Cores in Dwarf Galaxies from Dark Matter with a Yukawa Potential

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We show that cold dark matter particles interacting through a Yukawa potential could naturally explain the recently observed cores in dwarf galaxies without affecting the dynamics of objects with a much larger velocity dispersion, such as clusters of galaxies. The velocity dependence of the associated cross-section as well as the possible exothermic nature of the interaction alleviates earlier concerns about strongly interacting dark matter. Dark matter evaporation in low-mass objects might explain the observed deficit of satellite galaxies in the Milky Way halo and have important implications for the first galaxies and reionization.

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Introduction. The collisionless cold dark matter (CDM) model has been highly successful in accounting for the gravitational growth of density perturbations from their small observed amplitude at early cosmic times (as imprinted on the cosmic microwave background anisotropies [1]) to the present-day structure of the Universe on large scales. However, it is far from clear that the predictions of this model are valid on small scales.

New data on low mass galaxies indicate that their dark matter distribution has a core [2], in contrast to the cusped profile expected from collisionless CDM simulations [3]. The mean value of the inner logarithmic slope of the mass density profile in seven dwarf galaxies within the THINGS survey is observed to be -0.29 ± 0.07 [4], much shallower than the expected slope of ~ -1 from pure CDM simulations. Moreover, the dynamics of dwarf spheroidal galaxies, such as Fornax [5], Ursa-Minor [6], and Sculptor [7], whose luminosities and dynamical masses are smaller by 2-3 orders of magnitude than the THINGS galaxies, indicates a characteristic core density of $\sim 0.1\pm0.05 M_\odot$ pc$^{-3} = (7\pm4)\times10^{-24}$ g cm^{-3}. Since these dwarf spheroidals are dominated by dark matter throughout, it is challenging to explain their inferred cores by the gravitational interaction of the dark matter with the baryons [8]. Although it is conceivable that powerful gas outflows from an early baryon-dominated nucleus would reduce the central dark matter density in luminous galaxies [9, 10], the formation of a massive baryonic nucleus would initially compress the CDM [11] and exacerbate the discrepancy that needs to be resolved [8], and also potentially violate the observed low luminosities from dwarf galaxies at higher redshifts [12, 13]. High-redshift observations of dwarf galaxies must find evidence for the required strong feedback phase, or else an alternative process is at play. Some recent simulations that include feedback do not observe the appearance of cores within the lowest luminosity galaxies [14].

To alleviate early signs of the above discrepancy, Spergel & Steinhardt [15] adopted the Strongly-Interacting Dark Matter (SIDM) model [16–18] in which the dark matter has a large cross-section for self interaction. It was expected that if dark matter scatters in the cores of galaxies, then it might resemble a fluid with a flatter central density profile. The SIDM proposal fell out of favor because: *(i)* gravitational lensing and X-ray data indicate that the cores of clusters of galaxies are dense and ellipsoidal, whereas SIDM would predict them to be shallow and spherical [19, 20]; *(ii)* relaxation of the core ultimately generates an even denser nucleus after many collision times due to the gravothermal catastrophe, familiar from core collapse of globular clusters [21], although this evolution might take more than the Hubble time; *(iii)* dwarf galaxies would be expected to evaporate when interacting with the higher velocity particles of their host halo; and *(iv)* theoretical biases suggested that the required cross section was incompatible with popular models of Weakly-Interacting Massive Particles (WIMPs).

Recently, there has been growing interest in the possibility that WIMPs exhibit "dark forces" as a means to address a wide range of anomalies [22]. In particular, it was realized that a new force carrier ϕ (scalar or vector) might naturally mediate a long-range interaction on the scale of the de-Broglie wavelength of the WIMPs, leading to a self-interaction cross-section for scattering that is much greater than for WIMP annihilation. The studied forces have a variety of scales in them, from the screening scale set by the mass of the carrier particle m_ϕ to the non-perturbative scale set by its coupling, $\alpha_d m_\phi$. Moreover, these forces are naturally accompanied by new energy states. Up- and down-scattering processes (which are endo- and exo-thermic, respectively) naturally introduce yet another scale into the problem, set by the energy splitting δ between the states. While similar models have been previously considered [23], our regime of interest was assumed to be unsuitable due to WIMP capture and WIMP annihilation. As it turns out, these processes are generally weaker than scattering and so this range of parameters remains open. Nonetheless, the absence of dramatic departures from CDM predictions has allowed important constraints to be placed [24, 25].

In this *Letter*, we examine the possible existence of a dark force from a different perspective. Rather than limit its allowed range of parameters based on observations, we show that it can *ameliorate* tensions in astrophysical data. In particular, we find that a Yukawa force in dark matter scattering would naturally produce cores in dwarf galaxies while avoiding the myriad constraints on SIDM which arise in systems with a much larger velocity dispersion, such as clusters of galaxies. The specific velocity dependence of the interaction cross-section, as well as the possible exothermic nature of the interaction, alleviate earlier concerns about the SIDM model. To distinguish from previous approaches with a constant cross section or a simple power law velocity dependence, we label this scenario as Yukawa-Potential Interacting Dark Matter (YIDM).

Dark Forces. The mediator of the force ϕ could be either a scalar or a vector, as magnetic-type interactions are negligible. The force could couple to standard model fields through kinetic mixing with the photon, or through mass mixing with the Higgs boson. Constraints on the presence of such a force come from a wide range of processes [26, 27], but ample parameter space remains for a small mixing angle, $\epsilon \lesssim 10^{-3}$. New searches are underway to find precisely such a force carrier at $\sim$ GeV energy experiments [28].

Scattering through a massive mediator is equivalent to having a Yukawa potential. The elastic scattering problem is then analogous to the screened Coulomb scattering in a plasma [29], which is well fit by a cross-section [24, 30],

$$\langle\sigma\rangle \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln(1+\beta^{-1}), & \beta \lesssim 0.1, \\ \frac{8\pi}{m_\phi^2}\beta^2/(1+1.5\beta^{1.65}), & 0.1 \lesssim \beta \lesssim 10^3, \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta \gtrsim 10^3, \end{cases} \tag{1}$$

where $\beta = \pi v_\sigma^2/v^2 = 2\alpha_d m_\phi/(m_\chi v^2)$, and v is the relative velocity of the particles. We use angular brackets to denote that this is the momentum-transfer weighted cross section. Here, v_σ is the velocity at which the momentum-weighted scattering rate $\langle\sigma v\rangle$ peaks at a cross section value of $\sigma_{\rm max} = 22.7/m_\phi^2$. The above expression can be approximately generalized to the inelastic case by substituting $m_\phi \rightarrow \sqrt{m_\chi\delta}$ for the characteristic minimum momentum transfer when $m_\phi < \sqrt{m_\chi\delta}$ (see discussion in [30]). This expression is derived using classical physics, and thus, it is important to note what quantum effects can come into play. In cases where the de Broglie wavelength is longer than the Compton wavelength of the force m_ϕ^{-1}, the quantum calculation should be considered for quantitative results. Nonetheless, the same qualitative features should remain: the cross section should saturate at low velocities near $\sigma \sim m_\phi^{-2}$, and at high velocities, where the classical approximation is valid, it should fall rapidly.

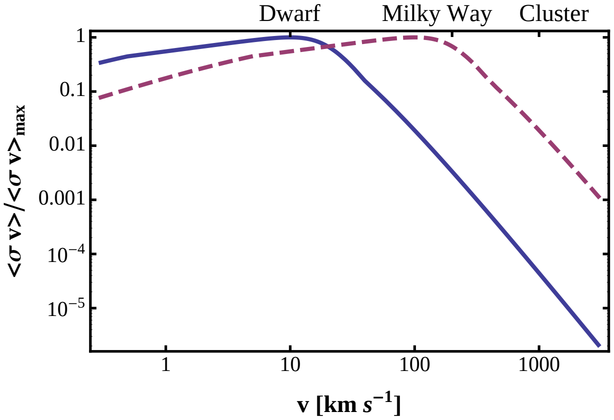

FIG. 1: Dependence of the self-interaction cross-section (σ) on the relative velocity (v) for dark matter interacting through a Yukawa potential. The normalizations of σ and v are set by free parameters in the underlying Lagrangian (see Appendix), and we show two possible curves peaking at $v_\sigma = 10$ km s^{-1} and $= 100$ km s^{-1} (*blue, solid* and *purple, dashed*, respectively).

Figure 1 depicts the velocity dependence of the elastic cross-section in Eq. (1). Interestingly, the scattering rate is nearly constant at low velocities, peaks at a velocity v_σ, and declines sharply at $v > v_\sigma$, allowing it to introduce cores in dwarf galaxies where the velocity dispersion is low ($v \sim 10$ km s^{-1}) but not in clusters of galaxies where the characteristic velocities are larger by two orders of magnitude ($v \sim 10^3$ km s^{-1}). The normalizations of the cross-section and velocity are determined by free parameters in the interaction Lagrangian (see Appendix), with the Compton wavelength of the interaction setting the relevant spatial scale. We show two possible values of the peak velocity, one that would produce cores only in dwarf galaxies ($v_\sigma = 10$ km s^{-1}), and another that would produce cores in more massive galaxies ($v_\sigma = 10^2$ km s^{-1}) as implied by data on low surface brightness galaxies [31]. At any given halo mass, we expect scatter in the core properties of individual halos, due to variations in their age and assembly history.

Having one collision per Hubble time at the characteristic core density of dwarf galaxies $\sim 0.1 M_\odot$ pc^{-3}, translates to the condition $(m_\chi/10{\rm GeV})(m_\phi/100{\rm MeV})^2 \sim 1$ (see Appendix). An order of magnitude larger cross-sections are also allowed by the data. Figure 2 shows the allowed parameter ranges [25] that would naturally explain the dark matter distribution in observed astrophysical objects. We find that even though collisions shape the central profiles of dwarf galaxies, the standard collisionless treatment still provides an excellent approximation for the dark matter dynamics in X-ray clusters.

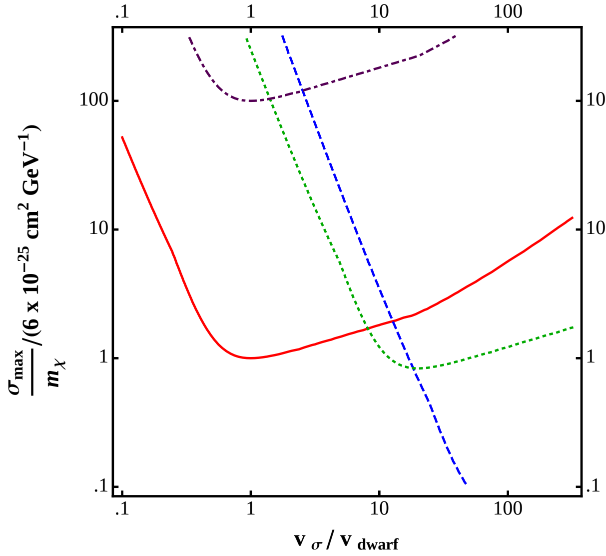

FIG. 2: Astrophysical constraints on the normalization of the self-interaction cross-section ($\sigma_{\max}$) as a function of the velocity at which the peak collision rate is obtained (v_σ) in Fig. 1. The *red solid* line is normalized to have $\langle\sigma\rangle_{max}/m_\chi \approx 6 \times 10^{-25}$ cm^2/GeV at $v_{\rm dwarf} \approx 10$ km s^{-1}, which should be regarded as the minimum interaction necessary to flatten the cores of dwarf galaxies. Additional lines indicate upper limits on the cross-section based on astrophysical considerations: X-ray cluster ellipticity (*blue, dashed*), limiting $(\sigma_{max}/m_\chi) \lesssim 4 \times 10^{-26}$ cm^2/GeV at $v \sim 10^3$km s^{-1}; destruction of dwarf sub-halos through collisions with high velocity particles from a larger parent halo in which these dwarfs are embedded (*green, dotted*), limiting $(\sigma_{max}/m_\chi) \lesssim 5 \times 10^{-25}$ cm^2/GeV [32] at $v \sim 200$km s^{-1}; and requiring the number of scatters in dwarfs to be less than $\sim 10^2$ during the age of the Universe to avoid the gravothermal catastrophe (*purple, dash-dotted*). Related limits are summarized in [25].

Exothermic interactions. The presence of excited states related to a new force has important implications for the properties of dark matter. In particular, upscattering ("inelastic dark matter" (iDM) [33]) or downscattering [34–38] off nuclei can dramatically affect direct detection experiments. Dark matter self scattering into an excited state ("eXciting Dark Matter" (XDM) [39]) has been invoked to explain the excess 511 keV flux observed by INTEGRAL [34, 39–41, 41, 42].

We focus here on the response of dwarf galaxies to the presence of excited states, YIDM*, which we assume are copiously present from the early universe. In particular, the release of kinetic energy in YIDM* collisions would help to evade the gravothermal catastrophe [21], in just the same way that the energy released by primordial stellar binaries weakens core collapse in globular clusters [43].

If excited states exist, then a major fraction of the CDM might be excited when the WIMPS decouple thermally in the early Universe. This excitation could be stable on cosmological times in models where the dark force mixes with electromagnetism [34, 35]. The scattering process can decouple in the early universe at temperatures above the splitting, leaving essentially equal abundances of all states of the dark matter. Alternatively, the excited states could be produced non-thermally. The former scenario tends to require light ($m_\chi \sim$ MeV) particles, while the latter would be more naturally weak-scale. After decoupling, the early CDM dynamics is identical to the standard collisionless model until dwarf galaxies form and the crossing of dark matter streams at low v occurs in their cores, giving rise to self-interactions on a timescale shorter than the age of the Universe.

We denote the velocity imparted to an initially slowly-moving WIMPs ($v < v_{\rm crit}$) upon scattering by $v_{\rm crit} = \sqrt{\delta/m}$. Since the gravitational potential of a dwarf galaxy halo is shallow, sufficiently exothermic collisions could eject colliding particles out of the halo if $v_{\rm crit}$ exceeds the local escape velocity. If $\chi\chi^* \to \chi\chi$ scatterings can occur (see Appendix), then the halo core will lose particles until it reaches a density such that the interaction time is comparable to the age of the halo. Requiring that the final core particles will interact only once over the current age of the Universe yields a final mass density of dark matter,

$$\rho_\chi \sim 0.1 \frac{M_\odot}{\rm pc^3} \left(\frac{\sigma/6\times10^{-25}{\rm cm}^2}{m_\chi/{\rm GeV}}\right)^{-1} \left(\frac{v}{10\ {\rm km\ s}^{-1}}\right)^{-1}. \quad (2)$$

The profile of ρ_χ will then be set by the velocity dependence of $\langle\sigma v\rangle$ and the gravitational potential in a steady state. Below we show that for an exothermic interaction $\langle\sigma v\rangle$ is constant, leading naturally to a constant density core in dwarf galaxies. This model predicts that dwarf galaxies of a similar age should have a similar core density, in agreement with interpretations of data for the nearest dwarf galaxies [44].

If the characteristic scattering velocity is much higher than $v_{\rm crit}$, the process is essentially elastic and one can employ Eq. (1). On the other hand, if the process is highly exothermic then the scattering rate is given simply by $\sigma v = 2\pi v_{\rm crit}\alpha_d^2/m_\phi^4$ for $m_\chi\delta < m_\phi^2$ (assuming the scattering process is still perturbative, i.e. $\beta < 1$). The resulting velocity-independent σv would naturally produce cores with a flat density profile in dwarf galaxies.

The density flattening in dwarf galaxies does not imply the same upper limit on the dark matter density in all its cusps. For massive halos, the release of excess kinetic energy by collisions has a marginal significance, since it only perturbs the low-velocity tail of the CDM distribution function and adds a negligible energy at high relative velocities where the majority of particles have a low interaction rate anyway.

The evaporation of exothermic YIDM* from dwarf galaxies with a gravitational binding energy below the energy released in collisions could potentially account for the deficit in the observed abundance of dwarf galaxies relative to theoretical CDM expectations [45]. Numerical simulations are necessary to reliably quantify this important effect. Also, dark matter halos which accrete cold gas at early times but evaporate at late time might leave behind a star cluster with little dark matter. If so, some old globular clusters [46] might be the sought-after remnants of the missing dwarf galaxies in the Milky Way halo.

Evolution with redshift. The primordial density perturbations are modified by WIMP scatterings, but for $m_\chi \gtrsim$ GeV this modification ends well before observable modes enter the horizon, leaving the standard nearly scale-invariant power-spectrum of density perturbations. The imprint of collisions on the density profile of halos is expected to evolve with redshift, because at earlier cosmic times halos are denser and younger. A halo of mass M collapsing at a redshift $z \gg 1$ has a characteristic virial radius [47],

$$r_{\rm vir} = 1.5 \left(\frac{M}{10^8 M_\odot}\right)^{1/3} \left(\frac{1+z}{10}\right)^{-1} \ {\rm kpc}\ , \qquad (3)$$

a corresponding circular velocity,

$$V_{\rm vir} = 17.0 \left(\frac{M}{10^8 M_\odot}\right)^{1/3} \left(\frac{1+z}{10}\right)^{1/2} \ {\rm km\ s^{-1}}\ , \qquad (4)$$

and an age limit of ~ 0.5 Gyr$[(1+z)/10]^{-3/2}$. It would be particularly interesting to explore the formation of the first galaxies using numerical simulations of the YIDM model. Deviations from the standard CDM predictions could be tested by upcoming galaxy surveys or 21-cm observations of the high-redshift Universe [47, 48]. For example, the scaling $\sigma \propto v^{-4}$ might not be allowed to continue to arbitrarily low velocities, as this would have delayed reionization beyond observational constraints [49].

Discussion. We have shown that a Yukawa potential interaction of dark matter can explain the recent data on dark matter cores in dwarf galaxies [4, 7], while evading the many constraints previously considered for SIDM. The new ingredients of the YIDM model involve the nontrivial velocity dependence of the scattering rate and the possibility of exothermic interactions.

The velocity dependence of the cross-section does not have a simple power-law form, as invoked previously [20, 32]. The presence of a plateau with a sharp cut-off in the scattering rate of YIDM allows the interaction to be effective for dwarf galaxies while being entirely suppressed at high velocities relevant for cluster cores and the evaporation of small sub-halos within bigger halos. At the same time, it does not rise indefinitely at low velocities and thus avoid other concerns [32].

Excited states naturally accompany a dark force and introduce a qualitatively new ingredient: the possibility of energy release. In deep gravitational potentials the scatterings will be similar to the standard elastic case, whereas in shallow gravitational potentials a single scatter can eject the colliding dark matter particles from the halo. Exothermic interactions drive dwarf halos to constant density cores. Moreover, for the earliest forming halos with the highest dark matter density, it is possible that the dark matter would evaporate at later times, leaving behind baryonically-dominated stellar clusters such as the oldest globular clusters.

Unlike SIDM with a single parameter of σ/m_χ, YIDM has a broader parameter space. Out of the possible combinations of the underlying particle physics parameters $(\alpha, \delta, m_\chi, m_\phi)$, only three affect the properties of halos: the cross-section $\sigma_{\rm max}$ and velocity v_σ at which the scattering rate $\langle \sigma v \rangle$ peaks; and in the YIDM* scenario there is the additional parameter of the velocity imparted to a particle undergoing an exothermic scattering, $v_{\rm crit}$.

Since halos form hierarchically and the coarse-grained phase-space density can only decrease through their mergers (Liouville's theorem), the development of a core in dwarf galaxies would trim the central cusp in bigger halos as well. Numerical simulations are required to quantify the average behavior as well as the scatter in the core properties of halos as a function of mass and redshift.

Finally, we note that the similarity between the required self-interaction cross-section per unit mass of the dark matter and baryons may indicate a deep underlying relationship between these components.

Appendix: Particle Physics Implications

Although a thorough investigation of the particle physics parameter space is beyond our scope here, it is worthwhile to at least briefly consider the range of parameter space available to us. As mentioned, the mediator of the force ϕ could be either a scalar or a vector, since magnetic-type interactions are negligible. Simple perturbative realizations of dark forces involve models with an additional boson ϕ_μ of a small mass $m_\phi \lesssim$ GeV. We can assume that the WIMPs are charged under a new $U(1)_{\rm dark}$ symmetry and allow the possibility of a small splitting between their Majorana states, leading to the Lagrangian,

$$\begin{aligned}\mathcal{L} = \bar{\chi}\, \not{D} \chi \ + \ \frac{1}{4} F^d_{\mu\nu} F^{d\mu\nu} + \epsilon F_{\mu\nu} F^{d\mu\nu} + m_\phi^2 \phi_\mu \phi^\mu \\ + \ m_\chi^2 \bar{\chi}\chi + \delta \chi\chi. \qquad (5)\end{aligned}$$

This can be trivially generalized to a non-Abelian model with multiple excited states [22, 50], which induces splittings between the states radiatively at order $\alpha_d m_\phi$, where α_d is the fine structure constant of the dark force. Similarly, the force can arise through a scalar exchange with the additional terms

$$\mathcal{L} \supset y \bar{\chi}\chi\phi \ + \ \partial_\mu \phi \partial^\mu \phi^* + m_\phi^2 \phi^* \phi. \qquad (6)$$

Here, the effective coupling constant $\alpha_d = y^2/4\pi$. Elastic scatterings can arise for both scalar and vector, while inelastic scatterings are most natural in the gauged case. We begin by focusing on the elastic scattering scenario.

The natural mass scale that determines the maximum momentum transfer cross section is m_ϕ. For large values of $0.1 \lesssim \beta \lesssim 10^3$ (above which the cross section in galaxy clusters is $\gtrsim 10^{-3}$ that in dwarf galaxies), Eq. (1) yields $\langle\sigma\rangle \approx (16\pi/m_\phi^2)\beta^2/(2+3\beta^{1.65})$. Requiring a cross section/mass of $6\times10^{-25}\mathrm{cm}^2\ \mathrm{GeV}^{-1}$ then implies $m_\chi m_\phi^2 = 3\times10^{-2}\beta^2/(2+3\beta^{1.65})\ \mathrm{GeV}^3$. Thus, for $m_\chi = 10\,(10^3)\,\mathrm{GeV}$, one has $m_\phi < 10^2\,(10)\,\mathrm{MeV}$. For standard WIMPs interacting through weak scale forces, such phenomena do not occur; however, for dark matter augmented by light dark forces it is possible. For lighter ($\sim$ GeV) WIMPs, a quantum calculation should be used to generate the precise quantitative results. The relevant mass range for ϕ is not surprising in light of the relatively weak constraints from galactic dynamics found by recent studies [24, 25].

Adopting $\beta = \beta_{\rm dwarf}$ in a typical dwarf galaxy implies through the above relation, $\alpha_d \approx 10^{-7}(m_\chi/\mathrm{GeV})^{3/2}\sqrt{3\beta_{\rm dwarf}^{1.65}/2+1}$. The dependence on $\beta_{\rm dwarf}$ and m_χ allows a wide range of values, $10^{-5} \lesssim \alpha_d \lesssim 1$, with the low end for $\beta_{\rm dwarf}\sim 1$ and $m_\chi \sim 10\mathrm{GeV}$, and the high end for $\beta_{\rm dwarf}\sim 10^3$ and $m_\chi \sim 10^3\mathrm{GeV}$.

Although α_d can in principle have any value in the above range, experience in the standard model suggests that gauge fields have coupling constants $\alpha_d \gtrsim 10^{-3}$, while forces arising from scalar exchange could have a much wider range (down to $y^2/4\pi \sim 10^{-12}$). Thus, it is instructive to consider whether we have any additional constraints from cosmology. One possible assumption is that the dark matter is a thermal relic. This is a strong assumption, with compelling alternative models of asymmetric dark matter that relate the dark matter density to the baryon asymmetry (see, e.g. Refs. [51–56]), but it is nevertheless a general category worth examining.

The basic requirement of a thermal relic is that the average annihilation cross section $\langle\sigma_{\rm ann}v\rangle \approx 3\times10^{-26}\mathrm{cm}^3\ \mathrm{s}^{-1}$ at decoupling. Annihilation into new bosons is characterized by a rate constant $\langle\sigma_{\rm ann}v\rangle \approx \pi\alpha^2/m_\chi^2$, but it is important to recognize that there can be many additional annihilation channels into other charged states or even into other force carriers that simply happen not to be the dominant contributors to present-day scattering. Thus, this should be properly taken as a upper bound on α_d. Thus, all but the largest values of α_d are acceptable from the perspective of thermal freezeout, which would require a primordial asymmetry.

It is important to emphasize that for our purposes, it is the lightest mediator that will set the characteristic scattering scale, not necessarily the one with the largest coupling constant, simply because of the saturation that sets in at low velocities. Thus, it could well be that the underlying Lagrangian is described by a gauge theory, spontaneously broken by a Higgs field, and the light Higgs through a small Yukawa ϕ could mediate the self-interaction, even if the gauge interaction is mediated by a field too heavy to induce CDM scatterings.

For the exothermic scenario, the parameter range for dark matter mass is much narrower. We can determine this range by requiring that the scattering in the early universe had ceased by the time the CDM had reached a low enough temperature to thermally deplete the excited states through the same size cross section that is relevant today, i.e.

$$\rho_\chi \frac{\langle\sigma v\rangle}{m_\chi} \lesssim 3H, \tag{7}$$

after the time at which $v_\chi < v_{\rm dwarf} \approx 10\ \mathrm{km\,s}^{-1}$ (where H is the Hubble parameter). The temperature T_χ at which the WIMPs slow down to the speed in current dwarf galaxies is determined by the temperature $T_{\rm dec}$ at which they decouple from the photon bath, $T_\chi \sim T_\gamma^2/T_{\rm dec}$, where $T_\gamma \sim T_0(1+z)$. Thus, setting $\rho_\chi = \Omega_\chi\rho_{c0}(T_\gamma/T_0)^3$, where ρ_{c0} is the present-day critical density and $H^2 \sim (8\pi G/3)g_* T_\gamma^4$, yields $m_\chi \lesssim m_e \times \mathrm{MeV}/T_{\rm dec}$. Since it would be unnatural to have $T_{\rm dec} \ll m_e$ (as we assume the WIMPs are not charged), this suggests WIMPs in the sub-MeV mass range. In such a case, it would be most natural to have an asymmetric model such as described in Ref. [56].

Another possibility would be that the excited states are produced non-thermally, i.e., a heavier state freezes out and populates the excited states after they are adequately dilute that they cannot down-scatter on themselves until the present day. In this case, our expectation would be for characteristically weak-scale masses in order to have the appropriate relic abundance.

From a model building perspective, such scenarios would most naturally be constructed within non-Abelian gauge theories. This is because for Abelian gauge theories, the scattering always changes the number of excited states by a multiple of two, i.e., $11 \Longleftrightarrow 22$ and $12 \Longleftrightarrow 21$. This suggests that it will be difficult to inelastically scatter the 1 states. However, in the case of a non-Abelian theory, more states, and thus more scattering possibilities, are present. For instance, $13 \Longrightarrow 22$ would allow an exothermic scattering for even ground-state particles.

In summary, there is a significant but nonetheless constrained range of parameters which could yield the YIDM and YIDM* phenomenology. We leave detailed model building for future work.

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