The 130 GeV Fingerprint of Right-handed Neutrino Dark Matter

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Recently, an interesting indication for a dark matter signal in the form of a narrow line, or maybe two lines and/or an internal bremsstrahlung feature, has been found in analyses of public data from the Fermi-LAT satellite detector. As recent analyses have also shown that there is little sign of extra contributions to continuum photons, it is natural to investigate leptophilic interacting massive particle (LIMP) models. We show that a model of radiatively generated neutrino masses may have the properties needed to explain the Fermi-LAT structure around 130 GeV. This model was proposed some 10 years ago, and predicted a clearly observable $\gamma$-ray signal in the Fermi-LAT (then GLAST) detector. Here, we update and improve that analysis, and show as an example that a right-handed neutrino of mass 135 GeV should give rise to three conspicuous effects: a broad internal bremsstrahlung bump with maximum around 120 GeV, a $2\gamma$ line around 135 GeV, and a $Z\gamma$ line at 119.6 GeV (neglected in the previous work). These features together give a good fit to the 130 GeV structure, given the present energy resolution of the Fermi-LAT data. An attractive feature of the model is that the particle physics properties are essentially fixed, once the relic density and the mass of the right-handed neutrino dark matter particle have been set. Puzzling features of the data at present are a slight displacement of the signal from the galactic center, and a needed boost factor of order $5-15$. This presents interesting challenges for numerical simulations including both baryons and dark matter on scales of 100 pc, and perhaps a need to go beyond the simplest halo models. With upcoming experiments having better energy resolution, or with future Fermi-LAT data, the double-peak structure with a definite predicted ratio of the strengths of the two lines and the internal bremsstrahlung feature should be seen, if this model is correct. With the planned satellite GAMMA-400, a striking fingerprint of this dark matter candidate should then appear.

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I. INTRODUCTION

For $\gamma$-rays coming from annihilations of dark matter particles in the halo, the Fermi-LAT instrument [1] has very successfully delivered bounds that have recently started to probe into the parameter space of viable models, in line with pre-launch expectations [2], in particular for dwarf spheroidal galaxies [3] and galaxy clusters [4].

Interestingly, there have very recently appeared analyses of public Fermi-LAT data [5] where a rather strong tentative dark matter signal has been seen, in a line-search from the halo in the vicinity of the galactic centre [6, 7]. There is a feature, which has been interpreted as either originating from internal bremsstrahlung [8, 9] around 150 GeV [6], or a $\gamma$-ray line [10] at around 130 GeV [6]. This discovery has already gained considerable attention from theorists (see, e.g., [11] and [12, 13] for recent reviews). The line signal has subsequently been independently verified by other analyses of the same public data [14, 15]. In particular, in the analysis [15] a signal of more than 5$\sigma$ was claimed, with some evidence also for a second line, with energy consistent with annihilation into $Z\gamma$, which generally also should exist in many models [16].

There have already appeared quite a number of proposed models for this feature around 130 GeV [11], although the previously much studied supersymmetric models now seem disfavoured in most of the supersymmetric scenarios, due to the non-appearance of a characteristic $\gamma$-ray continuum that should result from fragmentation of quarks, $Z$- and $W$-bosons or gluons [17]. (See, however, [13] for some interesting surviving parts of the huge supersymmetric parameter space.)

Let us now turn to another attractive model from the particle physics point of view, namely radiative see-saw models for neutrino masses (for a recent review containing many of the original references, see [18]).

Some 10 years ago, an interesting model was proposed [19], where a right-handed neutrino of mass less than about a TeV plays a crucial role in giving mass to the otherwise massless standard model neutrinos through a high-order loop mechanism. (This is a version of the Zee model [20]. See also [21, 22] for a more recent formulation of models with similar phenomenology.)

In this model, neutrino masses appear only at the three loop level, achieved by supplementing in the simplest version the Standard Model (SM) fields with two charged singlet scalars $S_1$ and $S_2$ and one right handed neutrino $N_R$. (We will here stick to this simplest model, as we expect the $\gamma$-ray features studied here depend very little on the details of more elaborate, and perhaps more realistic schemes, such as elaborated upon in [18, 21, 23].) Lepton number is broken explicitly by including a Majorana mass term for the right-handed neutrino, and imposing a discrete $Z_2$ symmetry under which the SM fields and

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The potential coupling, and a mild hierarchy of masses $M_1 < M_2 < M_3 < \cdots$ for the neutrinos. This gives the Lagrangian

$$\mathcal{L} = f_{\alpha\beta} \bar{L}_{\alpha} \gamma_5 \tau_2 L_{\beta} S^1 + g_N N_R S^2 \bar{L}_R + M_R N_R^2 C N_R + V(S_1, S_2) + \text{h.c.}. \quad (2)$$

The potential $V(S_1, S_2)$ contains in particular a $(S_1 S_2)^2$, coupling, and a mild hierarchy of masses $M_R < M_S < M_{S_2} \sim 100$ GeV - 1 TeV is assumed. Furthermore, the Yukawa couplings $f_{\alpha\beta}$ are of order unity, making $N_R$ stable in view of the discrete symmetry. Left-handed neutrino masses are first induced at three loops. For $M_{S_2}$ of the order of a TeV, one finds an effective dimension-five effective mass scale of $\Lambda > 10^5$ GeV, giving remarkably neutrino masses at the 0.1 eV scale without involving fundamental mass scales larger than a TeV.

In this leptonically interacting massive particle model (a leptoWIMP, named LIMP in the paper by Baltz and Bergström [24], BB in the following), $N_R$ becomes stable and is therefore a natural dark matter (DM) candidate. Through $S_2$ exchange it couples extremely weakly today, due to the low DM velocities in the galactic halo. The reason for this is its Majorana nature, which means that the couplings in the S-wave are proportional to the mass of charged leptons in the final state. In the early universe, on the other hand, P-annihilation was important and set the relic density $\Omega_{DM} h^2 \sim 0.11$ (the scaled Hubble constant $h \approx 0.7$). It was noted in the original proposal [12] that this would be a fine DM candidate, but thought to be essentially undetectable, as the rate of direct detection through scattering on nucleons would be very small. Similarly, indirect detection through neutrinos from the Earth or the Sun will not be possible, as the cross section for capture is negligibly small.

However, in BB [24] it was pointed out that this candidate, on the contrary, has excellent detection probability in indirect detection through the annihilation $N_R N_R \rightarrow 2\gamma$ or through the internal bremsstrahlung process $N_R N_R \rightarrow l^+ l^- \gamma$ (the last process with its surprising avoidance of helicity suppression, and the relation to the $2\gamma$ line was first discovered in [8], in the context of supersymmetric models for dark matter, with refinements over the last few years [8, 9, 26, 27]). Thus, this model has the intriguing property of connecting the dark matter problem with that of neutrinos masses. The unique window is through $\gamma$-ray detection of annihilation of the typical fingerprint of this model: an internal bremsstrahlung broad enhancement with maximum near 90 % of the $N_R$ mass, supplemented with two $\gamma$-rays lines from the $\gamma\gamma$ and $Z\gamma$ final states, where the $\gamma\gamma$ line will appear at $E_\gamma = m_R$ and the $Z\gamma$ line at $E_\gamma = m_R (1 - m_Z^2 / (4 m_R^2))$, as dictated by energy and momentum conservation. Both lines are intrinsically very narrow, meaning that in practice the energy resolution of the detector will be decisive for their detection. (Note that for Majorana particles, the annihilation in the S-wave takes place from a pseudoscalar state, and therefore no $H\gamma$ line, with $H$ the Higgs boson, is expected, as a $0 \rightarrow 0$ radiative transition is forbidden.)

In BB, $Z\gamma$ electroweak mixing and therefore the $Z\gamma$ annihilation channel was neglected (and in [8] it was not kinematically allowed). That this model has a very good chance of giving an observable structure in Fermi-LAT is in fact strengthened by a more complete analysis, which will be briefly presented here. We will find a striking agreement of the shape of the structure with the (admittedly still scarce) Fermi-LAT data analyzed in [7] [8]. A very interesting aspect, which contrasts with supersymmetric DM, is the essential lack of freedom of choice of parameters and therefore the predictive power of the model.

The cross determining the relic $N_R$ density can be written

$$\sigma v \approx 6 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}.$$

For a given $N_R$ of mass $m_R$, this sets the normalization of the combination $\sum_i g_i^4 (1 + f_i^4) / (m_i^2 (1 + f_i^4)^2)$ which governs many annihilation processes. The total annihilation rate into lepton lines $\ell^+ \ell^-$ at rest (putting $v = 0$ in Eq. (3)) is for each flavour (assuming flavour universal couplings)

$$\sigma v_{\ell^+ \ell^-} \approx 10^{-25} \left( \frac{m^2_\ell}{m_R^2} \right) \text{ cm}^3 \text{ s}^{-1}.$$

It was noted [13, 24] that in order that the couplings $g_\ell$ not be larger than 1, for nearly degenerate $N_R$ and
$S_2, m_R$ cannot be too much heavier than 1 TeV, but could be significantly lighter. We now thus insert the value found in \[7\] of around 130 GeV for $m_R$. Actually with $m_R = 135$ GeV we find a slightly better fit, and we will use that value in the following.\(^2\) Assuming near degeneracy, but choosing for simplicity $f = 1.1$, to avoid complications of possible coannihilations (this could of course be relaxed in a more refined treatment), we find a value of $g \sim 0.52$, where we for simplicity assume flavor universality, i.e., $g_e = g_\mu = g_\tau = g$ (see [21] for a more realistic ansatz in a more elaborate model). LIMPs with these values of the parameters have a very small annihilation rate for the $e^+e^-$ and $\mu^+\mu^-$ channels. Even for $\tau^+\tau^-$, the helicity suppression is of the order of $10^{-4}$. At that level, the $P$-wave term in the galactic halo also may contribute a small amount. We neglect that here, but include continuum $\gamma$-rays from decays of directly produced $\tau$ leptons in our Figures. They turn out to be not very important, however. Also, there is a contribution to $\gamma$-rays from $Z$ decays produced in the similar ‘gaugestrahlung’ process with the final state $\ell^+\ell^-Z$ which also is surprisingly large [26, 27]. (There is no corresponding $W$-strahlung for these singlet fields.) This contribution from $Z$ decays is also included in the numerical estimates, but also turn out to be inessential.

In fact, predictions for a 100 GeV LIMP were made in BB (see Fig. 2 (a) in [24]), and shown to be possibly quite spectacular. (This is in contrast with the predictions for positrons from the same process which need a “boost factor” of more than several thousand to match the anomalous positron ratio of which there were indications already at that time [24].) Thus there is a reason for scrutinizing present Fermi-LAT data to see whether the 135 GeV LIMP fits the spectral feature recently discovered.\(^3\) Indeed, we will find that this model, especially when augmented with the $Z\gamma$ line (which was left out in BB) and having both that line, the $2\gamma$ line and the internal bremsstrahlung contribution fits the Fermi-LAT feature surprisingly well. We will compare with the original analysis in [7] and choose for convenience the Einasto profile Reg. 3 “SOURCE” events in the parlance of that reference.\(^4\)

We note that we are not making a “best fit” analysis as this is not very meaningful given the presently rather scarce data. The point is that with more and better data in the future, the $\gamma$-ray “fingerprint” of this model should present itself, if this model for the dark matter is correct.

To make sure that continuum $\gamma$s are not overproduced in $Z$ decays from the $Z\gamma$ final state, we include this contribution using the freely available DARKSUSY code [28], but also this flux is quite small. In recent versions of the DARKSUSY code all three processes: internal bremsstrahlung, $2\gamma$ and $Z\gamma$ are included and well documented in the original literature [18, 29, 30, 31] and [32], respectively, so here we only show and discuss the results. We note that all three processes have to exist in this type of model, and have to be included for consistency.\(^5\)

Normalizing to the correct relic density, the internal bremsstrahlung contributes around $6.7 \times 10^{-29}$ cm$^3$s$^{-1}$ to the annihilation of these slow LIMPs in the halo. The bulk forms a broad bump around $E_\gamma \sim 0.9 m_R$ (see Fig. 1). The $2\gamma$ line gives $2.3 \times 10^{-29}$ cm$^3$s$^{-1}$ (including a factor 2 for the two photons), and the $Z\gamma$ line has a $(\sigma v)_{\nu\nu}$ of $1.0 \times 10^{-29}$ cm$^3$s$^{-1}$. The combined rate in the galactic halo is thus

$$\left( \sigma v \right)_{\nu\nu}^{\text{tot}} = 1.0 \times 10^{-28} \text{ cm}^3\text{s}^{-1}, \quad (6)$$

a value not too far from the estimate of the experimentally observed effect in [7] of $(12.7 \pm 5.7^{+3.2}_{-2.8}) \times 10^{-28}$ cm$^3$s$^{-1}$ (for the favoured Einasto profile). In [7], this was interpreted only in terms of one $\gamma$ line, but the limited energy resolution of the Fermi-LAT instrument, around 10 % FWHM [34], is only barely enough to resolve the structure into its separate components (see Fig. 1). Note, however, that [15] favour, although not very strongly, a two-line structure, especially when selecting data in the detector from directions where the photons pass more matter in the calorimeter and the energy resolution is therefore improved by a factor around two [15]. We will soon return to our prediction for an instrument with this better energy resolution.

In Fig. 1 is shown the total $\gamma$-ray differential flux and the respective contributing process. The results are given for the particle physics factor $d(N_{\gamma}\sigma v)/dE_{\gamma}$ for slow annihilations such as in the galactic halo, i.e., in units of cm$^3$s$^{-1}$GeV$^{-1}$, and are very robust around this mass range, as the normalization is set by the relic density constraint.

In Fig. 2 a comparison with of these results is made with the Fermi-LAT data as analyzed by Weniger [7], multiplied by $E_\gamma^2$, and at arbitrary normalization constant (of order 10) to match the overall size of the ef-

\(^2\) One should be aware that there is an up to a few GeV uncertainty of the exact value, depending on the present low statistics and also factors like the calibration of the Fermi-LAT instrument. The relative location of the three $\gamma$-ray features is however fixed once the mass is set.

\(^3\) This feature often is referred to as the “130 GeV line”. However, as we will see, in the present model it is a rather complicated composite structure, which is why we prefer to call it the “130 GeV fingerprint”, for $m_R = 135$ GeV consists of a 135 GeV $\gamma\gamma$ line, a 119.6 GeV $Z\gamma$ line and an internal bremsstrahlung continuum, from $\ell^+\ell^-\gamma$.

\(^4\) This is the preferred density profile, see Fig. 3 in a remarkable recent analysis [13] – actually, the first to use this tentative signal to constrain details of the halo distribution.

\(^5\) It would be important if a new independent calculation of the loop-induced $Z\gamma$ rate could be made, as the results of the two existing calculations [30, 31] agree well in models where intermediate $W$ bosons dominate, but in the “bino-like” case of relevance here, there seem to be some discrepancies [33].
FIG. 1: The differential photon spectrum for the process $N_R N_R \rightarrow e^{+} e^{-} \gamma \gamma$ and $Z \gamma$, smeared with the present Fermi-LAT energy resolution, $\Delta E/E \sim 0.1$. The total spectrum is given by the black solid line, the internal bremsstrahlung by the dashed red line, the smeared $\gamma\gamma$ line by the green dash-dotted line and the smeared $Z \gamma$ line by the blue double-dash-dotted line. At the lower left corner the small contributions from the $\tau^+ \tau^-$ final state as well as that from $Z$ decays can be seen.

The dashed red line, the smeared $\gamma\gamma$ given by the black solid line, the internal bremsstrahlung by $E/E$LAT energy resolution, $\Delta E/E$.

flect. The reason for this “boost factor” is presently unknown, but in this model it has to be explained by astrophysical effects, such as the detailed distribution of dark matter near the galactic centre. (So-called Sommerfeld enhancement is not expected in this model. There may in principle be fine-tuned mechanisms like S-wave pseudoscalar resonances or particles with higher electric charge running the loop, but we do not employ such exotica here.) The required boost may be related to another puzzle of the signal, which is a displacement from the exact galactic centre by around 200 pc.\footnote{In fact, a preprint recently appeared\cite{36} where such a displacement is shown not to be unnatural in simulations of the combined baryon and dark matter system. It remains to be seen whether the larger than expected density near the emission region can also be explained by similar effects. The off-set could perhaps also be explained by the low statistics of the tentative signal\cite{37}.}

As can be seen, once the overall strength has been set, the agreement with present data is (perhaps fortuitously) intriguing. For the rather low average energy resolution (10% FWHM) of Fermi-LAT, the double-peak structure is much clearer. This is quite interesting. It was shown in\cite{8} how these features are crucial for reproducing the effective axial anomaly in these theories (which lack anomalies at the fundamental level). In fact, the strength of the $\gamma\gamma$ line can almost trivially be computed by using the anomaly result ($|F| = 1$ in\cite{8}). Also, compact formulas for the internal bremsstrahlung contribution can be found there (recently checked independently\cite{27}). The validity of these formulas is more general than for the specific $N_R$ case discussed here. The strength of the $Z \gamma$ line is trickier to compute due to the non-zero $m_Z$, but we can use DarkSUSY (based on the continuous background has been made, and is also shown.

In Fig 3 is also shown what one may expect from the next generation of $\gamma$-ray space detectors with energy resolution at the one percent level, such as GAMMA-400\cite{39} and DAMPE (see\cite{40} and references therein). Given that the type of model described here is the correct explanation of dark matter, the features of the signal would be striking. With such an instrument one could start analyzing the dark matter halo density distribution in some detail. In fact, the property of the fingerprint of this model is, besides the two strong lines, the rather broad and slightly asymmetric bremsstrahlung bump. The absence of this bump would rule out the model.

The theoretical reason for the necessity of the internal bremsstrahlung bump and its relation to the line signal is quite interesting. It was shown in\cite{8} how these features are crucial for reproducing the effective axial anomaly in these theories (which lack anomalies at the fundamental level). In fact, the strength of the $\gamma\gamma$ line can almost trivially be computed by using the anomaly result ($|F| = 1$ in\cite{8}). Also, compact formulas for the internal bremsstrahlung contribution can be found there (recently checked independently\cite{27}). The validity of these formulas is more general than for the specific $N_R$ case discussed here. The strength of the $Z \gamma$ line is trickier to compute due to the non-zero $m_Z$, but we can use DarkSUSY (based observational search strategy so as to favour these side-ways entering events. If this can be done technically, this interesting proposal could mean that Fermi-LAT may establish the existence of this dark matter fingerprint with high confidence over the next couple of years.

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on [32] for its calculation.

**FIG. 3:** The $\gamma$-ray differential energy results (multiplied by $E^2$) for a 135 GeV right-handed neutrino dark matter candidate are shown, with the present Fermi-LAT energy resolution $\Delta E/E = 10\%$ FWHM (solid black line), with a factor of 2 improvement (red dashed line) and with a future $\gamma$-ray instrument, such as GAMMA-400 [39] (dash-dotted blue line) with resolution at the one percent level. The extrapolated power-law $\sim E^{-2.6}$ of the presently measured continuous $\gamma$-ray background is also shown.

Of course, one should also be aware of the possibility that the feature in the Fermi-LAT may be spurious. Although it seems unlikely that it is caused by a statistical fluctuation, one cannot yet exclude that its origin is in some (unknown) instrumental effect. Hence one should wait for the results of the analysis of the Fermi-LAT collaboration itself before taking our comparison with data too seriously.

It will also be interesting to see if data can be independently reproduced by the HESS-II instrument which just has seen first light (see [41], where also the potential of CTA [38] and an instrument like GAMMA-400 [39] is analyzed). Also, it remains to be seen if the recent rather statistically shaky indications of a signal from galaxy clusters [42] will survive more data. This will most immediately come from the Fermi-LAT instrument, which will continue to collect an amazing amount of impressively clean and interesting data over the next few years.

The type of model discussed here has been rather extensively studied in the neutrino and particle physics communities in recent years, thanks to their ability to explain the observed neutrino masses without invoking a super-high mass scale. If couplings are not flavour diagonal, dangerous non-observed decays like $\mu \to e\gamma$ may occur. However, this can be rather easily avoided, without affecting appreciably the results presented here, by invoking discrete symmetries, as explained in [18]. In that reference, it is also pointed out that, remarkably, in the case of having $m_R$ and $m_S$ of the order of 100 GeV and $g \sim 0.5$, i.e., precisely the range of values that are forced upon us if we want to explain the Fermi-LAT structure, also the enigmatic discrepancy of the measured $(g-2)_\mu$ value [33] with the theoretical prediction [44] has a chance to be explained. (See, however, [8] for a problem in a related generic model.) This is an interesting topic for further studies.

Of course, even if the present indications from the public Fermi-LAT would disappear, this model still gives an interesting signal to search for using present and new $\gamma$-ray detectors. The signal would naturally appear between 100 GeV and a TeV (perhaps, then, with its canonically predicted rate, a factor of 10 lower than that indicated in [6,7]). This energy region will be closely watched in the near future [41].

One should note that there are interesting very recent indications that the dark matter density, at least locally, may be a factor of around 3 higher than the generally adopted value [45]. It would be interesting to analyze the predicted rates in such models with either a dark disk and/or an oblate dark matter halo. This could in principle explain the boost of order 10 needed to fit the $N_R$ dark matter model to the Fermi-LAT data as analyzed by Weniger [7].

Finally, a note on other ways to test the hypothesis of LIMP dark matter. Unfortunately, the scattering cross section on nuclei will be very small. This was recently shown [46] for an effective description of the $2\gamma$ vertex. Also the radiative scattering process with one photon exchange responsible for scattering on nuclei has a depressingly low rate (see [47] for a detailed explanation of the reason for this suppression).

The low scattering rate also means a very low capture rate, which hurts detection by neutrinos from the Sun or Earth.

Whether there will be traces of this new sector, only interacting leptonically with standard model particles, at the LHC remains to be seen. In principle, there could be mediators that for instance also would explain the somewhat too high 2$\gamma$ decay rate of the Higgs boson candidate indicated by recent LHC data [48]. It would then, similarly to in our case, be important to detect and measure the rate of $H \to Z\gamma$ ([49] [51]), which in the standard model is closely related to $H \to 2\gamma$.

Another possibility for a future linear $e^+e^-$ collider may be contemplated. The $S_1$ and $S_2$ states have unit electric charge and would appear as (rather slowly rising) enhancements in the total $e^+e^-$ cross section, both starting around 150 GeV energy per beam.

There is actually another, challenging, idea to directly probe the dark matter nature of the right handed neutrino. The idea is to excite with a strong electron beam ambient $N_R$ LIMPs to the nearly degenerate $S_2$, which would then immediately decay isotropically back to an electron and $N_R$. This was first suggested and computed in the supersymmetric scenario in [47], and recently re-
discovered. It seems that substantial experimental development would be needed, however. It would also be interesting to work out the possible γ-ray signals that could appear from very powerful electron jets emanating from centres of active galaxies, along the ideas of Ref. [53], for a 135 GeV $N_R$.

Multiwavelength studies of the region around the galactic centre, in particular radio data, could be important for these models with positron and electron emission (see, e.g., [54]). It seems, judging from a recent detailed study, however, that for the Einasto profile current limits are not constraining [55], but maybe with future experiments this could give an important cross-check.

To conclude, for indirect detection of dark matter, the excellent Fermi-LAT data – made public to the scientific community with many excellent analysis tools – has opened a very exciting opportunity for studies of detailed predictions from models such as the one discussed here. Within a few years, the aquired data (and here the verdict of the Fermi-LAT collaboration itself will be important) could make us accept the model with confidence – or disprove it. These are interesting times for dark matter studies, indeed.

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[1] W. B. Atwood et al. [LAT Collaboration], Astrophys. J. 697 (2009) 1071 [arXiv:0902.1089 [astro-ph.IM]].
[2] E. A. Baltz, B. Berenji, G. Bertone, L. Bergström, E. Bloom, T. Bringmann, J. Chiang, J. Cohen-Tanugi et al., JCAP 0807 (2008) 013. [arXiv:0806.2911 [astro-ph]].
[3] M. Ackermann et al. [Fermi-LAT Collaboration], Phys. Rev. Lett. 107 (2011) 241302 [arXiv:1108.3546 [astro-ph.HE]].
[4] M. Ackermann et al., JCAP 1005, 025 (2010) [arXiv:1002.2239 [astro-ph.CO]].
[5] Data downloaded from Fermi-LAT data server, http://fermi.gsfc.nasa.gov/ssc/data/access/lat/. For a description of the Fermi-LAT instrument, see [1].
[6] T. Bringmann, X. Huang, A. Ibarra, S. Vogl and C. Weniger, arXiv:1203.1312 [hep-ph].
[7] C. Weniger, JCAP 1208 (2012) 007 [arXiv:1204.2797 [hep-ph]].
[8] L. Bergström, Phys. Lett. B225 (1989) 372.
[9] R. Flores, K. A. Olive and S. Rudaz, Phys. Lett. B 232 (1989) 377. L. Bergström, T. Bringmann and J. Edsjö, Phys. Rev. D 78 (2008) 103520 [arXiv:0808.3725 [astro-ph]]; T. Bringmann, L. Bergström and J. Edsjö, JHEP 0801 (2008) 049 [arXiv:0710.3169 [hep-ph]]; V. Barger, W.-Y. Keung and D. Marfatia, Phys. Lett. B 707 (2012) 385 [arXiv:1111.4523 [hep-ph]].
[10] L. Bergström and H. Snellman, Phys. Rev. D 37 (1988) 3737; L. Bergström, P. Ullio and J. H. Buckley, Astropart. Phys. 9, 137 (1998) [arXiv:astro-ph/9712318].
[11] E. Dudas, Y. Mambrini, S. Pokorski and A. Romagnoni, arXiv:1205.1520 [hep-ph]; J. M. Cline, arXiv:1205.2688 [hep-ph]; K.-Y. Choi and O. Seto, arXiv:1205.3276 [hep-ph]; B. Kyae and J. -C. Park, arXiv:1205.4151 [hep-ph]; H. M. Lee, M. Park and W. -I. Park, arXiv:1205.4675 [hep-ph]; B. S. Acharya, G. Kane, P. Kumar, R. Lu and B. Zheng, arXiv:1205.5789 [hep-ph]; M. R. Buckley and D. Hooper, arXiv:1205.6811 [hep-ph]; X. Chu, T. Hambye, T. Scarna and M. H. G. Tytgat, arXiv:1206.2279 [hep-ph]; D. Das, U. Ellwanger and P. Mitropoulos, arXiv:1206.2639 [hep-ph]; N. Weiner and I. Yavin, arXiv:1206.2910 [hep-ph]; J. H. Heo and C. S. Kim, arXiv:1207.1341 [astro-ph.HE]; I. Oda, arXiv:1207.1537 [hep-ph]; K. Cheung, Y. -L. S. Tsai, P. -Y. Teng, T. -C. Yuan and A. Zee, arXiv:1207.4930 [hep-ph]; J. -C. Park and S. C. Park, arXiv:1207.4981 [hep-ph]; S. Tulin, H. -B. Yu and K. M. Zurek, arXiv:1208.0099 [hep-ph]; T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1208.1999 [hep-ph]; J. M. Cline, A. R. Frey and G. D. Moore, arXiv:1208.2685 [hep-ph]; Y. Bai and J. Shelton, arXiv:1208.4100 [hep-ph].
[12] L. Bergström, arXiv:1205.4882 [astro-ph.HE], Annalen der Physik, in press (2012).
[13] T. Bringmann and C. Weniger, arXiv:1208.5481 to appear in Physics of the Dark Universe, vol. 1 (2012).
[14] E. Tempel, A. Hektor and M. Raidal, arXiv:1205.1045 [hep-ph].
[15] M. Su and D. P. Finkbeiner, arXiv:1206.1616 [astro-ph.HE].
[16] L. Bergström and J. Kaplan, Astropart. Phys. 2 (1994) 261 [hep-ph/9403239].
[17] T. Cohen, M. Lisanti, T. R. Slatyer and J. G. Wacker, arXiv:1207.0800 [hep-ph]; W. Buchmuller and M. Garny, arXiv:1206.7056 [hep-ph]; I. Cholis, M. Tavakoli and P. Ullio, arXiv:1207.1468 [hep-ph]; X. -Y. Huang, Q. Yuan, P. -F. Yin, X. -J. Bi and X. -L. Chen, arXiv:1208.0267 [astro-ph.HE].
[18] Y. Farzan, S. Pascoli and M. A. Schmidt, arXiv:1208.2732 [hep-ph].
[19] L. Krauss, S. Nasri and M. Trodden, Phys. Rev. D 67 (2003) 085002 [hep-ph/0210389].
[20] A. Zee, Phys. Lett. B 93 (1980) 389 [Erratum-ibid. B 95 (1980) 461].
[21] K. Cheung and O. Seto, Phys. Rev. D 69 (2004) 113009 [hep-ph/0403003].
[22] Q. -H. Cao, E. Ma and G. Shaughnessy, Phys. Lett. B 673 (2009) 152 [arXiv:0901.1334 [hep-ph]].
[23] M. -C. Chen and J. Huang, Mod. Phys. Lett. A 26 (2011) 1147 [arXiv:1105.3188 [hep-ph]].
[24] E. A. Baltz and L. Bergström, Phys. Rev. D 67 (2003) 043516.
