



Light Particle Solution to the Cosmic Lithium Problem

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We point out that the cosmological abundance of ${}^7\text{Li}$ can be reduced down to observed values if during its formation, big bang nucleosynthesis is modified by the presence of light electrically neutral particles X that have substantial interactions with nucleons. We find that the lithium problem can be solved without affecting the precisely measured abundances of deuterium and helium if the following conditions are satisfied: the mass (energy) and lifetimes of such particles are bounded by $1.6\text{ MeV} \leq m_X(E_X) \leq 20\text{ MeV}$ and $\text{few}100\text{s} \lesssim \tau_X \lesssim 10^4\text{ s}$, and the abundance times the absorption cross section by either deuterium or ${}^7\text{Be}$ are comparable to the Hubble rate, $n_X \sigma_{\text{abs}} v \sim H$, at the time of ${}^7\text{Be}$ formation. We include X -initiated reactions into the primordial nucleosynthesis framework, observe that it leads to a substantial reduction of the freeze-out abundances of ${}^7\text{Li} + {}^7\text{Be}$, and find specific model realizations of this scenario. Concentrating on the axionlike-particle case, $X = a$, we show that all these conditions can be satisfied if the coupling to d quarks is in the range of $f_d^{-1} \sim \text{TeV}^{-1}$, which can be probed at intensity frontier experiments.

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Introduction.—Big bang nucleosynthesis (BBN) is a cornerstone of modern cosmology [1,2]. Its success rests on the agreement among the observationally inferred and predicted primordial values for the deuterium and helium abundances. In particular, the latest measurements of the deuterium abundance, $(\text{D}/\text{H})_{\text{obs}} = (2.53 \pm 0.04) \times 10^{-5}$ [3], are in remarkable accord with BBN predictions under standard cosmological assumptions, and using the baryon-to-photon ratio—precisely measured via the anisotropies in the cosmic microwave background (CMB) [4]—as an input. However, the BBN success is not complete: the predicted value of the lithium abundance [2], $({}^7\text{Li}/\text{H})_{\text{BBN}} = (4.68 \pm 0.67) \times 10^{-10}$, is significantly higher, by a factor of $\sim(2-5)$, than the value inferred from the atmospheres of PopII stars, $({}^7\text{Li}/\text{H})_{\text{obs}} = (1.6 \pm 0.3) \times 10^{-10}$ [5]. What prevents this discrepancy, known as the *cosmological lithium problem*, from becoming a full-blown crisis for cosmology is the questionable interpretation of $({}^7\text{Li}/\text{H})_{\text{obs}}$ as being the truly primordial value, unaltered by subsequent astrophysical evolution. Indeed, several astrophysical mechanisms of how the reduction of lithium may have come about have been proposed (see, e.g., Refs. [6,7]), none of which resolve the problem completely. Thus, *new physics* (NP) scenarios, such as modifications of standard BBN, can be entertained as solutions to this long-standing discrepancy.

The (over)abundance of lithium is ultimately related to the excessive production of the ${}^7\text{Be}$ isotope, that radiatively decays to ${}^7\text{Li}$ during the post-BBN evolution. Its reduction occurs at $T \gtrsim 25\text{ keV}$ via the sequence of neutron capture in the ${}^7\text{Be}(n, p){}^7\text{Li}$ reaction, followed

by ${}^7\text{Li}(p, \alpha){}^4\text{He}$. For a while, NP scenarios supplying *extra* neutrons, thereby reducing the ${}^7\text{Li} + {}^7\text{Be}$ abundance [8–10], were considered to be attractive solutions to the lithium problem. However, in light of the latest (D/H) measurements [3], *any* such solution is strongly disfavored [11,12] as extra neutrons lead to the overproduction of deuterium, quite generically resulting in $(\text{D}/\text{H})_{\text{BBN}} > 3 \times 10^{-5}$, far from the allowed range. This excludes a variety of models with late decays of electroweak-scale particles, including many supersymmetric scenarios. Nevertheless, isolated cases of NP models, typically involving sub-GeV particles, can reduce lithium while keeping deuterium and helium consistent with observations [13,14]. We also note that BBN catalyzed by the presence of negatively charged weak-scale particles [15–17] still has potential for reducing the ${}^7\text{Be}$ abundance.

In this Letter we suggest a new mechanism for selectively reducing the lithium abundance, while keeping other BBN predictions intact. ${}^7\text{Be}$ is formed in the narrow temperature range from 60 to 40 keV, after deuterium formation and during ${}^3\text{He}$ formation, in a rather slow, sub-Hubble rate reaction ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$. This is why its abundance is very small, $({}^7\text{Be}/{}^3\text{He}) \ll 1$, and it contrasts with other nuclear reactions responsible for ${}^4\text{He}$, ${}^3\text{He}$, D, which remain very fast in that temperature window. Therefore, if BBN is modified by a new light and metastable neutral particle X that has direct interactions with nucleons and can react as in Fig. 1, *either* with ${}^7\text{Be}$ or deuterium (or both) via



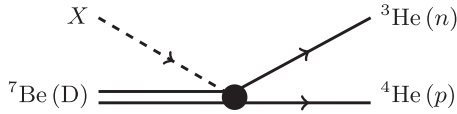


FIG. 1. Spallation of a nucleus due to absorption of a bosonic state X .

at $T \sim 50$ keV, then one should expect that the ${}^7\text{Be}$ (and consequently the observed ${}^7\text{Li}$) abundance will be reduced. Most importantly, if reactions R1 and R2 occur relatively early, $T > 10$ keV, and the energy carried by the X particle is below the ${}^4\text{He}$ binding energy, the helium and deuterium abundance will not be altered in a significant way, as neutrons generated in R2 will be incorporated back to deuterium via the process $p(n, \gamma)\text{D}$ that remains faster than neutron decay down to temperatures of $T \sim 10$ keV. Note that X cannot be a light standard model particle; nonthermal photons at these temperatures are quickly degraded in energy below nuclear binding thresholds, and neutrinos have too small an interaction rate.

In the remainder of this Letter, we show that these qualitative expectations are supported by detailed BBN calculations. We determine the required properties of X , provide concrete particle physics realizations, and point out experimental avenues to test the proposed scenarios.

New light metastable particles during BBN.—Light, very weakly coupled particles X can selectively affect BBN processes if their number density is large, but their energy density remains subdominant to that of photons. Therefore, as a guideline, we shall assume that their number density during BBN satisfies the bound

$$n_b \lesssim n_X < \frac{T}{E_X} \times n_\gamma, \quad (2)$$

where E_X is the energy carried by these particles (and $E_X = m_X$ for the nonrelativistic case). Since the respective baryon and photon number densities n_b and n_γ are widely different, $n_b/n_\gamma = 6.1 \times 10^{-10}$ [4], the abundance of n_X [Eq. (2)] can vary in a rather large range. We distinguish two different scenarios. *Scenario A* assumes that X is nonrelativistic, with mass in the range from 1.6 to 20 MeV, and it participates in the reactions [Eq. (1)] before decaying either to standard model (SM) radiation, or to a beyond-SM radiation species. *Scenario B* assumes that there is an inert, almost noninteracting neutral progenitor particle X_p that decays to (nearly) massless states X which participate in the nuclear reactions before being redshifted below nuclear reaction thresholds. For the two-body decay, $X_p \rightarrow XX$, the mass X_p must lie in the range from 3.2 to 40 MeV, and the mass of X should be less than ~ 1 eV (to avoid hot dark matter constraints.) The upper mass bound in both scenarios ensures that ${}^4\text{He}$ is not directly affected by X -induced splitting.

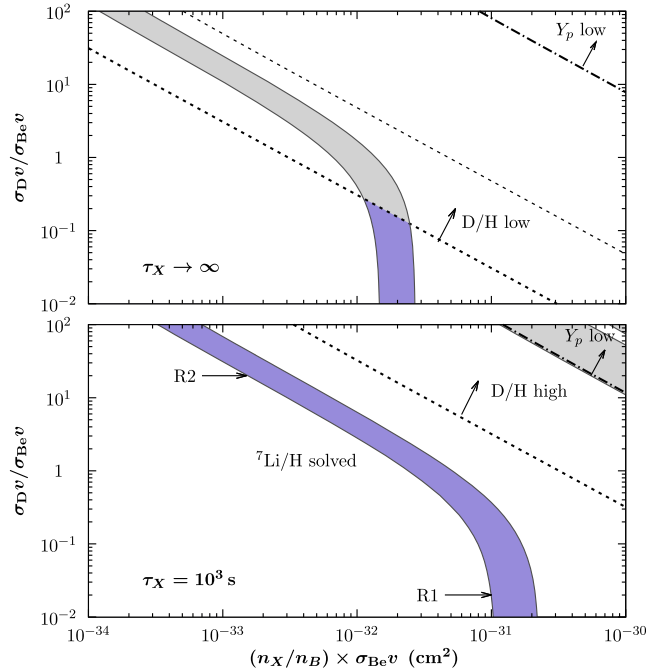


FIG. 2. The contours of light element abundances as a function of the two reaction rates R1 and R2 in Scenario A, for $\tau_X \gg t_{\text{BBN}}$ (top panel), and $\tau_X = 10^3$ s (lower panel); σ_D is constant along the dotted lines. Inside the shaded regions, the lithium problem is solved.

We modify our BBN code [18] to include the effects of X particles. In the following we expose the relevant physics by using Scenario A for which we add the parameters $\{m_X, \tau_X, n_X/n_b, \sigma_{\text{Be}}v, \sigma_{\text{D}}v\}$ to the code, where n_X stands for the initial (undecayed) abundance of X and $\sigma_{\text{Be}}v, \sigma_{\text{D}}v$ are the respective reaction cross sections for Eq. (1). We assume that they are dominated by the s wave of initial particles, for which they become temperature-independent parameters. The reactions with $A = 3$ elements, e.g., ${}^3\text{He}(X, p)\text{D}$, are generically less important and, in the interest of concision, we avoid them altogether by taking $2.2 \text{ MeV} < m_X < 5.5 \text{ MeV}$. We note in passing, though, that $m_X > 5 \text{ MeV}$ may be beneficial since ${}^7\text{Be}(X, p){}^6\text{Li}$ opens as an additional depleting channel. Note that the assumed small couplings of X and large abundances [Eq. (2)] make the reverse reactions, e.g., $n(p, X)\text{D}$, negligible.

The results of our calculations are presented in Fig. 2. The dark shaded regions correspond to reaction rates that reduce lithium to the range ${}^7\text{Li}/\text{H} = (1-2) \times 10^{-10}$ without affecting other elements. In the top panel, the lifetime of X is taken to be large with respect to the cosmic time at BBN and, consequently, the late reaction R2 reduces the deuterium abundance too much, unless $\sigma_{\text{Be}} > 10\sigma_{\text{D}}$. Such a hierarchy of cross sections would require additional tuning of the properties of X . In contrast, lifetimes around 10^3 seconds (lower panel) allow for a *generic solution* to the lithium problem, without altering deuterium beyond the

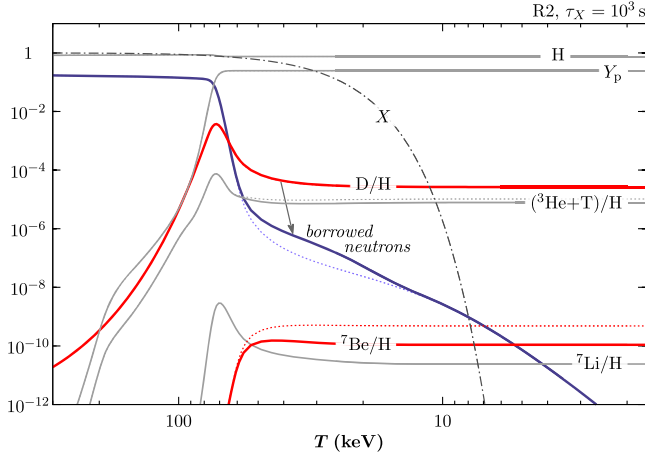


FIG. 3. Temperature evolution of elemental abundances, with BBN modified by R2, initiated by X with $\tau_X = 10^3$ s and $(n_X/n_b)\sigma_D v = 5 \times 10^{-32}$ cm². The temporary increase in n leads to the suppression of ${}^7\text{Be}$ but does not affect $(\text{D}/\text{H})_{\text{BBN}}$. The dotted lines correspond to the prediction of standard BBN.

observational bounds. In the vertical part of the shaded band, corresponding to small values of σ_D , ${}^7\text{Be}$ is directly depleted via R1, while in the diagonal part σ_{Be} is small and ${}^7\text{Be}$ reduction is achieved via neutrons generated through R2. Note that contrary to models of decaying weak-scale particles these are not extra neutrons, but *borrowed* ones, that return to deuterium via the fast reaction $p(n, \gamma)\text{D}$. Thus for $\tau_X \sim 10^3$ s, the preferred R1 or R2 reaction rates solving the ${}^7\text{Li}$ overproduction problem are

$$\begin{aligned} \text{R1: } & (n_X/n_b) \times \sigma_{\text{Be}} v \approx (1-2) \times 10^{-31} \text{ cm}^2, \quad \text{or} \\ \text{R2: } & (n_X/n_b) \times \sigma_D v \approx (3-7) \times 10^{-31} \text{ cm}^2. \end{aligned} \quad (3)$$

The observational constraints in Fig. 2 are $2.45 \times 10^{-5} \leq \text{D}/\text{H} \leq 3 \times 10^{-5}$ (lower limit nominal 2σ from [3]; upper limit conservative) and $Y_p \geq 0.24$; also shown is the unlabeled D/H contour 10^{-5} . The effect of the “borrowed” neutrons resulting from R2 is shown in Fig. 3.

The absorption rates in Eq. (3), determined for τ_X on the order of 10^3 seconds, are comparable to the Hubble rate during ${}^7\text{Be}$ synthesis as should be expected from the NP-modified BBN scenarios that achieve a factor of $O(\text{few})$ reduction of the beryllium abundance. Short X lifetimes, $\tau_X \ll 10^4$ s, have the additional benefit of reducing the sensitivity to visible decays of X to $\gamma\gamma$ or e^+e^- , as BBN is largely insensitive to electromagnetic energy injections at early times (see, e.g., Ref. [18]). Similar solutions can be found in Scenario B, where τ_{X_p} should be chosen in a similar range, while the R1/R2 reaction rates will receive an additional temperature dependence due to the redshift of E_X . A full scan of the viable parameter space will be presented in a more detailed publication [19].

Model realization: couplings, cross sections, abundance.—The respective ranges Eqs. (2) and (3) for the abundances and reaction rates suggest a typical size for the R1 and/or R2 cross sections. If we choose X particles of ~ 5 MeV mass (or energy) to contribute 1% of the photon energy density at $T = 50$ keV, we arrive at $\sigma_{\text{abs}} v \sim 10^{-38}$ cm². This is much smaller than the typical ($\sim \text{mbn}$) range for photonuclear reactions, and much larger than typical weak scale cross sections $\sim G_F^2 (E_X)^2$. Yet, the lifetimes of X particles are commensurate with β -decay lifetimes, implying very small couplings to electrons, photons, and neutrinos. It is then clear that only selected particle physics models can simultaneously account for Eqs. (2), (3), and $\tau_X \sim 10^3$ s.

A variety of models involving light, weakly interacting particles have been extensively studied in recent years [20], including axions, axionlike particles (ALPs), and “dark” vectors. The MeV-mass range has been independently motivated in [21,22], as an ideal range for the force carrier that mediates dark matter self-interactions, as well as its interactions with the SM. Here we provide “proof of existence” of models that satisfy the requirements on τ_X , σ_{abs} , and n_X derived from our BBN analysis.

If X is massive (Scenario A), its decay to leptons will scale as $\Gamma_{e^+e^-} \propto m_X g_e^2 / (4\pi)$. Given a lifetime of 10^3 s, the coupling to electrons would have to be smaller than $g_e \lesssim 10^{-12}$. At the same time, the coupling g_N to nucleons will have to be much larger, pointing to “leptophobic” models of light particles. Models with “dark photons” [20] would hence not provide viable solutions, while models based on gauged baryon number $U(1)_B$ [23,24] would have to be tuned to suppress the loop-induced couplings to leptons. Models based on so-called ALPs represent a better candidate, and below we outline their main features. We consider a model where the X particle is an ALP a which interacts mainly with down-type quarks. To avoid strong constraints from the flavor-violating K and B meson decays, mediated by the top- W loop, the coupling to up-type quarks is assumed to be suppressed. We note in passing that such construction can be UV-completed by using multiple Higgs bosons and an interaction $H_u H_d \exp\{ia/f_a\}$, that gives $f_d \gg f_u$ when $\langle H_u \rangle \gg \langle H_d \rangle$. Going from the quark-ALP to the meson-nucleon-ALP interaction, we obtain the most important interactions with neutrons, protons and pions.

$$\begin{aligned} \mathcal{L}_{aq} &= \frac{\partial_\mu a}{f_d} \bar{d} \gamma_\mu \gamma_5 d \Rightarrow \\ \mathcal{L}_{a\pi N} &= \frac{\partial_\mu a}{f_d} \left[f_\pi \partial_\mu \pi^0 + \frac{4}{3} \bar{n} \gamma_\mu \gamma_5 n - \frac{1}{3} \bar{p} \gamma_\mu \gamma_5 p \right]. \end{aligned} \quad (4)$$

We have used a naive quark model estimate for the spin content of the nucleons, and $f_\pi = 93$ MeV. The kinetic mixing of the two scalars results in a small admixture of π^0 to an on-shell a , with the mixing angle

$\theta = (f_\pi/f_d) \times (m_a^2/m_\pi^2)$, and induces the decay $a \rightarrow \gamma\gamma$. Upon appropriate rescaling, $\Gamma_{\gamma\gamma}^a \approx \theta^2 (m_a/m_\pi)^3 \Gamma_{\gamma\gamma}^{\pi^0}$, which gives the lifetime in the right ballpark for $f_d \sim \text{TeV}$ and $m_a \sim 5 \text{ MeV}$. The coupling of a to the $\gamma_\mu \gamma_5$ nucleon current leads to the nonrelativistic Hamiltonian proportional to nucleon helicities. To estimate the absorption cross sections we follow the method of Ref. [25] that relates the ALP absorption to the photoelectric effect in the dipole ($E1$) approximation. Assuming a very simple model of ${}^7\text{Be}$ as a bound state of nonrelativistic ${}^3\text{He}$ and ${}^4\text{He}$, and D as a bound state of n and p , and neglecting nuclear spin forces, we arrive at the following estimate for the relation between the R1 and R2 cross sections and those of the ${}^7\text{Be}(\gamma, \alpha){}^3\text{He}$ and $\text{D}(\gamma, p)n$ processes:

$$\frac{\sigma_{\text{abs},i} v}{\sigma_{\text{photo},i} c} \approx \frac{C_i}{4\pi\alpha} \times \frac{m_a^2}{f_d^2}, \quad (5)$$

where $i = {}^7\text{Be}, \text{D}$ and the coefficients $C_{{}^7\text{Be}} = \frac{64}{3}$, $C_{\text{D}} = \frac{59}{9}$ reflect spin combinatorial factors. The photoabsorption cross section by D is well known, while for ${}^7\text{Be}$ we use recent evaluations [26]. We conclude that $f_d \sim \text{TeV}$ yields both lifetimes and absorption cross sections in the desired ballpark.

The remaining undetermined parameter is the abundance n_a prior to decay. It is easy to see that obtaining the correct abundance range would require some depletion of a : despite its small width, a will get thermally populated during the QCD epoch. We have examined several ways of depleting its abundance, all of which require additional particles in the light sector. Disregarding the issue of technical naturalness of small scalar masses, one can imagine that a coupling to a nearly massless scalar s , $(\lambda/4)a^2 s^2$, mediates the depletion of a at $T \sim m_a$ via $aa \rightarrow ss$. Given the annihilation cross section $\sigma_{\text{ann}} v = \lambda^2 / (64\pi m_a^2)$, the entire range of abundances is covered for $10^{-5} \lesssim \lambda \lesssim < 10^{-1}$. Alternatively, one can achieve a similar depletion of a via co-annihilation with another light species, or via the $3a \rightarrow 2a$ process as, e.g., in Ref. [27]. More details on viable cosmological models of ALPs will be provided in Ref. [19].

Scenario B, with unstable particles decaying to massless (or nearly massless) ALPs, $X_p \rightarrow aa$, is even easier to implement. Consider a nearly massless ALP a , and its progenitor X_p coupled to the SM via

$$\mathcal{L}_{XX_p} = AX_p(H^\dagger H) + BX_p a^2 + \mathcal{L}_{aq}, \quad (6)$$

where H is the SM Higgs field. The required abundance of a parent scalar X_p can be achieved via the ‘‘freeze-in’’ mechanism (see, e.g., Ref. [13]) by dialing the mixing with the SM Higgs, $A \sim (10^{-9} - 10^{-5}) \text{ GeV}$. The decay of X_p to ALPs is controlled by the B parameter, and $\tau_{X_p} \sim 10^3 \text{ s}$ is achieved with $B \sim 10^{-11} \text{ MeV}$. The nuclear breakup cross sections due to a massless axion can again be related to the

photonuclear cross section [25]. Performing calculations similar to Eq. (5), we find

$$\frac{\sigma_{\text{abs},i}}{\sigma_{\text{photo},i}} \approx \frac{D_i}{4\pi\alpha} \times \frac{E_a^2}{f_d^2}, \quad (7)$$

with $D_{{}^7\text{Be}} = \frac{128}{9}$, $D_{\text{D}} = \frac{118}{27}$. In calculating the impact on BBN in this scenario, we account for the redshifting of E_a from $m_{X_p}/2$ to R1 and R2 thresholds.

Searching for hadronic ALPs at the intensity frontier.— Our proposal for the lithium reduction mechanism involves light particles in the several MeV range, but with rather small couplings. Such particles are being searched for at intensity frontier experiments [20]. To better define the parameter space of interest, we take Scenario B, and vary τ_{X_p} , and f_d , by fixing a fiducial value of n_{X_p} , the X_p abundance prior to decay. The results are shown in Fig. 4. The ‘‘pileup’’ from redshifted X results in sensitivity to lifetimes before the end of the D bottleneck, $\tau_{X_p} < 100 \text{ s}$; with $n_{X_p} \sim 10^4 n_b$ a depletion of lithium by a factor of a few is possible with $f_d \sim \text{TeV}$.

Next, we estimate the expected signal in beam dump experiments such as LSND [28]. The ALP production in p -nucleus collisions is followed by the scattering or absorption of a by nuclei of the target. We assume that the number of produced ALPs scales with the number of produced π mesons as $N_a \sim (f_\pi/f_d)^2 \times N_\pi$. Concentrating on the photon production in the $p(a, \gamma)p$ process, we estimate its cross section [25] as $\sigma_{ap} \sim \alpha (E_a/f_d)^2 m_p^{-2} \sim (100 \text{ MeV}/f_d)^2 \times 10^{-29} \text{ cm}^2$, where $E_a \sim 200 \text{ MeV}$ is a typical energy of produced mesons and ALPs [29]. The estimated number of events

$$N_{\text{events}} \sim \frac{N_a N_p \sigma_{ap}}{4\pi L^2} \sim 6 \times \left(\frac{\text{TeV}}{f_d} \right)^4 \quad (8)$$

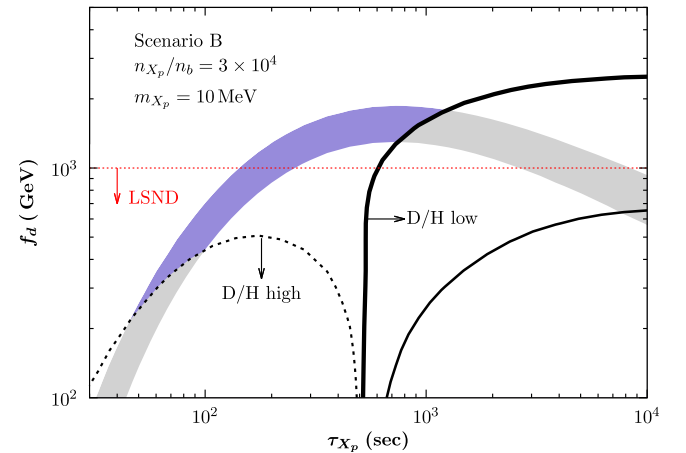


FIG. 4. Lithium solution by ALPs that are injected from a progenitor state X_p with mass $m_{X_p} = 10 \text{ MeV}$. The LSND sensitivity line is fixed, but all other contours can move vertically by adjusting the X_p initial abundance n_{X_p}/n_b .

should be compared to the number of prompt energetic events in the detector, $O(10)$, which implies a sensitivity up to $f_d \sim 1$ TeV. Here, $L = 30$ m, $N_\pi \sim 10^{23}$ and $N_p = 6.7 \times 10^{30}$ is the number of target protons inside the fiducial volume. One can see, Fig. 4, that—depending on the assumed abundance of the progenitor X_p —LSND can probe large fractions of relevant parameter space; further significant improvements can be achieved by deploying beam dump experiments next to large underground neutrino detectors [30].

Conclusions.—We have shown that particle physics solutions of the cosmological lithium problem are far from being exhausted. Light, very weakly interacting particles with energy or mass of ~ 10 MeV and lifetimes of $O(10^3)$ seconds can deplete ${}^7\text{Be} + {}^7\text{Li}$ without affecting other elements. This is because, unlike in many weak-scale solutions, the suggested mechanism does not inject any new neutrons into the primordial medium, and operates either via direct destruction of ${}^7\text{Be}$, or through its indirect reduction via neutrons that are temporarily “borrowed” from deuterium. A variety of particle physics realizations of this idea is possible, and in particular ALPs with small couplings to d quarks represent a clear target of opportunity for upcoming searches at the intensity frontier.

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