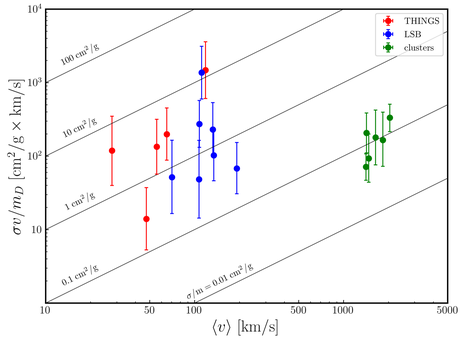
Cosmologically Consistent Self-interacting Dark Matter and Small-scale Galaxy Anomalies

Amin Aboubrahim [1] Wan-Zhe Feng [2] Pran Nath [1] Zhu-Yao Wang[1]

[1]Department of Physics, Northeastern University, Boston, MA 02115-5000, USA
[2]Center for Joint Quantum Studies and Department of Physics, School of Science, Tianjin University, Tianjin 300350, PR. China

Introduction

Data from The HI Nearby Galaxy Survey (THINGS), Low Surface Brightness (LSB) galaxies, Galaxy clusters:



Anomaly:

- Cross section is dependent on velocity
- Cold Dark Matter model is collisionless

Need a model:

- Can fit galaxy data from small scale to large scale
- Easy computation of relic density

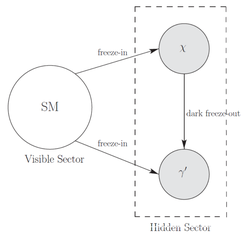
Model with a dark photon and a dark fermion

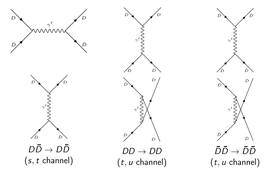
Stueckelberg $U(1)$ extension to the Standard Model:

$$\mathcal{L} \supset -\frac{1}{4}C^{\mu\nu}C_{\mu\nu} - g_X \bar{D}\gamma^\mu D C_\mu - m_D \bar{D}D - \frac{\delta}{2}C^{\mu\nu}B_{\mu\nu} - \frac{1}{2}(M_1 C_\mu + M_2 B_\mu + \partial_\mu \sigma)^2,$$

- C_μ, B_μ: gauge field of $U(1)_X$ and $U(1)_Y$
- D: Dirac fermion, only charged under $U(1)_X$
- δ: kinetic mixing parameter
- M_1, M_2: Stueckelberg masses.
- σ: axion field which gives mass to C_μ

Mass eigenstates: the photon (γ), the Z boson, and massive γ'.





Evolution of two temperature universe

In our model, only the total entropy is conserved, including both the hidden sector and the visible sector:

$$\frac{d}{dt}(sR^3) = 0 \tag{1}$$

where $s = s_h + s_v$.

$$s = \frac{2\pi^2}{45}\left(h^h_{\rm eff} T_h{}^3 + h^v_{\rm eff} T^3\right), \tag{2}$$

The Hubble parameter also depends on both T and T_h as can be seen from the Friedman equation,

$$H^2 = \frac{8\pi G_N}{3}(\rho_v(T) + \rho_h(T_h)), \tag{3}$$

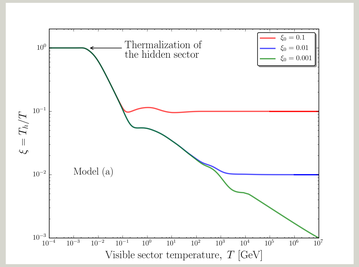
$$\frac{dn_D}{dt} + 3Hn_D = \Big[\langle\sigma v\rangle_{i\bar{i}\to D\bar{D}}(T) n_i^{\rm eq}(T)^2 - \langle\sigma v\rangle_{D\bar{D}\to\gamma'\gamma'}(T_h) n_D(T_h)^2 + \langle\sigma v\rangle_{\gamma'\gamma'\to D\bar{D}}(T_h) n_{\gamma'}(T_h)^2\Big]. \tag{4}$$

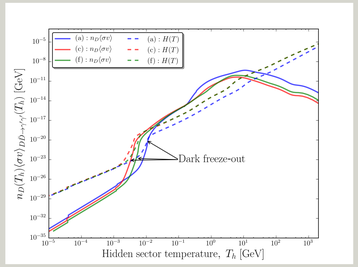
$$\frac{dn_{\gamma'}}{dt} + 3Hn_{\gamma'} = \Big[\langle\sigma v\rangle_{D\bar{D}\to\gamma'\gamma'}(T_h) n_D(T_h)^2 - \langle\sigma v\rangle_{\gamma'\gamma'\to D\bar{D}}(T_h) n_{\gamma'}(T_h)^2 + \langle\sigma v\rangle_{i\bar{i}\to\gamma'}(T) n_i^{\rm eq}(T)^2 - \langle\Gamma_{\gamma'\to i\bar{i}}(T_h)\rangle n_{\gamma'}(T_h)\Big]. \tag{5}$$

$$\frac{d\eta}{dT_h} = -\frac{\eta}{T_h} + \frac{\zeta\rho_v + \rho_h(\zeta - \zeta_h) + j_h/(4H)}{\zeta_h\rho_h - j_h/(4H)} \frac{\frac{d\rho_h}{dT_h}}{T_h\frac{d\rho_v}{dT}}, \tag{6}$$

where $T = \eta T_h$, $\zeta = \frac{3}{4}(1 + p/\rho)$. Here $\zeta = 1$ is for the radiation dominated era and $\zeta = 3/4$ for the matter dominated universe. j_h is defined by

$$\frac{d\rho_h}{dt} + 3H(\rho_h + p_h) = j_h, \tag{7}$$



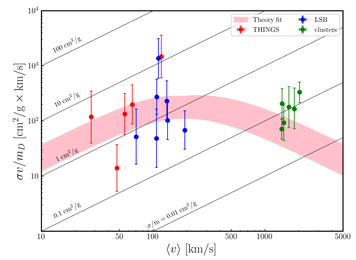


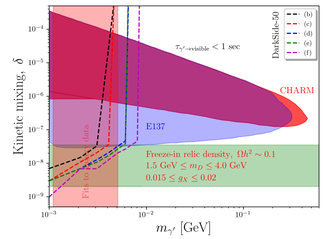
- Left side: Evolution of $\xi = T_h/T$ as a function of T for different initial conditions.
- Right side: Showing the evolution of the dark sector

Evolution history:

- D, γ' is produced via freeze-in
- D becomes abundant, $D\bar{D} \leftrightarrow \gamma'\gamma'$ becomes important
- Freeze out in dark sector. D decouples from γ'
- $i\bar{i} \to \gamma'$ remains efficient, causes increase in γ'
- γ' decays before BBN

Galaxy fit and experimental constraints





- Left side: Galaxy fit of our model constraining $m_{\gamma'} = (1-5)$ MeV, $m_D = (1-4)$ GeV
- Right side: Experimental constraints from CHARM, E137, DarkSide-50 etc.

Benchmarks

Model	m_D (GeV)	M_1 (MeV)	g_X	$\delta(10^{-9})$
(a)	1.50	1.20	0.016	28
(b)	2.0	1.22	0.014	4.0
(c)	2.16	1.13	0.015	4.7
(d)	3.2	1.77	0.018	3.8
(e)	3.26	1.99	0.018	3.5
(f)	4.0	2.20	0.020	3.6

Model	σ/m_D (cm^2/g)	Ωh^2	$\Gamma_{\gamma'\to e^+e^-}$ (GeV)	τ (ms)
(a)	2.48	0.1215	1.4×10^{-21}	0.49
(b)	1.97	0.1233	2.9×10^{-23}	22.7
(c)	3.69	0.1218	3.0×10^{-23}	21.8
(d)	1.79	0.1191	4.9×10^{-23}	13.4
(e)	1.24	0.1185	4.8×10^{-23}	13.8
(f)	1.43	0.1229	5.6×10^{-23}	11.7

Conclusion

- The SIDM model with a hidden sector dark fermion and a dark photon with mass ranges

$$m_{\gamma'} = (1-5)\ \text{MeV},\ m_D = (1-4)\ \text{GeV}$$

  fits data on σv from galaxy scales to galaxy clusters.
- All relevant constraints on $m_{\gamma'}$, m_D, δ are satisfied.
- We developed a new formalism solving Boltzmann equations with two temperatures.
- The velocity dependence of the cross sections within this model points to the existence of a dark fifth force and thus further data will help confirm the existence of such a force.

References

[1] Amin Aboubrahim, Wan-Zhe Feng, Pran Nath, and Zhu-Yao Wang. Self-interacting hidden sector dark matter, small scale galaxy structure anomalies, and a dark force. *Phys. Rev. D*, 103(7):075014, 2021.

[2] Sean Tulin and Hai-Bo Yu. Dark Matter Self-interactions and Small Scale Structure. *Phys. Rept.*, 730:1–57, 2018.