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Weakly interacting massive particle dark matter and radiative neutrino mass from Peccei-Quinn symmetry

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The Peccei-Quinn anomalous global $U(1)_{PQ}$ symmetry is important for solving the strong CP problem with a cosmologically relevant axion. We add to this the simple (but hitherto unexplored) observation that it also has a residual Z_2 symmetry which may be responsible for a second component of dark matter, i.e., an absolutely stable weakly interacting singlet scalar. This new insight provides a theoretical justification for this simplest of all possible dark-matter models. It also connects with the notion of generating radiative neutrino mass through dark matter. Two such specific realizations are proposed. In our general scenario, dark-matter detection is guaranteed at existing direct-detection experiments and/or axion searches. Observable signals at the Large Hadron Collider are discussed.

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I. INTRODUCTION

The standard model (SM) of particle interactions is missing at least three important pieces: (1) a natural explanation of the absence or suppression of strong CP violation, (2) the existence of dark matter (DM), and (3) the presence of neutrino mass. The best motivated solution to the strong CP problem is the well-known Peccei-Quinn anomalous global $U(1)_{PQ}$ symmetry [1], which predicts a very light pseudoscalar particle—the axion [2,3], which may very well also be the DM. An elegant way to get small neutrino masses is the seesaw mechanism (see Ref. [4] for a review), which postulates heavy neutral singlet fermions coupling to the observed neutrinos, elevating their masses from zero to small nonzero values.

Recognizing that the $U(1)_{PQ}$ breaking scale and the seesaw scale are both very high, say 10^{10} GeV, it was proposed some years ago [5] that they may be related in the context of supersymmetry. In that scenario, the lightest neutralino (which may be the axino) is also a DM candidate. DM has thus two components. The very light axion is not absolutely stable but has a lifetime much longer than that of the Universe. The heavy neutralino is absolutely stable because of the usual R parity from supersymmetry, and it behaves as a weakly interacting massive particle (WIMP) in the usual cold DM scenario.

In this paper, we show that $U(1)_{PQ}$ can address all the three deficiencies of the SM without invoking supersymmetry. The $U(1)_{PQ}$ symmetry not only cures the strong CP problem (1) but is also the origin of a previously unidentified residual Z_2 symmetry that may be responsible for a heavy second component of DM (2), which is absolutely stable, as well as radiative neutrino mass (3).

There are three generic realistic implementations of $U(1)_{PQ}$, differing mainly in the choice of colored fermions charged under $U(1)_{PQ}$. In the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model [6,7], new heavy electroweak singlet quarks transforming under $U(1)_{PQ}$ are added. In the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) model [8,9], the regular quarks are chosen to transform under $U(1)_{PQ}$, but additional Higgs fields are added. In the gluino axion model [10], supersymmetry is assumed, and $U(1)_{PQ}$ is identified with $U(1)_R$ so that gluinos are the only colored fermions transforming under $U(1)_{PQ}$. All these three realizations satisfactorily explain the smallness of the strong CP violation [11,12]. We now proceed to explain DM and neutrino masses.

We start with the simple (but hitherto unexplored) observation that in all these axion models, the spontaneous breaking of $U(1)_{PQ}$ actually also leaves a discrete Z_2 symmetry which is exactly conserved (see Refs. [13–15] for some related ideas). In the DFSZ model, it is $(-1)^{3B}$, where B is baryon number. In the gluino axion model, it is R parity. In the KSVZ model, it is a new symmetry distinguishing the heavy singlet quarks and any additional particles charged under $U(1)_{PQ}$ from all other particles. Hence, the lightest new heavy neutral particle, odd under the Z_2 symmetry, will be absolutely stable and a potential WIMP candidate for DM. Similarly, neutrino mass terms may be forbidden at tree level by this same Z_2 symmetry and arise only radiatively [16]. This new residual Peccei-Quinn Z_2 symmetry is thus tailor made for having an absolutely stable DM component (in addition to the axion) and realizing the notion that neutrino mass is induced radiatively by DM. Note that we do not have to introduce an extra symmetry by hand; it is already built into the axion model.

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In the following, we will first present the simplest implementation of the above mechanism in the KSVZ model, to provide a stable heavy DM candidate and discuss its phenomenology. Then we elaborate on two specific models of radiative neutrino mass derived from the above, together with the associated new particles and their collider phenomenology.

II. WIMPS IN AXION MODELS

Consider the KSVZ model, using a heavy singlet quark Q of charge $-1/3$ for the color anomaly which generates the axion. Note that the domain wall number is 1 in this case, so the model is cosmologically safe [17]. We add a neutral complex singlet scalar χ, which transforms under $U(1)_{PQ}$, to provide a heavy DM candidate. The axion is contained in the scalar field ζ, which couples to $\bar{Q}Q$, and $\chi\chi$. Consider the Lagrangian relevant for $Q_{L,R}$, ζ, and χ,

$$\mathcal{L} = \mu_\zeta^2|\zeta|^2 + \frac{1}{2}\lambda_\zeta|\zeta|^4 + \mu_\chi^2|\chi|^2 + \frac{1}{2}\lambda_\chi|\chi|^4 + \lambda'|\zeta|^2|\chi|^2 + \{f_Q\zeta\bar{Q}_L Q_R + f_d\chi\bar{Q}_L d_R + \epsilon_\chi\zeta^*\chi\chi + \text{H.c.}\}, \quad (1)$$

where $\chi = (\chi_1 + i\chi_2)/\sqrt{2}$. Let $\zeta = e^{ia/F_a}(F_a + \sigma)/\sqrt{2}$, where a is the axion and $F_a = \sqrt{-2\mu_\zeta^2/\lambda_\zeta}$, the vacuum expectation value (VEV) that also acts as the axion decay constant.

In general, in axion models $U(1)_{PQ}$ is broken by the VEV of a scalar that couples to some $\bar{Q}_L Q_R$ (e.g., the first term on second line in Eq. (1)). After $U(1)_{PQ}$ symmetry breaking, one finds that $(\sigma, a) \to +(\sigma, a)$ and $Q_{L,R} \to \pm Q_{L,R}$ is a residual symmetry of the Lagrangian. Thus, $\mathcal{L}$ has a Z_2 symmetry under which σ and a must be even, whereas the particle Q is odd, as also in Ref. [13]. If the fermion Q were a known fermion, e.g., a regular quark for the DFSZ model or a gluino for the gluino axion model, the Z_2 would be identified with $(-1)^{3B}$ or R parity, respectively. As Q is a new fermion, this Z_2 is a new symmetry, say "Q parity." The complex scalar χ is also forced to be odd under Q parity (by the second term on second line in Eq. (1)), thus stabilizing it (unless d is charged, which would take us back to the DFSZ model). Q parity must be *exactly* preserved; otherwise, the axion solution to the strong CP problem is spoiled.

Assuming ϵ_χ to be real for simplicity, the mass eigenvalues of χ are $m_{1,2}^2 = \mu_\chi^2 + (1/2)\lambda' F_a^2 \pm \epsilon_\chi F_a\sqrt{2}$. Without loss of generality, we choose $\epsilon_\chi < 0$ and find that $m_1 < m_2$, so that then χ_1 could be DM. Since $F_a > 4 \times 10^8$ GeV from supernova SN1987 A data [18], fine-tuning is unavoidable for $m_{1,2} \sim$ TeV. However, this problem plagues all (nonsupersymmetric) axion models because the electroweak Higgs doublet also has a large quantum correction. On the other hand, there is a justification for ϵ_χ to be small, from the fact that the limit $\epsilon_\chi = 0$ corresponds to an extra $U(1)$ symmetry, i.e., χ, Q_L, $Q_R \sim 1$ independent of $U(1)_{PQ}$. The heavy KSVZ quark Q with $m_Q = f_Q F_a/\sqrt{2}$ may also be observable if $m_Q \sim$ TeV, i.e., $f_Q \sim 10^{-6}$ for $F_a \sim 10^9$ GeV.

The are therefore two DM candidates in this model—a light ultracold axion a and a heavy cold WIMP-like χ_1. The total cosmological DM density is the sum of their densities, i.e., $\Omega_{\rm DM} = \Omega_a + \Omega_{\chi_1}$. The axion is massless until color chiral symmetry breaking, and it gets a mass $m_a \approx 6\ \mu\text{eV}(10^{12}\ \text{GeV}/F_a)$ [19–21]. For reheating temperatures lower than F_a, the only process relevant for axion production is coherent oscillation due to vacuum misalignment [22]. The axion density is given by [23]

$$\Omega_a h^2 \approx 0.18\theta_a^2 \left(\frac{F_a}{10^{12}\ \text{GeV}}\right)^{1.19}, \quad (2)$$

where θ_a is the initial axion misalignment angle.

The WIMP DM candidate χ_1 has two main interactions with SM particles—with down-type quarks through $f_d\bar{Q}_L d_R\chi$ and with the SM Higgs boson h through the $\lambda_{\chi h}\chi^2(\Phi^\dagger\Phi) \to (1/4)\lambda_{\chi h}\chi_1^2(v_{\rm SM} + h)^2$ term. The annihilation cross section to down-type quark pairs is $\langle\sigma v\rangle \approx 3f_d^4 m_d^2/(16\pi(m_Q^2 + m_1^2)^2)$, which for m_Q and $m_1 \sim$ TeV turns out to be too small by a few orders of magnitude to yield the correct relic density. The true χ_1 abundance is then set by the chemical freeze-out of its annihilation processes through the Higgs coupling. However, there is also the nonthermal production of χ from the decay of the radial field σ which may be significant. This potential problem is absent in our model because the $\bar{Q}_L d_R\chi$ interaction, already built into the model, helps to keep Q, χ, and d in thermal equilibrium until late times, so that any nonthermal population of χ_1 is quickly rethermalized. Our scenario is then identical to that of the scalar singlet DM model [24–26], and our results provide a theoretical justification of this well-studied simplest of all possible dark-matter models. The phenomenology of this model was recently updated in Ref. [27], and we can directly use the results and constraints therein.

The relic abundance of χ_1 is determined by its coupling to the Higgs. For a heavy DM, $m_1 >$ few $\times$ 100 GeV, the cross section simply goes as $\lambda_{\chi h}^2/m_1^2$, and an annihilation cross section of $\langle\sigma v\rangle \approx$ few $\times 10^{-26}$ cm^3 s^{-1} [28] may be achieved quite easily. The relic density of DM in this case is approximately fit by [27]

$$\frac{\Omega_{\chi_1}}{\Omega_{\rm DM}} \approx 4 \times 10^{-7}\,\frac{(m_1/\text{GeV})^2}{\lambda_{\chi h}^2}. \quad (3)$$

Our scenario is related to the mixed axion-neutralino models reviewed in Ref. [29] (see references therein for details). Interestingly, although σ imitates the role of the saxion, we have a built-in mechanism to keep σ decay products in equilibrium, first by equilibrating them with the

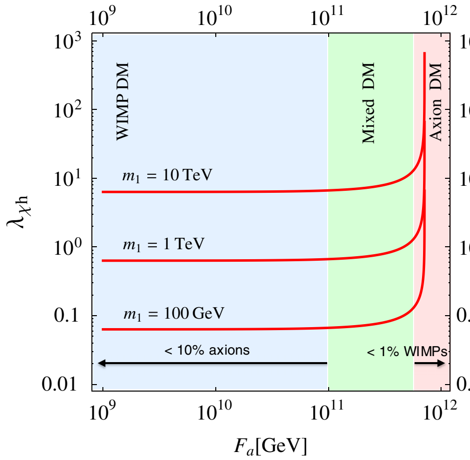

FIG. 1 (color online). Correlated values of WIMP-Higgs coupling $\lambda_{\chi h}$ and axion decay constant F_a for various DM masses m_1, so that the total DM density in axions and χ_1 are the observed value $\Omega_{\rm DM} h^2 = 0.12$. For concreteness, $\theta_a = 1$ is assumed.

heavy quarks and then through color interactions with the SM quarks. This allows us to consider the simplified DM production discussed above. However, more careful treatment may be needed in some cases, e.g., if the σ decays to axions become important [30]. Then one has to solve several coupled Boltzmann equations to study the model in detail. It should be noted, however, that our insight into the hidden Z_2 symmetry of axion models provides a general mechanism for mixed axion-WIMP DM, independent of supersymmetry and without introducing an *ad hoc* stabilization of DM.

In Fig. 1, we see that over a wide range of F_a and $\lambda_{\chi h}$, one can produce the observed DM abundance easily. All of cosmological DM can be axions, if $F_a \approx 10^{12}$ GeV, so that $\Omega_a \approx \Omega_{\rm DM}$. A large scalar coupling $\lambda_{\chi h}$ suppresses the WIMP density $\Omega_{\chi_1} \lesssim 10^{-2}\Omega_{\rm DM}$. In this limit, there is effectively no WIMP DM component, and only axion searches are expected to be successful. The other extreme limit is if almost all of DM is comprised of χ_1. If $F_a \sim 10^9$ GeV, it suppresses the axion abundance to $\Omega_a \lesssim 10^{-2}\Omega_{\rm DM}$, and one can expect $\Omega_\chi \approx \Omega_{\rm DM}$. This regime is promising for traditional WIMP searches, but axion searches would not find a signal. An intermediate possibility is to have mixed DM with two components—axions and χ_1. For example, if $F_a \sim {\rm few} \times 10^{11}$ GeV and $m_1/\lambda_{\chi h} \approx 10^3$ GeV, then $\Omega_a \approx \Omega_{\chi_1} \approx \Omega_{\rm DM}/2$. The phenomenology of this mixed DM can be quite rich. We now discuss constraints on and the detectability of DM in our scenario.

A strong constraint comes from the invisible width of the observed 126 GeV Higgs boson, which rules out χ_1 lighter than $m_h/2 = 62.5$ GeV if $\lambda_{\chi h} > 10^{-2}$. Bounds from XENON100 also rule out $m_1 \lesssim 10^{1.9}$ GeV [27]. WIMP masses greater than 10 TeV require too large values of $\lambda_{\chi h}$. We have therefore considered χ_1 in the range 100 GeV $< m_1 <$ few TeV, which restricts the range of $\lambda_{\chi h}$ to $\sim$(0.1–10). F_a is constrained to be in the range (10^9–10^{12}) GeV [31].

Prospects for detection of DM are very promising. This may be counterintuitive because now DM densities of each species are lower, and makes it hard to detect them. However, χ interacts via the Higgs portal at direct detection experiments where there is very high sensitivity. Existing underground experiments, e.g., XENON100 (in 20yrs) or XENON1T, can probe the entire viable range of $\lambda_{\chi h}$, as long as WIMPs comprise even a few percent of the total DM [27], i.e., for $F_a < {\rm few} \times 10^{11}$ GeV. However, indirect detection in Fermi, Cherenkov Telescope Array, and Planck is possible only if χ_1 forms almost all of DM [27]—the annihilation signal degrades quadratically for smaller density and evades upcoming searches. Axion Dark Matter eXperiment is expected to probe the axion decay constant F_a in the range (10^{11}–10^{12}) GeV [32]. So existing direct detection and axion searches will complementarily probe all of the viable parameter space in Fig. 1. In other words, a signal in at least one existing experiment is guaranteed. A smoking-gun signature of mixed DM would be signals for both direct detection searches and axion searches.

III. NEUTRINO MASS IN AXION MODELS

The KSVZ model has heavy quarks $Q_{L,R}$ and a complex scalar ζ. We added the scalar χ as the dark matter candidate. Neutrino mass may be generated radiatively in these models, if the new particles charged under $U(1)_{PQ}$ are added. We provide two concrete realizations of this idea.

A. Model I

To get neutrino masses, we only add a neutral singlet fermion N_R (per generation) and a new scalar doublet $\eta = (\eta^+, \eta^0)^T$ with $\eta^0 = (\eta_1 + i\eta_2)/\sqrt{2}$, all of which transform under $U(1)_{PQ}$. Quantum numbers of the new particles are listed in Table I.

Radiative neutrino mass is then generated in one loop as shown in Fig. 2 (left), in analogy to the original Z_2 scotogenic model [16] as ζ acquires a VEV, thus breaking $U(1)_{PQ}$ to Z_2.

The particles Q, $\chi_{1,2}$, $\eta_{1,2}$, $\eta^\pm$, and N_i are odd under Z_2, whereas all others (including σ and a) are even. Although σ

TABLE I. New particles in the one-loop radiative seesaw model with Peccei-Quinn symmetry.

	Q_L	Q_R	ζ	χ	N_R	η
Spin	1/2	1/2	0	0	1/2	0
$SU(3)_c$	**3**	**3**	**1**	**1**	**1**	**1**
$SU(2)_L$	**1**	**1**	**1**	**1**	**1**	**2**
$U(1)_Y$	−1/3	−1/3	0	0	0	1/2
$U(1)_{PQ}$	1	−1	2	1	1	1

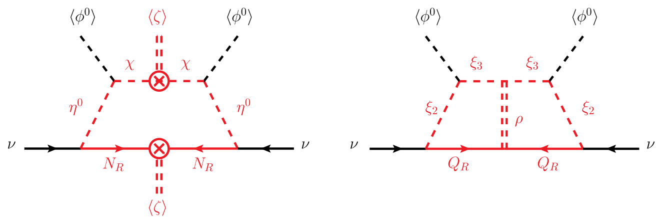

FIG. 2 (color online). Diagrams for the one-loop (left panel) and two-loop (right panel) radiative neutrino masses.

mixes with h, they are almost mass eigenstates because $v_{\rm SM} \ll F_a$. As for $\chi_{1,2}$ and $\eta_{1,2}$, they are completely mixed in a 4×4 matrix (including the $\Phi^\dagger \eta\chi\zeta^*$ term not shown in Fig. 2), the lightest of which is now the WIMP-DM candidate.

The radiative neutrino mass is of the generic form

$$(\mathcal{M})_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2} \sum_\alpha \frac{(U_{1\alpha}^2 - U_{2\alpha}^2)m_\alpha^2}{m_\alpha^2 - M_k^2} \ln\frac{m_\alpha^2}{M_k^2}, \quad (4)$$

where $U_{1\alpha}$ and $U_{2\alpha}$ are the unitary matrices which link $\eta_{1,2}$ to the four mass eigenstates of mass m_α, h_{ij} are the Yukawa couplings, and M_k are the heavy neutrino masses. Note that in the original model [16], there are only two mass eigenstates with $U_{11} = U_{22} = 1$ and $U_{12} = U_{21} = 0$. Radiative lepton flavor violation (LFV) $\ell_i \to \ell_j\gamma$ is induced in general by $\eta^\pm$ exchange, which may be suppressed by small h_{ik}, as in Ref. [16].

B. Model II

Another interesting possibility is to consider scalar leptoquarks and diquarks transforming under $U(1)_{PQ}$. Quantum numbers of the new particles are listed in Table II.

Radiative neutrino mass is then generated in two loops as shown in Fig. 2 (right), in analogy with the recent proposal of Ref. [33]. Note the remarkable result that a Majorana neutrino mass is radiatively generated without breaking $U(1)_{PQ}$. The Lagrangian relevant for the extended sector is given by

$$\mathcal{L} = y_Q \bar{Q}_R \nu_L \xi_2 + h_{QQ'}\rho^* Q_R Q'_R - \epsilon_\xi \phi^0 \xi_2^* \xi_3 - \epsilon_\rho \rho^* \xi_3 \xi_3 + \text{H.c.} \quad (5)$$

TABLE II. New particles in the two-loop radiative seesaw model with the Peccei-Quinn symmetry.

	Q_L	Q_R	ζ	χ	(ξ_1, ξ_2)	ξ_3	ρ
Spin	1/2	1/2	0	0	0	0	0
$SU(3)_c$	**3**	**3**	**1**	**1**	**3**	**3**	**6**
$SU(2)_L$	**1**	**1**	**1**	**1**	**2**	**1**	**1**
$U(1)_Y$	−1/3	−1/3	0	0	1/6	−1/3	−2/3
$U(1)_{PQ}$	1	−1	2	1	−1	−1	−2

The ϵ_ξ term mixes ξ_2 and ξ_3 with angle θ_ξ to form mass eigenstates. The two-loop neutrino mass matrix is then calculated as

$$(\mathcal{M})_{ij} = \sum_{Q,Q'} 8h_{QQ'} \sum_{\alpha,\beta} \kappa_{\alpha\beta} y_Q^i m_\alpha I_{\alpha\beta}^{QQ'} m_\beta y_{Q'}^j, \quad (6)$$

where

$$\kappa_{\alpha\beta} = \epsilon_\rho \begin{pmatrix} \sin^2\theta_\xi & \sin\theta_\xi\cos\theta_\xi \\ \sin\theta_\xi\cos\theta_\xi & \cos^2\theta_\xi \end{pmatrix}, \quad (7)$$

$$I_{\alpha\beta}^{QQ'} = + \int \frac{d^4k_1}{(2\pi)^4} \int \frac{d^4k_2}{(2\pi)^4} \frac{1}{k_1^2 - M_Q^2} \frac{1}{k_2^2 - M_{Q'}^2} \times \frac{1}{(k_1+k_2)^2 - M_\rho^2} \frac{1}{k_1^2 - m_\alpha^2} \frac{1}{k_2^2 - m_\beta^2}. \quad (8)$$

The LFV process, $\ell_i \to \ell_j\gamma$, is induced by the $\xi_1^{2/3}$ leptoquark. These branching fractions could be easily suppressed by choosing relatively small Yukawa coupling y_Q without making the two-loop neutrino mass too small. This would have been difficult if a three-loop neutrino mass were considered.

IV. COLLIDER PHENOMENOLOGY

While the scale of $U(1)_{PQ}$ symmetry breaking must be very high, the KSVZ singlet quark Q may be light enough to be copiously produced at the LHC via $gg \to Q\bar{Q}$. Once produced, it decays into a d quark and either χ_1 or χ_2. Whereas χ_1 appears as missing energy, χ_2 decays to $\chi_1 d\bar{d}$. Similar studies where a heavy quark decays into a top quark plus DM have appeared [34] and its experimental search at the LHC reported [35]. Although we have assumed specifically that Q has charge $-1/3$, our model is easily adapted to $2/3$ as well. Future LHC analysis of such heavy quark decays will be important in testing our proposal. For example, the exclusive search for supersymmetric scalar quarks may be reinterpreted as mass bounds on Q.

In model II, we have additional signals at colliders. There can be copious production of the leptoquarks and diquarks also via $gg \to \xi^{+1/3}\xi^{-1/3}, \xi^{+2/3}\xi^{-2/3}, \rho^{-2/3}\rho^{+2/3}$. There are many possible decay chains. For example, $\xi^{2/3}$ may decay into a charged lepton plus $Q^{-1/3}$ with the latter decaying into d and χ_1. This may contaminate $t\bar{t}$ pair production with $t \to bW^+ \to b\ell^+\nu$. The reinterpretation of $t\bar{t}$ events may give a constraint on $\xi^{2/3}$. This phenomenology is rich, and we leave it for further study.

V. CONCLUSION

We have proposed a unified framework for solving three outstanding problems in particle physics and astrophysics.

We invoke the usual Peccei-Quinn symmetry to solve the strong *CP* problem, resulting in a very light axion. However, we also make the simple (but hitherto unexplored) observation that in all axion models, $U(1)_{PQ}$ also leaves a residual Z_2 symmetry, and in the KSVZ model, it may be used for stabilizing dark matter. Thus, DM stability is related to the absence of strong *CP* violation. We make the minimal addition of a complex scalar field $\chi = (\chi_1 + i\chi_2)/\sqrt{2}$ to the the KSVZ model with the interaction $\chi \bar{Q}_L d_R$ as well as the usual extra terms which appear in the Higgs potential. Consequently, χ_1 behaves naturally as the singlet scalar, thus providing a theoretical justification for this otherwise *ad hoc*, but simple and elegant, model. Phenomenologically, our scenario is extremely promising, with guaranteed signals at direct-detection experiments or axion searches, *or both*. The same Z_2 symmetry may also be connected to the well-studied notion of radiative neutrino mass through dark matter. To implement this idea, new particles, which are charged under $U(1)_{PQ}$, are required. Collider searches for these new particles are also promising, especially model II where leptoquark and diquark scalars may be produced copiously at the LHC.

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