Cosmic-Ray Neutrinos from the Decay of Long-Lived Particle

– Implication to the IceCube Results –

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(向こう側からきました、お手柔らかにお願いします)

Refs:

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

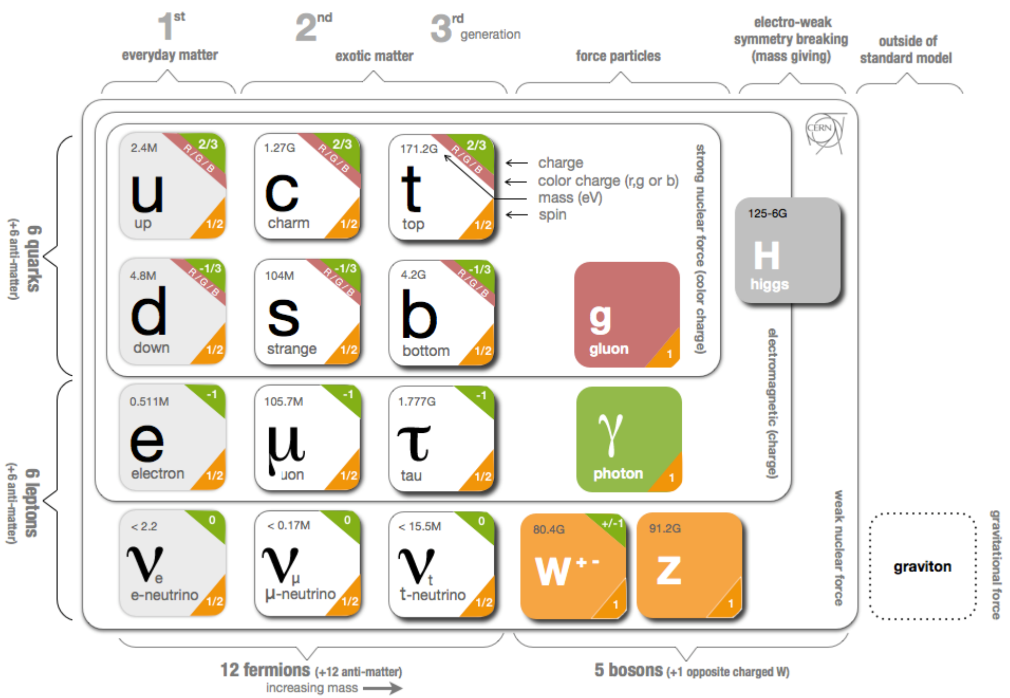
Ema, Jinno & TM, JHEP 1410 ('14) 150 [arXiv:1408.1745]

Rironkon, Mitaka (Christmas Eve, 2014)

1. Introduction

Recent big news in particle physics: Discovery of Higgs boson

- Higgs: the last piece of standard-model particles



The biggest issue: What's next?

- There is no sign of new physics at colliders so far
- What can we do?

Our (or my) motto:

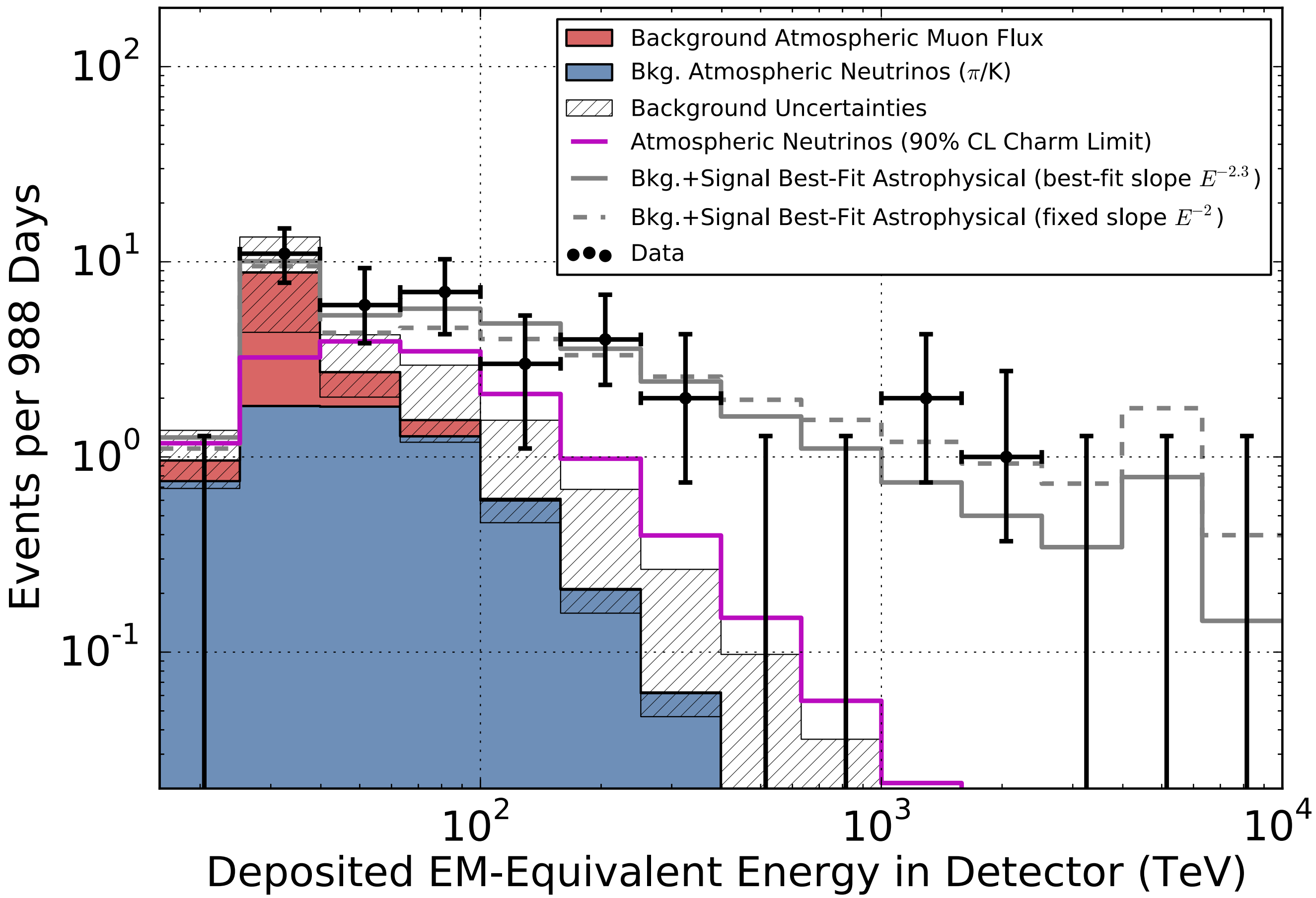
- Use whatever information available!

High-energy cosmic rays seem interesting

- Many particle-physics models predict "signals" in cosmic rays
- There are many on-going projects which have provided interesting results (i.e., "anomalies")
  - PAMELA
  - Fermi-LAT
  - ...
  - IceCube

Today, I concentrate on the recent IceCube result:

First observation of sub-PeV – PeV neutrinos



[IceCube 3 years result (May, '14); Talk by Yoshida-san]

IceCube found 37 high energy neutrino events

- The observed flux is well-above the expected background
  - 8.4 ± 4.2 from cosmic-ray muons
  - $6.6^{+5.9}_{-1.6}$ from atmospheric neutrinos
- The flux is consistent with E^{-2} power-law with a cut-off

  $\Rightarrow$ 3.1 events above $E_{\text{obs}} > 2$ PeV, if no cut-off

  $\Rightarrow$ Cut-off at $\sim$ PeV (or softer spectrum)?

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

- $\sim E^{-2}$ power-law @ $E \lesssim$ PeV
- Cut-off @ $E \sim$ PeV
- Isotropic

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

$\Rightarrow$ PeV neutrinos from the decay of long-lived particle

Today, I will talk about:

- Possibility to explain IceCube results with the neutrino production via the decay of long-lived particle
- "The early-decay scenario," which explains the IceCube events with a particle X with $\tau_X \ll t_{\text{now}}$ and $m_X \gg$ PeV

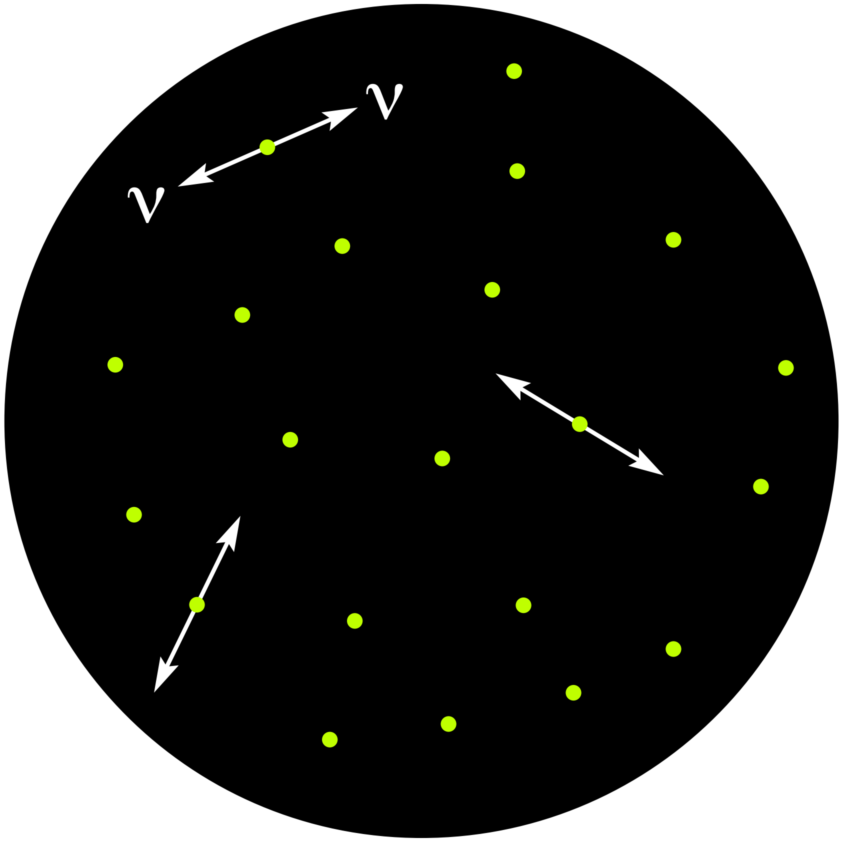
Outline

1. Introduction
2. Scenario
3. Case with Dark-Matter Decay
4. The Early Decay Scenario
5. Summary

2. The Scenario

Assumption: There exists a long-lived particle X

- X is somehow produced in the early universe
- Neutrinos are produced by the decay of X



What is the parent particle X?

- Dark matter

  $\Rightarrow \tau_X \gg t_{\text{now}}$ & $m_X \sim O(\text{PeV})$

- Something else ("early-decay scenario")

  $\Rightarrow \tau_X \ll t_{\text{now}}$ & $m_X \gg O(\text{PeV})$ is possible

BTW, why particle-physics explanation?

- I am particle physicist
- No convincing explanation so far, so we should be open-minded
- The observed neutrino events do not have any correlation with known sources (like AGN, γ-ray burst, $\cdots$)

3. Case with Dark-Matter Decay

Neutrino flux can be classified into:

- Galactic contribution $\Phi_\nu^{(\mathsf{Galaxy})}$
- Cosmological contribution $\Phi_\nu^{(\mathsf{Cosmo})}$

$\Phi_\nu^{(\mathsf{Galaxy})}$ depends on direction

$$\Phi_\nu^{(\mathrm{Galaxy})}(E,\hat{l}) = \frac{1}{4\pi}\frac{1}{\tau_X}\frac{dN_\nu^{(X)}}{dE}\int_{\mathrm{l.o.s.}} d\vec{l}\,\frac{\rho_X(\vec{l})}{m_X}$$

Boltzmann equation for $\Phi_\nu^{(\mathsf{Cosmo})}$

$$\dot{\Phi}_\nu^{(\mathsf{Cosmo})}(t,E) = -2H\Phi_\nu^{(\mathsf{Cosmo})}(t,E) + HE\frac{\partial}{\partial E}\Phi_\nu^{(\mathsf{Cosmo})}(t,E) + \frac{1}{4\pi}\frac{1}{\tau_X}\frac{\rho_X(t)}{m_X}\frac{dN_\nu^{(X)}}{dE}$$

The present neutrino flux depends on the primary spectrum

$\Rightarrow$ Hereafter, I consider two examples

Case 1: Monochromatic neutrino injection

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

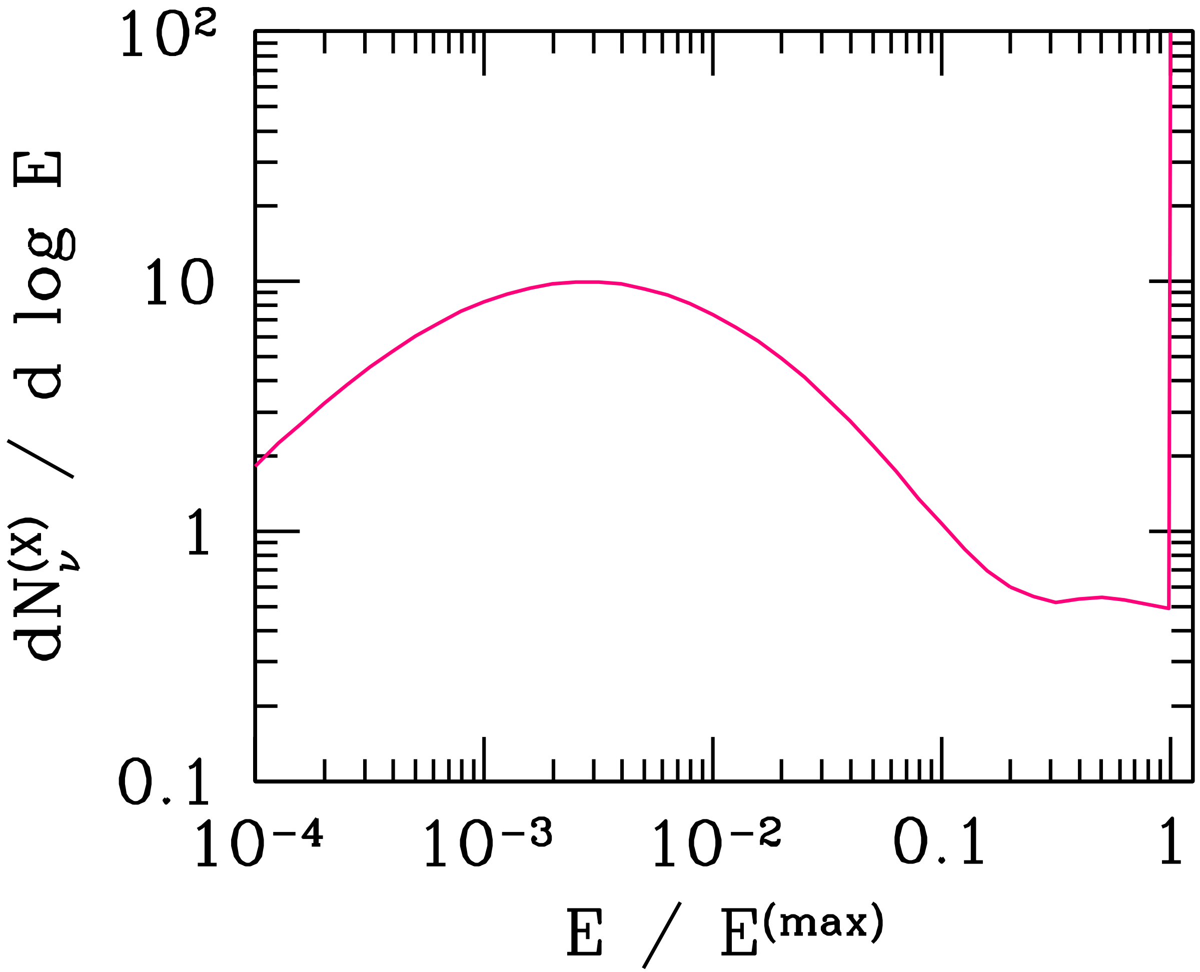
$$X \to \nu\nu \quad \Rightarrow \quad \frac{dN_\nu^{(X)}}{dE} = 2\delta(E - m_X/2)$$

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

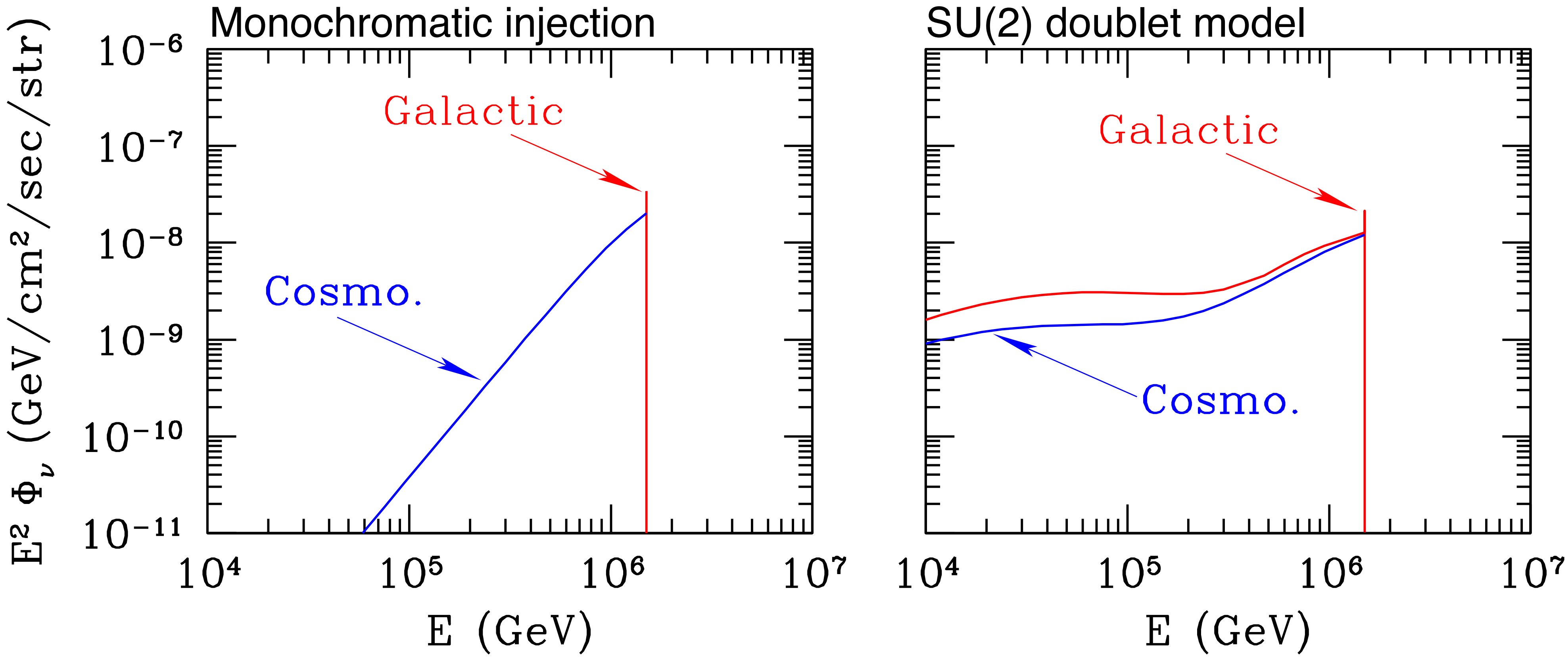
- $\mathcal{L} = M_L \bar{L} L + \epsilon \bar{L} \ell + y_l \bar{e} \ell H + \cdots$
- L^0 can play the role of X

$$X \to \nu Z^0, \ e^{\pm} W^{\mp}$$

Neutrino distribution for $SU(2)_L$ doublet model



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



- $\rho_X = \rho_{\rm DM}$ with $\tau_X \simeq 3 \times 10^{28}$ sec
- NFW dark matter density is used

Cut-off scale of the neutrino spectrum: $E_{\text{cut}} \sim m_X$

$\Rightarrow$ Mass of DM is required to be $O(\text{PeV})$

Dark-matter density is enhanced at the Galactic center

$\Rightarrow$ 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 is proportional to τ_X^{-1}

$\Rightarrow$ In order to explain the IceCube result, $\tau_X \sim O(10^{28}\ \text{sec})$

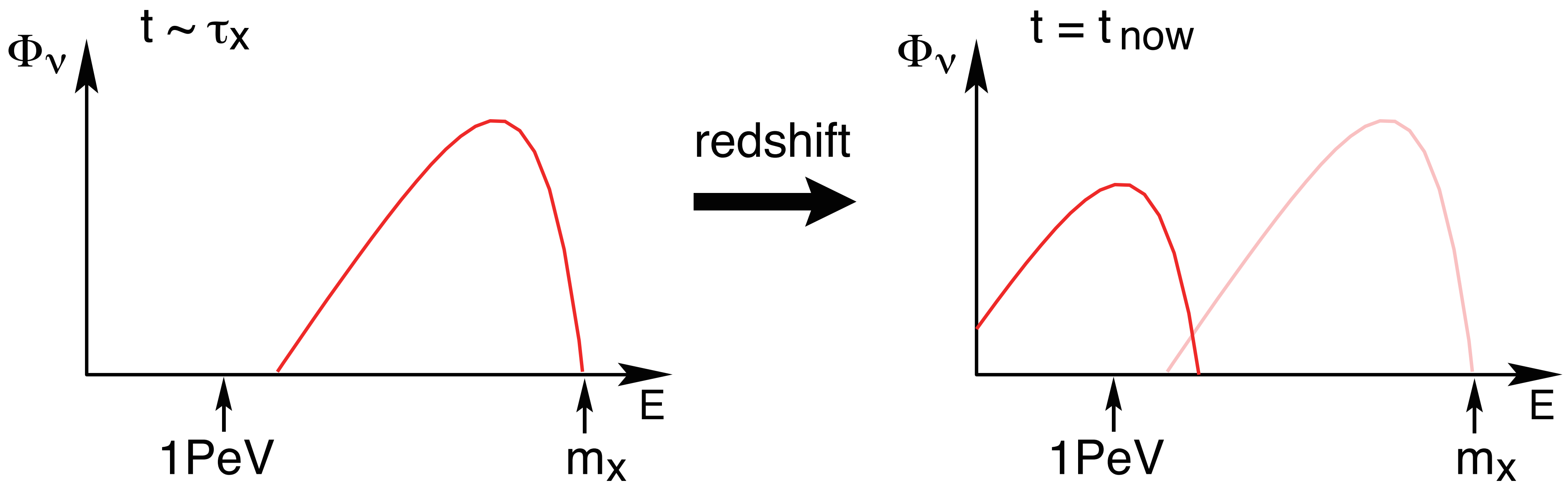
4. The Early-Decay Scenario

[Ema, Jinno & TM]

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

- X decays into neutrinos before the present epoch

  $\Rightarrow$ The energy is redshifted: $E = (1 + z_{\text{prod.}})^{-1} E_{\text{prod.}}$



- PeV neutrino at present is realized due to the redshift

  $\Rightarrow$ Mass of X can be much higher than PeV scale

Important quantities:

- Mass: m_X
- Lifetime: $\tau_X \;\; \Rightarrow \;\; z_* = z(t = \tau_X) \equiv \frac{a_{\text{now}}}{a(t = \tau_X)} - 1$
- Abundance: $Y_X \equiv \left[\frac{n_X}{s} \right]_{t \ll \tau_X}$
- Neutrino distribution from the decay of X: $\frac{dN_\nu^{(X)}}{dE}$

The case of decaying dark matter (for comparison):

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

In the early-decay scenario:

- Neutrino with higher energy is produced at later epoch

  $\Rightarrow$ (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

  – $\nu + \bar{\nu}_{\rm BG} \rightarrow \nu + \bar{\nu}', \ \ell + \bar{\ell}', \ q + \bar{q}$

  – $\nu + \bar{\nu}'_{\rm BG} \rightarrow \nu + \bar{\nu}', \ \ell + \bar{\ell}'$

  – $\nu + \nu_{\rm BG} \rightarrow \nu + \nu$

  – $\nu + \nu'_{\rm BG} \rightarrow \nu + \nu'$

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

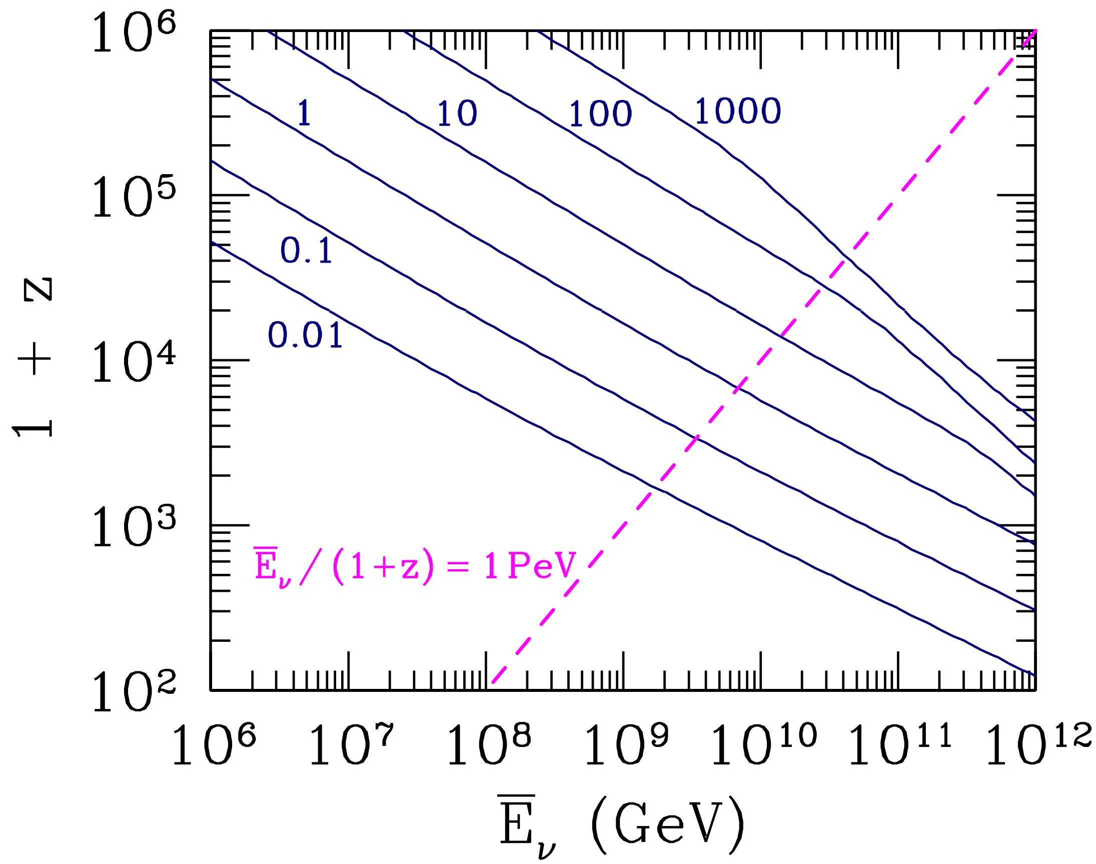
$$\begin{aligned}\dot{\Phi}_\nu^{(\mathsf{Cosmo})}(t,E) = & -2H\Phi_\nu^{(\mathsf{Cosmo})}(t,E) + HE\frac{\partial}{\partial E}\Phi_\nu^{(\mathsf{Cosmo})}(t,E) \\ & -\gamma_\nu(t;E)\Phi_\nu^{(\mathsf{Cosmo})}(t,E) \\ & +\int dE'\Phi_\nu^{(\mathsf{Cosmo})}(t,E')\frac{d\gamma_\nu^{(\mathsf{eff})}(t;E',E)}{dE}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

γ_ν: Scattering rate

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

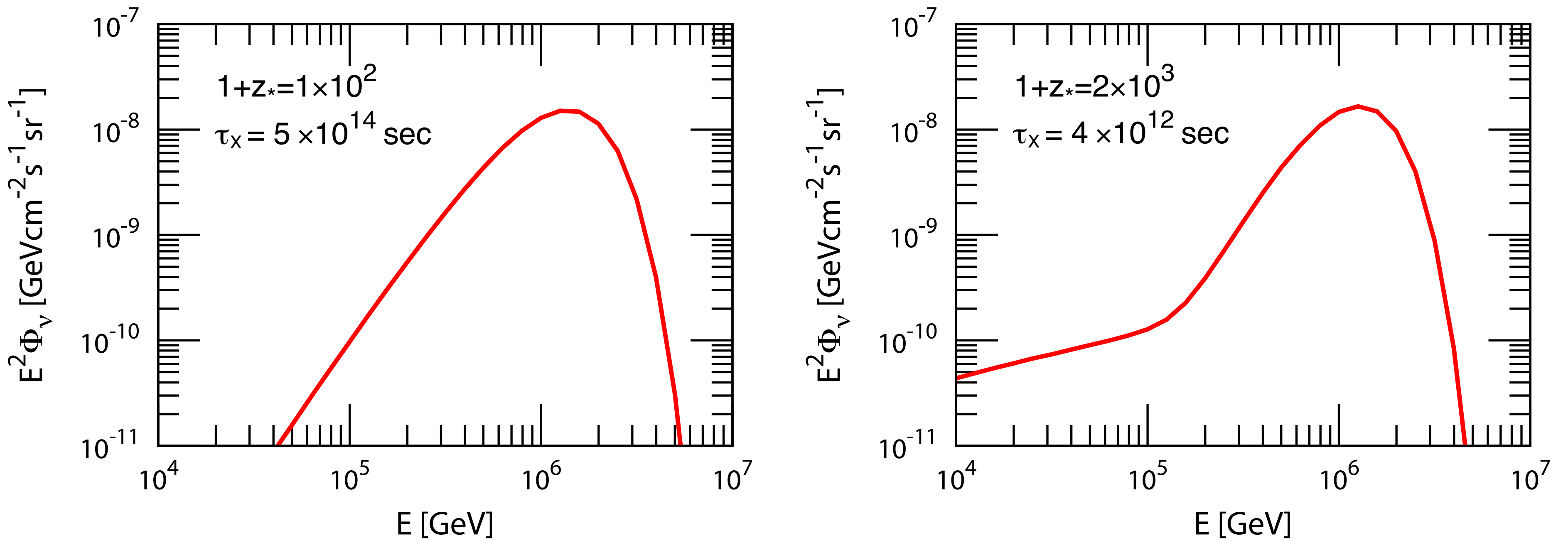
- "Survival probability" $\sim e^{-\tau_\nu}$
- If $\tau_\nu \gtrsim 1$, the scattering processes become important

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



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

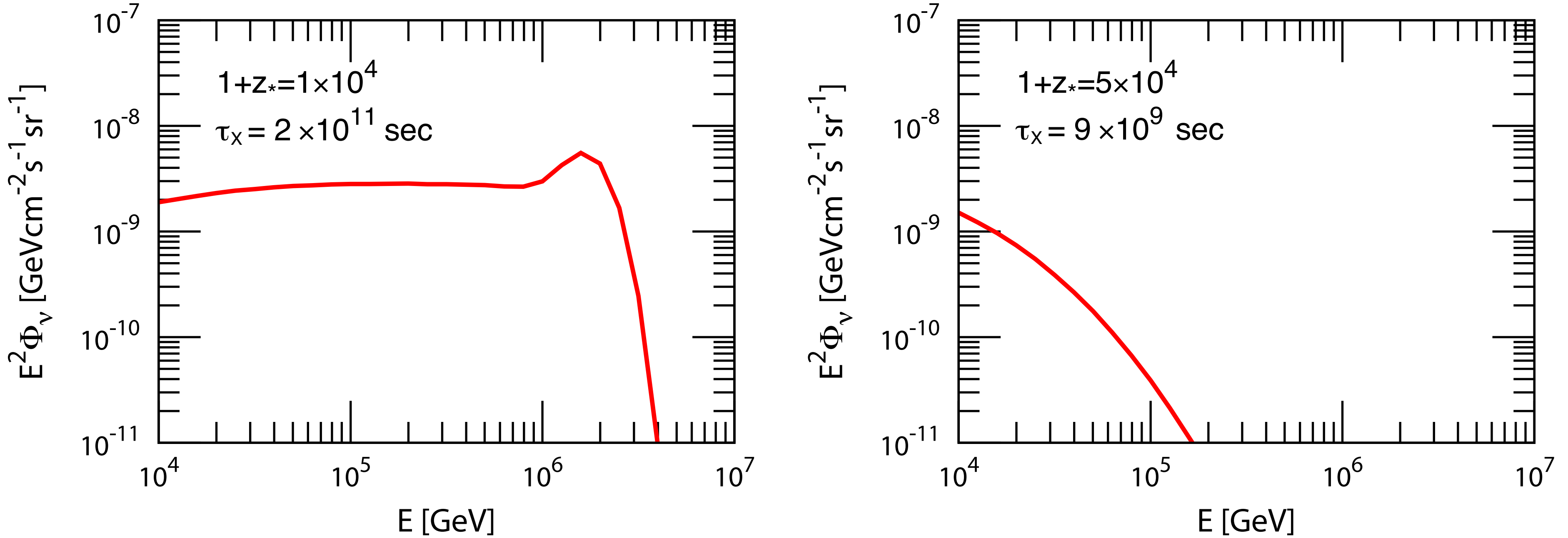
Neutrino spectrum: (1) Relatively long lifetime



- Monochromatic neutrino injection: $\bar{E}_\nu = 1$ PeV $\times (1 + z_*)$
- $Y_X = [n_X/s]_{t \ll \tau_X} = 10^{-26}$

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

Neutrino spectrum: (2) Short lifetime

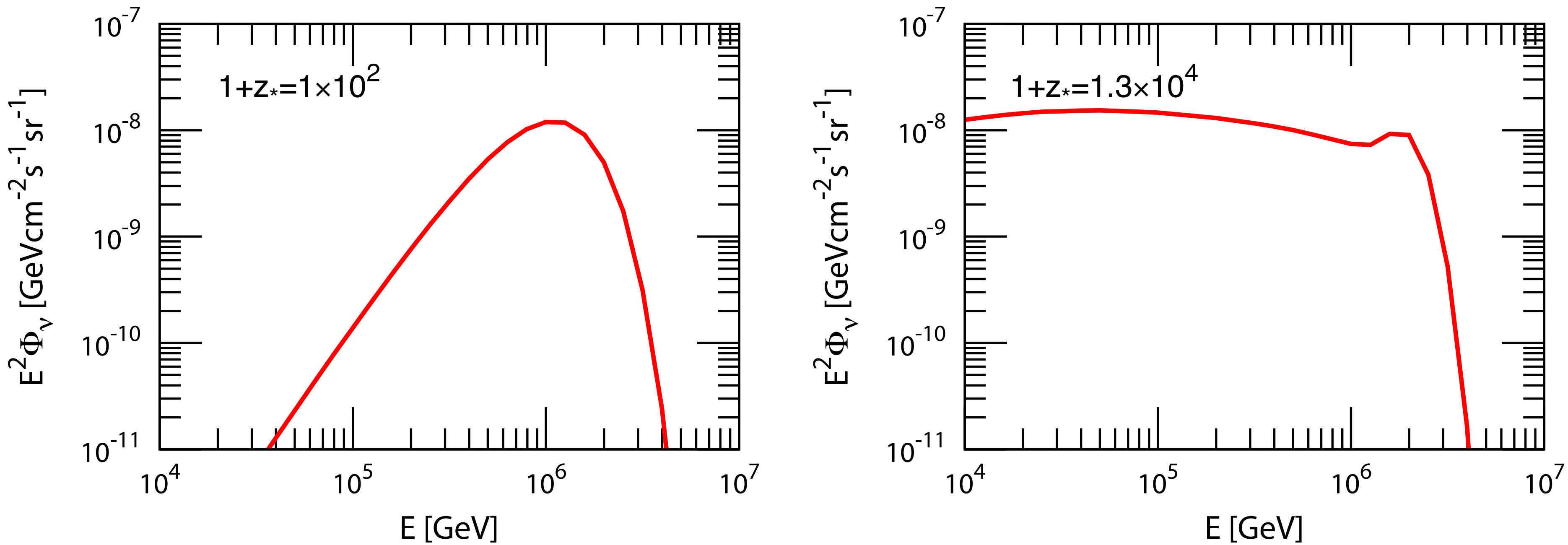


- Monochromatic neutrino injection: $\bar{E}_\nu = 1$ PeV $\times (1+z_*)$
- $Y_X = [n_X/s]_{t \ll \tau_X} = 10^{-26}$

$\Rightarrow$ If $z_* \gtrsim$ (a few) $\times 10^3$, effect of the scattering becomes important

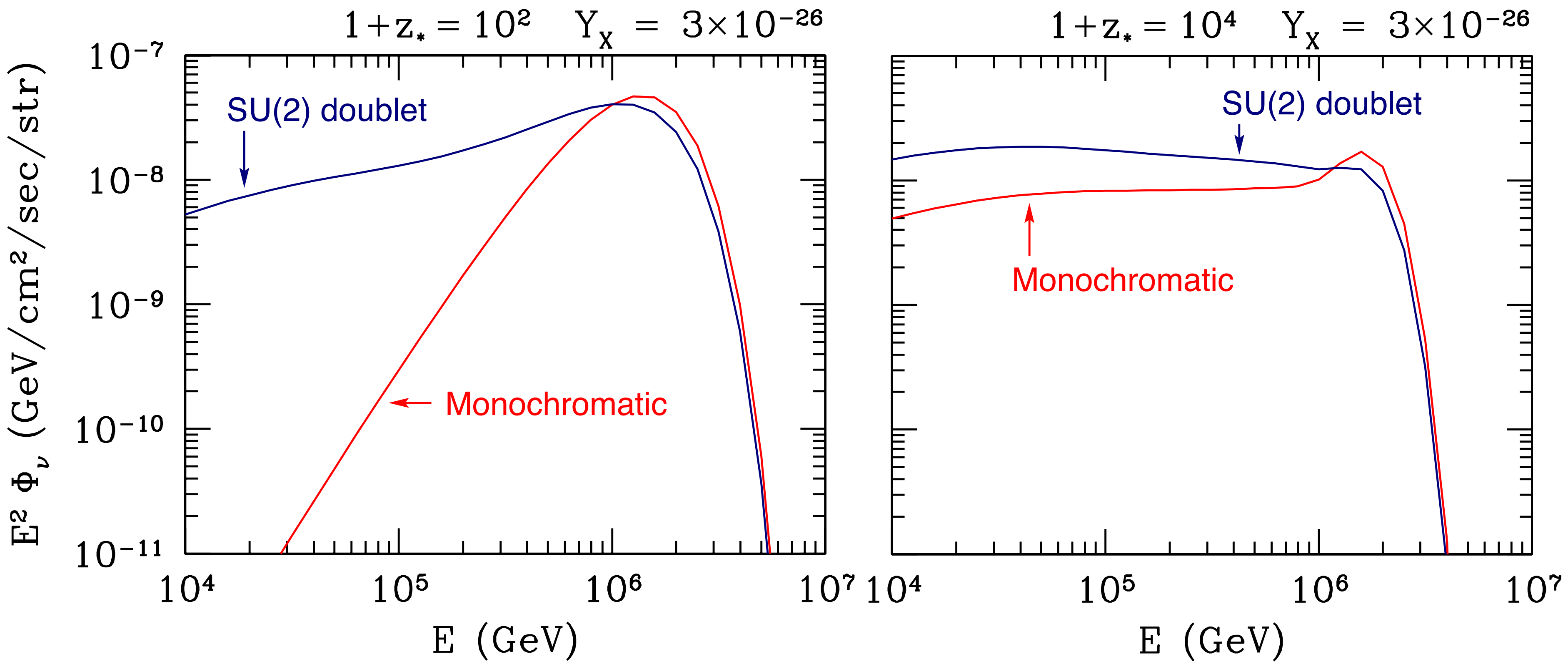
Can we realize E^{-2} power-law flux with a cut-off?

$\Rightarrow$ Case with monochromatic neutrino injection



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

Non-monochromatic neutrino injection (preliminary)



$\Rightarrow$ Neutrino flux at $E \ll E_{\rm cut}$ is enhanced

$\Rightarrow$ Neutrino flux with $\sim E^{-2}$ behavior with cut-off is possible

One interesting check point: CMB distortion

- In the early decay scenario, sizable amount of EM energy may be injected due to the scattering process
- CMB spectrum may deviate from black-body

μ- or y-distortion may occur, if $\tau_\nu \sim 1$

$\Rightarrow y \sim O(10^{-9}),\ \mu \sim O(10^{-9})$

Current constraint from COBE-FIRAS

$$|y| < 1.5 \times 10^{-5},\ |\mu| < 9 \times 10^{-5}$$

In the future, distortion of $O(10^{-9})$ may be within the reach

- PRISM
- PIXIE

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

5. Summary

I discussed "early-decay scenario" for IceCube events

- $z_* \lesssim O(10^4)$, which corresponds to $\tau_X \gtrsim 10^{10}$ sec
- $m_X \sim (1 + z_*) \times 1$ PeV $\lesssim O(10^{10}$ 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, $\cdots$)