

SIMPlE Dark Matter: Self-Interactions and keV Lines

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We consider a simple supersymmetric hidden sector: pure $SU(N)$ gauge theory. Dark matter is made up of hidden glueballinos with mass m_X and hidden glueballs with mass near the confinement scale Λ . For $m_X \sim 1$ TeV and $\Lambda \sim 100$ MeV, the glueballinos freeze out with the correct relic density and self-interact through glueball exchange to resolve small-scale structure puzzles. An immediate consequence is that the glueballino spectrum has a hyperfine splitting of order $\Lambda^2/m_X \sim 10$ keV. We show that the radiative decays of the excited state can explain the observed 3.5 keV X-ray line signal from clusters of galaxies, Andromeda, and the Milky Way.

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Introduction. The field of particle dark matter is at an interesting juncture. Direct, indirect, and collider searches for dark matter are improving rapidly, but have not yet yielded unambiguous signals. At the same time, the astrophysical evidence for dark matter with $\Omega_{\text{DM}} h^2 = 0.1196 \pm 0.0031$ [1] remains as strong as ever, and there are now tantalizing astrophysical indications that dark matter may be self-interacting [2–5] or the source of an observed 3.5 keV X-ray line from galaxies and clusters of galaxies [6, 7]. Self-interactions and the 3.5 keV line have each merited a great deal of attention, although typically separately, without any attempt to relate them in a simple framework.

Given the existing evidence for dark matter, a natural possibility is that dark matter is in a hidden sector, composed of particles with no standard model gauge interactions [8]. In general, hidden sectors are decoupled from most of particle physics, both in terms of their theoretical motivations and their testable predictions. In the framework of supersymmetry, however, hidden sectors may emerge from more fundamental theories and contain particles that have the desired thermal relic density through the WIMPless miracle [9–13]. Although much of our analysis below will be independent of supersymmetry, the possibility of preserving this fundamental feature of WIMPs is a significant virtue, and for concreteness, we will consider hidden sectors with supersymmetry.

Here we consider the simplest possible UV-complete supersymmetric hidden sector: a pure $SU(N)$ gauge theory. This sector introduces only two new particles: gluons g and gluinos \tilde{g} , which hadronize into glueballs $G \equiv (gg)$ and glueballinos $\tilde{G} \equiv (\tilde{g}g)$. Throughout this work, references to color, gluons, gluinos, and their composite states refer to the hidden sector. For other work on strongly-interacting dark matter, see Refs. [14–27].

We find that this simple hidden sector may explain all of the above-noted astrophysical observations. For gluino mass $m_X \sim \text{TeV}$ and glueball mass near the confinement scale $\Lambda \sim 100$ MeV, glueballinos have both the correct

relic density and self-interaction cross section to resolve small-scale structure puzzles [25]. These considerations fix the glueballino spectrum’s hyperfine splitting $\Delta E = m_{\tilde{G}^*} - m_{\tilde{G}} \sim \Lambda^2/m_X \sim 10$ keV. Introducing connector fields that couple the hidden and visible sectors, we find that radiative decays $\tilde{G}^* \rightarrow \tilde{G}\gamma$ may have the energy and flux required to explain the observed X-ray line signals in both “short lifetime” and “long lifetime” scenarios.

Glueballino Relic Density and Reannihilation. The supersymmetric pure $SU(N)$ hidden sector may be completely characterized by the four parameters

$$m_X, \Lambda, N, \xi_f, \quad (1)$$

which are the gluino mass, the confinement scale, the number of colors, and the ratio of hidden to visible sector temperatures at gluino freezeout, respectively. In terms of these parameters, the fine-structure constant at the scale m_X is given by the renormalization group relation

$$\alpha_X = \frac{6\pi}{11N \ln(m_X/\Lambda)}. \quad (2)$$

Gluinos freeze out with relic density [10]

$$\Omega_{\tilde{g}} \approx \frac{s_0}{\rho_{c0}} \frac{\sqrt{g_*^{\text{tot}}}}{g_{*S}(T_f)} \frac{3.79 x_f}{M_{\text{Pl}} \langle \sigma v \rangle}, \quad (3)$$

where s_0 is the visible sector entropy today, ρ_{c0} is the critical density today, $g_{*S}(T_f)$ is the entropy effective number of degrees of freedom in the visible sector at freezeout, $g_*^{\text{tot}}(T_f) = g_*(T_f) + \xi_f^4 2(N^2 - 1)$, $M_{\text{Pl}} \simeq 1.2 \times 10^{19}$ GeV, and $x_f \equiv m_X/T_f \approx 25\xi_f$. The gluinos annihilate through the S -wave process $\tilde{g}\tilde{g} \rightarrow gg$ with cross section

$$\langle \sigma v \rangle = \frac{3}{8} \frac{N^2}{N^2 - 1} \frac{\pi \alpha_X^2}{m_X^2}. \quad (4)$$

When the Universe cools to a temperature below Λ , the gluinos and gluons hadronize into glueballinos and

glueballs. The glueballinos then interact with an enhanced geometric cross section $\sim \Lambda^{-2}$, which may initiate an era of reannihilation, depleting the gluino relic density. However, the glueballinos typically form in a state with high angular momentum L [14]. For the constituent gluinos to annihilate, this bound state must first decay to a low- L state by radiating glueballs. (Note that there are no hidden light pions or photons.) Reannihilation therefore requires $\alpha_X^2 m_X \gtrsim N_G \Lambda$, where N_G is the number of glueballs radiated. N_G is at least 1. More typically, it is the angular momentum of the bound state $N_G \sim L \sim m_X v r \sim m_X \sqrt{\Lambda/m_X} \Lambda^{-1}$. Below, we will therefore exclude regions where $\alpha_X^2 \gtrsim \sqrt{\Lambda/m_X}$, and reannihilation may be significant. Note that this constraint may be overly stringent, since glueballs will readily break apart high- L bound states.

Glueball Relic Density and Cannibalization. After gluinos freeze out, the gluons maintain thermal equilibrium. Upon confinement, the gluon energy density becomes the glueball energy density [25]

$$\Omega_G \approx \frac{s_0}{\rho_{c0}} \frac{2(N^2 - 1)}{g_{*S}(T_f)} \xi_f^3 \times \begin{cases} T_d^h & \text{for } T_d^h < \Lambda \\ \Lambda & \text{otherwise,} \end{cases} \quad (5)$$

where T_d^h is the hidden sector temperature at the time of chemical decoupling. Equation (5) may be understood as follows: In the absence of self-interactions, the glueballs decouple early, and the relic density is simply the thermal number density multiplied by the glueball mass $\sim \Lambda$. With significant self-interactions, however, the glueballs may remain in chemical equilibrium even after the temperature drops below Λ through, for example, $3 \rightarrow 2$ number-changing processes. This depletion of glueball number is referred to as cannibalization [28]. Eventually, the expansion of the Universe causes the glueballs to decouple at a temperature T_d^h , and entropy and glueball number conservation after decoupling imply that $\Omega_G \propto T_d^h$. We have numerically solved for the glueball density accounting for cannibalization, following Ref. [28], and find that cannibalization reduces Ω_G by less than a factor of two in the parameter range of interest.

It is also possible to eliminate the glueball relic density altogether by postulating additional interactions with the visible sector. For example, before confinement, gluons may annihilate to sterile neutrinos, which quickly decay to light visible sector particles before they can annihilate back into gluons [25]. We will consider cases in which the glueball relic density is given by Eq. (5), and also those in which glueballs are effectively absent.

Self-Interactions. Discrepancies between simulations and observations on small scales may be resolved if dark matter self-interacts with cross section-to-mass ratio $\sigma/m \sim 1 \text{ cm}^2/\text{g} \sim 1 \text{ barn}/\text{GeV}$. To determine the self-interactions of glueballs and glueballinos, we follow the analysis of Ref. [25], which we summarize here.

For glueballs, we take the geometric cross section $\sigma_G = 4\pi/\Lambda^2$, which is of the desired size for $\Lambda \sim 100 \text{ MeV}$.

Glueballino self-interactions are mediated by glueball exchange, which we model as an attractive Yukawa potential $V(r) = -e^{-\Lambda r}/r$. The self-interaction cross section $\sigma_{\tilde{G}}$ is $\langle \sigma_T \rangle$, the transfer cross section $\sigma_T = \int d\Omega (1 - \cos\theta)(d\sigma/d\Omega)$, averaged over Maxwell-Boltzmann velocity distributions with characteristic velocities $v_0 = 40, 100, \text{ and } 1000 \text{ km/s}$ for dwarf galaxies, LSBs, and clusters, respectively. For $m_X \sim \text{TeV}$, $\Lambda \sim 10 \text{ MeV}$ gives the desired self-interactions.

The case of mixed glueballino-glueball dark matter is much more complicated. As a very simple measure in this general case, we define

$$\sigma/m = \frac{\sigma_{\tilde{G}}}{m_X} \frac{\Omega_{\tilde{G}}}{\Omega_{\text{DM}}} + \frac{\sigma_G}{\Lambda} \frac{\Omega_G}{\Omega_{\text{DM}}}, \quad (6)$$

which has the correct behavior in the limits of pure \tilde{G} or pure G dark matter and interpolates between them.

Glueballino Hyperfine Structure and Transitions. There are two S -wave glueballino states: the spin-1/2 ground state \tilde{G} and the spin-3/2 excited state \tilde{G}^* [29]. In the case of atomic hydrogen, the hyperfine splitting created by the electromagnetic interactions is $\sim \alpha_{\text{EM}}^4 m_e^2/m_p$. In the present case, we expect the hidden chromomagnetic interactions to yield hyperfine splittings

$$\Delta E = m_{\tilde{G}^*} - m_{\tilde{G}} = c_E \Lambda^2/m_X, \quad (7)$$

with $c_E \sim 1$ an order one coefficient that depends on the strong dynamics. Lattice results for the hyperfine splittings of B mesons [30] suggest $c_E \approx 5$ for those systems.

In the absence of other interactions, the \tilde{G}^* state is stable. To make contact with the X-ray observations, we introduce a connector field with mass m_C and both hidden color and visible electromagnetic quantum numbers. Dipole operators vanish, since the gluino is a Majorana fermion. But one-loop diagrams with virtual heavy connectors induce at leading order the Kähler potential term

$$c_\tau \frac{1}{m_C^3} \int d^4\theta W_\alpha^h W^\alpha \bar{D}^{\dot{\alpha}} \bar{W}_{\dot{\alpha}}^h \bar{S}. \quad (8)$$

This leads to the dimension-6 interaction

$$c_\tau \frac{m}{m_C^3} \bar{g} \gamma^\mu D^\nu \tilde{g} F_{\mu\nu}, \quad (9)$$

where W^h (W) is the hidden (visible) gauge superfield, F is the visible electromagnetic field strength, $\langle S \rangle = \tilde{m} \theta^2$ is a spurion representing the influence of supersymmetry breaking, and c_τ is a dimensionless coefficient, which we estimate to be $c_\tau \sim e\alpha_h/(4\pi)$. At the hadronic level, this mediates the decay $\tilde{G}^* \rightarrow \tilde{G} \gamma$ with lifetime

$$\begin{aligned} \tau &\sim \frac{32\pi^2}{\alpha_{\text{EM}} \alpha_h^2} \frac{m_C^6}{\tilde{m}^2 \Lambda^2 \Delta E^3} \sim 6.2 \times 10^{14} \text{ s} \\ &\times \left[\frac{0.01}{\alpha_h} \right]^2 \left[\frac{m_C}{\text{TeV}} \right]^6 \left[\frac{\text{TeV}}{\tilde{m}} \right]^2 \left[\frac{100 \text{ MeV}}{\Lambda} \right]^2 \left[\frac{3.5 \text{ keV}}{\Delta E} \right]^3, \end{aligned} \quad (10)$$

TABLE I: 3.5 keV line fluxes and cored halo parameters.

	Flux $10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$	J $\text{kpc GeV}^2/\text{cm}^6$	Σ $\text{kpc GeV}/\text{cm}^3$
Perseus	$21.4_{-6.3}^{+7.0}$ [6]	2.3	20
M31	$4.9_{-1.3}^{+1.6}$ [7]	8.2	13
MW	29 ± 5 [31]	41	37

where $m_X \lesssim \tilde{m} \lesssim m_C$. Decays to neutrinos or multiple photons are also possible, but will be suppressed by additional powers of m_C and phase space.

The 3.5 keV Line. The stacked XMM-Newton spectrum of 73 clusters of galaxies has revealed a weak X-ray line at 3.55 – 3.57 keV [6]. The line is also seen in the Perseus cluster by both XMM-Newton and Chandra [6, 7], in the stacking of Centaurus, Ophiuchus and Coma, and in the stacking of all clusters except these four [6]. A line close to this energy is also seen towards the Andromeda galaxy (M31) [7] and the center of the Milky Way (MW) [31]. The measured fluxes by XMM-Newton from Perseus (without the core), M31, and the MW are shown in Table I. The initial analyses have motivated a great deal of follow-up activity, including supporting evidence, null results, and proposed explanations in terms of line emission from ions [32–36].

Here we consider the possibility that this line is a signal from the de-excitation of dark matter. There are two limiting scenarios. In the “short lifetime” scenario, the \tilde{G}^* lifetime is $\tau \lesssim 10^{15}$ s. \tilde{G}^* states are created in inelastic collisions $\tilde{G}\tilde{G} \rightarrow \tilde{G}\tilde{G}^*$ and then decay. The signal is a dark matter analogue to the 21 cm line of neutral hydrogen [37–39] and is proportional to ρ^2 , where ρ is the dark matter mass density. The predicted flux is

$$F_{\text{short}} = \frac{\langle \sigma_{\tilde{G}^*} v \rangle}{8\pi m_X^2} \langle \int \rho^2 d\ell \rangle_{\text{FOV}} \text{FOV} = \frac{1.1 \times 10^{-3}}{\text{cm}^2 \text{ s}} \quad (11)$$

$$\times \left[\frac{\text{TeV}}{m_X} \right] \left[\frac{\langle \sigma_{\tilde{G}^*} v / c \rangle / m_X}{10^{-3} \text{ barn/GeV}} \right] \left[\frac{J}{\text{kpc GeV}^2/\text{cm}^6} \right] \left[\frac{\text{FOV}}{\text{deg}^2} \right],$$

where the integral is along the line of sight, FOV is the field of view of the measurement, $J \equiv \langle \int \rho^2 d\ell \rangle_{\text{FOV}}$ is an average over this FOV, and $\sigma_{\tilde{G}^*} = \sigma(\tilde{G}\tilde{G} \rightarrow \tilde{G}\tilde{G}^*)$ is the cross section for creating excited states \tilde{G}^* . For $m_X \sim \text{TeV}$, the kinetic energy in $\tilde{G}\tilde{G}$ scattering is typically large compared to the hyperfine splitting. We therefore expect the inelastic and elastic cross sections to be similar to each other and to the transfer cross section, as is the case in an atomic dark matter model [40]. It is tantalizing that the indicated cross sections from self-interactions and the 3.5 keV line are roughly similar, despite their being completely disparate phenomena.

Before we determine what values of $\sigma_{\tilde{G}^*}$ are favored, however, we must ask if *any* value of $\sigma_{\tilde{G}^*}$ can explain all the data. To do this, we must determine J for halo profiles that are consistent with self-interacting dark matter

and compare them to the observed fluxes. For the MW and M31, the FOV is a cone with 14’ half-angle. The MW observations are centered on the galactic center. The equilibrium self-interacting dark matter solution [41] requires that the core radius be set by the gravitational potential of the stars, since they dominate at the center. We use a modified NFW profile, $\rho(r) \propto 1/(r+r_c)/(r+r_s)^2$ with $r_s = 21$ kpc and core radius $r_c = 0.5$ kpc, normalized to a local density of 0.4 GeV/cm³ [41]. For M31, we use a similar profile, but with a density at 8.5 kpc of 0.2 GeV/cm³. For Perseus, we compute the flux in a projected radius of 240 kpc using $M_{\text{vir}} = 1.1 \times 10^{15} M_{\odot}$ and a concentration parameter $R_{\text{vir}}/r_s = 6$, which gives rise to the same surface density within 240 kpc as that in Ref. [6]. The resulting J values are given in Table I.

Eq. (11) and the J and flux values of Table I imply

$$\frac{\sigma_{\tilde{G}^*}}{m_X} \sim 0.016 (0.005) [0.006] \frac{\text{barn}}{\text{GeV}} \left[\frac{m_X}{\text{TeV}} \right] \left[\frac{\Omega_{\text{DM}}}{\Omega_{\tilde{G}}} \right]^2, \quad (12)$$

for Perseus (M31) [MW]. Taken at face value, these results are in tension because we expect $\sigma_{\tilde{G}^*}$ to follow $\sigma_{\tilde{G}}$ and be smaller in the clusters due to the larger relative velocities. At the same time, there are considerable uncertainties from halo modeling [38] and line flux measurements. Below, we focus on Perseus for the short lifetime scenario, keeping this tension in mind.

Dwarf spheroidal satellite galaxies of the Milky Way constrain the short lifetime scenario. For most dwarfs, we expect $J \gtrsim (0.1 M_{\odot}/\text{pc}^3)^2 \times 0.6 \text{ kpc} \sim 10 \text{ kpc GeV}^2/\text{cm}^6$, using the observed commonality of halo masses within 300 pc [42]. Using $v/c \sim 10^{-4}$ and $\sigma_{\tilde{G}^*}/m_X = 0.01 \text{ barn/GeV}$, we predict a flux of $2 \times 10^{-6}/\text{cm}^{-2} \text{ s}^{-1}$, about an order of magnitude larger than the stacked dwarf limit [34]. However, for dwarfs and $m_X \sim 100 \text{ GeV} - 1 \text{ TeV}$, the kinetic energy of the collision satisfies $m_X v^2/2 \lesssim \Delta E$, and so a detailed analysis of $\sigma_{\tilde{G}^*}$ is required to predict the flux from dwarfs.

Alternatively, in the “long lifetime” scenario, the \tilde{G}^* lifetime is longer than the age of the Universe, $\tau \gtrsim 10^{18}$ s. The \tilde{G}^* states are created at the time of hadronization, and since the hyperfine splitting is small compared to the temperature at confinement, the number densities of \tilde{G} and \tilde{G}^* are identical at that time. The \tilde{G}^* states then slowly decay, with a signal proportional to ρ and flux

$$F_{\text{long}} = \frac{1}{4\pi m_X \tau} \langle \int \rho d\ell \rangle_{\text{FOV}} \text{FOV} \quad (13)$$

$$= \frac{7.5 \times 10^{-7}}{\text{cm}^2 \text{ s}} \left[\frac{\text{TeV}}{m_X} \right] \left[\frac{10^{20} \text{ s}}{\tau} \right] \left[\frac{\Sigma}{\text{kpc GeV}/\text{cm}^3} \right] \left[\frac{\text{FOV}}{\text{deg}^2} \right],$$

where $\Sigma = \langle \int \rho d\ell \rangle_{\text{FOV}}$ is the surface density. Values of Σ for the halo models described above are given in Table I.

Eq. (13) and the Σ and flux values of Table I imply

$$\tau \sim 200 (500) [300] \text{ Gyr} \left[\frac{\text{TeV}}{m_X} \right] \left[\frac{\Omega_{\tilde{G}^*}}{\frac{1}{2}\Omega_{\text{DM}}} \right], \quad (14)$$

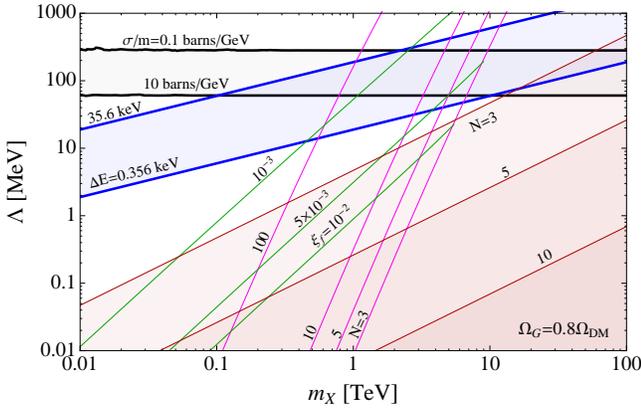


FIG. 1: Thermal SIMPle dark matter with $\Omega_G = 0.8\Omega_{\text{DM}}$ and $\Omega_{\tilde{g}} = 0.2\Omega_{\text{DM}}$. For fixed (m_X, Λ) , N and ξ_f are determined by the relic densities; contours of $N = 3, 5, 10, 100$ and $\xi_f = 10^{-3}, 5 \times 10^{-3}, 10^{-2}$ are shown. In the indicated bands, $\sigma/m = 0.1 - 10$ barn/GeV and $\Delta E = 0.356 - 35.6$ keV. Where these overlap, the model may explain both self-interactions and the 3.5 keV line through long-lifetime \tilde{G}^* decays (see text). In the lower-right shaded regions, \tilde{G} re-annihilation may be significant for the values of N indicated.

for Perseus (M31) [MW]. Given the large systematic uncertainties in the M31 measurement [7], these three signals are consistent in the long lifetime scenario.

We have checked that the required lifetimes are not in conflict with cosmic microwave background observations. Adapting existing constraints on the annihilation cross section of dark matter particles [43] by equating the energy injection rates in the annihilation and decay processes at $z = 1091$, we find $\tau \gtrsim 2 \text{ Myr} [\text{TeV}/m_X][2\Omega_{\tilde{G}^*}/\Omega_{\text{DM}}][\Delta E/3.5 \text{ keV}]$.

Results. We now have all the ingredients to identify viable example models and their observational implications. We begin by considering a completely thermal scenario, in which the gluino and glueball relic densities are given by Eqs. (3) and (5). As an example, we consider the case with $\Omega_G = 0.8\Omega_{\text{DM}}$ and $\Omega_{\tilde{g}} = 0.2\Omega_{\text{DM}}$. The required values of N and ξ_f are shown in the (m_X, Λ) plane in Fig. 1. Relatively cold hidden sectors are required to avoid glueballs overclosing the Universe.

In this glueball-dominated scenario, the self-interaction cross section is essentially σ_G , and so is in the desired range for $\Lambda \sim 100$ MeV. This constraint and the $\Delta E = 3.56$ keV band are also shown in Fig. 1. These bands overlap, for example, at $(m_X, \Lambda) = (3 \text{ TeV}, 70 \text{ MeV})$, where $\alpha_X \approx 0.013$, $N \approx 10$, and $\xi_f \approx 4 \times 10^{-3}$. At this point, $\sigma_{\tilde{G}^*}$ is far too small to explain the keV line flux in the short lifetime scenario. However, the flux can be explained by long-lifetime decays. Equation (14) implies $\tau \sim 30$ Gyr, which, given Eq. (10), implies a connector mass $m_C \sim 4 - 6$ TeV.

We now consider the case where the gluon density is depleted to $\Omega_G \approx 0$ through some mechanism, such as the one of Ref. [25] described above. Glueballs then do

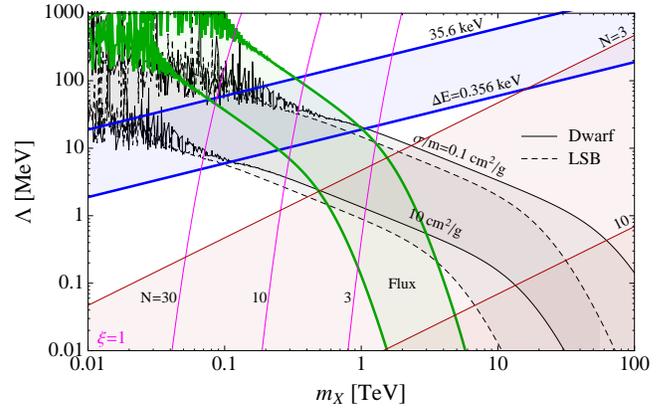


FIG. 2: Pure glueballino SIMPle dark matter with $\xi_f = 1$. For fixed (m_X, Λ) , N is determined by $\Omega_{\tilde{g}} = \Omega_{\text{DM}}$; contours of $N = 3, 10, 30$ are shown. In the indicated bands, $\sigma/m = 0.1 - 10$ barn/GeV, $\Delta E = 0.356 - 35.6$ keV, and short-lifetime \tilde{G}^* decays give a keV line flux within an order of magnitude to explain the Perseus observations, assuming $\sigma_{\tilde{G}^*} = \sigma_{\tilde{G}}$. The flux may also be explained by long-lifetime \tilde{G}^* decays (see text). In the lower-right shaded regions, \tilde{G} re-annihilation may be significant for the values of N indicated.

not overclose the Universe for any ξ_f , and we consider $\xi_f = 1$. The resulting parameters are shown in Fig. 2.

In this pure \tilde{G} scenario, the preferred self-interactions and keV line energy overlap, for example, at $(m_X, \Lambda) = (350 \text{ GeV}, 20 \text{ MeV})$, where $\alpha_X \approx 0.019$ and $N \approx 10$. The keV line flux may again be explained by long-lifetime decays; in this case, Eq. (14) implies $\tau \sim 1000$ Gyr, which, given Eq. (10), implies $m_C \sim 3 - 9$ TeV. In this case, however, the self-interactions also imply a large up-scattering rate, and so the short lifetime scenario is also viable where all three bands overlap in Fig. 2. A lifetime of $\tau \sim 10^{15}$ s implies $m_C \sim 500 - 700$ GeV, which is beyond collider limits on particles that have electric charge, but not strong interactions, in the visible sector.

Conclusions. Currently there are tantalizing astrophysical indications that dark matter may be self-interacting and the source of a 3.5 keV X-ray line. Although neither of the indications for self-interactions and keV lines is unambiguously compelling individually, they are both interesting, and more so if they may be explained simultaneously in a simple model.

We have explored these in the context of a simple hidden sector: a supersymmetric pure $SU(N)$ gauge theory. The astrophysical hints favor $m_X \sim \text{TeV}$ thermal relics interacting with $\Lambda \sim 100$ MeV force carriers, with photons created by transitions between highly degenerate states with $\Delta E \sim 10$ keV. In this model, the qualitative hierarchy $\Delta E \ll \Lambda \ll m_X$ and the quantitative relation $\Delta E m_X \sim \Lambda^2$ are naturally explained by asymptotic freedom and, essentially, atomic physics. Despite its simple formulation, the model has a rich cosmology, with both glueballs and glueballinos contributing to dark matter, and decays that can be either short and long compared

to the age of the Universe. The short lifetime possibility is remarkable in that the desired self-interactions imply a keV line flux roughly in accord with observations, albeit with some tension between the various datasets, while the long lifetime scenario provides a beautifully consistent explanation for the X-ray line observed in clusters of galaxies, M31, and MW observations.

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- [1] **Planck** Collaboration, P. Ade *et al.*, “Planck 2013 results. XVI. Cosmological parameters,” *Astron.Astrophys.* (2014), [arXiv:1303.5076 \[astro-ph.CO\]](#).
- [2] M. Rocha, A. H. G. Peter, J. S. Bullock, M. Kaplinghat, S. Garrison-Kimmel, J. Oñorbe, and L. A. Moustakas, “Cosmological Simulations with Self-Interacting Dark Matter I: Constant Density Cores and Substructure,” *Mon. Not. R. Astron. Soc.* **430** (2013) 81–104, [arXiv:1208.3025 \[astro-ph.CO\]](#).
- [3] A. H. G. Peter, M. Rocha, J. S. Bullock, and M. Kaplinghat, “Cosmological Simulations with Self-Interacting Dark Matter II: Halo Shapes vs. Observations,” *Mon. Not. R. Astron. Soc.* **430** (2013) 105–120, [arXiv:1208.3026 \[astro-ph.CO\]](#).
- [4] M. Vogelsberger, J. Zavala, and A. Loeb, “Subhaloes in Self-Interacting Galactic Dark Matter Haloes,” *Mon. Not. R. Astron. Soc.* **423** (2012) 3740–3752, [arXiv:1201.5892 \[astro-ph.CO\]](#).
- [5] J. Zavala, M. Vogelsberger, and M. G. Walker, “Constraining Self-Interacting Dark Matter with the Milky Way’s Dwarf Spheroidals,” *Mon. Not. R. Astron. Soc.* **431** (2013) L20–L24, [arXiv:1211.6426 \[astro-ph.CO\]](#).
- [6] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, *et al.*, “Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters,” *Astrophys.J.* **789** (2014) 13, [arXiv:1402.2301 \[astro-ph.CO\]](#).
- [7] A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy, and J. Franse, “An Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster,” [arXiv:1402.4119 \[astro-ph.CO\]](#).
- [8] I. Y. Kobsarev, L. B. Okun, and I. Y. Pomeranchuk *Sov. J. Nucl. Phys.* **3** (1966) 837.
- [9] J. L. Feng and J. Kumar, “The WIMPless Miracle: Dark-Matter Particles without Weak-Scale Masses or Weak Interactions,” *Phys.Rev.Lett.* **101** (2008) 231301, [arXiv:0803.4196 \[hep-ph\]](#).
- [10] J. L. Feng, H. Tu, and H.-B. Yu, “Thermal Relics in Hidden Sectors,” *JCAP* **0810** (2008) 043, [arXiv:0808.2318 \[hep-ph\]](#).
- [11] J. L. Feng and Y. Shadmi, “WIMPless Dark Matter from Non-Abelian Hidden Sectors with Anomaly-Mediated Supersymmetry Breaking,” *Phys.Rev.* **D83** (2011) 095011, [arXiv:1102.0282 \[hep-ph\]](#).
- [12] J. L. Feng, V. Rentala, and Z. Surujon, “WIMPless Dark Matter in Anomaly-Mediated Supersymmetry Breaking with Hidden QED,” *Phys.Rev.* **D84** (2011) 095033, [arXiv:1108.4689 \[hep-ph\]](#).
- [13] J. L. Feng, V. Rentala, and Z. Surujon, “WIMPless Dark Matter from an AMSB Hidden Sector with No New Mass Parameters,” *Phys.Rev.* **D85** (2012) 055003, [arXiv:1111.4479 \[hep-ph\]](#).
- [14] J. Kang, M. A. Luty, and S. Nasri, “The Relic abundance of long-lived heavy colored particles,” *JHEP* **0809** (2008) 086, [arXiv:hep-ph/0611322 \[hep-ph\]](#).
- [15] G. D. Kribs, T. S. Roy, J. Terning, and K. M. Zurek, “Quirky Composite Dark Matter,” *Phys.Rev.* **D81** (2010) 095001, [arXiv:0909.2034 \[hep-ph\]](#).
- [16] D. S. Alves, S. R. Behbahani, P. Schuster, and J. G. Wacker, “Composite Inelastic Dark Matter,” *Phys.Lett.* **B692** (2010) 323–326, [arXiv:0903.3945 \[hep-ph\]](#).
- [17] A. Falkowski, J. Juknevich, and J. Shelton, “Dark Matter Through the Neutrino Portal,” [arXiv:0908.1790 \[hep-ph\]](#).
- [18] M. Lisanti and J. G. Wacker, “Parity Violation in Composite Inelastic Dark Matter Models,” *Phys.Rev.* **D82** (2010) 055023, [arXiv:0911.4483 \[hep-ph\]](#).
- [19] D. Spier Moreira Alves, S. R. Behbahani, P. Schuster, and J. G. Wacker, “The Cosmology of Composite Inelastic Dark Matter,” *JHEP* **1006** (2010) 113, [arXiv:1003.4729 \[hep-ph\]](#).
- [20] K. Kumar, A. Menon, and T. M. Tait, “Magnetic Fluffy Dark Matter,” *JHEP* **1202** (2012) 131, [arXiv:1111.2336 \[hep-ph\]](#).
- [21] T. Higaki, K. S. Jeong, and F. Takahashi, “A Parallel World in the Dark,” *JCAP* **1308** (2013) 031, [arXiv:1302.2516 \[hep-ph\]](#).
- [22] M. Heikinheimo, A. Racioppi, M. Raidal, C. Spethmann, and K. Tuominen, “Physical Naturalness and Dynamical Breaking of Classical Scale Invariance,” *Mod.Phys.Lett.* **A29** (2014) 1450077, [arXiv:1304.7006 \[hep-ph\]](#).
- [23] Y. Bai and P. Schwaller, “The Scale of Dark QCD,” *Phys.Rev.* **D89** (2014) 063522, [arXiv:1306.4676 \[hep-ph\]](#).
- [24] J. M. Cline, Z. Liu, G. D. Moore, and W. Xue, “Composite strongly interacting dark matter,” *Phys.Rev.D* **90** (2014) 015023, [arXiv:1312.3325 \[hep-ph\]](#).
- [25] K. K. Boddy, J. L. Feng, M. Kaplinghat, and T. M. P. Tait, “Self-Interacting Dark Matter from a Non-Abelian Hidden Sector,” *Phys.Rev.* **D89** (2014) 115017, [arXiv:1402.3629 \[hep-ph\]](#).
- [26] Y. Hochberg, E. Kuflik, T. Volansky, and J. G. Wacker, “The SIMP Miracle,” [arXiv:1402.5143 \[hep-ph\]](#).
- [27] J. M. Cline and A. R. Frey, “Nonabelian dark matter models for 3.5 keV X-rays,” [arXiv:1408.0233](#)

- [hep-ph].
- [28] E. D. Carlson, M. E. Machacek, and L. J. Hall, “Self-Interacting Dark Matter,” *Astrophys. J.* **398** (1992) 43–52.
- [29] M. S. Chanowitz and S. R. Sharpe, “Spectrum of Gluino Bound States,” *Phys. Lett. B* **126** (1983) 225.
- [30] R. Dowdall, C. Davies, T. Hammant, and R. Horgan, “Precise heavy-light meson masses and hyperfine splittings from lattice QCD including charm quarks in the sea,” *Phys.Rev.* **D86** (2012) 094510, [arXiv:1207.5149 \[hep-lat\]](#).
- [31] A. Boyarsky, J. Franse, D. Iakubovskiy, and O. Ruchayskiy, “Checking the dark matter origin of 3.53 keV line with the Milky Way center,” [arXiv:1408.2503 \[astro-ph.CO\]](#).
- [32] S. Riemer-Sorensen, “Questioning a 3.5 keV dark matter emission line,” [arXiv:1405.7943 \[astro-ph.CO\]](#).
- [33] T. E. Jeltema and S. Profumo, “Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line,” [arXiv:1408.1699 \[astro-ph.HE\]](#).
- [34] D. Malyshev, A. Neronov, and D. Eckert, “Constraints on 3.55 keV line emission from stacked observations of dwarf spheroidal galaxies,” [arXiv:1408.3531 \[astro-ph.HE\]](#).
- [35] M. E. Anderson, E. Churazov, and J. N. Bregman, “Non-Detection of X-Ray Emission From Sterile Neutrinos in Stacked Galaxy Spectra,” [arXiv:1408.4115 \[astro-ph.HE\]](#).
- [36] A. Boyarsky, J. Franse, D. Iakubovskiy, and O. Ruchayskiy, “Comment on the paper ”Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line” by T. Jeltema and S. Profumo,” [arXiv:1408.4388 \[astro-ph.CO\]](#).
- [37] J. M. Cline, Y. Farzan, Z. Liu, G. D. Moore, and W. Xue, “3.5 keV X-Rays as the “21 cm Line” of Dark Atoms, and a Link to Light Sterile Neutrinos,” *Phys. Rev. D* **89** (2014) 121302, [arXiv:1404.3729 \[hep-ph\]](#).
- [38] D. P. Finkbeiner and N. Weiner, “An X-Ray Line from eXciting Dark Matter,” [arXiv:1402.6671 \[hep-ph\]](#).
- [39] M. T. Frandsen, F. Sannino, I. M. Shoemaker, and O. Svendsen, “X-ray Lines from Dark Matter: The Good, The Bad, and The Unlikely,” *JCAP* **1405** (2014) 033, [arXiv:1403.1570 \[hep-ph\]](#).
- [40] J. M. Cline, Z. Liu, G. Moore, and W. Xue, “Scattering properties of dark atoms and molecules,” *Phys.Rev.* **D89** (2014) 043514, [arXiv:1311.6468 \[hep-ph\]](#).
- [41] M. Kaplinghat, R. E. Keeley, T. Linden, and H.-B. Yu, “Tying Dark Matter to Baryons with Self-interactions,” *Phys.Rev.Lett.* **113** (2014) 021302, [arXiv:1311.6524 \[astro-ph.CO\]](#).
- [42] L. E. Strigari, J. S. Bullock, M. Kaplinghat, J. D. Simon, M. Geha, *et al.*, “A common mass scale for satellite galaxies of the Milky Way,” *Nature* **454** (2008) 1096–1097, [arXiv:0808.3772 \[astro-ph\]](#).
- [43] S. Galli, F. Iocco, G. Bertone, and A. Melchiorri, “Updated CMB constraints on Dark Matter annihilation cross-sections,” *Phys.Rev.* **D84** (2011) 027302, [arXiv:1106.1528 \[astro-ph.CO\]](#).