DEUTSCHES ELEKTRONEN-SYNCHROTRON
Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY 19-209
IPMU19-0171
arXiv:1911.12342
November 2019

Asymmetric Matters from a Dark First-Order Phase Transition

E. Hall, R. McGehee

Department of Physics, University of California, Berkeley, USA

and

Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, USA

T. Konstandin

Deutsches Elektronen-Synchrotron DESY, Hamburg

H. Murayama

Department of Physics, University of California, Berkeley, USA

and

Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Japan

and

Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, USA

and

Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 - 22607 HAMBURG

IPMU19-0171, DESY 19-209

Asymmetric Matters from a Dark First-Order Phase Transition

Eleanor Hall,[1, 2, *] Thomas Konstandin,[3, †] Robert McGehee,[1, 2, ‡] and Hitoshi Murayama[1, 4, 2, 3, §]

[1]*Department of Physics, University of California, Berkeley, CA 94720, USA*
[2]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3]*DESY, Notkestrae 85, D-22607 Hamburg, Germany*
[4]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan*

We introduce a model for matter*s*-genesis in which both the baryonic and dark matter asymmetries originate from a first-order phase transition in a dark sector with an $SU(3) \times SU(2) \times U(1)$ gauge group and minimal matter content. In the simplest scenario, we predict that dark matter is a dark neutron with mass either $m_n = 1.33$ GeV or $m_n = 1.58$ GeV. Alternatively, dark matter may be comprised of equal numbers of dark protons and pions. This model, in either scenario, is highly discoverable through both dark matter direct detection and dark photon search experiments. The strong dark matter self interactions may ameliorate small-scale structure problems, while the strongly first-order phase transition may be confirmed at future gravitational wave observatories.

arXiv:1911.12342v1 [hep-ph] 27 Nov 2019

I. INTRODUCTION

Two of the greatest mysteries in physics are the origin of the baryon asymmetry and the nature of dark matter. The first is puzzling because, although baryon and lepton number are individually conserved at tree level in the Standard Model (SM), cosmological measurements observe a net baryon asymmetry. A mechanism to generate this asymmetry must contain three ingredients outlined by Sakharov: (1) C- and CP-violation, (2) baryon number violation, and (3) departure from thermal equilibrium [1].

One of the most historically popular mechanisms is electroweak baryogenesis [2–12], in which the departure from thermal equilibrium arises from a strongly first-order electroweak phase transition. Because the minimal SM phase transition is a crossover [13–15] and CP-violation is too small [16–19], models typically introduce additional singlet scalars [8, 20] or an extra Higgs doublet [5–7, 9–11, 21–23]. However, strong constraints on SM CP-violation have made these models increasingly in tension with experiment [24].

The SM must also be extended to account for dark matter, which observations [25] show to be roughly five times as abundant as visible matter. The similarity of dark and baryon abundances has motivated studies of asymmetric dark matter, in which the baryon and dark matter asymmetries originate from the same mechanism (see the classic reviews [26–28] and references therein).

In this paper, we introduce a minimal model in which the baryon and dark matter asymmetries originate from electroweak-like baryogenesis in a dark sector with an $SU(3) \times SU(2) \times U(1)$ gauge group, two Higgs doublets, and one generation of SM-like matter content. This paper builds upon recent work [29] in which the SM baryon asymmetry is the result of electroweak-like baryogenesis in a dark sector with an $SU(2)$ gauge group and two "lepton" doublets. A right-handed neutrino singlet and the SM electroweak sphaleron transfer the dark lepton asymmetry into an SM baryon asymmetry. We show that by extending the gauge group to $SU(3) \times SU(2) \times U(1)$, one may straightforwardly obtain GeV-scale asymmetric dark hadronic dark matter. The symmetric component of the dark baryons annihilates into massive dark photons, which decay to SM states via a testable kinetic mixing, leaving the asymmetric component as dark matter.

We consider two dark matter possibilities in detail. In the first, the dark neutron is the lightest baryon and comprises all of dark matter. In the second, the dark proton is the lightest baryon and acts as dark matter together with dark pions. We find both of these scenarios are testable at current and future dark photon and direct detection experiments. Because the dark matter consists of GeV-scale dark hadrons, they may also have velocity-dependent self-interactions at the correct scale to address small-scale structure issues [30].

There is an extensive history of dark sectors with an $SU(3) \times SU(2) \times U(1)$ gauge group, particularly in the context of mirror world models (see [31, 32] for a review). Additionally, dark $SU(3)$ gauge groups are common features of baryonic dark matter and many models of asymmetric dark matter. Often, mirror asymmetric dark matter models assume high-scale leptogenesis produces the asymmetries and sometimes, that an exact $\mathbf{Z}_2$ symmetry between the standard and mirror sectors exists (see [33–35] for recent interesting examples).

The idea that the SM baryon asymmetry is the result of a dark phase transition ("darkogenesis") was originally proposed in Ref. [36]; other mechanisms have been developed in *e.g.*, [37–40]. However, whereas darkogenesis models typically rely on higher-dimensional operators or a messenger sector in order to transfer the baryon asymmetry to the SM, we use a neutrino portal in a minimal, renormalizable model.

The rest of this paper is organized as follows. In Sec. II, we define the model content and investigate the conditions for dark-sector baryogenesis. In Sec. III, we calcu-

* nellhall@berkeley.edu
† thomas.konstandin@desy.de
‡ robertmcgehee@berkeley.edu
§ hitoshi@berkeley.edu, Hamamatsu Professor

late the resulting SM- and dark-sector asymmetries and investigate the features and signatures of two possible dark matter scenarios in depth. Conclusions follow in Sec. IV.

II. DARK-SECTOR BARYOGENESIS

In this section, we introduce the particle content of our model and discuss how the dark and SM baryon asymmetries are generated. The dark sector contains an $SU(3)' \times SU(2)' \times U(1)'$ gauge group, one SM-like matter generation (including a right-handed singlet neutrino), and two Higgs doublets:

$$Q', u'_{\rm R}, d'_{\rm R}, L', e'_{\rm R}, N'_{\rm R}, \, \Phi_1, \Phi_2. \tag{1}$$

Throughout this paper, superscripts $'$ on SM particles refer to their dark-sector counterparts which are charged analogously under the dark gauge group. $N'_{\rm R}$ refers to the right-handed neutrino singlet, while $\Phi_{\{1,2\}}$ refer to the two dark Higgs doublets. In contrast with the usual SM mass hierarchy, we assume that leptons are heavy while quarks are light. In particular, e' is assumed to have a dark Yukawa coupling similar to that of the SM top quark.

The dark gauge sector is directly analogous to the SM with the exception that the the dark $U(1)'_{\rm EM}$ photon is massive and dark hypercharge kinetically mixes with SM hypercharge. After electroweak symmetry breaking in both the dark and SM sectors, these features may be parameterized in terms of the dark photon as

$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{\gamma'} A'_\mu A'^\mu. \tag{2}$$

The right-handed neutrino singlet is coupled to both dark sector Higgses as well as the SM Higgs

$$\mathcal{L} \supset Y^a_n \bar{L}' \tilde{\Phi}_a N'_{\rm R} + y_N \bar{L} \tilde{H} N'_{\rm R} + c.c., \tag{3}$$

for $a \in \{1,2\}$ where $\tilde{H} = i\sigma_2 H^*$ and similarly for $\tilde{\Phi}_a$. Each particle may possess distinct Yukawa couplings Y^a to the two Higgs doublets. It is also possible that the dark neutrino has a Majorana mass term; we will consider this to be small.

Dark-sector baryogenesis proceeds as follows. At high temperatures, the dark sector is in the unbroken electroweak phase. At some temperature T_C, the dark sector undergoes a strongly first-order electroweak phase transition, which provides a departure from thermal equilibrium. At the phase transition, explicit CP-violating terms in the dark Higgs potential induce a changing CP-violating phase in the fermion mass terms across the bubble wall; this in turn leads to a CP-violating force across the bubble wall. Together with the dark electroweak sphaleron, this results in a $B' + L'$ asymmetry that is primarily driven by the dark electron, which we take to have an $\mathcal{O}(1)$ Yukawa coupling.

The precise parameter space over which the two-Higgs doublet mechanism may generate a sufficient baryon asymmetry has been the subject of extensive study; see *e.g.* [5–7, 9–11, 21–23]. Baryogenesis with two Higgs doublets favors light Higgs masses and large quartic couplings, and in the context of extensions of the SM Higgs sector, this can cause issues such as Landau poles; together with recent electric dipole measurements [24], this leads to significant constraints on the parameter space over which baryogenesis may occur. However, in the present setup, electroweak baryogenesis is easier to realize. Among other things, leptons diffuse further into the symmetric phase and do not suffer from suppression by the strong sphalerons [41]. Besides, EDM constraints do not apply and the parameter space in the dark scalar sector is almost entirely unconstrained. Hence, we expect that it should not be difficult to achieve the required baryon asymmetry and will not perform an in-depth analysis in this paper.

Acoustic sound waves and magnetohydrodynamic turbulence generated in the aftermath of a first-order phase transition will generically produce a gravitational wave signal with a characteristic spectrum determined by the rate and energy release of the phase transition. With the advent of gravitational wave astronomy, gravitational wave signals from dark phase transitions have become a subject of considerable interest; see *e.g.* [42–45]. The spectrum of the gravitational waves from this model could likely fall in the detection range of future gravitational wave observatories such as LISA, BBO, and DECIGO. Because the spectrum is generic and our model space is so unconstrained, we will not perform an in-depth investigation of gravitational wave signals here; see [29] for the expected spectrum.

Following dark-sector baryogenesis [29], the dark leptons are in equilibrium with the SM through the neutrino portal via the process $\Phi'\nu' \leftrightarrow H\nu$ and $N'_{\rm R} \leftrightarrow H\nu$. Together with the SM sphaleron, this will transfer some of the initial dark lepton asymmetry into an SM baryon and lepton asymmetry. At some temperature, the remaining leptons will decay to the SM through the processes $e' \to \nu' \bar{u}' d'$ and $\nu' \to \nu H$, leaving only quarks and photons in the dark sector. Following hadronization, the symmetric component of the dark baryons will annihilate into dark photons (through *e.g.*, $\pi'^+\pi'^- \to \gamma'\gamma'$ and $\pi'^+\pi'^- \to \pi'^0\pi'^0$, $\pi'^0 \to \gamma'\gamma'$) which in turn decay into the SM.

The remaining baryonic asymmetry forms asymmetric dark matter with the dark matter mass set by the relative SM and dark matter abundances. The precise behavior of the dark hadronic content and the nature of dark matter depend on the parameters of the model and is discussed in depth in Sec. III.

We now recall the values for the SM lepton and baryon asymmetries [29]. We assume there are no new particles in the SM and hence the SM electroweak phase transition is a crossover. If the dark neutrino decays after the SM sphaleron has decoupled, we find

$$B = \frac{36}{133} B' \,, \quad L = -\frac{97}{133} B' \,. \tag{4}$$

If on the other hand the dark neutrino is heavy and decays before the SM sphaleron has decoupled, we obtain asymmetries

$$B = \frac{12}{37} B' \,, \quad L = -\frac{25}{37} B'. \tag{5}$$

The asymmetries will be different if the SM electroweak phase transition is strongly first-order instead of a crossover and may be found in Ref. [29]; we do not discuss these cases further as they require additional extensions of the SM sector.

Although the model presented in this section is in some sense the most minimal, it generalizes quite straightforwardly to a fully mirrored model in which the dark sector has three SM-like generations with a similar mass hierarchy. A full mirror sector with three families of quarks would also motivate some GUT-scale equivalence of the $SU(3)$ and $SU(3)'$ gauge couplings, which could in turn follow similar RG flows to the IR. This would explain the coincidence of the dark and SM matter densities and is an advantage of mirror world models generally.

One might also want to consider a model with three generations but only one Higgs doublet in which the dark baryon asymmetry is generated according to the mechanism originally suggested by Farrar and Shaposhnikov for minimal-SM baryogenesis [12, 17–19]. In this mechanism, the CKM or PMNS matrix would lead to CP-violating coefficients for fermionic reflections off the bubble wall of a strongly first-order electroweak phase transition. However, our non-perturbative analysis following [19] found that even with the largest possible degree of CP-violation and $\mathcal{O}(1)$ Yukawa couplings, it was impossible to generate a sufficiently large dark baryon asymmetry even in the optimistic limit of a thin wall, a fast sphaleron, and no diffusion.

III. DARK MATTER AND EXPERIMENTAL SIGNATURES

In this section, we discuss the fate of the dark sector following dark-sector baryogenesis. The remaining asymmetric hadronic content will be dark matter and is overall neutral due to individual conservation of both dark and SM $U(1)_{\rm EM}$ charges. Below the confinement scale of $SU(3)'$, $\Lambda_{SU(3)'}$, the only remaining dark sector particles are hadrons and photons. Since the dark quark masses do not affect the baryogenesis mechanism (as long as their Yukawas are sufficiently smaller than the much heavier dark leptons), there are different viable dark matter scenarios. We will enumerate the few simplest cases below, but first discuss the phenomenology that is common to all of them.

Since the dark leptons are heavy, much of the dark hadronic symmetric entropy density is transferred into π'^0. To ensure the dark sector does not overclose the universe, we require π'^0 to decay. This is easily achieved through the dominant decay mode to two dark photons as long as $m_{\gamma'} \leq m_{\pi'_0}/2$. In order for the dark photon to decay into the SM, we require $m_{\gamma'} \geq 2m_e$. The decay rate of the dark photon to a pair of SM leptons is

$$\Gamma_{\gamma' \to l\bar{l}} = \frac{\alpha \epsilon^2 \left(m_{\gamma'}^2 + 2m_l^2\right)}{3m_{\gamma'}} \sqrt{1 - \frac{4m_l^2}{m_{\gamma'}^2}}. \tag{6}$$

For dark photon masses below a GeV, the decay rate into hadronic channels is non-perturbative. We infer the decay rates from the branching ratios derived from measured ratios of hadronic final-state cross sections to those of muons in e^+e^- collisions [46]. We require the resulting total decay rate of the dark photon to be faster than Hubble before SM neutrinos decouple around $T \sim 3\,\text{MeV}$ [47], which is true for all dark photon masses we consider as long as $\epsilon \gtrsim \mathcal{O}(10^{-10})$.

With these common considerations outlined, we discuss two distinct limits: one in which all of dark matter is the dark neutron, n', and the other in which dark matter is comprised of equal numbers of dark protons, p', and π'^-, assuming $|m_{n'} - m_{p'}| \gtrsim 100$ MeV. These scenarios predict different dark matter masses and direct detection constraints and prospects. If n' and p' masses are closer, the situation is between these two limits.

A. Dark Neutron Dark Matter

In this scenario, the lightest dark baryon is the neutron with $m_{p'} - m_{n'} \approx m_{u'} - m_{d'} \gtrsim 100$ MeV, while both quarks are light, $m_{u'}, m_{d'} < \Lambda_{SU(3)'}$. After annihilations $p'\,\pi'^- \to n'\,\gamma'$, $\pi'^+\,\pi'^- \to \pi'^0\,\pi'^0$ and decays $\pi'^0 \to \gamma'\gamma'$, $\gamma' \to \text{SM}$, the entire dark baryon asymmetry is in n' which forms all of dark matter. While there is a subcomponent of p', the strong interactions and large dark neutron-proton mass splitting allow us to safely assume n' comprises the vast majority of dark matter. Since the relative dark and SM baryon asymmetries are set above, the dark matter mass is precisely determined by the relative baryon and dark matter abundances [25],

$$\frac{\Omega_c}{\Omega_b} = \frac{B'}{B} \frac{m_{n'}}{m_p} = 5.238. \tag{7}$$

In the case Eq. (4) that $N'_{\rm R}$ is light, we predict a dark matter mass[1]

$$m_{n'} = 1.33\,\text{GeV}. \tag{8}$$

[1] These predictions are subject to calculable α_s/π corrections in chemical equilibrium at the percent level.

In the case Eq. (5) that $N'_{\rm R}$ is heavier than the scale of the SM electroweak crossover, we predict

$$m_{n'} = 1.59\,{\rm GeV}. \tag{9}$$

Although the n' is neutral, it should possess a magnetic moment similar to that of the SM neutron. This, combined with the γ'-γ kinetic mixing, allows n' to scatter off protons in nuclei with a cross section[2]

$$\sigma_{n'p} \approx \epsilon^2 e^2 e'^2 F_2^{n'2} v^4 \frac{m_p^4 m_{n'}^2 \left(3m_p^2 + 2m_p m_{n'} + 5m_{n'}^2\right)}{6\pi m_{\gamma'}^4 \left(m_p + m_{n'}\right)^6}, \tag{10}$$

where v is the incoming dark matter velocity and $F_2^n \approx -1.913$ for the SM neutron. The most stringent spin-independent, per-nucleon cross section constraint on dark matter with masses $m_\chi \sim 1$ GeV comes from XENON1T [48]. In particular, for $m_{n'} = 1.33\,{\rm GeV}$, the bound on the dark matter-nucleon cross section is $\sigma^{\rm SI} < 7.6 \times 10^{-40}$ cm^2. This bound assumes equal couplings of the dark matter to neutrons and protons, but n' only scatters off protons, so the upper limit for $n'p$ scattering is slightly larger:

$$\sigma_{n'p} < \left(\frac{A}{Z}\right)^2 7.6 \times 10^{-40}\ {\rm cm}^2 \approx 4.4 \times 10^{-39}\ {\rm cm}^2. \tag{11}$$

In addition to constraints from direct detection, there are also limits on the self-interaction among dark matter particles from galaxy clusters $\sigma \lesssim 0.2\,{\rm cm}^2/{\rm g}$ [49–51]. The neutrons in the SM have an astoundingly large cross section at low energies, $\sigma \approx 4.5 \times 10^{-23}\,{\rm cm}^2$, much larger than the geometric cross section $\approx 10^{-25}\,{\rm cm}^2$. This is regarded as a consequence of accidental (and unnatural) cancellations in the effective field theory (see, *e.g.*, [52–54]) and is not generic. According to recent lattice QCD calculations from the HAL QCD collaboration [55], the self-interaction among n' is below the limit for rather heavy dark pions, $m_{\pi'} \gtrsim 0.4 m_{n'}$.[3] Therefore, this scenario prefers $m_{u'} \gtrsim 100$ MeV, which in turn allows for larger dark photon masses since $m_{\gamma'} < m_{\pi'_0}/2$. However, it is difficult to have a larger cross section at lower velocities to address the small-scale structure problems as shown with the effective range theory framework [59].

The viable dark photon parameter space for the neutron dark matter scenario is shown in Fig. 1 (**Left**) with current constraints from experiments [60, 61], supernovae [62, 63], and BBN [64], as well as the projected sensitivities of upcoming experiments including LHCb [65, 66], Belle-II [60, 67], AWAKE [68] (10^{16} electrons of 50 GeV), HPS [69], SeaQuest [70], LDMX [71] (HL-LDMX with $E_{\rm beam} = 16$ GeV), FASER [72] (LHC Run 3 with 150 fb^{-1}), NA62 [73], and SHiP [74]. Additionally, the NA64 bounds should improve soon [75]. Note also that even spectroscopy of resonance states is possible at e^+e^- colliders [76, 77]. The figure assumes the scenario in which $m_{n'} = 1.33\,{\rm GeV}$ (cf. Eq. (8)) and u' prefers $m_u \gtrsim 100$ MeV so that $m_{\pi'} \sim 0.5 m_{n'}$. In addition to making the n' self-interactions consistent with constraints, this allows dark photons as heavy as $m_{\gamma'} \sim 0.25 m_{n'} = 0.3\,{\rm GeV}$.[4]

Interestingly, while there is currently decades of viable parameter space in which the dark photon mass and kinetic mixing can achieve the asymmetric dark neutron dark matter, much of this will be probed by future experiments. Since the cross section in Eq. (10) is velocity-suppressed, current and future direct detection experiments are far from probing the viable dark photon parameter space. To illustrate this, we naïvely assume the XENON1T bound in Eq. (11) scales linearly with exposure and project the constraint for XENON1T with 100 times its current exposure (as in DARWIN [79]) as a thin dashed line in the upper left of Fig. 1. Additionally, we incorrectly assume that all incoming dark matter have the largest possible velocity $v_{\rm max} = v_{\rm esc} + v_{\rm E} \sim (550 + 240)$ km/s (the sum of the escape and Earth velocities in the galactic frame). Clearly, such neutral dark matter seems well outside the current direct detection bounds and future dark photon searches will better probe the viable parameter space.

B. Dark Proton & Pion Dark Matter

Next, we consider the case $m_{u'} < m_{d'} < \Lambda_{SU(3)'}$ so that the proton is the lightest dark baryon. Similar to the dark neutron case, we assume $m_{d'} - m_{u'} \gtrsim 100$ MeV to guarantee that the n' abundance is negligible. Conservation of $U(1)'_{\rm EM}$ charge implies an equal number of π'^- comprising a subcomponent of dark matter. Even though the relative dark and SM baryon asymmetries are set above, the additional pion dark matter component gives a range of possible dark matter subcomponent masses. To reproduce the observed relic abundance, they satisfy

$$\frac{B'}{B}\frac{m_{p'} + m_{\pi'^-}}{m_p} = 5.238. \tag{12}$$

It is interesting to note that p' and π'^- may scatter resonantly in the p-wave through Δ'^0. In this case, it becomes an ideal resonant self-interacting dark matter to

[2] Both the dark neutron charge radius and the possible Higgs portal give subdominant contributions to this scattering.

[3] This is still subject to uncertainties given disagreements with the NPLQCD collaboration [56, 57] (with a possible resolution [58]), and the calculations are in the flavor $SU(3)$ limit. It is also possible that much smaller $m_{\pi'}$ leads to small self-interaction, but it is currently beyond what can be studied on lattice.

[4] This upper bound on the dark photon mass will relax at higher values of kinetic mixing because $\pi'^0 \to \gamma'\gamma'^* \to \gamma' e^+ e^-$ would be possible, but we do not consider this further.

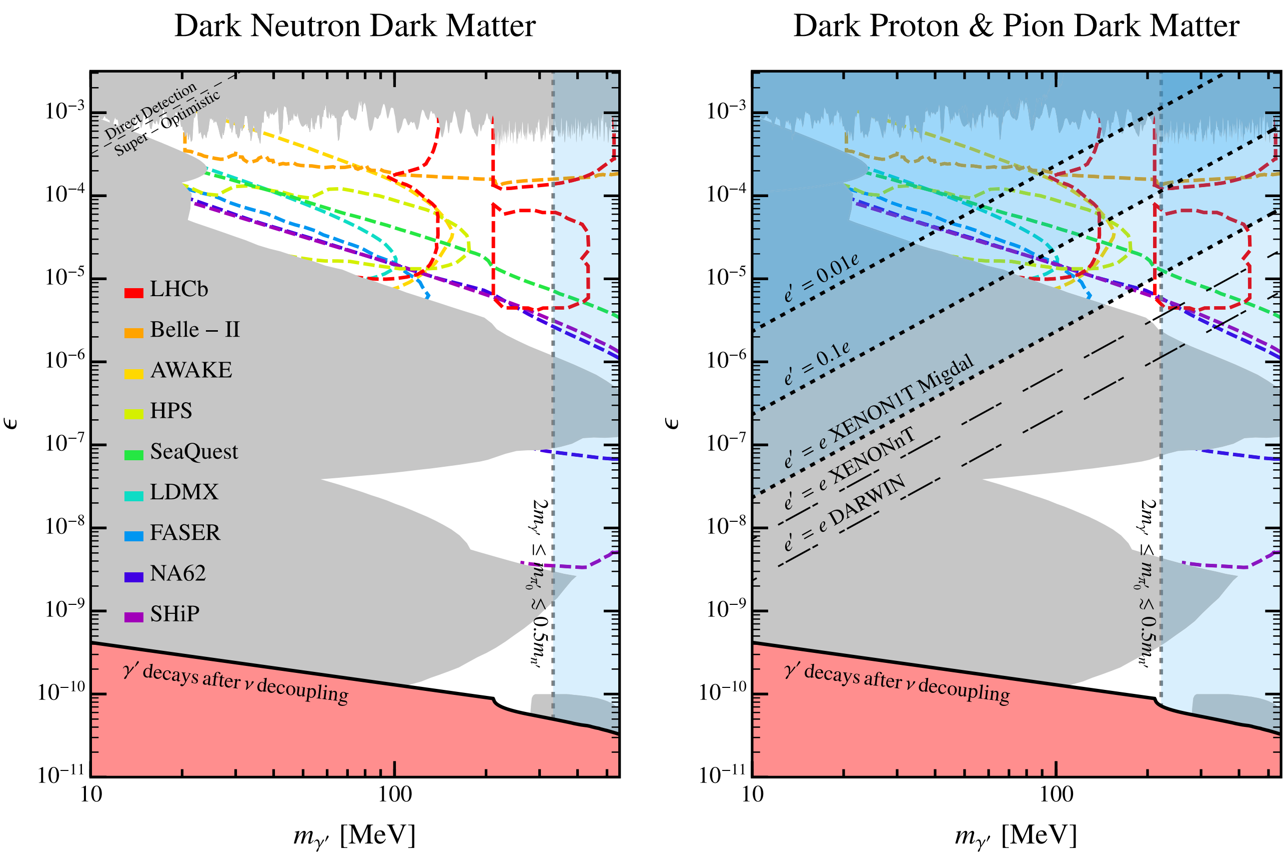

Figure 1. Viable dark photon parameter space for asymmetric dark hadron dark matter. Existing constraints on dark photons from experiments [60, 61], supernovae [62, 63], and BBN [64] are dark gray. The constraints specific to our models, namely that $m_{\gamma'} \leq m_{\pi'^0}/2$ and that the dark photon decays before SM neutrinos decouple around $T \sim 3\,\mathrm{MeV}$, are in light blue and red, respectively. Also shown in rainbow colors are projections from future experiments [60, 65–74]. **Left:** Viable parameter space for the dark neutron dark matter case with the predicted $m_{n'} = 1.33\,\mathrm{GeV}$ and assuming $m_{\pi'} \sim 0.5 m_{n'}$. **Right:** Viable parameter space for the dark proton and pion dark matter case assuming $m_{p'} = 2m_{\pi'} = 0.887\,\mathrm{GeV}$. The direct detection constraint from XENON1T [48] for various e'/e is shown in blue, as are naïve projections for XENONnT [78] and DARWIN [79].

address the small-scale structure problems if the resonant velocity is $v_R \sim 100\,\mathrm{km/s}$ with a constant s-wave cross section with $\sigma/m \sim 0.1\,\mathrm{cm}^2/\mathrm{g}$ [30]. The possibility of this threshold resonance prefers $m_{\pi'^-}/m_{p'} \sim 0.4$, which is also desirable to permit larger dark photon masses. The "Coulomb" potential barrier may also lead to a $p'p'$ resonance in the s-wave.

For illustrative purposes, we pick the dark proton and pion masses to be $m_{p'} = 2m_{\pi'} = 0.887\,\mathrm{GeV}$ to yield the observed relic abundance in the case that N'_{R} is light. While any masses satisfying Eq. (12) with the baryon asymmetry ratio given by Eq. (4) are possible, a larger dark pion mass leads to a wider viable dark photon parameter space. Likewise, in the case Eq. (5) that N'_{R} is heavier than the scale of the SM electroweak crossover, we set the masses to be $m_{p'} = 2m_{\pi'} = 1.06\,\mathrm{GeV}$.

For the available parameter space, the would-be Bohr radius $\alpha'/m_{\pi'^-}$ of the p'-π'^- "atom" is longer than the range of the dark-photon exchange force, $1/m_{\gamma'}$, so we do not expect these atoms to form. Therefore, direct detection experiments can probe p'-p scattering with

$$\sigma_{p'p} \approx \epsilon^2 e^2 e'^2 \frac{m_p^2 m_{p'}^2}{\pi (m_p + m_{p'})^2 m_{\gamma'}^4}, \tag{13}$$

and similarly for π'-p scattering. The XENON1T [48] bound is quite weaker in this heavy-ish pion case since for $m_{p'} = 0.887\,\mathrm{GeV}$, the bound on the dark matter-nucleon cross section is $\sigma^{\mathrm{SI}} < 2.0 \times 10^{-39}\ \mathrm{cm}^2$. Additionally, the upper limit for $p'p$ (or $\pi'^- p$) scattering is larger by $(A/Z)^2$ due to the lack of coupling to neutrons.

The viable dark photon parameter space for the dark proton and pion dark matter scenario is shown in Fig. 1 (**Right**) for $m_{p'} = 2m_{\pi'} = 0.887\,\mathrm{GeV}$ to give the widest parameter space. The direct detection limit also weakens if e' is much smaller than e. To demonstrate this, we show the XENON1T constraint assuming $e'/e = \{1, 0.1, 0.01\}$ as dashed black contours. There is still a large viable parameter space and future improvements in the limits appear promising. We naïvely assume that XENONnT [78] with its larger exposure will increase the current bound by an order of magnitude, though the exact improvement in sensitivity from this Migdal effect analysis is not so obvious [48]. We also show what DARWIN [79] may probe with its possible additional order of magnitude improvement. Interestingly, it appears that future direct detection experiments may be competitive with and even exceed the sensitivity of dark photon experiments.

C. Other Dark Hadron Dark Matter

Yet another possibility is that there is only one light dark quark, let's say u'. Then, dark matter is partially comprised of a dark $\Delta'^{++}(u'u'u')$ baryon whose abundance comes from the dark baryon asymmetry. There are also twice the number of dark "pions" $\pi'^{-}(\bar{u}'d')$, now heavier than $\Lambda_{SU(3)'}$. To produce the observed dark matter relic abundance, we require

$$\frac{B'}{B}\frac{m_{\Delta'^{++}}+2m_{\pi'^{-}}}{m_p}=5.238, \tag{14}$$

where $m_{\Delta'^{++}} \approx \Lambda_{SU(3)'}$. Besides the possible difference in masses, the direct detection would be similar to the p' and π'^{-} dark matter case above. The symmetric component annihilates into $\eta(\bar{u}'u') \to \gamma'\gamma' \to 2(e^+e^-)$. We do not discuss this and other variants further.

IV. CONCLUSION

We have introduced a minimal renormalizable model of asymmetric matter*s* from a dark first-order phase transition which leads to a detectable gravitational wave signature. Electroweak-like baryogenesis in the dark sector generates a dark-sector asymmetry which is then ferried to the SM via a neutrino portal. Kinetic mixing between the dark and SM photons allows for the symmetric dark-sector entropy to safely transfer to the SM, while also providing a means for the remaining asymmetric dark matter to scatter in direct detection experiments. In the case of dark neutron dark matter, we find decades of viable dark photon parameter space which will be explored in the near future by many upcoming experiments. If instead the asymmetric dark matter is comprised of dark protons and pions, the parameter space is currently being tested by direct detection experiments. In the latter case, self interactions among the dark matter may also ameliorate small-scale problems such as the diversity problem. If the energy scale of the dark first-order phase transition temperature is below 1000 TeV, we expect a gravitational wave signal at future observatories.

ACKNOWLEDGMENTS

We thank Géraldine Servant for discussions at the early stages of this work. We also thank Tetsuo Hatsuda, Takashi Inoue, André Walker-Loud, and Emanuele Mereghetti for useful information about nucleon nucleon effective range parameters. The work of HM was supported by the NSF grant PHY-1915314, by the U.S. DOE Contract DE-AC02-05CH11231, by the JSPS Grant-in-Aid for Scientific Research JP17K05409, MEXT Grant-in-Aid for Scientific Research on Innovative Areas JP15H05887, JP15K21733, by WPI, MEXT, Japan, Hamamatsu Photonics, and by the Deutsche Forschungsgemeinschaft under Germanys Excellence Strategy - EXC 2121 Quantum Universe - 390833306. The work of EH was supported by the NSF GRFP.

[1] A. D. Sakharov, "*Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*," Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32–35. [Usp. Fiz. Nauk161,no.5,61(1991)].

[2] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, "*On the Anomalous Electroweak Baryon Number Nonconservation in the Early Universe*," Phys. Lett. **155B** (1985) 36.

[3] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, "*WEAK SCALE BARYOGENESIS*," Phys. Lett. **B245** (1990) 561–564.

[4] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, "*Baryogenesis at the weak phase transition*," Nucl. Phys. **B349** (1991) 727–742.

[5] N. Turok and J. Zadrozny, "*Dynamical generation of baryons at the electroweak transition*," Phys. Rev. Lett. **65** (1990) 2331–2334.

[6] N. Turok and J. Zadrozny, "*Electroweak baryogenesis in the two doublet model*," Nucl. Phys. **B358** (1991) 471–493.

[7] L. D. McLerran, M. E. Shaposhnikov, N. Turok, and M. B. Voloshin, "*Why the baryon asymmetry of the universe is approximately 10**-10*," Phys. Lett. **B256** (1991) 451–456.

[8] M. Dine, P. Huet, R. L. Singleton, Jr, and L. Susskind, "*Creating the baryon asymmetry at the electroweak phase transition*," Phys. Lett. **B257** (1991) 351–356.

[9] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, "*Spontaneous baryogenesis at the weak phase transition*," Phys. Lett. **B263** (1991) 86–92.

[10] A. E. Nelson, D. B. Kaplan, and A. G. Cohen, "*Why there is something rather than nothing: Matter from weak interactions*," Nucl. Phys. **B373** (1992) 453–478.

[11] A. G. Cohen, D. B. Kaplan, and A. E. Nelson, "*Debye screening and baryogenesis during the electroweak phase transition*," Phys. Lett. **B294** (1992) 57–62, `arXiv:hep-ph/9206214`.

[12] G. R. Farrar and M. E. Shaposhnikov, "*Baryon asymmetry of the universe in the standard electroweak theory*," Phys. Rev. **D50** (1994) 774,

arXiv:hep-ph/9305275.

[13] K. Kajantie, M. Laine, K. Rummukainen, and M. E. Shaposhnikov, "*The Electroweak phase transition: A Nonperturbative analysis*," Nucl. Phys. **B466** (1996) 189–258, arXiv:hep-lat/9510020.

[14] K. Kajantie, M. Laine, K. Rummukainen, and M. E. Shaposhnikov, "*A Nonperturbative analysis of the finite T phase transition in SU(2) x U(1) electroweak theory*," Nucl. Phys. **B493** (1997) 413–438, arXiv:hep-lat/9612006.

[15] K. Rummukainen, M. Tsypin, K. Kajantie, M. Laine, and M. E. Shaposhnikov, "*The Universality class of the electroweak theory*," Nucl. Phys. **B532** (1998) 283–314, arXiv:hep-lat/9805013.

[16] C. Jarlskog, "*Commutator of the Quark Mass Matrices in the Standard Electroweak Model and a Measure of Maximal CP Violation*," Phys. Rev. Lett. **55** (1985) 1039.

[17] M. B. Gavela, P. Hernandez, J. Orloff, and O. Pene, "*Standard model CP violation and baryon asymmetry*," Mod. Phys. Lett. **A9** (1994) 795–810, arXiv:hep-ph/9312215.

[18] M. B. Gavela, P. Hernandez, J. Orloff, O. Pene, and C. Quimbay, "*Standard model CP violation and baryon asymmetry. Part 2: Finite temperature*," Nucl. Phys. **B430** (1994) 382–426, arXiv:hep-ph/9406289.

[19] P. Huet and E. Sather, "*Electroweak baryogenesis and standard model CP violation*," Phys. Rev. **D51** (1995) 379–394, arXiv:hep-ph/9404302.

[20] J. R. Espinosa, B. Gripaios, T. Konstandin, and F. Riva, "*Electroweak Baryogenesis in Non-minimal Composite Higgs Models*," JCAP **1201** (2012) 012, arXiv:1110.2876.

[21] J. M. Cline, K. Kainulainen, and A. P. Vischer, "*Dynamics of two Higgs doublet CP violation and baryogenesis at the electroweak phase transition*," Phys. Rev. **D54** (1996) 2451–2472, arXiv:hep-ph/9506284.

[22] J. M. Cline and P.-A. Lemieux, "*Electroweak phase transition in two Higgs doublet models*," Phys. Rev. **D55** (1997) 3873–3881, arXiv:hep-ph/9609240.

[23] L. Fromme, S. J. Huber, and M. Seniuch, "*Baryogenesis in the two-Higgs doublet model*," JHEP **11** (2006) 038, arXiv:hep-ph/0605242.

[24] **ACME**, V. Andreev *et al.*, "*Improved limit on the electric dipole moment of the electron*," Nature **562** (2018) no. 7727, 355–360.

[25] **Planck**, N. Aghanim *et al.*, "*Planck 2018 results. VI. Cosmological parameters*," arXiv:1807.06209.

[26] H. Davoudiasl and R. N. Mohapatra, "*On Relating the Genesis of Cosmic Baryons and Dark Matter*," New J. Phys. **14** (2012) 095011, arXiv:1203.1247.

[27] K. Petraki and R. R. Volkas, "*Review of asymmetric dark matter*," Int. J. Mod. Phys. **A28** (2013) 1330028, arXiv:1305.4939.

[28] K. M. Zurek, "*Asymmetric Dark Matter: Theories, Signatures, and Constraints*," Phys. Rept. **537** (2014) 91–121, arXiv:1308.0338.

[29] E. Hall, T. Konstandin, R. McGehee, H. Murayama, and G. Servant, "*Baryogenesis From a Dark First-Order Phase Transition*," arXiv:1910.08068.

[30] X. Chu, C. Garcia-Cely, and H. Murayama, "*Velocity Dependence from Resonant Self-Interacting Dark Matter*," Phys. Rev. Lett. **122** (2019) no. 7, 071103, arXiv:1810.04709.

[31] Z. Berezhiani, "*Mirror world and its cosmological consequences*," Int. J. Mod. Phys. **A19** (2004) 3775–3806, arXiv:hep-ph/0312335.

[32] R. Foot, "*Mirror matter-type dark matter*," Int. J. Mod. Phys. **D13** (2004) 2161–2192, arXiv:astro-ph/0407623.

[33] M. Ibe, A. Kamada, S. Kobayashi, and W. Nakano, "*Composite Asymmetric Dark Matter with a Dark Photon Portal*," JHEP **11** (2018) 203, arXiv:1805.06876.

[34] M. Ibe, A. Kamada, S. Kobayashi, T. Kuwahara, and W. Nakano, "*Ultraviolet Completion of a Composite Asymmetric Dark Matter Model with a Dark Photon Portal*," JHEP **03** (2019) 173, arXiv:1811.10232.

[35] M. Ibe, A. Kamada, S. Kobayashi, T. Kuwahara, and W. Nakano, "*Baryon-Dark Matter Coincidence in Mirrored Unification*," Phys. Rev. **D100** (2019) no. 7, 075022, arXiv:1907.03404.

[36] J. Shelton and K. M. Zurek, "*Darkogenesis: A baryon asymmetry from the dark matter sector*," Phys. Rev. **D82** (2010) 123512, arXiv:1008.1997.

[37] B. Dutta and J. Kumar, "*Asymmetric Dark Matter from Hidden Sector Baryogenesis*," Phys. Lett. **B699** (2011) 364–367, arXiv:1012.1341.

[38] K. Petraki, M. Trodden, and R. R. Volkas, "*Visible and dark matter from a first-order phase transition in a baryon-symmetric universe*," JCAP **1202** (2012) 044, arXiv:1111.4786.

[39] D. G. E. Walker, "*Dark Baryogenesis*," arXiv:1202.2348.

[40] G. Servant and S. Tulin, "*Baryogenesis and Dark Matter through a Higgs Asymmetry*," Phys. Rev. Lett. **111** (2013) no. 15, 151601, arXiv:1304.3464.

[41] J. De Vries, M. Postma, and J. van de Vis, "*The role of leptons in electroweak baryogenesis*," JHEP **04** (2019) 024, arXiv:1811.11104.

[42] C. Grojean and G. Servant, "*Gravitational Waves from Phase Transitions at the Electroweak Scale and Beyond*," Phys. Rev. **D75** (2007) 043507, arXiv:hep-ph/0607107.

[43] P. Schwaller, "*Gravitational Waves from a Dark Phase Transition*," Phys. Rev. Lett. **115** (2015) no. 18, 181101, arXiv:1504.07263.

[44] C. Caprini *et al.*, "*Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions*," JCAP **1604** (2016) no. 04, 001, arXiv:1512.06239.

[45] C. Caprini *et al.*, "*Detecting gravitational waves from cosmological phase transitions with LISA: an update*," arXiv:1910.13125.

[46] J. Liu, N. Weiner, and W. Xue, "*Signals of a Light Dark Force in the Galactic Center*," JHEP **08** (2015) 050, arXiv:1412.1485.

[47] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti, and P. D. Serpico, "*Effects of non-standard neutrino-electron interactions on relic neutrino decoupling*," Nucl. Phys. **B756** (2006) 100–116, arXiv:hep-ph/0607267.

[48] **XENON**, E. Aprile *et al.*, "*A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T*," arXiv:1907.12771.

[49] O. D. Elbert, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, A. S. Graus, and M. Rocha, "*A Testable Conspiracy: Simulating Baryonic Effects on*

Self-Interacting Dark Matter Halos," Astrophys. J. **853** (2018) no. 2, 109, arXiv:1609.08626.

[50] K. Bondarenko, A. Boyarsky, T. Bringmann, and A. Sokolenko, "*Constraining self-interacting dark matter with scaling laws of observed halo surface densities*," JCAP **1804** (2018) no. 04, 049, arXiv:1712.06602.

[51] D. Harvey, A. Robertson, R. Massey, and I. G. McCarthy, "*Observable tests of self-interacting dark matter in galaxy clusters: BCG wobbles in a constant density core*," Mon. Not. Roy. Astron. Soc. **488** (2019) no. 2, 1572–1579, arXiv:1812.06981.

[52] D. B. Kaplan, M. J. Savage, and M. B. Wise, "*A New expansion for nucleon-nucleon interactions*," Phys. Lett. **B424** (1998) 390–396, arXiv:nucl-th/9801034.

[53] D. B. Kaplan, M. J. Savage, and M. B. Wise, "*Two nucleon systems from effective field theory*," Nucl. Phys. **B534** (1998) 329–355, arXiv:nucl-th/9802075.

[54] P. F. Bedaque and U. van Kolck, "*Effective field theory for few nucleon systems*," Ann. Rev. Nucl. Part. Sci. **52** (2002) 339–396, arXiv:nucl-th/0203055.

[55] **HAL QCD**, T. Inoue, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, N. Ishii, K. Murano, H. Nemura, and K. Sasaki, "*Two-Baryon Potentials and H-Dibaryon from 3-flavor Lattice QCD Simulations*," Nucl. Phys. **A881** (2012) 28–43, arXiv:1112.5926.

[56] **NPLQCD**, S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H. W. Lin, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, and A. Walker-Loud, "*Light Nuclei and Hypernuclei from Quantum Chromodynamics in the Limit of SU(3) Flavor Symmetry*," Phys. Rev. **D87** (2013) no. 3, 034506, arXiv:1206.5219.

[57] **NPLQCD**, S. R. Beane *et al.*, "*Nucleon-Nucleon Scattering Parameters in the Limit of SU(3) Flavor Symmetry*," Phys. Rev. **C88** (2013) no. 2, 024003, arXiv:1301.5790.

[58] **HAL QCD**, T. Iritani, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, T. Inoue, N. Ishii, H. Nemura, and K. Sasaki, "*Consistency between Lschers finite volume method and HAL QCD method for two-baryon systems in lattice QCD*," JHEP **03** (2019) 007, arXiv:1812.08539.

[59] X. Chu, C. Garcia-Cely, and H. Murayama, "*A Practical and Consistent Parametrization of Dark Matter Self-Interactions*," arXiv:1908.06067.

[60] J. Alexander *et al.*, "*Dark Sectors 2016 Workshop: Community Report*," 2016. arXiv:1608.08632. http://lss.fnal.gov/archive/2016/conf/fermilab-conf-16-421.pdf.

[61] **NA64**, D. Banerjee *et al.*, "*Search for a Hypothetical 16.7 MeV Gauge Boson and Dark Photons in the NA64 Experiment at CERN*," Phys. Rev. Lett. **120** (2018) no. 23, 231802, arXiv:1803.07748.

[62] J. H. Chang, R. Essig, and S. D. McDermott, "*Revisiting Supernova 1987A Constraints on Dark Photons*," JHEP **01** (2017) 107, arXiv:1611.03864.

[63] E. Hardy and R. Lasenby, "*Stellar cooling bounds on new light particles: plasma mixing effects*," JHEP **02** (2017) 033, arXiv:1611.05852.

[64] A. Fradette, M. Pospelov, J. Pradler, and A. Ritz, "*Cosmological Constraints on Very Dark Photons*," Phys. Rev. **D90** (2014) no. 3, 035022, arXiv:1407.0993.

[65] P. Ilten, J. Thaler, M. Williams, and W. Xue, "*Dark photons from charm mesons at LHCb*," Phys. Rev. **D92** (2015) no. 11, 115017, arXiv:1509.06765.

[66] P. Ilten, Y. Soreq, J. Thaler, M. Williams, and W. Xue, "*Proposed Inclusive Dark Photon Search at LHCb*," Phys. Rev. Lett. **116** (2016) no. 25, 251803, arXiv:1603.08926.

[67] **Belle**, I. Jaegle, "*Search for the dark photon and the dark Higgs boson at Belle*," Phys. Rev. Lett. **114** (2015) no. 21, 211801, arXiv:1502.00084.

[68] A. Caldwell *et al.*, "*Particle physics applications of the AWAKE acceleration scheme*," arXiv:1812.11164.

[69] **HPS**, A. Celentano, "*The Heavy Photon Search experiment at Jefferson Laboratory*," J. Phys. Conf. Ser. **556** (2014) no. 1, 012064, arXiv:1505.02025.

[70] A. Berlin, S. Gori, P. Schuster, and N. Toro, "*Dark Sectors at the Fermilab SeaQuest Experiment*," Phys. Rev. **D98** (2018) no. 3, 035011, arXiv:1804.00661.

[71] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, and N. Toro, "*Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX*," Phys. Rev. **D99** (2019) no. 7, 075001, arXiv:1807.01730.

[72] **FASER**, A. Ariga *et al.*, "*FASERs physics reach for long-lived particles*," Phys. Rev. **D99** (2019) no. 9, 095011, arXiv:1811.12522.

[73] **NA62 Collaboration**, C. NA62, "*2018 NA62 Status Report to the CERN SPSC*," Tech. Rep. CERN-SPSC-2018-010. SPSC-SR-229, CERN, Geneva, Apr, 2018. http://cds.cern.ch/record/2312430.

[74] S. Alekhin *et al.*, "*A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*," Rept. Prog. Phys. **79** (2016) no. 12, 124201, arXiv:1504.04855.

[75] **NA64, Physics Beyond Colliders Conventional Beams Working Group**, D. Banerjee, "*Search for Dark Sector Physics at the NA64 experiment in the context of the Physics Beyond Colliders Project*," in *29th International Conference on Lepton and Photon Interactions (LP2019) Toronto, Ontario, Canada, August 5-10, 2019*. 2019. arXiv:1909.04363.

[76] Y. Hochberg, E. Kuflik, and H. Murayama, "*SIMP Spectroscopy*," JHEP **05** (2016) 090, arXiv:1512.07917.

[77] Y. Hochberg, E. Kuflik, and H. Murayama, "*Dark spectroscopy at lepton colliders*," Phys. Rev. **D97** (2018) no. 5, 055030, arXiv:1706.05008.

[78] **XENON**, E. Aprile *et al.*, "*Dark Matter Search Results from a One Ton-Year Exposure of XENON1T*," Phys. Rev. Lett. **121** (2018) no. 11, 111302, arXiv:1805.12562.

[79] **DARWIN**, J. Aalbers *et al.*, "*DARWIN: towards the ultimate dark matter detector*," JCAP **1611** (2016) 017, arXiv:1606.07001.