Cosmological Constraints on neutrino injection

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Introduction

physics beyond the Standard model

To solve
- hierarchy problem
- dark matter
- ⋮

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Supersymmetry (SUSY) is a prominent candidate.

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the existence of exotic long-lived particle X, e.g. gravitino

(In the framework of string theories, moduli)

We derive general and model-independent constraints on the relic abundance of X.

The decay of X have significant effects on cosmology, especially,

- the Big-Bang Nucleosynthesis (BBN) $(10^{-2} - 10^{12}\text{sec})$
- the Cosmic Microwave Background (CMB) $(10^{6} - 10^{12}\text{sec})$
- diffuse photon flux $(10^{12}\text{sec}-)$
- diffuse neutrino flux

What observation gives the most stringent constraints depends on the lifetime and decay products of X.

decay product

an invisible particle

- $X \to Y + \gamma$
- $X \to Y + \nu$ main decay mode

$$\begin{cases} X \to Y + \nu + Z(Z^*) \\ X \to Y + l + W(W^*) \end{cases}$$

3,4-body decay mode (Branching ratio B_X)

3 free parameters: m_X, τ_X, B_X

$B_X \equiv \Gamma(X \to 3,4\text{body})/\Gamma(X \to \text{all})$

(Reno and Seckel 1988)
(Dimopoulos et.al. 1989)
(Kawasaki and Moroi 1995)
(Kawasaki, Kohri and Moroi 2005)

BBN constraints :

If the decay of X occur during or after BBN, the standard particles emitted in the decay can affect the abundance of primordial light elements.

Resultant abundances of light elements may significantly conflict with observations. As a result, the relic abundance of X is severely constrained.

- 2-body decay : $X \to Y + \nu$

$$\nu + \nu_{BG} \to \begin{cases} l^+ + l^- & \to \text{electromagnetic shower} \\ \pi^+ + \pi^- & \to \text{p-n conversion} \end{cases}$$

- 3,4-body decay : $X \to Y + \nu + Z(Z^*), Y + l + W(W^*)$

$$l, W, Z \to \text{electromagnetic shower}$$
$$W, Z \to \text{hadronic shower}$$

hadronic energy injection

- **p-n conversion** $(t \leq 10^2 \mathrm{sec})$

The mesons with relatively long lifetimes such as pions and kaons can cause p-n conversion.

e.g. $\pi^- + p \rightarrow n + \pi^0$

the overproduction of ^{4}He

- **hadronic shower** $(t \geq 10^2 \mathrm{sec})$

The high energy protons and neutrons interact with background hadrons before lose their energy and produce secondary hadrons.

the destruction of ^{4}He

the overproduction of D,T and ^{3}He

e.g. $n(p) + {}^4He \rightarrow D + T({}^3He)$

the overproduction of ^{6}Li and ^{7}Li

e.g. $T({}^3He) + {}^4He \rightarrow {}^6Li + n(p)$

electromagnetic energy injection

- electromagnetic shower

Emitted high energy photons and electrons induce electromagnetic shower and energetic photons are recursively produced in the shower.

Some of soft photons produced secondarily in the shower induce destruction and production processes of the light elements.

the destruction of D $(t \geq 10^4 \mathrm{sec})$

$$D + \gamma \rightarrow n + p$$

the destruction of ^{4}He $(t \geq 10^6 \mathrm{sec})$

the overproduction of D and ^{3}He

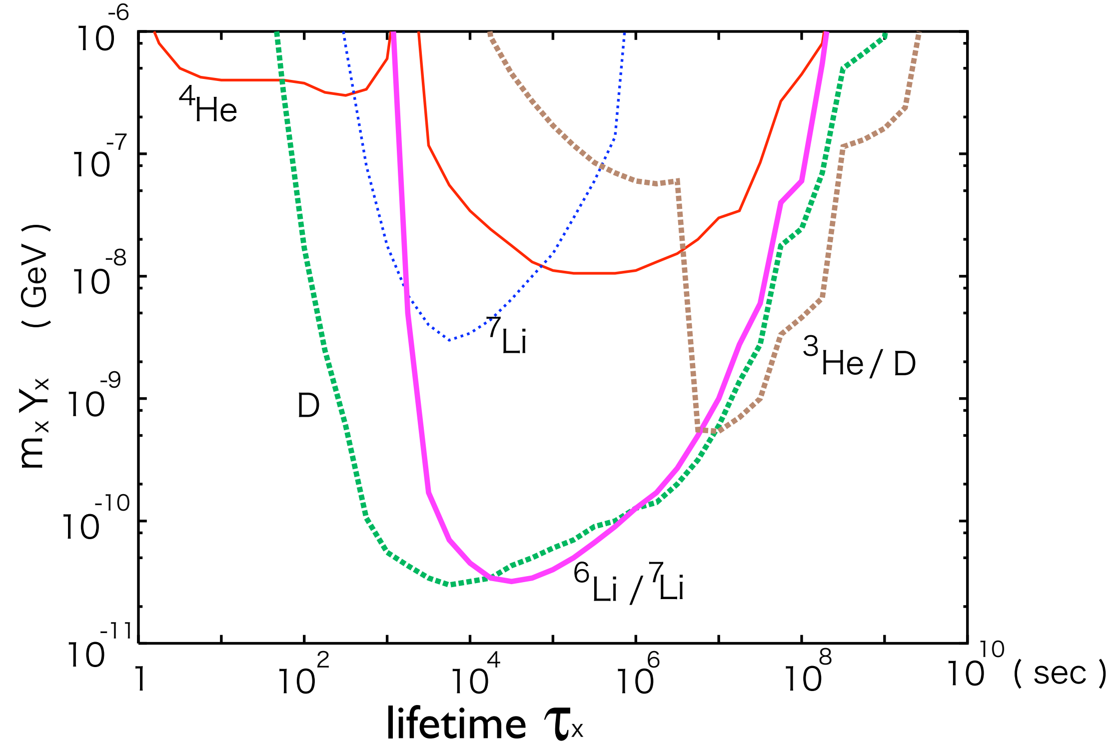
e.g.

$$^4He + \gamma \rightarrow {}^3He + n$$

$$^4He + \gamma \rightarrow D + n + p$$

Observational constraints on light elements

- $(D/H)_p = (2.82 \pm 0.26) \times 10^{-5}$ (O'Meara et. al. 2006)
- $({}^3\mathrm{He}/D)_p < (0.59 \pm 0.27)$ (Geiss 1993)
- $Y_p = 0.250 \pm 0.004$ (Fukugita and Kawasaki 2006)
- $\log_{10}({}^7\mathrm{Li}/H)_p = -9.63 \pm 0.06 \pm 0.3$ (Melendez and Ramirez 2004)
- $({}^6\mathrm{Li}/{}^7\mathrm{Li})_p < 0.046 \pm 0.022 + 0.084$ (Asplund et. al. 2006)



$$B_X = 10^{-3}$$

$$m_X = 300\text{GeV}$$

Here we define yield value : $Y_X \equiv \left[\frac{n_X}{s}\right]_{t \ll \tau_X}$

- p-n conversion : ^{4}He overproduction
- hadronic shower : D and ^{6}Li overproduction
- electromagnetic shower : ^{3}He overproduction

lifetime

short

long

CMB constraints : y and μ distortions

(Silk and Stebbins 1983)
(Kawasaki and Sato 1986)
(Hu and Silk 1993)

COBE observations show that the CMB spectrum is almost perfect blackbody.

Therefore, any photon energy injection that cause distortions in the spectum of CMB are severely constrained.

- μ distortion : $\mu \simeq \frac{1}{0.714}\frac{\Delta\rho_\gamma}{\rho_\gamma}$ $\quad (10^5 \leq z \leq 10^7)$ $\quad |\mu| \leq 9\times 10^5$
- y distortion : $y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma}$ $\quad (10^3 \leq z \leq 10^5)$ $\quad |y| \leq 1.2\times 10^5$

(COBE 1996, Smoot and Scott 1997)

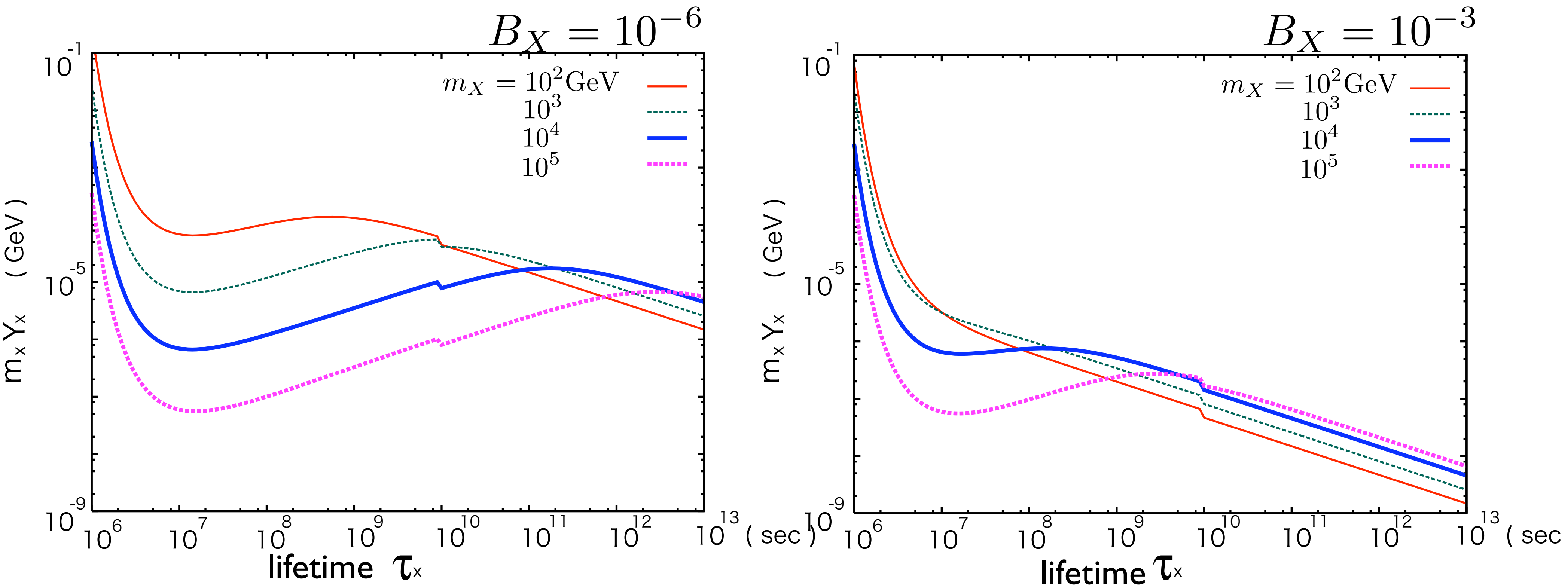
- 2-body decay

$$\nu + \nu_{\rm BG} \rightarrow l^+ + l^- \rightarrow \text{ exotic photon energy}$$

- 3,4-body decay

$$X \rightarrow Y + \nu + Z(Z^*), Y + l + W(W^*)$$

Some of the energy of these particles convert to photon energy.



- When lifetime is short, the constraints are determined by 2-body decay.

  The constraints become severe with larger m_X

- When lifetime is long, the constraints are determined by 3,4-body decay.

  The constraints become severe with smaller m_X

$$E_{X\to\gamma}/E_X = 0.253 \qquad (m_X = 100\text{GeV})$$

$$E_{X\to\gamma}/E_X = 0.056 \qquad (m_X = 10^5\text{GeV})$$

Constraints on relativistic energy

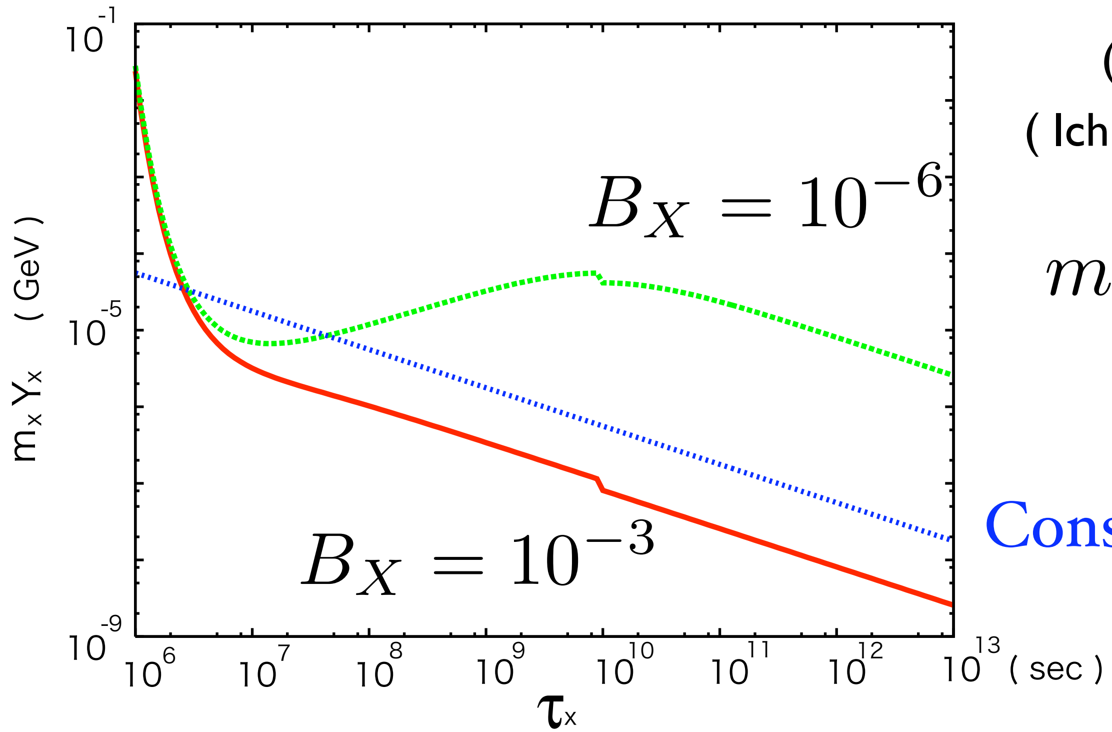
A late injection of relativistic energy could be spotted in the CMB or in large scale structure (LSS) regardless of the emitted species.

The combined analysis of CMB and LSS data leads to an upper bound on the excess relativistic energy density at recombination.

the effective number of neutrino species : $\Delta N_\nu^{\rm eff} \leq 4.6$

(WMAP 3rd-year and SDSS LRGs)

(Ichikawa, Kawasaki and Takahashi 2006)



$m_X = 10^3 \mathrm{GeV}$

Constraints from $\Delta N_\nu^{\rm eff}$

diffuse neutrino constraints :

(Ellis et. al. 1992)
(Gondolo, Gelmini and Sarkar 1993)
(Beacom, Bell and Mack 2006)

- 2-body decay : $X \to Y + \nu$ $\quad (E_\nu = m_X/2)$

When neutrino injection takes place at late time, the emitted neutrinos may produce an observable peak in the diffuse neutrino $\nu_\mu + \bar{\nu}_\mu$ spectrum.

The atmospheric neutrino $(\nu_\mu + \bar{\nu}_\mu)$ has been observed by

- Super-Kamiokande $(3.0 \times 10^{-1} - 1.0 \times 10^3 \mathrm{GeV})$ (Ashie et. al. 2005) (Gonzalez-Garcia et. al. 2006)
- AMANDA $(1.3 \times 10^3 - 3.0 \times 10^5 \mathrm{GeV})$ (Geenen et. al. 2003)

To obtain the constraints on the neutrino flux, we require that the signal from injected neutrino should not exceed the atmospheric neutrino.

No appreciable signal of $\bar{\nu}_e$ was detected at SK.

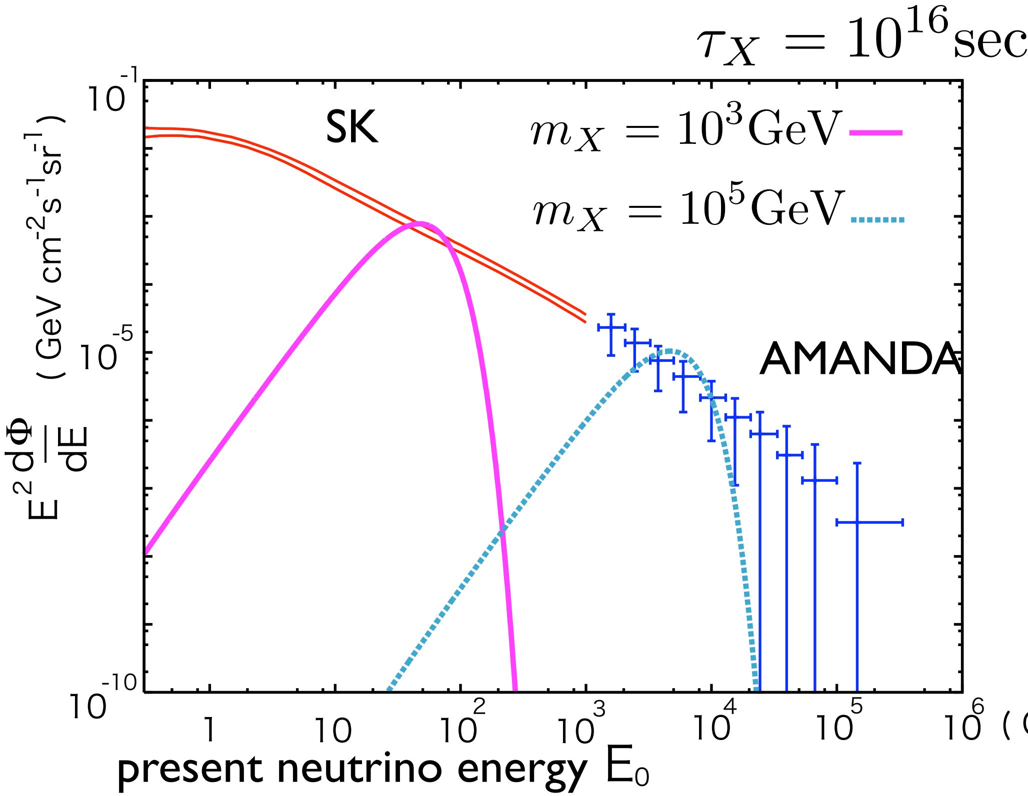
through $(\bar{\nu}_e + p \rightarrow n + e^+)$

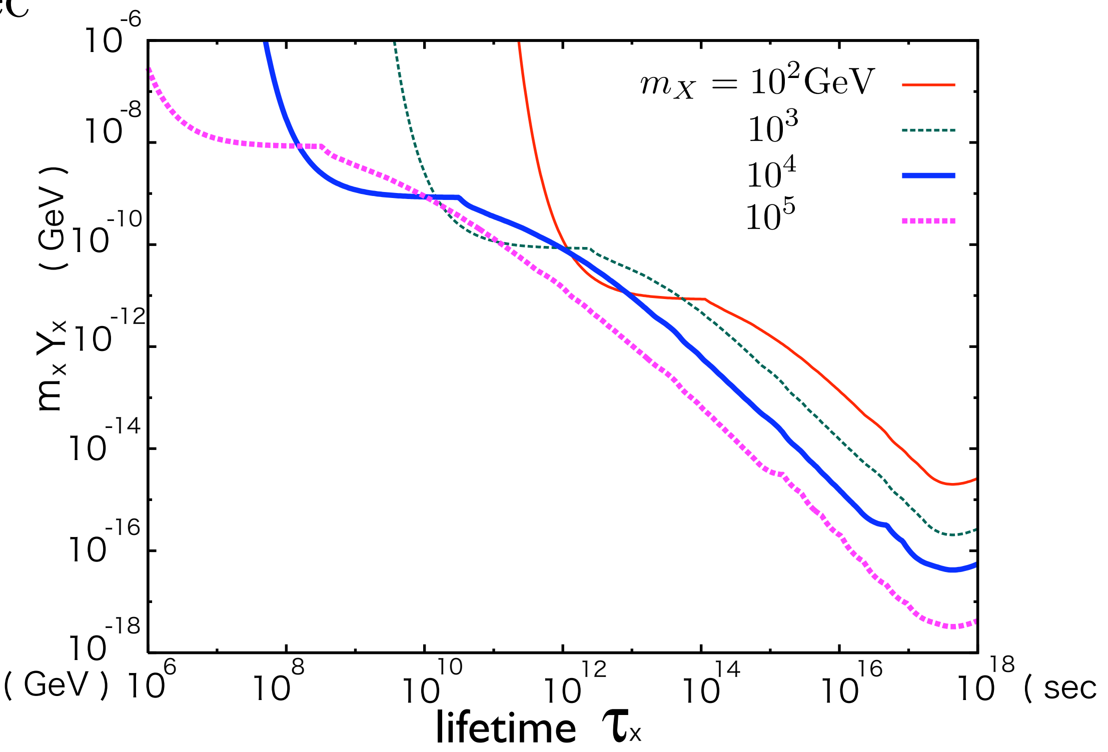
This experiment set the upper bound of $\bar{\nu}_e$ background flux above a threshold energy.

The upper bound of the diffuse signal $\bar{\nu}_e$ is given by

Super-Kamiokande $\Phi_\nu < 1.2\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for $E_\nu > 19.3\mathrm{MeV}$

(Malek et. al. 2003)





- When lifetime is short, the constraints are determined by diffuse $\bar{\nu}_e$.

  The constraints are in proportion to m_X

- When lifetime is long, the constraints are determined by atmospheric neutrino.

  The constraints are roughly in inverse proportion to m_X

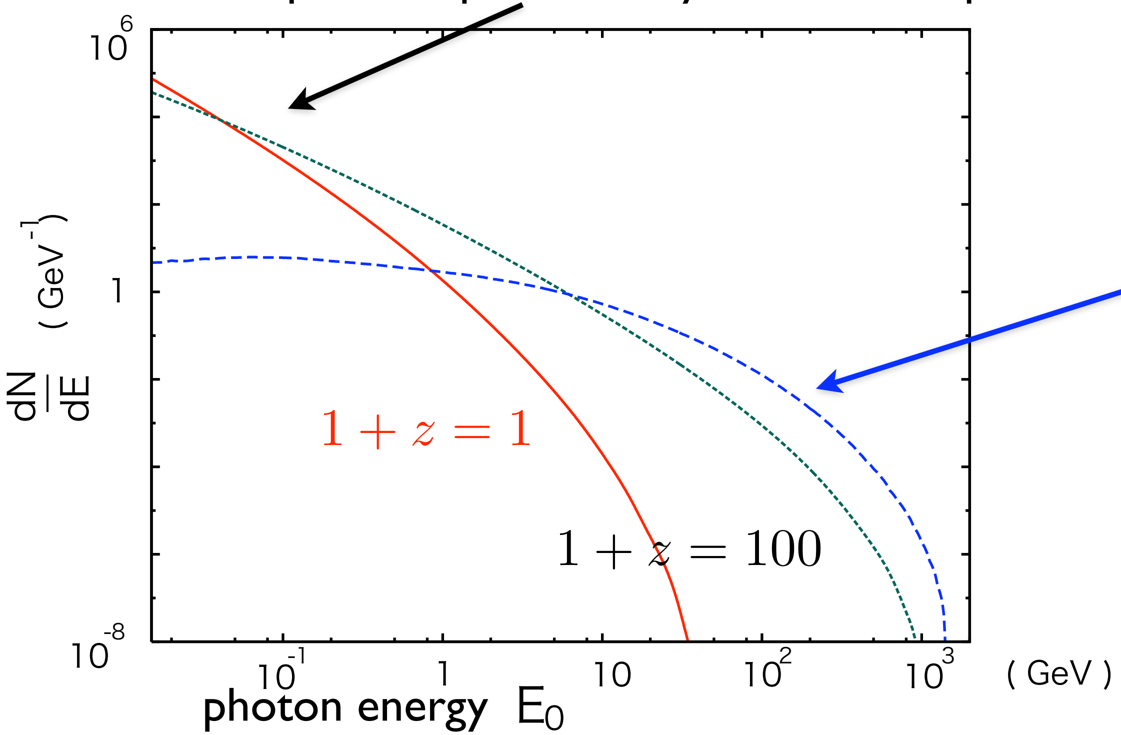
diffuse photon constraints :

There are two points different from atmospheric neutrino case :

- Injected photon spectrum is not monoenergetic.

  - photons from 3,4-body decay of X $\quad X \to \gamma$
  - photons produced by inverse Compton process $\quad X \to e$ **and** $e + \gamma_{\rm BG} \to e + \gamma$

photons produced by inverse Compton



$$m_X = 10^4 \mathrm{GeV}$$

photons from decay of X

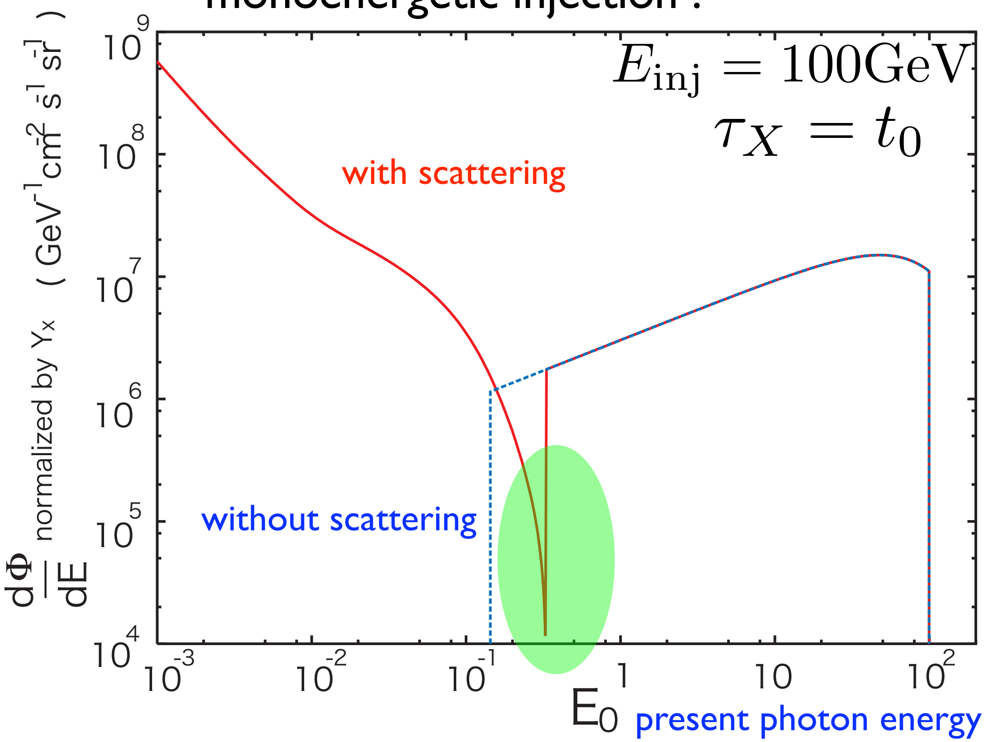
High energy photons scatter through various processes.

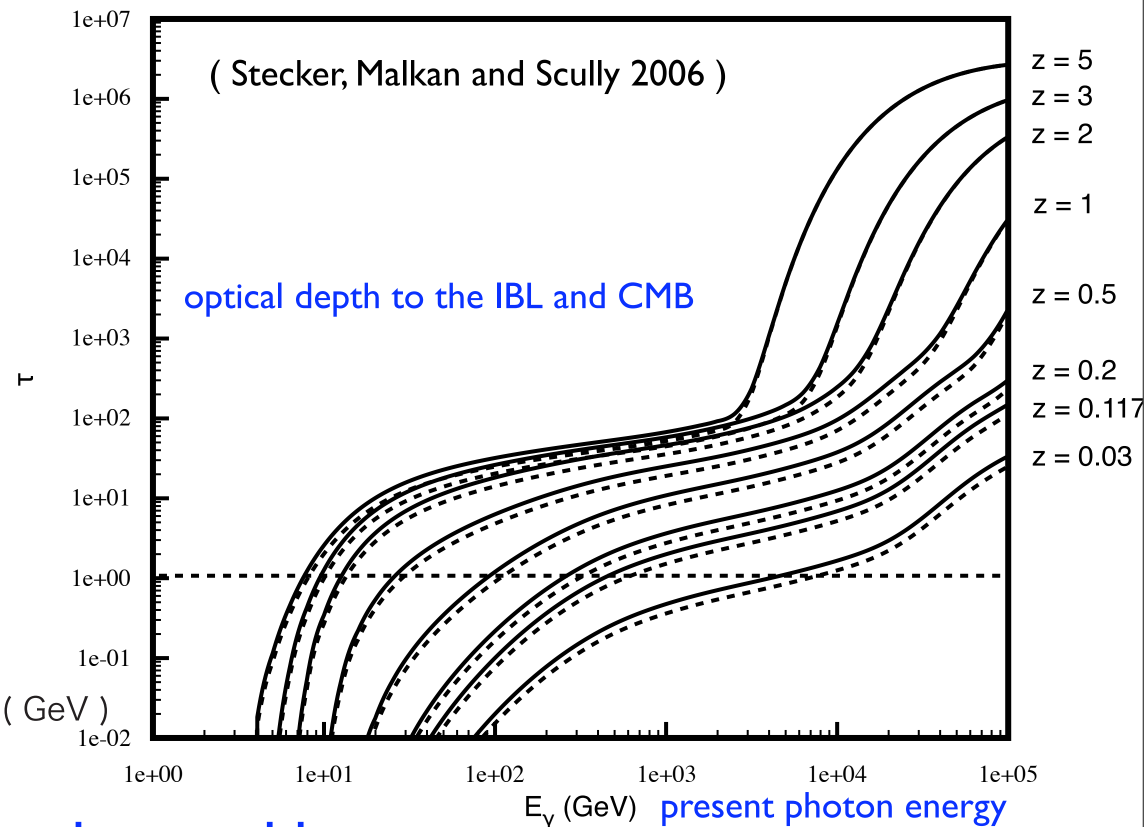
$$\begin{cases} \gamma + \gamma_{\rm CMB} \rightarrow \gamma + \gamma, e^+ + e^- \\ \gamma + \gamma_{\rm IBL} \rightarrow e^+ + e^- \quad (0 < z < 5) \end{cases}$$

(Zdziarski and Svensson 1989)
(Kribs and Rothstein 1997)

(Salamon and Stecker 1998)
(Primack et. al. 2001)
(Stecker, Malkan and Scully 2006)

monoenergetic injection :

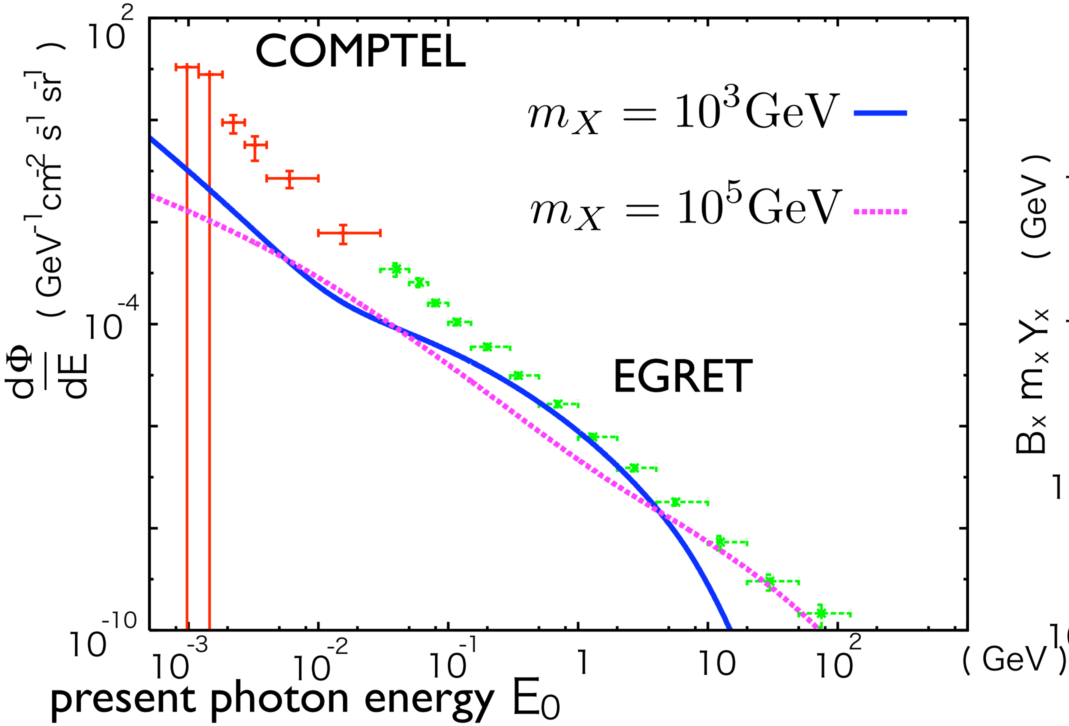


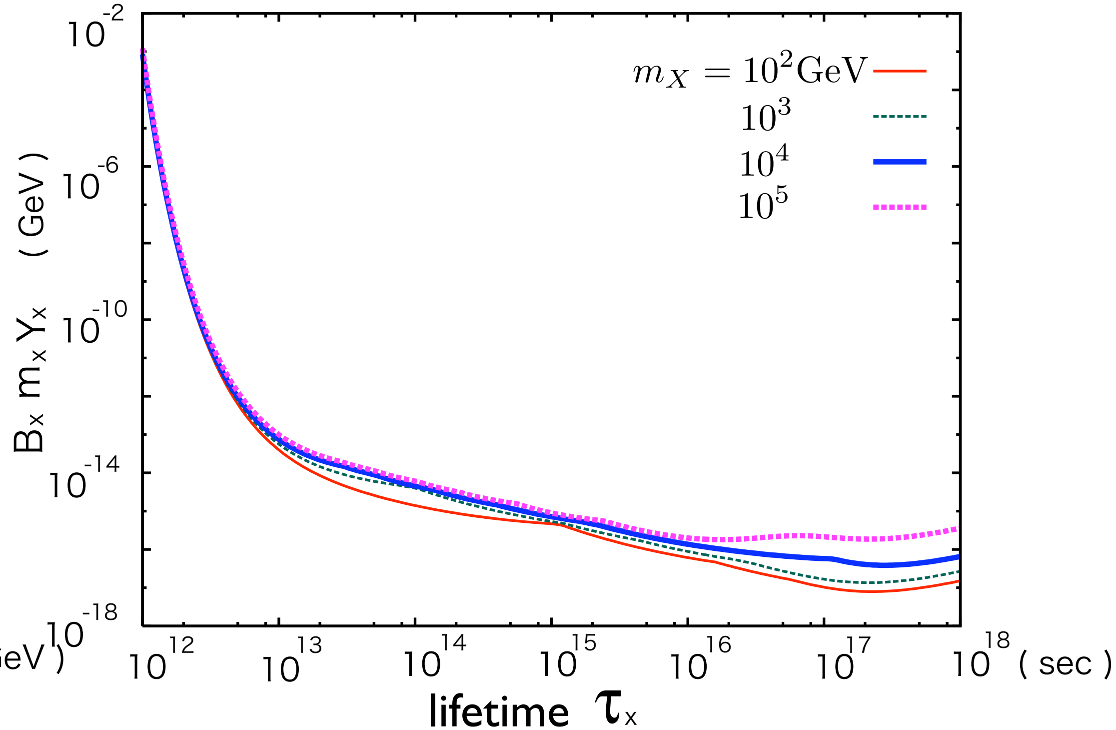


The diffuse photon flux has been observed by

- COMPTEL $(0.8 - 30{\rm MeV})$ (Kappadath et. al. 1996)
- EGRET $(30{\rm MeV} - 100{\rm GeV})$ (Sreekumarand et. al. 1998)

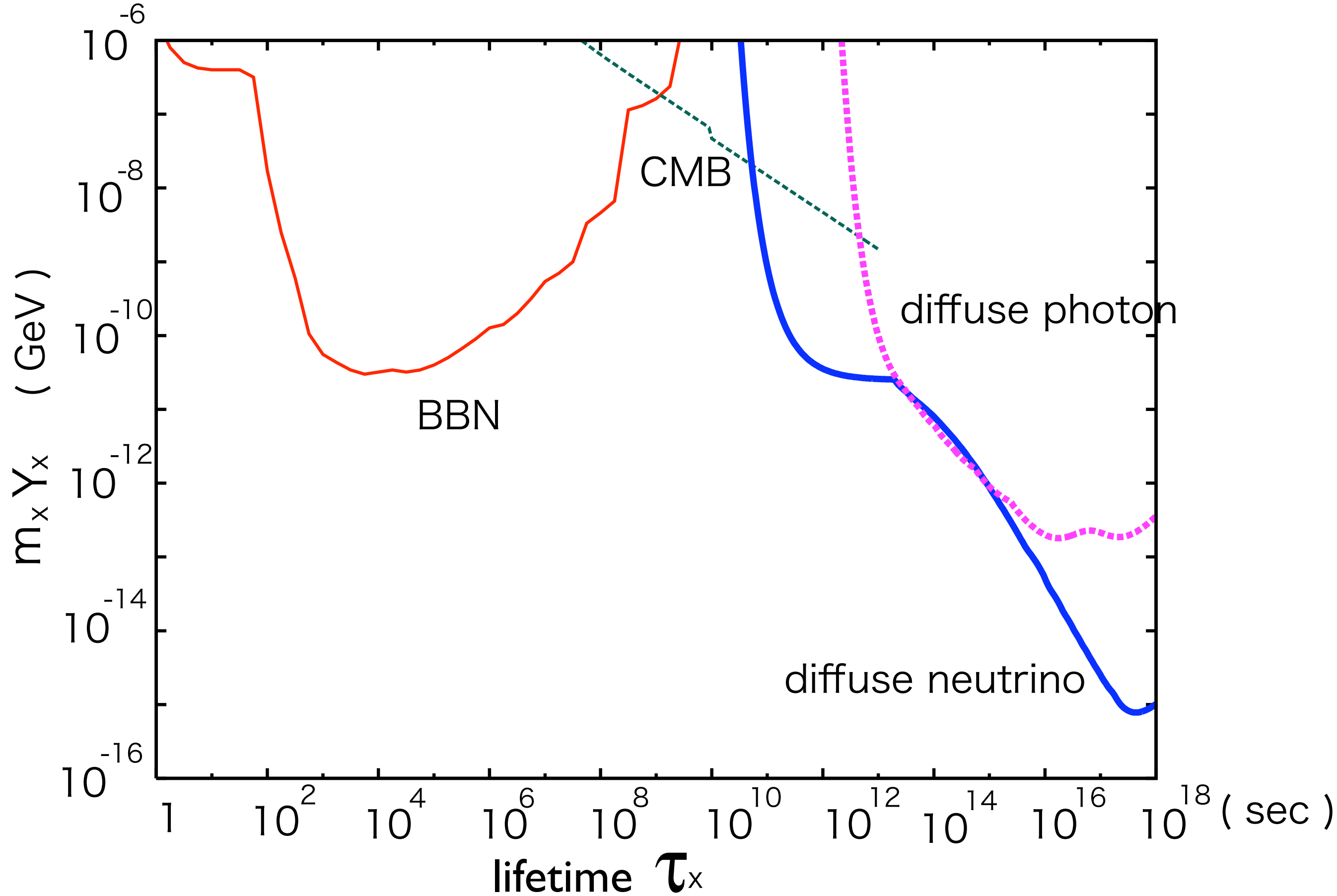
$$\tau_X = 10^{16}\text{sec}$$





- The constraints are almost independent of m_X at early time.
- High energy photons are effectively absorbed by IBL photons.

Results :



$$B_X = 10^{-3}$$

$$m_X = 300\text{GeV}$$

	BBN	CMB (early time / late time)	diffuse neutrino	diffuse photon
$m_X \uparrow$	severe	severe loose	severe	loose
$B_X \uparrow$	severe	irrelevant severe	irrelevant	severe

Conclusions :

- We have considered the long-lived particle X which mainly decay into neutrino and investigated the effect of decay of X on cosmology.

- We derive general and model-independent constraints on the abundance of X from the BBN, CMB, diffuse neutrino and diffuse photon flux.

- We show that the BBN and diffuse neutrino flux provide stringent constraints on the abundance of X with larger mass.