Strong Constraints on Self-Interacting Dark Matter with Light Mediators

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Coupling dark matter to light new particles is an attractive way to combine thermal production with strong velocity-dependent self-interactions. Here we point out that in such models the dark matter annihilation rate is generically enhanced by the Sommerfeld effect, and we derive the resulting constraints from the cosmic microwave background and other indirect detection probes. For the frequently studied case of s-wave annihilation, these constraints exclude the entire parameter space where the self-interactions are large enough to address the small-scale problems of structure formation.

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Introduction.—Although dark matter (DM) particles can have only very weak interactions with standard model (SM) states, it is an intriguing possibility that they experience much stronger self-interactions and thereby alter the behavior of DM on astrophysical and cosmological scales in striking ways. In particular, self-interacting DM (SIDM) may offer an attractive solution to some of the long-standing small-scale structure problems encountered in the collisionless cold DM paradigm [1,2]. At the same time, a conclusive observation of collisionality of DM on astrophysical scales would have striking implications for the particle physics properties of DM. For these reasons, SIDM has been the subject of increasing interest in the past few years.

In order to affect astrophysical observations, the DM self-scattering cross section typically has to be of the order of $\sigma/m_\chi \sim 1\ \mathrm{cm}^2\,\mathrm{g}^1$ [3–8]. Such large cross sections can arise in essentially two different ways: either from new strong forces in the dark sector, similar to QCD, or from a more weakly coupled theory with a very light mediating particle. In the former case, large self-interactions are expected for all DM velocities, leading to strong bounds, in particular, from galaxy clusters [9–15]. In contrast, in models with a very light mediator, self-interactions become stronger at smaller DM velocities, so that large effects on small scales can be consistent with the stronger astrophysical constraints on larger scales [3–6,15–18].

Another attractive feature of SIDM with a very light mediator is that the DM abundance today can be explained by thermal production in the early Universe. In contrast to the standard weakly interacting massive particle (WIMP) scenario [19], where DM annihilates directly into SM states (see [20]), the DM particle χ annihilates into the mediator particles ϕ, which subsequently decay into SM states: $\chi\chi \to \phi\phi \to \mathrm{SM}$ [21]. This can naturally yield the observed relic abundance even if interactions with the SM are strongly suppressed.

From a particle physics perspective, the presence of very weakly coupled light mediators can be easily motivated, e.g., if the stability of the DM particle arises from a charge under a new spontaneously broken $U(1)'$ gauge group. Nevertheless, the mediator should couple to the SM at *some* level [22,23] in order (i) to bring the dark and visible sector into thermal equilibrium at early times and (ii) to decay sufficiently quickly to avoid overclosing the Universe. Such scenarios provide a both attractive and minimal realization of the SIDM idea and have hence been one of the main avenues of model building [24–26].

The required interaction strength between mediators and the SM turns out to be rather small and is therefore usually assumed to be essentially unconstrained. In this Letter, we demonstrate that decays of the mediator into SM states are, instead, very strongly constrained in a rather model-independent way. The reason is that the large self-interaction cross sections are achieved via nonperturbative enhancements which at the same time also enhance the DM annihilation cross section, in particular, for small DM velocities [27–30]. The subsequent decays of the mediators into SM states would then typically change the reionization history of the Universe and thereby lead to significant distortions of the cosmic microwave background (CMB) or be observed in indirect detection experiments today. Analogous constraints have been explored previously in the context of possible DM explanations of the cosmic-ray positron excess [31]; see, e.g., [28,29,32–37]. Here, we update these constraints specifically for SIDM, using the latest CMB and indirect detection data.

This Letter is organized as follows. We first revisit the required properties of the DM and mediator particles to reproduce the observed relic abundance and give rise to phenomenologically relevant DM self-interactions. We then discuss CMB and indirect detection constraints, with special emphasis on strongly velocity-dependent DM annihilation rates. We illustrate their impact on the most popular class of models, in which the DM relic density is set by s-wave annihilation. Finally, we comment on how the resulting strong constraints may be relaxed.

Self-interacting DM with light mediators.—We consider a nonrelativistic DM species χ that interacts via a light vector or scalar mediator ϕ. The DM self-interactions that result from exchanging ϕ can be described by a Yukawa potential, which leads to a strong dependence of the self-interaction rate on the relative velocity v of the scattering DM particles. The phenomenology of this scenario is fully characterized by the two masses, m_χ and m_ϕ, and the coupling strength $\alpha_\chi \equiv g^2/4\pi$.

In the *Born limit* ($\alpha_\chi m_\chi \lesssim m_\phi$), the momentum transfer cross section σ_T can be calculated perturbatively [4]. For larger coupling strengths or DM masses, nonperturbative effects become important. In the following, we use the improved parametrization from Ref. [38] for the *classical limit* ($m_\chi v \gtrsim m_\phi$) and adopt the analytical expressions from Ref. [18], which have been obtained from approximating the Yukawa potential by a Hulthén potential, in the *intermediate (resonant) regime*. To estimate the effect of DM self-interactions on dwarf galaxies, we define $\langle\sigma_T\rangle_{30}$ as σ_T averaged over a Maxwellian velocity distribution with a most probable velocity of 30 $\mathrm{km\,s^{-1}}$. To obtain observationally relevant effects, e.g., to alleviate the cusp-core [39–41] and too-big-to-fail [42,43] problems, we require $\langle\sigma_T\rangle_{30}/m_\chi \sim 0.1$–$10\ \mathrm{cm^2\,g^{-1}}$ [7,8].

As motivated in the introduction, a second important constraint can be obtained under the assumption that the dark sector was in thermal equilibrium with the SM sector at early times and the DM relic abundance is set by thermal freeze-out. This assumption is well motivated if the mediator couples also to SM states but may need to be revisited if these interactions are very weak (see below). As the dominant DM annihilation channel is $\chi\chi \to \phi\phi$, we can effectively eliminate α as a free parameter by requiring that the relic density matches the observed value of $\Omega_\chi h^2 = 0.1188 \pm 0.0010$ [44].

The required value of α depends on the particle masses and on whether the annihilation proceeds via an s- or a p-wave process. The former implies a constant annihilation rate $(\sigma v)_0$ at the perturbative level, for $v \ll 1$, while the latter implies $(\sigma v)_0 \propto v^2$. In both cases, we can combine the requirement of sizable self-interaction rates with the observed relic density for the three regimes mentioned above [18]. As visualized later in Fig. 2, this yields very roughly ($m_\chi \gtrsim 100$ GeV, $m_\phi \lesssim 10$ MeV) in the classical regime, (10 GeV $\lesssim m_\chi \lesssim 100$ GeV, 1 MeV $\lesssim m_\phi \lesssim 1$ GeV) in the resonant regime, and ($m_\chi \lesssim 10$ GeV, $m_\phi \lesssim 10$ MeV) in the Born limit.

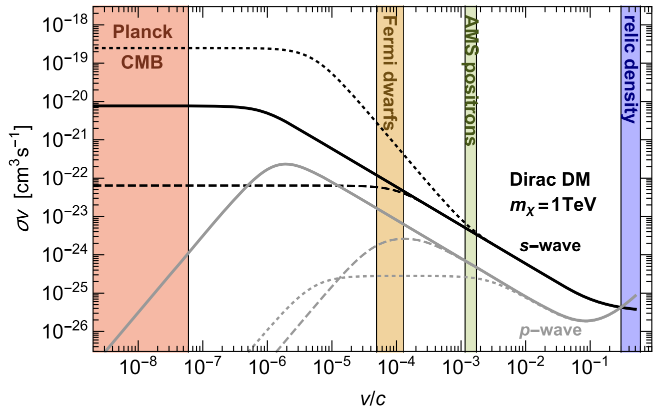

FIG. 1. Comparison of cross sections for s-wave and p-wave annihilation, as a function of the relative DM-DM velocity. The coupling α_χ is fixed by the relic density requirement. Solid (dashed) curves correspond to $m_\chi = 1$ TeV and $m_\phi = 1$ MeV ($m_\phi = 100$ MeV), while dotted lines show the case of m_ϕ tuned to 1.119 GeV (1.066 GeV) for resonant s-wave (p-wave) annihilation. In addition, the typical velocity ranges of different experimental probes are indicated.

Sommerfeld enhancement.—The Yukawa potential due to a light mediator exchange not only affects DM self-interactions, but it also modifies the wave function of the annihilating DM pair [31,45]. For small velocities, this can lead to significant nonperturbative corrections to the tree-level annihilation rate, $\sigma v = S \times (\sigma v)_0$, with the Sommerfeld enhancement factor S given in Refs. [46–48]. For $\alpha_\chi m_\phi \ll m_\chi v^2$, the Yukawa potential becomes indistinguishable from a Coulomb potential, and no strong resonances appear in S.

This effect is usually taken into account for relic density calculations in SIDM models, and we adopt here the results from Refs. [17,18]. Quantitatively, the required value of α_χ differs from the perturbative result only by an $\mathcal{O}(1)$ factor independent of m_ϕ, because for most of the parameter space of interest we are in the Coulomb regime during chemical freeze-out. We neglect the model-dependent effect of a second period of DM annihilation *after kinetic decoupling* that can occur for Sommerfeld-enhanced DM annihilation [28,29,49,50]. While this may, in principle, decrease Ω_χ by up to 3 orders of magnitude if DM annihilation occurs very close to a resonance, it changes the calculation only at the percent level off resonance [50]. Similarly, we neglect the effect of bound-state formation, which becomes important only close to the unitarity bound [51] (for details, see [52]).

As the Universe continues to cool down after DM freeze-out, the DM velocities decrease. The crucial observation for the purpose of this Letter is that the Sommerfeld enhancement at late times is therefore much larger than during freeze-out. We illustrate this in Fig. 1, where we show s-wave and p-wave annihilation cross sections as a function of the DM velocity for different mediator masses, with α_χ being fixed by the relic density requirement. Away from any resonance, the enhancement scales like $1/v$ and $1/v^3$ for the s-wave and p-wave case, respectively, so that effectively the cross sections scale like $1/v$ in both cases. For the p-wave case, however, there is an offset compared to the thermal cross section due to the initial v^2 suppression. In both cases, the saturation of the Sommerfeld enhancement occurs at about $v \sim m_\phi/2m_\chi$, leading to a plateau for the s-wave and a maximum for the p-wave case. For masses tuned to a resonance (as shown for the dotted lines), the s-wave enhancement grows like $1/v^2$ and saturates later.

This figure clearly demonstrates that probes of DM annihilation at small velocities have the potential to seriously impact SIDM models with light mediators, in particular, for s-wave annihilation. In the following, we will discuss the relevant observational constraints in turn and then quantify our general expectation by considering a popular concrete model realization that leads to s-wave-dominated DM annihilation.

CMB constraints.—Mediator particles decaying into SM particles at a rate larger than the Hubble rate can bring the model in conflict with the robust constraints on DM annihilation from CMB observations [34,35,53–56]. At 95% C.L., the most recent Planck data result in [44]

$$\frac{\langle\sigma v\rangle_{\rm rec}}{N_\chi} \lesssim 4\times 10^{-25}\ {\rm cm^3\ s^{-1}}\left(\frac{f_{\rm eff}}{0.1}\right)^{-1}\left(\frac{m_\chi}{100\ {\rm GeV}}\right), \qquad (1)$$

where $\langle\sigma v\rangle_{\rm rec}$ is the annihilation rate at recombination ($z_{\rm rec} \sim 1100$) averaged over the distribution of DM velocities and $N_\chi = 1$ ($N_\chi = 2$) for Majorana (Dirac) DM. The efficiency factor $f_{\rm eff}$ is related to the fraction of the released energy ending up in photons or electrons (see, e.g., [57]) with $f_{\rm eff} \gtrsim 0.1$ for any SM final state apart from neutrinos.

The typical DM velocity v_χ during recombination depends on the temperature of kinetic decoupling $T_{\rm kd}$ via $\langle v_\chi^2\rangle_{\rm rec} = \frac{1}{2}\langle v^2\rangle_{\rm rec} = 3(T_{\rm kd}/m_\chi)(z_{\rm rec}/z_{\rm kd})^2$ [58], where $z_{\rm kd}$ is the redshift at kinetic decoupling. For standard WIMPs, one expects $10\ {\rm MeV} \lesssim T_{\rm kd} \lesssim 1\ {\rm GeV}$ [58]. In the presence of light mediators, however, kinetic decoupling can be significantly delayed [50]. Nevertheless, observations of the Lyman-α forest [59,60] robustly exclude $T_{\rm kd} \lesssim 100$ eV (see Refs. [61,62] for a recent discussion). This translates into an upper bound on the relative DM velocity at recombination of

$$v_{\rm rec} \lesssim 2\times 10^{-7}\left(\frac{m_\chi}{100\ {\rm GeV}}\right)^{-1/2}. \qquad (2)$$

Such small velocities imply enormously enhanced DM annihilation rates.

As an illustrative example, let us estimate the effect on the classical regime of DM self-scattering, assuming that annihilation proceeds via an s-wave process. Since there are no resonances, the Sommerfeld enhancement saturates for $v \lesssim v_{\rm sat} \equiv m_\phi/2m_\chi$. For phenomenologically relevant values of $\langle\sigma_T\rangle_{30}$, this mass ratio is numerically larger than the minimal velocity in Eq. (2). The annihilation rate relevant for CMB constraints thus becomes *maximal*,

$$\langle\sigma v\rangle_{\rm rec} \sim \langle\sigma v\rangle_{\rm cd}\frac{v^*}{v_{\rm sat}} \sim \langle\sigma v\rangle_{\rm cd}v^*\frac{m_\chi}{m_\phi}, \qquad (3)$$

where the annihilation rate at freeze-out is approximately $\langle\sigma v\rangle_{\rm cd}/N_\chi \sim 3\times 10^{-26}\ {\rm cm^3\ s^{-1}}$ in order to obtain the correct relic density and $v^* \sim 0.1$ denotes the velocity below which $\sigma v \propto 1/v$. Comparing Eq. (1) to Eq. (3), we conclude that for s-wave annihilation in the classical scattering regime this class of models is ruled out unless either $m_\phi \gtrsim 1$ GeV, in which case no sizable DM self-interactions can be achieved, or $f_{\rm eff} \ll 0.1$.

Other indirect detection constraints.—In the Born and resonant regimes there are additional strong constraints from observations probing somewhat larger DM velocities, specifically from searches for present-day DM annihilation into light mediators ϕ, which in turn decay into SM particles. For simplicity, we will consider only light leptonic decay modes, implying branching ratios ${\rm BR}(\phi\to\ell\ell)<1$ for $m_\phi \gtrsim 2m_{\pi^0}$. Including further channels would lead to more stringent constraints.

Dwarf galaxy observations with the Fermi gamma-ray space telescope provide one of the most robust ways to constrain DM annihilation, and we implement them using the likelihood functions provided by the Fermi-LAT Collaboration which extend down to photon energies of 500 MeV [63]. To obtain the gamma-ray spectrum, we first calculate the distribution of photon energies from $\phi\to\ell^+\ell^-\gamma$, in the rest frame of ϕ, and then boost it to the DM frame as in Ref. [32]. Kinematical data constrain the DM velocities to be much smaller than the $v_\chi \sim 10^{-3}$ observed in our Galaxy; here, we adopt a relative velocity of $v = 10^{-4}$, which independently of the assumed profile is a conservative choice [64]. We use the J factors assuming a Burkert profile from Ref. [65].

Local DM annihilation to positrons are strongly constrained by the high-accuracy data of the AMS-02 experiment [66,67], with only moderate uncertainties related to the local normalizations of the DM profile and radiation density [68]. We take the bounds from Ref. [69] for one-step cascade annihilations with the intermediate state decaying to e^+e^- and $\mu^+\mu^-$. These bounds extend down to DM masses of 10 GeV and, for $m_\phi \ll m_\chi$, are to a good approximation independent of the mediator mass.

Example model.—Let us now apply the above constraints to an often-discussed example of a model with s-wave DM annihilations [5,18,22,31,70]. Here, χ is a Dirac fermion that couples to a massive vector ϕ. The latter can obtain couplings to SM particles via kinetic mixing with the hypercharge field strength $B^{\mu\nu}$ or via mass mixing with the Z [20,71,72]:

$$\mathcal{L} \supset -g_\chi^V\phi^\mu\bar\chi\gamma_\mu\chi - \frac{1}{2}\sin\epsilon B_{\mu\nu}\phi^{\mu\nu} - \delta m^2\phi^\mu Z_\mu. \qquad (4)$$

We first focus on the case of negligible mass mixing, $\delta m \ll m_\phi$. For $m_\phi \ll m_Z$, the couplings of the mediator are then largely photonlike, so this situation is very similar to kinetic mixing with electromagnetism [73,74]. The

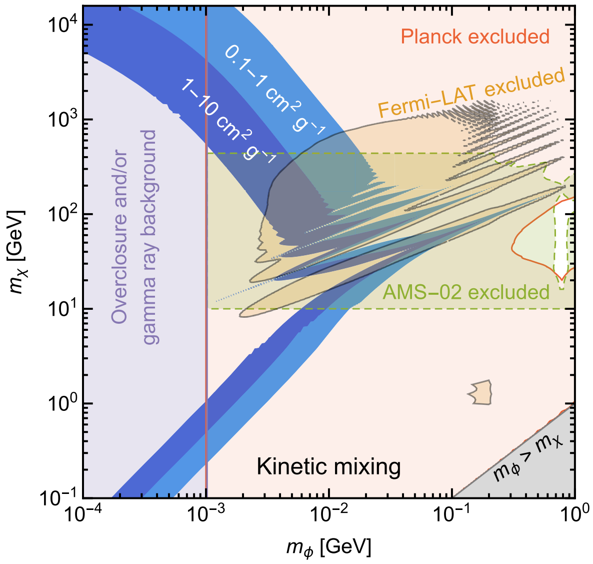

FIG. 2. Constraints at 95% C.L. on DM annihilating into vector mediators that kinematically mix with hypercharge as a function of the DM and mediator masses. The blue shaded region shows the combinations of DM mass m_χ and mediator mass m_ϕ that lead to a DM self-interaction cross section of $0.1\ \mathrm{cm}^2\,\mathrm{g}^{-1} < \langle\sigma_T\rangle_{30}/m_\chi < 10\ \mathrm{cm}^2\,\mathrm{g}^{-1}$, which would visibly affect astrophysical observables at the dwarf galaxy scale [18].

dominant decay mode for $m_\phi \lesssim 1$ MeV is then $\phi \to 3\gamma$, which is so small that ϕ would effectively be stable; in such a scenario, the mediator would either overclose the Universe or, close to the threshold, produce gamma rays in excess of the extragalactic gamma-ray background [74]. Heavier mediators decay into both leptons and hadrons, and we adopt $\mathrm{BR}(\phi \to \ell\ell)$ from Ref. [75].

For each combination of DM and mediator mass in this model, we calculate the Sommerfeld enhancement factor using the conservative upper bound on v_{rec} from Eq. (2). By comparing the result to Eq. (1), we can determine the parameter region excluded by CMB constraints. To calculate the appropriate value of f_{eff} as a function of m_χ and m_ϕ, we multiply the different decay modes with the efficiency factors from Ref. [57]. Our results are shown in Fig. 2, where we also show the Fermi and AMS-02 bounds discussed above. We observe that the CMB constraints, and partially also the other indirect detection constraints, exclude all combinations of m_χ and m_ϕ that lead to interesting self-interaction cross sections (note that for sufficiently light DM the model is already excluded by these constraints without a Sommerfeld enhancement).

We emphasize that very close to a resonance both the preferred SIDM region and the various constraints may be modified by the impact of a potential second period of DM annihilation on the relic density calculation (see above). For late kinetic decoupling, the resulting modifications will be small, but we expect even larger effects not to change our results qualitatively.

Discussion.—The bounds shown in Fig. 2 have been obtained under very conservative assumptions and are expected to apply in a similar way to other DM models with a light mediator, e.g., scalar and vector DM, for which annihilation into mediator pairs generically proceeds via s wave. The CMB constraints, in particular, are very robust, because we probe DM annihilation in a kinematical situation where the Sommerfeld enhancement is typically already saturated, so that the redshift dependence of the energy injection rate is the same as for standard s-wave annihilation. Even for parameter combinations where this is not the case, our constraints are extremely conservative, because we evaluate σv no later than at recombination and for larger values of v_{rec} than expected in a realistic treatment of kinetic decoupling. Nevertheless, our analysis does rely on a number of assumptions, which we will now review in detail.

For our calculations so far, there was no need to specify the kinetic mixing parameter ϵ, as long as mixing is sufficiently large that the mediator decays in time to affect the reionization history. Nevertheless, we have assumed implicitly that ϵ is large enough to thermalize the visible sector and the dark sector before freeze-out. Depending on the DM mass, the required value of ϵ for this to happen is of the order of 10^{-7}–10^{-5} [76]. However, DM direct detection experiments (as well as astrophysical constraints for $m_\phi \lesssim 1$ MeV [77]) typically require much smaller values of ϵ [22]. The conclusion is that a different mechanism must be responsible for bringing the visible and the dark sector into thermal contact.

The simplest possibility would be a thermal contact at higher temperatures, via a different portal. After this interaction ceases to be effective, the temperatures of both sectors would then evolve independently, depending on the number of degrees of freedom in each sector. For sizable α_χ, the DM relic abundance will still be determined by dark sector freeze-out but at a different temperature. For reasonable temperature ratios, as we discuss in detail in Supplemental Material [78], such a situation does not lead to qualitatively different results compared to the case where the two sectors have the same temperature. For the case where the two sectors never reach thermal equilibrium and the DM relic abundance is, for example, set via the freeze-in mechanism, we refer to Ref. [25].

A second important assumption is that the DM annihilation to mediator pairs proceeds via an s-wave process. While the Sommerfeld enhancement can be significant also in the p-wave case (see Fig. 1), the resulting cross sections are significantly smaller and indirect detection gives no relevant constraints. CMB constraints are also evaded for most of the parameter space, because for $v \lesssim v_{\mathrm{sat}}$ the cross section again decreases like v^2 and therefore becomes unobservably small at recombination. Only if the ratio m_χ/m_ϕ is very large and close to a resonance may effects be observable—in particular, with stage-4 CMB experiments.

Detailed predictions depend however on $v_{\rm rec}$ and hence on $T_{\rm kd}$. We note that p-wave annihilation requires scalar rather than vector mediators, which is strongly constrained from independent model-building considerations, in particular, the combination of constraints from direct detection experiments and primordial nucleosynthesis [22].

Finally, our conclusions can be modified if the mediator decays in a different way than via kinetic mixing. As a specific example, we discuss the case of mass mixing [78]. In this case, the mediator obtains a significant coupling to neutrinos, which alleviates constraints from both DM annihilation and the mediator lifetime but, in principle, offers exciting prospects for indirect detection [17]: DM annihilation into a pair of mediators followed by the decay $\phi \to \bar{\nu}\nu$ would result in a characteristic spectral feature [82]. While currently unconstrained for the models considered here, such a signal is in reach for IceCube observations of the Galactic halo [83–86].

In general, however, the constraints derived above are so strong that they can even be applied to models where mediator decays into leptons are subdominant. As a result, large self-interactions are excluded also for the case of mass mixing, as long as $m_\phi > 2m_e$. Even weaker constraints could, in principle, be obtained if the mediators couple to another very light state in the dark sector, such as sterile neutrinos. Such models are particularly interesting, because they can significantly delay kinetic decoupling and thus provide a solution also to the missing satellite problem [17,62,87–91].

Conclusions.—Models of DM with velocity-dependent self-interactions have recently received a great deal of attention for their potential to produce a number of interesting effects on astrophysical scales. We have shown in this Letter that these models face very strong constraints from the CMB and DM indirect detection. In the most natural realization of this scenario with a light vector mediator with kinetic mixing, these constraints rule out the entire parameter space where the self-scattering cross section can be relevant for astrophysical systems. These bounds remain highly relevant for a number of generalizations of the scenario, such as a different dark sector temperature and different mediator branching ratios. Clearly, future efforts to develop particle physics models for SIDM need to address these issues in order to arrive at models that provide a picture consistent with all observations in cosmology, astrophysics, and particle physics.

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