

# New physics decaying into metastable particles : impact on cosmic neutrinos

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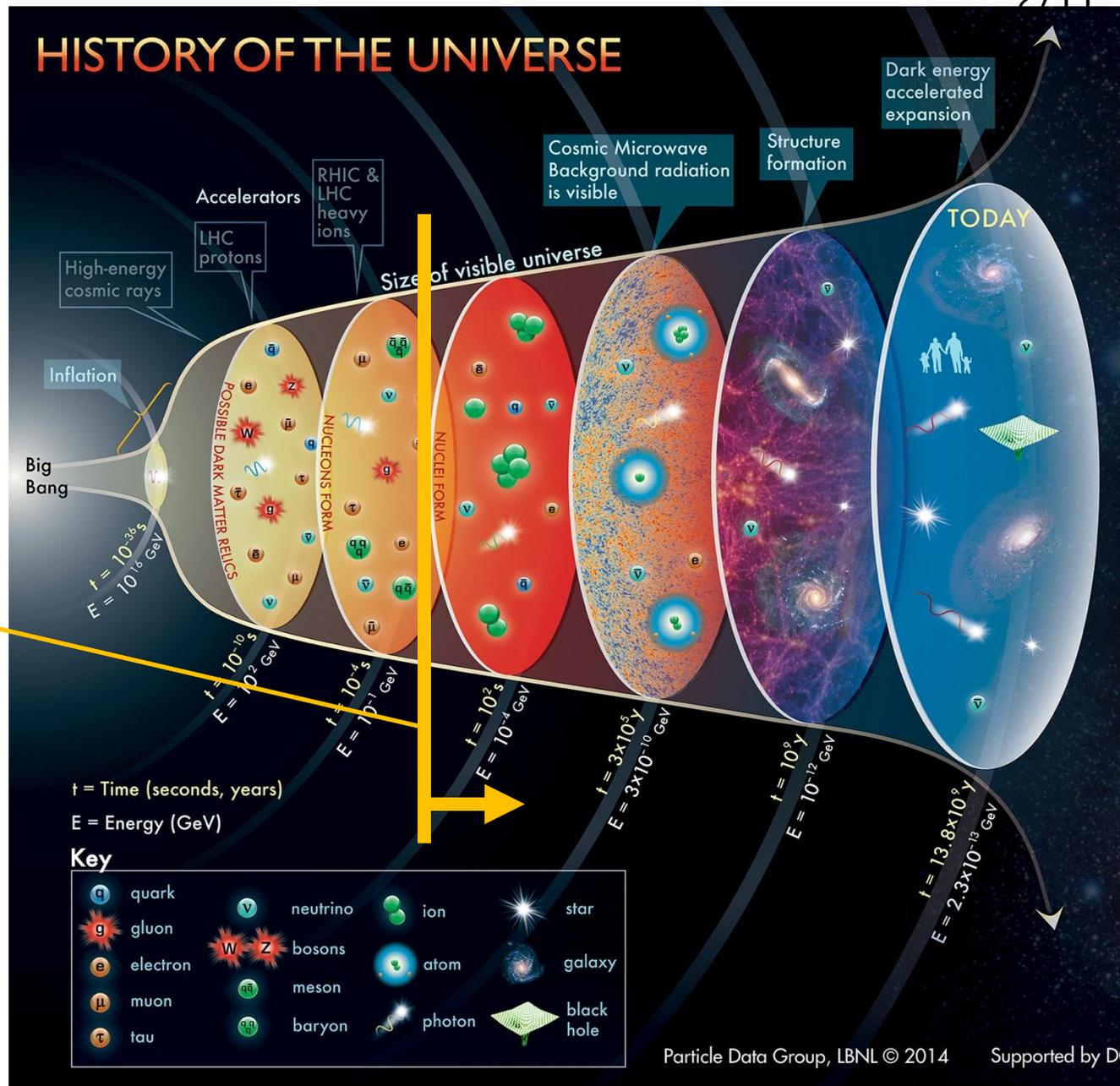
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# Introduction

- The universe is a sensitive probe of new physics.
- New physics can alter neutrino properties at neutrino decoupling ( $t \sim 1$  s).
- Neutrino properties may affect BBN and CMB.
- Even if new physics does NOT couple to  $\nu$ , it may indirectly affect  $\nu$  (e.g.  $\rho_\nu / \rho_{EM}$ ).



# Effective number of neutrinos $N_{\text{eff}}$

- One of key observable: Effective number of neutrinos

$$N_{\text{eff}} = \frac{8}{7} \left( \frac{11}{4} \right)^{\frac{4}{3}} \frac{\rho_{\text{rad}} - \rho_{\gamma}}{\rho_{\gamma}} \simeq 3 \text{ in the SM}$$

Photons, neutrinos and new physics effects

- Planck and future CMB observations can test  $N_{\text{eff}}$  precisely (via <sup>the MR equality</sup> neutrino free-streaming )

$$N_{\text{eff}} = 2.99_{-0.33}^{+0.34} \text{ at 95\% CL}$$

Planck 2018 results VI.

$$\text{Future CMB-S4: } \sigma(N_{\text{eff}}) = 0.03$$

CMB-S4 collaboration 2019

# Long-Lived Particles (LLPs)

- Many new physics scenarios include long-lived particles

Axion-like particles, heavy right-handed neutrinos, dark higgs, ...

- Neutrino decoupling may be sensitive to LLPs with lifetime  $\sim 1\text{s} \sim 1/(3 \times 10^5\text{km})$ .



It may be complementary to direct experiments.

- Heavy LLPs at  $t \sim 1\text{ s}$  ( $T \sim 2\text{MeV}$ ) can decay into hadrons, muons, taus.
- Subsequent decays of metastable SM particles can produce **neutrinos!**

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$$

**75%** of  $m_{\pi^-}$  roughly goes to **neutrino** energy!

# Metastable SM particles at MeV primordial plasma

What happens for pions, ... from LLP decays in the early universe?

- **Decay?**  $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Short lifetime, weak interaction process, neutrinos!

- **Annihilation?**  $\pi^- + \pi^+ \rightarrow \pi^0 + \pi^0$

Few pions from LLP decay, strong interaction process.

- **Interaction with nucleons?**  $\pi^- + p \rightarrow n + \pi^0$

Few p and n, strong interaction process, changing p/n ratio!

- **Electromagnetic (EM) scattering?**  $\pi^- + e^\pm \rightarrow \pi^- + e^\pm$

Many electrons, EM process. The dominant process.

Charged pions disappear

[K. Kohri (2001)]

[M. Kawasaki, K. Kohri and T. Moroi (2004)]

Which are effective? How do they affect comic neutrinos and  $N_{\text{eff}}$  ?

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# Dynamics of metastable particles

- First, charged pions are almost stopped due to electromagnetic scattering,  $\pi^- + e^\pm \rightarrow \pi^- + e^\pm$ .
- Dynamics of metastable particles (Y) from LLP (X) decays:

$$\begin{cases} \frac{dn_Y}{dt} + 3Hn_Y = \frac{n_X}{\tau_X} N_Y^X - \frac{n_Y}{\tau_Y} - \underbrace{n_Y n_{\bar{Y}} \langle \sigma_{\text{ann}}^Y v \rangle}_{\text{Y annihilations}} - \underbrace{n_Y \sum_{\mathcal{N}} n_{\mathcal{N}} \langle \sigma_{\mathcal{N}}^Y v \rangle}_{\text{Y interactions with nucleons}} + \underbrace{\sum_{Y' \neq Y} n_{Y'} \Gamma_{Y' \rightarrow Y}}_{\text{Y' \to Y processes with } m_{Y'} > m_Y}, \\ \frac{dn_{Y'}}{dt} + 3Hn_{Y'} = \dots \end{cases}$$

Y production from X decays   
 Y decays

- Probability of each processes ( $Y > Y'$ ):

$$P_{\text{decay}}^Y(t) = \frac{\tau_Y^{-1}}{\tau_Y^{-1} + \sum_{\mathcal{N}} n_{\mathcal{N}} \langle \sigma_{\mathcal{N}}^Y v \rangle + n_{\bar{Y}} \langle \sigma_{\text{ann}}^Y v \rangle}, \quad P_{\text{ann}}^Y(t) = \dots, \quad P_{\mathcal{N}}^Y(t) = \dots$$

Actually, we solve the above equations directly and numerically.

# Examples

- A non-relativistic LLP abundance at  $T_0 = 5 \text{ MeV}$ ,

$$n_X = n_{X,0} \left( \frac{a(t_0)}{a(t)} \right)^3 \exp \left[ -\frac{t - t_0}{\tau_X} \right] \quad \tau_X = 0.03 \text{ s}$$

$$n_{X,0} = 0.1 n_{\text{UR}}(T_0) = 0.1 \frac{\zeta(3)}{\pi^2} T_0^3$$

- We assume that LLPs decay only to muons or pions.

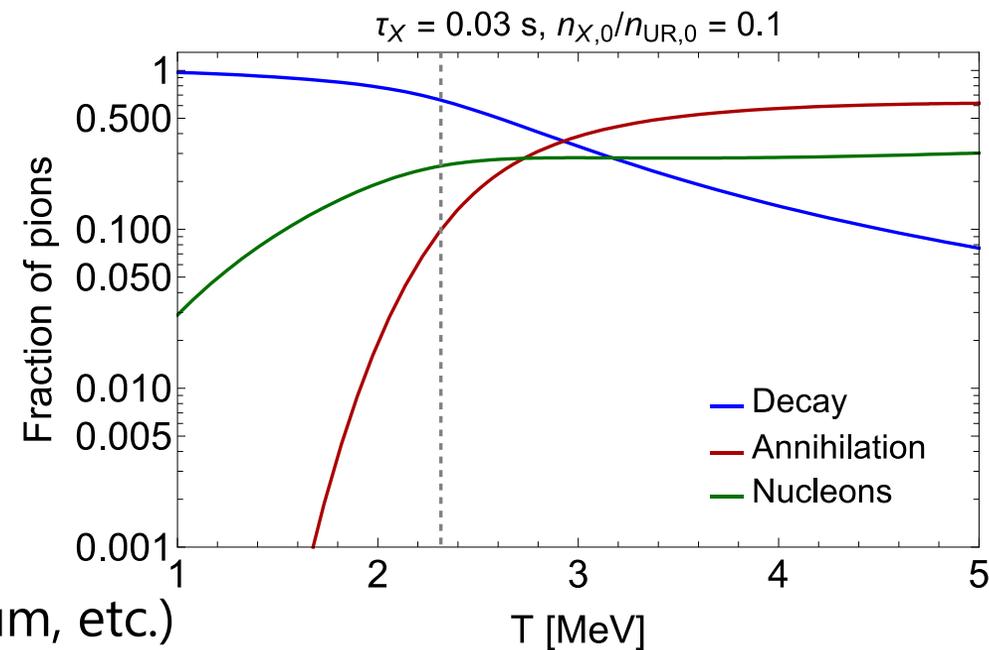
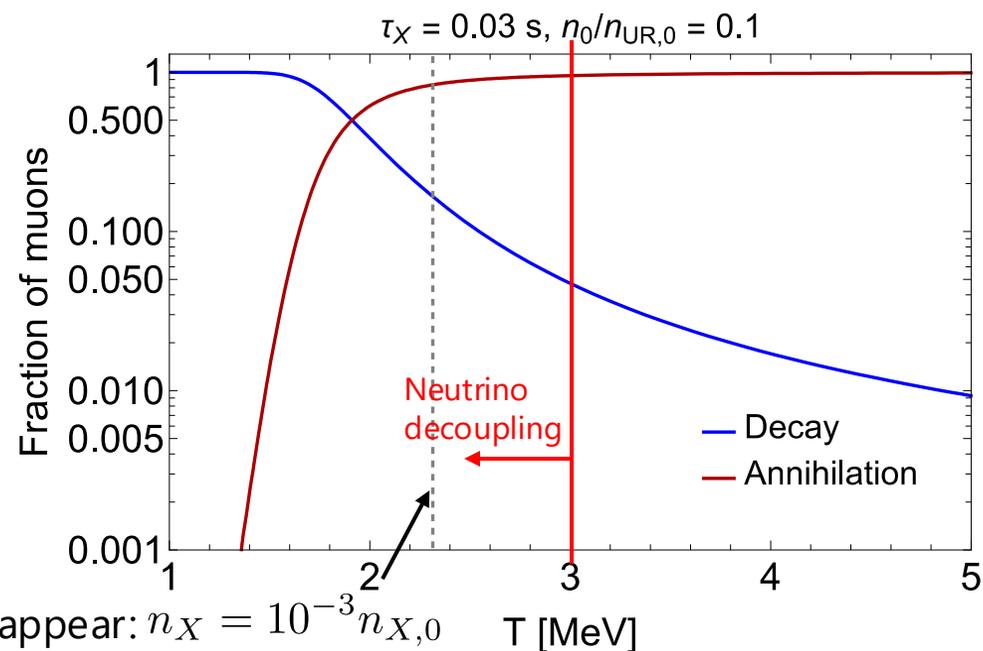
For muons, **annihilations** are important.

For pions, **all processes** are important.

**The results highly depends on the setup for LLPs!**

→ Any simple assumptions would not be valid.

(we neglect annihilations or assume pions are in equilibrium, etc.)



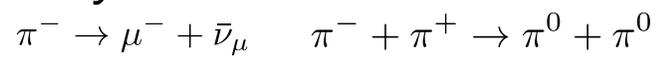
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# Impact on neutrinos and $N_{\text{eff}}$

- First, charged pions are stopped due to EM scattering.  
→ Kinetic energy is transferred to the EM sector,  $\Delta N_{\text{eff}} < 0$ .

- Decay vs annihilation, ... can significantly alter  $\Delta N_{\text{eff}}$ .

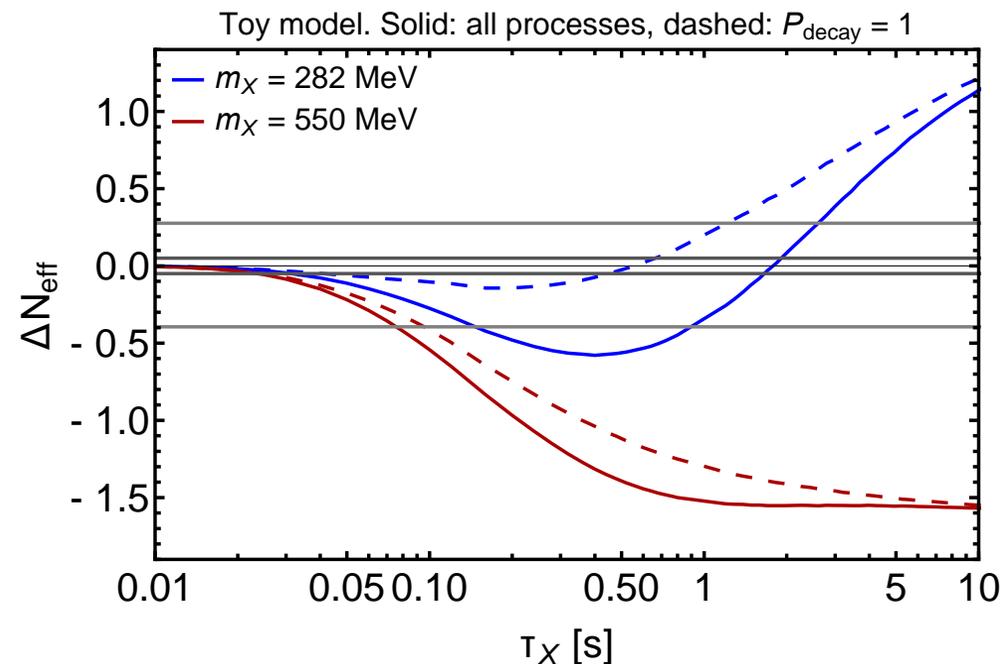
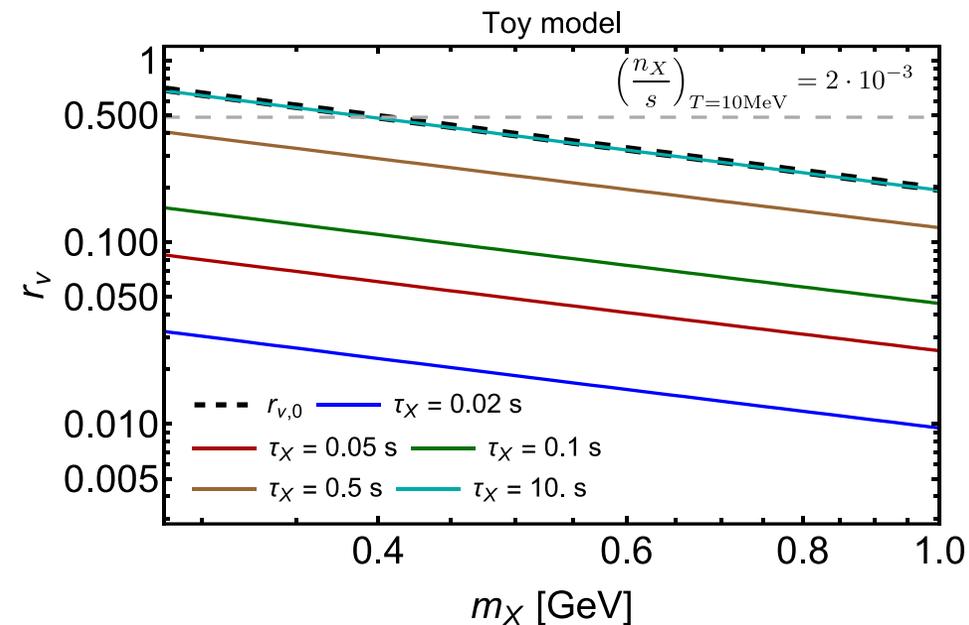


- We define a quantitative quantity for injected neutrinos

$$r_\nu = \left. \frac{\rho_{\text{inj},\nu}}{\rho_{\text{inj}}} \right|_{t=\infty}$$

100 % decay: dash line  
100 % annihilation:  $r_\nu = 0$

- Toy model of LLP decaying into pions: right figures.  
Realistic results for  $r_\nu$  and  $\Delta N_{\text{eff}}$  are different from simple assumptions of 100 % decays or annihilations!



# Conclusions

- CMB and BBN can probe long-lived particles with lifetime of  $\gtrsim 1$  sec.
- Heavy LLPs can decay into metastable SM particles such as pions.
- The subsequent processes such as decay, annihilation, ... of injected metastable particles highly depends on the LLP parameter space.
- Any simple assumptions (100% decays or annihilations of metastable particles, etc) are not valid to estimate effects of LLPs on  $N_{\text{eff}}$  precisely! We need compute evolutions of metastable SM particles carefully!

***Thank you!***