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Light dark matter: A common solution to the lithium and H_0 problems

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ABSTRACT

Currently, the standard cosmological model faces some tensions and discrepancies between observations at early and late cosmological time. One of them concerns the well-known H_0-tension problem, i.e., a $\sim 4.4\sigma$-difference between the early-time estimate and late-time measurements of the Hubble constant, H_0. Another puzzling question rests in the cosmological lithium abundance, where again local measurements differ from the one predicted by Big Bang Nucleosynthesis (BBN). In this work, we show that a mechanism of light dark matter production might hold the answer for these questions. If dark matter particles are sufficiently light and a fraction of them were produced non-thermally in association with photons, this mechanism has precisely what is needed to destroy Lithium without spoiling other BBN predictions. Besides, it produces enough radiation that leads to a larger H_0 value, reconciling early and late-time measurements of the Hubble expansion rate without leaving sizable spectral distortions in the Cosmic Microwave Background spectrum.

1. Introduction

The standard Λ-Cold Dark Matter (ΛCDM) model provides a successful description of the structure and evolution of the universe from its early stages to the present. However, as cosmological observations increase in number and accuracy – some of the current constraints on the cosmological parameters can reach now sub-percent level – tensions and discrepancies between early and late time cosmic evolution emerged, requiring either a better understanding of the systematic errors or an extension of the standard model or the discovery of new physics – we refer the reader to [1] for a recent review.

One of these tensions concerns the current difference between the early-time estimates and late-time measurements of the Hubble constant, H_0 ($\equiv 100h$ km/s/Mpc). Using distance measurements of galaxies in the local universe calibrated by Cepheid variables and type Ia Supernovae (SNe Ia), Riess *et al.* [2] reported $H_0 = 74.03 \pm 1.42$ km/s/Mpc, which differs by $\sim 4.4\sigma$ from the latest Cosmic Microwave Background (CMB) estimate assuming the

ΛCDM model, $H_0 = 67.36 \pm 0.54$ km/s/Mpc [3]. Such a discrepancy can reach $\sim 5.8\sigma$ when other late-time measurements of H_0 [4,5] are combined, reinforcing what is known nowadays as the H_0-tension problem [1].

Another ongoing issue in the standard cosmology concerns a long-standing problem of the Lithium (^7Li) abundance, known as the Lithium problem [6]. It is well known that during the first few minutes of the universe lifetime, nuclear reactions took place and produced light elements such as ^4He, D, ^3He and ^7Li. Using standard calculations one can determine the abundance of these elements and find good agreement with the observations up to the baryon-to-photon ratio, η, which is extracted from CMB measurements [7,8]. Moreover, by fixing η, no free parameter is left in the Big Bang Nucleosynthesis (BBN) calculations and the primordial abundances of these elements are thus affected only by tamed uncertainties in the nuclear cross-section [9]. It is also remarkable that the calculated primordial abundances nicely match the astronomical observations. Albeit, there is a puzzling discrepancy in the ^7Li abundance by roughly a factor of three. The predicted abundance reads $^7Li/H = 4.68(\pm 0.67) \times 10^{-10}$ [10] while measurements point to $^7Li/H = 1.58(\pm 0.31) \times 10^{-10}$ [7]. This difference between the calculated and observed Lithium primordial abundances has been reconciled neither by new observations nor by nuclear physics. Therefore, the long-standing Lithium problem

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casts doubt either on the success of BBN or on our understanding of the thermal history of the universe.

In the past few years, several attempts have been put forth trying to solve individually one of these problems. Some of them invoked connections to the cosmological dark sector (see e.g. [11] and references therein). In many cases, they end up altering too much the abundances of the other light elements or distorting the CMB power spectrum. It has been noticed that an increase in the number of relativistic degrees of freedom is a viable solution to the H_0 problem and that late electromagnetic injection may solve the Lithium problem. Aren't these two problems connected? Aren't they connected to dark matter? Instead of trying to solve these two problems individually we explore a common origin. Indeed, in this work we present a possible unified solution to both problems via the production of light dark matter particles in the early universe. It is known that the bulk of the dark matter particles cannot be relativistic at the matter-radiation equality for the sake of structure formation. However, considering that only a small fraction of it is relativistic, we show that both Lithium and H_0 problems may be solved.

2. Light dark matter and H_0

In order to understand how the production of light dark matter can lead to larger values of H_0 one needs to go over a few steps. If dark matter, χ, is produced via a two body decay, i.e., $\chi' \rightarrow \chi + \gamma$, then energy and momentum conservation implies $E_{\chi'} = E_\gamma + m_\chi \gamma_\chi$ and $p_{\chi'} = E_\gamma + p_\chi$. Now, assuming that χ' decays at rest we obtain $\gamma_\chi = m_{\chi'}/2m_\chi + m_\chi/2m_{\chi'}$. In the radiation-dominated era, $a = (t/t_0)^{1/2}$, thus the prompt decay of χ' yields

$$\gamma_\chi(t) = \sqrt{\frac{\left(m_{\chi'}^2 - m_\chi^2\right)^2}{4m_{\chi'}^2 m_\chi^2} \frac{\tau}{t} + 1}, \qquad (1)$$

which represents the boost factor of the dark matter particles as a function of time in a radiation-dominated universe, and where τ corresponds to the time at which χ' instantaneously decays. We emphasize that this equation is strictly valid only in the ultra-relativistic case, which happens for $m_{\chi'} \gg m_\chi$. Our goal here is to illustrate the framework. The dark matter number density scales with a^{-3}, which implies $\rho_\chi(a) = \rho_c \Omega_\chi a^{-3}$, whereas the density of relativistic neutrinos evolves as $\rho_\nu(a) = \rho_c \Omega_\nu a^{-4} N_\nu/3$, where N_ν is the number of neutrino species. Hence, at the matter-radiation equality, $a_{eq} \sim 3 \times 10^{-4}$, one neutrino species represents about 16% of the dark matter density [12]. In other words, if dark matter particles had a boost of $\sim 16\%$ they could mimic the effect of neutrino species, increasing the Hubble rate. In this way, the additional radiation density is given by $\rho_{extra} = f \times \rho_\chi(\gamma_\chi - 1)$, where f accounts for the fraction of the dark matter particles produced via this mechanism, with $\Delta N_{eff} \equiv N_{eff} - N_{eff}^{SM} = \rho_{extra}/\rho_{1\nu}$, N_{eff}^{SM} being the number of relativistic degrees of freedom in the ΛCDM model. Using the relations above we obtain,

$$\Delta N_{eff} = f \times (\gamma_\chi - 1)/0.16, \qquad (2)$$

which implies

$$\Delta N_{eff} \sim 5 \times 10^{-3} \left(\frac{\tau}{10^6 \text{ s}}\right)^{1/2}$$
$$\times \left[\left(\frac{m_{\chi'}}{2m_\chi} + \frac{m_\chi}{2m_{\chi'}} - 1\right)\right] \times f, \qquad (3)$$

for $t = t_{CMB}$. Therefore, if a fraction of the dark matter particles are non-thermally produced, with $m_{\chi'} \gg m_\chi$, they generate extra relativistic degrees of freedom. Several works have assessed
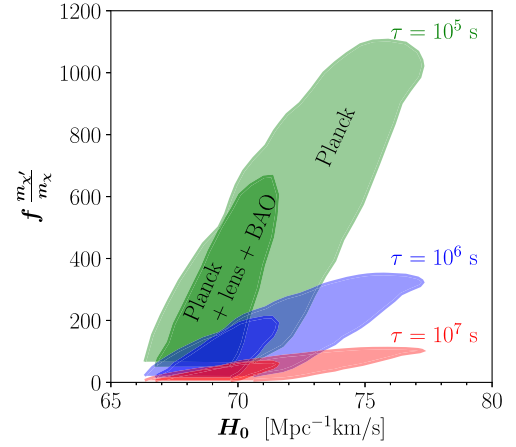

Fig. 1. Effect of the dark matter production mechanism on H_0 for lifetime $\tau = 10^5$ s (green), $\tau = 10^6$ s (blue) and $\tau = 10^7$ s (red). The contours correspond to 95% CL constraints from Planck 2015 power spectra excluding high l polarisation (light colors) and adding CMB lensing and BAO (dark colors) [15].

the impact of $N_{eff} > 3$ on the CMB power spectrum, as N_{eff} and H_0 are positively correlated [13–17]. We translate this correlation to our framework using Eq. (3) and find the results displayed in Fig. 1, which is based on the CMB and Baryonic Acoustic Oscillation (BAO) data [15]. Clearly, for $150 < f m_{\chi'}/m_\chi < 350$ and $\tau = 10^6$ s, we may obtain $H_0 \sim 74$ Mpc^{-1}km/s. As mentioned earlier, the fraction of dark matter produced via this mechanism is expected to be small since the bulk of the dark matter should be non-relativistic at the matter-radiation equality. Moreover, one can show that the fraction of dark matter produced via this mechanism becomes non-relativistic before matter-radiation equality, thus not constituting an additional relativistic degree of freedom at late times (see Appendix A).

To illustrate how that works we need to invoke the concept of free-streaming, which is the scale below which a dark matter particle do not cluster. Therefore on sufficiently small scales, the growth of perturbations is suppressed if the dark matter production mechanism discussed here were the main one. We can estimate the free streaming of the dark matter particles, produced via this mechanism with $m_{\chi'} \gg m_\chi$ to be [18],

$$\lambda_{FS} \sim 1 \text{ Mpc} \left(\frac{\tau}{10^6 \text{ s}}\right)^{1/2} \left(\frac{m_{\chi'}}{2m_\chi} - \frac{m_\chi}{2m_{\chi'}}\right), \qquad (4)$$

which leads to a λ_{FS} much larger than a Mpc scale, in complete disagreement with the Lyman-alpha forest that sets $\lambda_{FS} \ll 1$ Mpc [19]. We therefore conclude that such a production mechanism cannot be responsible for the overall dark matter density, as expected from CMB observations, which completely disqualify a hot dark matter candidate. In order to have a more quantitative assessment about the fraction f of dark matter particles that can be produced in this way we need to study the matter power spectrum [20,21].

In the matter-dominated phase of the universe, the linear fluctuation evolves below the free-steaming length as, $\delta \propto a^{1-3/5f}$ [22] for $f \ll 1$. Hence, the suppression that such production mechanism above brings to the matter-power spectrum is quantified by $\Delta = \frac{\delta_{f\neq0}}{\delta_{f=0}} = (a_{eq}/a)^{-3f/5} \sim \exp(-4.9f)$. Considering current measurements of the amplitude of matter clustering, σ_8 [23–26], CMB data [3], the clustering power in the Lyman-alpha forest [19], and the results of cosmological simulations [27–29] one needs a nearly pure cold dark matter regime. In other words, we require $\Delta > 0.95$, which implies that $f < 0.01$. Therefore, only a small fraction of dark matter may be produced via the proposed mecha-

nism, in order to be consistent with large-scale structure observations. Interestingly, although small it provides a possible solution to the H_0-tension problem discussed above. Generally speaking N_{eff} could be generated via new light thermal relics and new interactions with the active neutrinos, etc [30]. In our work, the increase in N_{eff} and consequently in H_0 are tied to the dark matter production mechanism. In what follows, we discuss the effect of this dark matter production on the long-standing ^7Li problem.

3. Light dark matter and the lithium problem

The primordial Lithium abundance is derived from low-metallicity halo stars observations [6], whereas the theoretical prediction is based on the baryon-to-photon ratio, which is extracted from CMB observations. These determinations of the ^7Li abundance differ by roughly a factor of three [6], and the fact that nuclear reactions, cosmological modifications, modified statistics, possible primordial magnetic fields, and exotic decays involving charged particles all failed to solve the Lithium problem represents an incomplete success for cosmology, as reviewed in [10]. Some solutions to this problem have been proposed in the past years (see e.g. [31] and references therein).

In a three-body decay the photon in the final state would have a continuous spectrum with energy sufficiently large to alter the abundance of several elements since these photons would induce numerous nuclear reactions. On the other hand, having an arbitrary two-body decay with high energetic photons does not suffice either because secondary nuclear reactions occur. For instance, taking our scenario as an example, in the two-body decay with $m_{\chi'} \gg m_\chi$, photons are emitted with $E_\gamma \simeq m_{\chi'}/2$, electromagnetic cascades would be induced by the injection of an energetic γ in a medium comprised of radiation, magnetic fields and matter [32]. Such photon emission could be catastrophic to the abundance of light elements because these photons may induce nuclear reactions and alter the BBN predictions, which is precisely the problem with past proposals.

However, if the energy of the photon injected is small enough, between $1.59 - 2.22$ MeV the electromagnetic cascades develop differently, allowing to destroy enough ^7Li without affecting the abundance of other elements. This energy window has to do with the Beryllium nucleus that has a photon dissociation threshold of 1.59 MeV and Deuterium whose threshold is 2.22 MeV. Taking into account the fact that MeV photons induce non-thermal nucleosynthesis processes where the final spectrum of the photons is significantly different from the injected one it has been shown that one could successfully solve the Lithium problem via electromagnetic injection [33]. Now, knowing that the total electromagnetic energy released is $\zeta_{\text{em}} = E_\gamma Y_\gamma$, where Y_γ is the ratio of the number density of photons produced in the decay to the number density of CMB photons, which yields,

$$\zeta_{\text{em}} \sim 1.5 \times 10^{-8} \text{ MeV} \left(\frac{m_{\chi'}}{m_\chi} - \frac{m_\chi}{m_{\chi'}} \right) \left(\frac{f}{0.01} \right), \qquad (5)$$

we can obtain the region in the parameter space, lifetime vs ζ_{em}, in which the Lithium abundance is reduced from 20% up to 80% for instance. Using Eq. (5) we may display this region in terms of $f m_{\chi'}/m_\chi$ vs lifetime. Considering the region of the parameter space favored in Fig. 1, which fix $f m_{\chi'}/m_\chi$, we assess whether is possible to reconcile both the H_0 and the Lithium problems, as $f m_{\chi'}/m_\chi$ governs the overall energy injection as well. In Fig. 2 we show in green the region of parameter space in which the ^7Li abundance is diluted in 20%-80%.[1] As mentioned earlier, the

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[1] Compared to Ref. [33], here a bigger range was used. The results were rescaled using the fact that dilution due to entropy injection scales linearly.
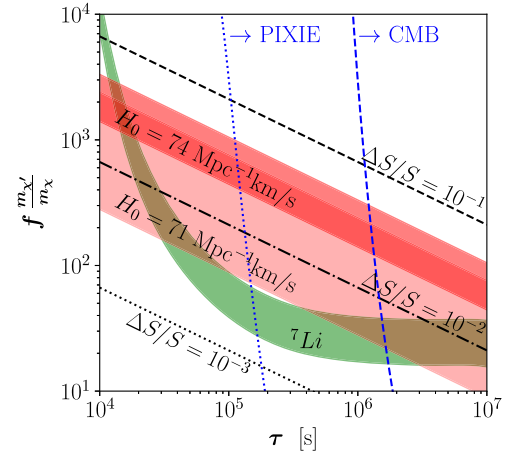

Fig. 2. Region of parameter space in which the Lithium abundance is diluted by 20-80% from BBN original prediction (green), and where $H_0 = 71$ Mpc^{-1}km/s (light red) or $H_0 = 74$ Mpc^{-1}km/s (dark red). The blue curves correspond to current (dashed) and projected (dotted) CMB spectral distortion bounds. We also display the $\Delta S/S_i$ contours to show that our region of interest yields a small entropy change. For $\tau \simeq 2 \times 10^4$ s one can simultaneously accommodate the Lithium and H_0 problems with light dark matter. Notice if one assumes $f \ll 1$, sub-keV dark matter arises. See text for details.

photon should be emitted with an energy of about 2 MeV. As our reasoning is built under the assumption that $m_{\chi'} \gg m_\chi$, thus $m_{\chi'} = 4$ MeV throughout. One can easily fix the fraction of dark matter produced in this mechanism, f, to extract the dark matter mass. For instance, with $f m_{\chi'}/m_\chi = 10^3$, we get $m_\chi = 0.04$ keV for $f = 0.01$.

In Fig. 2 the dashed (dotted) blue curves correspond to the limits based on the CMB spectral distortion. An additional energy injection in the form of photons brings distortions to the CMB black-body spectrum. For $\tau < 10^3$ s, these photons produced in the decay quickly thermalize via processes such as Compton scattering $e\gamma \to e\gamma$ and double Compton scattering $e\gamma \to e\gamma\gamma$ [34]. Although, for larger lifetimes these processes are not sufficiently efficient and end up altering the photon spectrum of the CMB to a Bose-Einstein distribution with a chemical potential ($\mu \neq 0$). Therefore, constraints on a chemical potential, $\mu < 9 \times 10^{-5}$, lead to bounds on the total energy injection [35] which is related to $m_{\chi'}/m_\chi$, as displayed in Fig. 2. The dotted blue curve represents a projection using the PIXIE setup corresponding to $\mu < 5 \times 10^{-8}$ [36]. These CMB spectral distortion bounds exclude the region at the right of the curves and are the strongest constraints on such early time energy injection episodes [37–41].

Besides these bounds, one could imagine that the energetic photons produced in the proposed mechanism lead to a large entropy injection. However, such photons yield a small entropy change which is quantified by (see Appendix B),

$$\frac{\Delta S}{S_i} \sim 10^{-4} \left(\frac{\zeta_{\text{em}}}{10^{-6} \text{ MeV}} \right) \left(\frac{\tau}{10^6 \text{ s}} \right)^{1/2}. \qquad (6)$$

The contours of $\Delta S/S_i$ are exhibited in Fig. 2. One may conclude that the entropy change of our mechanism is small and fully consistent baryometer tests (see Appendix B).

4. Discussion

Fig. 2 also shows that there is a region of the parameter space corresponding to $\tau \simeq 2 \times 10^4$ s and $f m_{\chi'}/m_\chi \simeq 2 \times 10^3$ which is capable of diluting the Lithium abundance while simultaneously reproducing $H_0 \simeq 74$ Mpc^{-1}km/s, as indicated by recent local measurements – while being consistent structure formation and CMB constraints. These results rely on the existence of very

light dark matter with sub-keV mass, with a small fraction of them being produced in association with photons. In other words, the production of sub-keV dark matter seems to provide a possible solution to current problems in the standard cosmology. We emphasize that our results do depend on the dark matter abundance. Thus, in order to solve both problems dark matter must appear in the final state of the decay channel proposed. It could not have been any particle, as the abundance of dark matter determines the amount of extra radiation in the early universe which is directly associated with the increase in H_0. Notice that in the deduction of Eq. (2) we used ρ_{extra}, which is related to the dark matter density. Consequently our findings concerning H_0 are tied to the dark matter density. Therefore, if new independent measurements of H_0 converge increasing the need for new physics, sub-keV dark matter stands as a viable possibility, strengthening the need for new detectors sensitive to very light dark matter [42].

Finally, sub-keV dark matter could have been produced non-thermally in the early universe via the freeze-in mechanism [43]. In fact, if the production channel has a small available phase-space, the dark matter free-streaming length is suppressed and therefore the Lyman-alpha constraint can be avoided [44,45]. A very light dark matter could also be produced via the misalignment mechanism typical of axion dark matter models [46]. It is also important to mention that the Fermi-Dirac statistics limits dark matter mass to be higher of few hundreds of eV, independent of the production mechanism [47,48]. Therefore, a sub-keV dark matter model is perfectly conceivable once we invoke non-thermal processes. Moreover, as a small fraction of dark matter may be produced via this mechanism larger-scale structures are not affected [49].

5. Final remarks

Recently, several proposals have surfaced trying to induce a larger expansion rate via an increase on N_{eff}, such as dark matter interactions with active neutrinos or via the introduction of new light species. Moreover, numerous attempts to solve the Lithium have been put forth in the context of late particle decays involving particles with an electric charge, neutral particles and even decays having dark matter-like particles in the final state. Often times dark matter in these works refer to neutral particles which are stable and interact weakly. However, being stable and a weakly interacting massive particle does not warrant a particle the role of dark matter in our universe.

In this work, we go beyond that and propose a possible, unified solution to the Lithium and H_0-tension problems which is connected to the production of dark matter. Such result is obtained through a mechanism of light (sub-keV) dark matter production in which a fraction of the dark matter particles are produced non-thermally in association with photons. We highlight that in this case the increase in N_{eff}, and consequently in H_0, is tied to the dark matter production mechanism. We have discussed the observational viability of this framework in light of the current large-scale structure and CMB data and shown that for an interval of the parameter values the Lithium abundance may be significantly reduced without altering other elements abundance, while simultaneously increasing the current expansion rate in agreement with current local measurements.

As is well known, light dark matter has gained attention recently as the still popular WIMPs (Weakly Interacting Massive Particles) subject to intense experimental searches have not been observed. We believe that the results discussed in this paper further motivate experimental searches for sub-keV dark matter. Finally, we want to notice that even if we expect the analytical approximations used in this analysis to be valid, a full numerical analysis could be done.

Appendix A

In this appendix we are going to show that a 40 eV dark matter particle, χ is non-relativistic at the matter-radiation equality when it is produced via the $\chi' \to \chi + \gamma$ mechanism. As this decay happens in the radiation-dominated era, the dark matter temperature is governed by

$$T = T_\tau \frac{a_\tau}{a}. \tag{A.1}$$

Moreover, the scale factor a evolves as

$$\frac{a}{a_0} = \left(\frac{t}{t_0}\right)^{1/2}. \tag{A.2}$$

In this way,

$$a_\tau = \left(\frac{\tau}{13.7 \times 10^9 \text{ yr}}\right)^{1/2}, \tag{A.3}$$

which implies that $a_\tau = 1.52 \times 10^{-7}$, for $\tau \sim 10^4$ s, which is our the benchmark value. We used 1 yr $= 4.3 \times 10^8$ s.

As $T = T_0/a$, $T_\tau = 1500$ eV. With these results at hand we can now determine the temperature of χ at the matter-radiation equality, i.e. for $a_{\text{eq}} = 3 \times 10^{-4}$. As

$$T_{\text{eq}} = T_\tau \frac{a_\tau}{a_{\text{eq}}} \tag{A.4}$$

we get, $T_{\text{eq}} \sim 0.76$ eV which is smaller than $m_\chi = 40$ eV. Therefore, χ is certainly non-relativistic at the matter-radiation equality. A further note concerning our mechanism is related to BAO. We may use again Eq. (A.1) to find that during BAO times ($a \sim 4 \times 10^{-5}$), $T \sim 5.7$ eV. Therefore, our mechanism behaves like the standard cold dark matter paradigm.

Appendix B

In this appendix we will show why the energetic photon produced in the proposed mechanism does not imply a large entropy injection. We will arrive at this conclusion step by step.

As we know there is no fundamental reason for the baryometer $\eta = n_b/n_\gamma$ inferred from BBN and CMB inputs to be the same as they refer to different epochs of the universe evolution. Knowing that number of baryon is

$$N_B = n_B a^3 = \eta\, n_\gamma a^3 = \eta\, \frac{2\zeta(3)}{\pi^2}\, T^3 a^3 \tag{B.1}$$

and that the entropy S is proportional to $T^3 a^3$, we get

$$\frac{\eta_f}{\eta_i} = \frac{S_f}{S_i}, \tag{B.2}$$

where "f" and "i" indices indicate the values of these quantities at times t_f and t_i.

As we know the abundance of light elements restrict the value for η, which is in agreement with CMB measurement. Therefore, it prevents any significant entropy production between BBN and CMB decoupling. Our scenario advocates χ' decays precisely between BBN and CMB decoupling, but we will show that for the region of interest, there is no significant entropy injection. To assess the amount of entropy injected between t_i and t_f due to the χ' decay with number density $n_{\chi'}$, we need to compute the differential change in entropy in a comoving volume at temperature T,

$$dS = \frac{dQ}{T}, \qquad \text{with} \qquad dQ = \zeta_{\text{em}}\, n_{\chi'}\, a^3 \frac{dt}{\tau}. \tag{B.3}$$

Using the entropy relation with the scale factor,

$$S = g_{s*} \frac{2\pi^2}{45} T^3 a^3 \tag{B.4}$$

we can rewrite Eq. (B.3) to obtain,

$$\frac{S_f}{S_i} = \exp\left[\int_{t_i}^{t_f} \zeta_{\text{em}} \frac{45}{2\pi^2 g_{s*} T^4} n_{\chi'} \frac{dt}{\tau} \right]. \tag{B.5}$$

As χ' decays its number density falls exponentially, therefore

$$n_{\chi'} = n_{\chi'_i} \frac{a_i^3}{a^3} \exp\left[-\frac{t}{\tau} \right] = n_{\chi'_i} \frac{g_{s*} T^3 S_i}{g_{s*}^i T_i^3 S} \exp\left[-\frac{t}{\tau} \right] \tag{B.6}$$

which can use it to substitute into Eq. (B.5) to find,

$$\frac{S_f}{S_i} = \exp\left[\int_{t_i}^{t_f} \zeta_{\text{em}} \frac{45}{2\pi^2 g_{s*} T^4} \left(n_{\chi'_i} \frac{g_{s*} T^3 S_i}{g_{s*}^i T_i^3 S} \exp\left[-\frac{t}{\tau} \right] \right) \frac{dt}{\tau} \right] \tag{B.7}$$

which simplifies to,

$$\frac{S_f}{S_i} = \exp\left[\zeta_{\text{em}} \frac{45 n_{\chi'_i}}{2\pi^2 g_{s*}^i T_i^4} \int_{t_i}^{t_f} \left(\frac{T_i S_i}{T S} \exp\left[-\frac{t}{\tau} \right] \right) \frac{dt}{\tau} \right]. \tag{B.8}$$

Notice that we have not made any strong assumption up until now. We need to solve Eq. (B.8) and to do so we have to carry out the integral. We will write the temperature as function of the time, and for that we will use some known relations. First, having in mind that χ' decays during the radiation-dominated era,

$$\frac{\rho_{\chi'}}{\rho_R} = m_{\chi'} Y_{\chi'} \frac{60\zeta(3)}{\pi^2 g_* T^4} \ll 1 \tag{B.9}$$

where we used $\rho_R = \frac{\pi^2}{30} g_* T^4$.

Solving the Friedmann equations for a radiation-dominated universe we get,

$$t = \frac{1}{2H}, \qquad \text{where} \qquad H^2 = \frac{8\pi}{3M_{pl}} \rho_R. \tag{B.10}$$

Now with these relations we may write the temperature as a function of the time and compute the integral in Eq. (B.8). Assuming g_* to be constant throughout ($g_* = 3.36$) we get [50],

$$\frac{\Delta S}{S_i} \sim \ln \frac{S_f}{S_i} \simeq 10^{-4} \left(\frac{\zeta_{\text{em}}}{10^{-6}\,\text{MeV}} \right) \left(\frac{\tau}{10^6\,s} \right)^{1/2} \tag{B.11}$$

Finally, using Eqs. (3) and (5) we obtain,

$$\frac{\Delta S}{S_i} \sim 0.06 \Delta N_{\text{eff}} \tag{B.12}$$

in the limit $m_{\chi'} \gg m_\chi$.

As our region of interest yields $0.1 < \Delta N_{\text{eff}} < 0.7$, through Eq. (B.12) we find that it leads to a small entropy change. Recent results point to $0.021 < \Omega_b = 0.022$ [3,51,52], where $\Omega_b = \rho_b/\rho_c$, where ρ_c is the critical density. Knowing that $\Omega_b = \eta \times 10^{10} h^{-2}/(274) = (0.021 - 0.024) h^{-2}$, we conclude that $5.8 < \eta < 6.6$ [53]. Hence, our mechanism is in agreement baryometer tests. This fact can be easily observed by looking at Fig. 2.

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