arXiv:1408.1745]

WIMPs and Axions, IBS, Daejeon, Korea '14.10.15

1. Introduction

Recent result of IceCube:

First observation of sub-PeV – PeV neutrinos



[IceCube 3 years result (May, '14); Talk by Carsten Rott]

The observed flux is above the expectation

⇒ We need a new source of high-energy cosmic-ray neutrinos

IceCube found 37 high energy neutrino events

- The observed flux is well-above the expected background
 - 8.4 ± 4.2 from cosmic-ray muons
 - $6.6_{-1.6}^{+5.9}$ from atmospheric neutrinos
- The data is consistent with E^{-2} power-law flux with a cut-off at \sim PeV
 - ⇒ 3.1 events above $E_{\text{obs}} > 2$ PeV, if no cut-off
 - ⇒ Cut-off at \sim PeV (or softer spectrum)?

What is the origin of high-energy cosmic-ray neutrinos?

- Astrophysical origin

[Kalashev, Kusenko & W. Essey; Stecker; Cholis & Hooper; Murase & Ioka; Razzaque; Winter; Fox, Kashiyama & Mszars; Liu et al.; Murase, Ahlers & Lacki; N. Gupta; Gonzalez-Garcia et al.; Ahlers & Murase; Gao et al.; Roulet et al.; Laha et al.; Anchordoqui et al.; He et al.]

- Particle-physics origin

[Feldstein, Kusenko, Matsumoto & Yanagida; Esmaili & Serpico; Ema, Jinno & TM; Bai, Lu & Salvado; Bhattacharya, Reno & Sarcevic; Zavala; Chen & Nomura; Higaki, Kitano & Sato; Rott, Kohri & Park]

I consider one of the possibilities of particle-physics origin

⇒ PeV neutrinos from the decay of long-lived particle X

Today, I will talk about: “The early-decay scenario”

- Possibility to explain IceCube results with the neutrino production via the decay of long-lived particle X
- PeV neutrinos can be produced by the decay of X with $\tau_X \ll t_{\text{now}}$ and $m_X \gg \text{PeV}$

Outline

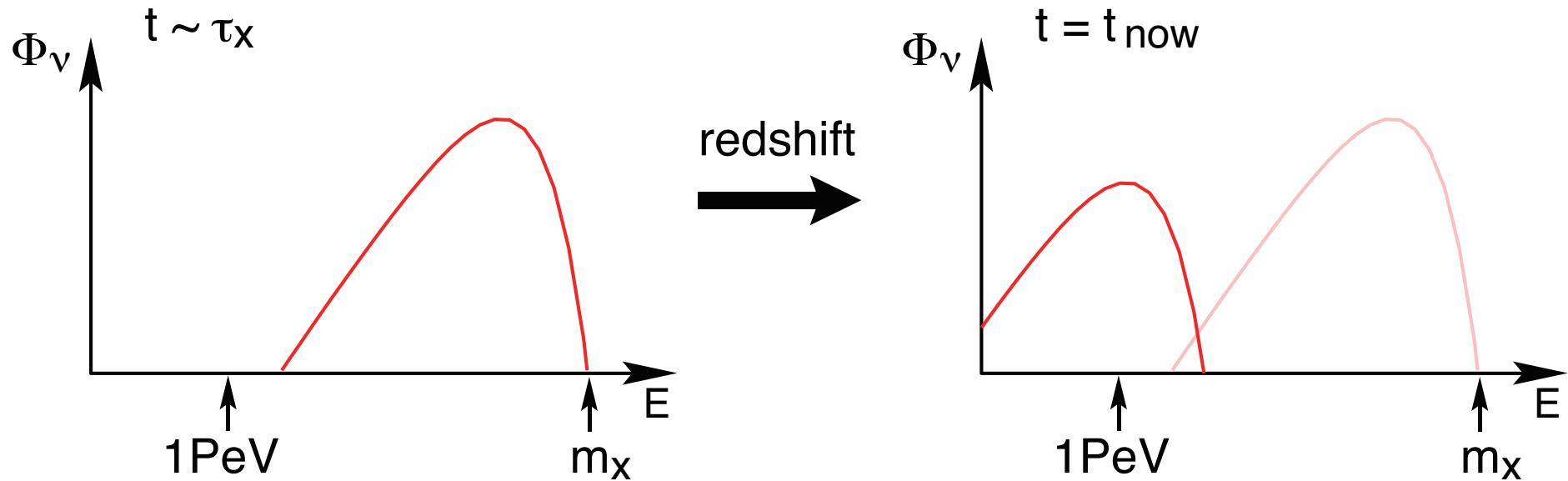
1. Introduction
2. “The Early-Decay Scenario”
3. Numerical Results: Neutrino flux
4. Summary

2. The Early-Decay Scenario

[Ema, Jinno & TM]

The early-decay scenario: $\tau_X \ll t_{\text{now}}$

- X decays into neutrinos before the present epoch
⇒ The energy is redshifted: $E = (1 + z_{\text{prod.}})^{-1} E_{\text{prod.}}$



- PeV neutrino at present is realized due to the redshift
⇒ Mass of X can be much higher than PeV scale

The case of decaying dark matter (for comparison):

- $m_X \sim O(1 \text{ PeV})$
- Neutrino flux from the galactic center is enhanced

Can we find another class of model?

⇒ Early-decay scenario

Important parameters:

- Mass: m_X
- Lifetime: $\tau_X \Rightarrow z_* = z(t = \tau_X) \equiv \frac{a_{\text{now}}}{a(t = \tau_X)} - 1$
- Abundance: $Y_X \equiv \left[\frac{n_X}{s} \right]_{t \ll \tau_X}$

In the early-decay scenario:

- Neutrino with higher energy is produced at later epoch

$$\Rightarrow (\text{Number density of } X) \propto e^{-t/\tau_X}$$

\Rightarrow For $E \gtrsim (1 + z_*)^{-1} m_X$, flux is exponentially suppressed

- Scattering processes of neutrinos may be important

$$- \nu + \bar{\nu}_{\text{BG}} \rightarrow \nu + \bar{\nu}', \ell + \bar{\ell}', q + \bar{q}$$

$$- \nu + \bar{\nu}'_{\text{BG}} \rightarrow \nu + \bar{\nu}', \ell + \bar{\ell}'$$

$$- \nu + \nu_{\text{BG}} \rightarrow \nu + \nu$$

$$- \nu + \nu'_{\text{BG}} \rightarrow \nu + \nu'$$

Neutrinos from cosmological distance: $\Phi_\nu^{(\text{Cosmo})}$

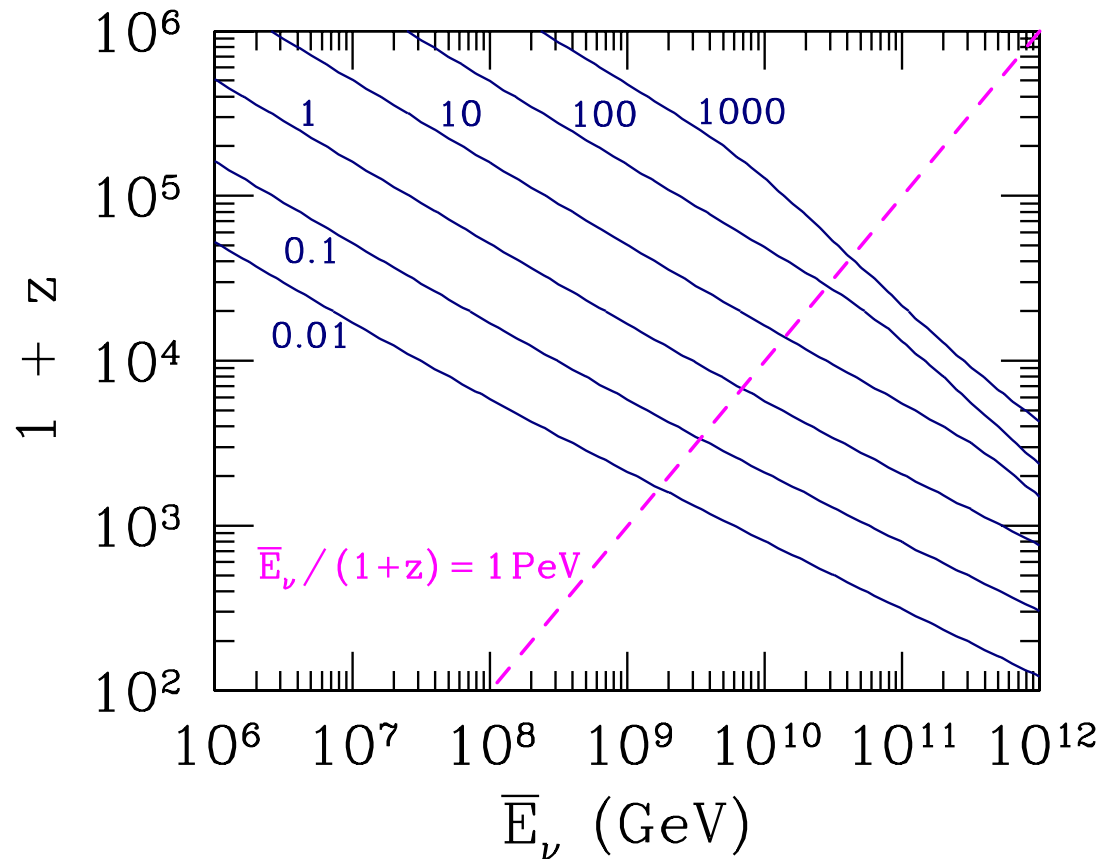
$$\begin{aligned}\dot{\Phi}_\nu^{(\text{Cosmo})}(t, E) &= -2H\Phi_\nu^{(\text{Cosmo})}(t, E) + HE\frac{\partial}{\partial E}\Phi_\nu^{(\text{Cosmo})}(t, E) \\ &\quad -\gamma_\nu(t; E)\Phi_\nu^{(\text{Cosmo})}(t, E) \\ &\quad + \int dE'\Phi_\nu^{(\text{Cosmo})}(t, E')\frac{d\gamma_\nu^{(\text{eff})}(t; E', E)}{dE} \\ &\quad + (\text{Source Term})\end{aligned}$$

γ_ν : Scattering rate

Optical depth: $\tau_\nu(z) \equiv \int_{t(z)}^{t_{\text{now}}} dt' \gamma_\nu(t'; (1+z(t'))^{-1}\bar{E}_\nu)$

- “Survival probability” $\sim e^{-\tau_\nu}$
- If $\tau_\nu \gtrsim 1$, the scattering processes become important

Optical depth: $\tau_\nu(z) \equiv \int_{t(z)}^{t_{\text{now}}} dt' \gamma_\nu(t'; (1+z(t'))^{-1} \bar{E}_\nu)$



\Rightarrow To explain IceCube result, $1+z_* \lesssim O(10^4)$ is necessary

3. Numerical Results: Neutrino flux

The present neutrino flux depends on the primary spectrum

⇒ Hereafter, I consider two examples

Case 1: Monochromatic neutrino injection

- X as a neutral component of $SU(2)_L$ triplet

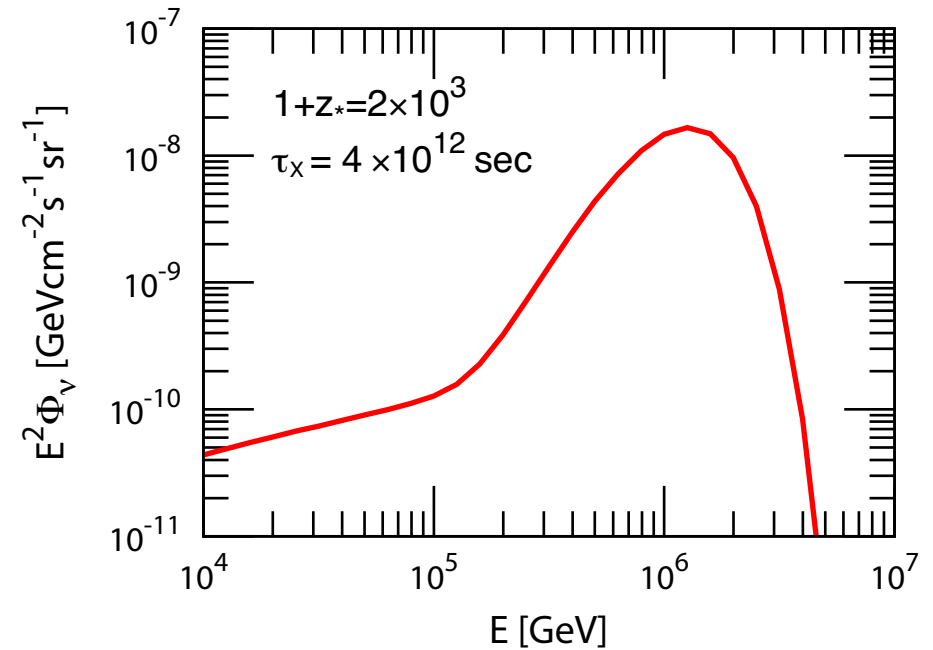
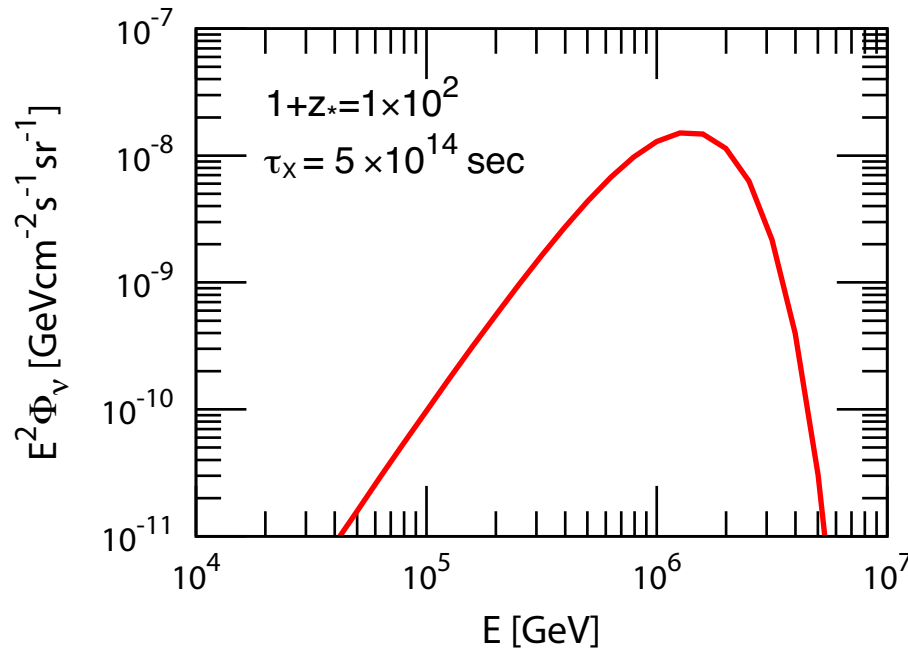
$$X \rightarrow \nu\nu$$

Case 2: Vector-like $SU(2)_L$ doublet L , mixed with leptons

- $\mathcal{L} = M_L \bar{L}L + \epsilon \bar{L}\ell + y_l \bar{e}\ell H + \dots$
- L^0 can play the role of X

$$X \rightarrow \nu Z^0, e^\pm W^\mp$$

Neutrino spectrum: (1) Relatively long lifetime

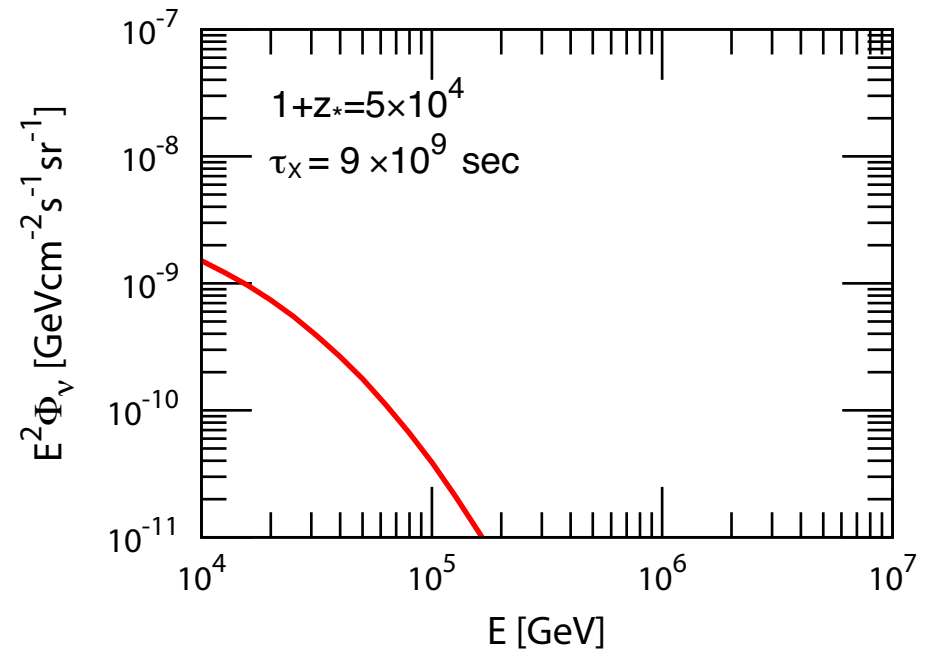
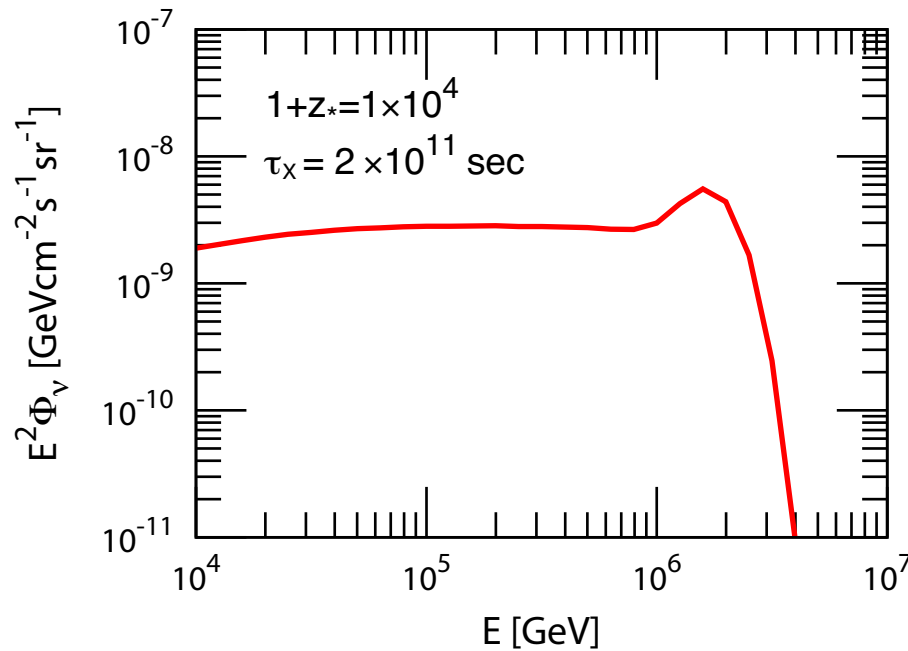


- Monochromatic neutrino injection: $\bar{E}_\nu = 1 \text{ PeV} \times (1 + z_*)$

- $Y_X = [n_X/s]_{t \ll \tau_X} = 10^{-26}$

\Rightarrow If $z_* \lesssim (\text{a few}) \times 10^3$, spectrum is (almost) unaffected by the scatterings

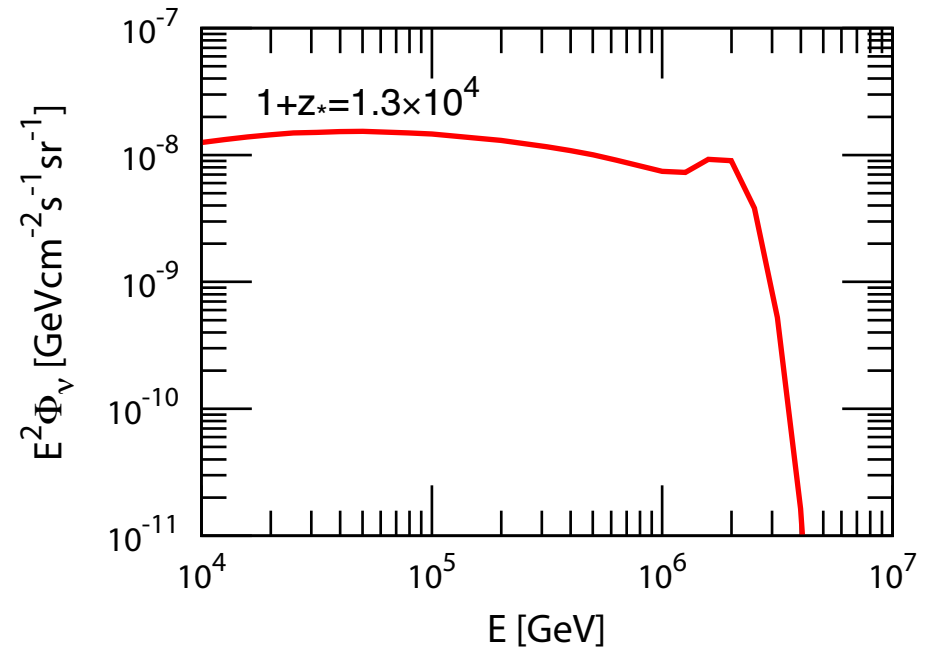
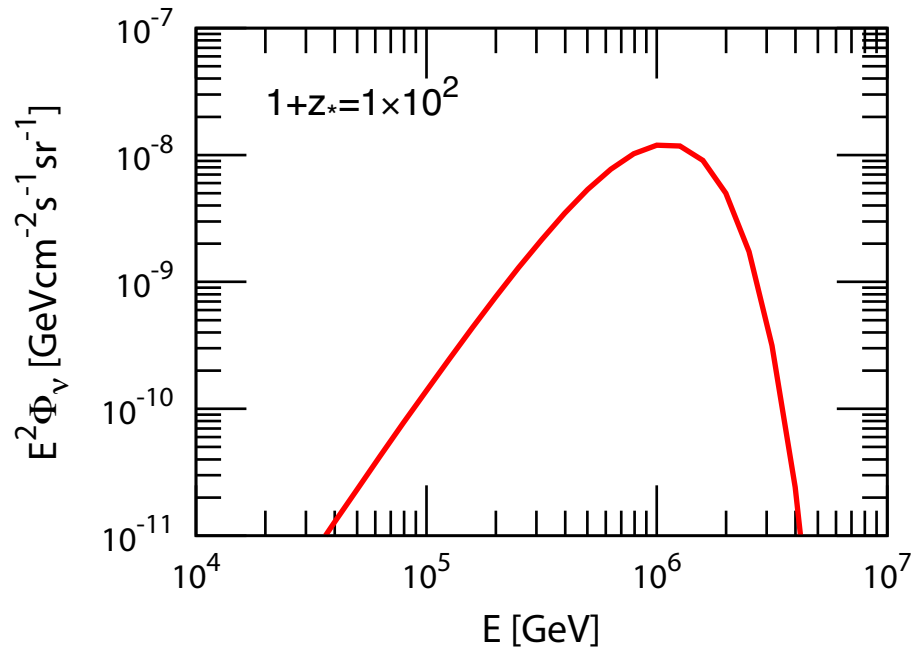
Neutrino spectrum: (2) Short lifetime



- Monochromatic neutrino injection: $\bar{E}_\nu = 1 \text{ PeV} \times (1 + z_*)$
 - $Y_X = [n_X/s]_{t \ll \tau_X} = 10^{-26}$
- ⇒ If $z_* \gtrsim (\text{a few}) \times 10^3$, effect of the scattering becomes important

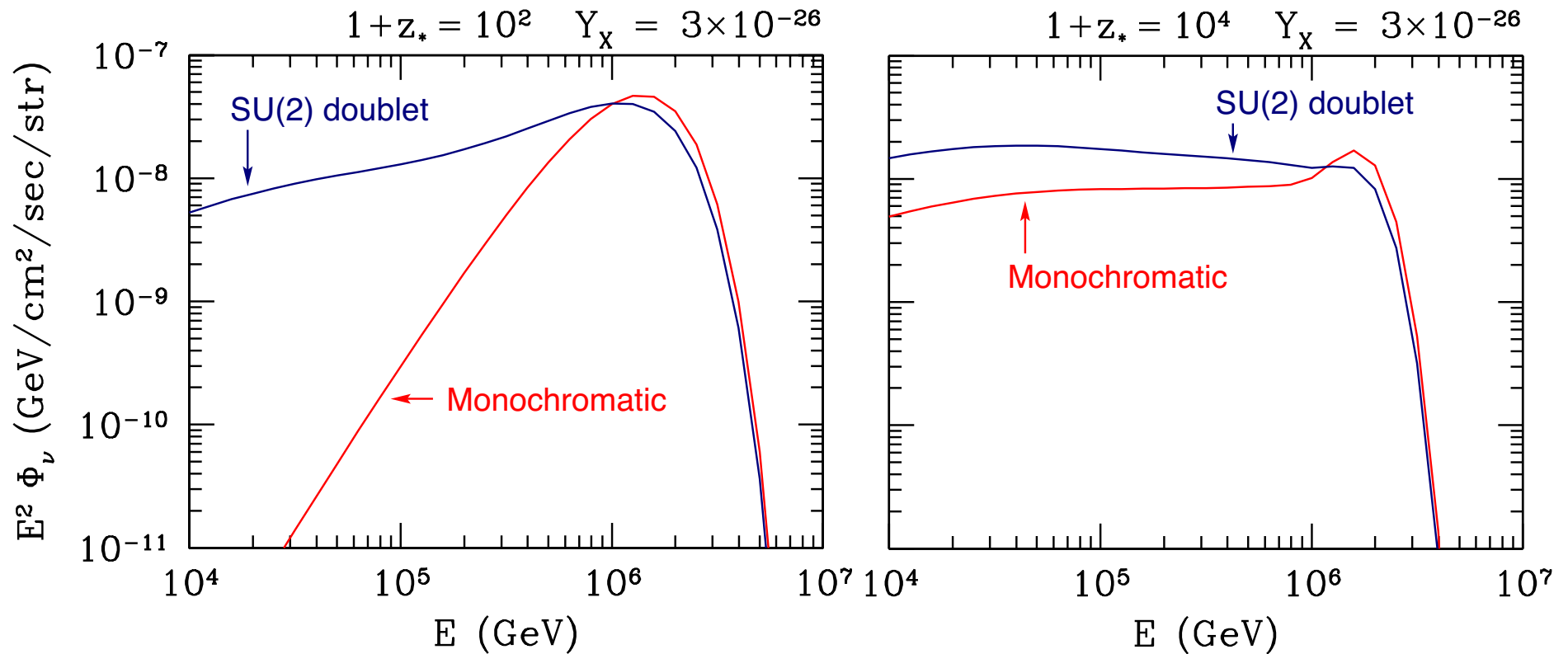
Can we realize E^{-2} power-law flux with a cut-off?

⇒ Case with monochromatic neutrino injection



⇒ With monochromatic injection, E^{-2} power-law flux requires $1 + z_* \sim (1 - 1.5) \times 10^4$

Non-monochromatic neutrino injection (preliminary)



⇒ Neutrino flux at $E \ll E_{\text{cut}}$ is enhanced

⇒ Neutrino flux with $\sim E^{-2}$ behavior with cutoff is possible

Early-decay scenario vs. dark-matter-decay scenario

	Early-decay scenario	Dark-matter decay
$z_* = z(\tau_X)$	$\lesssim 10^4$	—
m_X	$\lesssim 10^{10}$ GeV	~ 1 PeV
τ_X	$\gtrsim 10^{11}$ sec	$\sim 10^{28}$ sec
$Y_X = [n_X/s]_{t \ll \tau_X}$	$\sim 10^{-26}$	$\sim 10^{-16}$
Direction	Isotropic	\sim Galactic center

$1 + z_* \lesssim 10^4$ is required to avoid:

- Too much deformation of the spectrum via scatterings
- BBN constraints & CMB distortion

4. Summary

I discussed “early-decay scenario” for IceCube events

- $z_* \lesssim O(10^4)$, which corresponds to $\tau_X \gtrsim 10^{10}$ sec
- $m_X \sim (1 + z_*) \times 1 \text{ PeV} \lesssim O(10^{10} \text{ GeV})$
- The neutrino spectrum is isotropic
- The scenario may be tested by future observations of CMB distortion (like PIXIE / PRISM)
- The direct-detection constraints on X are irrelevant

Issues:

- Primordial abundance of X : non-thermal production
- Models (PQ model, messengers in GMSB, ...)

Back Up

Case with decaying dark matter

- $E_\nu^{(\text{cut})} \sim O(1 \text{ PeV})$

$$\Rightarrow m_X \sim O(1 \text{ PeV})$$

- $E^2 \Phi_\nu^{(\text{IceCube})} \sim 10^{-8} \text{ GeV/cm}^2/\text{sec/str}$

$$\Rightarrow \tau_X \sim 10^{29} \text{ sec} \times \left(\frac{\Omega_X}{\Omega_{\text{DM}}} \right)$$

- $\Phi_\nu^{(\text{Galaxy})} \gtrsim \Phi_\nu^{(\text{Cosmo})}$

\Rightarrow Flux from the direction of galactic center is enhanced

$$\frac{\Phi_\nu^{(\text{Galaxy})}(\theta < 90^\circ)}{\Phi_\nu^{(\text{Galaxy})}(\theta > 90^\circ)} \sim 2$$

Neutrino flux for $\tau_X \gg t_{\text{now}}$ (with $m_X = 3$ PeV)

