New physics decaying into metastable particles: impact on cosmic neutrinos

Kensuke Akita,[1, *] Gideon Baur,[2, 3, †] Maksym Ovchynnikov,[4, 2, ‡] Thomas Schwetz,[2, §] and Vsevolod Syvolap[5, ¶]

[1] Department of Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[2] Institut für Astroteilchen Physik, Karlsruher Institut für Technologie (KIT),
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[3] Bethe Center for Theoretical Physics, Universität Bonn, D-53115, Germany
[4] Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland
[5] Instituut-Lorentz, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands

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We investigate decays of hypothetical unstable new physics particles into metastable species such as muons, pions, or kaons in the early Universe, when temperatures are in the MeV range, and study how they affect cosmic neutrinos. We demonstrate that decays of the metastable particles compete with their annihilations and interactions with nucleons, which reduces the production of high-energy neutrinos and increases energy injection into the electromagnetic sector. This energy reallocation alters the impact of the new physics particles on the effective number of neutrino degrees of freedom, $N_{\rm eff}$, modifies neutrino spectral distortions, and may induce asymmetries in neutrino and antineutrino energy distributions. These modifications have important implications for observables such as Big Bang Nucleosynthesis and the Cosmic Microwave Background, especially in light of upcoming CMB observations aiming to reach percent-level precision on $N_{\rm eff}$. We illustrate our findings with a few examples of new physics particles and provide a computational tool available for further exploration.

Introduction. The thermal plasma of the Early Universe is a sensitive probe of new physics. In particular, any modifications of the standard evolution in the period when neutrinos decouple from the thermal bath at temperatures $T \lesssim 5$ MeV can alter primordial neutrino properties [1], which then may affect key cosmological observables, including primordial nuclear abundances [2–8], Cosmic Microwave Background (CMB) [5, 9–20], and constraints on neutrino masses [21–24].

A common scenario with new physics involves beyond the Standard Model Long-Lived Particles (LLPs) with lifetimes $\tau_X \lesssim 1\,\mathrm{s}$ decaying into metastable Standard Model (SM) particles ($Y = \mu^{\pm}, \pi^{\pm}, K^{\pm}, K_L$) [25–28]. When these Y particles subsequently decay themselves, they inject high-energy neutrinos, which cause two independent effects. First, they affect the effective number of relativistic neutrino species, $N_{\rm eff}$, defined as

$$N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \frac{\rho_{\rm UR}-\rho_\gamma}{\rho_\gamma}\bigg|_{m_\nu \ll T \ll m_e}, \qquad (1)$$

where $\rho_{\rm UR}, \rho_\gamma$ are the energy densities of all ultra-relativistic particles and photons, respectively, T is the electromagnetic (EM) plasma temperature, and m_ν, m_e are the masses of neutrinos and electrons. Second, they induce spectral distortions [18, 20, 29, 30]. The latter is important for the proton-to-neutron conversion, which defines the onset of Big Bang Nucleosynthesis. Also, they break the degeneracy between $N_{\rm eff}$ and the number density of neutrinos, affecting the role of neutrino mass in cosmology after they become non-relativistic. Previous studies [14, 15, 17, 18, 20, 31] analyzing the impact of LLPs on cosmic neutrinos have assumed that the metastable particles always decay after thermalizing.

In this letter, we perform a detailed investigation of the evolution of the Y particles in the MeV plasma and their impact on cosmic neutrinos. We demonstrate that if injected at MeV temperatures, Ys can disappear by efficiently annihilating or interacting with nucleons before decaying, which qualitatively changes their impact on neutrino properties. Hence, this discovery has significant implications for constraining or discovering new physics through cosmological observations. Our approach applies to a wide range of new physics scenarios, including vanilla decaying LLPs, low-temperature reheating scenarios with hadronically decaying particles, and low-temperature baryogenesis models [32, 33]. Detailed methodologies, comprehensive analyses, and extended case studies are provided in the companion paper [34].

Dynamics of metastable particles. The rates of several processes involving metastable particles are significantly larger than the Hubble expansion rate at MeV temperatures, which leads to a complicated evolution in the primordial plasma. The processes include (see Fig. 1):

(a) **Decay**: $Y \to$ SM particles. Decays are governed by weak interactions. As a result, the lifetimes $\tau_Y \sim 10^{-8} - 10^{-6}$ s are not short enough to neglect the possibility of various scattering processes with Ys prior to the decay. Decay products of Ys include high-energy non-thermal neutrinos, which lead to neutrino spectral distortions.

(b) **Annihilation**: $Y + \bar{Y} \to$ SM particles. Both particles and antiparticles participating in the process originate from decays of LLPs. The process is driven

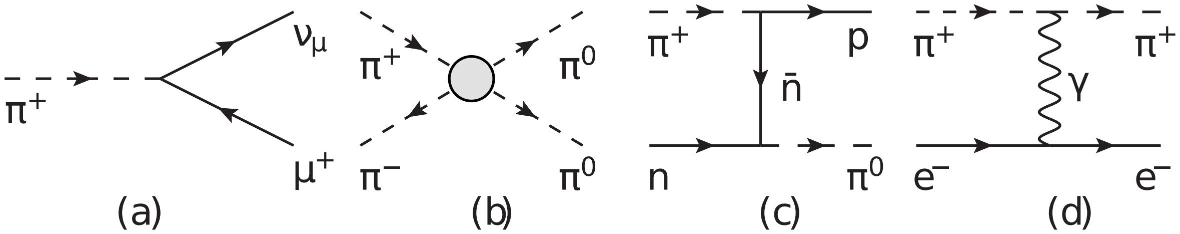

FIG. 1. Interaction processes of the injected metastable particles Y in the MeV primordial plasma: decay (a), annihilation with the injected antiparticle (b), interaction with nucleons (c), and elastic EM scattering (d). The process (a) injects non-thermal neutrinos, the reactions (b), (c) lead to the disappearance of Ys without decaying, injecting energy either to the electromagnetic plasma or to lighter Ys, whereas (d) places most of the Ys kinetic energy in the EM plasma.

by electromagnetic or strong forces, and the largeness of the cross-section compensates for the smallness of the $\bar{Y}$ yield available for the annihilation with Y.

(c) **Interaction with nucleons** $\mathcal{N}$: various quasi-elastic processes of the type $Y+\mathcal{N}\to\mathcal{N}^{(\prime)}+$other particles. Examples are $\pi^-+p\to n+\pi^0$ and $K^-+p\to n+2\pi$, changing the nucleon type, and $K^-+p\to p+2\pi$, that leave it unchanged. The process's rate is parametrically suppressed by the nucleon number density. Because of this, the process is only efficient in the case of mesonic Ys, as it is then driven by the strong force.[1]

(d) **Elastic electromagnetic scatterings**: $Y+\text{EM}\to Y+\text{EM}$. It transfers the kinetic energy of the charged Y particles to the EM plasma, leading to the thermalization of the kinetic energy of Ys with photons and electrons. This process is typically the most efficient one, as both the number density of interacting counterparts and the cross-section are large.

Processes (b)-(d) do not directly inject energy into the neutrino sector. Consequently, when annihilation and interactions with nucleons dominate over decays, the metastable particles transfer all their energy to the electromagnetic sector instead of producing high-energy neutrinos.

To quantify the impact of these processes on primordial neutrinos, we have implemented a two-step analysis. First, we have solved the coupled Boltzmann equations governing the number densities of Y particles and nucleons in the presence of the decaying LLPs. Second, we have incorporated the resulting dynamics into the solver of the unintegrated neutrino Boltzmann equations to the source part of the collision integral. For a detailed description of the methodology and cross-section calculations, see Refs. [34, 38].

Impact on the properties of neutrinos. The suppression of Y decays due to annihilation and interactions with nucleons alters the expected neutrino properties. We summarize them below:

- *Effective number of relativistic neutrino species (N_{eff}):* As there is less energy injection into the neutrino sector, there is a decrease in N_{eff} compared to the setup where Y decays are inevitable.
- *Neutrino spectral distortions:* Less Y decays imply fewer injected high-energy neutrinos, and hence there is no enhanced high-energy neutrino tail, implying smaller spectral distortions.
- *Neutrino-antineutrino energy distribution asymmetry:* The dynamics of K^+ and K^- are not symmetric: whereas K^- may efficiently disappear because of the interactions with nucleons, there is no such a process for K^+.[2] As a result, K^+ decays more often than K^-. It leads to producing more high-energy neutrinos than antineutrinos in the energy range $E_\nu > m_\mu/2$. On the other hand, the same reason leads to an excess of μ^+,π^+, which induces more antineutrinos than neutrinos in the energy range $E_\nu < m_\mu/2$. Hence, although a neutrino-antineutrino asymmetry in number densities is bounded due to lepton, baryon, and electric charge conservation, the resulting asymmetry in their energy distributions may be sizeable, as the interactions with nucleons are very efficient.

These modifications may have profound implications for Big Bang Nucleosynthesis (BBN) and CMB

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[1] The $p\leftrightarrow n$ processes have been included in the works [4, 7, 8, 16, 35–37], studying the impact of various scenarios with LLPs decaying into Ys on primordial nuclear abundances. However, to the best of our knowledge, they have not been included in any previous study of the impact on neutrinos.

[2] This is because the thresholdless scatterings occur via intermediate resonances Λ,Σ. The processes involving K^+ require the resonances with positive baryon number and strangeness that do not exist [35].

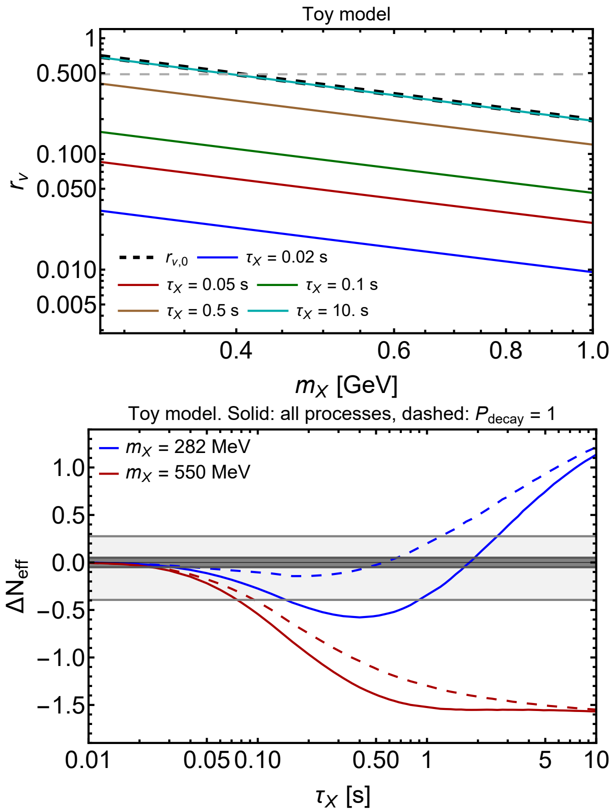

FIG. 2. Impact of the particle X decaying solely into charged pions as a function of its mass m_X and lifetime τ_X on neutrinos. The plots are obtained using the results of this study for the evolution of metastable particles and Ref. [38] for solving the neutrino Boltzmann equation. *Top panel*: cumulative fraction of the energy from X decays injected into neutrinos, r_ν, as a function of the X mass for different X lifetimes. The black dashed line ($r_{\nu,0}$) corresponds to the case when all Y particles decay, whereas solid lines take into account annihilations and nucleon interactions of Ys. *Bottom panel*: correction to the effective number of neutrino species, $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\Lambda\rm CDM}$, as a function of LLP lifetime for two representative masses. Solid curves include annihilations and decays of Y particles, whereas dashed curves assume inevitable decays. The gray band represents the Planck 95%CL constraints $N_{\rm eff} = 2.99^{+0.33}_{-0.34}$ [39], whereas the black band shows the forecasted sensitivity of the Simons Observatory, which we assume to be centered at $\Delta N_{\rm eff} = 0$ [40].

anisotropies. Particularly, the shape of the neutrino distribution, as well as a possible neutrino/antineutrino asymmetry, is important for the proton-to-neutron conversion rates (determining the onset of BBN) and the energy density of non-relativistic neutrinos.

Case studies. To demonstrate the impact of the Y dynamics on the neutrino properties, we consider three models with LLPs X: a toy model where X decays solely into pions, Higgs-like scalars, and Heavy Neutral Leptons (HNLs).

In the toy model case, we fix the LLP abundance and branching ratios, allowing the mass m_X and lifetime τ_X to vary. The abundance is chosen as

$$\mathcal{Y}_X \equiv \left(\frac{n_{\rm LLP}}{s}\right)_{T=10\text{ MeV}} = 2\cdot 10^{-3}, \tag{2}$$

which corresponds to a scenario where the LLP was in thermal equilibrium and decoupled while still relativistic. The decay of the pions produces muons, and so their evolution is coupled.

Figure 2 illustrates the impact of the LLP decays on neutrinos. A useful quantity to study the impact of the Y evolution on neutrinos is the ratio of the total energy injected directly into neutrinos to the total injected energy:

$$r_\nu = \left.\frac{\rho_{\text{inj},\nu}}{\rho_{\text{inj}}}\right|_{t=\infty}. \tag{3}$$

This quantity becomes maximal when all Y particles decay — we denote this maximal value by $r_{\nu,0}$, whereas annihilations and interactions with nucleons lead to $r_\nu < r_{\nu,0}$. In the top panel of Fig. 2 we show r_ν for the toy model as a function of the mass of the LLP X, for different lifetimes τ_X. In the absence of the direct LLP decays into neutrinos, r_ν is determined by the decays of pions and muons, reaching the value $r_{\nu,0}$ when all of them decay. However, as the figure shows, metastable particles prefer to disappear via annihilation or nucleon interactions before decaying for LLP lifetimes $\tau_X \lesssim 1$ s, which leads to a significant drop in r_ν and it reaches the percent level for lifetimes $\tau_X \sim 0.01$ s. As the lifetime increases, more and more Ys decay, and r_ν approaches $r_{\nu,0}$ for $\tau_X \gtrsim 1$ s.

The bottom panel of Fig. 2 shows how $r_\nu < r_{\nu,0}$ affects the deviation of the effective neutrino species from its standard value: $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\Lambda\rm CDM}$. We show $\Delta N_{\rm eff}$ for two representative values of LLP masses as a function of their lifetime, chosen such that the value of $\Delta N_{\rm eff}$ for lifetimes $t_X \gtrsim 10$ s tends to a positive and a negative value. The comparison of the solid and dashed curves highlights the importance of annihilations and nucleon interactions for the pions and muons. For both examples, the value of $\Delta N_{\rm eff}$ is significantly lower, in some regions even changing its sign. We compare the size of the effect with the present accuracy on $\Delta N_{\rm eff}$ from Planck, as well as the sensitivity of the future Simons Observatory, which clearly shows that the impact of the effect pointed out here is comparable to present uncertainties and much larger than future sensitivities.

In contrast to the toy model, where we arbitrarily fix the abundance, in specific particle physics models for the LLP, its abundance is determined by its interactions and is, therefore, fixed by specifying m_X and τ_X. Another important difference is that, depending on the model, there may be multiple decay modes, including EM particles, the Ys, and neutrinos. This is the case for our next two examples, the Higgs-like scalars and HNLs.

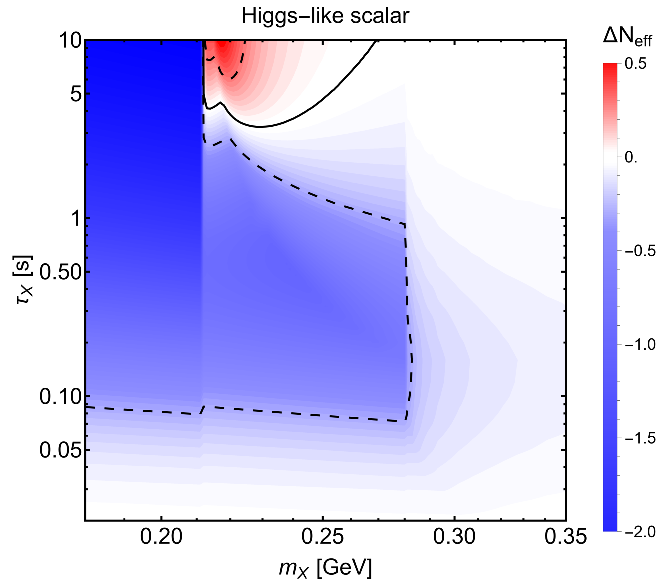

FIG. 3. Effect of Higgs-like scalars on $\Delta N_{\rm eff}$ in the parameter space of the scalar mass m_X and lifetime τ_X. The solid black line marks the parameter space where $\Delta N_{\rm eff} = 0$, while dashed lines indicate regions where $\Delta N_{\rm eff}$ exceeds the Planck 95% CL bound [41].

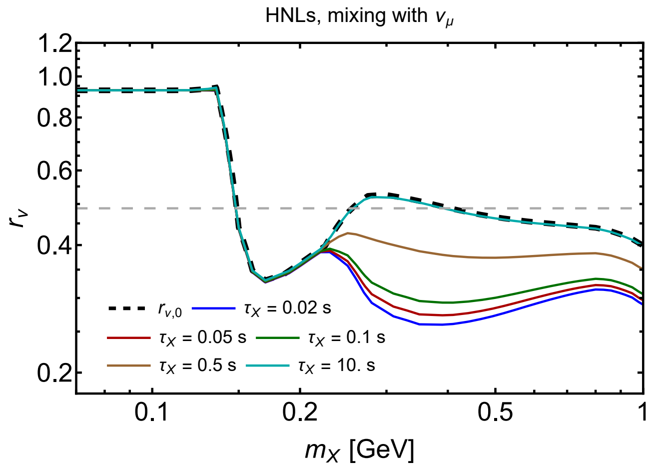

FIG. 4. Impact of HNL decays on neutrino injection: dependence of r_ν on HNL lifetime, demonstrating the suppression of neutrino injection due to annihilation and nucleon interactions compared to the standard assumption of inevitable decays.

Higgs-like scalars predominantly decay into a pair of the heaviest possible SM particles kinematically available, resulting in final states containing pions, muons, and kaons for $m_S \gtrsim 2m_\mu$. Figure 3 illustrates the impact on $\Delta N_{\rm eff}$ as a function of scalar mass m_S and lifetime τ_S. We concentrate on the mass range $m_\mu < m_X \lesssim 2m_\pi$, where the scalar abundance is large enough to significantly affect the Early Universe's plasma [15, 34], and where it mainly decays into a pair of muons. The realistic setup, accounting for annihilation and nucleon interactions, shows a significant reduction in $|\Delta N_{\rm eff}|$ compared to the standard assumption of inevitable decays. Similarly to the toy model case, in the mass range $2m_\mu < m_S \lesssim 2m_\pi$, the sign of $\Delta N_{\rm eff}$ changes due to the interplay between energy injection into neutrinos and the EM plasma: from a negative value at small lifetimes $\tau \lesssim 1$ s to a positive at higher lifetimes.

HNLs N interact with the SM via mixing with active neutrinos. For HNL masses $m_N \sim \mathcal{O}(200 \text{ MeV})$, they often decay into pions and muons, but unlike the toy model and the Higgs-like scalar case, their decay modes also include direct decays into neutrinos. Figure 4 shows r_ν as a function of HNL lifetime, highlighting the significant suppression of neutrino injection due to annihilation and nucleon interactions, even when direct decays into neutrinos are present.

Conclusion. We have identified a crucial oversight in previous studies of the impact of Long-Lived Particles (LLPs) on cosmic neutrinos: the potential for metastable particles such as muons, pions, and kaons produced by decays of LLPs to annihilate or interact with nucleons before decaying. These effects can significantly alter the expected impact on primordial neutrinos, reducing $\Delta N_{\rm eff}$, mitigating spectral distortions, and inducing an asymmetry between the energy distributions of neutrinos and antineutrinos. Our findings necessitate a revision of cosmological studies on broad new physics models. With the analysis presented in this letter, we have studied in detail the effects on $\Delta N_{\rm eff}$ and spectral distortions; the neutrino-antineutrino energy asymmetry as a result of decays into charged kaons will be analyzed in future work.

To facilitate further research, we provide a publicly accessible computational tool that incorporates the dynamics of Y particles in a model-independent manner. Detailed methodologies, comprehensive analyses, and additional case studies are presented in the accompanying publication [34].

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[*] kensuke@hep-th.phys.s.u-tokyo.ac.jp
[†] gbaur@uni-bonn.de
[‡] maksym.ovchynnikov@cern.ch

§ schwetz@kit.edu
¶ v.syvolap@umail.leidenuniv.nl

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