Cores in Dwarf Galaxies from Dark Matter with a Yukawa Self-Interaction

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We show that a Yukawa interaction among cold dark matter particles 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. The similarity between the required self-interaction cross-section per unity mass of dark matter to that baryons may indicate an underlying relationship between these dominant components of cosmic matter.

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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 dwarf galaxies indicates that their dark matter distribution has a core in contrast to the cusped profile expected from collisionless CDM simulations [2]. The mean value of the logarithmic inner slope of the mass density profile in seven dwarf galaxies is observed to be -0.29 ± 0.07 [3], much shallower than the expected slope of ~ -1 from pure CDM simulations. The latest data agree with earlier studies of the dynamics of individual cases, such as Fornax [4], Ursa-Minor [5], and Sculptor [6], in which a characteristic core density of $\sim 0.1 \pm 0.05 M_\odot$ pc^{-3} $= (7 \pm 4) \times 10^{-24}$ g cm^{-3} was inferred. Since these dwarf galaxies are dominated by dark matter throughout, it is challenging to explain the inferred cores by the gravitational interaction of the dark matter with the baryons [7]. Although it is conceivable that strong gas outflows from an early baryon-dominated nucleus would reduce the central dark matter density [8], the formation of this baryonic nucleus would initially compress the CDM [9] and exacerbate the discrepancy that needs to be resolved.

To alleviate early signs of the above discrepancy, Spergel & Steinhardt [10] adopted the Strongly-Interacting Dark Matter (SIDM) model [11] 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 core 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 they are shallow and spherical [12, 13]; *(ii)* relaxation of the core ultimately generates an even denser cusp after many collision times due to the gravothermal catastrophe, familiar from core collapse of globular clusters [14], although this evolution might take more than the Hubble time; and *(iii)* 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". In particular, it was realized theoretically 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 exo- and endo-thermic, respectively) naturally introduces yet another scale into the problem, set by the energy splitting δ between the states.

In this *Letter*, we show that a Yukawa self-force for the dark matter would naturally produce cores in dwarf galaxies where the velocity dispersion is low but not affect halos with a much larger velocity dispersions, 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. We label our model as Yukawa-Interacting Dark Matter (YIDM).

Dark Forces. The simplest perturbative realizations of dark forces involve models with an additional gauge boson ϕ_μ with a mass m_ϕ. We assume that the WIMPs are charged under a new $U(1)_{dark}$ with gauge field ϕ_μ, then add a small $\lesssim$ GeV mass to the gauge boson, and maintain the possibility of a small splitting δ between the Majorana states for the WIMPs. This leads to the Lagrangian,

$$\mathcal{L} = \bar{\chi}\, \not{D}\chi \;+\; \frac{1}{4}F^{d}_{\mu\nu}F^{d\mu\nu} + \epsilon F_{\mu\nu}F^{d\mu\nu} + m^2\phi_\mu\phi^\mu \\ +\; M\bar{\chi}\chi + \delta\chi\chi. \tag{1}$$

This model can be trivially generalized to a non-Abelian model with multiple excited states, which induces the splittings between the states radiatively, at order $\alpha_D m_\phi$.

The 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, which is well fit by a cross-section

$$\sigma \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2\ln(1+\beta^{-1}), & \beta < 0.1, \\ \frac{8\pi}{m_\phi^2}\beta^2/(1+1.5\beta^{1.65}), & 0.1 \le \beta \le 1000, \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 1000, \end{cases} \tag{2}$$

where $\beta = 2\alpha_D m_\phi/(m_\chi v_{\rm rel}^2)$, and $v_{\rm rel}$ is the relative velocity of the particles. This expression can be generalized to the inelastic case by substituting $m_\phi \rightarrow \sqrt{m_\chi\delta}$ as the characteristic minimum momentum transfer. Figure 1 depicts the velocity dependence of the elastic cross-section in Eq. (2). Interestingly, the scattering rate peaks over a limited range of velocities and declines sharply at higher velocities, allowing it to introduce cores in dwarf galaxies where the velocity dispersion is low ($v_{\rm rel} \sim 10$ km s^{-1}) but not in clusters of galaxies where the characteristic velocities are larger by two orders of magnitude ($v_{\rm rel} \sim 10^3\ |rmkm\ s^{-1}$). The normalizations of the cross-section and velocity are set by the free parameters of the interaction Lagrangian in Eq. (1). Figure 2 shows the regimes of these parameters that would naturally explain the dark matter distribution in observed astrophysical objects. We find that if 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.

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FIG. 1: Dependence of the self-interaction cross-section (σ) on the relative velocity ($v_{\rm rel}$) for dark matter interacting through a Yukawa potential. The normalizations of σ and $v_{\rm rel}$ are set by the free parameters of the Lagrangian in Eq. (1).

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FIG. 2: Astrophysical constraints on the normalizations of the self-interaction cross-section (σ) as a function of the relative velocity ($v_{\rm rel}$) in Fig. 1.

Exothermic interaction. The response of dwarf galaxies to the presence of YIDM can be enhanced in the presence of the excited states. In particular, the release of kinetic energy in YIDM collisions would help to evade the gravothermal catastrophe [14] on arbitrary timescales, in just the same way that the energy released by primordial stellar binaries weakens core collapse in globular clusters [15].

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, one can imagine a non-Abelian model where the processes $22 \Longrightarrow 11$, $33 \Longrightarrow 11$, but most importantly $13 \Longrightarrow 22$, would all be exothermic with comparable cross-sections. Thus, in a non-Abelian model, all WIMPs can scatter in an exothermic process.

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. Hence, the early dynamics of CDM will be identical to the standard collisionless model until dwarf galaxies form and the crossing of dark matter streams at low $v_{\rm rel}$ occurs in their cores, giving rise to self-interactions on a timescale shorter than the age of the Universe. Since the gravitational potential of a dwarf galaxy halo is shallow, sufficiently exothermic collisions could eject colliding particles out of the halo. The halo core will lose particles until it reaches a density such that the interaction time is comparable to the age of the galaxy. 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,

$$\rho_\chi \;=\; \frac{H_0^{-1}}{\langle\sigma v_{\rm rel}\rangle/m_\chi} \approx 10^{-24}\ {\rm g\ cm}^{-3} \\ \times\; \left(\frac{\langle\sigma v_{\rm rel}\rangle/m_\chi}{10^{-24}{\rm cm}^2 \times 10\ {\rm km\ s}^{-1}\ /{\rm GeV}}\right). \tag{3}$$

The profile of ρ_χ will then be set by the velocity dependence of $\langle\sigma v_{\rm rel}\rangle$ 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 have a similar core density, in agreement with observations of the local Universe [16].

In the perturbative regime of $\alpha_D/(v_{\rm rel}/c) \ll 1$, we may derive analytically the velocity dependence of the inelastic cross-section. We assume the energy transfer is given by δ, which is positive for exothermic scatterings in which the outgoing WIMPs have a final relative velocity,

$$v_r = \sqrt{v_{\rm rel}^2 + \delta/m_\chi}. \tag{4}$$

We define $\epsilon_\delta = \delta/m_\chi v_{\rm rel}^2$, so that $\epsilon_\delta \ll 1$ means a highly elastic scattering and $\epsilon_\delta \gg 1$ means a highly inelastic scattering.

For a scattering angle θ, the differential cross section

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{4m_\chi^2 v_{\rm rel}} \frac{m_\chi v_r}{16\pi m_\chi} |M|^2, \quad (5)$$

involves the Matrix element,

$$|M|^2 = \frac{8g_d^4 m_\chi^4}{max\{m_\phi^4, m_\chi^2\delta^2, q^4\}}. \quad (6)$$

In the regime where the characteristic scale in the propagator is q^4 (i.e., the inelasticity is irrelevant and the momentum is larger than m_ϕ), one finds the usual Rutherford scattering (which was considered non-perturbatively above). Otherwise, one gets

$$\sigma v_{\rm rel} = C_0\sqrt{|v_{\rm rel}^2 - \delta/m_\chi|}. \quad (7)$$

Thus, if the system is dominantly elastic (i.e., $\epsilon_\delta \ll 1$) then $\sigma v_{\rm rel} \simeq C\ _0 v_{\rm rel}$, providing the standard regime explored in previous models of SIDM. However, in the deep *inelastic* and exothermic regime, one finds

$$\sigma v_{\rm rel} = C_0\sqrt{\delta/m_\chi}. \quad (8)$$

The resulting velocity-independent collision rate would naturally produce cores with a flat density profile in dwarf galaxies.

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

The evaporation of exothermic YIDM from dwarf galaxies (with a gravitational binding energy below the energy released in YIDM collisions) could potentially account for the deficit in observed dwarf galaxies relative to theoretical CDM expectations [17]. Numerical simulations are necessary to reliably quantify this important effect.

Evolution with redshift. 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 collapsing at a redshift $z \gg 1$, has a characteristic virial radius,

$$r_{\rm vir} = 1.5\left(\frac{M}{10^8 M_\odot}\right)^{1/3}\left(\frac{1+z}{10}\right)^{-1} \text{ kpc}\ , \quad (9)$$

a corresponding circular velocity,

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

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 [18, 19].

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. Such a relation might also explain the coincidence between the cosmic mass densities of these two dominant components.

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