Flavor inspired model for dark matter

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The discrepancies between data on rare b-hadron decays, controlled by the underlying neutral-current transitions $b \to s\ell^+\ell^-(\ell = e, \mu)$, and the corresponding Standard Model predictions constitute one of the most intriguing hints for new physics. Leptoquarks are prime candidates to solve these anomalies and, in particular, the scalar leptoquark, S_3, triplet under $SU(2)_L$ with hypercharge $Y = -1/3$, provides a very good fit to data. Here, we entertain the possibility that the same scalar leptoquark S_3, responsible for the lepton flavor universality anomalies, is the *portal* to a fermionic dark sector consisting of two additional vectorlike fermions, one of which is a candidate for the cosmological dark matter. We study two scenarios, where the dark matter candidate belongs to an $SU(2)_L$ singlet and triplet respectively, and discuss the theory parameter space in the context of the dark matter candidate's relic density and prospects for direct and indirect dark matter searches. Direct detection rates are highly suppressed and generically below the neutrino floor. Current observations with, and future prospects for, high-energy gamma-ray telescopes such as HESS and the Cherenkov Telescope Array are much more promising, as they already provide powerful constraints on the models under consideration, and will potentially probe the full parameter space in the future.

I. INTRODUCTION

Two of the most compelling and suggestive puzzles in modern particle physics are the particle nature of the cosmological dark matter and the hints for the violation of lepton flavor universality (LFU) in B decays, as emerging from a variety of collider data in recent years (for recent reviews on the two topics see Refs. [1–5]). While a continuing and extraordinarily intense program of searches for nongravitational signals from dark matter has yet to deliver uncontroversial evidence for discovery of new physics [6], mounting evidence for LFU violation makes it timely to investigate possible *connections* between the two sectors, with the hope of outlining and pinpointing expected signals especially for planned experiments and observatories. This, in short, is the spirit of the present paper: the new particle responsible for the flavor anomalies (here a scalar leptoquark triplet) might be the mediator

between the visible and the dark sector, the latter containing the particle making up the cosmological dark matter.

In the Standard Model (SM) of particle physics, LFU is satisfied by the gauge interactions and is only violated by the lepton Yukawa couplings. In recent years, several measurements have shown a coherent pattern of deviations from the SM predictions in rare b-hadron decays controlled by the underlying neutral current transition $b \to s\ell^+\ell^-(\ell = e, \mu)$ [7–15]. Even though no single result exceeds the 5σ threshold, conventionally considered a necessary condition to claim discovery of physics deviating from the SM, the combined analysis of the LFU ratios $R(K^{(*)})$, the branching ratio of $B_s \to \phi\mu^+\mu^-$ and angular observables in $B \to K^*\mu^+\mu^-$, show a preference for new physics (NP) scenarios over the SM hypothesis with an intriguing significance [16–21]. In particular, all these observables together point convincingly toward an effect in the dimuon channel.

Among the several SM extensions proposed in the literature to solve the $b \to s\ell^+\ell^-$ anomalies, leptoquarks are prime candidates [22–53]. Indeed, it turns out that the scalar leptoquark transforming as a triplet under $SU(2)_L$, which we will denote as S_3 hereafter, with couplings to muons, gives a very good fit to data.

In the literature, leptoquarks have been discussed as mediators to dark matter in Refs. [54–63]. Here, we

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entertain the possibility that the same scalar leptoquark S_3, responsible for the LFU anomalies in neutral current B decays, is the *portal* to a fermionic dark sector[1] consisting of two additional vectorlike fermions[2]; of these, the lighter one, which we indicate with χ_L is neutral under $SU(3)_C$ and electromagnetism, and is the particle dark matter candidate; the second, colored one, χ_Q, plays a key role in setting the thermal relic density and in shaping the outlook for perspective dark matter searches to test this scenario.

Even though in the following we focus only on the solutions to the anomalies in rare B decays and to dark matter, it is interesting to note that S_3, together with simple extensions of the leptoquark sector can also provide solutions to the tension in the W mass within the EW fit [64–66], recently confirmed and strengthened by the CDF measurement [67].

The remainder of this note is as follows: the next section describes the field content of the theory under consideration; the following section details the requirements to fit LFU violation observations on the model under consideration; Sec. III elaborates on the dark sector and its leptoquark portal, and studies the implications of the model for the dark matter abundance and its direct and indirect search signals; finally, Sec. IV presents our discussion and conclusions.

II. THE FLAVOR MODEL

The scalar leptoquark triplet, S_3, with quantum numbers $(3, 3, -1/3)$ under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, has only one Lorentz- and gauge-invariant coupling to SM quark-lepton pairs:

$$\mathcal{L}_{NP} = Y_{ij}\bar{Q}_i^c i\tau_2 S_3^\dagger L_j + \text{H.c.,} \tag{1}$$

where Q and L are the quark and lepton doublets under $SU(2)_L$ and our convention for S_3 is

$$S_3 = \frac{1}{2}\begin{pmatrix} S^{-1/3} & \sqrt{2}S^{-4/3} \\ \sqrt{2}S^{2/3} & -S^{-1/3} \end{pmatrix}. \tag{2}$$

It is well known that S_3 can also have a dangerous diquark coupling (allowed by gauge invariance), which would lead to proton decay [68]. This can be in general avoided by the choice of an appropriate symmetry. For instance, in our case, it is sufficient to assign a baryon/lepton number to the leptoquark and assume that baryon/lepton number is conserved, ensuring the stability of the proton. (Note that this

requires also an according assignment of quantum numbers to the dark sector discussed in the next section). In the following analysis we assume that the couplings Y_{ij} are given in the down-quark basis. Therefore, after electroweak (EW) symmetry breaking the Lagrangian in Eq. (1) reads

$$\mathcal{L}_{NP} = -\frac{Y_{ij}}{2\sqrt{2}}\bar{d}_i^c(S^{-4/3})^\dagger \ell_j - \frac{V_{ik}^* Y_{kj}}{4}\bar{u}_i^c(S^{-1/3})^\dagger \ell_j$$
$$- \frac{Y_{ij}}{4}\bar{d}_i^c(S^{-1/3})^\dagger \nu_j + \frac{V_{ik}^* Y_{kj}}{2\sqrt{2}}\bar{u}_i^c(S^{2/3})^\dagger \nu_j + \text{H.c.} \tag{3}$$

where V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix.

As stated in the Introduction, S_3 is a well-known candidate to solve the anomalies in rare b-hadron decays controlled by the underlying quark-level transition $b \to s\ell^+\ell^-$. Following the conventions in Ref. [69], we define the effective Hamiltonian

$$\mathcal{H}_{NP}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^* \sum_i (C_i O_i + C_i' O_i'), \tag{4}$$

where the operators relevant for our discussion are

$$O_9^{ij} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}_i \gamma^\mu \ell_j),$$
$$O_{10}^{ij} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}_i \gamma^\mu \gamma_5 \ell_j). \tag{5}$$

The analysis of data within the framework of effective theories has been performed by several theory group in the last years: we point the reader to Refs. [16,19,70,71] for the most complete and updated ones.

A scenario strongly favored by data is $C_9^{22} = -C_{10}^{22} \simeq -0.39$, with new physics required only in the muon sector. Here and in the following we use the numerical results of Ref. [16] (note that apart from small numerical differences, this is a result common to all analyses).

The leptoquark triplet generates, at tree level, exactly the pattern of Wilson coefficients $C_9^{22} = -C_{10}^{22}$. Indeed, the couplings in Eq. (3) give the following contributions

$$C_9^{ij} = -C_{10}^{ij} = \frac{\sqrt{2}\pi}{32\alpha G_F V_{tb}V_{ts}^*}\frac{Y_{3i}Y_{2j}^*}{M_{S_3}^2}. \tag{6}$$

With the inputs of Ref. [72] we find the following correlation between couplings and mass:

$$Y_{3i}Y_{2j}^* = 10^{-8}\left(\frac{M_{S_3}}{\text{GeV}}\right)^2. \tag{7}$$

Note that current constraints from $B \to K\nu\nu$ are negligible [73], but future Belle II sensitivity will probe this scenario [74].

The most stringent bounds on leptoquarks (LQs) come from direct searches at colliders. Specifically, ATLAS and CMS search for LQs pair production with second and/or

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[1]We indicate the two vectorlike fermions as belonging to a "dark sector" simply to emphasize that they are *additional* particles to the Standard Model, not because they are inert under the Standard Model gauge groups, since both actually do share quantum numbers with Standard Model particles.

[2]The Majorana or Dirac nature of these fermions is irrelevant for the phenomenology discussed here, so we do not specify it.

third fermion generations final state. The results of these searches, assuming that the pair production is dominated by QCD interactions ($gg \to LQLQ^\dagger$), lead to model-independent bounds on the mass and branching fractions of the LQs [75]. The best lower limit on the mass of the scalar triplet is given by the 2-jet-2-muon final state and is in the range 1400–1700 GeV for a branching ratio between 0.5 and 1 [76].

A complementary constrain comes from the analysis of high-p_T tails in Drell-Yan processes $pp \to \ell\ell$, which probe the t-channel exchange of a LQ. Recasting ATLAS searches for Z' at 36.1 fb^{-1}, Ref. [75] shows the allowed region for the mass vs the couplings of S_3. In the whole mass range analyzed, the maximum values allowed for its couplings to fermions are well above the ones required by Eq. (7).

In the following, we take a conservative stand and study dark matter scenarios for a LQ with a mass above 1.6 TeV. In addition, we consider only the couplings to SM fermions required to realize the scenario $C_9^{22} = -C_{10}^{22}$ to explain the tension in $b \to s\ell^+\ell^-$ data: Y_{32} and Y_{22}, which are taken to be real and equal, as the flavor data depend only on the combination $Y_{32}Y_{22}^*$. The couplings to first quark and lepton generations would anyway strongly affect the bounds from direct searches and are usually set to zero, while the remaining couplings to second and third generations would only change the branching ratios of the leptoquark.

III. THE DARK MATTER MODEL

We assume that the scalar leptoquark is the mediator between the "visible" SM sector and a dark sector containing the dark matter candidate. Specifically, we assume that the latter consists of two new vectorlike fermions,[3] χ_Q and χ_L. To prevent their mixing with SM fermions,[4] and the stability of the dark matter candidate, both χ_Q and χ_L are assumed to be odd under a $\mathcal{Z}_2$-type symmetry, whereas all other particles are chosen to be $\mathcal{Z}_2$-even. The interaction Lagrangian of our model reads:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + Y_{ij}\bar{Q}_i^c i\tau_2 S_3^\dagger L_j + \lambda\bar{\chi}_Q^c i\tau_2 S_3^\dagger \chi_L + \text{H.c.} \quad (8)$$

We want the dark matter (DM) candidate to be color neutral, and we choose it to be a component of the χ_L multiplet. To suppress direct detection rates, we assume that χ_L transforms as singlet under $SU(3)_C$, and requiring gauge invariance, χ_Q as a triplet [77]. Furthermore, χ_L must have null hypercharge. In fact, DM with $Y \neq 0$ would have vector-like interactions with the Z boson that produce spin-independent elastic cross sections orders of magnitude larger than current bounds [78]. Gauge invariance again forces χ_Q to have the same hypercharge of the leptoquark,

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[3]The generalization to more than one family is straightforward.
[4]This requirement avoids the mass bounds from electroweak precision observables and direct searches at colliders.

TABLE I. Possible quantum numbers for the dark sector.

		$SU(2)_L$	$U(1)_Y$	$SU(3)_C$
SINGLET	χ_L	1	0	1
	χ_Q	3	$-1/3$	3
TRIPLET	χ_L	3	0	1
	χ_Q	1	$-1/3$	3

$Y_{\chi_Q} = -1/3$. Finally, we require the DM candidate to be electromagnetically neutral. This, together with the requirement of null hypercharge, forces χ_L to be in a odd representation of $SU(2)_L$: a singlet, a triplet, a quintuplet, and so on. In the following, we discuss the two scenarios with the lowest dimensional representations for χ_L and χ_Q, as shown in Table I. Note, that higher dimensional representations are also possible. In these cases, we expect the results discussed in the following to be shifted to higher DM masses, due to the smaller mass splitting between the charge and neutral components of the multiplets, up to the point where perturbativity of the $SU(2)_L$ coupling is lost at energies below the Planck scale for large-dimensional representations [78].

A. Singlet

We start with the case where χ_L is an $SU(2)_L$ singlet with hypercharge 0. With these quantum numbers, χ_L does not couple to any SM field. The case with $\lambda = 0$ is trivial, as the DM would be stable and completely inert, with a relic density solely dictated by initial conditions. Turning on the coupling λ, the relic density is dominantly determined by the annihilation processes shown in Fig. 1(c), the coannihilation diagrams in Fig. 1(d) and 1(e), and the annihilation processes for the χ_Q shown in Fig. 1(a): if χ_Q is close-enough in mass such that at the freeze-out of the χ_L its abundance is non-negligible, the relic density will result from a large set of interconnected processes involving $\chi_L\chi_L \leftrightarrow SM$, $\chi_L\chi_Q \leftrightarrow SM$, and $\chi_Q\chi_Q \leftrightarrow SM$ processes, where χ_Q indicates any member of the associated $SU(2)_L$ triplet and SM any possible combination of Standard Model particles.

The scattering rates associated with the processes shown in Fig. 1 are sensitive to the coupling λ, the leptoquark mass, M_{S_3} and the masses of vectorlike fermions. In the present study, we have implemented the model's Lagrangian and resulting Feynman rules in the microOMEGAs package [79], and numerically computed all of the relevant annihilation and coannihilation rates. We show our results in Fig. 2, top, which shows the relic density of dark matter as a function of M_{χ_L}, for a fixed coupling, $\lambda = 2$, and different values of M_{S_3} and of the mass splitting between the χ_Q and the χ_L, which we indicate with Δ.

For zero mass splitting, $\Delta = M_{\chi_L} - M_{\chi_Q} = 0$, the coannihilation processes and the $\chi_Q\chi_Q$ annihilation processes
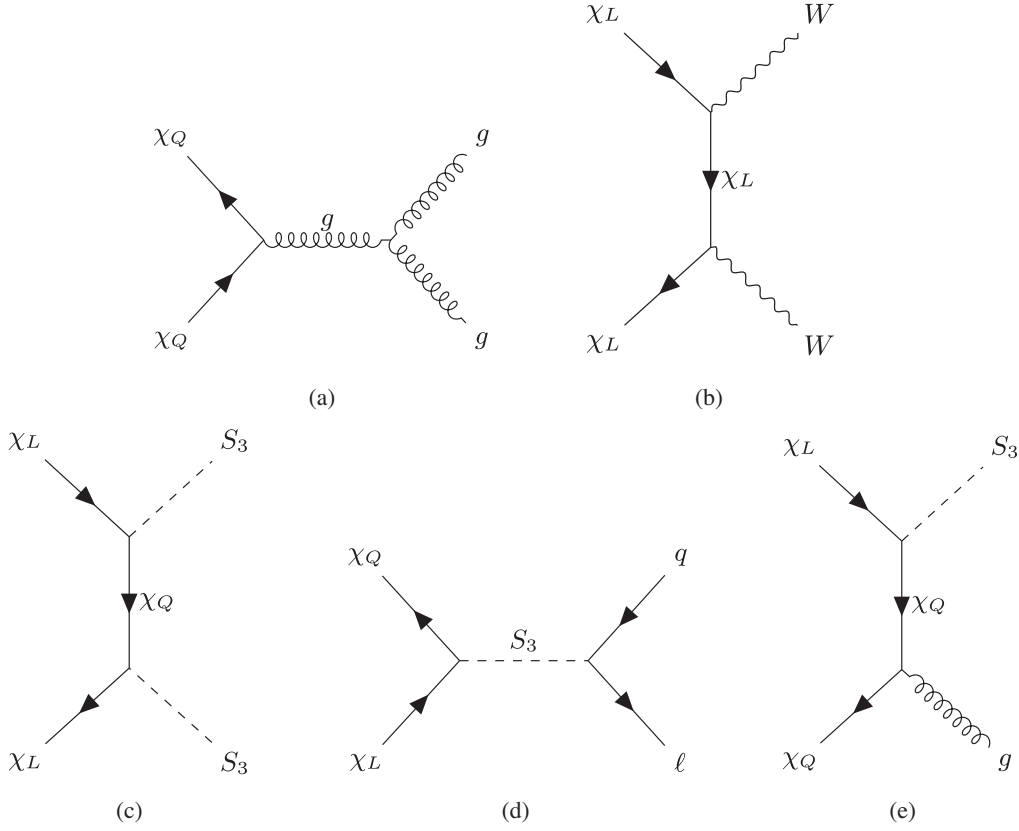
FIG. 1.   Feynman diagrams of processes relevant for the determination of the dark matter relic density. Diagrams (a) and (b) show the self-annihilation of χ_L and χ_Q into SM gauge bosons, diagram (c) χ_L self-annihilation into two leptoquarks and diagrams (d) and (e) the co-annihilation of χ_L and χ_Q.

are very efficient, driving to low values the thermal relic density of the χ_L as well. Furthermore, the lighter the leptoquark, the larger the coannihilation processes, whose rates scale as $\propto \lambda^2/M_{S_3}^4$, and the smaller the thermal relic density: this is why the blue lines are much lower than the yellow lines in the plot. An increment to the mass splitting causes the suppression of the coannihilation processes, as the thermal relic density of the χ_Q at χ_L freeze-out, $T_{\text{f.o.}} \approx M_{\chi_L}/20$, is Boltzmann-suppressed by an approximate factor

$$\propto \frac{\exp\left(-M_{\chi_Q}/T_{\text{f.o.}}\right)}{\exp\left(-M_{\chi_L}/T_{\text{f.o.}}\right)} \approx \exp\left(-20\Delta/M_{\chi_L}\right).$$

In the figure, we find in fact that for light enough χ_L, such that $20\Delta/M_{\chi_L} \sim 1$, the relic density steeply increases, as the coannihilation network with χ_Q is shut off.

There are two additional interesting features in the behavior of the thermal relic density as a function of M_{χ_L}: the dip at $M_{\chi_L} + M_{\chi_Q} \sim M_{S_3}$ corresponds to the coannihilation diagram in Fig. 1(d) being resonantly enhanced because of the quasi-on-shell exchange of the scalar leptoquark; similarly, the threshold at $M_{\chi_L} + M_{\chi_Q} \sim M_{S_3}$ signals that the diagram in Fig. 1(e) is kinematically

allowed, also driving the thermal relic density to lower values. At the lowest end of the mass range we consider, we note that we stop the lines where collider searches would have unveiled strongly interacting particles associated with the χ_Q triplet.

In sum, the observed relic density, $\Omega h^2 = 0.12 \pm 0.0012$ [80], can be obtained only with DM masses above 2 TeV for small mass splittings between χ_Q and χ_L. Increasing the mass splitting, solutions with lower masses become possible, including around 1 TeV, and around half the mass of the scalar leptoquark. A higher(lower) value for λ would decrease(increase) the relic density, without changing the general behavior shown in Fig. 2. In general, the relic density *increases* as the masses of vectorlike fermions become larger, with the two exceptions alluded to above:

(i) For $M_{\chi_L} + M_{\chi_Q} = M_{S_3}$ the relic density drops significantly because of the enhancement of the process shown in Fig. 1(d) where the leptoquark can be on-shell;

(ii) For $M_{\chi_L} = M_{S_3}$ the relic density drops since the final state in Figs. 1(c) and 1(e) can be produced on-shell, enhancing the contribution of these processes.

Moving on to dark matter direct searches, in the top panel of Fig. 3, we show the prediction for the spin-independent dark matter-proton cross section, as a function
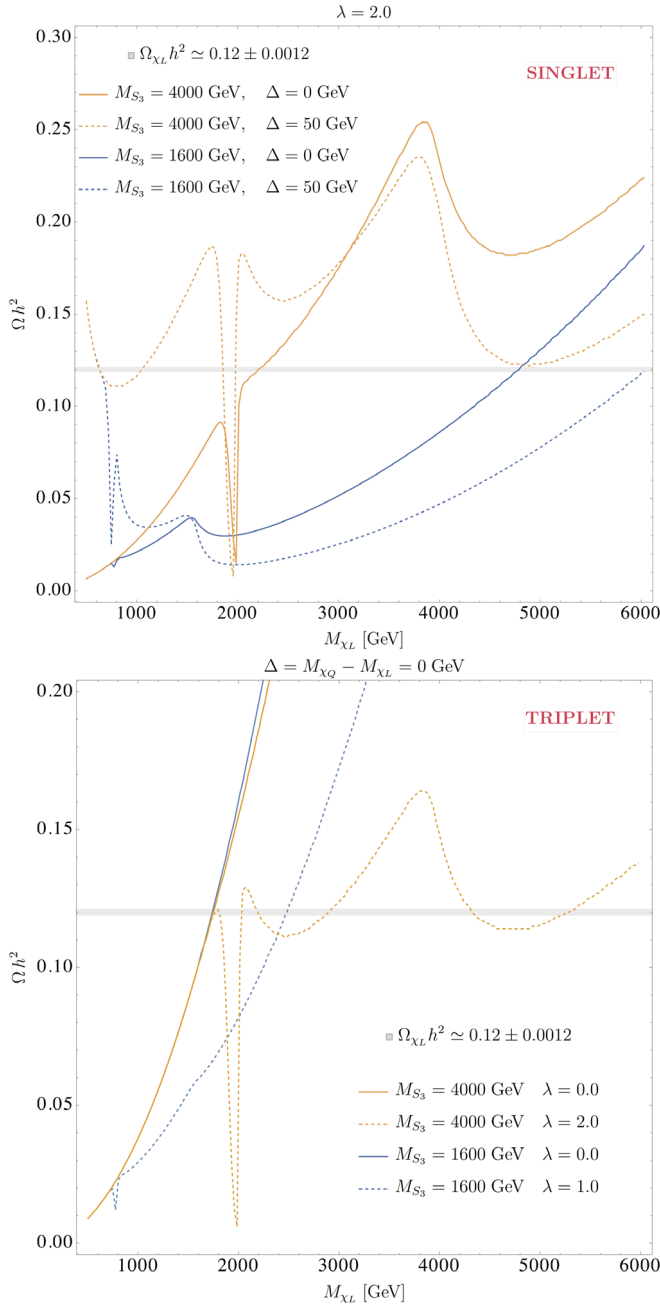
FIG. 2. Relic abundance as a function of the dark matter mass for different values of the leptoquark mass M_{S_3} and coupling. λ. The current experimental average for Ωh^2 is also shown as a gray band.

of M_{χ_L} and for different value of M_{S_3} and Δ (and thus M_{χ_Q}). For each point, the value of the coupling λ has been fixed in order to reproduce the correct relic density. In the whole mass range considered, this results in a perturbative value for λ, between 0 and 2. We find that the predicted cross section is too small to be probed by current experiments [72] and is always below the neutrino coherent scattering floor [81]. This is a direct consequence of the requirement $Y_{\chi_L} = 0$ which avoids the vectorial coupling to the

Z boson, leaving, to leading order, the loop-suppressed diagram with $\chi_Q - S_3$ in the loop; as visible in the orange lines, we find that for $M_{\chi_L} \simeq 2.5$ TeV cancellations occur and the scattering cross section goes to zero in a certain interval of dark matter particle masses.

As far as indirect searches are concerned, for the same combinations of M_{S_3} and Δ, we show the predicted pair-annihilation rate as a function of M_{χ_L} in the top panel of Fig 4. Here, the situation is far more promising. The relevant process is the pair production of an on-shell or off-shell leptoquark pair in the final state, which subsequently decays into SM quarks and leptons. With the minimal couplings needed to solve the flavor anomalies, this leads to $\mu^-, \nu_\mu, b, t, c, s$ and respective antiparticles in the final state. We find that by far the largest contributions stem from two leptoquarks on-shell, which produces a pair-annihilation cross section comparable to current experimental limits. Here we show both current constraints from 6 year-long observations of nearby dwarf spheroidal galaxies (dSph) from the Fermi-LAT, for a $\bar{b}b$ final state [82], closest to the spectrum expected from leptoquark decay, and from observations of the Galactic center from HESS [83], for the same final state; additionally, we show projections for Fermi LAT (again for the $\bar{b}b$ final state) that build on anticipated additional dSph discoveries with LSST [84], and projections for the Cherenkov Telescope Array (CTA) for both the $\bar{b}b$ and the WW final state (we refer the reader to Ref. [85] for details and assumptions for the CTA analysis; we use here their predicted sensitivity as shown in Fig. 14).

For light leptoquark masses, a large portion of M_{χ_L} can be probed by HESS [86], while future bounds from the Cherenkov Telescope Array (CTA) on $b\bar{b}$ final states [85] will be very powerful in probing the whole mass spectrum of our model, as long as leptoquarks can be produced on shell. On the other hand, we find that the current bounds and the future projections from Fermi LAT cannot probe, nor will they probe in the future, this model.

B. Triplet

A second viable scenario is one where χ_L is an $SU(2)_L$ triplet with hypercharge 0: the triplet $\chi_L = (\chi_L^+, \chi_L^0, \chi_L^-)$. There is in this case an additional class of processes relevant for the relic density involving the coupling to W bosons, shown in Fig. 1(b); the resulting contribution depends only on the mass of the fermions in the dark sector, as the couplings to gauge bosons are fixed by the choice of the representation. As before, strongly interacting processes [Fig. 1(a)] drive the pair-annihilation rate for χ_Q, while a second class of processes involves the coupling with a leptoquark, shown in Figs. 1(c)–1(e). The latter processes are therefore sensitive also to the coupling λ and to the leptoquark mass, M_{S_3}.

Figure 2, bottom, shows the relic density of dark matter as a function of the triplet mass for different values of M_{S_3}
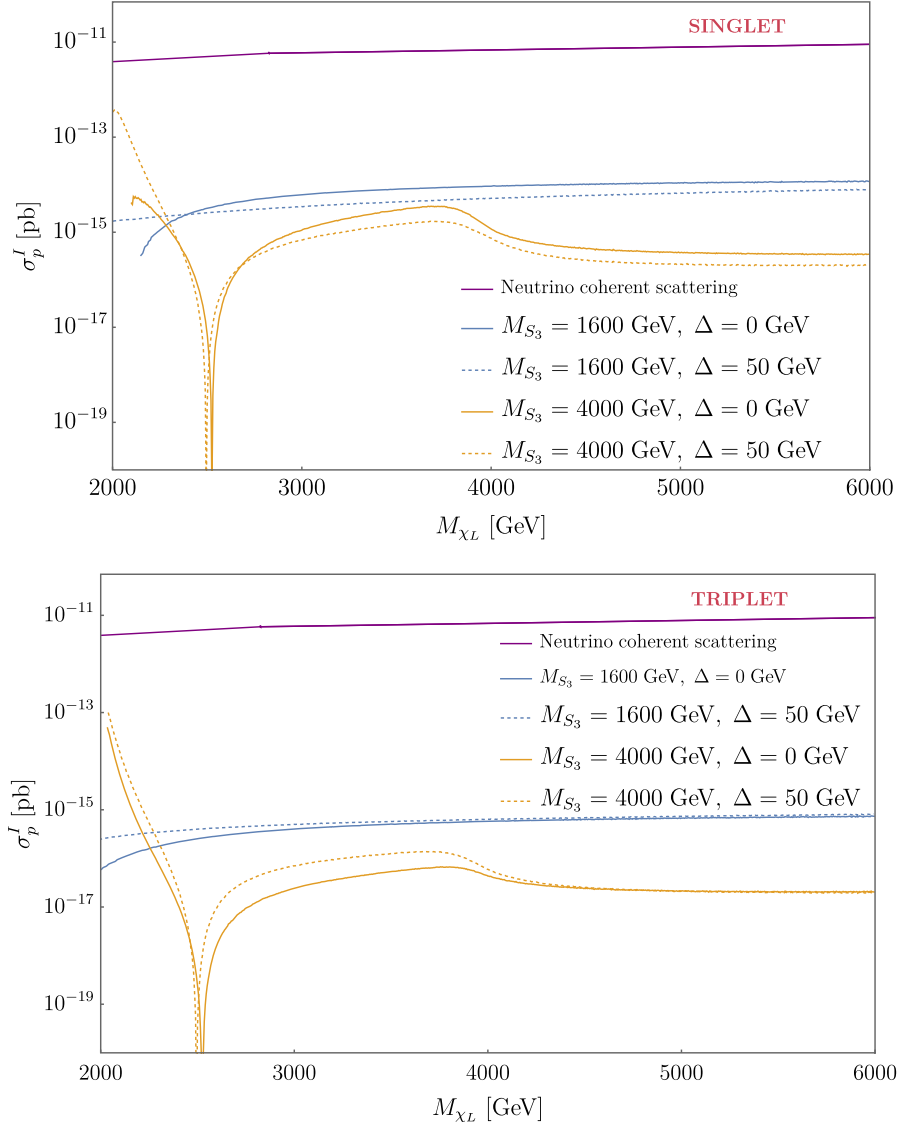
FIG. 3.   Spin-independent dark matter-proton cross section as a function of the dark matter mass, predicted requiring the observed relic abundance for different values of the leptoquark mass and mass splitting.

and λ, assuming $\Delta = M_{\chi_L} - M_{\chi_Q} = 0$, thus complete degeneracy and hence maximal effect of coannihilation processes between χ_Q and χ_L, for nonvanishing λ. The observed value of the cosmological dark matter is also shown as a gray band. As expected, for $\lambda = 0$ the relic density is almost independent on the mass of the leptoquark (the observable small dependence is due to the fact that S_3 can still contribute at loop level via its couplings with SM fields). For $\lambda = 0$ coannihilation are shut off, and the relic density is almost exclusively set by weak processes within the χ_L triplet, schematically shown in Fig. 1(b). Processes $\chi_L^{0(+)}\chi_L^{0(-)} \to W^+W^-$ with the exchange of a $\chi_L^{\pm(0)}$ in the t-channel are also very efficient. Since these contributions cannot be turned off, we can set a lower limit on the mass of the triplet by requiring the correct relic density. For $\Delta = 0$ we find $M_{\chi_L} \gtrsim 1750$ GeV, while for a decoupling color singlet we find $M_{\chi_L} \gtrsim 1600$ GeV.

For $\lambda \neq 0$, the dependence of Ωh^2 on the triplet mass becomes more complicate, as can be seen in Fig. 2, and a discussion similar to the singlet case applies. It is easy to generalize the results shown in Fig. 2 to different values of Δ and λ: the effect of a larger Δ is to shift the dashed lines to the left, while the effect of a larger(smaller) λ is to shift the same lines upwards(downwards).

Fixing the value of the coupling λ to reproduce the correct relic density, we show in Fig. 3 the prediction for the spin-independent dark matter-proton cross section, σ_p^I, and in Fig. 4 the predicted pair-annihilation rate $\langle \sigma v \rangle$, as a function of the triplet mass and for different value of M_{S_3} and Δ. Similarly to the singlet case, in the whole mass range considered, λ is found in a perturbative range, with values between 0 and 4. As for the singlet, we find that current experimental limits on σ_p^I [72] cannot probe the predicted cross section which lies below the neutrino
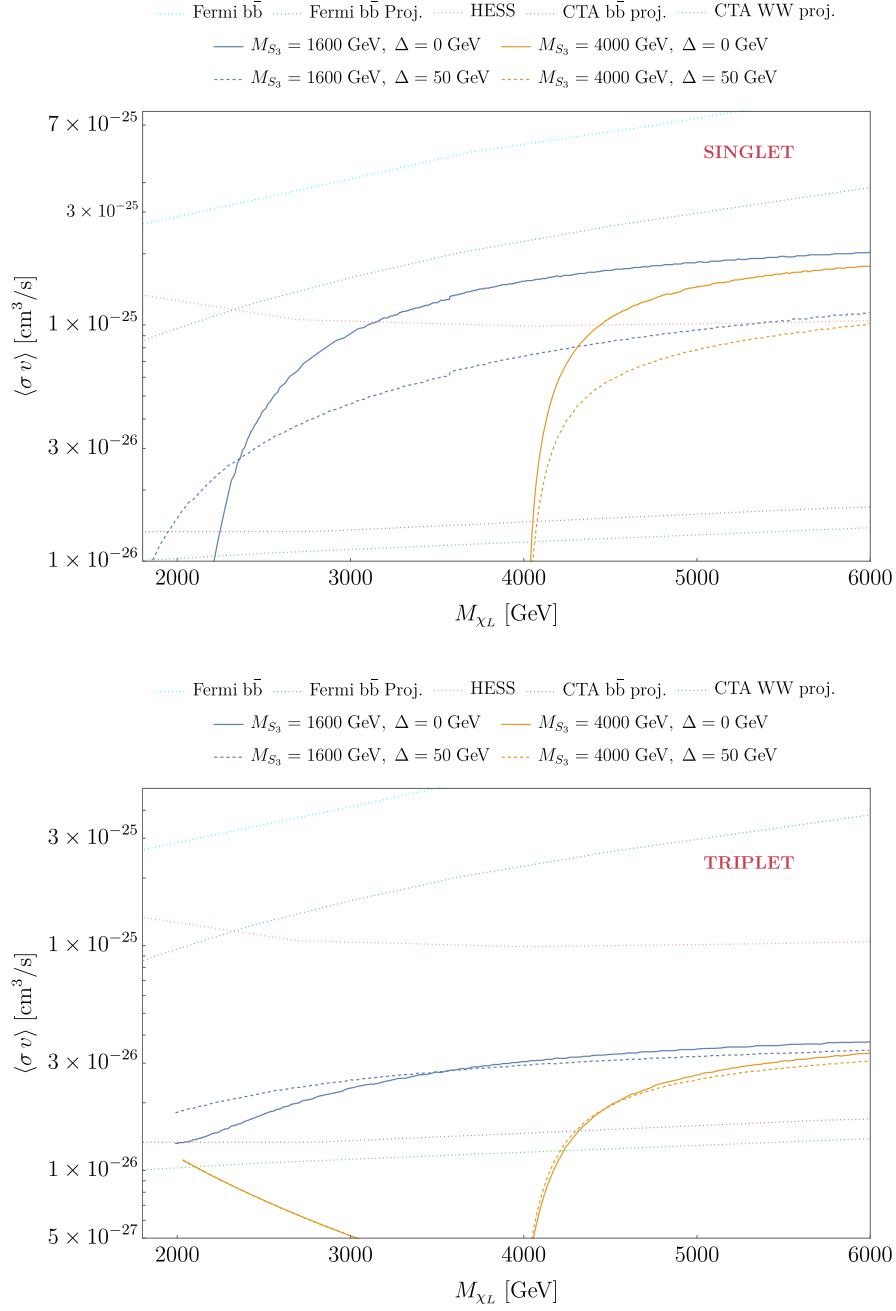
FIG. 4.   Pair-annihilation cross section as a function of the dark matter mass, predicted requiring the observed relic abundance for different values of the leptoquark mass and mass splitting.

coherent scattering floor [81]. On the other hand, we find that for light leptoquark masses, the anticipated sensitivity of the Cherenkov Telescope Array on $b\bar{b}$ and W^+W^- [85] will potentially test a large range of the triplet mass. Here, the most relevant processes are the pair production of W^+W^- and $S_3 S_3$, for a light and a heavy triplet, respectively. In general, CTA bounds become relevant when the two leptoquarks in the final state can be produced on-shell. The contribution from processes with off-shell leptoquarks are not included in Fig. 4, however we checked that they are suppressed by several orders of magnitude

with respect to the on-shell ones that are part of the results we show.

IV. DISCUSSION AND CONCLUSION

Based on persistent experimental signals of lepton flavor universality violation, and on the as-persistent lack of any evidence in favor of any particular particle dark matter candidate, in this study we entertain the following scenario: we posit that the dark matter belongs to a *dark sector* whose portal to the *visible*, Standard Model sector is a scalar

leptoquark $SU(2)_L$ triplet that also provides a solution and an explanation to the flavor anomalies.

We showed that the dark sector must include new fields charged under $SU(2)_L$ and $SU(3)_C$; we assumed the new fields to consist of two vectorlike multiplets, one singlet under $SU(3)_C$, denoted as χ_L, that contains the dark matter candidate of the theory, and one triplet under $SU(3)_C$, denoted as χ_Q. We considered the two lowest-dimensional $SU(2)_L$ representation assignments for χ_L such that the resulting hypercharge is 0, as required by direct dark matter searches.

We computed in detail the thermal relic density of the χ_L, and studied which processes drive it, and where and how such relic density corresponds to the observed abundance of the cosmological dark matter.

Finally, we explored direct and indirect dark matter searches: broadly, direct detection rates are loop-suppressed and consistently below the neutrino floor, thus inaccessible with current detector technology. For indirect detection, the model is not accessible with Fermi LAT observations, but it is at present constrained by higher-energy ground-based telescopes such as HESS, and will be probed in most of the relevant parameter space by the next generation Cherenkov Telescope Array.

While we focus on the anomalies in neutral current B decays, leptoquarks as a solution to the anomalies in charged current B decays and as mediators to dark matter have already been discussed in Ref. [56]. The key differences between the dark matter phenomenology between the model in Ref. [56] and the one under discussion here are related to the fact that the leptoquark mediator and the second fermionic field are $SU(2)_L$ singlets in Ref. [56], while they are triplets here; additionally, unlike in Ref. [56], we also entertain that the dark matter candidate χ_L be charged under $SU(2)_L$, transforming as a triplet.

It is difficult to compare in detail the results of Ref. [56] with ours; generally, it appears that the processes driving the main features in the relic abundance of the dark matter candidate are similar: resonant leptoquark exchange, coannihilation processes, on-shell leptoquark production; the fact that the direct detection cross section is loop-mediated is also a common feature of the two models, albeit we find smaller scattering rates than Ref. [56] does; finally, albeit not discussed in Ref. [56], we expect the indirect detection phenomenology to also be broadly similar although different in specific details (for instance driven by the fact that there exist additional electroweak contributions in the model discussed here).

If indeed lepton flavor universality violation is a signal of new physics, and such new physics sector includes a dark matter candidate, we show here, under certain unavoidable assumptions, what the resulting phenomenology might unfold. Our main conclusion is that the expectation is for a heavy, TeV or heavier, dark matter candidate with a very weak coupling to nucleons, but with large-enough pair-annihilation rates so that indirect detection with very high-energy gamma rays is the most promising path to discovery.

[1] S. Profumo, *An Introduction to Particle Dark Matter* (World Scientific, Singapore, 2017).

[2] S. Profumo, L. Giani, and O. F. Piattella, Universe **5**, 213 (2019).

[3] J. M. Camalich and M. Patel, Sci. Bull. **67**, 1 (2022).

[4] A. Crivellin and M. Hoferichter, Science **374**, 1051 (2021).

[5] O. Fischer *et al.*, Eur. Phys. J. C **82**, 665 (2022).

[6] G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, S. Profumo, and F. S. Queiroz, Eur. Phys. J. C **78**, 203 (2018).

[7] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **111**, 191801 (2013).

[8] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **113**, 151601 (2014).

[9] V. Khachatryan *et al.* (CMS and LHCb Collaborations), Nature (London) **522**, 68 (2015).

[10] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 02 (2016) 104.

[11] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 08 (2017) 055.

[12] M. Aaboud *et al.* (ATLAS Collaboration), J. High Energy Phys. 04 (2019) 098.

[13] A. M. Sirunyan *et al.* (CMS Collaboration), J. High Energy Phys. 04 (2020) 188.

[14] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **125**, 011802 (2020).

[15] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **126**, 161802 (2021).

[16] W. Altmannshofer and P. Stangl, Eur. Phys. J. C **81**, 952 (2021).

[17] L.-S. Geng, B. Grinstein, S. Jäger, S.-Y. Li, J. Martin Camalich, and R.-X. Shi, Phys. Rev. D **104**, 035029 (2021).

[18] M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, and M. Novoa-Brunet, Eur. Phys. J. C **82,** 326 (2022).

[19] T. Hurth, F. Mahmoudi, D. M. Santos, and S. Neshatpour, Phys. Lett. B **824,** 136838 (2022).

[20] G. Isidori, D. Lancierini, P. Owen, and N. Serra, Phys. Lett. B **822,** 136644 (2021).

[21] M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, New Physics without bias: Charming Penguins and Lepton Universality Violation in $b \rightarrow s\ell^+\ell^-$ decays, Report Nos. DESY 21-168, HU-EP-21/42, TTP21-040, P3H-21-077, YITP-SB-2021-20 (2021), arXiv:2110.10126.

[22] C. Bobeth, G. Hiller, and G. Piranishvili, J. High Energy Phys. 12 (2007) 040.

[23] G. Hiller and M. Schmaltz, Phys. Rev. D **90,** 054014 (2014).

[24] R. Alonso, B. Grinstein, and J. Martin Camalich, J. High Energy Phys. 10 (2015) 184.

[25] L. Calibbi, A. Crivellin, and T. Ota, Phys. Rev. Lett. **115,** 181801 (2015).

[26] G. Hiller, D. Loose, and K. Schönwald, J. High Energy Phys. 12 (2016) 027.

[27] B. Bhattacharya, A. Datta, J.-P. Guévin, D. London, and R. Watanabe, J. High Energy Phys. 01 (2017) 015.

[28] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, J. High Energy Phys. 11 (2017) 044.

[29] R. Barbieri, G. Isidori, A. Pattori, and F. Senia, Eur. Phys. J. C **76,** 67 (2016).

[30] R. Barbieri, C. W. Murphy, and F. Senia, Eur. Phys. J. C **77,** 8 (2017).

[31] L. Calibbi, A. Crivellin, and T. Li, Phys. Rev. D **98,** 115002 (2018).

[32] A. Crivellin, D. Müller, and T. Ota, J. High Energy Phys. 09 (2017) 040.

[33] A. Crivellin, D. Müller, A. Signer, and Y. Ulrich, Phys. Rev. D **97,** 015019 (2018).

[34] M. Bordone, C. Cornella, J. Fuentes-Martín, and G. Isidori, J. High Energy Phys. 10 (2018) 148.

[35] J. Kumar, D. London, and R. Watanabe, Phys. Rev. D **99,** 015007 (2019).

[36] A. Crivellin, C. Greub, D. Müller, and F. Saturnino, Phys. Rev. Lett. **122,** 011805 (2019).

[37] A. Crivellin and F. Saturnino, Proc. Sci., DIS2019 (**2019**) 163.

[38] C. Cornella, J. Fuentes-Martin, and G. Isidori, J. High Energy Phys. 07 (2019) 168.

[39] M. Bordone, O. Catà, and T. Feldmann, J. High Energy Phys. 01 (2020) 067.

[40] J. Bernigaud, I. de Medeiros Varzielas, and J. Talbert, J. High Energy Phys. 01 (2020) 194.

[41] J. Aebischer, A. Crivellin, and C. Greub, Phys. Rev. D **99,** 055002 (2019).

[42] J. Fuentes-Martín, G. Isidori, M. König, and N. Selimović, Phys. Rev. D **101,** 035024 (2020).

[43] O. Popov, M. A. Schmidt, and G. White, Phys. Rev. D **100,** 035028 (2019).

[44] S. Fajfer and N. Košnik, Phys. Lett. B **755,** 270 (2016).

[45] M. Blanke and A. Crivellin, Phys. Rev. Lett. **121,** 011801 (2018).

[46] I. de Medeiros Varzielas and J. Talbert, Eur. Phys. J. C **79,** 536 (2019).

[47] I. de Medeiros Varzielas and G. Hiller, J. High Energy Phys. 06 (2015) 072.

[48] A. Crivellin, D. Müller, and F. Saturnino, J. High Energy Phys. 06 (2020) 020.

[49] S. Saad, Phys. Rev. D **102,** 015019 (2020).

[50] S. Saad and A. Thapa, Phys. Rev. D **102,** 015014 (2020).

[51] V. Gherardi, D. Marzocca, and E. Venturini, J. High Energy Phys. 01 (2021) 138.

[52] L. Da Rold and F. Lamagna, Phys. Rev. D **103,** 115007 (2021).

[53] J. Heeck and A. Thapa, Eur. Phys. J. C **82,** 480 (2022).

[54] S.-M. Choi, Y.-J. Kang, H. M. Lee, and T.-G. Ro, J. High Energy Phys. 10 (2018) 104.

[55] R. Mandal, Eur. Phys. J. C **78,** 726 (2018).

[56] G. Belanger et al., J. High Energy Phys. 02 (2022) 042.

[57] F. S. Queiroz, K. Sinha, and A. Strumia, Phys. Rev. D **91,** 035006 (2015).

[58] M. J. Baker et al., J. High Energy Phys. 12 (2015) 120.

[59] A. Mohamadnejad, Nucl. Phys. **B949,** 114793 (2019).

[60] F. D'Eramo, N. Košnik, F. Pobbe, A. Smolkovič, and O. Sumensari, Phys. Rev. D **104,** 015035 (2021).

[61] B. Belfatto, D. Buttazzo, C. Gross, P. Panci, A. Strumia, N. Vignaroli, L. Vittorio, and R. Watanabe, J. High Energy Phys. 06 (2022) 084.

[62] M. J. Baker, D. A. Faroughy, and S. Trifinopoulos, J. High Energy Phys. 11 (2021) 084.

[63] D. Guadagnoli, M. Reboud, and P. Stangl, J. High Energy Phys. 10 (2020) 084.

[64] T. A. Chowdhury and S. Saad, Phys. Rev. D **106,** 055017 (2022).

[65] P. Athron, A. Fowlie, C.-T. Lu, L. Wu, Y. Wu, and B. Zhu, The W boson mass and muon $g-2$: Hadronic uncertainties or new physics? (2022), arXiv:2204.03996.

[66] A. Bhaskar, A. A. Madathil, T. Mandal, and S. Mitra, Combined explanation of W-mass, muon $g-2$, $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies in a singlet-triplet scalar leptoquark model (2022), arXiv:2204.09031.

[67] T. Aaltonen et al. (CDF Collaboration), Science **376,** 170 (2022).

[68] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik, Phys. Rep. **641,** 1 (2016).

[69] B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, and J. Virto, J. High Energy Phys. 01 (2018) 093.

[70] M. Algueró, B. Capdevila, A. Crivellin, S. Descotes-Genon, P. Masjuan, J. Matias, M. Novoa Brunet, and J. Virto, Eur. Phys. J. C **79,** 714 (2019); **80,** 511(A) (2020).

[71] M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, and M. Valli, Phys. Rev. D **103,** 015030 (2021).

[72] P. A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. **2020,** 083C01 (2020).

[73] J. Grygier et al. (Belle Collaboration), Phys. Rev. D **96,** 091101 (2017); **7,** 099902(A) (2018).

[74] T. Abe et al. (Belle-II Collaboration), Belle II technical design report, Report No. KEK-REPORT-2010-1 (2010), arXiv:1011.0352.

[75] A. Angelescu, D. Bečirević, D. A. Faroughy, and O. Sumensari, J. High Energy Phys. 10 (2018) 183.

[76] G. Aad et al. (ATLAS Collaboration), J. High Energy Phys. 10 (2020) 112.

[77] S. Profumo, Phys. Rev. D **102,** 035008 (2020).

[78] M. Cirelli, N. Fornengo, and A. Strumia, Nucl. Phys. **B753,** 178 (2006).

[79] D. Barducci, G. Belanger, J. Bernon, F. Boudjema, J. Da Silva, S. Kraml, U. Laa, and A. Pukhov, Comput. Phys. Commun. **222,** 327 (2018).

[80] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **641,** A6 (2020); **652,** C4(E) (2021).

[81] L. E. Strigari, New J. Phys. **11,** 105011 (2009).

[82] M. Ackermann *et al.* (Fermi-LAT Collaboration), Phys. Rev. Lett. **115,** 231301 (2015).

[83] H. Abdallah *et al.* (H.E.S.S. Collaboration), Phys. Rev. Lett. **117,** 111301 (2016).

[84] A. Drlica-Wagner *et al.* (LSST Dark Matter Group), Probing the fundamental nature of dark matter with the large synoptic survey telescope, Report No. FERMILAB-PUB-19-048-A-AE (2019), arXiv:1902.01055.

[85] A. Acharyya *et al.* (CTA Collaboration), J. Cosmol. Astropart. Phys. 01 (2021) 057.

[86] H. Abdalla *et al.* (H.E.S.S. Collaboration), Astrophys. J. **918,** 17 (2021).