Cosmological Lithium Solution from Discrete Gauged *B-L*

Seth Koren*

Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA

(Received 10 July 2022; revised 10 January 2023; accepted 16 August 2023; published 1 September 2023)

The cosmological lithium problem—that theory predicts a primordial abundance far higher than the observed value—has resisted decades of attempts by cosmologists, nuclear physicists, and astronomers alike to root out systematics. We reconsider this problem in the setting of the standard model extended by gauged baryon minus lepton number, which we spontaneously break by a scalar with charge six. Cosmic strings from this breaking can support interactions converting three protons into three positrons, and we argue that an "electric"-"magnetic" interplay can give this process an amplified, strong-scale cross section in an analog of the Callan-Rubakov effect. We suggest such cosmic strings have disintegrated $\mathcal{O}(1)$ of the primordial lithium nuclei, and lay out what is necessary for this scheme to succeed. To our knowledge this is the first new physics mechanism with microphysical justification for the abundance of lithium uniquely to be modified after big bang nucleosynthesis.

DOI: 10.1103/PhysRevLett.131.091003

The lithium problem.—Big bang nucleosynthesis (BBN) is the theory of the formation of light nuclei a few minutes after the hot big bang, and is the earliest epoch of the Universe for which we have direct evidence. In the framework of the standard models (SM) of particle physics and cosmology, BBN is essentially a parameter-free cross-check on our understanding of the universe. The status is given by the comparison of theoretical predictions and empirical observations of just three quantities [1–4]: The primordial abundances of deuterium with one proton, of helium-4 with two protons, and of lithium-7 with three protons.

While theory and observation agree well for hydrogen and helium, there has been a consistent mystery regarding the abundance of lithium [5,6] beginning with observations in 1982 by Spite and Spite [7,8], and the current best values are shown in Table I. Physicists have spent decades looking for systematics, and the uncertainties initially present in the relevant SM, nuclear, and ΛCDM parameters have long since been ironed out by fantastic precision experimental and observational programs.

The remaining worry arises since the empirical data on "primordial" lithium comes primarily from measurements of its abundance in the atmospheres of metal-poor, population II stars in the Milky Way. While we must necessarily use nearby sources due to the scarcity of lithium, elementary stellar dynamics suggests we can access the primordial abundance by observing the "Spite plateau" of lithium as a function of stellar temperature flattening out above the point where convection becomes confined to the upper, cooler layers of the star. There are now observations of the Spite plateau in many diverse environments (e.g., [9–22]).

The situation is still under active investigation by many scientists. On the theoretical side, there is no well-accepted new stellar dynamics mechanism that could be responsible, though there have been proposals [23–30]. On the observational side, astronomers continue to further probe the Spite plateau in a variety of innovative directions [31–40].

After so long with the prospects for an astrophysical resolution still unclear, some new physics mechanisms have been explored—mainly fundamental constants varying to modify early-Universe nuclear rates [41–51] or decaying dark matter disrupting reactions [52–77]. See also [78–92] for further ideas. In our diagnosis, these approaches have been stymied by not uniquely picking out lithium to be affected, and they generally encounter severe difficulties with putting other observables into tension.

TABLE I. For reference, the status of the number density of lithium-7 relative to that of hydrogen, taken from the recent review and status update [1].

	$(^7\mathrm{Li/H})$
Observation	$(1.6 \pm 0.3) \times 10^{-10}$
Theory	$(4.7 \pm 0.7) \times 10^{-10}$

TABLE II. Representations of the left-handed SM Weyl fermions (and the sterile neutrino) under the classical symmetries of the SM.

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$	$\bar{\nu}$
$\mathrm{SU}(3)_C$	3	$\bar{3}$	$\bar{3}$	...	...	...
$\mathrm{SU}(2)_L$	2	...	...	2	...	...
$\mathrm{U}(1)_Y$	+1	−4	+2	−3	+6	...
$\mathrm{U}(1)_B$	+1/3	−1/3	−1/3	...	...	...
$\mathrm{U}(1)_L$	...	...	...	+1	−1	−1

We are motivated by the surprisingly long lifetime of the proton and its exact stability in the SM to take advantage of the exact SM selection rule

$$\begin{aligned}\Delta\,(\#\,\text{of baryons}) &= \Delta\,(\#\,\text{of leptons}) \\ &= 0\,(\text{mod number of generations}).\end{aligned}$$

Since the SM has $N_g = 3$ generations of particles and the BBN predictions first fail for lithium with three protons, this symmetry could explain why elements with one or two protons are unaffected. This allows us to construct—to our knowledge—the first new physics mechanism for the lithium abundance to be discrepant, which does not require tuning to avoid modifying the abundances of other elements.

We must go only slightly beyond the SM to find our effect of interest. In brief, we will break gauged baryon minus lepton number to a discrete subgroup which will produce a large abundance of cosmic string loops. These topological defects amplify the $B+L$ violation, and we introduce a model in which leptoquarks communicate this violation in a way which picks out solely processes in which three protons are turned into three positrons. We propose that such cosmic strings have disintegrated lithium nuclei in the early Universe, reducing the primordial abundance to the level inferred from astronomical observations. In this Letter we will put together the various pieces of field theory and cosmology behind this mechanism, and estimate the rate to demonstrate its plausibility. Precise predictions will require much further work.

New physics setting.—We extend the standard model by gauging $\mathrm{U}(1)_{B-L}$, and address the 't Hooft anomaly [93] and neutrino oscillations by adding right-handed neutrinos. The fermion charges are given in Table II. To Higgs this gauge symmetry we introduce a scalar Φ with

$$[\Phi]_{B-L} = 2N_g, \qquad [\Phi]_{B+L} = 0, \qquad \langle\Phi\rangle = v, \quad (1)$$

which condenses in the early Universe at a temperature $T_c \sim v$. The global symmetry-breaking pattern providing selection rules is

$$U(1)_{B-L} \times \mathbb{Z}^L_{N_g} \to \mathbb{Z}^{B-L}_{2N_g} \times \mathbb{Z}^L_{N_g} \supset \mathbb{Z}^{B+L}_{2N_g}, \qquad (2)$$

where the anomaly-free subgroup of baryon plus lepton number is generated by $(1,1) \in \mathbb{Z}^{B-L}_{2N_g} \times \mathbb{Z}^L_{N_g}$. While this Higgsing is "nonminimal" in the sense that $[\Phi] > 1$, this choice of $[\Phi]$ preserves the SM selection rule that stabilizes the proton [94–98].

Discrete gauge theory.—The nontrivial Higgs charge $[\Phi]_{B-L}$ means its condensation preserves an unbroken discrete $\mathbb{Z}^{B-L}_{2N_g}$ gauge symmetry [99–103] and stable cosmic string solutions exist with tension $\mu \sim v^2$. The transverse slices of a static, z-independent string are Abrikosov-Nielsen-Olesen vortices [104,105] and have asymptotics

$$\Phi(\rho,\theta) \to v e^{ik\theta}, \qquad \vec{A}(\rho,\theta) \to \frac{k}{g}\frac{1}{2N_g}\frac{\hat{\theta}}{\rho}, \qquad (3)$$

with $\vec{A}$ the $B-L$ gauge boson, g the $\mathrm{U}(1)_{B-L}$ "electric" charge, and $k \in \mathbb{Z}$ the winding number of Φ. With nonzero winding, continuity in the interior demands a zero in the Higgs field and indeed the B-L symmetry is unbroken in a string "core" of radius $R \sim v^{-1}$. These solutions have discrete $\mathrm{U}(1)_{B-L}$ "magnetic" fluxes

$$\Phi_B = \frac{2\pi}{g}\frac{k}{2N_g} \qquad (4)$$

confined to their cores. This magnetic flux is in "fractional" units of $1/(2N_g)$ that of the Dirac magnetic charge quantum $\Phi_0 = 2\pi/g$ [106], so the string is stable and interacts via the Aharonov-Bohm (AB) effect [107,108] for the unbroken discrete symmetry. The cosmic strings undergo elastic AB scattering with all the SM fermions of differential cross section per unit length (for a plane wave of $B-L$ charge q and momentum p incident on a string) [109]

$$\frac{1}{\ell}\frac{d\sigma}{d\theta} = \frac{\sin^2(\pi q \Phi_B/\Phi_0)}{2\pi p \sin^2(\theta/2)}, \qquad (5)$$

which is independent of any high scales or small couplings.

Strings in cosmology.—During an early Universe phase transition, topological defects are produced proportional to the correlation length ξ of the order parameter fluctuations. Causality ensures this is no larger than the Hubble distance $\xi \lesssim d_h$, so that at a critical temperature $T_c \sim v$, $\mathcal{O}(1)$ horizon-crossing strings of length $d_h = 2H^{-1}(T_c) \sim M_{\rm pl}/v^2 = (G\mu)^{-1}\ell_{pl}$ per Hubble volume are formed [110,111], d_h being the Hubble size, H the Hubble parameter, and $G\mu \sim v^2/M_{\rm pl}^2$ a dimensionless measure of the gravitational effects of the strings. At formation, these long strings contain energy density

$$\rho_{\rm string} \sim \frac{\mu d_h}{d_h^3} \sim (G\mu)^{+1}\rho_{\rm tot}, \qquad (6)$$

a small fraction of the total. The elastic AB scattering with the SM plasma provides a total transverse cross section per unit length of $\sigma_\perp/\ell \sim 1/T$, which leads to a long epoch of friction-dominated evolution until the temperature drops below $T_f \lesssim v^2/M_{\rm pl}$ [112].

When cosmic strings encounter each other, they "intercommute" with probability approaching unity [113–126]. This results in the production of small-scale structure on the strings [127–131] and many closed loops from strings crossing themselves. String loops oscillate and shrink via gravitational radiation [132–134], which dissipates energy and prevents the strings from dominating the density budget [135].

After decades, we now understand the behavior of the cosmic string network at late times and on large scales: There is an attractor "scaling" solution where the length spectrum of loops depends only on the ratio with the horizon distance ℓ/d_h [114,115,136–140]. The small scale behavior of this scaling population is assumed to continue down to the "gravitational cutoff" scale $\ell \sim (G\mu)d_h$, at which length a loop evaporates within a Hubble time, which leads to a large number of "small" such loops, $n \sim (G\mu)^{-0.7}$ [141].

However, the regime relevant for their effects on lithium requires understanding cosmic strings far before the infrared fixed point is reached. In addition to being very difficult to study, this is sensitive to details such as the strength of the phase transition, since the correlation length of Higgs fluctuations may, in fact, be quite small compared to the horizon length $\xi \ll d_h$, resulting in a far greater initial number density of defects [142–144]. The small-scale behavior is also sensitive to the details of intercommutation dynamics, and furthermore the presence of currents on the strings may stabilize them against decay and result in a large portion of energy density in cosmic string "vortons" [145–151]. For these reasons, rather than attempting to model the evolution of the phase space of cosmic strings, below we will simply parametrize their effects on lithium disintegration in terms of the fraction of the energy density which is in cosmic strings.

Topological defect catalysis.—We wish to consider interactions which destroy lithium nuclei by turning three protons into three positrons, thereby violating $B+L$ by $2N_g$ units. We utilize a stringy analog of the Callan-Rubakov effect where grand unified monopoles "catalyze" proton decay at strong scale rates $\sigma(p^+ + \text{monopole} \to e^+ + \text{monopole}) \sim \Lambda_{\rm QCD}^{-2}$. For monopoles, the inevitability of such inelastic interactions can be seen purely from the infrared [106,152–166]. An ultraviolet description for the monopole [167–175] allows one to resolve the microphysical interactions and see $p^+ \to e^+$ arising from interactions with leptoquarks in the core and the anomalous violation of $B+L$ [176–194].

The cosmic string case has seen far less study, and no infrared argument for this catalysis effect is yet known. To provide an explicit benchmark—and to give a microphysical model targeting this mechanism toward the cosmological lithium problem—we introduce ultraviolet physics which lets us map our case on to a model studied by Alford, March-Russell, and Wilczek in 1989 [195] in which a leptoquark condenses inside cosmic strings of some broken gauged $\widetilde{U(1)} \to \mathbb{Z}_N$. In that model the leptoquark allows $p^+ \to e^+$ violation of $B+L$, but here we instead introduce a gauge-singlet scalar χ with

$$[\chi]_{B-L} = 0, \qquad [\chi]_{B+L} = 2N_g, \qquad \langle\chi\rangle = 0, \quad (7)$$

but which condenses on the string core so long as

$$\partial_\chi^2 V(\Phi,\chi)|_{\Phi=0} < 0 \to \langle\chi\rangle_{\Phi=0} = v_\chi. \quad (8)$$

This breaks solely the global approximate $\mathrm{U}(1)_{B+L}$ on the string core down to the subgroup preserved by the SM, and the condensate allows the string core to exchange $2N_g$ units of $B+L$ charge with the outside world [196].

The infrared symmetries forbid interactions of χ with fewer than twelve SM fermions, but we can explicitly generate one such interaction by introducing the scalar leptoquark ω_ℓ with hypercharge 8 and its analog diquark ω_q, as well as the gauge singlet scalar ω_s with $B=L=1$. This choice of scalars (see Table III) allows the nontrivial interactions

$$\mathcal{L} \supset \lambda_\ell \omega_\ell \bar{d}\,\bar{e} + \lambda_q \omega_q^\dagger \bar{u}\,\bar{u} + \kappa \omega_\ell^\dagger \omega_q \omega_s + \lambda_\chi \omega_s^3 \chi^\dagger. \quad (9)$$

Around the vacuum the Feynman diagram portrayed in Fig. 1 generates the operator

$$\mathcal{L} \sim \frac{1}{v^{15}} \chi(\bar{u}\,\bar{u}\,\bar{d}\,\bar{e})^3, \quad (10)$$

and $B+L$ violation on the string core is communicated only to electrons and protons in our model. We further take the mediators ω to be light in the string core, so this suppression by v disappears when the SM fermions are

TABLE III. Representations of the scalars added in our benchmark model. Cosmic strings appear from the winding of Φ in the vacuum, the condensation of χ on the string allows it to freely exchange $B+L$, and the scalars ω communicate $B+L$-breaking by χ to the right-handed SM fields.

	Φ	χ	ω_ℓ	ω_q	ω_s
$\mathrm{SU}(3)_C$	...	...	3	3	...
$\mathrm{SU}(2)_L$	...	...	...	...	...
$\mathrm{U}(1)_Y$	...	...	−8	−8	...
$\mathrm{U}(1)_B$	+3	+3	+1/3	−2/3	+1
$\mathrm{U}(1)_L$	−3	+3	+1	0	+1

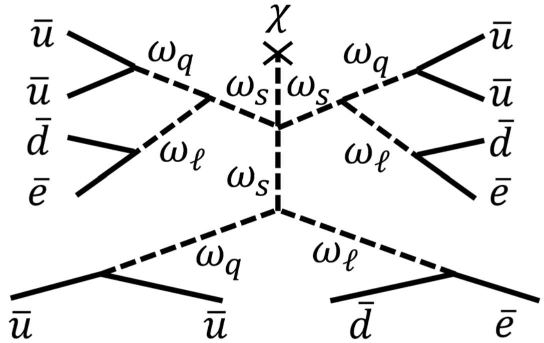

FIG. 1. A Feynman diagram portraying our benchmark for how the $B + L$-breaking effects of the χ vev get communicated to the SM fermions at low energies.

interacting with the χ vev in the core, and we have set all couplings to unity and scales equal for simplicity.

In the model of Alford, March-Russell, and Wilczek [195], the Yukawa interaction allows an incoming quark to inelastically scatter into a lepton by exciting the leptoquark condensate, and the $\mathbb{Z}_N$ discrete gauge field background enhances the cross section. When the discrete gauge charge of the incoming quark is maximal, the cross section is unsuppressed by ultraviolet scales, as in the Callan-Rubakov effect. In our case, we instead have an interaction of many SM partons with the string condensate.

However, in the cosmological case of interest, a ^{7}Li nucleus delivers a state of three protons $\psi_{3p} \sim (\bar{u}\,\bar{u}\,\bar{d})^3$ incident upon the string. To map our model to [195], we rewrite Eq. (10) as a Yukawa interaction between ψ_{3p}, the nine quarks in three protons, and ψ_{3e}, the three positrons. Adapting their results while ignoring many subtleties about this matching, we infer that an incoming plane wave of B-L charge q and momentum p undergoes enhanced inelastic scattering with a long cosmic string as

$$\frac{\sigma}{\ell} \sim \frac{1}{p}\sin^2(\pi\alpha)\left(\frac{p}{v}\right)^{4|\alpha-\frac{1}{2}|}, \qquad \alpha \equiv \frac{kq}{2N_g}, \tag{11}$$

where we are generalizing Eqs. [18–21] of [195]. The inelastic scattering is unsuppressed by ultraviolet scales for an incoming state with B-L charge $q = N_g$ in the case of a single-winding string. We note also that topological defect interactions can violate crossing symmetry, as may be understood simply for monopoles [165], so, for example, crossing one proton to an outgoing antiproton results in a drastically suppressed cross section because the incoming state no longer has maximal $\mathbb{Z}_{2N_g}$ charge nor half-integer spin, which is also crucial for catalysis [195]. This suppression is useful for ensuring consistency with observations of primordial helium, and it would be interesting to understand precisely the subleading rate at which helium might be affected.

Parameter space.—In the early Universe after BBN, just such a $q = N_g$ state of three protons may be delivered to the string within the nuclear potential well of ^{7}Li. (In fact BBN initially produces ^{7}Be which then captures an electron to produce ^{7}Li [197]. While in much of the parameter space it is ^{7}Be which is being destroyed, in any case these are the only elements with more than 2 protons, so our selection rule still serves to distinguish them.) We assume string loops have a cross section per unit length

$$\frac{\sigma}{\ell}(3p^+ + \text{string} \to 3e^+ + \text{string}) \sim \Lambda_{\text{QCD}}^{-1}, \tag{12}$$

but note again that there are necessarily large theoretical uncertainties here.

However a first question is just whether such interactions can plausibly destroy an order-one fraction of lithium nuclei after BBN. Because of the complications discussed above, we will not attempt to model the evolution of the phase space of string loops, but instead content ourselves to parametrize their effects as a function of the fraction of energy density in cosmic strings. We simply ask that the rate for a lithium nucleus to encounter a cosmic string be greater than Hubble,

$$\Gamma \simeq \int d\ell \frac{dn}{d\ell}\sigma \simeq \Lambda_{\text{QCD}}^{-1}\int d\ell \frac{dn}{d\ell}\ell = \frac{\rho_{\text{string}}}{\Lambda_{\text{QCD}}\mu} \gtrsim H, \tag{13}$$

where we have begun with a general differential number density of cosmic strings $(dn/d\ell)$, assumed the interaction is characterized as $\sigma/\ell = \Lambda_{\text{QCD}}^{-1}$, which makes the rate proportional to the energy density. Then introducing $f \equiv \rho_{\text{string}}/\rho_{\text{tot}}$ we require

$$f \gtrsim \frac{\Lambda_{\text{QCD}}}{M_{\text{pl}}}\frac{\mu}{T_\star^2}, \tag{14}$$

where $\Lambda_{\text{QCD}}/M_{\text{pl}} \sim 10^{-20}$, and $T_\star$ is the temperature at which disintegration occurs. We note that this is a greater fraction than that eventually expected in long strings $f \sim G\mu$, underscoring the necessity of understanding the nonequilibrium behavior of strings after the phase transition. Along similar lines, we emphasize also that the precise requirement to destroy the correct fraction of lithium will depend on the duration over which these interactions are efficient. We plot this relation in Fig. 2, where we assume that $\mu \gtrsim T_{\text{BBN}}^2$ such that the B-L phase transition takes place before BBN, and $T_{\text{CMB}} \lesssim T_\star \lesssim T_{\text{BBN}}$ to avoid severe constraints on exotic energy injection which are sensitive even down to the level of $\mathcal{O}(10^{-10})$ at the time of recombination [198–202]. If the B-L-breaking scale is low then one requires relatively small gauge coupling [203–205], but the electric-magnetic interplay of the Callan-Rubakov effect means that this does not suppress the cross section, as above. Nevertheless if the scale is so low that the string width is larger than nuclear scales, the benchmark cross section, which does not account for the

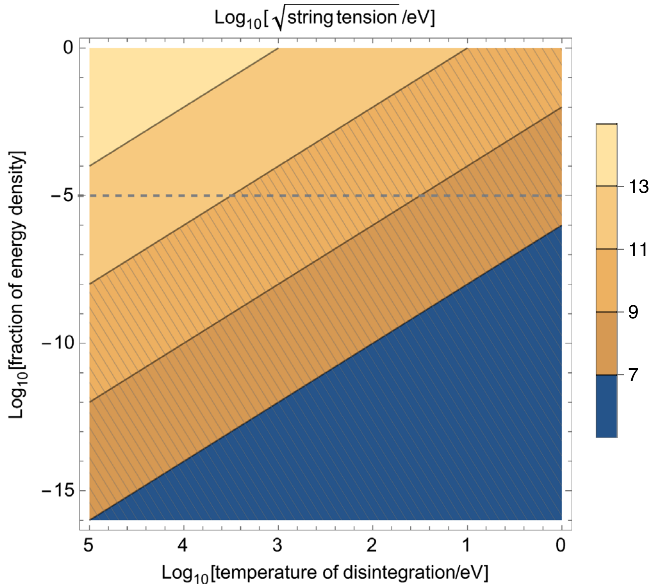

FIG. 2. A contour plot of the string tension scale required for $\mathcal{O}(1)$ lithium to be disintegrated as a function of the temperature and the fraction of energy density in cosmic strings from Eq. (14). The hatched region is constrained in simple models of gauged B-L with a massive Z', taking $\sqrt{\mu} \sim v \sim m_{Z'}/g > 100$ GeV as a benchmark [203]. The dashed line is an approximate upper bound on the energy density in strings near the Hubble length from CMB and gravitational wave constraints [210,211].

string's internal structure, seems less applicable. In Fig. 2 we also show a benchmark constraint on gauged B-L with massive Z' from [203], assuming the tension goes as $\sqrt{\mu} \sim m'_Z/g$, though we note that this constraint does assume a particular right-handed neutrino sector and it is possible these constrains are modified either with non-standard neutrino interactions (see, e.g., [206]) or exotic neutrino sectors (see, e.g., [207–209]).

Complementary signatures.—Cosmic strings may generally be searched for through their gravitational effects either in affecting the CMB anisotropies or in contributing to the stochastic gravitational wave background. However, the details of the spectra and the ensuing constraints depend strongly on the size distribution of strings. To guide the eye, we offer in Fig. 2 the rough constraint applicable to the scaling population of strings. For discussions on how the constraints depend on some characteristics of the spectrum we refer to [141,210,212–215] and [211,216–220].

The nontrivial dynamics of cosmic strings means there may be a non-negligible number density at any time, so one may hope to constrain their existence with direct detection experiments. General B-L cosmic strings may be probed through their unitarity-limited elastic Aharonov-Bohm scattering, but this requires a detailed understanding of the kinematics of such interactions in direct detection experiments. The inelastic effect is more striking, but one must also understand the cross section for general nuclei, such as the many oxygen in Super-Kamiokande. Experimentally, dedicated analysis or new searches may be required for the "hard" signature of three outgoing positrons, their ensuing showers, and possible delayed decays of the leftover nucleus.

While such effects are too rare with solely the scaling population of large cosmic strings, in scenarios with increased number density such as with vorton end states this would be an interesting signature to understand. Alternatively it would be interesting to integrate over cosmic volumes and look for indirect effects of B-L strings in astrophysical settings.

Conclusion.—In this work we have stirred together a mélange of ingredients from particle theory and cosmology to write down a mechanism through which the lithium problem is an entrée to fundamental physics beyond the SM. This scenario motivates various important directions of inquiry, which are interesting more generally than in their application here: (i) It is clearly important to better conceptually understand the cosmic string analog of the Callan-Rubakov effect, which likely requires understanding BF theory with light fermions. (ii) Any precise rate predictions will require understanding the evolution and interactions of small cosmic string loops, which is a difficult problem. (iii) It would be useful to think about other interesting applications for unitarity-limited interactions of fermions with cosmic strings—perhaps in effecting baryogenesis or dark matter production. (iv) For any such applications it will be necessary to understand better how to translate from many-parton interactions with cosmic strings to nuclear effects.

Theoretical physicists have been captivated by the interplay of electric and magnetic effects for centuries now, from Maxwell [221] up to its grandest form in Montonen-Olive duality [222–224] with maximal supersymmetry. The case of *less* symmetry, as with our discrete $\mathbb{Z}_N$, has received far less attention. In addition to their fascinating topological character, these interactions may have interesting, heretofore-underappreciated phenomenological applications in the early Universe.

I am grateful to many colleagues for relevant conversations, including Wen Han Chiu, Clay Cordova, Brian Fields, Christina Gao, Andrew Long, Ryan Plestid, Carlos Wagner, Liantao Wang, and Yiming Zhong; and I thank especially T. Daniel Brennan and Sungwoo Hong for discussion and many useful comments. I further thank Samuel Alipour-fard and Sungwoo Hong for helpful comments on earlier drafts of this manuscript, and an anonymous referee for pointing out an inconsistency among assumptions in a prior draft. This work was supported by an Oehme Postdoctoral Fellowship from the Enrico Fermi Institute at the University of Chicago, and I also thank organizers at the Galileo Galilei Institute, Stony Brook University, the University of Chicago, and the Aspen Center for Physics who allowed me to present this work in progress.

*sethk@uchicago.edu, they/him

[1] B. D. Fields, K. A. Olive, T.-H. Yeh, and C. Young, Big-bang nucleosynthesis after Planck, J. Cosmol. Astropart. Phys. 03 (2020) 010; 11 (2020) E02.

[2] F. Iocco, G. Mangano, G. Miele, O. Pisanti, and P. D. Serpico, Primordial nucleosynthesis: From precision cosmology to fundamental physics, Phys. Rep. **472**, 1 (2009).

[3] A. Coc and E. Vangioni, Primordial nucleosynthesis, Int. J. Mod. Phys. E **26**, 1741002 (2017).

[4] G. J. Mathews, M. Kusakabe, and T. Kajino, Introduction to big bang nucleosynthesis and modern cosmology, Int. J. Mod. Phys. E **26**, 1741001 (2017).

[5] B. D. Fields, The primordial lithium problem, Annu. Rev. Nucl. Part. Sci. **61**, 47 (2011).

[6] F. Iocco, The lithium problem. A phenomenologist's perspective, Mem. Soc. Astron. Ital. Suppl. **22**, 19 (2012).

[7] M. Spite and F. Spite, Lithium abundance at the formation of the Galaxy, Nature (London) **297**, 483 (1982).

[8] F. Spite and M. Spite, Abundance of lithium in unevolved stars and old disk stars: Interpretation and consequences, Astron. Astrophys. **115**, 357 (1982).

[9] R. Rebolo, P. Molaro, and J. E. Beckman, Lithium abundances in metal-deficient dwarfs, Astron. Astrophys. **192**, 192 (1988).

[10] S. Balachandran, Lithium depletion and rotation in main-sequence stars, Astrophys. J. **354**, 310 (1990).

[11] A. M. Boesgaard, A. Stephens, and C. P. Deliyannis, Lithium and lithium depletion in halo stars on extreme orbits, Astrophys. J. **633**, 398 (2005).

[12] C. Charbonnel and F. Primas, The lithium content of the Galactic Halo stars, Astron. Astrophys. **442**, 961 (2005).

[13] D. S. Aguado, G. C. Myeong, V. Belokurov, N. W. Evans, S. E. Koposov, C. Allende Prieto, G. A. Lanfranchi, F. Matteucci, M. Shetrone, L. Sbordone, C. Navarrete, J. I. González Hernández, J. Chanamé, L. Peralta de Arriba, and Z. Yuan, The S2 stream: The shreds of a primitive dwarf galaxy, Mon. Not. R. Astron. Soc. **500**, 889 (2021).

[14] P. Bonifacio, L. Pasquini, F. Spite, A. Bragaglia, E. Carretta, V. Castellani, M. Centuriòn, A. Chieffi, R. Claudi, G. Clementini, F. D'Antona, S. Desidera, P. Francois, R. G. Gratton, F. Grundahl, G. James, S. Lucatello, C. Sneden, and O. Straniero, The lithium content of the globular cluster NGC 6397, Astron. Astrophys. **390**, 91 (2002).

[15] A. Mucciarelli, M. Salaris, L. Lovisi, F. R. Ferraro, B. Lanzoni, S. Lucatello, and R. G. Gratton, Lithium abundance in the globular cluster M4: From the turn-off to the red giant branch bump, Mon. Not. R. Astron. Soc. **412**, 81 (2011).

[16] M. Spite, F. Spite, and P. Bonifacio, The cosmic lithium problem. An observer's perspective, Mem. Soc. Astron. Ital. Suppl. **22**, 9 (2012).

[17] J. Schiappacasse-Ulloa, S. Lucatello, M. J. Rain, and A. Pietrinferni, Lithium abundances as a tracer of asymptotic giant branch star pollution in the globular cluster NGC 6752, Mon. Not. R. Astron. Soc. **511**, 231 (2022).

[18] V. Hill, Á. Skúladóttir, E. Tolstoy, K. A. Venn, M. D. Shetrone, P. Jablonka, F. Primas, G. Battaglia, T. J. L. de Boer, P. Francois, A. Helmi, A. Kaufer, B. Letarte, E. Starkenburg, and M. Spite, VLT/FLAMES high-resolution chemical abundances in Sculptor: A textbook dwarf spheroidal galaxy, Astron. Astrophys. **626**, A15 (2019).

[19] P. Molaro, G. Cescutti, and X. Fu, Lithium and beryllium in the Gaia-Enceladus galaxy, Mon. Not. R. Astron. Soc. **496**, 2902 (2020).

[20] J. D. Simpson *et al.* (GALAH Collaboration), The GALAH survey: Accreted stars also inhabit the Spite plateau, Mon. Not. R. Astron. Soc. **507**, 43 (2021).

[21] A. Mucciarelli, M. Salaris, P. Bonifacio, L. Monaco, and S. Villanova, The cosmological lithium problem outside the Galaxy: The Sagittarius globular cluster M54, Mon. Not. R. Astron. Soc. **444**, 1812 (2014).

[22] F. Matteucci, M. Molero, D. S. Aguado, and D. Romano, The evolution of lithium: Implications of a universal Spite plateau, Mon. Not. R. Astron. Soc. **505**, 200 (2021).

[23] O. Richard, G. Michaud, and J. Richer, Implications of WMAP observations on Li abundance and stellar evolution models, Astrophys. J. **619**, 538 (2005).

[24] L. Piau, T. C. Beers, D. S. Balsara, T. Sivarani, J. W. Truran, and J. W. Ferguson, From first stars to the Spite plateau: A possible reconciliation of halo stars observations with predictions from big bang nucleosynthesis, Astrophys. J. **653**, 300 (2006).

[25] A. J. Korn, F. Grundahl, O. Richard, P. S. Barklem, L. Mashonkina, R. Collet, N. Piskunov, and B. Gustafsson, A probable stellar solution to the cosmological lithium discrepancy, Nature (London) **442**, 657 (2006).

[26] N. Prantzos, Production and evolution of Li, Be, and B isotopes in the Galaxy, Astron. Astrophys. **542**, A67 (2012).

[27] R. Ouyed, A resolution of the cosmic lithium problem, arXiv:1304.3715.

[28] C. Marrder, G. Mathews, L. Boccioli, and I.-S. Suh, Lithium destruction in metal-poor halo stars and the cosmological lithium problem, in *APS Division of Nuclear Physics Meeting Abstracts*, APS Meeting Abstracts Vol. 2020 (2020), p. RD.002.

[29] E. Tognelli, P. G. Prada Moroni, S. Degl'Innocenti, M. Salaris, and S. Cassisi, Protostellar accretion in low mass metal poor stars and the cosmological lithium problem, Astron. Astrophys. **638**, A81 (2020).

[30] V. Grisoni, F. Matteucci, D. Romano, and X. Fu, Evolution of lithium in the Milky Way halo, discs, and bulge, Mon. Not. R. Astron. Soc. **489**, 3539 (2019).

[31] T. Prodanović and B. D. Fields, Probing primordial and pre-galactic lithium with high-velocity clouds, Astrophys. J. Lett. **616**, L115 (2004).

[32] G. R. Ruchti *et al.*, Metal-poor lithium-rich giants in the radial velocity experiment survey, Astrophys. J. **743**, 107 (2011).

[33] E. Caffau, P. Bonifacio, P. Francois, L. Sbordone, L. Monaco, M. Spite, F. Spite, H.-G. Ludwig, R. Cayrel, S. Zaggia, F. Hammer, S. Randich, P. Molaro, and V. Hill, An extremely primitive star in the Galactic halo, Nature (London) **477**, 67 (2011).

[34] A. Mucciarelli, M. Salaris, and P. Bonifacio, Giants reveal what dwarfs conceal: Li abundance in lower red giant branch stars as diagnostic of the primordial Li, Mon. Not. R. Astron. Soc. **419**, 2195 (2012).

[35] T. Hansen, C. J. Hansen, N. Christlieb, D. Yong, M. S. Bessell, A. E. García Pérez, T. C. Beers, V. M. Placco, A. Frebel, J. E. Norris, and M. Asplund, Exploring the origin of lithium, carbon, strontium, and barium with four new ultra metal-poor stars, Astrophys. J. **787**, 162 (2014).

[36] M. Spite, F. Spite, E. Caffau, and P. Bonifacio, Lithium abundance in a turnoff halo star on an extreme orbit, Astron. Astrophys. **582**, A74 (2015).

[37] X. Fu *et al.*, The Gaia-ESO survey: Lithium enrichment histories of the Galactic thick and thin disc, Astron. Astrophys. **610**, A38 (2018).

[38] T. Bensby and K. Lind, Exploring the production and depletion of lithium in the Milky Way stellar disk, Astron. Astrophys. **615**, A151 (2018).

[39] D. L. Lambert and B. E. Reddy, Lithium abundances of the local thin disc stars, Mon. Not. R. Astron. Soc. **349**, 757 (2004).

[40] A. M. Matas Pinto, M. Spite, E. Caffau, P. Bonifacio, L. Sbordone, T. Sivarani, M. Steffen, F. Spite, P. Francois, and P. Di Matteo, The metal-poor end of the Spite plateau. II. Chemical and dynamical investigation, Astron. Astrophys. **654**, A170 (2021).

[41] T. Dent, S. Stern, and C. Wetterich, Primordial nucleosynthesis as a probe of fundamental physics parameters, Phys. Rev. D **76**, 063513 (2007).

[42] V. F. Dmitriev, V. V. Flambaum, and J. K. Webb, Cosmological variation of the deuteron binding energy, strong interaction, and quark masses from big bang nucleosynthesis, Phys. Rev. D **69**, 063506 (2004).

[43] V. V. Flambaum, Variation of fundamental constants in space and time: Theory and observations, Eur. Phys. J. Spec. Top. **163**, 159 (2008).

[44] J. C. Berengut, V. V. Flambaum, and V. F. Dmitriev, Effect of quark mass variation on big bang nucleosynthesis, Phys. Lett. B **683**, 114 (2010).

[45] M.-K. Cheoun, T. Kajino, M. Kusakabe, and G. J. Mathews, Time dependent quark masses and big bang nucleosynthesis revisited, Phys. Rev. D **84**, 043001 (2011).

[46] S. J. Landau, M. E. Mosquera, and H. Vucetich, Primordial nucleosynthesis with varying fundamental constants: A semianalytical approach, Astrophys. J. **637**, 38 (2006).

[47] A. Coc, N. J. Nunes, K. A. Olive, J.-P. Uzan, and E. Vangioni, Coupled variations of fundamental couplings and primordial nucleosynthesis, Phys. Rev. D **76**, 023511 (2007).

[48] K. Mori and M. Kusakabe, Roles of ^{7}Be (n, p) ^{7}Li resonances in big bang nucleosynthesis with time-dependent quark mass and a possible Li reduction, Phys. Rev. D **99**, 083013 (2019).

[49] S. A. Franchino-Viñas and M. E. Mosquera, The cosmological lithium problem, varying constants and the H_0 tension, arXiv:2107.02243.

[50] M. T. Clara and C. J. A. P. Martins, Primordial nucleosynthesis with varying fundamental constants: Improved constraints and a possible solution to the lithium problem, Astron. Astrophys. **633**, L11 (2020).

[51] L. W. H. Fung, L. Li, T. Liu, H. N. Luu, Y.-C. Qiu, and S. H. H. Tye, Axi-Higgs cosmology, J. Cosmol. Astropart. Phys. 08 (2021) 057.

[52] M. Pospelov, Particle Physics Catalysis of Thermal Big Bang Nucleosynthesis, Phys. Rev. Lett. **98**, 231301 (2007).

[53] K. Jedamzik, The cosmic Li-6 and Li-7 problems and BBN with long-lived charged massive particles, Phys. Rev. D **77**, 063524 (2008).

[54] J. R. Ellis, K. A. Olive, and E. Vangioni, Effects of unstable particles on light-element abundances: Lithium versus deuterium and He-3, Phys. Lett. B **619**, 30 (2005).

[55] K. A. Olive, P. Petitjean, E. Vangioni, and J. Silk, Higher D or Li: Probes of physics beyond the standard model, Mon. Not. R. Astron. Soc. **426**, 1427 (2012).

[56] A. Coc, M. Pospelov, J.-P. Uzan, and E. Vangioni, Modified big bang nucleosynthesis with nonstandard neutron sources, Phys. Rev. D **90**, 085018 (2014).

[57] D. G. Yamazaki, M. Kusakabe, T. Kajino, G. J. Mathews, and M.-K. Cheoun, The new hybrid BBN model with the photon cooling, X particle, and the primordial magnetic field, Int. J. Mod. Phys. E **26**, 1741006 (2017).

[58] R. H. Cyburt, J. Ellis, B. D. Fields, K. A. Olive, and V. C. Spanos, Bound-state effects on light-element abundances in gravitino dark matter scenarios, J. Cosmol. Astropart. Phys. 11 (2006) 014.

[59] M. Kaplinghat and A. Rajaraman, Big bang nucleosynthesis with bound states of long-lived charged particles, Phys. Rev. D **74**, 103004 (2006).

[60] C. Bird, K. Koopmans, and M. Pospelov, Primordial lithium abundance in catalyzed big bang nucleosynthesis, Phys. Rev. D **78**, 083010 (2008).

[61] K. Kohri and F. Takayama, Big bang nucleosynthesis with long-lived charged massive particles, Phys. Rev. D **76**, 063507 (2007).

[62] M. Kusakabe, T. Kajino, T. Yoshida, and G. J. Mathews, New results on catalyzed big bang nucleosynthesis with a long-lived negatively charged massive particle, Phys. Rev. D **81**, 083521 (2010).

[63] M. Kusakabe, T. Kajino, and G. J. Mathews, SUSY-catalyzed big bang nucleosynthesis as a solution of lithium problems, J. Phys. Conf. Ser. **312**, 042012 (2011).

[64] L. A. Anchordoqui, Decaying dark matter, the H_0 tension, and the lithium problem, Phys. Rev. D **103**, 035025 (2021).

[65] J. Alcaniz, N. Bernal, A. Masiero, and F. S. Queiroz, Light dark matter: A common solution to the lithium and H 0 problems, Phys. Lett. B **812**, 136008 (2021).

[66] J. Sato, T. Shimomura, and M. Yamanaka, A solution to lithium problem by long-lived stau, Int. J. Mod. Phys. E **26**, 1741005 (2017).

[67] R. H. Cyburt, J. Ellis, B. D. Fields, F. Luo, K. A. Olive, and V. C. Spanos, Gravitino decays and the cosmological lithium problem in light of the LHC Higgs and supersymmetry searches, J. Cosmol. Astropart. Phys. 05 (2013) 014.

[68] A. Goudelis, M. Pospelov, and J. Pradler, Light Particle Solution to the Cosmic Lithium Problem, Phys. Rev. Lett. **116**, 211303 (2016).

[69] M. Pospelov and J. Pradler, Metastable GeV-scale particles as a solution to the cosmological lithium problem, Phys. Rev. D **82**, 103514 (2010).

[70] S. Bailly, K. Jedamzik, and G. Moultaka, Gravitino dark matter and the cosmic lithium abundances, Phys. Rev. D **80**, 063509 (2009).

[71] D. Cumberbatch, K. Ichikawa, M. Kawasaki, K. Kohri, J. Silk, and G. D. Starkman, Solving the cosmic lithium problems with primordial late-decaying particles, Phys. Rev. D **76**, 123005 (2007).

[72] K. Jedamzik, K.-Y. Choi, L. Roszkowski, and R. Ruiz de Austri, Solving the cosmic lithium problems with gravitino dark matter in the CMSSM, J. Cosmol. Astropart. Phys. 07 (2006) 007.

[73] R. H. Cyburt, J. Ellis, B. D. Fields, F. Luo, K. A. Olive, and V. C. Spanos, Metastable charged sparticles and the cosmological Li7 problem, J. Cosmol. Astropart. Phys. 12 (2012) 037.

[74] T. Jittoh, K. Kohri, M. Koike, J. Sato, K. Sugai, M. Yamanaka, and K. Yazaki, Big-bang nucleosynthesis with a long-lived charged massive particle including ^{4}He spallation processes, Phys. Rev. D **84**, 035008 (2011).

[75] M. Kawasaki and M. Kusakabe, Destruction of ^{7}Be in big bang nucleosynthesis via long-lived sub-strongly interacting massive particles as a solution to the Li problem, Phys. Rev. D **83**, 055011 (2011).

[76] M. Kusakabe, G. J. Mathews, T. Kajino, and M.-K. Cheoun, Review on effects of long-lived negatively charged massive particles on big bang nucleosynthesis, Int. J. Mod. Phys. E **26**, 1741004 (2017).

[77] M. Kusakabe, M.-K. Cheoun, and K. S. Kim, General limit on the relation between abundances of D and ^{7}Li in big bang nucleosynthesis with nucleon injections, Phys. Rev. D **90**, 045009 (2014).

[78] G. J. Mathews, A. Kedia, N. Sasankan, M. Kusakabe, Y. Luo, T. Kajino, D. Yamazaki, T. Makki, and M. E. Eid, Cosmological solutions to the lithium problem, J. Phys. Soc. Jpn. Conf. Proc. **31**, 011033 (2020).

[79] Y. Luo, T. Kajino, M. Kusakabe, and G. J. Mathews, Big bang nucleosynthesis with an inhomogeneous primordial magnetic field strength, Astrophys. J. **872**, 172 (2019).

[80] T. R. Makki, M. F. El Eid, and G. J. Mathews, Impact of neutrino properties and dark matter on the primordial lithium production, Int. J. Mod. Phys. E **28**, 1950065 (2019).

[81] R. A. Malaney and G. J. Mathews, Probing the early universe: A review of primordial nucleosynthesis beyond the standard big bang, Phys. Rep. **229**, 145 (1993).

[82] G. J. Mathews, T. Kajino, and T. Shima, Big bang nucleosynthesis with a new neutron lifetime, Phys. Rev. D **71**, 021302(R) (2005).

[83] S. Q. Hou, J. J. He, A. Parikh, D. Kahl, C. A. Bertulani, T. Kajino, G. J. Mathews, and G. Zhao, Non-extensive statistics to the cosmological lithium problem, Astrophys. J. **834**, 165 (2017).

[84] R. Nakamura, M.-A. Hashimoto, R. Ichimasa, and K. Arai, Big-bang nucleosynthesis: Constraints on nuclear reaction rates, neutrino degeneracy, inhomogeneous and Brans-Dicke models, Int. J. Mod. Phys. E **26**, 1741003 (2017).

[85] Y. Lu and M. Kusakabe, Effect of magnetic field dissipation on primordial Li abundance, Astrophys. J. Lett. **926**, L4 (2022).

[86] V. V. Flambaum and A. R. Zhitnitsky, Primordial lithium puzzle and the axion quark nugget dark matter model, Phys. Rev. D **99**, 023517 (2019).

[87] M. Pospelov and N. Afshordi, Lithium diffusion in the post-recombination universe and spatial variation of [Li/H], arXiv:1208.0793.

[88] S. Bailly, Gravitino dark matter and the lithium primordial abundance within a pre-BBN modified expansion, J. Cosmol. Astropart. Phys. 03 (2011) 022.

[89] R. H. Cyburt, J. Ellis, B. D. Fields, F. Luo, K. A. Olive, and V. C. Spanos, Nuclear reaction uncertainties, massive gravitino decays and the cosmological lithium problem, J. Cosmol. Astropart. Phys. 10 (2010) 032.

[90] K. A. Olive, P. Petitjean, E. Vangioni, and J. Silk, Higher D or Li: Probes of physics beyond the standard model, Mon. Not. R. Astron. Soc. **426**, 1427 (2012).

[91] A. Coc, J.-P. Uzan, and E. Vangioni, Mirror matter can alleviate the cosmological lithium problem, Phys. Rev. D **87**, 123530 (2013).

[92] M. Pospelov and J. Pradler, Big bang nucleosynthesis as a probe of new physics, Annu. Rev. Nucl. Part. Sci. **60**, 539 (2010).

[93] G. 't Hooft, Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking, NATO Sci. Ser. B **59**, 135 (1980).

[94] D. Tong, Line operators in the standard model, J. High Energy Phys. 07 (2017) 104.

[95] S. Koren, A note on proton stability in the standard model, Universe **8**, 308 (2022).

[96] M. M. Anber and E. Poppitz, Nonperturbative effects in the standard model with gauged 1-form symmetry, J. High Energy Phys. 12 (2021) 055.

[97] J. Davighi, A. Greljo, and A. E. Thomsen, Leptoquarks with exactly stable protons, Phys. Lett. B **833**, 137310 (2022).

[98] J. Wang, Z. Wan, and Y.-Z. You, Proton stability: From the Standard Model to ultra unification, Phys. Rev. D **106**, 025016 (2022).

[99] L. M. Krauss and F. Wilczek, Discrete Gauge Symmetry in Continuum Theories, Phys. Rev. Lett. **62**, 1221 (1989).

[100] M. G. Alford, J. March-Russell, and F. Wilczek, Discrete quantum hair on black holes and the nonabelian Aharonov-Bohm effect, Nucl. Phys. **B337**, 695 (1990).

[101] J. Preskill and L. M. Krauss, Local discrete symmetry and quantum mechanical hair, Nucl. Phys. **B341**, 50 (1990).

[102] S. R. Coleman, J. Preskill, and F. Wilczek, Quantum hair on black holes, Nucl. Phys. **B378**, 175 (1992).

[103] T. Banks, Effective Lagrangian description of discrete gauge symmetries, Nucl. Phys. **B323**, 90 (1989).

[104] A. A. Abrikosov, On the magnetic properties of superconductors of the second group, Sov. Phys. JETP **5**, 1174 (1957).

[105] H. B. Nielsen and P. Olesen, Vortex line models for dual strings, Nucl. Phys. **B61**, 45 (1973).

[106] P. A. M. Dirac, Quantised singularities in the electromagnetic field, Proc. R. Soc. A **133**, 60 (1931).

[107] Y. Aharonov and D. Bohm, Significance of electromagnetic potentials in the quantum theory, Phys. Rev. **115**, 485 (1959).

[108] Y. Aharonov, C. K. Au, E. C. Lerner, and J. Q. Liang, Aharonov-Bohm effect as a scattering event, Phys. Rev. D **29**, 2396 (1984).

[109] M. G. Alford and F. Wilczek, Aharonov-Bohm Interaction of Cosmic Strings with Matter, Phys. Rev. Lett. **62**, 1071 (1989).

[110] T. W. B. Kibble, Topology of cosmic domains and strings, J. Phys. A **9**, 1387 (1976).

[111] T. W. B. Kibble, Some implications of a cosmological phase transition, Phys. Rep. **67**, 183 (1980).

[112] A. Vilenkin, Cosmic string dynamics with friction, Phys. Rev. D **43**, 1060 (1991).

[113] N. S. Manton, A remark on the scattering of BPS monopoles, Phys. Lett. **110B**, 54 (1982).

[114] E. P. S. Shellard, Cosmic string interactions, Nucl. Phys. **B283**, 624 (1987).

[115] R. A. Matzner, Interaction of U(1) cosmic strings: Numerical intercommutation, Comput. Phys. **2**, 51 (1988).

[116] P. J. Ruback, Vortex string motion in the Abelian Higgs model, Nucl. Phys. **B296**, 669 (1988).

[117] E. P. S. Shellard, Understanding intercommuting, in *Workshop on Current Status of Cosmic String Scenarios* (Elsevier, Amsterdam, 1988).

[118] M. F. Atiyah and N. J. Hitchin, Low-energy scattering of non-Abelian monopoles, Phys. Lett. **107A**, 21 (1985).

[119] G. W. Gibbons and N. S. Manton, Classical and quantum dynamics of BPS monopoles, Nucl. Phys. **B274**, 183 (1986).

[120] C. Rosenzweig and A. M. Srivastava, Towards a qualitative understanding of the scattering of topological defects, Phys. Rev. D **43**, 4029 (1991).

[121] T. M. Samols, Vortex scattering, Commun. Math. Phys. **145**, 149 (1992).

[122] F. Abdelwahid and J. Burzlaff, Existence theorems for 90-degree vortex-vortex scattering, J. Math. Phys. (N.Y.) **35**, 4651 (1994).

[123] R. MacKenzie, Remarks on gauge vortex scattering, Phys. Lett. B **352**, 96 (1995).

[124] J. P. Gauntlett, C.-j. Kim, K.-M. Lee, and P. Yi, General low-energy dynamics of supersymmetric monopoles, Phys. Rev. D **63**, 065020 (2001).

[125] A. Hanany and K. Hashimoto, Reconnection of colliding cosmic strings, J. High Energy Phys. 06 (2005) 021.

[126] K. Hashimoto and D. Tong, Reconnection of non-Abelian cosmic strings, J. Cosmol. Astropart. Phys. 09 (2005) 004.

[127] J. J. Blanco-Pillado, K. D. Olum, and B. Shlaer, Cosmic string loop shapes, Phys. Rev. D **92**, 063528 (2015).

[128] T. W. B. Kibble and E. J. Copeland, Evolution of small scale structure on cosmic strings, Phys. Scr. T **36**, 153 (1991).

[129] E. J. Copeland and T. W. B. Kibble, Kinks and small-scale structure on cosmic strings, Phys. Rev. D **80**, 123523 (2009).

[130] X. Siemens and K. D. Olum, Gravitational radiation and the small-scale structure of cosmic strings, Nucl. Phys. **B611**, 125 (2001); **B645**, 367(E) (2002).

[131] X. Siemens, K. D. Olum, and A. Vilenkin, On the size of the smallest scales in cosmic string networks, Phys. Rev. D **66**, 043501 (2002).

[132] A. Vilenkin, Cosmic strings, Phys. Rev. D **24**, 2082 (1981).

[133] A. Vilenkin, Gravitational radiation from cosmic strings, Phys. Lett. **107B**, 47 (1981).

[134] A. Vilenkin and E. P. S. Shellard, *Cosmic Strings and Other Topological Defects* (Cambridge University Press, Cambridge, England, 2000).

[135] N. Turok and P. Bhattacharjee, Stretching cosmic strings, Phys. Rev. D **29**, 1557 (1984).

[136] A. Albrecht and N. Turok, Evolution of Cosmic Strings, Phys. Rev. Lett. **54**, 1868 (1985).

[137] D. P. Bennett and F. R. Bouchet, Evidence for a Scaling Solution in Cosmic String Evolution, Phys. Rev. Lett. **60**, 257 (1988).

[138] E. P. S. Shellard and P. J. Ruback, Vortex Scattering in Two-dimensions, Phys. Lett. B **209**, 262 (1988).

[139] K. J. M. Moriarty, E. Myers, and C. Rebbi, Dynamical interactions of cosmic strings, J. Comput. Phys. **88**, 467 (1990).

[140] E. Myers, C. Rebbi, and R. Strilka, A study of the interaction and scattering of vortices in the Abelian Higgs (or Ginzburg-Landau) model, Phys. Rev. D **45**, 1355 (1992).

[141] J. J. Blanco-Pillado, K. D. Olum, and B. Shlaer, The number of cosmic string loops, Phys. Rev. D **89**, 023512 (2014).

[142] A. H. Guth and E. J. Weinberg, Could the universe have recovered from a slow first order phase transition?, Nucl. Phys. **B212**, 321 (1983).

[143] W. H. Zurek, Cosmological experiments in superfluid helium?, Nature (London) **317**, 505 (1985).

[144] H. Murayama and J. Shu, Topological dark matter, Phys. Lett. B **686**, 162 (2010).

[145] R. L. Davis and E. P. S. Shellard, Cosmic vortons, Nucl. Phys. **B323**, 209 (1989).

[146] R. H. Brandenberger, B. Carter, A.-C. Davis, and M. Trodden, Cosmic vortons and particle physics constraints, Phys. Rev. D **54**, 6059 (1996).

[147] A.-C. Davis and W. B. Perkins, Dissipating cosmic vortons and baryogenesis, Phys. Lett. B **393**, 46 (1997).

[148] B. Carter and A.-C. Davis, Chiral vortons and cosmological constraints on particle physics, Phys. Rev. D **61**, 123501 (2000).

[149] P. Peter and C. Ringeval, A Boltzmann treatment for the vorton excess problem, J. Cosmol. Astropart. Phys. 05 (2013) 005.

[150] P. Auclair, P. Peter, C. Ringeval, and D. Steer, Irreducible cosmic production of relic vortons, J. Cosmol. Astropart. Phys. 03 (2021) 098.

[151] R. A. Battye, S. J. Cotterill, and J. A. Pearson, A detailed study of the stability of vortons, J. High Energy Phys. 04 (2022) 005.

[152] P. A. M. Dirac, The theory of magnetic poles, Phys. Rev. **74**, 817 (1948).

[153] A. S. Goldhaber, Role of spin in the monopole problem, Phys. Rev. **140**, B1407 (1965).

[154] S. Weinberg, Photons and gravitons in perturbation theory: Derivation of Maxwell's and Einstein's equations, Phys. Rev. **138**, B988 (1965).

[155] D. Zwanziger, Exactly soluble nonrelativistic model of particles with both electric and magnetic charges, Phys. Rev. **176**, 1480 (1968).

[156] A. Peres, Rotational invariance of magnetic monopoles, Phys. Rev. **167**, 1449 (1968).

[157] H. J. Lipkin, W. I. Weisberger, and M. Peshkin, Magnetic charge quantization and angular momentum, Ann. Phys. (N.Y.) **53**, 203 (1969).
[158] T. T. Wu and C. N. Yang, Dirac's monopole without strings: Classical Lagrangian theory, Phys. Rev. D **14**, 437 (1976).
[159] J. S. Schwinger, Magnetic charge and quantum field theory, Phys. Rev. **144**, 1087 (1966).
[160] D. Zwanziger, Quantum field theory of particles with both electric and magnetic charges, Phys. Rev. **176**, 1489 (1968).
[161] D. Zwanziger, Local Lagrangian quantum field theory of electric and magnetic charges, Phys. Rev. D **3**, 880 (1971).
[162] D. Zwanziger, Angular distributions and a selection rule in charge-pole reactions, Phys. Rev. D **6**, 458 (1972).
[163] Y. Kazama, C. N. Yang, and A. S. Goldhaber, Scattering of a dirac particle with charge Ze by a fixed magnetic monopole, Phys. Rev. D **15**, 2287 (1977).
[164] C. G. Callan, Jr. and S. R. Das, Boundary Conditions on the Monopole Dirac Equation, Phys. Rev. Lett. **51**, 1155 (1983).
[165] C. Csaki, S. Hong, Y. Shirman, O. Telem, J. Terning, and M. Waterbury, Scattering amplitudes for monopoles: Pairwise little group and pairwise helicity, J. High Energy Phys. 08 (2021) 029.
[166] C. Csáki, S. Hong, Y. Shirman, O. Telem, and J. Terning, Completing Multiparticle Representations of the Poincaré Group, Phys. Rev. Lett. **127**, 041601 (2021).
[167] G. 't Hooft, Magnetic monopoles in unified gauge theories, Nucl. Phys. **B79**, 276 (1974).
[168] A. M. Polyakov, Particle spectrum in quantum field theory, JETP Lett. **20**, 194 (1974).
[169] J. Arafune, P. G. O. Freund, and C. J. Goebel, Topology of Higgs fields, J. Math. Phys. (N.Y.) **16**, 433 (1975).
[170] M. K. Prasad and C. M. Sommerfield, An Exact Classical Solution for the 't Hooft Monopole and the Julia-Zee Dyon, Phys. Rev. Lett. **35**, 760 (1975).
[171] B. Julia and A. Zee, Poles with both magnetic and electric charges in non-Abelian gauge theory, Phys. Rev. D **11**, 2227 (1975).
[172] P. Hasenfratz and D. A. Ross, Anomalous angular momenta in a quantized theory of monopoles, Nucl. Phys. **B108**, 462 (1976).
[173] E. Tomboulis and G. Woo, Soliton quantization in gauge theories, Nucl. Phys. **B107**, 221 (1976).
[174] C. G. Callan, Jr. and D. J. Gross, Quantum perturbation theory of solitons, Nucl. Phys. **B93**, 29 (1975).
[175] D. G. Boulware, L. S. Brown, R. N. Cahn, S. D. Ellis, and C.-k. Lee, Scattering on magnetic charge, Phys. Rev. D **14**, 2708 (1976).
[176] R. Jackiw and C. Rebbi, Solitons with fermion number 1/2, Phys. Rev. D **13**, 3398 (1976).
[177] P. Hasenfratz and G. 't Hooft, A Fermion-Boson Puzzle in a Gauge Theory, Phys. Rev. Lett. **36**, 1119 (1976).
[178] A. S. Goldhaber, Spin and Statistics Connection for Charge-Monopole Composites, Phys. Rev. Lett. **36**, 1122 (1976).
[179] A. S. Goldhaber, Dirac particle in a magnetic field: Symmetries and their breaking by monopole singularities, Phys. Rev. D **16**, 1815 (1977).
[180] C. G. Callan, Jr., Monopole catalysis of baryon decay, Nucl. Phys. **B212**, 391 (1983).
[181] V. A. Rubakov, Superheavy magnetic monopoles and proton decay, JETP Lett. **33**, 644 (1981).
[182] V. A. Rubakov, Adler-Bell-Jackiw anomaly and fermion number breaking in the presence of a magnetic monopole, Nucl. Phys. **B203**, 311 (1982).
[183] C. G. Callan, Jr., Dyon-fermion dynamics, Phys. Rev. D **26**, 2058 (1982).
[184] C. G. Callan, Jr., Disappearing dyons, Phys. Rev. D **25**, 2141 (1982).
[185] C. G. Callan, Jr., The monopole catalysis S-matrix, in *Workshop on Problems in Unification and Supergravity* (AIP, Melville, 1983), pp. 45–53.
[186] S. Dawson and A. N. Schellekens, Monopole—fermion interactions: The soliton picture, Phys. Rev. D **28**, 3125 (1983).
[187] A. Sen, Role of Conservation Laws in the Callan-Rubakov Process with Arbitrary Number of Generation of Fermions, Phys. Rev. Lett. **52**, 1755 (1984).
[188] J. Polchinski, Monopole catalysis: The fermion rotor system, Nucl. Phys. **B242**, 345 (1984).
[189] K. Isler, C. Schmid, and C. A. Trugenberger, Monopole core excitations and the Rubakov-Callan effect, Nucl. Phys. **B294**, 925 (1987).
[190] V. A. Rubakov, Monopole catalysis of proton decay, Rep. Prog. Phys. **51**, 189 (1988).
[191] I. Affleck and J. Sagi, Monopole catalyzed baryon decay: A boundary conformal field theory approach, Nucl. Phys. **B417**, 374 (1994).
[192] T. D. Brennan, Callan-Rubakov effect and higher charge monopoles, J. High Energy Phys. 02 (2023) 159.
[193] T. D. Brennan, Index-like theorem for massless fermions in spherically symmetric monopole backgrounds, J. High Energy Phys. 03 (2022) 095.
[194] C. Csáki, Y. Shirman, O. Telem, and J. Terning, Monopoles Entangle Fermions, Phys. Rev. Lett. **129**, 181601 (2022).
[195] M. G. Alford, J. March-Russell, and F. Wilczek, Enhanced baryon number violation due to cosmic strings, Nucl. Phys. **B328**, 140 (1989).
[196] E. Witten, Superconducting strings, Nucl. Phys. **B249**, 557 (1985).
[197] R. Khatri and R. A. Sunyaev, Time of primordial Be-7 conversion into Li-7, energy release and doublet of narrow cosmological neutrino lines, Astron. Lett. **37**, 367 (2011).
[198] V. Poulin, P. D. Serpico, and J. Lesgourgues, A fresh look at linear cosmological constraints on a decaying dark matter component, J. Cosmol. Astropart. Phys. 08 (2016) 036.
[199] S. K. Acharya and R. Khatri, CMB anisotropy and BBN constraints on pre-recombination decay of dark matter to visible particles, J. Cosmol. Astropart. Phys. 12 (2019) 046.
[200] K. R. Dienes, J. Kumar, P. Stengel, and B. Thomas, Cosmological constraints on unstable particles: Numerical bounds and analytic approximations, Phys. Rev. D **99**, 043513 (2019).
[201] T. R. Slatyer and C.-L. Wu, General constraints on dark matter decay from the cosmic microwave background, Phys. Rev. D **95**, 023010 (2017).

[202] S. K. Acharya and R. Khatri, New CMB spectral distortion constraints on decaying dark matter with full evolution of electromagnetic cascades before recombination, Phys. Rev. D **99**, 123510 (2019).

[203] J. Heeck, Unbroken B—L symmetry, Phys. Lett. B **739**, 256 (2014).

[204] P. Ilten, Y. Soreq, M. Williams, and W. Xue, Serendipity in dark photon searches, J. High Energy Phys. 06 (2018) 004.

[205] M. Bauer, P. Foldenauer, and J. Jaeckel, Hunting all the hidden photons, J. High Energy Phys. 07 (2018) 094.

[206] O. G. Miranda and H. Nunokawa, Non standard neutrino interactions: Current status and future prospects, New J. Phys. **17**, 095002 (2015).

[207] J. Wang, Ultra unification, Phys. Rev. D **103**, 105024 (2021).

[208] J. Wang, Anomaly and cobordism constraints beyond the standard model: Topological force, arXiv:2006.16996.

[209] J. Wang, Anomaly and cobordism constraints beyond grand unification: Energy hierarchy, arXiv:2008.06499.

[210] S. A. Sanidas, R. A. Battye, and B. W. Stappers, Constraints on cosmic string tension imposed by the limit on the stochastic gravitational wave background from the European pulsar timing array, Phys. Rev. D **85**, 122003 (2012).

[211] I. Y. Rybak and L. Sousa, CMB anisotropies generated by cosmic string loops, Phys. Rev. D **104**, 023507 (2021).

[212] R. R. Caldwell and B. Allen, Cosmological constraints on cosmic string gravitational radiation, Phys. Rev. D **45**, 3447 (1992).

[213] S. Blasi, V. Brdar, and K. Schmitz, Has NANOGrav found first evidence for cosmic strings?, Phys. Rev. Lett. **126**, 041305 (2021).

[214] C.-F. Chang and Y. Cui, Gravitational waves from global cosmic strings and cosmic archaeology, J. High Energy Phys. 03 (2022) 114.

[215] J. J. Blanco-Pillado, K. D. Olum, and J. M. Wachter, Comparison of cosmic string and superstring models to NANOGrav 12.5-year results, Phys. Rev. D **103**, 103512 (2021).

[216] C. Contaldi, M. Hindmarsh, and J. Magueijo, The Power Spectra of CMB and Density Fluctuations Seeded by Local Cosmic Strings, Phys. Rev. Lett. **82**, 679 (1999).

[217] A. Lazanu and P. Shellard, Constraints on the Nambu-Goto cosmic string contribution to the CMB power spectrum in light of new temperature and polarisation data, J. Cosmol. Astropart. Phys. 02 (2015) 024.

[218] A. Lazanu, E. P. S. Shellard, and M. Landriau, CMB power spectrum of Nambu-Goto cosmic strings, Phys. Rev. D **91**, 083519 (2015).

[219] J. Lizarraga, J. Urrestilla, D. Daverio, M. Hindmarsh, and M. Kunz, New CMB constraints for Abelian Higgs cosmic strings, J. Cosmol. Astropart. Phys. 10 (2016) 042.

[220] T. Charnock, A. Avgoustidis, E. J. Copeland, and A. Moss, CMB constraints on cosmic strings and superstrings, Phys. Rev. D **93**, 123503 (2016).

[221] J. C. Maxwell, A dynamical theory of the electromagnetic field, Phil. Trans. R. Soc. London **155**, 459 (1865).

[222] C. Montonen and D. I. Olive, Magnetic monopoles as gauge particles?, Phys. Lett. **72B**, 117 (1977).

[223] P. Goddard, J. Nuyts, and D. I. Olive, Gauge theories and magnetic charge, Nucl. Phys. **B125**, 1 (1977).

[224] H. Osborn, Topological charges for $N = 4$ supersymmetric gauge theories and monopoles of spin 1, Phys. Lett. **83B**, 321 (1979).