New physics decaying into metastable particles : impact on cosmic neutrinos

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with

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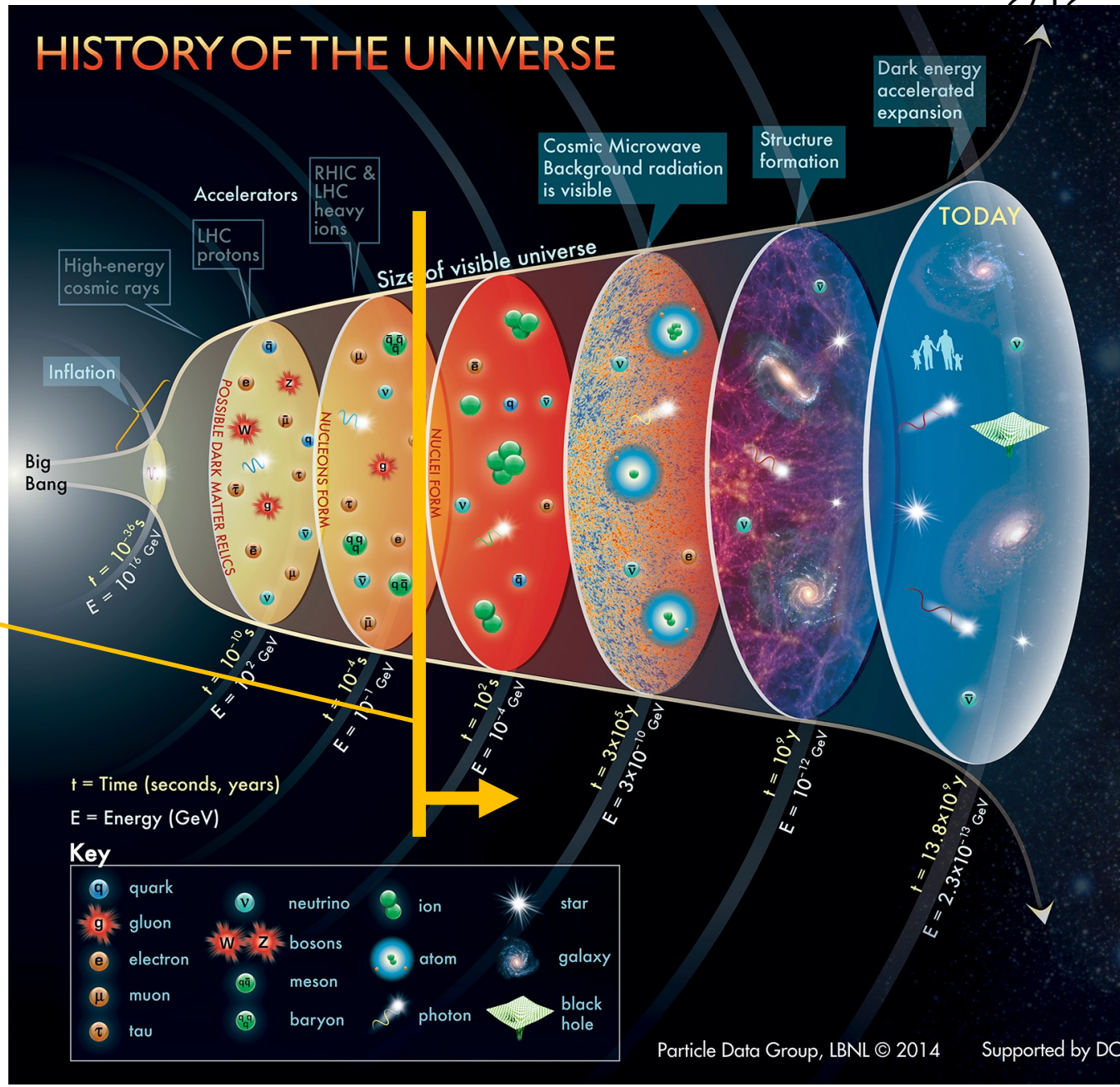
Introduction

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



https://www.mn.uio.no/fysikk/english/research/groups/hep/

Effective number of neutrinos $N_{\rm eff}$

- One of key observables: Effective number of neutrinos

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

Photons, neutrinos and new physics effects

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

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \text{ at } 95\% \text{ CL}$$ **Planck 2018 results VI.**

The ongoing Simons Observatory (expected): $\sigma(N_{\rm eff}) = 0.05$

Simons Observatory 2019

Long-Lived Particles (LLPs)

- Many new physics scenarios include long-lived particles

  Axion-like particles, heavy right-handed neutrinos, higgs-like scalar, …

- Neutrino decoupling may be sensitive to LLPs with lifetime ~ 1s ~ $1/(3\times10^5\text{km})$.

  ⟷ It may be complementary to direct experiments.

- Heavy LLPs at t ~ 1 s (T ~ 2MeV) can decay into hadrons, muons, taus.

- Subsequent decays of metastable SM particles can produce neutrinos!

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\mu^- \to \nu_\mu + \bar{\nu}_e + e^-$$

75% of m_{π^-} roughly goes to neutrino energy!

Metastable SM particles at MeV primordial plasma

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

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

  Short lifetime, weak interaction process, neutrinos!

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

  Few pions from LLP decay, strong interaction process.

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

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

Charged pions disappear

[K. Kohri (2001)]
[M. Kawasaki, K. Kohri and T. Moroi (2004)]

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

  Many electrons, EM process. The dominant process.

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

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- Introduction
- Dynamics of metastable particles
- Impact on cosmic neutrinos and N_{eff}
- Conclusion

Dynamics of metastable particles

- First, charged pions are almost stopped due to electromagnetic scattering, $\pi^- + e^\pm \to \pi^- + e^\pm$.

- Dynamics of metastable SM particles (Y) from LLP (X) decays:

$$\begin{cases} \frac{dn_Y}{dt} + 3Hn_Y = \frac{n_X}{\tau_X} N_Y^X - \frac{n_Y}{\tau_Y} - n_Y n_{\bar{Y}} \langle \sigma_{\rm ann}^Y v \rangle - n_Y \sum_{\mathcal{N}} n_{\mathcal{N}} \langle \sigma_{\mathcal{N}}^Y v \rangle + \sum_{Y' \neq Y} n_{Y'} \Gamma_{Y' \to Y}, \\ \frac{dn_{Y'}}{dt} + 3Hn_{Y'} = \ldots \end{cases}$$

Y production from X decays

Y decays

Y annihilations

Y interactions with nucleons

Y′→Y processes with $m_{Y'} > m_Y$

- Probability of each processes (Y>Y′):

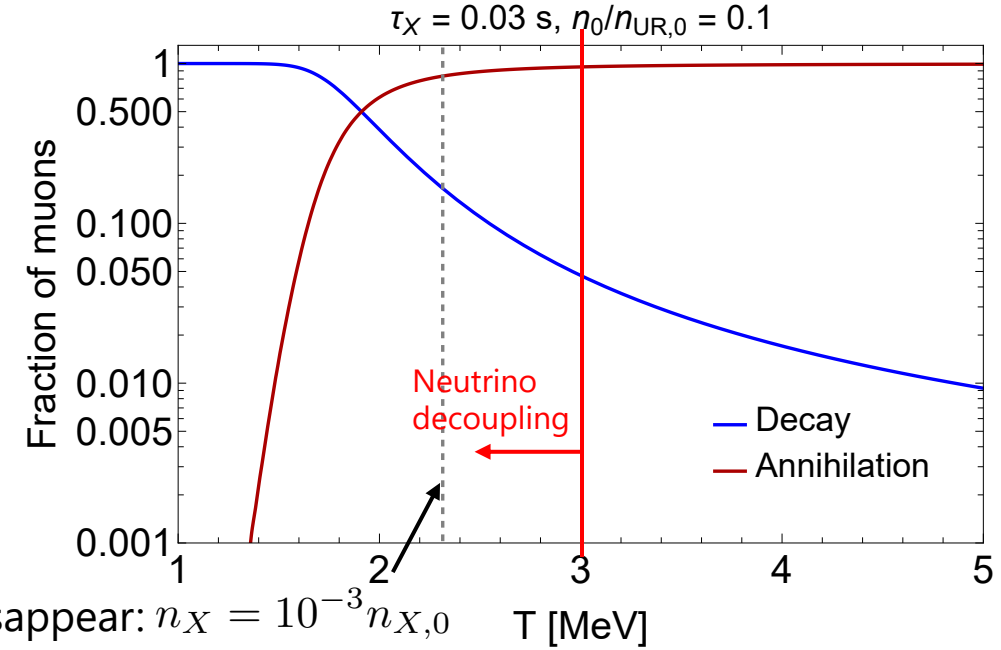
$$P_{\rm decay}^Y(t) = \frac{\tau_Y^{-1}}{\tau_Y^{-1} + \sum_{\mathcal{N}} n_{\mathcal{N}} \langle \sigma_{\mathcal{N}}^Y v \rangle + n_{\bar{Y}} \langle \sigma_{\rm ann}^Y v \rangle}, \quad P_{\rm ann}^Y(t) = \ldots, \quad P_{\mathcal{N}}^Y(t) = \ldots$$

Examples

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

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

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

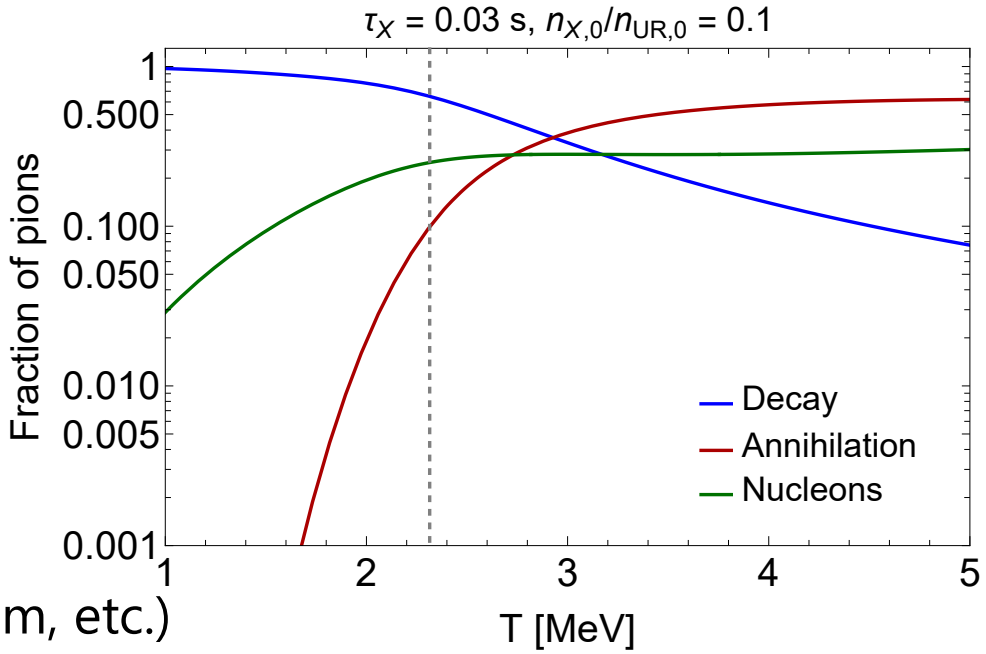


LLPs disappear: $n_X = 10^{-3} n_{X,0}$

- 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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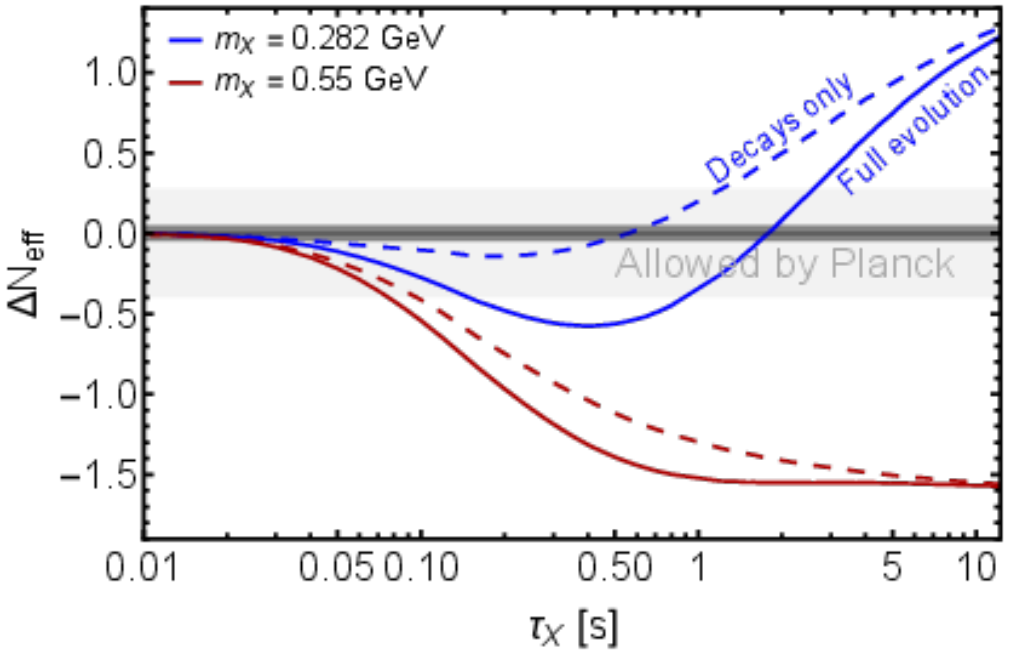
Impact on neutrinos and $N_{\rm eff}$

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

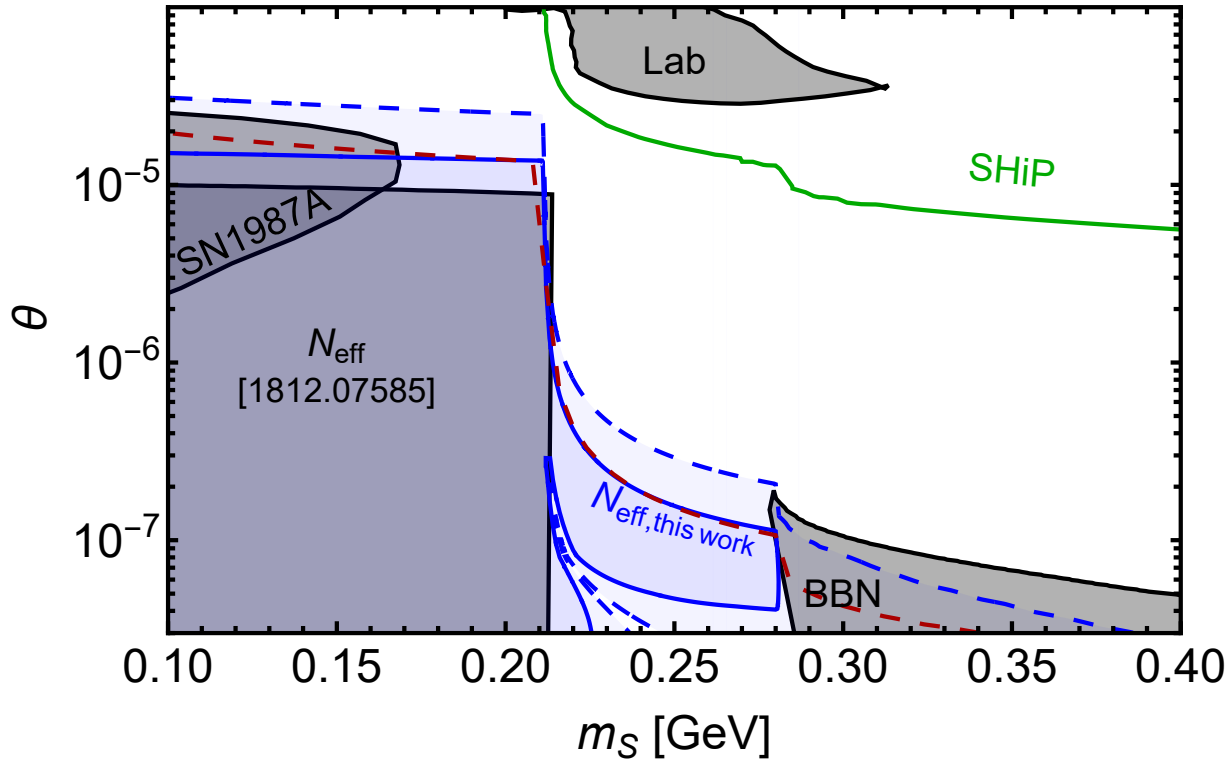
- Decay vs annihilation, … can significantly alter $\Delta N_{\rm eff}$.
  $\pi^- \to \mu^- + \bar{\nu}_\mu$ $\pi^- + \pi^+ \to \pi^0 + \pi^0$

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



$$\left(\frac{n_X}{s}\right)_{T=10\mathrm{MeV}} = 2 \cdot 10^{-3}$$

Implications for Higgs sector



- Effective Lagrangian: $\mathcal{L} = \theta m_h^2 h S + \mathcal{L}_{\rm kinetic}$

  Higgs — Higgs-like scalar

- Decay modes: $S \to e^+e^-/\mu^+\mu^-/\pi^+\pi^-/2\pi^0/K^+K^-/K_LK_S,$

Conclusions

- CMB and BBN can probe long-lived particles with lifetime of $\gtrsim 1\ \mathrm{sec}$.
- 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 setup.
- Any simple assumptions (100% decays or annihilations of metastable particles, etc) are not proper to estimate effects of LLPs on N_{eff} precisely! We need compute evolutions of metastable SM particles carefully!

Thank you!