Big Bang Darkleosynthesis

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In a popular class of models, dark matter comprises an asymmetric population of composite particles with short range interactions arising from a confined nonabelian gauge group. We show that coupling this sector to a well-motivated light mediator particle yields efficient darkleosynthesis, a dark-sector version of big-bang nucleosynthesis (BBN), in generic regions of parameter space. Dark matter self-interaction bounds typically require the confinement scale to be above $\Lambda_{QCD}$, which generically yields large ($\gg$ MeV/dark-nucleon) binding energies. These bounds further suggest the mediator is relatively weakly coupled, so repulsive forces between dark-sector nuclei are much weaker than coulomb repulsion between standard-model nuclei, which results in an exponential barrier-tunneling enhancement over standard BBN. Thus, darklei are easier to make and harder to break than visible species with comparable mass numbers. This process can efficiently yield a dominant population of states with masses significantly greater than the confinement scale and, in contrast to dark matter that is a fundamental particle, may allow the dominant form of dark matter to have high spin ($S \gg 3/2$).

I. INTRODUCTION

There is abundant evidence for the existence of dark matter (DM) but its particle nature is still unknown \cite{1}. A popular, well motivated class of models \cite{2–7} features a composite dark sector with asymptotically free confinement and a matter asymmetry in analogy with standard model (SM) quantum chromodynamics (QCD). At temperatures below the confinement scale $\Lambda_D$, this sector comprises hadron-like particles with short-range self-interactions and requires no ad-hoc discrete or global symmetries to protect its cosmological abundance from decays.

In this paper we consider the implications of big bang darkleosynthesis (BBD) – the synthesis of darklei (dark-sector nuclei) from darkleons (dark-sector nucleons) in the early universe — in an asymmetric nonabelian sector coupled to a lighter “mediator” ($m \ll \Lambda_D$) particle. A mediator is well motivated in asymmetric DM as it facilitates annihilation in the early universe to avoid a higher than observed dark-matter abundance \cite{8, 9} and allows for DM self interactions, which can resolve puzzles in simulations of large scale structure formation \cite{10}, and may explain anomalies in direct and indirect detection experiments (see \cite{11, 12} and references therein).

In the limit where the mediator is sufficiently weakly coupled, the initial conditions in the dark sector are analogous to those considered in the “alphabetical article” by Alpher and Gamow \cite{13}, who sought to build up all the observed chemical elements from only an initial population of SM neutrons during big bang nucleosynthesis (BBN). Although this proposal ultimately failed as an efficient and complete model of nucleosynthesis, we show here that this need not be the case when considering the build up of darklei from darkleons. In the dark sector, such a setup can be realized more generically and need not encounter the (perhaps accidental) coincidences (e.g., $m_n - m_p \sim T_{BBN}$) that prevent visible BBN from building up species with large mass numbers. Though other work has considered the cosmology of dark-sector bound states via dark “recombination” \cite{16, 22}, and in the con-
text of mirror matter [23,25], to our knowledge this is the first demonstration that dark-sector nucleosynthesis is a generic possibility for confined dark matter scenarios.

We assume only that the dark sector is populated with self-interacting, non-annihilating darkleons that also couple to a light mediator, which enables di-darkleon formation; in the absence of this coupling, there is no available energy loss mechanism for di-darkleon formation. Although in principle the coupling to the mediator state can induce both attractive and repulsive interactions between darkleons, to be conservative and demonstrate viable phenomenology despite coulomb repulsion, we assume here that all dark-nuclear formation rates feature repulsive barriers.

The outline of this paper is as follows. Section II outlines the basic ingredients of our scenario, Section III outlines a concrete UV complete realization, and Section IV offers some concluding remarks and speculations.

II. BASIC INGREDIENTS

**Nonabelian Sector** Our starting point is to consider a matter asymmetric dark sector with a single species of fermionic dark-"quarks" charged under an SU(N) gauge group. We assume this group becomes confining at some scale $\Lambda_D$ at which the quarks form darkleons $\chi$. In the simplest scenario, the darkleon mass comes predominantly from strong dynamics, so the constituent quark masses can be neglected. However, we assume them to be nonzero, so if an approximate chiral symmetry is broken by confinement, the dark "pions" will be massive and decay to the visible sector through the mediator described below.

**Light Mediator:** To demonstrate nucleosynthesis in the dark sector, we couple our darkleis to a lighter particle $V$ that enables di-nucleon formation $\chi + \chi \rightarrow 2\chi + V$, where $A\chi$ denotes a darkleus with mass number $A$; in the absence of $V$ emission this process is kinematically forbidden. Furthermore, in order for any dark matter scenario to have observable consequences, there needs to be an operator that connects dark and visible sectors.

Both problems can be solved with a light mediator particle uncharged under the confining gauge group. One well motivated example identifies the mediator $\phi$ with a kinetically-mixed $U(1)_D$ gauge boson $V$ whose lagrangian is

$$\mathcal{L} \supset \frac{F_{\mu\nu}^2}{2} + \frac{m_V^2}{2} V \chi + \chi (i\gamma_\mu D_\mu + m_\chi) \chi ,$$

where $F_{\mu\nu}^V = \partial_{[\mu} V_{\nu]}$ is its field strength, $m_V$ is its mass, $\alpha_D$ is the dark fine-structure constant, and $\chi$ is a dark-nucleon with $U(1)_D$ charge $Z_e$ and mass $m_e$. Independently of the connection to BBD this mediator can resolve the persistent $(g - 2)_\mu$ anomaly [27]. Phenomenologically, $V$ must decay before visible BBN, which can easily accommodated in our regime of interest $\Lambda_D \gg \Lambda_{QCD}, m_V$ [28], where $\Lambda_{QCD} = 200$ MeV.

In a matter asymmetric sector, $U(1)_D$ charge neutrality requires at least one additional species of with opposite charge, which yield a variety of net nuclear charges after darklesynthesis. We will return to this possibility in Sec. III but note that having identical, repulsive charges under the mediator is a conservative choice that yields the maximum repulsion between fusing species to suppress formation rates.

![FIG. 2: Example mass fractions $X_A = A n_A / n_D$ for various inputs with darkleol mass $m_\chi = m_n (\Lambda_D / \Lambda_{QCD})$ computed by solving the Boltzmann system in Eq. 4. The blue curve (color online) in each plot is the free darkleol fraction ($A = 1$), the red curve ($A = A_{max}$) is the maximum occupancy number included in the simulation, and the green curves are the dark "deuterium" ($A = 2$) mass fraction computed in both the Saha approximation (dashed) and the full Boltzmann solution (solid). The purple curves are number fractions for all other species. We simulate all species $A = 1 - 20$ (including $A = 5, 8$) for each data point, but our results are qualitatively similar when species $A = 5, 8$ are removed (as in Fig 1). All plots assume the binding model parameters described in the text and, to be conservative, we also assume all $A > 2$ species start with zero abundance and solve the system out to final temperature $T = B(2, 2)/1000$. The initial condition for $A = 2$ is set by the Saha solution at initial temperature $T = B(2, 2)/20$.](image)
**Binding Model:** In the visible sector, the liquid drop model \[29\, 30\] gives the approximate binding energy for a species with mass number \(A\) and electric charge \(Z\)

\[
B(A, Z) = a_V A - a_S A^{2/3} - a_C Z^2 A^{-1/3} - a_A A^{-1} (A - 2Z)^2 - \sigma(A, Z) ,
\]

where \(a_V, a_S, a_C,\) and \(a_A\) are respectively the volume, surface, coulomb, and asymmetry terms, while \(\sigma(A, Z) = \pm \alpha_p A^{-1/2}\) is the pairing term; \(+(-)\) for \(A\) and \(A - Z\) both odd (even) and 0 otherwise.

Some intuition into the physical relationship between these coefficients in this binding model can be gained by calculating the Yukawa self-energy \(B_{SE}\) of a uniform-density sphere in an effective theory of nuclear reactions mediated by pion-like scalars of mass \(m_{\Pi}\). For finite \(m_{\Pi} \sim O(\Lambda_D)\) it is straightforward to show that \(B_{SE} \lesssim \kappa_{\nu}(\Lambda_D^3/m_{\Pi}^2)A - \kappa_S(\Lambda_D^3/m_{\Pi}^2)A^{2/3}\), and thus the relative importance of the surface term compared to the volume term depends on the range of nuclear forces (parametrized as \(\Lambda_D/m_{\Pi}\)).

We adopt this simple model (along with the notation) to calculate dark nuclear binding energies for species with mass number \(A\) and interpret \(Z\) to be the number of darkleons. We note for large \(A\), where \(\delta \ll a_S, a_C\) the most tightly bound species has mass number \(A^* \simeq 2a_S/2a_C\), which maximizes \(A^{-1}B(A, A)\), the binding energy per darkleon. We note for a fixed volume term smaller \(A^*\) occurs for a shorter nuclear range (smaller \(a_S\) or larger \(\alpha_D\) (larger \(a_C\)).

For our numerical studies, we work in the \(A = Z\) regime and assume \(a_C, a_S, a_A,\) and \(a_P\) are of order the confinement scale \(\Lambda_D\), but take the \(U(1)\) Coulomb term to be parametrically smaller to reflect the absence of long range self interactions at late times.

**Formation & Destruction Rates:** The generic “strong” reaction involving species \(A\) and \(B\) with net darkleon transfer \(C\) is \(A^+ + B^- \rightarrow (A+B)^+ + \chi\). We adopt the prescription in \[31\] (and references therein) to parametrize the strong cross-section for this process as

\[
\sigma(E) = \frac{S(E)}{E} e^{-F(A, B)/E^{1/2}} ,
\]

where \(E\) is the kinetic energy and \(F(A, B) \equiv \alpha_D Z_A Z_B(2\mu)^{1/2}\) is the coulomb-barrier tunneling coefficient, \(Z_{A,B}\) are the \(U(1)\) charges of the initial state particles, and \(\mu\) is their reduced mass. In visible BBN, the function \(S(E)\) is extracted from nuclear scattering data, which is unavailable in our context, but the dark-nuclear force is short range, so we adopt the simplifying geometric ansatz \(S(E) \equiv (A^{1/3} + B^{1/3})^2/\Lambda_D\).

Thermal averaging with the Maxwell-Boltzmann distribution yields

\[
\langle \sigma_A \rangle = \frac{2}{\sqrt{\pi T^{3/2}}} \int_0^{\infty} \frac{dE}{\sqrt{E}} S(E) v(E) e^{-E/T - F/E^{1/2}} .
\]

In standard BBN \[31\], thermal averaging is evaluated using the “Gamow peak” approximation, which fails in the \(\alpha_D \ll \alpha_{EM}\) regime, so we perform the integral in Eq. 1 directly.

Since we require a population of light mediators to initiate di-darkleon formation via \(\chi + \chi \rightarrow \chi + V\), there will also be a \(V\)-emission processes \(\chi + B \rightarrow (A+B)\chi + V\), in which a mediator particle is radiated off an initial or final state particle. This process is modeled using the simple ansatz \(\langle \sigma_{\chi V} \rangle = \alpha_D \langle \sigma_{\chi V} \rangle\) in accordance with the \(\alpha_{EM}\) scaling of analogous visible-sector processes (e.g. \(p + n \rightarrow d \gamma\)). We define \(\Gamma_{A,B}\) to be the \(V\)-disintegration rate for the reverse process \(V + A\chi \rightarrow (A-B)\chi + B\chi\).

**Boltzmann Equations:** We solve the Boltzmann equations for \(N\) species of darkleons built up from a population of identical \(\chi\) darkleons. In terms of number fractions \(Y_i \equiv n_i/n_D\), these can be written as

\[
\frac{dY_A}{dt} = \sum_{B=A+1}^{N} \Gamma_{B,A} Y_B Y_V - \sum_{B=1}^{A-1} \Gamma_{A,B} Y_A Y_V
\]

\[
+ n_D \sum_{B=1}^{B=A-1} \langle \sigma_{\chi V} \rangle Y_B Y_{A-B} - \langle \sigma_{\chi V} \rangle Y_A Y_V
\]

\[
+ n_D \sum_{B=A-1}^{B=1} \sum_{C=1}^{N-A-1} \langle \sigma_{\chi V} \rangle Y_B Y_{A-C} - \langle \sigma_{\chi V} \rangle Y_A Y_B ,
\]

where \(n_D = \rho_{DM}/m_\chi\) is the darkleon density. If multiple species of darkleons are present, there is a separate equation for each combination of \(A\) and \(Z\).

The first line of Eq. 4 contains every \(V\)-disintegration process that adds or removes an \(A\), the second contains all allowed \(V\)-emission processes \(A + B \rightarrow (A + B) + V\), and the third features all allowed strong-darkleak processes \(A + B \rightarrow (A + C) + (B - C)\) that exchange \(C\) darkleons. All soichiometric coefficients and Boltzmann exponents for endothermic (“reverse”) processes are absorbed into the thermally averaged cross sections \(\langle \sigma_{\chi V} \rangle^\pm\) and \(\langle \sigma_{\chi V} \rangle^\pm\) for creating (+) or destroying (−) \(\chi\) darklei.

Figure 1 shows a density plot of the expected mass number \(\langle A\rangle = \sum A^2 Y_A\) for a population of darklei with mass numbers \(A = 1 - 20\) over a range of \(\alpha_D\) and \(\Lambda_D\) values. We use the binding model in Eq. 2 with parameters \(a_V = 1.9 r, a_S = 1.3 r, a_P = 0.2 r, a_A = 0.6 r\) set by the confinement scale through \(r \equiv (\Lambda_D/\Lambda_{QCD})\)GeV; the Coulomb term is \(a_C = 3 \times 10^{-7} r\). The initial conditions assume a single-species of \(\chi\) darkleons with identical \(U(1)\) charges so that each process encounters the maximum coulomb barrier in every interaction. A more realistic setup also features a small enhancement and differentiation in some rates due to attractive interactions between oppositely charged species, but we leave these details for future investigation. Figure 2 shows the distribution of individual species for particular \(\alpha_D\) and \(\Lambda_D\) under the same assumptions and conditions used in Figure 1.

We can roughly estimate the freeze out temperature assuming a fully asymmetric dark sector \(n_a \sim (m_a \Omega_{DM}/m_b \Omega_b)n_b\). BBD is controlled by the formation
of the $^2\chi$ state via $\chi + \chi \to V + ^2\chi$, so the relevant reaction rate scales as $\langle \sigma v \rangle \sim \alpha_D \Lambda_D^{-2} (T/m_\chi)^{1/2}$. Evaluating $n_\chi (\sigma v) \sim H$ yields

$$T_f \sim \text{GeV} \left( \frac{10^{-5}}{\alpha_D} \right)^{2/3} \left( \frac{\Lambda_D}{10^2 \text{GeV}} \right)^{4/3} \left( \frac{m_\chi}{10^2 \text{GeV}} \right)^{1/2},$$

which is consistent with our results in Fig. 2.

### III. UV COMPLETION

An example UV model that generates a dark matter-asymmetry and yields BBD contains an $SU(3)_D \times U(1)_D$ dark gauge symmetry, $N_f$ flavors of Weyl fermions $\psi, \xi \sim 3_{\pm 1}$, $N_f$ flavors of their Dirac partners $\psi^c, \xi^c \sim \bar{3}_{\mp 1}$, and $N_s$ flavors of scalars $\varphi \sim 3_0$. The lagrangian

$$\mathcal{L} = \lambda \varphi \xi \psi + \lambda' \varphi^\dagger \xi^c \psi^c + m_\xi \xi \varphi^c + M^2 \varphi^\dagger \varphi + \mu \varphi \varphi + h.c.,$$

satisfies the Sakharov conditions [32] for the dark sector: the matrices $\lambda, \lambda'$ contain irreducible $CP$ violating phases, the trilinear scalar interaction explicitly violates a global DM “baryon” number under which $\varphi \sim -2$ and $\xi, \psi (\psi^c, \xi^c) \sim \pm 1$, and the scalars $\varphi, \varphi^\dagger$ can decay out of equilibrium in the early universe. All gauge and flavor indices in the couplings and masses of Eq. (7) have been suppressed. Interference between tree and loop decay-diagrams induce $C$ and $CP$ violation and yield a matter asymmetry in the dark sector following standard methods [33].

A confining phase transition occurs at $T \sim \Lambda_D$, below which the stable confined darkleons come in different species $\chi_i = (\psi \psi \xi), \chi_{-1} = (\psi \psi \xi^c), \chi_{+-} = (\psi \psi \xi) + \Lambda_D^{-2} \psi \psi \xi$ which carry $U(1)_D$ charges $3, 1, -1, -3$, respectively. Each combination of states can fuse to form darklei; however, the initial condition is no longer an identifiable population of $\chi_i$, but a distribution of distinct $\chi_i$ with both attractive and repulsive interactions during BBD.

For $m_\psi, \xi \ll \Lambda_D$, the confinement breaks an approximate $SU(N_f) \times SU(N_f)$ chiral symmetry under which $\chi (\xi)$ and $\psi (\xi^c)$ can be independently rotated. In this regime, the IR spectrum contains pseudo-goldstone bosons (dark-pions) with mass-squared proportional to $m_\psi, \xi$ in analogy with low-energy QCD. The $U(1)_D$ neutral pions (e.g. $\psi^c \psi^c$ states) decay to the visible sector via kinetic mixing, while charged pions (e.g. $\psi \xi^c$) are matter-symmetric and annihilate to visible states.

### IV. DISCUSSION

In this paper we have conservatively shown that, in broad regions of viable parameter space, asymmetric dark matter models with nonabelian confinement efficiently produce darklei, dark-sector nuclei, in the early universe. Unlike visible BBN, which involves several (possibly anthropic) coincidences that impede the synthesis of heavier nuclei, darkleosynthesis can be highly efficient and proceed to high mass states. Indeed, the light mediator particle that enables dark-deuterium formation can have a smaller coupling than $\alpha_{EM}$, so coulomb-like barriers that prevent the formation of high-$Z$ elements are less inhibiting. Furthermore, the dark confinement-scale, which sets the binding energy scale, can be much larger than typical binding energies in the visible sector, so larger species are more tightly bound. Finally, and most importantly, nucleosynthesis in the dark sector can begin at higher temperatures, and thus closer to thermal equilibrium for most formation reactions.

For simplicity we have only computed the yields for each species and ignored other novel features of the darkleal isotope distribution at late times, which we leave for future work. Our approach does not attempt to understand the precise details of dark-nuclear interactions; we model formation rates with geometric cross-sections and binding energies with the liquid drop model merely to demonstrate the hitherto overlooked possibility of dark-leo nucleosynthesis; a more realistic understanding of confined dynamics would allow for a more detailed investigation.

Since darkleons can be significantly lighter than large-$A$ darklei, their particle-antiparticle annihilations (or those of their constituents) can still be efficient at high temperatures, while assembling large-$A$ composites at later times. Thus, naive overclosure need not be a limitation for heavy, thermally produced DM. Furthermore, as with many nuclei in the visible sector, BBD can potentially form composites darkleal states with spins greater than 3/2, so scattering at direct detection experiments may offer novel directional signatures with multiple species and form factors that respond differently to various target materials; spin-independent interactions will also feature a coherent $A^2$ rate enhancement.

We note in passing that darkleosynthesis may be an extended process that continues until late times, perhaps even in dark matter halos in the present epoch to realize a novel form of self-interacting dark matter. Furthermore, if metastable excited states are long lived, exothermic darkleal scattering at late times may facilitate “dark disk” formation [34, 35] in dark matter halos subject to the cosmological limits on dark matter interaction with relativistic species [36, 37].

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