PeV Neutrinos from Heavy Relic Decays in Early Universe
— the Early Decay Scenario —

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Refs:

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

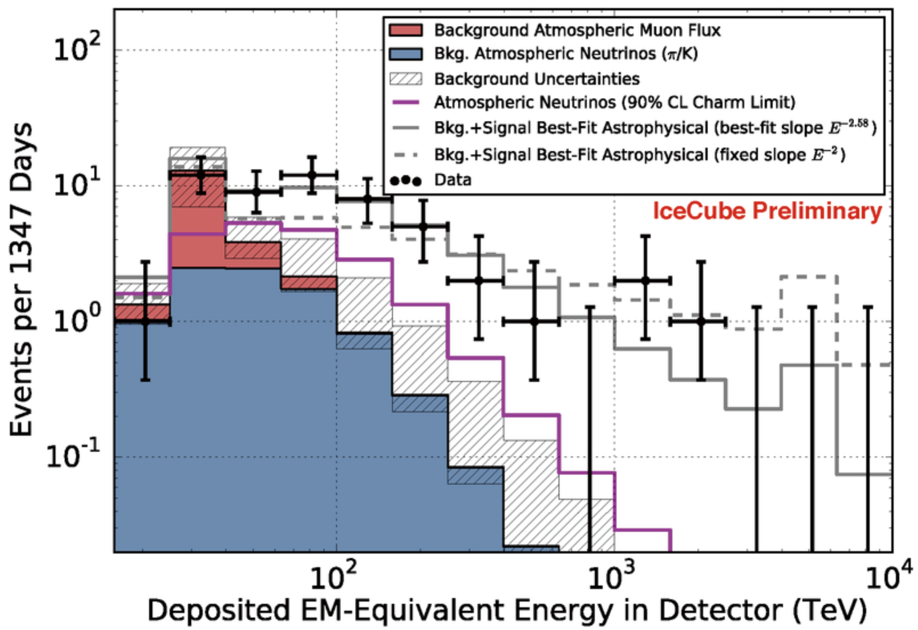
Ema, Jinno & TM, JHEP 1410 ('14) 150 [arXiv:1408.1745]

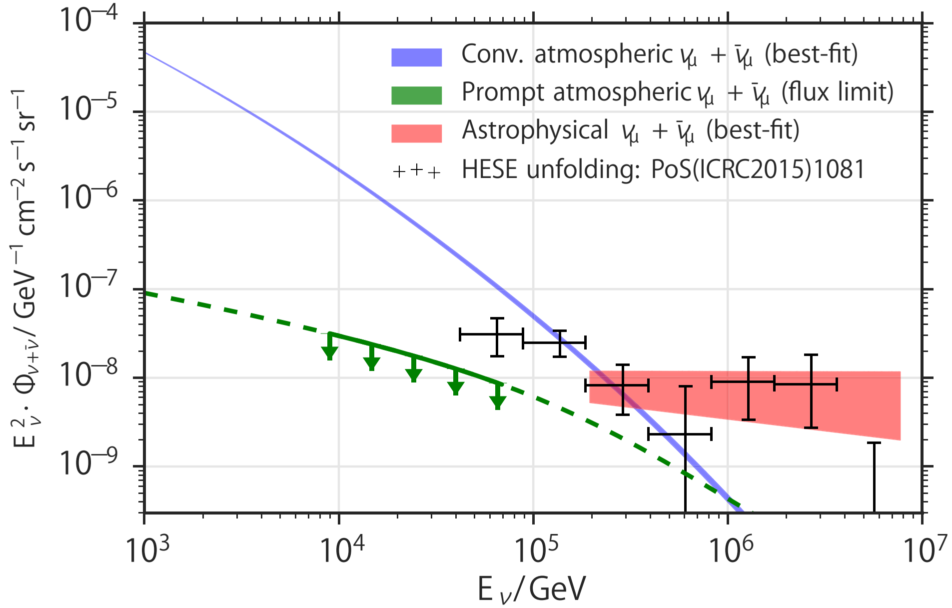
Ema & TM, PLB 762 ('16) 353 [arXiv:1606.04186]

PAHEN 2017, Naples '17.09.25

1. Introduction

IceCube is observing high-energy cosmic-ray neutrinos





[Left: IceCube 4 years result; Right: IceCube 6 years result for $\nu_\mu + \bar{\nu}_\mu$ 1607.08006]

The observed flux is above the atmospheric neutrino flux

$\Rightarrow$ We need to understand the source of cosmic-ray neutrinos

Two possibilities

- 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 a possibility of particle-physics origin

PeV neutrinos from the decay of long-lived particle X

One question from a particle physicist: Why PeV?

$\Rightarrow$ Is the scale particle-physics motivated?

$\Rightarrow$ I consider the case that m_X is around Peccei-Quinn scale

"The early-decay scenario"

PeV neutrinos from X with $m_X \gg$ PeV and $\tau_X \ll t_{\rm now}$

Outline

1. Introduction
2. "The Early-Decay Scenario"
3. Numerical Results: Neutrino Flux
4. Production Mechanism of X
5. Summary

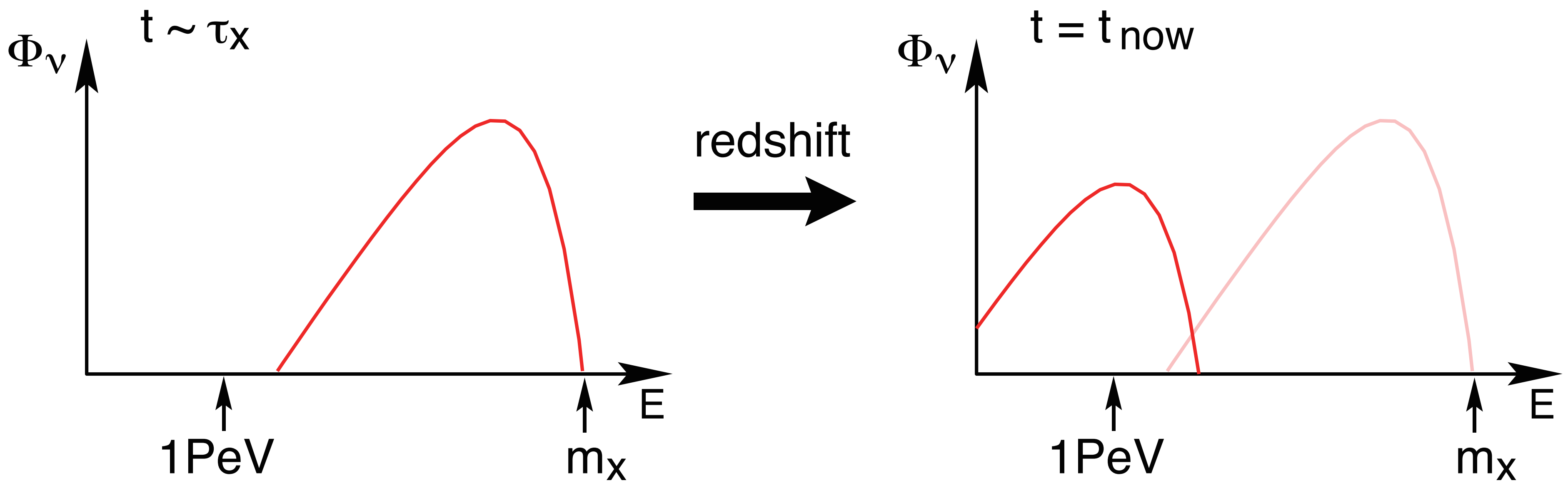
2. The Early-Decay Scenario

[Ema, Jinno & TM]

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

- X decays into neutrinos before the present epoch

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



- $E_{\rm now} \sim O(1)$ PeV is realized due to the redshift

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

Important quantities of the early decay scenario:

- Mass: m_X
- Lifetime: $\tau_X \quad \Rightarrow \quad z_* = z(t = \tau_X) \equiv \frac{a_{\text{now}}}{a(t = \tau_X)} - 1$
- Abundance: $Y_X \equiv \left[\frac{n_X}{s} \right]_{t \ll \tau_X}$
- Primary neutrino spectrum from the X decay: $\frac{dN_\nu}{dE_\nu}$

C.f.: The case of decaying dark matter

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

In the early-decay scenario:

- Neutrino with larger E_{now} is produced at later epoch

  $\Rightarrow$ $E_{\text{now}} \gtrsim (1+z_*)^{-1} m_X$: flux is exponentially suppressed

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

- 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: $\Phi_\nu^{(\mathrm{Cosmo})}$

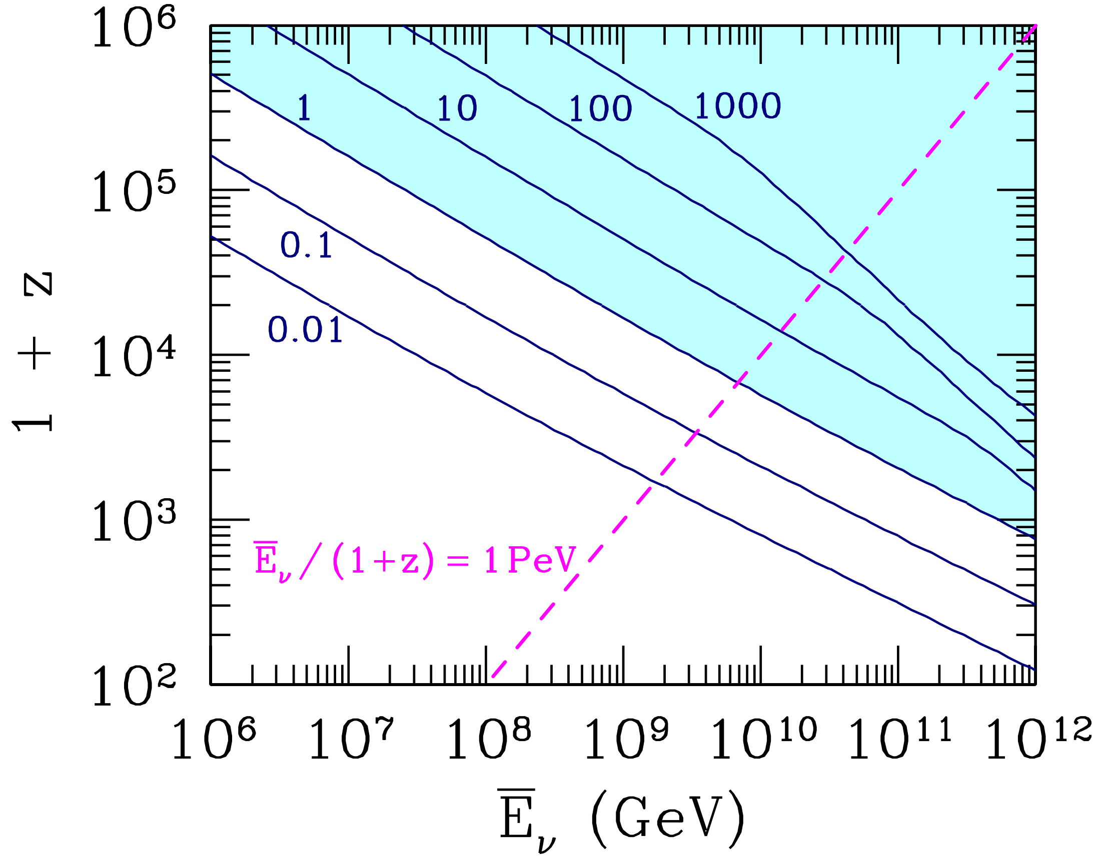
$$\begin{aligned}\dot{\Phi}_\nu^{(\mathrm{Cosmo})}(t,E) \;=\; & -2H\Phi_\nu^{(\mathrm{Cosmo})}(t,E) + HE\frac{\partial}{\partial E}\Phi_\nu^{(\mathrm{Cosmo})}(t,E) \\ & -\gamma_\nu(t;E)\Phi_\nu^{(\mathrm{Cosmo})}(t,E) \\ & +\int dE'\Phi_\nu^{(\mathrm{Cosmo})}(t,E')\frac{d\gamma_\nu^{(\mathrm{eff})}(t;E',E)}{dE}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

γ_ν: Scattering rate

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

- 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

3. Numerical Results: Neutrino flux

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

$$X \to \nu\nu$$

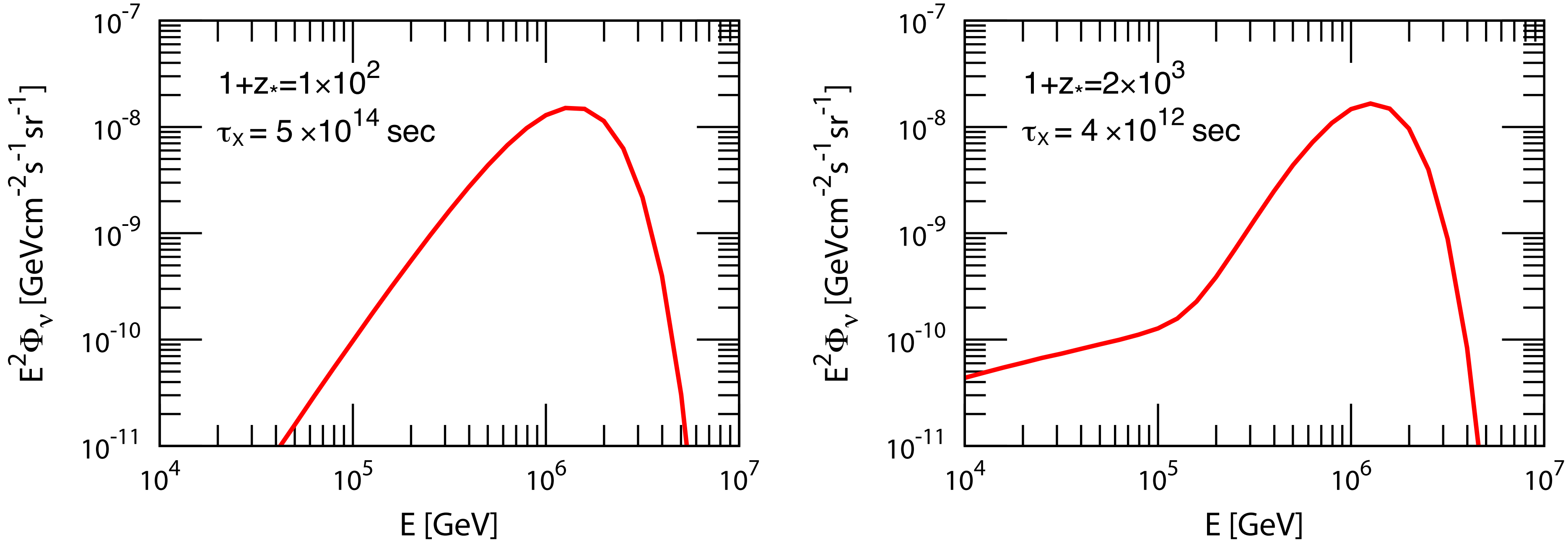
Case 2: Vector-like $SU(2)_L$ doublet L, mixed with leptons

- $\mathcal{L} = M_L \bar{L} L + \epsilon_y \bar{L} H e_R + \cdots$
- L^0 can play the role of X

$$X \to e^{\pm} W^{\mp}, \mu^{\pm} W^{\mp}, \tau^{\pm} W^{\mp}$$

- L may be an $SU(5)$ partner of the PQ fermion

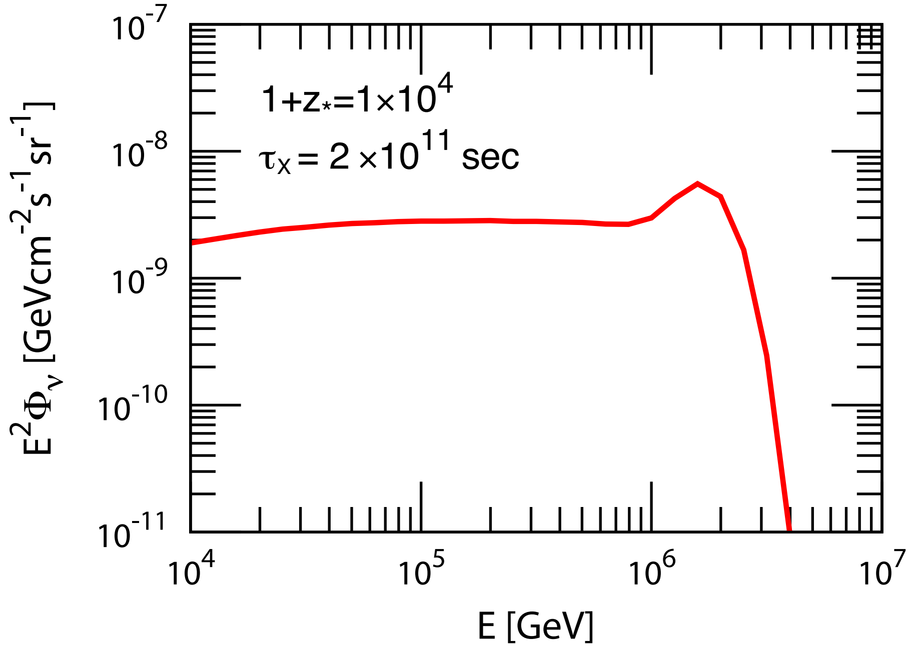
Monochromatic neutrino injection: (1) Long lifetime

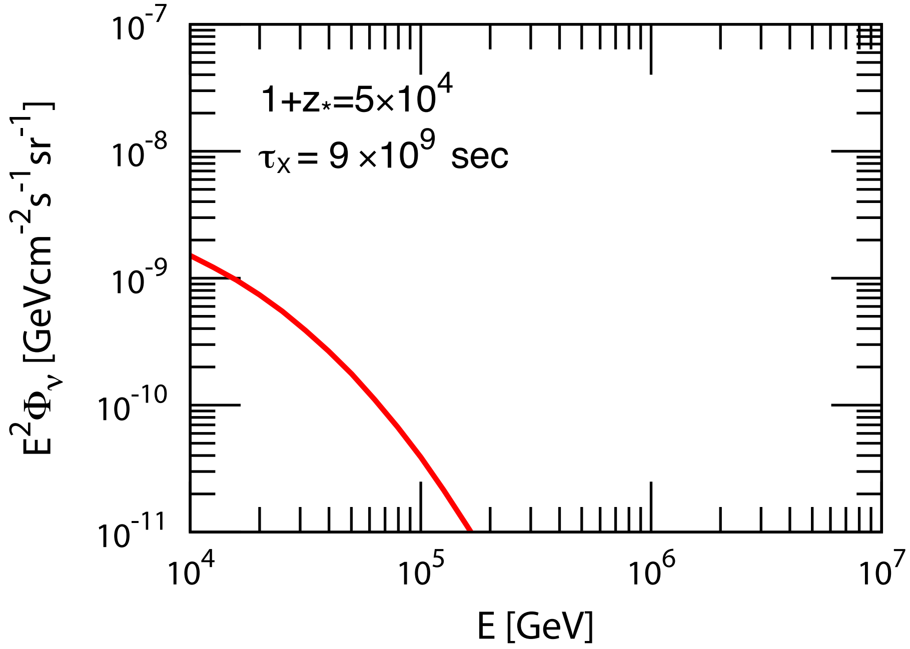


- $\bar{E}_\nu = 1$ PeV $\times\, (1 + z_*)$
- $Y_X = [n_X/s]_{t \ll \tau_X} = 10^{-26}$

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

Monochromatic neutrino injection: (2) Short lifetime



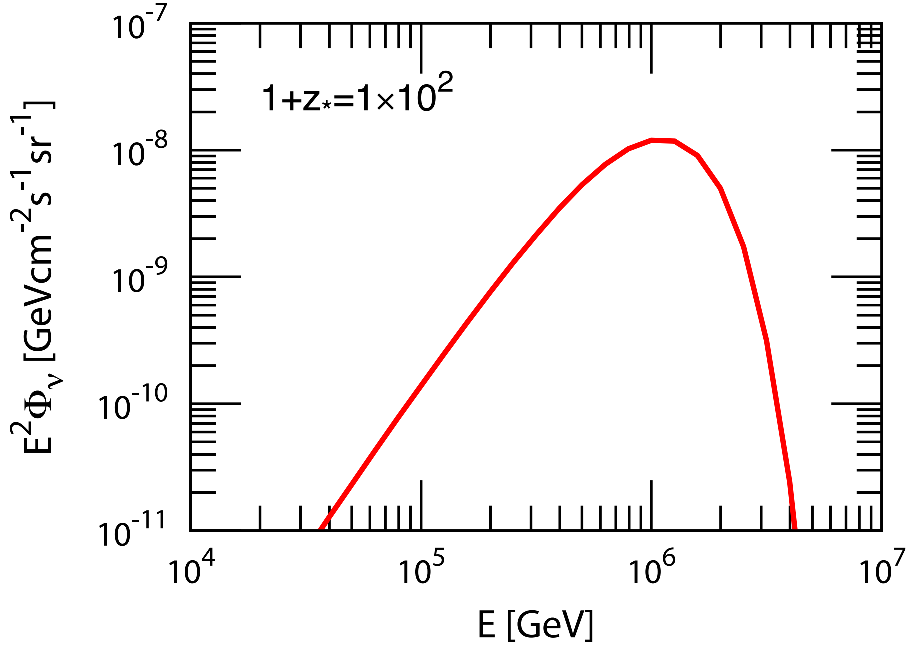


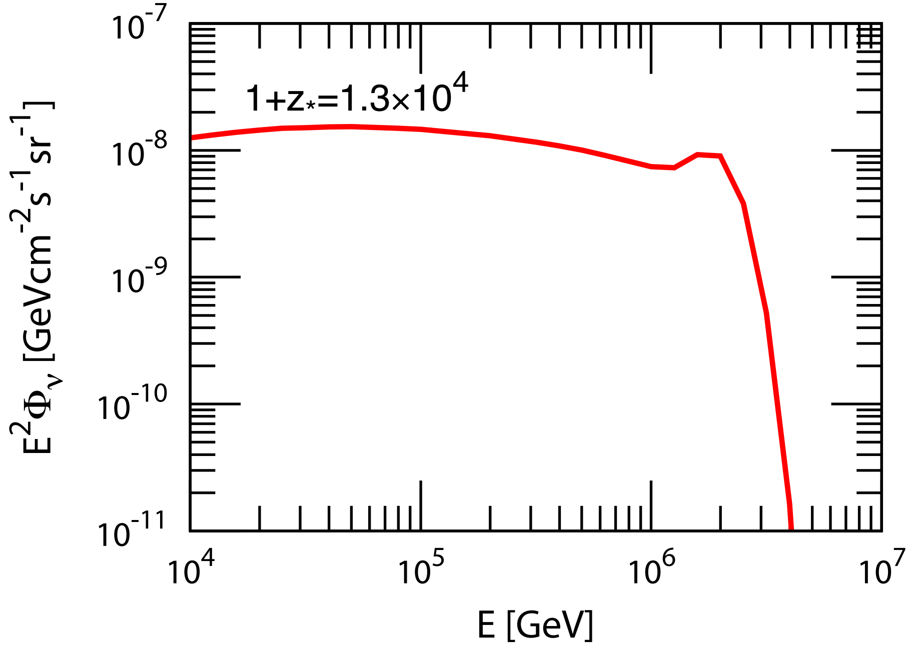
- $\bar{E}_\nu = 1$ PeV $\times (1+z_*)$
- $Y_X = [n_X/s]_{t\ll\tau_X} = 10^{-26}$

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

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

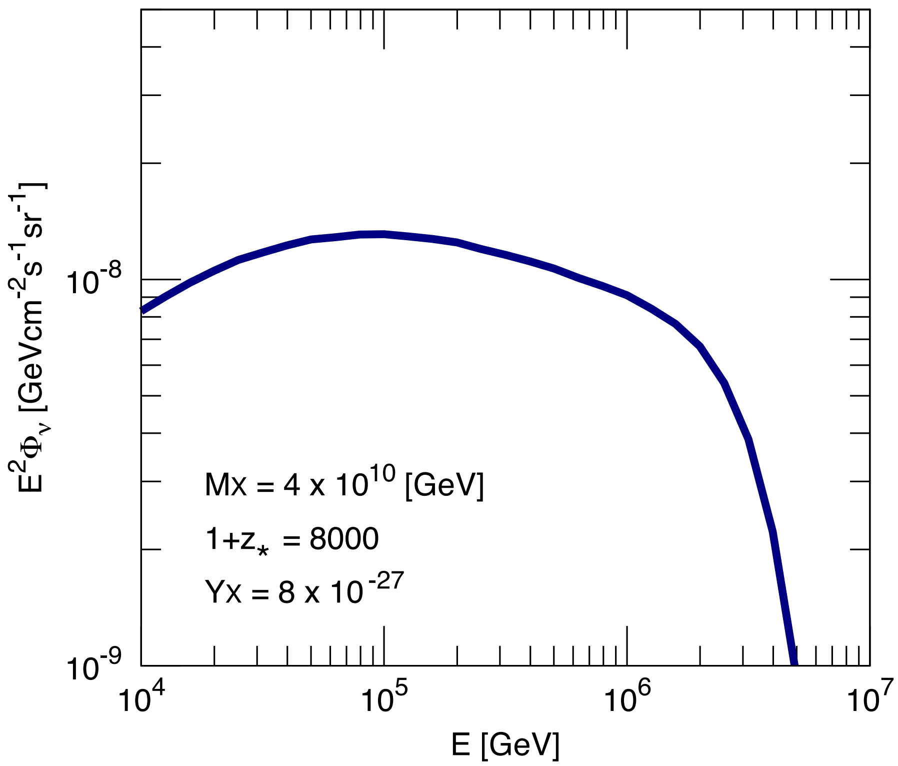
$\Rightarrow$ Case with monochromatic neutrino injection

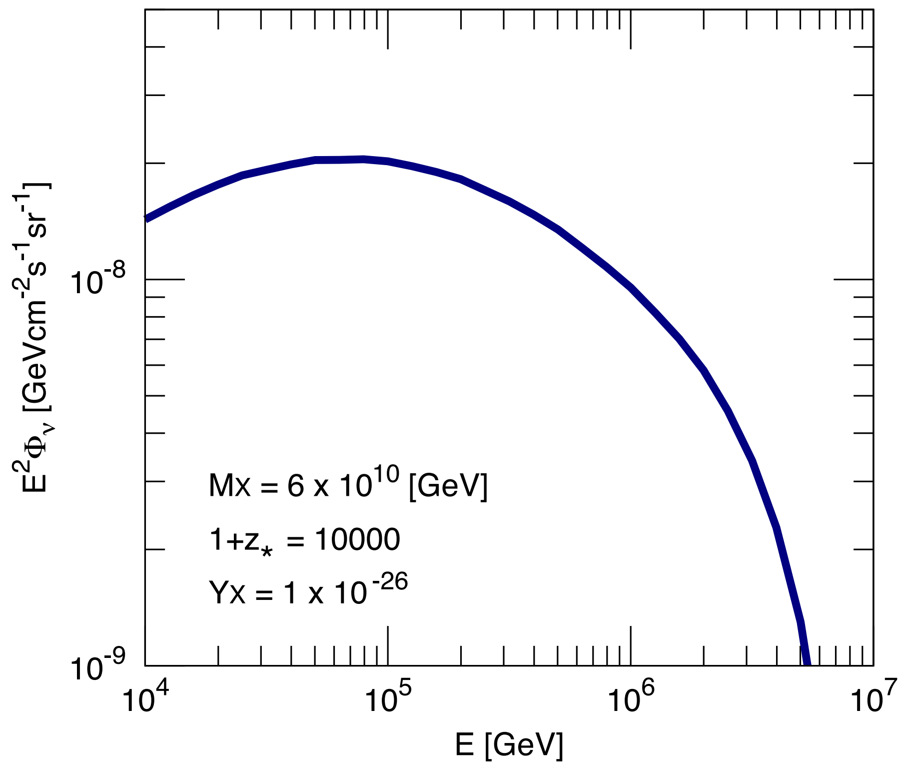




$\Rightarrow$ With monochromatic injection, E^{-2} power-law flux requires $1 + z_* \sim (1 - 1.5) \times 10^4$

Non-monochromatic neutrino injection





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

$\Rightarrow$ 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
$Y_X = [n_X/s]_{t \ll \tau_X}$	$\sim 10^{-26} - 10^{-25}$	$\sim 10^{-16}$
Direction	Isotropic	$\sim$ Galactic center

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

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

4. Production Mechanism

Suggested yield value

$$Y_X = \left[\frac{n_X}{s}\right]_{t \ll \tau_X} \sim 10^{-26} - 10^{-25}$$

How can we realise such a small abundance?

- Inflaton decay
- Thermal production by dilute plasma
- Non-thermal production through inelastic scattering
- $\cdots$

I consider the scenario of inflaton decay, assuming

- X is a neutral component of $SU(2)_L$ doublet
- Inflaton decays into right-handed neutrinos

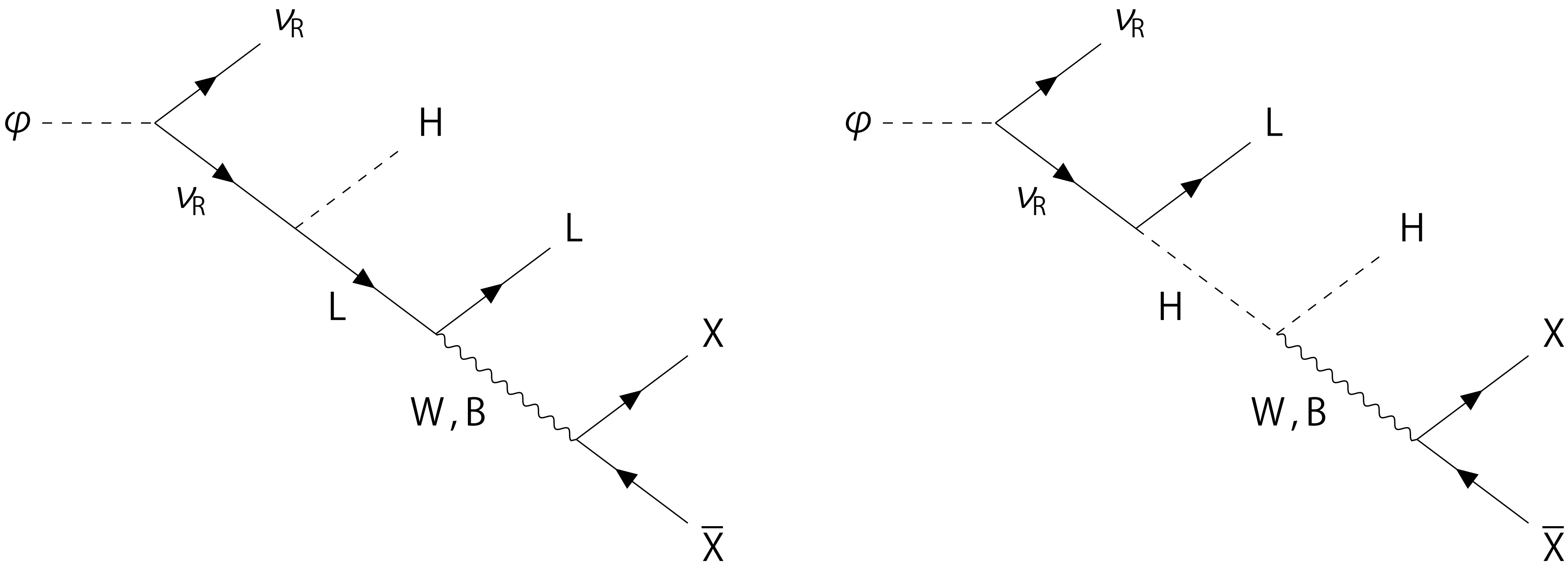
Inflaton φ is assumed to couple with right-handed neutrino:

- $\mathcal{L} \ni -\frac{1}{2}\lambda\varphi\overline{\nu_R^c}\nu_R - y_\nu\bar{\ell}H\nu_R + \cdots + \frac{1}{2}m_X\bar{L}L$ with $L^0 = X$
- Assumption: $m_\varphi > m_X > m_{\nu_R}$

In our scenario:

1. The universe was dominated by the inflaton φ
2. φ decays mainly into ν_R, and reheats the universe
$$T_R \sim 10^3\,\mathrm{GeV} \times \left(\frac{\lambda}{10^{-11}}\right)\left(\frac{m_\varphi}{10^{11}\,\mathrm{GeV}}\right)^{1/2}$$
3. A small fraction of φ decays as $\varphi \to X\bar{X}\nu_R LH$

X production via the inflaton decay (with $m_\varphi > m_X > m_{\nu_R}$)



$$
\begin{aligned}
Y_X &\sim \frac{T_R}{m_X} Br(\varphi \to X + \cdots) \\
&\sim 10^{-26} \times \left(\frac{y_\nu}{10^{-6}}\right)^2 \left(\frac{m_\varphi}{10^{11}\,\mathrm{GeV}}\right)^{-1} \left(\frac{T_R}{10^3\,\mathrm{GeV}}\right)
\end{aligned}
$$

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 is consistent with CMB / BBN constraints
- The scenario may be tested by future observations of CMB distortion (like PIXIE / PRISM)

A possible particle physics model:

- $SU(5)$ partner of Peccei-Quinn fermion
- X may be produced by the inflaton decay

Back Up

Case with decaying dark matter

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

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

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

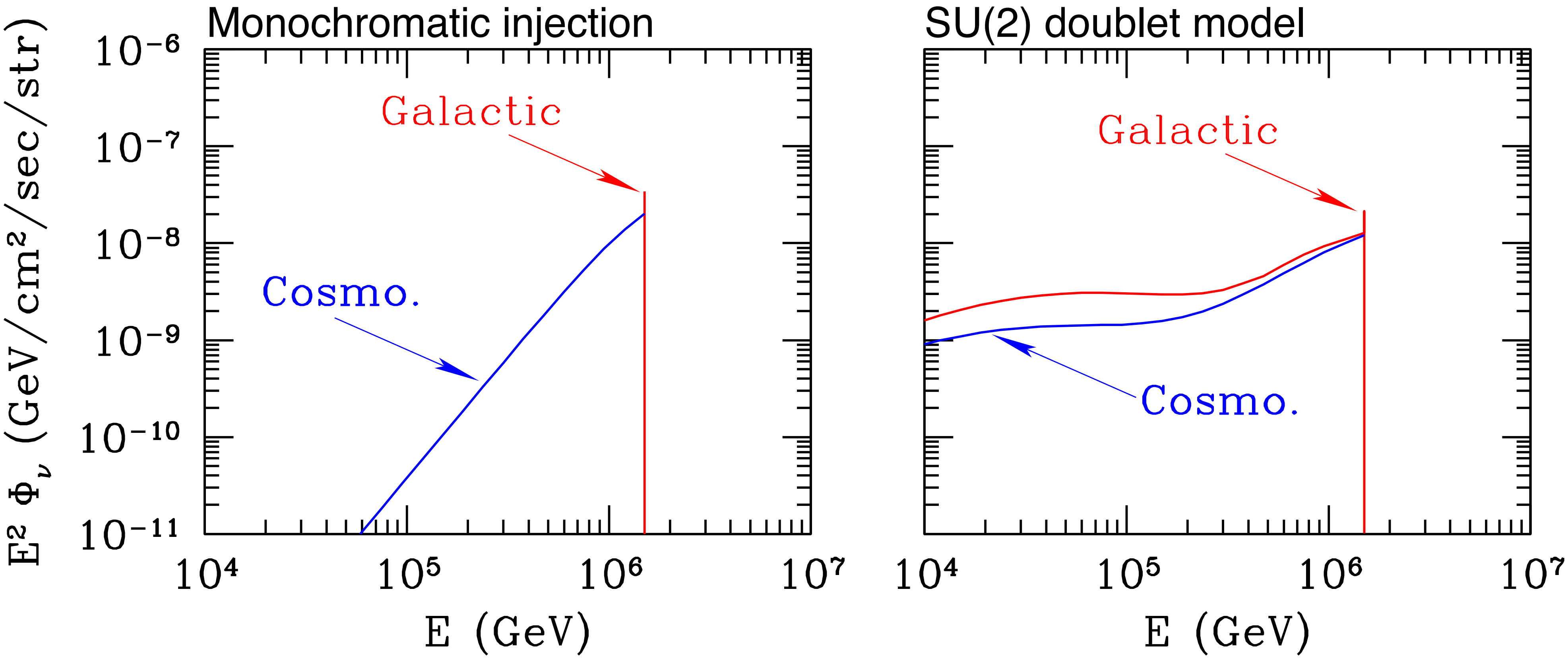
  $$\Rightarrow \tau_X \sim 10^{29}\ \mathsf{sec} \times \left(\frac{\Omega_X}{\Omega_{\mathsf{DM}}}\right)$$

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

  $\Rightarrow$ Flux from the direction of galactic center is enhanced

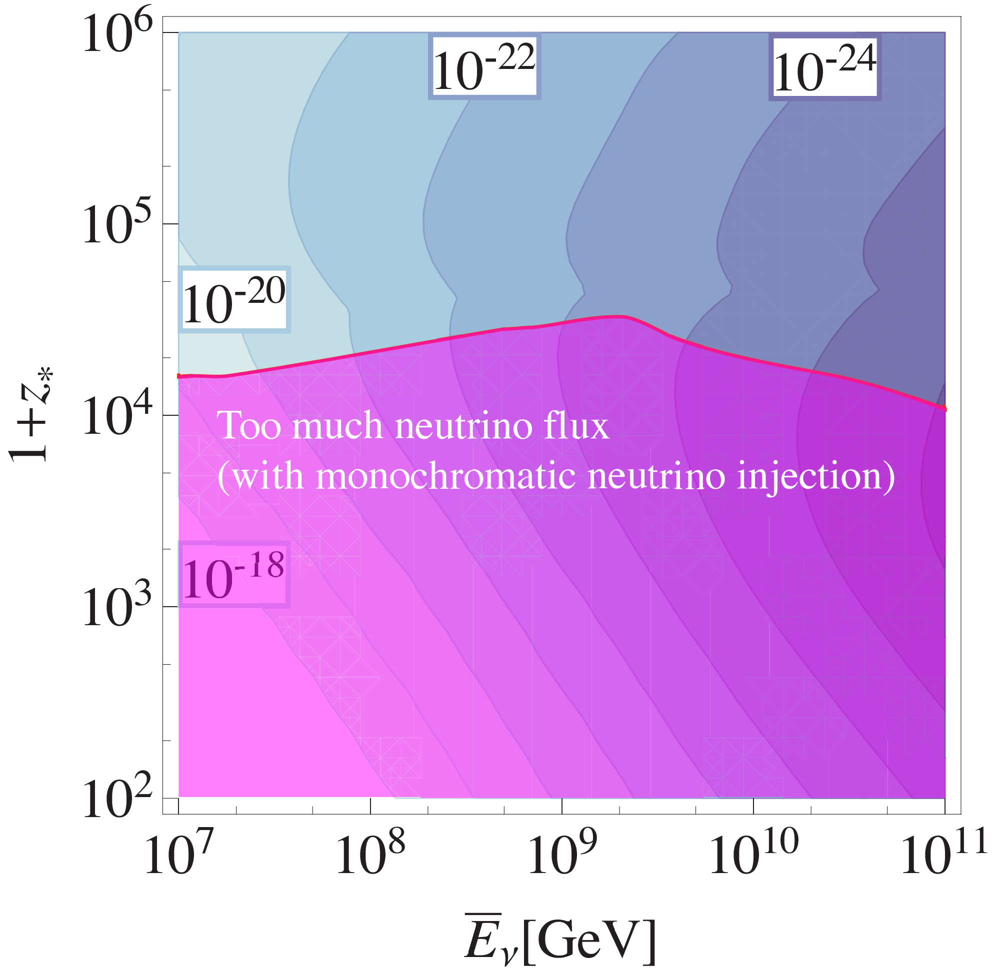
  $$\frac{\Phi_\nu^{(\mathsf{Galaxy})}(\theta < 90^\circ)}{\Phi_\nu^{(\mathsf{Galaxy})}(\theta > 90^\circ)} \sim 2$$

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



Expected 5σ sensitivity of PIXIE on Y_X

Monochromatic neutrino injection



- $|y^{(\mathrm{PIXIE})}| = 1 \times 10^{-8}$
- $|\mu^{(\mathrm{PIXIE})}| = 5 \times 10^{-8}$