ALP-portal heavy neutrino dark matter

[2106.00547]

Shivam Gola, Sanjoy Mondal, Nita Sinha

The Institute of Mathematical Sciences, Chennai, India

Homi Bhabha National Institute, Mumbai, India

shivamg@imsc.res.in

Introduction

Motivation:

- There are several observations ranging from sub-galactic scale to large cluster of galaxies have accumulated data in support of the presence of Dark matter.
- Planck collaboration [1] has constrained the current abundance of DM in the Universe, $0.1126 \leq \Omega_{DM}h^2 \leq 0.1246$.
- A particle candidate to DM is needed which must have lifetime longer then age of Universe and have no electromagnetic interaction.

Model: The model is the minimal combination of type-I seesaw and effective ALP interaction with additional $\mathbb{Z}_2$ symmetry.

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
q_L^i	3	2	$\frac{1}{6}$	+
u_R^i	3	1	$\frac{2}{3}$	+
d_R^i	3	1	$-\frac{1}{3}$	+
ℓ_L^i	1	2	$-\frac{1}{2}$	+
e_R^i	1	1	-1	+
$N_R^{2,3}$	1	1	0	+
N_R^1	1	1	0	-
Φ	1	2	$-\frac{1}{2}$	+
a	1	1	0	+

Table 1: Minimal Particle and symmetry content of the model where $i(=1,2,3)$.

here N_R^i and 'a' are the heavy neutrinos and axion fields respectively.

The Lagrangian: The effective interaction lagrangian of the model is described by equations (1-5).

$$\mathcal{L}=\mathcal{L}_{\text{SM}}+\mathcal{L}_{\text{ALP}}+\mathcal{L}_{\text{RHN}}+\mathcal{L}_{\text{ALP-RHN}} \tag{1}$$

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}M_a^2 a^2 - \frac{C_{\tilde{G}}}{f_a} aG_{a\mu\nu}\tilde{G}^{\mu\nu a} - \frac{C_{\tilde{B}}}{f_a} aB_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{C_{\tilde{W}}}{f_a} aW_{a\mu\nu}\tilde{W}^{a\mu\nu} + iC_{a\Phi}\times\left[(\bar{Q}_L Y_U \tilde{\Phi} u_R - \bar{Q}_L Y_D \Phi d_R - \bar{L}_L Y_E \Phi e_R)\frac{a}{f_a} + h.c.\right] \tag{2}$$

$$\mathcal{L}_{\text{RHN}} = i\sum_{i=1}^{3}\bar{N}_i\gamma^\mu\partial_\mu N_i - \sum_{j=2}^{3} Y_{\alpha j}\bar{L}_\alpha\tilde{\Phi}N_j - \sum_{i,j=2}^{3} M_{ij}\bar{N}_i^c N_j - M_{N_1}\bar{N}_1^c N_1 + \text{h.c.} \tag{3}$$

$$\mathcal{L}_{\text{ALP-RHN}} = -\sum_{i=1}^{3}\frac{C_{aN_i}}{f_a}(\bar{N}_i\gamma^\mu\gamma^5 N_i)\partial_\mu a \tag{4}$$

$$\mathcal{L}_{a\gamma} = -C_{a\gamma} aF_{\mu\nu}\tilde{F}^{\mu\nu}, \text{ with } C_{a\gamma} = \frac{(C_{\tilde{B}}\cos^2\theta_W + C_{\tilde{W}}\sin^2\theta_W)}{f_a} \tag{5}$$

Constraints & Benchmark

Constraints: Constraints on sub-GeV ALP particle from several experiments are listed in the table below-

Bound on Coupling	ALP Mass Range	Observable
$\frac{C_{\tilde{G}}}{f_a} \leq 10^{-4}$ GeV^{-1}	$M_a \leq 0.1$ GeV	mono-jet8TeV@LHC
$\frac{C_{\tilde{W}}}{f_a} \sim 10^{-6} - 10^{-4}$ GeV^{-1}	$M_a \leq 500$ MeV	Beam Dump
$\frac{C_{a\Phi}}{f_a} \sim 10^{-8} - 10^{-6}$ GeV^{-1}	1 MeV $< M_a <$ 3 GeV	Rare meson decay
$\frac{C_{a\gamma}}{f_a} \leq 10^{-5}$ GeV^{-1}	$M_a \sim 1$ MeV	Beam Dump

Table 2: Summary of existing constraint on ALP couplings.

Benchmark: $C_{\tilde{B}} = C_{\tilde{W}}$, $\frac{C_{a\gamma}}{f_a} \sim \mathcal{O}(10^{-4})$ GeV^{-1}, $C_{\tilde{G}} \sim \mathcal{O}(10^{-4})$ GeV^{-1}, $\frac{C_{a\Phi}}{f_a} \sim 10^{-6}$ GeV^{-1}.

Feynman diagrams

The relevant processes responsible for the freeze-out of DM in the early universe are shown in the figure below. All together, they determine the relic abundance of our assumed DM, N_1.

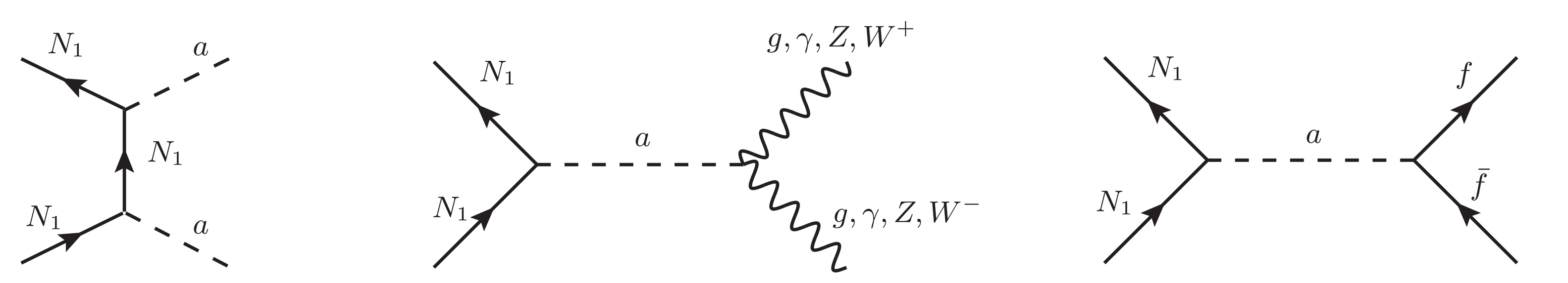

Fig. 1: Annihilation diagrams contributing to the relic abundance of N_1.

Themal average annihilation cross sections

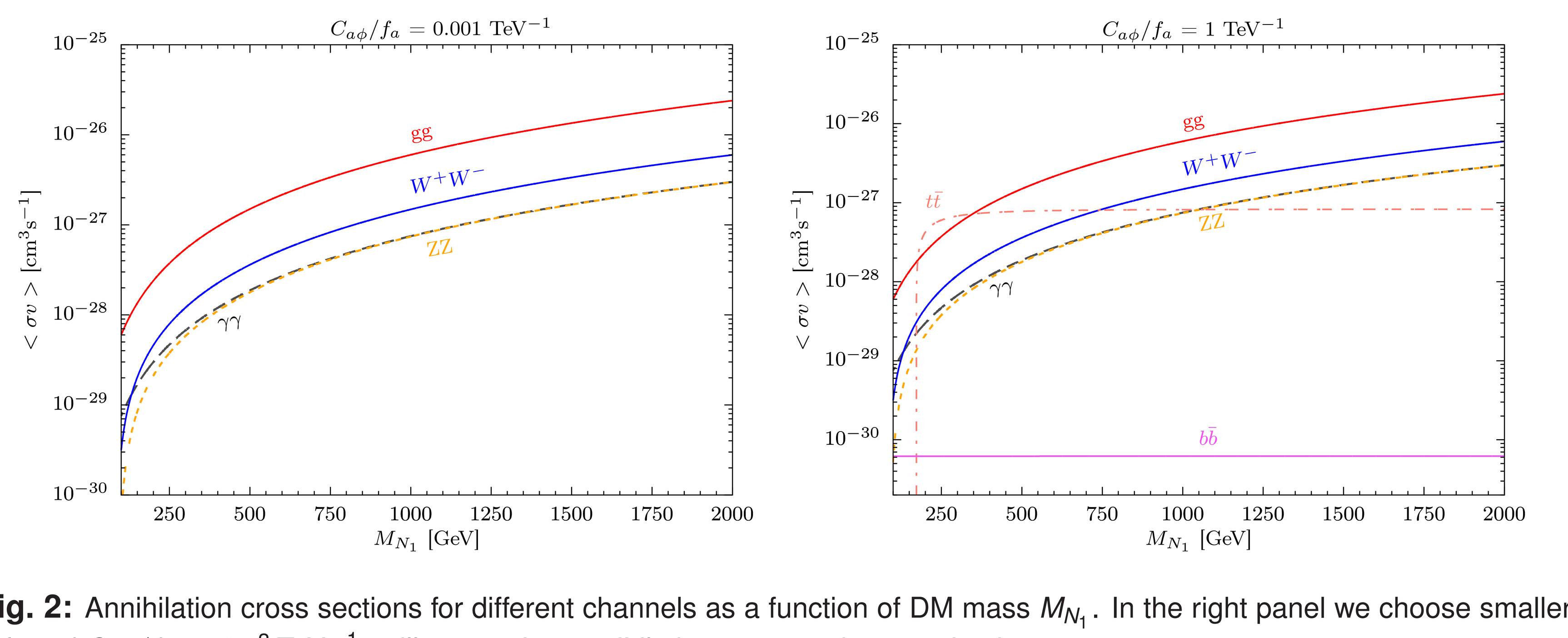

Fig. 2: Annihilation cross sections for different channels as a function of DM mass M_{N_1}. In the right panel we choose smaller value of $C_{a\Phi}/f_a = 10^{-3}$ TeV^{-1} to illustrate that annihilation to gauge bosons dominate.

Relic density analysis

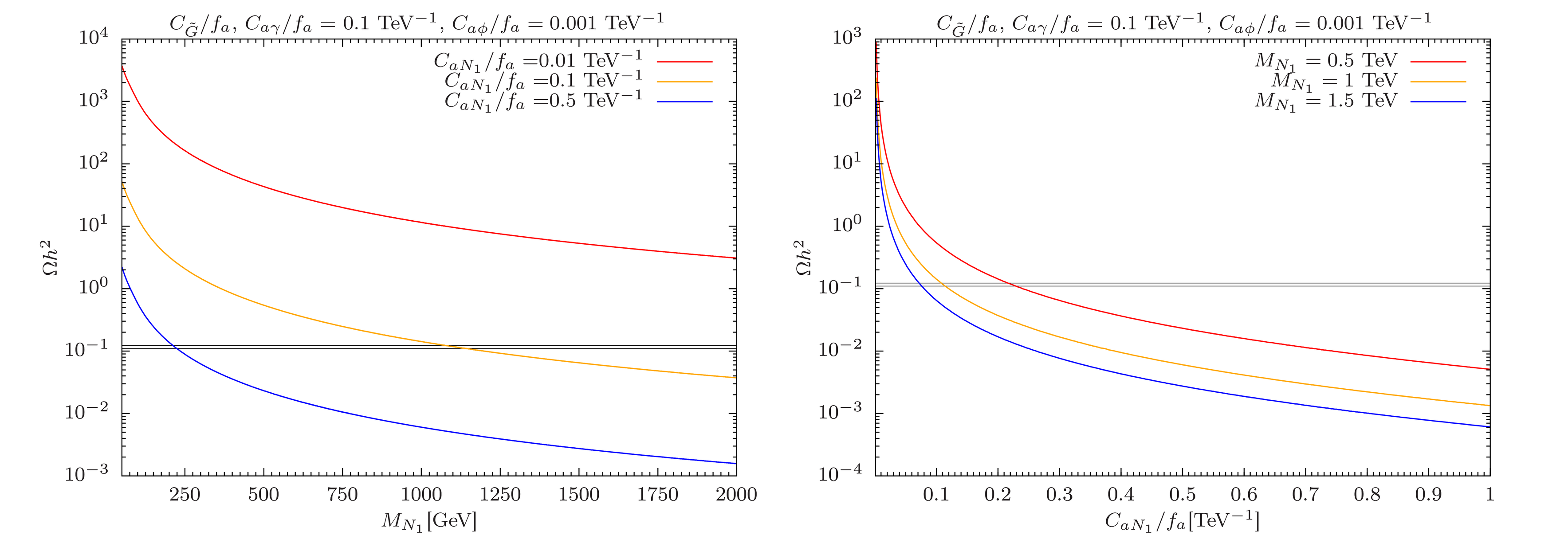

Fig. 3: The left panel shows the relic density ($\Omega_{N_1}h^2$) behavior with DM mass M_{N_1} for the chosen ALP parameters, labeled at the top. The three colored curves are due to three discrete choice of ALP-N_1 coupling. The region inside the horizontal black lines stands for the measured 3σ relic density range given by Planck satellite data. The right panel is done using same analysis but with ALP-N_1 coupling varying continuously on the horizontal axis whereas mass of N_1 has been chosen discretely.

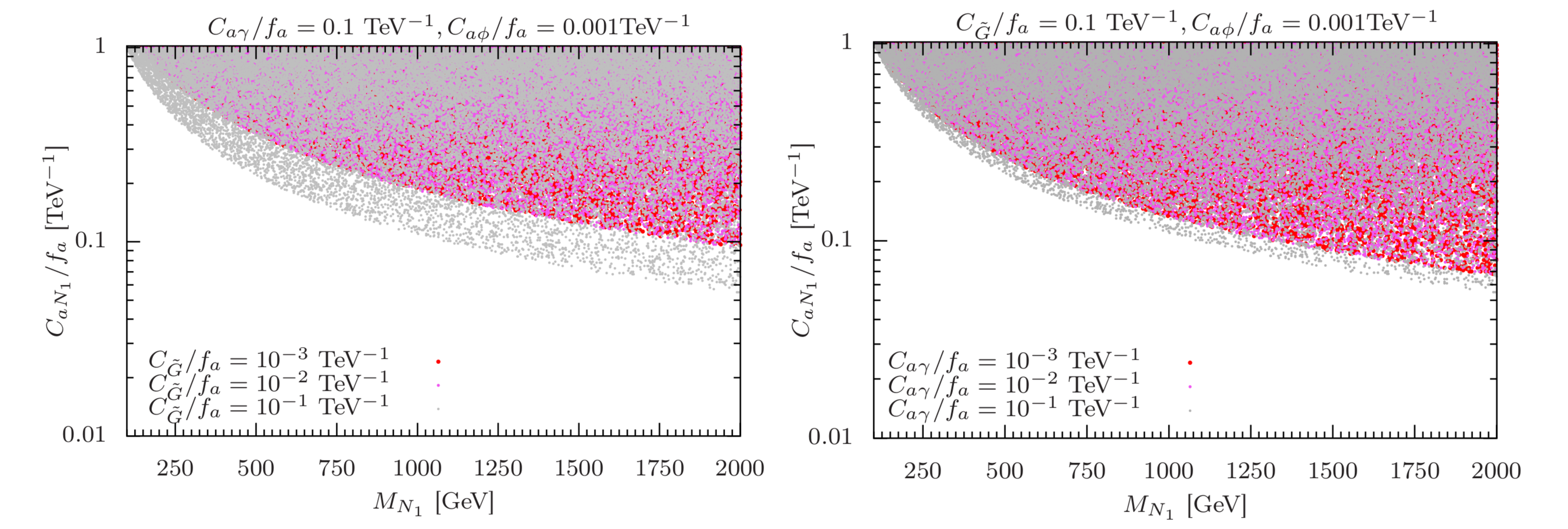

Fig. 4: The left panel describe the colored regions where the relic density bound ($\Omega_{N_1}h^2 \leq 0.12$) holds on the m_{N_1}-C_{aN_1} plane. We have chosen the three discrete values for the ALP-gluon coupling ($C_{\tilde{G}}$) labeled by the corresponding colors. In the right panel the same analysis is done but now with three discrete values for ALP-photon coupling ($C_{a\gamma}$).

Direct detection

- The XENON1T experiment [3] currently has the best sensitivity for spin-independent and spin-dependent DM-nucleon interactions in our interested GeV mass range of DM.
- The interaction between DM N_1 and a quark q can be described by the following effective Lagrangian:

$$\mathcal{L} = \frac{C_{a\Phi}C_{aN_1}}{f_a^2 M_a^2} m_q M_{N_1}\bar{q}\gamma_5 q\bar{N}_1\gamma_5 N_1. \tag{6}$$

  this is only valid when mediator ALP mass M_a is relatively large compared to momentum transferred involved in the scattering process.
- In non-relativistic limit, the differential scattering cross section to scatter of a nucleus is $d\sigma/dE_R \propto q^4$, where $q^2 = 2m_N E_R$ is the momentum transfer, m_N is the mass of nucleus and E_R is the nuclear recoil energy.
- In direct detection experiments typical recoil energy is $\mathcal{O}(10\,\text{KeV})$, hence direct detection cross section is heavily suppressed.

Indirect detection

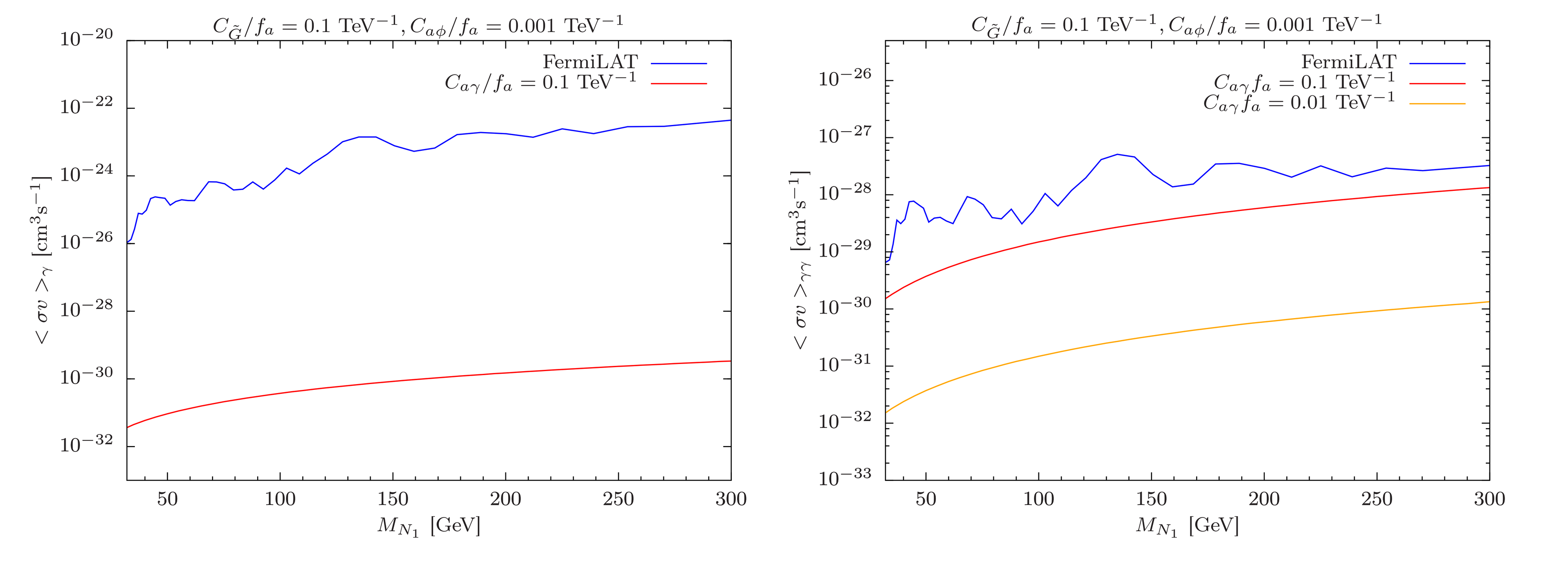

Fig. 5: The left (right) panel shows the thermally averaged annihilation cross section for single (di) photon emissions. In both panels, the blue curve represents the experimental limit obtained from FermiLAT data [5]. The red line in the left panel and red, orange lines in the right panel shows the model predictions for different choices of ALP-photon couplings $C_{a\gamma}/f_a$.

Conclusions

- We have analyzed heavy neutrino DM candidate in a minimal extension of SM, which features three RHNs and one ALP.
- The model is well motivated as it accounts for two well motivated BSM physics problems, DM and the neutrino oscillations.
- We have considered the lightest RHN as DM which is odd under $\mathbb{Z}_2$ symmetry and identified the region of parameters where DM predictions are in agreement with DM relic abundance.
- The model also quite naturally explain the null results of LUX and XENON1T due to the pseudoscalar nature of interactions with quarks.
- The current limits from Fermi-LAT lie above the predicted signals for our choice of parameter space, future sensitivities of Fermi-LAT might offer promising prospects to probe both the low as well as high DM mass regions.

References

[1] Aghanim, N. and others; Planck 2018 results. VI. Cosmological parameters [arXiv:1807.06209].

[2] Mimasu, Ken and Sanz, Verónica; ALPs at Colliders [arXiv:1409.4792].

[3] Aprile, E. and other; Dark Matter Search Results from a One Ton-Year Exposure of XENON1T [arXiv:1805.12562].

[4] Dolan, Matthew J. and Kahlhoefer, Felix and McCabe, Christopher and Schmidt-Hoberg, Kai; A taste of dark matter: Flavour constraints on pseudoscalar mediators [arXiv:1412.5174].

[5] Ackermann, M. and others; Search for Gamma-ray Spectral Lines with the Fermi Large Area Telescope and Dark Matter Implications [arXiv:1305.5597].